THE UNIVERSITY
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Exploration of Novel Carbon(II) and Carbon(0) Catalyst Systems for Organic Synthesis

Thesis Submitted in Accordance with the Requirement of The University of Edinburgh for the Degree of Doctor of Philosophy

By

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DECLARATION

I, Xun Lu, hereby declare that, except where specific reference is made to other resources, the work presented in this thesis is the original work of my own research since the start of my PhD degree in September 2012. This thesis has been composed by myself and has not been submitted, in whole or part, for any other degree, diploma or other qualification.

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Finally I would like to thank my parents for your continued support in these years.

LIST OF ABBREVIATIONS

μL	microlitre
aq	aqueous
Ar	aryl
BAC	bis(dialkylamino)cyclopropenylidene
BBN	9-borabicyclo[3.3.1]nonane
BINAP	2,2'-*bis*(diphenylphosphino)-1,1'-binaphthalene
BINOL	(±)-1,1'-Binaphthalene-2,2'-diol
TBME	*tert*-butyl methyl ether
bn	benzyl
Boc	*t*-butyloxycarbonyl
br	broad
BTF	Benzotrifluoride or α,α,α–trifluorotoluene
bu	butyl
CAAC	Cyclic alkyl amino carbene
cat.	catalyst
CDC	carbodicarbene
COT	cyclooctatetraene
Cy	cyclohexyl
d	doublet
DABCO	1,4-diazabicyclo[2.2.2]octane
DBU	1,8-diazabicyclo[5.4.0]undec-7-ene
DBE	dibenzyl ether
DCE	1,2-dichloroethane
DCM	dichloromethane
DEAD	diethyl azaodicarboxylate
DIAD	diisopropyl azaodicarboxylate

DMAP	4-(dimethylamino)pyridine
DME	1,2-dimethoxyethane
DMF	*N*,*N*-dimethylformamide
ee	enantiomeric excess
equiv	equivalent
Et	ethyl
ESI	electrospray ionisation
EWG	electron-withdrawing group
EDG	electron-donating group
g	gram
h	hour(s)
hex	hexyl
HMDS	hexamethyldisilazane
HPLC	high performance liquid chromatography
HQD	3-hydroxy-2-methyl-1H-quiolin-4-one
^{i}Pr	isopropyl
IR	infrared
LDA	lithium diisopropylamide
LTMP	lithium tetramethylpiperidide
m	Multiplet
MBH	Morita–Baylis–Hillman
Me	methyl
mg	milligram
MHz	megahertz
min	minute(s)
mL	milliliter
MS	molecular sieves
MVK	methyl vinyl ketone

m/z	mass to charge ratio
Nasyl	naphthalenesulfonyl
NBS	*N*-bromosuccinimide
NCS	*N*-chlorosuccinimide
NHC	*N*-heterocyclic carbene
NIS	*N*-iodosuccinimide
NMR	nuclear magnetic resonance
Ns	4-nitrobenzenesulfonyl
NR	no reaction
Nu	nucleophilic
Ph	phenyl
pin	pinacolyl
PMP	paramethoxyphenyl
ppm	parts per million
pTLC	preparative thin-layer chromatography
py	pyridine
q	quartet
rt	room temperature
s	singlet
TCE	tetrachloroethane
THF	tetrahydrofuran
TLC	thin-layer chromatography
TMS	trimethylsilyl
TMG	1,1,3,3,-tetramethylguanidine
TON	turn-over number
t	tertiary
Ts	4-toluenesulfonyl
UV	ultraviolet spectroscopy

ABSTRACT

This PhD thesis is focused on the development of novel carbon(II) and carbon(0) catalysis for organic synthesis. More specifically, the major objective has been to explore and design non-toxic and effective catalysts based on: an unusual Bertrand carbene type, a so-called bis(dialkylamino)cyclopropenylidene (BAC), and the carbodicarbene (CDC) framework; the central carbon atom in these molecules is in the formal low-oxidation state '+II' and '0', respectively. These species may be used in base catalysis or as ligands in metal catalysis, and in the context of frustrated Lewis pair (FLP) or dual catalysis. Prior to catalysis studies, the Lewis basicity of such carbon-based compounds has been assessed with ^{11}B NMR analysis using various boron-based Lewis acids. Boron binding has been detected in all cases with a BAC, thereby confirming its strongly nucleophilic character and decreased steric demand. In contrast, only few ate complexes have been identified with CDCs (or precursors thereof), which means that CDCs may be more suitable for FLP catalysis. A preliminary electrophile binding study with a BAC has provided interesting data, based on which unprecedented aldimine *Umpolung* may be developed in the future. In the context of organocatalysis, BAC-mediated C–C bond formations between various Michael acceptors and *N*-tosyl imines have been developed (aza-Morita–Baylis–Hillman chemistry). In addition, C–N or C–Hal bond formations between various Michael acceptors and azodicarboxylates or electrophilic halogen reagents have been developed. The characteristic features of these unprecedented BAC catalyses include low catalyst loading, mild reaction conditions, and broad substrate scopes. Importantly, several novel chiral BACs have been synthesized and characterized, and excellent results have been achieved in BAC-catalysed asymmetric aza-MBH reactions (ee up to 97%). To the best of our knowledge, these data represent the first highly enantioselective BAC catalysis; chiral N-heterocyclic carbenes (NHCs) have proved to be substantially less effective in this context (ee up to 38%). In the same line, BAC-catalysed asymmetric borylations and silylations of Michael acceptors have been developed (preliminary ee up to 69%). These results demonstrate the high potential of the newly developed chiral BACs in asymmetric organocatalysis. Meanwhile, several BAC–gallium and BAC–iron complexes have been synthesized and characterized. These novel complexes may be used in Lewis acid catalysis after appropriate activation of the corresponding metal sites. Finally, the exploration of the catalysis potential of various C(0) compounds, namely CDCs, is still under investigation.

Contents

1 ORGANOCATALYSIS WITH AN UNUSUAL CARBENE

1.1 Introduction

1.1.1 General Introduction to Carbene Chemistry

A carbene is a divalent, neutral carbon species with the central carbon atom bearing six valence electrons. Generally, carbenes may exist in two states: the singlet and the triplet state (Figure 1.1).[1] Singlet carbenes have a vacant p orbital and a lone pair in a non-bonding sp^2 orbital. In contrast, triplet carbenes have two unpaired electrons, one in a p orbital and another one in an sp^2 orbital.[1] The population of a specific carbene type is influenced by the substituents L bound to the carbon atom: π donation from an adjacent electron-rich heteroatom into the vacant p orbital favors the singlet state, whereas the associated decreased electron–electron repulsion favors the triplet state.

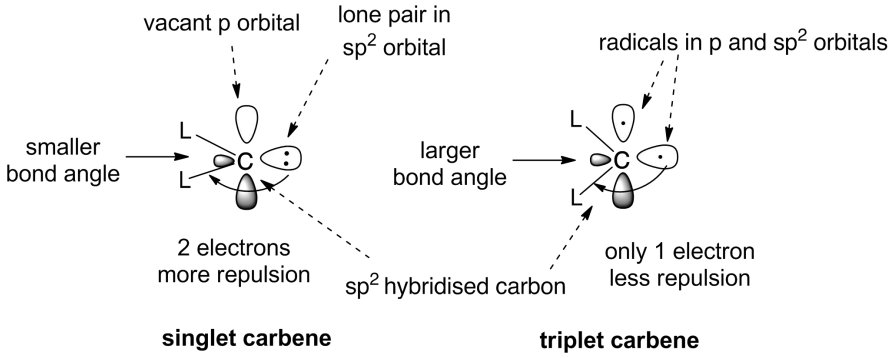


Figure 1.1 Schematic representation of singlet and triplet carbenes[1]

An electronic stabilization of carbenes is required. Singlet carbenes are stabilized through a so-called 'push–pull' effect: π donation of lone pair electron density from an adjacent heteroatom into the vacant p orbital of the carbon atom, and σ withdrawal by an adjacent electronegative heteroatom along an sp^2 hybridized orbital axis (Figure 1.2).[1] The π donation effect dominates over the σ withdrawal effect. Meanwhile, a steric stabilization of carbenes is optional.[1] Sterically demanding substituents on the adjacent nitrogen atom(s) provide kinetic stabilization of carbenes, which means the access to the carbene center is rendered more difficult.

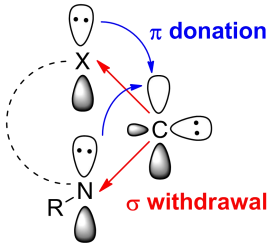
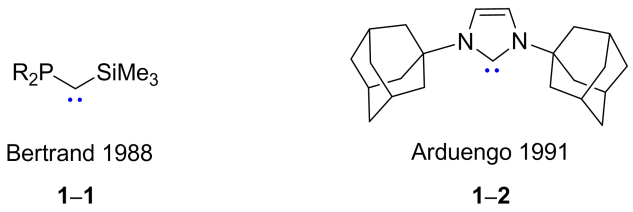


Figure 1.2 Schematic representation of 'push–pull' effect[1]

Since the first isolation of a singlet carbene, phosphinosilyl carbene **1–1**, by Bertrand *et al.* in 1988 (Figure 1.3),[2] a variety of carbenes have been investigated.[3] Among these, *N*-heterocyclic carbenes

(NHCs) have proved to be the most popular species. The adjacent heteroatoms serve to stabilize the carbon center through the described 'push–pull' effect. Thus, NHCs are neutral electron-rich species, and thus considered as strong σ donors with easily tunable electronic and steric properties making them good nucleophilic organocatalysts,[4] and ligands in metal catalysis.[5] After the first isolation of NHC **1–2** by Arduengo *et al.* in 1991 (Figure 1.3),[6] remarkable catalytic transformations have been triggered by NHCs in recent years.

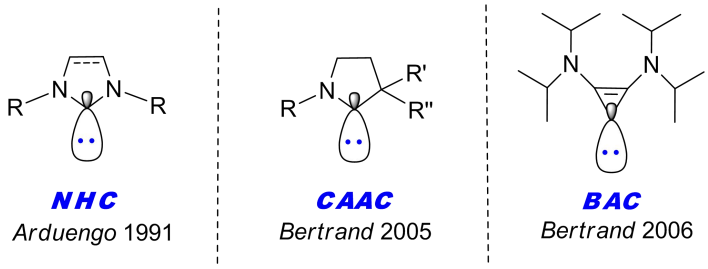


Bertrand 1988 **1–1** Arduengo 1991 **1–2**

Figure 1.3 The first isolated singlet and *N*-heterocyclic carbenes

1.1.2 Introduction to CAAC and BAC Chemistry

In addition to 'classic' NHCs, a few other types of more recently reported carbenes such as cyclic (alkyl)(amino)carbenes (CAACs)[7] and bis(dialkylamino)cyclopropenylidenes (BACs)[8] have been investigated (Figure 1.4). Both species do not show the usual N–C–N motif present in NHCs. In the case of a CAAC, a quaternary carbon adjacent to the carbene site replaces one nitrogen atom in the structure of classic NHCs. In a BAC, two dialkylamino groups are located at the β positions relative to the carbene centre. Thus, these novel carbenes are expected to display distinct reactivity. Unlike the popular use of NHCs in organocatalysis, only few examples involving CAACs and BACs in catalysis have been reported. At the outset of our study, BAC organocatalysis had not been reported. In addition, although metal complexes –using a BAC as a ligand– had been synthesized, only two examples of metal catalysis have been reported.[14,15]



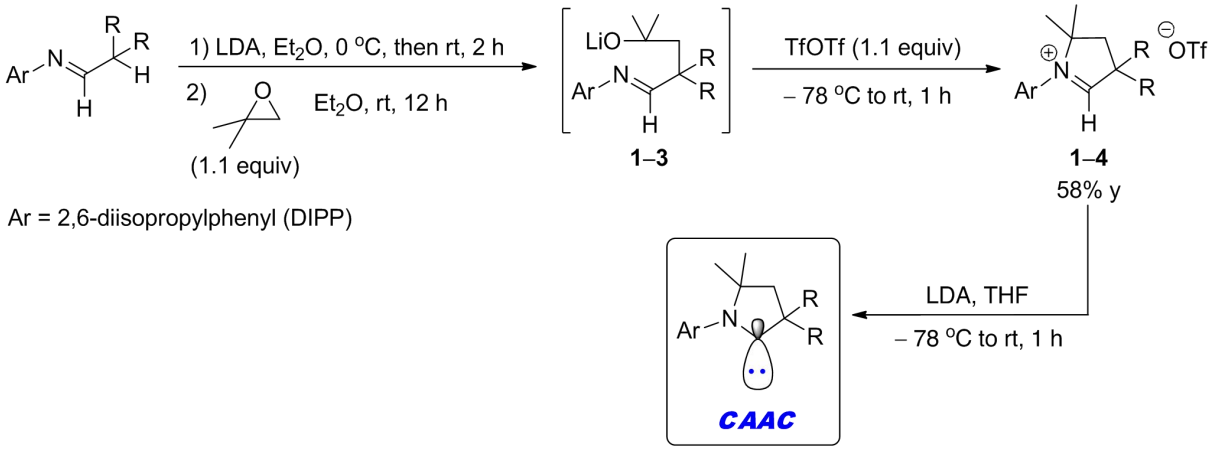
NHC *Arduengo* 1991 ***CAAC*** *Bertrand* 2005 ***BAC*** *Bertrand* 2006

Figure 1.4 Examples of various types of carbenes

1.1.3 Synthesis of CAACs and BACs

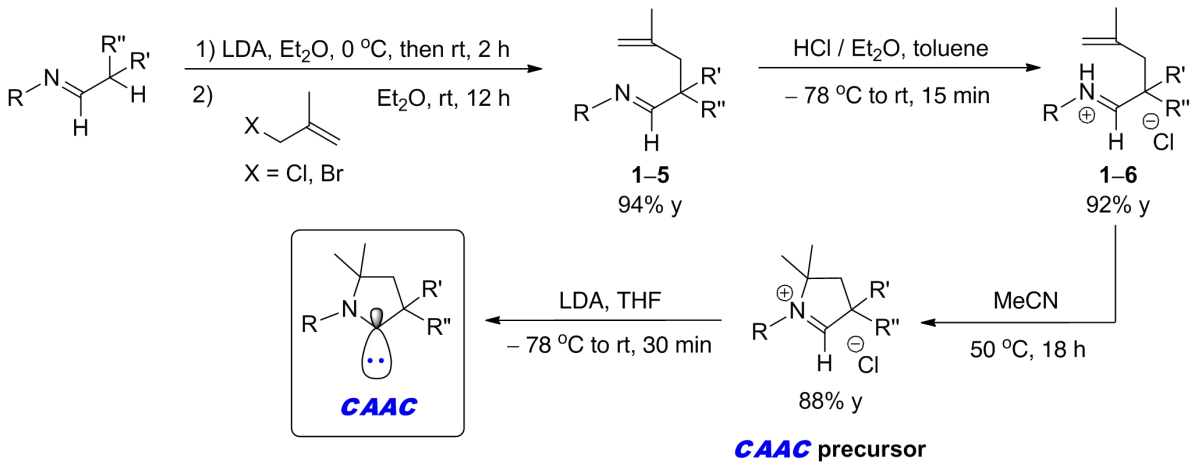
In 2005, Bertrand *et al.* reported the first synthesis of CAACs (Scheme 1.1).[7] The reaction between an imine precursor and lithium diisopropylamide (LDA) afforded the corresponding azaenolate, which triggered regioselective ring-opening of 1,2-epoxy-2-methylpropane to give the corresponding imino alkoxide **1–3**. Subsequent addition of triflic anhydride at –78 °C and warming to room temperature

afforded –through an intramolecular C–N bond formation– aldiminium salt **1–4** in up to 58% yield. This direct carbene precursor was then deprotonated with a second equivalent of LDA to form the free CAAC, which proved to be isolable.



Scheme 1.1 CAAC preparation through epoxide ring-opening[7]

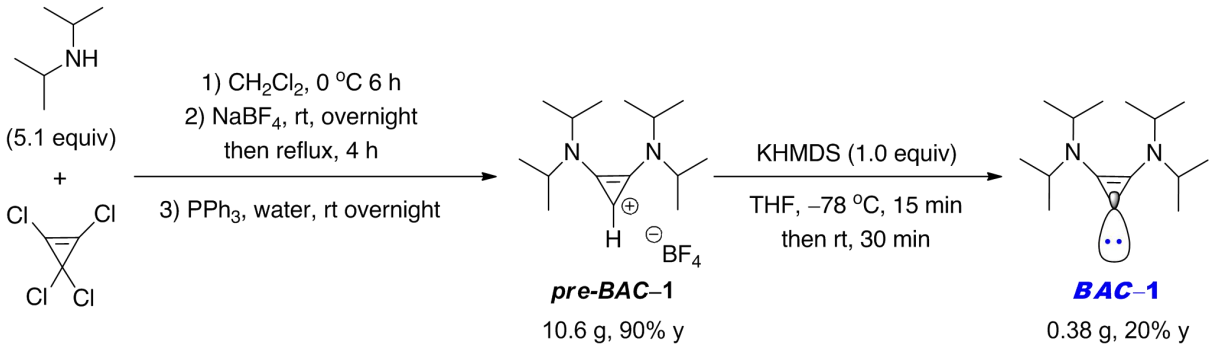
In 2007, Bertrand *et al*. reported a second synthetic route involving a hydroiminiumation of alkenes (Scheme 1.2).[9] First, an aldimine was deprotonated using LDA to provide the corresponding azaenolate, which reacted with 3-bromo-2-methylpropene to give alkenyl aldimine **1–5**. The addition of one equivalent of hydrochloric acid in diethyl ether to a solution of **1–5** in toluene afforded alkenyl aldiminium salt **1–6**. Heating a solution of this salt in acetonitrile at 50 °C for 18 h resulted in the formation of the corresponding direct CAAC precursor, which was deprotonated in the usual way to form the free CAAC. This synthesis offers advantages over the earlier method (Scheme 1.1), as it avoids expensive and toxic reagents.



Scheme 1.2 CAAC preparation through intramolecular hydroiminiumation[9]

In 2006, Bertrand *et al.* reported the first synthesis of a BAC (Scheme 1.3).[8] An excess of diisopropyl amine was added to a solution of tetrachlorocyclopropene in dichloromethane at 0 °C, followed by an anion metathesis using sodium tetraphenylborate to afford a cyclopropenium tetraphenylborate, ***pre-BAC*–1**. This direct BAC precursor was then deprotonated with potassium

hexamethyldisilazide at –78 °C to generate the corresponding free BAC. NMR spectroscopic analysis confirmed the presence of the BAC; crystals thereof were obtained in an overall yield of 20%.



Scheme 1.3 ***pre-BAC*–1** and ***BAC*–1** preparation[8]

In contrast to previously isolated carbenes, this BAC does not require a heteroatom adjacent to the electron-deficient carbene center to confer stability. Indeed, a BAC contains two dialkylamino groups located at the β positions relative to the carbene site, which itself is situated at the apex of a cyclopropene unit. This distance between the amino groups and the carbene center indicates that this new BAC species is sterically less demanding compared to normal NHCs. Despite the presence of the dialkylamino groups, the geometric parameters of this cyclic skeleton –revealed by X-ray crystallography[8]– proved to be only slightly perturbed compared to the calculated structure of the non-substituted cyclopropenylidene (Figure 1.5).

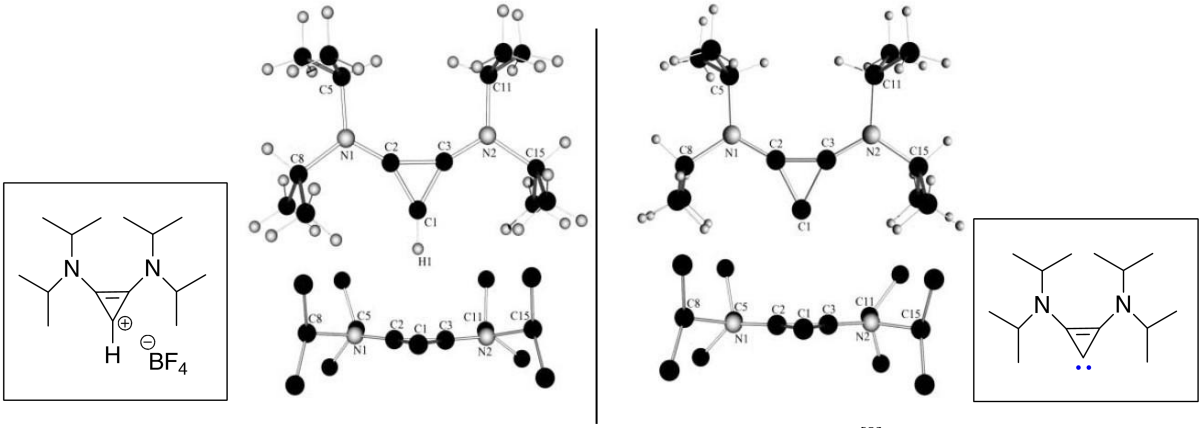


Figure 1.5 3D-view of ***pre-BAC*–1** and ***BAC*–1**[8]

1.1.4 Comparison of Properties: CAAC vs. BAC

Electronic Properties

The structural differences of NHCs, CAACs, and BACs result in different electronic and steric properties. In case of a CAAC, the replacement of one electron-withdrawing nitrogen atom by a σ donating alkyl group decreases the σ withdrawal effect, and thus increases the electron density at the carbene site. This modification renders a CAAC more basic compared to an NHC.[7] Likewise, in case of a BAC, the dialkylamino groups are located at a more distant position relative to the carbene

site, which renders this species also more basic than an NHC.[10] These considerations have been confirmed experimentally by IR studies measuring the average wavenumbers of the CO ligand in the corresponding *cis*-Ir and *cis*-Rh complexes (Figure 1.6). Indeed, for *cis*-[IrCl(CO)$_2$L] complexes (L = CAAC or NHC), the IR spectra showed a decrease in the average CO wavenumbers when CAAC was used (**1–7**; $\tilde{\nu}$ = 2013 cm^{-1}) compared to the use of an NHC (**1–8**; $\tilde{\nu}$ = 2017–2020 cm^{-1}).[7] Similarly, for *cis*-[RhCl(CO)$_2$L] complexes (L = BAC or NHC), the IR spectra showed a decrease in the average CO wavenumbers when BAC was used (**1–9**; $\tilde{\nu}$ = 2031 cm^{-1}) compared to the use of an NHC (**1–10**; $\tilde{\nu}$ = 2038–2041 cm^{-1}).[10] In both cases, these observations indicated a stronger σ donor property, i.e., a stronger basicity of a CAAC or a BAC compared to their NHC counterparts. A direct comparison between CAAC and BAC was not drawn as different metal complexes were used.

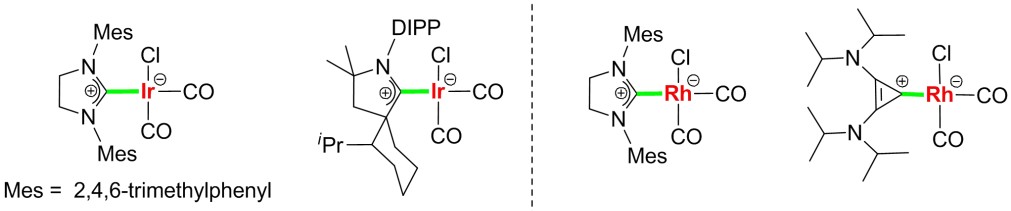


Figure 1.6 Donor ability–comparison between NHC, CAAC, and BAC[7,10]

Despite the fact that CAACs and BACs may act as strong σ donors, the electrophilic component in these species cannot be ignored.[11] This π acceptor ability is possible through donation of external electron density into the vacant p orbital of the central carbon atom. This phenomenon was confirmed experimentally by ^{31}P NMR spectroscopy of the corresponding phosphinidene complexes through comparison of the relative chemical shift of the phosphorous atom: a stronger electrophile gives a higher chemical shift due to a de-shielding effect (Figure 1.7). Accordingly, when the corresponding L=PPh adducts were examined (L = NHC, CAAC, BAC), the NHC proved to display a moderate electrophilicity (**1–11**; δ = –10 ppm) whereas the CAAC was found to be substantially more electrophilic (**1–12**; δ = 69 ppm). On the other hand, the BAC was shown to be the weakest π acceptor (**1–13**; δ = –35 ppm).[11] Based on these data, the electrophilicity order was suggested to be as follows: CAAC > NHC > BAC.

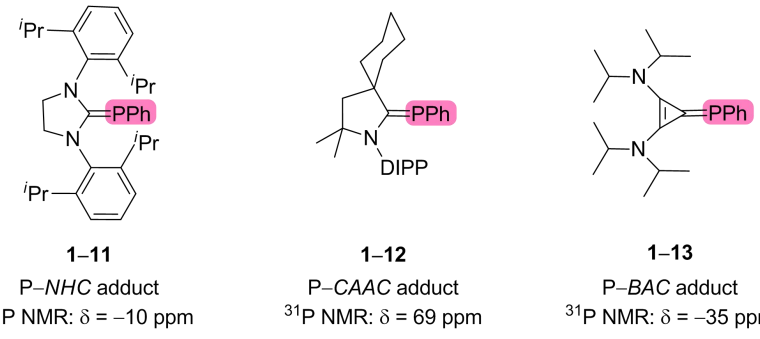
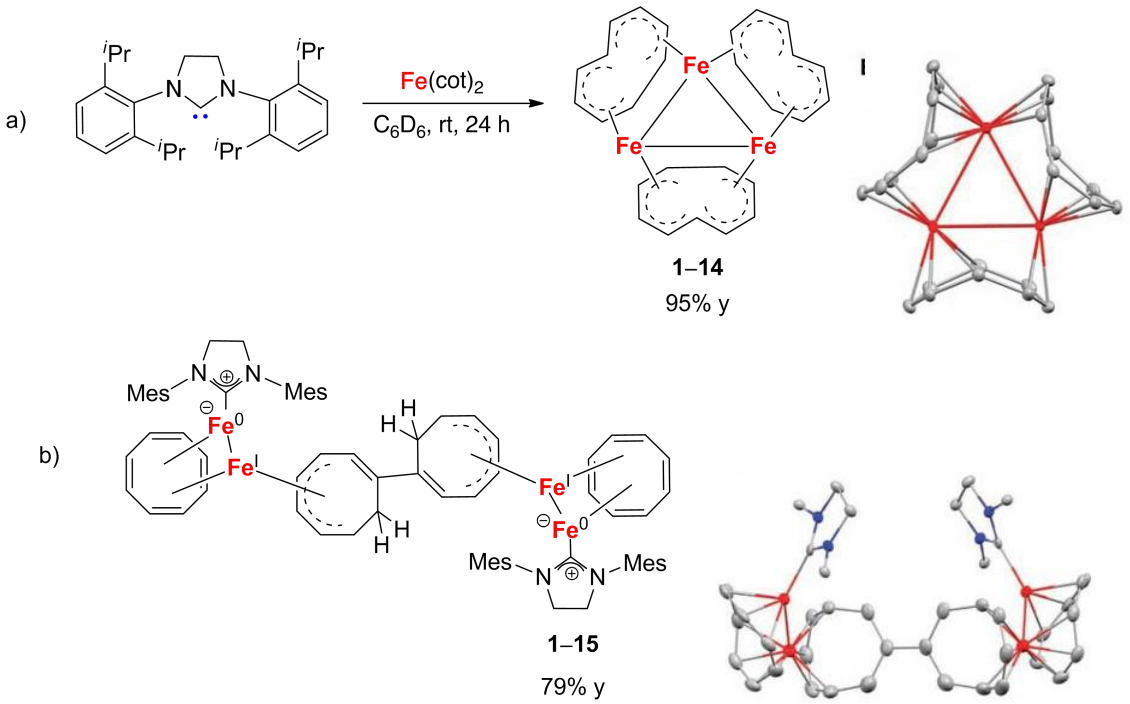


Figure 1.7 π acceptor ability–comparison between NHC, CAAC, and BAC[11]

Steric Properties

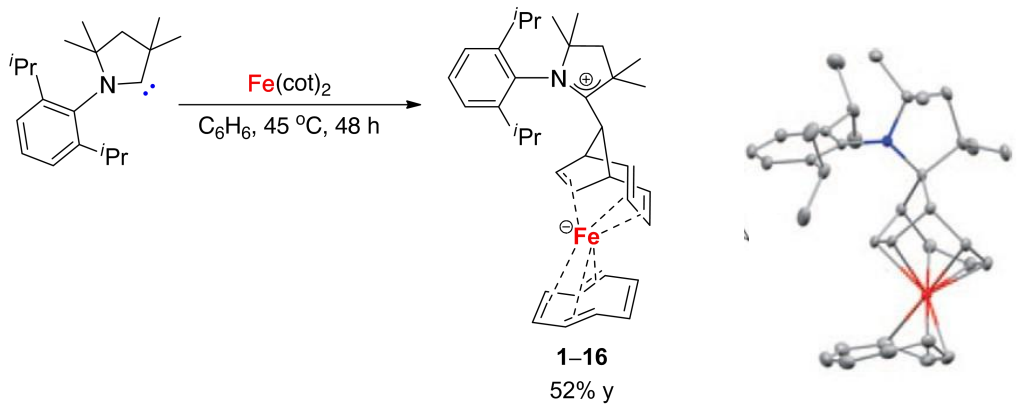
Compared to NHCs and CAACs, BACs have a significantly decreased steric bulk due to their unique cyclopropene-based structure. In 2011, a direct comparison of the steric demand between NHCs, CAACs, and BACs was described in a seminal study, reported by Grubbs *et al.*, on the carbene-triggered aggregation of bis(cyclooctatetraene)iron, $Fe(cot)_2$ (Schemes 1.4 ~ 1.6).[12]

In the reactions between different NHCs and $Fe(cot)_2$, surprising results were obtained.[12] The addition of one equivalent of a bulky NHC to $Fe(cot)_2$ at room temperature provided tri-nuclear iron cluster **1–14** [Scheme 1.4 a)]. On the other hand, the interaction between a less sterically demanding NHC and $Fe(cot)_2$ yielded tetra-nuclear iron complex **1–15** [Scheme 1.4 b)]. Although the mechanistic details of these transformations were not fully elucidated, it is supposedly the steric bulk of the NHC that prevented the formation of the dimer with release of the free NHC in the first case.



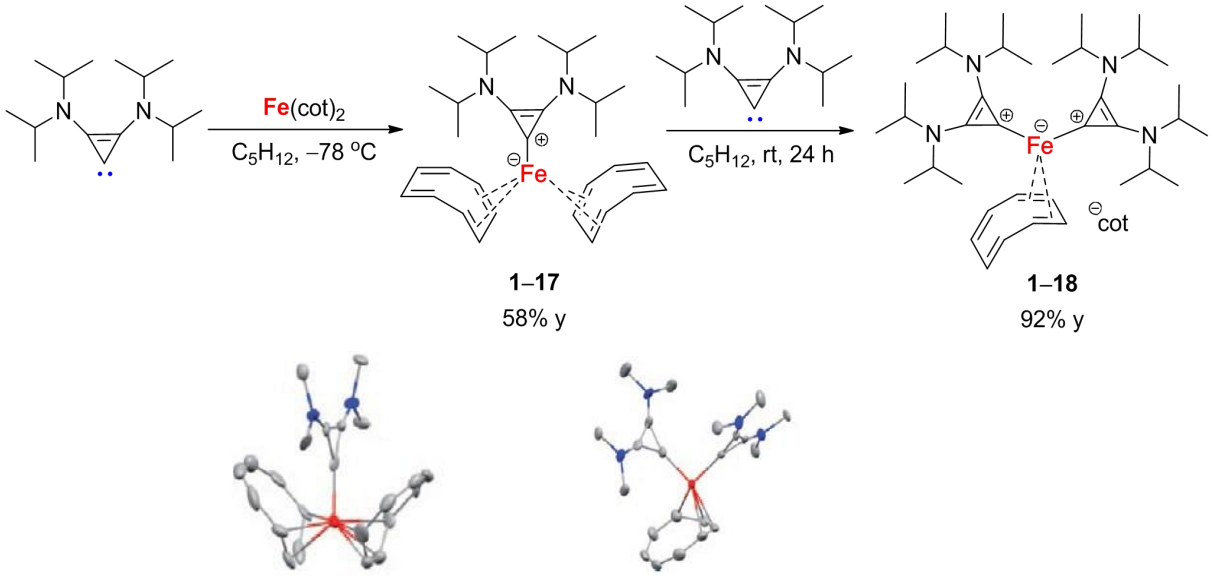
Scheme 1.4 Synthesis of tri- and tetranuclear NHC–iron clusters[12]

In contrast, the reaction between $Fe(cot)_2$ and a bulky CAAC at 45 °C gave a substantially different result (Scheme 1.5).[12] Indeed, the formal [4+1] cycloaddition product **1–16** was formed in 52% yield; this complex was found to be thermally stable at 120 °C for at least two days.



Scheme 1.5 Synthesis of an [Fe(cot)$_2$(CAAC)] complex[12]

Finally, the use of a BAC gave a different result as well (Scheme 1.6).[12] The reaction of the free BAC with Fe(cot)$_2$ at –78 °C generated the "mono-substituted" Fe(cot)$_2$(BAC) complex **1–17**. However, the addition of another equivalent of BAC at room temperature resulted in the formation of the "di-substituted" Fe(cot)(BAC)$_2$ complex **1–18**.

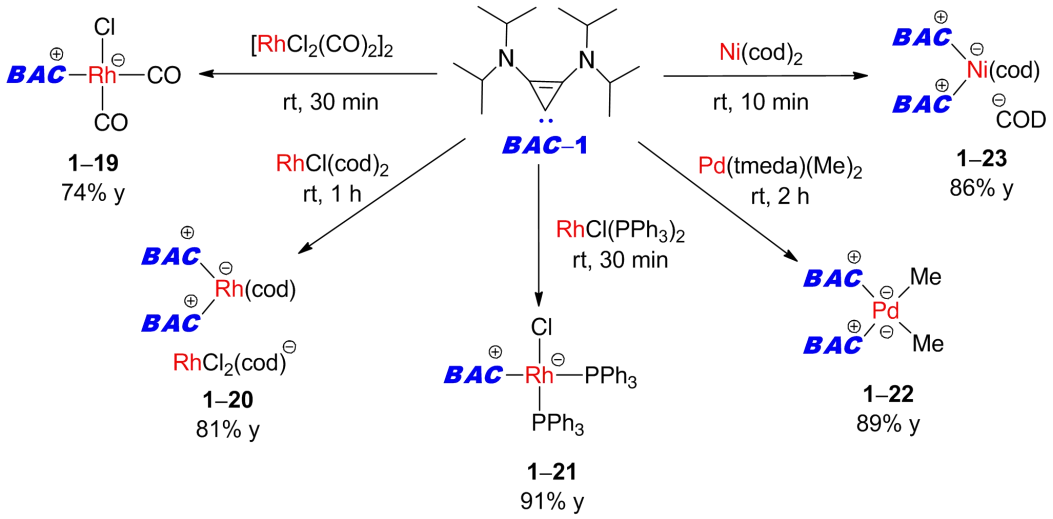


Scheme 1.6 Synthesis of [Fe(cot)$_2$(BAC)] and [Fe(cot)(BAC)$_2$] complexes[12]

The above studies clearly emphasize the steric differences between these three carbenes. Compared with an NHC and a CAAC, the decreased size of the BAC ligand has allowed for a single 'substitution' of Fe(cot)$_2$ without displacement of one of the COT ligands. *Considering the ease of preparation and bearing in mind the distinct electronic and steric properties of NHCs, CAACs, and BACs, we decided to investigate BACs in the context of various types of catalysis.*

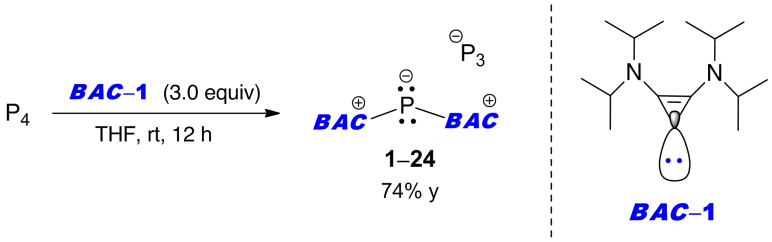
1.1.5 BAC–Metal Complexes in Literature

A few transition metal complexes have been prepared from the free cyclopropenylidene,[10] which may be facilitated by its minimal steric bulk (Scheme 1.7). The used metals include rhodium, palladium, and nickel.[10] Indeed, ***BAC*–1** has proved to react with $[RhCl_2(CO)_2]_2$ to afford $RhCl(CO)_2$(***BAC***) (**1–19**), which was typically used to assess the σ donor ability of BACs. ***BAC*–1** was also shown to react with $[RhCl(cod)]_2$ to give a salt, $Rh(cod)(BAC)_2^+$ $RhCl_2(cod)^-$ (**1–20**); such a species has been rarely obtained with normal NHCs. ***BAC*–1** was also demonstrated to displace standard or neutral bidentate ligands, as shown through the formation of $RhCl(PPh_3)_2$(***BAC***) (**1–21**) and $PdMe_2$(***BAC***)$_2$ (**1–22**), respectively. Such a ligand-exchange was found to be also efficient for metal(0) complexes, as evidenced by the synthesis of $Ni(cod)(BAC)_2^+$ COD^- (**1–23**).



Scheme 1.7 Literature-reported BAC–metal complexes[10]

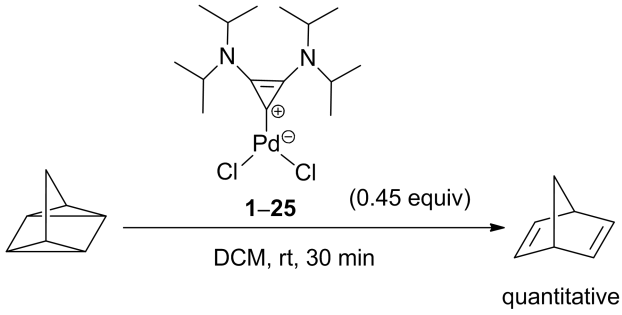
Furthermore, BACs have also been shown to react with elemental phosphorous as a main group non-metal. For example, in 2009 Bertrand *et al.* reported the reaction between ***BAC*–1** and white phosphorous to give the corresponding P_1 fragment **1–24** in 74% yield (Scheme 1.8).[13]



Scheme 1.8 BAC-facilitated formation of a P_1 fragment[13]

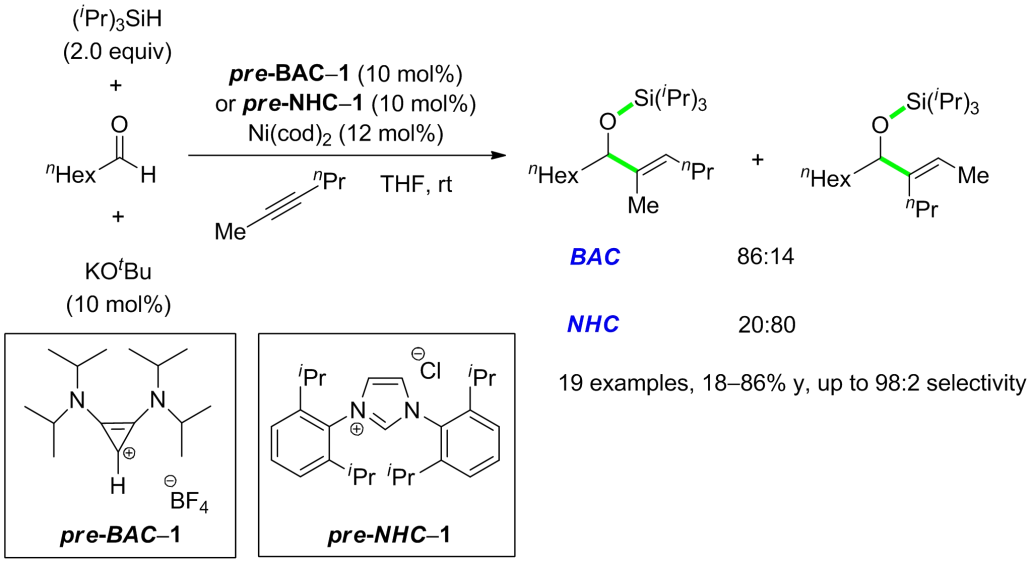
1.1.6 Catalysis with BAC–Metal Complexes

At the outset of our investigations, only two examples of metal–BAC catalysis have been reported. In 1988, Yoshida *et al.* reported the exothermic isomerization of quadricyclane to norbornadiene catalysed by Pd–BAC complex **1–25** (Scheme 1.9).[14]



Scheme 1.9 A single example of a Pd–BAC-catalysed isomerization[14]

In 2010, Montgomery *et al.* introduced a general strategy for the nickel-catalysed regioselective reductive coupling between aldehydes and alkynes, including aliphatic or aromatic internal, conjugated, and terminal alkynes (Scheme 1.10).[15] The corresponding major regioisomer was obtained with a selectivity of up to 98:2 through the use of *in situ*-formed ***BAC*–1** as a ligand. Interestingly, the use of *in situ*-formed ***NHC*–1** displayed the opposite regioselectivity.



Scheme 1.10 Ni–carbene-catalysed reductive cross-coupling[15]

1.1.7 Aims

The aims of this project were focused on the development of novel catalysis using new BACs as potential catalysts (Figure 1.9). After the synthesis of these species, their Lewis basicity or nucleophilicity had to be assessed by ^{11}B NMR spectroscopy using various boron Lewis acids.

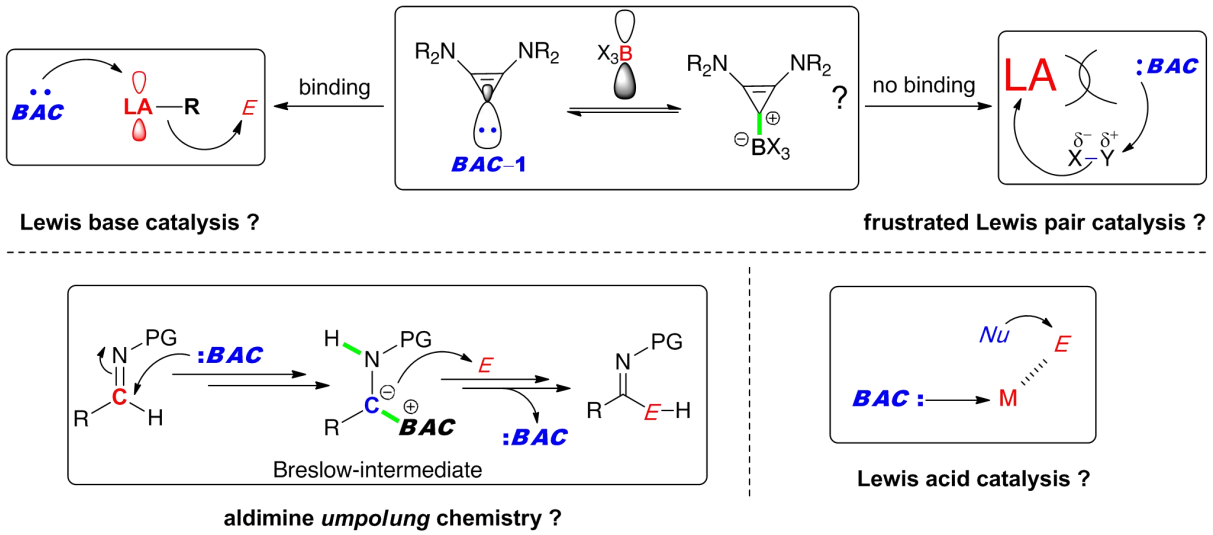


Figure 1.9 Aims for Chapter 1

If a boron–ate complex is detected with a specific boron Lewis acid, direct BAC Lewis base catalysis would be envisaged provided the boron reagent bears a transferable organic group. If such a boron–carbene binding is not observed, the couple would be considered as a frustrated Lewis pair (FLP) in view of strong-bond activation in small molecules, i.e., CO_2 or N_2O.

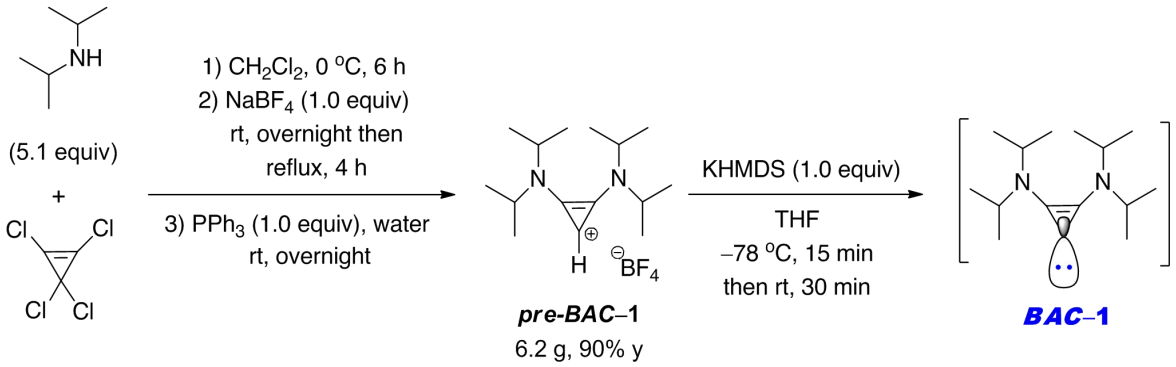
Another goal was to examine the unprecedented catalytic *umpolung* of aldimines. In this scenario, the nucleophilic BAC may add to the initially electrophilic site to form –after proton transfer– a nucleophilic Breslow-type intermediate. The latter may add to a suitable electrophile and –following another proton transfer– the functionalized ketimine product would be formed with concomitant regeneration of the BAC catalyst.

Finally, metal–BAC Lewis acid or redox catalysis was another potential application. The metal Lewis acid center would coordinate to a suitably basic electrophile, thus facilitating the nucleophilic addition of another reagent. Here, due to the unique properties of BAC ligands –compared with NHCs and CAACs– a distinct activity and selectivity for metal–BAC-catalysed processes may be anticipated.

1.2 Results and Discussions

1.2.1 Synthesis of a Pre-BAC and a BAC

***BAC*–1** was synthesized on a gram-scale according to the literature procedures (Scheme 1.11).[8] The reaction of an excess of diisopropylamine and tetrachlorocyclopropene in DCM –followed by successive treatment of the reaction mixture with sodium tetrafluoroborate, triphenyl phosphine, and water– afforded **pre-*BAC*–1** in 90% yield.



Scheme 1.11 Preparation of ***pre-BAC*–1** and ***BAC*–1**[8]

This precursor was then deprotonated by using one equivalent of potassium hexamethyldisilazide in THF at –78 °C. After warming to room temperature the mixture was stirred for 30 min, and the solvents were evaporated to yield BAC in its crude form. This *in situ* formation of ***BAC*–1** was verified in the presence of a boron Lewis acid through ^{11}B NMR spectroscopy (see Section 1.2.2; P11).

1.2.2 Evaluation of Lewis Basicity: BAC vs. Other Carbenes

Generally speaking, the Lewis basicity or nucleophilicity of molecules may be examined by reacting these with tri-coordinate boron Lewis acids. Potentially, a tetra-coordinate boron species, i.e., a so-called boron–ate complex, may be formed *in situ*; boron compounds can be detected by ^{11}B NMR spectroscopy, and so the reaction between the boron Lewis acid and the corresponding Lewis base can be monitored easily. In this context, the general chemical shifts of boron compounds can be summarized as shown in Chart 1.1.

^{11}B NMR spectroscopy can be considered as a scale for the Lewis acidity of boron compounds; the chemical shift of the boron signal decreases with an increasing number of bound heteroatoms, i.e., oxygen or nitrogen.[16] This effect can be ascribed to the fact that e.g. an oxygen atom can partially donate electron density to the vacant p orbital of the adjacent boron center. Typically, a tri-coordinate boron compound would give a signal in the range from +90 ppm to +15 ppm. In contrast, tetra-coordinate species, such as boron–ate complexes, have a much higher electron density around the boron atom and hence display a signal in the range from +10 ppm to –40 ppm.

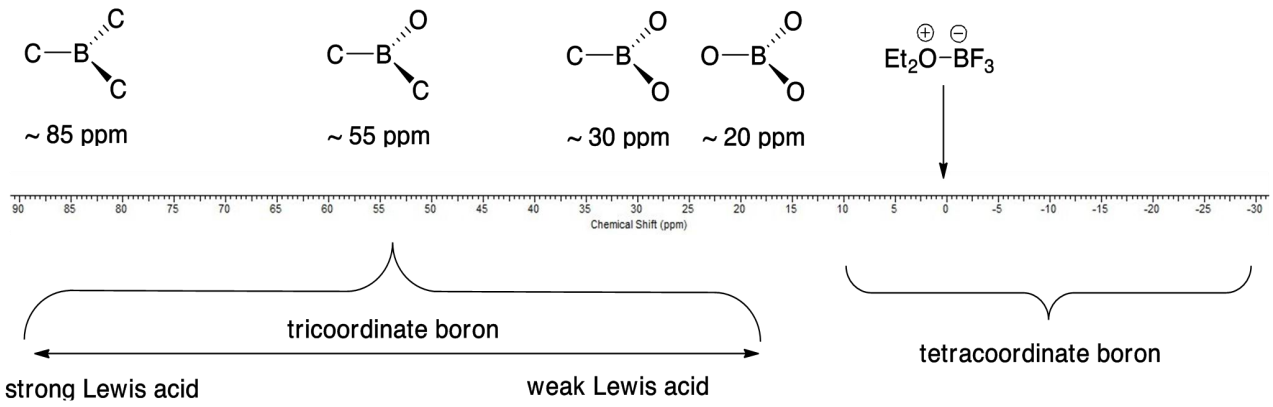


Chart 1.1 ^{11}B NMR spectroscopy as a Lewis acidity scale[16]

All boron Lewis acids used in this study and their corresponding chemical shifts in ^{11}B NMR spectroscopy are shown in Figure 1.10. The general goal in this part of study was to detect whether a boron–ate complex was generated by combining an *in situ*-formed BAC and the corresponding boron reagent. As BACs are considerably more basic than the traditional NHCs and less sterically demanding than CAACs, the carbene's lone pair was anticipated to more easily attack the electrophilic boron atom. According to the experimental procedure, a solution of the *in situ*-formed BAC in benzene was reacted with the various boron reagents at room temperature, and the resulting mixture was transferred into an NMR tube for ^{11}B NMR spectroscopic analysis. A new signal appearing in the range from –40 ppm to +10 ppm would show the formation of a boron–ate complex, and thus demonstrate the nucleophilicity of the BAC towards a specific boron species.

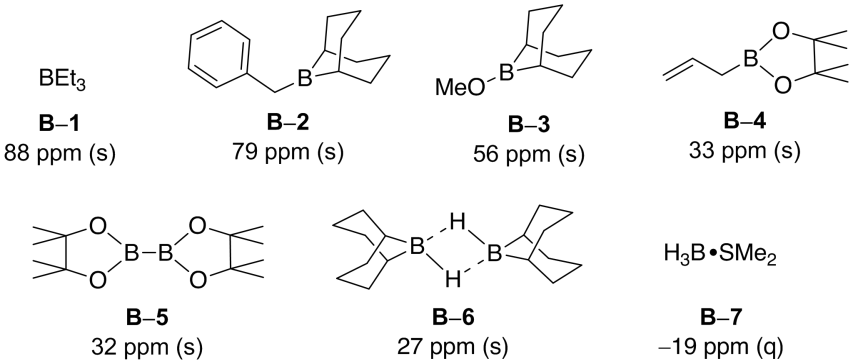


Figure 1.10 Boron reagents examined and their chemical shifts

The spectra for these boron binding experiments are illustrated in Charts 1.2a–g). In case of triethylborane (**B–1**), the starting material displayed a signal at ~ +87 ppm [Chart 1.2a)]. The reaction of ***BAC*–1** with **B–1** afforded a *carbene* boron–ate complex, as evidenced by a signal at –13.3 ppm. In this context, a control experiment has also been carried out using **B–1** in the presence of KHMDS; an *amide* boron–ate complex was detected at –1.7 ppm. This result confirmed that the signal at –13.3 ppm was indeed the complex formed through addition of ***BAC*–1** to **B–1**.

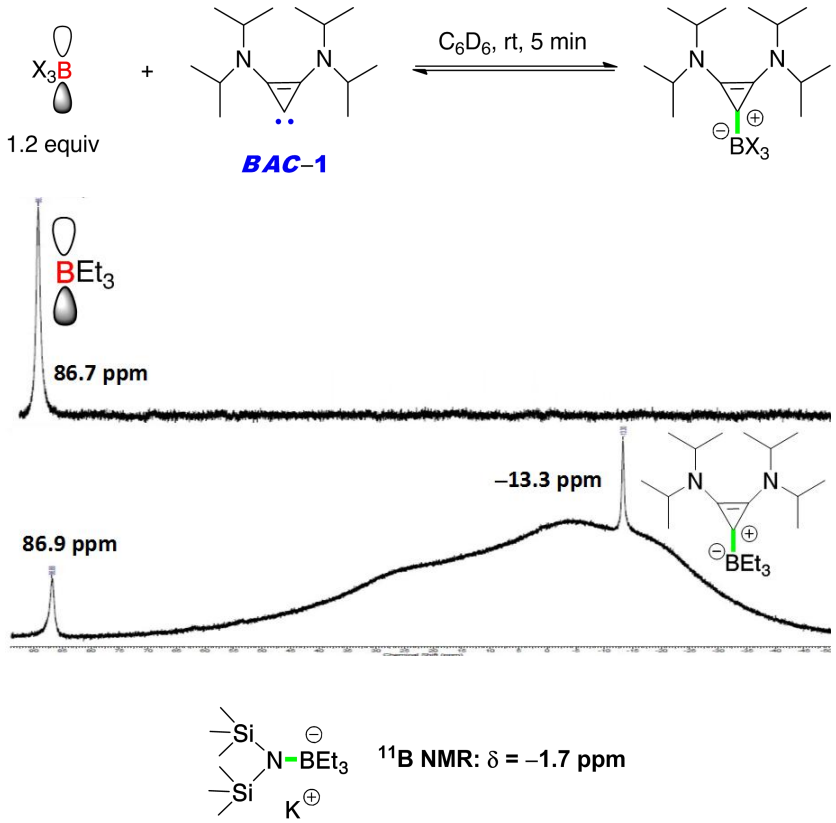
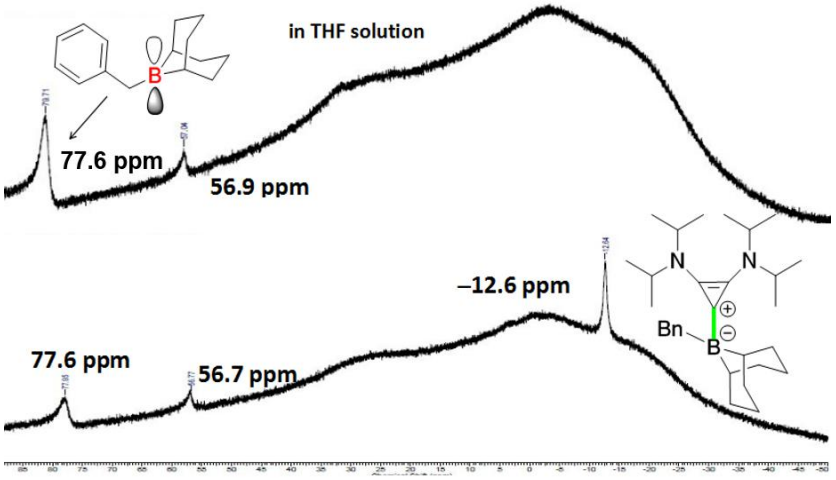


Chart 1.2a) ^{11}B NMR spectra for **B–1** and the corresponding BAC boron–ate complexes

In case of Bn–B(9BBN) (**B–2**), the starting material showed a signal at ~ +77 ppm [Chart 1.2b)]. The reaction of ***BAC*–1** with **B–2** provided a *carbene* boron–ate complex, as evidenced by a signal at –12.6 ppm. The signal at ~ +56 ppm may be an impurity [HO–B(9BBN)] formed from **B–2** and water present in the starting material. In this context, a control experiment has also been carried out using **B–2** in the presence of KHMDS; an *amide* boron–ate complex was detected at –6.2 ppm. This result confirmed that the signal at –12.6 ppm was the complex formed between ***BAC*–1** and **B–2**.



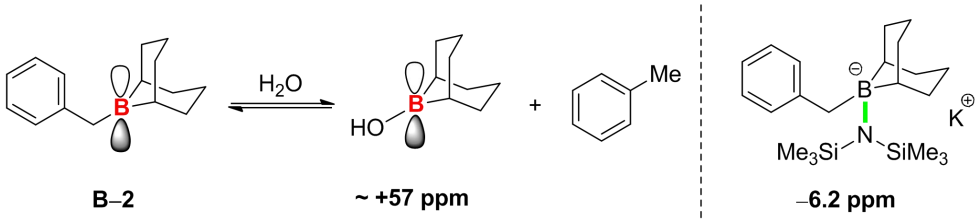


Chart 1.2b) ^{11}B NMR spectra for **B–2** and the corresponding BAC boron–ate complexes

In case of MeO–B(9BBN) (**B–3**), the starting material showed a signal at ~ +57 ppm [Chart 1.2c)]. The reaction of ***BAC*–1** with **B–3** gave a *carbene* boron–ate complex, which displayed a signal at +1.4 ppm. The control experiment between **B–3** and KHMDS formed an *amide* boron–ate complex, which was detected at +5.0 ppm. This result confirmed that the signal at +1.4 ppm ppm was the complex formed between ***BAC*–1** and **B–3**.

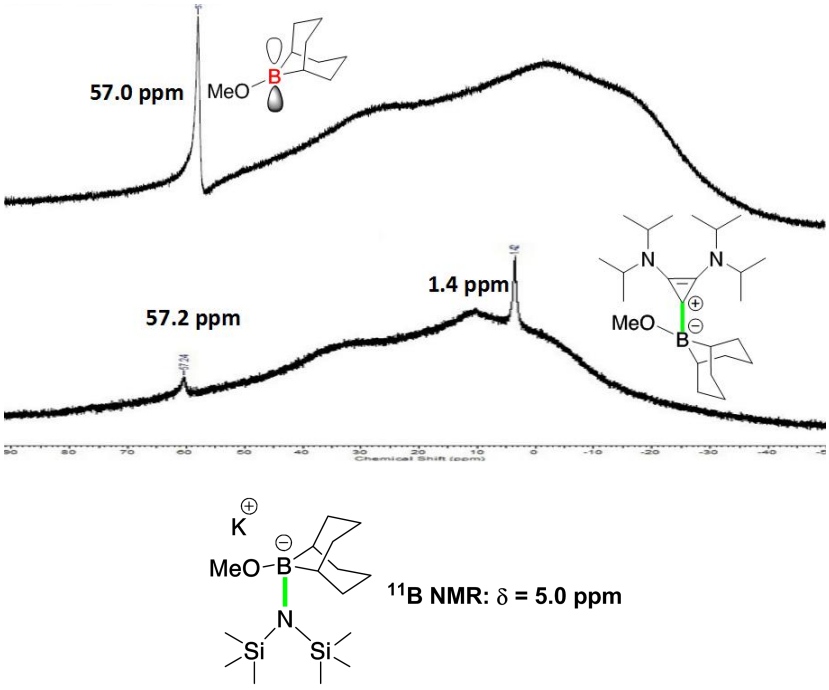


Chart 1.2c) ^{11}B NMR spectra for **B–3** and the corresponding BAC boron–ate complexes

In case of allyl–B(pin) (**B–4**), the starting material showed a signal at ~ +33 ppm [Chart 1.2d)]. The reaction of ***BAC*–1** with **B–4** gave a *carbene* boron–ate complex, which displayed a singlet at –2.1 ppm. Here, the control experiment using **B–4** and KHMDS gave a signal at ~ +26 ppm, which could be ascribed to an equilibrium between **B–4** and an *amide* boron–ate complex. This result also confirmed that the signal at –2.1 ppm was the complex formed between ***BAC*–1** and **B–4**.

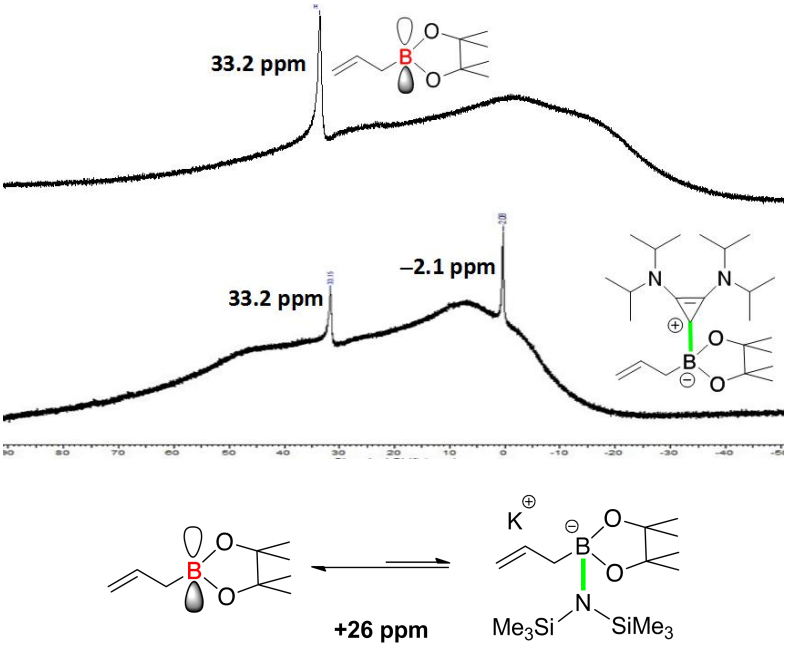


Chart 1.2d) ^{11}B NMR spectra for **B–4** and the corresponding BAC boron–ate complexes

In case of $B_2(pin)_2$ (**B–5**), the starting material displayed a signal at ~ +31 ppm [Chart 1.2e)]. The reaction between ***BAC*–1** and **B–5** afforded a *carbene* boron–ate complex, as evidenced by a signal at +7.5 ppm. The control experiment using **B–5** and KHMDS led to an *amide* boron–ate complex that was detected at –3.1 ppm. This result confirmed that the signal at +7.5 ppm corresponded to the complex between ***BAC*–1** and **B–5**.

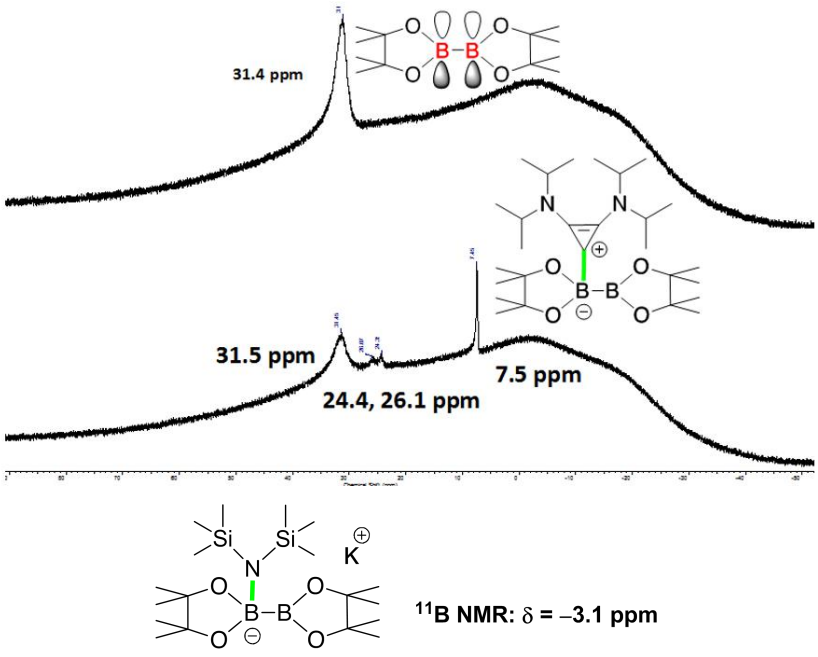


Chart 1.2e) ^{11}B NMR spectra for **B–5** and the corresponding BAC boron–ate complexes

In case of H–B(9BBN) (**B–6**), the starting material displayed a signal at ~ +28 ppm [Chart 1.2f)]. The reaction of ***BAC*–1** with **B–6** afforded a *carbene* boron–ate complex, as evidenced by a signal at –16.0 ppm. The control experiment using **B–6** and KHMDS generated an *amide* boron–ate complex detectable at –14.8 ppm, and thus confirmed the formation of the *carbene* boron–ate complex with

***BAC*–1** (–16.0 ppm).

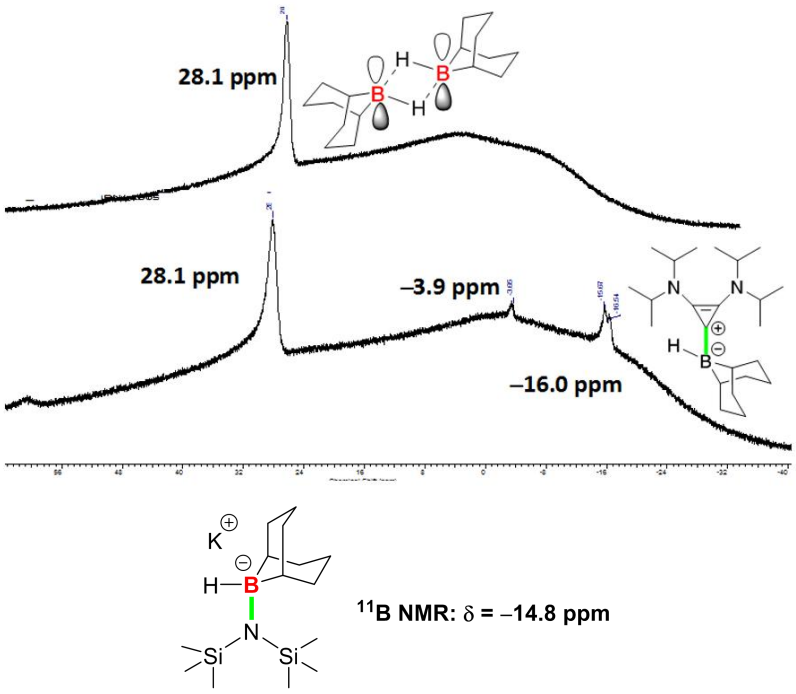


Chart 1.2f) ^{11}B NMR spectra for **B–6** and the corresponding BAC boron–ate complexes

In case of $H_3B{\bullet}SMe_2$ (**B–7**), the starting material displayed a signal at –19 ppm [q; Chart 1.2g)]. The reaction of ***BAC*–1** with **B–7** afforded a *carbene* boron–ate complex, as evidenced by a quartet at –35 ppm. The control experiment between **B–7** and KHMDS formed a signal at +40 ppm, which may be ascribed to an equilibrium between the amide boron–ate complex and a "BH_2 species" generated through intramolecular hydride transfer from boron-to-silicon. This result confirmed that the signal at –35.0 ppm was indeed the complex formed through addition of ***BAC*–1** to **B–7**.

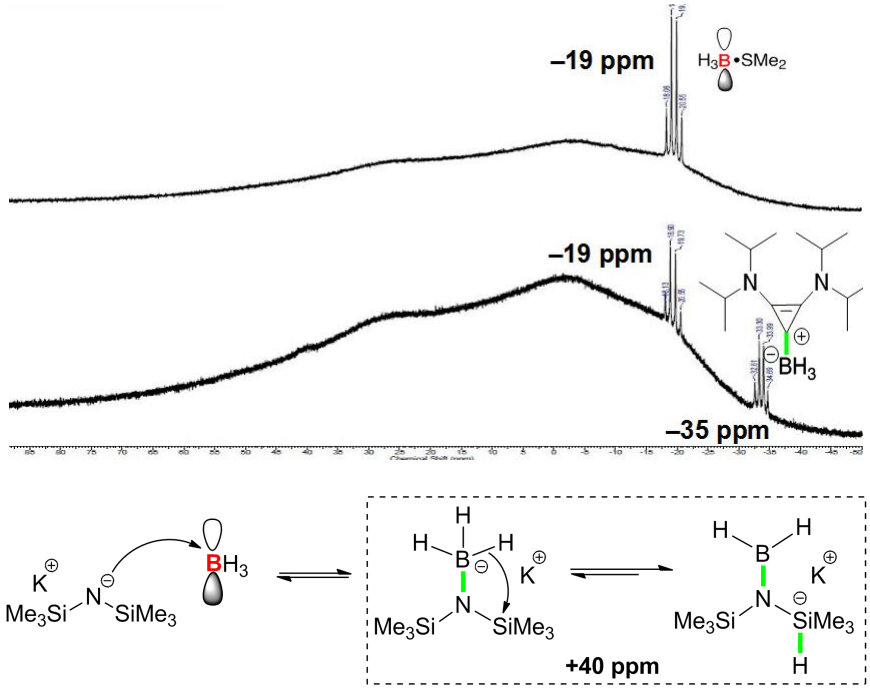
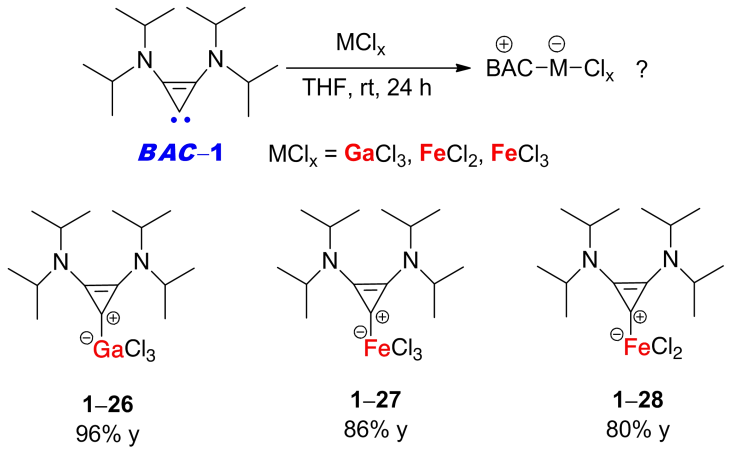


Chart 1.2g) ^{11}B NMR spectra for **B–7** and the corresponding BAC boron–ate complexes

In summary, as shown in all spectra [Charts 1.2a–g)], ***BAC*–1** formed ate complexes with *all* boron Lewis acids examined; control experiments using KHMDS alone confirmed these data. The ability of ***BAC*–1** to generate adducts with *virtually any* boron electrophile may be due to its highly nucleophilic and non-sterically demanding character. *Overall, these results indicated that a cyclopropenylidene may act as a potential nucleophilic catalyst for electrophilic metalloid reagents.*

1.2.3 Synthesis of Novel BAC–Metal Complexes

In 2007, Bertrand *et al.* reported the first complexes of cyclopropenylidenes with transition metals such as Rh, Pd, and Ni.[10] Those well-defined air- and moisture-stable BAC–M adducts may have a significant potential in π Lewis acid catalysis. Here, we were rather interested in non-precious metals such as main group and first-row transition metals; typically, these metals are considered as both less expensive and less toxic. In our study, gallium(III), iron(II), and iron(III) were reacted in the presence of a BAC to generate the corresponding complexes. These adducts were synthesized according to literature procedures (Scheme 1.12).[8,10]



Scheme 1.12 Preparation of BAC–metal complexes[8,10]

Free ***BAC*–1** was prepared *in situ* (see Scheme 1.11; P11), and subsequently reacted with the corresponding metal chloride at room temperature. After filtration, evaporation, and washing with anhydrous methanol, the corresponding BAC–metal adducts were obtained in high yields [gallium(III) (**1–26**): 96%; iron(II) (**1–27**): 86%; iron(III) (**1–28**): 80%]. The identity of these new complexes were confirmed by NMR spectroscopy and high-resolution mass spectroscopy (HRMS), as well as by comparison with reported data for analogous species.[10,17] In the ^{1}H NMR spectrum of ***pre-BAC*–1**, the *cyclopropenium* hydrogen atom displayed a signal at 7.42 ppm and the C*H* hydrogen atoms of two non-equivalent isopropyl groups showed signals at 4.03 ppm and 3.86 ppm, respectively [Chart 1.3a) *above*]. After deprotonation to form ***BAC*–1** (see Scheme 1.11; P11), the signal of the *cyclopropenium* hydrogen atom obviously disappeared, and C*H* hydrogen atoms of the equivalent isopropyl groups showed one signal only at 3.69 ppm [Chart 1.3a) *below*].

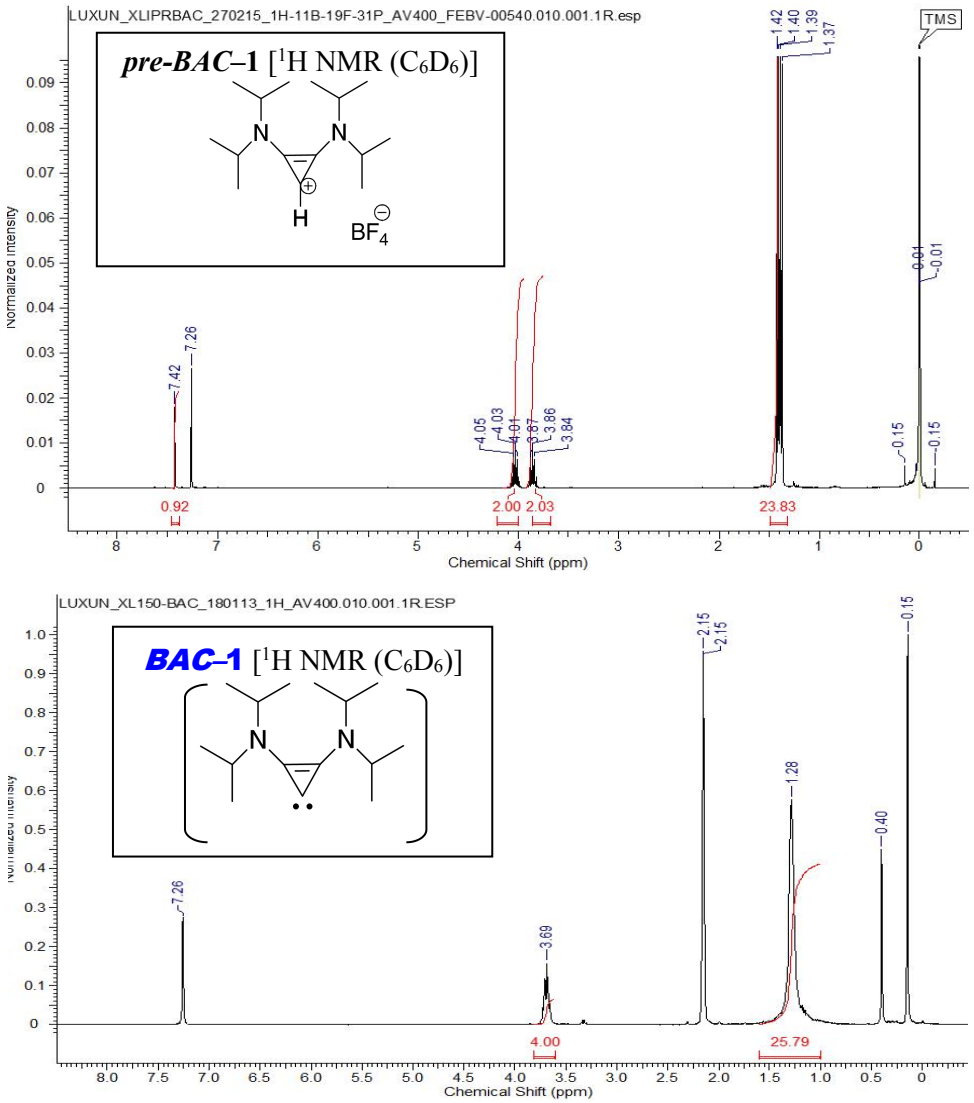


Chart 1.3a) ^{1}H NMR spectra of ***pre-BAC*–1** and ***BAC*–1**

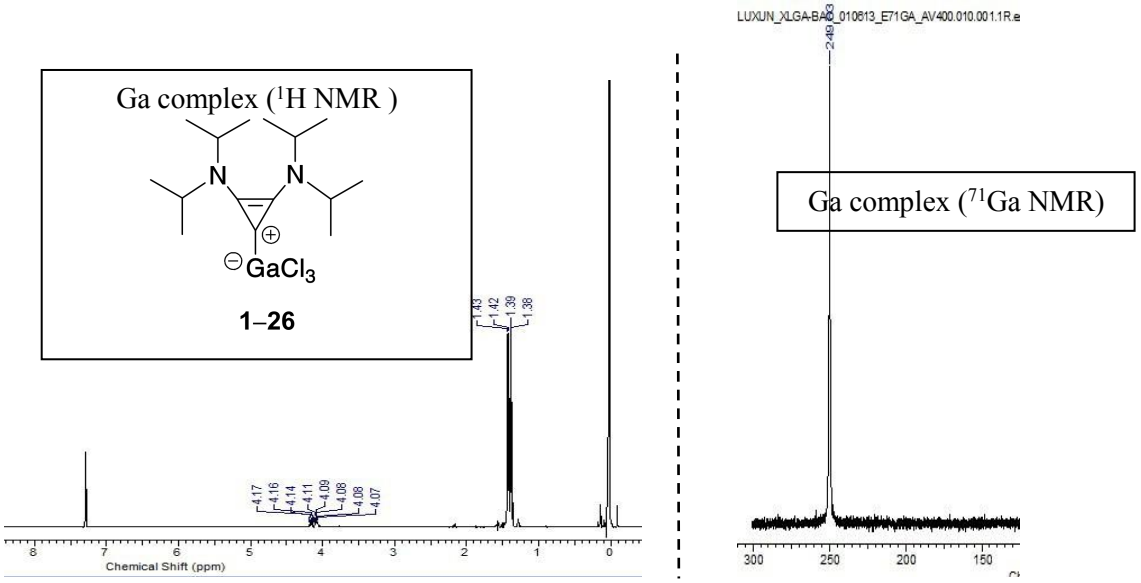


Chart 1.3b) ^{1}H NMR and ^{71}Ga NMR spectra of BAC–$GaCl_3$ complex **1–26**

In the ^{1}H NMR spectrum of the BAC–Ga(III) complex **1–26**, the C*H* hydrogen atoms of two non-

equivalent isopropyl groups displayed signals at 4.14 ppm and 4.08 ppm, respectively [Chart1.3b) *left*]. While the spectrum looked similar to the one recorded for ***pre-BAC*–1** [see Chart1.3a) *above*], the chemical shifts were clearly distinct, which suggested the formation of a BAC–gallium complex. Likewise, ^{71}Ga NMR spectroscopy indicated the formation of a "molecular" tetra-coordinated gallium complex rather than an "ionic" three-coordinated gallium species. Indeed, a singlet at ~ +249 ppm was observed [Chart1.3b) *right*], which is consistent with Gandon's data on related NHC–gallium complexes (+249 ~ +257 ppm).[17a] In addition, the anionic gallium halide species ($L–GaCl_2^+X^-$) displayed a signal at +365 ppm ~ +740 ppm,[17b] in which area no signals were detected in our ^{71}Ga NMR. Finally, gallium complex **1**–**26** was analyzed as well by high-resolution mass spectroscopy (HRMS), and the molecular (non-ionic) structure has been unambiguously confirmed by HRMS analysis, i.e., the corresponding "molecular gallium complex–Na^+" species was detected. In analogy, iron complexes **1**–**27** and **1**–**28** were characterized by ^{1}H and ^{13}C NMR spectroscopy, and the molecular (non-ionic) structures have been confirmed by HRMS analysis.

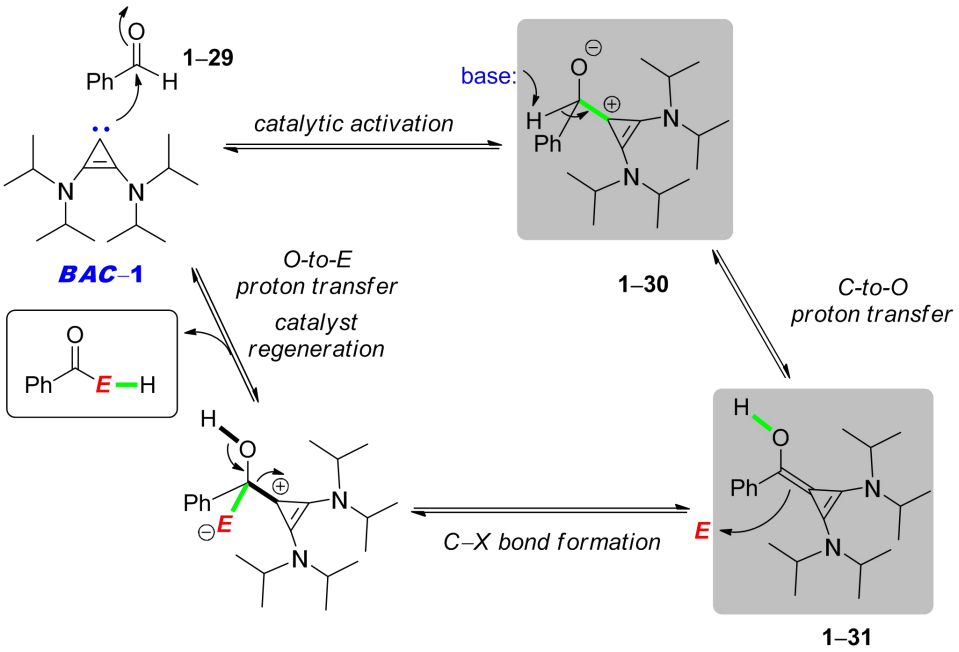
All three complexes seem to be bench-stable, and their use in Lewis acid catalysis will be investigated in the presence of an anion metathesis trigger.

1.2.4 Attempted Classic *Umpolung* by a BAC

After having confirmed the high degree of nucleophilicity of ***BAC*–1** in Section 1.2.2 (P11), a variety of reactions with different electrophilic substrates were performed in order to see whether *umpolung* catalysis using aldehyde or aldimine pro-nucleophiles was feasible.

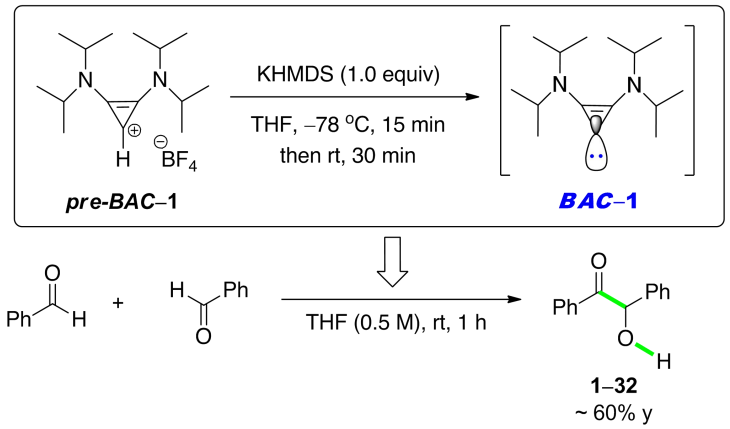
1.2.4.1 Benzaldehyde as a Potential Pro-Nucleophile

Benzaldehyde (**1–29**) was first used to react with the *in situ*-formed ***BAC*–1** to see whether this compound was suitable to convert **1–29** to an acylanion equivalent for subsequent intermolecular C–C bond formation with a suitable electrophile (Scheme 1.13). To date, analytical data regarding adduct **1–30** were not reported in literature. After a C-to-O proton transfer a so-called Breslow-intermediate, species **1–31**, would be formed. This acylanion equivalent may react with an electrophile; here, benzaldehyde may be the electrophile to undergo C–C bond formation, i.e., generation of homobenzoin adduct **1–32** (Scheme 1.14).



Scheme 1.13 Proposed pathway for BAC-catalysed aldehyde *umpolung* chemistry

Regarding the experimental procedure, one equivalent of benzaldehyde (**1–29**) was reacted with 30 mol% of *in situ*-formed ***BAC*–1** in THF at room temperature; both consumption of benzaldehyde and product formation were monitored by ^{1}H NMR spectroscopy (use of DBE as an internal standard; Scheme 1.14).



Scheme 1.14 BAC-catalysed homo-benzoin formation

According to related literature data, the relevant signals detectable in ^{1}H NMR spectroscopy would appear at 4.5 ppm and 6.0 ppm, respectively.[18,19] In our initial trial, homo-benzoin **1–32** was formed in ~60 %yield, which showed the potential of a BAC in *umpolung* catalysis. A presentative example of an aliquot NMR for this homo-benzoin formation displayed the benzylic hydrogen atom in **1–32** at ~ 5.0 ppm (d, J = 8.2 Hz; Chart 1.4).

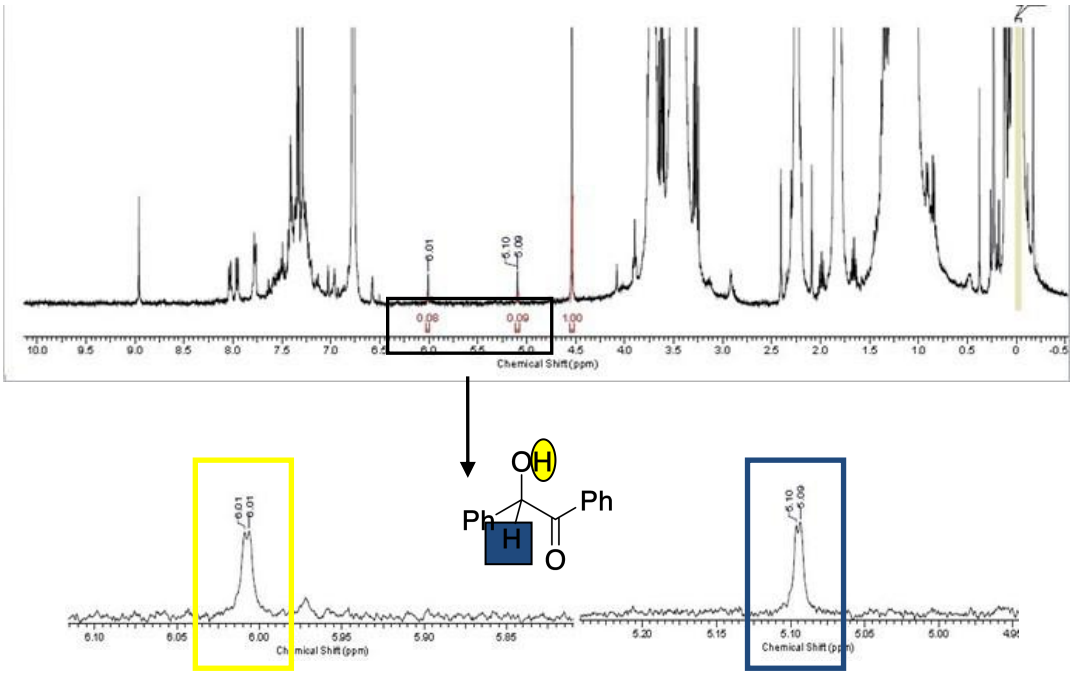
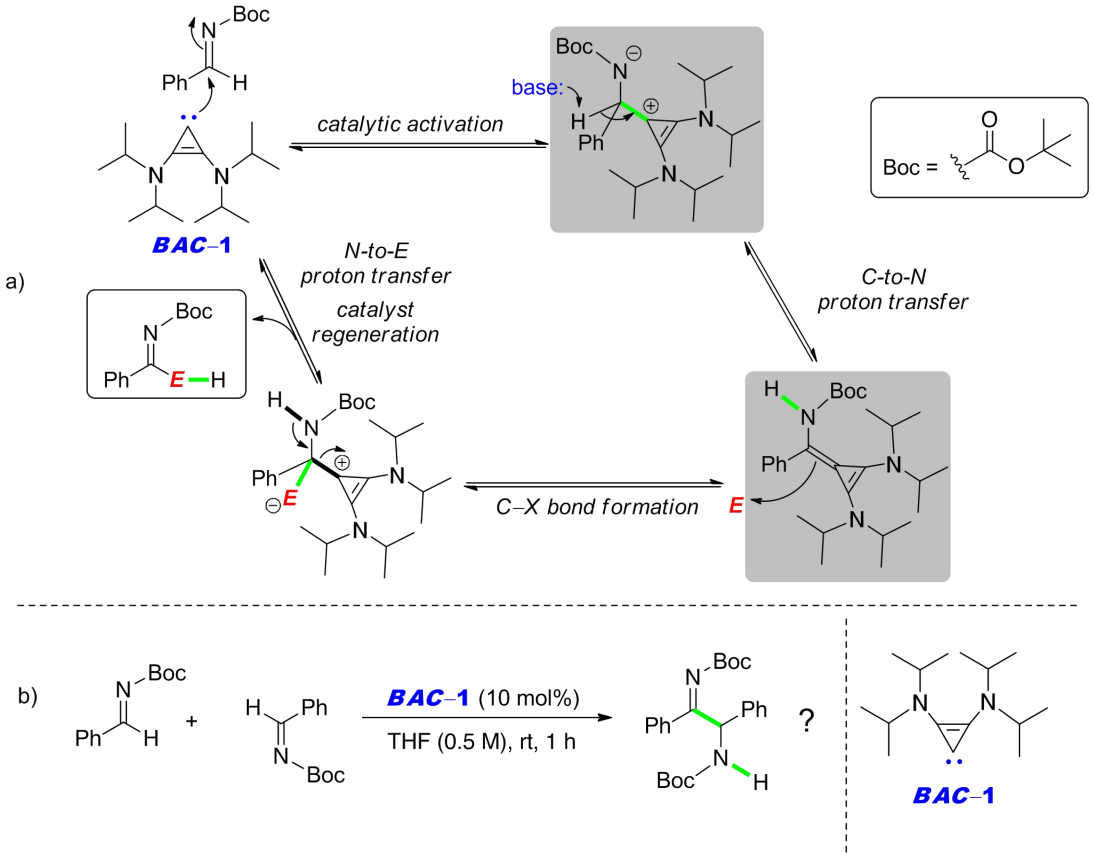


Chart 1.4 ^{1}H NMR spectroscopic analysis for homo-benzoin formation[18,19]

1.2.4.2 An Aldimine as a Potential Pro-Nucleophile

In addition, a benzaldehyde-derived *N*-Boc-imine was examined. Despite the fact that NHCs have proved to be good catalysts for the catalytic *umpolung* of aldehydes, these species were found to inactive in the *umpolung* of aldimines. As BACs have been shown to be stronger bases/nucleophiles than NHCs, we anticipated that a BAC may activate a suitable aldimine in the context of *umpolung* catalysis [Scheme 1.15a)]. The corresponding experiment was conducted using the benzaldehyde-derived *N*-Boc-imine in the presence of 10 mol% of *in situ*-formed ***BAC*–1** in THF at room temperature [Scheme 1.15b)]. Both consumption of *N*-Boc-imine as well as product formation were

monitored by ^{1}H NMR spectroscopy (use of DBE as an internal standard).



Scheme 1.15 Proposed pathway for BAC-catalysed *umpolung* of an aldimine for homo-aza-benzoin formation

The consumption of the electrophile, i.e., the benzaldehyde-derived *N*-Boc-imine, proceeded smoothly thus indicating an initial nucleophilic addition of ***BAC*–1** to the imine's C=N double bond, which is facilitated by the electron-withdrawing carbamate protecting group. Literature data have not been reported for this initial adduct nor for the final homo-aza-benzoin product. In our case, a new singlet at around 5.9 ppm was identified (Chart 1.5), and the consumption of imine was also detected. However, a dimeric product was *not* detected, which may be ascribed to the electron withdrawing group decreasing the basicity of the amide intermediate, i.e., a proton transfer may not occur and thus no *umpolung*. *In conclusion, this preliminary experiment revealed that an initial adduct between the cyclopropenylidene and the imine was likely formed, but it did not react further in a productive pathway.*

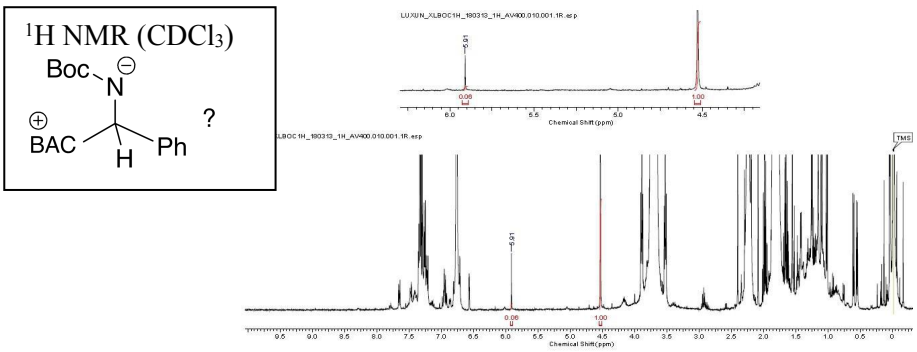
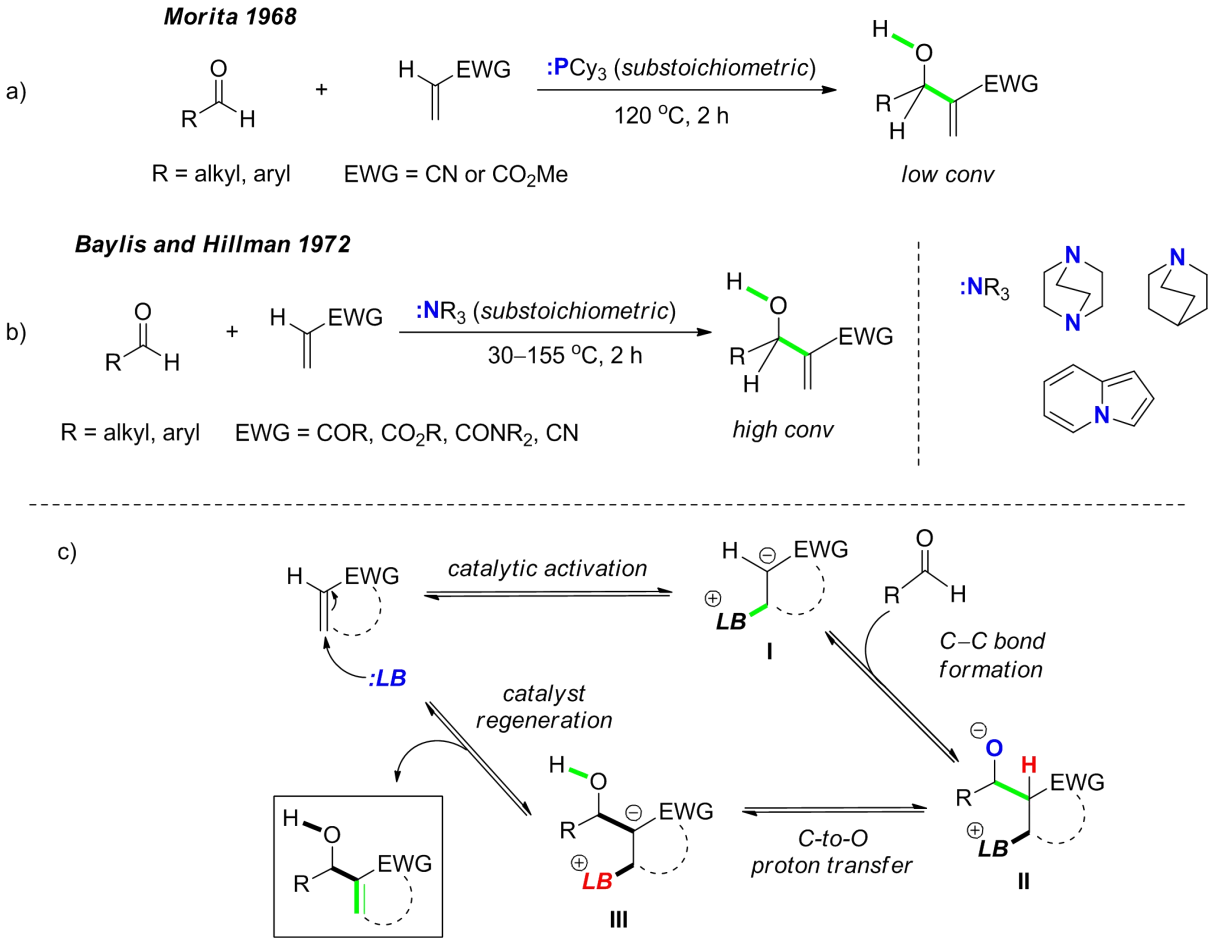


Chart 1.5 ^{1}H NMR spectroscopic analysis of the *umpolung* reaction using an aldimine (aliquot)

1.2.5 *Umpolung* of Michael Acceptors by a BAC

C–C Bond formations are among the most important reactions in organic chemistry, and represent thus an important area of organic synthesis and catalysis.[20] Among the various C–C bond-forming reactions, the Morita–Baylis–Hillman (MBH) reaction is one of the most useful and popular reactions due to its atom-economy and its high synthetic potential.[21]

The classic MBH reaction represents the formation of a C–C bond between the α-position of a Michael acceptor –such as an α,β-unsaturated aldehyde, ketone, or carboxylic acid derivative– and a carbonyl electrophile –such as an aldehyde or a ketone– in the presence of a nucleophilic catalyst, i.e., a tertiary amine or a phosphine (Scheme 1.16).[22] The first MBH reaction was reported in 1968 by Morita, using aldehydes and methyl acrylate or acrylonitrile as substrates, in the presence of a phosphine catalyst; the corresponding MBH adducts were obtained with low conversions [Scheme 1.16a)].[23] In 1972, Baylis and Hillman used cheaper and less toxic amine catalysts to carry out similar transformations [Scheme 1.16b)].[24]

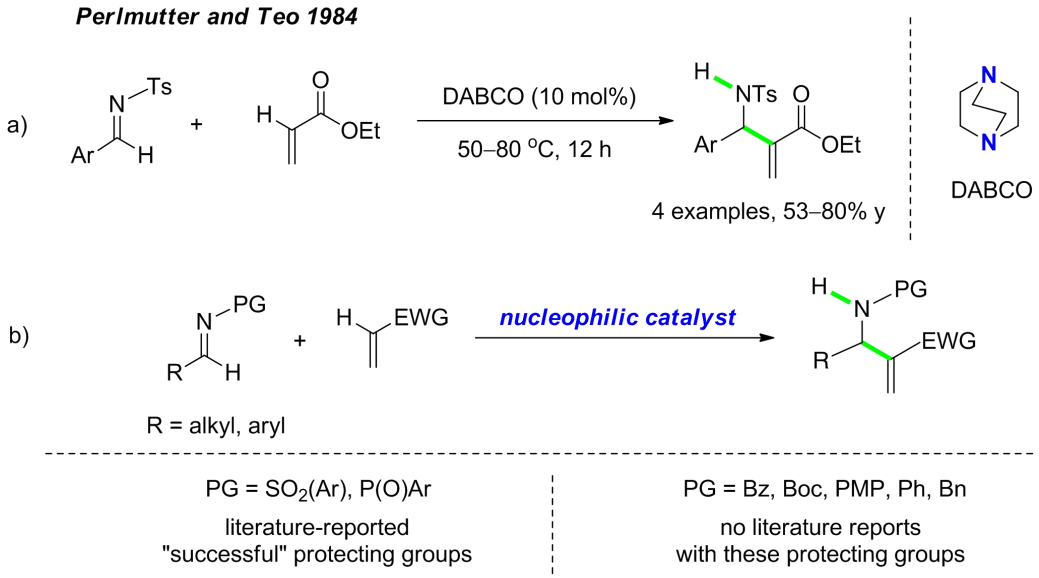


Scheme 1.16 First examples and commonly accepted mechanism of the MBH reaction[23,24]

The commonly accepted mechanism of the MBH reaction is shown in Scheme 1.16c).[22] The catalytic cycle is initiated by the conjugate addition of the Lewis basic catalyst to an electron-deficient alkene to generate zwitterionic enolate **I**. This nucleophile may add to the carbonyl group of the electrophile to

generate the C–C bond with adduct **II**. The following intermolecular proton transfer would lead to another zwitterionic intermediate **III**, which may undergo β-elimination to regenerate the initial C=C double bond thereby releasing the nucleophilic catalyst.

In addition, aldimines were shown to participate –as electrophiles– in this transformation provided these are sufficiently activated by an electron-withdrawing *N*-protecting group; in turn, this process has been called the aza-Morita–Baylis–Hillman (aza-MBH) reaction (Scheme 1.17).[22] The first aza-MBH reaction was reported in 1984 by Perlmutter and Teo using aromatic *N*-tosyl aldimines and ethyl acrylate as substrates in the presence of a cyclic tertiary amine, DABCO, as a catalyst [Scheme 1.17a)].[25] Subsequently, aliphatic aldimines and various Michael acceptors have been explored [Scheme 1.17b)]; the key to the imine's reactivity has proved to be the corresponding *N*-protecting group, which must be of sufficient electron-withdrawing character.



Scheme 1.17 First example and general scheme of the aza-MBH reaction[25]

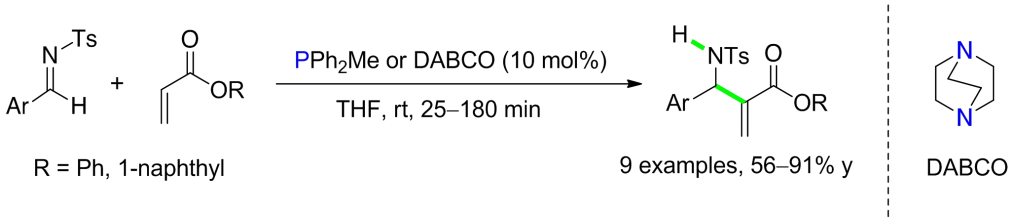
Catalytic (aza-)MBH reactions have evolved substantially over the past few years. The reasons for this fast growth may be attributed to the advantages of these transformations:[26] ***(i)*** the starting materials are commercially available or easily accessible, and the reactions are suitable for large-scale production; ***(ii)*** the reactions are atom-economic – waste is not generated; ***(iii)*** the products are flexible and multi-functional, thus facilitating further chemical transformations; ***(iv)*** a metal-free nucleophilic organocatalyst is typically sufficient for activity; ***(v)*** fairly mild reaction conditions may be used.

1.2.5.1 Aza-Morita–Baylis–Hillman Reactions in Literature

After the discovery of the first aza-MBH reaction more than 30 years ago [see Scheme 1.17a)], organocatalytic aza-MBH reactions were investigated in more detail in order to achieve high yields for a broad variety of electrophiles and pro-nucleophiles.

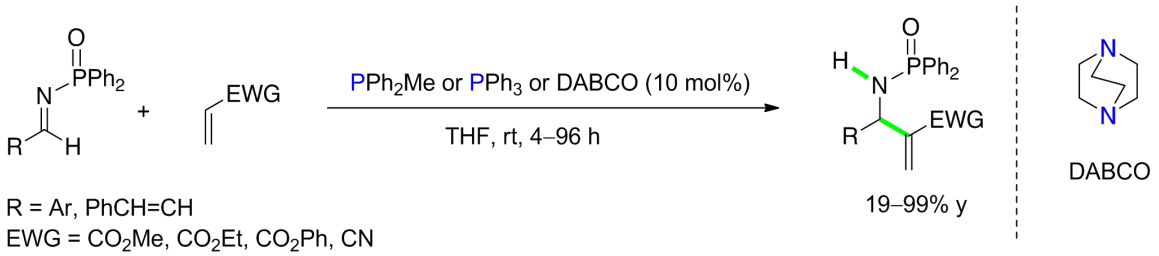
Acrylates, acryl amides, and acrylonitrile as pro-nucleophiles

In 2004, Shi *et al.* used two different Lewis basic catalysts, PPh_2Me or DABCO, to catalyze the aza-MBH reaction between aromatic *N*-tosyl aldimines and aromatic acrylates (Scheme 1.18).[27] The corresponding aza-MBH adducts were obtained in 56–91% yields.



Scheme 1.18 aza-MBH reactions between aromatic *N*-tosyl aldimines and aromatic acrylates[27]

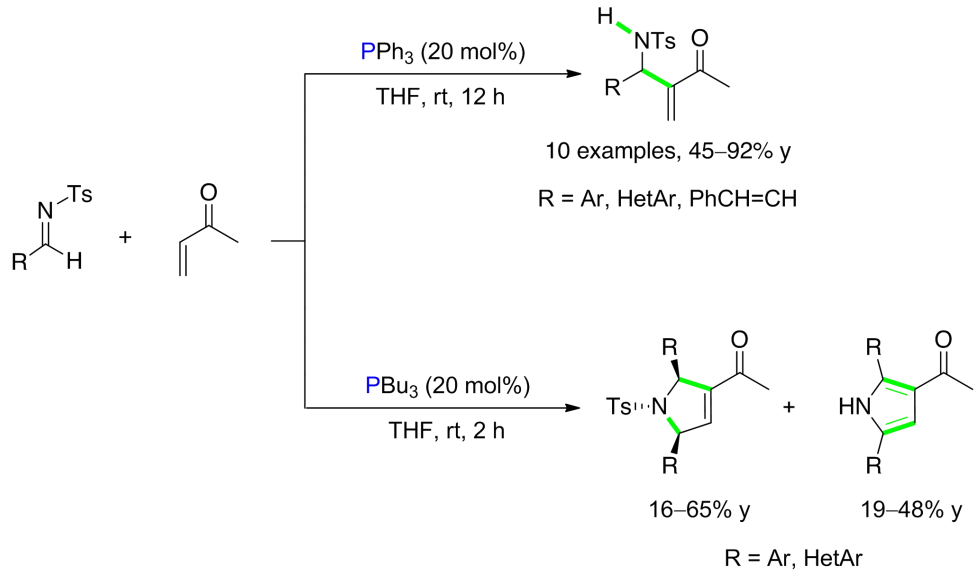
Similarly, in 2002 and 2004, *Shi et al.* reported catalytic aza-MBH reactions between *N*-phosphinoyl aldimines and acrylates or acrylonitrile (Scheme 1.19).[28,29] The corresponding aza-MBH adducts were obtained in 19–99% yields. It is important to note that the use of a less reactive pro-nucleophile, acrylamide, required a stoichiometric amount of the catalyst.



Scheme 1.19 aza-MBH reactions between *N*-phosphinoyl aldimines and different Michael acceptors[28,29]

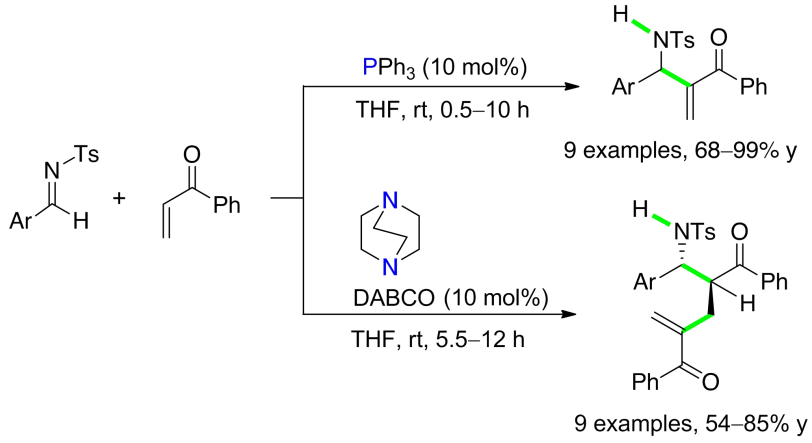
α,β-Unsaturated ketones as pro-nucleophiles

In 2002, Shi *et al.* reported phosphine-catalysed aza-MBH-type reactions between *N*-tosyl aldimines and methyl vinyl ketone (Scheme 1.20).[30] The corresponding "normal" aza-MBH adducts were obtained in 45–92% yields when PPh_3 was used as a catalyst. On the other hand, two cyclized products were observed in moderate yields when a more nucleophilic catalyst, PBu_3, was used.



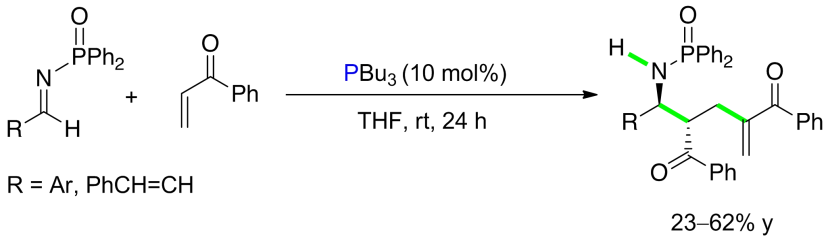
Scheme 1.20 PPh_3 vs. PBu_3 catalysis in aza-MBH-type reactions with methyl vinyl ketone[30]

In 2003, Shi *et al.* reported catalytic aza-MBH-type reactions between aromatic *N*-tosyl aldimines and phenyl vinyl ketone (Scheme 1.21).[31] The corresponding "normal" aza-MBH adducts were obtained in 68–99% yields when PPh_3 was used as a catalyst. However, when DABCO was used a "dimeric" aza-MBH product was obtained 54–85% yields as a single diastereoisomer (*anti*).



Scheme 1.21 PPh_3 vs. DABCO catalysis in aza-MBH-type reactions with phenyl vinyl ketone[31]

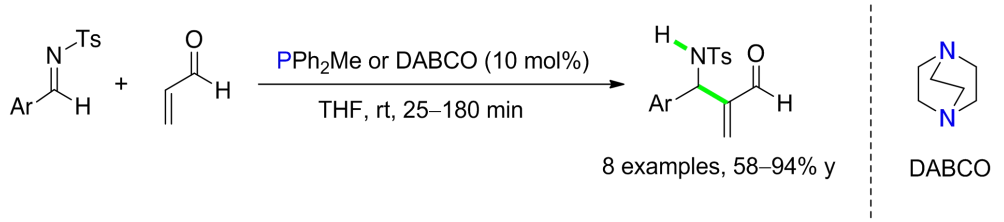
In 2004, Shi *et al.* reported a similar phosphine-catalysed aza-MBH-type reaction between *N*-phosphinoyl aldimines and phenyl vinyl ketone (Scheme 1.22); here, the "dimeric" aza-MBH adduct was obtained in 23–62% yields.[32]



Scheme 1.22 aza-MBH-type reaction between *N*-phosphinoyl aldimines and phenyl vinyl ketone[32]

Acrolein as a pro-nucleophile

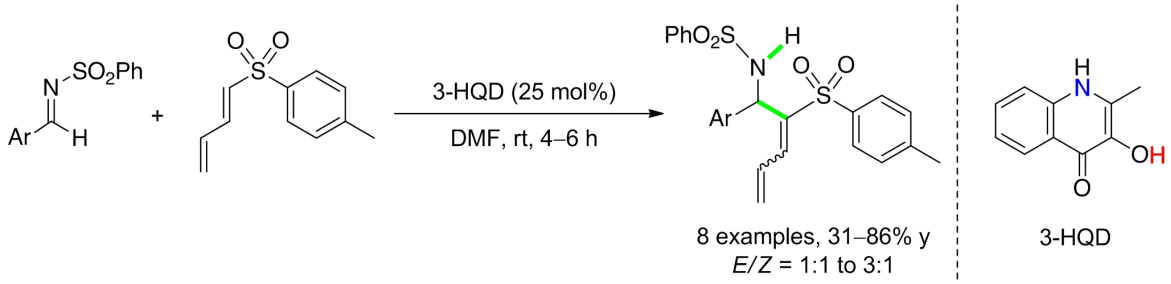
In 2004, Shi *et al.* developed a catalytic aza-MBH reaction between aromatic *N*-tosyl aldimines and acrolein (Scheme 1.23).[27] The corresponding aza-MBH adducts were obtained in 58–94% yields.



Scheme 1.23 PPh_2Me vs. DABCO catalysis in aza-MBH reaction with acrolein[27]

An α,β-unsaturated sulfone as a pro-nucleophile

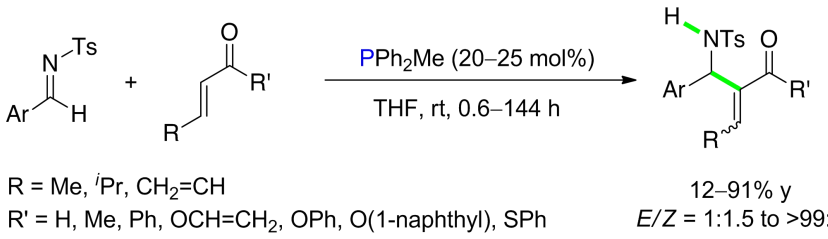
In 2005, Back *et al.* reported a dual catalytic aza-MBH reaction between aromatic *N*-tosyl aldimines and a buta-1,3-diene sulfone (Scheme 1.24).[34] 3-HQD was used as a dual acid–base catalyst to give the corresponding aza-MBH adducts in 31–86% yields as a mixture of *E* and *Z* geometric isomers.



Scheme 1.24 aza-MBH reaction between *N*-tosyl aldimines and sulfone[34]

β-Substituted Michael acceptors as pro-nucleophiles

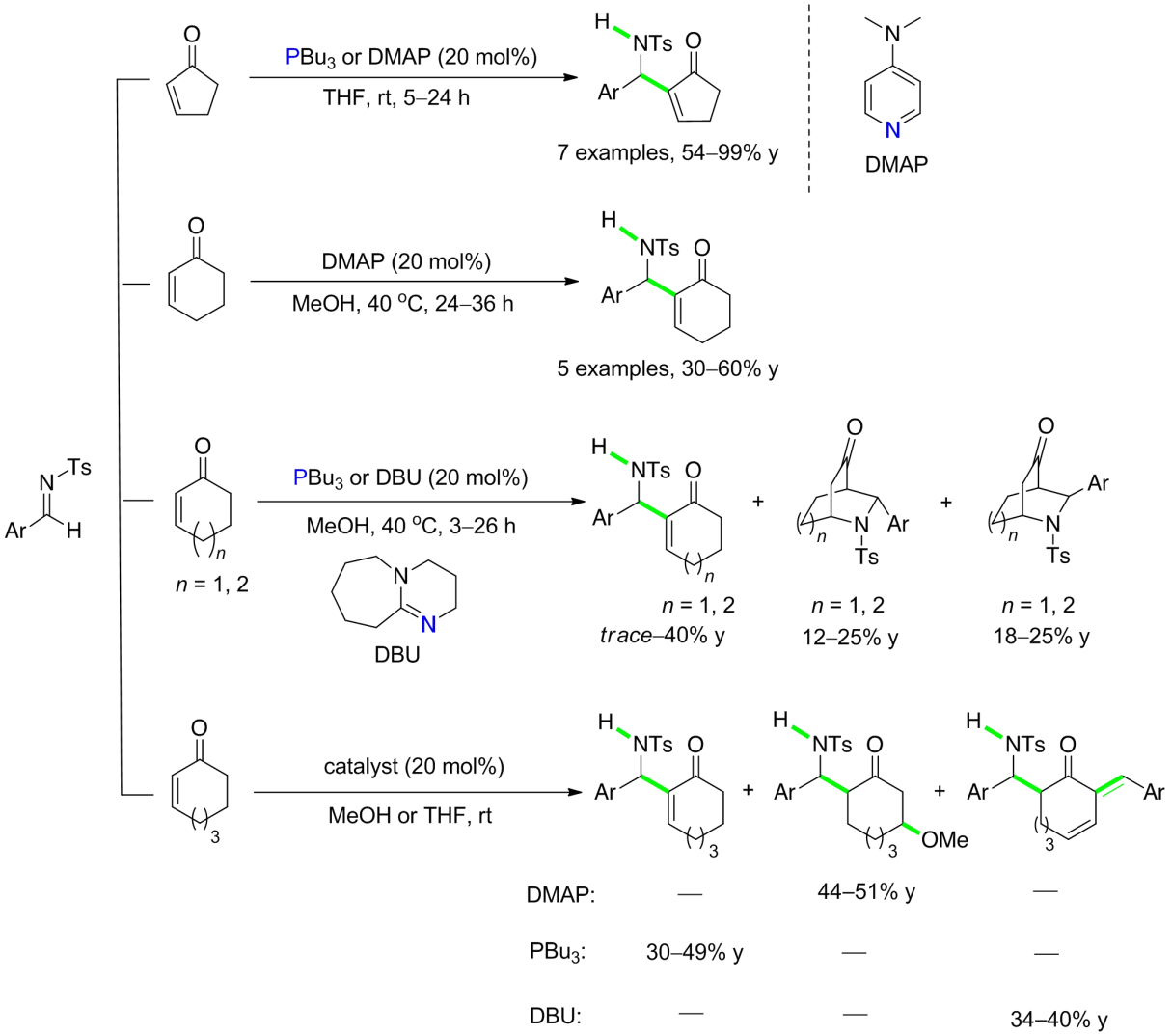
In 2004 and 2006, Shi *et al.* developed also phosphine-catalysed aza-MBH reactions between aromatic *N*-tosyl aldimines and different types of β-substituted Michael acceptors (Scheme 1.25).[35,36] The corresponding aza-MBH adducts were obtained in 12–91% yields as a mixture of *E* and *Z* geometric isomers.



Scheme 1.25 aza-MBH reaction of aromatic imines with β-substituted Michael acceptors[35,36]

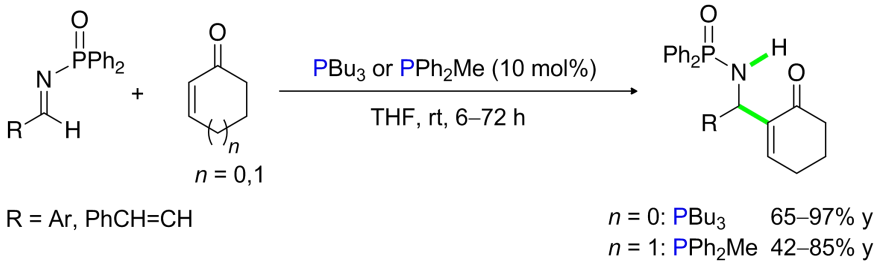
α,β-Unsaturated cyclic ketones as pro-nucleophiles

In 2002, Shi *et al.* reported catalytic aza-MBH-type reactions between aromatic *N*-tosyl aldimines and cycloalkenones (Scheme 1.26).[37] With cyclopentenone the corresponding aza-MBH adducts were obtained in 54–99% yields. The outcome for the use of cyclohexanone and cycloheptenone was shown to depend on the nature of the catalyst. With DMAP the corresponding aza-MBH adducts were obtained in 30–60% yields; on the other hand, the catalytic use of PBu_3 or DBU afforded the aza-MBH adducts in only up to 40% yield together with aza-Diels–Alder side-products in up to overall 50% yield. In case of cyclooctenone, various distinct products were observed selectively depending on the nature of the nucleophilic catalyst.



Scheme 1.26 aza-MBH-type reactions between aromatic *N*-tosyl aldimines and α,β-unsaturated cycloalkenones[37]

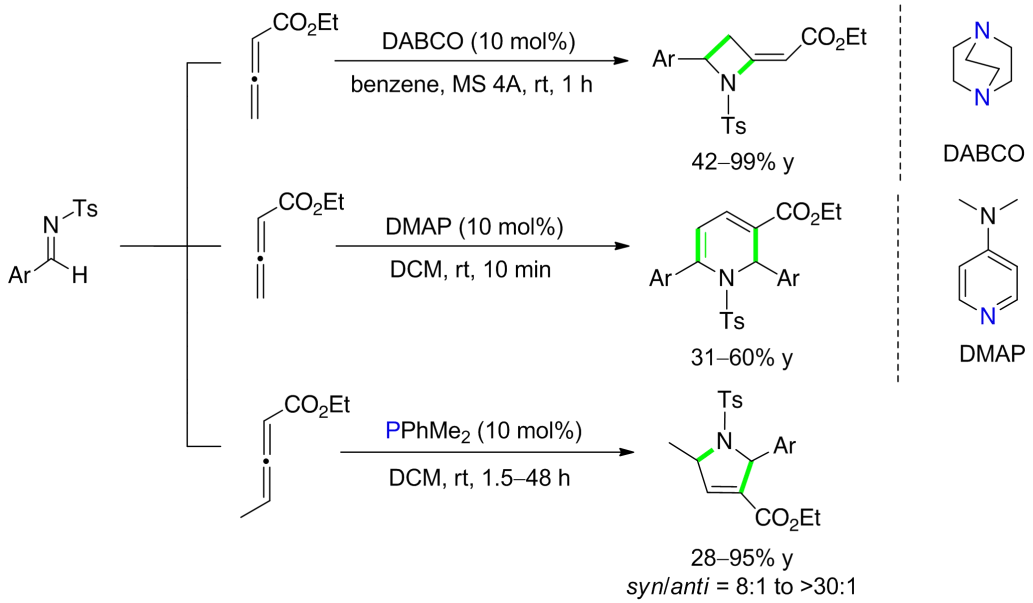
In 2004, Shi *et al.* reported phosphine-catalysed aza-MBH reactions between *N*-phosphinoyl imines and cycloalkenones (Scheme 1.27).[38] The corresponding aza-MBH adducts were obtained in 42–97% yields depending on the ring size of the Michael acceptor and the phosphine catalyst.



Scheme 1.27 aza-MBH reactions of *N*-phosphinoyl aldimines and cyclic ketones[38]

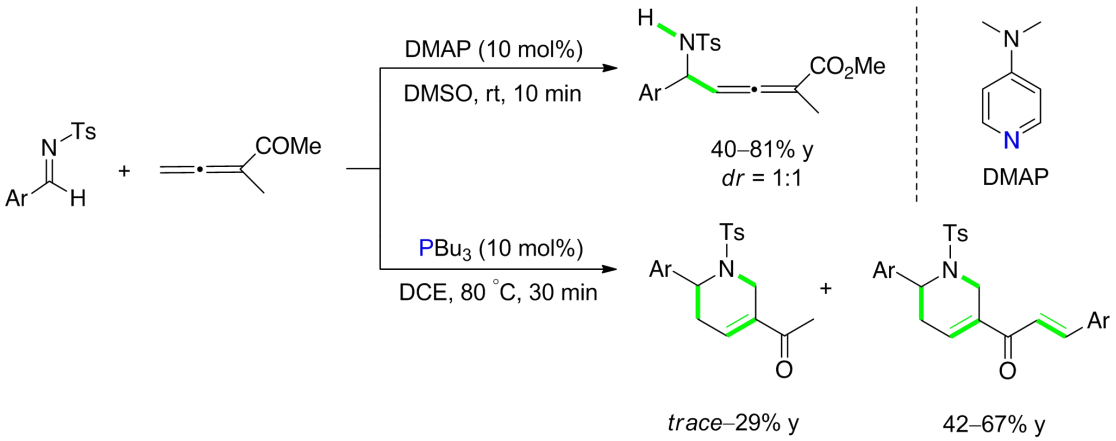
Allenic esters as pro-nucleophiles

In 2003, Shi *et al.* reported catalytic aza-MBH-type reactions between aromatic *N*-tosyl aldimines and various allenic esters (Scheme 1.28).[39] When DABCO was used as the catalyst, the corresponding azetidine products were formed in 42–99% yields through a formal [2+2] cycloaddition. In contrast, with DMAP as a catalyst, dihydropyridine products were observed in 31–60% yields. Interestingly, Shi *et al.* reported the formation of [3+2] cycloaddition products in 28–95% yields starting from a β-substituted allenic ester in the presence of a phosphine catalyst.[42] The observed diastereoselectivities proved to be synthetically useful.



Scheme 1.28 aza-MBH-type reactions of aromatic *N*-tosyl imine with allenic esters[39,42]

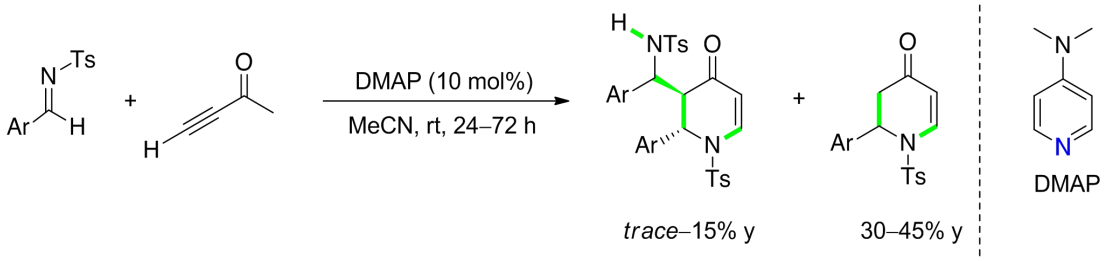
In 2005, Shi *et al.* also reported catalytic aza-MBH-type reactions between aromatic *N*-tosyl aldimines and an α-substituted allenic ester (Scheme 1.29).[40] In the presence of DMAP as a catalyst at room temperature, the corresponding aza-MBH adducts were formed in 40–81% yields as an equimolar mixture of diastereoisomers. On the other hand, the catalytic use of PBu_3 at 80 °C afforded two distinct tetrahydropyridine products in up to 67% yield through a formal [4+2] cycloaddition.



Scheme 1.29 aza-MBH-type reactions of aromatic *N*-tosyl imines with α-substituted allenic esters[40]

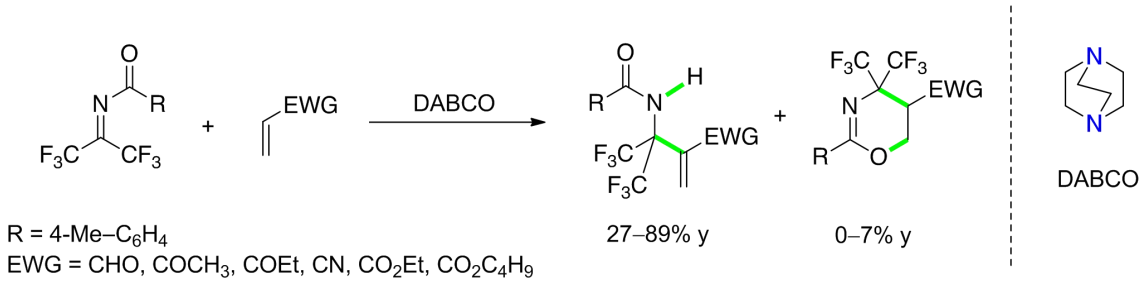
Miscellaneous examples

In 2005, Shi *et al.* used DMAP to catalyze the aza-MBH-type reaction between aromatic *N*-tosyl aldimines and but-3-yn-2-one (Scheme 1.30).[42] Here again, instead of the classic aza-MBH adduct two distinct tetrahydropyridine products were obtained in up to 45% yield through formal [4+2] cycloaddition pathways.



Scheme 1.30 aza-MBH-type reactions of aromatic *N*-tosyl aldimines with an alkynyl ketone[42]

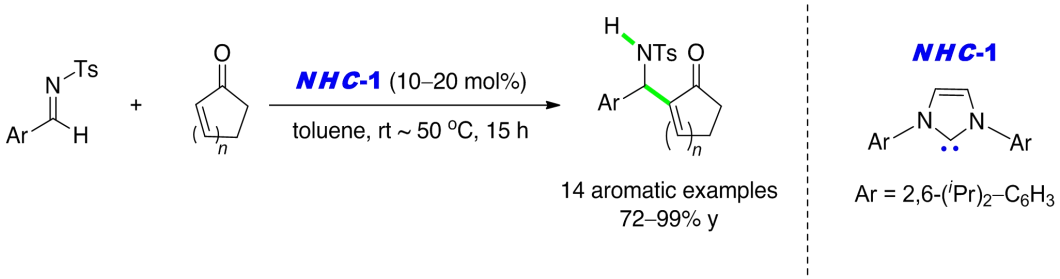
In 2001, Burger and Cyrener reported DABCO-catalysed aza-MBH-type reactions between an activated *N*-benzoyl ketimine and various Michael acceptors (Scheme 1.31).[33] The corresponding aza-MBH adducts were obtained in 27–89% yields together with traces of formal [4+2] cycloaddition side-products.



Scheme 1.31 aza-MBH type reactions between hexafluoroacetone-derived *N*-benzoylimine and Michael acceptors[33]

In addition to all phosphine and amine catalyses summarized above, Ye *et al.* reported in 2007 that an NHC was also apt to catalyze an aza-MBH reaction between a variety of aromatic *N*-tosyl aldimines

and two cycloalkenones (Scheme 1.32).[44] This transformation represents the first example of a carbene-catalysed aza-MBH reaction; the corresponding adducts were obtained in 72–99% yields. Drawbacks of this NHC catalysis include a limited scope (only two *cyclic* enones and only a limited number of *aromatic N*-tosyl aldimines; *no aliphatic* imines), rather harsh conditions (10–20 mol% catalyst loading and up to 50 °C), and the lack of an asymmetric version using an enantiopure NHC catalyst.

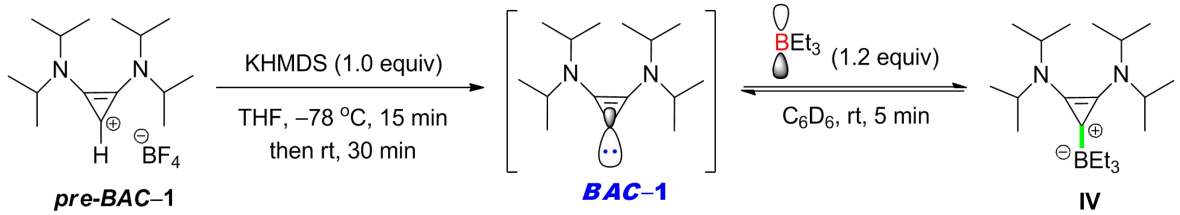


Scheme 1.32 First carbene-catalysed aza-MBH reaction[44]

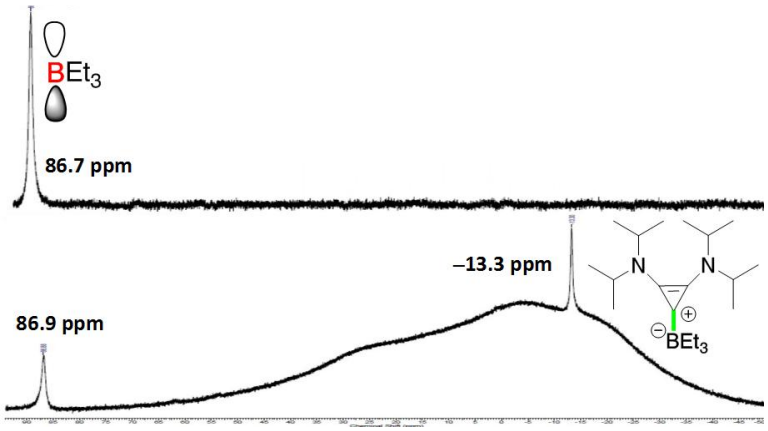
In light of this work and considering the distinct properties of BACs (stronger σ donor, less sterically demanding carbene), we anticipated that a BAC may be a more efficient catalyst for this important C–C bond formation. Overall, advantages may include: ***(i)*** the access to additional classes of Michael acceptors including α,β-unsaturated *aldehydes*, *acyclic* ketones, and *carboxylic acid* derivatives; ***(ii)*** a broader variety of accessible imines including various *aliphatic N*-tosyl aldimines, *ketimines*, and imines containing important *functional groups*; ***(iii)*** a substantially lower *catalyst loading*; ***(iv)*** the possibility of an *asymmetric* version using an enantiopure BAC catalyst.

1.2.5.2 Initial Experiments in BAC Catalysis

In order to test the feasibility of this BAC-catalysed C–C bond formation, a BAC was formed *in situ* according to Bertrand's method (see Scheme 1.11; P11) through deprotonation of a BAC precursor, ***pre-BAC*–1**, using one equivalent of a potassium amide (KHMDS) in THF at –78 °C (Scheme 1.33). The successful generation of ***BAC*–1** was confirmed by its subsequent reaction with triethyl borane (**B–1**) and ^{11}B NMR spectroscopic analysis of the formed boron–ate complex **IV**. The spectra of **B–1** and **IV** are displayed in Chart 1.6; an up-field shift from +87 ppm (tri-coordinate boron) to –13 ppm (tetra-coordinate boron) was observed, which confirmed the clean production of boron–ate complex **IV**. It is noted that a control reaction was also carried out using KHMDS and **B–1** resulting in the formation of a distinct boron–ate complex (–1.7 ppm). Hence, the successful *in situ* formation of the potential Lewis base catalyst, ***BAC*–1**, was demonstrated.



Scheme 1.33 *In situ* preparation of a BAC and subsequent formation of a boron–ate complex



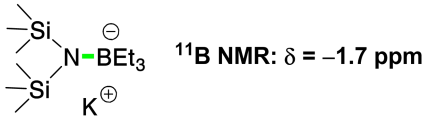
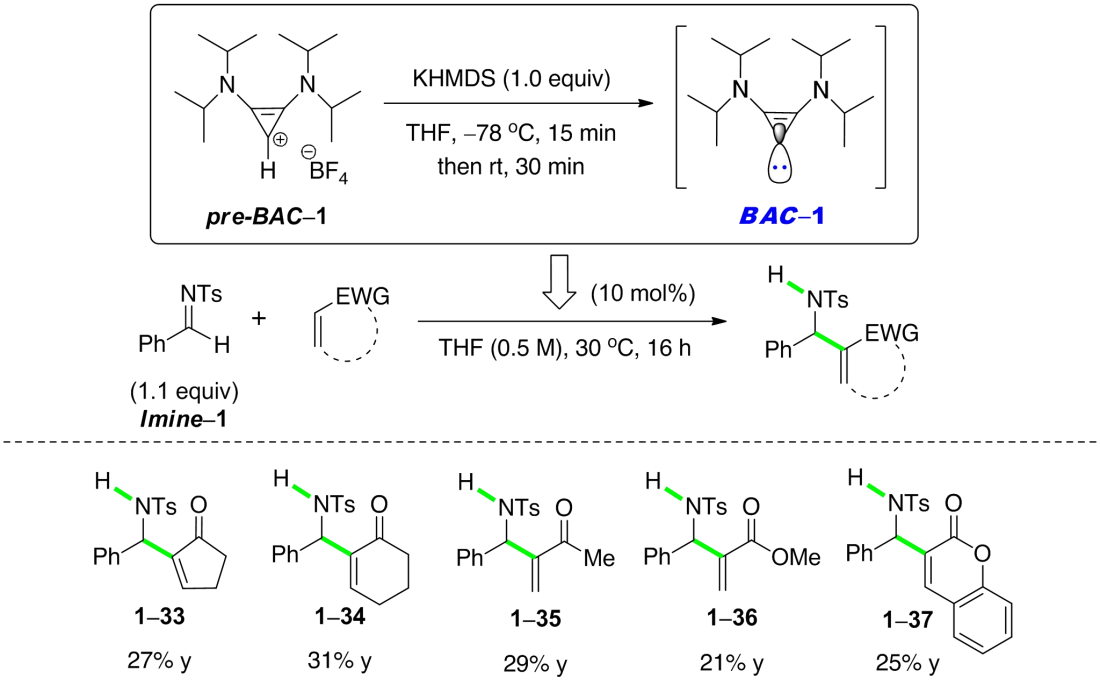


Chart 1.6 Comparison of ^{11}B NMR spectra for BEt_3 and the boron–ate complex involving a BAC

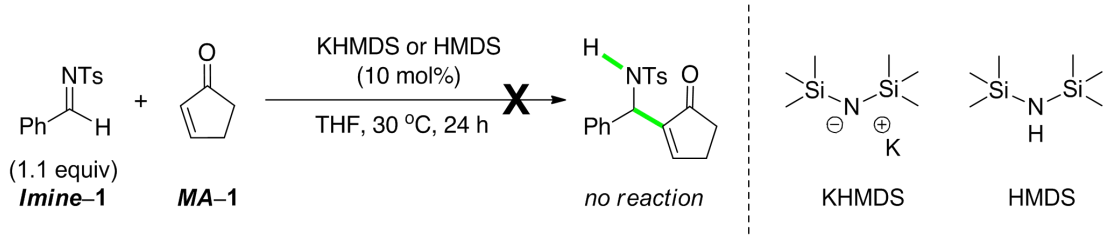
Next, a preliminary set of aza-MBH reactions was carried out using 10 mol% of the *in situ*-generated ***BAC*–1** (Scheme 1.34). The benzaldehyde-derived *N*-tosyl imine, ***Imine*–1**, and a variety of commercially available Michael acceptors –including cyclic and acyclic α,β-unsaturated ketones as well as carboxylic acid derivatives– were used as model substrates in this screening at 30 °C; the NMR yields were determined using dibenzyl ether (DBE) as an internal standard (^{1}H NMR spectroscopy of reaction aliquots taken after 16 h).



Scheme 1.34 Initial experiments of a BAC-catalysed aza-MBH reaction

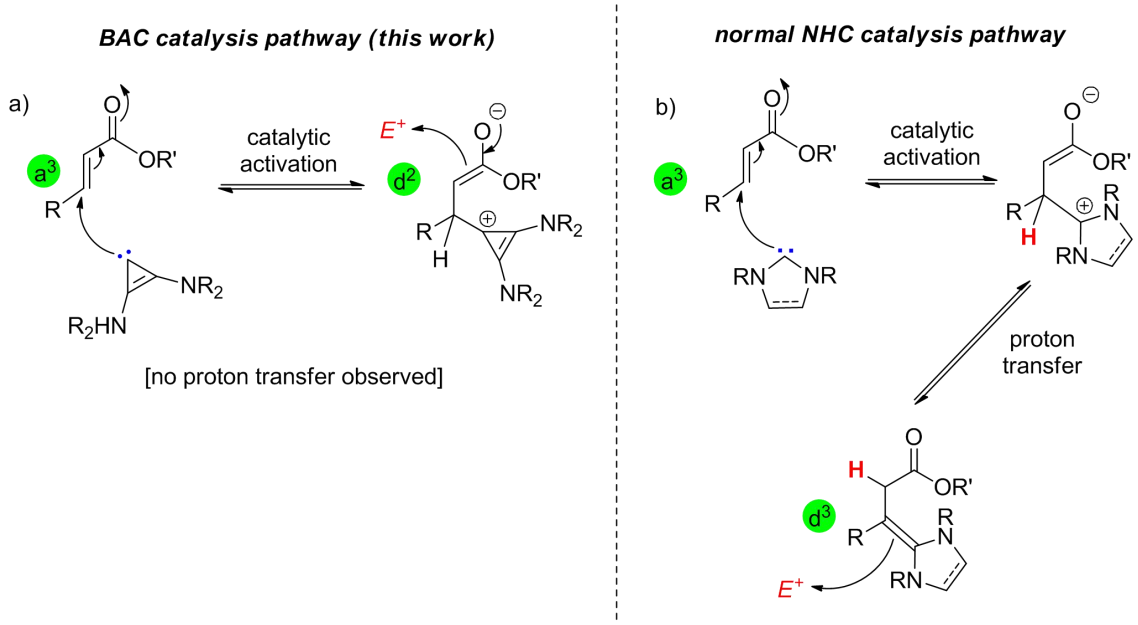
The intended C–C bond formations proceeded with *both* cyclic and acyclic ketones *and* esters, albeit in only 21–31% yields – however, a catalyst turnover was demonstrated (TON = 2–3). The only unreactive substrate proved to be acrylonitrile (**1–38**). It is important to point out that control

experiments were carried out using KHMDS and HMDS as potential catalysts under otherwise identical conditions (Scheme 1.35). Here, the aza-MBH adduct was not observed, which confirmed that the *in situ*-formed cyclopropenylidene, ***BAC*–1**, was the real catalyst in the experiments above.



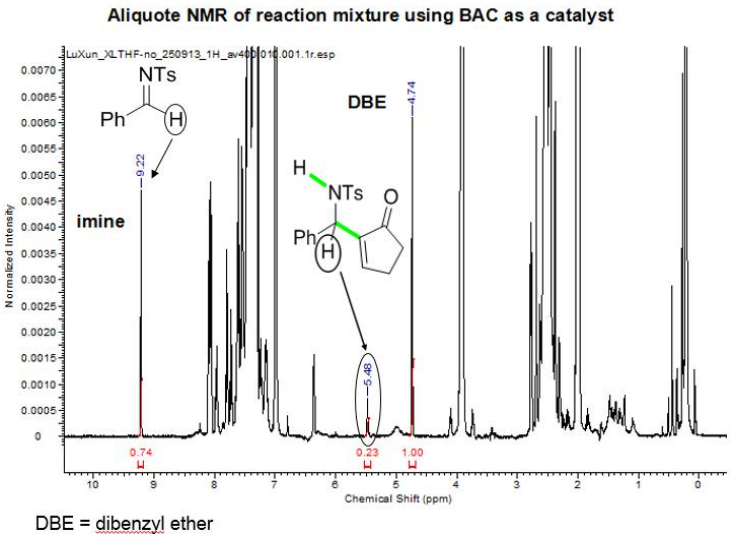
Scheme 1.35 Control experiments for catalytic aza-MBH reaction

Interestingly, in the case of the α,β-unsaturated ester and lactone, the observed products were formed through a BAC-catalysed a^3d^2 *umpolung* pathway [Scheme 1.36a)], which is clearly distinct from reported NHC catalysis with these types of pro-nucleophiles. Typically, under NHC catalysis these substrates undergo an a^3d^3 *umpolung* pathway to generate the corresponding *homoenolate* rather than a classic enolate [Scheme 1.36b)].[45]



Scheme 1.36 BAC vs. NHC catalysis in case of α,β-unsaturated carboxylic acid pro-nucleophiles[45]

As mentioned, the formation of the products was monitored by ^{1}H NMR spectroscopic analysis of reaction aliquots; a presentative example is shown for the reaction with cyclopentenone; the benzylic hydrogen atom in the aza-MBH adduct appeared at ~ 5.2 ppm (d, J = 8.4 Hz; Chart 1.7).



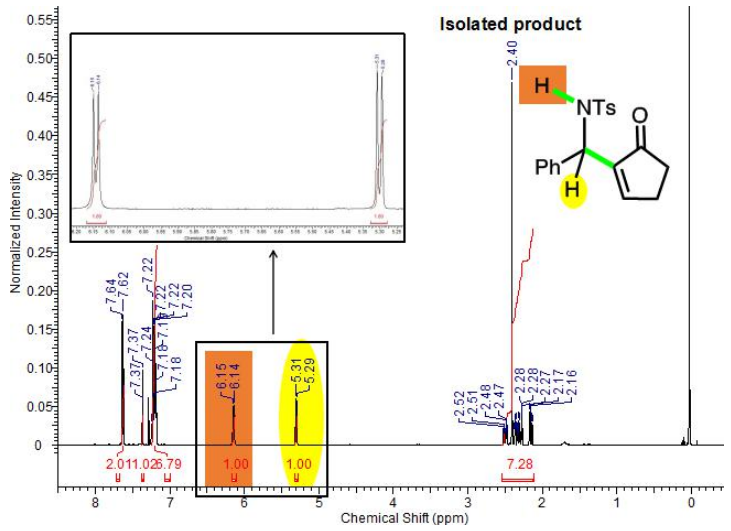
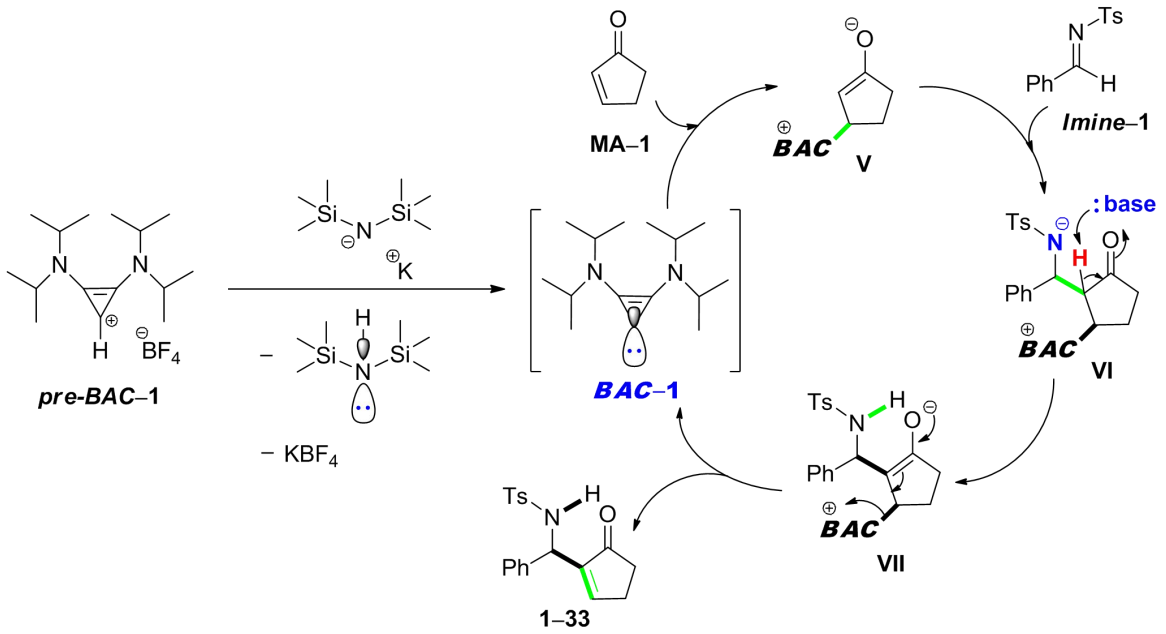


Chart 1.7 ^{1}H NMR spectroscopy of the aza-MBH product (DBE as an internal standard)

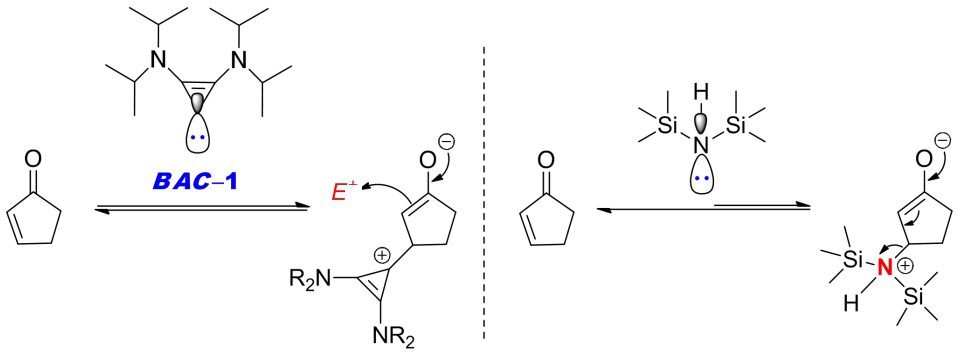
A plausible mechanism for this BAC-catalysed aza-MBH reaction is shown below (Scheme 1.37); it represents the classic pathway. As a nucleophile, ***BAC*–1** would add to the electrophilic β-position of ***MA*–1** to form zwitterionic enolate **V**. The latter would then add as a nucleophile to the electrophilic C=N double bond of ***Imine*–1** to generate the intended C–C bond in intermediate **VI**. The following intermolecular C-to-N proton transfer would lead to another zwitterionic enolate **VII**, which would undergo β-elimination to regenerate the C=C double bond in product **1–33** with concomitant regeneration the carbene catalyst, ***BAC*–1**.



Scheme 1.37 Proposed mechanism for the BAC-catalysed aza-MBH reaction

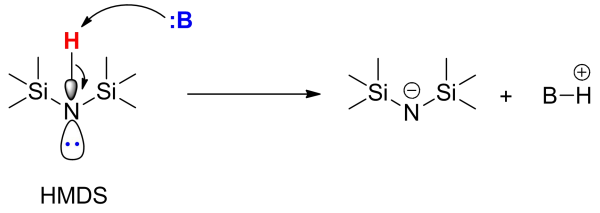
The proposed catalytic cycle is consistent with the commonly accepted mechanism published by Hoffman and supported by a kinetic study by Hill and Isaacs in the late-1980s.[46] They suggested that the C–C bond formation was the rate-determining step. In 2005 however, McQuade *et al.*[47,48] and Aggarwal *et al.*[49] independently re-evaluated the mechanism and demonstrated that the proton transfer, rather than C–C bond formation, was the rate-determining step.

Our promising early results encouraged us to further investigate this BAC catalysis. However, the yields had to be substantially improved in order to develop an appropriate novel synthetic method. One issue may be the use of a metal amide in the *in situ* BAC generation because a secondary amine (HMDS) was formed as a by-product (Scheme 1.37). Despite the fact that HMDS itself does not catalyze this C–C bond formation, the presence of a secondary amine may hamper the catalyst turnover. The structural differences between the BAC and HMDS result in different electronic and steric properties. In case of HMDS, the two bulky trimethylsilyl groups are located adjacent to the basic nitrogen atom. On the other hand, the bulky diisopropylamino groups in the BAC are located at a more distant position relative to the basic carbon atom. Thus, a BAC is considered to be sterically less hindered than HMDS; in turn, a BAC may add more easily to electrophiles than HMDS. Moreover, once the BAC is added to an electrophile, a 2π aromatic system (cyclopropenium) ion is formed (Scheme 1.38, *left*); therefore, the generated zwitterionic enolate should be well stabilized. Both BAC and HMDS can be considered as good leaving groups. A lower pK_a value represents a weaker conjugate base, i.e., a better leaving group, the corresponding pK_a value may account for the observed experimental results. The significantly lower pK_a value of an ammonium ion (~9–12 in DMSO)[50] compared with a cyclopropenium ion (estimated to be ~20 in DMSO)[51] indicates that HMDS should be a substantially better leaving group than a BAC. Thus, the HMDS-based zwitterionic enolate should be significantly less stable (Scheme 1.38, *right*).



Scheme 1.38 BAC vs. HMDS in the activation of cyclopentenone

Under certain conditions, HMDS may also potentially act as a weak Brønsted acid. Indeed, both the formed enolate or the BAC may deprotonate HMDS to liberate a basic amide, which may hamper the normal reaction pathway (Scheme 1.39).



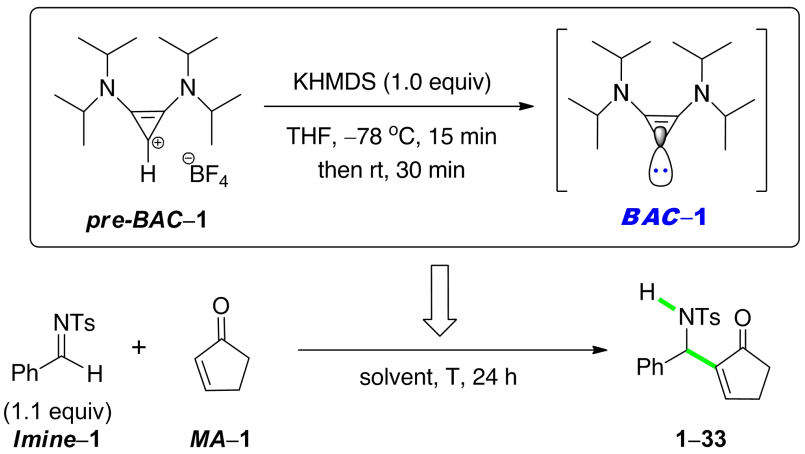
Scheme 1.39 Deprotonation of HMDS

In conclusion, although the catalyst turnover was low and acrylonitrile (**1–38**) proved to be unreactive, we established a proof-of-principle for BAC catalysis. The presence of a catalytic amount of HMDS in the reaction mixture may be a potential reason for the observed low yields. In turn, the reaction conditions for this BAC-catalysed aza-MBH reaction had to be optimized in order to obtain synthetically useful results.

1.2.5.3 Optimization and Control Experiments

First, a solvent screening was conducted for the model reaction between ***Imine*–1 and *MA*–1** using solvents of different polarity at 30 °C (Table 1.1). Here again, ***BAC*–1** was pre-formed in THF according to Bertrand's method[8] (see Scheme 1.11; P11).

Table 1.1: Solvent and temperature screening



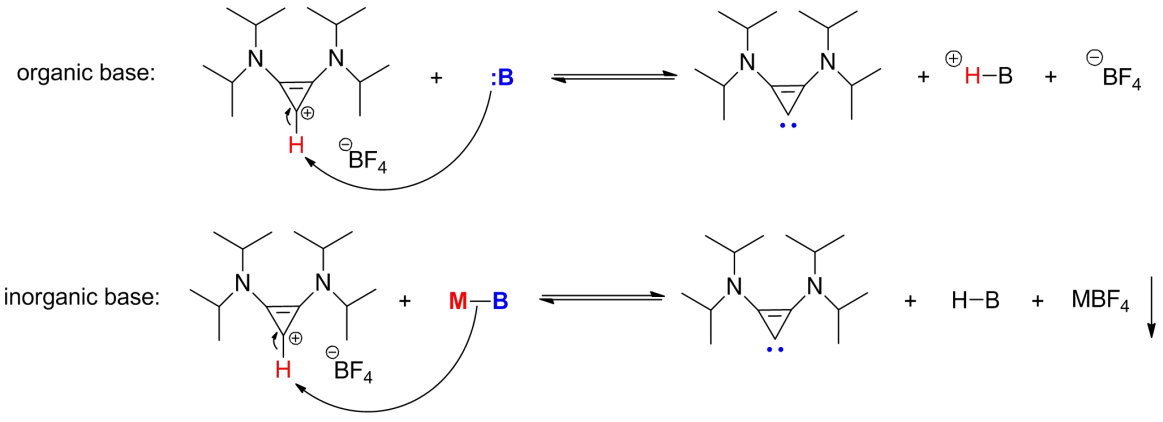
Entry	Solvent (Ɛ)	Temp (°C)	NMR yield (%)[a]	Mass Balance (*Imine*–1) / (*MA*–1) (%)[b]
1	dioxane (2.3)	30	10	98 / 97
2	toluene (2.4)	30	21	97 / 98
3	TBME (2.6)	30	31	96 / 96
4	Et_2O (4.3)	30	26	100 / 98
5	EtOAc (6.0)	30	19	93 / 88
6	DME (7.2)	30	38	97 / 98
7	TCE (7.3)	30	10	99 / 97
8	THF (7.5)	30	40	96 / 99
9	DCE (10.4)	30	9	102 / 100
10	MeCN (37.5)	30	18	95 / 99
11	TBME (2.6)	40	38	98 / 96
12	Et_2O (4.3)	40	45	92 / 100
13	DME (7.2)	40	43	97 / 99
14	THF (7.5)	40	61	96 / 95

[a] The yield was determined by ^{1}H NMR spectroscopic analysis of the reaction mixture; internal standard: dibenzyl ether (25 mol%). [b] Mass balance: the amount of product formed plus the amount of starting material remained.

First, different *apolar* solvents –including ethers, aromatic or chlorinated solvents, and an ester– were examined (entries 1–9). Among the ethers, TBME, Et_2O, DME, and THF provided product **1–33** in 31–40% yields (entries 3, 4, 6 and 8); the use of THF proved to be most effective (40%; entry 8). In literature, MBH and aza-MBH reactions typically rely on the use of a *polar aprotic* solvent,[34,37,42] which may stabilize the critical zwitterionic enolate. Interestingly however, the use of acetonitrile –a highly polar aprotic solvent with a high dielectric constant Ɛ[52]– proved to be less effective (entry 10). When the reaction in the most promising ethers was carried out at 40 °C, yields of **1–33** were slightly improved (entries 11–14); here again, THF was most efficient (61%; entry 14). Considering that a fairly high yield was obtained in a low-toxic solvent, THF was selected for further optimizations.

Optimization of the base co-catalyst

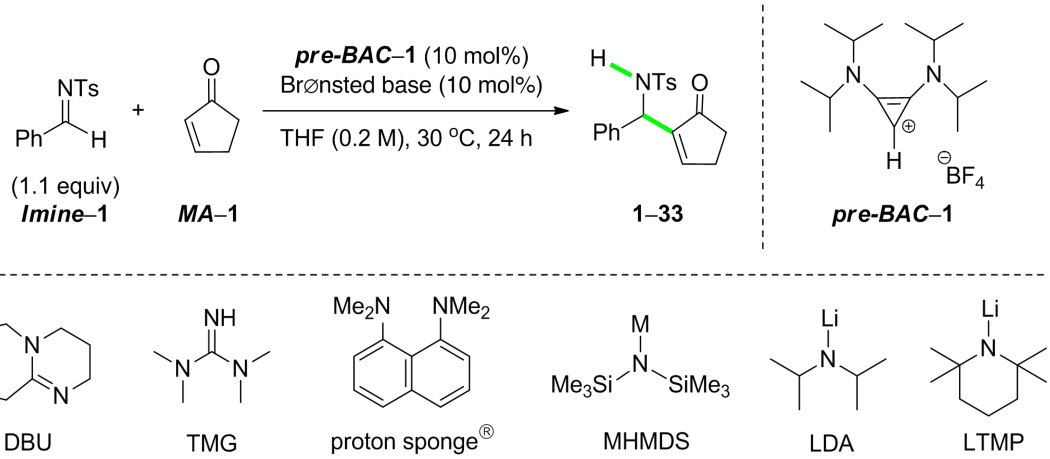
The role of the base co-catalyst is to deprotonate ***pre-BAC*–1** in order to generate *in situ* the reactive carbene catalyst, ***BAC*–1**; this step delivers as well the corresponding conjugate acid, which is expected to influence the reaction rate (Scheme 1.40).



Scheme 1.40 General method for the deprotonation of the BAC precursor

As mentioned, the obtained low yields of product **1–33** may be caused by the presence of HMDS, the conjugate acid of the base co-catalyst. In turn, next we examined the use of different base co-catalysts for the deprotonation of ***pre-BAC*–1**; a base screening for the model reaction in THF at 30 °C was carried out using a variety of organic and inorganic bases (Table 1.2). Here, ***BAC*–1** was prepared *in situ* in the presence of both substrates; the product yields were determined using DBE as the internal standard (^{1}H NMR spectroscopy).

Table 1.2: Brønsted base screening for the BAC-catalysed aza-MBH model reaction

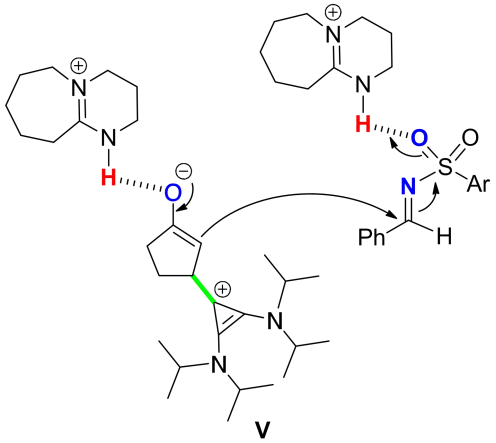


Entry	Pre-BAC	Brønsted base	NMR yield (%)[a]
1	+	–	*NR*[b]
2	+	KHMDS	26
3	+	NaHMDS	17
4	+	LiHMDS	10
5	+	LDA	12
6	+	LTMP	33
7	+	NaO^{t}Bu	*NR*[b]
8	+	KO^{t}Bu	24
9	+	Li_2CO_3	*NR*[b]
10	+	Na_2CO_3	26
11	+	K_2CO_3	36
12	+	Cs_2CO_3	57
13	+	DBU	79
14	–	DBU	*NR*[b]
15	+	TMG	60
16	+	proton sponge®	*NR*[b]
17	+	DBU (5 mol%)	76[c]
18	+	DBU (2 mol%)	64[d]
19	+	DBU (1 mol%)	90[e]

[a] The yield was determined by ^{1}H NMR spectroscopic analysis of the reaction mixture; internal standard: dibenzyl ether (25 mol%). [b] *NR* = no reaction; the desired product was not detectable, only unreacted starting materials were detected (^{1}H NMR analysis of the reaction mixture). [c] Reaction was carried out for 30 h. [d] Reaction was carried out for 48 h. [e] Reaction was carried out for 72 h.

Expectedly, the use of ***pre-BAC*–1** alone –in the absence of a base co-catalyst– did not afford aza-MBH product **1–33** (entry 1). Three types of metal–base co-catalysts were used in this screening; regarding amide bases (entries 2–6), the use of LTMP showed a better reactivity compared with MHMDS and LDA, but the yield of **1–33** was rather low (33%; entry 6). Regarding alkoxide bases (entries 7 and 8), the use of KO^{t}Bu displayed low reactivity, whereas product **1–33** was not detected when NaO^{t}Bu was used (entries 7 and 8). Among carbonate bases (entries 9–12), the use of Cs_2CO_3 afforded **1–33** in the highest yield (57%; entry 12). Next, several organic bases were examined (entries 13–16). The use of DBU as a base co-catalyst afforded **1–33** in a 79% yield (entry 13), whereas DBU alone displayed no activity (entry 14). In addition to the amidine base (DBU), a guanidine (TMG) and a diamine (proton sponge®) were used but proved less effective (entries 15 and 16). Overall, DBU was found to be the most effective base co-catalyst. It is important to note that the reaction still proceeded smoothly when a lower catalyst loading was used (1–5 mol%; entries 17–19). For instance, aza-MBH adduct **1–33** was obtained in 90% yield at 1 mol% carbene loading although a longer reaction time was required (entry 19).

Several factors may be considered to rationalize the efficiency of the base co-catalyst in this cyclopropenylidene-catalysed aza-MBH reaction: ***(i)*** solubility: according to our observation, DBU displayed a better solubility in THF than metal–base co-catalysts; when metal–base co-catalysts were used, a small amount of a solid at the bottom of the reaction vessel was observed, which may be only partially MBF_4; ***(ii)*** basicity: the acidity of the corresponding conjugate acid may play a role; a lower pK_a value represents a stronger conjugate acid, which means that the used base co-catalyst is weaker. The pK_a value of DBU–H$^+$ is high, which means that DBU is a strong base co-catalyst and therefore more of the active BAC catalyst should be formed *in situ*. In spite of the fact that the pK_a value of ^{t}BuOH is also high, the solubility issue may be one of the reason of low efficiency ***(iii)*** hydrogen bonding effect: despite its high pK_a value, DBU–H$^+$ may act as a hydrogen bond donor in order to stabilize the formed zwitterionic enolate and/or to increase the electrophilicity of the imine (Scheme 1.41); other conjugate acids may be less effective in this context.



V

Scheme 1.41 Nucleophilic addition of enolate intermediate to an imine electrophile

With DBU as the best base co-catalyst, the effect of various solvents was re-examined; these

experiments confirmed that THF was the most effective solvent in this *racemic* transformation. Interestingly, in contrast to literature reports,[74,75] the use of a polar aprotic solvent, acetonitrile, was substantially less efficient. Finally, the concentration of ***MA*–1** was optimized for the best reaction system (5 mol% DBU as base co-catalyst in THF at 30 °C; Chart 1.8).

Molarity (M)	Yield (%)
0.05	11
0.1	52
0.2	76
0.25	88
0.3	94
0.35	84
0.5	71
1.0	45

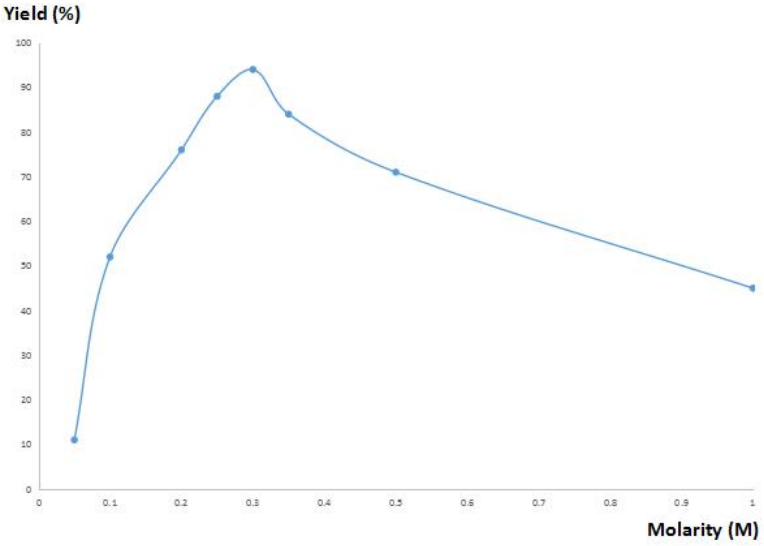


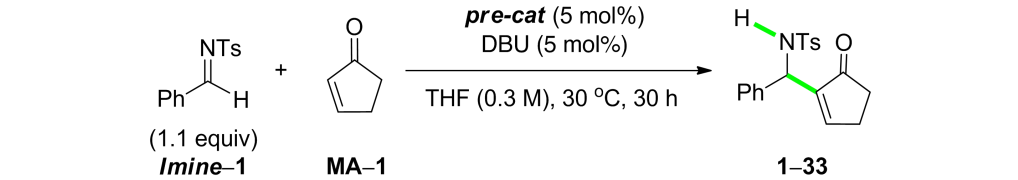
Chart 1.8 Optimization of the concentration of ***MA*–1**

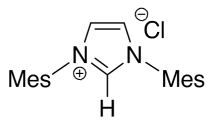
A variety of concentrations were tested (0.05–1.0 M). It was found that 0.3 M was the best concentration leading to a maximum product yield of 94%. The yield increased with an increasing concentration; however, if the concentration was too high, a detrimental effect was observed.

Control experiments with other carbenes

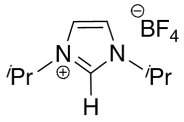
Next, we compared the developed BAC catalysis with the use of other carbenes: *in situ*-formed NHCs, a CAAC, and other BACs. All control reactions were carried out under the optimized conditions (Table 1.3).

Table 1.3: *Pre-BAC*–1 vs. other pre-carbene salts

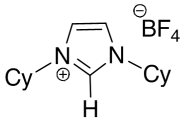




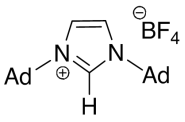
***pre-NHC*–2**
68% y



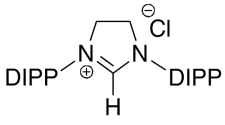
***pre-NHC*–3**
54% y



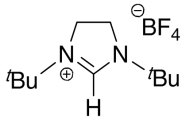
***pre-NHC*–4**
NR



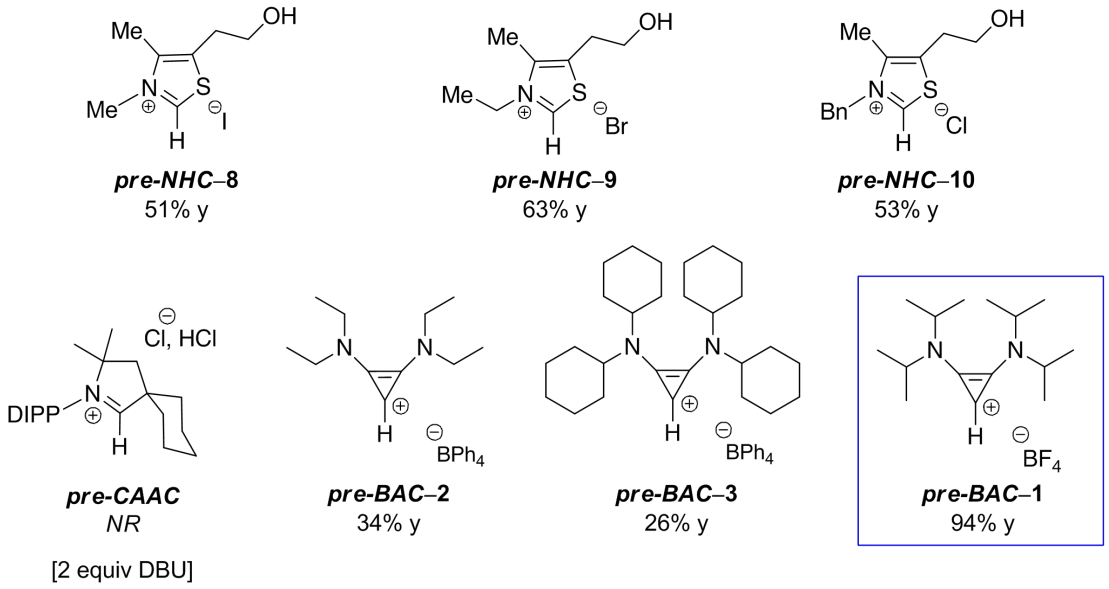
***pre-NHC*–5**
NR



***pre-NHC*–6**
68% y



***pre-NHC*–7**
NR

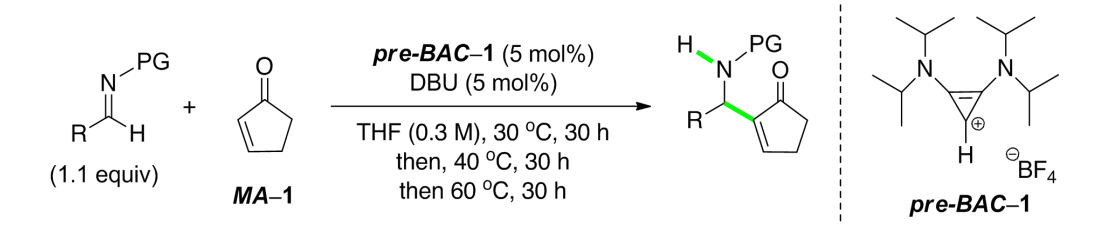


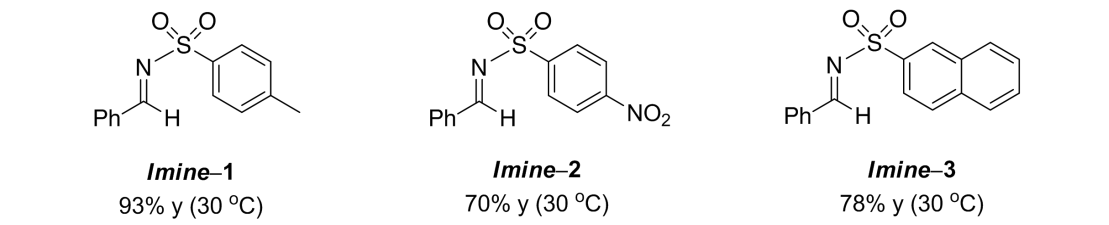
Several commercially available NHC precursors (***pre-NHC*–2 ~ *pre-NHC*–10**) proved to be tolerated pre-catalysts although the maximum yield of product **1–33** dropped to 68%. Interestingly, the *in situ*-generated CAAC did not display any catalytic activity under the mild conditions, which may be due to the steric demand of this carbene species. In addition, two other BAC pre-catalysts, ***pre-BAC*–2** and ***pre-BAC*–3**, proved to be rather ineffective. Potential reasons for this decreased catalytic activity include different steric demand (Et or Cy vs. ^{i}Pr) and counteranion (BPh_4^- vs. BF_4^-), which may result in differences regarding nucleophilicity (of the zwitterionic enolate) and solubility (of the conjugate acid). Overall, the initially used cyclopropenylidene precursor, ***pre-BAC*–1**, was shown to be the best pre-catalyst for the aza-MBH model reaction.

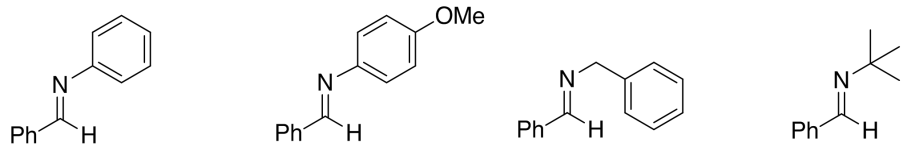
1.2.5.4 Substrate Scope

With the optimized BAC catalysis protocol in hand, the effect of the *N*-protecting group of benzaldehyde-derived imines was examined (Table 1.4).

Table 1.4 Influence of *N*-protecting group on the BAC-catalysed aza-MBH model reaction







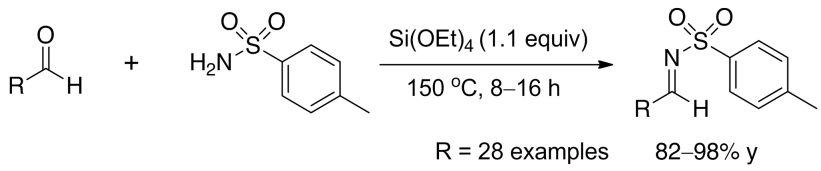
***Imine*–4**
NR (60 °C)

***Imine*–5**
NR (60 °C)

***Imine*–6**
NR (60 °C)

***Imine*–7**
NR (60 °C)

All imines with *N*-tosyl (***Imine*–1**), *N*-nosyl (***Imine*–2**), and *N*-nasyl (***Imine*–3**) protecting groups gave product **1–33** in high yields. ***Imine*–1** was found to be slightly more reactive than the two other imines. On the other hand, less electrophilic imines with less activating *N*-protecting groups, such as phenyl (***Imine*–4**), *para*-methoxyphenyl (***Imine*–5**), benzyl (***Imine*–6**), and *tert*-butyl (***Imine*–7**), were unreactive even at 60 °C; only starting materials were recovered. Considering the price of the commercially available sulfonyl amide precursors and the obtained yields, only the *N*-tosyl protecting group was considered for substrate scope. *N*-Tosyl aldimines were easily prepared from commercially available aldehydes, *N*-tosyl amide, and tetraethyl orthosilicate according to a literature method (Scheme 1.42).[54]

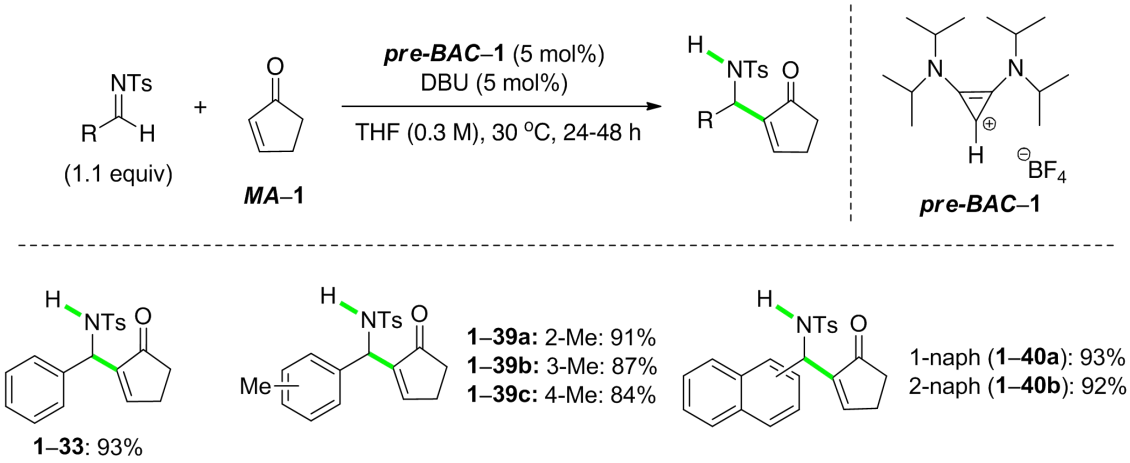


R = 28 examples 82–98% y

Scheme 1.42 Preparation of *N*-tosyl aldimines[54]

With a broad variety of aromatic, heteroaromatic, and aliphatic *N*-tosyl aldimines in hand, the scope of the BAC-catalysed aza-MBH reaction was investigated using cyclopentenone (***MA*–1**) under the optimized conditions (Table 1.5).

Table 1.5: Substrate imine scope for the BAC-catalysed aza-MBH reaction[a]



(1.1 equiv)

***MA*–1**

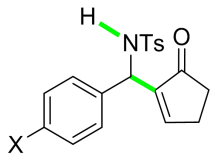
***pre-BAC*–1** (5 mol%)
DBU (5 mol%)
THF (0.3 M), 30 °C, 24-48 h

***pre-BAC*–1**

1–33: 93%

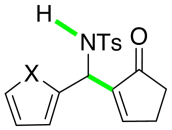
1–39a: 2-Me: 91%
1–39b: 3-Me: 87%
1–39c: 4-Me: 84%

1-naph (**1–40a**): 93%
2-naph (**1–40b**): 92%

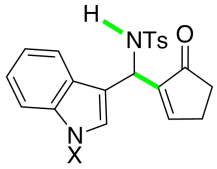


1–41: X = OMe: 92%
1–42: X = NMe_2: 92%
1–43: X = NH_2: 83%
1–44: X = OH: 70%
1–45: X = F: 91%

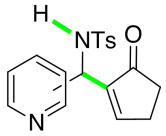
1–46: X = Cl: 95%
1–47: X = Br: 94%
1–48: X = CO_2Me: 94%
1–49: X = CF_3: 85%
1–50: X = CN: 91%
1–51: X = NO_2: 93%



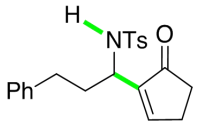
1–52: X = O: 83%
1–53: X = S: 92%
1–54: X = NH: 88%



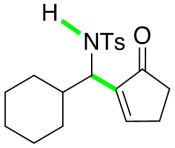
1–55: X = NH: 83%
1–56: X = NBoc: 89%



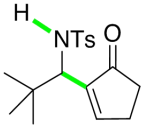
1–57: 2-pyr: 64%
1–58: 3-pyr: 76%
1–59: 4-pyr: 84%



1–60: 92%



1–61: 91%



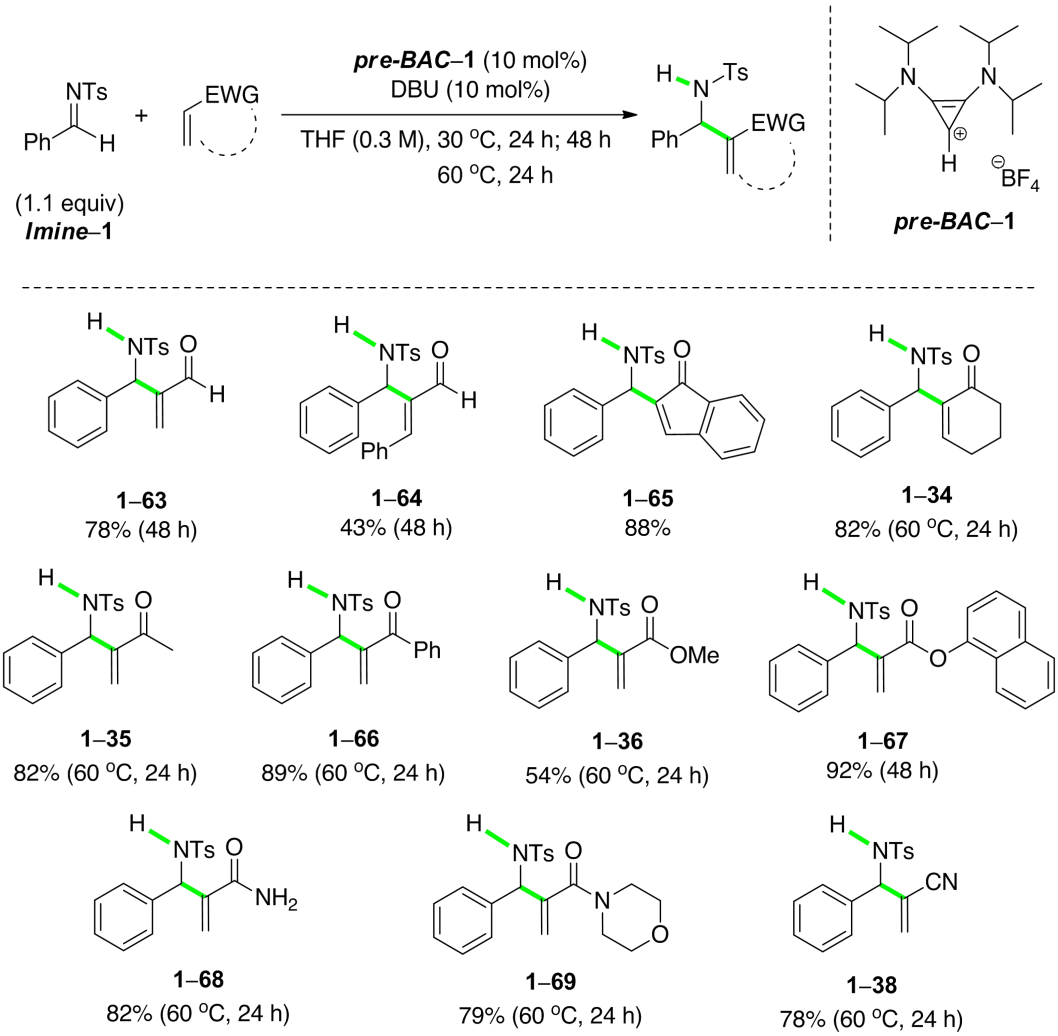
1–62: 78%

[a] Isolated yield of products after purification by preparative thin-layer chromatography (PTLC).

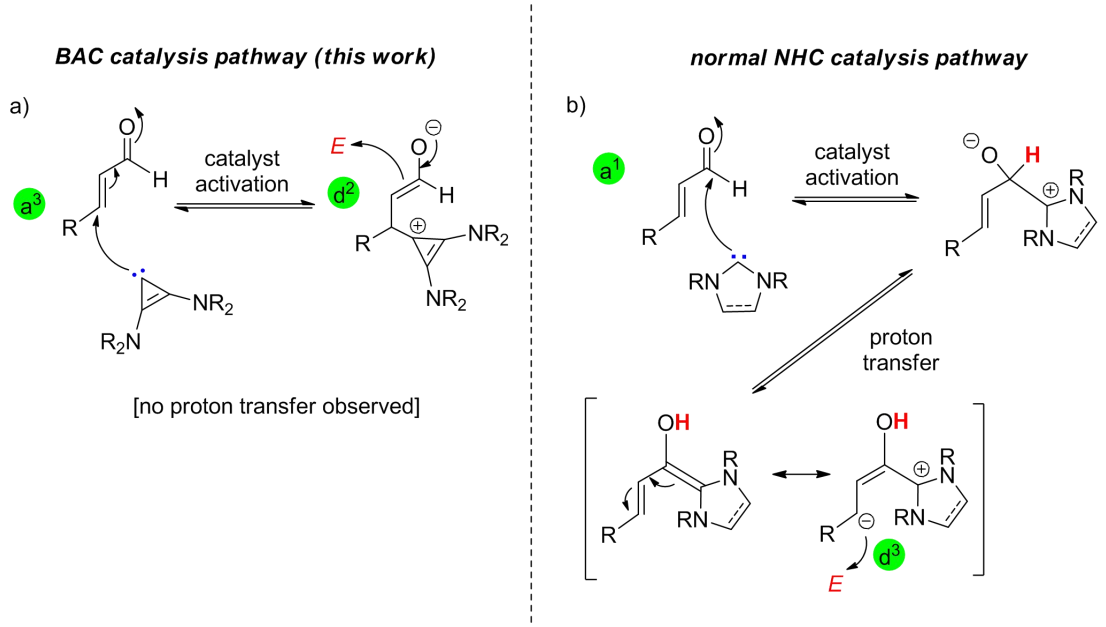
Interestingly, all aromatic imines with either electron-donating groups (Me, OMe, OH, NH_2, NMe_2) or electron-withdrawing groups (F, Cl, Br, CO_2Me, CF_3, CN, NO_2) were smoothly converted to the corresponding aza-MBH adducts in 84–95% isolated yields. In case of electron-withdrawing groups with a higher Hammett constant σ (CF_3: 0.54; CN: 0.66; NO_2: 0.78),[55] the reactions gave the corresponding products **1–49** ~ **1–51** in high yields after a short time reaction. It was found that some challenging functional groups such as unprotected OH and NH_2 groups (low σ values; OH: –0.37; NH_2: –0.66)[55] were also tolerated. Importantly, various heterocyclic imines with distinct electron demand also proved to be excellent substrates giving products **1–52** ~ **1–59** in 64–92% yields. It is noted that the cyclopropenylidene catalyst was also found to be compatible with primary, secondary, and tertiary *aliphatic* imines. In summary, the BAC-catalysed aza-MBH reaction between cyclopentenone (***MA*–1**) and various aromatic, heteroaromatic, and aliphatic imines has proceeded under mild conditions. Important functionalities such as amino and hydroxy groups have been tolerated. The electrophile scope for this BAC catalysis proved to be very broad and went far beyond the NHC catalysis reported by Ye.[44]

Next, we explored the scope of pro-nucleophiles for this aza-MBH reaction using ***Imine*–1** as electrophile (Table 1.6). Various types of Michael acceptors –including α,β-unsaturated aldehydes, cyclic or acyclic α,β-unsaturated ketones, and α,β-unsaturated carboxylic acid derivatives– were used at 30–60 °C.

Table 1.6: Pro-nucleophile scope for the catalytic aza-MBH reaction using ***pre-BAC*–1**



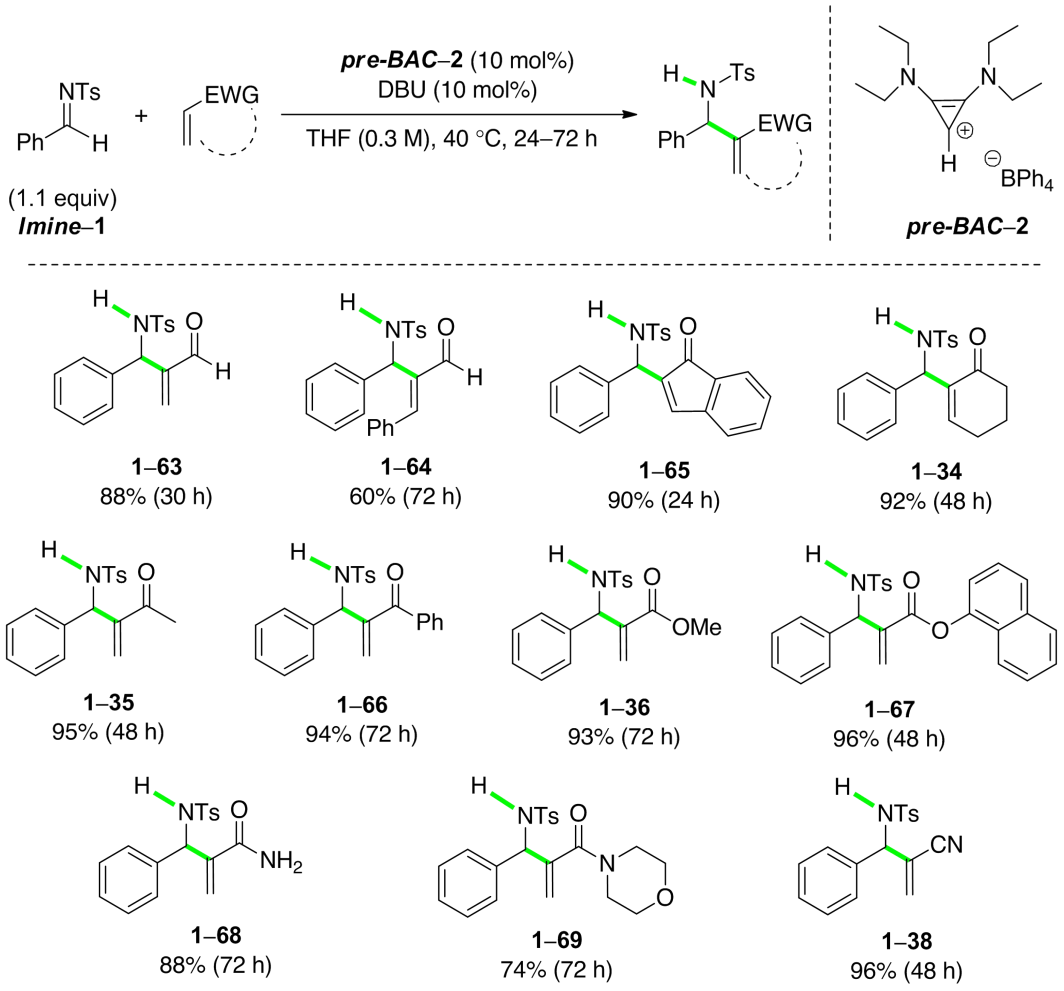
Michael acceptors such as α,β-unsaturated aldehydes, ketones, esters, amides, and acrylonitrile, were shown to be compatible to give the corresponding aza-MBH adducts **1–34** ~ **1–36**, **1–38**, and **1–63** ~ **1–69** in 43–92% yields even though in most cases a higher catalyst loading (10 mol%) and a higher temperature (60 °C) were required. Remarkably, the use of the two α,β-unsaturated aldehydes under *BAC* catalysis conditions resulted in a MBH-type a^3d^2 *umpolung* [Scheme 1.43a)]. Usually, under *NHC* catalysis these pro-nucleophiles undergo a "classic" a^1d^3 *umpolung* [Scheme 1.43b)].[56] In contrast to the initial trial (see Scheme 1.34; P33), even acrylonitrile (**1–38**) proved to be a successful substrate although under rather harsh conditions.



Scheme 1.43 BAC vs. NHC catalysis for Michael aldehyde pro-nucleophiles

Although a decent variety of pro-nucleophiles proved to react, the conditions were rather harsh (up to 60 °C). In turn, a less sterically demanding pre-catalyst, ***pre-BAC*–2**, was used with the aim to improve the results under milder conditions (Table 1.7).

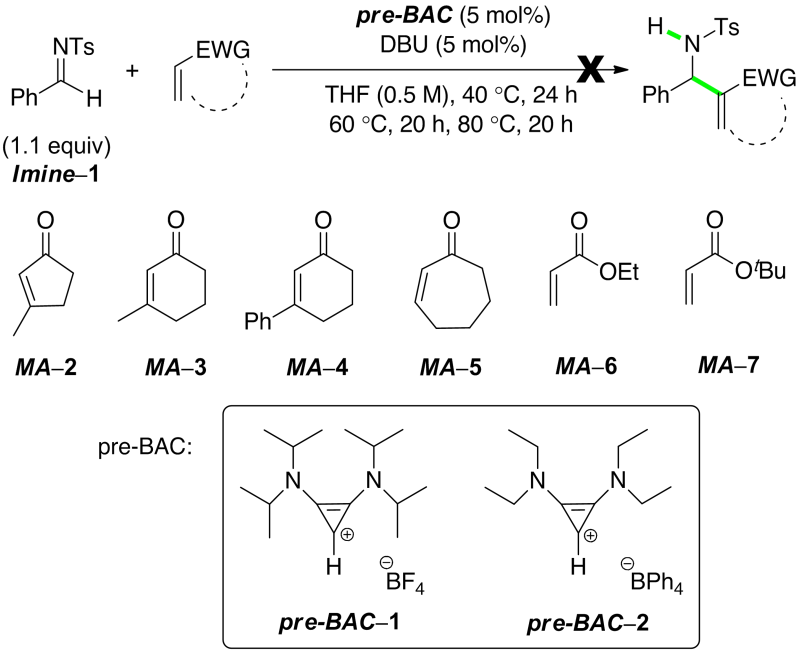
Table 1.7: Pro-nucleophile scope for the catalytic aza-MBH reaction using ***pre-BAC*–2**



Here, it was found that all Michael acceptors displayed good reactivity at 40 °C to give the corresponding aza-MBH adducts in 60–96% yields. This tendency may be due to the fact that the less sterically demanding cyclopropenylidene catalyst (Et vs. ^{i}Pr) was more apt to activate more challenging pro-nucleophiles.

Finally, even more challenging pro-nucleophiles were examined using the most efficient catalyst systems (Table 1.8). β-Substituted cycloalkenones ***MA*–2**, ***MA*–3**, and ***MA*–4**, and cycloheptenone (***MA*–5**) were found to be unreactive even at 80 °C; this lack of reactivity may be ascribed to the steric demand at the electrophilic site and the larger ring size, respectively. More sterically bulky Michael esters, such as ethyl and *tert*-butyl acrylate (***MA*–6** and ***MA*–7**), proved to be unreactive even under forcing conditions.

Table 1.8: Unsuccessful pro-nucleophiles in the BAC-catalysed aza-MBH reaction

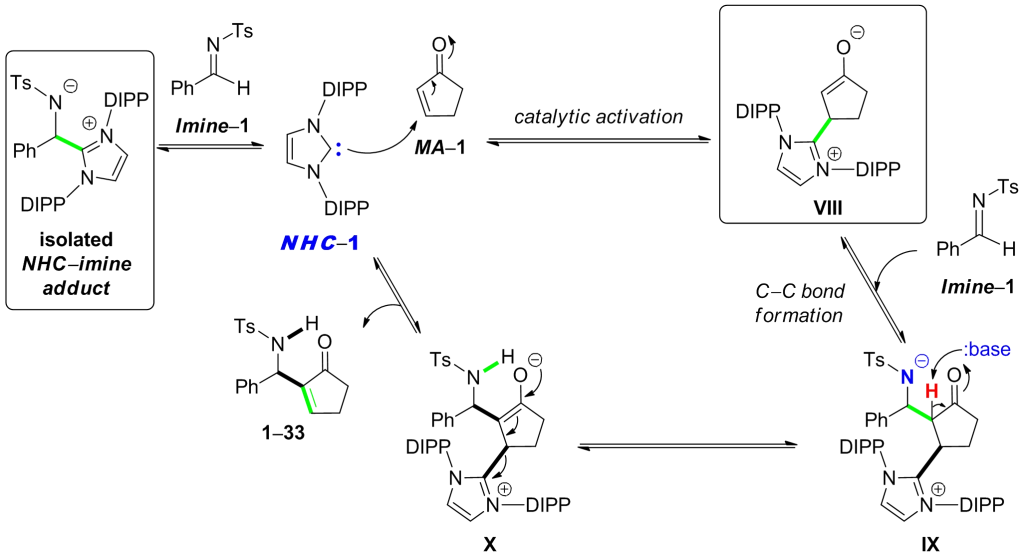


Next, we turned our attention to the reaction mechanism of this BAC catalysis with the aim to potentially detect reaction intermediates.

Detection of reaction intermediates

In Ye's work regarding the NHC-catalysed aza-MBH reaction,[44] a catalytic cycle was proposed that basically followed the classic aza-MBH mechanism (Scheme 1.44). The reaction between ***Imine*–1** and ***NHC*–1** resulted in the formation of the corresponding adduct, which was isolated in 82% yield. The reaction between this adduct and ***MA*–1** still afforded aza-MBH product **1–33**, which indicated that the addition of ***NHC*–1** to ***Imine*–1** was reversible, and the adduct represented a resting state of the carbene catalyst. In turn, a typical aza-MBH mechanism was proposed. The free NHC was would add as a nucleophile to the electrophilic β-position of cyclopentenone (***MA*–1**) to form zwitterionic enolate **VIII**. The latter would add to the C=N double bond of the *N*-tosyl imine to form a C–C bond. The following intermolecular C-to-N proton transfer in intermediate **IX** would lead to another zwitterionic

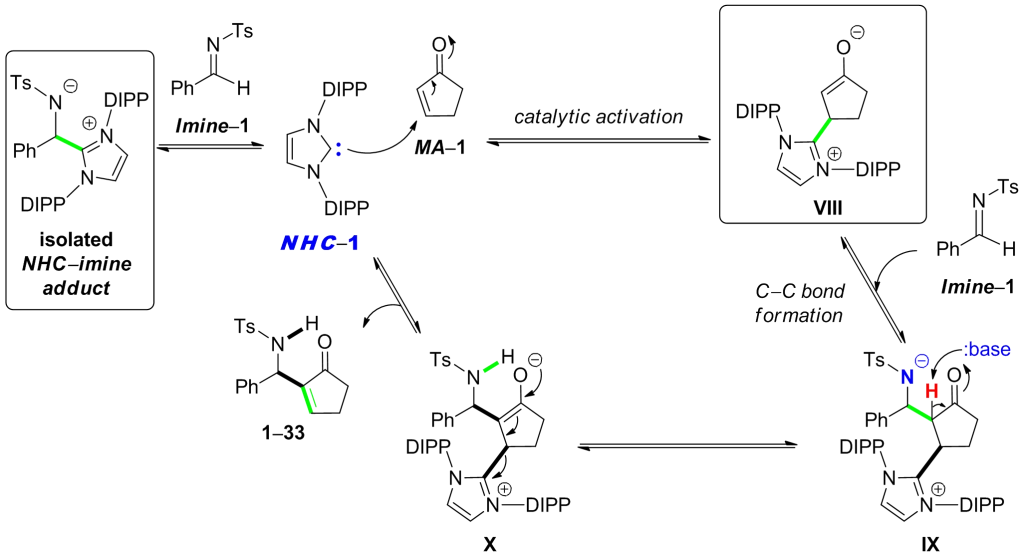
enolate **X**, which would undergo β-elimination to form the C=C double bond in product **1–33** with concomitant regeneration of the NHC catalyst.



Scheme 1.44 Proposed catalytic cycle for the NHC-catalysed aza-MBH reaction[44]

In order to provide further evidence for the proposed cycle, Ye *et al.* also conducted a reaction with an equimolar mixture of ***NHC*–1** and cyclopentenone (***MA*–1**) at room temperature. Although the thin-layer chromatography (TLC) showed the consumption of ***MA*–1**, the isolation of the anticipated intermediate **VIII** failed, and "*only some unidentified compounds were detectable*".[44]

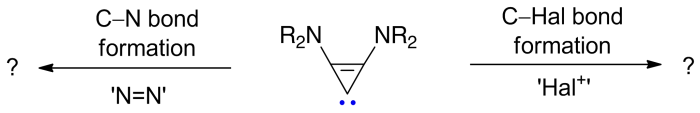
With these literature results in mind, we attempted to trap critical reaction intermediates (Scheme 1.45). In stoichiometric experiments, cyclopentenone (***MA*–1**) and *N*-tosyl imine (***Imine*–1**) were separately reacted with ***pre-BAC*–1** in the presence of DBU in THF. In case of ***MA*–1**, the proposed BAC-based enolate **V** was not detected in the reaction mixture; only a decreased amount of ***MA*–1** was observed (^{1}H NMR spectroscopy). In case of ***Imine*–1**, although a new singlet at ~ 5.0 ppm was observed (^{1}H NMR spectroscopy), efforts to isolate a potential adduct failed to date. At this stage, we assumed a classic aza-Morita–Baylis–Hillman mechanism (Scheme 1.45).



Scheme 1.45 Proposed catalytic cycle for the BAC-catalysed aza-MBH reaction

In this context, it is noted that Bertrand *et al.* reported a reactivity study using different stable cyclic and acyclic mono- and diamino carbenes in the presence of organic substrates such as methyl acrylate or benzaldehyde.[41] Similarly, transient species were not isolated, only the corresponding reaction products.

After the initial success with BAC-catalysed aza-MBH reactions, we were interested in extending this novel methodology to the use of other electrophiles, such as azodicarboxylates and halogenation reagents, in view of catalytic C–N and C–Hal bond formations (Scheme 1.46).



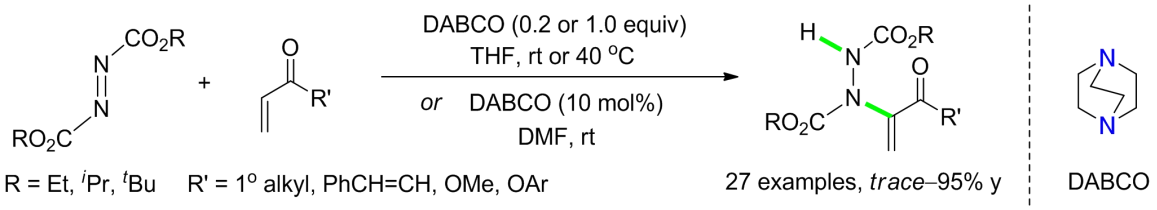
Scheme 1.46 Possibility for BAC-catalysed C–N and C–Hal bond formations

1.2.6 α-Hydrazination of Michael Acceptors

1.2.6.1 Literature: Azodicarboxylates in MBH-Type Reactions

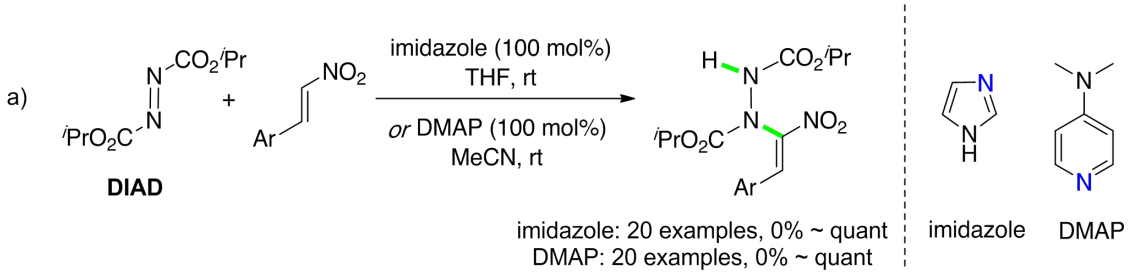
Although the coupling of the α-position of activated alkenes (vinyl anion equivalents) with various carbon electrophiles has emerged as an important C–C bond formation in organic synthesis, the equally important C–X bond formation through a similar strategy has received less attention.[57] In fact, the electrophilic amination of carbanion equivalents is an important C–N bond-forming strategy offering a convenient entry into both natural and non-natural amino acids and other synthetically and biologically useful building blocks.[58] Commonly used electrophiles for this purpose are azodicarboxylates, azides, oxaziridines etc.

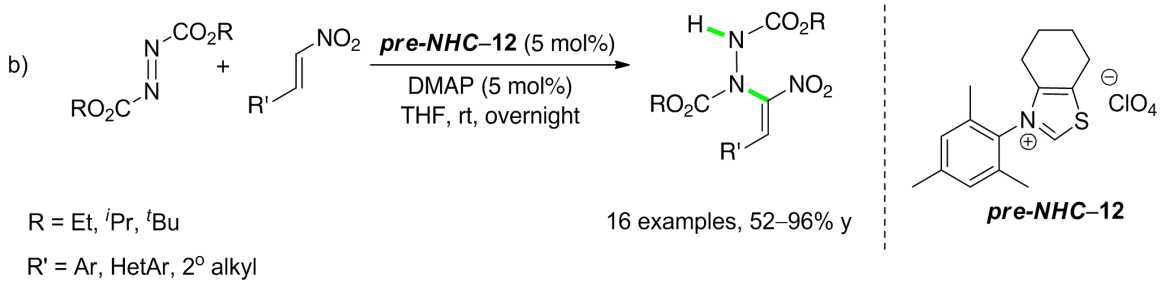
In 1998, Kamimura *et al.* used DABCO to mediate an aza-MBH-type reaction between diethyl azodicarboxylate (DEAD) or di-*tert*-butyl azodicarboxylate and α,β-unsaturated *ketones* in THF (Scheme 1.47).[59] The corresponding products were obtained in high yields. Most of these reactions required a high catalyst loading or even a stoichiometric amount of DABCO. In contrast, the corresponding reaction between DEAD and different *acrylates*, under otherwise identical conditions, did not proceed. In order to overcome this limitation, Shi *et al.* investigated the same DABCO-triggered aza-MBH-type reaction in *DMF*, which proved to be successful even for acrylates (Scheme 1.47).[60] The corresponding products were obtained in moderate to good yields.



Scheme 1.47 First DABCO-catalysed α-hydrazination

In contrast to the well-developed MBH reaction of *terminal* alkenes, such as acrylates and vinyl ketones, *β-substituted* alkenes remain challenging substrates for both the MBH and the aza-MBH reaction. In 2006, Namboothiri *et al.* reported the first aza-MBH-type coupling between azodicarboxylates and various β-nitro styrenes mediated by imidazole or DMAP [Scheme 1.48a)].[61] The corresponding products were obtained in up to quantitative yield.



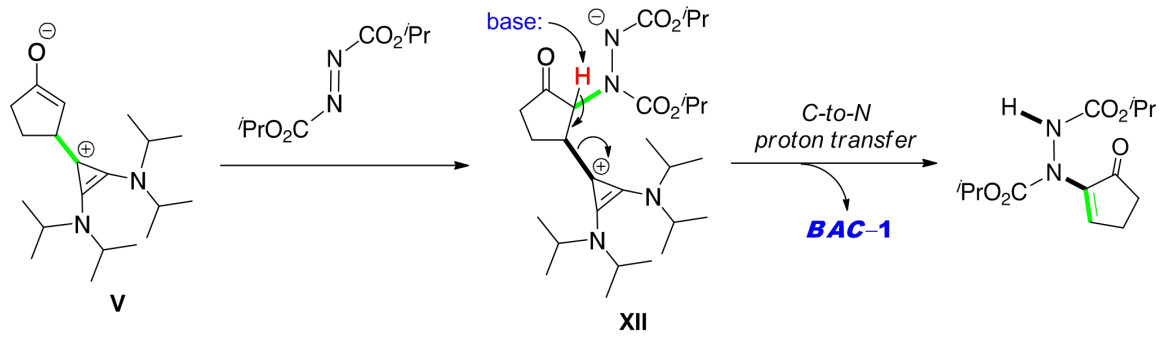


Scheme 1.48 Stoichiometric and catalytic α-hydrazination of α-nitro alkenes

In 2013, *Shi et al.* reported an efficient NHC-catalysed coupling between azodicarboxylates and various β-nitro alkenes [Scheme 1.48b)].[62] Importantly, aromatic *and* aliphatic Michael acceptors proved to be applicable, and only 5 mol% of ***pre-NHC*–12** were required in the presence of DMAP as a base co-catalyst; the use of DMAP alone proved to be ineffective.

1.2.6.2 BAC-Catalysed α-Hydrazination of Michael Acceptors

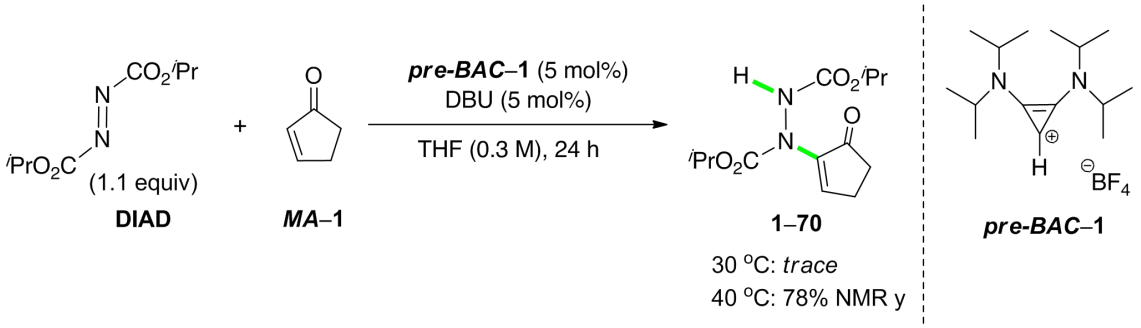
In light of the limited earlier work on catalytic α-hydrazination of Michael acceptors,[59-62] and encouraged by the success regarding the BAC-catalysed aza-MBH reaction, we envisioned the developed BAC catalysis to be applicable to α-hydrazination. Although the N=N double bond of azodicarboxylates is not polarized, based on the bond energies of C=N (615 kJ/mol) and N=N (418 kJ/mol) double bonds,[63] we expected a cyclopropenylidene to be active enough to trigger C–N cross-coupling with Michael acceptors in an aza-MBH-type fashion (Scheme 1.49).



Scheme 1.49 Proposed pathway for the BAC-catalysed α-hydrazination of cyclopentenone

The critical zwitterionic enolate **V** would be formed through conjugate addition of the BAC catalyst to cyclopentenone. Subsequent C–N bond formation would occur between **V** and DEAD to generate the corresponding adduct **XII**. The following intermolecular C-to-N proton transfer followed by β-elimination would form the C=C double bond in the product with regeneration of the catalyst.

In an initial experiment, we used the commercially available substrates DIAD and ***MA*–1** in the presence of ***pre-BAC*–1** and DBU in THF (Scheme 1.50).



Scheme 1.50 Initial trials of BAC-catalysed C–N bond formation

While the experiment at 30 °C failed to give the expected product **1–70**, heating to 40 °C resulted in the formation of **1–70** in 78% NMR yield. In this context, the separate use of ***pre-BAC*–1** and DBU failed to give **1–70**. Likewise, the use of other metal-free and metal–base co-catalysts or other solvents proved to be less effective. Finally, the concentration of ***MA*–1** was optimized under the best reaction conditions, i.e., the use of 5 mol% DBU as base co-catalyst in THF at 40 °C (24 h; Chart 1.9).

Molarity (M)	Yield (%)
0.05	*NR*
0.1	12
0.2	41
0.25	62
0.3	79
0.5	91
1.0	95

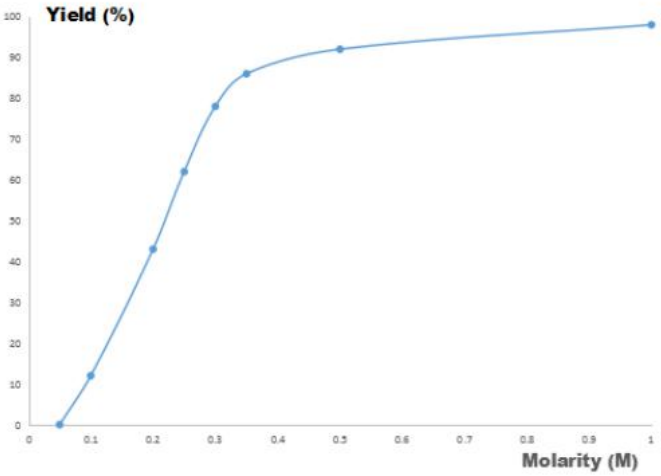
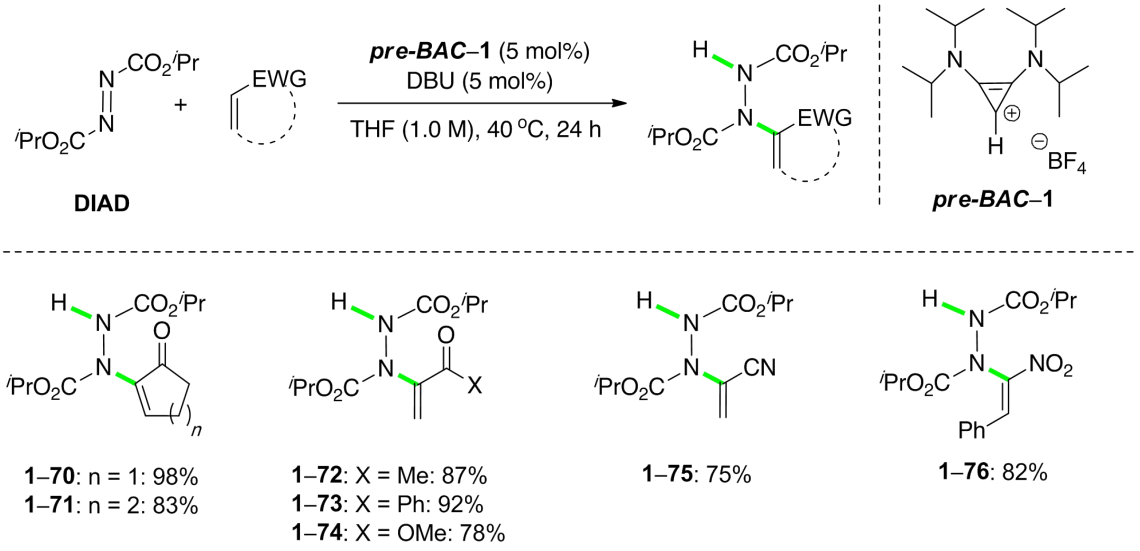


Chart 1.9 Optimization of concentration of ***MA*–1**

A variety of concentrations of ***MA*–1** were tested (0.05–1.0 M). According to our observation, the product yields increased with an increasing concentration of ***MA*–1**. It was found that 1.0 M was the best concentration of ***MA*–1** leading to a maximum yield of 95% for **1–70**.

With the optimized BAC catalysis protocol in hand, the scope of pro-nucleophiles for this α-hydrazination was investigated (Scheme 1.51). α,β-Unsaturated cyclic and acyclic ketones, acrylates, acrylonitrile, and β-nitro styrene were used. It was found that all pro-nucleophiles were tolerated under the optimized conditions; the corresponding products **1–70** ~ **1–78** were obtained in 75–98% yields.



Scheme 1.51 Scope for the BAC-catalysed α-hydrazination of Michael Acceptors

In summary, we developed a general BAC-catalysed α-hydrazination of different types of Michael acceptors using an azodicarboxylate at low catalyst loading (5 mol%). The corresponding products were obtained in high yields under mild conditions. *This simple carbene catalysis has provided a substantial advance with respect to the current state-of-the-art in literature.*

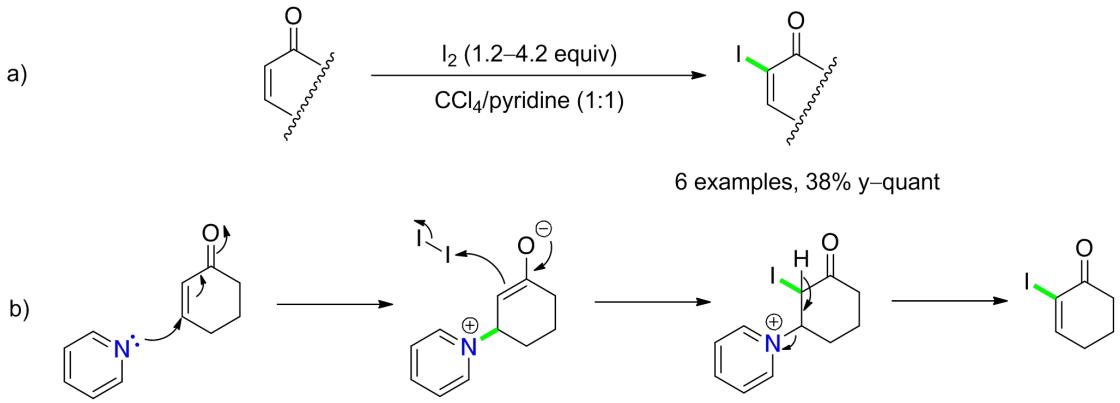
1.2.7 α-Halogenation of Michael Acceptors

In light of the earlier BAC-catalysed C–C and C–N bond formations, we anticipated that C–Hal bond-forming reactions using electrophilic halogenation reagents may be feasible.

1.2.7.1 Literature: "Electrophilic Halogen" in MBH-Type Reactions

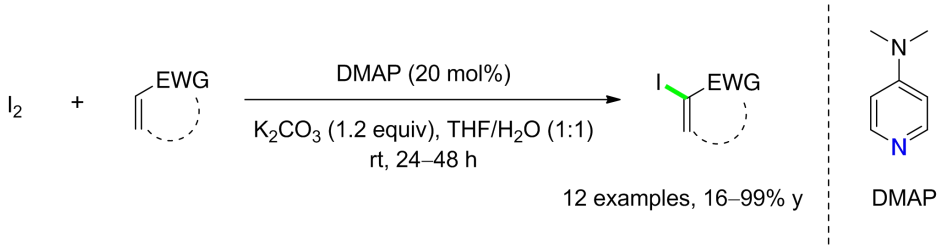
α-Halo enones and derivatives are versatile intermediates, which have been used for the generation of α-carbon-substituted enones. Specifically, α-iodinated α,β-unsaturated carbonyl compounds have proved to be useful substrates in organic synthesis, especially in transition metal-mediated reactions.[64a] Although transition metal-mediated halogenations have been reported by Hardy,[64b] Ritter,[64c] and Cramer,[64d] a convenient general procedure for the synthesis of α-halo enones does not exist. Here, only metal-free protocols for α-halogenation are discussed in more detail.

In 1992, Johnson *et al.* reported a pyridine-mediated synthesis of α-iodo cycloalkenones using molecular iodine in tetrachloromethane [Scheme 1.52a)].[43] The intended products were obtained in up to quantitative yield. Compared to previous routes using iodo azides[65] or a combination of iodine and ceric ammonia nitrate,[66] Johnson's method represents the most common approach. The proposed mechanism follows a Morita–Baylis–Hillman-type pathway [Scheme 1.52b)].



Scheme 1.52 A pyridine-mediated direct α-iodination and mechanism

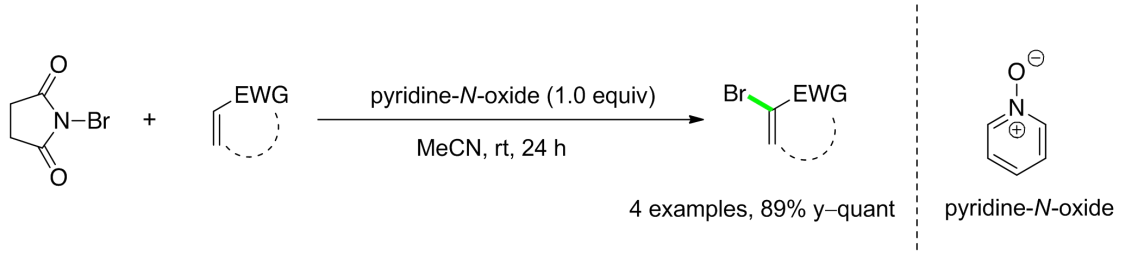
In 2005, Krafft *et al.* reported a more convenient protocol for the C–I bond formation between α,β-unsaturated carbonyl compounds and molecular iodine (Scheme 1.53).[67] The corresponding products were obtained 16–99% yields. Here, a more nucleophilic *catalyst*, DMAP, was used; the aqueous media may stabilize the zwitterionic intermediate through solvation. This method required the use of a stoichiometric amount of a base, K_2CO_3, to neutralize the *in situ* formed HI. It is noted that the reactions proceeded slowly in the absence of K_2CO_3 if a *stoichiometric* amount of DMAP was used. In the absence of DMAP, an iodination was not detected.



Scheme 1.53 DMAP-catalysed α-iodination of α,β-unsaturated carbonyl compounds[67]

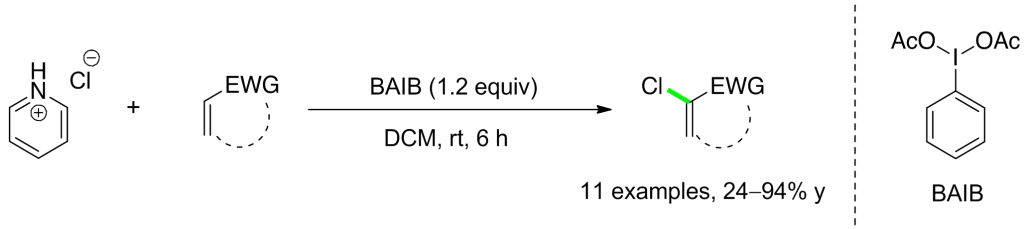
Although some progress has been made in α-iodination, the conditions explored have proved to be not suitable for α-chlorination and α-bromination. Indeed, such transformations would not be practical due to the handling difficulty as well as the toxicity of both molecular bromine and chlorine.

In 2007, Bovonsombat *et al.* reported a stoichiometric method for the formation of cyclic α-bromo enones and linear α-bromo enals, which are useful templates for organic synthesis (Scheme 1.54).[68] Here, the combination of a nucleophilic mediator, pyridine-*N*-oxide, and an electrophilic bromination reagent, *N*-bromosuccinimide (NBS), were used in MeCN at room temperature. The corresponding products were obtained in up to quantitative yield.



Scheme 1.54 Pyridine-*N*-oxide-mediated α-bromination of α,β-unsaturated carbonyl compounds[68]

When these conditions were applied to the α-chlorination using *N*-bromosuccinimide (NCS), the conversion to the corresponding products was only up to 16% even though two equivalents of NCS were used. In 2009, Lupton *et al.* reported a stoichiometric method for the α-chlorination using bisacetoxyiodobenzene (BAIB) and the HCl salt of pyridine (Scheme 1.55).[69] A number of α,β-unsaturated carbonyls proved to be tolerated, and the corresponding products were obtained in 24–94% yields.

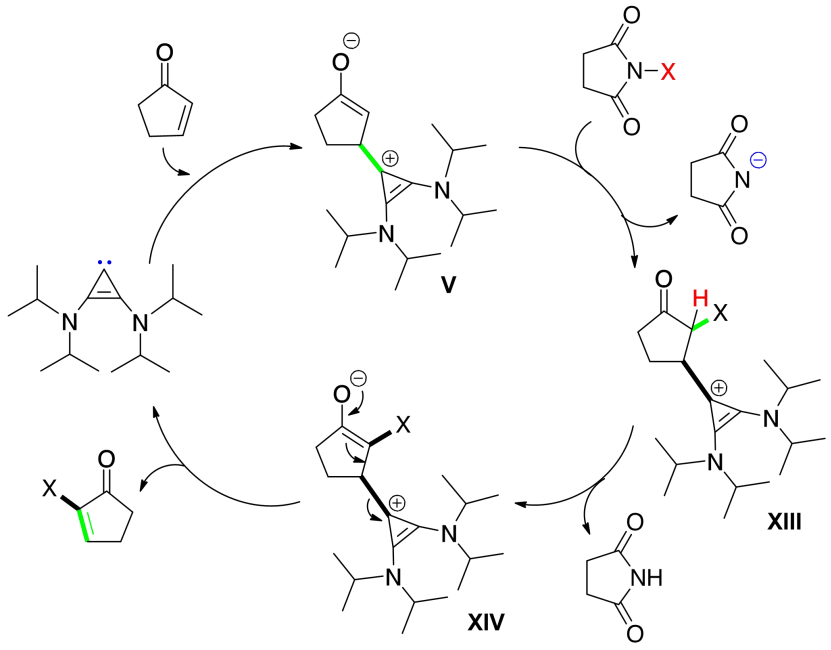


Scheme 1.55 α-Chlorination of α,β-unsaturated carbonyl compounds[69]

1.2.7.2 BAC-Catalysed α-Halogenation of Michael Acceptors

Based on the fact that a stoichiometric amount of mediator was required in most α-halogenations of Michael acceptors, we became interested in exploring a cyclopropenylidene catalyst in combination with a suitable *halogen electrophile*. A mechanistic scenario for this anticipated BAC catalysis is

shown in Scheme 1.56.

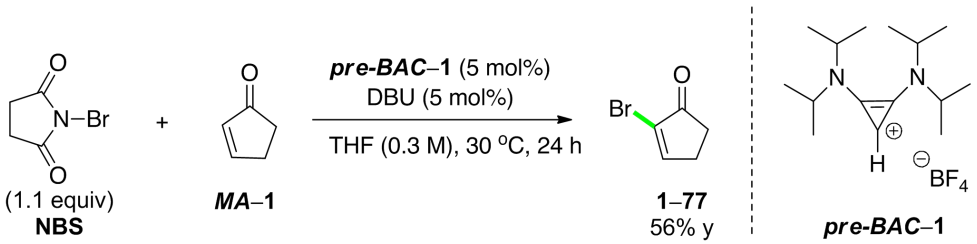


Scheme 1.56 Proposed cycle for the BAC-catalysed α-halogenation of cyclopentenone

The BAC catalyst would undergo conjugate addition to the Michael acceptor to form zwitterionic enolate **V**. The latter would add to an "electrophilic halogen" reagent, i.e., *N*-halogenosuccinimide. This C–X bond formation would liberate the cationic intermediate **XIII** together with the succinimide anion. The latter would deprotonate **XIII** to form succinimide, as a stoichiometric by-product, and another zwitterionic enolate, **XIV**. This intermediate would undergo β-elimination to form the C=C double bond in the final product with concomitant regeneration of the catalyst.

Bromination

First, we explored electrophilic bromination using commercially available *N*-bromosuccinimide (NBS) and cyclopentenone (***MA*–1**) as substrates under standard BAC catalysis conditions (Scheme 1.57). The catalytic C–Br bond formation to generate product **1–77** was observed, and the product was isolated in 56% yield (59% NMR yield). In this context, the sole use of DBU as a potential catalyst failed to give **1–77**. Thus, the proof-of-principle for BAC catalysis was realized in the very first attempt.



Scheme 1.57 Initial trial for BAC-catalysed α-bromination

Next, a base co-catalyst screening was carried out but all alternatives proved to be less effective. It is important to note that the reaction still proceeded smoothly when a lower catalyst loading was used.

For instance, the product was obtained in 46% yield after 24 hours when virtually 2 mol% of the *in situ*-formed BAC catalyst were used. THF was found to be the most suitable solvent. The conditions were further optimized in terms of temperature and substrate concentration. A variety of concentrations of ***MA*–1** (0.2–1.0 M) were tested at 25 °C, 30 °C, and 40 °C (Chart 1.10).

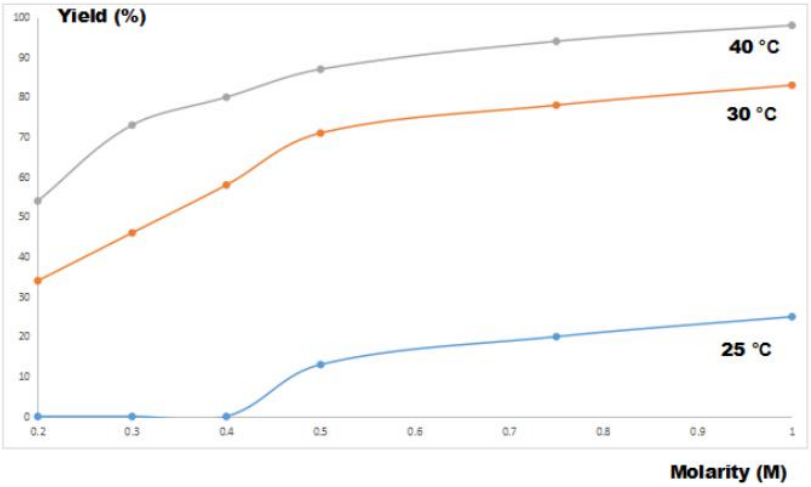
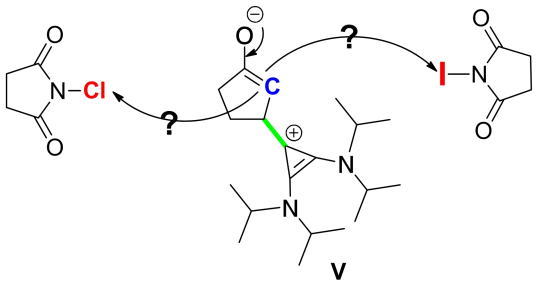


Chart 1.10 Optimization of the concentration of ***MA*–1** and of the temperature for α-bromination

The yields of product **1–77** at 25 °C (0–22%), 30 °C (34–79%), and 40 °C (53–98%) revealed that a slightly higher temperature was critical for reacticity. In addition, it was found that an increasing substrate concentration from 0.2 M to 1.0 M also provided substantially increased product yields. The optimal conditions were determined to be a concentration of 1.0 M of ***MA*–1** at 40 °C giving product **1–77** in 98% yield.

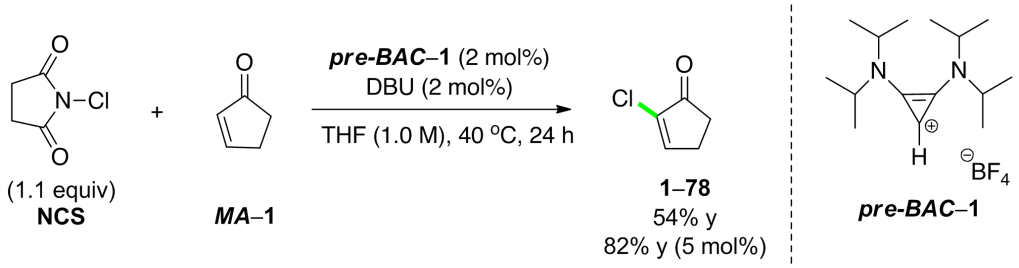
Chlorination and Iodination

Based on the postulated catalytic formation of enolate **V** (Scheme 1.58), we also explored electrophilic chlorinating and iodinating reagents.



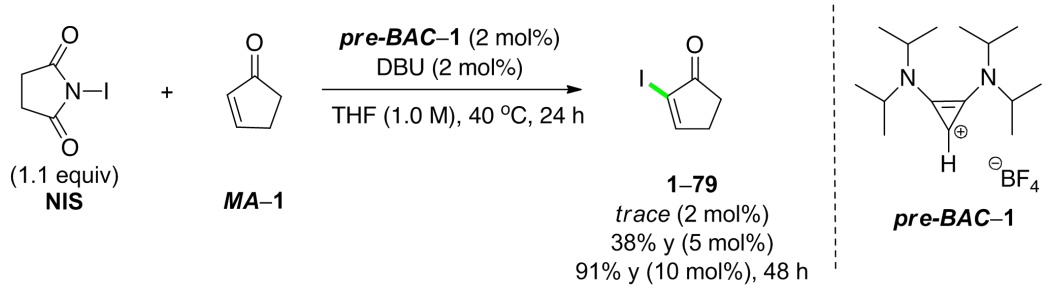
Scheme 1.58 Possible extension to BAC-catalysed C–Cl and C–I bond formations

A preliminary set of experiments was carried out using *N*-chlorosuccinimide (NCS) and cyclopentenone (***MA*–1**) under standard BAC catalysis conditions (Scheme 1.59).



Scheme 1.59 Initial trials for BAC-catalysed C–Cl bond formation

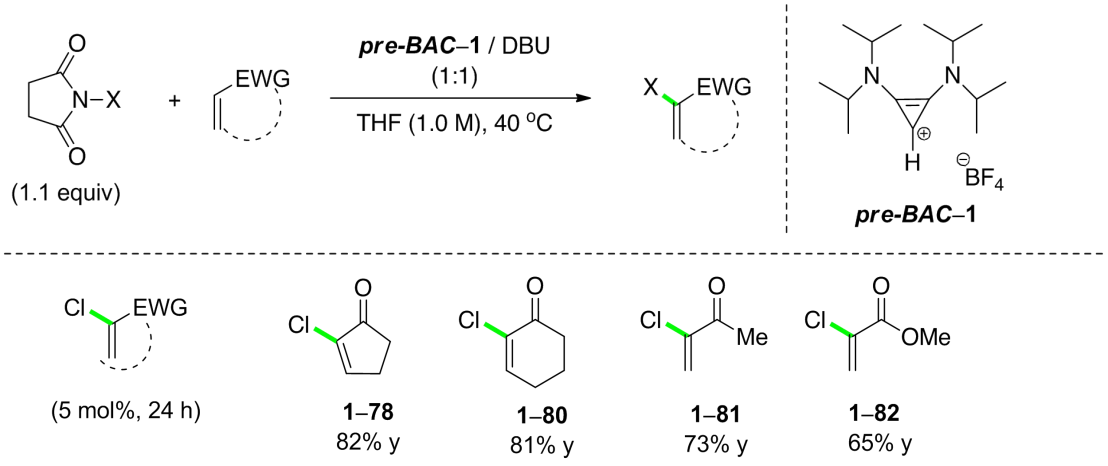
The C–Cl bond formation proceeded smoothly, and product **1–78** was isolated in 54% yield (57% NMR yield); the catalytic use of DBU alone failed to give **1–78**. The use of 5 mol% catalyst loading provided product **1–78** in 82% yield. In analogy, we used commercially available *N*-iodosuccinimide (NIS) under standard BAC catalysis conditions (Scheme 1.60).

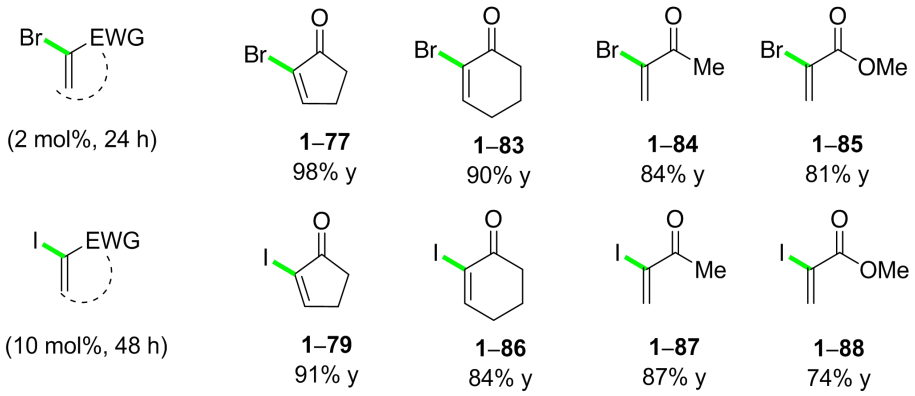


Scheme 1.60 Initial trials for BAC-catalysed C–I bond formations

Unfortunately, only a trace amount of product **1–79** was detected, and the use of 5 mol% catalyst loading gave **1–79** in only 38% yield. Eventually, product **1–79** was obtained in 91% yield when 10 mol% of the BAC catalyst were used for 48 h.

With these optimized BAC catalysis conditions in hand, the scope of pro-nucleophiles was explored (Scheme 1.61). It was found that cyclic and acyclic α,β-unsaturated ketones as well as methyl acrylate were tolerated. At 5 mol% catalyst loading, the chlorinated products **1–78** and **1–80** ~ **1–82** were obtained in 65–82% yields. At 2 mol% catalyst loading, the brominated products **1–77** and **1–83** ~ **1–85** were obtained in 81–98% yields. The iodinated products **1–79** and **1–86** ~ **1–88** were obtained in 74–91% yields, but 10 mol% catalyst loading and a reaction time of 48 h were required.





Scheme 1.61 Scope for BAC-catalysed α-halogenations of Michael acceptors

In summary, BAC catalysis was uncovered as an effective method for α-halogenations of a variety of Michael acceptors.

1.3 Summary

In this chapter, novel BAC pre-catalysts, such as ***pre-BAC–1***, were synthesized and characterized. In ^{11}B NMR studies the nucleophilicity of the *in situ*-formed ***BAC–1*** was assessed using a variety of boron electrophiles (Figure 1.10). In all cases, the corresponding boron–ate complexes were detected, which indicated that ***BAC–1*** may be a suitable metal-free catalyst for the nucleophilic transfer of organic fragments or hydride to suitable electrophiles.

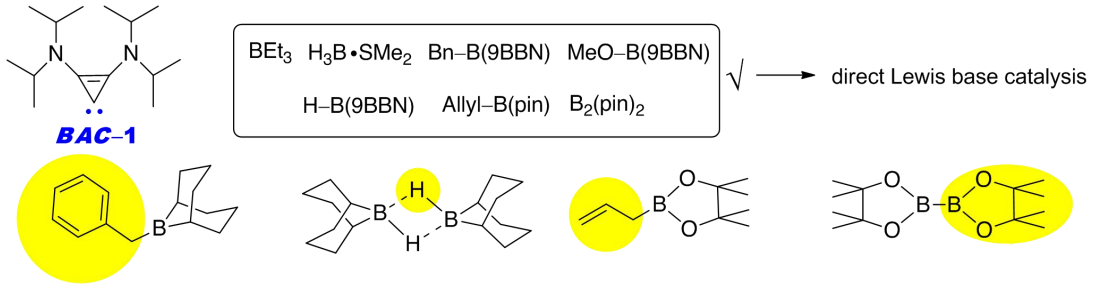
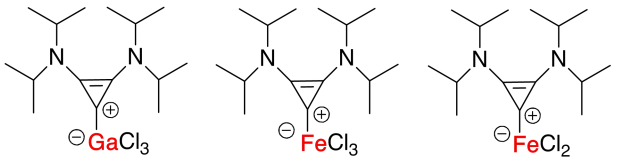


Figure 1.10 Results for boron binding study

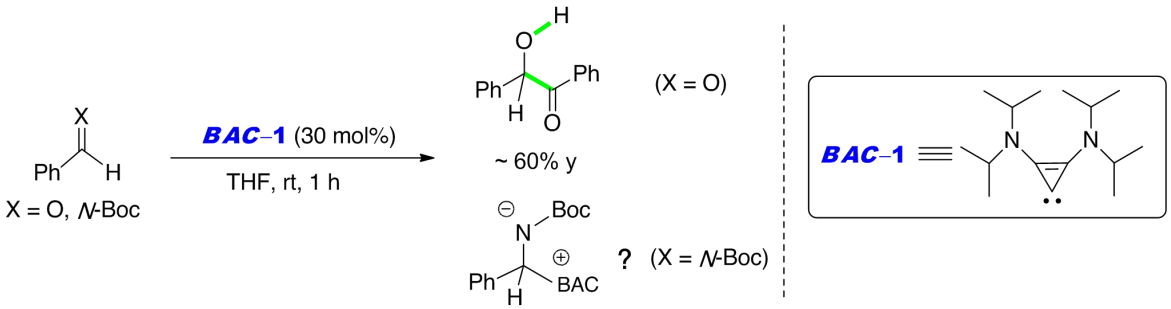
Next, three novel BAC–metal complexes have been successfully synthesized and characterized (Figure 1.11). In all cases, both NMR spectroscopic analysis (^{1}H, ^{13}C, and ^{71}Ga) and high-resolution mass spectroscopy (HRMS) confirmed the formation of these non-precious metal-based BAC complexes ("molecular" structure rather than "ionic").



1–26 96% y **1–27** 86% y **1–28** 80% y

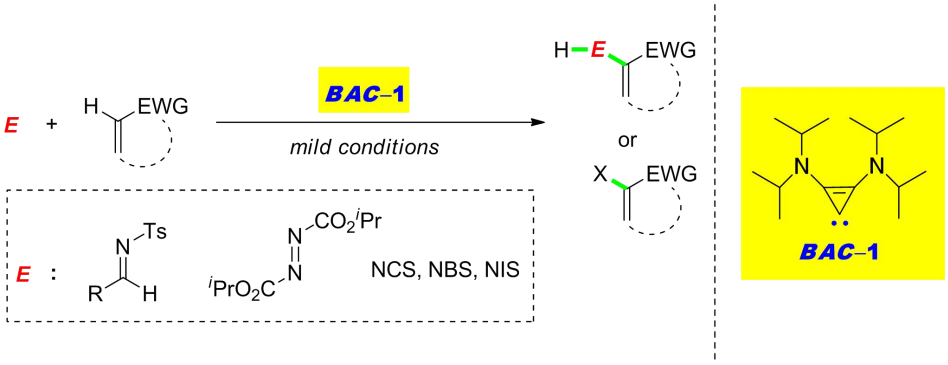
Figure 1.11 Synthesized BAC–metal complexes

In preliminary experiments, *in situ*-formed ***BAC–1*** (30 mol%) was shown to trigger catalytic *umpolung* of benzaldehyde to afford the homo-benzoin product in ~ 60% yield (Scheme 1.60). In case of the corresponding *N*-Boc-imine, the initial adduct formation was confirmed; further experimentation will be required in order to exploit this chemistry in the context of useful bond transformations.



Scheme 1.60 BAC-catalysed C=X *umpolung* reactions

Most significantly, a rare BAC catalysis was accomplished at low catalyst loading under mild reaction conditions (Scheme 1.61). Regarding aza-MBH reactions, a variety of substrates including aromatic, heteroaromatic, and aliphatic imines, as well as acyclic or cyclic α,β-unsaturated ketones and carboxylic acid derivatives were tolerated; intriguingly, functionalities such as unprotected amino and hydroxy groups were tolerated. This novel catalytic method for C–C bond formations was subsequently applied to α-hydrazination and α-halogenations of Michael acceptors.



Scheme 1.61 Summary of BAC-catalysed aza-MBH(-type) reactions

In light of these promising results regarding racemic BAC catalysis, investigations into asymmetric BAC catalysis were the next logical stage of this project.

In 2007, Tamm *et al.* reported the synthesis of the first enantiopure BAC precursor, for which an application in asymmetric organocatalysis seemed challenging:[70] "*... our initial studies on the benzoin condensation of benzaldehyde employing (BAC*–H)BF$_4$ in combination with KO^{t}Bu as the catalyst system ... only up to 18% ee could be observed*". Nonetheless, we have been interested in exploring asymmetric organocatalysis with these types of *chiral non-NHC* species (Figure 1.12).

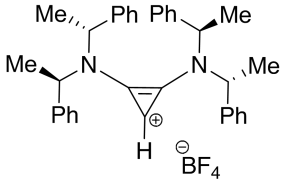
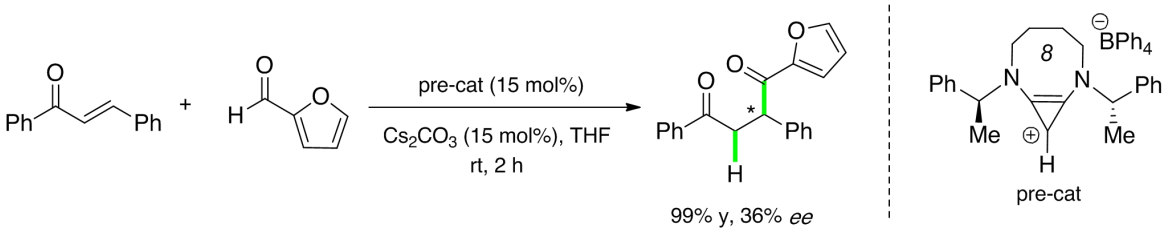


Figure 1.12 First enantiopure acyclic BAC precursor

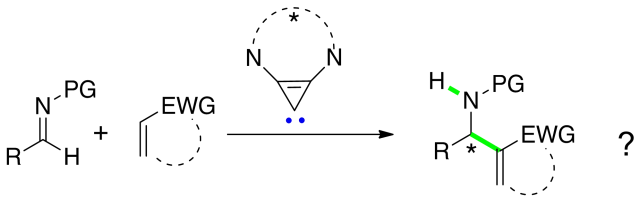
In 2013, during our cyclopropenylidene studies, Gravel *et al.* reported the first organocatalytic BAC-catalysed intermolecular Stetter reactions.[71] In their work, an enantiopure *bicyclic* BAC precursor was synthesized for the first time (Scheme 1.62). Its combined use with Cs_2CO_3 as a base co-catalyst was shown to induce asymmetry in one example of an intermolecular Stetter reaction (36% *ee*).



Scheme 1.62 BAC-catalysed asymmetric Stetter reaction reported by Gravel[71]

Inspired by this seminal study, we envisioned the development of an asymmetric version for BAC-

catalysed aza-MBH reactions (Scheme 1.63).



Scheme 1.63 Possibility of BAC-catalysed asymmetric aza-MBH reactions

2 BAC-CATALYSED ASYMMETRIC AZA-MBH REACTIONS

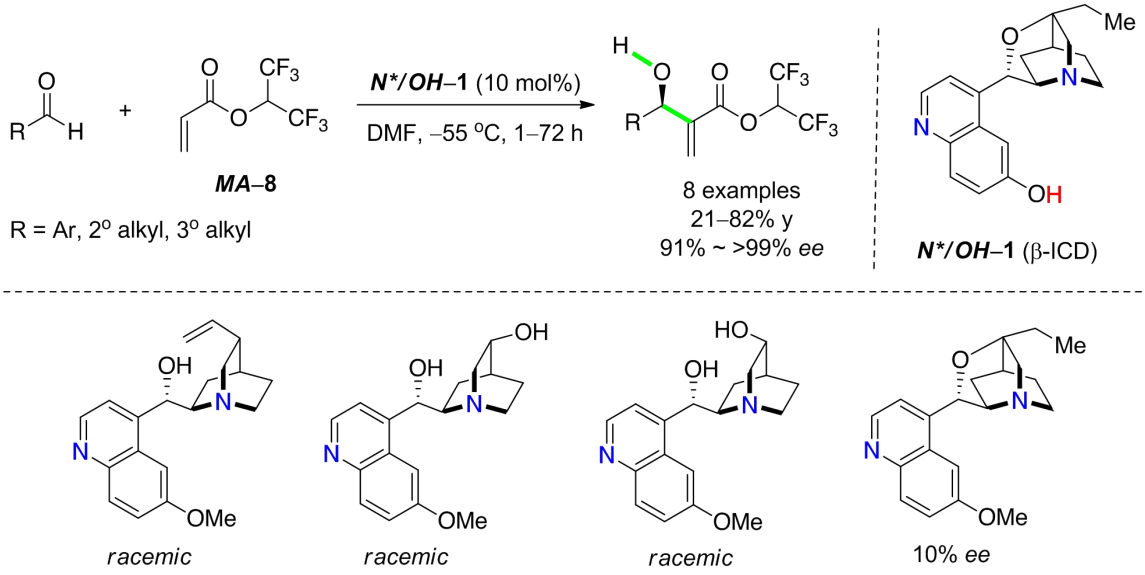
2.1 Introduction

Parallel to the emerging concept of bifunctional asymmetric catalysis, the development of asymmetric versions of the aza-Morita–Baylis–Hillman reaction has remarkably evolved over the past decade.[72] Indeed, various acid–base catalysts have been newly introduced in order to achieve high asymmetric induction for a broad variety of pro-nucleophiles.

2.1.1 Use of a Single Catalyst System in Literature

Catalyst system composed of an amine Lewis base and a hydrogen bond donor in one molecule

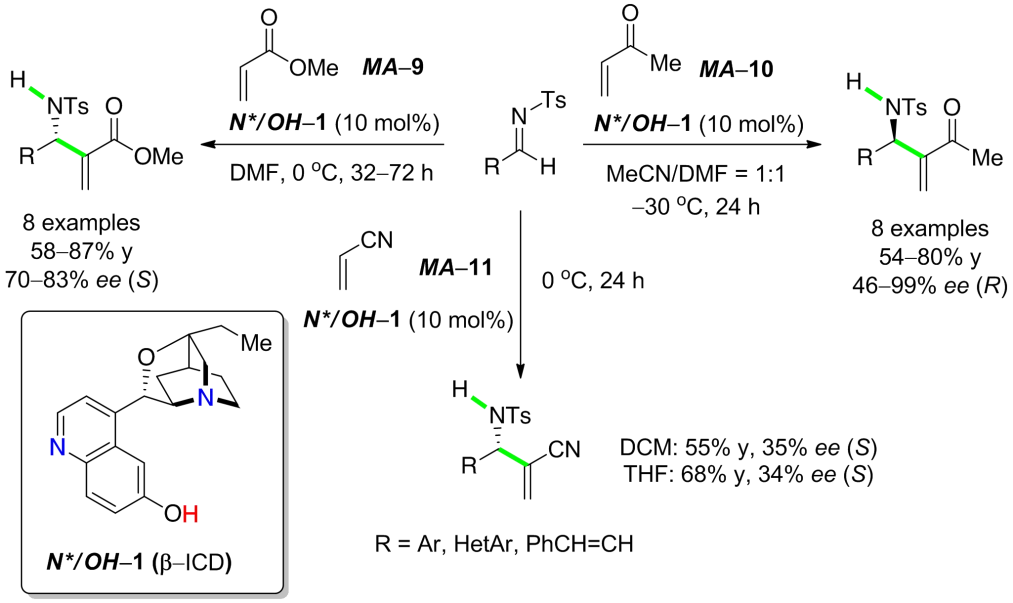
Initially, enantiopure tertiary amine catalysts based on the quinidine framework have been investigated. In 1999, Hatakeyama *et al.* used the modified cinchona alkaloid β-ICD (***N*/OH*–1**) to catalyze the first highly enantioselective MBH reaction between aldehydes and acrylate ***MA*–8** (Scheme 2.1).[73] The corresponding MBH adducts were obtained with 91% to >99% *ee*; other quinidine derivatives have proved to be inefficient. This seminal report has initiated further studies into catalytic asymmetric MBH and aza-MBH reactions.



Scheme 2.1 First catalytic asymmetric MBH reaction using the Hatakeyama catalyst[73]

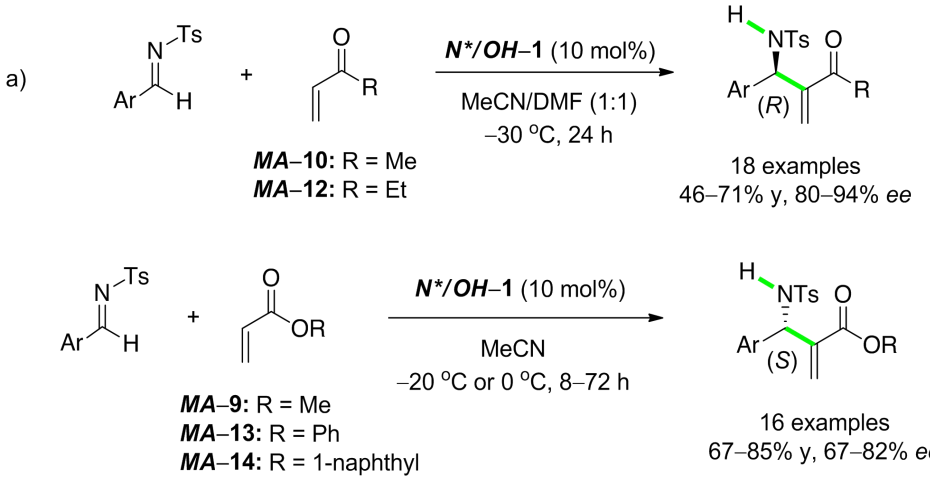
In 2002, Shi *et al.* reported the first highly enantioselective aza-MBH reactions between aromatic *N*-tosyl aldimines and a variety of Michael acceptors, including methyl acrylate (***MA*–9**), methyl vinyl ketone (MVK; ***MA*–10**), and acrylonitrile (***MA*–11**; Scheme 2.2).[74] Using the Hatakeyama catalyst (***N*/OH*–1**), the corresponding aza-MBH adducts were obtained with 34–99% *ee*. However, under the explored conditions the use of aliphatic imines gave unidentified side-products. Furthermore, it was found that the absolute configuration of the products varied depending on the nature of the pro-

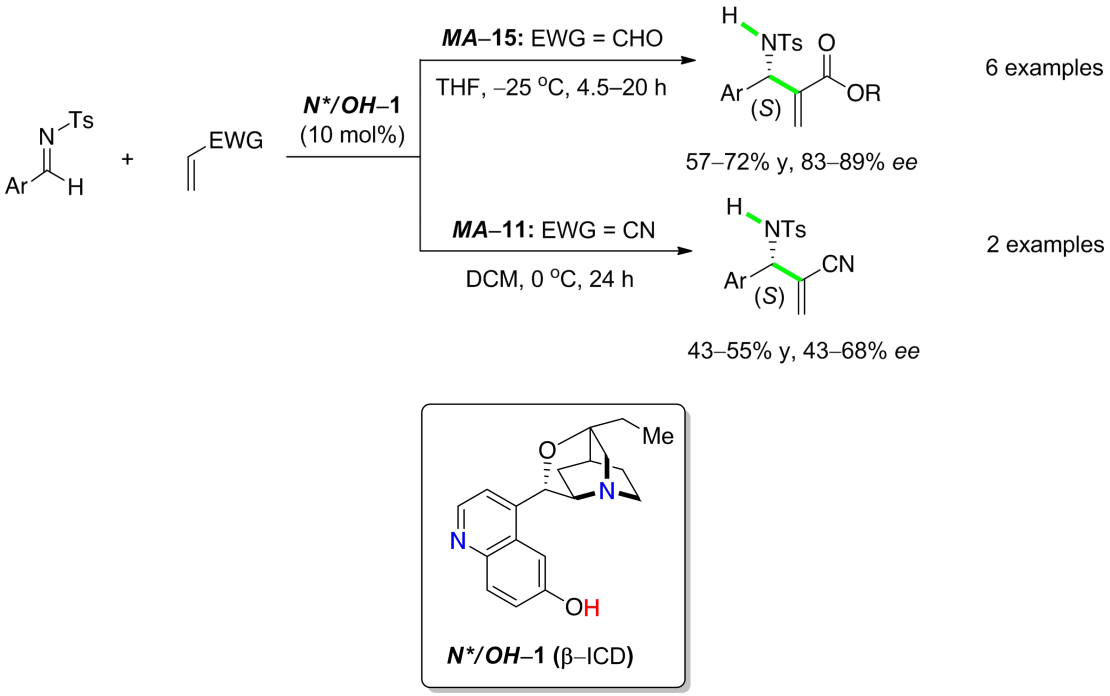
nucleophiles. The use of an α,β-unsaturated ketone (***MA*–10**) afforded the (*R*)-adducts, whereas the use of an acrylate (***MA*–9**) and acrylonitrile (***MA*–11**) provided the (*S*)-adducts.



Scheme 2.2 First catalytic asymmetric aza-MBH reactions with various Michael acceptors[74]

After identifying this difference in the stereochemical outcome, Shi *et al.* used the same catalyst to reinvestigate systematically the aza-MBH reaction between aromatic *N*-tosyl aldimines and various Michael acceptors (Scheme 2.3).[75] It was found that when α,β-unsaturated ketones ***MA*–10** and ***MA*–12** were used, the corresponding (*R*)-adducts were formed [Scheme 2.3a)]. Here again, the corresponding (*S*)-adducts were obtained when acrylates ***MA*–9**, ***MA*–13**, ***MA*–14**, acrolein (***MA*–15**), and acrylonitrile (***MA*–11**) were used [Scheme 2.3b),c)]. The corresponding products were obtained with 43–94% *ee*.

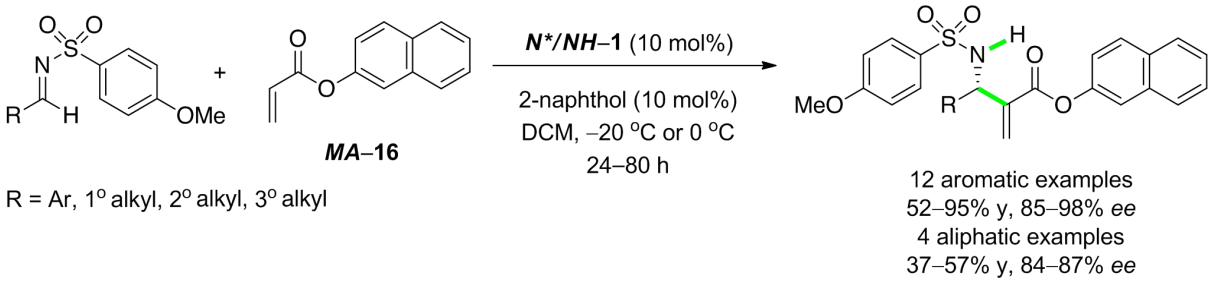


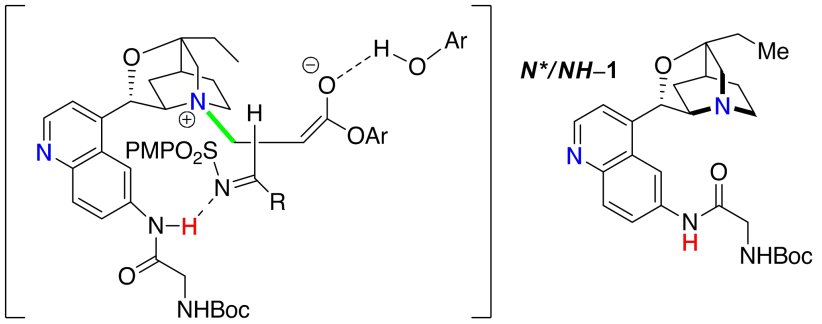


Scheme 2.3 Catalytic asymmetric aza-MBH reactions with various Michael acceptors[75]

Despite the fact that catalyst ***N*/OH*–1** has proved to be highly efficient in asymmetric aza-MBH reactions, the scope remained limited to *aromatic* aldimines. In turn, several novel bifunctional catalysts derived from ***N*/OH*–1** have been developed in order to achieve high asymmetric induction for the use of both aromatic *and aliphatic* aldimines.

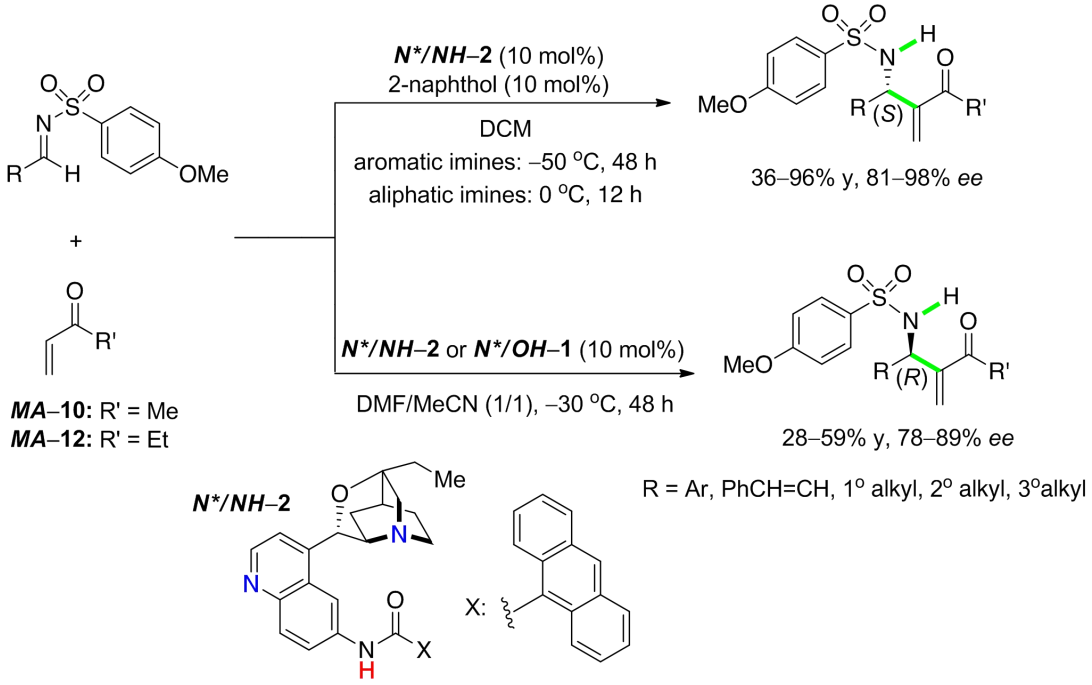
In 2008, Zhu and Masson *et al*. developed a new β-ICD-type bifunctional compound, ***N*/NH*–1**, that served –in combination with 2-naphthol– as a highly effective dual catalyst for the enantioselective aza-MBH reaction between various *N*-tosyl aldimines and acrylate ***MA*–16** (Scheme 2.4).[76] It is noted that the reaction proceeded smoothly even for aliphatic aldmines to give the corresponding adducts with 84–87% *ee*. Considering the role of the dual catalyst, it was proposed that a pairing of cooperative hydrogen bonds was critical for asymmetric induction; these non-covalent interactions favor nucleophilic addition of the zwitterionic enolate to the imine from the *Re* face in a less crowded transition state, which accounts for the observed absolute configuration.





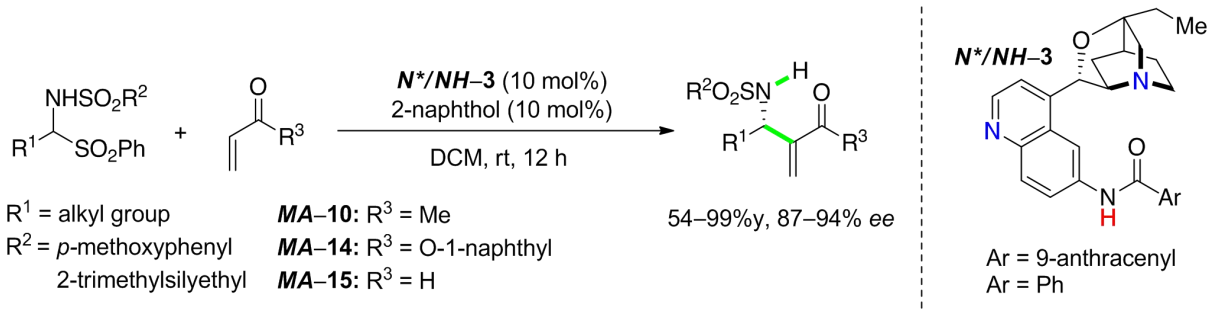
Scheme 2.4 Catalytic asymmetric aza-MBH reactions with 2-naphthyl acrylate (***MA*–16**)[76]

Based on this mechanistic assumption, Zhu *et al.* anticipated that this type of dual catalytic system should favor the formation of (*S*)-adducts regardless of the nature of the Michael acceptor used. Therefore, a new β-ICD-type catalyst, ***N*/NH*–2**, was used in aza-MBH reactions of *N*-tosyl imines with Michael ketones ***MA*–10** and ***MA*–12** (Scheme 2.5).[77] It was found that the presence 2-naphthol as an achiral protic additive was critical to provide the products with (*S*)-configuration. In contrast, in the absence of 2-naphthol or when ***N*/OH*–1** was used, (*R*)-adducts were formed. The corresponding products were obtained with 78–98% *ee*.



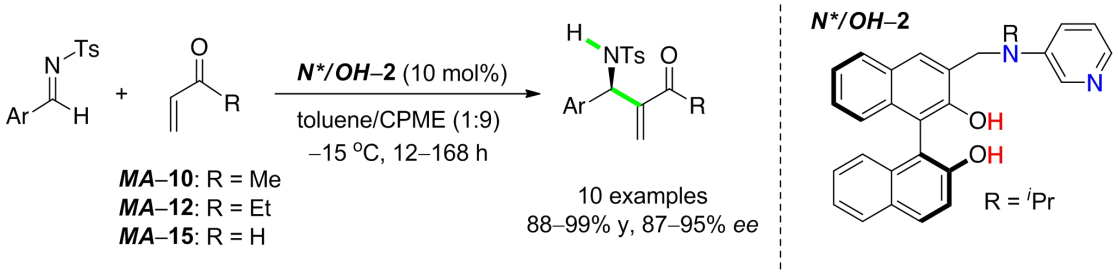
Scheme 2.5 Catalytic asymmetric aza-MBH reactions with alkyl vinyl ketones[77]

Soon after this discovery, Zhu *et al.* reported bifunctional compound ***N*/NH*–3**, which served –in combination with 2-naphthol– as an effective catalyst for highly enantioselective aza-MBH reactions between aliphatic amidosulfones and Michael acceptors ***MA*–10**, ***MA*–14**, and ***MA*–15** (Scheme 2.6).[78] Here, the absolute configuration of the corresponding adducts proved to be the same for each pro-nucleophile (87–94% *ee*).



Scheme 2.6 Catalytic asymmetric aza-MBH reactions between α-amidosulfones and various Michael acceptors[78]

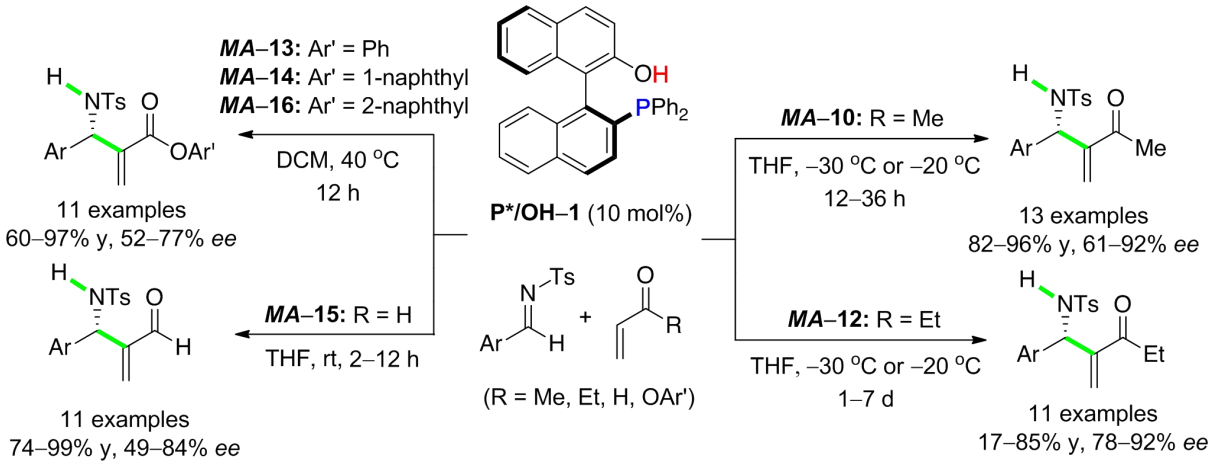
In 2005, Sasai *et al.* designed the bifunctional organocatalyst ***N*/OH–2*** for enantioselective aza-MBH reactions between aromatic *N*-tosyl aldimines and Michael acceptors ***MA*–10**, ***MA*–12**, and ***MA*–15** (Scheme 2.7).[79] The corresponding adducts were obtained with 87–95% *ee*. It was found that the stereochemical outcome was influenced to a large extent by the critical factors: ***(1)*** the position of the Lewis base attached to the BINOL skeleton; ***(2)*** the acid–base functionalities (basic site for the nucleophilic addition to the Michael acceptor, and acidic site for pairing of cooperative hydrogen bonds) for the activation of both substrates; ***(3)*** the fixed conformation of the organocatalyst.



Scheme 2.7 Catalysed asymmetric aza-MBH reactions with various Michael acceptors[79]

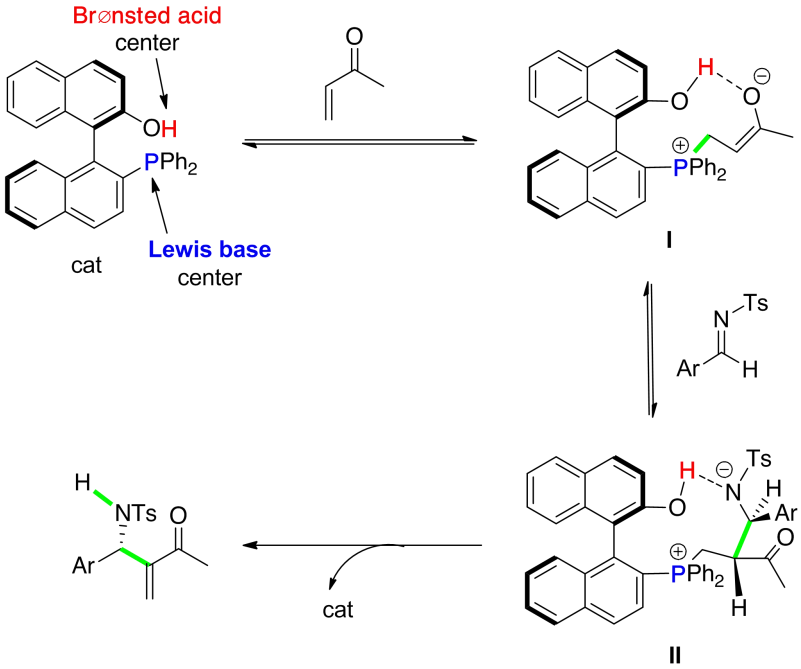
Catalyst system composed of a phosphine Lewis base and a hydrogen bond donor in one molecule

In 2003, Shi *et al.* used the enantiopure bifunctional phosphine ***P*/OH*–1** to catalyze asymmetric aza-MBH reactions between aromatic *N*-tosyl aldimines and Michael acceptors ***MA*–10**, ***MA*–12**, ***MA*–13**, ***MA*–14**, ***MA*–15**, and ***MA*–16** (Scheme 2.8).[80] The corresponding adducts were obtained with 49–92% *ee*. It was found that the presence of the hydroxy group in the catalyst was critical for the reactivity; a simple phosphine did not catalyze this reaction. It is noted that in all cases the absolute configuration of the products did not depend on the nature of the Michael acceptor.



Scheme 2.8 Catalytic asymmetric aza-MBH reactions with various Michael acceptors[80]

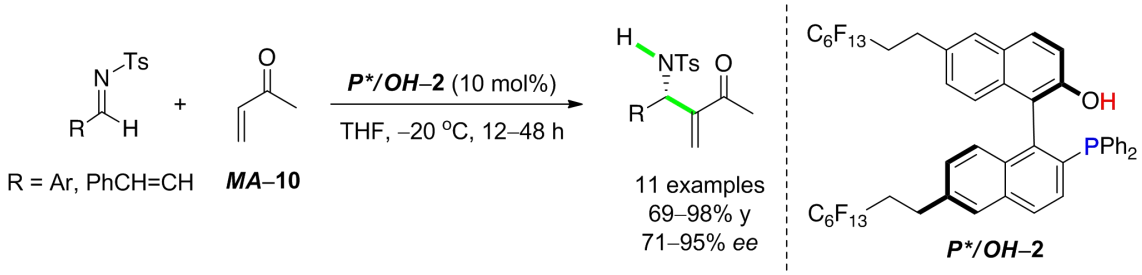
A detailed mechanism was proposed to rationalize the absolute configuration of the aza-MBH adducts (Scheme 2.9).[80] The catalytic pathway was proposed to be initiated by conjugate addition of the Lewis basic phosphorus atom of ***P*/OH*–1** to the corresponding Michael acceptor (e.g. methyl vinyl ketone) to form zwitterionic enolate **I**, which may be stabilized through hydrogen bonding to the aromaticic hydroxy group within ***P*/OH*–1**. Intermediate **I** was detected by ^{1}H and ^{31}P NMR spectroscopic analysis. **I** would add to the C=N double bond of the imine to form adduct **II**. A subsequent intermolecular proton transfer followed by β-elimination would from the C=C double bond in the product with concomitant release of the catalyst.



Scheme 2.9 Proposed mechanism of the asymmetric aza-MBH reaction catalysed by ***P*/OH*–1**[80]

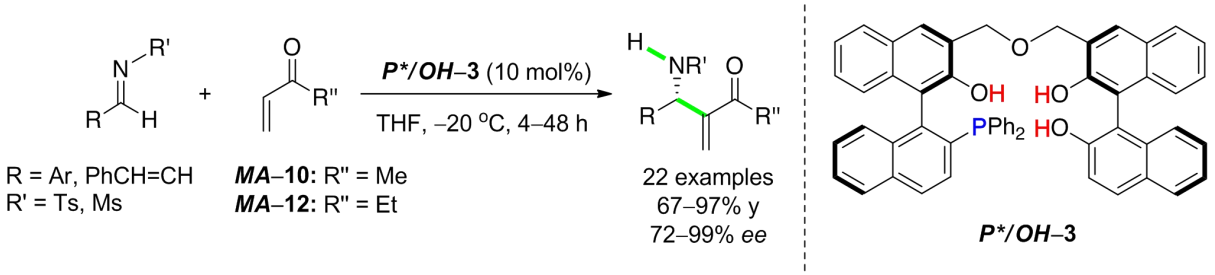
In 2005, Shi *et al.* synthesized an enantiopure phosphine catalyst, ***P*/OH*–2**, bearing long perfluoroalkyl chains (Scheme 2.10).[83] This idea was inspired by the observation that long perfluoroalkyl chains in a variety of chiral ligands improved the asymmetric induction in specific cases.[82] Catalyst ***P*/OH*–2** was shown to catalyze an asymmetric aza-MBH reaction between *N*-tosyl

aldimines and methyl vinyl ketone (***MA*–10**).[83] The corresponding (*S*)-adducts were obtained with 71–95% *ee*.



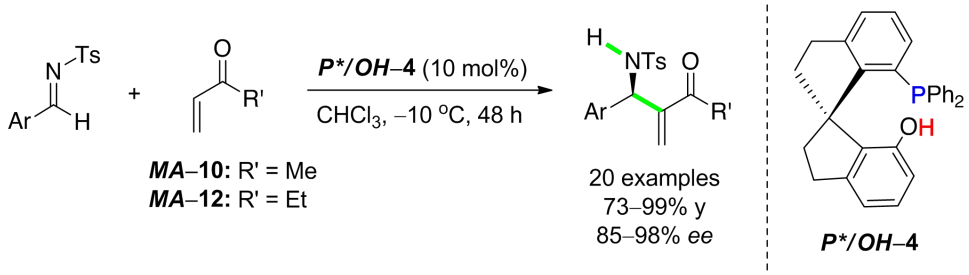
Scheme 2.10 Catalytic asymmetric aza-MBH reaction with methyl vinyl ketone (***MA*–10**)[83]

In 2006, Shi *et al.* developed another enantiopure phosphine catalyst, ***P**/OH*–3**, bearing three hydroxy groups.[84] It was used to catalyze asymmetric aza-MBH reactions between *N*-sulfonyl aldimines and vinyl ketones ***MA*–10** and ***MA*–12** (Scheme 2.11).[84] The corresponding (*S*)-adducts were obtained with 72–99% *ee*.



Scheme 2.11 Catalytic asymmetric aza-MBH reactions with α,β-unsaturated ketones ***MA*–10** and ***MA*–12**[84]

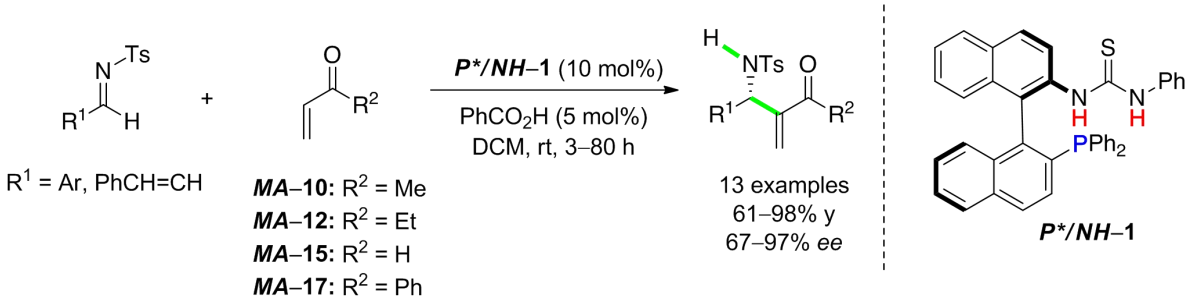
In 2011, Sasai *et al.* developed bifunctional spiro-type phosphine ***P**/OH*–4** (Scheme 2.12).[86] It was used to catalyze highly enantioselective aza-MBH reactions between aromatic *N*-tosyl aldimines and vinyl ketones ***MA*–10** and ***MA*–12**.[86] The corresponding products were obtained with 85–98% *ee*; it is noted that the absolute configuration observed for the adducts, (*R*), was opposite Shi's previous work[80,83,84] [(*S*); see Scheme 2.8, 2.10, and 2.11).



Scheme 2.12 Catalytic asymmetric aza-MBH reactions with α,β-unsaturated ketones ***MA*–10** and ***MA*–12**[86]

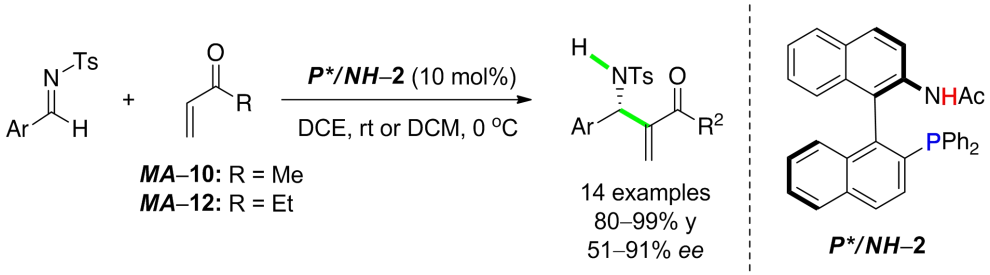
Having studied in detail these bifunctional ***P**/OH*** catalysts for the asymmetric aza-MBH reaction, Shi *et al.* continued exploring the potential of this dual catalysis. The aromatic hydroxy group in the catalyst was replaced by another hydrogen bond donor such as a thiourea, i.e., ***P**/NH*–1** (Scheme 2.13).[81] Shi *et al.* used ***P**/NH*–1** –combined with benzoic acid– to catalyze highly enantioselective aza-MBH reactions between *N*-tosyl aldimines and Michael acceptors ***MA*–10**, ***MA*–12**, ***MA*–15**, and

***MA*–17**. The corresponding products were obtained with 67–97% *ee*. This study represented the first example of synthesis and application of a bifunctional thiourea in asymmetric catalysis.



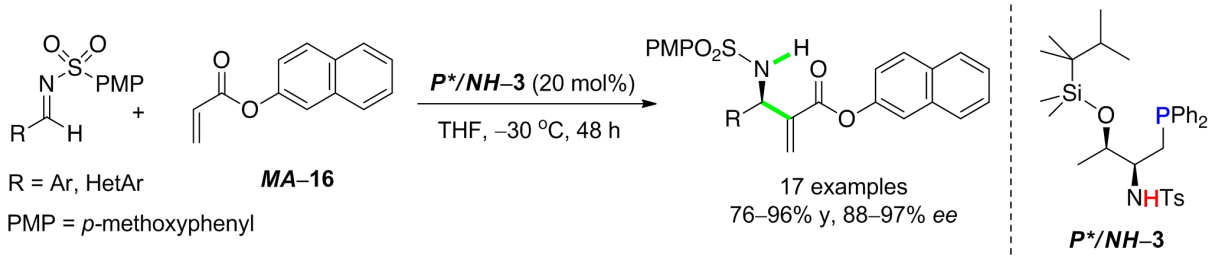
Scheme 2.13 Catalytic asymmetric aza-MBH reactions with various Michael acceptors[81]

In 2008, Shi *et al.* developed another enantiopure phosphine catalyst, ***P*/NH*–2**, bearing an aromatic amide hydrogen atom (Scheme 2.14).[82a] ***P*/NH*–2** was used to catalyze asymmetric aza-MBH reactions between aromatic *N*-tosyl aldimines and vinyl ketones ***MA*–10** and ***MA*–12**. The corresponding products were obtained with 51–91% *ee*.



Scheme 2.14 Catalytic asymmetric aza-MBH reactions with ***MA*–10** and ***MA*–12**[82a]

In 2011, Lu *et al.* designed another novel bifunctional phosphine sulfonamide catalyst, ***P*/NH*–3**, derived from L-threonine.[85] ***P*/NH*–3** was used to catalyze an asymmetric aza-MBH reaction between aromatic *N*-sulfonyl imines and acrylate ***MA*–16** (Scheme 2.15). The corresponding products were obtained with 88–97% *ee*. It is noted that *ortho*-substituted aromatic imines were found to be suitable substrates, while these proved to be challenging in aza-MBH chemistry.



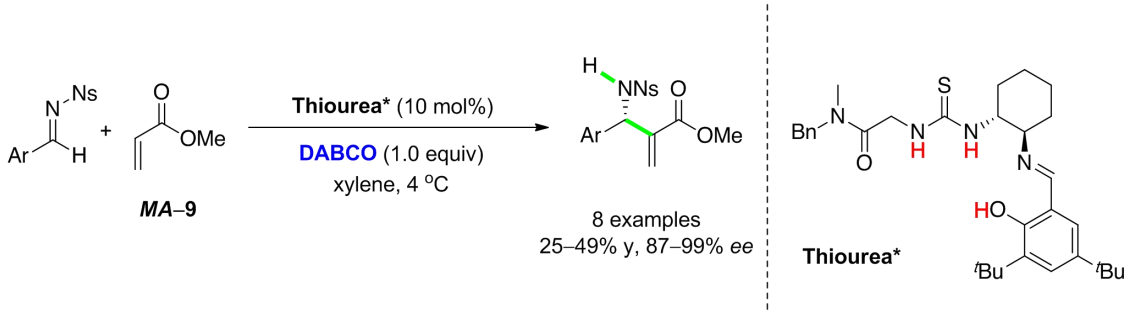
Scheme 2.15 Catalytic asymmetric aza-MBH reaction with 2-naphthyl acrylate (***MA*–16**)[85]

2.1.2 Use of a Two-Catalyst Component System in Literature

Beside catalysts with Lewis base and hydrogen bond donor in one molecule, two-catalyst component systems with an achiral Lewis base and an enantiopure hydrogen bond donor were also developed.

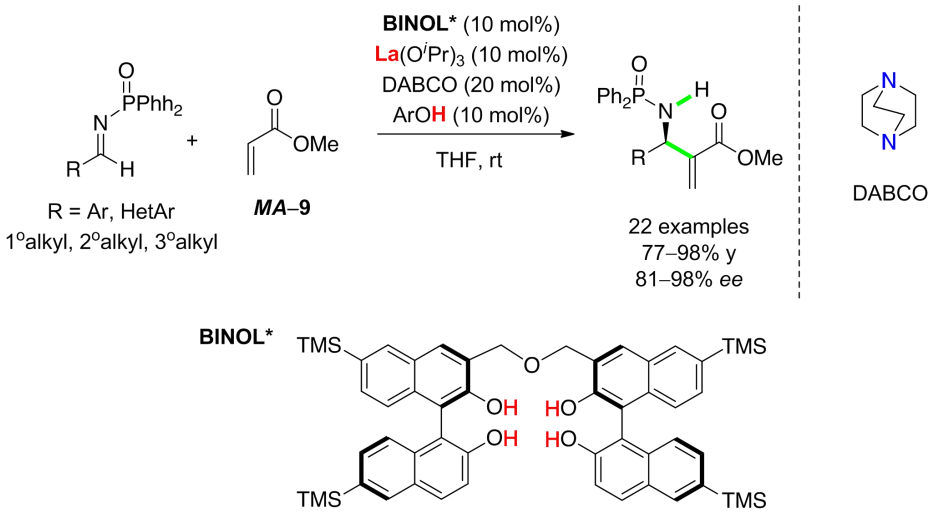
In 2005, Jacobsen *et al.* used enantiopure **Thiourea***, together with a stoichiometric amount of

DABCO, to catalyze an asymmetric aza-MBH reaction between aromatic *N*-nosyl aldimines and methyl acrylate (***MA*–9**; Scheme 2.16).[87] The corresponding products were obtained with 87–99% *ee*.



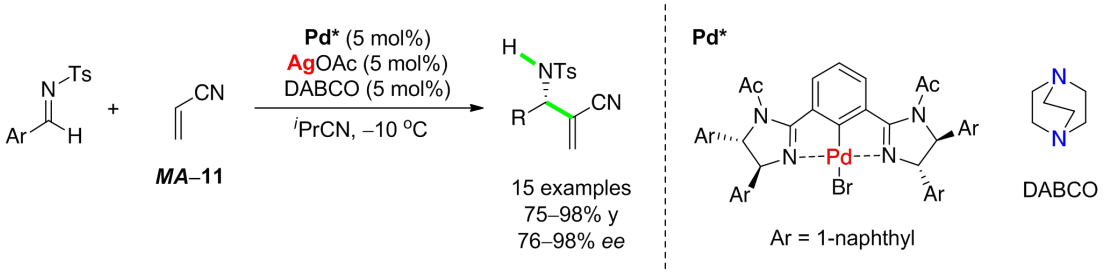
Scheme 2.16 DABCO-mediated asymmetric aza-MBH reaction catalysed by an enantiopure thiourea[87]

In 2010, Shibasaki *et al.* found that the combined use of a La alkoxide, a linked BINOL, an aromatic carboxylic acid, and DABCO effectively catalysed an aza-MBH reaction between various *N*-phosphinoyl imines and methyl acrylate (***MA*–9**; Scheme 2.17).[88] The corresponding products were obtained with 81–98% *ee*.



Scheme 2.17 Asymmetric aza-MBH reaction catalysed by DABCO and an enantiopure La complex [88]

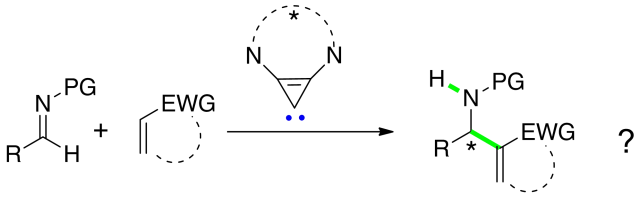
In 2012, Shibata *et al.* used an enantiopure Pd Lewis acid catalyst together with a catalytic amount of DABCO as a Lewis base to catalyze an asymmetric aza-MBH reaction between aromatic *N*-tosyl aldimines and acrylonitrile (***MA*–11**; Scheme 2.18).[89] The corresponding products were obtained with 76–98% *ee*.



Scheme 2.18 Asymmetric aza-MBH reaction catalysed by DABCO and an enantiopure Pd complex[89]

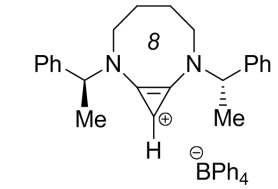
2.1.3 Aims

We aimed to develop novel enantiopure BAC catalysts for *general* asymmetric aza-MBH reactions (Scheme 2.19). A highly asymmetric BAC catalysis had *not* been reported. Although several catalytic asymmetric aza-MBH reactions have been reported using different types of enantiopure (dual) catalysts, several drawbacks were apparent, including the lack of generality (*limited* substrate scope), the necessity of a very low reaction temperature, and the use of rather complex (dual) catalyst systems. We wanted to develop a general method that could tolerate a broad variety of aromatic *and* aliphatic imines as well as different types of Michael acceptors (α,β-unsaturated aldehydes, ketones, esters, amides, and nitriles), including sterically demanding substrates.

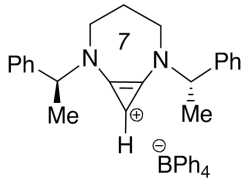


Scheme 2.19 Potential for asymmetric BAC catalysis?

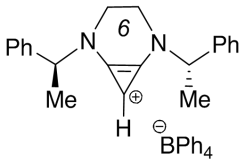
In order to achieve this goal, different types of enantiopure BAC precursors were considered (Figure 2.1): *bicyclic* diamine-derived ***pre-BAC*–1*** ~ ***pre-BAC*–3**; [71] *acyclic* species ***pre-BAC*–4**;[70] *bicyclic* BINOL-derived ***pre-BAC*–4**; *acyclic* imidazolidinone-derived ***pre-BAC*–6**.



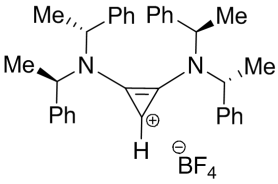
***pre-BAC*–1**
[Gravel pre-catalyst]



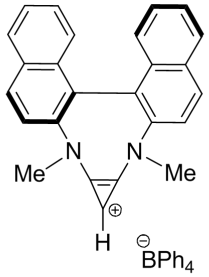
***pre-BAC*–2**



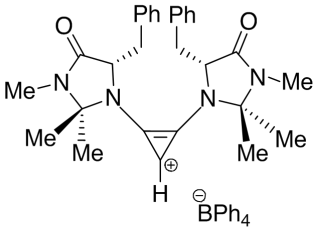
***pre-BAC*–3**



***pre-BAC*–4**
[Tamm pre-catalyst]



***pre-BAC*–5**



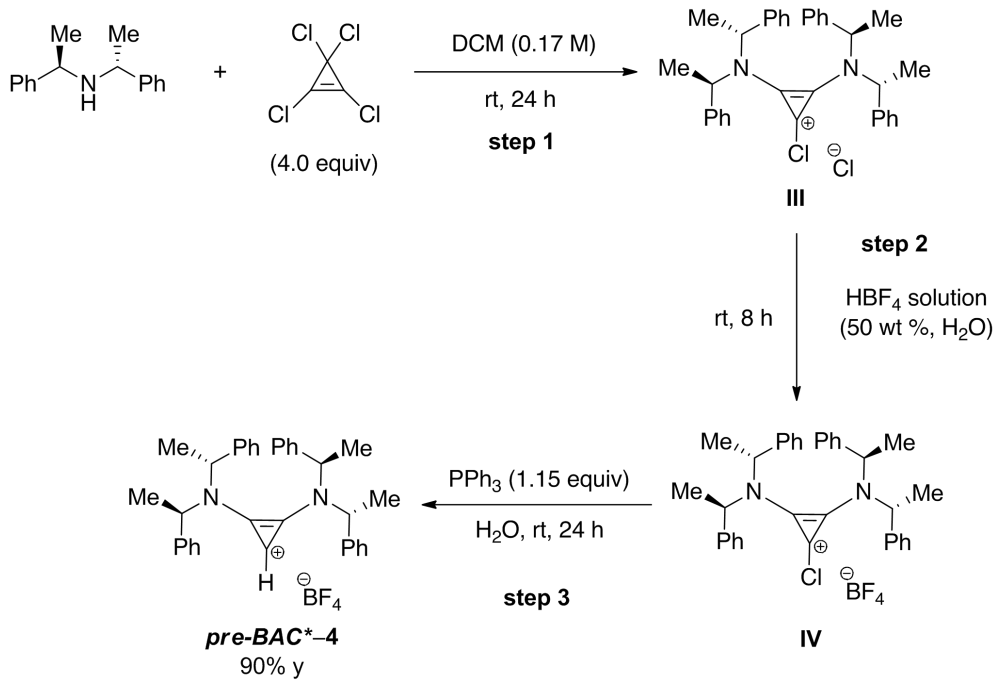
***pre-BAC*–6**

Figure 2.1 Envisaged enantiopure BAC precursors

2.2 Results and Discussion

2.2.1 Synthesis of Enantiopure BAC Precursors

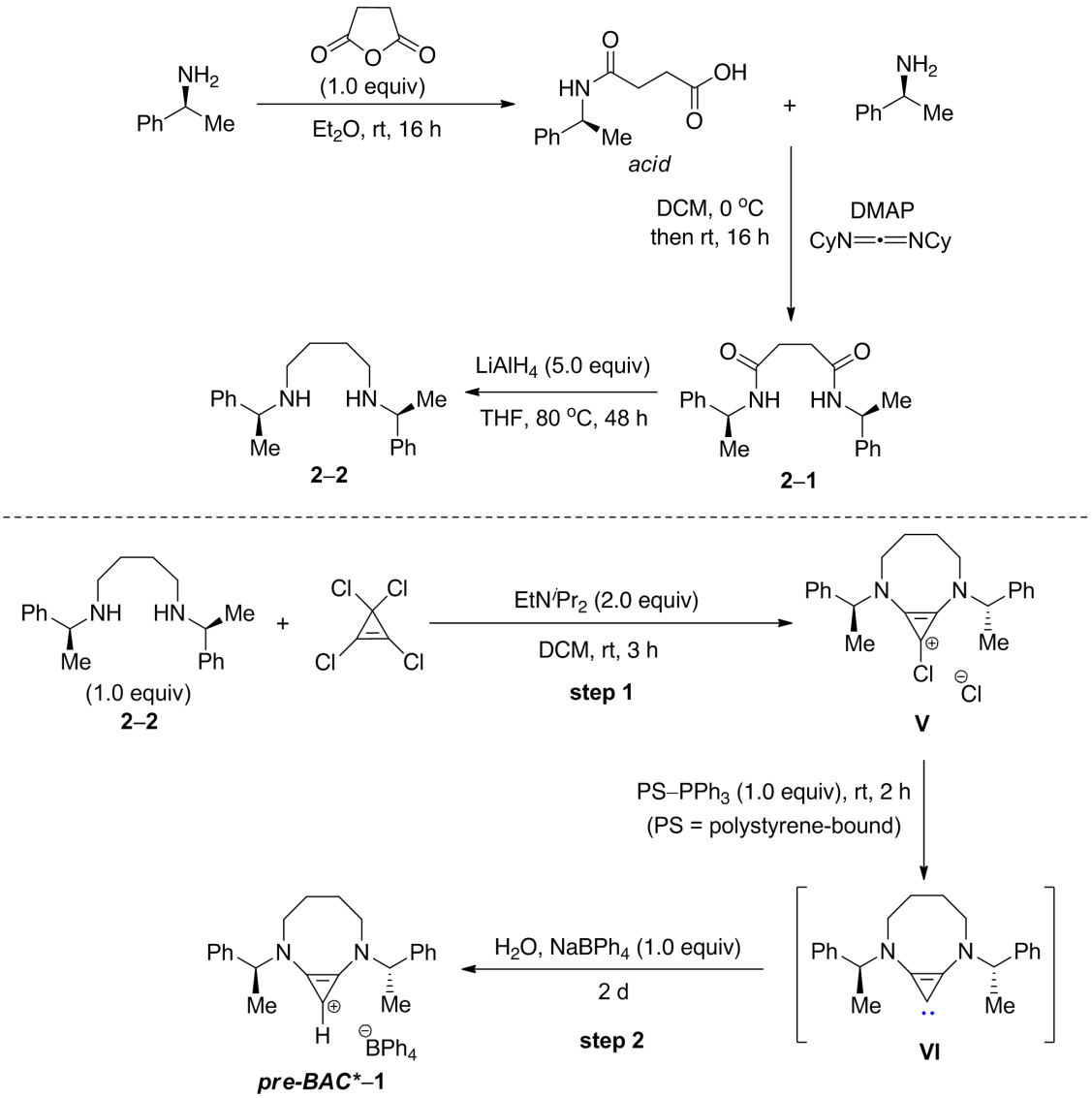
In 2007, Tamm *et al.* reported the synthesis of an *acyclic* ennatiopure BAC precursor from a commercially available diamine, (+)-bis[(*R*)-1-phenylethyl]amine (Scheme 2.20).[70]



Scheme 2.20 Synthesis of ***pre-BAC*–4*** by Tamm[70]

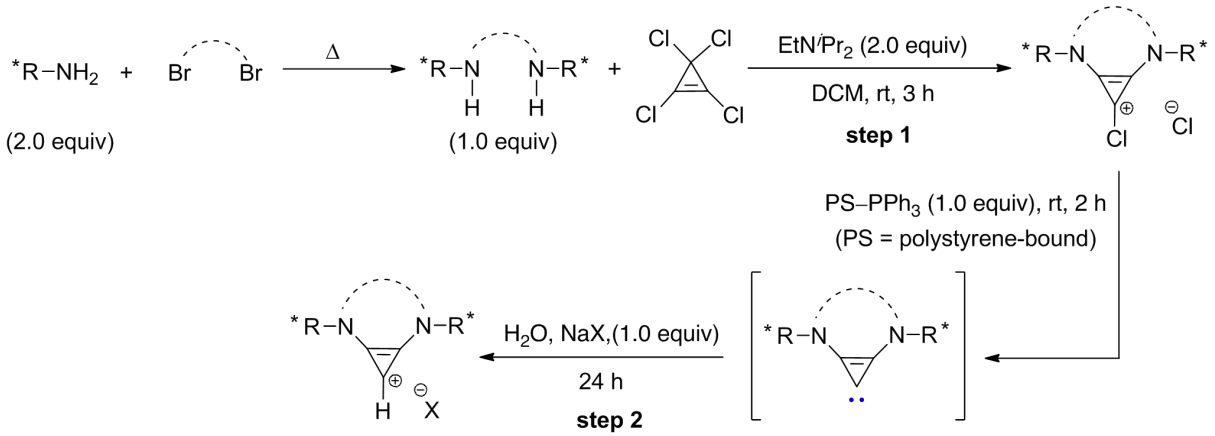
The commercially available diamine and tetrachlorocyclopropene were reacted in dichloromethane to afford intermediate **III**. Upon treatment with tetrafluoroboric acid intermediate **IV** was formed through an anion exchange. Successive reactions with triphenyl phosphine and water the enantiopure cyclopropenylidene precursor ***pre-BAC*–4*** as a colorless solid.

In 2013, Gravel *et al.* reported the synthesis of a *bicyclic* enantiopure BAC precursor bearing an 8-membered ring as a chiral backbone (Scheme 2.21).[71] The treatment of commercially available (*S*)-(–)-α-methylbenzyl amine and succinic anhydride afforded the ring-opened condensate (*acid*), which was reacted with another equivalent of (*S*)-(–)-α-methylbenzyl amine in the presence of stoichiometric amounts of DMAP and 1,3-dicyclohexylcarbodiimide to form chiral bis(amide) **2–1**.[90] The latter was fully reduced using an excess of $LiAlH_4$ to afford the corresponding chiral bis(amine) **2–2**.[90] Tetrachlorocyclopropene and **2–2** were reacted in the presence of an excess of *Hünig's* base to form chlorocyclopropenium salt **V**. Treatment of **V** with polystyrene-supported triphenyl phosphine gave the corresponding BAC intermediate **VI**, which was *in situ* treated with water and sodium tetraphenylborate to give cyclopropenylidene precursor ***pre-BAC*–1*** as a colorless solid.



Scheme 2.21 Synthesis of ***pre-BAC*–1*** by Gravel[71,90]

Based on the synthesis of achiral BAC precursors (see Scheme 1.11), and the literature reports (Schemes 2.20 and 2.21), a general scheme was considered for the synthesis of a variety of enantiopure cyclopropenylidene precursors (Scheme 2.22). An enantiopure diamine had to be synthesized from the corresponding commercially available chiral amine. The reaction between this diamine and tetrachlorocyclopropene, followed by successive treatment of the reaction mixture with sodium tetrafluoroborate, polymer-supported triphenyl phosphine, and water, should afford the corresponding enantiopure BAC precursor.



Scheme 2.22 Proposed synthetic procedure for enantiopure BAC precursors

Gravel's pre–catalyst bearing an 8-membered ring, ***pre-BAC*–1***, as well as its 7- and 6-membered ring analogs, ***pre-BAC*–2*** and ***pre-BAC*–3***, were successfully synthesized according to this procedure (Scheme 2.22). The corresponding enantiopure BAC precursors were obtained in 80–86% yields over three steps (Figure 2.2). The ^{1}H NMR spectroscopic data and molecular models for these compounds are shown in Chart 2.1.

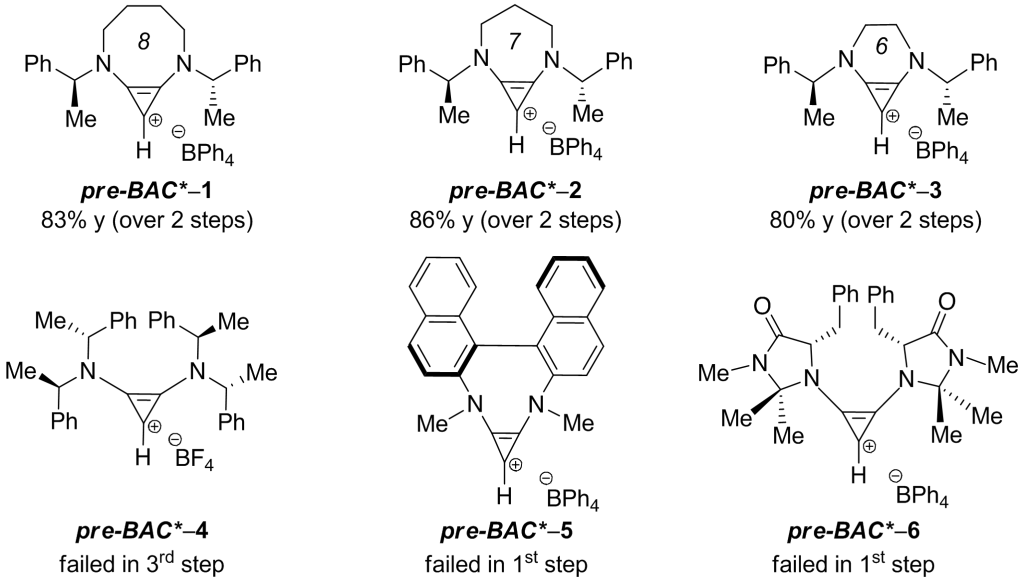


Figure 2.2 Overview for the (attempted) synthesis of enantiopure BAC precursors

Attempts were also made to prepare the other enantiopure BAC precursors (Figure 2.2). We tried to synthesize Tamm's salt ***pre-BAC*–4***.[70] However, after successful preparation of intermediates **III** and **IV** (see Scheme 2.20) –as confirmed by ^{1}H, ^{11}B, and ^{19}F NMR spectroscopic analysis– the final proto-dechlorination step of **IV** failed in our hands. Regarding the synthesis of ***pre-BAC*–5*** and ***pre-BAC*–6***, the first double condensation between tetrachlorocyclopropene and the corresponding enantiopure secondary amine proved to be too challenging. The intended reactions did not occur under mild conditions, and messy reaction mixtures were obtained under more forcing conditions.

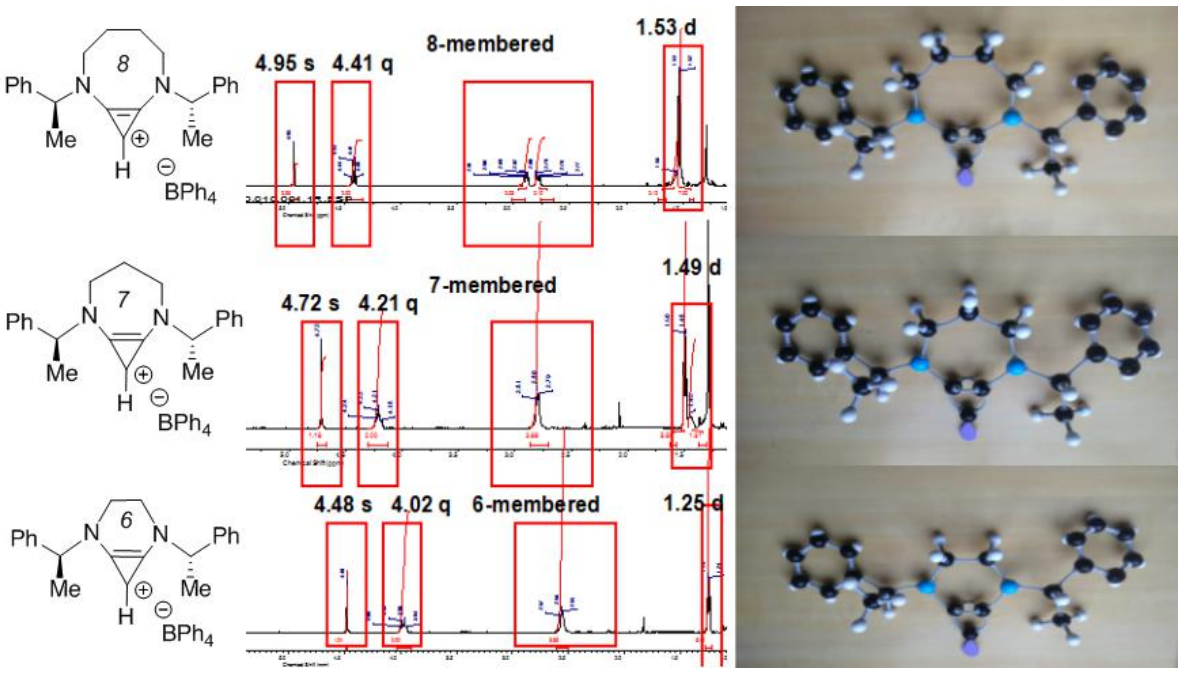
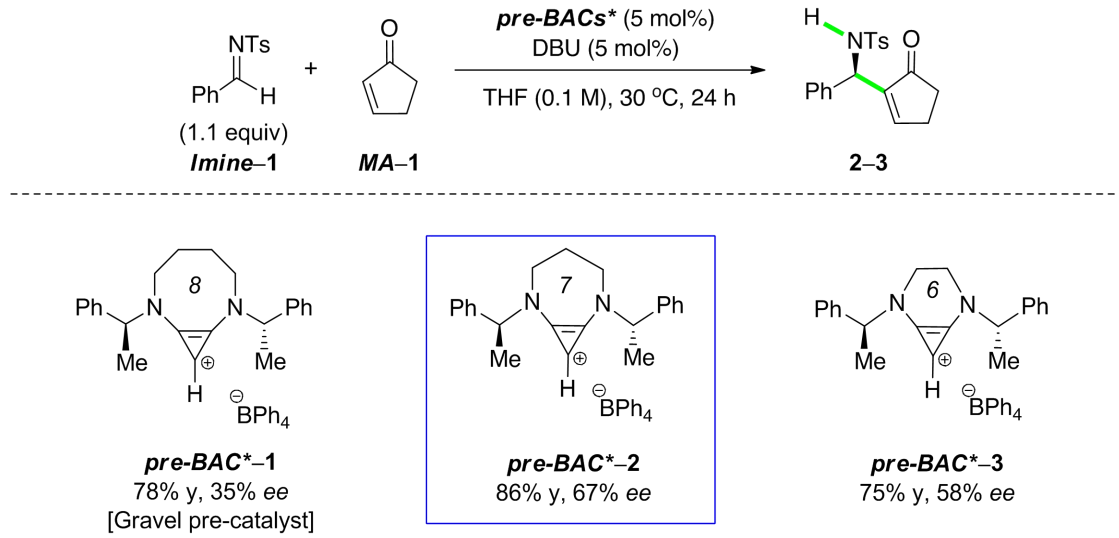


Chart 2.1 ^{1}H NMR spectra for ***pre-BAC**–1 ~ *pre-BAC**–3*** and molecular models for the corresponding BACs

2.2.2 Asymmetric BAC Catalysis – Initial Experiments

With the three enantiopure BAC precursors in hand, a first set of asymmetric aza-MBH reactions was carried out between benzaldehyde-derived *N*-tosyl imine ***Imine*–1** and cyclopentenone (***MA*–1**) under "racemic BAC catalysis" conditions (Scheme 2.23).



Scheme 2.23 Initial trials in asymmetric catalysis with the ennatiopure BAC pre-catalysts

The intended C–C bond formation proceeded smoothly in each case. The use of Gravel's ***pre-BAC*–1** (8-membered ring backbone) gave product **2–3** in 78% isolated yield with 35% *ee*. Importantly, the use of the novel BAC precursor ***pre-BAC*–2** (7-membered ring backbone) gave product **2–3** in 86% isolated yield with 67% *ee*. The use of the third pre-catalyst, ***pre-BAC*–3** (6-membered ring backbone), did not allow to further improve this result (75% y, 58% *ee*). At this stage, the absolute configuration of the enantiomerically enriched product **2–3** was determined. By analogy with a literature report,[74] chiral HPLC analysis determined the absolute configuration of all three samples to be *R* (Chart 2.2).

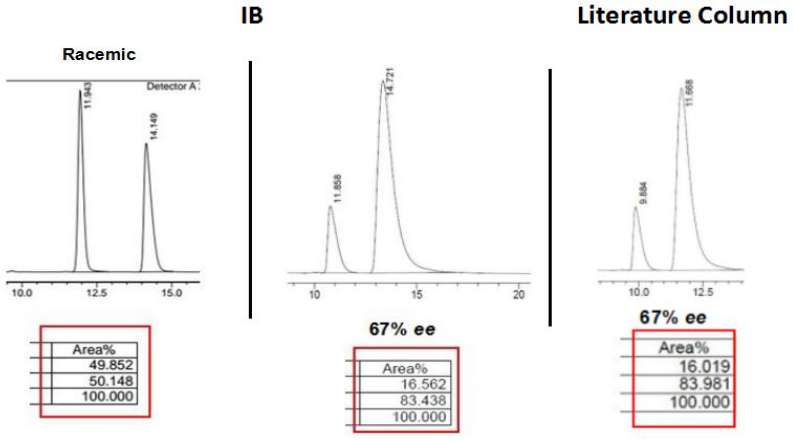


Chart 2.2 Comparison of chiral HPLC analyses of product **2–3**

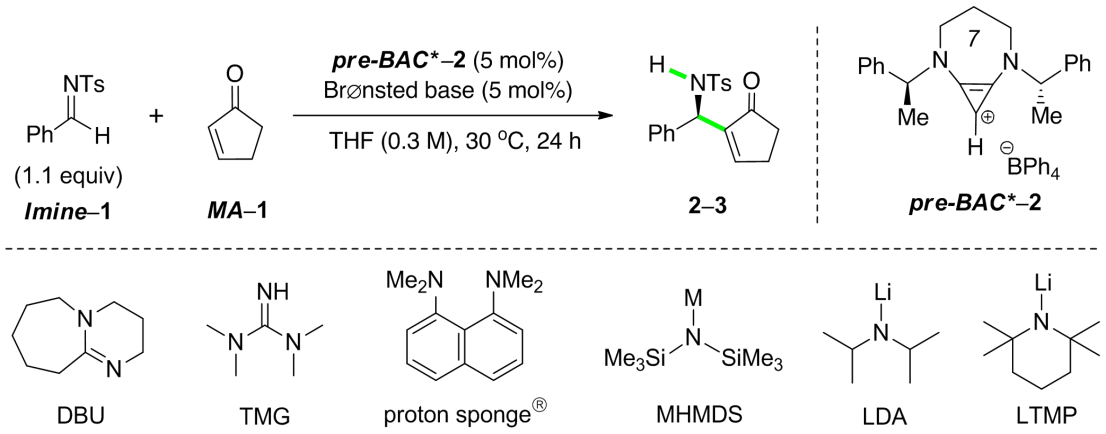
Since the ***pre-BAC*–2** proved to be substantially more selective than the two analogs, further

optimizations were carried out using this novel pre-catalyst.

2.2.3 Optimization of Reaction Parameters

First, a base co-catalyst screening was carried out under otherwise identical conditions (Table 2.1). The yields were determined after purification by preparative thin-layer chromatography (PTLC), and the optical purity (*ee*) was determined by chiral HPLC analysis.

Table 2.1: Base co-catalyst screening for the BAC-catalysed asymmetric aza-MBH reaction



Entry	*pre-BAC*–2*	Brønsted base	Yield (%)[a]	*ee* (%)[c]
1	+	DBU	82	67
2	+	—	*NR*[b]	—
3	+	TMG	62	56
4	+	proton sponge®	*NR*[b]	—
5	+	KHMDS	25	45
6	+	NaHMDS	17	41
7	+	LiHMDS	10	37
8	+	LDA	10	32
9	+	LTMP	30	38
10	+	LiO^{t}Bu	15	18
11	+	NaO^{t}Bu	23	19
12	+	KO^{t}Bu	35	18
13	+	Li_2CO_3	*NR*[b]	—
14	+	Na_2CO_3	*NR*[b]	—
15	+	K_2CO_3	*NR*[b]	—
16	+	Cs_2CO_3	75	80
17	—	Cs_2CO_3	*NR*[b]	—

[a] Yields were determined after purification by preparative thin-layer chromatography (PTLC). [b] *NR* = no reaction; the desired product was not detectable, only unreacted starting materials were detected (^{1}H NMR analysis of the reaction mixture). [c] The *ee* was determined by chiral HPLC analysis.

In contrast to the initial benchmark result in asymmetric catalysis with DBU as a base co-catalyst (82% y, 67% *ee*; entry 1), the sole use of ***pre-BAC*–2*** as a potential catalyst did not give product **2–3** (entry 2). The use of other metal-free base co-catalysts proved to be less effective in terms of both

reactivity and asymmetric induction (entries 3 and 4). Next, several metal–base co-catalysts were examined (entries 5–16). Among amide and alkoxide bases (entries 5–12), the use of KHMDS as a co-catalyst gave product **2–3** with the best optical purity (45% *ee*; entry 5). Among carbonates (entries 13–16), only the use of the Cs_2CO_3 co-catalyst gave product **2–3** (75%; entry 16); in addition, the optical purity of product **2–3** proved to be best among all base co-catalysts examined (80% *ee*). In this context, in the absence of ***pre-BAC*–2***, the use of Cs_2CO_3 alone did not catalyze this reaction; only starting materials were recovered (entry 17). The HPLC charts of the enantiomerically enriched product **2–3** obtained using DBU and Cs_2CO_3 as co-catalyst are displayed in Chart 2.3.

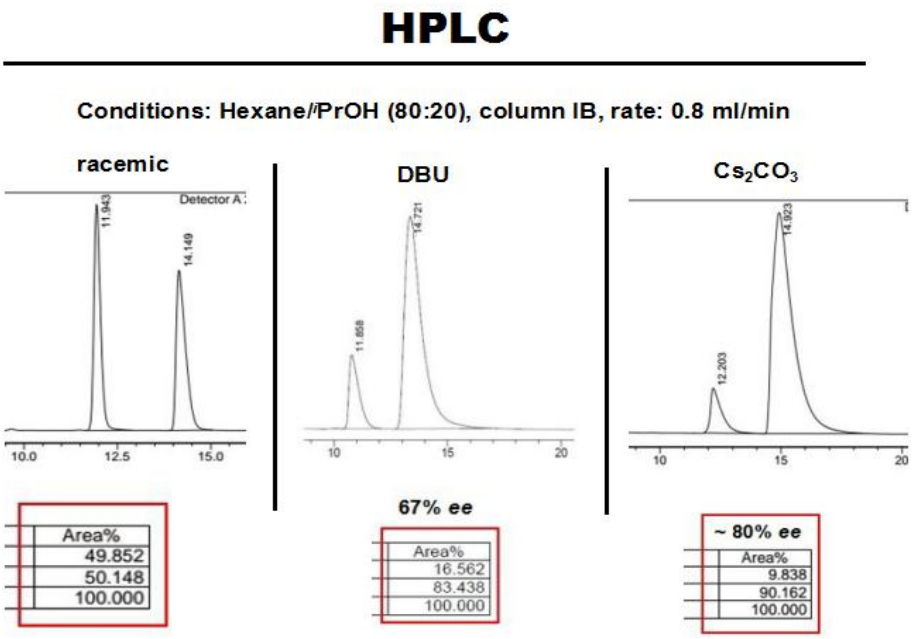
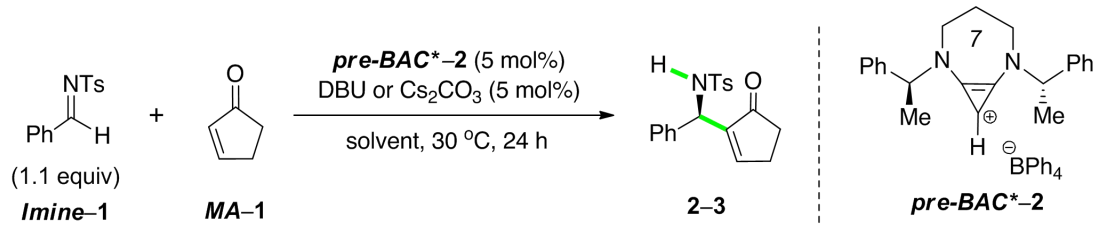


Chart 2.3 Chiral HPLC charts for the use of DBU and Cs_2CO_3 as co-catalyst

The base screening revealed DBU and Cs_2CO_3 to be the most effective co-catalysts for the *in situ* generation of the enantiopure BAC catalyst. Thus, both base co-catalysts were used to examine the solvent effect (Table 2.2).

Table 2.2: Solvent screening for the BAC-catalysed asymmetric aza-MBH reaction



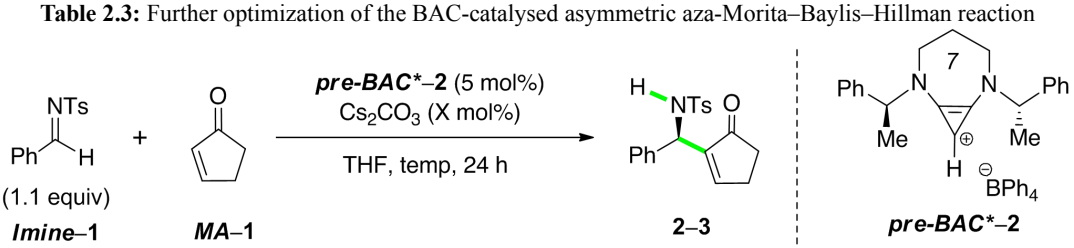
Entry	Base	Solvent (Ɛ)	Yield (%)[a]	*ee* (%)[c]
1	DBU	dioxane (2.3)	70	40
2		toluene (2.4)	74	67
3		TBME (2.6)	28	20
4		Et_2O (4.3)	15	15
5		THF (7.5)	82	67
6		DCM (9.1)	*NR*[b]	–
7		^{t}BuOH (18.0)	70	42
8		EtOH (24.6)	69	48
9		MeOH (33)	52	53
10		MeCN (37.5)	24	35
11		DMF (38.0)	48	50
12	Cs_2CO_3	dioxane (2.3)	72	37
13		toluene (2.4)	70	35
14		TBME (2.6)	19	30
15		Et_2O (4.3)	*NR*[b]	–
16		THF (7.5)	76	81
17		DCM (9.1)	*NR*[b]	–
18		^{t}BuOH (18.0)	68	48
19		EtOH (24.6)	70	50
20		MeOH (33)	55	58
21		MeCN (37.5)	28	40
22		DMF (38.0)	50	62

[a] Yields were determined after purification by preparative thin-layer chromatography (PTLC). [b] *NR* = no reaction; the desired product was not detectable, only unreacted starting materials were detected (^{1}H NMR analysis of the reaction mixture). [c] The *ee* was determined by chiral HPLC analysis.

First, aromatic and etheral solvents were examined (entries 1–5 and 12–16). Among these, the use of THF provided the best results regarding reactivity and asymmetric induction, although toluene proved to be competitive when DBU was used as a co-catalyst (entries 2, 5, and 16). Usually, in catalytic asymmetric aza-MBH reactions, THF or a more polar solvent (e.g. MeCN) have been used. Interestingly however, the use of more *polar* aprotic and protic solvents provided product **2–3** with a substantially lower asymmetric induction (entries 6–11 and 17–22). In turn, the system ***pre-BAC*–2*** / Cs_2CO_3 / THF was used for further optimizations.

Next, the substrate concentration, the amount of Cs_2CO_3, and the reaction temperature were optimized (Table 2.3).

Table 2.3: Further optimization of the BAC-catalysed asymmetric aza-Morita–Baylis–Hillman reaction



Entry	*MA*–1 (M)	Cs_2CO_3 (mol%)	temp (°C)	Yield (%)[a]	*ee* (%)[c]
1	0.05			48	81
2	0.075			51	83
3	0.1			57	84
4	0.125	5.0	30	66	81
5	0.2			75	79
6	0.3			81	80
7	0.5			80	69
8		2.5		32	76
9		4.5		52	78
10	0.1	5.0	30	55	84
11		5.5		79	85
12		6.0		75	84
13		7.5		81	82
14			0	*NR*[b]	—
15			10	*NR*[b]	—
16	0.1	5.5	20	39	84
17			25	54	86
18			30	79	85

[a] Yield were determined after purification by preparative thin-layer chromatography (PTLC). [b] *NR* = no reaction; the desired product was not detectable, only unreacted starting materials were detected (^{1}H NMR analysis of the reaction mixture). [c] The *ee* was determined by chiral HPLC analysis.

At 5 mol% loading of ***pre-BAC**–2*** and Cs_2CO_3 in THF at 30 °C, several substrate concentrations (0.05–0.5 M) were tested (entries 1–7). It was found that 0.1 M was the optimal concentration of ***MA*–1**; product **2–3** was obtained in 57% yield with 84% *ee* (entry 3). Using this substrate concentration in the presence of 5 mol% of ***pre-BAC**–2***, the amount of Cs_2CO_3 (2.5–7.5 mol%) was examined (entries 8–13). These experiments revealed that a slight excess of the base co-catalyst was required; the use of 5.5 mol% of Cs_2CO_3 gave product **2–3** in 79% yield with 85% *ee* (entry 11). With these optimized conditions in hand, the effect of the reaction temperature (0–30 °C) was investigated (entries 14–18). All starting materials, including ***pre-BAC**–2*** and Cs_2CO_3, were reacted at the corresponding temperature; the enantiopure BAC was *not* pre-formed. At 0–10 °C the reaction did not proceed at all (entries 14 and 15). These results are likely to be ascribed to the failed *in situ* formation of the BAC catalyst at these lower temperatures. The experiments at 20–30 °C revealed that 25 °C was the optimal temperature (entries 16–18); product **2–3** was formed in a lower yield (54%), but with a slightly increased asymmetric induction (86% *ee*; entry 17).

As bicyclic ***pre-BAC**–2*** with the 7-membered ring backbone displayed the best potential for asymmetric catalysis, several analogues with the same ring size were synthesized (see Scheme 2.22;

P75, Figure 2.3): salt ***pre-BAC*–7*** contains a distinct counteranion, BF_4^- instead of BPh_4^-; analogue ***pre-BAC*–8*** bears a more sterically demanding alkyl substituent, Et instead of Me; analogues ***pre-BAC*–9*** and ***pre-BAC*–10*** vary regarding the corresponding aromatic substituent, 1- and 2-naphthyl instead phenyl.

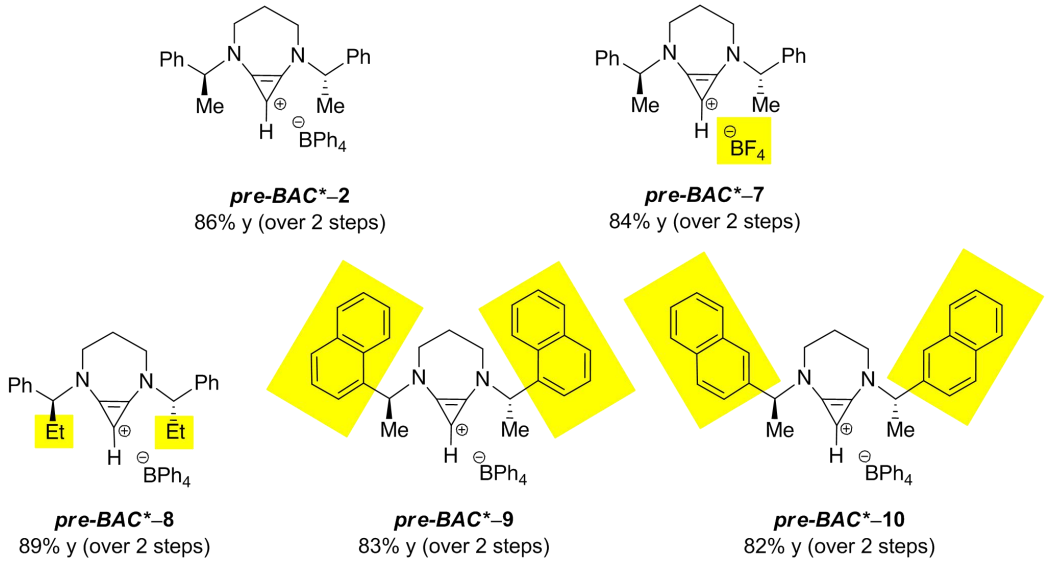
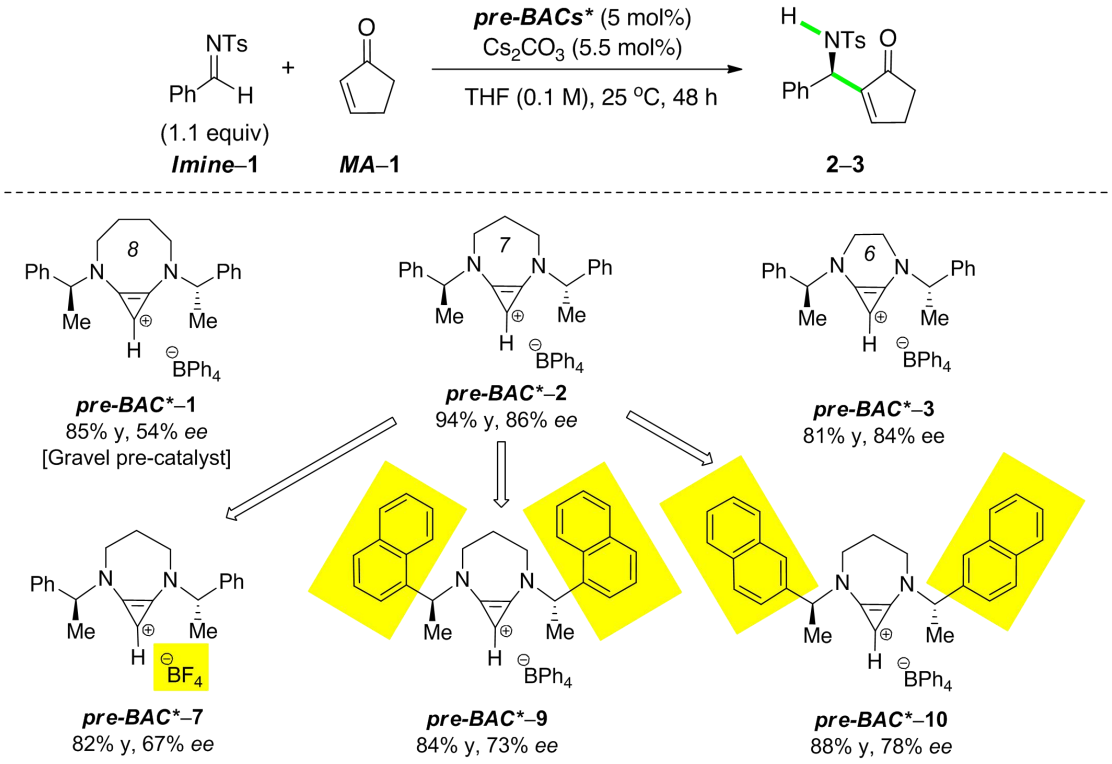
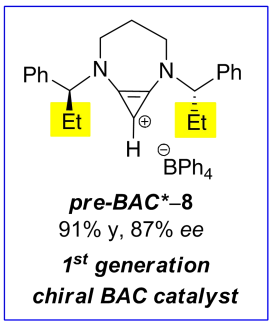


Figure 2.3 A variety of enantiopure BAC precursors

With these novel enantiopure BAC precursors and the optimized BAC catalysis protocol in hand, the effect on the asymmetric induction was investigated at 25 °C (48; Scheme 2.24).





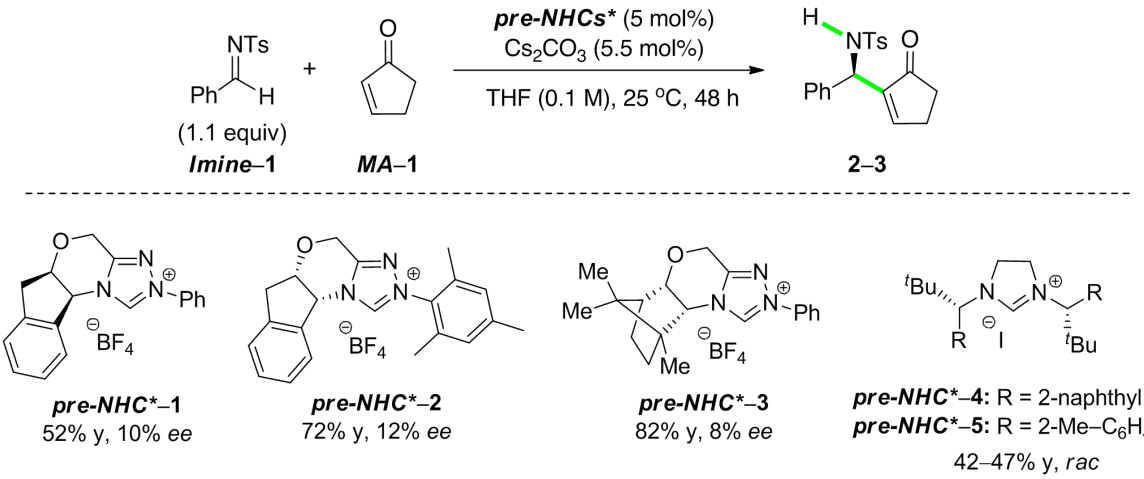
Scheme 2.24 Comparison of various enantiopure BAC precursors

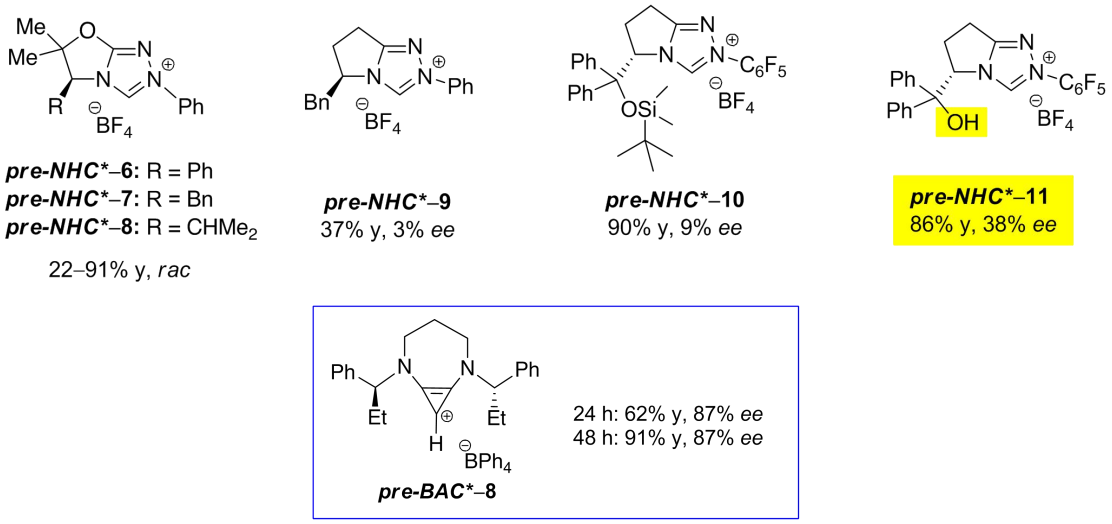
It was found in that product **2–3** was obtained in high yields in all cases. The use of Gravel's pre-catalyst (***pre-BAC*–1***), bearing an 8-membered ring backbone, gave **2–3** with 54% *ee*. The use of novel BAC precursors ***pre-BAC*–2*** and ***pre-BAC*–3***, bearing 7- and 6-membered ring backbones, afforded **2–3** with 86% *ee* and 84% *ee*, respectively. When the counteranion in ***pre-BAC*–2*** was changed from BPh_4^- to BF_4^-, the resulting pre-catalyst (***pre-BAC*–7***) gave **2–3** only with 67% *ee*. Likewise, when the aromatic substituent in ***pre-BAC*–2*** was changed from phenyl to 1-naphthyl and 2-napthyl, the resulting pre-catalysts (***pre-BAC*–9*** and ***pre-BAC*–10***) gave **2–3** only with 73% *ee* and 78% *ee*, respectively. Importantly, when the aliphatic substituent in ***pre-BAC*–2*** was changed from methyl to ethyl, the resulting pre-catalyst (***pre-BAC*–8***) gave **2–3** with 87% *ee*, which represented the highest asymmetric induction of all BAC precursors used in this context.

2.2.4 Asymmetric Carbene Catalysis: Enantiopure BAC vs. NHC Precursors

Next, we compared the potential of the best enantiopure BAC pre-catalyst (***pre-BAC*–8***) with various enantiopure NHC pre-catalysts under otherwise identical conditions (Table 2.4). Several of these NHC precursors, ***pre-NHC*–1*** ~ ***pre-NHC*–5***, are commercially available while others were *donated by Professor Andrew Smith's laboratory at the University of St Andrews*.

Table 2.4: Asymmetric catalysis – enantiopure BAC vs. NHC precursors

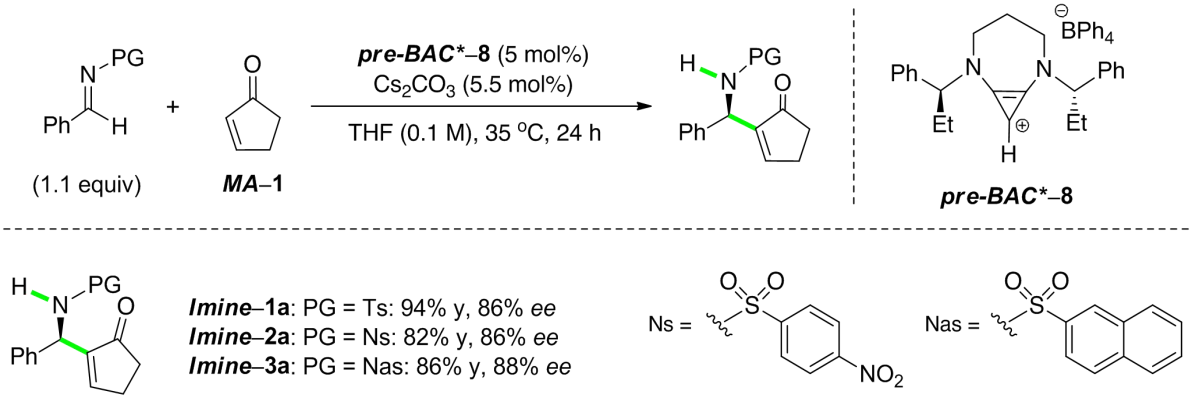




The use of *in situ* generated enantiopure NHCs gave product **2–3** in 22–91% yields. However, the asymmetric induction in this aza-MBH adduct proved to be low for all these *non-BAC* pre-catalysts (0–38% *ee*). The best asymmetric induction was obtained with NHC precursor ***pre-NHC**–11*** bearing a hydroxy group in proximity to the carbene site (38% *ee*). In light of these results, the excellent asymmetric induction displayed by the novel enantiopure BAC pre-catalyst ***pre-BAC**–8*** must be regarded therefore even more remarkable (87% *ee*). Next, we investigated the substrate scope for this catalytic asymmetric aza-MBH reaction.

2.2.5 Scope for 1st Generation Asymmetric BAC Catalysis

With the optimized *asymmetric BAC catalysis* protocol in hand, we briefly examined the effect of the *N*-protecting group of benzaldehyde-derived substrates: ***Imine*–1a** (PG = Ts), ***Imine*–2a** (PG = Ns), and ***Imine*–3a** (PG = Nas; Scheme 2.25).



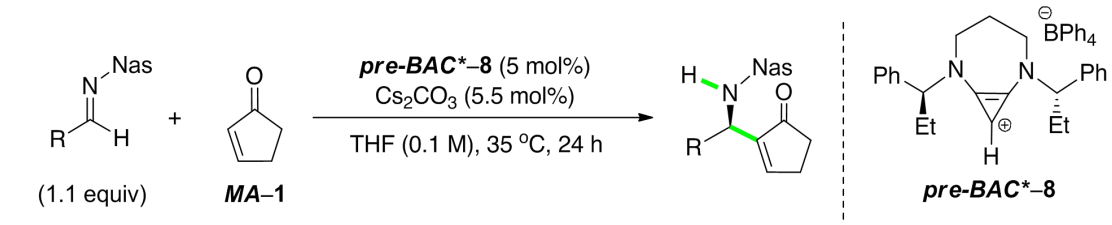
Scheme 2.25 Refinement of the *N*-protecting group in the imine

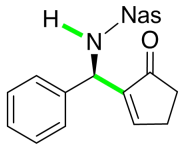
It was found that under the optimized conditions (25 °C), only the *N*-tosyl imine (***Imine*–1a**) reacted smoothly whereas the use of ***Imine*–2a** (PG = Ns) and ***Imine*–3a** (PG = Nas) gave product **2–3** only in trace amounts. In turn, the experiments were conducted at 35 °C, and this modification gave **2–3** in high yields for all imines (82–94%). In case of ***Imine*–1a** (PG = Ts), the asymmetric induction in product **2–3** was found to be slightly decreased from 87% *ee* (25 °C) to 86% *ee* (35 °C); the same

result was observed for the use of ***Imine*–2a** (PG = Ns; 86% *ee*). Importantly however, the use of ***Imine*–3a** (PG = Nas) gave product **2–3** with 88% *ee*, which turned out to be the best enantiomeric excess at this stage of the study.

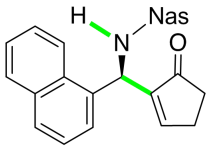
Next, the scope was investigated with aromatic, heteroaromatic, and aliphatic *N*-Nas imines using ***MA*–1** as the pro-nucleophile (Table 2.5).

Table 2.5: Imine scope for the BAC-catalysed asymmetric aza-MBH reaction

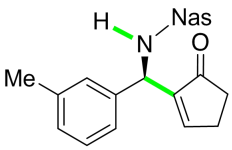




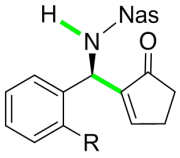
2–4
86% y, 88% *ee*



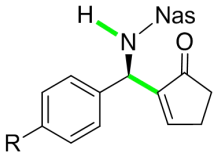
2–5
89% y, 84% *ee*



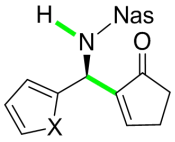
2–6
92% y, 74% *ee*



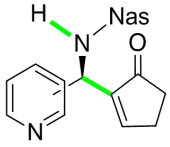
2–7: R = *o*-Me: 92% y, 76% *ee*
2–8: R = *o*-OMe: 87% y, 66% *ee*
2–9: R = *o*-OH: 85% y, 93% *ee*
2–10: R = *o*-F: 95% y, 87% *ee*
2–11: R = *o*-Cl: 98% y, 85% *ee*
2–12: R = *o*-CN: 74% y, 89% *ee*



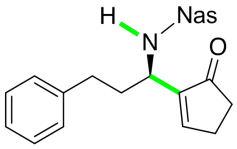
2–13: R = *p*-Me: 88% y, 58% *ee*
2–14: R = *p*-OH: 74% y, 81% *ee*
2–15: R = *p*-F: 97% y, 75% *ee*
2–16: R = *p*-Cl: 95% y, 78% *ee*
2–17: R = *p*-Br: 85% y, 73% *ee*
2–18: R = *p*-CN: 68% y, 71% *ee*
2–19: R = *p*-CO_2Me: 95% y, 80% *ee*
2–20: R = *p*-CF_3: 92% y, 69% *ee*
2–21: R = *p*-NO_2: 81% y, 90% *ee*



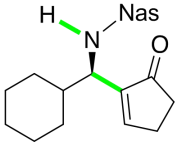
2–22: X = O: 97% y, 90% *ee*
2–23: X = S: >99% y, 91% *ee*
2–24: X = NH, 84% y, 91% *ee*



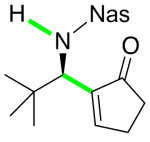
2–25: 2-pyr 84% y, 89% *ee*
2–26: 3-pyr 81% y, 82% *ee*
2–27: 4-pyr 72% y, 76% *ee*



2–28
48%y, 52% *ee*



2–29
69%y, 34% *ee*



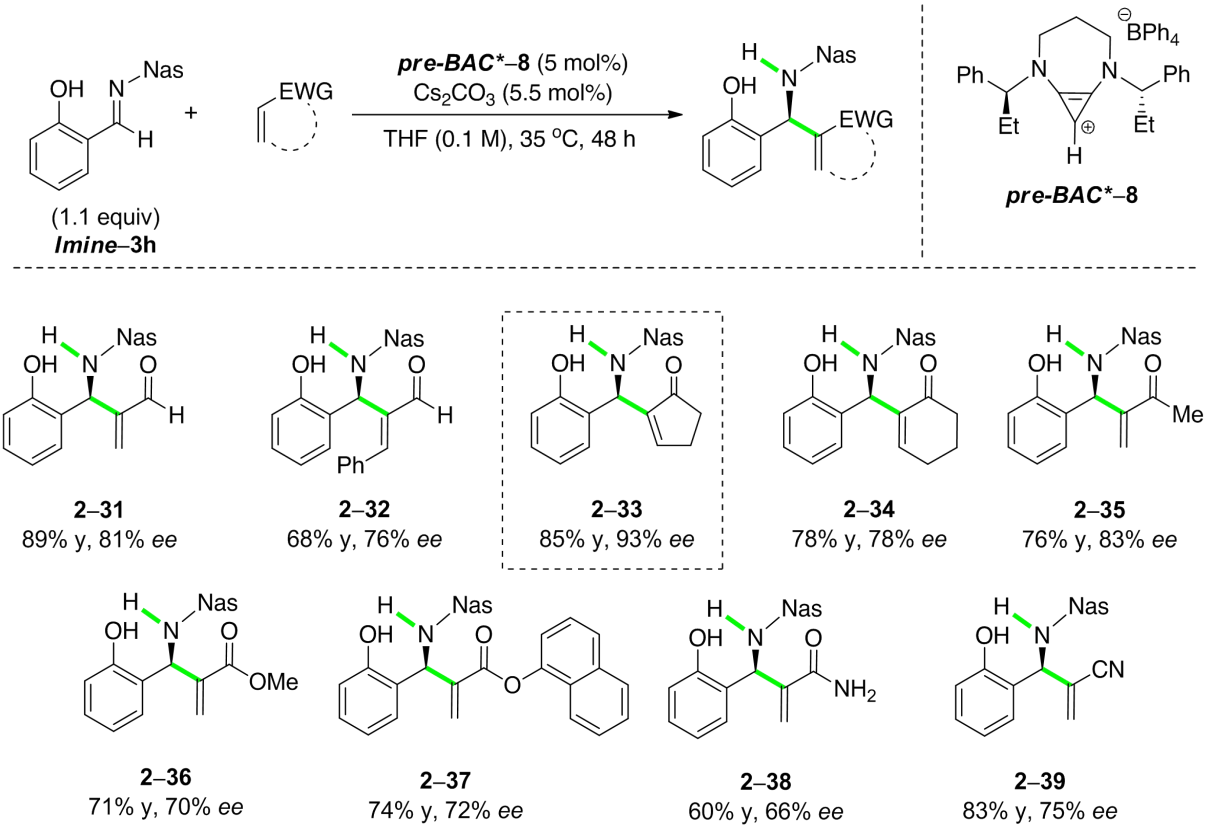
2–30
62%y, 64% *ee*

It was found that all aromatic imines were smoothly converted to the corresponding aza-MBH adducts in 72–97% yields with 58–93% *ee*. Several tendencies regarding the asymmetric induction were observed. It is found that the use of *o*-substituted imines gave products **2–7** ~ **2–12** with a higher asymmetric induction (66–93% *ee*) than *p*-substituted imines; here, products **2–13** ~ **2–21** were formed with 58–90% *ee*. It is also noted that the use of electron-poor imines (R = F, Cl, Br, CN, CO_2Me, CF_3, NO_2) gave aza-MBH-adducts with a higher asymmetric induction (69–90% *ee*) than electron-rich imines (R = Me, OMe; 58–76% *ee*). The best result was obtained with *o*-phenol-based imine, which

gave product **2–9** with 93% *ee*. Interestingly, the use of electron-rich heteroaromatic imines (furan, thiophene, pyrrole) provided the corresponding products **2–22** ~ **2–24** with 90–91% *ee*, while the eletron-poor pyridine derivatives proved to be less effective (**2–25** ~ **2–27**; 76–89% *ee*). Finally, it is noted that this novel methodology proved to be compatible with less reactive primary, secondary, and tertiary aliphatic imines although the asymmetric induction dropped substantially (**2–28** ~ **2–30**; 34–64% *ee*). Among all three aliphatic imines used, the use of the tertiary substrate gave the highest asymmetric induction (64% *ee*).

Next, we explored the scope of pro-nucleophiles for the BAC-catalysed asymmetric aza-MBH reaction using *o*-phenol-derived *N*-Nas imine, ***Imine*–3h**, as the electrophile (Table 2.6). Various Michael acceptors were examined, including α,β-unsaturated aldehydes, ketones, esters, and amides, as well as acrylonitrile.

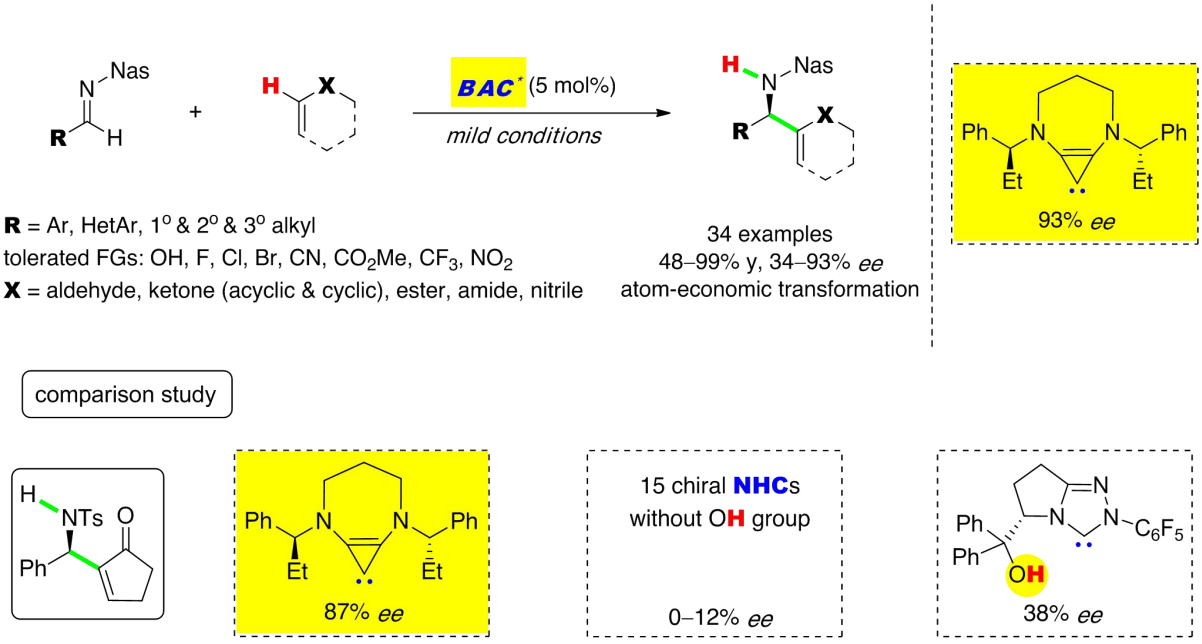
Table 2.6 Pro-nucleophile scope for BAC-catalysed asymmetric aza-MBH reaction



It was found that all Michael acceptors reacted smoothly under the optimized conditions to give the corresponding aza-MBH adducts in 60–89% yields with 66–93% *ee*. Interestingly, alike the racemic version, both α,β-unsaturated aldehydes underwent an a^3d^2 *umpolung* exclusively to give products **2–31** and **2–32** with 81% and 76% *ee*, respectively – the typical NHC-catalysed a^1d^3 *umpolung* was not observed.[56] The use of α,β-unsaturated ketones afforded products **2–33** ~ **2–35** with up to 93% *ee*. Importantly, the α,β-unsaturated carboxylic acid derivatives were shown to undergo an unusual a^3d^2 *umpolung* exclusively to give products **2–36** ~ **2–39** with 66–75% *ee*, whereas the NHC-catalysed a^3d^3 *umpolung* was not detected.[45]

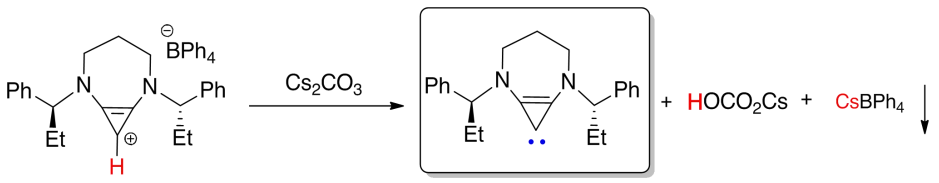
At this stage of the study, several enantiopure BAC pre-catalysts were successfully synthesized and

exploited in asymmetric aza-MBH reactions (Scheme 2.26). To the best of our knowledge, these data represent the first highly enantioselective BAC catalysis. Compared to "classic" NHC pre-catalysts these novel cyclopropenylidene precursors displayed a substantially higher asymmetric induction in the model reaction (87% *ee* vs. 0–38% *ee*). Remarkably, this *unprecedented* asymmetric *BAC* catalysis went beyond the asymmetric catalysis using *established NHC*s.



Scheme 2.26 Summary of BAC-catalysed asymmetric aza-MBH reactions

The skeleton of our new carbene catalyst bears only a Lewis base site without a supporting hydrogen bond donor fragment (Scheme 2.27). Therefore, the high asymmetric induction observed for a broad variety of both imines and Michael acceptors seems surprising.



Scheme 2.27 Deprotonation of an enantiopure BAC pre-catalyst using cesium carbonate

The optical purity for most aza-MBH adducts proved to be slightly lower compared to the best *dual* catalyst systems reported in literature.[72] Remarkably, the use of an enantiopure cyclopropenylidene – as a *simple Lewis base* catalyst– at *ambient* temperature represents a very distinct feature; a hydrogen bond donor assistance was *not* required for high asymmetric induction. It is noted that in our hands, all products were formed with an *R* configuration; an inversion of absolute configuration was *not* detected, which is another difference to certain dual catalyst systems.[72] Typically, a *bifunctional* acid–base catalyst system was required; both a Lewis base and a hydrogen bond donor site have been crafted in the chiral backbone of such cooperative organocatalyst (Figure 2.4). The Lewis base functionality serves to activate the Michael acceptor, while the hydrogen bond donor was thought to stabilize zwitterionic intermediates through charge–dipole interactions. Both Hatakeyama's catalyst[73-

[78] and Shi's catalyst[80-84] were the most representative metal-free catalysts, and proved to tolerate various Michael acceptors. However, ***N*/OH*–1** and ***P*/OH*–1** had to be used at a rather low reaction temperature, –55 °C and –30 °C, respectively. Shibata's ***N/Pd**** system was shown to rely on the combined use of an enantiopure palladium Lewis acid and an achiral Lewis base at –10 °C. However, only acrylonitrile was tolerated by this metal-based catalyst.

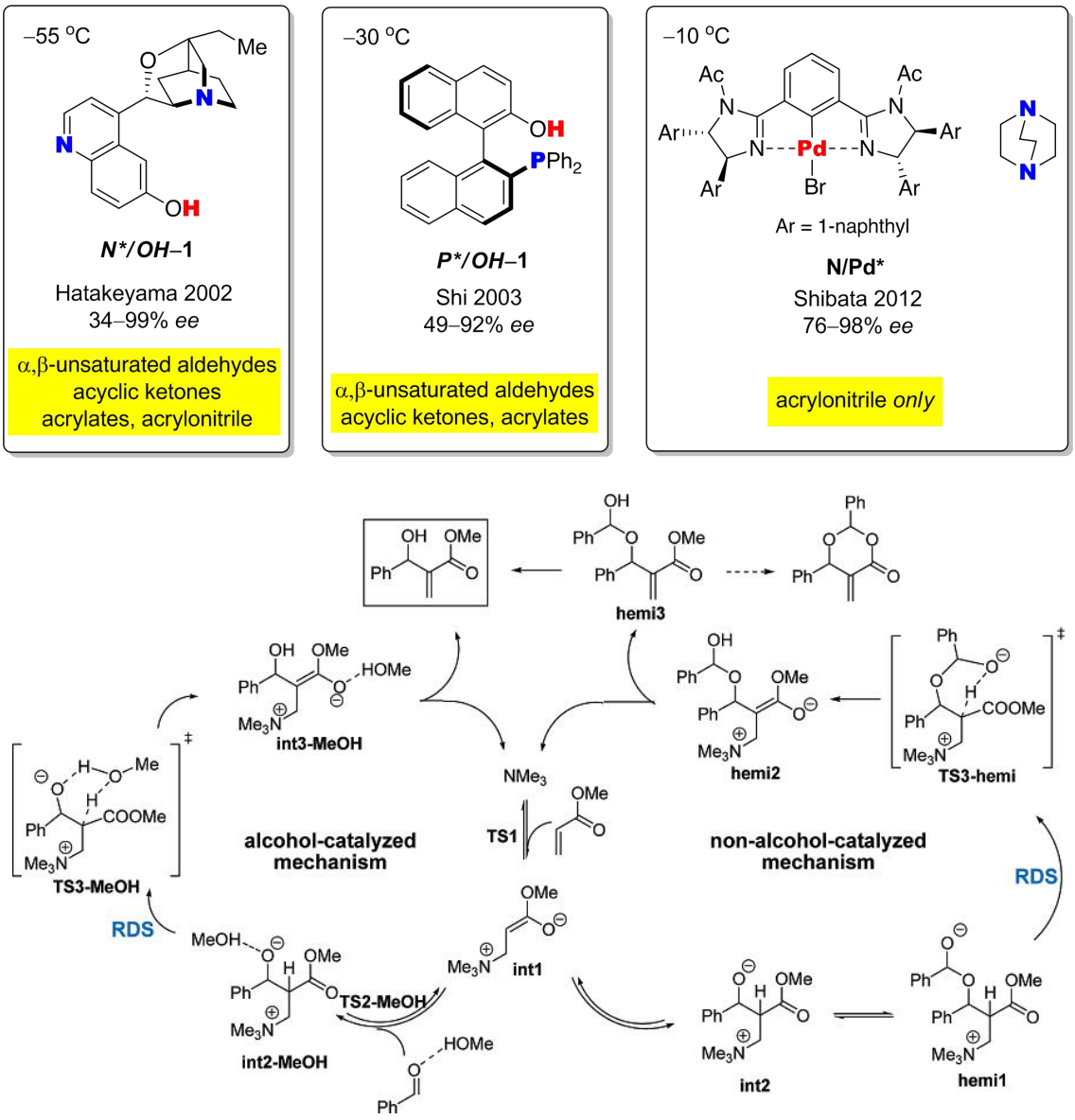


Figure 2.4 Most effective bifunctional catalyst systems for asymmetric aza-MBH chemistry

In Aggarwal's mechanism study,[49] two mechanisms were proposed for the proton-transfer process: (i) an alcohol-catalysed mechanism, in which the alcohol acts as a shuttle for transferring a proton from the α-position to alkoxide of **int2**; (ii) the addition of another equivalent aldehyde would facilitate the formation of a hemiacetal alkoxide. Their results gave the first time a clear understanding of the rate enhancement. The hydrogen-bond donors activate the reaction through a concerted lower-energy mechanism, in which the alcohol works as a shuttle to transfer the proton.

Although a high asymmetric induction was obtained in most cases (Tables 2.5 and 2.6), it was found

that the enantiomeric excess of products obtained from *aromatic* imines (58–93% *ee*) was substantially higher compared to products obtained from *aliphatic* imines (34–64% *ee*). This tendency suggested that *π stacking interactions*[91] might be critical. In literature, three types of π stacking interactions have been reported: *edge–to–face*, *face–to–face*, and *parallel displaced* (Figure 2.5).[92-94]

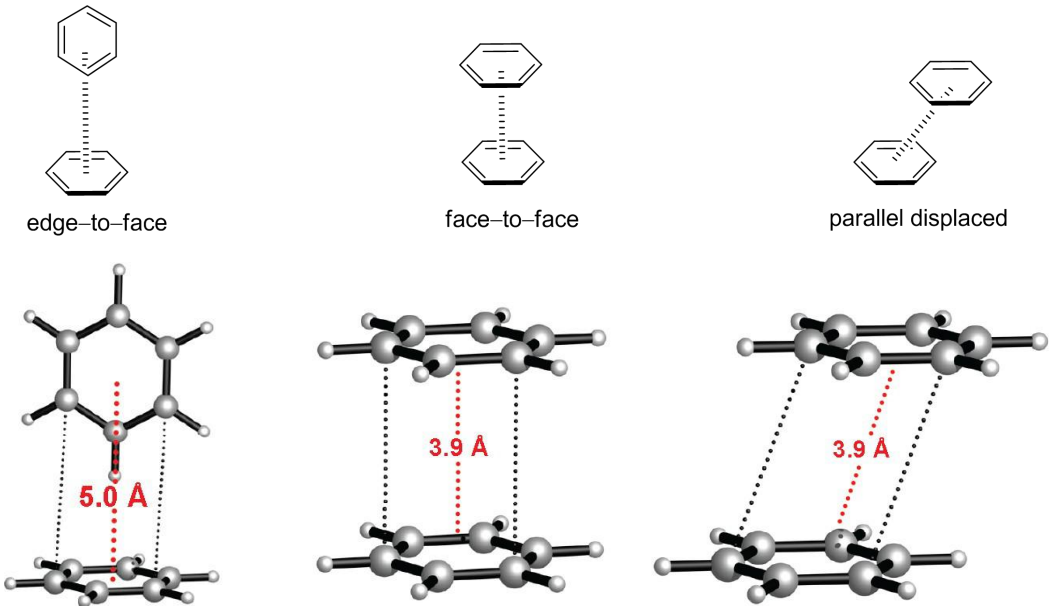


Figure 2.5 *Edge–to–face*, *face–to–face*, and *parallel displaced* π stacking interactions[92-94]

The benzene dimer has been the prototypical system for studying π stacking interactions. In case of an edge–to–face π stacking, the two benzene rings were perpendicular to each other with a distance of 5.0 Å between the two centres.[93] In the other two cases, a distance of 3.9 Å between the centers was measured.[93] Several specific examples of π stacking interactions have been reported. In 1994, Wilcox *et al.* reported on the effect of intramolecular edge–to–face interactions on conformational preferences. The X-ray crystallography analysis confirmed the edge–to–face interactions for the folded esters (Figure 2.6).[95]

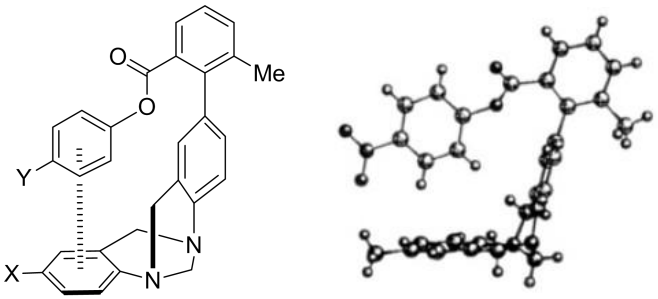


Figure 2.6 First example of *edge–to–face* conformational study[95]

Such interactions may offer great potential in drug design. For example, the existence of π–π, cation–π, and OH–π interactions was proposed to facilitate binding of a drug to the active site of the targeted enzyme (Figure 2.7).

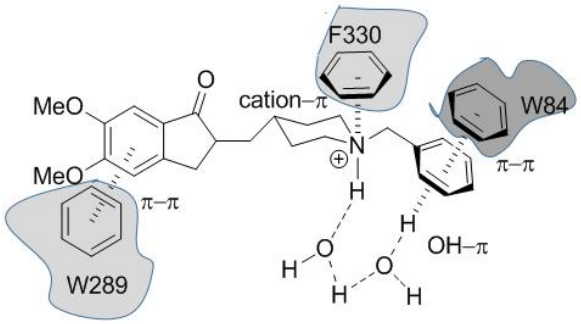


Figure 2.7 Binding of Eisai's anti-Alzheimer drug Aricept to the active site of acetylcholine esterase

Considering our catalyst system, the high asymmetric induction may be a result of the *o*-hydroxy group of aromatic ***Imine*–8**. Indeed, the hydroxy group may act as a hydrogen bond donor for the basic imine nitrogen atom (Figure 2.8). Cooperative hydrogen bonding may be important as these non-covalent interactions may favor a nucleophilic addition of the zwitterionic enolate to the imine. Considering a potential π stacking effect, a face–to–face interaction may not be possible as the two aromatic rings seem to be too distant to each other. However, edge–to–face interactions seem feasible as shown in the transition state model. Accordingly, the nucleophilic enolate may attack the imine from its *Re* face to provide the corresponding products predominantly with an *R* configuration.

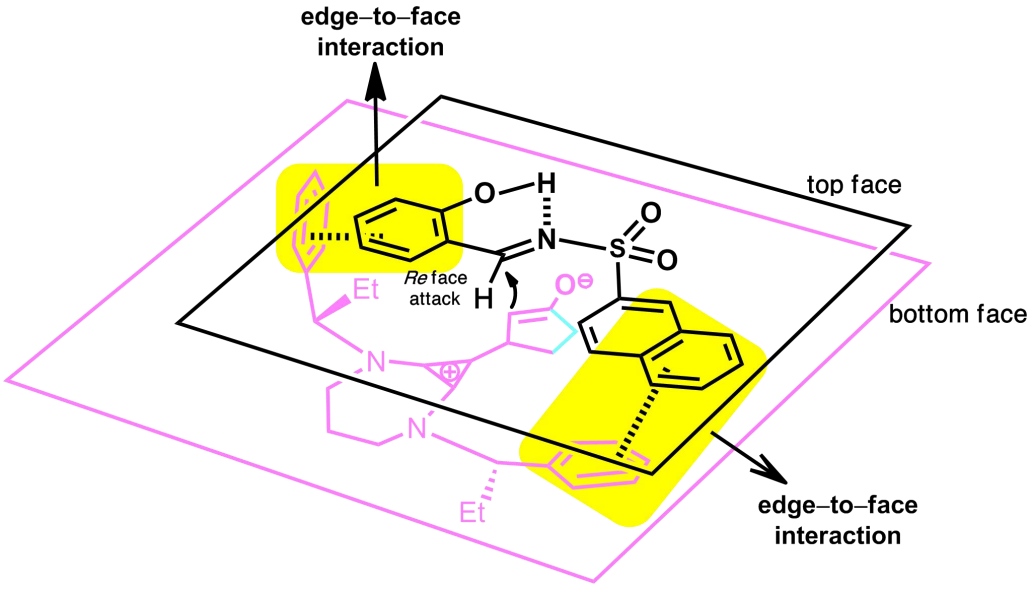
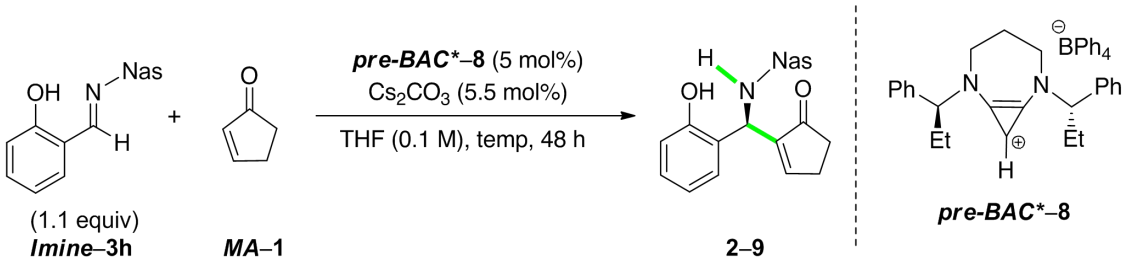


Figure 2.8 Proposed transition state for the 1st generation asymmetric BAC catalysis

2.2.6 Low-Temperature Experiments

In general, the temperature is considered as a critical factor for the level of asymmetric induction.[96] Despite the fact that up to 93% *ee* were observed at 35 °C *without* BAC pre-formation (Section 2.2.5; P84), the *reaction* temperature was re-examined *after BAC pre-formation* (Table 2.7).

Table 2.7: Low-temperature effect on the BAC-catalysed asymmetric aza-MBH reaction



(1.1 equiv)
***Imine*–3h** ***MA*–1** **2–9** ***pre-BAC**–8**

Entry	Temp (°C)	Yield (%)[a]	*ee* (%)[b]
1	35	90	93
2	20	87	93
3	0	80	94
4	–20	78	95
5	–40	70	95

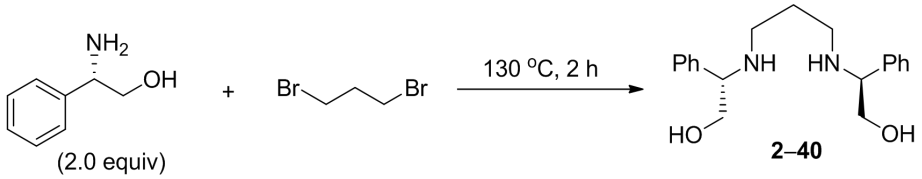
[a] Yields were determined after purification by preparative thin-layer chromatography (PTLC). [b] The *ee* was determined by chiral HPLC analysis.

The most effective enantiopure BAC precursor, ***pre-BAC**–8**, was reacted with Cs_2CO_3 at 35 °C to pre-form *in situ* the corresponding enantiopure BAC. To this catalyst solution at a specific temperature (+35 °C ~ –40 °C) were added the two reagents, ***Imine*–8** and ***MA*–1**. The experiments revealed that decreasing the reaction temperature increased the asymmetric induction for product **2–9**: from 93% *ee* (+35 °C) to 95% *ee* (–20 °C), although the yield slightly dropped (from 90% to 78%).

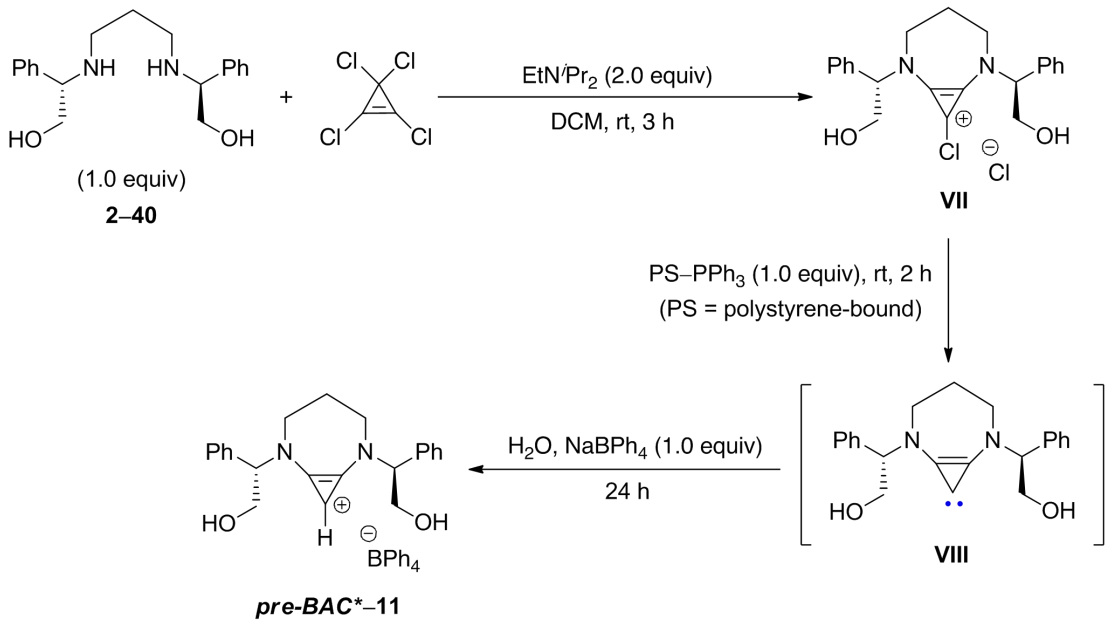
In conclusion, we have prepared a 1st generation of enantiopure BAC pre-catalysts and exploited these in asymmetric aza-MBH reactions. A variety of imines and Michael acceptors proved to be tolerated; the products were obtained with up to 95% *ee*.

2.2.7 2nd Generation Asymmetric BAC Catalysis

The presence of a *hydrogen bond donor* within the Lewis base catalyst has proved critical in asymmetric aza-MBH reactions.[74,75,79,80,83,84,86,87,88] In turn, we have attempted to synthesize an enantiopure cyclopropenylidene scaffold that contains *hydroxy groups* to examine the effect of such a potential dual catalyst in asymmetric aza-MBH reactions.[97] According to the earlier synthesis of the *simple* enantiopure BAC precursors (Scheme 2.22; P75), an appropriate synthetic scheme was used for the preparation of the *bifunctional* pre-catalyst ***pre-BAC**–11** (Scheme 2.28).



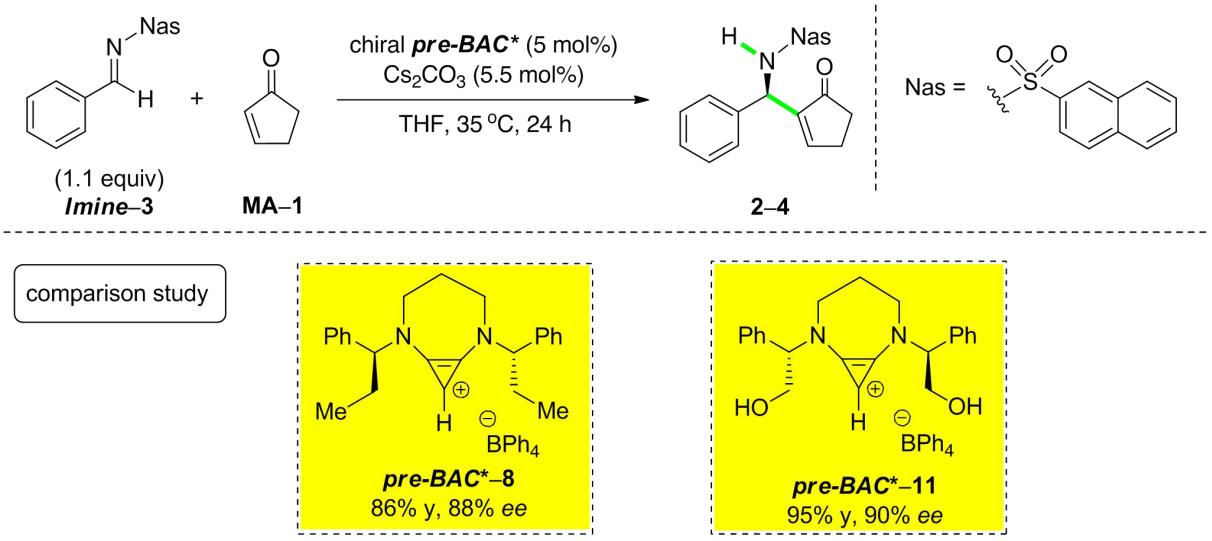
(2.0 equiv) **2–40**



Scheme 2.28 Synthesis of enantiopure cyclopropenylidene precursor ***pre-BAC*–11***[71,90,97]

Double condensation of (*S*)-(+)-2-phenylglycinol and 1,3-dibromopropane gave bis(amine) **2–40**.[97] The latter was reacted with tetrachlorocyclopropene in the presence of an excess of Hünig's base to form chlorocyclopropenium salt **VII**. Compound **VII** was treated with polystyrene-supported triphenyl phosphine, and the resulting intermediate **VIII** was reacted with water and sodium tetraphenylborate to give cyclopropenylidene precursor ***pre-BAC*–11** as a colorless solid.[71]

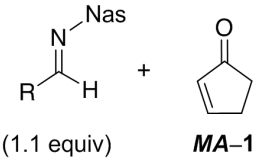
With ***pre-BAC*–11*** in hand, this enantiopure "2nd generation" pre-catalyst was evaluated against the most effective "1st generation" pre-catalyst, ***pre-BAC*–8*** (Scheme 2.29). Compared to the use of ***pre-BAC*–8***, the use of the OH-containing ***pre-BAC*–11*** gave product **2–4** with an increased asymmetric induction (90% *ee* vs. 88% *ee*); an inversion of absolute configuration was *not* detected. Based on this significant improvement, the substrate scope was re-investigated using ***pre-BAC*–11***.



Scheme 2.29 Comparison between ***pre-BAC*–8*** and ***pre-BAC*–11***

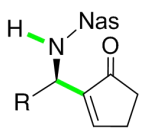
First, the scope for imines was re-examined (Table 2.8).

Table 2.8: Imine scope for the 2nd generation BAC-catalysed asymmetric aza-MBH reaction[a]

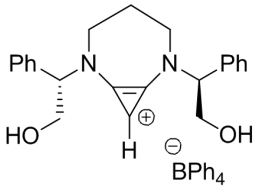


(1.1 equiv) ***MA*–1**

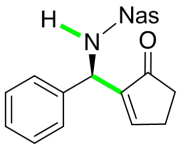
***pre-BAC**–11** (5 mol%)
Cs_2CO_3 (5.5 mol%)
THF (0.1 M)
35 °C, 48 h / –20 °C, 72 h



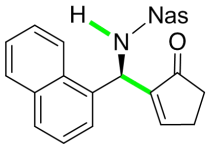
35 °C, 48 h, yields 52–97%
–20 °C, 72 h, yields 68–99%



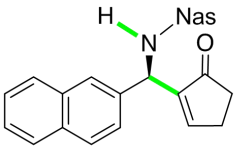
***pre-BAC**–11**



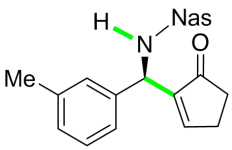
2–4
90% / 94% *ee*



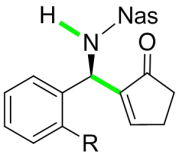
2–5
84% / 93% *ee*



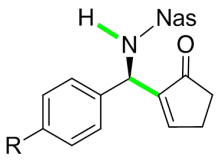
2–41
79% / 85% *ee*



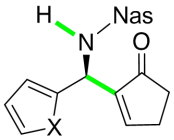
2–6
82% / 89% *ee*



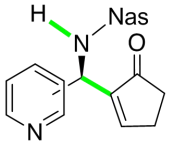
2–7: R = *o*-Me: 80% / 90% *ee*
2–8: R = *o*-OMe: 76% / 83% *ee*
2–9: R = *o*-OH: 92% / 97% *ee*
2–10: R = *o*-F: 77% / 87% *ee*
2–11: R = *o*-Cl: 89% / 92% *ee*
2–12: R = *o*-CN: 87% / 94% *ee*



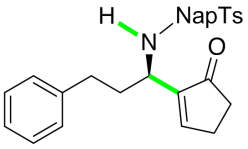
2–13: R = *p*-Me: 72% / 79% *ee*
2–14: R = *p*-OH: 86% / 91% *ee*
2–15: R = *p*-F: 76% / 86% *ee*
2–16: R = *p*-Cl: 78% / 81% *ee*
2–17: R = *p*-Br: 80% / 85% *ee*
2–18: R = *p*-CN: 76% / 81% *ee*
2–19: R = *p*-CO_2Me: 81% / 92% *ee*
2–20: R = *p*-CF_3: 73% / 82% *ee*
2–21: R = *p*-NO_2: 86% / 92% *ee*



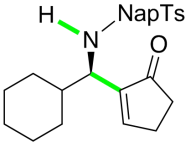
2–22: X = O: 89% / 94% *ee*
2–23: X = S: 90% / 96% *ee*
2–24: X = NH, 91% / 94% *ee*



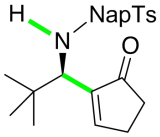
2–25: 2-pyr 89% / 92% *ee*
2–26: 3-pyr 81% / 89% *ee*
2–27: 4-pyr 75% / 87% *ee*



2–28
68% / 78% *ee*



2–29
52% / 59% *ee*



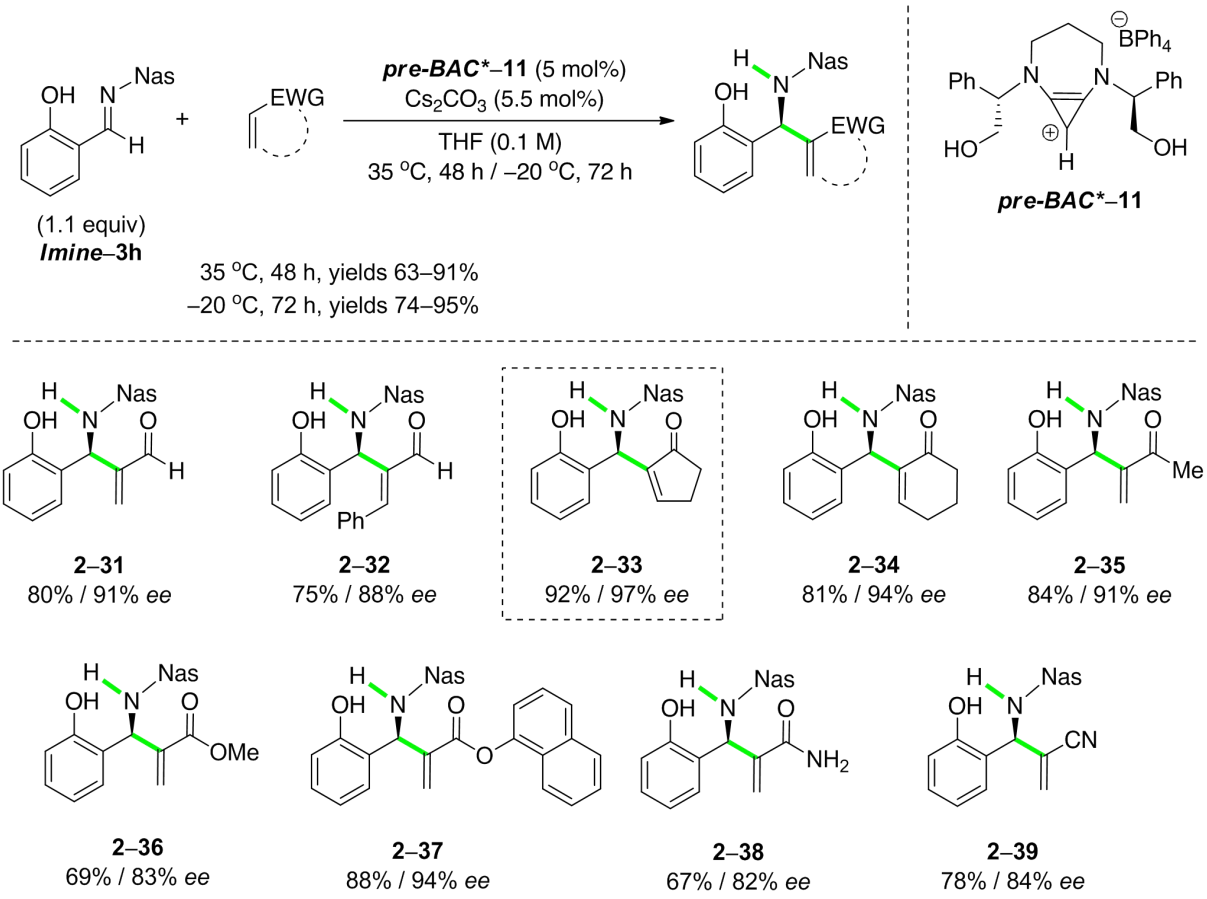
2–30
75% / 84% *ee*

[a] The asymmetric induction was displayed as follows: % *ee* [at +35 °C] / % *ee* [at –20 °C].

It was found that all *aromatic* imines were smoothly converted to the corresponding aza-MBH adducts with 72–92% *ee* (+35 °C) and 79–97% *ee* (–20 °C), respectively. For benchmark products **2–4**, **2–5**, and **2–41** the asymmetric induction proved to be high: 79–90% *ee* (+35 °C) vs. 85–94% *ee* (–20 °C). Similar general tendencies were observed with respect to data in Section 2.2.5 (P84). Here again, the best result was obtained with the *o*-phenol-based imine: product **2–9** was obtained with 97% *ee*. Most importantly, the asymmetric induction for primary, secondary, and tertiary aliphatic imines were significantly increased to 59–84% *ee* for products **2–28** ~ **2–30**.

Next, the scope for Michael acceptors was re-examined (Table 2.9).

Table 2.9: Michael acceptor scope for the 2nd generation BAC-catalysed asymmetric aza-MBH reaction



[a] enantiomeric excess were displayed as: (+35 °C) / (–20 °C) *ee*.

Here again, all Michael acceptors reacted smoothly to give the corresponding aza-MBH adducts with 67–92% *ee* (+35 °C) and 82–97% *ee* (–20 °C), respectively. Both Michael aldehydes underwent an a^3d^2 *umpolung* to give products **2–31** and **2–32** with 88–91% *ee* (–20 °C); an NHC-catalysed a^1d^3 *umpolung* was *not* detected.[56] The use of Michael ketones gave products **2–33** ~ **2–35** with up to 97% *ee* (–20 °C). The α,β-unsaturated carboxylic acid derivatives were shown to undergo an a^3d^2 *umpolung* to give products **2–36** ~ **2–39** with 82–94% *ee* (–20 °C); an NHC-catalysed a^3d^3 *umpolung* was *not* detected.[45] An inversion of the absolute configuration was *not* detected.

In conclusion, the OH-containing cyclopropenylidene precursor ***pre-BAC*–11** was successfully exploited in asymmetric aza-MBH reactions with the best results being obtained at –20 °C. The corresponding products were obtained with 59–97% *ee*, which represents a substantial advance compared to ***pre-BAC*–8** (34–93% *ee*). The higher levels of asymmetric induction may be the result of the hydroxy groups in both certain aromatic imines and the catalyst. Specifically, the hydroxy group in the imine may act as a hydrogen bond donor to the imine nitrogen atom, whereas the hydroxy group in the catalyst may act as a hydrogen bond donor to an oxygen atom of the sulfone *N*-protecting group (Figure 2.9). Such pairing of cooperative hydrogen bonds may be critical to favor the facial approach of the zwitterionic enolate to the imine. In addition, edge–to–face π interactions may be anticipated as shown in the transition state model. Accordingly, the zwitterionic enolate may attack the imine through its *Re* face (from top to bottom) to give the corresponding products with an *R*

configuration.

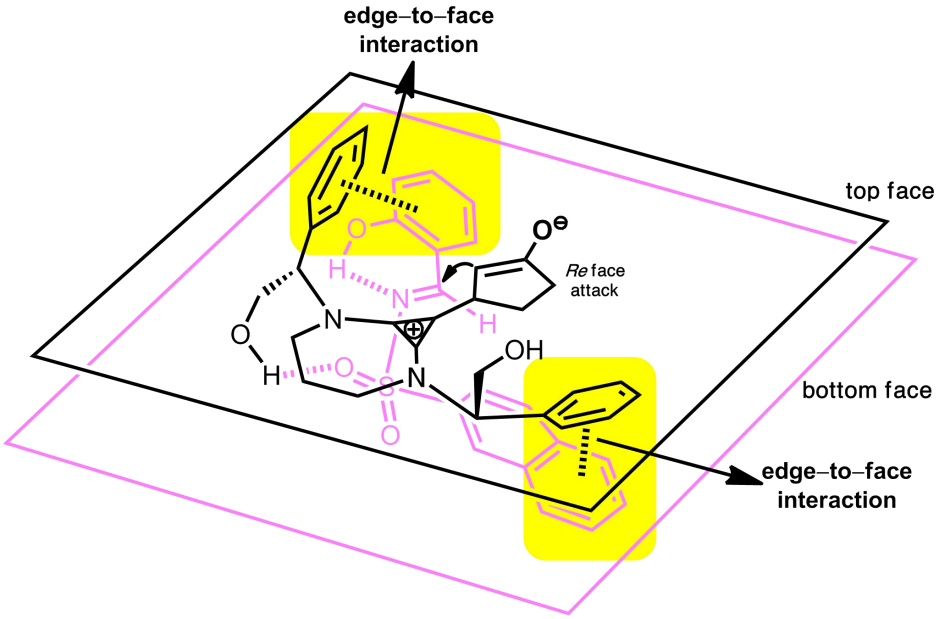
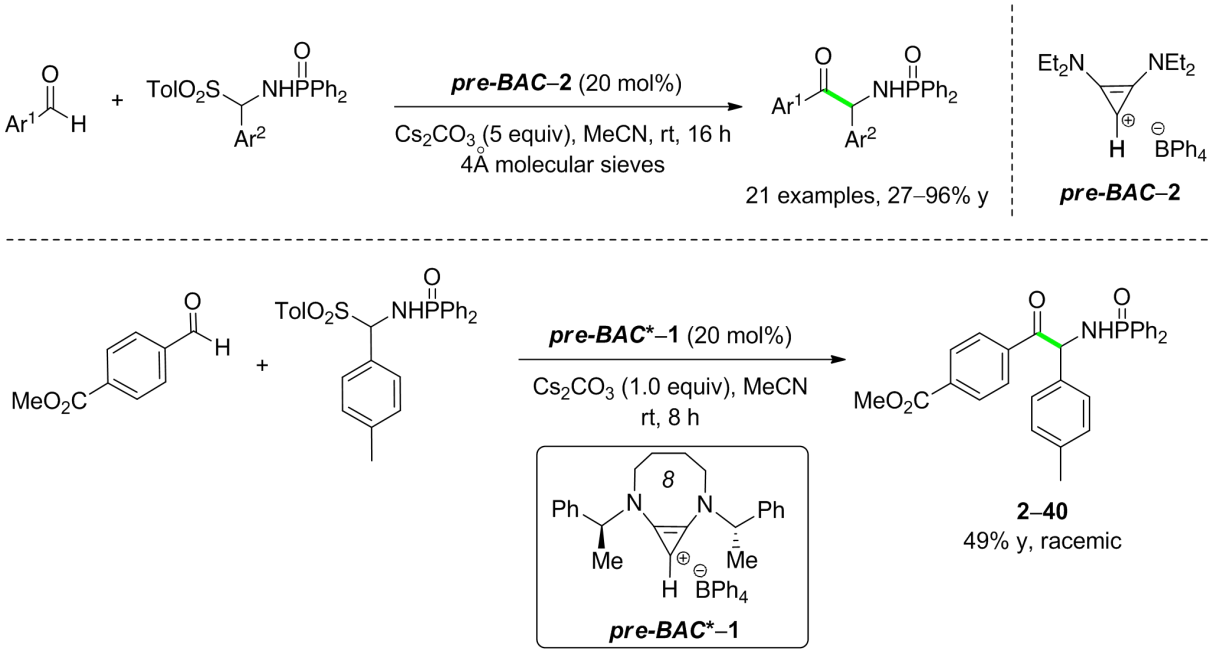


Figure 2.9 Proposed transition state for 2nd generation asymmetric BAC catalysis

During the course of our studies …

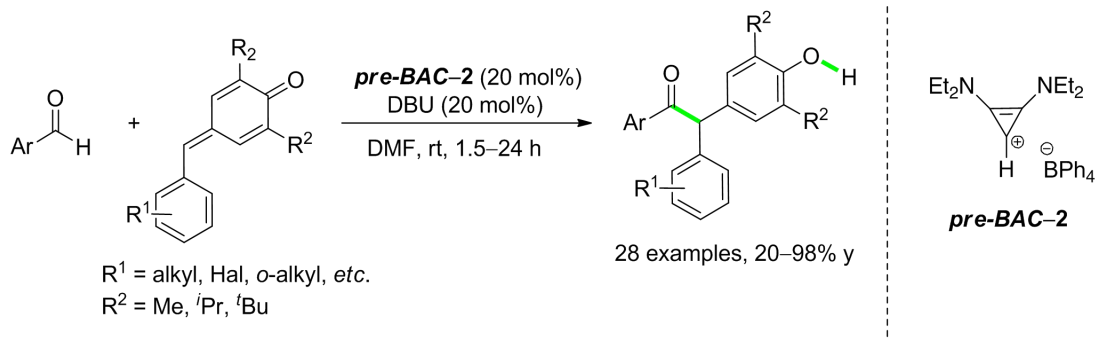
Two additional examples of BAC-catalysed *umpolung* reactions using simple aldehydes as pro-nucleophiles were published.

In 2014, Gravel *et al.* reported BAC-catalysed aza-benzoin reactions between aromatic aldehydes and aromatic *N*,*S*-aminals as imine surrogates (Scheme 2.30).[98] The corresponding products were obtained in 27–96% yields. However, the asymmetric version using Gravel's enantiopure pre-catalyst, ***pre-BAC*–1**, gave product **2–40** with 0% *ee*.



Scheme 2.30 BAC-catalysed aza-benzoin condensation by Gravel[98]

In 2015, Anand *et al.* reported BAC-catalysed vinylogous Stetter reactions between various aromatic aldehydes and *para*-quinone methides (Scheme 2.31).[99] The corresponding α,α'-diarylated ketones were obtained in 20–98% yields. An asymmetric version was *not* reported.

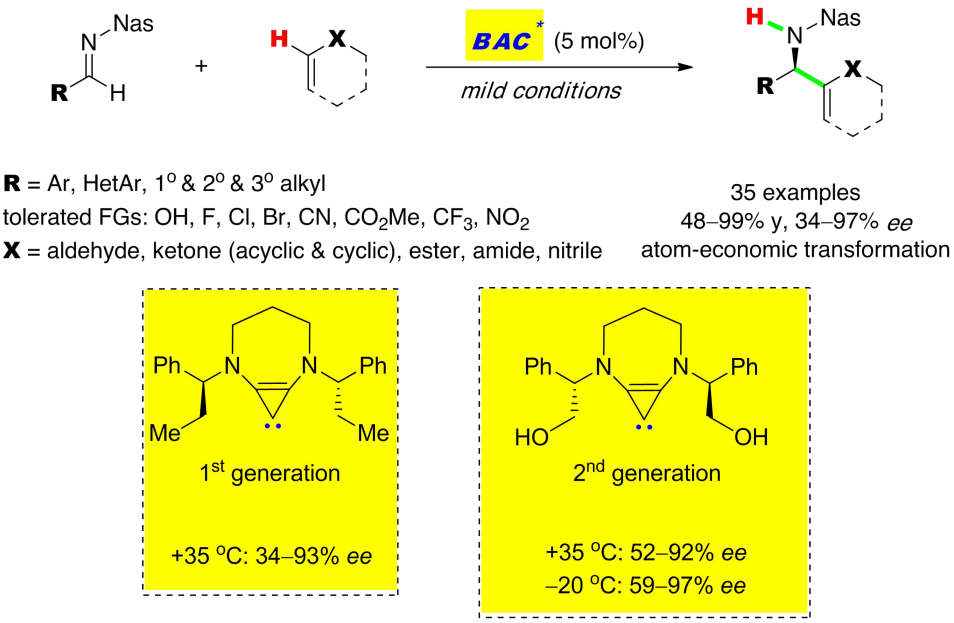


R^1 = alkyl, Hal, *o*-alkyl, *etc*.
R^2 = Me, ^{i}Pr, ^{t}Bu

Scheme 2.31 BAC-catalysed vinyloguous Stetter reaction by Anand[99]

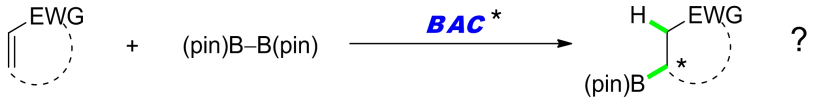
2.3 Summary

We have accomplished the first highly enantioselective BAC catalysis. Two generations of novel enantiopure BAC pre-catalysts were developed and applied in catalytic asymmetric aza-MBH reactions. Importantly, it was found that a variety of naphthalene-sulfonated imines and various types of Michael acceptors were tolerated by this novel method. The use of ***pre-BAC*–8*** (*without* OH groups) gave the products with 34–93% *ee* (+35 °C), whereas the use of ***pre-BAC*–11*** (*with* OH groups) gave the products with 52–92% *ee* (+35 °C) and 59–97% *ee* (–20 °C), respectively.



Scheme 2.32 Summary of asymmetric BAC-catalysed aza-MBH chemistry

In light of the outlined synthetic potential of this innovative catalyst in asymmetric aza-MBH reactions, we next explored other electrophiles, such as diboron reagents, in asymmetric catalysis.



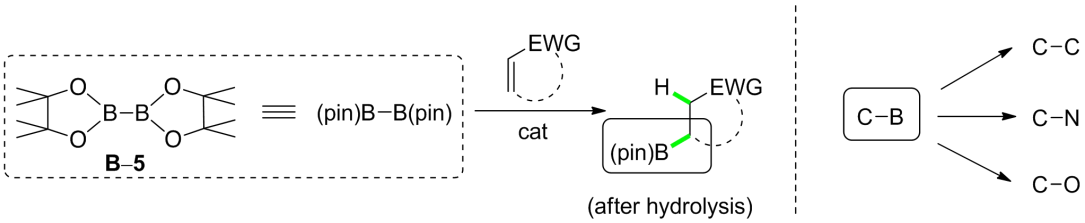
Scheme 2.33 Possibility of BAC-catalysed asymmetric conjugate borylation

3 TOWARDS BAC-catalysed ASYMMETRIC BORYLATION

3.1 Introduction

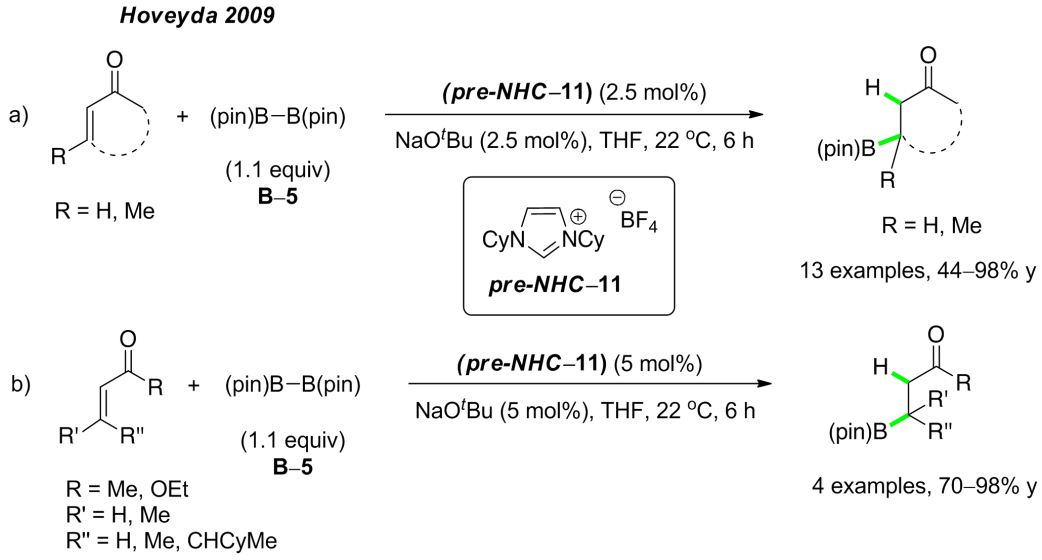
3.1.1 Literature-Reported Organocatalytic Conjugate Borylation

The development of metal-free catalysis is crucial for the ecological synthesis of organic compounds.[100] In addition to C–C bond formation, C–B bond-forming reactions are also an important area of organic synthesis including catalysis.[101] Within C–B bond formation, the conjugate borylation of Michael acceptors using diboron reagents has recently attracted a lot of attention in the synthetic community (Scheme 3.1).[102] The C–B bond thus formed in the product can be exploited in C–C cross-coupling chemistry.[103] Alternatively, the C–B bond can be oxidized to generate compounds bearing new C–O[104] or C–N bonds.[105]



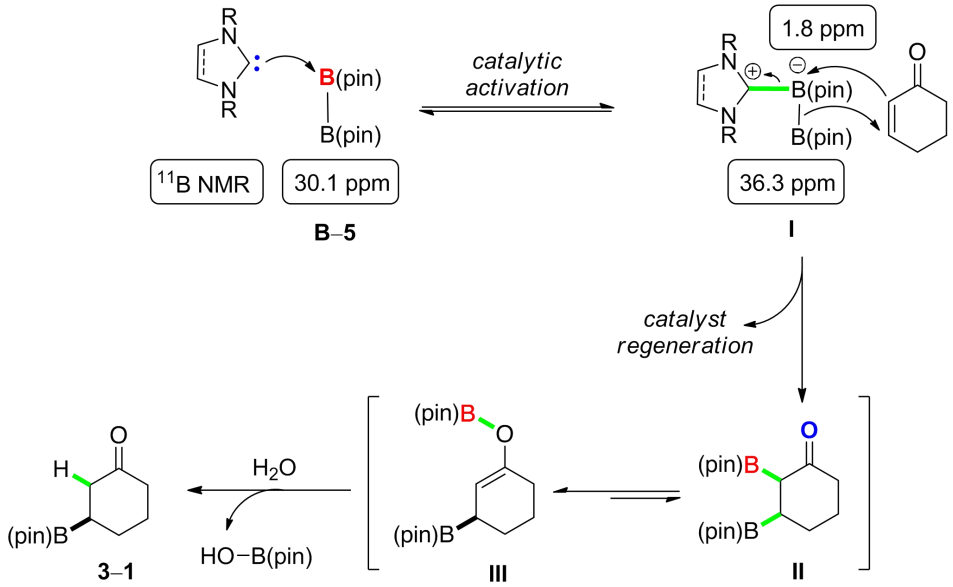
Scheme 3.1 Conjugate borylation of Michael acceptors and subsequent C–B bond transformations

Classically, the conjugate borylation of Michael acceptors has been facilitated through metal catalysis involving metal complexes based on transition metals such as Pt,[106] Rh,[107] Ni,[102a] and Cu.[108] This methodology includes asymmetric catalysis as well. In 2009, the first metal-free C–B bond formation using (pin)B–B(pin) (**B–5**) was reported by Hoveyda *et al.* (Scheme 3.2).[109] In the presence of an NHC as a catalyst –pre-formed from ***pre-NHC*–11** and NaO^{t}Bu– acyclic and cyclic α,β-unsaturated ketones and esters were smoothly converted to the corresponding secondary and tertiary boronic esters in 44–98% yields.



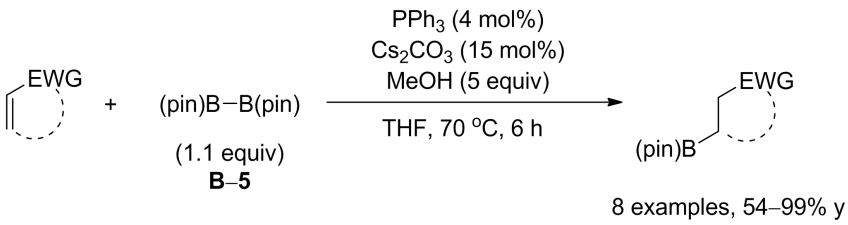
Scheme 3.2 First NHC-catalysed conjugate borylation[109]

The mechanism for this unusual NHC catalysis was proposed to involve initial nucleophilic addition of the Lewis basic carbene to a Lewis acidic boron atom of the diboron reagent to form boron–ate complex **I** (Scheme 3.3). The B–B bond of this boron–ate complex should thus be sufficiently activated for nucleophilic addition of the tri-coordinate boryl group to the electrophilic β-carbon of cyclohexenone, and subsequent transfer of the second boryl group to the nucleophilic α-carbon. This bond transformation would result in the generation of *C*-boron enolate **II** (Scheme 3.3) and recycle the NHC catalyst. This *C*-boron enolate may be in equilibrium with the corresponding *O*-boron enolate **III** (Scheme 3.3), and the hydrolysis of these basic intermediates would result in the formation of the corresponding β-boryl cyclohexanone (**3–1**; Scheme 3.3). Overall, this process has been monitored by ^{11}B NMR spectroscopy; the (pin)B–B(pin) reagent (**B–5**) displays a signal at 30.1 ppm, whereas boron–ate complex **I** (Scheme 3.3) was shown to resonate at 1.8 ppm (tetra-coordinate boron) and 36.3 ppm (tri-coordinate boron), respectively.



Scheme 3.3 Hoveyda's proposed mechanism for the NHC-catalysed conjugate borylation[109]

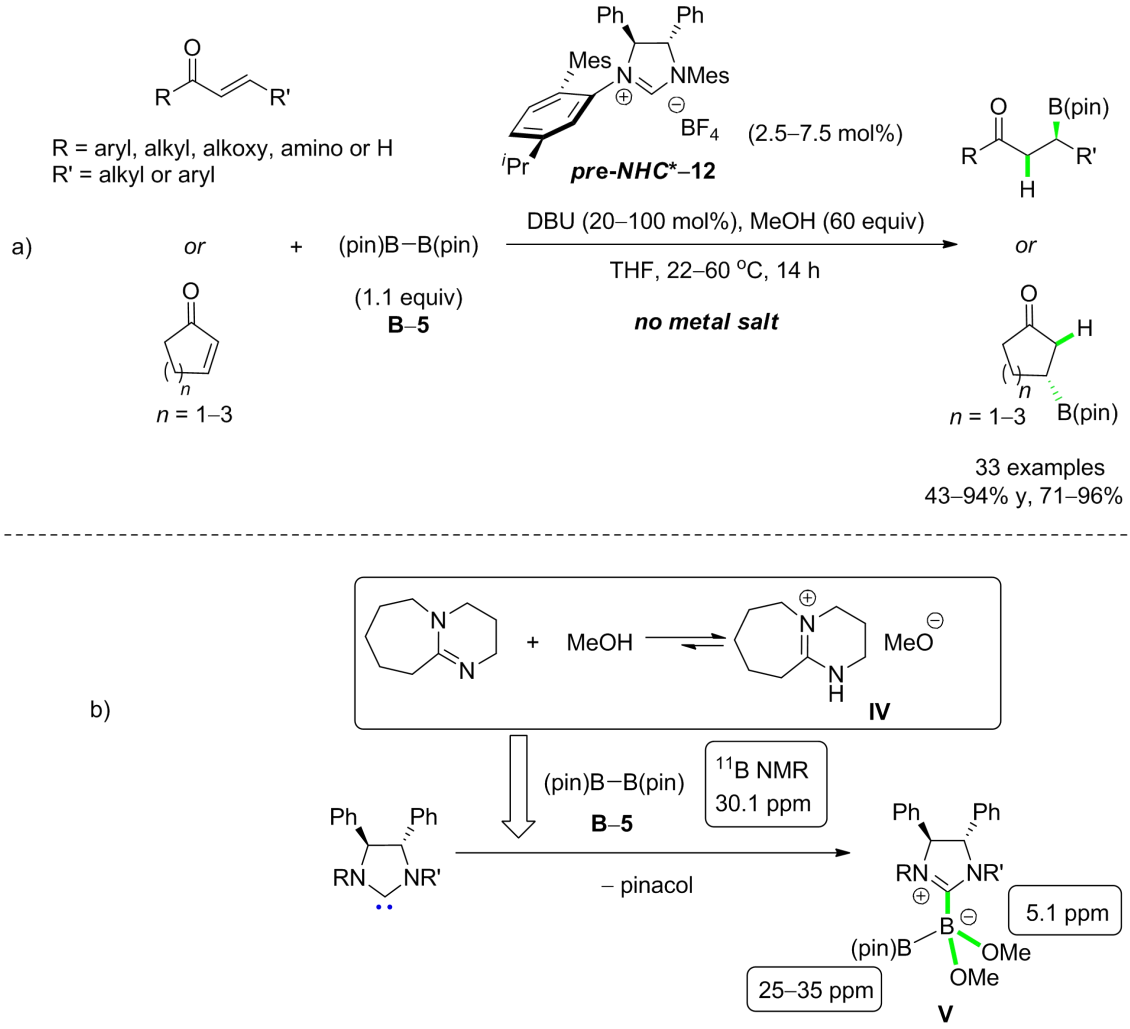
In 2010, Fernández *et al.* reported a phosphine-catalysed C–B bond formation between various α,β-unsaturated ketones or acrylates and (pin)B–B(pin) (**B–5**; Scheme 3.4).[110] Interestingly, Cs_2CO_3 as a base and methanol as a protic additive proved to be critical for reactivity; the products were obtained in 54–99% yields. The proposed mechanism was very similar to the pathway published by Hoveyda.[109]



Scheme 3.4 First phosphine-catalysed conjugate borylation[110]

In 2012, Hoveyda *et al.* developed the first NHC-catalysed asymmetric conjugate borylation of α,β-

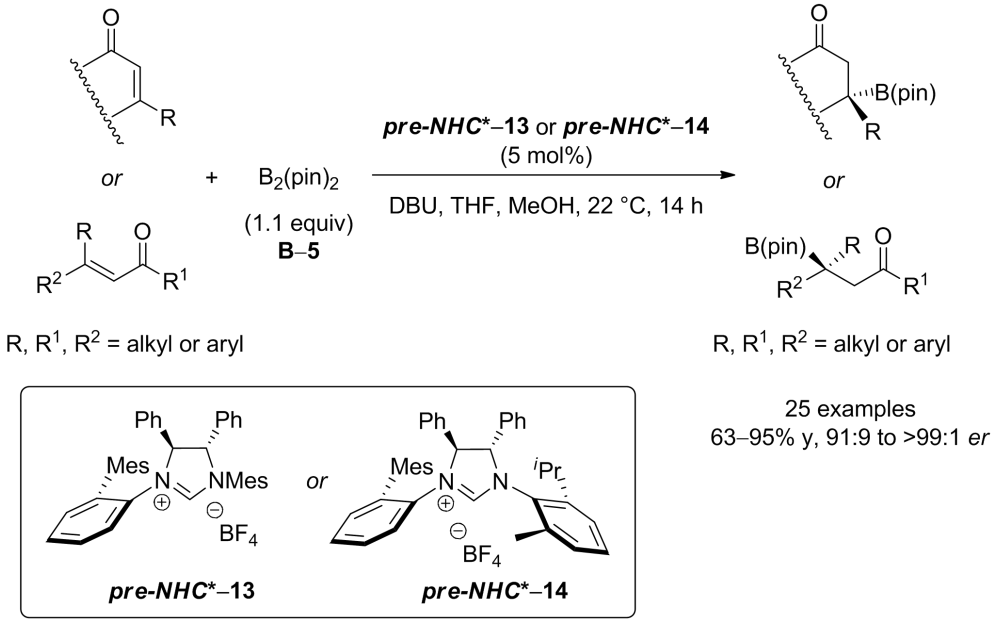
unsaturated aldehydes, ketones, esters, and amides using (pin)B–B(pin) [**B–5**; Scheme 3.5 a)].[111] Specifically, enantiopure NHC –pre-formed from ***pre-NHC**–12*** and DBU– bearing two phenyl groups in the chiral backbone and a non-symmetric N–Ar moiety, afforded the products with 71–96% *ee*. It is important to note that a large excess of methanol was required for high efficiency, and a ligand exchange at boron was suggested to explain this phenomenon [Scheme 3.5 b)].[111] Indeed, DBU should deprotonate methanol to form the corresponding amidinium methoxide [**IV**; Scheme 3.5 b)], two equivalents of which may replace one pinacolato ligand at a boron center. The generated intermediate, (pin)B–B(OMe)$_2$, may then undergo facilitated nucleophilic addition of the enantiopure NHC to the less hindered boron atom to generate the postulated critical key intermediate, chiral boron–ate complex **V** [Scheme 3.5 b)].



Scheme 3.5 First NHC-catalysed asymmetric conjugate borylation[111]

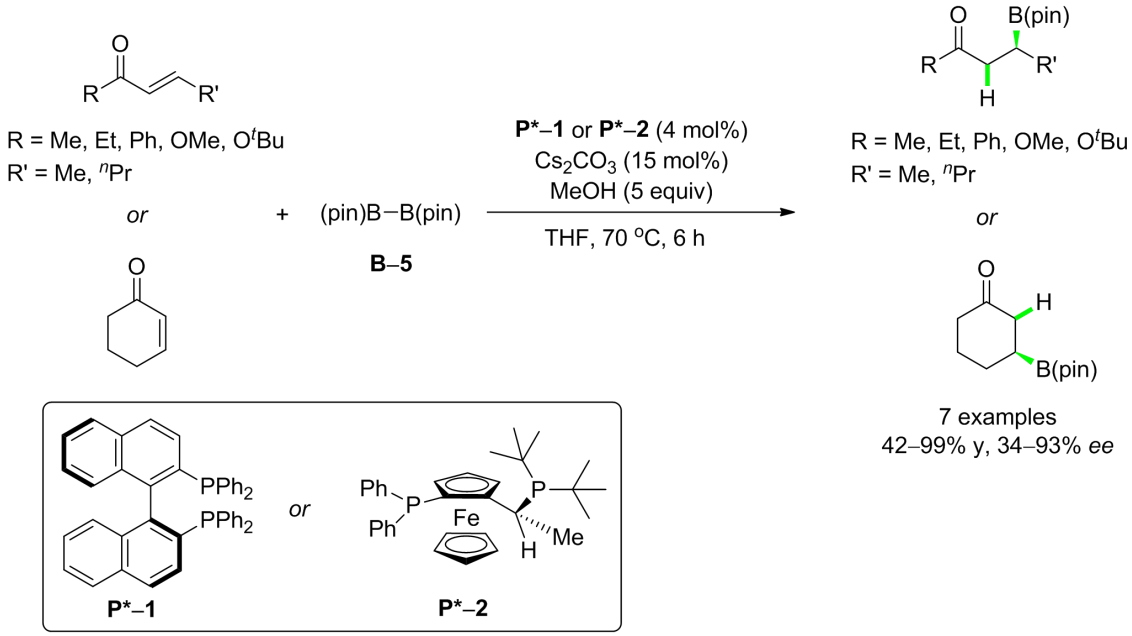
Although this successful asymmetric C–B bond-forming method resulted in the efficient formation of different types of optically enriched secondary boronic esters, the analogous synthesis of the corresponding tertiary boronic esters was not mentioned in this initial report. In 2014, Hoveyda *et al.* applied this approach to the formation of enantiomerically enriched tertiary boronic esters using α,β-unsaturated cyclic or acyclic ketones and (pin)B–B(pin) (**B–5**; Scheme 3.6).[112] These products were

obtained with 82–99% *ee*. Interestingly, this asymmetric NHC catalysis proved to be applicable to the total synthesis of a natural product bearing an optically pure tertiary alcohol moiety.



Scheme 3.6 NHC-catalysed asymmetric formation of tertiary boronic esters[112]

In 2010, Fernández *at el.* developed the first phosphine-catalysed asymmetric conjugate borylation of α,β-unsaturated ketones and acrylates using (pin)B–B(pin) (**B–5**; Scheme 3.7).[110] In this context, (*R*)-BINAP (**P*–1**) and (*R*,*S*)-Josiphos-type (**P*–2**) ligands proved to be most efficient; the corresponding secondary boronic esters were obtained with 34−93% *ee*.

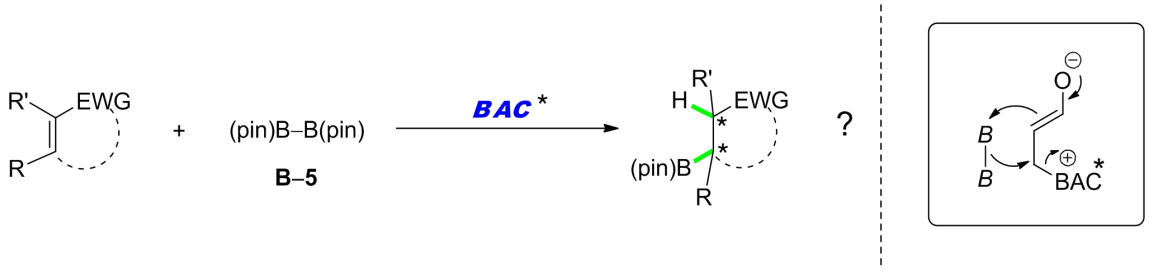


Scheme 3.7 First phosphine-catalysed asymmetric conjugate borylation[110]

3.1.2 Aims

In light of the state-of-the-art of asymmetric conjugate borylation (see Section 3.1.1), and encouraged by our earlier success regarding asymmetric BAC catalysis, we aimed to develop BAC-catalysed asymmetric conjugate borylation. In our anticipated scenario, the asymmetric C–B bond formation may proceed between an *in situ*-formed enantiomerically enriched zwitterionic MBH-type enolate and the B–B substrate.

This scenario would be substantially different compared to Hoveyda's suggested mechanism (Scheme 3.3).[109] Interestingly however, based on our earlier ^{11}B NMR binding study, a Hoveyda-type boron–ate complex was shown to be generated between a BAC and (pin)B–B(pin) (**B–5**) under mild conditions (see Section 1.2.2; P11). In turn, we were intrigued to see whether a BAC was apt to catalyze such a conjugate borylation, and which reaction pathway would be viable. Based on the unique electronic and steric features of the BACs, the major goals were (Scheme below):



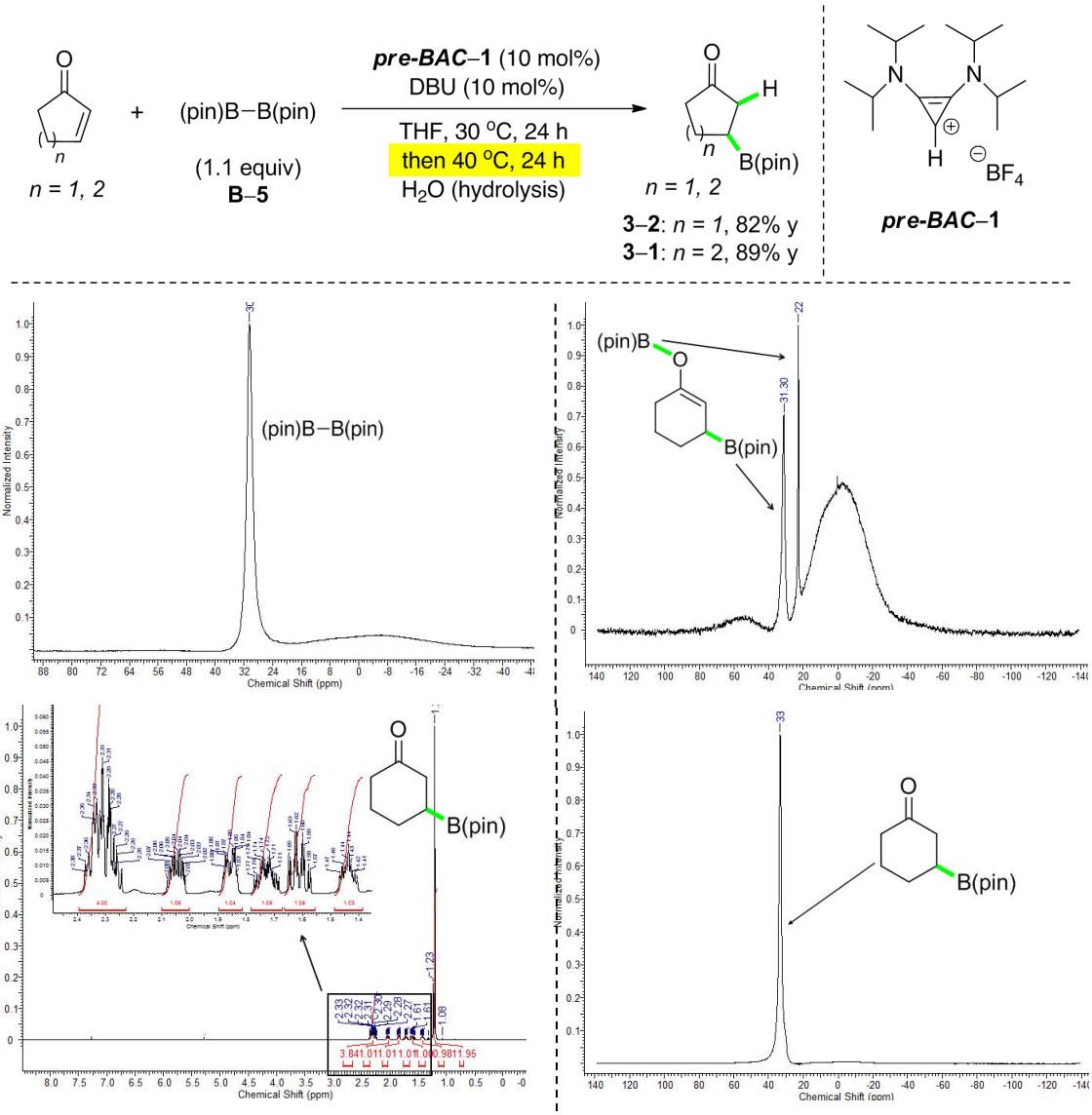
Scheme 3.8 Possibility of BAC-catalysed asymmetric conjugate borylation

(i) to explore a broad variety of Michael acceptors (α,β-unsaturated aldehydes, ketones, esters, amides, and nitriles), including sterically demanding substrates; ***(ii)*** to examine potentially diastereoselective transformations using α,β-disubstituted Michael acceptors; ***(iii)*** to attempt an asymmetric conjugate borylation based on our earlier success in the asymmetric aza-MBH chemistry.

3.2 Results and Discussion

3.2.1 BAC-catalysed Conjugate Borylation

In order to test the feasibility of this BAC-catalysed C–B bond formation, a preliminary set of experiments at 10 mol% catalyst loading was carried out using cyclopentenone and cyclohexenone in combination with (pin)B–B(pin) (**B–5**) in THF (Scheme 3.9).



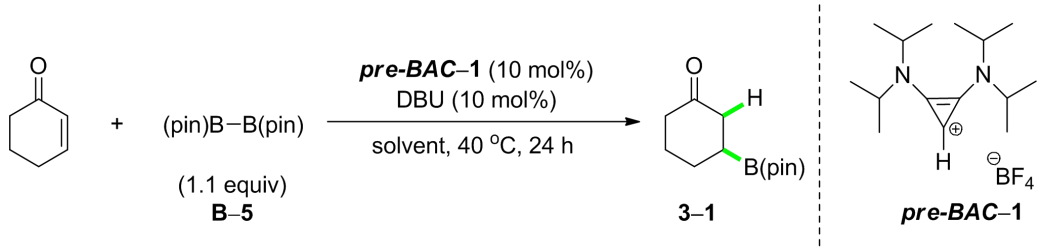
Scheme 3.9 Initial experiments for BAC-catalysed conjugate borylation of cyclopentenone and -hexenone

Unfortunately, the initial experiments at 30 °C failed to give the expected products. However, heating to 40 °C resulted in the smooth formation of the β-boryl products **3–1** and **3–2** in 82% and 89% isolated yields, respectively. These reactions were monitored by ^{11}B NMR spectroscopy. The signals of the used diboron reagent, (pin)B–B(pin) (**B–5**), and the β-borylated *O*-boron enolate (**III**; see Scheme 3.3) prior to hydrolysis, are shown in the corresponding ^{11}B NMR charts in Scheme 3.9 (*middle*). The single resonance of the starting material, (pin)B–B(pin) (**B–5**), at 30 ppm (*left*) disappeared, and two new signals of intermediate **III** appeared at 31 ppm [*C*–B(pin)] and 21 ppm [*O*–

B(pin)], respectively (*right*). As expected, these new signals were found to be roughly in a 1:1 molar ratio. After hydrolysis, the corresponding product was isolated thus leading to the displayed ^{1}H and ^{11}B NMR charts of β-boryl cyclohexanone (**3–1**; Scheme 3.9, *below*).

Since the use of cyclohexenone provided a slightly higher yield, further optimization of the reaction parameters were carried out using this substrate. First, a brief Brønsted base screening in THF at 40 °C was conducted using various organic and inorganic bases together with precursor ***pre-BAC*–1**. Generally speaking, metal-based bases such as amides, alkoxides, and carbonates were shown to be more efficient than metal-free bases such as tetramethyl guanidine and proton sponge®. Nevertheless, none of these bases was found to be more effective than DBU, in turn, this amidine base was selected as a base co-catalyst for the solvent screening (Table 3.1).

Table 3.1: Solvent screening for BAC-catalysed conjugate borylation

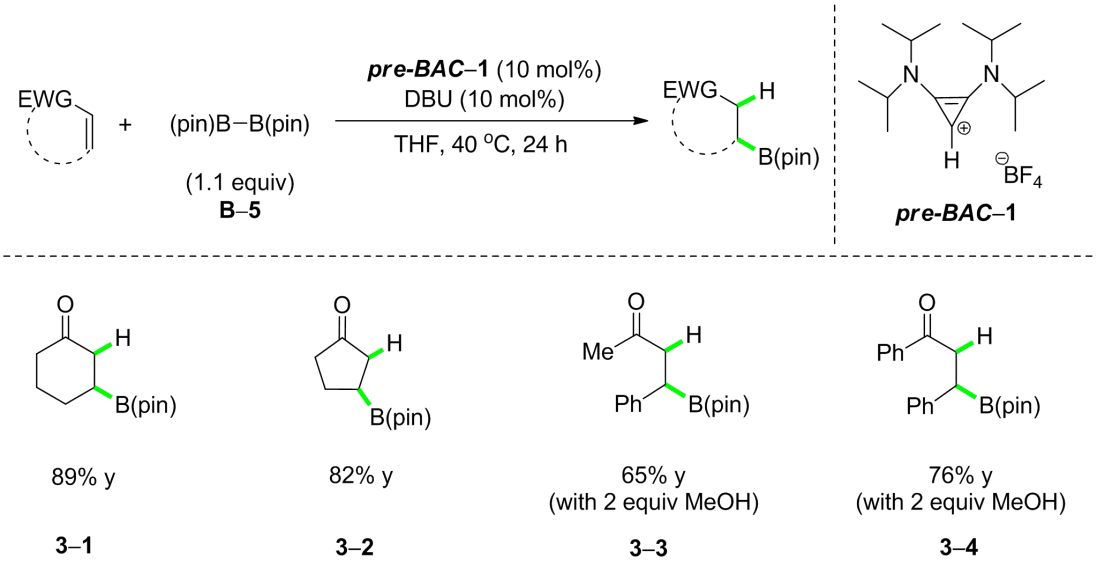


Entry	Solvent (Ɛ)	Isolated yield (%)[a]	Entry	Solvent (Ɛ)	Isolated yield (%)[a]
1	dioxane (2.3)	76	10	BTF (9.2)	45
2	toluene (2.4)	65	11	DCE (10.4)	68
3	TBME (2.6)	74	12	^{t}BuOH (12.5)	47
4	Et_2O (4.3)	67	13	^{i}PrOH (12.5)	50
5	EtOAc (6.0)	57	14	EtOH (25.0)	45
6	DME (7.2)	72	15	MeOH (33.0)	39
7	TCE (7.3)	64	16	MeCN (37.5)	18
8	THF (7.5)	89	17	DMF (38.0)	24
9	DCM (9.1)	23	18	THF/H_2O	72

[a] Isolated yield of products after purification by preparative thin-layer chromatography (PTLC).

With a few exceptions, all examined solvents were found to give the corresponding borylated product **3–1** (Table 3.1, entries 1–18). THF proved to be most appropriate (89%; entry 8). Interestingly, it was found that the use of polar protic solvents such as various alcohols gave decent yields (39–50%; entries 12–15). This fact may be important considering that –with reference to Hoveyda's work[111]– a protic source may be required as an additive in a potential asymmetric version of this transformation. Polar aprotic solvents such as acetonitrile and DMF failed to give high yields (18–24%; entries 16 and 17). Remarkably, the *in situ* generated BAC catalyst was found to tolerate an aqueous solvent mixture (THF/H_2O = 1:1; 72%; entry 18). Typically, carbenes have been considered unstable in aqueous media. However, this result indicated that carbene catalysis might be conducted as well in aqueous media or pure water.

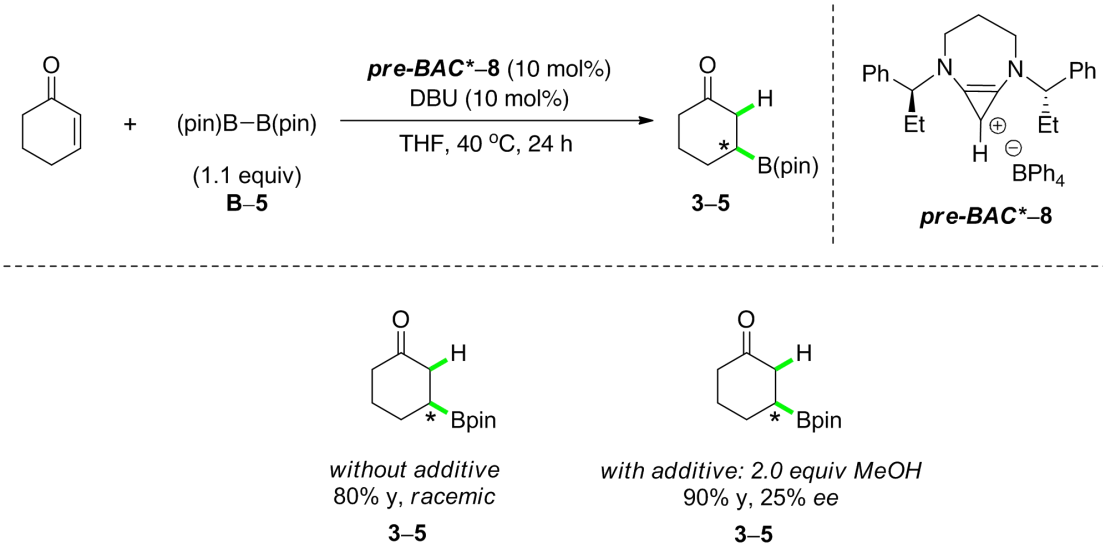
With this preliminary BAC catalysis protocol in hand, we also examined two acyclic α,β-unsaturated ketones that proved to be less reactive (Scheme 3.10). However, when the reactions were carried out in the presence of two equivalents of methanol the desired products were obtained in 65–76% isolated yields.



Scheme 3.10 Preliminary scope for BAC-catalysed conjugate borylation

3.2.2 Towards an Asymmetric Version

In light of the reported earlier work on NHC-catalysed asymmetric conjugate borylation (see Section 3.1),[111,112] and encouraged by our success in asymmetric BAC catalysis, we attempted to apply our novel enantiopure BAC catalysts to asymmetric C–B bond formation. The first experiment was conducted in THF at 40 °C using cyclohexenone and (pin)B–B(pin) (**B–5**), in the presence of our best 1st generation precursor ***pre-BAC**–8*** and DBU as the catalyst system (Scheme 3.11). The reaction proceeded smoothly, and the product **3–5** was formed in 80% yield albeit as a *racemic* mixture.



Scheme 3.11 Initial attempts of asymmetric BAC catalysis

However, when the same experiment was carried out in the presence of two equivalents of methanol,

product **3–5** was obtained in 90% yield with 25% *ee* (Scheme 3.11 and Chart 3.1). While the observed asymmetric induction proved to be rather low, the proof-of-principle for asymmetric BAC catalysis was established.

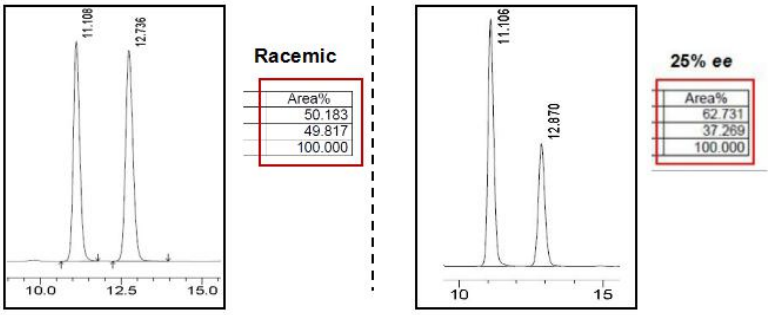
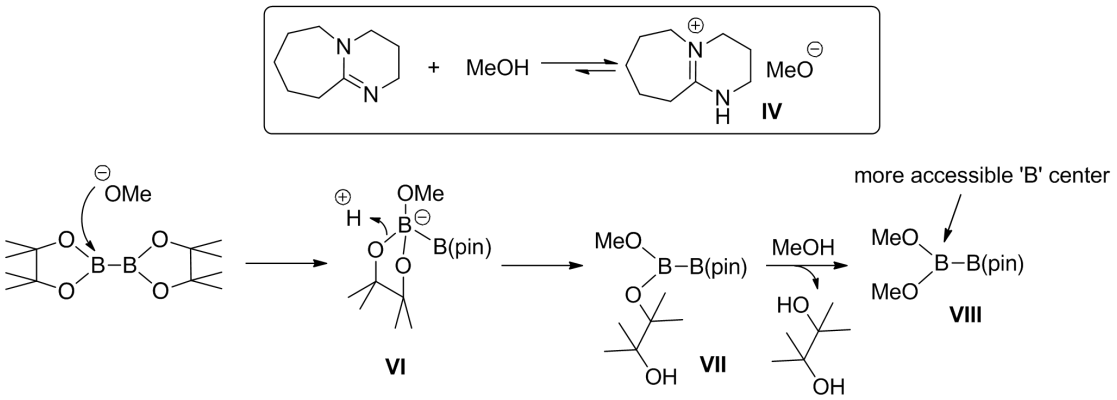


Chart 3.1 Chiral HPLC analysis for asymmetric BAC catalysis (2.0 equiv of MeOH)

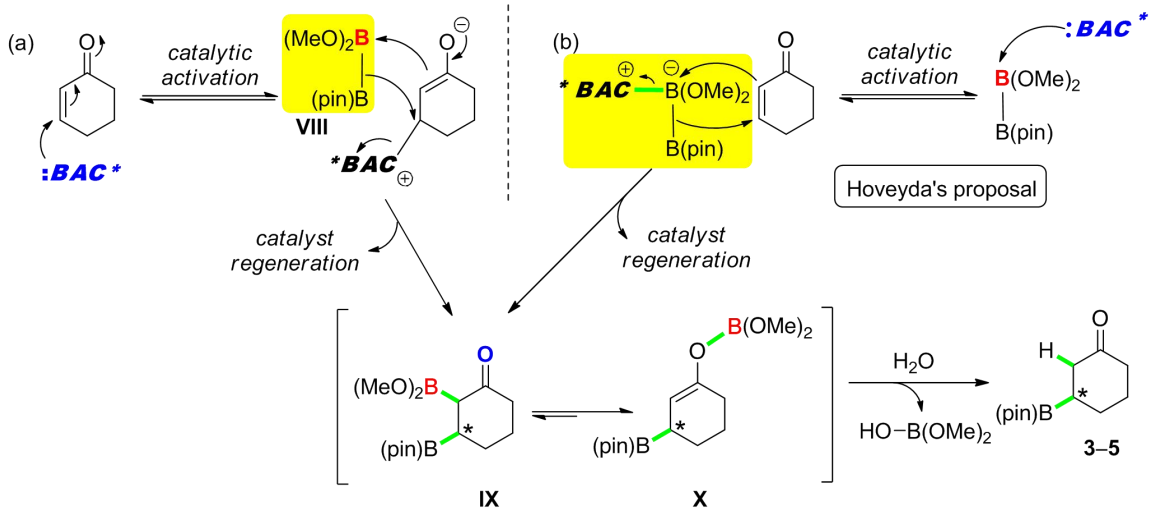
The use of such a protic additive in asymmetric carbene catalysis paralleled the earlier studies by Hoveyda in this context.[111] Similarly, it seemed that the use of methanol in the presence of a catalytic amount of DBU played an important role for the asymmetric induction. Indeed, the combined use of the amidine base and methanol should lead to the irreversible formation of the corresponding conjugate acid–base pair, i.e., amidinium methoxide **IV** (Scheme 3.12, *upper* equation). The Lewis basic methoxide may then add to a Lewis acidic boron atom of (pin)B–B(pin) (**B–5**) to generate boron–ate complex **VI** (Scheme 3.12, *lower* equation). An activated B–O bond of the pinacolato moiety of **VI** may then undergo protonation to form the corresponding diboron intermediate **VII**, which may react with a second equivalent of methoxide to generate –after protonation and loss of pinacol– diboron species **VIII**. It is conceivable that the Lewis acidic $B(OMe)_2$ center of **VIII** may be less sterically hindered, which may be of critical importance for a higher reactivity *and* a better asymmetric induction. *Further experiments will be required to clarify this effect.*



Scheme 3.12 Plausible role of DBU and MeOH in B–B bond activation[111]

Starting from the diboron species **VIII**, two plausible mechanistic pathways may be anticipated. The first route may follow the MBH-type mechanism [Scheme 3.13 a)], which would involve an initial nucleophilic addition of the chiral BAC to the electrophilic β-position of the Michael acceptor to form an enantiomerically enriched zwitterionic enolate. The latter may then add to the more accessible

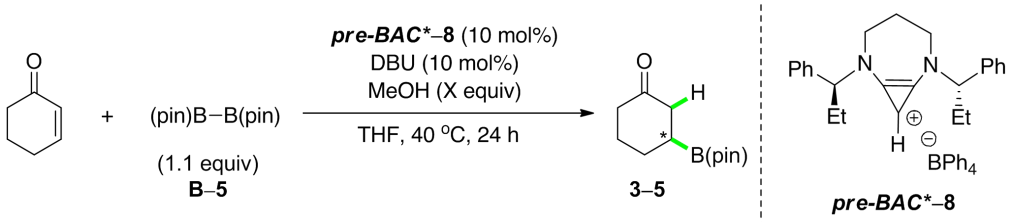
boron center of $(MeO)_2B–B(pin)$ (**VIII**; Scheme 3.13), thus triggering B(pin) transfer to the β-carbon; this scenario would regenerate the chiral BAC catalyst. The other plausible route may follow a direct addition of the enantiopure BAC to the more accessible boron center of **VIII** [Scheme 3.13 b)]. Such a scenario was proposed by Hoveyda *et al.* and has been discussed earlier [see Section 3.1.1, Scheme 3.3].[109,111]



Scheme 3.13 Two plausible mechanistic pathways for the carbene-catalysed asymmetric conjugate borylation

Since the presence of methanol seemed to be critical for an asymmetric induction, we attempted to optimize this reaction system by varying the amount of methanol (2–60 equiv) under otherwise identical conditions (Table 3.2). These experiments revealed that a large excess of this protic additive was required to induce a higher optical purity of the product. Indeed, the asymmetric induction in product **3–5** was found to increase from 25% *ee*, when using 2 equiv of MeOH (entry 1), to 62% *ee*, when using 25 equiv of MeOH (entry 6). When an even larger amount of methanol (30–60 equiv) was used, an erosion of the asymmetric induction was observed (entries 7–9).

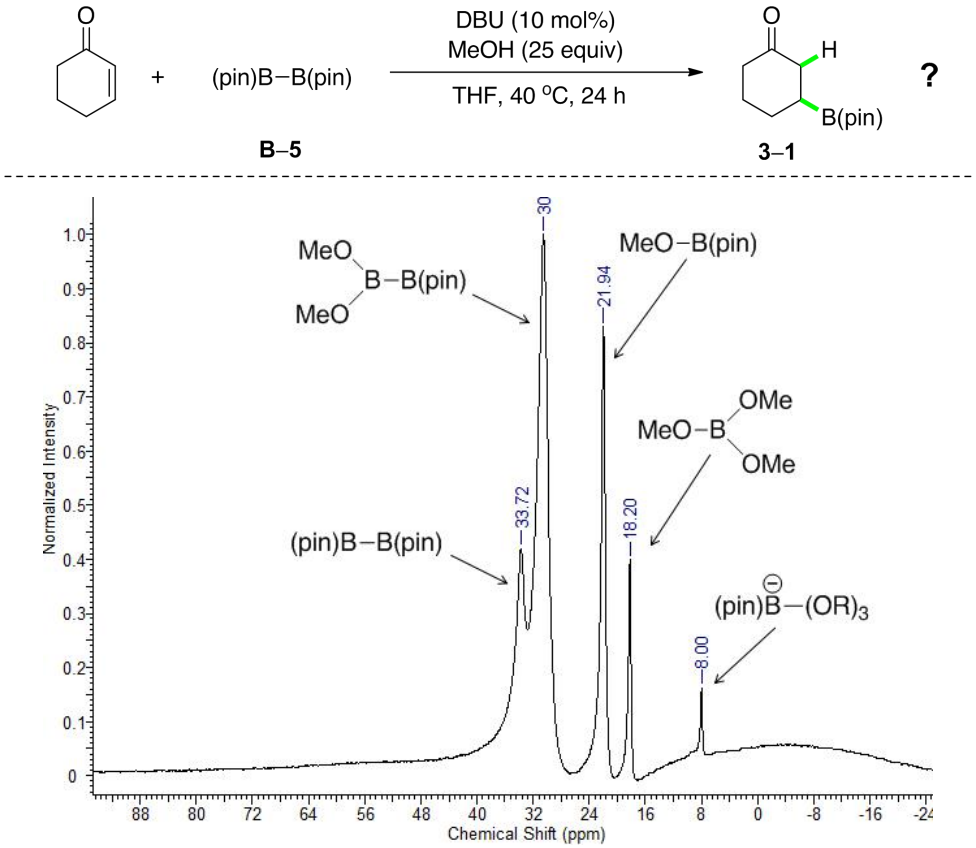
Table 3.2: Effect of MeOH stoichiometrically on BAC-catalysed asymmetric conjugate borylation



Entry	MeOH (equiv)	Yield (%)[a]	*ee* (%)[b]
1	2.0	90	25
2	5.0	91	45
3	10	93	52
4	15	95	58
5	20	98	60
6	25	96	62
7	30	97	55
8	40	96	52
9	60	95	46

[a] Isolated yield of products after purification by preparative thin-layer chromatography (PTLC). [b] The *ee* was determined by chiral HPLC analysis.

While an asymmetric induction of 62% *ee* was good but not excellent, we wondered whether the combined use of DBU and methanol could result in a *racemic background reaction*. We carried out the same reaction as in entry 6, but in the absence of the enantiopure BAC precursor (Scheme 3.14, *equation*).



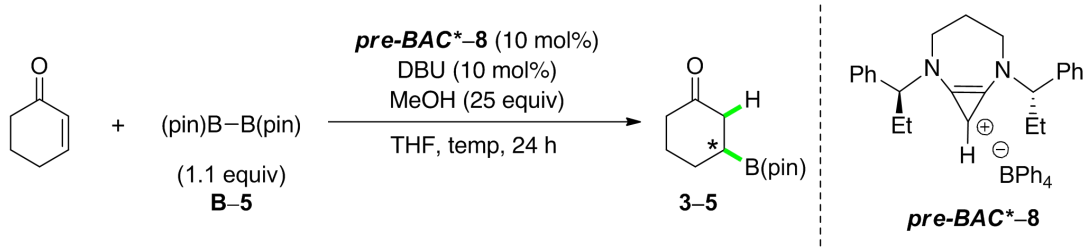
Scheme 3.14 Control experiment using DBU/MeOH in the conjugate borylation

In the event, the intended *C–B bond formation did not proceed*. Indeed, potential reaction products involving the Michael acceptor were not detected in the ^{1}H NMR spectroscopic analysis of a reaction aliquot, or by TLC analysis. Interestingly, the ^{11}B NMR spectroscopic analysis of a reaction aliquot ($CDCl_3$) revealed the detection of five signals in the chart (Scheme 3.14, *chart*). Assuming the irreversible formation of DBU–H^+ $^-$OMe (**IV**; see Scheme 3.12, *upper* equation), several boron species may have been formed through an initial reaction between $^-$OMe and (pin)B–B(pin) (**B–5**), followed by a series of subsequent acid–base reactions. The initial starting material, (pin)**B**–**B**(pin) (**B–5**), displays a signal at 33 ppm. Based on our experience in ^{11}B NMR spectroscopy, the other signals may be ascribed to the following boron-based species: $(MeO)_2$**B**–B(pin) at 30 ppm; (MeO)**B**(pin) at 21 ppm; $(MeO)_3$**B** at 18 ppm; various plausible ate complexes of the type L_4**B**$^-$ at 8 ppm. These data revealed that –in the absence of a suitably reactive electrophile/nucleophile pair– the activated B–B bond of a boron–ate complex may be cleaved through simple protonation, and the resulting H–BL_2 species may generate subsequently MeO–BL_2 and molecular hydrogen. *These results may suggest that a BAC-catalysed reductive aldol or Mannich reaction may be conceivable if a Michael acceptor and H–B(pin)*

could be used as reagents under specific conditions.

This experiment supported our assumption that the enantiopure BAC catalyst was the real catalytically active species for C–B bond formation; based on the control experiment, a racemic background reaction was excluded. In turn, another set of experiments dealt with the optimization of the reaction temperature under otherwise identical conditions (40 °C ~ –20 °C; Table 3.3). A preformation of catalyst using ***pre-BAC**–8*** and Cs_2CO_3 was carried out under room temperature for 20 hours before moving to a lower temperature.

Table 3.3: Temperature effect on the BAC-catalysed asymmetric conjugate borylation

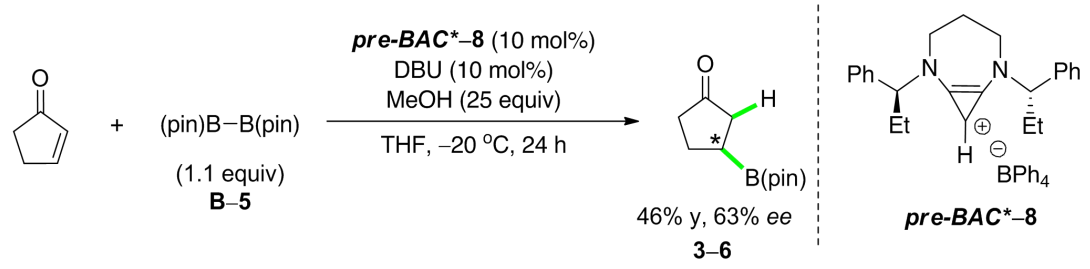


Entry	Temp (°C)	y (%)[a]	*ee* (%)[b]
1	40	96	62
2	30	87	63
3	25	79	66
4	0	56	67
5	–20	45	69

[a] Isolated yield of products after purification by preparative thin-layer chromatography (PTLC). [b] The *ee* was determined by chiral HPLC analysis.

Expectedly, compared to the benchmark result at 40 °C (62% *ee*; entry 1), all other experiments resulted in a lower reactivity but a slightly increased asymmetric induction in product **3–5** (63–69% *ee*; entries 2–5). To date, the best selectivity was obtained at –20 °C (69% *ee*), albeit the isolated yield for **3–5** proved to be insufficient (45%; entry 5).

These optimized conditions were subsequently applied to the use of cyclopentenone (Scheme 3.15). The corresponding product **3–6** was obtained in 46% yield with 63% *ee*.

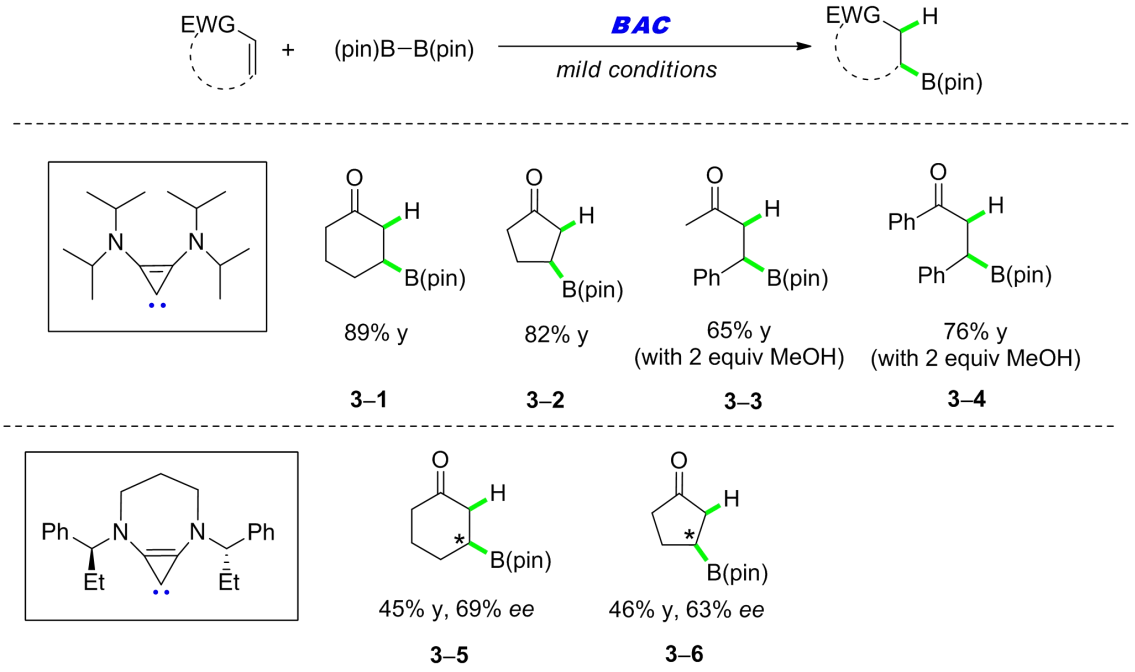


Scheme 3.15 BAC-catalysed asymmetric conjugate borylation of cyclopentenone

Overall, further experimentation will be required in order to attain a synthetically useful asymmetric induction for this type of transformation.

3.3 Summary

We have successfully achieved BAC-catalysed C–B bond formation under mild conditions using a commercially available diboron reagent, (pin)B–B(pin) (**B–5**), and different Michael ketones. This transformation was shown to be applicable to asymmetric BAC catalysis (up to 69% *ee*). It was found that both reactivity and enantioselectivity were improved in the presence of an excess of methanol. Expectedly, the asymmetric induction has proved to be optimal at low temperature.



Scheme 3.16 Summary of BAC-catalysed asymmetric conjugate borylation

This chemistry seems to require a substantial modification of the structure of the enantiomerically enriched BAC in order to obtain very high asymmetric induction.

4 THE CHEMISTRY OF CARBONES

4.1 Introduction

In parallel to our investigations into *carbene* [C(II)] catalysis, *carbones* [C(0)] were also examined in view of potential applications in base and dual catalysis, which may have a significant impact on "Green" Chemistry. Carbones, i.e., molecules with the central carbon atom in the formal "0" oxidation state, include so-called "bent" allenes or carbodicarbenes.[113]

4.1.1 Classic or "Bent" Allenes vs. Carbodicarbenes

Classic allenes are organic compounds with a linear three-carbon-based structure that contain an sp hybridised central carbon atom, which forms a C=C double bond to both adjacent carbon fragments,[1] i.e., the central carbon shares its four valence electrons to form two covalent bonds each with the orthogonal pairs of substituents (Figure 4.1).

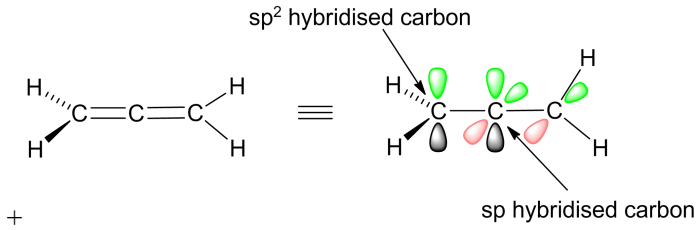


Figure 4.1 Classic allenes[1]

However, in certain allenes deviations from linearity (180 °) of a few or more degrees have also been observed. In 1995, Weber *et al.* reported the crystal structure of allene **4–1** with an unusually large bent at the central carbon due to so-called packing effects.[114,121] Indeed, this "bent" acyclic allene has a C=C=C bond angle of 170.1 ° (Figure 4.2).

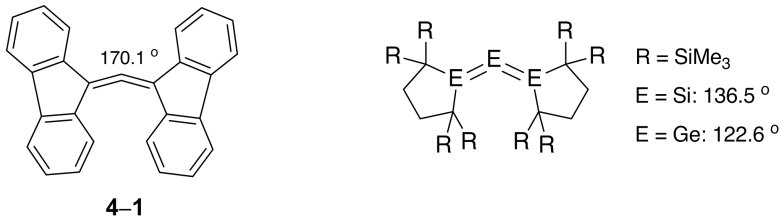


Figure 4.2 Examples of a bent allene and its heavier homologues[114,115,121]

In addition to the studies of all-carbon allenes (C=C=C), several research groups explored the chemistry of allene analogues involving heavier group 14 elements (E=E=E; E = Si, Ge; Figure 4.2).[115] These "heavier" allenes have been shown to display a highly flexible, non-linear structure (Si=Si=Si: 136.5°; Ge=Ge=Ge: 122.6°).[115] The difference between all-carbon allenes and silicon or germanium analogues may arise from the weakness of the π bonds in the latter. Unlike first long-row elements (carbon), which tend to form hybrids from s and p orbitals, second and higher-row elements

can largely avoid hybridization; those heavier elements are generally reluctant to form multiple bonds as their π bonds are rather weak. This phenomenon has been coined as the "first long-row anomaly" by Grützmacher.[116] Based on this analysis, Bertrand *et al.* made the conclusion that weakening the π bonds in C=C=C allenes could make them more flexible and lead to a higher degree of bending of the linear C=C=C skeleton.[117] In this context, polarization seems to be the only possible way to weaken the C=C π bonds of allenes; it can be realized by *push–pull* or *push–push* substitution patterns (Figure 4.3).[118] Push–pull substitution means one terminal carbon atom is bound to two donor groups (D), while the other terminal carbon is connected to two acceptor groups (A). Push–pull-substituted allenes show partial carbene character at the central carbon and tend to dimerize. However, so-called push–push allenes may contain a double carbanion character at the central carbon atom that is connected with two formally positively charged donor groups; this pattern may be the best choice for the synthesis of "bent" allenes.

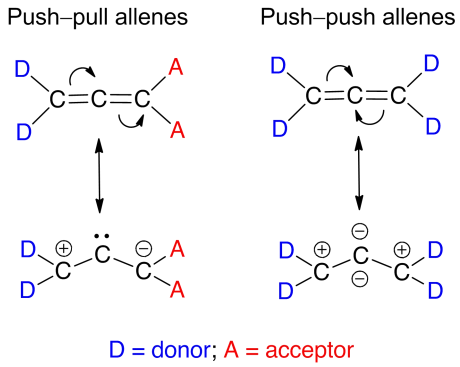


Figure 4.3 Resonance structures for push–pull and push–push allenes[118]

Several chemists synthesized and analyzed "bent" allenes according to the push–push substitution pattern. In these cases, the central carbon atom is no longer sp hybridized like in classic allenes; rather, it should be considered to have two lone pairs of electrons. Thus, the bonding situation is likely best described as a carbene–*C* donor–acceptor interaction (Figure 4.4). This bonding model is usually prevalent in the "classic" complexation of a metal center by ligands (e.g. ligand–metal donor–acceptor complex). Thus, the non-metal element carbon may be considered to behave "metal-like", as it acts as the central atom of a "non-classic" coordination compound.

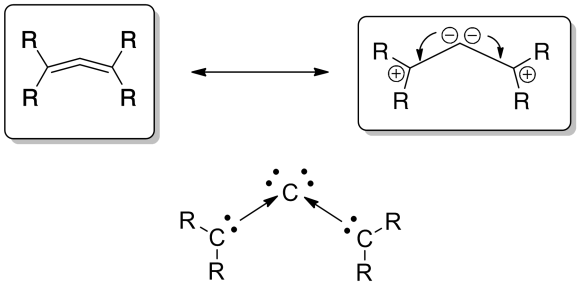


Figure 4.4 General structure of carbodicarbenes (CDCs)

4.1.2 Carbenes [C(II)] vs. Carbones [C(0)]

As a consequence, these compounds have been described as "carbodicarbenes" (CDCs).[119] A carbodicarbene is a strongly basic compound featuring "a divalent carbon(0)" centre coordinated by two carbene ligands. The central carbon of a carbodicarbene is sp^2-like hybridized with both substituents being a strong σ donor *and* a weak π acceptor. A high proton affinity was calculated for these carbon(0) species (carbodicarbenes), which are considered to be stronger bases than "classic" carbon(II) compounds (carbenes).[120]

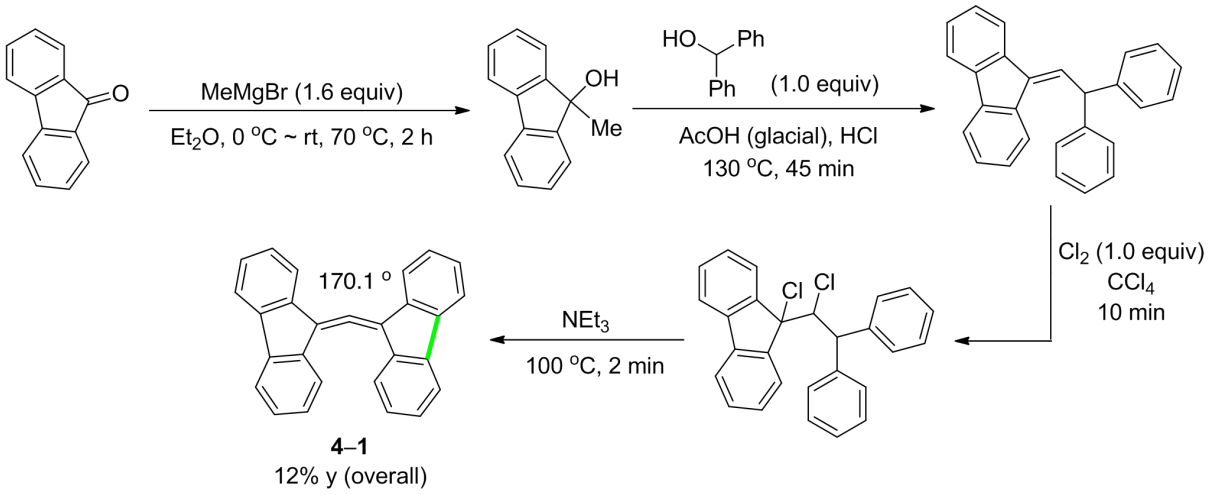
As carbodicarbenes feature a divalent central atom with two carbene ligands, the difference between classic carbenes [carbon(II)] and carbodicarbenes [carbon(0)] should be recognized (Figure 4.5).

Figure 4.5 A comparison between carbenes and carbones

In carbenes, such as *N*-heterocyclic carbenes (NHCs), the central carbon atom is in the oxidation state "+II". It has only one lone pair in the σ orbital and a vacant π orbital. In contrast, in carbodicarbenes the central carbon atom is divalent and does not form "classic" double bonds, but formally owns two lone pairs. Thus, the formal oxidation state of the central carbon atom is considered to be "0". These low-oxidation state carbon compounds have been calculated to be substantially stronger Lewis or Brønsted bases than carbenes.

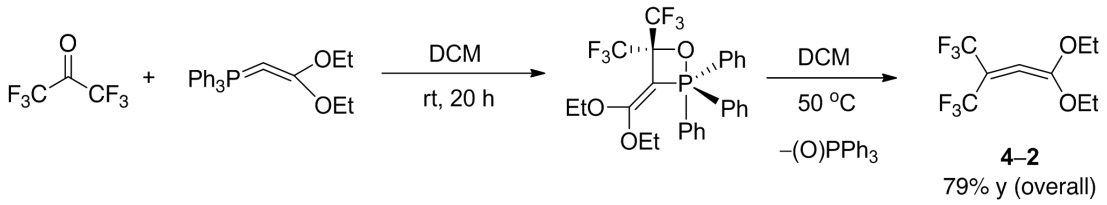
4.1.3 Carbodicarbenes in Literature

In this section, the chemistry of "bent" allenes or carbodicarbenes will be summarized including their properties and synthetic methods. The first two "bent" allenes were prepared by two different research groups, respectively, although both compounds were not defined as "carbodicarbenes" *per se*. In 1964, Fischer *et al*. reported the synthesis and isolation of an acyclic allene, **4–1**, with a C=C=C bond angle of 170.1 ° (Scheme 4.1).[114] This compound was prepared on a gram-scale in four steps in 12% overall yield. This species was shown to be stable at room temperature, and its crystal structure was reported by Weber *et al.* in 1995.[121]



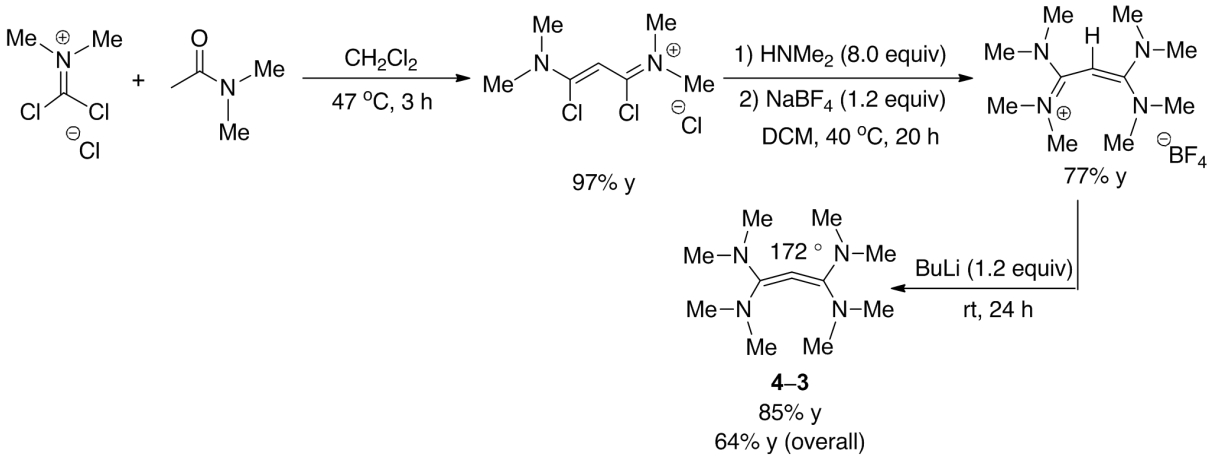
Scheme 4.1 Synthesis of the first bent allene[114]

The "bent" allene **4–2** was prepared by Liebenow *et al.* in 1980 (Scheme 4.2).[122] It was synthesized on a gram-scale from commercially available starting materials in two steps in 79% overall yield. The desired product was isolated as colorless crystals storable at –78 °C under argon.



Scheme 4.2 Synthesis of bent allene **4–2**[122]

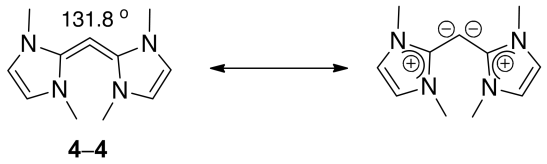
Several studies focusing on tetraaminoallenes have been carried out in view of their coordination chemistry. In 2009, Fürstner *et al.* reported a new method for the preparation of tetrakis(dimethylamino)allene (**4–3**; Scheme 4.3).[123] This compound was synthesized on a gram-scale in three steps from commercially available starting materials in 64% overall yield. The product was isolated as a colorless oil that can be stored at –20 °C under argon for months without decomposition. The C=C=C bond angle in this compound was measured to be 172 °.



Scheme 4.3 Synthesis of acyclic carbodicarbene **4–3**[123]

In 2007, Frenking *et al.* carried out a computational study on "bent" allene **4–4** and coined the

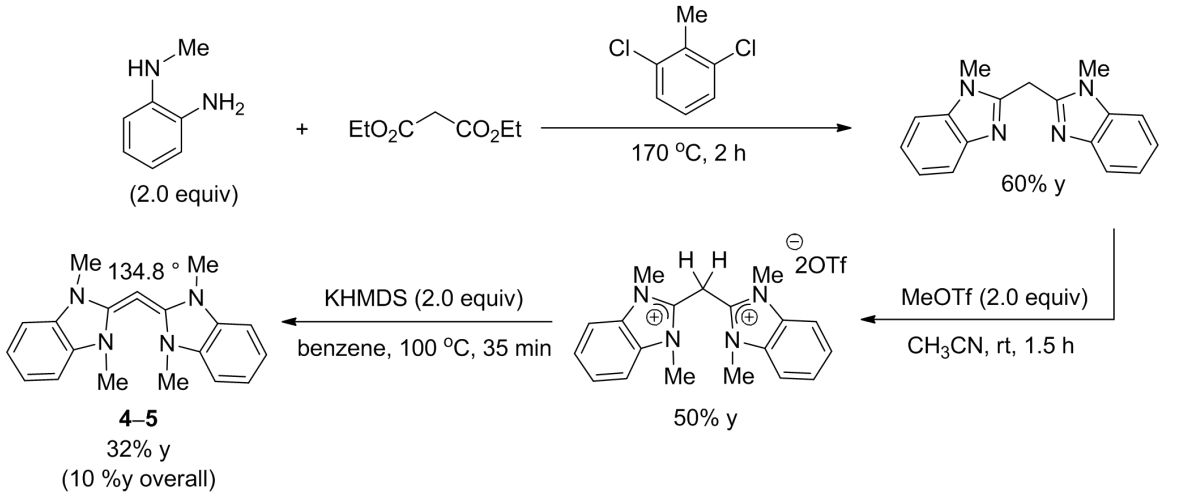
expression "carbodicarbene" for the first time (Figure 4.6).[120] The allene framework and the π system in this allene were both shown to be severely perturbed with a C=C=C bond angle of 131.8 °, and the C–C bond lengths involving the central carbon atom were measured as 1.359 Å, which are shorter than "normal" single C–C bonds. The central carbon atom is no longer sp hybridized as in typical allenes, but rather considered to have two lone pairs.

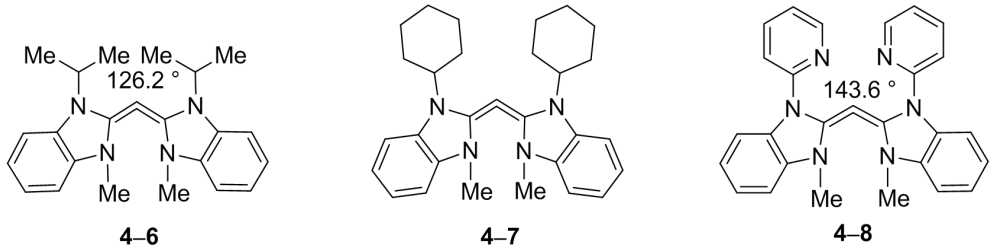


4–4

Figure 4.6 Resonance forms of carbodicarbene **4–4**[120]

Similarly in 2008, Bertrand *et al.* reported the synthesis and isolation of the aromatic acyclic carbodicarbene **4–5** with a C=C=C bond angle of 134.8 ° (Scheme 4.4, *above*).[117] This compound was synthesized on a gram-scale in three steps from *N*-methyl-1,2-phenylenediamine in 32% overall yield. Although this product was found to be extremely water-sensitive, it was demonstrated to be stable –under an inert atmosphere– at room temperature both in solution and in the solid state. During the course of our studies, Ong *et al.* synthesized –based on the same methodolgy– acyclic carbodicarbenes **4–6** ~ **4–8** bearing more sterically demanding *N*-substituents such as isopropyl, cyclohexyl, and 2-pyridyl (Scheme 4.4, *below*).[124,125]



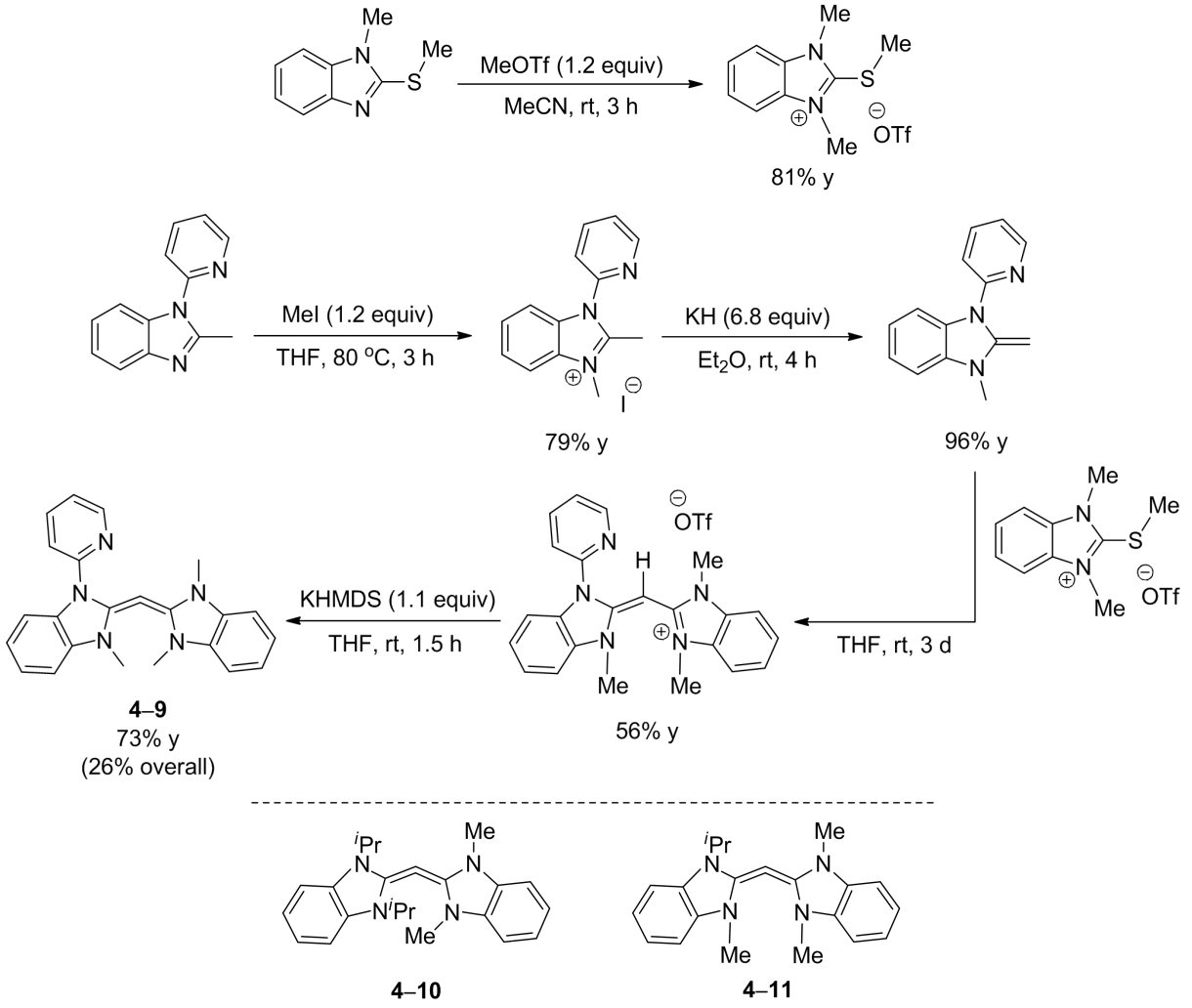


4–6 **4–7** **4–8**

Scheme 4.4 Synthesis of acyclic "symmetric" carbodicarbenes **4–5** ~ **4–8**[117,124,125]

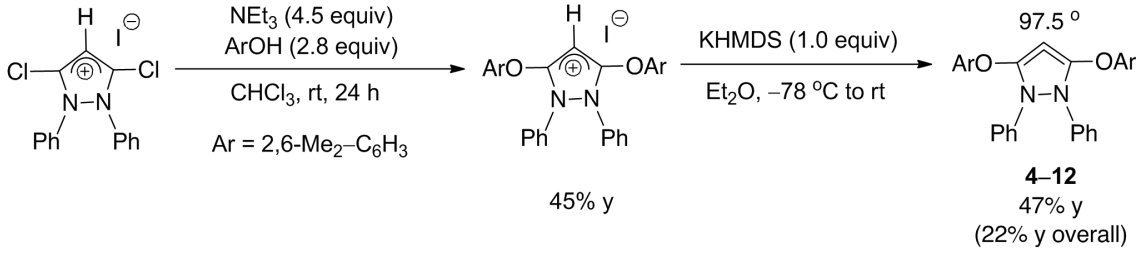
In addition, in 2015 Ong *et al.* synthesized "non-symmetric" carbodicarbenes **4–9** ~ **4–11** bearing different substituents on the two lateral carbon atoms (Scheme 4.5).[126] Compound **4–9** was

synthesized in five steps from the corresponding enediamine in 73% overall yield. Although this product was shown to be extremely air-sensitive, it was demonstrated to be stable –under an inert atmosphere– at room temperature both in solution and in the solid state. However, suitable single crystals for X-ray diffraction were not obtained.



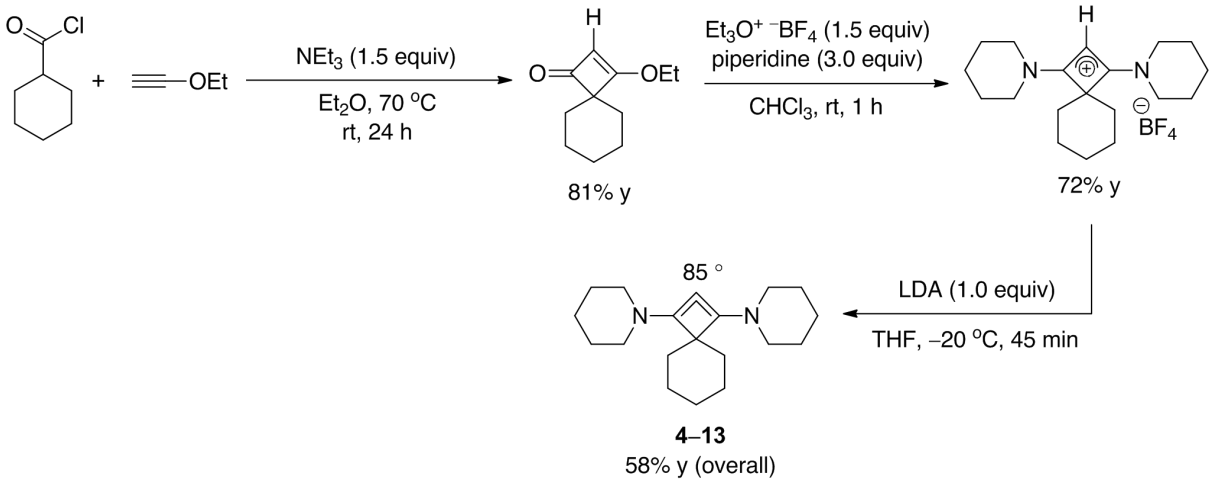
Scheme 4.5 Synthesis of acyclic "non-symmetric" carbodicarbenes **4–9** ~ **4–11**[126]

In addition, several *cyclic* carbodicarbenes, within relatively small ring systems, were also synthesized. Suitable donor groups were chosen (e.g. aryloxy groups), which were considered to be weaker π donor and more electronegative in order to make the central carbon atom slightly less basic. In 2008, Bertrand *et al.* reported the synthesis and isolation of five-membered ring allene **4–12** with a C=C=C bond angle of 97.5 ° (Scheme 4.6).[127] This compound was synthesized on a gram-scale in two steps in 47% overall yield as a pale yellow solid; it was shown to be stable at room temperature and up to 95 °C.



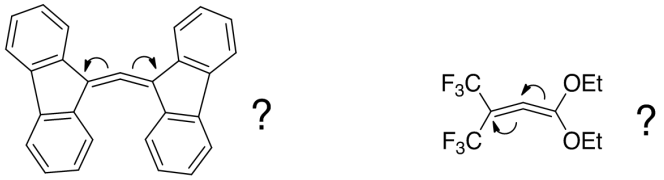
Scheme 4.6 Synthesis of cyclic five-membered ring allene **4–12**[127]

In 2009, Bertrand *et al.* investigated the synthesis of an even smaller allene-containing ring system, 1,2-cyclobutadiene (Scheme 4.7).[128] Final product **4–13** displays a C=C=C bond angle of 85 °. This compound was synthesized on a gram-scale in three steps starting from cyclohexane carbonyl chloride, ethoxyacetylene, and triethyl amine. The desired product was found to be stable at –20 °C, but readily decomposed above –5 °C. For the direct precursor, the overall yield was 58% over two steps.



Scheme 4.7 Synthesis of cyclic four-membered ring allene **4–13**[128]

To date, different types of "bent" allenes or "carbodicarbenes" were synthesized including acyclic and cyclic structures (Figure 4.7). Compound **4–1** displayed a *pull–pull* substitution pattern, and was considered as an electron-poor (Lewis acidic) allene rather than a carbodicarbene. In 2010, Alcarazo *et al.* showed its non-reactivity towards a very bulky *N*-heterocyclic carbene to generate a frustrated Lewis pair (FLP), which was exploited in the heterolytic S–S bond cleavage of disulfides.[136] In contrast, compound **4–2** showed a *push–pull* substitution pattern, and may display a "hidden carbene" character rather than that of a carbodicarbene. All other "bent" allenes, compounds **4–3** ~ **4–13**, demonstrated a *push–push* substitution pattern. Based on the unique structure and properties of these *formal carbon(0) species*, a variety of studies were carried out in literature.



4–1
Bertrand 1995

4–2
Liebenow 1980

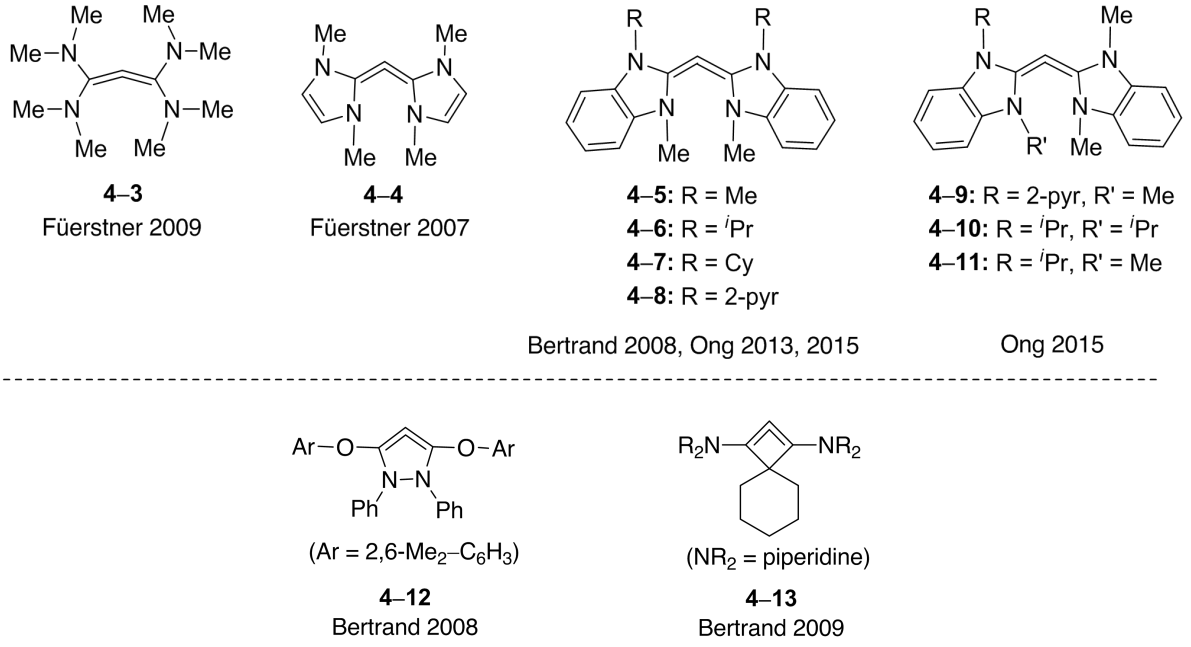
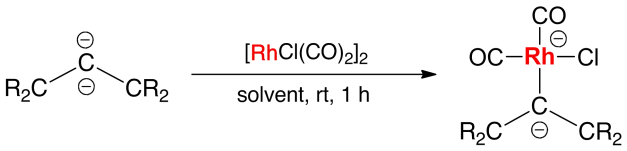


Figure 4.7 Examples of "bent" allenes or carbodicarbenes **4–1** ~ **4–13**[117,121-128]

4.1.4 Carbodicarbene–Metal Complexes: Preparation and Properties

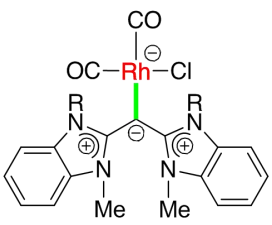
With the successful synthesis of various carbodicarbenes being accomplished, several investigations were carried out to see whether these bases bind to metal centers; according to calculations these strongly basic carbon(0) compounds should be excellent ligands for metals. Thus, various metal complexes have been prepared in order to study the ligand properties of C(0) species. Frenking *et al.* concluded that because the $C(NHC)_2$ can be electronically modified in many ways through variation of the NHC skeleton, these molecules should be promising ligands for metal complexes.[120] In mono-metallated complexes, the central carbon atom of the carbodicarbene ligand would coordinate to one metal centre. Among these complexes, rhodium proved to be the most popular metal used in order to evaluate the σ donor ability of C(0) ligands. The general method for metal complex formation with various carbones is shown in Scheme 4.8.



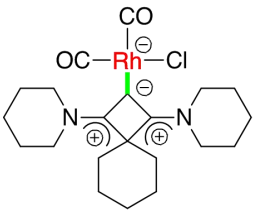
Scheme 4.8 General method for the preparation of CDC–metal complexes[120]

The method used to study the donor property was the classic evaluation, which relies on the carbonyl wave numbers of the corresponding *trans*-carbonyl (CO) ligand in the rhodium complex formed. The *trans* effect concerns the electronic effect of one ligand (e.g. carbodicarbene) on another ligand (e.g. CO) when these are *trans* (opposite) to one another. Considering the π back-bonding effect, electrons are partially transferred from a metal d orbital to the π* (anti-bonding) orbital of CO. This electron transfer –which relies on the σ donor strength of the *anti*-ligand– would strengthen and weaken the

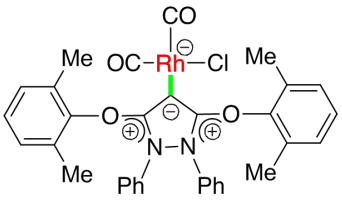
corresponding *anti* metal–CO and C–O bonds, respectively. The strengthening of the M–CO bond is reflected by an increased vibrational frequency for the M–CO bond; the weakening of the C–O bond is indicated by a decreased carbonyl stretching frequency for the C–O bond. By comparison of the data collected for both carbenes and carbodicarbenes, the relative σ donor ability of these species can be "measured"; the lower the wavenumber for the carbonyl ligand, the stronger donating is the *anti* carbon-based ligand (Figure 4.8).



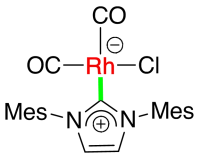
4–14: R = Me; $\tilde{\upsilon}$ = 2014 cm^{-1}
4–15: R = ^{i}pr; $\tilde{\upsilon}$ = 2022 cm^{-1}
4–16: R = Cy; $\tilde{\upsilon}$ = 2016 cm^{-1}



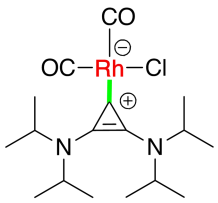
4–17: $\tilde{\upsilon}$ = 2016 cm^{-1}



4–18: $\tilde{\upsilon}$ = 2018 cm^{-1}



4–19: $\tilde{\upsilon}$ = 2058 cm^{-1}

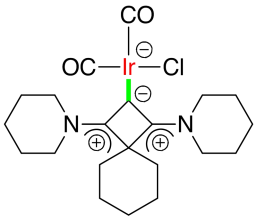


4–20: $\tilde{\upsilon}$ = 2020 cm^{-1}

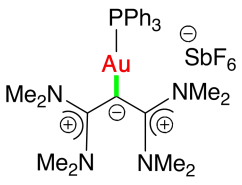
Figure 4.8 Carbonyl wavenumbers of CDC–metal vs. NHC–metal and BAC–metal complexes[117,124-128]

The carbonyl wavenumbers for *carbone*-based [RhCl(CO)$_2$(L)] complexes **4–14** ~ **4–18**[117,124-128] were shown to be significantly lower than the ones recorded for the corresponding *carbene*-based [RhCl(CO)$_2$(L)] complexes **4–19** and **4–20**. This tendency indicated that *carbones* were stronger σ donors and weaker π acceptors than *carbenes*.

In case of the four-membered ring carbodicarbene **4–13**, its iridium complex **4–21** has also been evaluated (Figure 4.9).[128] The average value of the carbonyl wavenumbers for Ir–*carbone* complex **4–21** ($\tilde{\nu}$ = 2002 cm^{-1}) was also at the lower end of the range observed for literature-known Ir–*carbene* complexes ($\tilde{\nu}$ = 1999–2020 cm^{-1}).



4–21
$\tilde{\upsilon}$ = 2002 cm^{-1}



4–22

Figure 4.9 CDC–iridium and CDC–gold complexes

Fürstner *et al.* also used acyclic carbodicarbene **4–3** as a ligand for a gold(I) species to form **4–22** (Figure 4.9).[123] The metalated carbon atom was shown to exhibit a trigonal-planar coordination with

the in-plane lone pair of the ligand binding to the gold centre. Hence, gold complex **4–22** was shown to contain a η^1-coordinated "allene" ligand, whereas "classic" allenes react with metal fragments to give η^2 complexes involving one of the C=C π bonds.

4.1.5 Carbodicarbenes: Carbene vs. Carbone Character

As shown, mono-metallated complexes have been formed based on various carbodicarbenes. The next question was whether *both* lone pairs at the central carbon of CDCs can be chemically exploited or not. Do date, all metal salts and carbodicarbenes explored in this context proved to be unsuitable for dimetallation, which may be ascribed to steric reasons (Figure 4.10).[117,123,127,128]

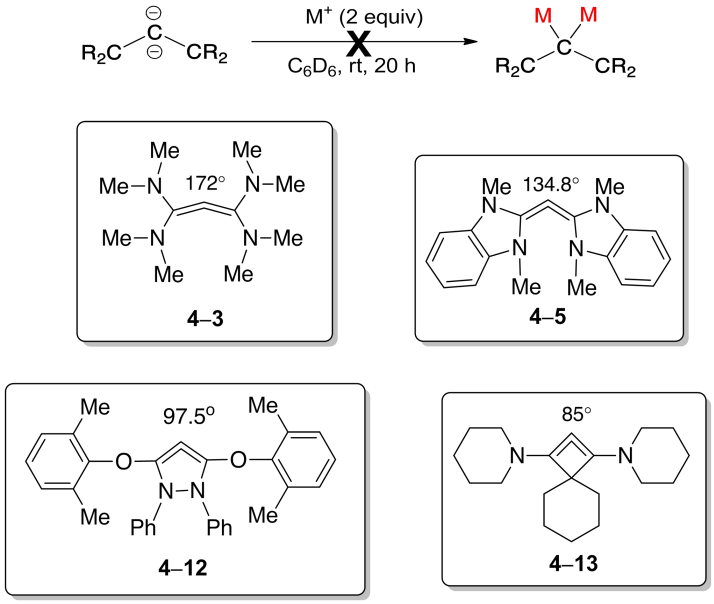
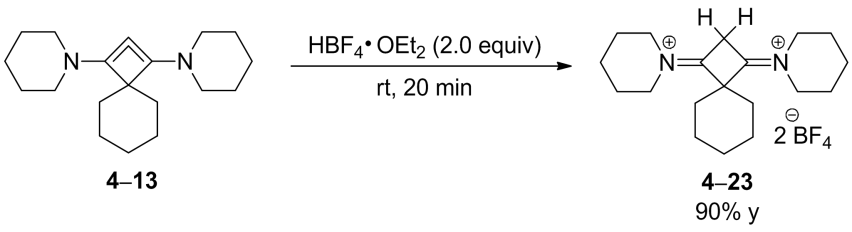


Figure 4.10 Carbodicarbenes and metal salts involved in attempted CDC dimetallation[117,123,127,128]

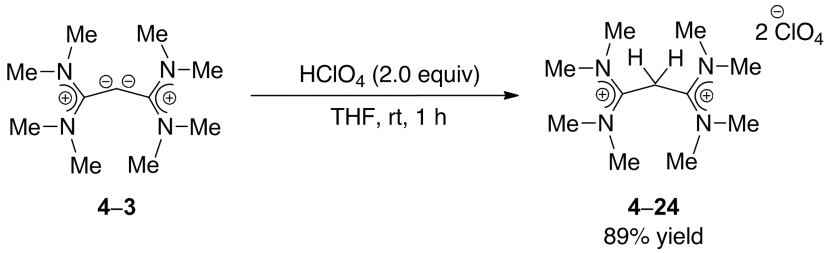
Despite the fact that dimetallation was not realized yet, Bertrand *et al.* investigated the potential chemical usage of both lone pairs at the central carbon atom of "bent" allene **4–13**; indeed, a double protonation of **4–13** was conducted using tetrafluoroboric acid under mild conditions to form bis(iminium) salt **4–23** as colorless crystals in 90% yield (Scheme 4.9).[128]



Scheme 4.9 Double protonation of cyclic four-membered ring allene **4–13**[128]

The fact that compound **4–13** was protonated twice proved the hypothesis that this compound potentially displayed a *carbon(0)* character and that this compound may be employed in dual catalysis. Similarly, a double protonation was realized using "bent" allene **4–3** in the presence two equivalents of

$HClO_4$ (Scheme 4.10);[123] the corresponding bis(iminium) salt **4–24** was isolated in 89% yield.

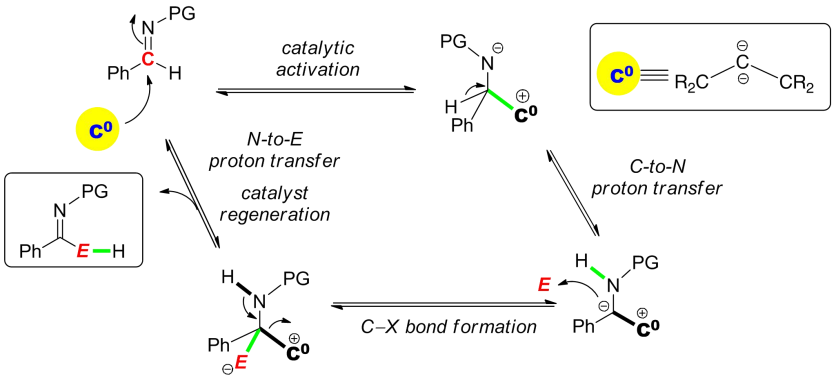


Scheme 4.10 Double protonation of acyclic allene **4–3**[123]

Despite the fact that several "bent" allenes or carbodicarbenes have been successfully synthesized, at the outset of our project a *catalytic* application had not been reported.

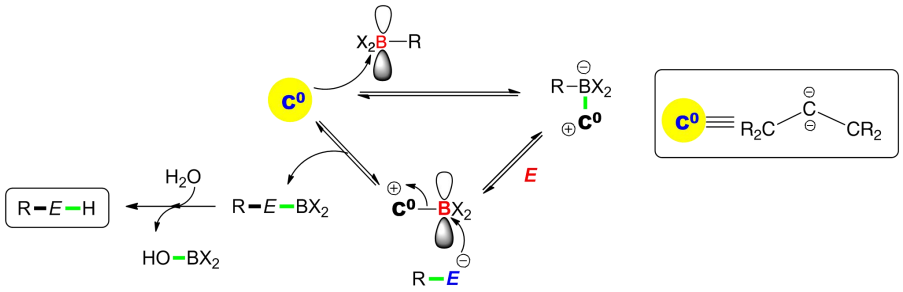
4.1.6 Aims for Unprecedented Carbone [C(0)] Catalysis

Carbones, such as carbodicarbenes (CDCs) or "bent" allenes, bear two lone pairs and were reported to be more basic than carbenes [C(II)]; both lone pairs may be exploited for chemical reactivity.
Carbones may be used to trigger catalytic *umpolung* of aldimines for subsequent intermolecular C–C bond formation with suitable electrophiles (Scheme 4.11).



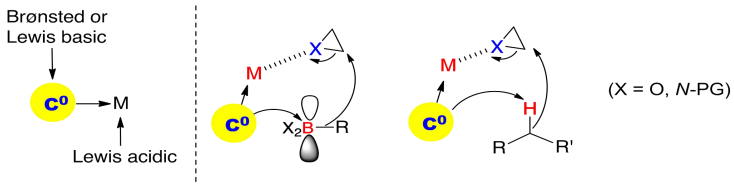
Scheme 4.11 Proposed C(0)-catalysed *umpolung* of aldimines

Carbones may also be used to activate electrophilic boron-based pro-nucleophiles for subsequent intermolecular C–C bond formation with suitable electrophiles (Scheme 4.12).



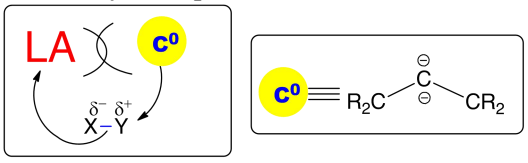
Scheme 4.12 Proposed C(0) nucleophilic catalysis using an electrophilic boron pro-nucleophile

Metal–carbone complexes could be used as potential acid–base dual catalysts to activate *both* electrophiles *and* pro-nucleophiles for subsequent bond formations (Scheme 4.13).



Scheme 4.13 Proposed metal–carbone dual catalysis

In the presence of a sterically demanding Lewis acid, carbones may act the Lewis base part of a frustrated Lewis pair (FLP), which may be exploited for small molecule activation (Scheme 4.14).

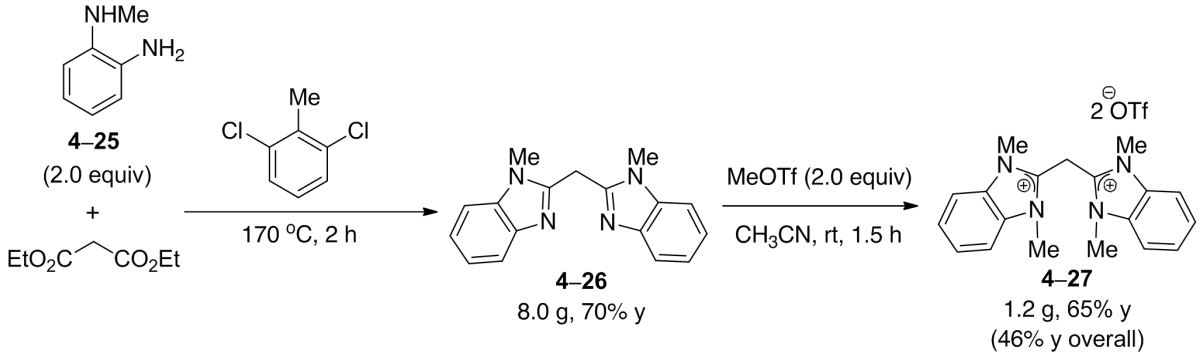


Scheme 4.14 Proposed carbone-based frustrated Lewis pair (FLP) catalysis

4.2 RESULTS AND DISCUSSION

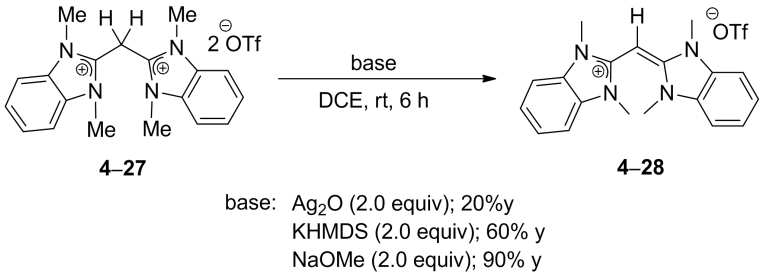
4.2.1 Synthesis of Carbodicarbene Precursors 4–27, 4–28 and Carbodicarbene 4–5

We started our investigations with the synthesis of an *acyclic* carbodicarbene, which was prepared on a gram-scale in four steps from *N*-methyl-1,2-phenylenediamine (**4–25**; Scheme 4.15). The first step involved a double condensation using diethyl malonate, according to Field's method,[129] to give bis(amidine) **4–26** as a beige solid in 70% yield. Double *N*-methylation of the latter using methyl triflate (2 equiv) in acetonitrile gave bis(amidinium) salt **4–27** as a colorless solid in 65% yield.



Scheme 4.15 Synthesis of double salt **4–27**[117,129]

Next, the deprotonation of double salt **4–27** was conducted to form carbodicarbene precursor **4–28**.[124] The use of three different bases was examined (Scheme 4.16).[124] The reactions were monitored by ^{1}H NMR spectroscopic analysis of the reaction mixture through the detection of product formation and substrate consumption.

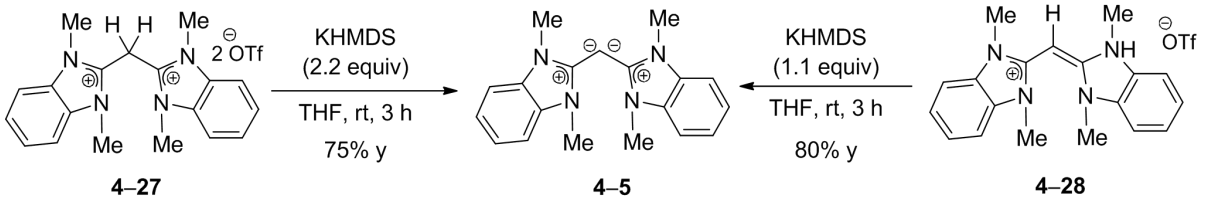


Scheme 4.16 Synthesis of mono salt **4–28** through deprotonation of **4–27**[124]

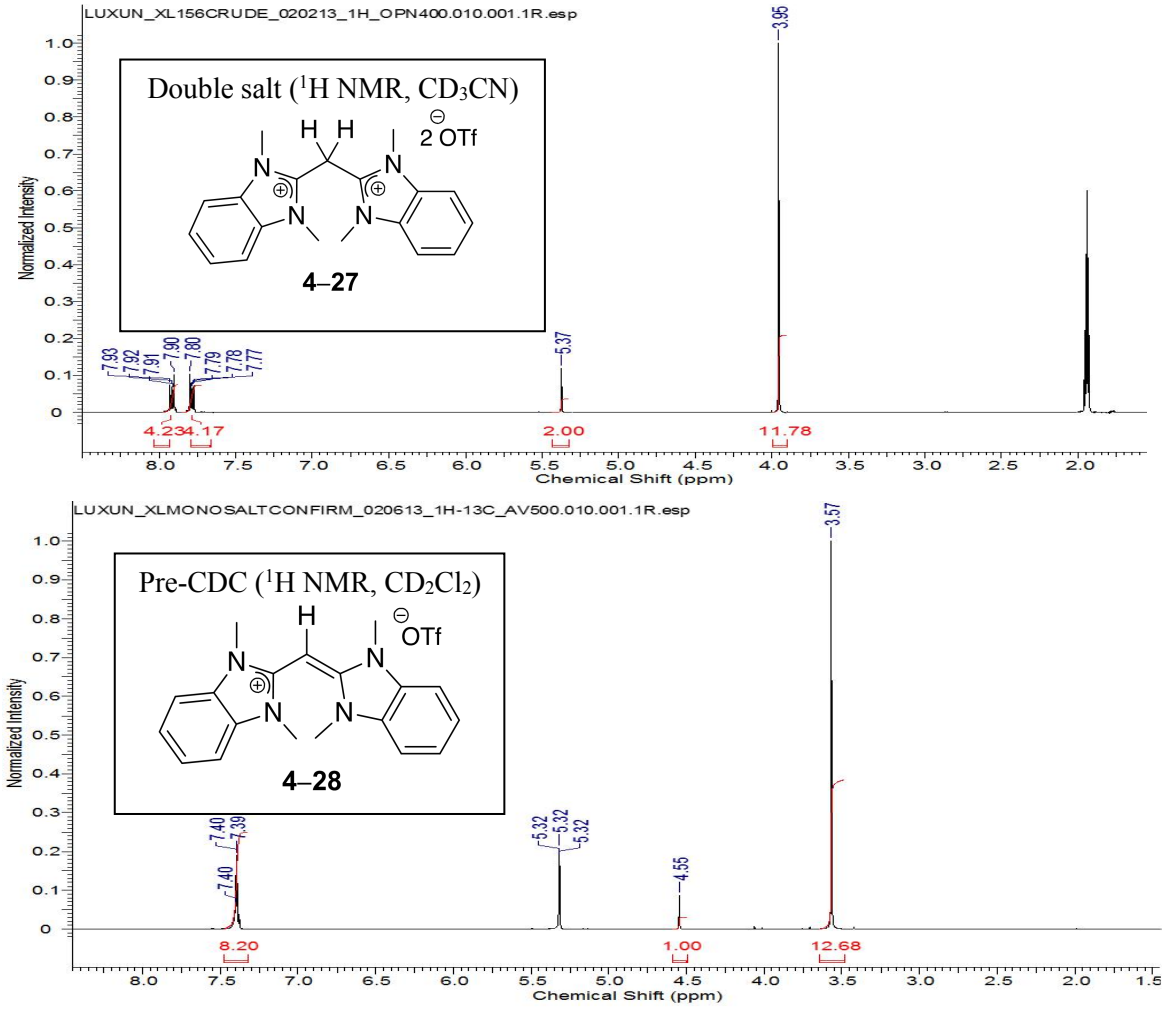
The solubility of silver(I) oxide in DCE was rather low, which may be the reason for the low yield of **4–28** (20%). The product identity was confirmed by both ^{1}H and ^{13}C NMR spectroscopy. The use of a stronger base, KHMDS, gave **4–28** in 60% yield. In our hands however, the use of NaOMe proved to be most effective (90% yield). Thus, CDC precursor **4–28** was synthesized in three steps in 41% overall yield.

Next, we examined the complete deprotonation of both double salt **4–27** and CDC precursor **4–28** in order to prepare carbodicarbene **4–5** (Scheme 4.17).[117,124] Two methods were used in this case. The first one –double deprotonation of double salt **4–27** using KHMDS (2.2 equiv)– gave product **4–5** as a

yellow solid in 75% yield. The second one –single deprotonation of CDC precursor **4–28** using KHMDS (1.1 equiv)– gave product **4–5** in 80% yield. The identity of product **4–5** was confirmed by both ^{1}H and ^{13}C NMR spectroscopy. The ^{1}H NMR charts are displayed in Chart 4.1.



Scheme 4.17 Synthesis of carbodicarbene **4–5** through deprotonation using KHMDS



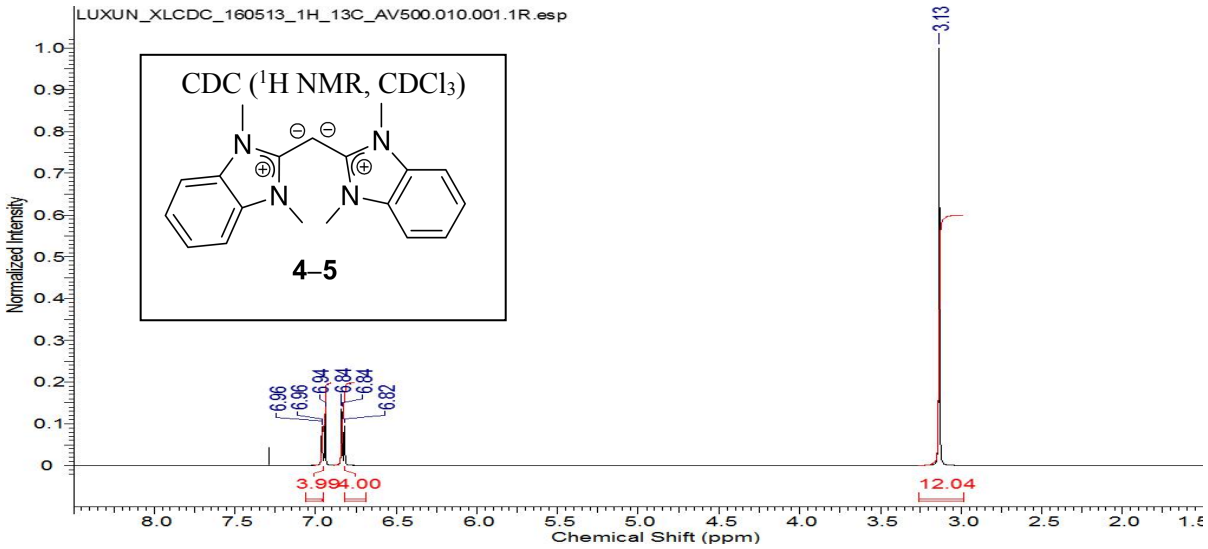
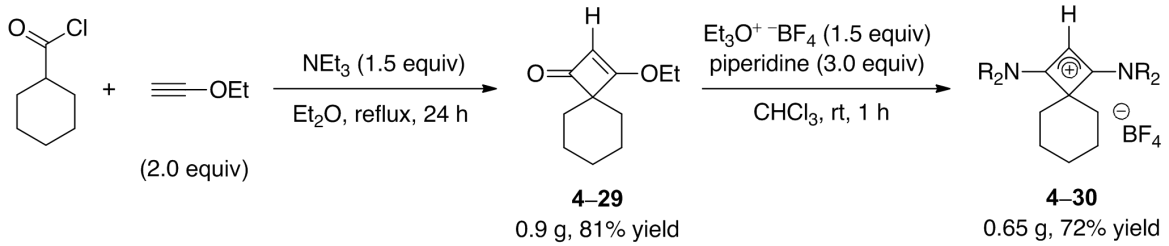


Chart 4.1 ^{1}H NMR spectra of isolated double salt **4-27**, CDC precursor **4-28**, and CDC **4-5**

Next, we turned our attention to the preparation of *cyclic* four-membered ring carbodicarbene **4–13**.[128] In order to prepare this species, the corresponding precursor needs to be synthesized. CDC precursor **4–30** was synthesized in two steps from cyclohexane carbonyl chloride and ethoxyacetylene (Scheme 4.18).



Scheme 4.18 Synthesis of CDC precursor **4–30**[128]

In the first step, cyclohexane carbonyl chloride and ethoxyacetylene in diethyl ether were reacted in the presence of triethyl amine under reflux. Spirobicyclic cyclobutenone **4–29** was obtained as a brown oil in 81% yield. In the second step, *O*-alkylation using Meerwein's reagent, followed by double amination of the cationic four-membered carbocycle with piperidine afforded CDC precursor **4–30** as light yellow crystals in 72% yield.

4.2.2 Evaluation of Nucleophilicity in ^{11}B NMR Spectroscopy

4.2.2.1 Examination of Carbodicarbene Precursor 4–28

In order to determine the nucleophilicity of CDC precursor **4–28**, it was reacted with a variety of electrophilic boron reagents to see whether the corresponding boron–ate complex can be formed. The boron reagents used are the same as in the earlier BAC study (Figure 4.11).

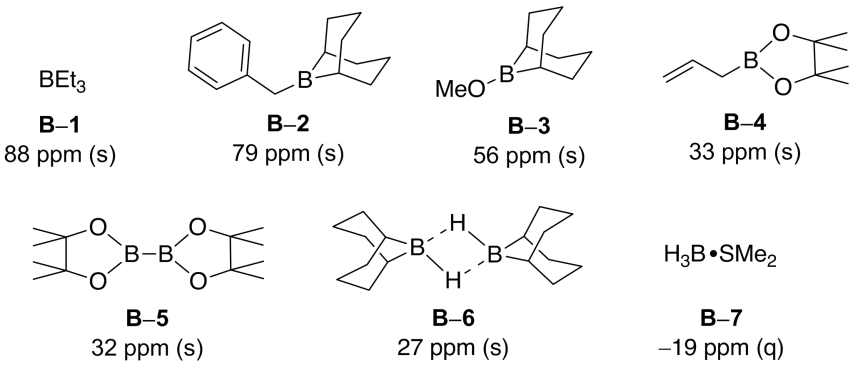
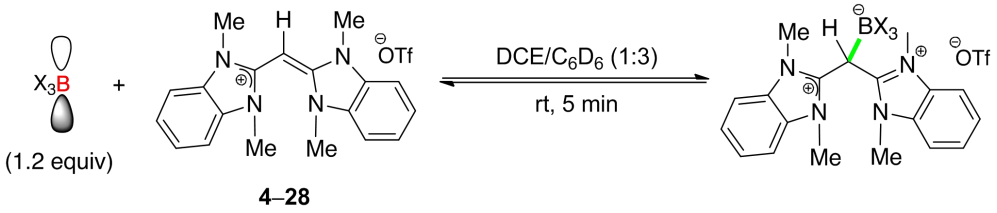


Figure 4.11 Boron reagents used and their chemical shifts in ^{11}B NMR spectroscopy

As CDC precursor **4–28** was isolated, it was just dissolved in dichloroethane (DCE) followed by the addition of the corresponding boron reagent (1.2 equiv) at room temperature (Table 4.1).

Table 4.1 ^{11}B NMR study using CDC precursor **4–28** and boron Lewis acids **B–1** ~ **B–7**



Entry	Boron Reagent	^{11}B NMR (ppm)	New ^{11}B signal (ppm)	Complex?
1	BEt_3 (**B–1**)	~ +87	–13.2	+
2	Bn–B(9BBN) (**B–2**)	+77.6	–14.5	+
3	MeO–B(9BBN) (**B–3**)	+57.0	–1.0	+
4	allyl–B(pin) (**B–4**)	+33.2	*no change*	–
5	(pin)B–B(pin) (**B–5**)	+32.1	*no change*	–
6	H–B(9BBN) (**B–6**)	+27.9	*no change*	–
7	H_3B•SMe_2 (**B–7**)	–19.0	+25.2 (minor)	+/–

The ^{11}B NMR spectra of boron observed binding including BEt_3 (**B–1**), Bn–B(9BBN) (**B–2**), MeO–B(9BBN) (**B–3**), H_3B•SMe_2 (**B–7**), were shown below in Chart 4.2. Compared to the earlier ^{11}B NMR study carried out with an *in situ*-formed BAC (see Section 1.2.2), CDC precursor **4–28** seemed to be less nucleophilic, which may be ascribed to the higher steric demand of this species. While boron–ate

complexes were detected with BEt_3 (**B–1**), Bn–B(9BBN) (**B–2**), MeO–B(9BBN) (**B–3**), and to some extent $H_3B{\bullet}SMe_2$ (**B–7**), other trials failed to give a detectable donor–acceptor interaction. The boron–ate complexes were identified with a signal in the tetravalent boron area (–40 to 10 ppm) in ^{11}B NMR spectra (Chart 4.2).

In case of BEt_3 (**B–1**), the starting material displayed a signal at ~ +87 ppm [Chart 4.2a), *above*]. The reaction between **B–1** and CDC precursor **4–28** gave a new signal at –13.2 ppm, which can be ascribed to the corresponding boron–ate complex [Chart 4.2a), *below*].

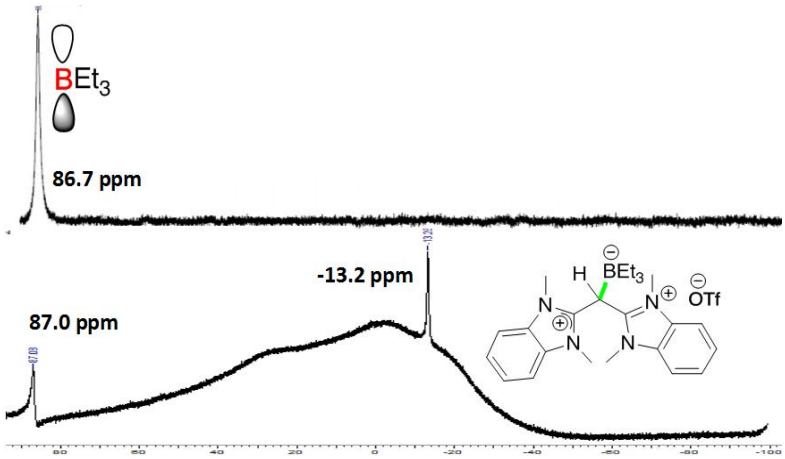


Chart 4.2a) ^{11}B NMR spectra for **B–1** and the corresponding boron–ate complex

In case of Bn–B(9BBN) (**B–2**), the starting material showed a signal at +77.6 ppm [Chart 4.2b), *above*]. The reaction between **B–2** and CDC precursor **4–28** gave a new signal at –14.5 ppm, which can be ascribed to the corresponding boron–ate complex [Chart 4.2b), *middle*]. The signal at ~ +57 ppm was assigned to a minor impurity [HO–B(9BBN)] present in **B–2** [Chart 4.2b), *below*].

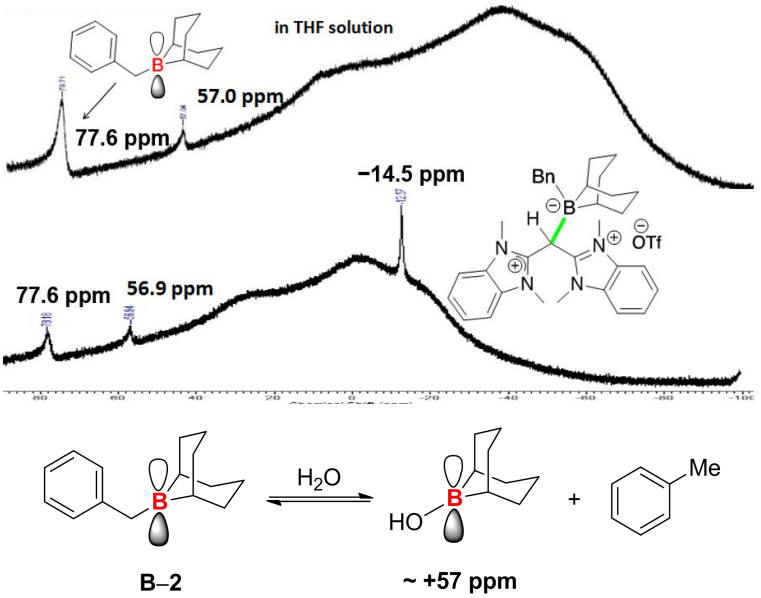


Chart 4.2b) ^{11}B NMR spectra for **B–2** and the corresponding boron–ate complex

In case of MeO–B(9BBN) (**B–3**), the starting material displayed a signal at +57 ppm [Chart 4.2c), *above*]. The reaction between **B–3** and CDC precursor **4–28** gave a new signal at –1.0 ppm, which can be ascribed to the corresponding boron–ate complex [Chart 4.2c), *below*].

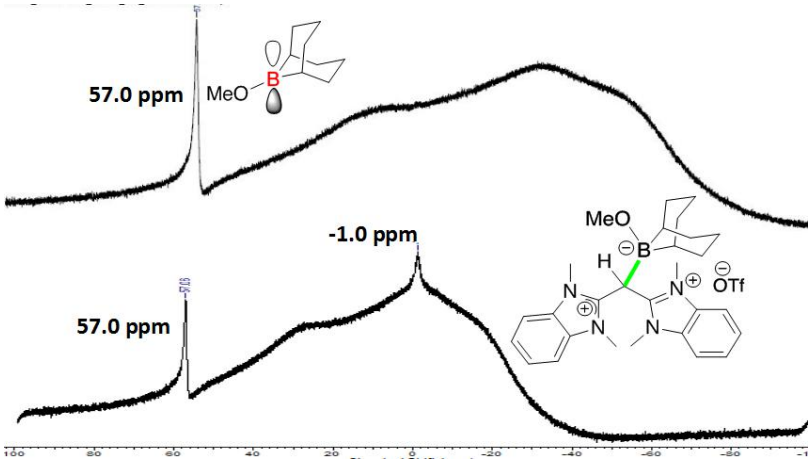


Chart 4.2c) ^{11}B NMR spectra for **B–3** and the corresponding boron–ate complex

If a boron–ate complex was not stable, it may further react in an intra- or intermolecular fashion. Indeed, in case of $H_3B{\bullet}SMe_2$ (**B–7**), a new minor signal at ~ +25 ppm was observed (Chart 4.3).

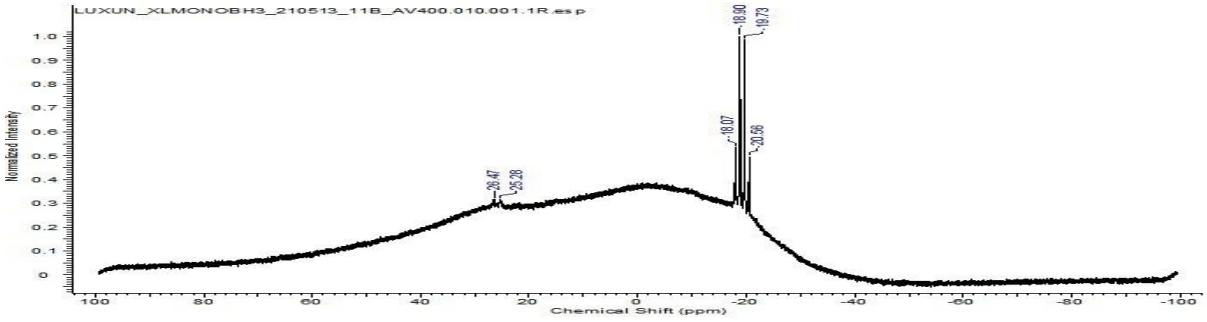
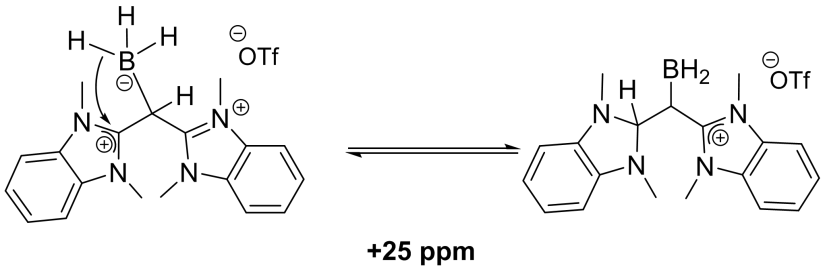


Chart 4.3 ^{11}B NMR spectrum for **B–7** and the new species

The starting material, $H_3B{\bullet}SMe_2$ (**B–7**), displayed a signal at –19 ppm. If a stable boron–ate complex was formed, a signal in the range –40 ppm ~ +10 ppm would be expected. Here however, an *intra*molecular boron-to-carbon hydride transfer within the ate complex may have occurred to give a "carbon-ligated BH_2" species; a signal at ~ +80 ppm would have been expected for such compound (Scheme 4.19). In turn, the observed signal at ~ +25 ppm has been ascribed to a rapid equilibrium between the initially formed boron–ate complex and the corresponding "carbon-ligated BH_2" species.

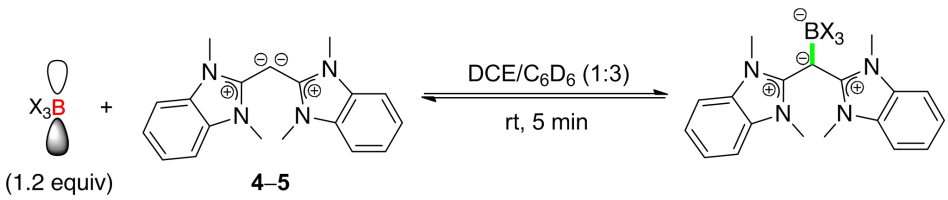


Scheme 4.19 *Intra*molecular hydride transfer within the initially formed boron–ate complex

4.2.2.2 Examination of Carbodicarbene 4–5

In analogy to the study with CDC precursor **4–28**, the isolated carbone **4–5** was also used with the boron reagents (Table 4.2). **4–5** was dissolved in DCE and reacted with the corresponding boron reagent (1.2 equiv) followed by ^{11}B NMR spectroscopic analysis.

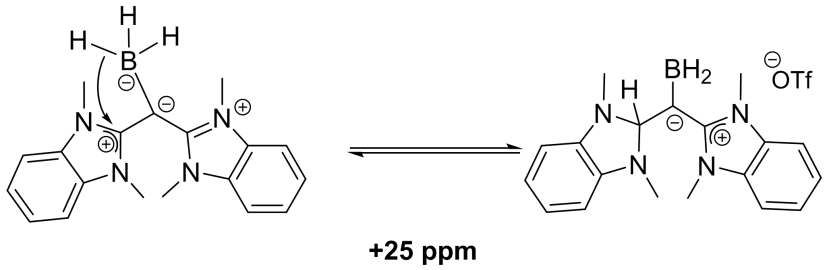
Table 4.2 ^{11}B NMR study using carbone **4–5** and boron Lewis acids **B–1** ~ **B–7**



Entry	Boron Reagent	^{11}B NMR (ppm)	New ^{11}B signal (ppm)	Complex?
1	BEt_3 (**B–1**)	~ +87	–6.2	+
2	Bn–B(9BBN) (**B–2**)	+77.6	–9.0	+
3	MeO–B(9BBN) (**B–3**)	+57.0	–2.5	+
4	allyl–B(pin) (**B–4**)	+33.2	*no change*	–
5	(pin)B–B(pin) (**B–5**)	+32.1	*no change*	–
6	H–B(9BBN) (**B–6**)	+27.9	*no change*	–
7	H_3B•SMe_2 (**B–7**)	–19.0	+25.1 (minor)	+/–

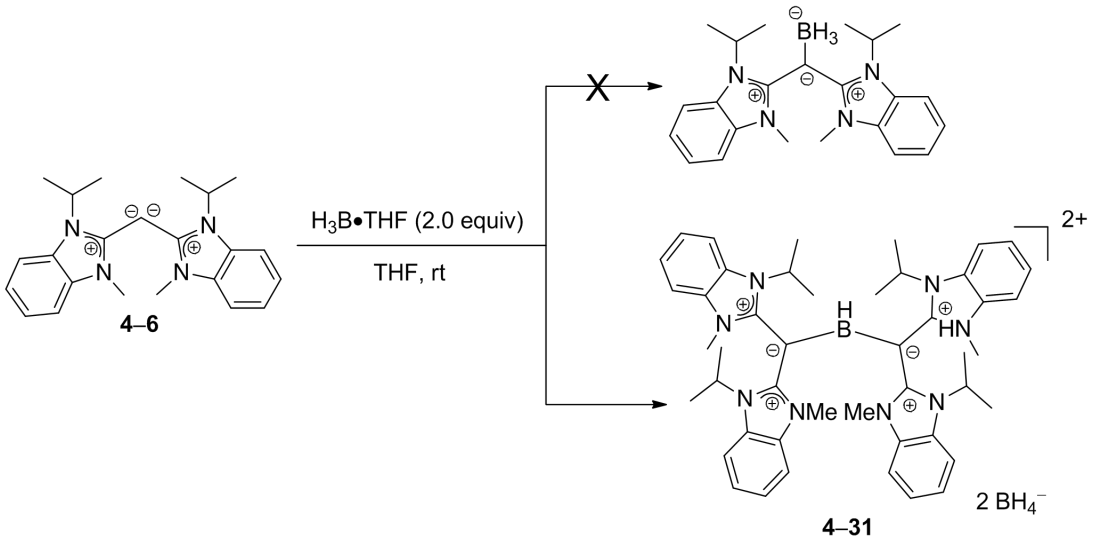
Here again, boron–ate complexes were not detected in all the cases. With BEt_3 (**B–1**), Bn–B(9BBN) (**B–2**), MeO–B(9BBN) (**B–3**), and H_3B•SMe_2 (**B–7**), boron–ate complexes were formed (Table 4.2, entries1–3 and 7).

Here again, we propose that an *intra*molecular boron-to-carbon hydride transfer within the initially formed ate complex must have occurred to form a "carbon-ligated BH_2" species, which should display a signal at ~ +80 ppm. The observed signal at ~ +25 ppm has been ascribed to a rapid equilibrium between the initially formed boron–ate complex and the corresponding "carbon-ligated BH_2" species (Scheme 4.20).



Scheme 4.20 *Intra*molecular hydride transfer within the initially formed boron–ate complex

During the course of our studies, Ong *et al.* reported the formation of three-coordinate dicationic hydrido–boron complex **4–31** using carbodicarbene **4–6** and H_3B•THF (2.0 equiv; Scheme 4.21).[130] The corresponding product signals in ^{11}B NMR spectroscopy were detected at –38.6 ppm and –25.4 ppm, respectively. *In our case, we did not observe these types of signals.*

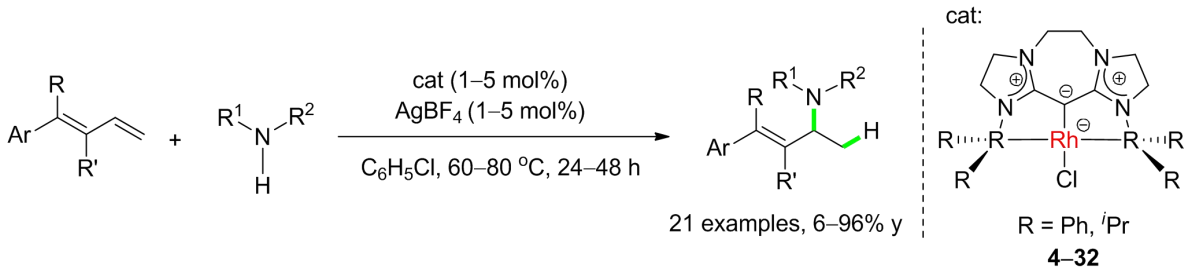


Scheme 4.21 Formation of three-coordinate dicationic hydrido–boron complex **4–31**[130]

With all other boron Lewis acids such as allyl–B(pin) (**B–4**), (pin)B–B(pin) (**B–5**), and H–B(9BBN) (**B–6**), boron–ate complexes were not detected even upon heating (60 °C). The steric hindrance of carbone **4–5** may be one reason for this rather low nucleophilicity; only less sterically demanding Lewis acids may be attacked by the bulky carbon centre of **4–5**. In cases where we observed boron–ate complex formation, *direct* Lewis base catalysis may be applicable in view of nucleophilic transfer of an organic group to a suitable electrophile. In cases where carbone **4–5** did not react with Lewis acidic boron reagents, both reagents are considered to form a so-called *frustrated Lewis pair* (FLP), which could be exploited in the activation of strong σ bonds in small molecules.

During the Course of Our Studies: Applications in Catalysis

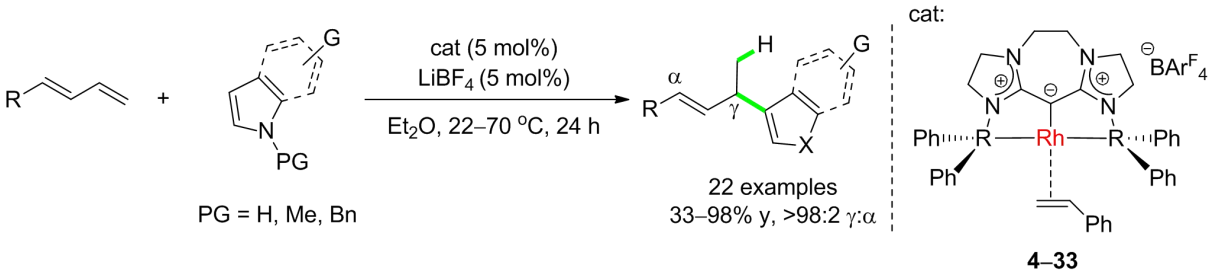
Despite the fact that a variety types of carbodicarbenes were synthesized in literature, catalytic applications were only reported very recently. In 2014, Meek *et al.* developed novel cyclic bis(phosphino)carbodicarbene–rhodium complexes of type **4–32** and exploited these in the intermolecular hydroamination of dienes using secondary amines or anilines (Scheme 4.22).[131] The corresponding products were obtained in 6–96% yields. It is important to note that this chemistry represented the first example for the catalytic use of well-defined carbodicarbene–metal complexes.



Scheme 4.22 CDC–Rh-catalysed intermolecular hydroamination[131]

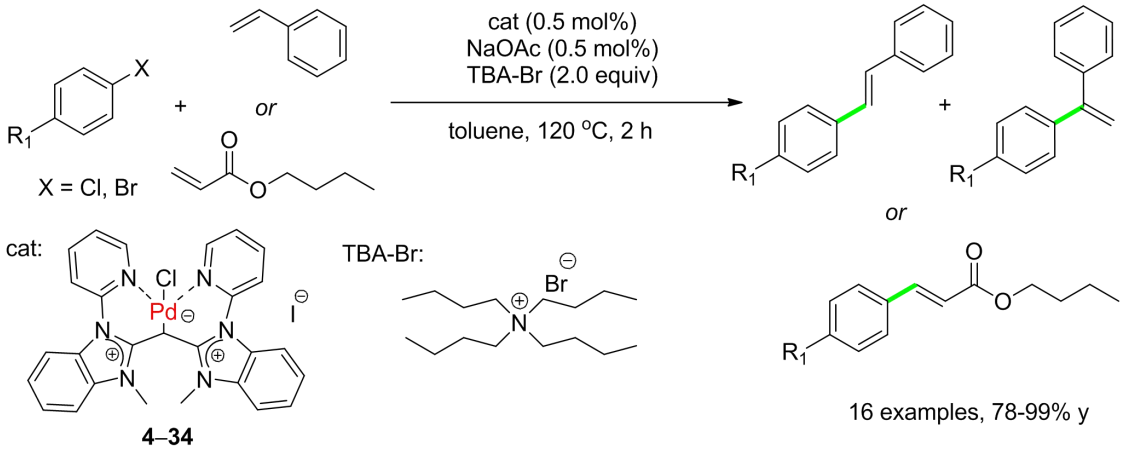
Similarily, Meek *et al.* developed a styrene-stabilized cationic bis(phosphino)carbodicarbene–rhodium complex, **4–33** (Scheme 4.23).[132] Here, it was exploited in catalytic hydroheteroarylation between

dienes and various *N*-heteroarenes. The corresponding products were obtained in 33–98% yields with excellent regioselectivity (γ:α = >98:2). It is noted that the reactions were shown to be compatible with a variety of terminal and internal dienes, and tolerant of ester, alkyl halide, and boronic ester functional groups.

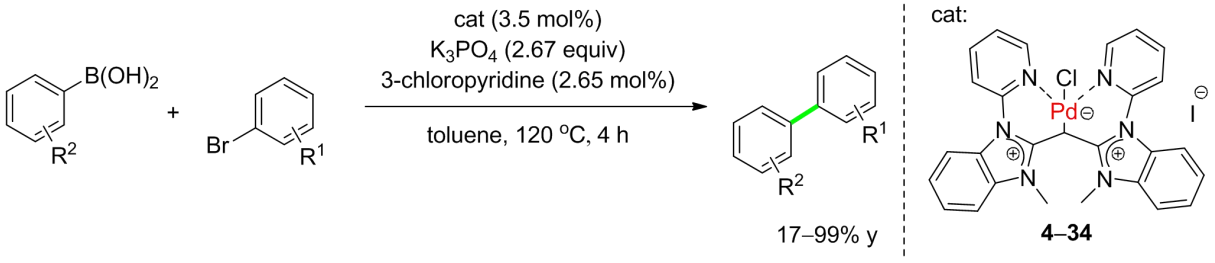


Scheme 4.23 CDC–Rh styrene complex-catalysed intermolecular hydroheteroarylation[132]

In 2015 –as mentioned in 5.1.4– Ong *et al.* synthesized the first isolable pincer-carbodicarbene **4–8** with a C=C=C bond angle of 143 °.[125] The corresponding tridentate pincer-CDC–Pd complex **4–34** was shown to catalyze Mizoroki–Heck and Suzuki–Miyaura cross-coupling reactions, respectively (Schemes 4.24 and 4.25).

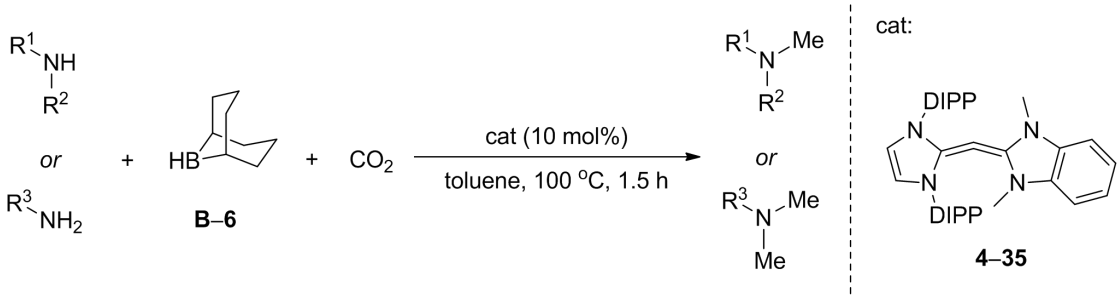


Scheme 4.24 CDC–Pd-catalysed Mizoroki–Heck cross-coupling reactions[125]



Scheme 4.25 CDC–Pd-catalysed Suzuki–Miyaura cross-coupling reactions[125]

In 2015, Ong *et al.* reported the first organocatalytic application using a carbodicarbene (Scheme 4.26).[126] In this work, carbodicarbene **4–35** was used for the reductive *N*-methylation of amines in the presence of CO_2 and H–B(9BBN) (**B–6**). The corresponding products were obtained in 24–97% yields.



Scheme 4.26 First organocatalytic application of a carbodicarbene[126]

4.3 Summary

In the final part of this thesis project, an *acyclic* bis(amidinium) salt (**4–27**), an *acyclic* carbodicarbene precursor (**4–28**), an *acyclic* carbodicarbene (**4–5**), and a *cyclic* carbodicarbene precursor (**4–30**) were synthesized and characterized. In subsequent ^{11}B NMR studies, the nucleophilicity of the isolated species **4–28** and **4–5** have been assessed using a variety of boron electrophiles (Figure 4.12). For both carbon-based nucleophiles, stable boron–ate complexes were detected using three boron electrophiles: BEt_3 (**B–1**), Bn–B(9BBN) (**B–2**), and MeO–B(9BBN) (**B–3**). This promising data may suggest that a *direct* Lewis base catalysis using **4–28** and **4–5** might be applicable in view of transferring an organic group to a suitable electrophile. In case of $H_3B{\bullet}SMe_2$ (**B–7**), a minor signal was observed at +25 ppm, which has been ascribed to a rapid equilibrium between tetra- and tri-coordinated boron species. For boron reagents **B–4** ~ **B–6** that did not react with **4–28** and **4–5**, the corresponding acid/base combinations represent potential candidates for frustrated Lewis Pair (FLP) catalysis in view of the activation of strong σ bonds in small molecules.

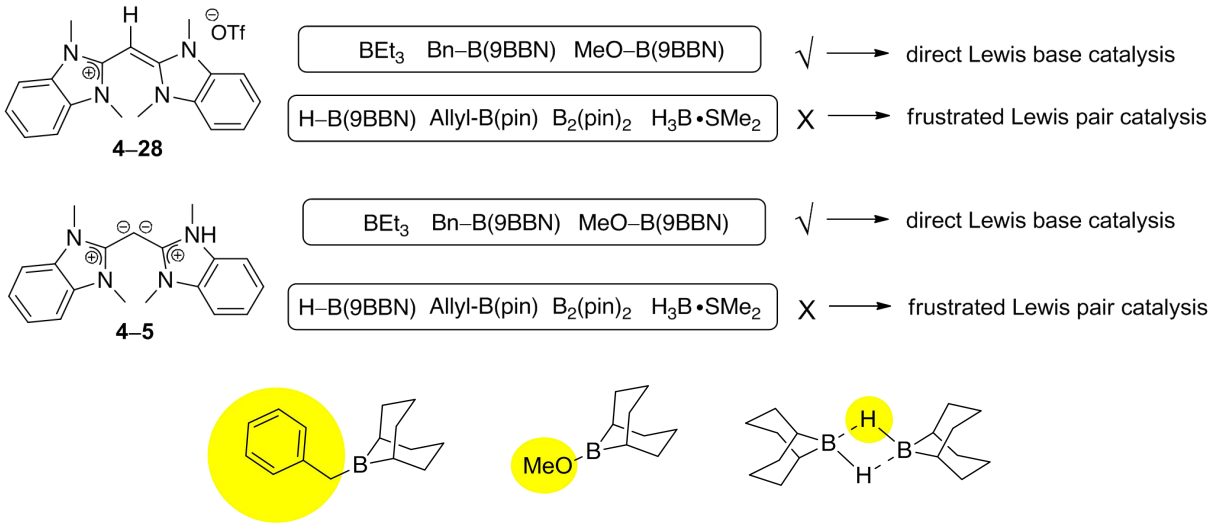


Figure 4.12 Summary of ^{11}B NMR study using species **4–28** and **4–5**

Future work

The synthesized metal–BAC complexes **1–26** ~ **1–28** should be examined in Lewis acid catalysis in the presence of an anion metathesis trigger (e.g. silver or sodium salt); the non-sterically demanding BAC ligand may induce interesting selectivity. In metal-free BAC catalysis, further base-catalysed reactions may be uncovered; if a hydrogen bond donor is included in the catalyst structure dual catalysis may be developed (e.g. ring-opening reactions). In asymmetric BAC catalysis, other important asymmetric reactions should be examined. Regarding the catalyst structure, the chiral backbone of the enantiopure catalyst may be re-investigated, and another hydrogen bond donor may be introduced. Such modifications may be critical to improve the level of asymmetric induction in the conjugate borylation (or silylation) chemistry. In addition, as mentioned earlier, an application to reductive aldol or Mannich reactions may be conceivable using H–B(pin). Finally, the synthesized carbodicarbene, and some analogues thereof, may be exploited in Lewis base catalysis using boron-based reagents. Likewise, catalytic *umpolung* chemistry of aldehydes or other suitable pro-nucleophiles such as aldimines may be investigated.

5 Experimental

5.1 General Experimental Section

Nuclear Magnetic Resonance (NMR) spectra were recorded on Bruker AVA 400, Bruker AVA 500, Bruker PRO 500, and Bruker AVA 600 spectrometers, respectively. These spectrometers operate at the following frequencies: 400 MHz, 500 MHz, or 600 MHz for ^{1}H NMR; 100 MHz, 125 MHz, or 150 MHz for ^{13}C NMR; 128 MHz or 160 MHz for ^{11}B NMR; 128 MHz for ^{19}F NMR. Chemical shifts (δ) were quoted in parts per million (ppm) down-field to tetramethylsilane (TMS; δ = 0 ppm), or in the scale relative to the corresponding NMR solvent used as an internal reference. Coupling constants (*J*) are quoted to the nearest 0.1 Hz. Abbreviations used in the description of resonances are: s (singlet), d (doublet), t (triplet), q (quartet), sept (septet), m (multiplet), and br (broad). Infrared (IR) spectra were recorded on a Shimadzu IR Affinity–1 instrument using the corresponding isolated NMR sample in $CDCl_3$ (attenuated total reflectance sampling technique). High-resolution mass spectra (HRMS) were recorded on a Finnigan MAT 900 XLT spectrometer [electrospray ionization (ESI) technique]. Thin layer chromatography (TLC) was carried out on pre-coated silica gel plates from Merck (DF ALufolien 60F_{254}; 0.2 mm). Preparative thin-layer Chromatography (PTLC) was carried out on self-prepared plates using silica gel from Wakogel (B–5F; particle size: 45 μm). Flash column chromatography was carried out using silica gel from Fisher Scientific (60 Å; particle size: 40–63 μm). Product spots were visualized by UV light at 254 nm or with an appropriate stain solution. Melting points were recorded on a Gallenkamp melting point apparatus (uncorrected).

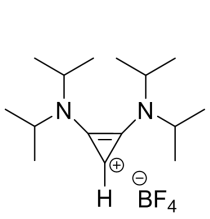
All bases for base screening were purchased with the highest available purity. LiHMDS (97%, Aldrich), NaHMDS (99%, Aldrich), KHMDS (0.5 M in toluene, Aldrich), LDA (97%, Aldrich), LTMP (97%, Aldrich), NaO^{t}Bu (99.9%, Aldrich), KO^{t}Bu (99.99%, Aldrich), NaO^{t}Bu (99.9%, Aldrich), Li_2CO_3 (≥99.0%, Aldrich), Na_2CO_3 (≥99.0%, Aldrich), K_2CO_3 (99.9995%, Aldrich), Cs_2CO_3 (99.9995%, Aldrich), 1,8-Diazabicyclo[5.4.0]undec-7-ene (≥99.0%, Aldrich), *N*,*N*,*N*,*N*-tetramethylguanidine (TMG, ≥99.0%, Aldrich) and proton sponge (≥99.0%, Aldrich) were purchased. All NHC precursors for control experiments were purchased with the highest available purity. NHC precursors ***pre-NHC*–2** (95%, Aldrich), ***pre-NHC*–3** (96%, Aldrich), ***pre-NHC*–4** (97%, Aldrich), ***pre-NHC*–5** (97%, Aldrich), ***pre-NHC*–6** (97%, Aldrich), ***pre-NHC*–7** (95%, Aldrich), ***pre-NHC*–8** (98%, Aldrich), ***pre-NHC*–9** (≥98%, Aldrich) and ***pre-NHC*–10** (98%, Aldrich) were purchased. CAAC precursor ***pre-CAAC*** was donated from Rhodia, Marseille in France. Bis(dialkylamino)cyclopropenylidene precursors ***pre-BAC*–1**,[8] **2**,[71] and **3** were prepared according to literature methods with slight modifications. Imines **1a, j, l, s, t, u**,[54] **1b**,[35] **1c-e, h, k, b'**,[36] **1f, p**,[53] **1g**,[134] **1m, q**,[135] **1n–o**,[137] **1r**,[138] **1v**,[139] **1w**, **x**, **y**,[140] **1z**, **a'**,[141] are literature-known and were prepared accordingly. Imine **1h** was unknown and prepared according to literature method.[54] Michael acceptors ***MA*–1** (98%, Aldrich), ***MA*–2** (99%, Aldrich), ***MA*–3** (98%, Aldrich), ***MA*–4** (98%, Aldrich), ***MA*–5** (98%, Aldrich), ***MA*–6** (98%, Aldrich), ***MA*–7** (98%, Aldrich), ***MA*–9** (99%, Aldrich),

***MA*–10** (99%, Aldrich), ***MA*–11** (99%, Aldrich), ***MA*–15** (99%, Aldrich) and ***MA*–16** (90%, Aldrich) were purchased and distilled before use, and stored over molecular sieves (4 Å) in a nitrogen glove box. The obtained analytical data were in full agreement with the reported data. Unless otherwise stated, all reagents purchased from commercial suppliers were used directly without further purification. THF, toluene, and diethyl ether were distilled over sodium–benzophenone and stored over molecular sieves (4 Å) in a nitrogen glove box. All other solvents –including dioxane, DME, DCM, DCE, and MeCN– were used non-distilled, but stored over molecular sieves (4 Å) in a nitrogen glove box. Solvent dryness was confirmed using a Karl–Fischer apparatus.

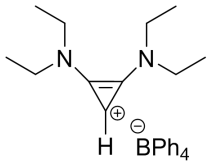
All catalytic reactions were carried out in in oven-dried glassware (typically sealed screw-caped test tubes) under an inert atmosphere. Conventional stirring and heating was carried out using a magnetic stirring bar and a hot plate magnetic stirrer (sand bath).

5.2 ORGANOCATALYSIS WITH AN UNUSUAL CARBENE

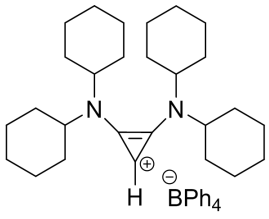
5.2.1 Preparation of Bis(dialkylpropylamino)cyclopropenium precursors



***pre-BAC*–1**



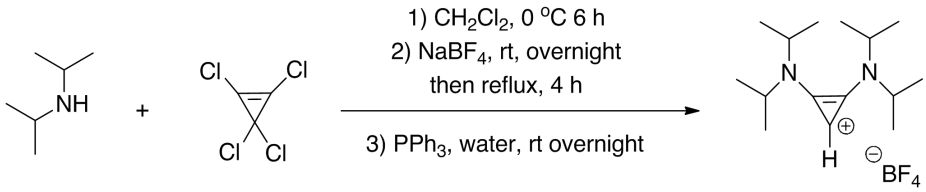
***pre-BAC*–2**



***pre-BAC*–3**

Various bis(dialkylamino)cyclopropenium salts were synthesized according to previously reported procedures. [8,71]

Bis(diisopropylamino)cyclopropenium tetrafluoroborate (*pre-BAC*–1)



10.6 g, 90% y

The compound was prepared according to Bertrand's reported literature procedure.[8] Diisopropyl amine (11.1 g, 110 mmol, 5.00 equiv) was added drop-wise to a stirred solution of tetrachlorocyclopropene (3.87 g, 22.0 mmol, 1.00 equiv) in CH_2Cl_2 (150 mL) at 0 °C under a nitrogen atmosphere. After 6 hours at 0 °C, the solution was warmed to room temperature and sodium tetrafluoroborate (7.50 g, 22.0 mmol, 1.00 equiv) was added. The suspension was stirred overnight, and then refluxed for 4 hours. After cooling to room temperature were added successively triphenyl phosphine (5.71 g, 22.0 mmol, 1.00 equiv) and water (100 mL), and the mixture was stirred overnight (open air). The organic layer was washed with water (3 x 250 mL), dried (MgSO4), and concentrated *in vacuo*. After washing with pentane (100 mL), and drying *in vacuo*, the cyclopropenium salt was obtained as a pale-yellow solid. Recrystallization from CH_2Cl_2/Et_2O at –20 °C afforded the final product as yellow needle-like crystals.

Yellow needle-like crystals (mp 132–134 °C).
Yield: 10.6 g (90%).

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.46 (s, 1H), 4.05 (sept, *J* = 11.3 Hz, 2H), 3.86 (sept, *J* = 11.3 Hz, 2H), 1.41 (d, *J* = 11.3 Hz, 12H), 1.38 (d, *J* = 11.3 Hz, 12H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 133.8 (2C), 99.3, 56.9 (2C), 49.2 (2C), 20.8 (4C), 20.7 (4C) ppm.

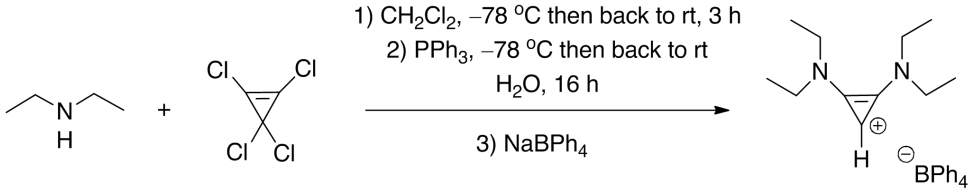
^{11}B NMR ($CDCl_3$, 128 MHz): δ = –1.70 ppm.

^{19}F NMR ($CDCl_3$, 128 MHz): δ = –152.3 ~ –152.2 (m) ppm.

IR (CH_2Cl_2): ν = 3122, 2983, 2268, 1880, 1566, 1055, 1033, 912, 727 cm^{-1}.

HRMS (ESI+): calculated for $C_{15}H_{29}N_2^+ = [M]^+$: m/z = 237.2319, found: m/z = 237.2325.

Bis(diethylamino)cyclopropenium tetraphenylborate (*pre-BAC*–2)



4.3 g, 92% y

The compound was prepared according to reported literature procedures.[71] Diethyl amine (4.70 mL, 45.0 mmol, 4.50 equiv) was added dropwise to a stirred solution of tetrachlorocyclopropene (1.38 mL, 12.0 mmol, 1.00 equiv) in CH_2Cl_2 (200 mL) at –78 °C under a nitrogen atmosphere. The reaction mixture was warmed to room temperature over 3 hours, and then cooled to –78 °C. Triphenyl phosphine (2.96 g, 12.0 mmol, 1.00 equiv) was then quickly added and the mixture was warmed to room temperature. At that stage, distilled water (40 mL) was added and the two-phase mixture was stirred vigorously for 16 hours before adding sodium tetraphenylborate (3.86 g, 12.0 mmol, 1.00 equiv). The organic layer was successively washed with aqueous HCl (0.5 M; 15 mL), aqueous $NaHCO_3$ (saturated; 15 mL), and water (10 mL), then dried over Na_2SO_4 and concentrated *in vacuo* to provide the crude as a light yellow oil (4.50 g, 96% yield). Recrystallization from hot MeOH afforded the final product. *The obtained analytical data fit accurately with the reported data.*[71]

White wedge-shaped crystals

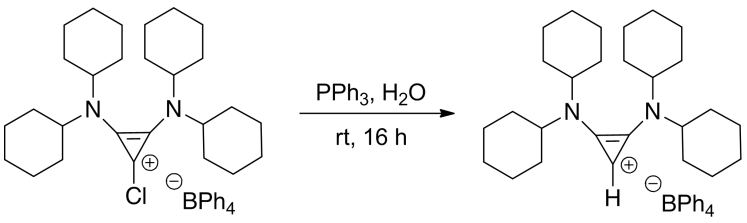
Mp. 132–134 °C (132–133 °C).[71]

Yield: 4.50 g (96%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.51 (br s, 8H), 7.03 (t, *J* = 7.1 Hz, 8H), 6.86 (t, *J* = 7.1 Hz, 4H), 4.46 (br s, 1H), 3.20 (q, *J* = 7.5 Hz, 4H), 3.10 (q, *J* = 7.5 Hz, 4H), 1.21 (t, *J* = 7.5 Hz, 6H), 1.11 (t, *J* = 7.5 Hz, 6H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.4 (q, *J* = 49.0 Hz, 4C), 136.2 (4C), 135.4 (2C), 125.9 (8C), 122.0 (8C), 98.2, 48.1 (2C), 46.9 (2C), 14.2 (2C), 12.9 (2C) ppm.

Bis(dicyclohexylamino)cyclopropenium tetrafluoroborate (*pre-BAC*–3)



810 mg, 85% y

The compound was prepared according to a modified literature procedure.[71] Dicyclohexylamine (5.14 mL, 45.0 mmol, 4.50 equiv) was added drop-wise to a stirred solution of tetrachlorocyclopropene (1.38 mL, 12.0 mmol, 1.00 equiv) in CH_2Cl_2 (200 mL) at –78 °C under a nitrogen atmosphere. The reaction mixture was warmed to room temperature over 3 hours, and then distilled water (40 mL) was added and the two-phase mixture was stirred vigorously for 16 hours before adding sodium tetraphenylborate (3.86 g, 12.0 mmol, 1.00 equiv). The organic layer was successively washed with aqueous HCl (0.5 M; 15 mL), aqueous $NaHCO_3$ (saturated; 15 mL), and water (10 mL), then dried over Na_2SO_4 and concentrated *in vacuo* to provide the crude as a light-yellow solid. Recrystallization from hot MeOH afforded the final product as a colorless solid (mp 132–133 °C). The chlorocyclopropenium salt (1.00 g, 1.30 mmol, 1.00 equiv) was dissolved in DCM (50 mL) and cooled to –78 °C. Triphenyl phosphine (0.35 g, 1.30 mmol, 1.00 equiv) was then quickly added and the mixture was warmed to room temperature. At that stage, distilled water (10 mL) was added and the two-phase mixture was stirred vigorously for 16 hours. The organic layer was successively washed with aqueous HCl (0.5 M; 20.0 mL), aqueous $NaHCO_3$ (saturated; 20.0 mL), and water (15.0 mL), then dried over Na_2SO_4 and concentrated *in vacuo* to obtain the crude. Recrystallization from DCM/Et_2O afforded the final product.

Light yellow star-like crystals (mp 152–153 °C).
Yield: 0.81 g (85%)

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.57 (br s, 8H), 7.09 (t, *J* = 8.5 Hz, 8H), 6.63 (t, *J* = 8.5 Hz, 4H), 4.61 (br s, 1H), 3.39 (q, *J* = 7.5 Hz, 2H), 3.36 (q, *J* = 7.5 Hz, 2H), 1.92-1.89 (m, 15H), 1.77-1.75 (m, 2H), 1.53-1.52 (m, 15H), 1.38-1.35 (m, 8H) ppm.

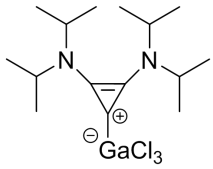
^{13}C NMR ($CDCl_3$, 125 MHz): δ = 167.5 (q, *J* = 44.3 Hz, 4C), 138.9 (4C), 138.1 (2C), 127.5 (8C), 122.5 (8C), 99.2, 57.3 (4C), 31.2 (4C), 25.9 (8C), 25.4 (8C) ppm.

^{11}B NMR ($CDCl_3$, 160 MHz): δ = –6.14 ppm.

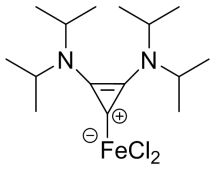
IR (CH_2Cl_2): ν = 3110, 3045, 2984, 1620, 1593, 1567 cm^{-1}.

HRMS (ESI+): calculated for $C_{27}H_{45}N_2^+ = [M]^+$: m/z = 397.6578, found: m/z = 397.6581.

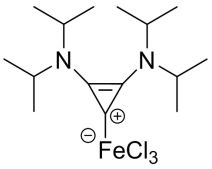
5.2.2 Preparation of Novel BAC–Metal Complexes



1–26



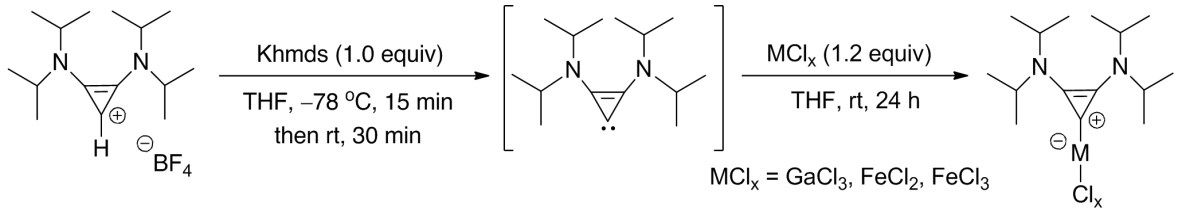
1–27



1–28

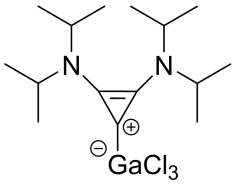
Bis(diisopropylamino)cyclopropenylidene–metal complexes were synthesized according to previously reported procedures.[3,8,17]

General Procedure A **[Preparation of BAC-Metal Complexes]**



To an oven-dried 5 mL test tube with a magnetic stirring bar in a nitrogen glove box were added ***pre-BAC*–1** (16.0 mg, 0.05 mmol, 1.00 equiv) and THF (450 μL). After stirring the reaction mixture at –78 °C for 15 minutes, KHMDS (1.0M in THF; 50 μL, 0.05 mmol, 1.00 equiv) was added drop-wise to the test tube. The reaction mixture was kept at –78 °C for another 15 minutes before warming to room temperature. After stirring at room temperature for 30 minutes, the reaction mixture was introduced to the glove box, where the corresponding metal chloride salt (0.06 mmol, 1.2 equiv) was added in one portion. The reaction mixture was stirred at room temperature overnight. The solvent was then evaporated and the residue was washed with methanol (2 mL). The corresponding complex was obtained after filtration and dried *in vacuo*.

[Bis(diisopropylamino)cyclopropenium]gallium(III) Chloride (1–26)



1–26

Prepared from ***pre-BAC*–1** (16.0 mg, 0.05 mmol, 1.00 equiv) and $GaCl_3$ (10.6 mg, 0.06 mmol, 1.20 equiv) according to *General Procedure A*. **1–26** was washed with methanol (2 mL).

Light yellow solid (mp 220–223 °C).

Yield: 20.0 mg (96%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 4.16 (sept, *J* = 6.7 Hz, 2H), 4.07 (sept, *J* = 6.7 Hz, 2H), 1.40 (d, *J* = 7.8 Hz, 12H), 1.36 (d, *J* = 7.8 Hz, 12H) ppm.

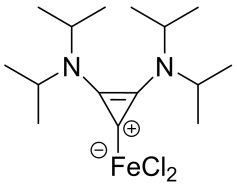
^{13}C NMR ($CDCl_3$, 125 MHz): δ = 143.2 (2C), 140.8, 53.1 (2C), 51.4 (2C), 21.6 (4C), 20.9 (4C) ppm.

^{71}Ga NMR ($CDCl_3$, 244 MHz): δ = 249.8 ppm.

IR (CH_2Cl_2): ν = 2980, 2937, 2877, 1847, 1523, 1454, 1375, 1340, 1151, 904, 727, 650 cm^{-1}.

HRMS (ESI+): calculated for $C_{15}H_{28}Cl_3GaNaN_2$ = $[M+Na]^+$: m/z = 434.6871, found: m/z = 434.6876.

[Bis(diisopropylamino)cyclopropenium]iron(II) Chloride (1–27)



1–27

Prepared from ***pre-BAC*–1** (16.0 mg, 0.05 mmol, 1.00 equiv) and $FeCl_2$ (9.70 mg, 0.06 mmol, 1.20 equiv) according to *General Procedure A*. **1–27** was washed with methanol (2 mL).

Light purple solid (mp 110–113 °C).

Yield: 15.2 mg (80%).

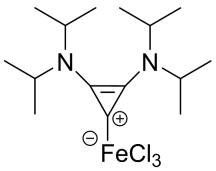
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 4.08 (sept, *J* = 7.2 Hz, 2H), 4.00 (sept, *J* = 7.2 Hz, 2H), 1.45 (d, *J* = 7.8 Hz, 12H), 1.42 (d, *J* = 7.8 Hz, 12H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 149.2 (2C), 133.8, 56.2 (2C), 49.7 (2C), 21.1 (4C), 21.0 (4C) ppm.

IR (CH_2Cl_2): ν = 3120, 2981, 2933, 2880, 2268, 1880, 1566, 1348, 1051, 1033, 908, 727, 648 cm^{-1}.

HRMS (ESI+): calculated for $C_{15}H_{28}Cl_2FeNaN_2$ = $[M+Na]^+$: m/z = 385.3203, found: m/z = 385.3210.

[Bis(diisopropylamino)cyclopropenium]iron(III) Chloride (1–28)



1–28

Prepared from ***pre-BAC*–1** (16.0 mg, 0.05 mmol, 1.00 equiv) and $FeCl_3$ (9.80 mg, 0.06 mmol, 1.20 equiv) according to *General Procedure A*. **1–28** was washed with methanol (2 mL).

Brown solid (mp 116–120 °C).

Yield: 19.0 mg (86%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 4.06 (sept, *J* = 7.2 Hz, 2H), 3.98 (sept, *J* = 7.2 Hz, 2H), 1.33 (d, *J* = 8.0 Hz, 12H), 1.29 (d, *J* = 8.0 Hz, 12H) ppm.

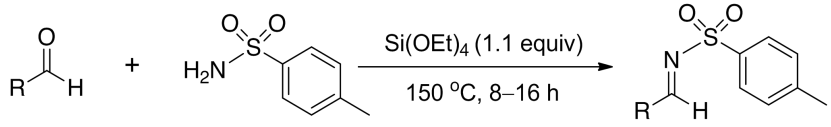
^{13}C NMR ($CDCl_3$, 125 MHz): δ = 149.9 (2C), 143.6, 57.9 (2C), 51.4 (2C), 21.9 (4C), 21.3 (4C) ppm.

IR (CH_2Cl_2): ν = 3128, 2939, 2880, 1600, 1577, 1541, 1394, 1347, 1215, 1136, 1014, 904, 848, 727, 650 cm^{-1}.

HRMS (ESI+): calculated for $C_{15}H_{28}Cl_3FeNaN_2$ = $[M+Na]^+$: m/z = 420.5323, found: m/z = 420.5319.

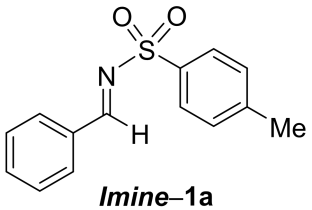
5.2.3 Preparation of Imines

General Procedure B **[Preparation of Imines]**



To an oven-dried 50 mL round-bottom flask with a magnetic stirring bar under an argon atmosphere were added *p*-toluenesulfonamide (1.00 equiv), tetraethyl orthosilicate (1.10 equiv), and the respective aldehyde (1.00 equiv). The flask was connected to a short distillation head (approximately 3–4 cm long) and a receptor flask. The reaction mixture was heated at 140–160 °C for 8–16 hours; the by-product, ethanol, was collected in the receptor flask. After confirming the end-point of the reaction by ^{1}H NMR spectroscopic analysis, the reaction mixture was cooled to room temperature, and washed with hexane (10 mL). The mixture was filtered, and volatiles were removed *in vacuo* to give the crude imine, which was recrystallized from ethyl acetate to yield the corresponding pure imine, which was powdered and dried over 4 Å MS in DCM prior to use in catalysis.

4-Methyl-*N*-(phenylmethylene)benzenesulfonamide (*Imine*–1a)



***Imine*–1a**

Prepared from benzaldehyde (6.10 g, 55.0 mmol, 1.10 equiv), tosyl amide (8.60 g, 50.0 mmol, 1.00 equiv), and $Si(OEt)_4$ (11.5 g, 55.0 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–1a** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [54]

Colorless needle–like crystals.

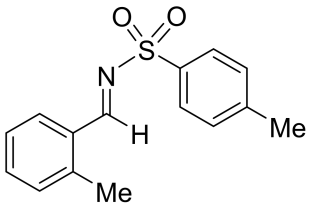
Mp. 109−111 °C (110−111 °C) [54]

Yield: 12.7 g (98%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.06 (s, 1H), 7.96–7.91 (m, 4H), 7.62–7.53 (m, 1H), 7.51–7.46 (m, 2H), 7.37 (d, *J* = 8.1 Hz, 2H), 2.46 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 170.1, 144.6, 135.2, 134.9, 132.1, 131.3 (2C), 129.8 (2C), 129.2 (2C), 128.1 (2C), 21.7 ppm.

4-Methyl-*N*-[(2-tolyl)methylene]benzenesulfonamide (*Imine*–<u>1b</u>)



***Imine*–1b**

Prepared from 2-methylbenzaldehyde (2.48 g, 17.7 mmol, 1.10 equiv), tosyl amide (3.10 g, 16.1 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.70 g, 17.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 12 h. ***Imine*–1b** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [35]

Colorless star–like crystals.

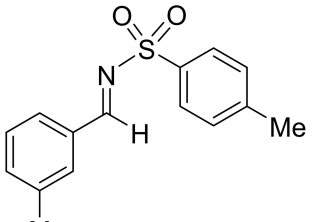
Mp. 89−90 °C (88−90 °C) [35]

Yield: 4.21 g (96%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.37 (s, 1H), 8.06–8.04 (m, 1H), 7.92 (d, *J* = 7.6 Hz, 2H), 7.51–7.47 (m, 1H), 7.37 (d, *J* = 7.6 Hz, 2H), 7.31–7.28 (m, 2H), 2.64 (s, 3H), 2.47 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 168.7, 144.5, 142.3, 135.5, 134.6, 131.6, 130.7, 130.5, 129.8 (2C), 128.0 (2C), 126.6, 21.7, 19.7 ppm.

4-Methyl-*N*-[(3-tolyl)methylene]benzenesulfonamide (*Imine*–<u>1c</u>)



***Imine*–1c**

Prepared from 3-methylbenzaldehyde (2.48 g, 17.7 mmol, 1.10 equiv), tosyl amide (3.10 g, 16.1 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.70 g, 17.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 12 h. ***Imine*–1c** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [36]

Colorless star–like crystals.

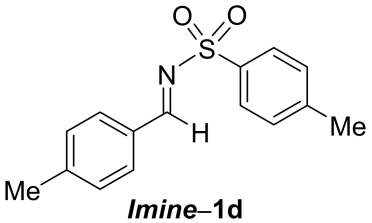
Mp. 88−90 °C (88−89 °C) [36]

Yield: 4.30 g (98%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.00 (s, 1H), 7.89 (d, *J* = 8.0 Hz, 2H), 7.76–7.75 (m, 1H), 7.67 (d, *J* = 8.0 Hz, 2H), 7.40–7.31 (m, 3H), 2.43 (s, 3H), 2.39 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 170.4, 144.5, 139.1, 135.9, 135.3, 132.4, 131.4, 129.8 (2C), 128.8, 128.7, 128.1 (2C), 21.7, 21.2 ppm.

4-Methyl-*N*-[(4-tolyl)methylene]benzenesulfonamide (*Imine*–1d)



***Imine*–1d**

Prepared from 4-methylbenzaldehyde (2.48 g, 17.7 mmol, 1.10 equiv), tosyl amide (3.10 g, 16.1 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.70 g, 17.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 12 h. ***Imine*–1d** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [36]

Colorless star–like crystals.

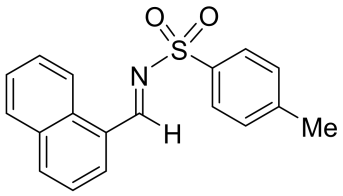
Mp. 111−113 °C (110−112 °C) [36]

Yield: 4.10 g (93%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.99 (s, 1H), 7.88 (d, *J* = 8.0 Hz, 2H), 7.77 (d, *J* = 8.4 Hz, 2H), 7.36 (d, *J* = 8.0 Hz, 2H), 7.29 (d, *J* = 8.4 Hz, 2H), 2.43 (s, 3H), 2.43 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 169.9, 146.4, 144.4, 135.5, 131.4, 129.9 (2C), 129.4 (2C), 129.0 (2C), 128.1 (2C), 22.0, 21.7 ppm.

4-Methyl-*N*-[(naphthalen-1-yl)methylene]benzenesulfonamide (*Imine*–1e)



***Imine*–1e**

Prepared from 1-naphthaldehyde (2.62 g, 17.9 mmol, 1.10 equiv), tosyl amide (3.20 g, 16.4 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.73 g, 17.9 mmol, 1.10 equiv) according to *General Procedure B* at 180 °C for 12 h. ***Imine*–1e** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [36]

Brown feather–like crystals.

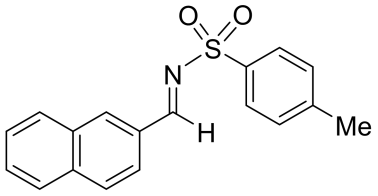
Mp. 136−139 °C (135−140 °C) [36]

Yield: 4.30 g (94%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.62 (s, 1H), 8.99 (d, *J* = 10.8 Hz, 1H), 8.15 (d, *J* = 9.0 Hz, 1H), 8.07 (d, *J* = 9.0 Hz, 1H), 7.95 (d, *J* = 10.8 Hz, 2H), 7.90 (d, *J* = 10.8 Hz, 1H), 7.68–7.64 (m, 1H), 7.59–7.54 (m, 2H), 7.34 (d, *J* = 10.8 Hz, 2H), 2.44 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 169.8, 144.5, 136.1, 135.8, 135.1, 133.8, 131.9, 129.8 (2C), 129.1, 128.1 (2C), 127.9, 127.8, 126.9, 125.1, 124.3, 21.7 ppm.

4-Methyl-*N*-[(naphthalen-2-yl)methylene]benzenesulfonamide (*Imine*–1f)



***Imine*–1f**

Prepared from 2-naphthaldehyde (2.62 g, 17.9 mmol, 1.10 equiv), tosyl amide (3.20 g, 16.4 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.73 g, 17.9 mmol, 1.10 equiv) according to *General Procedure B* at 180 °C for 12 h. ***Imine*–1f** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [53]

Brown wedge−shaped crystals.

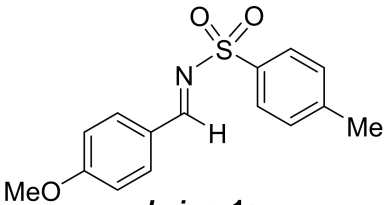
Mp. 122−125 °C (124−126 °C) [53]

Yield: 4.28 g (94%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.18 (s, 1H), 8.34–8.32 (m, 1H), 7.95 (d, *J* = 8.3 Hz, 1H), 7.93–7.88 (m, 5H), 7.59 (d, *J* = 7.6 Hz, 2H), 7.37 (d, *J* = 7.6 Hz, 2H), 2.44 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 170.0, 144.6, 136.6, 136.1, 135.2, 132.7, 131.8, 130.0, 129.8 (2C), 129.4, 129.1, 128.1 (2C), 127.8, 127.3, 124.2, 21.7 ppm.

4-Methyl-*N*-(4-methoxybenzylidene)benzenesulfonamide (*Imine*–1g)



***Imine*–1g**

Prepared from 4-methoxy benzaldehyde (2.59 g, 19.0 mmol, 1.10 equiv), tosyl amide (3.00 g, 17.3 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.96 g, 19.0 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–1g** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [134]

Colorless needle–like crystals.

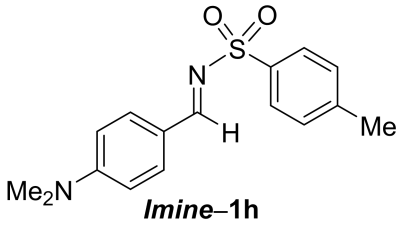
Mp. 125−128 °C (126−127 °C) [134]

Yield: 4.40 g (95%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.97 (s, 1H), 7.92–7.89 (m, 4H), 7.36 (d, *J* = 8.4 Hz, 2H), 6.99 (d, *J* = 8.4 Hz, 2H), 3.91 (s, 3H), 2.46 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 169.2, 165.3, 144.2, 135.8, 133.7 (2C), 129.7 (2C), 127.9 (2C), 125.3, 114.7 (2C), 55.7, 21.6 ppm.

4-Methyl-*N*-[(4-dimethylamino)benzylidene]benzenesulfonamide (*Imine*–1h)



***Imine*–1h**

Prepared from 4-dimethylamino benzaldehyde (2.71 g, 18.1 mmol, 1.10 equiv), tosyl amide (2.80 g, 16.7 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.77 g, 18.1 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–1h** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data*. [36]

Yellow hexagon−shaped crystals.

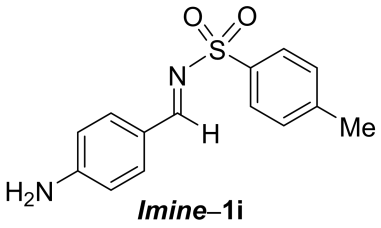
Mp. 172−177 °C (173−175 °C) [36]

Yield: 4.00 g (92%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.82 (s, 1H), 7.86 (d, *J* = 8.4 Hz, 2H), 7.77 (d, *J* = 9.0 Hz, 2H), 7.29 (d, *J* = 8.4 Hz, 2H), 6.65 (d, *J* = 9.0 Hz, 2H), 3.09 (s, 6H), 2.41 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 169.0, 154.8, 143.5, 136.9, 133.9, 129.6 (2C) 129.5 (2C), 127.6 (2C), 119.9 (2C), 40.1 (2C), 21.6 ppm.

4-Methyl-*N*-[(4-amino)benzylidene]benzenesulfonamide (*Imine*–1i)



***Imine*–1i**

Prepared from 4-amino benzaldehyde (2.44 g, 20.0 mmol, 1.10 equiv), tosyl amide (3.10 g, 18.2 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.17 g, 20.0 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–1i** was recrystallized from EtOAc (10 mL).

Colorless oil.

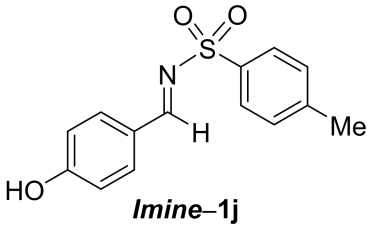
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.72 (s, 1H), 7.73 (d, *J* = 7.0 Hz, 2H), 7.49 (d, *J* = 7.6 Hz, 2H), 7.33 (d, *J* = 7.0 Hz, 2H), 7.19 (d, *J* = 7.6 Hz, 2H), 6.39 (br s, NH_2, 2H), 2.32 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 168.1, 149.1, 144.3, 138.2, 132.7, 130.1 (2C), 129.7 (2C), 127.2 (2C), 114.3 (2C), 21.6 ppm.

IR (CH_2Cl_2): ν = 3408, 2978, 2882, 1618, 1460, 1376, 1325, 1148, 856 cm^{-1}.

HRMS (ESI): calculated for $C_{14}H_{14}NaN_2O_2S = [M+Na]^+$: m/z = 297.0801, found: m/z = 297.0810.

4-Methyl-*N*-[(4-hydroxy)benzylidene]benzenesulfonamide (*Imine*–1j)



***Imine*–1j**

Prepared from 4-hydroxy benzaldehyde (2.42 g, 20.0 mmol, 1.10 equiv), tosyl amide (3.10 g, 18.2 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.17 g, 20.0 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–1j** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data*.[54]

Pink lens−shaped crystals.

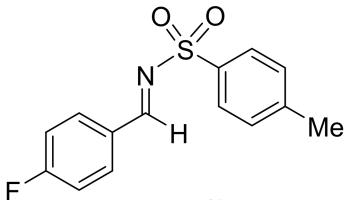
Mp. 110−113 °C (109−111 °C)[54]

Yield: 3.80 g (87%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.76 (s, 1H), 9.24 (br s, OH, 1H), 7.81 (d, *J* = 9.0 Hz, 2H), 7.76 (d, *J* = 6.0 Hz, 2H), 7.37 (d, *J* = 6.0 Hz, 2H), 7.03 (d, *J* = 9.0 Hz, 2H), 2.98 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.0, 157.8, 144.3, 138.2, 132.7, 129.7 (2C), 128.5 (2C), 127.3 (2C), 115.0 (2C), 21.3 ppm.

4-Methyl-*N*-[(4-fluoro)benzylidene]benzenesulfonamide (*Imine*–1k)



***Imine*–1k**

Prepared from 4-fluoro benzaldehyde (2.53 g, 20.4 mmol, 1.10 equiv), tosyl amide (3.50 g, 18.5 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.25 mL, 20.4 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–1k** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data*.[36]

Colorless feather−shaped crystals.

Mp. 111−113 °C (111−112 °C)[36]

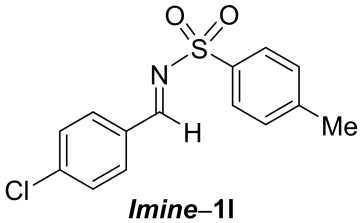
Yield: 4.80 g (96%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.00 (s, 1H), 7.97–7.95 (m, 2H), 7.88 (d, *J* = 8.1 Hz, 2H), 7.35 (d, *J* = 7.8 Hz, 2H), 7.18–7.16 (m, 2H), 2.44 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 168.5, 166.8 (d, *J* = 257.1 Hz), 144.7, 135.1, 133.8 (d, *J* = 9.7 Hz, 2C), 129.8 (2C), 128.6 (d, *J* = 2.6 Hz), 128.1 (2C), 116.6 (d, *J* = 22.2 Hz, 2C), 21.7 ppm.

^{19}F NMR ($CDCl_3$, 128 MHz): δ = – 101.2 ~ – 101.1 (m) ppm.

4-Methyl-*N*-[(4-chloro)benzylidene]benzenesulfonamide (*Imine*–1l)



***Imine*–1l**

Prepared from 4-chloro benzaldehyde (2.32 g, 19.7 mmol, 1.10 equiv), tosyl amide (3.00 g, 17.9 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.11 g, 19.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–1l** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [54]

Colorless feather−shaped crystals.

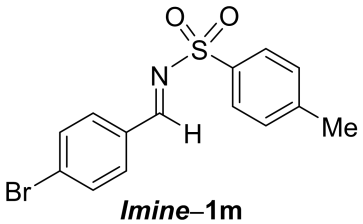
Mp. 173−175 °C (174−175 °C) [54]

Yield: 4.50 g (92%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.99 (s, 1H), 7.89 (d, *J* = 8.8 Hz, 2H), 7.86 (d, *J* = 8.0 Hz, 2H), 7.46 (d, *J* = 8.8 Hz, 2H), 7.35 (d, *J* = 8.0 Hz, 2H), 2.44 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 168.6, 144.7, 141.4, 134.9, 132.4 (2C), 130.9, 129.8 (2C), 129.6 (2C), 128.2 (2C), 22.2 ppm.

4-Methyl-*N*-[(4-bromo)benzylidene]benzenesulfonamide (*Imine*–1m)



***Imine*–1m**

Prepared from 4-bromo benzaldehyde (1.30 g, 6.50 mmol, 1.10 equiv), tosyl amide (1.30 g, 5.90 mmol, 1.00 equiv), and $Si(OEt)_4$ (1.36 g, 6.50 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–1m** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [135]

Colorless feather−shaped crystals.

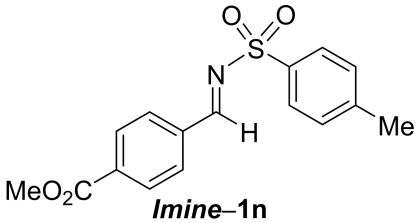
Mp. 196−197 °C (196−197 °C) [135]

Yield: 2.00 g (99%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.98 (s, 1H), 7.89 (d, *J* = 8.0 Hz, 2H), 7.78 (d, *J* = 7.6 Hz, 2H), 7.64 (d, *J* = 8.0 Hz, 2H), 7.35 (d, *J* = 7.6 Hz, 2H), 2.44 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 168.8, 144.8, 134.9, 132.6 (2C), 132.4 (2C), 130.0, 131.9, 129.9 (2C), 128.2 (2C), 21.7 ppm.

4-Methyl-*N*-[(4-methoxycarbonyl)benzylidene]benzenesulfonamide (*Imine*–1n)



***Imine*–1n**

Prepared from methyl 4-formylbenzoate (1.11 g, 6.80 mmol, 1.10 equiv), tosyl amide (1.60 g, 6.20 mmol, 1.00 equiv), and $Si(OEt)_4$ (1.42 g, 6.80 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–1n** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [137]

Colorless needle−like crystals.

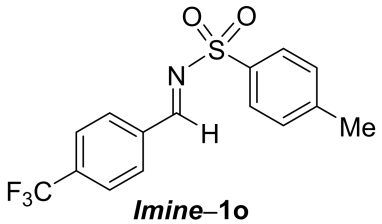
Mp. 184−185 °C (183−185 °C) [137]

Yield: 1.70 g (94%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.07 (s, 1H), 8.13 (d, *J* = 8.4 Hz, 2H), 7.99 (d, *J* = 8.5 Hz, 2H), 7.89 (d, *J* = 8.4 Hz, 2H), 7.36 (d, *J* = 8.5 Hz, 2H), 3.95 (s, 3H), 2.45 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 168.8, 165.9, 144.9, 135.9, 135.3, 134.7, 131.0 (2C), 130.1 (2C), 129.9 (2C), 128.2 (2C), 52.6, 21.7 ppm.

4-Methyl-*N*-[(4-trifluoromethyl)benzylidene]benzenesulfonamide (*Imine*–1o)



***Imine*–1o**

Prepared from 4-trifluoromethyl benzaldehyde (0.99 g, 5.70 mmol, 1.10 equiv), tosyl amide (1.50 g, 5.20 mmol, 1.00 equiv), and $Si(OEt)_4$ (1.19 g, 5.70 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–1o** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [137]

Colorless needle−like crystals.

Mp. 158−160 °C (159−160 °C) [137]

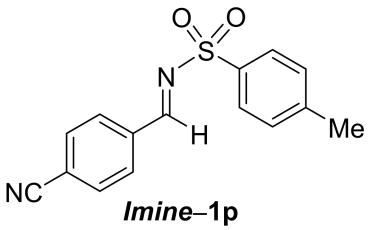
Yield: 1.81 g (90%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.08 (s, 1H), 8.05 (d, *J* = 8.4 Hz, 2H), 7.90 (d, *J* = 8.4 Hz, 2H), 7.76 (d, *J* = 8.1 Hz, 2H), 7.39 (d, *J* = 8.1 Hz, 2H), 2.45 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 168.3, 145.0, 135.7 (q, *J* = 257.0 Hz), 134.5 (2C), 131.4 (2C), 129.9 (q, *J* = 72.9 Hz), 128.3 (q, *J* = 23.4 Hz, 2C), 126.1, 126.0 (q, *J* = 7.6 Hz, 2C), 123.4 (q, *J* = 3.8 Hz), 21.7 ppm.

^{19}F NMR ($CDCl_3$, 128 MHz): δ = – 63.3 (s) ppm**.**

4-Methyl-*N*-[(4-cyano)benzylidene]benzenesulfonamide (*Imine*–1p)



***Imine*–1p**

Prepared from 4-cyano benzaldehyde (2.16 g, 18.2 mmol, 1.10 equiv), tosyl amide (2.90 g, 16.5 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.79 g, 18.2 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–1p** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [53]

Colorless hexagon−shaped crystals.

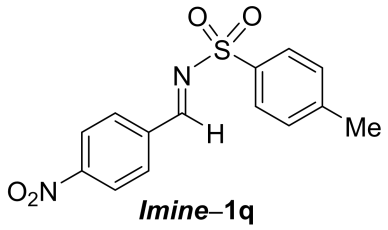
Mp. 172−173 °C (171−173 °C) [53]

Yield: 3.80 g (87%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.05 (s, 1H), 8.03 (d, *J* = 8.4 Hz, 2H), 7.89 (d, *J* = 8.1 Hz, 2H), 7.78 (d, *J* = 8.1 Hz, 2H), 7.37 (d, *J* = 8.4 Hz, 2H), 2.45 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 167.8, 145.3, 135.9, 134.0, 132.7 (2C), 131.3 (2C), 129.9 (2C), 128.3 (2C), 117.6, 117.5, 21.6 ppm.

4-Methyl-*N*-[(4-nitro)benzylidene]benzenesulfonamide (*Imine*–1q)



***Imine*–1q**

Prepared from 4-nitro benzaldehyde (2.76 g, 18.1 mmol, 1.10 equiv), tosyl amide (2.80 g, 16.5 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.77 g, 18.1 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 10 h. ***Imine*–1q** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [135]

Colorless hexagon−shaped crystals.

Mp. 211−213 °C (211−212 °C) [135]

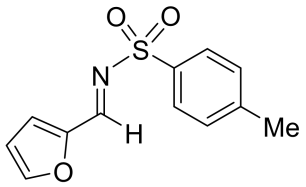
Yield: 4.30 g (92%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.10 (s, 1H), 8.33 (d, *J* = 9.0 Hz, 2H), 8.11 (d, *J* = 8.7 Hz, 2H), 7.91 (d, *J* = 8.7 Hz, 2H), 7.38 (d, *J* = 9.0 Hz, 2H), 2.46 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 167.3, 151.2, 145.3, 137.4, 134.2, 131.8 (2C), 130.0 (2C), 128.4

(2C), 124.2 (2C), 21.7 ppm.

4-Methyl-*N*-(2-furanylmethylene)benzenesulfonamide (*Imine*–1r)



***Imine*–1r**

Prepared from 2-furaldehyde (2.10 g, 20.8 mmol, 1.10 equiv), tosyl amide (3.50 g, 18.9 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.34 g, 20.8 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 10 h. ***Imine*–1r** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [138]

Grey hexagon−shaped crystals.

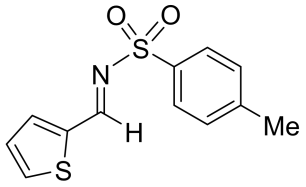
Mp. 99−101 °C (99−102 °C) [138]

Yield: 4.60 g (94%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.84 (s, 1H), 7.89 (d, *J* = 8.4 Hz, 2H), 7.76–7.72 (m, 2H), 7.36 (d, *J* = 8.4 Hz, 2H), 6.66–6.64 (m, 1H), 2.45 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 155.6, 149.7, 149.1, 144.5, 135.2, 129.8 (2C), 128.0 (2C), 124.6, 113.7, 21.6 ppm.

4-Methyl-*N*-(2-thienylmethylene)benzenesulfonamide (*Imine*–1s)



***Imine*–1s**

Prepared from 2-thienyl aldehyde (2.32 g, 20.7 mmol, 1.10 equiv), tosyl amide (3.40 g, 18.8 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.34 g, 20.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 10 h. ***Imine*–1s** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [54]

Brown hexagon−shaped crystals.

Mp. 99−102 °C (98−103 °C) [54]

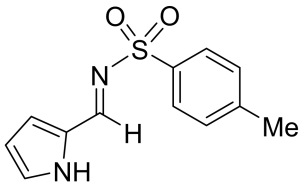
Yield: 4.30 g (94%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.11 (s, 1H), 7.86 (d, *J* = 8.4 Hz, 2H), 7.77 (d, *J* = 8.4 Hz, 2H), 7.33–7.30 (m, 2H), 7.20 (t, *J* = 4.4 Hz, 1H), 2.43 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 162.2, 144.4, 139.0, 138.1, 136.6, 135.3, 129.7 (2C), 128.8, 127.9

(2C), 21.6 ppm.

4-Methyl-*N*-(1*H*-pyrrol-2-ylmethylene)benzenesulfonamide (*Imine*–1t)



***Imine*–1t**

Prepared from 2-pyrrolyl aldehyde (2.09 g, 22.1 mmol, 1.10 equiv), tosyl amide (3.70 g, 20.1 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.63 g, 22.1 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 10 h. ***Imine*–1t** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [54]

Brown wedge−shaped crystals.

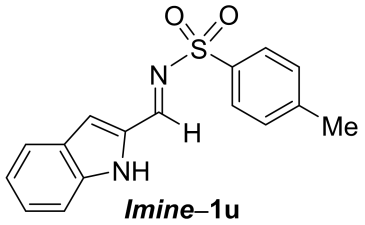
Mp. 94−95 °C (93−95 °C) [54]

Yield: 3.83 g (85%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.65 (s, 1H), 8.15 (d, *J* = 6.0 Hz, 1H), 7.75 (d, *J* = 9.0 Hz, 2H), 7.52 (d, *J* = 6.0 Hz, 1H), 7.33 (d, *J* = 9.0 Hz, 2H), 6.37–6.36 (m, 1H), 4.82 (br s, NH, 1H), 2.45 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 166.4, 144.3, 138.2, 137.4, 129.7 (2C), 127.6 (2C), 123.5, 111.9, 110.3, 21.3 ppm.

4-Methyl-*N*-(1*H*-indol-3-ylmethylene)benzenesulfonamide (*Imine*–1u)



***Imine*–1u**

Prepared from 3-indolyl aldehyde (2.63 g, 18.4 mmol, 1.00 equiv), tosyl amide (2.90 g, 16.8 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.85 g, 18.4 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 10 h. ***Imine*–1u** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [54]

Red needle−like crystals.

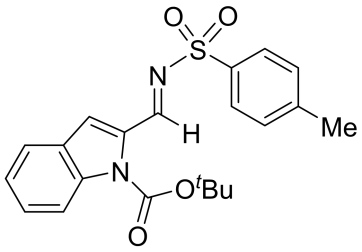
Mp. 131−132 °C (130−132 °C) [54]

Yield: 2.85 g (52%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.84 (s, 1H), 8.53 (s, 1H), 7.96 (d, *J* = 8.0, 1H), 7.75 (d, *J* = 7.9, 1H), 7.64 (d, *J* = 7.9, 2H), 7.31 (d, *J* = 7.9, 2H), 7.26 (dd, *J* = 7.9, 8.0, 1H), 7.17–7.15 (m, 1H), 4.77 (br s, NH, 1H), 2.46 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 243.4, 198.9, 185.2, 163.4, 146.6, 138.2, 135.1, 129.9 (2C), 126.7, 126.5 (2C), 124.5, 123.1, 111.4, 21.5 ppm.

4-Methyl-*N*-(1*H*-indol-1-carboxlic acid-3-ylmethylene)benzenesulfonamide (*Imine*–1v)



***Imine*–1v**

Prepared from 3-Boc-indolyl aldehyde (1.32 g, 5.50 mmol, 1.10 equiv), tosyl amide (1.40 g, 5.00 mmol, 1.00 equiv), and $Si(OEt)_4$ (1.15 g, 5.50 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 12 h. ***Imine*–1v** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data*.[139]

Yellow needle−like crystals.

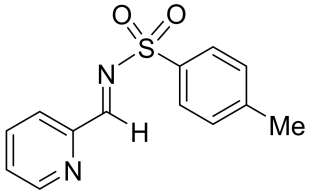
Mp. 139−141 °C (139−140 °C)[139]

Yield: 1.21 g (60%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.16 (s, 1H), 8.28 (s, 1H), 8.14 (d, *J* = 8.3 Hz, 2H), 7.90 (d, *J* = 8.3 Hz, 2H), 7.41–7.40 (m, 1H), 7.36–7.30 (m, 3H), 2.42 (s, 3H), 1.70 (s, 9H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 163.2, 152.6, 148.3, 144.0, 137.8, 136.2, 135.9, 129.6, 127.8 (2C), 126.2 (2C), 124.6, 122.7, 116.5, 115.1, 85.9, 27.9 (3C), 21.5 ppm.

4-Methyl-*N*-(2-pyridinylmethylene)benzenesulfonamide (*Imine*–1w)



***Imine*–1w**

Prepared from 2-pyridinecarbaldehyde (2.26 g, 21.1 mmol, 1.10 equiv), tosyl amide (3.30 g, 19.2 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.42 g, 21.1 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 12 h. ***Imine*–1w** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data*.[140]

Yellow needle−like crystals.

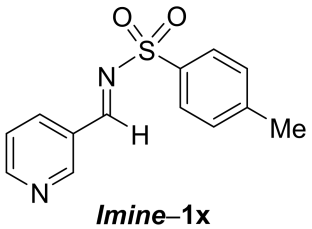
Mp. 120−122 °C (121−122 °C)[140]

Yield: 3.80 g (77%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.74 (s, 1H), 8.86 (d, *J* = 6.0 Hz, 1H), 8.30 (d, *J* = 9.0 Hz, 1H), 8.04 (dd, *J* = 6.0, 9.0 Hz, 1H), 7.85 (d, *J* = 9.0 Hz, 2H), 7.73 (d, *J* = 9.0 Hz, 2H), 7.32 (d, *J* = 6.0, 9.0 Hz, 1H), 2.33 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 152.8, 149.7, 146.6, 144.3, 138.2, 137.3, 129.3 (2C), 127.0 (2C), 126.3, 123.4, 21.3 ppm.

4-Methyl-*N*-(2-pyridinylmethylene)benzenesulfonamide (*Imine*–1x)



***Imine*–1x**

Prepared from 3-pyridinecarbaldehyde (2.26 g, 21.1 mmol, 1.10 equiv), tosyl amide (3.30 g, 19.2 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.42 g, 21.1 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 12 h. ***Imine*–1x** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [140]

Yellow needle−like crystals.

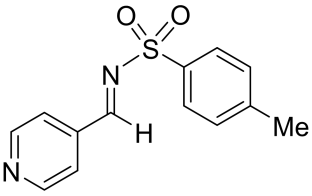
Mp. 129−130 °C (128−131 °C) [140]

Yield: 4.51 g (89%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.09 (s, 1H), 9.05 (s, 1H), 8.81 (d, *J* = 4.8 Hz, 1H), 8.27 (d, *J* = 7.8 Hz, 1H), 7.90 (d, *J* = 7.9 Hz, 2H), 7.45 (dd, *J* = 4.8, 7.8 Hz, 1H), 7.37 (d, *J* = 7.9 Hz, 2H), 2.45 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 167.6, 155.1, 152.9, 145.1, 136.9, 134.5, 129.5 (2C), 128.9, 128.3 (2C), 124.1, 21.7 ppm.

4-Methyl-*N*-(2-pyridinylmethylene)benzenesulfonamide (*Imine*–1y)



***Imine*–1y**

Prepared from 4-pyridinecarbaldehyde (2.26 g, 21.1 mmol, 1.10 equiv), tosyl amide (3.30 g, 19.2 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.42 g, 21.1 mmol, 1.10 equiv) according to *General Procedure B* at 180 °C for 12 h. ***Imine*–1y** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [140]

Yellow needle−like crystals.

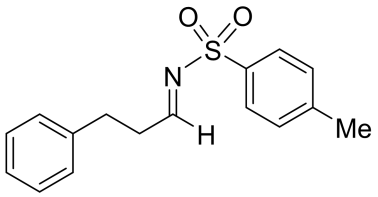
Mp. 138−140 °C (137−141 °C) [140]

Yield: 2.80 g (72%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.85 (s, 1H), 8.86 (d, *J* = 9.0 Hz, 1H), 8.65–8.60 (m, 2H), 8.17 (d, *J* = 9.0 Hz, 1H), 7.76 (d, *J* = 7.9 Hz, 2H), 7.32 (d, *J* = 7.9 Hz, 2H), 2.30 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.0, 150.4 (2C), 138.2, 134.1, 131.4, 129.2 (2C), 127.3 (2C), 121.4 (2C), 21.8 ppm.

4-Methyl-*N*-(3-phenylpropylidene)benzenesulfonamide (*Imine*–1z)



***Imine*–1z**

Prepared from 3-phenyl propionaldehyde (2.56 g, 19.1 mmol, 1.00 equiv), tosyl amide (3.00 g, 17.4 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.98 g, 19.1 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 12 h. ***Imine*–1z** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [141]

Colorless rose−like crystals.

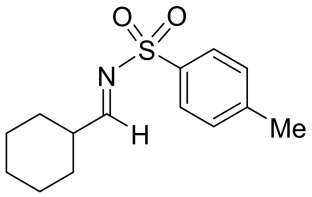
Mp. 123−126 °C (125−126 °C) [141].

Yield: 4.40 g (90%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.62 (t, *J* = 7.2 Hz, 1H), 7.70 (d, *J* = 8.0 Hz, 2H), 7.34 (d, *J* = 8.0 Hz, 2H), 7.29–7.25 (m, 3H), 7.16–7.14 (m, 2H), 3.05–3.03 (m, 2H), 2.81–2.78 (m, 2H), 2.34 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 146.6, 144.2, 138.2 (2C), 131.5, 129.3 (2C), 129.0 (2C), 128.3, 127.4 (2C), 126.8, 30.0, 29.1, 21.3 ppm.

4-Methyl-*N*-(cyclohexylmethylene)benzenesulfonamide (*Imine*–1a')



***Imine*–1a'**

Prepared from cyclohexanecarbaldehyde (2.32 g, 20.7 mmol, 1.10 equiv), tosyl amide (3.20 g, 18.9 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.31 g, 20.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 10 h. ***Imine*–1a'** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [140]

Colorless hexagon−shaped crystals.

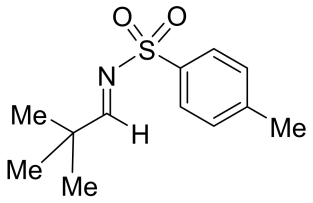
Mp. 80−82 °C (79−81 °C) [140].

Yield: 4.40 g (90%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.48 (d, *J* = 4.5 Hz, 1H), 7.80 (d, *J* = 8.3 Hz, 2H), 7.32 (d, *J* = 8.3 Hz, 2H), 2.44 (s, 3H), 1.85–1.65 (m, 6H), 1.36–1.12 (m, 5H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 181.0, 144.5, 134.9, 129.8 (2C), 128.1 (2C), 43.7, 28.4 (2C), 25.8 (2C), 25.1, 21.6 ppm.

4-Methyl-*N*-(2,2-dimethylpropylidene)benzenesulfonamide (*Imine*–1b')



***Imine*–1b'**

Prepared from pivaldehyde (1.97 g, 22.9 mmol, 1.10 equiv), tosyl amide (3.00 g, 20.9 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.77 g, 22.9 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 12 h. ***Imine*–1b'** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data.* [141]

Colorless needle−like crystals.

Mp. 67−68 °C (67−69 °C) [141].

Yield: 4.30 g (82%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.45 (s, 1H), 7.79–7.78 (m, 2H), 7.30–7.28 (m, 2H), 2.37 (s, 3H), 1.10 (s, 9H) ppm.

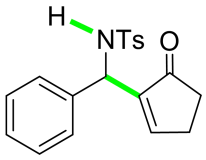
^{13}C NMR ($CDCl_3$, 125 MHz): δ = 169.8, 145.1, 129.6 (2C), 129.4 (2C), 127.8, 33.2, 27.8 (3C), 23.4 ppm.

5.2.4 BAC-catalysed aza-MBH Reactions – eletrophile(imine) test

General Procedure C **[imine scope]**

To an oven-dried test tube with a magnetic stirring bar in a nitrogen glovebox were added ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), the corresponding imine (0.22 mmol, 1.10 equiv), Michael acceptor ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv), THF (0.66 mL, 0.3 M), and DBU (1.50 mg, 10.0 μmol, 5.00 mol%). The reaction mixture was stirred at 30 °C for 24–48 h, at which point TLC and/or ^{1}H NMR analysis indicated complete consumption of Michael acceptor ***MA*–1**. Volatiles were removed *in vacuo*, and the residue was purified by flash column chromatography or PTLC on silica gel (eluent: EtOAc/PE = 1:2, or DCM/acetone = 100:1) to give the intended products.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(phenyl)methyl]benzenesulfonamide (1–33)[44, 142]



1–33

Prepared from ***Imine*–1a** (57.0 mg, 0.22 mmol, 1.10 equiv), and ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 30 h. **1–33** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2). *The obtained analytical data were in full agreement with the reported data.* [44, 142]

Colorless solid.

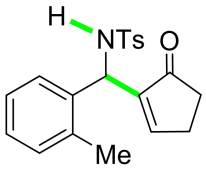
Mp. 110−112 °C (111−112 °C) [142]

Yield: 64.2 mg (93%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.61 (d, *J* = 8.3 Hz, 2H), 7.37 (t, *J* = 5.7 Hz, 1H), 7.21-7.16 (m, 7H), 6.12 (d, *J* = 8.4 Hz, 1H), 5.28 (d, *J* = 8.4 Hz, 1H), 2.49–2.14 (m, 4H), 2.38 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 160.6, 143.5, 143.2, 138.6, 137.4, 129.4 (2C), 128.6 (2C), 127.8, 127.4 (2C), 126.7 (2C), 55.2, 34.9, 26.7, 21.4 ppm.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(2-toyl)methyl]benzenesulfonamide (1–39a)



1–39a

Prepared from ***Imine*–1b** (60.4 mg, 0.22 mmol, 1.10 equiv), and ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 24 h. **1–39a** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Colorless solid (mp 156–157 °C).

Yield: 64.7 mg (91%).

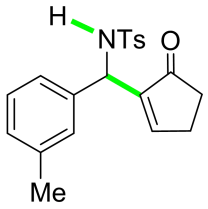
^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.60 (d, *J* = 8.4 Hz, 2H), 7.35 (t, *J* = 6.3 Hz, 1H), 7.18 (d, *J* = 8.4 Hz, 2H), 7.12–7.03 (m, 4H), 5.82 (d, *J* = 7.6 Hz, 1H), 5.49 (d, *J* = 7.6 Hz, 1H), 2.49–2.13 (m, 4H), 2.38 (s, 3H), 2.28 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 208.3, 160.2, 143.9, 143.2, 137.3, 136.7, 135.7, 130.7, 129.3 (2C), 127.9, 127.4 (2C), 126.9, 126.3, 51.8, 34.9, 26.7, 21.5, 19.4 ppm.

IR (CH_2Cl_2): ν = 3302, 2958, 1697, 1441, 1339, 1161, 904, 864, 741, 650 cm^{-1}.

HRMS (ESI): calculated for $C_{20}H_{21}NaNO_3S$ = $[M+Na]^+$: m/z = 378.1134, found: m/z = 378.1120.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(3-toyl)methyl]benzenesulfonamide (1–39b)



1–39b

Prepared from ***Imine*–1c** (60.4 mg, 0.22 mmol, 1.10 equiv), and ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 24 h. **1–39b** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Colorless solid (mp 160–161 °C).

Yield: 63.1 mg (87%).

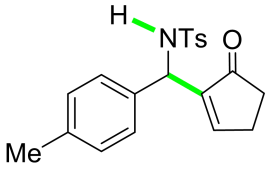
^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.61 (d, *J* = 8.2 Hz, 2H), 7.35 (t, *J* = 6.1 Hz, 1H), 7.19 (d, *J* = 8.2 Hz, 2H), 7.12–7.10 (m, 1H), 7.02 (d, *J* = 7.6 Hz, 1H), 6.93 (d, *J* = 7.6 Hz, 2H), 6.02 (d, *J* = 8.4 Hz, 1H), 5.25 (d, *J* = 8.4 Hz, 1H), 2.50–2.15 (m, 4H), 2.39 (s, 3H), 2.23 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 208.3, 160.4, 143.6, 143.1, 138.5, 138.3, 137.5, 129.3 (2C), 128.6, 128.5, 127.5, 127.4 (2C), 123.7, 55.4, 34.9, 26.7, 21.4, 21.3 ppm.

IR (CH_2Cl_2): ν = 3275, 2920, 2849, 1695, 1437, 1330, 1159, 1091, 904, 815, 742, 665 cm^{-1}.

HRMS (ESI): calculated for $C_{20}H_{21}NaNO_3S$ = $[M+Na]^+$: m/z = 378.1134, found: m/z = 378.1115.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-toyl)methyl]benzenesulfonamide (1–39c)[44]



1–39c

Prepared from ***Imine*–1d** (60.4 mg, 0.22 mmol, 1.10 equiv), and ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 24 h. **1–39c** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2). *The obtained analytical data were in full agreement with the reported data.*[44]

Colorless solid.

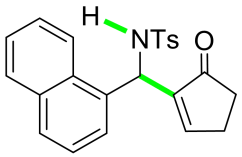
Mp. 164−166 °C (164−165 °C) [44]

Yield: 57.9 mg (84%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.64 (d, *J* = 8.2 Hz, 2H), 7.36 (t, *J* = 2.7 Hz, 1H), 7.20 (d, *J* = 8.2 Hz, 2H), 7.08–7.04 (m, 4H), 5.97 (d, *J* = 8.4 Hz, 1H), 5.25 (d, *J* = 8.4 Hz, 1H), 2.54–2.17 (m, 4H), 2.42 (s, 3H), 2.30 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.4, 160.3, 143.6, 143.2, 137.6, 137.5, 135.7, 129.3 (2C), 129.2 (2C), 127.4 (2C), 126.7 (2C), 55.1, 35.0, 26.7, 21.5, 21.0 ppm.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(2-naphthalenyl)methyl]benzenesulfonamide (1–40a)



1–40a

Prepared from ***Imine*–1e** (68.2 mg, 0.22 mmol, 1.10 equiv), and ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 48 h. **1–40a** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:1).

Colorless solid (mp 176–178 °C).

Yield: 77.2 mg (93%).

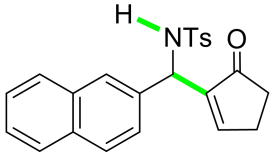
^{1}H NMR ($CDCl_3$, 600 MHz): δ = 8.07–8.06 (m, 1H), 7.84–7.82 (m, 1H), 7.76–7.74 (m, 1H), 7.60 (d, *J* = 8.2 Hz, 2H), 7.49–7.47 (m, 2H), 7.42–7.41 (t, *J* = 6.3 Hz, 1H), 7.33–7.30 (m, 2H), 7.14 (d, *J* = 8.2 Hz, 2H), 6.10 (d, *J* = 7.8 Hz, 1H), 6.04 (d, *J* = 7.8 Hz, 1H), 2.46–2.19 (m, 4H), 2.39 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 208.4, 161.3, 143.4, 143.2, 137.0, 133.9, 130.3, 129.2 (2C), 128.9, 128.8, 127.5 (2C), 126.6, 126.2, 125.8, 125.3, 125.0, 123.1, 51.7, 34.9, 26.7, 21.4 ppm.

IR (CH_2Cl_2): ν = 3163, 3005, 2943, 1440, 1375, 1037, 918, 748 cm^{-1}.

HRMS (ESI): calculated for $C_{23}H_{21}NaNO_3S$ = $[M+Na]^+$: m/z = 414.1134, found: m/z = 414.1111.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(2-naphthalenyl)methyl]benzenesulfonamide (1–40b)



1–40b

Prepared from ***Imine*–1f** (68.2 mg, 0.22 mmol, 1.10 equiv), and ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 48 h. **1–40b** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:1).

Colorless solid (mp 175–179 °C).

Yield: 76.2 mg (92%).

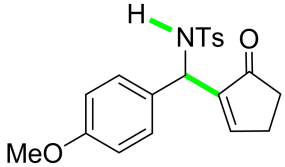
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.76–7.75 (m, 1H), 7.70 (d, *J* = 8.6 Hz, 2H), 7.60 (d, *J* = 8.2 Hz, 2H), 7.59 (s, 1H), 7.45–7.44 (m, 2H), 7.42 (t, *J* = 5.4 Hz, 1H), 7.31–7.30 (m, 1H), 7.10 (d, *J* = 8.2 Hz, 2H), 6.18 (d, *J* = 8.4 Hz, 1H), 5.45 (d, *J* = 8.4 Hz, 1H), 2.54–2.20 (m, 4H), 2.30 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 208.5, 160.8, 139.5, 137.9, 133.7, 133.0, 132.8, 129.7, 129.3 (2C), 128.6, 127.9, 127.5, 127.4 (2C), 126.4, 126.3, 125.7, 125.4, 58.1, 32.5, 26.2, 21.3 ppm.

IR (CH_2Cl_2): ν = 3165, 3003, 2943, 1701, 1436, 1375, 1161, 1039, 918, 736, 669 cm^{-1}.

HRMS (ESI): calculated for $C_{23}H_{21}NaNO_3S$ = $[M+Na]^+$: m/z = 414.1134, found: m/z = 414.1093.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-methoxylphenyl)methyl]benzenesulfonamide (1–41)[44, 142]



1–41

Prepared from ***Imine*–1g** (63.8 mg, 0.22 mmol, 1.10 equiv), and cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 30 h. **1–41** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2). *The obtained analytical data were in full agreement with the reported data.* [44, 142]

Colorless solid.

Mp. 119−122 °C (118−120 °C) [142]

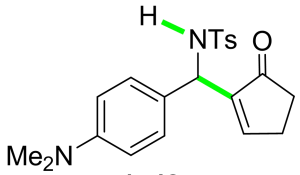
Yield: 70.2 mg (92%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.62 (d, *J* = 8.3 Hz, 2H), 7.34 (t, *J* = 5.4 Hz, 1H), 7.22 (d, *J* = 8.3 Hz, 2H), 7.08 (d, *J* = 8.8 Hz, 2H), 6.76 (d, *J* = 8.8 Hz, 2H), 5.93 (d, *J* = 8.3 Hz, 1H), 5.22 (d, *J* = 8.3 Hz,

1H), 3.75 (s, 3H), 2.51–2.16 (m, 4H), 2.39 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.4, 160.3, 159.2, 143.7, 143.1, 137.5, 130.8, 129.3 (2C), 128.0 (2C), 127.4 (2C), 113.8 (2C), 55.2, 54.9, 35.0, 26.7, 21.5 ppm.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-dimethylaminophenyl)methyl]benzenesulfon-amide (1–42)[142]



1–42

Prepared from ***Imine*–1h** (67.1 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 48 h. **1–42** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2). *The obtained analytical data were in full agreement with the reported data.* [142]

Pale−yellow solid.

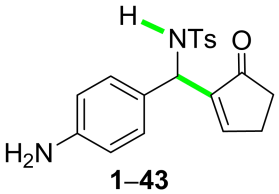
Mp. 174−176 °C (175−176 °C) [142]

Yield: 72.3 mg (92%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.64 (d, *J* = 8.7 Hz, 2H), 7.37 (t, *J* = 5.0 Hz, 1H), 7.22 (d, *J* = 8.2 Hz, 2H), 7.00 (d, *J* = 8.7 Hz, 2H), 6.57 (d, *J* = 8.2 Hz, 2H), 5.84 (d, *J* = 8.1 Hz, 1H), 5.19 (d, *J* = 8.1 Hz, 1H), 2.91 (s, 6H), 2.54–2.14 (m, 4H), 2.42 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.3, 160.4, 144.3, 139.5, 137.9, 130.7, 129.7 (2C), 129.3, 127.6 (2C), 127.4 (2C), 112.9 (2C), 58.1, 40.3 (2C), 32.5, 26.2, 21.3 ppm.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-aminophenyl)methyl]benzenesulfonamide (1–43)



1–43

Prepared from ***Imine*–1i** (60.2 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 24 h. **1–43** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Colorless Solid (mp 157–159 °C).

Yield: 59.2 mg (83%).

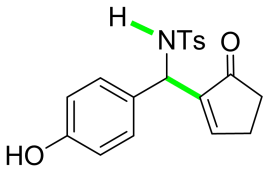
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.65 (br s, 2H), 7.66 (d, *J* = 8.1 Hz, 2H), 7.40 (d, *J* = 8.1 Hz, 2H), 7.26 (t, *J* = 5.4 Hz, 1H), 7.05 (d, *J* = 8.2 Hz, 2H), 6.62-6.59 (m, 2H), 5.85 (d, *J* = 8.2 Hz, 1H), 5.21 (d, *J* = 8.2 Hz, 1H), 2.52-2.17 (m, 4H), 2.41 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 151.1, 146.3, 141.5, 139.9, 132.7, 131.7 (2C), 131.2, 129.5 (2C), 129.1 (2C), 116.1 (2C), 60.7, 35.1, 28.8, 23.9 ppm.

IR (CH_2Cl_2): ν = 3028, 2924, 2835, 2291, 2250, 1705, 1587, 1494, 1346, 1180, 914, 825, 750, 700, 663, 623 cm^{-1}.

HRMS (ESI): calculated for $C_{19}H_{20}NaN_2O_3S$ = $[M+Na]^+$: m/z = 356.4432, found: m/z = 356.4433.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-hydroxyphenyl)methyl]benzenesulfonamide (1–44)



1–44

Prepared from ***Imine*–1j** (59.4 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 µmol, 5.00 mol%), DBU (1.50 mg, 10.0 µmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 24 h. **1–44** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Colorless Solid (mp 169–170 °C).

Yield: 50.0 mg (70%).

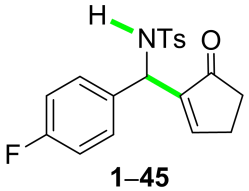
^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.80 (d, *J* = 8.3 Hz, 2H), 7.52 (d, *J* = 8.1 Hz, 2H), 7.45 (t, *J* = 5.3 Hz, 1H), 7.26 (d, *J* = 8.3 Hz, 2H), 6.93-6.91 (m, 2H), 6.10 (d, *J* = 8.4 Hz, 1H), 5.83 (br s, 1H), 5.25 (d, *J* = 8.4 Hz, 1H), 2.55-2.19 (m, 4H), 2.43 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.3, 157.8, 144.3, 139.5, 137.7, 130.7, 129.8 (2C), 129.5 (2C), 127.6, 125.1 (2C), 115.1 (2C), 58.1, 32.5, 26.2, 21.3 ppm.

IR (CH_2Cl_2): ν = 3062, 2922, 2835, 2250, 1705, 1647, 1587, 1435, 1346, 180, 750, 698, 611 cm^{-1}.

HRMS (ESI+): calculated for $C_{19}H_{19}NaNO_4S$ = $[M+Na]^+$: m/z = 380.5824, found: m/z = 380.5821.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-fluorophenyl)methyl]benzenesulfonamide (1–45)[44]



1–45

Prepared from ***Imine*–1k** (71.0 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 µmol, 5.00 mol%), DBU (1.50 mg, 10.0 µmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 30 h. **1–45** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2). *The obtained analytical data were in full agreement with the reported data.*[44]

Colorless solid.

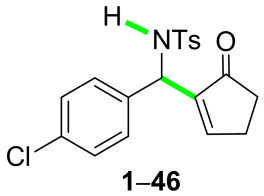
Mp. 186−187 °C (186−187 °C) [44]

Yield: 66.3 mg (91%).

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.60 (d, *J* = 8.2 Hz, 2H), 7.33 (t, *J* = 5.3 Hz, 1H), 7.22 (d, *J* = 8.2 Hz, 2H), 7.18–7.16 (m, 2H), 6.91–6.88 (m, 2H), 6.05 (d, *J* = 8.5 Hz, 1H), 5.26 (d, *J* = 8.5 Hz, 1H), 2.52–2.16 (m, 4H), 2.39 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 163.0 (d, *J* = 245.8 Hz), 160.6, 143.3 (d, *J* = 3.0 Hz), 137.4, 134.5, 129.4 (2C), 128.6 (d, *J* = 6.6 Hz, 2C), 128.1, 127.4 (2C), 115.5 (d, *J* = 21.4 Hz, 2C), 54.8, 34.9, 26.8, 21.5 ppm.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-chlorophenyl)methyl]benzenesulfonamide (1–46)[44, 142]



1–46

Prepared from ***Imine*–1l** (64.6 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 30 h. **1–46** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2). *The obtained analytical data were in full agreement with the reported data.* [44, 142]

Colorless solid.

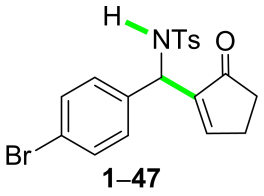
Mp. 190−192 °C (190−191 °C) [142]

Yield: 72.3 mg (95%).

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.82 (d, *J* = 8.3 Hz, 1H), 7.59 (t, *J* = 5.7 Hz, 2H), 7.33–7.30 (m, 2H), 7.20–7.17 (m, 4H), 7.11–7.10 (m, 2H), 6.04 (d, *J* = 8.5 Hz, 1H), 5.25 (d, *J* = 8.5 Hz, 1H), 2.51–2.18 (m, 4H), 2.40 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 160.8, 143.4, 143.0, 137.4, 137.1, 129.4 (2C), 128.7 (2C), 128.2 (2C), 127.4 (2C), 126.5, 54.9, 34.9, 26.8, 21.5 ppm.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-bromophenyl)methyl]benzenesulfonamide (1–47)[142]



1–47

Prepared from ***Imine*–1m** (67.4 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 30 h. **1–47** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2). *The obtained analytical data were in full agreement with the reported data.* [142]

Colorless solid.

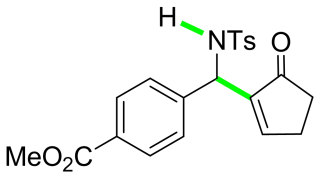
Mp. 197−200 °C (198−201 °C) [142]

Yield: 80.2 mg (94%).

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.51 (d, *J* = 8.3 Hz, 2H), 7.27–7.26 (m, 3H), 7.19 (d, *J* = 8.0 Hz, 2H), 6.98 (d, *J* = 8.3 Hz, 2H), 6.02 (d, *J* = 8.6 Hz, 1H), 5.16 (d, *J* = 8.6 Hz, 1H), 2.46–2.10 (m, 4H), 2.33 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 160.9, 143.5, 142.9, 137.7, 137.3, 131.7 (2C), 129.4 (2C), 128.5 (2C), 127.3 (2C), 121.9, 54.9, 34.9, 26.8, 21.5 ppm.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-methoxycarbonylphenyl)methyl]benzene-sulfonamide (1–48)



1–48

Prepared from ***Imine*–1n** (69.8 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 24 h. **1–48** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Colorless solid (mp 181–183 °C).

Yield: 67.4 mg (94%).

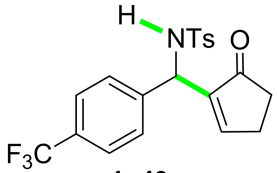
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.90 (d, *J* = 8.4 Hz, 2H), 7.61 (d, *J* = 8.3 Hz, 2H), 7.36 (t, *J* = 5.3 Hz, 1H), 7.26 (d, *J* = 8.3 Hz, 2H), 7.20 (d, *J* = 8.4 Hz, 2H), 6.12 (d, *J* = 8.7 Hz, 1H), 5.34 (d, *J* = 8.7 Hz, 1H), 3.90 (s, 3H), 2.56–2.14 (m, 4H), 2.40 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 207.3, 165.6, 160.0, 142.5, 142.4, 141.8, 136.3, 128.9 (2C), 128.6, 128.4 (2C), 126.3 (2C), 125.7 (2C), 54.2, 51.1, 33.9, 25.9, 20.5 ppm.

IR (CH_2Cl_2): ν = 3258, 3032, 2917, 1743, 1613, 1431, 1256, 1121, 1099, 910, 812, 732, 654 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{21}NaNO_5S$ = $[M+Na]^+$: m/z = 422.5612, found: m/z = 466.5619.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-trifluoromethyphenyl)methyl]benzenesulfon-amide (1–49)



1–49

Prepared from ***Imine*–1o** (72.0 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 24 h. **1–49** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Colorless solid (mp 190–192 °C).

Yield: 76.4 mg (85%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.58 (d, *J* = 8.2 Hz, 2H), 7.46 (d, *J* = 8.5 Hz, 2H), 7.37 (t, *J* = 5.9 Hz, 1H), 7.30 (d, *J* = 8.5 Hz, 2H), 7.18 (d, *J* = 8.2 Hz, 2H), 6.19 (d, *J* = 8.6 Hz, 1H), 5.36 (d, *J* = 8.6 Hz, 1H), 2.56–2.18 (m, 4H), 2.39 (s, 3H) ppm.

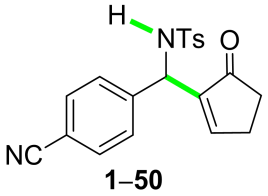
^{13}C NMR ($CDCl_3$, 150 MHz): δ = 208.4, 161.1, 144.3, 143.5, 142.7, 137.3, 132.0 (q, *J* = 1.3 Hz, 2C), 130.7 (q, *J* = 270.3 Hz), 129.4 (2C), 128.9 (q, *J* = 3.8 Hz, 2C), 127.2 (2C), 125.5 (q, *J* = 32.5 Hz), 55.2, 34.9, 26.9, 21.4 ppm.

^{19}F NMR ($CDCl_3$, 128 MHz): δ = – 62.7 (s) ppm.

IR (CH_2Cl_2): ν = 3275, 2916, 2850, 1693, 1436, 1328, 1159, 906, 745, 665 cm^{-1}.

HRMS (ESI): calculated for $C_{20}H_{18}F_3NaNO_3S$ = $[M+Na]^+$: m/z = 432.0852, found: m/z = 432.0857.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-cyanophenyl)methyl]benzenesulfonamide (<u>1–50</u>)



1–50

Prepared from ***Imine*–1p** (62.6 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 24 h. **1–50** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Colorless solid (mp 170–172 °C).

Yield: 67.8 mg (91%).

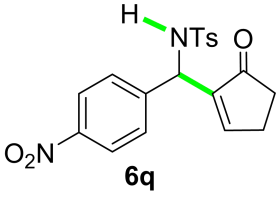
^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.60 (d, *J* = 8.3 Hz, 2H), 7.52 (d, *J* = 8.4 Hz, 2H), 7.34 (t, *J* = 4.8 Hz, 1H), 7.33 (d, *J* = 8.4 Hz, 2H), 7.22 (d, *J* = 8.3 Hz, 2H), 6.19 (d, *J* = 8.8 Hz, 1H), 5.33 (d, *J* = 8.8 Hz, 1H), 2.56–2.20 (m, 4H), 2.41 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 208.3, 161.4, 143.8, 143.7, 142.3, 137.7, 132.4 (2C), 129.5 (2C), 127.5 (2C), 127.3 (2C), 118.4, 111.8, 55.0, 34.9, 26.9, 21.5 ppm.

IR (CH_2Cl_2): ν = 3319, 2898, 2819, 2234, 1716, 1672, 1567, 1423, 1398, 1189, 934, 783, 643 cm^{-1}.

HRMS (ESI): calculated for $C_{20}H_{18}NaN_2O_3S$ = $[M+Na]^+$: m/z = 389.5345, found: m/z = 389.5350.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-nitrophenyl)methyl]benzenesulfonamide (<u>1–51</u>)[44, 142]



6q

Prepared from ***Imine*–1q** (67.1 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20

mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) at 30 °C for 24 h. **1–51** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2). *The obtained analytical data were in full agreement with the reported data.*[44, 142]

Pale−yellow solid.

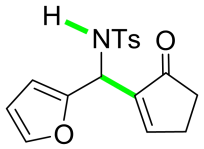
Mp. 187−189 °C (187−188 °C) [142]

Yield: 72.3 mg (93%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.10 (d, *J* = 8.7 Hz, 2H), 7.62 (d, *J* = 8.2 Hz, 2H), 7.40 (d, *J* = 8.7 Hz, 2H), 7.39 (t, *J* = 5.0 Hz, 1H), 7.23 (d, *J* = 8.2 Hz, 2H), 6.18 (d, *J* = 8.6 Hz, 1H), 5.38 (d, *J* = 8.6 Hz, 1H), 2.58–2.22 (m, 4H), 2.41 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 161.5, 147.4, 145.7, 143.8, 142.2, 137.1, 129.5 (2C), 127.7 (2C), 127.3 (2C), 123.8 (2C), 54.7, 34.8, 26.5, 21.3 ppm.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(2-furanyl)methyl]benzenesulfonamide (1–52)[44]



1–52

Prepared from ***Imine*–1r** (54.8 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 24 h. **1–52** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2). *The obtained analytical data were in full agreement with the reported data.* [44]

Yellow solid.

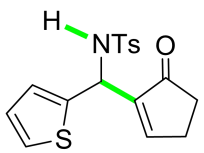
Mp. 154−156 °C (155−156 °C) [44]

Yield: 55.9 mg (83%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.65 (d, *J* = 8.1 Hz, 2H), 7.44 (t, *J* = 6.1 Hz, 1H), 7.24 (d, *J* = 8.1 Hz, 2H), 7.23–7.21 (m, 1H), 6.22–6.21 (m, 1H), 6.10–6.09 (m, 1H), 5.94 (d, *J* = 8.5 Hz, 1H), 5.39 (d, *J* = 8.5 Hz, 1H), 2.52–2.20 (m, 4H), 2.40 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 207.8, 160.9, 150.7, 143.3, 142.3, 141.5, 137.4, 129.4 (2C), 127.3 (2C), 110.5, 107.6, 49.2, 34.8, 26.7, 21.5 ppm.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(2-thienyl)methyl]benzenesulfonamide (1–53)



1–53

Prepared from ***Imine*–1s** (58.4 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 24 h. **1–53** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Pale-yellow solid (mp 160–164 °C).

Yield: 70.4 mg (92%).

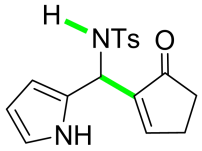
^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.66 (d, *J* = 8.1 Hz, 2H), 7.41 (t, *J* = 5.2 Hz, 1H), 7.24 (d, *J* = 8.1 Hz, 2H), 7.16–7.15 (m, 1H), 6.86–6.84 (m, 1H), 6.78–6.77 (m, 1H), 6.03 (d, *J* = 9.0 Hz, 1H), 5.54 (d, *J* = 9.0 Hz, 1H), 2.56–2.17 (m, 4H), 2.41 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 208.1, 160.4, 143.4, 143.0, 142.3, 141.9, 137.4, 129.4 (2C), 127.4 (2C), 126.9, 125.4, 51.3, 34.9, 26.3, 21.5 ppm.

IR (CH_2Cl_2): ν = 3163, 3001, 2943, 1735, 1442, 1375, 1246, 1039, 918, 748 cm^{-1}.

HRMS (ESI): calculated for $C_{17}H_{17}NaNO_3S_2$ = $[M+Na]^+$: m/z = 370.0542, found: m/z = 370.0540.

4-Methyl-N-[(5-oxocyclopent-1-enyl)(2-pyrrolyl)methyl]benzenesulfonamide (1–54)



1–54

Prepared from ***Imine*–1t** (54.6 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) at 30 °C for 48 h. **1–54** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Brown solid (mp 145–147 °C).

Yield: 64.8 mg (88%).

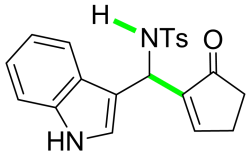
^{1}H NMR ($CDCl_3$, 600 MHz): δ = 8.61 (br s, NH, 1H), 7.67 (d, *J* = 8.1 Hz, 2H), 7.46 (t, *J* = 5.6 Hz, 1H), 7.26 (d, *J* = 8.1 Hz, 2H), 7.25–7.23 (m, 1H), 6.15–6.13 (m, 1H), 6.02–6.01 (m, 1H), 5.86 (d, *J* = 9.0 Hz, 1H), 5.29 (d, *J* = 9.0 Hz, 1H), 2.55–2.29 (m, 4H), 2.42 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.8, 144.3, 137.9, 137.5, 130.9, 129.7 (2C), 128.6, 127.5 (2C), 123.5, 111.9, 110.3, 58.3, 32.9, 26.3, 20.9 ppm.

IR (CH_2Cl_2): ν = 3001, 2941, 2252, 1707, 1440, 1375, 1346, 1182, 916, 754, 702 cm^{-1}.

HRMS (ESI): calculated for $C_{17}H_{18}NaN_2O_3S$ = $[M+Na]^+$: m/z = 353.5632, found: m/z = 353.5634.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(1*H*-indol-3-yl)methyl]benzenesulfonamide (1–55)



1–55

Prepared from ***Imine*–1u** (65.6 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) at 30 °C for 48 h. **1–55** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Colorless solid (mp 175–179 °C).

Yield: 63.2 mg (83%).

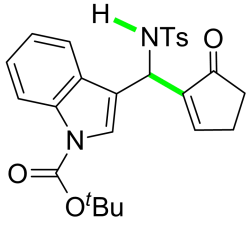
^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.68–7.65 (m, 2H), 7.60 (d, *J* = 8.1 Hz, 2H), 7.34 (t, *J* = 5.0 Hz, 1H), 7.31 (d, *J* = 8.1 Hz, 2H), 7.12–7.08 (m, 1H), 7.00–6.97 (m, 1H), 6.73–6.72 (m, 1H), 6.02 (d, *J* = 8.4 Hz, 1H), 5.17 (br s, NH, 1H), 4.20 (d, *J* = 8.4 Hz, 1H), 2.53–2.16 (m, 4H), 2.38 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 146.3, 139.9, 139.0, 132.7, 131.7 (2C), 130.9, 129.8, 129.5 (2C), 127.7, 124.2, 124.1, 122.2, 121.3, 113.6, 60.1, 34.9, 28.6, 23.7 ppm.

IR (CH_2Cl_2): ν = 2924, 2251, 1703, 1662, 1587, 1346, 1180, 914, 752, 696 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{20}NaN_2O_3S$ = $[M+Na]^+$: m/z = 403.6171, found: m/z = 403.6174.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(1*H*-indol-1-carboxlic acid-3-yl)methyl]benzene-sulfonamide (1–56)



1–56

Prepared from ***Imine*–1v** (87.6 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 30 h. **1–56** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Colorless Solid (mp 189–194 °C).

Yield: 95.4 mg (89%).

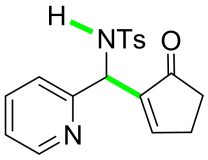
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.23 (d, *J* = 8.1 Hz, 1H), 8.02–8.00 (m, 1H), 7.78 (d, *J* = 8.1 Hz, 2H), 7.66 (d, *J* = 8.1 Hz, 1H), 7.31 (d, *J* = 8.1 Hz, 2H), 7.22–7.20 (m, 1H), 7.10–7.08 (m, 1H), 6.73 (t, *J* = 5.7 Hz, 1H), 6.08 (d, *J* = 8.4 Hz, 1H), 5.34 (d, *J* = 8.4 Hz, 1H), 2.54–2.18 (m, 4H), 2.39 (s, 3H), 1.44 (s, 9H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.3, 149.3, 144.3, 139.5, 135.4, 130.7, 129.7 (2C), 129.2, 128.5, 128.1, 127.6 (2C), 126.7, 122.9, 120.2, 119.2, 115.2, 81.4, 58.1, 32.5, 28.2, 26.2, 21.3 ppm.

IR (CH_2Cl_2): ν = 3061, 3028, 2922, 2833, 2250, 1703, 1574, 1346, 1180, 914, 750, 698 cm^{-1}.

HRMS (ESI): calculated for $C_{26}H_{28}NaN_2O_5S$ = $[M+Na]^+$: m/z = 503.7325, found: m/z = 503.7330.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(2-pyridinyl)methyl]benzenesulfonamide (1–57)



1–57

Prepared from ***Imine*–1w** (57.2 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 48 h. **1–57** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Pale-yellow solid (mp 162–164 °C).

Yield: 48.2 mg (64%).

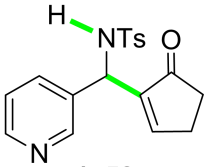
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.50–8.47 (m, 1H), 7.62–7.60 (m, 1H), 7.58 (d, *J* = 8.1 Hz, 2H), 7.31 (t, *J* = 5.3 Hz, 1H), 7.29 (d, *J* = 8.1 Hz, 2H), 7.20–7.18 (m, 1H), 6.70 (d, *J* = 8.1 Hz, 1H), 6.25 (d, *J* = 8.4 Hz, 1H), 5.36 (d, *J* = 8.4 Hz, 1H), 2.61–2.24 (m, 4H), 2.45 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.3, 152.0, 148.5, 144.3, 138.6, 137.9, 130.7, 129.8 (2C), 129.2, 127.6 (2C), 123.4, 122.0, 58.1, 29.8, 23.4, 18.5 ppm.

IR (CH_2Cl_2): ν = 3252, 3047, 2975, 2836, 2282, 2255, 1874, 1726, 1651, 1590, 1433, 1349, 1184, 1172, 928, 756 cm^{-1}.

HRMS (ESI): calculated for $C_{18}H_{18}NaN_2O_3S$ = $[M+Na]^+$: m/z = 365.5734, found: m/z = 365.5739.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(3-pyridinyl)methyl]benzenesulfonamide (1–58)



1–58

Prepared from ***Imine*–1x** (57.2 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure A* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 48 h. **1–58** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Pale-yellow solid (mp 161–165 °C).

Yield: 59.4 mg (76%).

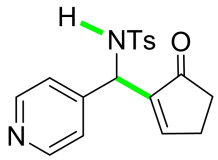
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.47–8.45 (m, 2H), 7.74–7.72 (m, 1H), 7.57 (d, *J* = 8.1 Hz, 2H), 7.37–7.35 (m, 1H), 7.28 (d, *J* = 8.1 Hz, 2H), 6.69 (t, *J* = 2.3 Hz, 1H), 6.12 (d, *J* = 8.4 Hz, 1H), 5.43 (d, *J* = 8.4 Hz, 1H), 2.57–2.21 (m, 4H), 2.42 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.3, 149.7, 149.0, 144.3, 138.8, 138.0, 134.6, 130.7, 129.6 (2C), 129.1, 127.3 (2C), 123.9, 58.1, 32.5, 26.2, 21.3 ppm.

IR (CH_2Cl_2): ν = 3247, 3110, 2943, 2867, 2395, 2197, 1870, 1737, 1658, 1591, 1457, 1328, 1195, 1164, 938, 752, 710 cm^{-1}.

HRMS (ESI): calculated for $C_{18}H_{18}NaN_2O_3S$ = $[M+Na]^+$: m/z = 365.5734, found: m/z = 365.5741.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(4-pyridinyl)methyl]benzenesulfonamide (1–59)



1–59

Prepared from ***Imine*–1y** (57.2 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 48 h. **1–59** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Pale-yellow solid (mp 160–164 °C).

Yield: 71.4 mg (84%).

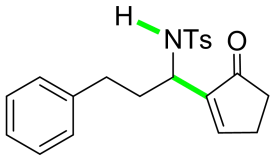
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.55–8.53 (m, 2H), 7.60 (d, *J* = 8.1 Hz, 2H), 7.31 (d, *J* = 8.1 Hz, 2H), 7.20–7.18 (m, 2H), 6.72 (t, *J* = 5.2 Hz, 1H), 6.02 (d, *J* = 8.4 Hz, 1H), 5.23 (d, *J* = 8.4 Hz, 1H), 2.58–2.22 (m, 4H), 2.40 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.3, 149.8, 144.3, 139.5, 137.9, 130.7, 130.0, 129.7 (2C), 129.4, 129.1, 127.6 (2C), 120.7, 57.9, 32.3, 25.9, 21.1 ppm.

IR (CH_2Cl_2): ν = 3030, 2924, 2291, 2251, 1703, 1654, 1587, 1438, 1346, 1180, 1165, 914, 750 cm^{-1}.

HRMS (ESI): calculated for $C_{18}H_{18}NaN_2O_3S$ = $[M+Na]^+$: m/z = 365.5734, found: m/z = 365.5743.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(3-phenylpropyl)methyl]benzenesulfonamide (1–60)



1–60

Prepared from ***Imine*–1z** (63.2 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 30 h. **1–60** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Colorless solid (mp 178–182 °C).

Yield: 75.0 mg (92%).

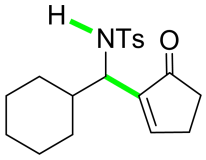
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.69 (d, *J* = 8.0 Hz, 2H), 7.32 (d, *J* = 8.0 Hz, 2H), 7.28–7.25 (m, 2H), 7.17–7.14 (m, 3H), 6.69 (d, *J* = 5.4 Hz, 1H), 6.12 (d, *J* = 8.4 Hz, 1H), 4.93 (t, *J* = 8.4 Hz, 1H), 2.55–2.50 (m, 2H), 2.42 (s, 3H), 2.38–2.30 (m, 4H), 2.21 (q, *J* = 7.4 Hz, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.4, 164.3, 144.3, 140.8, 130.8, 129.7 (2C), 129.1, 128.7 (2C), 128.4 (2C), 127.9, 127.5 (2C), 58.1, 32.9, 32.5, 30.7, 26.2, 21.3 ppm.

IR (CH_2Cl_2): ν = 3324, 2976, 2913, 2876, 2423, 2231, 1897, 1701, 1687, 1512, 1428, 1387, 1176, 1143, 921, 754 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{23}NaNO_3S$ = $[M+Na]^+$: m/z = 392.2453, found: m/z = 392.2459.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(3-cyclohexyl)methyl]benzenesulfonamide (1–61)



1–61

Prepared from ***Imine*–1a'** (58.4 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 30 h. **1–61** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Pale-yellow solid (mp 130–132 °C).

Yield: 70.4 mg (91%).

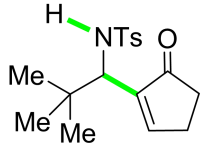
^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.62 (d, *J* = 8.1 Hz, 2H), 7.23 (d, *J* = 8.1 Hz, 2H), 7.00 (t, *J* = 5.4 Hz, 1H), 5.72 (d, *J* = 8.9 Hz, 1H), 3.81 (dd, *J* = 8.9, 9.3 Hz, 1H), 2.40 (s, 3H), 2.39–2.38 (m, 1H), 2.19–2.18 (m, 1H), 2.09–2.08 (m, 1H), 1.96–1.95 (m, 2H), 1.94–1.92 (m, 4H), 1.42–1.39 (m, 1H), 1.15–1.10 (m, 3H), 0.90–0.81 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 209.1, 160.6, 142.9, 141.9, 137.9, 129.2 (2C), 127.4 (2C), 57.4, 40.8, 34.8, 29.9, 29.4 (2C), 26.6 (2C), 26.1, 21.4 ppm.

IR (CH_2Cl_2): ν = 3396, 3176, 2997, 2941, 1597, 1575, 1411, 1375, 1037, 918, 688 cm^{-1}.

HRMS (ESI): calculated for $C_{19}H_{25}NaNO_3S$ = $[M+Na]^+$: m/z = 370.1447, found: m/z = 370.1438.

4-Methyl-*N*-[(5-oxocyclopent-1-enyl)(2,2-dimethylpropyl)methyl]benzenesulfonamide (1–62)



1–62

Prepared from ***Imine*–1b'** (52.6 mg, 0.22 mmol, 1.10 equiv), cyclopentenone ***MA*–1** (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure C* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 5.00 mol%) in THF (0.66 mL, 0.3 M) at 30 °C for 30 h. **1–62** was

purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2).

Colorless solid (mp 106–110 °C).

Yield: 56.8 mg (78%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.60 (d, *J* = 8.1 Hz, 2H), 7.21 (d, *J* = 8.1 Hz, 2H), 6.99 (t, *J* = 5.4 Hz, 1H), 5.70 (d, *J* = 8.1 Hz, 1H), 4.95 (d, *J* = 8.1 Hz, 1H), 2.50–2.14 (m, 4H), 2.32 (s, 3H), 0.82 (s, 9H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 206.1, 144.3, 137.9, 130.7, 129.7 (2C), 129.4, 127.5 (2C), 57.8, 35.4, 32.2, 26.3 (3C), 26.2, 20.9 ppm.

IR (CH_2Cl_2): ν = 3401, 3198, 2978, 2939, 2897, 1603, 1577, 1423, 1398, 1365, 1045, 923, 712, 685 cm^{-1}.

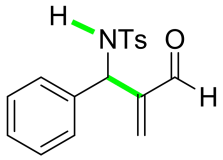
HRMS (ESI): calculated for $C_{17}H_{23}NaNO_3S = [M+Na]^+$: m/z = 344.5376, found: m/z = 344.5381.

5.2.5 BAC-catalysed aza-MBH Reactions – pro-nucleophiles test

General Procedure D **[Michael acceptor scope]**

To an oven-dried test tube with a magnetic stirring bar in a nitrogen glovebox were added ***pre-BAC*–2** (5.00 mg, 10.0 μmol, 10.0 mol%), imine ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv), the corresponding Michael acceptor (0.10 mmol, 1.00 equiv), THF (0.33 mL, 0.3 M), and DBU (1.50 mg, 10.0 μmol, 10.0 mol%). The reaction mixture was stirred at 40 °C for 24–72 h, at which point TLC and/or ^{1}H NMR analysis indicated complete consumption of the corresponding Michael acceptor. The volatiles were removed *in vacuo*, and the residue was purified by flash column chromatography or PTLC on silica gel (eluent: EtOAc/PE = 1:5) to give the intended products.

4-Methyl-*N*-(2-formyl-1-allyl)benzenesulfonamide (1–63) [133]



1–63

Prepared from ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv) and acrolein (6.50 mg, 0.10 mmol, 1.00 equiv) according to the *general procedure D* using ***pre-BAC*–2** (5.00 mg, 10 μmol, 10 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.33 mL, 0.3 M) at 40 °C for 30 h. **1–63** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[133]

Colorless solid.

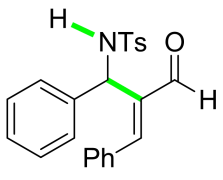
Mp. 106−108 °C (107−108 °C) [133]

Yield: 32.3 mg (88%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.39 (s, 1H), 7.66 (d, *J* = 8.7 Hz, 2H), 7.25 (d, *J* = 8.7 Hz, 2H), 7.19–7.22 (m, 3H), 7.06–7.09 (m, 2H), 6.54 (s, 1H), 6.12 (s, 1H), 5.49 (d, *J* = 8.1 Hz, 1H), 5.26 (d, *J* = 8.1 Hz, 1H), 2.46 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 192.8, 148.0, 143.5, 138.0, 137.1, 135.9, 129.5 (2C), 128.6 (2C), 127.9 (2C), 127.2 (2C), 126.7, 56.7, 21.5.

4-Methyl-*N*-(2-formyl-1-allyl)benzenesulfonamide (1–64)



1–64

Prepared from ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv) and cinnamaldehyde (10.2 mg, 0.10 mmol, 1.00 equiv) according to the *general procedure D* using ***pre-BAC*–2** (5.00 mg, 10 μmol, 10 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.33 mL, 0.3 M) at 40 °C for 72 h. **1–64** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[133]

Colorless solid.

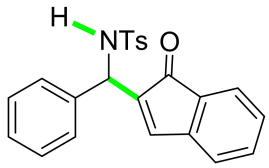
Mp. 119−120 °C (118−121 °C) [133]

Yield: 25.6 mg (60%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.72 (s, 1H), 7.63 (d, *J* =8.0 Hz, 2H), 7.36–7.35 (m, 1H), 7.42 (d, *J* =7.9 Hz, 2H), 7.38 (d, *J* =7.9 Hz, 2H), 7.31 (d, *J* =8.0 Hz, 2H), 7.28 (d, *J* =7.8 Hz, 2H), 7.26 (d, *J* =7.8 Hz, 2H), 7.23–7.21 (m, 1H), 6.81 (s, 1H), 6.14 (d, *J* =8.3 Hz, 1H), 5.23 (d, *J* =8.3 Hz, 1H), 2.32 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 189.2, 154.2, 144.3, 139.5, 138.7, 137.4, 131.9, 129.7 (2C), 129.6, 129.2 (2C), 128.9, 128.7 (2C), 128.4 (2C), 127.5 (2C), 126.9 (2C), 58.6, 21.4 ppm.

4-Methyl-*N*-[(inden-1-one)(phenyl)methyl]benzenesulfonamide (1–65)



1–65

Prepared from ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv) and inden-1-one (12.5 mg, 0.10 mmol, 1.00 equiv) according to the *general procedure D* using ***pre-BAC*–2** (5.00 mg, 10 μmol, 10 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.33 mL, 0.3 M) at 40 °C for 24 h. **1–65** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5).

Colorless solid (mp 172–177 °C).

Yield: 39.1 mg (90%).

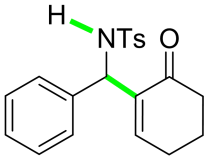
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.98 (t, *J* = 5.2 Hz, 1H), 7.77–7.70 (m, 3H), 7.61–7.59 (m, 2H), 7.57-7.54 (m, 1H), 7.32 (d, *J* = 8.3 Hz, 2H), 7.27–7.19 (m, 5H), 6.15 (d, *J* = 9.3 Hz, 1H), 5.09 (d, *J* = 9.3 Hz, 1H), 2.32 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 194.5, 144.3, 143.5, 139.5, 137.9, 133.7, 130.7, 129.7 (2C), 129.2 (2C), 128.9 (2C), 128.6, 128.4, 127.5 (2C), 127.0, 126.9, 126.1, 121.7, 58.1, 21.4 ppm.

IR (CH_2Cl_2): ν = 3394, 3214, 2989, 2902, 2896, 1954, 1756, 1698, 1585, 1432, 1376, 1389, 1187, 916, 787, 698 cm^{-1}.

HRMS (ESI): calculated for $C_{23}H_{19}NaNO_3S$ = $[M+Na]^+$: m/z = 412.2145, found: m/z = 412.2152.

4-Methyl-*N*-[(6-oxocyclohex-1-enyl)(phenyl)methyl]benzenesulfonamide (1–34) [44]



1–34

Prepared from ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv) and cyclohexenenone (10.4 mg, 0.10 mmol, 1.00 equiv) according to the *general procedure D* using ***pre-BAC*–2** (5.00 mg, 10 μmol, 10 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.33 mL, 0.3 M) at 40 °C for 48 h. **1–34** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[44]

Colorless solid.

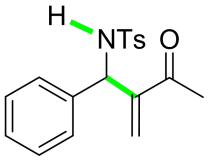
Mp. 148−150 °C (148−149 °C) [44]

Yield: 66.7 mg (92%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.64 (d, *J* = 8.3 Hz, 2H), 7.24–7.19 (m, 7H), 6.82 (t, *J* = 5.0 Hz, 1H), 5.94 (d, *J* = 9.3 Hz, 1H), 5.11 (d, *J* = 9.3 Hz, 1H), 2.41 (s, 3H), 2.39–1.60 (m, 6H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 195.4, 144.3, 139.5, 129.7 (2C), 129.1, 128.7 (2C), 127.8, 127.5 (2C), 126.9, 126.3 (2C), 126.0, 59.4, 37.2, 25.3, 21.9, 21.3 ppm.

4-Methyl-*N*-(2-methozoyl-1-benzylallyl)benzenesulfonamide (1–35)[143]



1–35

Prepared from ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv) and methyl vinyl ketone (8.20 mg, 0.10 mmol, 1.00 equiv) according to the *general procedure D* using ***pre-BAC*–2** (5.00 mg, 10 μmol, 10 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.33 mL, 0.3 M) at 40 °C for 48 h. **1–35** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[143]

Colorless solid.

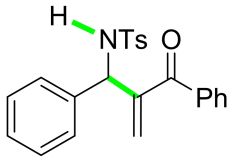
Mp. 119−121 °C (120−121 °C) [143]

Yield: 30.8 mg (95%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.65 (d, *J* = 8.1 Hz, 2H), 7.23–7.20 (m, 5H), 7.10 (d, *J* = 8.1 Hz, 2H), 6.09 (s, 1H), 6.08 (s, 1H), 5.75 (d, *J* = 8.6 Hz, 1H), 5.28 (d, *J* = 8.6 Hz, 1H), 2.40 (s, 3H), 2.15 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 196.8, 144.3, 139.5, 137.9, 129.7 (2C), 129.2, 128.9, 128.6 (2C), 127.5 (2C), 126.9 (2C), 114.3, 58.1, 29.2, 21.3 ppm.

4-Methyl-*N*-(2-benzoyl-1-benzylallyl)benzenesulfonamide (1–66)[144]



1–66

Prepared from ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv) and phenyl vinyl ketone (13.1 mg, 0.10 mmol, 1.00 equiv) according to the *general procedure D* using ***pre-BAC*–2** (5.00 mg, 10 μmol, 10 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.33 mL, 0.3 M) at 40 °C for 72 h. **1–66** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[144]

Colorless solid.

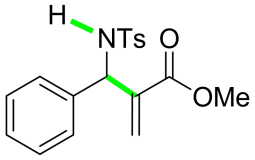
Mp. 142−143 °C (141−143 °C) [143]

Yield: 37.4 mg (94%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.72 (d, *J* = 8.7 Hz, 2H), 7.56–7.50 (m, 3H), 7.40 (d, *J* = 8.7 Hz, 2H), 7.25–7.19 (m, 7H), 6.13 (s, 1H), 5.99 (d, *J* = 8.4 Hz, 1H), 5.75 (s, 1H), 5.49 (d, *J* = 8.4 Hz, 1H), 2.40 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 182.1, 144.3, 139.4, 138.1, 137.9, 129.7 (2C), 129.1, 128.9 (2C), 128.8 (2C), 128.6 (2C), 128.5, 128.4, 127.5 (2C), 126.9 (2C), 114.3, 59.7, 21.5 ppm.

Methyl-α–Methylene-β-[(*p*-toluenesulfonyl)-amino]-3-phenylpropionate (1–36)[145,146]



1–36

Prepared from ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv) and methyl acrylate (9.32 mg, 0.10 mmol, 1.00 equiv) according to the *general procedure D* using ***pre-BAC*–2** (5.00 mg, 10 μmol, 10 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.33 mL, 0.3 M) at 40 °C for 72 h. **1–36** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[145,146]

Colorless solid.

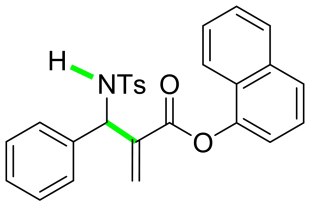
Mp. 140−143 °C (142−143 °C) [145, 146]

Yield: 32.1 mg (93%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.70 (d, *J* = 8.4 Hz, 2H), 7.58 (d, *J* = 8.4 Hz, 2H), 7.24 (m, 3H), 7.21–7.18 (m, 2H), 6.24 (s, 1H), 5.85 (s, 1H), 5.72 (d, *J* = 8.9 Hz, 1H), 5.33 (d, *J* = 8.9 Hz, 1H), 3.62 (s, 3H), 2.43 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 165.1, 143.6, 139.5, 137.9, 129.7 (2C), 129.0, 128.6 (2C), 127.6 (2C), 127.2, 126.9 (2C), 114.3, 59.3, 51.9, 21.3 ppm.

1-Naphthyl-2-[phenyl-(toluene-4-sulfonylamino)methyl]acrylate (1–67)[145,146]



1–67

Prepared from ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv) and 1-naphthyl acrylate (19.8 mg, 0.10 mmol, 1.00 equiv) according to the *general procedure D* using ***pre-BAC*–2** (5.00 mg, 10 μmol, 10 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.33 mL, 0.3 M) at 40 °C for 48 h. **1–67** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.* [145,146]

Colorless solid.

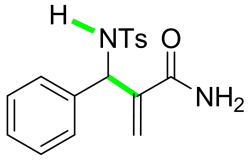
Mp. 153−155 °C (152−154 °C) [145, 146]

Yield: 41.9 mg (96%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.84 (d, *J* = 7.5 Hz, 2H), 7.75 (d, *J* = 7.5 Hz, 2H), 7.71 (d, *J* = 9.1 Hz, 1H), 7.46–7.19 (m, 9H), 7.00 (d, *J* = 7.5 Hz, 2H), 6.59 (s, 1H), 6.14 (s, 1H), 5.55 (d, *J* = 8.8 Hz, 1H), 5.48 (d, *J* = 8.8 Hz, 1H), 2.45 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 165.1, 146.8, 144.3, 139.5, 137.9, 134.1, 129.7 (2C), 129.6, 129.4, 128.6 (2C), 128.0, 127.9, 127.5 (2C), 126.9 (2C), 126.6, 126.5, 125.9, 122.8, 122.1, 121.4, 114.3, 59.0, 21.5 ppm.

2-[Phenyl-(toluene-4-sulfonylamino)methyl]-acrylamide (1–68)[147]



1–68

Prepared from ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv) and acrylamide (7.12 mg, 0.10 mmol, 1.00 equiv) according to the *general procedure D* using ***pre-BAC*–2** (5.00 mg, 10 μmol, 10 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.33 mL, 0.3 M) at 40 °C for 72 h. **1–68** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[147]

Colorless solid.

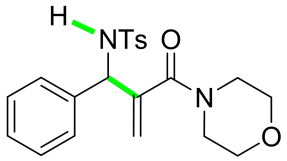
Mp. 200−203 °C (201−203 °C) [145, 146]

Yield: 29.3 mg (88%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.72 (d, *J* = 8.8, 2H), 7.48 (d, *J* = 8.8, 2H), 7.16–7.10 (m, 5H), 7.10 (br s, 2H), 6.58 (s, 1H), 5.93 (d, *J* = 8.4 Hz, 1H), 5.30 (s, 1H), 4.76 (d, *J* = 8.4 Hz, 1H), 2.30 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 166.7, 144.3, 139.6, 137.6, 129.7, 129.2, 128.9 (2C), 128.6 (2C), 127.6 (2C), 126.9 (2C), 114.3, 58.1, 21.3 ppm.

2-[Phenyl-(toluene-4-sulfonylmorphlinyl)methyl]acrylamide (1–69)



1–69

Prepared from ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv) and 4-acryloylmorpholine (14.1 mg, 0.10 mmol, 1.00 equiv) according to the *general procedure D* using ***pre-BAC*–2** (5.00 mg, 10 μmol, 10 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.33 mL, 0.3 M) at 40 °C for 72 h. **1–69** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5).

Colorless solid (mp 156–159 °C).

Yield: 33.1 mg (74%).

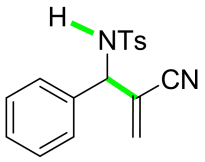
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.60 (d, *J* = 8.7 Hz, 2H), 7.32 (d, *J* = 8.7 Hz, 2H), 7.26–7.22 (m, 3H), 7.14–7.11 (m, 2H), 6.26 (d, *J* = 8.1 Hz, 1H), 6.19 (s, 1H), 5.94 (s, 1H), 5.70 (d, *J* = 8.1 Hz, 1H), 3.64–3.57 (m, 8H), 2.32 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 166.7, 144.3, 139.6, 137.6, 129.7, 129.2, 128.9 (2C), 128.6 (2C), 127.6 (2C), 126.9 (2C), 114.3, 66.4 (2C), 58.1, 44.1 (2C), 21.3 ppm.

IR (CH_2Cl_2): ν = 3421, 3100, 3080, 2975, 2635, 1682, 1645, 1523, 1459, 1324, 1130, 990, 910, 720 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{24}N_2O_4NaS$ = $[M+Na]^+$: m/z = 400.4965, found: m/z = 400.4974.

4-methyl-*N*-(2-Cyano-1-phenylpropen-2-yl)benzenesulfonamide (1–38)[147]



1–38

Prepared from ***Imine*–1a** (28.5 mg, 0.11 mmol, 1.10 equiv) and acrylonitrile (5.30 mg, 0.10 mmol, 1.00 equiv) according to the *general procedure D* using ***pre-BAC*–2** (5.00 mg, 10 μmol, 10 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.33 mL, 0.3 M) at 40 °C for 48 h. **1–38** was purified

by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[147]

Colorless solid.

Mp. 126−128 °C (126−127 °C) [147]

Yield: 30.1 mg (96%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.70 (d, *J* = 8.1 Hz, 2H), 7.31–7.28 (m, 5H), 7.12 (d, *J* = 8.1 Hz, 2H), 6.06 (s, 1H), 6.00 (s, 1H), 5.41 (d, *J* = 7.8 Hz, 1H), 5.08 (d, J = 7.8 Hz, 1H), 2.44 (s, 3H) ppm.

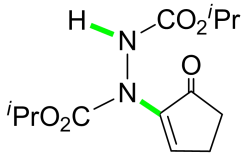
^{13}C NMR ($CDCl_3$, 125 MHz): δ = 144.2, 139.5, 137.9, 129.9 (2C), 129.4, 128.6 (2C), 127.5 (2C), 127.0, 126.8 (2C), 115.9, 114.3, 59.9, 21.7 ppm.

5.2.6 BAC-catalysed α-hydrazination

General Procedure E

To an oven-dried test tube with a magnetic stirring bar in a nitrogen glovebox were added ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), diisopropyl azodicarboxylate (**DIAD**; 87.0 mg, 0.22 mmol, 1.10 equiv), the corresponding Michael acceptor (0.20 mmol, 1.00 equiv), THF (0.2 mL, 1.0 M), and DBU (1.50 mg, 10.0 μmol, 5.00 mol%). The resulting mixture was stirred at 40 °C for 24 h, at which point TLC and/or ^{1}H NMR analysis indicated complete consumption of the corresponding Michael acceptor. The volatiles were removed *in vacuo*, and the residue was purified by flash column chromatography or PTLC on silica gel (eluent: EtOAc/PE = 1:5) to give the intended products.

(*E*)-Diisopropyl-2-(5-oxocyclopenyl)hydrazine-1,2-dicarboxylate (1–70)[60]



1–70

Prepared from **DIAD** (87.0 mg, 0.22 mmol, 1.10 equiv) and cyclohpentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure E* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.2 mL, 1.0 M) at 40 °C for 24 h. **1–70** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[60]

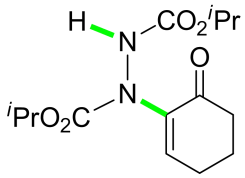
Yellow oil.

Yield: 58.5 mg (98%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.50 (br s, 1H), 7.03 (t, *J* = 5.1, 1H), 4.81 (septet, *J* = 5.8, 1H), 4.76 (septet, *J* = 6.4, 1H), 2.57–2.47 (m, 4H), 1.42 (dd, *J* = 5.8, 6.4 Hz, 12H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 197.5, 155.2, 150.8, 137.5, 108.6, 72.3, 69.9, 34.0, 30.4, 21.7, 21.6, 21.5, 21.4 ppm.

(*E*)-Diisopropyl-2-(6-oxocyclohex-1-enyl)hydrazine-1,2-dicarboxylate (1–71)[59,60]



1–71

Prepared from **DIAD** (87.0 mg, 0.22 mmol, 1.10 equiv) and cyclohexenenone (20.8 mg, 0.20 mmol,

1.00 equiv) according to the *general procedure E* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.2 mL, 1.0 M) at 40 °C for 24 h. **1–71** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[59,60]

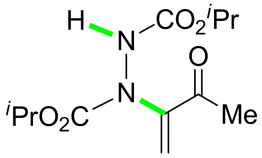
Yellow oil.

Yield: 54.1 mg (83%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.00 (br s, 1H), 6.48 (m, 1H), 4.80 (septet, *J* = 5.8 Hz, 1H), 4.74 (septet, *J* = 6.4 Hz, 1H), 2.40–2.38 (m, 2H), 2.20–2.18 (m, 2H), 1.89–1.84 (m, 2H), 1.43 (dd, *J* = 5.8, 6.4 Hz, 12H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 190.6, 155.2, 150.8, 137.5, 108.3, 71.2, 69.6, 38.8, 23.3, 22.6, 22.0, 21.9, 21.8, 21.6 ppm.

(*E*)-Diisopropyl-2-(1-methylene-2-oxopropyl)hydrazine-1,2-dicarboxylate (1–72)[59]



1–72

Prepared from **DIAD** (87.0 mg, 0.22 mmol, 1.10 equiv) and methyl vinyl ketone (16.4 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure E* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.2 mL, 1.0 M) at 40 °C for 24 h. **1–72** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[59]

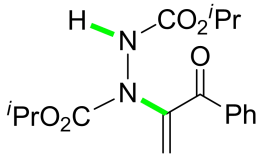
Colorless oil.

Yield: 48.3 mg (87%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.30 (br s, 1H), 5.92 (s, 1H), 5.91 (s, 1H), 4.98 (septet, *J* = 5.8 Hz, 1H), 4.92 (septet, *J* = 6.4 Hz, 1H), 2.37 (s, 3H), 1.27 (dd, *J* = 5.8, 6.4 Hz, 12H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 194.8, 162.5, 155.6, 146.6, 118.8, 71.2, 69.7, 25.8, 21.8, 21.7, 21.5, 20.7 ppm.

(*E*)-Diisopropyl-2-(1-phenyl-2-oxopropyl)hydrazine-1,2-dicarboxylate (1–73)[60]



1–73

Prepared from **DIAD** (87.0 mg, 0.22 mmol, 1.10 equiv) and phenyl vinyl ketone (26.2 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure E* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%),

DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.2 mL, 1.0 M) at 40 °C for 24 h. **1–73** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[60]

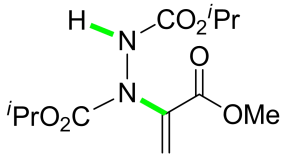
Colorless oil.

Yield: 67.9 mg (92%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.58–7.54 (m, 3H), 7.46–7.42 (m, 2H), 6.92 (br s, 1H), 6.47–6.44 (m, 2H), 4.79 (septet, *J* = 5.8 Hz, 1H), 4.73 (septet, *J* = 6.4 Hz, 1H), 1.32 (dd, *J* = 5.8, 6.4 Hz, 12H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 181.0, 155.2, 150.8, 137.5, 136.1, 129.5 (2C), 129.1, 128.5 (2C), 107.4, 71.2, 69.9, 21.7, 21.6, 21.5, 21.4 ppm.

(*E*)-Diisopropyl-2-[1-(methoxycarbonyl)ethenyl]hydrazine-1,2-dicarboxylate (1–74)[59,60]



1–74

Prepared from **DIAD** (87.0 mg, 0.22 mmol, 1.10 equiv) and methyl acrylate (18.6 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure E* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.2 mL, 1.0 M) at 40 °C for 24 h. **1–74** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[59,60]

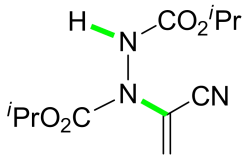
Colorless oil.

Yield: 46.2 mg (78%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.11 (br s, 1H), 6.17 (s, 1H), 5.98 (s, 1H), 5.05 (septet, *J* = 5.8 Hz, 1H), 4.96 (septet, *J* = 6.4 Hz, 1H), 3.80 (s, 3H), 1.27 (dd, *J* = 5.8, 6.4 Hz, 12H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 163.9, 155.6, 154.2, 138.5, 122.7, 71.1, 69.9, 52.2, 21.8, 21.7, 21.6, 21.5 ppm.

(*E*)-Diisopropyl 2-(1-cyanoethenyl)hydrazine-1,2-dicarboxylate (1–75)[59,60]



1–75

Prepared from **DIAD** (87.0 mg, 0.22 mmol, 1.10 equiv) and acrylonitrile (10.6 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure E* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.2 mL, 1.0 M) at 40 °C for 24 h. **1–75** was purified

by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[59,60]

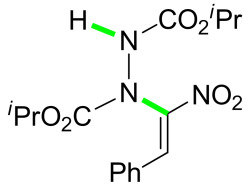
Colorless oil.

Yield: 42.4 mg (75%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 6.87 (br s, 1H), 6.40 (s, 1H), 6.32 (s, 1H), 4.64 (septet, *J* = 5.8 Hz, 1H), 4.60 (septet, *J* = 6.4 Hz, 1H), 1.27 (dd, *J* = 5.8, 6.4 Hz, 12H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 155.2, 150.8, 137.5, 113.9, 107.4, 71.1, 69.9, 21.8, 21.7, 21.6, 21.5 ppm.

(*E*)-Diisopropyl 1-(1-nitro-2-phenylvinyl)hydrazine-1,2-dicarboxylate (1–76)[61]



1–76

Prepared from **DIAD** (87.0 mg, 0.22 mmol, 1.10 equiv) and *trans*-β-styrene (30.2 mg, 0.20 mmol, 1.00 equiv) according to the *general procedure E* using ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 5.00 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) in THF (0.2 mL, 1.0 M) at 40 °C for 24 h. **1–76** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[61]

Colorless oil.

Yield: 57.9 mg (82%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.81 (s, 1H), 7.75–7.73 (m, 2H), 7.70–7.68 (m, 1H), 7.47–7.44 (m, 2H), 6.96 (br s, 1H), 4.85 (septet, *J* = 5.8 Hz, 1H), 4.74 (septet, *J* = 6.4 Hz, 1H), 1.12 (dd, *J* = 5.8, 6.4 Hz, 12H) ppm.

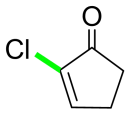
^{13}C NMR ($CDCl_3$, 150 MHz): δ = 155.2, 150.8, 133.1, 128.9, 128.8 (2C), 128.1, 127.7 (2C), 119.1, 72.9, 70.5, 21.9, 21.8, 21.7, 21.6 ppm.

5.2.7 BAC-catalysed α-halogenation

General Procedure F

To an oven-dried test tube with a magnetic stirring bar in a nitrogen glove box were successively added ***pre-BAC*–1** (1.32 mg, 6.00 μmol, 2.00 mol%), THF (0.1 mL, 1.0 M), the corresponding Michael acceptor (in molecular sieves, 0.30 mmol, 1.00 equiv), electrophilic halogen reagents (0.33 mmol, 1.10 equiv) and DBU (0.60 mg, 6.00 μmol, 2.00 mol%). The resulting mixture was stirred at 40 °C for 24 h, at which point TLC and/or ^{1}H NMR analysis indicated complete consumption of the corresponding Michael acceptor. The volatiles were removed *in vacuo*, and the residue was purified by flash column chromatography or PTLC on silica gel (eluent: EtOAc/PE = 1:5) to give the intended products.

2-Chloro-2-cyclopenten-1-one (1–78)[69]



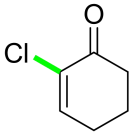
1–78

Prepared from *N*-Chlorosuccinimide (44.1 mg, 0.33 mmol, 1.10 equiv) and cyclopentenone (24.6 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (4.86 mg, 15.0 μmol, 5.00 mol%), DBU (2.58 mg, 15.0 μmol, 5.00 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 24 h. **1–78** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[69]

Colorless oil.
Yield: 29.8 mg (82%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.79 (t, *J* = 3.0 Hz, 1H), 2.71–2.70 (m, 2H), 2.45–2.43 (m, 2H) ppm.
^{13}C NMR ($CDCl_3$, 150 MHz): δ = 194.2, 162.2, 126.7, 34.0, 30.4 ppm.

2-Chloro-2-cyclohexen-1-one (1–80)[69]



1–80

Prepared from *N*-Chlorosuccinimide (44.1 mg, 0.33 mmol, 1.10 equiv) and cyclohexenone (45.2 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (4.86 mg, 15.0 μmol, 5.00 mol%), DBU (2.58 mg, 15.0 μmol, 5.00 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 24 h. **1–80**

was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[69]

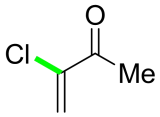
Colorless oil.

Yield: 33.2 mg (81%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.28 (t, *J* = 4.4 Hz, 1H), 2.40 (t, *J* = 6.6 Hz, 2H), 2.29–2.27 (m, 2H), 1.95-1.92 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 190.9, 141.2, 126.6, 38.7, 27.1, 22.6 ppm.

3-Chloro-3-buten-2-one (1–81)[69]



1–81

Prepared from *N*-Chlorosuccinimide (44.1 mg, 0.33 mmol, 1.10 equiv) and methyl vinyl ketone (24.6 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (4.86 mg, 15.0 μmol, 5.00 mol%), DBU (2.58 mg, 15.0 μmol, 5.00 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 24 h. **1–81** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[69]

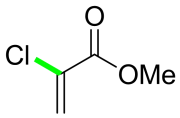
Colorless oil.

Yield: 24.1 mg (73%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 3.95 (d, *J* = 5.4 Hz, 1H), 3.79 (d, *J* = 5.4 Hz, 1H), 2.39 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 194.5, 145.6, 120.9, 24.5 ppm.

2-Chloro-methylacrylate (1–82)[69]



1–82

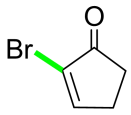
Prepared from *N*-Chlorosuccinimide (44.1 mg, 0.33 mmol, 1.10 equiv) and methyl acrylate (41.9 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (4.86 mg, 15.0 μmol, 5.00 mol%), DBU (2.58 mg, 15.0 μmol, 5.00 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 24 h. **1–82** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[69]

Colorless oil.

Yield: 27.6 mg (65%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 6.85 (d, *J* = 5.4 Hz, 1H), 6.68 (d, *J* = 5.4 Hz, 1H), 3.70 (s, 3H) ppm.
^{13}C NMR ($CDCl_3$, 150 MHz): δ = 163.1, 131.8, 126.8, 54.1 ppm.

2-Bromo-2-cyclopenten-1-one (1–77)[68]



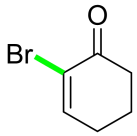
1–77

Prepared from *N*-Bromosuccinimide (58.8 mg, 0.33 mmol, 1.10 equiv) and cyclopentenone (24.6 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (1.95 mg, 6.00 µmol, 2.00 mol%), DBU (1.03 mg, 6.00 µmol, 2.00 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 24 h. **1–77** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[68]

Colorless oil.
Yield: 48.3 mg (98%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.77 (t, *J* = 2.9 Hz, 1H), 2.71–2.69 (m, 2H), 2.54–2.53 (m, 2H) ppm.
^{13}C NMR ($CDCl_3$, 150 MHz): δ = 201.6, 161.6, 126.4, 32.4, 27.9 ppm.

2-Bromo-2-cyclohexen-1-one (1–83)[68]



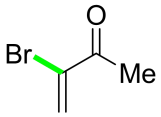
1–83

Prepared from *N*-Bromosuccinimide (58.8 mg, 0.33 mmol, 1.10 equiv) and cyclohexenone (45.2 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (1.95 mg, 6.00 µmol, 2.00 mol%), DBU (1.03 mg, 6.00 µmol, 2.00 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 24 h. **1–83** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[68]

Colorless oil.
Yield: 51.1 mg (90%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.40 (t, *J* = 4.4 Hz, 1H), 2.62 (t, *J* = 7.2 Hz, 2H), 2.44–2.42 (m, 2H), 2.10–2.04 (m, 2H) ppm.
^{13}C NMR ($CDCl_3$, 150 MHz): δ = 190.8, 150.6, 124.1, 38.4, 28.4, 22.8 ppm.

3-Bromo-3-buten-2-one (1–84)[68]



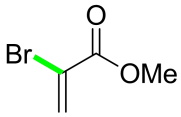
1–84

Prepared from *N*-Bromosuccinimide (58.8 mg, 0.33 mmol, 1.10 equiv) and methyl vinyl ketone (24.6 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (1.95 mg, 6.00 µmol, 2.00 mol%), DBU (1.03 mg, 6.00 µmol, 2.00 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 24 h. **1–84** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[68]

Colorless oil.
Yield: 39.0 mg (84%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 6.52 (d, *J* = 5.4 Hz, 1H), 6.47 (d, *J* = 5.4 Hz, 1H), 2.23 (s, 3H) ppm.
^{13}C NMR ($CDCl_3$, 150 MHz): δ = 194.5, 120.1, 114.2, 28.7 ppm.

2-Bromo-methylacrylate (1–85)[68]



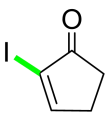
1–85

Prepared from *N*-Bromosuccinimide (58.8 mg, 0.33 mmol, 1.10 equiv) and methyl acrylate (41.9 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (1.95 mg, 6.00 µmol, 2.00 mol%), DBU (1.03 mg, 6.00 µmol, 2.00 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 24 h. **1–85** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[68]

Colorless oil.
Yield: 45.0 mg (81%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 6.55 (d, *J* = 5.6 Hz, 1H), 6.45 (d, *J* = 5.6 Hz, 1H), 3.67 (s, 3H) ppm.
^{13}C NMR ($CDCl_3$, 150 MHz): δ = 162.4, 130.7, 120.9, 53.4 ppm.

2-Iodo-2-cyclopenten-1-one (1–79)[67]



1–79

Prepared from *N*-Iodosuccinimide (74.2 mg, 0.33 mmol, 1.10 equiv) and cyclopentenone (24.6 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (9.72 mg, 30.0 μmol, 10.0 mol%), DBU (5.15 mg, 30.0 μmol, 10.0 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 48 h. **1–79** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[67]

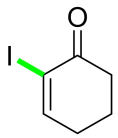
Purple oil.

Yield: 57.2 mg (91%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.03 (t, *J* = 2.9 Hz, 1H), 2.80–2.79 (m, 2H), 2.53–2.51 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 204.1, 169.6, 102.9, 31.3, 30.9 ppm.

2-Iodo-2-cyclohexen-1-one (1–86)[67]



1–86

Prepared from *N*-Iodosuccinimide (74.2 mg, 0.33 mmol, 1.10 equiv) and cyclohexenone (45.2 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (9.72 mg, 30.0 μmol, 10.0 mol%), DBU (5.15 mg, 30.0 μmol, 10.0 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 48 h. **1–86** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[67]

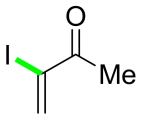
Purple oil.

Yield: 56.8 mg (84%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.68 (t, *J* = 4.4 Hz, 1H), 2.55 (t, *J* = 7.2 Hz, 2H), 2.37-2.36 (m, 2H), 2.02-1.98 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 192.0, 159.7, 103.7, 37.2, 28.9, 22.8 ppm.

3-Iodo-3-buten-2-one (1–87)[67]



1–87

Prepared from *N*-Iodosuccinimide (74.2 mg, 0.33 mmol, 1.10 equiv) and methyl vinyl ketone (24.6 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (9.72 mg, 30.0 μmol, 10.0 mol%), DBU (5.15 mg, 30.0 μmol, 10.0 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 48 h. **1–87** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[67]

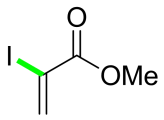
Purple oil.

Yield: 51.4 mg (87%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.24 (d, *J* = 2.4 Hz, 1H), 6.85 (d, *J* = 2.4 Hz, 1H), 2.50 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 192.6, 138.4, 113.2, 24.0 ppm.

2-Iodo-methylacrylate (1–88)[67]



1–88

Prepared from *N*-Iodosuccinimide (74.2 mg, 0.33 mmol, 1.10 equiv) and methyl acrylate (41.9 mg, 0.30 mmol, 1.00 equiv) according to the *general procedure F* using ***pre-BAC*–1** (9.72 mg, 30.0 μmol, 10.0 mol%), DBU (5.15 mg, 30.0 μmol, 10.0 mol%) in THF (0.3 mL, 1.0 M) at 40 °C for 48 h. **1–88** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[67]

Purple oil.

Yield: 54.0 mg (74%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.55 (d, *J* = 5.6 Hz, 1H), 6.67 (d, *J* = 5.6 Hz, 1H), 3.92 (s, 3H) ppm.

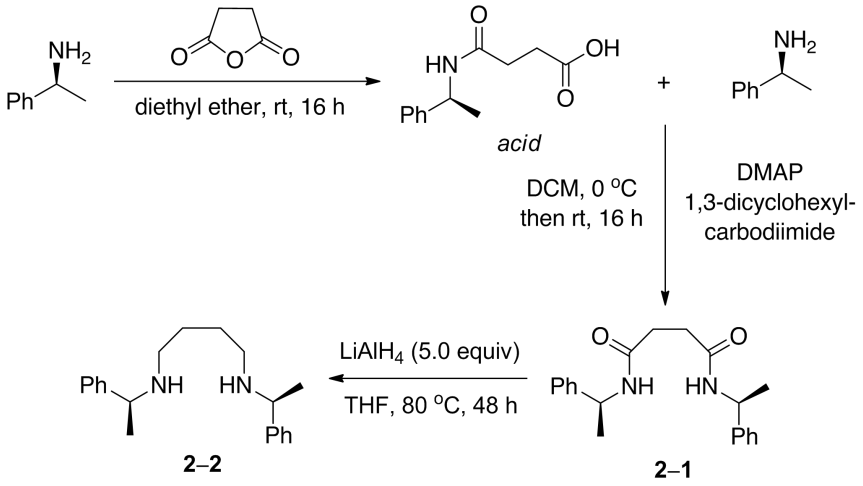
^{13}C NMR ($CDCl_3$, 150 MHz): δ = 169.1, 125.9, 91.8, 52.3 ppm.

5.3 BAC-catalysed ASYMMETRIC AZA-MBH REACTIONS

5.3.1 Preparation of Chiral Bis(dialkylpropylamino)cyclopropenium precursors

Enantiomerically enriched diamine preparation

Two methods were used for the preparation of enantiomerically enriched diamines.[90,135] First, compound **2–2** was prepared according to the literature procedure.[90]



Succinic anhydride (0.70 g, 7.00 mmol, 1.00 equiv) was dissolved in diethyl ether (10 mL) at room temperature, and a solution of (*S*)-phenylethyl amine (0.90 mL, 7.00 mmol, 1.00 equiv) in diethyl ether (2 mL) was added drop-wise over 10 min. The mixture was stirred at room temperature overnight. The *acid* product was purified by column chromatography on silica gel (hexane/EtOAc = 1:1) and isolated as a colorless solid.

Colorless solid (mp 102–104 °C).
Yield: 1.40 g (95%).

^{1}H NMR (CD_3OD, 500 MHz): δ = 10.5 (br s, 1H), 7.32–7.25 (m, 5H), 6.41–6.39 (m, 1H), 5.10 (q, *J* = 6.6 Hz, 1H), 2.60–2.58 (m, 2H), 2.41–2.39 (m, 2H), 1.40 (d, *J* = 6.6 Hz, 3H) ppm.

^{13}C NMR (CD_3OD, 125.8 MHz): δ = 176.6, 171.5, 142.8, 127.4 (2C), 126.7, 126.1 (2C), 49.2, 30.7, 29.7, 21.8 ppm.

To a stirred solution of the *acid* (0.44 g, 2.10 mmol, 1.00 equiv) in CH_2Cl_2 (20 mL) at 0 °C under a nitrogen atmosphere were successively added DMAP (10.3 g, 2.10 mmol, 1.00 equiv), 1,3-dicyclohexylcarbodiimide (10.4 g, 2.10 mmol, 1.00 equiv), and (*S*)-α-phenylethyl amine (0.27 mL, 2.10 mmol, 1.00 equiv). The reaction mixture was stirred at room temperature for 16 h, and filtered to remove the colorless precipitate. The filtrate was extracted with water and CH_2Cl_2 (3 x 10 mL). The organic layer was dried (Na_2SO_4) and filtered, and volatiles were removed under reduced pressure.

The residue was purified by column chromatography on silica gel (hexane/EtOAc = 4:1) to obtain product **2–1** as a colorless solid.

Colorless solid (mp 206–207 °C).

Yield: 0.58 g (80%).

^{1}H NMR (CD_3OD, 500 MHz): δ = 7.30–7.20 (m, 10H), 4.82 (q, *J* =7.0 Hz, 2H), 3.45 (br s, 2H), 2.51-2.45 (m, 4H), 1.45 (d, *J* = 7.0 Hz, 6H) ppm.

^{13}C NMR (CD_3OD, 125.8 MHz): δ = 172.4 (2C), 144.0 (2C), 129.8 (2C), 128.3 (2C), 127.5 (2C), 126.8 (2C), 125.9 (2C), 48.9 (2C), 31.0 (2C), 21.4 (2C) ppm.

A solution of compound **2–1** (0.23 g, 0.70 mmol, 1.00 equiv) in THF (2 mL) was added slowly to a vigorously stirred suspension of $LiAlH_4$ (0.13 g, 3.50 mmol, 5.00 equiv) in THF (10 mL) at room temperature. The resulting mixture was refluxed at 60 °C for 48 h, and quenched by careful addition of an aqueous solution of sodium hydroxide (10%; 10 mL). The mixture was stirred vigorously for 30 min and filtered. The filtrate was concentrated, dissolved in CH_2Cl_2 (20 mL), dried over anhydrous Na_2SO_4, filtered, and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (hexanes/EtOAc = 1:1) to obtain product **2–2** as a colorless oil (0.19 g, 90% yield).

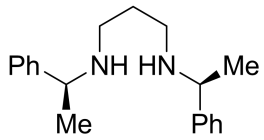
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.32–7.21 (m, 10H), 4.54 (br s, 2H), 3.71 (q, *J* = 6.6 Hz, 2H), 2.40-2.36 (m, 4H), 1.71-1.70 (m, 2H), 1.67 (d, *J* = 6.6 Hz, 6H), 1.23-1.21 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125.8 MHz): δ = 143.8 (2C), 134.5 (2C), 130.4 (2C), 128.6 (2C), 127.3 (2C), 126.7 (2C), 58.2 (2C), 46.9 (2C), 27.0 (2C), 23.2 (2C) ppm.

General preparation procedure G **[synthesis of enantiomerically enriched diamines]**

To an oven-dried flask containing the corresponding enantiomerically enriched amine (2.00 equiv) at 130 °C was added drop-wise 1,3-dibromopropane (1.00 equiv). After one hour at 130 °C, the mixture was cooled to 80 °C and an aqueous solution of potassium hydroxide (4 M; 5.50 equiv) was added. After extraction of the reaction mixture with ethyl acetate and concentration of the organic phase, the residue was fractionally distilled at 2.5 mbar. The corresponding enantiomerically enriched diamines were obtained at ~155 °C as a colorless liquid.

***N,N'*-Bis[(*S*)-α-phenylethyl]propane-1,3-diamine (*Diamine*–1)**[90]



Diamine–1

Prepared from (*S*)-(–)-α-methylbenzylamine (0.87 mL, 6.8 mmol, 2.00 equiv) and 1,3-dibromopropane (0.40 mL, 3.90 mmol, 1.00 equiv). ***Diamine*–1** was purified by distillation. *The obtained analytical data were in full agreement with the reported data.* [90]

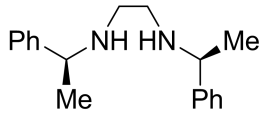
Colorless oil.

Yield: 1.00 g (91%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.36–7.21 (m, 10H), 3.77 (q, *J* = 7.0 Hz, 2H), 2.83 (br s, 2H), 2.63–2.59 (m, 2H), 2.55–2.51 (m, 2H), 1.73–1.69 (m, 2H), 1.40 (d, *J* = 7.0 Hz, 6H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 144.7 (2C), 128.6 (4C), 127.2 (2C), 126.5 (4C), 58.5, 46.6 (2C), 30.3 (2C), 23.9 (2C) ppm.

***N,N'*-Bis[(*S*)-α-phenylethyl]ethane-1,3-diamine (*Diamine*–2)** [90]



Diamine–2

Prepared from (*S*)-(–)-α-methylbenzylamine (0.87 mL, 6.8 mmol, 2.00 equiv) and 1,3-dibromoethane (0.33 mL, 3.90 mmol, 1.00 equiv). ***Diamine*–2** was purified by distillation. *The obtained analytical data were in full agreement with the reported data.* [90]

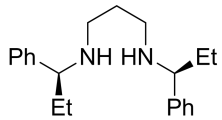
Colorless oil.

Yield: 0.97 g (93%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.39–7.25 (m, 10H), 3.70 (q, *J* = 6.3 Hz, 2H), 2.59–2.55 (m, 4H), 2.23 (br s, 2H), 1.39 (d, *J* = 6.3 Hz, 6H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 145.8 (2C), 128.4 (2C), 126.8 (4C), 126.6 (4C), 58.2 (2C), 47.4 (2C), 24.4 (2C) ppm.

***N,N'*-Bis[(*S*)-α-benzylethyl]propane-1,3-diamine (*Diamine*–3)** [90]



Diamine–3

Prepared from (*S*)-(–)-α-ethylbenzylamine (1.96 mL, 13.6 mmol, 4.00 equiv) and 1,3-dibromopropane (0.40 mL, 3.90 mmol, 1.00 equiv). ***Diamine*–3** was purified by distillation. *The obtained analytical data were in full agreement with the reported data.* [90]

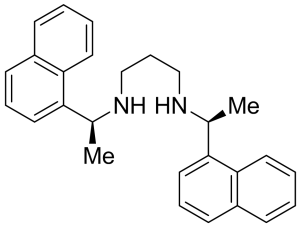
Colorless oil.

Yield: 1.11 g (92%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.36–7.21 (m, 10H), 4.05 (q, *J* = 7.0 Hz, 2H), 2.64–2.60 (m, 4H), 1.52–1.50 (m, 2H), 1.78 (dq, *J* = 7.0, 7.7 Hz, 4H), 1.34 (br s, 2H), 0.92 (t, *J* = 7.7 Hz, 6H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 143.9 (2C), 128.9 (2C), 128.6 (4C), 126.7 (4C), 57.2 (2C), 43.1 (2C), 27.6, 26.1 (2C), 10.4 (2C) ppm.

***N,N'*-Bis[(*S*)-(1-naphthaleny)lethyl]propane-1,3-diamine (*Diamine*–4)** [90]



Diamine–4

Prepared from (*S*)-(–)-α-(1-naphthyl)ethylamine (2.18 mL, 13.6 mmol, 4.00 equiv) and 1,3-dibromopropane (0.40 mL, 3.90 mmol, 1.00 equiv). ***Diamine*–4** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.*[90]

Colorless solid.

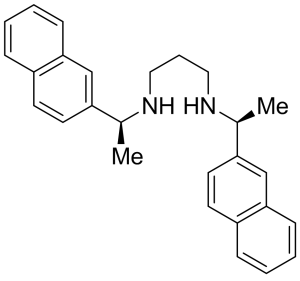
Mp. 125−126 °C (125−127 °C) [90]

Yield: 1.33 g (89%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.71–7.52 (m, 14H), 4.38 (q, *J* = 6.7 Hz, 2H), 2.69–2.65 (m, 4H), 1.53–1.51 (m, 2H), 1.32 (s, 6H), 1.24 (br s, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 132.7 (2C), 130.8 (2C), 130.6 (2C), 129.1 (2C), 128.4 (2C), 126.7 (2C), 126.1 (2C), 125.8 (2C), 124.6 (2C), 122.9 (2C), 51.3 (2C), 43.1 (2C), 27.6, 22.3 (2C) ppm.

***N,N'*-Bis[(*S*)-(2-naphthaleny)lethyl]propane-1,3-diamine (*Diamine*–5)** [90]



Diamine–5

Prepared from (*S*)-(–)-α-(2-naphthyl)ethylamine (2.18 mL, 13.6 mmol, 4.00 equiv) and 1,3-

dibromopropane (0.40 mL, 3.90 mmol, 1.00 equiv). ***Diamine*–5** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2). *The obtained analytical data were in full agreement with the reported data.*[90]

Colorless solid.

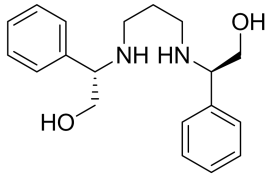
Mp. 136−138 °C (135−137 °C) [90]

Yield: 1.20 g (87%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.93–7.69 (m, 14H), 4.31 (q, *J* = 6.7 Hz, 2H), 2.70–2.65 (m, 4H), 1.53–1.51 (m, 2H), 1.29 (s, 6H), 1.20 (br s, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 139.7 (2C), 133.8 (2C), 133.1 (2C), 128.5 (2C), 128.1 (2C), 127.7 (2C), 127.0 (2C), 126.6 (2C), 126.5 (2C), 125.5 (2C), 51.3 (2C), 43.1 (2C), 27.5, 22.3 (2C) ppm.

***N,N'*-Bis[(*S*)-α-benzylethanol]propane-1,3-diamine (*Diamine*–6)** [90]



Diamine–6

Prepared from (*S*)-(+)-2-phenylglycinol (1.87 mg, 13.6 mmol, 4.00 equiv) and 1,3-dibromopropane (0.40 mL, 3.90 mmol, 1.00 equiv). ***Diamine*–6** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2). *The obtained analytical data were in full agreement with the reported data.* [90]

Colorless solid.

Mp. 118−121 °C (118−119 °C) [90]

Yield: 1.10 g (90%).

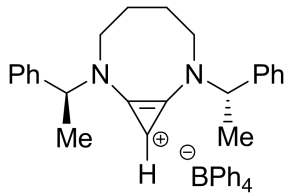
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.40–7.20 (m, 10H), 4.21 (q, *J* = 5.7 Hz, 2H), 3.58 (d, *J* = 5.7 Hz, 4H), 2.67–2.62 (m, 4H), 2.43 (brs, 2H), 1.52–1.50 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 138.7 (2C), 129.1 (4C), 128.6 (2C), 127.1 (4C), 54.3 (2C), 51.3 (2C), 43.8 (2C), 27.6 ppm.

General Procedure H **[synthesis of enantiomerically enriched BAC precursors]**

Enantiomerically enriched BACs were synthesized according to a slightly modified literature procedure.[71] Under a nitrogen atmosphere, a pre-cooled solution of the corresponding enantiomerically enriched diamine (83.0 mg, 0.28 mmol, 1.00 equiv) in CH_2Cl_2 (0.6 mL) at –78 °C was slowly added to a solution of tetrachlorocyclopropene (34.0 µL, 0.28 mmol, 1.00 equiv) in CH_2Cl_2 (5.0 mL) at –78 °C. After addition of diisopropylethylamine (98.0 µL, 0.56 mmol, 2.00 equiv), the reaction mixture was warmed to room temperature, and stirred under room temperature over three hours. Then the flask was re-cooled to –78 °C, at which stage polystyrene-bound triphenylphosphine (3.0 mmol/g; 100 mg, 0.56 mmol, 2.00 equiv) was added in one portion. The reaction mixture was warmed to room temperature over two hours before successive addition of distilled water (5 mL) and sodium tetraphenylborate (98.0 mg, 0.28 mmol, 1.00 equiv). The reaction mixture was vigorously stirred for two days before filtration and transfer of the filtrate to a separating funnel with CH_2Cl_2. After phase separation, the organic layer was successively washed with aqueous HCl (0.5 M), aqueous $NaHCO_3$ (sat), and water. The organic phase was then dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The crude product was purified by flash column chromatography on silica gel (acetone/DCM = 1:100) to obtain the pure product.

2-(*S*)-1-Phenylethyl-7-[(*S*)-1-phenylethyl]-2,7-diazabicyclo[6.1.0]non-1(8)-en-9-yliumtetraphenyl-borate (*pre-BAC–1)**



pre-BAC**–1

Prepared from **2–2** (83.0 mg, 0.28 mmol, 1.00 equiv), tetrachlorocyclopropene (34.0 µL, 0.28 mmol, 1.00 equiv), diisopropylethylamine (98.0 µL, 0.56 mmol, 2.00 equiv), polystyrene-bound triphenylphosphine (3.0 mmol/g; 100 mg, 0.56 mmol, 2.00 equiv), distilled water (5 mL) and sodium tetraphenylborate (98.0 mg, 0.28 mmol, 1.00 equiv) according to *General Procedure H*. ***pre-BAC**–1*** was purified by PTLC on silica gel (eluent: DCM/acetone = 19:1). *The obtained analytical data were in full agreement with the reported data.*[71]

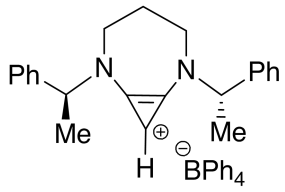
Colorless solid.
Mp. 135−138 °C (135−137 °C) [71]
Yield: 151.1 mg (83%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.50 (br s, 8H), 7.40–7.36 (m, 6H), 7.09–7.05 (m, 4H), 7.00 (t, *J* = 7.0 Hz, 8H), 6.86 (t, *J* = 7.0 Hz, 4H), 4.95 (s , 1H), 4.41 (q, *J* = 6.8 Hz, 2H), 2.73 (dd, *J* = 7.6, 12.0 Hz 2H), 2.61 (dd, *J* = 7.6, 12.0 Hz, 2H), 1.53–1.50 (m, 2H), 1.46 (d, *J* = 7.0 Hz ,6 H), 1.36–1.30 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.4 (q, *J* = 49.1 Hz, 4C), 138.2 (4C), 136.3 (2C), 132.2 (2C), 129.4 (4C), 129.0 (4C), 126.9 (8C), 125.8 (q, *J* = 2.8 Hz, 8C), 121.9 (2C), 95.5, 63.1 (2C), 48.3 (2C), 23.5 (2C), 18.6 (2C) ppm.

^{11}B NMR ($CDCl_3$, 160 MHz): δ = –5.6 (s) ppm.

2-(*S*)-1-Phenylethyl-6-[(*S*)-1-phenylethyl]-2,6-diazabicyclo[5.1.0]non-1(7)-en-8-yliumtetraphenyl-borate (*pre-BAC–2)**



pre-BAC**–2

Prepared from ***Diamine*–1** (78.9 mg, 0.28 mmol, 1.00 equiv), tetrachlorocyclopropene (34.0 µL, 0.28 mmol, 1.00 equiv), diisopropylethylamine (98.0 µL, 0.56 mmol, 2.00 equiv), polystyrene-bound triphenylphosphine (3.0 mmol/g; 100 mg, 0.56 mmol, 2.00 equiv), distilled water (5 mL) and sodium tetraphenylborate (98.0 mg, 0.28 mmol, 1.00 equiv) according to *General Procedure H*. ***pre-BAC**–2** was purified by PTLC on silica gel (eluent: DCM/acetone = 19:1).

Colorless solid (mp 130–133 °C).

Yield: 151.1 mg (83%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.48 (br s, 8H), 7.38–7.35 (m, 6H), 7.08–7.04 (m, 4H), 6.98 (t, *J* = 7.1 Hz, 8H), 6.78 (t, *J* = 7.1 Hz, 4H), 4.72 (s , 1H), 4.21 (q, *J* = 7.0 Hz, 2H), 2.67 (dd, *J* = 6.5, 14.1 Hz, 2H), 2.64 (dd, *J* = 6.5, 14.1 Hz, 2H), 1.49 (d, *J* = 7.0 Hz, 6H), 1.46–1.45 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.5 (q, *J* = 49.0 Hz, 4C), 138.1 (4C), 136.0 (2C), 132.4 (2C), 129.6 (4C), 129.3 (4C), 127.1 (8C), 125.4 (q, *J* = 2.6 Hz, 8C), 121.5 (2C), 95.1, 63.3 (2C), 48.0 (2C), 23.4, 17.9 (2C) ppm.

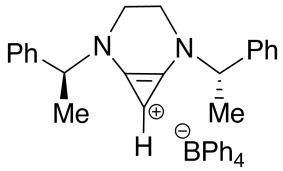
^{11}B NMR ($CDCl_3$, 160 MHz): δ = –6.1 (s) ppm.

IR (CH_2Cl_2): ν = 3097, 3058, 2987, 2836, 1892, 1610, 945, 732, 710 cm^{-1}.

HRMS (ESI): calculated for $C_{22}H_{26}N_2^+$= $[M]^+$: m/z = 318.4625, found: m/z = 318.4628.

$[\alpha]_D^{25}$ = –8.0 ° (*c* = 1.0, $CHCl_3$).

2-(*S*)-1-Phenylethyl)-5-[(*S*)-1-phenylethyl]-2,5-diazabicyclo[5.1.0]non-1(6)-en-7-yliumtetra-phenylborate (*pre-BAC–3)**



pre-BAC**–3

Prepared from ***Diamine*–2** (73.4 mg, 0.28 mmol, 1.00 equiv), tetrachlorocyclopropene (34.0 µL, 0.28 mmol, 1.00 equiv), diisopropylethylamine (98.0 µL, 0.56 mmol, 2.00 equiv), polystyrene-bound triphenylphosphine (3.0 mmol/g; 100 mg, 0.56 mmol, 2.00 equiv), distilled water (5 mL) and sodium tetraphenylborate (98.0 mg, 0.28 mmol, 1.00 equiv) according to *General Procedure H*. ***pre-BAC**–3*** was purified by PTLC on silica gel (eluent: DCM/acetone = 19:1).

Colorless solid (mp 120–122 °C).

Yield: 139.7 mg (80%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.68 (br s, 8H), 7.34–7.32 (m, 6H), 7.20–7.19 (m, 4H), 6.95 (t, *J* = 7.1 Hz, 8H), 6.73 (t, *J* = 7.1 Hz, 4H), 4.48 (s , 1H), 4.02 (q, *J* = 6.8 Hz, 2H), 2.11 (dd, *J* = 7.7, 12.2 Hz, 2H), 2.09 (dd, *J* = 7.7, 12.2 Hz, 2H), 1.25 (d, *J* = 6.8 Hz, 6H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 163.9 (q, *J* = 46.3 Hz, 4C), 137.5 (4C), 134.8 (2C), 130.2 (2C), 128.4 (4C), 128.1 (4C), 127.5 (8C), 124.6 (q, *J* = 2.9 Hz, 8C), 120.7 (2C), 92.3, 47.5 (2C), 42.7 (2C), 19.0 (2C) ppm.

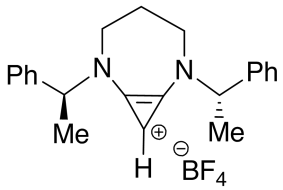
^{11}B NMR ($CDCl_3$, 160 MHz): δ = –5.9 (s) ppm.

IR (CH_2Cl_2): ν = 3123, 3092, 2992, 1867, 1621, 981, 769, 723 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{24}N_2^+$= $[M]^+$: m/z = 304.4328, found: m/z = 304.4329.

$[\alpha]_D^{25}$ = –9.0 ° (*c* = 1.0, $CHCl_3$).

2-(*S*)-1-Phenylethyl-6-[(*S*)-1-phenylethyl]-2,6-diazabicyclo[5.1.0]non-1(7)-en-8-ylium tetrafluoro-borate (*pre-BAC–7)**



pre-BAC**–7

Prepared from ***Diamine*–1** (78.9 mg, 0.28 mmol, 1.00 equiv), tetrachlorocyclopropene (34.0 µL, 0.28 mmol, 1.00 equiv), diisopropylethylamine (98.0 µL, 0.56 mmol, 2.00 equiv), polystyrene-bound triphenylphosphine (3.0 mmol/g; 100 mg, 0.56 mmol, 2.00 equiv), distilled water (5 mL) and sodium tetrafluoroborate (30.7 mg, 0.28 mmol, 1.00 equiv) according to *General Procedure H*. ***pre-BAC**–7*** was purified by PTLC on silica gel (eluent: DCM/acetone = 19:1).

Colorless solid (mp 110–115 °C).

Yield: 95.3 mg (84%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.80 (s, 1H), 7.38–7.35 (m, 6H), 7.08–7.04 (m, 4H), 4.19 (q, *J* = 7.0 Hz, 2H), 2.63–2.60 (m, 4H), 1.50 (d, *J* = 7.0 Hz, 6H), 1.48–1.46 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 136.3 (2C), 134.6 (4C), 132.2 (4C), 121.8 (2C), 95.5, 63.1 (2C), 48.3 (2C), 23.5, 18.6 (2C) ppm.

^{11}B NMR ($CDCl_3$, 160 MHz): δ = –2.0 (s) ppm.

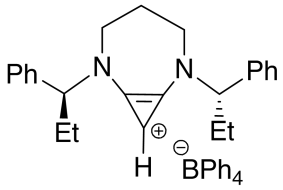
^{19}F NMR ($CDCl_3$, 128 MHz): δ = –151.8 ~ –151.8 ppm.

IR (CH_2Cl_2): ν = 3198, 3037, 2876, 2087, 1896, 1623, 984, 736 cm^{-1}.

HRMS (ESI): calculated for $C_{22}H_{26}N_2^+$= $[M]^+$: m/z = 318.4625, found: m/z = 318.4630.

$[\alpha]_D^{25}$ = –8.0 ° (*c* = 1.0, $CHCl_3$).

2-(*S*)-1-Benzylethyl-6-[(*S*)-1-benzylethyl]-2,6-diazabicyclo[5.1.0]non-1(7)-en-8-ylium tetraphenylborate (*pre-BAC–8)**



***pre-BAC**–8**

Prepared from ***Diamine*–3** (86.9 mg, 0.28 mmol, 1.00 equiv), tetrachlorocyclopropene (34.0 µL, 0.28 mmol, 1.00 equiv), diisopropylethylamine (98.0 µL, 0.56 mmol, 2.00 equiv), polystyrene-bound triphenylphosphine (3.0 mmol/g; 100 mg, 0.56 mmol, 2.00 equiv), distilled water (5 mL) and sodium tetraphenylborate (98.0 mg, 0.28 mmol, 1.00 equiv) according to *General Procedure H*. ***pre-BAC**–8** was purified by PTLC on silica gel (eluent: DCM/acetone = 19:1).

Colorless solid (mp 150–155 °C).

Yield: 165.9 mg (89%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.49 (br s, 8H), 7.40–7.38 (m, 6H), 7.09–7.04 (m, 4H), 6.99 (t, *J* = 7.1 Hz, 8H), 6.75 (t, *J* = 7.1 Hz, 4H), 4.72 (s, 1H), 4.29 (q, *J* = 7.3 Hz, 2H), 2.43–2.40 (m, 2H), 2.39–2.35 (m, 2H), 1.89–1.80 (m, 4H), 1.86–1.83 (m, 2H), 0.82 (t, *J* = 7.6 Hz, 6H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 163.8 (q, *J* = 49.2 Hz, 4C), 137.2 (4C), 135.9 (2C), 132.8 (2C), 129.9 (4C), 129.5 (4C), 126.7 (8C), 124.8 (q, *J* = 2.8 Hz, 8C), 120.8 (2C), 95.1, 62.9 (2C), 47.3 (2C), 26.2, 21.5 (2C), 18.4 (2C) ppm.

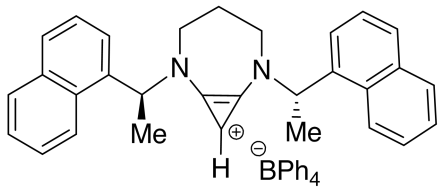
^{11}B NMR ($CDCl_3$, 160 MHz): δ = –5.8 (s) ppm.

IR (CH_2Cl_2): ν = 3098, 3052, 2987, 2876, 1887, 1610, 1486, 1376, 723, 710 cm^{-1}.

HRMS (ESI): calculated for $C_{24}H_{30}N_2^+$= $[M]^+$: m/z = 346.5187, found: m/z = 346.5191.

$[\alpha]_D^{25}$ = –5.0 ° (*c* = 1.0, $CHCl_3$).

2-(*S*)-1-(1-naphthylethyl)-6-[(*S*)-1-(1-naphthylethyl)]-2,6-diazabicyclo[5.1.0]non-1(7)-en-8-ylium tetraphenylborate (*pre-BAC–9)**



***pre-BAC**–9**

Prepared from ***Diamine*–4** (107.1 mg, 0.28 mmol, 1.00 equiv), tetrachlorocyclopropene (34.0 μL, 0.28 mmol, 1.00 equiv), diisopropylethylamine (98.0 μL, 0.56 mmol, 2.00 equiv), polystyrene-bound triphenylphosphine (3.0 mmol/g; 100 mg, 0.56 mmol, 2.00 equiv), distilled water (5 mL) and sodium tetraphenylborate (98.0 mg, 0.28 mmol, 1.00 equiv) according to *General Procedure H*. ***pre-BAC*–9*** was purified by PTLC on silica gel (eluent: DCM/acetone = 19:1).

Colorless solid (mp 160–163 °C).

Yield: 171.5 mg (83%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.95–7.91 (m, 4H), 7.90–7.71 (m, 6H), 7.57–7.54 (m, 4H), 7.50 (br s, 8H), 7.40–7.36 (m, 6H), 7.09–7.04 (m, 6H), 4.79 (s, 1H), 4.28 (q, *J* = 7.0 Hz, 2H), 3.46–3.42 (m, 2H), 3.43–3.40 (m, 2H), 1.56–1.55 (m, 2H), 1.46 (d, *J* = 7.0 Hz, 6H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.9 (q, *J* = 48.0 Hz, 4C), 138.6 (4C), 137.6 (2C), 136.7 (2C), 132.8 (2C), 132.2 (2C), 130.8 (2C), 130.6 (2C), 129.5 (2C), 128.4 (2C), 126.6 (8C), 126.4 (2C), 125.8 (q, *J* = 2.8 Hz, 8C), 124.1 (2C), 123.2 (2C), 96.5, 63.1, 49.3 (2C), 26.5 (2C), 20.6 (2C) ppm.

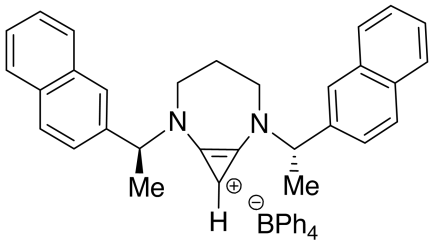
^{11}B NMR ($CDCl_3$, 160 MHz): δ = –6.5 (s) ppm.

IR (CH_2Cl_2): ν = 3098, 2963, 2873, 2564, 1639, 1420, 1387, 983, 716 cm^{-1}.

HRMS (ESI): calculated for $C_{30}H_{30}N_2^+$= $[M]^+$: m/z = 418.5764, found: m/z = 418.5768.

$[\alpha]_D^{25}$ = –10.0 ° (*c* = 1.0, $CHCl_3$).

2-(*S*)-1-(2-naphthylethyl)-6-[(*S*)-1-(2-naphthylethyl)]-2,6-diazabicyclo[5.1.0]non-1(7)-en-8-ylium tetraphenylborate (*pre-BAC–10)**



***pre-BAC**–10**

Prepared from ***Diamine*–5** (107.1 mg, 0.28 mmol, 1.00 equiv), tetrachlorocyclopropene (34.0 μL, 0.28 mmol, 1.00 equiv), diisopropylethylamine (98.0 μL, 0.56 mmol, 2.00 equiv), polystyrene-bound triphenylphosphine (3.0 mmol/g; 100 mg, 0.56 mmol, 2.00 equiv), distilled water (5 mL) and sodium tetraphenylborate (98.0 mg, 0.28 mmol, 1.00 equiv) according to *General Procedure H*. ***pre-BAC*–10*** was purified by PTLC on silica gel (eluent: DCM/acetone = 19:1).

Colorless solid (mp 162–166 °C).

Yield: 170.6 mg (82%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.95–7.90 (m, 4H), 7.90–7.72 (m, 6H), 7.58–7.54 (m, 4H), 7.52 (br s, 8H), 7.48–7.39 (m, 6H), 7.08–7.05 (m, 6H), 4.72 (s, 1H), 4.36 (q, *J* = 7.0 Hz, 2H), 3.42–3.40 (m, 2H), 3.40–3.37 (m, 2H), 1.52–1.49 (m, 2H), 1.45 (d, *J* = 7.0 Hz, 6H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 165.8 (q, *J* = 48.2 Hz, 4C), 139.6 (4C), 137.3 (2C), 135.7 (2C), 131.8 (2C), 131.0 (2C), 130.2 (2C), 129.8 (2C), 129.1 (2C), 128.0 (2C), 125.8 (8C), 125.6 (q, *J* = 2.6 Hz, 8C), 124.7 (2C), 124.0 (2C), 122.1 (2C), 97.5, 63.8, 48.7 (2C), 27.3 (2C), 22.9 (2C) ppm.

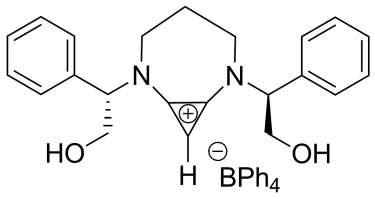
^{11}B NMR ($CDCl_3$, 160 MHz): δ = –6.2 (s) ppm.

IR (CH_2Cl_2): ν = 3108, 2966, 2880, 2568, 1645, 1423, 1389 cm^{-1}.

HRMS (ESI): calculated for $C_{30}H_{30}N_2^+$= $[M]^+$: m/z = 418.5765, found: m/z = 418.5769.

$[\alpha]_D^{25}$ = –5.0 ° (*c* = 1.0, $CHCl_3$).

2-(*S*)-1-(benzylethanol)-6-[(*S*)-1-benzylethanol]-2,6-diazabicyclo[5.1.0]non-1(7)-en-8-ylium tetraphenylborate (*pre-BAC–11)**



***pre-BAC**–11**

Prepared from ***Diamine*–6** (88.0 mg, 0.28 mmol, 1.00 equiv), tetrachlorocyclopropene (34.0 µL, 0.28 mmol, 1.00 equiv), diisopropylethylamine (98.0 µL, 0.56 mmol, 2.00 equiv), polystyrene-bound triphenylphosphine (3.0 mmol/g; 100 mg, 0.56 mmol, 2.00 equiv), distilled water (5 mL), and sodium tetraphenylborate (98.0 mg, 0.28 mmol, 1.00 equiv) according to *General Procedure H*. ***Pre-BAC**–11** was purified by flash column chromatography on silica gel (eluent: DCM/acetone = 19:1).

Colorless solid (mp 213–218 °C).

Yield: 159 mg (85%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.45 (br s, 13H), 7.40–7.35 (m, 7H), 7.07–7.04 (m, 4H), 7.01–6.98 (m, 3H), 6.85 (dd, *J* = 7.1, 7.1 Hz, 3H), 5.61 (br s, OH, 2H), 4.92 (s, 1H), 3.81 (dd, *J* = 8.1, 4.1 Hz, 2H), 3.73 (dd, *J* = 10.9, 4.1 Hz, 2H), 3.62 (dd, *J* = 10.9, 8.1 Hz, 2H), 2.65–2.53 (m, 4H), 1.72–1.67 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.5 (q, *J* = 49.0 Hz, 4C), 138.6 (4C), 136.5 (2C), 133.4 (4C), 129.2 (4C), 128.5 (2C), 127.5 (8C), 125.1 (q, *J* = 2.8 Hz, 8C), 120.7 (2C), 92.7, 61.9 (2C), 46.4 (2C), 26.8 (2C), 24.7 ppm.

^{11}B NMR ($CDCl_3$, 128 MHz): δ = –6.9 (s) ppm.

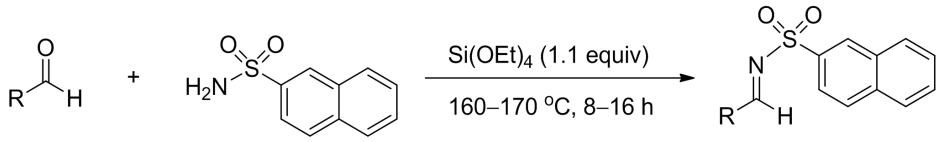
IR (neat): ν = 3284, 3065, 2931, 2890, 2865, 2456, 1656, 1640, 1486, 1343, 1107 cm^{-1}.

HRMS (ESI): calculated for $C_{22}H_{25}N_2O_2^+$ = $[M]^+$: m/z = 349.4562, found: m/z = 349.4567.

$[\alpha]_D^{25}$ = –6.0 ° (*c* = 1.0, $CHCl_3$).

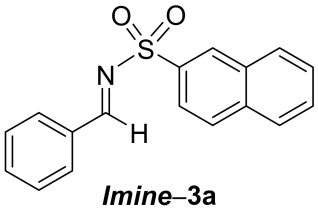
5.3.2 Preparation of *Imine* 3a-b'

General Procedure B[54]



To an oven-dried 50 mL round-bottom flask with a magnetic stirring bar under an argon atmosphere were added 2-naphthalene sulfonamide (1.00 equiv), tetraethyl orthosilicate (1.10 equiv), and the respective aldehyde (1.00 equiv). The flask was connected to a short distillation head (approximately 3–4 cm long) and a receptor flask. The reaction mixture was heated at 160–170 °C for 8–16 hours, and the by-product, ethanol, was collected in the receptor flask. After confirming the end-point of the reaction by ^{1}H NMR spectroscopic analysis, the reaction mixture was cooled to room temperature, and washed with hexane (10 mL). The mixture was filtered, and volatiles were removed *in vacuo* to give the crude imine, which was recrystallized from ethyl acetate to yield the corresponding pure imine, which was powered and dried over 4Å MS in DCM prior to use in catalysis.

2-Naphthalene-(*N*-benzylidene)sulfonamide (*Imine*–3a) [54]



***Imine*–3a**

Prepared from benzaldehyde (5.84 g, 55.0 mmol, 1.10 equiv), 2-naphthalene sulfonamide (10.4 g, 50.0 mmol, 1.00 equiv), and $Si(OEt)_4$ (11.5 g, 55.0 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3a** was recrystallized from EtOAc (10 mL). *The obtained analytical data were in full agreement with the reported data*. [54]

Colorless solid.

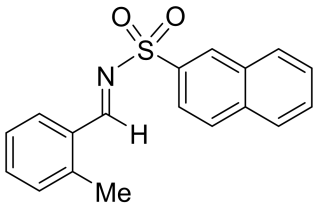
Mp. 175−176 °C (174−176 °C) [54]

Yield: 13.9 g (95%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.12 (s, 1H), 8.61 (s, 1H), 8.01–7.94 (m, 6H), 7.65–7.61 (m, 3H), 7.50–7.49 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 170.5, 135.3, 135.1, 133.6, 132.9, 132.7, 131.4, 130.8, 130.0, 129.7, 129.4, 129.2 (2C), 127.9 (2C), 127.6, 122.9 ppm.

2-Naphthalene-[*N*-(2-methylbenzylidene)]sulfonamide (*Imine*–3b)



***Imine*–3b**

Prepared from 2-methylbenzaldehyde (2.17 g, 17.7 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.30 g, 16.1 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.69 g, 17.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3b** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 176–180 °C).

Yield: 4.82 g (95%).

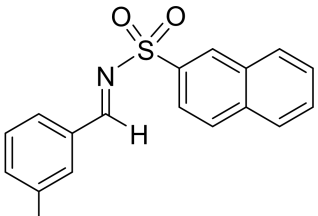
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.45 (s, 1H), 8.63 (s, 1H), 8.06–7.97 (m, 4H), 7.94–7.92 (m, 1H), 7.70–7.68 (m, 1H), 7.63–7.61 (m, 1H), 7.50–7.48 (m, 1H), 7.32–7.29 (m, 2H), 2.64 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 169.1, 142.4, 135.4, 135.3, 134.7, 132.4, 131.6, 130.8, 130.5, 129.5, 129.4, 129.2, 127.9, 127.6, 126.7, 126.5, 123.0, 19.7 ppm.

IR (CH_2Cl_2): ν = 3115, 3034, 3021, 2990, 2941, 1894, 1731, 1559, 1433, 1387, 1180, 1162, 1134, 1123, 752, 723, 691 cm^{-1}.

HRMS (ESI): calculated for $C_{18}H_{15}NaNO_2S$ = $[M+Na]^+$: m/z = 332.1896, found: m/z = 332.1890.

2-Naphthalene-[*N*-(3-methylbenzylidene)]sulfonamide (*Imine*–3c)



***Imine*–3c**

Prepared from 3-methylbenzaldehyde (2.17 g, 17.7 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.30 g, 16.1 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.69 g, 17.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3c** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 175–180 °C).

Yield: 4.72 g (93%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.48 (s, 1H), 8.62 (s, 1H), 8.02–7.92 (m, 4H), 7.86 (d, *J* = 8.6 Hz, 2H), 7.70–7.67 (m, 2H), 7.61–7.58 (m, 2H), 2.82 (s, 3H) ppm.

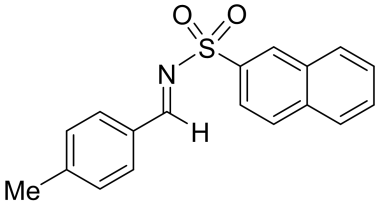
^{13}C NMR ($CDCl_3$, 125 MHz): δ = 169.3, 146.5, 135.4, 134.9, 134.1, 133.6, 132.3, 130.5, 128.5, 128.4, 128.2, 127.8, 127.6, 127.5, 126.6, 126.5, 123.5, 23.9 ppm.

IR (CH_2Cl_2): ν = 3120, 3051, 3035, 2987, 2952, 1884, 1743, 1569, 1447, 1392, 1194, 1141, 1138,

1120, 751, 725, 692 cm^{-1}.

HRMS (ESI): calculated for $C_{18}H_{15}NaNO_2S$ = $[M+Na]^+$: m/z = 332.1896, found: m/z = 332.1894.

2-Naphthalene-[*N*-(4-methylbenzylidene)]sulfonamide (*Imine*–3d)



***Imine*–3d**

Prepared from 4-methylbenzaldehyde (2.17 g, 17.7 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.30 g, 16.1 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.69 g, 17.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3d** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 175–180 °C).

Yield: 4.74 g (94%).

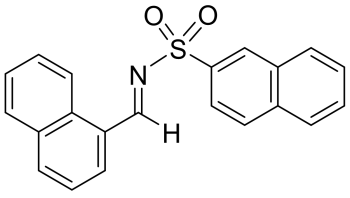
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.04 (s, 1H), 8.62 (s, 1H), 8.03–7.99 (m, 3H), 7.94–7.92 (m, 3H), 7.65 (d, *J* = 8.4 Hz, 2H), 6.99 (d, *J* = 8.4 Hz, 2H), 2.66 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 169.6, 145.4, 135.7, 135.2, 133.8, 132.2, 129.3 (2C), 129.1, 129.0 (2C), 127.9, 127.6, 127.5, 125.3, 123.8, 114.7, 25.6 ppm.

IR (CH_2Cl_2): ν = 3123, 3054, 3040, 2989, 2954, 1891, 1763, 1578, 1421, 1384, 1169, 1139, 1123, 754, 722, 697 cm^{-1}.

HRMS (ESI): calculated for $C_{18}H_{15}NaNO_2S$ = $[M+Na]^+$: m/z = 332.1896, found: m/z = 332.1892.

2-Naphthalene-[*N*-(1-naphthalenyl)methylene]sulfonamide (*Imine*–3e)



***Imine*–3e**

Prepared from 1-naphthaldehyde (2.82 g, 18.0 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.44 g, 16.4 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.75 g, 18.0 mmol, 1.10 equiv) according to *General Procedure B* at 170 °C for 16 h. ***Imine*–3e** was recrystallized from EtOAc (10 mL).

Light yellow solid (mp 192–195 °C).

Yield: 5.26 g (92%).

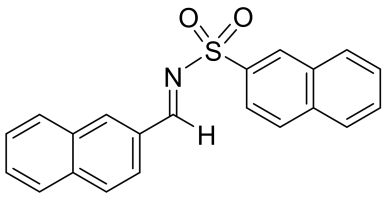
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.71 (s, 1H), 9.02 (s, 1H), 8.67–8.65 (m, 1H), 8.18 (d, *J* = 8.4 Hz, 1H), 8.14 (d, *J* = 8.2 Hz, 1H), 8.03–7.99 (m, 3H), 7.94 (d, *J* = 8.4 Hz, 2H), 7.68–7.57 (m, 5H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 170.2, 136.2, 135.4, 133.6, 132.8, 132.4, 130.8, 130.7, 129.1, 128.3, 128.2, 128.1, 127.8, 127.7, 127.5, 126.7, 126.6, 126.5, 126.4, 124.5, 123.5 ppm.

IR (CH_2Cl_2): ν = 3120, 3067, 3013, 2978, 2936, 1981, 1741, 1564, 1428, 1378, 1205, 1178, 1137, 1121, 751, 724, 698 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{15}NaNO_2S$ = $[M+Na]^+$: m/z = 368.5247, found: m/z = 368.5252.

2-Naphthalene-[*N*-(2-naphthalenyl)methylene]sulfonamide (*Imine*–3f)



***Imine*–3f**

Prepared from 2-naphthaldehyde (2.82 g, 18.0 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.44 g, 16.4 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.75 g, 18.0 mmol, 1.10 equiv) according to *General Procedure B* at 170 °C for 16 h. ***Imine*–3f** was recrystallized from EtOAc (10 mL).

Light yellow solid (mp 193–195 °C).

Yield: 5.32 g (94%).

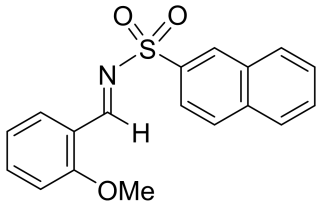
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.26 (s, 1H), 8.65 (s, 1H), 8.36 (s, 1H), 8.08–8.03 (m, 2H), 7.97–7.87 (m, 5H), 7.68–7.62 (m, 3H), 7.60–7.57 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 170.5, 136.6, 136.3, 135.3, 135.2, 132.7, 132.2, 130.1, 129.7, 129.6, 129.5, 129.4, 129.3, 129.2, 128.1, 127.9, 127.8, 127.6, 127.3, 124.2, 123.0 ppm.

IR (CH_2Cl_2): ν = 3119, 3074, 3025, 2991, 2974, 2924, 1985, 1747, 1558, 1436, 1371, 1214, 1184, 1169, 1114, 759, 736, 691 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{15}NaNO_2S$ = $[M+Na]^+$: m/z = 368.5247, found: m/z = 368.5250.

2-Naphthalene-[*N*-(2-methoxybenzylidene)]sulfonamide (*Imine*–3g)



***Imine*–3g**

Prepared from 2-methoxy benzaldehyde (2.59 g, 19.0 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.65 g, 17.3 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.96 g, 19.0 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3g** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 184–187 °C).

Yield: 5.17 g (90%).

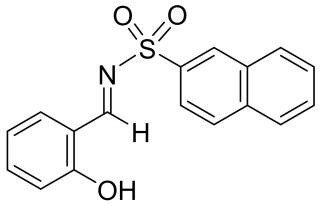
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.64 (s, 1H), 8.60 (s, 1H), 8.06–8.04 (m, 1H), 7.98–7.95 (m, 3H), 7.90–7.88 (m, 1H), 7.64–7.60 (m, 2H), 7.59–7.57 (m, 1H), 6.97–6.95 (m, 2H), 3.93 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 166.7, 161.8, 142.3, 136.9, 135.6, 135.1, 132.2, 131.9, 130.5, 129.4, 129.3, 129.0, 127.9, 123.0, 121.0, 120.9, 111.5, 55.7 ppm.

IR (CH_2Cl_2): ν = 3123, 3062, 3037, 2989, 2971, 2936, 1989, 1752, 1564, 1440, 1381, 1246, 1219, 1191, 1175, 1123, 1051, 753, 739, 695 cm^{-1}.

HRMS (ESI): calculated for $C_{18}H_{15}NaNO_3S$ = $[M+Na]^+$: m/z = 348.2808, found: m/z = 348.2814.

2-Naphthalene-[*N*-(2-hydroxybenzylidene)]sulfonamide (*Imine*–3h)



***Imine*–3h**

Prepared from 2-hydroxy benzaldehyde (2.33 g, 19.0 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.77 g, 18.2 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.96 g, 19.0 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3h** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 171–175 °C).

Yield: 5.03 g (89%).

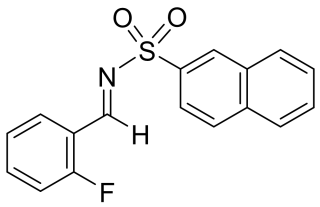
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 10.8 (s, 1H), 9.16 (s, 1H), 8.59 (s, 1H), 7.99–7.97 (m, 2H), 7.92–7.90 (m, 2H), 7.67-7.64 (m, 2H), 7.56-7.51 (m, 2H), 7.01-6.98 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 171.8, 162.3, 137.5, 135.5, 135.4, 134.9, 132.2, 129.8, 129.7, 129.5, 129.4, 128.0, 127.8, 122.5, 120.4, 118.0, 116.7 ppm.

IR (CH_2Cl_2): ν = 3121, 3058, 3042, 2993, 2982, 2931, 1875, 1739, 1569, 1434, 1381, 1356, 1246, 1182, 1154, 1130, 750, 723, 696 cm^{-1}.

HRMS (ESI): calculated for $C_{17}H_{13}NaNO_3S$ = $[M+Na]^+$: m/z = 357.1568, found: m/z = 357.1572.

2-Naphthalene-[*N*-(2-fluorobenzylidene)]sulfonamide (*Imine*–3i)



***Imine*–3i**

Prepared from 2-fluoro benzaldehyde (0.24 g, 2.04 mmol, 1.10 equiv), 2-naphthalene sulfonamide (0.38 g, 1.85 mmol, 1.00 equiv), and $Si(OEt)_4$ (0.43 g, 2.04 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3i** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 168–171 °C).

Yield: 0.56 g (96%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.45 (s, 1H), 8.62 (s, 1H), 8.10–8.08 (m, 1H), 8.03–8.01 (m, 2H), 8.00–7.98 (m, 1H), 7.93 (d, *J* = 7.7 Hz, 1H), 7.70–7.60 (m, 3H), 7.22–7.17 (m, 1H), 7.16–7.15 (m, 1H) ppm.

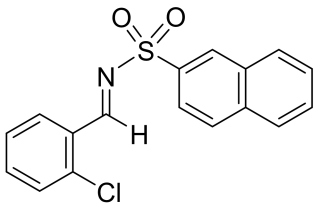
^{13}C NMR ($CDCl_3$, 125 MHz): δ = 165.2, 164.0 (d, *J* = 238.3 Hz), 163.5, 137.1 (d, *J* = 9.2 Hz), 135.4, 134.7, 132.2, 129.8, 129.5 (d, *J* = 6.4 Hz), 129.4, 129.3, 127.9, 127.7, 124.9 (d, *J* = 17.0 Hz), 122.9, 120.5 (d, *J* = 8.6 Hz), 116.4 (d, *J* = 20.6 Hz) ppm.

^{19}F NMR ($CDCl_3$, 128 MHz): δ = –116.0 ~ –115.9 (m) ppm.

IR (CH_2Cl_2): ν = 3122, 3059, 3026, 2981, 2939, 1880, 1737, 1568, 1438, 1355, 1188, 1157, 1138, 1118, 1058, 1031, 750, 721, 696 cm^{-1}.

HRMS (ESI): calculated for $C_{17}H_{12}FNaNO_2S$ = $[M+Na]^+$: m/z = 336.2168, found: m/z = 336.2174.

2-Naphthalene-[*N*-(2-chlorobenzylidene)]sulfonamide (*Imine*–3j)



***Imine*–3j**

Prepared from 2-chloro benzaldehyde (2.32 g, 19.7 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.74 g, 17.9 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.11 g, 19.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3j** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 178–181 °C).

Yield: 5.50 g (93%).

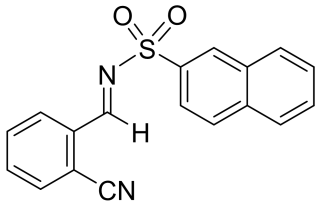
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.59 (s, 1H), 8.62 (s, 1H), 8.16–8.14 (m, 1H), 8.00–7.98 (m, 2H), 7.96–7.92 (m, 1H), 7.87 (d, *J* = 8.6 Hz, 1H), 7.68–7.64 (m, 2H), 7.52–7.50 (m, 1H), 7.48–7.47 (m, 1H), 7.32–7.30 (m, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 167.2, 139.1, 135.7, 135.4, 134.9, 133.7, 132.7, 132.4, 129.5, 129.3, 129.1, 128.3, 128.2, 128.0, 127.7, 127.4, 123.0 ppm.

IR (CH_2Cl_2): ν = 3125, 3069, 3031, 2994, 2943, 1878, 1754, 1561, 1434, 1352, 1197, 1151, 1136, 756, 727, 698 cm^{-1}.

HRMS (ESI): calculated for $C_{17}H_{12}ClNaNO_2S$ = $[M+Na]^+$: m/z = 352.1396, found: m/z = 352.1394.

2-Naphthalene-[*N*-(2-cyanobenzylidene)]sulfonamide (*Imine*–3k)



***Imine*–3k**

Prepared from 2-cyano benzaldehyde (2.16 g, 18.2 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.53 g, 16.5 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.79 g, 18.2 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3k** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 170–173 °C).

Yield: 4.54 g (85%).

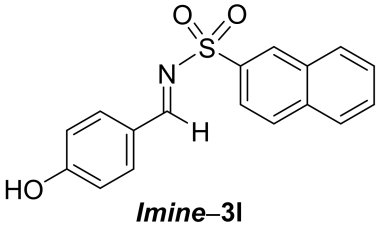
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.82 (s, 1H), 8.45 (s, 1H), 8.09–8.00 (m, 3H), 7.96 (d, *J* = 8.4 Hz, 2H), 7.87 (d, *J* = 8.4 Hz, 1H), 7.81 (d, *J* = 8.4 Hz, 1H), 7.78–7.73 (m, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.4, 143.5, 136.1, 135.4, 133.6, 132.4, 130.3, 130.1, 129.9, 129.6, 128.3, 127.8, 127.7, 127.5, 126.5, 123.5, 116.0, 112.5 ppm.

IR (CH_2Cl_2): ν = 3126, 3058, 3047, 2984, 2936, 2234, 1857, 1739, 1559, 1458, 1350, 1189, 1156, 1139, 752, 721, 697 cm^{-1}.

HRMS (ESI): calculated for $C_{18}H_{12}NaN_2O_2S$ = $[M+Na]^+$: m/z = 343.2654, found: m/z = 343.2659.

2-Naphthalene-[*N*-(4-hydroxybenzylidene)]sulfonamide (*Imine*–3l)



***Imine*–3l**

Prepared from 4-hydroxy benzaldehyde (2.33 g, 19.0 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.77 g, 18.2 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.96 g, 19.0 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3l** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 171–175 °C).

Yield: 5.16 g (90%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.10 (s, 1H), 8.47 (s, 1H), 7.96 (d, *J* = 8.4 Hz, 1H), 7.91 (d, *J* = 8.4 Hz, 1H), 7.79 (d, *J* = 7.8 Hz, 1H), 7.76 (d, *J* = 7.8 Hz, 1H), 7.74–7.72 (m, 1H), 7.70–7.68 (m, 1H), 7.51–7.49 (m, 2H), 7.13–7.12 (m, 2H), 6.91 (br s, 1H) ppm.

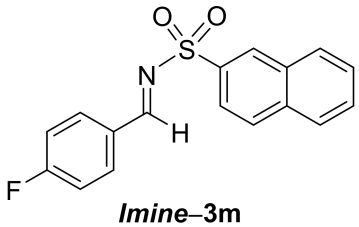
^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.3, 157.8, 135.4, 133.6, 132.8, 132.4, 128.7, 128.4 (2C), 128.2, 127.7, 127.5 (2C), 126.7, 126.5, 123.5, 115.0 ppm.

IR (CH_2Cl_2): ν = 3123, 3055, 3039, 2987, 2980, 2678, 1874, 1785, 1543, 1497, 1374, 1349, 1251,

1190, 1147, 1133, 755, 734, 692 cm^{-1}.

HRMS (ESI): calculated for $C_{17}H_{13}NaNO_3S$ = $[M+Na]^+$: m/z = 357.1568, found: m/z = 357.1570.

2-Naphthalene-[*N*-(4-fluorobenzylidene)]sulfonamide (*Imine*–3m)



***Imine*–3m**

Prepared from 4-fluoro benzaldehyde (0.24 g, 2.04 mmol, 1.10 equiv), 2-naphthalene sulfonamide (0.38 g, 1.85 mmol, 1.00 equiv), and $Si(OEt)_4$ (0.43 g, 2.04 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3m** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 170–172 °C).

Yield: 0.61 g (97%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.07 (s, 1H), 8.60 (s, 1H), 8.00–7.94 (m, 3H), 7.91 (d, *J* = 8.4 Hz, 2H), 7.79 (d, *J* = 8.4 Hz, 2H), 7.68–7.66 (m, 2H), 7.62–7.61 (m, 1H) ppm.

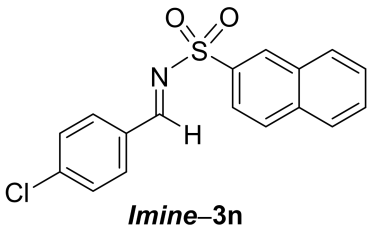
^{13}C NMR ($CDCl_3$, 125 MHz): δ = 168.9, 167.8 (d, *J* = 245.3 Hz), 135.3, 135.0, 133.9 (d, *J* = 21.0 Hz, 2C), 132.2, 129.7, 129.5, 129.4 (d, *J* = 3.3 Hz), 129.3, 127.9, 127.6, 126.4, 123.5, 116.5 (d, *J* = 7.7 Hz, 2C) ppm.

^{19}F NMR ($CDCl_3$, 128 MHz): δ = –115.5 ~ –115.0 (m) ppm.

IR (CH_2Cl_2): ν = 3121, 3062, 3027, 2980, 2936, 1884, 1740, 1567, 1439, 1358, 1190, 1159, 1137, 1120, 1056, 1034, 752, 727, 694 cm^{-1}.

HRMS (ESI): calculated for $C_{17}H_{12}FNaNO_2S$ = $[M+Na]^+$: m/z = 336.2168, found: m/z = 336.2170.

2-Naphthalene-[*N*-(4-chlorobenzylidene)]sulfonamide (*Imine*–3n)



***Imine*–3n**

Prepared from 4-chloro benzaldehyde (2.32 g, 19.7 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.74 g, 17.9 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.11 g, 19.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3n** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 177–181 °C).

Yield: 5.55 g (93%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.07 (s, 1H), 8.61 (s, 1H), 8.01–8.00 (m, 2H), 7.98–7.96 (m, 2H),

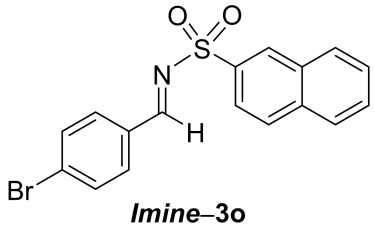
7.90–7.88 (m, 2H), 7.68 (d, *J* = 8.6 Hz, 2H), 7.48 (d, *J* = 8.6 Hz, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 167.2, 139.1, 135.7, 135.4, 134.9, 133.7, 132.7, 132.4, 129.5 (2C), 129.3, 128.3, 128.2, 127.7 (2C), 127.4, 123.0 ppm.

IR (CH_2Cl_2): ν = 3122, 3068, 3035, 2991, 2956, 1884, 1769, 1557, 1467, 1358, 1191, 1155, 1139, 754, 721, 695 cm^{-1}.

HRMS (ESI): calculated for $C_{17}H_{12}ClNaNO_2S$ = $[M+Na]^+$: m/z = 352.1396, found: m/z = 352.1399.

2-Naphthalene-[*N*-(4-bromobenzylidene)]sulfonamide (*Imine*–3o)



***Imine*–3o**

Prepared from 4-bromo benzaldehyde (1.30 g, 6.50 mmol, 1.10 equiv), 2-naphthalene sulfonamide (1.31 g, 5.90 mmol, 1.00 equiv), and $Si(OEt)_4$ (1.36 g, 6.50 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3o** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 187–189 °C).

Yield: 2.12 g (96%).

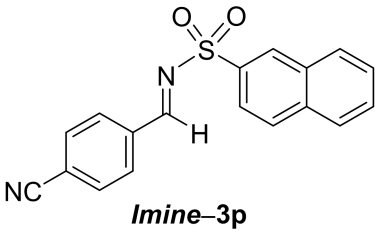
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.10 (s, 1H), 8.58 (s, 1H), 8.05 (d, *J* = 8.5 Hz, 2H), 7.95 (d, *J* = 8.5 Hz, 2H), 7.91 (d, *J* = 7.5 Hz, 1H), 7.78 (d, *J* = 8.4 Hz, 1H), 7.75 (dd, *J* = 7.5, 7.8 Hz, 1H), 7.73 (dd, *J* = 7.5, 7.8 Hz, 1H), 7.70 (d, *J* = 7.8 Hz, 1H), 7.58 (d, *J* = 8.4 Hz, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.1, 141.3, 135.5, 133.6, 132.7, 132.4, 131.9, 129.3, 128.8 (2C), 128.2, 127.7, 127.5 (2C), 126.5, 124.0, 123.4 ppm.

IR (CH_2Cl_2): ν = 3121, 3063, 3038, 3001, 2961, 1890, 1767, 1569, 1464, 1361, 1199, 1157, 1145, 756, 727, 693 cm^{-1}.

HRMS (ESI): calculated for $C_{17}H_{12}BrNaNO_2S$ = $[M+Na]^+$: m/z = 396.0841, found: m/z = 396.0845.

2-Naphthalene-[*N*-(4-cyanobenzylidene)]sulfonamide (*Imine*–3p)



***Imine*–3p**

Prepared from 4-cyano benzaldehyde (2.16 g, 18.2 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.53 g, 16.5 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.79 g, 18.2 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3p** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 171–175 °C).

Yield: 4.86 g (87%).

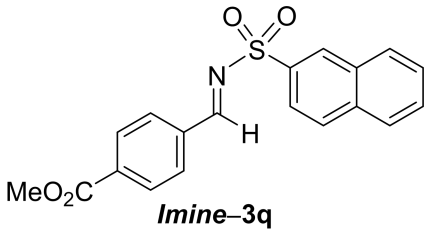
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.85 (s, 1H), 8.59 (s, 1H), 8.18 (d, *J* = 8.4 Hz, 2H), 8.10 (d, *J* = 8.4 Hz, 1H), 8.00 (d, *J* = 7.4 Hz, 1H), 7.97 (d, *J* = 8.4 Hz, 1H), 7.81 (d, *J* = 8.4 Hz, 2H), 7.78 (dd, *J* = 7.4, 7.9 Hz, 1H), 7.72 (d, *J* = 7.9 Hz, 1H), 7.55 (dd, *J* = 7.4, 7.9 Hz, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.2, 142.3, 140.1, 135.4, 133.6, 133.1, 132.7, 132.3, 128.3, 128.1, 127.8 (2C), 127.7, 127.5, 126.5 (2C), 123.5, 118.6 ppm.

IR (CH_2Cl_2): ν = 3123, 3061, 3049, 2991, 2939, 2240, 1856, 1741, 1567, 1459, 1356, 1162, 1151, 1137, 756, 722, 695 cm^{-1}.

HRMS (ESI): calculated for $C_{18}H_{12}NaN_2O_2S$ = $[M+Na]^+$: m/z = 343.2654, found: m/z = 343.2658.

2-Naphthalene-[*N*-(4-methoxycarbonyl)benzylidene)]sulfonamide (*Imine*–3q)



***Imine*–3q**

Prepared from methyl 4-formylbenzoate (1.11 g, 6.80 mmol, 1.10 equiv), 2-naphthalene sulfonamide (1.36 g, 6.20 mmol, 1.00 equiv), and $Si(OEt)_4$ (1.42 g, 6.80 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 12 h. ***Imine*–3q** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 192–195 °C).

Yield: 2.06 g (93%).

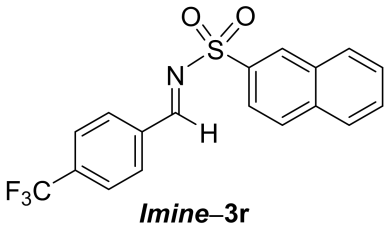
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.14 (s, 1H), 8.62 (s, 1H), 8.14 (d, *J* = 8.4 Hz, 2H), 8.03–7.98 (m, 3H), 7.95 (d, *J* = 8.4 Hz, 2H), 7.69–7.61 (m, 3H), 3.94 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 166.1, 163.0, 143.2, 135.4, 133.6, 132.7, 132.4, 130.7, 128.4, 128.2, 127.8 (2C), 127.7, 127.4, 126.4 (2C), 125.9, 123.5, 52.3 ppm.

IR (CH_2Cl_2): ν = 3121, 3058, 3046, 2989, 2937, 1878, 1746, 1737, 1562, 1454, 1352, 1280, 1167, 1159, 1138, 751, 728, 693 cm^{-1}.

HRMS (ESI): calculated for $C_{19}H_{15}NaNO_4S$ = $[M+Na]^+$: m/z = 376.2745, found: m/z = 376.2749.

2-Naphthalene-[*N*-(4-trifluoromethylbenzylidene)]sulfonamide (*Imine*–3r)



***Imine*–3r**

Prepared from 4-trifluoromethyl benzaldehyde (0.99 g, 5.70 mmol, 1.00 equiv), 2-naphthalene sulfonamide (1.14 g, 5.20 mmol, 1.00 equiv), and $Si(OEt)_4$ (1.19 g, 5.70 mmol, 1.10 equiv) according

to *General Procedure B* at 160 °C for 12 h. ***Imine*–3r** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 198–200 °C).

Yield: 1.74 g (92%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.19 (s, 1H), 8.69 (s, 1H), 8.05 (d, *J* = 8.4 Hz, 2H), 8.00 (d, *J* = 7.5 Hz, 1H), 7.98 (d, *J* = 8.4 Hz, 1H), 7.96 (d, *J* = 8.4 Hz, 2H), 7.81 (d, *J* = 8.4 Hz, 1H), 7.79 (d, *J* = 7.4 Hz, 1H), 7.76 (dd, *J* = 7.4, 7.5 Hz, 1H), 7.73–7.72 (m, 1H) ppm.

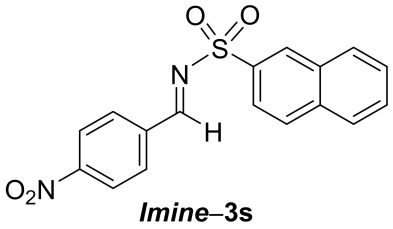
^{13}C NMR ($CDCl_3$, 125 MHz): δ = 168.2, 153.2, 144.7, 135.4, 134.6 (q, *J* = 271.1 Hz), 133.7, 133.5, 132.8, 131.9 (q, *J* = 1.3 Hz), 130.4, 129.7 (q, *J* = 3.9 Hz, 2C), 128.4, 127.9, 125.4 (q, *J* = 17.8 Hz, 2C), 120.6 (q, *J* = 32.3 Hz), 120.0 ppm.

^{19}F NMR ($CDCl_3$, 128 MHz): δ = –71.9 (s) ppm.

IR (CH_2Cl_2): ν = 3124, 3062, 3028, 2982, 2943, 1882, 1741, 1570, 1479, 1458, 1365, 1323, 1162, 1153, 1062, 1043, 723, 697 cm^{-1}.

HRMS (ESI): calculated for $C_{18}H_{12}F_3NaNO_2S$ = $[M+Na]^+$: m/z = 386.2546, found: m/z = 386.2551.

2-Naphthalene-[*N*-(4-nitrobenzylidene)]sulfonamide (*Imine*–3s)



***Imine*–3s**

Prepared from 4-nitro benzaldehyde (2.76 g, 18.1 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.47 g, 16.5 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.78 g, 18.1 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3s** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 195–198 °C).

Yield: 5.14 g (91%).

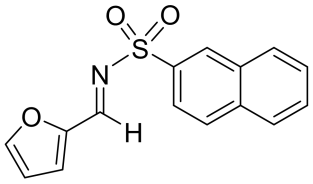
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.26 (s, 1H), 8.49 (s, 1H), 8.17 (d, *J* = 8.8 Hz, 2H), 8.09–8.07 (m, 1H), 8.01 (d, *J* = 7.5 Hz, 1H), 8.00 (d, *J* = 7.4 Hz, 1H), 7.97 (d, *J* = 8.8 Hz, 2H), 7.81–7.79 (m, 1H), 7.79 (dd, *J* = 7.4, 7.5 Hz, 1H), 7.76–7.74 (m, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 163.8, 148.0, 135.8, 133.6, 132.7, 132.4, 130.6, 129.1, 128.5, 128.2, 127.7, 127.5 (2C), 125.9 (2C), 124.0, 123.5 ppm.

IR (CH_2Cl_2): ν = 3122, 3057, 3030, 2984, 2938, 1878, 1739, 1559, 1548, 1471, 1459, 1365, 1354, 1331, 1160, 1157, 1062, 1046, 728, 692 cm^{-1}.

HRMS (ESI): calculated for $C_{17}H_{12}NaN_2O_4S$ = $[M+Na]^+$: m/z = 363.1568, found: m/z = 363.1572.

2-Naphthalene-[*N*-(2-furanylmethylene)]sulfonamide (*Imine*–3t)



***Imine*–3t**

Prepared from 2-furaldehyde (2.10 g, 20.8 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.92 g, 18.9 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.34 g, 20.8 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 10 h. ***Imine*–3t** was recrystallized from EtOAc (10 mL).

Grey solid (mp 168–170 °C).

Yield: 5.10 g (95%).

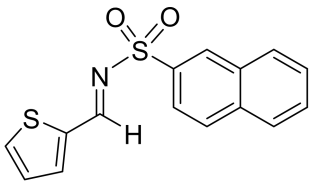
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.24 (s, 1H), 8.63 (s, 1H), 8.21 (d, *J* = 1.8 Hz, 1H), 7.96–7.94 (m, 1H), 7.91 (d, *J* = 8.6 Hz, 1H), 7.89 (d, *J* = 8.6 Hz, 1H), 7.85–7.83 (m, 1H), 7.78–7.76 (m, 1H), 7.72–7.70 (m, 1H), 7.65 (d, *J* = 3.5 Hz, 1H), 6.62 (dd, *J* = 1.8, 3.5 Hz, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.5, 150.6, 146.6, 143.3, 135.4, 133.6, 132.3, 128.3, 128.1, 127.7, 127.3, 126.5, 123.5, 112.4, 109.5 ppm.

IR (CH_2Cl_2): ν = 3120, 3057, 2981, 2954, 1876, 1742, 1545, 1478, 1462, 1369, 1358, 1340, 1158, 1069, 1048, 735, 691 cm^{-1}.

HRMS (ESI): calculated for $C_{15}H_{11}NaNO_3S$ = $[M+Na]^+$: m/z = 308.2514, found: m/z = 308.2519.

2-Naphthalene-[*N*-(2-thienylmethylene)]sulfonamide (*Imine*–3u)



***Imine*–3u**

Prepared from 2-thienyl aldehyde (2.32 g, 20.7 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.88 g, 18.8 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.34 g, 20.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 10 h. ***Imine*–3u** was recrystallized from EtOAc (10 mL).

Grey solid (mp 174–178 °C).

Yield: 5.06 g (90%).

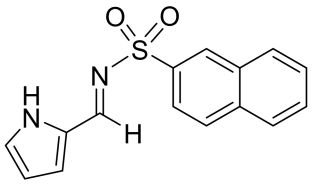
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.20 (s, 1H), 8.60 (s, 1H), 8.01–7.99 (m, 2H), 7.95–7.92 (m, 2H), 7.80 (d, *J* = 7.9 Hz, 1H), 7.78 (d, *J* = 7.3 Hz, 1H), 7.68–7.61 (m, 2H), 7.22 (dd, *J* = 7.3, 7.9 Hz, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 163.2, 146.6, 143.7, 135.5, 133.6, 132.4, 131.9, 130.2, 128.5, 128.2, 127.8, 127.6, 127.5, 126.5, 123.5 ppm.

IR (CH_2Cl_2): ν = 3123, 3003, 2943, 1879, 1740, 1564, 1440, 1375, 1156, 1142, 748, 724, 694 cm^{-1}.

HRMS (ESI): calculated for $C_{15}H_{11}NaNO_2S_2$ = $[M+Na]^+$: m/z = 324.2256, found: m/z = 324.2260.

2-Naphthalene-[*N*-(1*H*-pyrrol-2-ylmethylene)]sulfonamide (*Imine*–3v)



***Imine*–3v**

Prepared from 2-pyrrolyl aldehyde (2.12 g, 22.1 mmol, 1.10 equiv), 2-naphthalene sulfonamide (4.26 g, 20.1 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.63 g, 22.1 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3v** was recrystallized from EtOAc (10 mL).

Grey solid (mp 167–169 °C).

Yield: 4.86 g (85%).

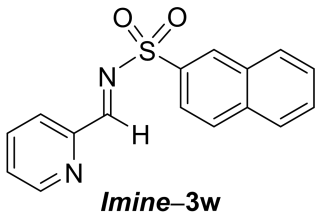
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.22 (s, 1H), 8.65 (s, 1H), 8.01 (d, *J* = 2.1 Hz, 1H), 7.95–7.94 (m, 1H), 7.91 (d, *J* = 8.6 Hz, 1H), 7.88 (d, *J* = 8.6 Hz, 1H), 7.83 (d, *J* = 7.9 Hz, 1H), 7.77 (d, *J* = 7.3 Hz, 1H), 7.48 (d, *J* = 3.5 Hz, 1H), 7.73 (dd, *J* = 7.3, 7.9 Hz, 1H), 6.36 (dd, *J* = 2.1, 3.5 Hz, 1H), 6.21 (br s, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 162.3, 146.7, 137.5, 135.4, 133.6, 132.4, 128.4, 128.2, 127.8, 127.5, 126.8, 123.5, 123.4, 111.9, 110.3 ppm.

IR (CH_2Cl_2): ν = 3121, 3012, 2954, 1883, 1754, 1569, 1441, 1379, 1161, 1148, 754, 721, 696 cm^{-1}.

HRMS (ESI): calculated for $C_{15}H_{12}NaN_2O_2S$ = $[M+Na]^+$: m/z = 307.2696, found: m/z = 306.2694.

2-Naphthalene-[*N*-(2-pyridinylmethylene)]sulfonamide (*Imine*–3w)



***Imine*–3w**

Prepared from 2-pyridinecarbaldehyde (2.26 g, 21.1 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.91 g, 19.2 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.42 g, 21.1 mmol, 1.10 equiv) according to *General Procedure B* at 180 °C for 12 h. ***Imine*–3w** was recrystallized from EtOAc (10 mL).

Yellow solid (mp 174–179 °C).

Yield: 4.31 g (77%).

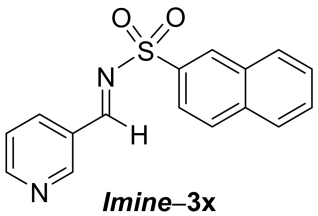
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.20 (s, 1H), 8.85 (d, *J* = 8.1 Hz, 1H), 8.68 (s, 1H), 8.28 (d, *J* = 8.2 Hz, 1H), 8.04 (dd, *J* = 8.1, 8.2 Hz, 1H), 8.02 (d, *J* = 7.5 Hz, 1H), 8.00 (d, *J* = 7.9 Hz, 1H), 7.97 (d, *J* = 8.4 Hz, 1H), 7.85–7.84 (m, 1H), 7.81 (d, *J* = 8.4 Hz, 1H), 7.79 (dd, *J* = 7.5, 7.9 Hz, 1H), 7.76–7.74 (m, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.5, 162.1, 152.8, 149.7, 146.7, 137.3, 135.4, 133.6, 132.4, 128.3, 127.7, 127.5, 126.6, 126.3, 123.5, 123.3 ppm.

IR (CH_2Cl_2): ν = 3124, 3054, 2982, 2924, 1886, 1756, 1738, 1571, 1437, 1376, 1354, 1189, 1152, 1136, 751, 729, 698 cm^{-1}.

HRMS (ESI): calculated for $C_{16}H_{12}NaN_2O_2S$ = $[M+Na]^+$: m/z = 319.2712, found: m/z = 319.2716.

2-Naphthalene-[*N*-(3-pyridinylmethylene)]sulfonamide (*Imine*–3x)



***Imine*–3x**

Prepared from 3-pyridinecarbaldehyde (2.26 g, 21.1 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.91 g, 19.2 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.42 g, 21.1 mmol, 1.10 equiv) according to *General Procedure B* at 180 °C for 12 h. ***Imine*–3x** was recrystallized from EtOAc (10 mL).

Light yellow solid (mp 173–176 °C).

Yield: 4.74 g (82%).

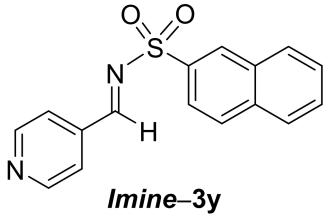
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.17 (s, 1H), 9.07 (s, 1H), 8.82–8.81 (m, 1H), 8.62 (s, 1H), 8.28–8.26 (m, 1H), 8.01 (d, *J* = 8.4 Hz, 1H), 7.97–7.93 (m, 3H), 7.70–7.66 (m, 2H), 7.45–7.43 (m, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 168.2, 164.1, 149.8, 145.3, 135.4, 133.6, 133.1, 132.4, 129.1, 128.4, 128.2, 127.7, 127.5, 126.5, 123.5, 123.3 ppm.

IR (CH_2Cl_2): ν = 3123, 3051, 2985, 2931, 1890, 1758, 1735, 1572, 1436, 1378, 1359, 1181, 1150, 1142, 752, 730, 694 cm^{-1}.

HRMS (ESI): calculated for $C_{16}H_{12}NaN_2O_2S$ = $[M+Na]^+$: m/z = 319.2712, found: m/z = 319.2714.

2-Naphthalene-[*N*-(4-pyridinylmethylene)]sulfonamide (*Imine*–3y)



***Imine*–3y**

Prepared from 4-pyridinecarbaldehyde (2.26 g, 21.1 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.91 g, 19.2 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.42 g, 21.1 mmol, 1.10 equiv) according to *General Procedure B* at 180 °C for 12 h. ***Imine*–3y** was recrystallized from EtOAc (10 mL).

Light yellow solid (mp 174–178 °C).

Yield: 4.45 g (78%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.10 (s, 1H), 8.80–8.78 (m, 2H), 8.62 (s, 1H), 8.02 (d, *J* = 7.5 Hz,

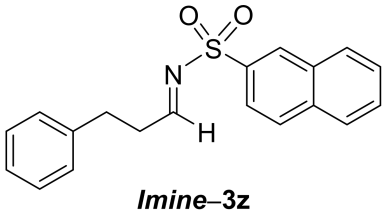
1H), 7.96–7.89 (m, 3H), 7.75–7.72 (m, 2H), 7.66–7.62 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 168.9, 163.9, 150.4, 145.6, 135.4, 134.1, 133.6, 132.4, 130.5, 128.4, 128.2, 127.7, 127.5, 126.4, 123.5, 121.4 ppm.

IR (CH_2Cl_2): ν = 3124, 3050, 2987, 2930, 1893, 1757, 1736, 1578, 1431, 1379, 1364, 1183, 1156, 1136, 756, 732, 691 cm^{-1}.

HRMS (ESI): calculated for $C_{16}H_{12}NaN_2O_2S$ = $[M+Na]^+$: m/z = 319.2712, found: m/z = 319.2715.

2-Naphthalene-[*N*-(3-phenylpropylidene)]sulfonamide (*Imine*–3z)



***Imine*–3z**

Prepared from 3-phenylpropionaldehyde (2.56 g, 19.1 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.64 g, 17.4 mmol, 1.00 equiv), and $Si(OEt)_4$ (3.98 g, 19.1 mmol, 1.10 equiv) according to *General Procedure B* at 170 °C for 12 h. ***Imine*–3z** was recrystallized from EtOAc (10 mL).

Light yellow solid (mp 184–188 °C).

Yield: 5.02 g (90%).

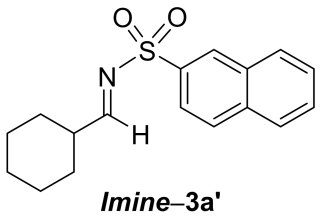
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.13 (s, 1H), 8.61 (s, 1H), 8.11 (d, *J* = 7.5 Hz, 1H), 8.02 (d, *J* = 7.9 Hz, 1H), 7.98 (d, *J* = 8.2 Hz, 1H), 7.83 (d, *J* = 8.2 Hz, 1H), 7.81 (dd, *J* = 7.5, 7.9 Hz, 1H), 7.79–7.77 (m, 1H), 7.31 (d, *J* = 7.8 Hz, 2H), 7.27–7.25 (m, 1H), 7.19 (d, *J* = 7.8 Hz, 2H), 4.85 (t, *J* = 7.2 Hz, 2H), 2.81–2.79 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 165.4, 145.6, 139.2, 135.4, 133.6, 132.4, 128.9, 128.7 (2C), 128.5, 128.3, 128.0, 127.7, 127.5 (2C), 124.6, 123.5, 30.0, 29.1 ppm.

IR (CH_2Cl_2): ν = 3122, 3063, 3031, 2984, 2931, 2865, 1892, 1740. 1572, 1362, 1327, 1186, 1163, 1167, 1112, 767, 745, 723, 694, 683, 652 cm^{-1}.

HRMS (ESI+): calculated for $C_{19}H_{17}NaNO_2S$ = $[M+Na]^+$: m/z = 346.5436, found: m/z = 346.5440.

2-Naphthalene-[*N*-(cyclohexylmethylene)]sulfonamide (*Imine*–3a')



***Imine*–3a'**

Prepared from cyclohexanecarbaldehyde (2.32 g, 20.7 mmol, 1.10 equiv), 2-naphthalene sulfonamide (3.93 g, 18.9 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.31 g, 20.7 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3a'** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 151–155 °C).

Yield: 4.52 g (79%).

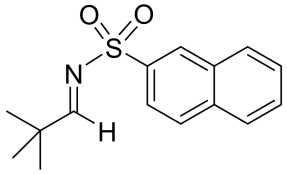
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.19 (s, 1H), 8.64 (s, 1H), 8.05 (d, *J* = 7.4 Hz, 1H), 8.03 (d, *J* = 7.9 Hz, 1H), 7.98 (d, *J* = 8.2 Hz, 1H), 7.83 (d, *J* = 8.2 Hz, 1H), 7.82 (dd, *J* = 7.4, 7.9 Hz, 1H), 7.79–7.77 (m, 1H), 2.88–2.87 (m, 1H), 1.84–1.79 (m, 4H), 1.55–1.43 (m, 4H), 1.34–1.31 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 162.3, 146.7, 135.4, 133.6, 132.4, 128.3, 128.0, 127.7, 127.5, 127.0, 123.5, 36.2, 29.9 (2C), 26.3 (2C), 25.6 ppm.

IR (CH_2Cl_2): ν = 3120, 3034, 2926, 1880, 1736. 1561, 1355, 1188, 1154, 1136, 769, 756, 747, 695, 680, 645, 581, 516 cm^{-1}.

HRMS (ESI): calculated for $C_{17}H_{19}NaNO_2S$ = $[M+Na]^+$: m/z = 324.3156, found: m/z = 324.3159.

2-Naphthalene-[*N*-(cyclohexylmethylene)]sulfonamide (*Imine*–<u>3b'</u>)



***Imine*–3b'**

Prepared from pivaldehyde (1.97 g, 22.9 mmol, 1.10 equiv), 2-naphthalene sulfonamide (4.36 g, 20.9 mmol, 1.00 equiv), and $Si(OEt)_4$ (4.77 g, 22.9 mmol, 1.10 equiv) according to *General Procedure B* at 160 °C for 8 h. ***Imine*–3b'** was recrystallized from EtOAc (10 mL).

Colorless solid (mp 138–141 °C).

Yield: 4.65 g (80%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.17 (s, 1H), 8.65 (s, 1H), 8.05 (d, *J* = 7.4 Hz, 1H), 8.02 (d, *J* = 7.9 Hz, 1H), 7.98 (d, *J* = 8.2 Hz, 1H), 7.83 (d, *J* = 8.2 Hz, 1H), 7.81 (dd, *J* = 7.4, 7.9 Hz, 1H), 7.78–7.76 (m, 1H), 1.31 (s, 9H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 164.2, 147.6, 135.4, 133.6, 132.4, 128.4, 128.2, 127.8, 127.5, 124.6, 123.5, 36.2, 27.0 (3H) ppm.

IR (CH_2Cl_2): ν = 3121, 3052, 2954, 1882, 1738. 1567, 1351, 1164, 1158, 1139, 766, 745, 682, 645, 582 cm^{-1}.

HRMS (ESI): calculated for $C_{15}H_{17}NaNO_2S$ = $[M+Na]^+$: m/z = 298.3219, found: m/z = 298.3224.

5.3.3 BAC-catalysed asymmetric aza-MBH Reactions

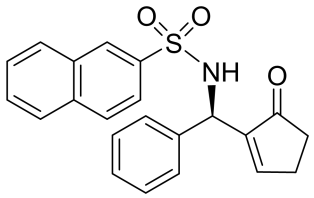
General Procedure I

To an oven-dried 2 mL-test tube with a magnetic stirring bar in a nitrogen glove box were added ***pre-BAC*–8*** (3.20 mg, 10.0 μmol, 5.00 mol%), the corresponding *N*-nasyl imine (0.22 mmol, 1.10 equiv), cyclopentenone (in molecular sieves, 16.4 mg, 0.20 mmol, 1.00 equiv), THF (2.00 mL, 0.1 M), and Cs_2CO_3 (3.60 mg, 11.0 μmol, 5.50 mol%). The reaction mixture was stirred at 35 °C for 24 h, at which point TLC or ^{1}H NMR analysis indicated complete consumption of cyclopentenone. The solvent was removed *in vacuo* and the residue was purified by flash column chromatography or PTLC on silica gel (EtOAc/PE = 1:1, or DCM/acetone = 100:1) to give the desired product.

General Procedure J

To an oven-dried 2 mL-test tube with a magnetic stirring bar in a nitrogen glove box were added ***pre-BAC*–11*** (3.30 mg, 10.0 μmol, 5.00 mol%), Cs_2CO_3 (3.60 mg, 11.0 μmol, 5.50 mol%) and THF (100 μL). The pre-catalyst mixture was pre-stirred at 35 °C for 20 h before cooling to –20 °C, at which stage a stock solution of the corresponding *N*-nasyl imine (0.22 mmol, 1.10 equiv) and cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) in THF (1.90 mL) was added to the pre-catalyst mixture. The reaction mixture was stirred at –20 °C for 72 h, at which point TLC or ^{1}H NMR analysis indicated complete consumption of cyclopentenone. The solvent was removed *in vacuo* and the residue was purified by flash column chromatography or PTLC on silica gel (EtOAc/PE = 1:1, or DCM/acetone = 100:1) to give the desired product.

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(phenyl)methyl]sulfonamide (2–4)**



2–4

Prepared from ***Imine*–3a** (65.6 mg, 0.22 mmol, 1.10 equiv) and cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–4** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*). *The obtained analytical data fit accurately with the reported data.*[54]

Colorless solid (mp 186–188 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 64.9 mg (86%), 89% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 72.4 mg (96%), 93% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.27 (s, 1H), 7.89-7.84 (m, 3H), 7.72–7.70 (m, 1H), 7.64–7.57 (m, 2H), 7.25 (t, *J* = 5.2 Hz, 1H), 7.18–7.11 (m, 4H), 7.08–7.07 (m, 1H), 6.27 (d, *J* = 8.9 Hz, 1H), 5.36 (d,

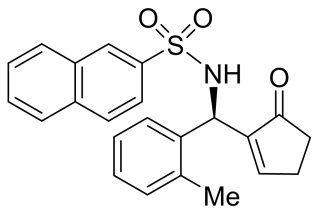
J = 8.9 Hz, 1H), 2.28–1.90 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.4, 160.6, 143.0, 138.4, 137.1, 134.6, 131.9, 129.1, 129.0, 128.9, 128.7, 128.6 (2C), 127.8, 127.7, 127.6, 126.7 (2C), 122.6, 55.5, 34.8, 26.6 ppm.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.8 mL/min; 220 nm, 25 ^{o}C): t_r (S) = 11.8 min, t_r (R) = 14.9 min.

$[\alpha]_D^{25}$ = +31.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2-toyl)methyl]sulfonamide (2–7)**



2–7

Prepared from ***Imine*–3b** (68.0 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–7** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 192–196 °C).

1st generation ***pre-BAC*–8**: +35 ^{o}C, 48 h; yield: 71.9 mg (92%), 76% *ee*.

2nd generation ***pre-BAC*–11**: –20 ^{o}C, 72 h; yield: 71.2 mg (91%), 90% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.27 (s, 1H), 7.90–7.86 (m, 3H), 7.71–7.69 (m, 1H), 7.63–7.56 (m, 2H), 7.26 (t, *J* = 5.3 Hz, 1H), 7.10 (d, *J* = 7.8 Hz, 1H), 7.00 (d, *J* = 7.8 Hz, 1H), 6.95–6.92 (m, 2H), 6.14 (d, *J* = 8.1 Hz, 1H), 5.60 (d, *J* = 8.1 Hz, 1H), 2.33 (s, 3H), 2.25–1.91 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 160.3, 143.4, 136.9, 136.6, 135.7, 134.6, 131.9, 130.7, 129.1, 129.0, 128.9, 128.8, 127.9, 127.7, 127.4, 126.8, 126.2, 122.6, 51.8, 34.8, 26.5, 19.4 ppm.

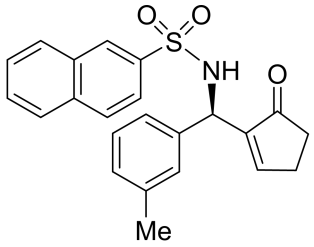
IR (CH_2Cl_2): ν = 3269, 3054, 2918, 2869, 2254, 1693, 1436, 1327, 1159, 906, 745, 665 cm^{-1}.

HRMS (ESI): calculated for $C_{23}H_{21}NaNO_3S$ = $[M+Na]^+$: m/z = 414.1134, found: m/z = 414.1137.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.7 mL/min; 220 nm, 25 ^{o}C): t_r (S) = 12.1 min, t_r (R) = 14.8 min.

$[\alpha]_D^{25}$ = +42.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(3-toyl)methyl]sulfonamide (2–6)**



2–6

Prepared from ***Imine*–3c** (68.0 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–6** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 194–197 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 71.9 mg (92%), 74% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 69.6 mg (89%), 89% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.20 (s, 1H), 7.82-7.79 (m, 3H), 7.78 (dd, *J* = 7.4, 7.5 Hz, 1H), 7.58 (d, *J* = 7.8 Hz, 1H), 7.54 (d, *J* = 7.5 Hz, 1H), 7.22 (t, *J* = 5.2 Hz, 1H), 7.02 (d, *J* = 7.4 Hz, 1H), 6.97–6.95 (m, 2H), 6.91–6.89 (m, 1H), 6.08 (d, *J* = 8.1 Hz, 1H), 5.53 (d, *J* = 8.1 Hz, 1H), 2.25 (s, 3H), 2.23–1.90 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.8, 162.3, 143.4, 139.5, 135.4, 134.9, 133.7, 132.4, 130.6, 129.2, 128.4, 128.2, 127.7, 127.6, 127.5, 127.0, 126.6, 126.5, 123.5, 58.1, 32.5, 26.2, 20.9 ppm.

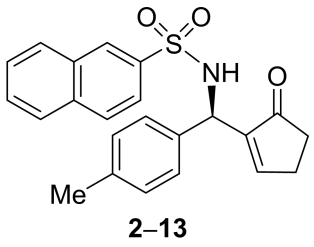
IR (CH_2Cl_2): ν = 3163, 2918, 2848, 2252, 1735, 1701, 1438, 1375, 1163, 1039, 916, 732, 661 cm^{-1}.

HRMS (ESI): calculated for $C_{23}H_{21}NaNO_3S$ = $[M+Na]^+$: m/z = 414.1134, found: m/z = 414.1150.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.7 mL/min; 220 nm, 25 °C): t_r (S) = 11.6 min, t_r (R) = 14.9 min.

$[\alpha]_D^{25}$ = +41.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(4-toyl)methyl]sulfonamide (2–13)**



2–13

Prepared from ***Imine*–3d** (68.0 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–13** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 193–197 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 68.8 mg (88%), 59% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 64.1 mg (82%), 79% *ee*.

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 8.25 (s, 1H), 7.89–7.85 (m, 3H), 7.77–7.72 (m, 3H), 7.27 (t, *J* = 5.6 Hz, 1H), 7.06 (d, *J* = 8.0 Hz, 2H), 6.95 (d, *J* = 8.0 Hz, 2H), 6.24 (d, *J* = 8.4 Hz, 1H), 5.33 (d, *J* = 8.4 Hz, 1H), 2.34–1.95 (m, 4H), 2.19 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.5, 160.5, 143.3, 137.7, 137.2, 135.4, 132.4, 130.7, 129.6, 129.2 (2C), 128.3, 128.1, 127.9, 127.8, 127.5, 126.7 (2C), 123.5, 55.4, 34.9, 26.6, 20.9 ppm.

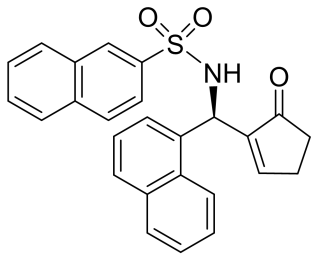
IR (CH_2Cl_2): ν = 3271, 2918, 2848, 2554, 1695, 1327, 1159, 904, 742, 663, 648 cm^{-1}.

HRMS (ESI): calculated for $C_{23}H_{21}NaNO_3S$ = $[M+Na]^+$: m/z = 414.1134, found: m/z = 414.1153.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.8 mL/min; 220 nm, 25 °C): t_r (S) = 11.9 min, t_r (R) = 14.8 min.

$[\alpha]_D^{25}$ = +47.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(naphthalen-1-yl)methyl]sulfonamide (2–5)**



2–5

Prepared from ***Imine*–3e** (51.8 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–5** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Light yellow solid (mp 208–211 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 76.0 mg (89%), 84% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 78.6 mg (92%), 93% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.22 (s, 1H), 8.09 (d, *J* = 8.4 Hz, 1H), 7.96 (d, *J* = 7.4 Hz, 1H), 7.92 (d, *J* = 7.8 Hz, 1H), 7.91 (d, *J* = 7.8 Hz, 1H), 7.90 (d, *J* = 7.4 Hz, 1H), 7.80 (d, *J* = 8.4 Hz, 1H), 7.77 (dd, *J* = 7.4, 7.8 Hz, 1H), 7.75 (dd, *J* = 7.4, 7.8 Hz, 1H), 7.72 (d, *J* = 6.9 Hz, 1H), 7.58 (dd, *J* = 6.9, 8.4 Hz, 1H), 7.53 (d, *J* = 8.4 Hz, 1H), 7.50–7.49 (m, 1H), 7.27 (t, *J* = 5.3 Hz, 1H), 7.19–7.18 (m, 1H), 6.30 (d, *J* = 8.8 Hz, 1H), 6.17 (d, *J* = 8.8 Hz, 1H), 2.19–1.92 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 208.4, 161.3, 143.2, 136.8, 133.6, 132.8, 132.4, 130.8, 130.7, 130.6, 129.3, 129.2, 128.9, 128.8, 128.1, 127.7, 127.5, 126.7, 126.6, 124.5, 124.4, 123.5, 122.9, 58.1, 32.5, 26.3 ppm.

IR (CH_2Cl_2): ν = 3271, 2918, 2848, 2554, 1695, 1327, 1159, 904, 742, 663, 648 cm^{-1}.

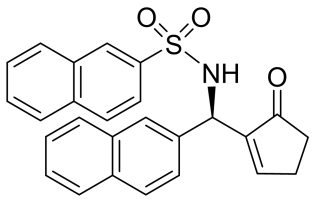
HRMS (ESI): calculated for $C_{23}H_{21}NaNO_3S$ = $[M+Na]^+$: m/z = 414.1134, found: m/z = 414.1153.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB

column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.4 mL/min; 220 nm, 25 ^{o}C): t_r (S) = 12.8 min, t_r (R) = 15.9 min.

[α]$_D^{25}$ = +75.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2-naphthalenyl)methyl]sulfonamide (2–40)**



2–40

Prepared from ***Imine*–3f** (51.8 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–40** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Light yellow solid (mp 209–211 °C).

1st generation ***pre-BAC**–8**: +35 ^{o}C, 48 h; yield: 78.6 mg (92%), 80% *ee*.

2nd generation ***pre-BAC**–11**: –20 ^{o}C, 72 h; yield: 75.2 mg (88%), 85% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.26 (s, 1H), 8.12 (d, *J* = 7.4 Hz, 1H), 7.96 (d, *J* = 8.4 Hz, 1H), 7.92 (d, *J* = 7.8 Hz, 1H), 7.90 (d, *J* = 8.4 Hz, 1H), 7.87 (d, *J* = 7.8 Hz, 1H), 7.80 (d, *J* = 7.4 Hz, 1H), 7.79 (dd, *J* = 7.4, 7.8 Hz, 1H), 7.72 (dd, *J* = 7.4, 7.8 Hz, 1H), 7.64 –7.62 (m, 1H), 7.55–7.54 (m, 1H), 7.45 (d, *J* = 8.1 Hz, 1H), 7.35 (d, *J* = 8.1 Hz, 1H), 7.31 (t, *J* = 5.3 Hz, 1H), 7.23–7.20 (m, 1H), 6.33 (d, *J* = 8.6 Hz, 1H), 5.56 (d, *J* = 8.6 Hz, 1H), 2.19–1.93 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 150 MHz): δ = 208.4, 163.4, 143.8, 139.5, 135.4, 133.7, 133.6, 133.0, 132.4, 132.1, 131.6, 131.0, 130.8, 129.2, 128.6, 128.3, 128.1, 127.5, 125.5, 126.9, 126.6, 125.5, 123.5, 58.1, 32.5, 26.2 ppm.

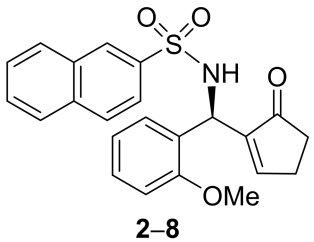
IR (CH_2Cl_2): ν = 3265, 2941, 2876, 2254, 1694, 1436, 1375, 1028, 912, 729, 664, 648 cm^{-1}.

HRMS (ESI): calculated for $C_{26}H_{21}NaNO_3S$ = $[M+Na]^+$: m/z = 450.1134, found: m/z = 450.1129.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.4 mL/min; 220 nm, 25 ^{o}C): t_r (S) = 12.3 min, t_r (R) = 15.9 min.

[α]$_D^{25}$ = +74.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2-methoxylphenyl)methyl]sulfonamide (2–8)**



2–8

Prepared from ***Imine*–3g** (71.6 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol,

1.00 equiv) according to *General Procedure I or J*. **2–8** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 196–200 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 70.8 mg (87%), 67% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 72.5 mg (89%), 83% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.28 (s, 1H), 7.90–7.84 (m, 2H), 7.78–7.77 (m, 1H), 7.69–7.68 (m, 1H), 7.65–7.61 (m, 2H), 7.39–7.38 (m, 1H), 7.18 (t, *J* = 5.3 Hz, 1H), 6.70 (d, *J* = 7.6 Hz, 1H), 6.62 (dd, *J* = 7.6, 8.3 Hz, 1H), 6.60 (d, *J* = 8.3 Hz, 1H), 6.38 (d, *J* = 7.6 Hz, 1H), 5.60 (d, *J* = 7.6 Hz, 1H), 3.66 (s, 3H), 2.29–2.12 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.0, 159.5, 155.8, 143.3, 137.2, 131.9, 130.7, 129.2, 128.9, 128.8, 128.6, 128.2, 128.0, 127.7, 127.3, 123.5, 122.6, 120.7, 110.5, 55.2, 51.1, 34.8, 26.4 ppm.

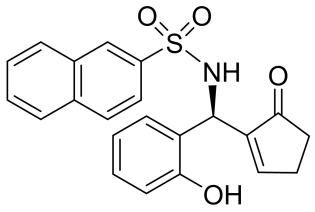
IR (CH_2Cl_2): ν = 3269, 2918, 1689, 1436, 1325, 1157, 1091, 906, 745, 663 cm^{-1}.

HRMS (ESI): calculated for $C_{23}H_{21}NaNO_4S$ = $[M+Na]^+$: m/z = 430.1084, found: m/z = 430.1119.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.8 mL/min; 220 nm, 25 °C): t_r (S) = 12.1 min, t_r (R) = 14.5 min.

$[\alpha]_D^{25}$ = +26.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2-hydroxyphenyl)methyl]sulfonamide (2–9)**



2–9

Prepared from ***Imine*–3h** (35.8 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–9** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 185–187 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 66.8 mg (85%), 93% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 69.2 mg (88%), 97% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 10.5 (br s, 1H), 8.30 (d, *J* = 8.3 Hz, 1H), 7.72–7.70 (m, 2H), 7.64–7.63 (m, 2H), 7.41–7.39 (m, 1H), 7.38–7.35 (m, 1H), 7.26 (t, *J* = 5.3 Hz, 1H), 7.23–7.21 (m, 2H), 6.72–6.70 (m, 2H), 6.23 (d, *J* = 8.4 Hz, 1H), 5.47 (d, *J* = 8.4 Hz, 1H), 2.03–1.68 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.3, 167.8, 148.2, 135.4, 133.6, 132.4, 131.9, 130.7, 129.2, 128.4, 128.2, 128.0, 127.7, 127.6, 127.3, 126.5, 126.0, 123.5, 107.2, 58.1, 32.6, 27.9 ppm.

IR (CH_2Cl_2): ν = 3248, 2941, 2252, 1701, 1375, 1256, 1163, 912, 729, 669, 648 cm^{-1}.

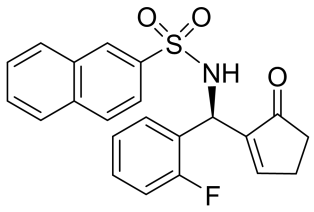
HRMS (ESI): calculated for $C_{22}H_{19}NaNO_4S$ = $[M+Na]^+$: m/z = 416.0927, found: m/z = 416.0938.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB

column (eluent: hexane/^{i}PrOH = 70:30; flow rate: 0.5 mL/min; 220 nm, 25 ^{o}C): t_r (S) = 12.3 min, t_r (R) = 15.2 min.

[α]$_D^{25}$ = +64.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2-fluorophenyl)methyl]sulfonamide (2–10)**



2–10

Prepared from ***Imine*–3i** (69.0 mg, 0.22 mmol, 1.10 equiv) and cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–10** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 196–198 °C).

1st generation ***pre-BAC**–8***: +35 ^{o}C, 48 h; yield: 75.1 mg (95%), 84% *ee*.

2nd generation ***pre-BAC**–11***: –20 ^{o}C, 72 h; yield: 76.6 mg (97%), 87% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.28 (s, 1H), 7.82–7.80 (m, 1H), 7.80–7.76 (m, 2H), 7.71–7.70 (m, 1H), 7.60–7.55 (m, 2H), 7.36 (d, *J* = 8.0 Hz, 1H), 7.29 (d, *J* = 8.0 Hz, 1H), 7.03–7.01 (m, 1H), 6.88 (d, *J* = 8.4 Hz, 1H), 6.79 (t, *J* = 5.3 Hz, 1H), 6.46 (d, *J* = 8.4 Hz, 1H), 5.64 (d, *J* = 8.4 Hz, 1H), 2.29–2.01 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 160.5, 160.3 (d, *J* = 237.5 Hz), 142.3, 136.9, 134.6, 131.9, 130.2, 129.5 (d, *J* = 6.4 Hz), 129.1, 128.8 (d, *J* = 3.2 Hz), 128.6, 127.7, 127.5 (d, *J* = 36.5 Hz), 124.2, 122.5, 121.4, 115.4 (d, *J* = 14.7 Hz), 115.2 (d, *J* = 17.0 Hz), 49.8, 34.8, 26.6 ppm.

^{19}F NMR ($CDCl_3$, 128 MHz): δ = –111.4 ~ –110.9 (m) ppm.

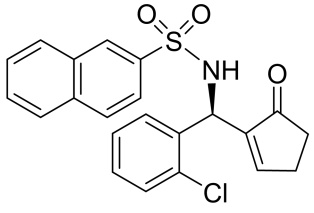
IR (CH_2Cl_2): ν = 3325, 2916, 2848, 2291, 2252, 1735, 1707, 1452, 1438, 1373, 1163, 1029, 916, 732, 700 cm^{-1}.

HRMS (ESI): calculated for $C_{22}H_{18}FNaNO_3S$ = $[M+Na]^+$: m/z = 418.0636, found: m/z = 418.0638.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.8 mL/min; 220 nm, 25 ^{o}C): t_r (S) = 11.3 min, t_r (R) = 14.2 min.

[α]$_D^{25}$ = +96.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2-chlorophenyl)methyl]sulfonamide (2–11)**



2–11

Prepared from ***Imine*–3j** (69.0 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–11** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 200–202 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 80.6 mg (98%), 85% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 78.9 mg (96%), 92% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.26 (s, 1H), 7.86–7.84 (m, 1H), 7.80–7.79 (m, 2H), 7.74–7.72 (m, 1H), 7.62–7.58 (m, 2H), 7.42–7.37 (m, 2H), 7.12 (t, *J* = 5.3 Hz, 1H), 6.97–6.94 (m, 2H), 6.58 (d, *J* = 8.0 Hz, 1H), 5.81 (d, *J* = 8.0 Hz, 1H), 2.37–2.04 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.7, 161.3, 141.6, 136.8, 136.2, 135.9, 133.0, 132.4, 129.4, 129.1, 129.0, 128.8, 128.7, 128.4, 127.9, 127.7, 127.5, 127.4, 122.5, 52.5, 34.8, 26.6 ppm.

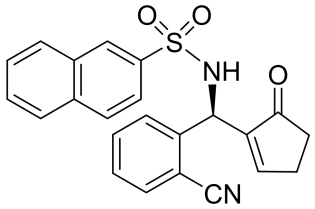
IR (CH_2Cl_2): ν = 3234, 2925, 1814, 1754, 1636, 1455, 1258, 1115, 917, 736, 689, 645 cm^{-1}.

HRMS (ESI): calculated for $C_{22}H_{18}ClNaNO_3S$ = $[M+Na]^+$: m/z = 434.5745, found: m/z = 434.5752.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 70:30; flow rate: 0.8 mL/min; 220 nm, 25 °C): t_r (S) = 11.6 min, t_r (R) = 14.1 min.

$[\alpha]_D^{25}$ = +87.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2-cyanophenyl)methyl]sulfonamide (2–12)**



2–12

Prepared from ***Imine*–3k** (70.4 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–12** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 192–194 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 59.5 mg (74%), 89% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 66.7 mg (83%), 94% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.61 (s, 1H), 8.01–7.99 (m, 2H), 7.98–7.96 (m, 2H), 7.92–7.91 (m, 1H), 7.67–7.66 (m, 1H), 7.64 (d, *J* = 8.0 Hz, 1H), 7.31–7.27 (m, 3H), 7.19 (t, *J* = 5.2 Hz, 1H), 6.22 (d, *J* = 8.4 Hz, 1H), 5.68 (d, *J* = 8.4 Hz, 1H), 2.15–1.87 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.8, 165.2, 143.6, 133.2, 133.1, 132.4, 130.8, 130.7, 129.9, 129.3, 128.3, 128.1, 127.7, 127.5, 126.5, 126.1, 123.4, 122.9, 116.0, 112.6, 58.2, 32.5, 26.1 ppm.

IR (CH_2Cl_2): ν = 3269, 2967, 2252, 1954, 1878, 1753, 1686, 1498, 1237, 1059, 931, 722, 639 cm^{-1}.

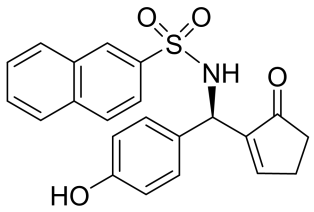
HRMS (ESI): calculated for $C_{23}H_{18}NaN_2O_3S$ = $[M+Na]^+$: m/z = 425.4587, found: m/z = 425.4596.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB

column (eluent: hexane/^{i}PrOH = 80:40; flow rate: 0.4 mL/min; 220 nm, 25 ^{o}C): t_r (S) = 11.1 min, t_r (R) = 14.5 min.

$[\alpha]_D^{25}$ = +69.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(4-hydroxyphenyl)methyl]sulfonamide (2–14)**



2–14

Prepared from ***Imine*–3l** (71.6 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–14** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 184–187 °C).

1st generation ***pre-BAC**–8**: +35 ^{o}C, 48 h; yield: 58.2 mg (74%), 81% *ee*.

2nd generation ***pre-BAC**–11**: –20 ^{o}C, 72 h; yield: 66.8 mg (85%), 91% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.10 (br s, 1H), 8.63 (s, 1H), 8.03–7.95 (m, 4H), 7.94 (d, *J* = 8.4 Hz, 2H), 7.67–7.65 (m, 1H), 7.30–7.28 (m, 1H), 7.18 (d, *J* = 8.4 Hz, 2H), 7.09 (t, *J* = 5.3 Hz, 1H), 6.07 (d, *J* = 8.8 Hz, 1H), 5.49 (d, *J* = 8.8 Hz, 1H), 2.22–1.94 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.3, 157.6, 139.5, 135.4, 133.6, 132.4, 130.7, 129.2, 128.4, 128.3, 127.7, 127.5, 126.8, 126.4 (2C), 125.0 (2C), 123.5, 115.0, 58.2, 32.6, 26.4 ppm.

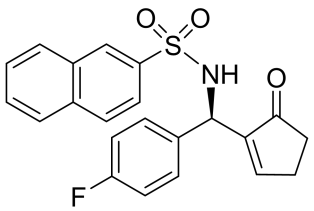
IR (CH_2Cl_2): ν = 3232, 2915, 2345, 1796, 1345, 1265, 1204, 915, 730, 664, 652 cm^{-1}.

HRMS (ESI): calculated for $C_{22}H_{19}NaNO_4S$ = $[M+Na]^+$: m/z = 416.0927, found: m/z = 416.0935.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 70:30; flow rate: 0.5 mL/min; 220 nm, 25 ^{o}C): t_r (S) = 12.1 min, t_r (R) = 15.0 min.

$[\alpha]_D^{25}$ = +56.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(4-fluorophenyl)methyl]sulfonamide (2–15)**



2–15

Prepared from ***Imine*–3m** (69.0 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–15** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 197–200 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 76.6 mg (97%), 75% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 75.1 mg (95%), 86% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.26 (s, 1H), 7.92–7.89 (m, 2H), 7.78–7.74 (m, 2H), 7.67–7.64 (m, 2H), 7.26 (t, *J* = 5.3 Hz, 1H), 7.19 (d, *J* = 8.4 Hz, 2H), 6.87 (d, *J* = 8.8 Hz, 2H), 6.21 (d, *J* = 8.8 Hz, 1H), 5.32 (d, *J* = 8.8 Hz, 1H), 2.36–1.89 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.5, 163.0 (d, *J* = 245.5 Hz), 160.8, 142.9, 137.0, 133.6, 131.9, 129.2 (d, *J* = 3.3 Hz), 129.1, 128.7, 128.5 (d, *J* = 20.5 Hz, 2C), 127.9, 127.8 (d, *J* = 7.6 Hz, 2C), 127.7, 122.5, 115.5, 115.4, 54.9, 34.9, 26.6 ppm.

^{19}F NMR ($CDCl_3$, 128 MHz): δ = –100.8 ~ –99.9 (m) ppm.

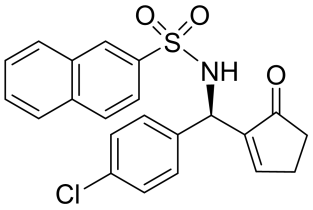
IR (CH_2Cl_2): ν = 3282, 2924, 2850, 2254, 1747, 1712, 1697, 1402, 1334, 1161, 1036, 904, 741, 650, 619 cm^{-1}.

HRMS (ESI): calculated for $C_{22}H_{18}FNaNO_3S$ = $[M+Na]^+$: m/z = 418.0636, found: m/z = 418.0642.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.8 mL/min; 220 nm, 25 °C): t_r (S) = 11.5 min, t_r (R) = 14.3 min.

$[\alpha]_D^{25}$ = +98.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(4-chlorophenyl)methyl]sulfonamide (2–16)**



2–16

Prepared from ***Imine*–3n** (69.0 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–16** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 199–202 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 78.1 mg (95%), 78% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 78.9 mg (96%), 81% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.26 (s, 1H), 7.89 (d, *J* = 8.4 Hz, 1H), 7.88–7.87 (m, 2H), 7.71–7.67 (m, 3H), 7.26 (t, *J* = 5.4 Hz, 1H), 7.13 (d, *J* = 8.6 Hz, 2H), 6.84 (d, *J* = 8.6 Hz, 2H), 6.26 (d, *J* = 8.0 Hz, 1H), 5.33 (d, *J* = 8.0 Hz, 1H), 2.26–1.94 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.6, 160.7, 139.5, 135.7, 135.4, 133.6, 132.4, 131.4, 130.7, 129.4, 128.6, 128.1 (2C), 127.9, 127.8, 127.5, 126.4 (2C), 123.5, 58.3, 32.7, 26.4 ppm.

IR (CH_2Cl_2): ν = 3314, 3254, 3019, 2905, 2079, 1953, 1865, 1758, 1634, 1532, 1198, 1102, 921, 754, 689, 618 cm^{-1}.

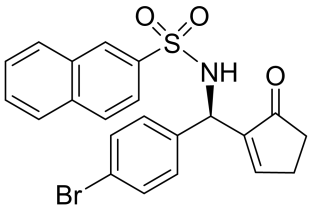
HRMS (ESI): calculated for $C_{22}H_{18}ClNaNO_3S$ = $[M+Na]^+$: m/z = 434.5745, found: m/z = 434.5750.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 70:30; flow rate: 0.8 mL/min; 220 nm, 25 °C): t_r (S) = 11.3 min, t_r (R)

= 14.5 min.

$[\alpha]_D^{25}$ = +80.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(4-bromophenyl)methyl]sulfonamide (2–17)**



2–17

Prepared from ***Imine*–3o** (72.2 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–17** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 205–208 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 77.3 mg (85%), 74% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 82.8 mg (91%), 85% *ee*.

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 8.63 (s, 1H), 8.04–8.02 (m, 2H), 7.96–7.94 (m, 2H), 7.92–7.90 (m, 2H), 7.61 (d, *J* = 8.2 Hz, 2H), 7.52 (d, *J* = 8.2 Hz, 2H), 7.31 (t, *J* = 5.3 Hz, 1H), 6.51 (d, *J* = 7.9 Hz, 1H), 5.68 (d, *J* = 7.9 Hz, 1H), 2.33–2.06 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.5, 164.3, 143.8, 139.5, 133.6, 132.4, 131.5 (2C), 131.2, 130.9, 130.1, 128.8 (2C), 128.5, 128.0, 127.7, 126.6, 124.0, 123.5, 57.9, 32.3, 25.9 ppm.

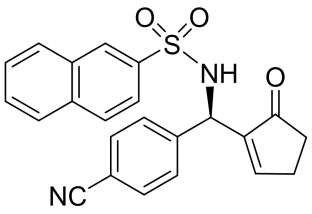
IR (CH_2Cl_2): ν = 3258, 3187, 3021, 2857, 2831, 1947, 1878, 1732, 1667, 1514, 1207, 1184, 912, 764, 741, 626 cm^{-1}.

HRMS (ESI): calculated for $C_{22}H_{18}BrNaNO_3S$ = $[M+Na]^+$: m/z = 478.3245, found: m/z = 478.3254.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 70:30; flow rate: 0.9 mL/min; 220 nm, 25 °C): t_r (S) = 11.7 min, t_r (R) = 14.9 min.

$[\alpha]_D^{25}$ = +60.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(4-cyanophenyl)methyl]sulfonamide (2–18)**



2–18

Prepared from ***Imine*–3p** (70.4 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–18** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 193–196 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 54.7 mg (68%), 71% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 63.5 mg (79%), 81% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.56 (s, 1H), 7.94–7.92 (m, 1H), 7.88 (d, *J* = 8.6 Hz, 1H), 7.80–7.77 (m, 2H), 7.60 (d, *J* = 8.6 Hz, 2H), 7.27 (t, *J* = 5.3 Hz, 1H), 7.23–7.20 (m, 3H), 6.37 (d, *J* = 8.8 Hz, 1H), 5.47 (d, *J* = 8.8 Hz, 1H), 2.21–1.96 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 165.2, 142.9, 139.4, 135.4, 133.6, 132.9, 130.7, 129.2, 128.4, 128.3, 127.8 (2C), 127.7, 126.6, 126.3 (2C), 123.5, 118.6, 112.2, 58.2, 32.6, 26.5 ppm.

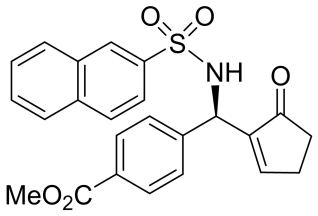
IR (CH_2Cl_2): ν = 3267, 2874, 2250, 1983, 1837, 1798, 1612, 1438, 1284, 1049, 912, 775, 648 cm^{-1}.

HRMS (ESI): calculated for $C_{23}H_{18}NaN_2O_3S$ = $[M+Na]^+$: m/z = 425.4587, found: m/z = 425.4593.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:40; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 11.8 min, t_r (R) = 14.2 min.

$[\alpha]_D^{25}$ = +78.0 ° (*c* = 1.0, $CHCl_3$).

(*R*)-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(4-methoxycarbonylphenyl)methyl]sulfonamide (2–19)



2–19

Prepared from ***Imine*–3q** (77.6 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–19** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 208–213 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 82.7 mg (95%), 84% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 84.4 mg (97%), 92% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.26 (s, 1H), 7.90–7.88 (m, 2H), 7.84–7.80 (m, 2H), 7.75–7.73 (m, 2H), 7.21 (d, *J* = 8.6 Hz, 2H), 7.25 (t, *J* = 5.2 Hz, 1H), 7.09 (d, *J* = 8.6 Hz, 2H), 6.11 (d, *J* = 8.8 Hz, 1H), 5.48 (d, *J* = 8.8 Hz, 1H), 3.88 (s, 3H), 2.39–1.96 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.4, 166.4, 161.1, 143.2, 142.4, 136.6, 134.6, 131.7, 129.8 (2C), 129.2, 128.9, 128.2, 127.8, 127.5, 127.1, 126.9, 126.7 (2C), 122.5, 55.4, 52.1, 34.8, 26.7 ppm.

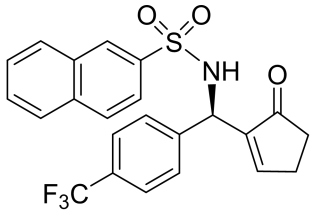
IR (CH_2Cl_2): ν = 3245, 3029, 2947, 1856, 1648, 1439, 1265, 1134, 1084, 915, 876, 798, 732, 634 cm^{-1}.

HRMS (ESI): calculated for $C_{24}H_{21}NaNO_5S$ = $[M+Na]^+$: m/z = 458.4156, found: m/z = 458.4162.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.6 mL/min; 220 nm, 25 °C): t_r (S) = 12.1 min, t_r (R) = 15.2 min.

$[\alpha]_D^{25}$ = +37.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(4-trifluoromethylphenyl)methyl]sulfonamide (2–20)**



2–20

Prepared from ***Imine*–3r** (79.8 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.8 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–20** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Colorless solid (mp 218–221 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 81.9 mg (92%), 69% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 84.6 mg (95%), 82% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.22 (s, 1H), 7.86–7.83 (m, 3H), 7.62–7.60 (m, 2H), 7.26–7.24 (m, 1H), 7.21 (t, *J* = 5.6 Hz, 1H), 7.06 (d, *J* = 8.6 Hz, 2H), 6.65 (d, *J* = 8.6 Hz, 2H), 6.13 (d, *J* = 9.0 Hz, 1H), 5.29 (d, *J* = 9.0 Hz, 1H), 2.30–1.95 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.4, 162.3, 145.6, 139.5, 135.4, 134.4, 133.6, 132.4, 130.7 (q, *J* = 269.7 Hz), 129.2 (q, *J* = 2.1 Hz, 2C), 128,4, 128.2, 127.9 (q, *J* = 3.4 Hz, 2C), 127.7, 127.5, 125.5 (q, *J* = 37.2 Hz), 124.0, 123.5, 58.1, 32.5, 26.3 ppm.

^{19}F NMR ($CDCl_3$, 128 MHz): δ = – 60.9 (s) ppm.

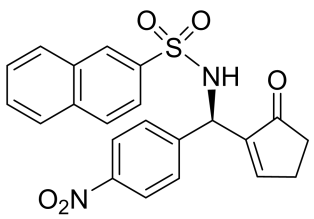
IR (CH_2Cl_2): ν = 3298, 3198, 3057, 2927, 2889, 1723, 1658, 1567, 1432, 1398, 1201, 912, 747, 732, 643, 621 cm^{-1}.

HRMS (ESI): calculated for $C_{23}H_{18}F_3NaNO_3S$ = $[M+Na]^+$: m/z = 468.4871, found: m/z = 468.4877.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:40; flow rate: 0.5 mL/min; 220 nm, 25 °C): t_r (S) = 11.8 min, t_r (R) = 15.4 min.

$[\alpha]_D^{25}$ = +28.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(4-nitrophenyl)methyl]sulfonamide (2–21)**



2–21

Prepared from ***Imine*–3s** (74.8 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.8 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–21** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Yellow solid (mp 195–197 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 68.3 mg (81%), 90% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 71.8 mg (85%), 92% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.62 (s, 1H), 8.03–8.00 (m, 2H), 7.95–7.92 (m, 2H), 7.69–7.67 (m, 2H), 7.62 (d, *J* = 8.6 Hz, 2H), 7.24 (t, *J* = 5.3 Hz, 1H), 7.00 (d, *J* = 8.6 Hz, 2H), 6.28 (d, *J* = 8.8 Hz, 1H), 5.43 (d, *J* = 8.8 Hz, 1H), 2.38–2.11 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.5, 165.9, 150.2, 141.7, 137.6, 135.8, 133.6, 132.8, 132.4, 131.8 (2C), 129.6, 129.2, 129.0, 128.9, 128.7 (2C), 125.9, 125.7, 60.2, 34.7, 28.3 ppm.

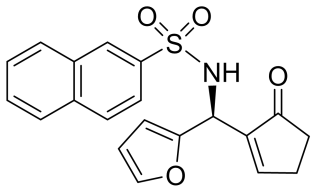
IR (CH_2Cl_2): ν = 3241, 3059, 2938, 2873, 1838, 1683, 1546, 1438, 1373, 1161, 1037, 908, 751, 727, 648, 639 cm^{-1}.

HRMS (ESI): calculated for $C_{22}H_{18}NaN_2O_5S$ = $[M+Na]^+$: m/z = 445.0829, found: m/z = 445.0830.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.8 mL/min; 220 nm, 25 °C): t_r (S) = 11.5 min, t_r (R) = 14.2 min.

$[\alpha]_D^{25}$ = +19.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2-furanyl)methyl]sulfonamide (2–22)**



2–22

Prepared from ***Imine*–3t** (62.8 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–22** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Yellow solid (mp 172–177 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 71.2 mg (97%), 90% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 72.7 mg (99%), 94% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.60 (s, 1H), 8.13–8.11 (m, 1H), 8.02–7.99 (m, 2H), 7.96–7.93 (m, 2H), 7.80 (d, *J* = 7.4 Hz, 1H), 7.67 (dd, *J* = 7.4, 7.5 Hz, 1H), 7.58 (d, *J* = 7.5 Hz, 1H), 7.33–7.32 (m, 1H), 7.22 (t, *J* = 5.7 Hz, 1H), 6.00 (d, *J* = 8.6 Hz, 1H), 5.18 (d, *J* = 8.6 Hz, 1H), 2.61–2.41 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.6, 160.2, 151.5, 142.4, 135.4, 133.6, 132.4, 130.7, 129.3, 128.3, 128.2, 127.6, 127.5, 126.5, 123.5, 110.5, 107.8, 58.1, 32.5, 26.2 ppm.

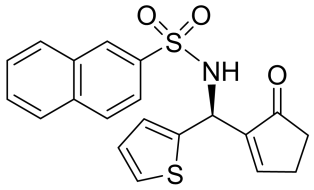
IR (CH_2Cl_2): ν = 3264, 3076, 2972, 2954, 1823, 1739, 1596, 1503, 1421, 1376, 1249, 1118, 1032, 918, 748, 721, 693, 612 cm^{-1}.

HRMS (ESI): calculated for $C_{20}H_{17}NaNO_4S$ = $[M+Na]^+$: m/z = 390.3987, found: m/z = 390.3994.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 70:30; flow rate: 0.6 mL/min; 220 nm, 25 °C): t_r (S) = 11.0 min, t_r (R) = 14.2 min.

$[\alpha]_D^{25}$ = –23.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2-thienyl)methyl]sulfonamide (2–23)**



2–23

Prepared from ***Imine*–3u** (66.4 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–23** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Yellow solid (mp 182–185 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 76.6 mg (>99%), 91% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 75.9 mg (>99%), 96% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.30 (s, 1H), 8.10–8.09 (m, 1H), 7.71–7.68 (m, 2H), 7.66–7.63 (m, 2H), 7.50 (d, *J* = 7.4 Hz, 1H), 7.47 (dd, *J* = 7.4, 7.5 Hz, 1H), 7.32 (d, *J* = 7.5 Hz, 1H), 6.95 (t, *J* = 5.3 Hz, 1H), 6.93–6.92 (m, 1H), 6.03 (d, *J* = 8.6 Hz, 1H), 5.21 (d, *J* = 8.6 Hz, 1H), 2.21–2.19 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.4, 161.2, 152.7, 141.4, 133.6, 132.4, 130.7, 129.2, 128.7, 128.3, 127.8, 127.5, 126.9, 126.3, 125.6, 125.3, 123.5, 58.1, 32.6, 26.2 ppm.

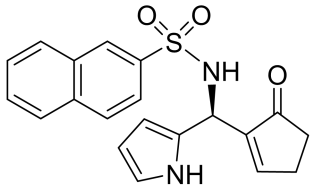
IR (CH_2Cl_2): ν = 3265, 3001, 2916, 2848, 1962, 1845, 1703, 1685, 1593, 1440, 1375, 1037, 916, 731, 650 cm^{-1}.

HRMS (ESI): calculated for $C_{20}H_{17}NaNO_3S_2$ = $[M+Na]^+$: m/z = 406.0542, found: m/z = 406.0492.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 90:10; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 11.3 min, t_r (R) = 14.5 min.

$[\alpha]_D^{25}$ = –17.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2-pyrrol)methyl]sulfonamide (2–24)**



2–24

Prepared from ***Imine*–3v** (62.6 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–24** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Brown solid (mp 167–173 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 61.5 mg (84%), 91% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 65.9 mg (90%), 94% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.56 (s, 1H), 7.97–7.94 (m, 2H), 7.86–7.82 (m, 2H), 7.77–7.75 (m, 2H), 7.67–7.65 (m, 1H), 7.60–7.58 (m, 1H), 7.28 (t, *J* = 5.2 Hz, 1H), 7.20–7.18 (m, 1H), 6.20 (d, *J* = 8.1 Hz, 1H), 5.78 (br s, NH, 1H), 5.22 (d, *J* = 8.1 Hz, 1H), 2.30–2.02 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 206.3, 162.3, 153.8, 137.5, 135.4, 133.6, 130.7, 129.2, 129.1, 128.3, 127.3, 127.0, 126.8, 126.2, 123.4, 111.9, 110.3, 58.3, 32.7, 26.3 ppm.

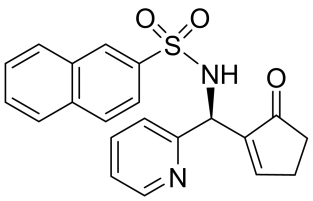
IR (CH_2Cl_2): ν = 3223, 3012, 2989, 2812, 2298, 1985, 1839, 1567, 1371, 1182, 913, 768, 623 cm^{-1}.

HRMS (ESI): calculated for $C_{20}H_{18}NaN_2O_3S$ = $[M+Na]^+$: m/z = 389.3254, found: m/z = 389.3261.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.6 mL/min; 220 nm, 25 °C): t_r (S) = 11.6 min, t_r (R) = 14.9 min.

$[\alpha]_D^{25}$ = –44.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2-pyridinyl)methyl]sulfonamide (2–25)**



2–25

Prepared from ***Imine*–3w** (65.2 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–25** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Yellow solid (mp 178–183 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 63.5 mg (84%), 89% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 67.3 mg (89%), 92% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.61 (s, 1H), 8.51 (s, 1H), 8.26–8.25 (m, 1H), 8.06 (d, *J* = 8.4 Hz, 1H), 7.47–7.44 (m, 2H), 7.41–7.39 (m, 2H), 7.23 (t, *J* = 5.2 Hz, 1H), 7.15–7.13 (m, 1H), 7.08–7.06 (m, 1H), 6.89 (d, *J* = 8.4 Hz, 1H), 6.27 (d, *J* = 8.1 Hz, 1H), 5.63 (d, *J* = 8.1 Hz, 1H), 2.21–1.95 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 169.2, 152.0, 149.0, 138.6, 133.6, 132.4, 129.2, 128.9, 128.3, 128.2, 127.7, 127.5, 127.0, 126.4, 123.5, 123.4, 122.0, 58.2, 32.6, 26.3 ppm.

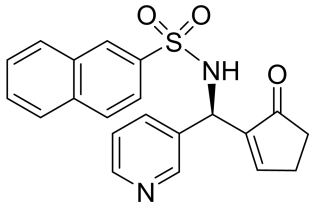
IR (CH_2Cl_2): ν = 3257, 3028, 2964, 2098, 1974, 1846, 1701, 1654, 1582, 1431, 1343, 1134, 1109, 912, 713, 625 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{18}NaN_2O_3S$ = $[M+Na]^+$: m/z = 401.1573, found: m/z = 401.1580.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:40; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 11.6 min, t_r (R) = 14.8 min.

$[\alpha]_D^{25}$ = –17.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(3-pyridinyl)methyl]sulfonamide (2–26)**



2–26

Prepared from ***Imine*–3x** (65.2 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–26** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Yellow solid (mp 177–181 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 61.3 mg (81%), 82% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 65.8 mg (87%), 89% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.74 (s, 1H), 8.50 (s, 1H), 8.03–8.01 (m, 2H), 7.93 (d, *J* = 7.5 Hz, 1H), 7.82 (d, *J* = 7.5 Hz, 1H), 7.78 (d, *J* = 8.4 Hz, 1H), 7.63–7.61 (m, 1H), 7.55–7.54 (m, 1H), 7.24 (t, *J* = 5.3 Hz, 1H), 7.10–7.08 (m, 1H), 7.01 (d, *J* = 8.4 Hz, 1H), 6.68 (d, *J* = 8.4 Hz, 1H), 5.84 (d, *J* = 8.4 Hz, 1H), 2.36–2.23 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.6, 169.6, 149.8, 149.0, 138.8, 135.4, 134.9, 134.6, 133.8, 132.4, 130.9, 129.5, 128.3, 127.4, 127.1, 126.5, 123.9, 123.5, 58.6, 32.4, 26.3 ppm.

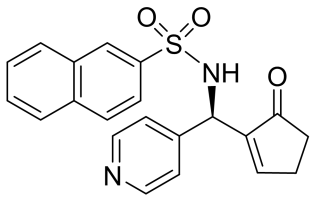
IR (CH_2Cl_2): ν = 3349, 3027, 2952, 2187, 2036, 1895, 1745, 1582, 1436, 1351, 1254, 1139, 918, 746, 725, 693 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{18}NaN_2O_3S$ = $[M+Na]^+$: m/z = 401.1573, found: m/z = 401.1578.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:40; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 11.3 min, t_r (R) = 14.5 min.

$[\alpha]_D^{25}$ = –18.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(4-pyridinyl)methyl]sulfonamide (2–27)**



2–27

Prepared from ***Imine*–3y** (32.6 mg, 0.11 mmol, 1.10 equiv), cyclopentenone (8.20 mg, 0.10 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–27** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Yellow solid (mp 179–182 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 54.4 mg (72%), 77% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 60.5 mg (80%), 87% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.64 (s, 1H), 8.50 (s, 1H), 7.93–7.90 (m, 2H), 7.91–7.88 (m, 1H), 7.83 (d, *J* = 8.4 Hz, 1H), 7.60–7.58 (m, 1H), 7.54 (d, *J* = 8.4 Hz, 1H), 7.42–7.41 (m, 1H), 7.40–7.38 (m, 1H), 7.25 (t, *J* = 5.3 Hz, 1H), 7.20–7.18 (m, 1H), 6.12 (d, *J* = 8.4 Hz, 1H), 5.34 (d, *J* = 8.4 Hz, 1H), 2.20–1.88 (m, 4H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.5, 168.4, 154.8, 141.2, 139.5, 133.7, 132.4, 130.7, 129.2, 128.3, 128.1, 127.7, 127.4, 126.6, 126.5, 125.4, 123.6, 120.7, 57.9, 32.4, 26.1 ppm.

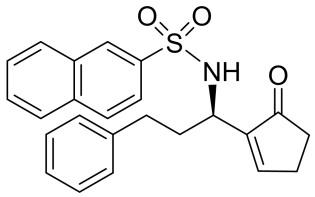
IR (CH_2Cl_2): ν = 3269, 3027, 2952, 2187, 2036, 1895, 1745, 1582, 1436, 1351, 1254, 1139, 918, 746, 721, 646 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{18}NaN_2O_3S$ = $[M+Na]^+$: m/z = 401.1573, found: m/z = 401.1581.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:40; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 11.4 min, t_r (R) = 14.8 min.

$[\alpha]_D^{25}$ = –9.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(3-phenylpropyl)methyl]sulfonamide (2–28)**



2–28

Prepared from ***Imine*–3z** (71.2 mg, 0.22 mmol, 1.10 equiv), cyclopentenone (16.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–28** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Yellow solid (mp 198–200 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 38.9 mg (48%), 55% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 46.9 mg (58%), 78% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.30 (s, 1H), 7.90–7.86 (m, 3H), 7.75 (d, *J* = 7.8 Hz, 1H), 7.68–7.66 (m, 1H), 7.65–7.64 (m, 1H), 7.28 (d, *J* = 7.8 Hz, 1H), 7.20–7.16 (m, 4H), 7.15 (t, *J* = 5.3 Hz, 1H), 6.29 (d, *J* = 8.1 Hz, 1H), 4.92 (t, *J* = 8.1 Hz, 1H), 2.65–2.62 (m, 2H), 2.52–2.49 (m, 2H), 2.30–2.28 (m, 2H), 2.28–2.26 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 162.0, 140.8, 135.4, 133.6, 132.4, 130.7, 129.2, 128.9, 128.7 (2C), 128.5, 128.3, 128.2, 127.7, 127.5, 126.5 (2C), 123.5, 58.2, 33.0, 32.6, 30.8, 26.3 ppm.

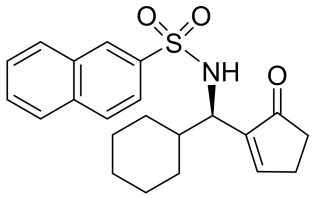
IR (CH_2Cl_2): ν = 3312, 2987, 2923, 2819, 2463, 2276, 1953, 1758, 1617, 1557, 1381, 1249, 1142, 911, 784, 748, 652 cm^{-1}.

HRMS (ESI): calculated for $C_{24}H_{23}NaNO_3S$ = $[M+Na]^+$: m/z = 428.1453, found: m/z = 428.1447.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 12.3 min, t_r (R) = 15.1 min.

[α]$_D^{25}$ = +19.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(3-cyclohexyl)methyl]sulfonamide (2–29)**



2–29

Prepared from ***Imine*–3a'** (33.2 mg, 0.11 mmol, 1.10 equiv), cyclopentenone (8.20 mg, 0.10 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–29** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Yellow solid (mp 164–169 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 52.9 mg (69%), 36% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 55.9 mg (73%), 59% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.52 (s, 1H), 8.02–8.00 (m, 2H), 7.96–7.93 (m, 2H), 7.69–7.66 (m, 2H), 6.99 (t, *J* = 5.2 Hz, 1H), 6.12 (d, *J* = 8.1 Hz, 1H), 4.71 (t, *J* = 8.1 Hz, 1H), 2.20–1.93 (m, 4H), 1.73–1.58 (m, 4H), 1.35–1.34 (m, 1H), 1.27–1.25 (m, 1H), 1.20–1.08 (m, 3H), 0.91–0.78 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.3, 161.3, 142.3, 135.4, 133.6, 132.4, 130.7, 129.2, 128.3, 127.7, 127.5, 126.6, 123.5, 58.1, 38.9, 32.5, 28.8 (2C), 26.3 (2C), 26.2, 25.8 ppm.

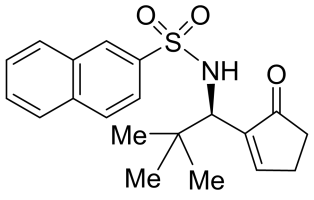
IR (CH_2Cl_2): ν = 3325, 3195, 3021, 2947, 1874, 1769, 1605, 1598, 1457, 1389, 1123, 919, 851, 796, 752, 742, 687, 623 cm^{-1}.

HRMS (ESI): calculated for $C_{22}H_{25}NaNO_3S$ = $[M+Na]^+$: m/z = 406.1649, found: m/z = 406.1658.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 10.4 min, t_r (R) = 12.1 min.

[α]$_D^{25}$ = –40.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(5-oxocyclopent-1-enyl)(2,2-dimethylpropyl)methyl]sulfonamide (2–30)**



2–30

Prepared from ***Imine*–3b'** (30.3 mg, 0.11 mmol, 1.10 equiv), cyclopentenone (8.20 mg, 0.10 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–30** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:2; *eluted twice*).

Yellow solid (mp 144–146 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 44.3 mg (62%), 65% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 56.4 mg (79%), 84% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.45 (s, 1H), 7.95–7.93 (m, 2H), 7.86–7.85 (m, 2H), 7.62–7.60 (m, 1H), 7.58–7.56 (m, 1H), 7.17 (t, *J* = 5.2 Hz, 1H), 6.17 (d, *J* = 8.1 Hz, 1H), 4.92 (d, *J* = 8.1 Hz, 1H), 2.12-1.86 (m, 4H), 0.84 (s, 9H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 208.7, 160.2, 143.6, 135.4, 133.6, 132.4, 130.7, 129.2, 128.4, 127.7, 127.5, 126.5, 123.5, 58.1, 35.4, 32.5, 29.3, 26.2 (3C) ppm.

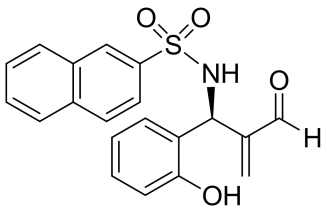
IR (CH_2Cl_2): ν = 3423, 3245, 2973, 2845, 2758, 1646, 1573, 1436, 1349, 1313, 1158, 916, 784, 736, 688, 631, 592 cm^{-1}.

HRMS (ESI): calculated for $C_{20}H_{23}NaNO_3S$ = $[M+Na]^+$: m/z = 380.4425, found: m/z = 380.4434.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 9.4 min, t_r (R) = 11.3 min.

[α]$_D^{25}$ = –30.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(2-formyl-1-allyl)(2-hydroxyphenyl)methyl]sulfonamide (2–31)**



2–31

Prepared from ***Imine* 3h** (68.4 mg, 0.22 mmol, 1.10 equiv) and acrolein (13.0 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–31** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5; *eluted twice*).

Colorless solid (mp 152–156 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 65.3 mg (81%), 81% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 68.5 mg (85%) 91% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.58 (s, 1H), 8.27 (br s, 1H), 8.21–8.20 (m, 1H), 7.93–7.81 (m, 3H), 7.72 (d, *J* = 7.6 Hz, 1H), 7.25–7.23 (m, 1H), 7.22–7.19 (m, 3H), 7.05 (d, *J* = 8.0 Hz, 1H), 6.90 (dd, *J* = 7.6, 8.0 Hz, 1H), 6.12 (s, 1H), 5.99 (d, *J* = 8.1 Hz, 1H), 5.75 (s, 1H), 5.48 (d, *J* = 8.1 Hz, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 189.2, 154.6, 141.3, 135.4, 133.6, 132.4, 131.9, 129.2, 128.3, 128.2, 128.0, 127.7, 127.5, 126.6, 123.5, 123.3, 122.5, 114.7, 114.3, 58.1 ppm.

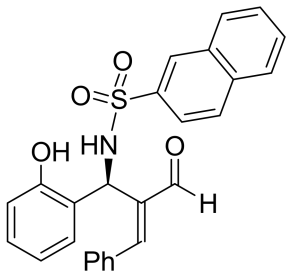
IR (CH_2Cl_2): ν = 3432, 3356, 2854, 2728, 1703, 1685, 1639, 1320, 1284, 1225, 730, 698 cm^{-1}.

HRMS (ESI): calculated for $C_{20}H_{17}NaNO_4S$ = $[M+Na]^+$: m/z = 390.5286, found: m/z = 390.5289.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 90:10; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 12.5 min, t_r (R) = 20.3 min.

[α]$_D^{25}$ = +10.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(2-formyl-1-phenylallyl)(2-hydroxyphenyl)methyl]sulfonamide (2–32)**



2–32

Prepared from ***Imine* 3h** (68.4 mg, 0.22 mmol, 1.10 equiv) and cinnamaldehyde (20.4 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–32** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5; *eluted twice*).

Colorless solid (mp 160–163 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 60.4 mg (68%), 76% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 70.2 mg (79%) 88% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 9.74 (s, 1H), 8.31–8.30 (m, 1H), 7.93–7.81 (m, 3H), 7.74–7.72 (m, 3H), 7.51–7.46 (m, 2H), 7.43 (d, *J* = 7.9 Hz, 2H), 7.39 (d, *J* = 7.9 Hz, 2H), 7.36 (d, *J* = 7.9 Hz, 2H), 7.23–7.03 (m, 2H), 6.08 (s, 1H), 5.64 (d, *J* = 8.4 Hz, 1H), 4.88 (d, *J* = 8.4 Hz, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 189.3, 154.6, 140.2, 135.4, 133.6, 132.4, 131.9, 131.8, 130.5, 129.6, 129.2, 128.9, 128.7 (2C), 128.3, 128.2, 128.0, 127.7, 127.5 (2C), 126.6, 123.5, 123.3, 122.5, 114.8, 58.1 ppm.

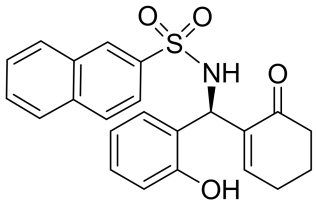
IR (CH_2Cl_2): ν = 3456, 3302, 2864, 2731, 1712, 1683, 1598, 1326, 1284, 1215, 728, 690 cm^{-1}.

HRMS (ESI): calculated for $C_{26}H_{21}NaNO_4S$ = $[M+Na]^+$: m/z = 466.6128, found: m/z = 466.6134.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 90:10; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 12.8 min, t_r (R) = 21.9 min.

$[\alpha]_D^{25}$ = +3.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(6-oxocyclohex-1-enyl)(2-hydroxyphenyl)methyl]sulfonamide (2–34)**



2–34

Prepared from ***Imine* 3h** (68.4 mg, 0.22 mmol, 1.10 equiv) and cyclohexenenone (20.8 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–34** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5; *eluted twice*).

Colorless solid (mp 167–172 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 63.5 mg (78%), 78% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 67.6 (83%), 94% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.21 (s, 1H), 7.93–7.81 (m, 3H), 6.08 (br s, 1H), 7.77–7.72 (m, 4H), 7.25 (dd, *J* = 7.6, 8.3 Hz, 1H), 6.95 (dd, *J* = 7.0, 7.6 Hz, 1H), 6.41 (t, *J* = 3.7 Hz, 1H), 6.00 (d, *J* = 8.3 Hz, 1H), 5.74 (d, *J* = 8.6 Hz, 1H), 5.34 (d, *J* = 8.6 Hz, 1H), 2.45–1.81 (m, 6H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 195.4, 154.6, 141.2, 135.4, 133.6, 132.4, 131.9, 129.2, 128.3, 128.2, 128.1, 127.7, 127.5, 126.6, 126.0, 123.5, 123.3, 122.5, 114.7, 58.1, 37.2, 25.3, 22.0 ppm.

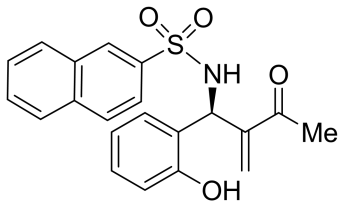
IR (CH_2Cl_2): ν = 3425, 3310, 2931, 2845, 1698, 1675, 1487, 1328, 1245, 1224, 731, 695 cm^{-1}.

HRMS (ESI): calculated for $C_{23}H_{21}NaNO_4S$ = $[M+Na]^+$: m/z = 430.5843, found: m/z = 430.5847.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 13.5 min, t_r (R) = 19.8 min.

$[\alpha]_D^{25}$ = +23.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[(2-methozoyl)-1-(2-hydroxylbenzylallyl)]sulfonamide (2–35)**



2–35

Prepared from ***Imine* 3h** (68.4 mg, 0.22 mmol, 1.10 equiv) and methyl vinyl ketone (16.8 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–35** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5; *eluted twice*).

Colorless solid (mp 156–162 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 63.7 mg (76%), 83% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 77.1 mg (92%), 91% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.32 (s, 1H), 7.96–7.81 (m, 3H), 7.75–7.70 (m, 4H), 7.20–6.82 (m, 3H), 6.18 (br s, 1H), 6.11 (s, 1H), 6.02 (s, 1H), 5.70 (d, *J* = 8.1 Hz, 1H), 5.24 (d, *J* = 8.1 Hz, 1H), 2.23 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 196.8, 154.6, 143.5, 135.4, 133.6, 132.4, 131.9, 129.2, 128.3, 128.2, 128.0, 127.7, 127.5, 126.5, 123.5, 123.3, 122.5, 114.7, 114.3, 58.1, 29.5 ppm.

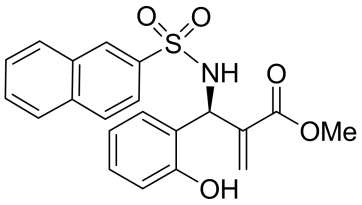
IR (CH_2Cl_2): ν = 3419, 3397, 2964, 2825, 1701, 1664, 1367, 1318, 1275, 1210, 731, 704 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{19}NaNO_4S$ = $[M+Na]^+$: m/z = 404.5612, found: m/z = 404.5617.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 100:20; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 14.6 min, t_r (R) = 21.4 min.

$[\alpha]_D^{25}$ = +16.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-Methyl-α–Methylene-β-[(2-naphthalenesulfonyl)-amino]-3-(2-hydroxyphenyl)propionate (2–36)**



2–36

Prepared from ***Imine* 3h** (68.4 mg, 0.22 mmol, 1.10 equiv) and methyl acrylate (18.6 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–36** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5; *eluted twice*).

Colorless solid (mp 169–174 °C).

1st generation ***pre-BAC*–8**: +35 °C, 48 h; yield: 56.4 mg (71%), 70% *ee*.

2nd generation ***pre-BAC*–11**: –20 °C, 72 h; yield: 58.8 mg (74%), 83% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.25 (s, 1H), 7.95–7.78 (m, 3H), 7.76–7.72 (m, 4H), 7.24–6.99 (m, 3H), 7.24 (br s, 1H), 6.25 (s, 1H), 5.87 (s, 1H), 5.80 (d, *J* = 8.1 Hz, 1H), 5.21 (d, *J* = 8.1 Hz, 1H), 3.78 (s, 3H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 165.1, 154.6, 145.2, 135.4, 133.6, 132.4, 131.9, 129.2, 128.3, 128.2, 128.0, 127.7, 127.5, 126.6, 123.4, 123.2, 122.5, 114.7, 114.3, 58.1, 51.9 ppm.

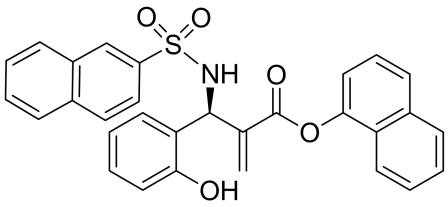
IR (CH_2Cl_2): ν = 3426, 3356, 2958, 2837, 1694, 1662, 1381, 1310, 1289, 1214, 1168, 720, 693 cm^{-1}.

HRMS (ESI): calculated for $C_{21}H_{19}NaNO_5S$ = $[M+Na]^+$: m/z = 420.9735, found: m/z = 420.9737.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 100:20; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 13.2 min, t_r (R) = 22.6 min.

$[\alpha]_D^{25}$ = +5.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-1-Naphthyl-2-[(2-hydroxyphenyl)-(2-naphthalenesulfonylamino)methyl]acrylate (2–37)**



2–37

Prepared from ***Imine* 3h** (68.4 mg, 0.22 mmol, 1.10 equiv) and α-naphthyl acrylate (39.6 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–37** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5; *eluted twice*).

Colorless solid (mp 187–194 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 75.6 mg (74%), 72% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 97.1 mg (95%), 94% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.45–8.44 (m, 1H), 7.92 (d, *J* = 8.2 Hz, 1H), 7.91 (d, *J* = 7.6 Hz, 1H), 7.90 (d, *J* = 7.6 Hz, 1H), 7.80 (d, *J* = 8.2 Hz, 1H), 7.76–7.72 (m, 3H), 7.66–7.61 (m, 3H), 7.38–7.32 (m, 2H), 7.25 (dd, *J* = 7.6, 8.2 Hz, 2H), 7.06 (d, *J* = 8.0 Hz, 1H), 6.95 (dd, *J* = 7.6, 8.2 Hz, 2H), 6.68 (s, 1H), 6.43 (s, 1H), 6.09 (d, *J* = 8.4 Hz, 1H), 5.87 (d, *J* = 8.4 Hz, 1H), 5.65 (br s, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 165.2, 154.6, 146.8, 142.3, 135.4, 134.6, 133.6, 132.4, 131.9, 130.5, 129.2, 128.3, 128.2, 128.1, 128.0, 127.7, 127.6, 127.5, 126.7, 126.6, 123.5, 123.3, 122.5, 122.1, 121.4, 120.4, 114.7, 125.9, 118.7, 58.0 ppm.

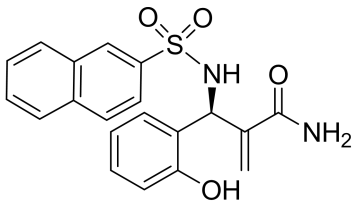
IR (CH_2Cl_2): ν = 3429, 3346, 1698, 1665, 1580, 1320, 1287, 1256, 1211, 1189, 728, 693 cm^{-1}.

HRMS (ESI): calculated for $C_{30}H_{23}NaNO_5S$ = $[M+Na]^+$: m/z = 532.6715, found: m/z = 532.6718.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.8 mL/min; 220 nm, 25 °C): t_r (S) = 15.6 min, t_r (R) = 17.5 min.

$[\alpha]_D^{25}$ = +38.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-[(2-hydroxyphenyl)-(2-naphthalenesulfonylamino)methyl]-acrylamide (2–38)**



2–38

Prepared from ***Imine* 3h** (68.4 mg, 0.22 mmol, 1.10 equiv) and acrylamide (14.2 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–38** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5; *eluted twice*).

Colorless solid (mp 135–139 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 45.9 mg (60%), 66% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 57.4 mg (75%), 82% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.15 (s, 1H), 7.82–7.80 (m, 3H), 7.77–7.72 (m, 4H), 7.34 (br s, 2H), 7.11 (d, *J* = 8.0 Hz, 1H), 7.05–7.03 (m, 2H), 6.48 (s, 1H), 5.70 (d, *J* = 8.1 Hz, 1H), 5.68 (br s, 1H), 5.29 (s, 1H), 5.02 (d, *J* = 8.1 Hz, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 166.7, 154.6, 142.3, 133.6, 135.4, 131.9, 130.8, 129.2, 128.3, 128.2, 128.0, 127.5, 125.6, 124.3, 123.6, 123.3, 122.5, 114.7, 114.3, 58.4 ppm.

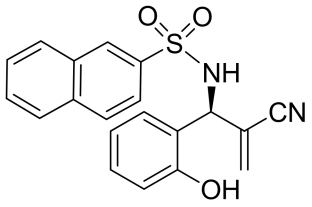
IR (CH_2Cl_2): ν = 3401, 3346, 3319, 1689, 1656, 1660, 1535, 1320, 1294, 1238, 1216, 1182, 722, 694, 678 cm^{-1}.

HRMS (ESI): calculated for $C_{20}H_{18}NaN_2O_4S$ = $[M+Na]^+$: m/z = 405.6347, found: m/z = 405.6354.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 11.2 min, t_r (R) = 16.5 min.

$[\alpha]_D^{25}$ = +9.0 ° (*c* = 1.0, $CHCl_3$).

***(R)*-2-Naphthalene-*N*-[2-cyano-1-(2-hydroxyphenyl)propen-2-yl]sulfonamide (2–39)**



2–39

Prepared from ***Imine* 3h** (68.4 mg, 0.22 mmol, 1.10 equiv) and acrylonitrile (10.6 mg, 0.20 mmol, 1.00 equiv) according to *General Procedure I or J*. **2–39** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5; *eluted twice*).

Colorless solid (mp 148–154 °C).

1st generation ***pre-BAC*–8***: +35 °C, 48 h; yield: 60.5 mg (83%),75% *ee*.

2nd generation ***pre-BAC*–11***: –20 °C, 72 h; yield: 65.6 mg (90%), 84% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 8.32 (s, 1H), 7.90-7.80 (m, 3H), 7.77-7.72 (m, 2H), 7.14-7.12 (m, 1H), 7.06 (d, *J* = 8.0 Hz, 1H), 7.00-6.68 (m, 3H), 6.47 (br s, 1H), 6.11 (s, 1H), 5.92 (s, 1H), 5.46 (d, *J* = 8.1 Hz, 1H), 5.10 (d, *J* = 8.1 Hz, 1H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 154.6, 140.3, 135.4, 133.6, 132.4, 131.9, 129.2, 128.3, 128.2, 128.0, 127.7, 127.5, 124.6, 123.5, 123.3, 122.5, 115.9, 114.7, 114.3, 58.1 ppm.

IR (CH_2Cl_2): ν = 3342, 3301, 2206, 1657, 1639, 1528, 1276, 765, 687 cm^{-1}.

HRMS (ESI): calculated for $C_{20}H_{16}NaN_2O_3S$ = $[M+Na]^+$: m/z = 387.5246, found: m/z = 387.5249.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 80:20; flow rate: 0.4 mL/min; 220 nm, 25 °C): t_r (S) = 15.5 min, t_r (R) = 18.9 min.

$[\alpha]_D^{25}$ = +18.0 ° (*c* = 1.0, $CHCl_3$).

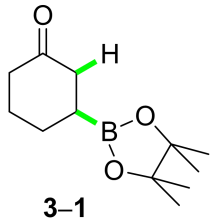
5.4 TOWARDS BAC-catalysed ASYMMETRIC BORYLATION

5.4.1 BAC-catalysed Conjugate Borylation

General Procedure K **[synthesis of conjugate borylated products]**

To an oven-dried test tube with a magnetic stirring bar in a nitrogen glovebox were added ***pre-BAC*–1** (3.20 mg, 10.0 μmol, 10.0 mol%), (pin)B–B(pin) (**B–5**) (27.9 mg, 0.11 mmol, 1.10 equiv), different Michael acceptors (0.10 mmol, 1.00 equiv), THF (0.33 mL, 0.3 M), and DBU (1.50 mg, 10.0 μmol, 10.0 mol%). In the cases of **3–3** and **3–4**, an additional amount of methanol (6.40 mg, 0.20 mmol, 2.00 equiv) was added. The reaction mixture was stirred at 40 °C for 24 h, at which point TLC and/or ^{1}H NMR analysis indicated complete consumption of Michael acceptor. The reaction was quenched by the addition of water (0.3 mL) and the mixture was allowed to stir for an additional 20 min. The aqueous layer was washed with diethyl ether (3 x 2 mL). Volatiles were removed *in vacuo*, and the residue was purified by flash column chromatography or PTLC on silica gel (eluent: EtOAc/PE = 1:5) to give the intended products.

3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohexanone (3-1)[109]



3–1

Prepared from (pin)B–B(pin) (**B–5**) (27.9 mg, 0.11 mmol, 1.10 equiv) and cyclohexenone (10.4 mg, 0.10 mmol, 1.00 equiv) according to *Procedure K*. **3–1** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.* [109]

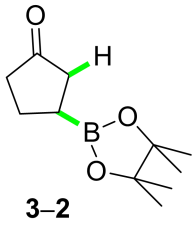
Colorless oil.

Yield: 20.2 mg (89%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 2.37–2.22 (m, 4H), 2.08–2.00 (m, 1H), 1.87–1.81 (m, 1H), 1.77–1.66 (m, 1H), 1.64–1.54 (m, 1H), 1.46–1.38 (m, 1H), 1.20 (s, 12H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 211.5, 83.1, 42.4, 41.5, 28.1, 26.2, 24.0 (2C), 22.3 (2C), 21.1 (2C) ppm.

3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopentanone (3-2) [109]



3–2

Prepared from (pin)B–B(pin) (**B–5**) (27.9 mg, 0.11 mmol, 1.10 equiv) and cyclopentenone (8.20 mg, 0.10 mmol, 1.00 equiv) according to *Procedure K*. **3–2** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.* [109]

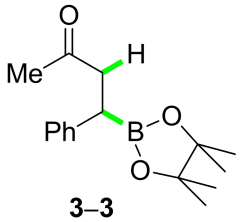
Colorless oil.

Yield: 18.3 mg (82%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 2.33–2.20 (m, 2H), 2.19–2.07 (m, 3H), 1.90–1.81 (m, 1H), 1.68–1.59 (m, 1H), 1.25 (s, 12H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 221.2, 83.7, 40.3, 39.1, 30.5, 25.4 (2C), 24.9 (2C), 22.3 (2C) ppm.

4-phenyl-4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)butan-2-one (3-3)[111]



3–3

Prepared from (pin)B–B(pin) (**B–5**) (27.9 mg, 0.11 mmol, 1.10 equiv) and *trans*-4-phenyl-3-buten-2-one (14.6 mg, 0.10 mmol, 1.00 equiv), methanol (6.40 mg, 0.20 mmol, 2.00 equiv) according to *Procedure K*. **3–3** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.* [111]

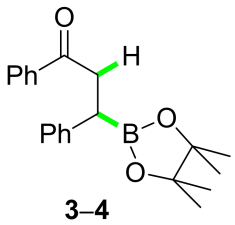
Colorless oil.

Yield: 18.9 mg (65%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.45–7.43 (m, 2H), 7.25–7.21 (m, 3H), 3.05 (dd, J = 20.0, 12.0 Hz, 1H), 2.85 (dd, J = 20.0, 4.0 Hz, 1H), 2.71 (dd, J = 12.0, 4.0 Hz, 1H), 1.94 (s, 3H), 1.29 (s, 12H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 205.9, 130.6, 128.9, 127.8 (2C), 127.5 (2C), 83.4, 30.5, 29.9 (2C), 25.1 (2C), 24.8 (2C), 22.8 ppm.

4-phenyl-4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)butan-2-one (3-4) [111]



3–4

Prepared from (pin)B–B(pin) (**B–5**) (27.9 mg, 0.11 mmol, 1.10 equiv) and 1,3-diphenyl-2-propenone (20.8 mg, 0.10 mmol, 1.00 equiv), methanol (6.40 mg, 0.20 mmol, 2.00 equiv) according to *Procedure K*. **3–4** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.* [111]

Colorless oil.

Yield: 26.4 mg (76%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 7.97–7.94 (m, 2H), 7.55–7.50 (m, 1H), 7.44–7.40 (m, 2H), 7.31–7.24 (m, 4H), 7.17–7.13 (m, 1H), 3.54 (dd, *J* = 18.4, 10.8 Hz, 1H), 3.41 (dd, *J* = 18.4, 5.2 Hz, 1H), 2.79 (dd, *J* = 10.8, 5.2 Hz, 1H), 1.23 (s, 6H), 1.15 (s, 6H) ppm.

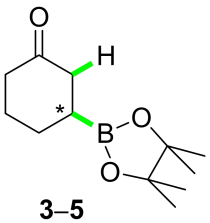
^{13}C NMR ($CDCl_3$, 125 MHz): δ = 199.2, 134.5, 130.7, 129.7, 128.9, 128.6 (2C), 128.4 (2C), 127.8 (2C), 127.6 (2C), 83.2, 30.5, 25.0 (2C), 24.8 (2C), 22.3 (2C) ppm.

5.4.2 Towards an Asymmetric Version

General Procedure L **[asymmetric borylation]**

To an oven-dried test tube with a magnetic stirring bar in a nitrogen glovebox were added ***pre-BAC*–8*** (3.20 mg, 10.0 μmol, 10.0 mol%), DBU (1.50 mg, 10.0 μmol, 10.0 mol%) and THF (0.17 mL). The pre-catalyst mixture was pre-stirred at 35 °C for 20 h before cooling to –20 °C, at which stage a stock solution of (pin)B–B(pin) (**B–5**) (27.9 mg, 0.11 mmol, 1.10 equiv), corresponding Michael acceptors (0.10 mmol, 1.00 equiv), dried methanol (80.1 mg, 2.50 mmol, 25.0 equiv) and THF (0.33 mL) was added to the pre-catalyst mixture. The reaction mixture was stirred at –20 °C for 48 h, at which point TLC and/or ^{1}H NMR analysis indicated complete consumption of Michael acceptor. The reaction was quenched by the addition of water (0.3 mL) and the mixture was allowed to stir for an additional 20 min. The aqueous layer was washed with diethyl ether (3 x 2 mL). Volatiles were removed *in vacuo*, and the residue was purified by flash column chromatography or PTLC on silica gel (eluent: EtOAc/PE = 1:5) to give the intended products.

(*R*)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohexanone (3-5) [111]



3–5

Prepared from (pin)B–B(pin) (**B–5**) (27.9 mg, 0.11 mmol, 1.10 equiv), cyclohexenone (10.4 mg, 0.10 mmol, 1.00 equiv), and methanol (80.1 mg, 2.50 mmol, 25.0 equiv) according to *Procedure K*. **3–5** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.* [111]

Colorless oil.

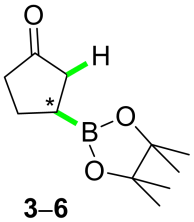
1st generation ***pre-BAC*–8***, –20 °C, 48 h; yield: 10.1 mg (45%), 69% *ee*.

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 2.39–2.24 (m, 4H), 2.09–2.03 (m, 1H), 1.89–1.84 (m, 1H), 1.79–1.70 (m, 1H), 1.66–1.57 (m, 1H), 1.45–1.42 (m, 1H), 1.23 (s, 12H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 210.9, 82.7, 41.7, 40.9, 27.8, 26.5, 24.5 (2C), 21.8 (2C), 20.9 (2C) ppm.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 98:2; flow rate: 0.3 mL/min; 220 nm, 25 °C): t_r (S) = 11.1 min, t_r (R) = 12.8 min.

(*R*)-3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopentanone (3-6) [111]



3–6

Prepared from (pin)B–B(pin) (**B–5**) (27.9 mg, 0.11 mmol, 1.10 equiv) and cyclopentenone (8.40 mg, 0.10 mmol, 1.00 equiv), and methanol (80.1 mg, 2.50 mmol, 25.0 equiv) according to *Procedure K*. **3–6** was purified by PTLC on silica gel (eluent: EtOAc/PE = 1:5). *The obtained analytical data were in full agreement with the reported data.* [111]

Colorless oil.

1st generation ***pre-BAC*–8***, –20 °C, 48 h; yield: 9.66 mg (46%), 63% *ee*.

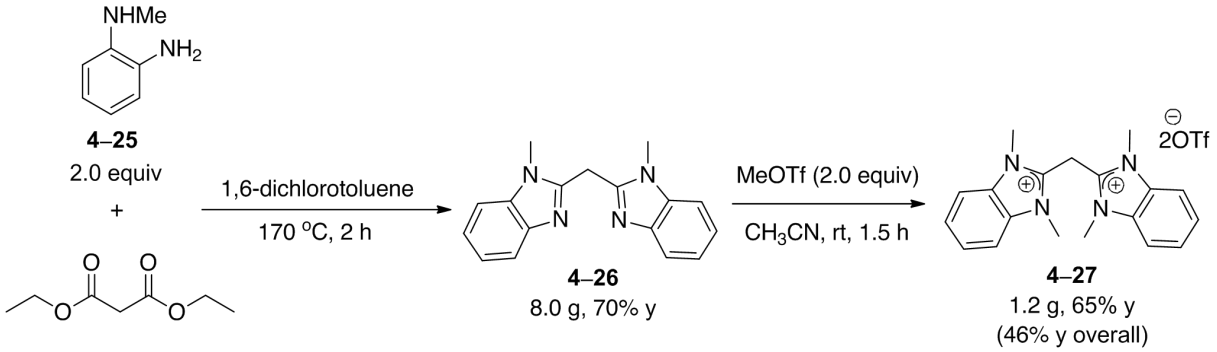
^{1}H NMR ($CDCl_3$, 500 MHz): δ = 2.31-2.18 (m, 2H), 2.15-2.06 (m, 3H), 1.88-1.79 (m, 1H), 1.67-1.56 (m, 1H), 1.24 (s, 12H) ppm.

^{13}C NMR ($CDCl_3$, 125 MHz): δ = 220.4, 85.2, 42.5, 38.1, 29.8, 25.1 (2C), 24.8 (2C), 21.6 (2C) ppm.

The enantiomeric excess was determined by chiral HPLC analysis using a DAICEL Chiracel IB column (eluent: hexane/^{i}PrOH = 98:2; flow rate: 0.3 mL/min; 220 nm, 25 °C): t_r (S) = 12.4 min, t_r (R)= 14.7 min.

5.5 THE CHEMISTRY OF CARBONES

5.5.1 Preparation of Carbone Precursors 4–28 and a Carbone 4–5



To a 50-mL two-neck, round-bottomed flask fitted with Dean-Sttark apparatus and additional funnel was placed the *N*-methyl-1,2-phenylenediamine (1.20 g, 9.30 mmol, 2.00 equiv) in 1,6-dichlorotoluene (5.00 mL). The solution was heated to 170 °C, and then diethyl malonate (1.00 g, 4.60 mmol, 1.00 equiv) was added drop-wise to the reaction flask over 90 min. The temperature gradually increased to 185 °C during the addition process and maintained around 185 °C to 190 °C for 2 hours. The ending point of the reaction can be monitored by ^{1}H NMR analysis. The resulting mixture was cooled down to ambient temperature. After filtration, the solid was washed with benzene (3 x 5 mL) and methanol (5 mL), and then dried *in vacuo* to afford the product **4–26** as a pale beige solid (8.05 g, 70% yield; mp 207–209°C). *The obtained analytical data fit accurately with the reported data.*[129]

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 7.76–7.71 (m, 2H), 7.33–7.22 (m, 6H), 4.69 (s, 2H), 3.90 (s, 6H) ppm.

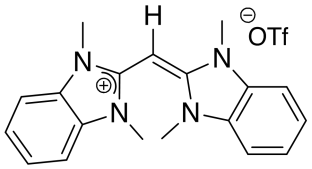
^{13}C NMR ($CDCl_3$, 100 MHz) δ = 149.8 (2C), 142.9 (2C), 136.7 (2C), 123.3 (2C), 122.7 (2C), 120.0 (2C), 109.9 (2C), 31.0, 29.1 (2C) ppm.

In a 50-mL, two-necked, round-bottomed flask was placed **4–26** (3.00 g, 10.9 mmol, 1.00 equiv) in anhydrous acetonitrile (10.0 mL). Methyl trifluoromethansulfonate (4.00 mL, 35.3 mmol, 3.50 equiv) was added dropwise to the reaction flask. The resulting mixture was then stirred at room temperature for one hour and then added diethyl ether (60.0 mL) to provide white precipitate. The white precipitate was then washed with CH_2Cl_2 (2 x 15 mL), and dried *in vacuo* to afford the product **4–27** as a colourless solid (1.22 g, 65% yield; mp 246–250 °C). *The obtained analytical data fit accurately with the reported data.*[117]

^{1}H NMR (CD_3CN, 400 MHz) δ = 7.95–7.90 (m, 4H), 7.80–7.76 (m, 4H), 5.37 (s, 2H), 3.95 (s, 12H) ppm.

^{13}C NMR (CD_3CN, 100 MHz): δ = 144.7 (2C), 133.5 (4C), 129.1 (4C), 126.5 (4C), 114.8 (q, J = 264.6 Hz), 34.2, 22.9 (4C) ppm.

Preparation of 4–28[124]



4–28

Prepared from **4–27** (0.50 g, 0.60 mmol, 1.00 equiv) and base (2.0 equiv) in anhydrous DCE (5.00 mL) at room temperature for 6 h. **4–28** was washed with hexane (10 mL). *The obtained analytical data were in full agreement with the reported data.*[124]

Colorless solid.

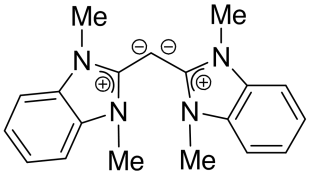
Mp. 152−155 °C (153−155 °C) [124]

Ag_2O; yield: 91.1 mg (20%); KHMDS; yield: 273 mg (60%); NaOMe; yield: 410 mg (90%).

^{1}H NMR (CD_2Cl_2, 500 MHz): δ = 7.42–7.32 (m, 8H), 4.55 (s, 1H), 3.57 (s, 12H) ppm.

^{13}C NMR (CD_2Cl_2, 150 MHz): δ = 153.1, 140.2, 137.6 (2C), 134.2 (2C), 132.9 (2C), 130.1 (2C), 128.7 (2C), 126.4 (2C), 124.3, 112.5 (q, J = 262.8 Hz), 32.2 (4C) ppm.

Bis(1,3-methyl-benzimidazol-2-ylidene)methane (4–5)[117]



4–5

Prepared from **4–28** (1.00 g, 1.50 mmol, 1.00 equiv) and KHMDS (0.37 g, 1.82 mmol, 1.10 equiv) in THF (6.70 mL) at room temperature for 3 h. **4–5** was washed with Et_2O (10 mL). *The obtained analytical data were in full agreement with the reported data.*[117]

Colorless solid.

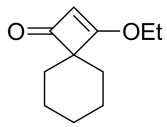
Mp. 151−152 °C (150−152 °C) [117]

Yield: 0.64 g (80%).

^{1}H NMR (C_6D_6, 400 MHz): δ = 6.96–6.94 (m, 4H), 6.84–6.82 (m, 4H), 3.13 (s, 12H) ppm.

^{13}C NMR (C_6D_6, 100 MHz): δ = 144.8 (2C), 135.9 (4C), 132.4 (4C), 130.5 (4C), 110.2, 29.7 (4C) ppm.

Preparation of 4–29



4–29

A 50 ml two-necked round-bottomed flask fitted with an efficient condenser was charged with diethylether (15.0 ml), cyclohexane carbonyl chloride (1.10 g, 7.50 mmol, 1.00 equiv) and ethoxyacetylene (2.10 g, 50%w/w in hexanes, 15.0 mmol, 2.00 equiv). The stirred solution was then treated dropwise at toom temperature with triethylamine (1.50 ml, 11.2 mmol, 1.50 equiv). After 30 min the suspension was heated to reflux at 60 °C and stirred for a further 24 h. The resulting turbid mixture was allowed to cool prior to removal of triethlammonium chloride by filtration and the filtrate was concentrated *in vacuo*. *The obtained analytical data fit accurately with the reported data.*[128]

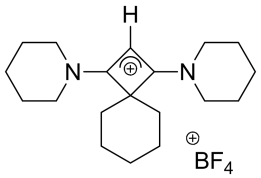
Brown oil.

Yield: 0.93 g (81%).

^{1}H NMR (C_6D_6, 400 MHz): δ = 5.37 (s, 1H), 4.25 (q, *J* = 7.9 Hz, 2H), 1.77–1.72 (m, 4H), 1.53–1.49 (m, 4H), 1.36–1.33 (m, 2H), 1.28 (t, *J* = 7.9 Hz, 3H) ppm.

^{13}C NMR (C_6D_6, 100 MHz): δ = 194.5, 155.7, 119.1, 66.5, 42.4 (2C), 35.4 (2C), 25.8, 22.2, 14.7 ppm.

Preparation of 4–30



4–30

A $CHCl_3$ solution (20.0 mL) of Et_3O^+ $^-$BF4 (3.10 g, 16.6 mmol) was added at room temperature to a $CHCl_3$ solution (30.0 mL) of **4–29** (2.00 g, 11.1 mmol). After stirring at 50 °C for 2 hours, and evaporation of the solvent, the residue was washed with dry ether (2 x 20 ml), and dissolved in dichloromethane (20 mL). Piperidine (3.85 mL, 33.0 mmol) was added at 0 °C, and the solution is stirred for 1 hour at room temperature. The solution was filtered through neutral alumina and the solvent removed under vacuum. Salt **4–30** was obtained from a concentrated solution of acetonitrile at –20 °C. *The obtained analytical data fit accurately with the reported data.*[128]

Light yellow solid.

Mp. 169−171 °C (168−171 °C) [128]

Yield: 0.65 g (72%).

^{1}H NMR ($CDCl_3$, 500 MHz): δ = 5.17 (s, 1H), 3.62–3.58 (m, 4H), 3.42–3.39 (m, 4H), 1.92–1.87 (m, 4H), 1.69–1.60 (m, 8H), 1.64–1.56 (m, 8H), 1.52–1.50 (m, 2H) ppm.

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 171.7 (2C), 92.8, 57.5, 50.1, 49.9, 35.6, 29.0 (2C), 26.0 (2C), 25.4 (2C), 23.1 (2C), 23.0 (2C), 21.9 (2C) ppm.

Reference

[1] J. Clayden, N. Greeves, S. Warren, P. Wothers, in *Organic Chemistry*, **2001** (Oxford Chemistry Press), London.

[2] G. Bertrand, A. Igau, H. Grtzmacher, A. Baceiredo, *J. Am. Chem. Soc.* **1988**, *110*, 6463.

[3] G. Bertrand, D. Martin, M. Melaimi, M. Soleilhavoup, *Organometallics* **2011**, *30*, 5304.

[4] F. Glorius, M.N. Hopkinson, C. Richter, M. Schedler, *Nature* **2014**, *510*, 485.

[5] F. Glorius, *N-Heterocyclic Carbenes in Transition Metal Catalysis*, **2007** (Springer-Verlag), Berlin/Heidelberg.

[6] A.J. Arduengo, M. Kline, R.L. Harlow, *J. Am. Chem. Soc.* **1991**, *113*, 361.

[7] V. Lavallo, Y. Canac, C. Präsang, B. Donnadieu, G. Bertrand, *Angew. Chem. Int. Ed.* **2005**, *44*, 5705.

[8] V. Lavallo, Y. Canac, B. Donnadieu, W.W. Schoeller, G. Bertrand, *Science* **2006**, *312*, 722.

[9] R. Jazzar, J.B. Bourg, R.D. Dewhurst, B. Donnadieu, G. Bertrand, *J. Org. Chem.* **2007**, *72*, 3492.

[10] G. Kuchenbeiser, B. Donnadieu, G. Bertrand, *J. Organomet. Chem*. **2008**, *693*, 899.

[11] O. Back, M. Henry-Ellinger, C.D. Martin, D. Martin, G. Bertrand, *Angew. Chem. Int. Ed.* **2013**, *52*, 2939.

[12] V. Lavallo, A. El-Batta, G. Bertrand, R.H. Grubbs, *Angew. Chem. Int. Ed.* **2011**, *50*, 268.

[13] O. Back, G. Kuchenbeiser, B. Donnadieu, G. Bertrand, *Angew. Chem. Int. Ed.* **2009**, *48*, 5530.

[14] S. Miki, T. Ohno, H. Iwasaki, Y. Maeda, Z. Yoshida, *Tetrahedron* **1988**, *44*, 55.

[15] H.A. Malik, G.J. Sormunen, J. Montgomery, *J. Am. Chem. Soc.* **2010**, *132*, 6304.

[16] G.R. Eaton, *J. Chem. Educ*. **1969**, *46*, 547.

[17] (a) S. Tang, J. Monot, A. El-Hallani, B. Michelet, R. Guillot, C. Bour, V. Gandon, *Chem. Eur. J.* **2012**, *18*, 10239. (b) Z. Černy, J. Macháček, J. Fusek, O. Kříž, B. Čásensky, *J. Organomet. Chem*. **1993**, *456*, 25.

[18] J.J. Meng, M. Gao, H. Lv, X. Zhang, *Org. Lett.* **2015**, *17*, 1842.

[19] V. Voorhees, R. Adams, *J. Am. Chem. Soc*. **1922**, *44*, 1397.

[20] A. T. Biju, A. Bhunia, S. R. Tetra, *Chem. Soc. Rev*. **2012**, *41*, 3140.

[21] M. Shi, Y. Wei, *Chem. Rev*. **2013**, *113*, 6659.

[22] a) S. France, D.J. Guerin, S.J. Miller, T. Lectka, *Chem. Rev*. **2003**, *103*, 2985; b) G.C. Fu, *Acc. Chem. Res.* **2004**, *37*, 542; c) X. Lu, C. Zhang, Z. Xu, *Acc. Chem. Res*. **2001**, *34*, 535; d) J.L. Methot, W.R. Roush, *Adv. Synth. Catal*. **2004**, *346*, 1035.

[23] a) K. Morita, Z. Suzuki, H. Hirose, *Bull. Chem. Soc. Jpn*. **1968**, *41*, 2815; b) K. Morita, Japan Patent, 6803364, **1968**.

[24] A.B. Baylis, M.E.D. Hillman, German Patent, 2155113, **1972**.

[25] P. Perlmutter, C.C. Teo, *Tetrahedron Lett*. **1984**, *25*, 5951.

[26] a) Y.-L. Shi, M. Shi, *Eur. J. Org. Chem*. **2007**, 2905; b) G. Masson, C. Housseman, J. Zhu, *Angew. Chem. Int. Ed.* **2007**, *46*, 4614; c) Y. Lu, S.-X. Wang, X. Han, F. Zhong, Y. Wang, *Synlett* **2011**, 2766; d)

D. Basavaiah, G. Veeraraghavaiah, *Chem. Soc. Rev*. **2012**, *41*, 68.

[27] Y.-M. Xu, M. Shi, *J. Org. Chem.* **2004**, *69*, 417.

[28] M. Shi, G.-L. Zhao, *Tetrahedron Lett.* **2002**, *43*, 4499.

[29] M. Shi, G.-L. Zhao, *Adv. Synth. Catal.* **2004**, *346*, 1205.

[30] M. Shi, Y.-M. Xu, *Eur. J. Org. Chem.* **2002**, 696.

[31] M. Shi, Y.-M. Xu, *J. Org. Chem.* **2003**, *68*, 4784.

[32] M. Shi, G.-L. Zhao, *Adv. Synth. Catal.* **2004**, *346*, 1205.

[33] a) J. Cyrener, K. Burger, *Monatsh. Chem.* **1995**, *126*, 319; b) N.N. Sergeeva, A.S. Golubev, K. Burger, *Synthesis* **2001**, 281.

[34] T. G. Back, D.A. Rankic, J.M. Sorbetti, J. E. Wullf, *Org. Lett.* **2005**, *7*, 2377.

[35] K.D. Hesp, R.G. Bergman, J.A. ELLman, *Org. Lett.* **2012**, *14*, 2304.

[36] R. Fan, D. Pu, P. Wen, Y. Ye, X. Wang, *J. Org. Chem.* **2008**,*73*, 3623.

[37] M. Shi, Y.-M. Xu, G.-L. Zhao, X.-F. Wu, *Eur. J. Org. Chem.* **2002**, 3666.

[38] M. Shi, G.-L. Zhao, *Adv. Synth. Catal.* **2004**, *346*, 1205.

[39] G.-L. Zhao, J.-W. Huang, M. Shi, *Org. Lett.* **2003**, *5*, 4737

[40] G.-L. Zhao, M. Shi, *Org. Biomol. Chem.* **2005**, *3*, 3686.

[41] D. Martin, Y. Canac, V. Lavallo, G. Bertrand, *J. Am. Chem. Soc.* **2014**, *136*, 5023.

[42] G.-L. Zhao, M. Shi, *J. Org. Chem.* **2005**, *70*, 9975.

[43] C.R. Johnson, J.P. Adams, M.P. Braun, C.B.W. Senanayake, *Tetrahedron Lett.* **1992**, *33*, 917.

[44] L. He, T.-Y. Jian, S. Ye, *J. Org. Chem.* **2007**, *72*, 7466.

[45] C. Fischer, S.W. Smith, D.A. Powell, G.C. Fu, *J. Am. Chem. Soc.* **2006**, *128*, 1472.

[46] a) H.M.R. Hoffmann, J. Rabe, *Angew. Chem. Int. Ed. Engl*. **1983**, *22*, 795; b) J.S. Hill, N.S.J. Isaacs, *Chem. Res.* **1988**, 330; c) J.S. Hill, N.S.J. Isaacs, *J. Phys. Org. Chem*. **1990**, *3*, 285; c) J.S. Hill, N.S.J. Isaacs, *Tetrahedron Lett*. **1986**, *41*, 5007.

[47] K.E. Price, S.J. Broadwater, H.M. Jung, D.T. McQuade, *Org. Lett*. **2005**, *7*, 147.

[48] K.E. Price, S.J. Broadwater, B.J. Walker, D.T. McQuade, *J. Org. Chem*. **2005**, *70*, 3980.

[49] V.K. Aggarwal, S.Y. Fulford, G.C. Lloyd-Jones, *Angew. Chem. Int. Ed.* **2005**, *44*, 1706.

[50] M.J. O'Neil, *An Encyclopedia of Chemicals, Drugs, and Biologicals*, **2001**, Merk and Co., Inc.

[51] T.L. Amyes, S.T. Diver, J.P. Richard, F.M. Rivas, K. Toth, *J. Am. Chem. Soc.* **2004**, *126*, 4366.

[52] C. Reichardt, T. Welton, *Solvents and Solvent Effects in Organic Chemistry*, **2010** (Wiley-VCH), Germany.

[53] Y. Dan, B. Zhou, J.-H. Lin, J.-C. Xiao, *Chem. Commun*, **2015**, *51*, 13127.

[54] J.H. Wynne, S.E. Price, J.R. Rorer, W.M. Stalick, *Synth. Commun.* **2003**, *33*, 341.

[55] J.E. Leffler, E. Grunwald, *Rates and Equilibria of Organic Reactions*, **1963** (Wiley-VCH), Germany.

[56] M. He, J.W. Bode, *Org. Lett*. **2005**, *7*, 3131.

[57] J.F. Hartwig, *Nature* **455**, 314.

[58] *a*) E. Erdik, *Tetrahedron* **2004**, *60*, 8747; *b*) C. Greck, B. Drouillat, C. Thomassigny, *Eur. J. Org. Chem.* **2004**, 1377; *c*) R.O. Duthaler, *Angew. Chem. Int. Ed.* **2003**, *42*, 975.

[59] A. Kamimura, Y. Gunjigake, H. Mitsudera, S. Yokoyama, *Tetrahedron Lett*. **1998**, *39*, 7323.

[60] M. Shi, G.-L. Zhao, *Tetrahedron* **2004**, *60*, 2083.

[61] M. Dadwal, S.M. Mobin, I.N.N. Namboothiri, *Org. Biomol. Chem.* **2006**, *4*, 2525.

[62] X.-Y Chen, F. Xia, S. Ye, *Org. Biomol. Chem.* **2013**, *11*, 5722.

[63] S.W. Benson, *J. Chem. Educ*. **1965**, *42*, 502.

[64] a) E. Djuardi, P. Bovonsombat, E. McNelis, *Synth. Commun.* **1997**, *27*, 2497; b) E. Negishi, Z.R. Owczarczyk, D.R. Swanson, *Tetrahedron Lett*. **1991**, *32*, 4453; c) L.S. Liebeskind, J. Wang, *Tetrahedron Lett*. **1990**, *31*, 4293; d) M. Kabat, J. Kiegiel, N. Cohen, K. Toth, P.M. Wovkulich, *Tetrahedron Lett*. **1991**, *23*, 2343.

[65] J.M. Mcintosh, *Can. J. Chem.* **1971**, *49*, 3045.

[66] T.H. Kim, J. Asakura, Y. Asaka, *Chem. Express.* **1990**, *5*, 221.

[67] M.E. Krafft, *Synlett* **2005**, *8*, 1263.

[68] P. Bovonsombat, R. Rujiwarangkul, T. Bowornkiengkai, J. Leykajarakul, *Tetrahedron Lett*. **2007**, *48*, 8607.

[69] M. Ngatimin, C.J. Gartshore, J.P. Kindler, S. Naidu, D.W. Lupton, *Tetrahedron Lett*. **2009**, *50*, 6008.

[70] D. Holschumacher, C.G. Hrib, P.G. Jones, M. Tamm, *Chem. Commun*. **2007**, 3661.

[71] M.M.D. Wilde, M. Gravel, *Angew. Chem. Int. Ed.* **2013**, *52*, 1.

[72] F. -Le, Hu, M. Shi, *Org. Chem. Front*. **2014**, *1*, 587.

[73] Y. Iwabuchi, M. Nakatani, N. Yokoyama, S. Hatakeyama, *J. Am. Chem. Soc.* **1999**, *121*, 10219.

[74] M. Shi, Y.-M. Xu, *Angew. Chem. Int. Ed.* **2002**, *41*, 4507.

[75] M. Shi, Y.-M. Xu, Y.-L. Shi, *Chem. Eur. J*. **2005**, *11*, 1794.

[76] N. Abermil, G. Masson, J. Zhu, *J. Am. Chem. Soc.* **2008**, *130*, 12596.

[77] N. Abermil, G. Masson, J. Zhu, *Org. Lett*. **2009**, *11*, 4648.

[78] N. Abermil, G. Masson, J. Zhu, *Adv. Synth. Catal*. **2010**, *352*, 656.

[79] K. Matsui, S. Takizawa, H. Sasai, *J. Am. Chem. Soc*. **2005**, *127*, 3680.

[80] M. Shi, L.-H. Chen, C.-Q. Li, *J. Am. Chem. Soc*. **2005**, *127*, 3790.

[81] Y.-L. Shi, M. Shi, *Adv. Synth. Catal.* **2007**, *349*, 2129.

[82] a) M.J. Qi, T. Ai, M. Shi, G. Li, *Tetrahedron* **2008**, *64*, 1181; b) X.-Y. Guan, Y.-Q. Jiang, M. Shi, *Eur. J. Org. Chem*. **2008**, 2150.

[83] a) M. Shi, L.-H. Chen, *Pure Appl. Chem*. **2005**, *77*, 2105; b) M. Shi, L.-H. Chen, W.-D. Teng, *Adv. Synth. Catal*. **2005**, *347*, 1781.

[84] Y.-H. Liu, L.-H. Chen, M. Shi, *Adv. Synth. Catal.* **2006**, *348*, 973.

[85] F. Zhong, Y. Wang, X. Han, K.-W. Huang, Y. Lu, *Org. Lett*. **2011**, *13*, 1310.

[86] S. Takizawa, K. Kiriyama, K. Ieki, H. Sasai, *Chem. Commun*. **2011**, *47*, 9227.

[87] I.T. Raheem, E.N. Jacobsen, *Adv. Synth. Catal*. **2005**, *347*, 1701.

[88] T. Yukawa, B. Seelig, Y. Xu, H. Morimoto, S. Matsunaga, A. Berkessel, M. Shibasaki, *J. Am. Chem. Soc*. **2010**, *132*, 11988.

[89] K. Hyodo, S. Nakamura, N. Shibata, *Angew. Chem. Int. Ed.* **2012**, *51*, 10337.

[90] V.M. Mastranzo, L. Quintero, C.A. de Parrodi, E. Juaristi, P.L. Walsh, *Tetrahedron* **2004**, *60*, 1781.

[91] C.R. Martineza, B.L. Iverson, *Chem. Sci*. **2012**, *3*, 2191.

[92] G.B. McGaughey, M. Gagné, A.K. Rappé, *J. Bio. Chem*. **1998**, *273*, 15458.

[93] S.K. Burley, G.A. Petsko, *Science* **1985**, *229*, 23.

[94] C.A. Hunter, J.K.M. Sanders, *J. Am. Chem. Soc*. **1990**, *112*, 5525.

[95] S. Paliwal, S. Geib, C.S. Wilcox, *J. Am. Chem. Soc*. **1994**, *116*, 4497.

[96] H.-C. Zhang, K.S. Chan, *J. Chem. Soc. Perkin Trans 1* **1999**, 381.

[97] a) L. Horner, L. Dickerhof, *Liebigs Ann. Chem*. **1984**, 124; b) R. Hulst, K. de Vries, B.L. Feringa, *Tetrahedron Asymmetry* **1994**, *5*, 1701.

[98] M.M.D. Wilde, M. Gravel, *Org. Lett*. **2014**, *16*, 5308.

[99] B.T. Ramanjaneyulu, S. Mahesh, R.V. Anand, *Org. Lett*. **2015**, *17*, 3952.

[100] a) P.I. Dalko, L. Moisan, *Angew. Chem. Int. Ed.* **2004**, *43*, 5138; b) A. Berkessel, H. Gröger, *Asymmetric Organocatalysis: From Biomimetic Concepts to Applications in Asymmetric Synthesis*, **2005**, VCH, Weinheim; c) B. List, C. Bolm, *Adv. Synth. Catal*. **2004**, *346*, 1007.

[101] For metal-catalysed non-conjugate C–B formation, see: a) I. Beletskaya, A. Pelter, *Tetrahedron* **1997**, *53*, 4957; b) T. Ishiyama, K. Ishida, N. Miyaura, *Tetrahedron* **2001**, *57*, 9813; c) H.E. Burks, J.P. Morken, *Chem. Commun*. **2007**, 4717; d) D.S. Laitar, E.Y. Tsui, J.P. Sadighi, *J. Am. Chem. Soc*. **2006**, *128*, 11036.

[102] a) K. Hirano, H. Yorimitsu, K. Oshima, *Org. Lett*. **2007**, *9*, 5031; b) for metal-catalysed element–element additions to unsaturated C–C bonds, see: I. Beletskaya, C. Moberg, *Chem. Rev*. **2006**, *106*, 2320.

[103] For a review on boron reagents for Suzuki–Miyaura coupling reactions, see: G.C. Lloyd-Jones, A.J.J. Lennox, *Chem. Soc. Rev*. **2014**, *43*, 412.

[104] G.M. Loudon, *Organic Chemistry*, **2002**, 168, Oxford University Press.

[105] For a review on C–N bond formation, see: J. Bariwalab, E. Eycken, *Chem. Soc. Rev*. **2013**, *42*, 9283.

[106] a) Y.G. Lawson, M.J.G. Lesley, T.B. Marder, N.C. Norman, C.R. Rice, *Chem. Commun*. **1997**, 2051; b) A.H. Goldberg, M. Sbrenik, *Organometallics* **2001**, *20*, 3962; c) N.J. Bell, A.J. Cox, N.R. Cameron, J.S.O. Evans, T.B. Marder, M.A. Duin, C.J. Elsevier, X. Baucherel, A.A.D. Tulloch, R.P. Tooze, *Chem. Commun*. **2004**, 1854.

[107] G.W. Kabalka, B.C. Das, S. Das, *Tetrahedron Lett*. **2002**, *43*, 2323.

[108] a) H. Yamanaka, J.I. Tateiwa, A. Hosomi, *Tetrahedron Lett*. **2000**, *41*, 6821; b) S. Mun, J.-E Lee,

J. Yun, *Org. Lett*. **2006**, *8*, 4887; c) J.-E Lee, J. Yun, *Chem. Commun*. **2008**, 733; for boron conjugate additions using stoichiometric amounts of Cu salts, see: d) K. Takahashi, T. Ishiyama, N.J. Miyaura, *J. Organomet. Chem*. **2001**, *625*, 47; e) G.W. Kabalka, B.C. Das, S. Das, *Tetrahedron Lett*. **2001**, *42*, 7145; for enantioselective versions, see: f) J.-E Lee, J. Yun, *Angew. Chem. Int. Ed*. **2008**, *47*, 145.

[109] A.H. Hoveyda, K.S. Lee, A.R. Zhugralin, *J. Am. Chem. Soc*. **2009**, *131*, 7253.

[110] E. Fernández, A. Bonet, H. Gulyás, *Angew. Chem. Int. Ed.* **2010**, *49*, 5130.

[111] A.H. Hoveyda, H. Wu, S. Radomkit, J.M. O'Brien, *J. Am. Chem. Soc*. **2012**, *134*, 8277.

[112] A.H. Hoveyda, S. Radomkit, *Angew. Chem. Int. Ed.* **2014**, *53*, 3387.

[113] M. Alcarazo, C.W. Lehmann, A. Anoop, W. Thiel, A. Fürstner, *Nature* **2009**, *1*, 295.

[114] Fishcher, H. *Chem. Ber.* **1964**, *97*, 2975.

[115] a) S. Ishida, T. Iwamoto, C. Kabuto, M. Kira, *Nature* **2003**, *421*, 725; b) T. Iwamoto, H. Masuda, C. Kabuto, M. Kira, *Organometallics* **2005**, *24*, 197; c) T. Iwamoto, T. Abe, S. Ishida, C. Kabuto, M. Kira, *J. Organomet. Chem.* **2007**, *692*, 263.

[116] H. Grützmacher, *Science* **2000**, *289*, 737.

[117] G. Bertrand, V. Lavallo, B. Donnadieu, *Angew. Chem. Int. Ed.* **2008**, *47*, 3206.

[118] a) R.W. Saalfrank, H. Maid, *Chem. Commun.* **2005**, *48*, 5953; b) R.W. Saalfrank, *Isr. J. Chem*. **1985**, *26*, 181.

[119] O. Kaufhold, F.E. Hahn, *Angew. Chem. Int. Ed.* **2008**, *47*, 4057.

[120] R. Tonner, G. Frenking, *Angew. Chem. Int. Ed*. **2007**, *46*, 8695.

[121] E. Weber, W. Seichter, *J. Phys. Org. Chem*. **1995**, *8*, 94.

[122] G. Kaupp, H.W. Griiter, *Angew. Chem. Int. Ed.* **1980**, *19*, 713.

[123] A. Fürstner, M. Alcarazo, H. Krause, *Org. Synth.* **2009**, *86*, 298.

[124] W.-C. Chen, Y.-C. Hsu, C.-Y. Lee, G.P.A. Yap, T.-G. Ong, *Organometallics* **2013**, *32*, 2435.

[125] Y.-C. Hsu, J.-S. Shen, B.-C. Lin, W.-C. Chen, Y.-T. Chan, W.-M. Ching, G.P.A. Yap, C.-P. Hsu, T.-G. Ong, *Angew. Chem. Int. Ed.* **2015**, *54*, 2420.

[126] W.-C. Chen, J.-S. Shen, T. Jurca, C.-J. Peng, Y.-H. Lin, Y.-P. Wang, W.-C. Shih, G.P.A. Yap, T.-G. Ong, *Angew. Chem. Int. Ed.* **2015**, *54*, 15207.

[127] V. Lavallo, C.A. Dyker, B. Donnadieu, G. Bertrand, *Angew. Chem. Int. Ed*. **2008**, *47*, 5411.

[128] M. Melaimi, B. Donnadieu, G. Frenking, G. Bertrand, *Angew. Chem. Int. Ed*. **2009**, *121*, 4886.

[129] S. Elgafi, L.D. Field, B.A. Messerle, P. Turner, T.W. Hambley, *J. Organomet. Chem.* **1999**, *588*, 69.

[130] W.-C. Chen, C.-Y. Lee, B.-C. Lin, Y.-C. Hsu, J.-S. Shen, C.-P. Hsu, G.P.A. Yap, T.-G. Ong, *J. Am. Chem. Soc*. **2014**, *136*, 914.

[131] M.J. Goldfogel, C.C. Roberts, S.J. Meek, *J. Am. Chem. Soc*. **2014**, *136*, 6227.

[132] C.C. Roberts, D.M. Matias, M.J. Goldfogel, S.J. Meek, *J. Am. Chem. Soc*. **2015**, *137*, 6488.

[133] M.Shi, L.-H. Chen, C.-Q. Li, *J. Am. Chem. Soc*. **2005**, *127*, 3790.

[134] T. Regiani, V.G. Santos, M.N. Godoi, B.G. Vaz, M.N. Eberlin, F. Coelho, *Chem. Commun*, **2011**,

47, 6593.

[135] L.O. Planes, C.R. Escrich, M. A. Pericàs, *Chem. Eur. J*, **2014**, *20*, 2367.

[136] Y. Dan, B. Zhou, J.-H. Lin, J.-C. Xiao, *Chem. Commun*, **2015**, *51*, 13127.

[137] B. Zhou, Y. Yang, S. Lin, Y. Li, *Adv. Synth. Catal*, **2013**, *355*, 360.

[138] Y. -W. Sun, X.-Y. Tang, M. Shi, *Chem. Commun*, **2015**, *51*, 13937.

[139] I. P. Andrews, O. Kwon, *Chem. Sci*, **2012**, *3*, 2510.

[140] M.H. Sarvari, H. Sharghi, *Phosphorus, Sulfur and Silicon and the Related Elements*, **2007**, *182*, 2125.

[141] Z. Cui, H.-J. Yu, R.-F. Yang, W.-Y. Gao, C.-G. Feng, G.-Q. Lin, *J. Am. Chem. Soc*, **2011**, *133*, 12394.

[142] M. Shi, Y. -M. Xu, G. -L. Zhao, X. -F. Wu, *Eur. J. Org. Chem*, **2002**, 2002, 3666.

[143] M. Shi, Y. -M. Xu, *Eur. J. Org. Chem*, **2002**, 696.

[144] M. Shi, Y. -M. Xu, *J. Org. Chem*, **2003**, *68*, 4784.

[145] D. Balan, H. Adolfsson, *J. Org. Chem*, **2001**, *66*, 6498.

[146] M. Shi, Y. -M. Xu, *J. Org. Chem*, **2004**, *69*, 417.

[147] Z. Wu, G. Zhou, J. Zhou, W. Guo, *Synth. Commun*, **2006**, *36*, 2491.