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On the understanding of $BF_3 \cdot Et_2O$-promoted intra- and intermolecular amination and oxygenation of unfunctionalized olefins†

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$BF_3 \cdot Et_2O$ was found to be effective for both intra- and intermolecular amination and oxygenation of unfunctionalized olefins. In the presence of 3 equiv. of $BF_3 \cdot Et_2O$, intramolecular hydroamination of *N*-(pent-4-enyl)-*p*-toluenesulfonamides, *N*-(hex-5-enyl)-*p*-toluenesulfonamides, intermolecular hydroamination between sulfonamides and cyclohexene, norbornene or styrene, lactonization of pent-4-enoic acid or hex-5-enoic acid compounds and esterification of cyclohexene with different carboxylic acids all proceeded readily, leading to the corresponding amination or oxygenation products in up to 99% isolated yields. Preliminary NMR experiments and DFT calculations suggested that the intramolecular hydroamination reactions proceeded *via* a sulfonimidic acid intermediate (N=S–OH), and formation of the corresponding Brønsted acid HF or HBF_4 was less likely.

Introduction

Heterocyclic compounds are privileged structures in medicinal chemistry.[1] Such moieties have also been frequently found as key skeletons in biologically active compounds.[2] For these reasons, significant efforts have been made to develop new methods for C–N or C–O bond formation and for heterocycle construction. In addition to the well-developed functional group transformation reactions,[3] hydroamination is also one of the most efficient methods for the preparation of nitrogen-containing heterocyclic compounds,[4] and tremendous efforts have been made in transition metal-catalyzed hydroamination reactions.[5]

In contrast to these achievements, Brønsted or Lewis acid-catalyzed intramolecular hydroamination reactions were relatively less successful possibly due to the overly strong interaction of the catalysts with the amino groups. Such interactions decreased both the reactivity of the amino groups and the catalytic activity of the Brønsted or Lewis acids, and high reaction temperature or longer reaction time was generally required.

This problem has been overcome by introducing sulfonyl groups into the amino groups to reduce the interaction between the nucleophiles and the catalysts. In their pioneer report, Hartwig *et al.* showed that in the presence of strong acids such as triflic acid, alkene sulfonamide substrates could be cyclized, leading to the corresponding 2-substituted piperidines and pyrrolidines in excellent isolated yields.[6] Later, different Brønsted acids,[7] heteropoly acids[8] and Lewis acids[9] were also reported to catalyze the hydroamination of different substrates.

It is our purpose to fully understand the important role of Lewis acids in the amination and oxygenation of unfunctionalized olefins. Herein, we wish to report our progress on $BF_3 \cdot Et_2O$-promoted amination and oxygenation of unfunctionalized olefins as a continuation to our program on the cyclization of alkene amine (amide) substrates.

Results and discussion

We have shown that zinc halides can be used to promote hydroamination of a variety of substrates,[10] but the reactions would have to be carried out at high temperature. We reasoned that this was due to the high affinity of Lewis acids to the amino groups in the substrates,[11] rendering the latter less reactive. We assumed that Lewis acid would be a viable promoter for hydroamination of isolated unfunctionalized C=C double bonds if the Lewis acid was carefully chosen.

During our study of (diacetoxyiodo)benzene-promoted intramolecular haloamination of unfunctionalized olefins, we found that $BF_3 \cdot Et_2O$ could be used as fluorine source, and

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† Electronic supplementary information (ESI) available: Cartesian coordinates and energies for calculated intermediates, copies of NMR spectra, X-ray diffraction results for **2h** and **2j**. CCDC 1403973 and 1403974. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c5ra10513g

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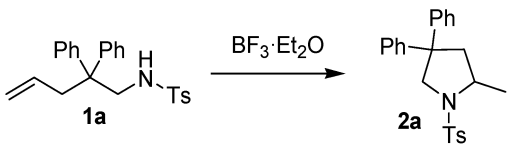
several fluoroamination products could be obtained in satisfactory isolated yields.[12] However, small amount of hydroamination product was detected when a control experiment was carried out in the absence of (diacetoxyiodo)benzene. We therefore decided to study the reaction in details to get further understanding of BF_3-mediated reactions. BF_3 has been used to promote hydroamination–glycosylation reactions.[13] However, to the best of our knowledge, this compound has not been used to promote hydroamination of unfunctionalized olefins.

On the basis of literature results[6] and our understanding of Lewis acid-promoted hydroamination reactions, $BF_3 \cdot Et_2O$-promoted intramolecular hydroamination of *N*-(2,2-diphenylpent-4-enyl)-*p*-toluenesulfonamide (**1a**) was studied in details to get further information. The reactions were carried out in the presence of different amount of $BF_3 \cdot Et_2O$ at different temperatures, and the results were summarized in Table 1.

As shown in Table 1, both the amount of $BF_3 \cdot Et_2O$ and the reaction temperature were very crucial for the reaction. Reaction proceeded sluggishly at low temperature even in the presence of 10 equiv. of $BF_3 \cdot Et_2O$ (entries 1–3). However, fast reactions were observed when the reaction was carried out at elevated temperature, and reaction could be completed in 24 h at 60 °C in the presence of 3 equiv. of $BF_3 \cdot Et_2O$ (entry 6) either under argon atmosphere or in open-air system. The use 1 equiv. of $BF_3 \cdot Et_2O$ was not successful, and only one third of the substrate could be converted at 60 °C (entry 8). Further reducing the amount of $BF_3 \cdot Et_2O$ led to significant drops of the conversion (entries 9–13). 1,2-Dichloroethane was the most suitable solvent among the reaction media tested (entry 6 *vs.* entries 14–17), and this reaction condition was used for the study of other substrates. Reactions in the presence of boron trichloride or boron tribromide were also tested. The substrate was consumed at 30 °C, but no desired hydroamination product was detected (entries 18 and 19).

N-Alkyl or *N*-carboxyamide substrates were unable to react possibly due to the strong interaction between $BF_3 \cdot Et_2O$ and the amino/amido groups. When *N*-Boc substrate was used, deprotection occurred and 2,2-diphenyl-4-penten-1-amine was recovered. Different sulfonamide substrates showed different reactivity, and trifluoromethanesulfonamide substrate failed to react possibly due to the low reactivity of the nitrogen atom. Different substrates were tested to study the scope of the reaction, and the results were summarized in Table 2.

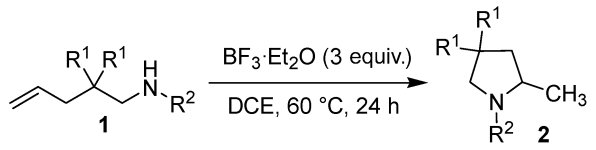
Table 1 $BF_3 \cdot Et_2O$-promoted hydroamination of **1a** under different conditions[a]

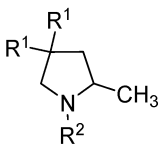


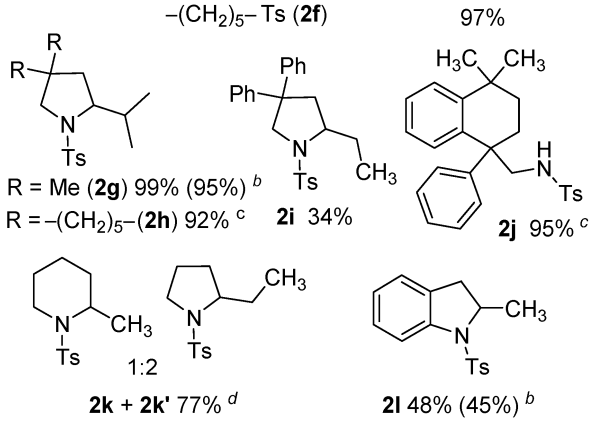
Entry	$BF_3 \cdot Et_2O$ (equiv.)	Temp (°C)	Time (h)	Solvent	**2a** : **1a**[b]
1	10	rt	48	DCM	31 : 69
2	10	40	24	DCM	40 : 60
3	10	50	24	DCE	78 : 22
4	10	60	24	DCE	>99 : 1
5	5	60	24	DCE	>99 : 1
6	3	60	24	DCE	98 : 2 (98 : 2)[c]
7	1.5	60	24	DCE	94 : 6
8	1	60	24	DCE	30 : 70
9	0.3	80	48	DCE	89 : 11
10	0.3	70	48	DCE	63 : 37
11	0.2	80	48	DCE	52 : 48
12	0.2	70	48	DCE	51 : 49
13	0.1	80	48	DCE	38 : 62
14	3	60	24	THF	Trace
15	3	60	24	CH_3CN	70 : 30
16	3	60	24	EA	30 : 70
17	3	60	24	Toluene	70 : 30
18	1 (BCl_3)	30 °C	24	DCE	—[d]
19	1 (BBr_3)	30 °C	24	DCE	—[d]

[a] The reactions were carried out with 0.25 mmol of **1a** and 2.5 mL of solvent under argon atmosphere. [b] Determined by crude ^{1}H NMR analysis. [c] Under air atmosphere. [d] No hydroamination product was detected.

Table 2 $BF_3 \cdot Et_2O$-promoted intramolecular hydroamination of N-electron deficient substrates[a]



Product	R^1	R^2	Isolated yield
	Ph	Ts (**2a**)	90% (85%)[b]
	Ph	Ms (**2b**)	93%
	Ph	*o*-O_2NPhSO_2- (**2c**)	73%
	Me	Ts (**2d**)	97%
	H	Ts (**2e**)	94% (91%)[b]
	–$(CH_2)_5$–	Ts (**2f**)	97%



[a] Reaction conditions: substrate: 1 mmol, $BF_3 \cdot Et_2O$: 3 mmol, reaction temperature = 60 °C, reaction time = 24 h, solvent = DCE (10 mL). [b] Reaction conditions: substrate: 1 mmol, $BF_3 \cdot Et_2O$ (30 mol%), 80 °C, 48 h, DCE (10 mL). [c] Structure confirmed with X-ray diffraction experiment. [d] The total isolated yield for **2k** and **2k′**. The ratio was determined with ^{1}H NMR.

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As shown in Table 2, *p*-toluene-, methane- or 2-nitrobenzenesulfonamide substrates gave good to excellent isolated yields, and the reactions were less dependent on the Thorpe–Ingold effect (**2a**, and **2d**–**2f**).[14] For substrates with substituents on the C=C double bond, the results depended on the substituents on the mainchain. For substrates with small substituents such as 2,2-dimethyl- (**1g**) or $-(CH_2)_5-$ (**1h**) on the mainchain, substituents on C=C double bonds showed little effect on the reaction, and normal hydroamination products **2g** and **2h** could be isolated in excellent yields.[15] For substrates with phenyl group on the mainchain (**1i** and **1j**), the substituents on the C=C double bonds could have drastic effects on the course of the reactions. When **1i** was used as the starting material, the desired product **2i** was isolated in a rather low yield (34%). When substrate **1j** was subjected to the same reaction, no hydroamination product was detected at all. In contrast, Friedel–Crafts alkylation product **2j** was isolated in high yield (Scheme 1).[15] Structures of both **2h** and **2j** were confirmed by X-ray diffraction experiments (Fig. 1).[16]

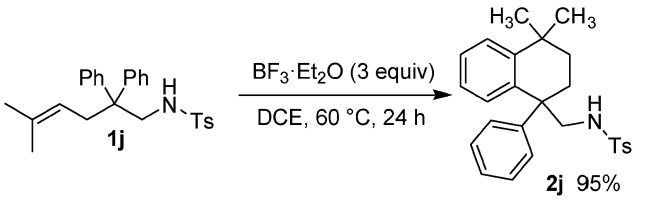
When *N*-(hex-5-en-1-yl)-*p*-toluenesulfonamide (**1k**) was subjected to the same reaction under otherwise identical conditions, both expected 1-tosyl-2-methylpiperidine (**2k**) and unexpected 1-tosyl-2-ethylpyrrolidine (**2k′**) were isolated with a ratio of 1 : 2. Other substituted 1-(*p*-toluenesulfonamido)-5-hexene substrates gave rather complicated results and the studies were not continued at this stage. The reaction of *N*-(2-allylphenyl)-*p*-toluenesulfonamide **1l** produced the corresponding indoline compound **2l** in moderate isolated yield. Substrates **1a**, **1e**, **1g** and **1l** were also tested for $BF_3 \cdot Et_2O$-catalyzed reactions. In the presence of 30 mol% of $BF_3 \cdot Et_2O$, hydroamination of these substrates could also be realized at elevated temperature and prolonged reaction time (80 °C/48 h *vs.* 60 °C/24 h), giving the corresponding cyclization products **2a**, **2e**, **2g** and **2l** in similar isolated yields.

After intramolecular hydroamination of different *N*-(pent-4-en-1-yl)sulfonamide substrates, intermolecular hydroamination of cyclohexene, norbornene and styrene were also studied, and the results were summarized in Table 3.

As shown in Table 3, sulfonamides were suitable nitrogen sources for the hydroamination of different substrates, and Markovnikov products were obtained for unsymmetrical substrates such as styrene. Substituents on nitrogen atom showed some impact on the results possibly due to the steric hindrance caused by the introduced substituents. Reactions of benzene- or *p*-toluenesulfonamide gave products in excellent isolated yields, and introducing substituents to nitrogen atoms caused a drop of isolated yields. Reactions using catalytic amount of $BF_3 \cdot Et_2O$ were also tested, and hydroamination products **4a**, **4b** and **4f** could be obtained in similar isolated yields when the reactions were carried out at elevated temperature (30 mol% of $BF_3 \cdot Et_2O$, 80 °C/48 h).

To further extend the scope of the reaction, intermolecular esterifications were carried out using cyclohexene (**3**) as the model substrates (Table 4). Both aromatic and aliphatic carboxylic acids could react with cyclohexene, and the corresponding cyclohexyl carboxylates were isolated in up to 95% isolated yields. No reaction was observed in the absence of $BF_3 \cdot Et_2O$.

Similarly, lactonization of alkene carboxylic acids gave the corresponding lactone compounds in up to 91% isolated yields (Table 5).



Scheme 1 Friedel–Crafts cyclization of substrate **1j**.

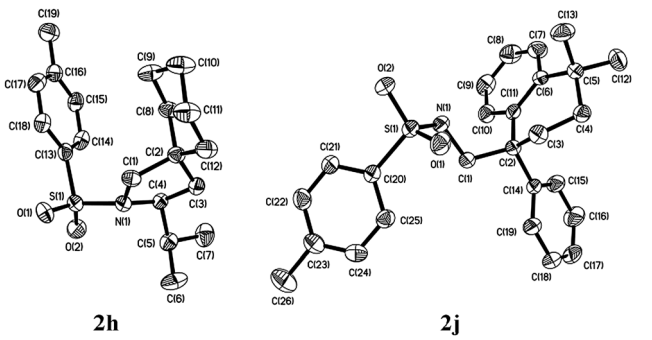
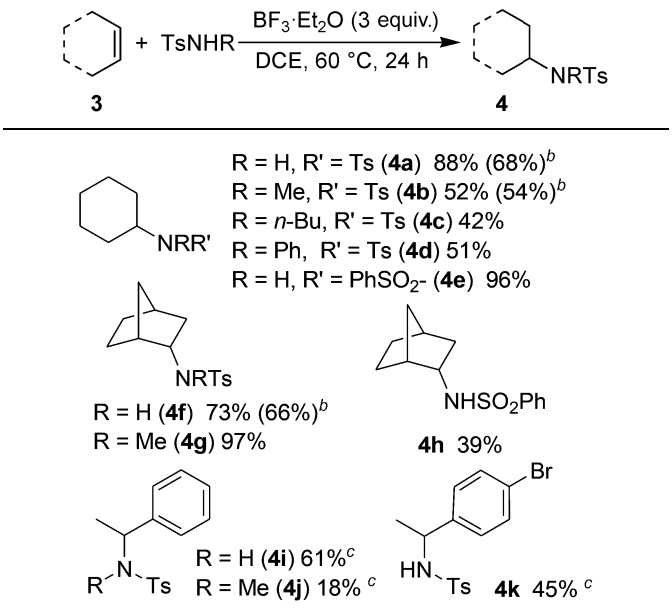


Fig. 1 ORTEP drawings of **2h** and **2j**. Hydrogen atoms were omitted for clarity.

Table 3 $BF_3 \cdot Et_2O$-promoted intermolecular hydroamination of olefins[a]



[a] Reaction conditions: olefin: 2 mmol, nucleophile: 4 mmol, $BF_3 \cdot Et_2O$: 6 mmol, DCE: 10 mL, 60 °C, 24 h. [b] Reaction conditions: olefin: 2 mmol, nucleophile: 4 mmol, $BF_3 \cdot Et_2O$: 30 mol%, 80 °C, 48 h, DCE (10 mL). [c] 1,4-Dioxane was used as solvent.

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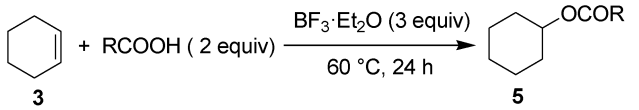
Table 4 $BF_3 \cdot Et_2O$-promoted intermolecular esterification reactions[a]



Entry	Acid	Product	5[b] (%)
1	PhCOOH	PhCOOCy (**5a**)	73
2	*o*-MePhCOOH	*o*-MePhCOOCy (**5b**)	73
3	*m*-MePhCOOH	*m*-MePhCOOCy (**5c**)	71
4	*p*-MePhCOOH	*p*-MePhCOOCy (**5d**)	73
5	*p*-*t*BuPhCOOH	*p*-*t*BuPhCOOCy (**5e**)	73
6	*p*-MeOPhCOOH	*p*-MeOPhCOOCy (**5f**)	53
7	*p*-ClPhCOOH	*p*-ClPhCOOCy (**5g**)	45
8	*p*-O_2NPhCOOH	*p*-O_2NPhCOOCy (**5h**)	36
9	CyCOOH	CyCOOCy (**5i**)	82
10	AcOH	AcOCy (**5j**)	95
11	iPrCOOH	iPrCOOCy (**5k**)	70

[a] The reactions were carried out with 2 mmol of cyclohexene, 4 mmol of acid and 6 mmol of $BF_3 \cdot Et_2O$ in 5 mL of DCE. [b] Isolated yield based on cyclohexene.

Tilley *et al.* have studied triflate-catalyzed hydroamination of olefins with sulfonamides[17] and concluded that the most possible reaction pathway would be the coordination of sulfonamide to metal and the subsequent generation of an acidic proton. Proton transfer to C=C double bond produced a carbenium cation intermediate which could be captured by the amide nitrogen to give the final hydroamination product. Using $PhNH_3B(C_6F_5)_4$ as catalyst, Bergman *et al.* were able to realize the hydroamination and hydroarylation of several alkenes with anilines. They pointed out the possible acid catalysis in many metal-catalyzed systems.[18] Szolcsányi *et al.* studied the intramolecular hydroamination of *N*-tosylalkenylamines using different metal triflate as catalyst, and concluded that triflic acid, generated *in situ* by hydrolysis of metal triflate, could be the true hydroamination catalyst of the reaction.[9c] Very recently, Sarpong *et al.* succeeded in the intramolecular hydroamination catalyzed by HI generated *in situ via* hydrolysis of iodotrimethylsilane.[19]

Several control experiments were carried out to study if the reaction was promoted by BF_3 or promoted by HF or HBF_4 formed during the reaction (Table 6). Given that interaction of HF with BF_3 gave HBF_4 as the final product,[20] reaction of **1a** in the presence of HBF_4 was first carried out under otherwise identical conditions (entry 1). Preliminary results indicated that aqueous HBF_4 was unable to promote the reaction. Adding excess amount of water to generate HBF_4 *in situ* was also unable to give expected high yields (entries 2 to 5). But complete conversion was observed when the reaction was carried out at 60 °C for 24 h using 1 equiv. of $HBF_4 \cdot Et_2O$ as the reaction promoter (entry 8).

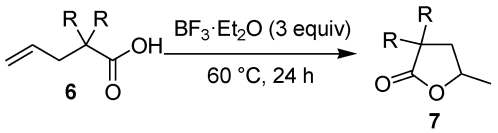
However, further experiments indicated that $BF_3 \cdot Et_2O$ and HBF_4 behaved very differently in several reactions. In a side-by-side comparison, reaction of *o*-methylbenzoic acid with cyclohexene always gave lower substrate conversion when HBF_4 was used as the reaction promoter (Table 7, entry 1 *vs.* entry 2, and entry 3 *vs.* entry 4). Similar trends were observed for intermolecular hydroamination of cyclohexene with *N*-methyl *p*-toluenesulfonamide (entry 5 *vs.* 6).

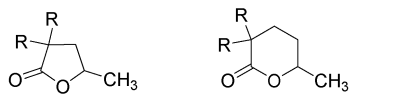
Especially, when the reactions were carried out in the presence of base, the reaction with HBF_4 as the promoter was completely suppressed by triethylamine, and the reactions promoted by BF_3 were less affected by the addition of the same amount of base (Table 8).

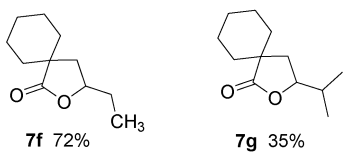
These results indicated that the BF_3-promoted hydroamination reactions were less affected by the addition of base, and the reaction pathway for BF_3-promoted heterocyclization reactions was different from the HBF_4-promoted ones.

NMR experiments were then carried out to study the possible interaction between $BF_3 \cdot Et_2O$ and substrate **1e**. While no significant chemical shift changes were observed for protons on C=C double bonds and protons adjacent to sulfonamido

Table 5 $BF_3 \cdot Et_2O$-promoted lactonization reactions[a,b]







[a] Reaction conditions: substrate = 1 mmol, $BF_3 \cdot Et_2O$ = 3 mmol, solvent = DCM (5 mL), 60 °C, 24 h. [b] Isolated yields.

Table 6 Control experiments for hydroamination of **1a**[a]

Entry	$BF_3 \cdot Et_2O$ (equiv.)	Additive	**2a** : **1a**[b]
1	0	HBF_4 (48 wt% in H_2O, 3 equiv.)	NR
2	3	H_2O (1 equiv.)	90 : 10
3	3	H_2O (2.5 equiv.)	80 : 20
4	3	H_2O (5 equiv.)	35 : 65
5	3	H_2O (10 equiv.)	NR
6	0	$HBF_4 \cdot Et_2O$ (3 equiv., rt)	91 : 9
7	0	$HBF_4 \cdot Et_2O$ (1 equiv., rt)	73 : 27
8	0	$HBF_4 \cdot Et_2O$ (1 equiv., 60 °C)	>99 : 1
9	0	$HBF_4 \cdot Et_2O$ (20 mol%, 60 °C)	61 : 39

[a] The reactions were carried out with 0.5 mmol of **1a** and 5 mL of DCE under argon atmosphere. Reaction temperature = 60 °C, reaction time = 24 h. [b] Determined by crude ^1H NMR analysis.

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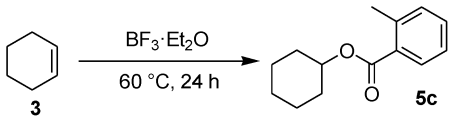
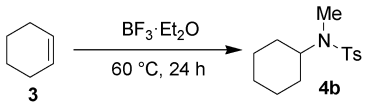
Table 7 Side-by-side comparison for $BF_3 \cdot Et_2O$ and HBF_4-promoted reactions[a,b]

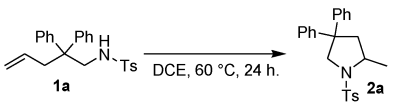
Entry	Promoter	Time (h)	*o*-MePhCOOH : **5c**
			
1	$BF_3 \cdot Et_2O$ 20%	12	72 : 28
2	$HBF_4 \cdot Et_2O$ 20%	12	84 : 16
3	$BF_3 \cdot Et_2O$ 20%	24	54 : 46
4	$HBF_4 \cdot Et_2O$ 20%	24	67 : 33
Entry	Promoter	Time (h)	TsNHMe : **4b**
			
5	$BF_3 \cdot Et_2O$ 20%	24	69 : 31
6	$HBF_4 \cdot Et_2O$ 20%	24	82 : 18

[a] The reactions were carried out at 60 °C with 1 mmol of substrate and 1 mmol of *o*-MePhCOOH in DCE (2.5 mL). The ratios of *o*-MePhCOOH-to-**5c** were determined with crude NMR analysis of the reaction mixture. [b] The reactions were carried out at 60 °C with 1 mmol of substrate and 1 mmol of TsNHMe in DCE (2.5 mL). The ratios of TsNHMe-to-**4b** were determined with crude NMR analysis of the reaction mixture.

group, the signal splitting pattern changed significantly. A triplet peak for amide proton and a quartet peak for adjacent methylene peak were observed for **1e** before the addition of BF_3 (Fig. 2a), but the triplet amide signal vanished and the quartet peak changed to triplet after the addition of BF_3 (Fig. 2b).

Similar phenomena were also observed when mixing *p*-toluenesulfonamide or *N*-methyl *p*-toluenesulfonamide with $BF_3 \cdot Et_2O$, and a very broad signal corresponding to amide proton was identified after careful examination of the NMR spectra of the mixture of *N*-methyl *p*-toluenesulfonamide and BF_3. The *N*-methyl group changed from doublet peak to a singlet peak after the addition of BF_3. These results indicated that a fast

Table 8 Effect of base on $BF_3 \cdot Et_2O$ and HBF_4-promoted reactions[a]



Entry	Promoter (equiv.)	Base (equiv.)	**2a : 1a**
1	$BF_3 \cdot Et_2O$ (3)	TEA (3)	NR
2	$BF_3 \cdot Et_2O$ (3)	TEA (2)	38 : 62
3	$BF_3 \cdot Et_2O$ (3)	TEA (1)	95 : 5
4	$BF_3 \cdot Et_2O$ (3)	TEA (20%)	>95 : 5
6	$HBF_4 \cdot Et_2O$ (1)	TEA (1)	NR

[a] The reactions were carried out with 0.25 mmol of substrate in 2.5 mL of DCE. The ratios of **2a : 1a** were determined with crude NMR analysis of the reaction mixture.

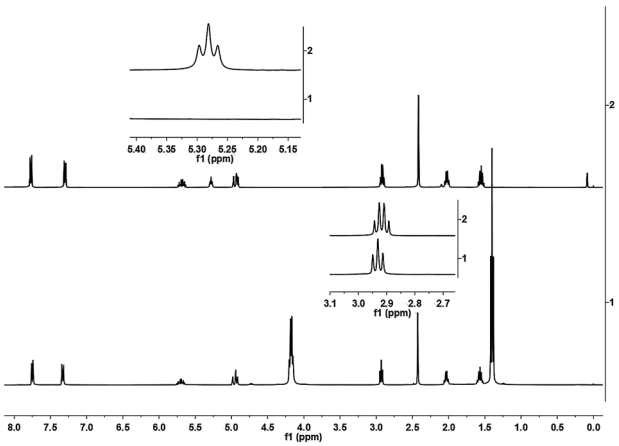


Fig. 2 NMR spectra of **1e** before and after the addition of $BF_3 \cdot Et_2O$. (a) Upper: NMR spectrum of **1e**. (b) Lower: NMR spectrum of **1e** after the addition of $BF_3 \cdot Et_2O$. Signals at 1.4 and 4.2 ppm were from diethyl ether.

protonation–deprotonation occurred on the sulfonamide functional group after adding BF_3 to *N*-methyl *p*-toluenesulfonamide.

Hartwig *et al.* showed that significant downfield shift for the *N*-methyl signal was observed on proton NMR spectrum when triflic acid was allowed to mix with *N*-methyl *p*-toluenesulfonamide.[6] Our own NMR study also showed a 0.4 ppm downfield shift for *N*-Me group after adding 1 equiv. of triflic acid to the $CDCl_3$ solution of the sample. However, after adding $BF_3 \cdot Et_2O$ to **1e**, the chemical shift change for adjacent proton signals were almost negligible. These results suggested that interaction between BF_3 and sulfonamide was weaker than the interaction between triflic acid and sulfonamide.

When BF_3 was allowed to mix with sulfonamide, it would interact with nitrogen or oxygen atom in the sulfonamide *via* an Lewis acid–base interaction. Such N···BF_3 or O···BF_3 interaction would increase the acidity of the sulfonamide proton, and the change of signal splitting pattern was caused by the fast

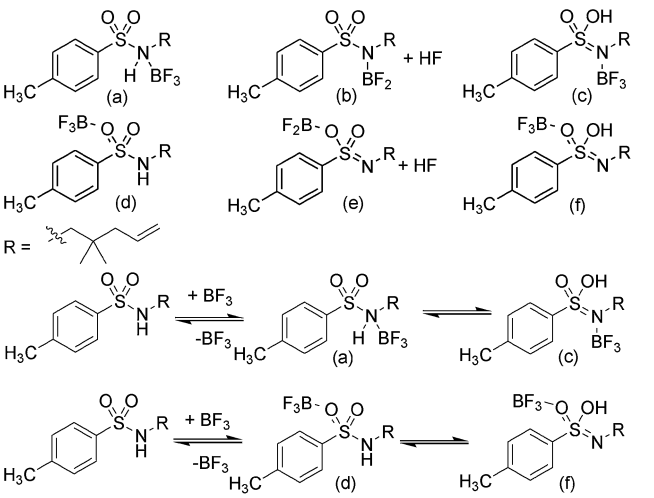


Fig. 3 Possible modes of interaction between BF_3 and sulfonamides.

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deprotonation–reprotonation of the sulfonamide nitrogen atom.

Further, H–F coupling was observed on ^{19}F NMR spectrum of HBF_4, and no H–F coupling could be observed when BF_3 was mixed with either *N*-methyl *p*-toluenesulfonamide or substrate **1e**. These results suggested that HF or HBF_4 was not formed when BF_3 was mixed with sulfonamides. These results were also in agreement with different reaction behaviours observed for $BF_3 \cdot Et_2O$- and HBF_4-promoted reactions (Table 7).

Several modes of action could be proposed when $BF_3 \cdot Et_2O$ was mixed with sulfonamides (Fig. 3) and structures **b** and **e** could be excluded based on the experimental results.

Protonation of C=C double bond was initially proposed as the key step of hydroamination reaction (Fig. 4). However, DFT calculation on the carbenium cations **g** and **h** indicated that these were high energy species, and reactions through these intermediates were less likely.

Detailed DFT calculations were then performed to study the possible interactions between BF_3 and the sulfonamide functional group. Structures for intermediates (**a–f**) and two different carbenium cations (**g**) and (**h**) were optimized at ωB97XD/6-311++G(d,p) level using an implicit solvation model (SMD)[21] with dichloroethane as the solvent, and the energies for these species were calculated.

The energy profiles were given in Fig. 5. The calculation results suggested that interaction between BF_3 and oxygen atom of the sulfonamide (**d**) was the most favorable one, but the formation of hydroamination product from this intermediate was difficult due to the high energy barriers (**f** and **g**). Alternatively, BF_3 could interact with sulfonamide through N···BF_3 Lewis pair (**a**). However, the energy for intermediate (**a**) was higher than the energy of (**d**), and elevated temperature was required in order for the intermediate (**d**) to overcome the energy barrier. The strong O···BF_3 interaction also accounted for the high amount of BF_3 used for the reaction. Reaction *via* sulfonimidic acid intermediate (**c**) was the most possible one.

It was then reasonable to assume that after the interaction of BF_3 with sulfonamide, a sulfonimidic acid intermediate (**c**) was formed at elevated temperature. The hydroamination was made possible *via* this intermediate similar to the Cope-type hydroamination reactions (Fig. 6).[22]

Results in Table 2 showed that Friedel–Crafts alkylation product **2j** rather than the corresponding hydroamination product was isolated when trisubstituted substrate **1j** was subjected to the reaction, and two products were obtained when substrate **1k** was used as the starting material. These results indicated that formation of carbenium cation became easier when the thus formed carbenium cation intermediates exhibited enough stability.

Based on the literature results and our preliminary study, a tentative reaction pathway was proposed as shown in Scheme 2. When BF_3 was added to the reaction mixture, it would interact with amide to form an LA–NHRTs adduct (**A**). This was a stable structure and elevated temperature is needed for the conversion from structure **A** to LA–O adduct **B** ($\Delta G = 5.9$ kcal mol^{-1}). Tautomerization of the LA–O adduct **B** produced sulfonimidic acid structure **C**. Hydroamination product was finally formed in a concerted manner similar to Cope-type hydroamination reactions. When olefins bearing carboxyamide groups were used as the substrates, tautomerization was difficult, and such substrates were difficult to undergo similar hydroamination reactions under current conditions. When substrate **1j** was used, formation of a tertiary carbenium cation became possible, and **2j** was formed as the final product *via* intramolecular Friedel–Crafts reaction. Excess amount of $BF_3 \cdot Et_2O$ was necessary due to the strong interaction between $BF_3 \cdot Et_2O$ and the oxygen atoms in both the substrates and the products.[23]

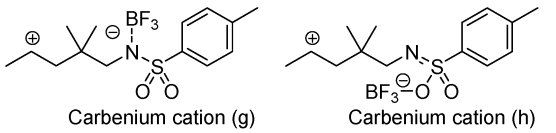


Fig. 4 Possible carbenium cation structures.

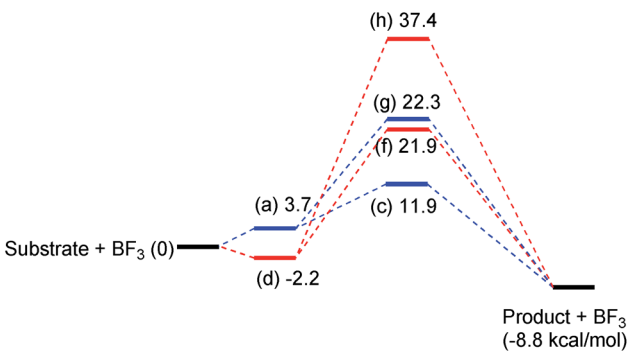


Fig. 5 Energy profiles for different reaction pathways.

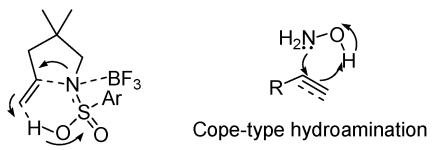
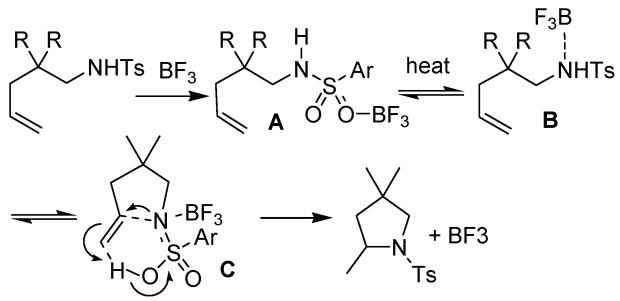


Fig. 6 A proposed reaction intermediate.



Scheme 2 A tentative mechanism for BF_3-promoted hydroamination reaction.

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Conclusions

In summary, we have shown that $BF_3 \cdot Et_2O$ is able to promote intra- and intermolecular amination and oxygenation of unactivated C=C double bonds. The current method would be more desirable for medicinal chemistry due to its non-transition metal feature. Preliminary study indicated that the substrate activation was realized through Lewis acid–base adducts between BF_3 and the sulfonamides. The key step involved the formation of a sulfonimidic acid intermediate N=S–OH *via* tautomerization of the NH$\cdots BF_3$ Lewis pair. HBF_4-promoted proton transfer was less likely based on the current control experiments and NMR studies. Further understanding the key role of sulfonimidic acid formation on the course of intramolecular hydroamination and further reducing the amount of reaction promoter are still underway, and the results will be reported in due time.

Experimental

General experimental information

Reactions were carried out using commercially available reagents in oven-dried apparatus. ^{1}H, ^{13}C and ^{19}F NMR spectra were recorded on a 400 MHz spectrometer at 298 K using deuterated chloroform as solvent and TMS as the internal reference. Column chromatography was performed employing 200–300 mesh silica gel unless otherwise noted. Thin layer chromatography (TLC) was performed on silica gel GF_{254}. Melting points were measured on a digital melting-point apparatus without correction of the thermometer. HRMS analyses were carried out with Varian FTICR-MS 7.0T. IR spectra were recorded with KBr pellet, and wavenumbers were given in cm^{-1}. Unless otherwise indicated, starting materials and reagents used in study were used as received without further purification. Substrates used were prepared according to our previous works.[10b,24]

Method for DFT calculation

The structures were optimized at ωB97XD/6-311++G(d,p) level with Gaussian 09 Revision B. 01.[25] Implicit solvation model (SMD)[21] was applied using dichloroethane as the reaction medium until a stationary point was found.

General procedure for intramolecular hydroamination

A sealed tube was charged with aminoalkene (1.0 mmol), 1,2-dichloroethane (10 mL) and $BF_3 \cdot Et_2O$ (3.0 mmol), the tube was sealed and heated in an oil bath (60 °C). The reaction mixture was stirred at this temperature for 24 h and was then cooled to room temperature. The tube was opened with care. The mixture was poured into water, and organic layer was separated. The aqueous layer was extracted with dichloromethane. The organic phase was combined, dried ($MgSO_4$), and concentrated to give a crude product which was purified by flash column chromatography to give the corresponding product.

***N*-(*p*-Toluenesulfonyl)-2-methyl-4,4-diphenylpyrrolidine 2a.** Compound **2a** was prepared according to the general procedure and was isolated as a white solid (355 mg, 90% yield) after flash chromatography (EtOAc/petroleum 5%); mp 105–106 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53 (d, J = 8.2 Hz, 2H), 7.17–7.01 (m, 12H), 4.10 (d, J = 10.4 Hz, 1H), 3.86 (d, J = 10.3 Hz, 1H), 3.70 (dd, J = 13.2, 6.7 Hz, 1H), 2.70 (dd, J = 12.6, 7.4 Hz, 1H), 2.30 (s, 3H), 2.18 (dd, J = 12.6, 6.9 Hz, 1H), 1.17 (d, J = 6.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.6, 143.8, 142.0, 134.4, 128.5, 127.5, 126.7, 126.2, 125.7, 125.5, 125.4, 125.3, 57.4, 54.5, 51.3, 45.0, 21.1, 20.3. Spectral data was consistent with the known *N*-(*p*-toluenesulfonyl)-2-methyl-4,4-diphenylpyrrolidine.[15]

1-Methanesulfonyl-2-methyl-4,4-diphenyl-pyrrolidine 2b. Compound **2b** was prepared according to the general procedure and was isolated as a white solid (294 mg, 93% yield) after flash chromatography (EtOAc/petroleum 5%); mp 119–121 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33 (d, J = 7.7 Hz, 2H), 7.23 (dd, J = 19.6, 9.3 Hz, 4H), 7.13 (d, J = 7.3 Hz, 4H), 4.26 (d, J = 10.7 Hz, 1H), 3.99 (d, J = 11.0 Hz, 1H), 3.81 (dd, J = 14.3, 6.3 Hz, 1H), 3.07 (dd, J = 13.1, 6.9 Hz, 1H), 2.29 (s, 3H), 2.16 (dd, J = 12.9, 9.1 Hz, 1H), 1.31 (d, J = 6.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 145.3, 144.4, 128.8, 128.6, 126.9, 126.8, 126.6, 126.5, 59.1, 55.4, 53.0, 46.0, 36.9, 22.2. IR: 3080, 3057, 2927, 2893, 2867, 1580, 1490, 1447, 1319, 1135, 964, 779, 704 cm^{-1}. HRMS-ESI (m/z): $[M + H]^+$ calcd for $C_{18}H_{21}NO_2S$, 316.1371; found: 316.1369.

***N*-(2-Nitrobenzenesulfonyl)-2-methyl-4,4-diphenylpyrrolidine 2c.** Compound **2c** was prepared according to the general procedure and was isolated as a yellow solid (312 mg, 73% yield) after flash chromatography (EtOAc/petroleum 5%); mp 114–116 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 (d, J = 7.8 Hz, 1H), 7.47–7.37 (m, 3H), 7.19–7.13 (m, 4H), 7.10–7.03 (m, 5H), 6.97 (t, J = 7.3 Hz, 1H), 4.49 (d, J = 10.8 Hz, 1H), 3.98–3.95 (m, 1H), 3.92 (d, J = 11.1 Hz, 1H), 2.87 (dd, J = 12.8, 6.2 Hz, 1H), 2.19 (dd, J = 12.6, 9.2 Hz, 1H), 1.15 (d, J = 6.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.0, 145.2, 143.9, 133.9, 133.3, 131.7, 130.1, 128.7, 128.6, 126.7, 126.7, 126.6, 126.6, 123.9, 58.7, 56.3, 52.8, 46.8, 21.3. Spectral data was consistent with *N*-(2-nitrobenzensulfonyl)-2-methyl-4,4-diphenylpyrrolidine.[15]

***N*-(4-Toluenesulfonyl)-2,4,4-trimethylpyrrolidine 2d.** Compound **2d** was prepared according to the general procedure and was isolated as a yellow solid (260 mg, 97% yield) after flash chromatography (EtOAc/petroleum 5%); mp 80–81 °C, lit.[26] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.63 (d, J = 8.1 Hz, 2H), 7.22 (d, J = 8.0 Hz, 2H), 3.55 (dd, J = 14.4, 6.9 Hz, 1H), 3.08 (d, J = 10.4 Hz, 1H), 2.98 (d, J = 10.4 Hz, 1H), 2.33 (s, 3H), 1.64 (dd, J = 12.5, 7.2 Hz, 1H), 1.32 (d, J = 6.2 Hz, 3H), 1.28 (d, 1H), 0.94 (s, 3H), 0.44 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.2, 135.2, 129.5, 127.5, 61.5, 56.1, 48.9, 37.1, 26.5, 25.9, 22.8, 21.6. Spectral data was consistent with *N*-(4-toluenesulfonyl)-2,4,4-trimethyl-pyrrolidine.[27]

***N*-(4-Toluenesulfonyl)-2-methylpyrrolidine 2e.** Compound **2e** was prepared according to the general procedure and was isolated as a white solid (226 mg, 94% yield) after flash chromatography (EtOAc/petroleum 5%); mp 93–94 °C, lit.[28] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.62 (d, J = 8.0 Hz, 2H), 7.22 (d, J = 8.0 Hz, 2H), 3.60 (dq, J = 13.0, 6.6 Hz, 1H), 3.36–3.31 (m, 1H), 3.08–3.02 (m, 1H), 2.33 (s, 3H), 1.72–1.71 (m, 1H), 1.57 (ddd, J = 19.9, 12.6, 7.5 Hz, 1H), 1.44–1.38 (m, 2H), 1.22 (d, J = 6.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.2, 134.7, 129.6, 127.4, 56.0, 49.1, 33.4,

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23.9, 22.9, 21.5. Spectral data was consistent with *N*-(4-toluenesulfonyl)-2-methylpyrrolidine.[29]

***N*-(*p*-Toluenesulfonyl)-3-methyl-2-azaspiro[4.5]decane 2f.** Compound **2f** was prepared according to the general procedure and was isolated as a yellow oil (300 mg, 97% yield) after flash chromatography (EtOAc/petroleum 5%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64 (d, J = 8.1 Hz, 2H), 7.22 (d, J = 7.9 Hz, 2H), 3.51–3.43 (m, 1H), 3.16 (d, J = 10.6 Hz, 1H), 3.06 (d, J = 10.7 Hz, 1H), 2.33 (s, 3H), 1.71 (dd, J = 12.7, 7.1 Hz, 1H), 1.32 (d, J = 6.1 Hz, 3H), 1.26–1.04 (m, 8H), 0.79–0.70 (m, 2H), 0.61 (dd, J = 11.6, 5.4 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.3, 135.0, 129.5, 127.3, 55.1, 40.9, 36.5, 34.2, 25.8, 23.7, 22.8, 22.7, 21.5. Spectral data was consistent with *N*-(*p*-toluenesulfonyl)-3-methyl-2-azaspiro[4.5]decane.[15]

2-Isopropyl-4,4-dimethyl-1-(toluene-4-sulfonyl)-pyrrolidine 2g. Compound **2g** was prepared according to the general procedure and was isolated as a white solid (293 mg, 99% yield) after flash chromatography (EtOAc/petroleum 10%); mp 83–85 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.65 (d, J = 8.1 Hz, 2H), 7.22 (d, J = 8.0 Hz, 2H), 3.63–3.58 (m, 1H), 3.19 (d, J = 10.8 Hz, 1H), 2.94 (d, J = 10.9 Hz, 1H), 2.45–2.43 (m, 1H), 2.35 (s, 3H), 1.43–1.36 (m, 2H), 0.92 (s, 3H), 0.75 (dd, J = 10.8, 6.9 Hz, 6H), 0.40 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.9, 136.2, 129.4, 127.2, 64.8, 61.8, 39.2, 37.1, 30.2, 26.1, 25.7, 21.5, 19.2, 14.5. HRMS-ESI (m/z): $[M + H]^+$ calcd for $C_{16}H_{25}NO_2S$, 296.1684; found: 296.1674.

3-Isopropyl-2-(toluene-4-sulfonyl)-2-aza-spiro[4.5]decane 2h. Compound **2h** was prepared according to the general procedure and was isolated as a white solid (310 mg, 92% yield) after flash chromatography (EtOAc/petroleum 10%); mp 103–105 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64 (d, J = 8.1 Hz, 2H), 7.21 (d, J = 8.0 Hz, 2H), 3.53–3.48 (m, 1H), 3.40 (d, J = 11.2 Hz, 1H), 2.86 (d, J = 11.2 Hz, 1H), 2.43–2.40 (m, 1H), 2.33 (s, 3H), 1.35–1.14 (m, 10H), 0.75 (dd, J = 14.2, 6.9 Hz, 6H), 0.68–0.62 (m, 1H), 0.57–0.53 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.8, 135.8, 129.3, 127.0, 63.8, 40.8, 36.3, 33.5, 30.2, 25.7, 23.7, 22.5, 21.3, 19.1, 14.4. IR: 3044, 2946, 2929, 2852, 2674, 2490, 1922, 1812, 1597, 1491, 1449, 1340, 1158, 1092, 1036, 816, 730, 660 cm^{-1}. HRMS-ESI (m/z): $[M + H]^+$ calcd for $C_{19}H_{29}NO_2S$, 336.1997; found: 336.1998.

Crystal data for ***2h****.* $C_{19}H_{29}NO_2S$, M = 335.49, orthorhombic, a = 9.2889(19) Å, b = 17.158(3) Å, c = 11.652(2) Å, α = 90.00°, β = 90.00°, γ = 90.00°, V = 1857.1(6) Å^3, T = 293(2) K, space group *Pna*2(1), Z = 4, μ(MoKα) = 0.184 mm^{-1}, 17 703 reflections measured, 4426 independent reflections (R_{int} = 0.0518). The final R_1 values were 0.0441 ($I > 2\sigma(I)$). The final w$R(F^2)$ values were 0.0986 ($I > 2\sigma(I)$). The final R_1 values were 0.0585 (all data). The final w$R(F^2)$ values were 0.1084 (all data). The goodness of fit on F^2 was 0.979. Flack parameter = 0.00(7).[16]

***N*-(*p*-Toluenesulfonyl)-2-ethyl-4,4-diphenylpyrrolidine 2i.** Compound **2i** was prepared according to the general procedure and was isolated as a thick paste (140 mg, 34% yield) after flash chromatography (EtOAc/petroleum 5%). ^{1}H NMR (400 MHz, $CDCl_3$) 7.50 (d, J = 8.2 Hz, 2H), 7.19–7.05 (m, 12H), 4.07 (d, J = 10.5 Hz, 1H), 3.96 (d, J = 10.5 Hz, 1H), 3.58–3.52 (m, 1H), 2.69 (dd, J = 12.7, 7.5 Hz, 1H), 2.31 (s, 3H), 2.26–2.21 (m, 1H), 2.00–1.94 (ddd, J = 13.4, 7.6, 3.2 Hz, 1H), 1.22 (dd, J = 15.4, 10.8 Hz, 1H), 0.75 (t, J = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 145.7, 144.7, 142.8, 135.6, 129.4, 128.4, 127.0, 126.6, 126.5, 126.5, 126.4, 126.2, 61.1, 58.6, 52.3, 42.4, 28.2, 21.4, 10.0. IR: 3056, 3025, 2946, 2929, 2879, 1949, 1806, 1598, 1494, 1448, 1334, 1262, 1093, 1026, 804 cm^{-1}. HRMS-ESI (m/z): $[M + H]^+$ calcd for $C_{25}H_{27}NO_2S$, 406.1841; found: 406.1842.

***N*-(4,4-Dimethyl-1-phenyl-1,2,3,4-tetrahydro-naphthalen-1-yl-methyl)-4-methyl-benzenesulfonamide 2j.** Compound **2j** was prepared according to the general procedure and was isolated as a white solid (400 mg, 95% yield) after flash chromatography (EtOAc/petroleum 10%); mp 148–150 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.61 (d, J = 8.2 Hz, 2H), 7.38 (d, J = 7.9 Hz, 1H), 7.24–7.06 (m, 6H), 6.99 (t, J = 7.1 Hz, 1H), 6.82 (d, J = 7.3 Hz, 2H), 6.64 (d, J = 7.8 Hz, 1H), 4.05 (d, J = 9.5 Hz, 1H), 3.64 (t, J = 11.2 Hz, 1H), 3.26 (dd, J = 11.9, 1.8 Hz, 1H), 2.42 (ddd, J = 13.6, 10.8, 5.4 Hz, 1H), 2.35 (s, 3H), 1.77 (dt, J = 7.5, 3.5 Hz, 1H), 1.36–1.33 (m, 2H), 1.22 (s, 3H), 1.17 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.7, 147.1, 143.4, 136.3, 136.0, 129.7, 128.1, 127.8, 127.4, 127.3, 127.2, 127.1, 126.4, 126.2, 51.7, 47.6, 34.1, 33.8, 31.9, 31.8, 31.5, 21.5. IR: 3296, 3057, 3019, 2959, 2916, 2860, 1931, 1807, 1598, 1490, 1424, 1328, 1162, 1093, 849, 757, 702, 669. IR: 3296, 3057, 3019, 2959, 2916, 2860, 1931, 1807, 1598, 1490, 1424, 1328, 1162, 1093, 849, 757, 702, 669. HRMS-ESI (m/z): $[M + H]^+$ calcd for $C_{26}H_{29}NO_2S$, 420.1997; found: 420.1994.

Crystal data for ***2j****.* $C_{26}H_{29}NO_2S$, M = 419.56, triclinic, a = 11.089(2) Å, b = 13.375(3) Å, c = 16.281(3) Å, α = 80.22(3)°, β = 77.60(3)°, γ = 77.15(3)°, V = 2280.3(8) Å^3, T = 293(2) K, space group $P\bar{1}$, Z = 4, μ(MoKα) = 0.164 mm^{-1}, 28 896 reflections measured, 10 801 independent reflections (R_{int} = 0.0359). The final R_1 values were 0.0540 ($I > 2\sigma(I)$). The final w$R(F^2)$ values were 0.1309 ($I > 2\sigma(I)$). The final R_1 values were 0.0868 (all data). The final w$R(F^2)$ values were 0.1512 (all data). The goodness of fit on F^2 was 1.018.[16]

2-Methyl-1-(toluene-4-sulfonyl)-2,3-dihydro-1*H*-indole 2l. Compound **2l** was prepared according to the general procedure and was isolated as a white solid (140 mg, 48% yield) after flash chromatography (EtOAc/petroleum 5%); mp 63–64 °C, lit.[28] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 (d, J = 8.1 Hz, 1H), 7.46 (d, J = 8.1 Hz, 2H), 7.10 (t, J = 7.6 Hz, 1H), 7.06 (d, J = 8.1 Hz, 2H), 6.93 (dt, J = 14.5, 7.2 Hz, 2H), 4.28–4.23 (m, 1H), 2.79 (dd, J = 16.0, 9.4 Hz, 1H), 2.33 (dt, J = 13.1, 6.5 Hz, 1H), 2.24 (s, 3H), 1.32 (d, J = 6.5 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.6, 140.9, 135.1, 131.5, 129.4, 127.5, 126.8, 125.2, 124.4, 117.0, 58.3, 36.0, 23.3, 21.4. Spectral data was consistent with 2-methyl-1-(toluene-4-sulfonyl)-2,3-dihydro-1*H*-indole.[30]

General procedure for intermolecular hydroamination

A sealed tube was charged dry with alkene (2.00 mmol), 1,2-dichloroethane (10 mL), sulfonamide (4.0 mmol) and $BF_3 \cdot Et_2O$ (6.0 mmol). The tube was sealed and heated in an oil bath (60 °C). The reaction mixture was stirred at this temperature for 24 h and was then cooled to room temperature. The tube was then opened with care. The mixture was poured into water, and the organic layer was separated. The aqueous layer was extracted with dichloromethane. The organic layers were combined, dried ($MgSO_4$), and concentrated to give a crude product which was purified by flash column chromatography to

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give the corresponding product. The yield was calculated based on the corresponding alkene.

***N*-Cyclohexyl *p*-toluenesulfonamide 4a.** Compound **4a** was prepared according to the general procedure and was isolated as a white solid (450 mg, 88% yield) after flash chromatography (EtOAc/petroleum 10%); mp 84–85 °C, lit.[31] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, J = 8.3 Hz, 2H), 7.22 (d, J = 8.0 Hz, 2H), 4.64 (s, 1H), 3.08–3.01 (m, 1H), 2.35 (s, 3H), 1.68–1.65 (m, 2H), 1.57–1.53 (m, 2H), 1.43 (dd, J = 8.7, 3.8 Hz, 1H), 1.16–1.01 (m, 5H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.8, 138.4, 129.4, 126.8, 52.4, 33.6, 25.0, 24.5, 21.3. Spectral data was consistent with *N*-cyclohexyl-*p*-toluenesulfonamide.[15]

***N*-Cyclohexyl-*N*-methyl-*p*-toluenesulfonamide 4b.** Compound **4b** was prepared according to the general procedure and was isolated as a white solid (280 mg, 52% yield) after flash chromatography (EtOAc/petroleum 5%); mp 74–75 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (d, J = 7.9 Hz, 2H), 7.19 (d, J = 7.9 Hz, 2H), 3.66 (s, 1H), 2.64 (s, 3H), 2.31 (s, 3H), 1.63 (d, J = 4.5 Hz, 2H), 1.49 (d, J = 12.9 Hz, 1H), 1.37 (s, 2H), 1.24–1.14 (m, 4H), 0.92–0.85 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.6, 137.1, 129.4, 126.6, 56.5, 30.0, 28.4, 25.5, 25.1, 21.2. Spectral data was consistent with *N*-cyclohexyl *N*-methyl *p*-toluenesulfonamide.[15]

***N*-Cyclohexyl-*N*-(*n*-butyl)-*p*-toluenesulfonamide 4c.** Compound **4c** was prepared according to the general procedure and was isolated as a yellow oil (260 mg, 42% yield) after flash chromatography (EtOAc/petroleum 5%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.63 (d, J = 8.2 Hz, 2H), 7.19 (d, J = 8.2 Hz, 2H), 3.56–3.51 (m, 1H), 3.04–3.00 (t, 2H), 2.34 (s, 3H), 1.65 (d, J = 12.4 Hz, 2H), 1.55–1.51 (m, 5H), 1.27–1.13 (m, 6H), 0.99–0.89 (m, 1H), 0.86–0.83 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.5, 138.7, 129.4, 126.7, 57.7, 43.5, 34.0, 31.6, 26.0, 25.2, 21.3, 20.1, 13.6. Spectral data was consistent with *N*-cyclohexyl *N*-*n*-butyl-*p*-toluenesulfonamide.[32]

***N*-Cyclohexyl-*N*-phenyl-*p*-toluenesulfonamide 4d.** Compound **4d** was prepared according to the general procedure and was isolated as a white solid (340 mg, 51% yield) after flash chromatography (EtOAc/petroleum 5%); mp 141–142 °C, lit.[33] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55 (d, J = 8.1 Hz, 2H), 7.28–7.22 (m, 3H), 7.17 (d, J = 8.2 Hz, 2H), 6.95 (d, J = 7.0 Hz, 2H), 4.11–4.05 (m, 1H), 2.35 (s, 3H), 1.76 (d, J = 11.4 Hz, 2H), 1.62 (d, J = 13.5 Hz, 2H), 1.45 (d, J = 13.5 Hz, 1H), 1.32–1.18 (m, 2H), 0.97 (qd, J = 12.4, 3.2 Hz, 2H), 0.78–0.74 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.8, 138.8, 135.6, 132.5, 129.4, 128.6, 128.5, 127.3, 59.1, 32.7, 25.9, 25.0, 21.5. Spectral data was consistent with *N*-cyclohexyl-*N*-phenyl-*p*-toluenesulfonamide.[32]

***N*-Cyclohexylbenzenesulfonamide 4e.** Compound **4e** was prepared according to the general procedure and was isolated as a white solid (460 mg, 96% yield) after flash chromatography (EtOAc/petroleum 10%); mp 88–89 °C, lit.[34] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.83 (d, J = 7.2 Hz, 2H), 7.46 (dt, J = 24.8, 7.2 Hz, 3H), 4.85 (d, J = 7.4 Hz, 1H), 3.07 (td, J = 13.5, 6.8 Hz, 1H), 1.66 (d, J = 7.8 Hz, 2H), 1.55 (dd, J = 9.1, 3.6 Hz, 2H), 1.44–1.41 (dd, J = 53.0, 11.4 Hz, 1H), 1.19–0.98 (m, 5H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.4, 132.3, 129.0, 126.8, 52.6, 33.8, 25.1, 24.5. Spectral data was consistent with *N*-cyclohexylbenzenesulfonamide.[34]

***N*-Bicyclo[2.2.1]hept-2-yl-*p*-toluenesulfonamide 4f.** Compound **4f** was prepared according to the general procedure and was isolated as a white solid (390 mg, 73% yield) after flash chromatography (EtOAc/petroleum 10%); mp 129–131 °C, lit.[34] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, J = 7.9 Hz, 2H), 7.23 (d, J = 7.9 Hz, 2H), 4.91 (s, 1H), 3.04 (t, 1H), 2.35 (s, 3H), 2.06 (d, 2H), 1.49–1.47 (m, 1H), 1.32–1.26 (m, 3H), 1.10 (d, J = 13.1 Hz, 1H), 1.02 (d, J = 10.3 Hz, 1H), 0.97–0.89 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.1, 137.9, 129.6, 127.0, 56.6, 42.4, 40.6, 35.5, 35.1, 28.0, 26.3, 21.5. Spectral data was consistent with *N*-bicyclo[2.2.1]hept-2-yl-*p*-toluenesulfonamide.[15]

***N*-Bicyclo[2.2.1]hept-2-yl-4′-*N*-dimethylbenzenesulfonamide 4g.** Compound **4g** was prepared according to the general procedure and was isolated as a yellow solid (545 mg, 97% yield) after flash chromatography (EtOAc/petroleum 5%); mp 67–68 °C, lit.[35] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (d, J = 8.2 Hz, 2H), 7.21 (d, J = 8.1 Hz, 2H), 3.74 (dd, J = 8.2, 6.0 Hz, 1H), 2.63 (s, 3H), 2.33 (s, 3H), 2.11–2.09 (m, 1H), 1.81–1.75 (m, 1H), 1.49–1.43 (m, 1H), 1.32 (ddd, J = 22.1, 12.3, 6.7 Hz, 4H), 1.07–0.95 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.0, 136.2, 129.6, 127.2, 59.9, 39.1, 36.8, 36.6, 35.7, 29.9, 29.2, 27.3, 21.5. Spectral data was consistent with *N*-bicyclo[2.2.1]hept-2-yl-4′-*N*-dimethylbenzenesulfonamide.[35]

***N*-Bicyclo[2.2.1]hept-2-ylbenzenesulfonamide 4h.** Compound **4h** was prepared according to the general procedure and was isolated as a white solid (190 mg, 39% yield) after flash chromatography (EtOAc/petroleum 10%); mp 92–94 °C, lit.[34] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.83 (d, J = 7.6 Hz, 2H), 7.50–7.40 (m, 3H), 5.35 (d, J = 7.2 Hz, 1H), 3.04 (td, J = 7.5, 3.2 Hz, 1H), 2.04 (d, J = 28.1 Hz, 2H), 1.46 (dd, J = 11.8, 8.4 Hz, 1H), 1.35–1.23 (m, 3H), 1.14–1.01 (m, 1H), 0.99–0.87 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.9, 132.5, 129.1, 127.0, 56.7, 42.5, 40.5, 35.6, 35.1, 28.0, 26.3. Spectral data was consistent with *N*-bicyclo[2.2.1]hept-2-ylbenzenesulfonamide.[34]

4-Methyl-*N*-(1-phenyl-ethyl)-benzenesulfonamide 4i. Compound **4i** was prepared according to the general procedure and was isolated as a white solid (340 mg, 61% yield) after flash chromatography (EtOAc/petroleum 10%); mp 69–71 °C, lit.[36] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 (d, J = 8.2 Hz, 2H), 7.13–7.08 (m, 5H), 7.03 (d, J = 7.6 Hz, 2H), 5.09 (d, J = 7.0 Hz, 1H), 4.38 (p, J = 6.9 Hz, 1H), 2.30 (s, 3H), 1.33 (d, J = 6.9 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.1, 142.1, 137.7, 129.4, 128.5, 127.4, 127.1, 126.1, 53.7, 23.6, 21.5. Spectral data was consistent with 4-methyl-*N*-(1-phenyl-ethyl) benzenesulfonamide.[37]

4′-*N*-Dimethyl-*N*-(1-phenyl-ethyl)benzenesulfonamide 4j. Compound **4j** was prepared according to the general procedure and was isolated as a white solid (110 mg, 18% yield) after flash chromatography (EtOAc/petroleum 5%); mp 69–70 °C, lit.[38] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.65 (d, J = 7.8 Hz, 2H), 7.22–7.17 (m, 7H), 5.20 (q, J = 6.9 Hz, 1H), 2.48 (s, 3H), 2.34 (s, 3H), 1.20 (d, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.2, 139.9, 137.2, 129.7, 128.4, 127.5, 127.3, 127.1, 54.8, 28.4, 21.5, 15.2. Spectral data was consistent with 4′-*N*-dimethyl-*N*-(1-phenylethyl)benzenesulfonoamide.[38]

***N*-[1-(4-Bromophenyl)ethyl]-4-methylbenzenesulfonamide 4k.** Compound **4k** was prepared according to the general procedure and was isolated as a white solid (320 mg, 45% yield) after flash chromatography (EtOAc/petroleum 5%); mp 135–137 °C, lit.[39] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50 (d, J = 8.3 Hz, 2H), 7.23 (d, 2H), 7.11 (d, J = 8.1 Hz, 2H), 6.90 (d, J = 8.4 Hz, 2H), 4.77 (d, J = 6.8 Hz, 1H), 4.36 (p, J = 6.8 Hz, 1H), 2.33 (s, 3H), 1.32 (d, J = 6.9 Hz,

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3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.4, 141.1, 137.4, 131.5, 129.5, 128.0, 127.1, 121.2, 53.1, 23.4, 21.5. Spectral data was consistent with *N*-[1-(4-bromo-phenyl)-ethyl]-4-methyl-benzenesulfonamide.[39]

General procedure for intermolecular esterification

A sealed tube was charged with olefin (2.0 mmol), carboxylic acid (4.0 mmol), 1,2-dichloroethane (5 mL) and $BF_3 \cdot Et_2O$ (6.0 mmol). The tube was sealed and heated in an oil bath (60 °C). The reaction mixture was stirred at this temperature for 24 h and was then cooled to room temperature. The tube was then opened with care. The mixture was poured into water, and the organic layer was separated. The aqueous layer was extracted with dichloromethane. The organic layer was combined, dried ($MgSO_4$), and concentrated to give a crude product which was purified by flash column chromatography to give the corresponding product.

Cyclohexyl benzoate 5a. Compound **5a** was prepared according to the general procedure and isolated as yellow oil (300 mg, 73% yield) after flash chromatography (petroleum). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98–7.96 (m, 2H), 7.47–7.43 (m, 1H), 7.34 (t, J = 7.6 Hz, 2H), 4.98–4.92 (m, 1H), 1.88–1.84 (m, 2H), 1.74–1.69 (m, 2H), 1.55–1.46 (m, 3H), 1.41–1.23 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.1, 132.8, 131.1, 129.6, 128.3, 73.1, 31.7, 25.6, 23.7. Spectral data was consistent with the known benzoic acid cyclohexyl ester.[40]

Cyclohexyl 2-methylbenzoate 5b. Compound **5b** was prepared according to the general procedure and isolated as yellow oil (320 mg, 73% yield) after flash chromatography (petroleum). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.82 (d, J = 7.6 Hz, 1H), 7.30 (t, J = 7.4 Hz, 1H), 7.16 (t, J = 7.4 Hz, 2H), 4.97–4.91 (m, 1H), 2.52 (s, 3H), 1.89–1.86 (m, 2H), 1.72–1.69 (m, 2H), 1.52–1.46 (m, 3H), 1.38–1.24 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.3, 139.9, 131.8, 131.7, 130.6, 130.6, 125.8, 73.1, 31.8, 25.6, 23.9, 21.9. Spectral data was consistent with the known 2-methyl-benzoic acid cyclohexyl ester.[41]

Cyclohexyl 3-methylbenzoate 5c. Compound **5c** was prepared according to the general procedure and isolated as yellow oil (310 mg, 71% yield) after flash chromatography (petroleum). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.78 (d, J = 6.7 Hz, 2H), 7.29–7.22 (m, 2H), 4.98–4.92 (m, 1H), 2.33 (s, 3H), 1.88–1.85 (m, 2H), 1.73–1.71 (m, 2H), 1.53–1.49 (m, 3H), 1.39–1.24 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.2, 137.9, 133.4, 130.9, 130.0, 128.1, 126.6, 72.9, 31.6, 25.5, 23.7, 21.3. Spectral data was consistent with the known 3-methyl-benzoic acid cyclohexyl ester.[42]

Cyclohexyl 4-methylbenzoate 5d. Compound **5d** was prepared according to the general procedure and isolated as yellow oil (320 mg, 73% yield) after flash chromatography (petroleum). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (d, J = 8.1 Hz, 2H), 7.13 (d, J = 8.0 Hz, 2H), 4.96–4.90 (m, 1H), 2.30 (s, 3H), 1.88–1.83 (m, 2H), 1.70–1.68 (m, 2H), 1.51–1.47 (m, 3H), 1.37–1.23 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.2, 143.3, 129.6, 129.0, 128.4, 72.8, 31.7, 25.7, 23.9, 21.8. Spectral data was consistent with the known 4-methyl-benzoic acid cyclohexyl ester.[43]

4-*tert*-Butyl-benzoic acid cyclohexyl ester 5e. Compound **5e** was prepared according to the general procedure and isolated as yellow oil (380 mg, 73% yield) after flash chromatography (petroleum). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (d, J = 8.3 Hz, 2H), 7.34 (d, J = 8.3 Hz, 2H), 4.95–4.89 (m, 1H), 1.84–1.80 (m, 2H), 1.69–1.65 (m, 2H), 1.49–1.43 (m, 3H), 1.35–1.26 (m, 3H), 1.22 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.9, 156.2, 129.4, 128.3, 125.2, 72.7, 35.0, 31.7, 31.1, 25.5, 23.7. Spectral data was consistent with the known 4-*tert*-butyl-benzoic acid cyclohexyl ester.[44]

Cyclohexyl 4-methoxybenzate 5f. Compound **5f** was prepared according to the general procedure and isolated as yellow oil (250 mg, 53% yield) after flash chromatography (petroleum). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, J = 8.9 Hz, 2H), 6.82 (d, J = 8.9 Hz, 2H), 4.94–4.88 (m, 1H), 3.75 (s, 3H), 1.87–1.82 (m, 2H), 1.71–1.68 (m, 2H), 1.51–1.44 (m, 3H), 1.37–1.22 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.8, 163.2, 131.6, 123.5, 113.5, 72.7, 55.4, 31.8, 25.6, 23.8. Spectral data was consistent with the known 4-methoxy-benzoic acid cyclohexyl ester.[45]

4-Chloro-benzoic acid cyclohexyl ester 5g. Compound **5g** was prepared according to the general procedure and isolated as yellow oil (215 mg, 45% yield) after flash chromatography (petroleum). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (d, J = 8.5 Hz, 2H), 7.31 (d, J = 8.5 Hz, 2H), 4.96–4.90 (m, 1H), 1.88–1.83 (m, 2H), 1.71–1.68 (m, 2H), 1.53–1.45 (m, 3H), 1.40–1.26 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.2, 139.1, 131.0, 129.5, 128.7, 73.5, 31.7, 25.5, 23.7. Spectral data was consistent with the known 4-chloro-benzoic acid cyclohexyl ester.[43]

4-Nitro-benzoic acid cyclohexyl ester 5h. Compound **5h** was prepared according to the general procedure and isolated as yellow oil (180 mg, 36% yield) after flash chromatography (petroleum). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.19 (d, J = 8.8 Hz, 2H), 8.12 (d, J = 8.8 Hz, 2H), 5.01–4.94 (m, 1H), 1.91–1.87 (m, 2H), 1.73–1.70 (m, 2H), 1.57–1.49 (m, 3H), 1.42–1.27 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.1, 150.4, 136.4, 130.7, 123.5, 74.4, 31.6, 25.4, 23.7. Spectral data was consistent with the known 4-nitro-benzoic acid cyclohexyl ester.[44]

Cyclohexyl cyclohexanecarboxylate 5i. Compound **5i** was prepared according to the general procedure and isolated as yellow oil (345 mg, 82% yield) after flash chromatography (petroleum). ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.70–4.65 (m, 1H), 2.19–2.18 (m, 1H), 1.81 (d, J = 13.1 Hz, 2H), 1.71–1.57 (m, 7H), 1.44–1.40 (m, 1H), 1.38–1.11 (m, 10H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 175.5, 71.8, 43.5, 31.6, 29.1, 25.9, 25.5, 23.7. Spectral data was consistent with the known cyclohexyl cyclohexanecarboxylate.[46]

Cyclohexyl acetate 5j. Compound **5j** was prepared according to the general procedure and isolated as yellow oil (270 mg, 95% yield) after flash chromatography (petroleum). ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.68–4.64 (m, 1H), 1.96 (s, 3H), 1.78 (d, J = 10.0 Hz, 2H), 1.66–1.64 (m, 2H), 1.49–1.47 (m, 1H), 1.37–1.16 (m, 5H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.7, 72.8, 31.8, 25.5, 23.9, 21.5. Spectral data was consistent with the known cyclohexyl acetate.[47]

Cyclohexyl isobutyrate 5k. Compound **5k** was prepared according to the general procedure and isolated as yellow oil (240 mg, 70% yield) after flash chromatography (petroleum). ^{1}H

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NMR (400 MHz, $CDCl_3$) δ 4.71–4.65 (m, 1H), 2.47–2.40 (m, 1H), 1.74–1.73 (m, 2H), 1.65–1.63 (m, 2H), 1.49–1.44 (m, 1H), 1.37–1.28 (m, 5H), 1.08 (d, $J = 7.0$ Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 176.7, 72.1, 34.3, 31.6, 25.5, 23.7, 19.1. Spectral data was consistent with the known cyclohexyl isobutyrate.[48]

General procedure for lactonization

A sealed tube was charged with substrate (1.0 mmol), 1,2-dichloroethane (5 mL) and $BF_3 \cdot Et_2O$ (3.0 mmol). The tube was sealed and heated in an oil bath (60 °C). The reaction mixture was stirred at this temperature for 24 h and was then cooled to room temperature. The tube was then opened with care. The mixture was poured into water, and the organic layer was separated. The aqueous layer was extracted with dichloromethane. The organic layer was combined, dried ($MgSO_4$), and concentrated to give a crude product which was purified by flash column chromatography to give the corresponding product.

5-Methyl-3,3-diphenyl-dihydro-furan-2-one 7a. Compound **7a** was prepared according to the general procedure and isolated as a white solid (230 mg, 91% yield) after flash chromatography (EtOAc/petroleum 5%); mp 114–115 °C, lit.[49] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26–7.08 (m, 10H), 4.36–4.30 (m, 1H), 2.93 (dd, $J = 12.9$, 4.7 Hz, 1H), 2.47–2.41 (m, 1H), 1.30 (d, $J = 6.1$ Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.3, 142.2, 140.0, 129.0, 128.4, 127.8, 127.7, 127.4, 127.2, 73.7, 58.7, 45.3, 20.3. Spectral data was consistent with the known 5-methyl-3, 3-diphenyl-dihydro-furan-2-one.[49]

3,3,5-Trimethyl-dihydrofuran-2(3*H*)-one 7b. Compound **7b** was prepared according to the general procedure and isolated as a white solid (98 mg, 75% yield) after flash chromatography (EtOAc/petroleum 5%); mp 48–50 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.53–4.48 (m, 1H), 2.14 (dd, $J = 12.7$, 5.8 Hz, 1H), 1.65 (dd, $J = 12.5$, 10.1 Hz, 1H), 1.34 (d, $J = 6.1$ Hz, 3H), 1.20 (s, 3H), 1.18 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.1, 73.4, 45.1, 40.9, 25.0, 24.3, 21.0. Spectral data was consistent with the known 3,3,5-trimethyl-dihydrofuran-2(3*H*)-one.[50]

3-Methyl-2-oxa-spiro[4.5]decan-1-one 7c. Compound **7c** was prepared according to the general procedure and isolated as a colorless solid (2 mmol scale, 280 mg, 83% yield) after flash chromatography (EtOAc/petroleum 5%); mp 64–66 °C, lit.[51] ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.52–4.45 (m, 1H), 2.34 (dd, $J = 12.9$, 6.1 Hz, 1H), 1.75–1.64 (m, 3H), 1.57–1.50 (m, 4H), 1.43 (d, $J = 12.9$ Hz, 1H), 1.34 (d, $J = 6.1$ Hz, 3H), 1.30–1.22 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 181.6, 73.7, 45.4, 41.2, 34.4, 31.5, 25.4, 22.2, 22.1, 21.4. Spectral data was consistent with the known 3-methyl-2-oxa-spiro[4.5]decan-1-one.[52]

6-Methyl-3,3-diphenyl-tetrahydro-pyran-2-one 7d. Compound **7d** was prepared according to the general procedure and isolated as a white solid (151 mg, 57% yield) after flash chromatography (EtOAc/petroleum 5%); mp 100–102 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25–7.06 (m, 10H), 4.38–4.29 (m, 1H), 2.62–2.58 (m, 1H), 2.52–2.47 (m, 1H), 1.83–1.78 (m, 1H), 1.60–1.55 (m, 1H), 1.21 (d, $J = 6.3$ Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.6, 143.0, 141.9, 128.5, 128.3, 128.3, 127.4, 127.1, 76.9, 56.8, 32.4, 27.6, 22.1. Spectral data was consistent with the known 6-methyl-3,3-diphenyl-tetrahydro-pyran-2-one.[53]

3-Methyl-2-oxa-spiro[5.5]undecan-1-one 7e. Compound **7e** was prepared according to the general procedure and isolated as a colorless oil (180 mg, 66% yield) after flash chromatography (EtOAc/petroleum 5%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.37–4.32 (m, 1H), 2.00–1.92 (m, 2H), 1.78–1.72 (m, 2H), 1.60–1.52 (m, 7H), 1.46–1.33 (m, 3H), 1.28 (d, $J = 6.2$ Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.5, 76.9, 41.3, 35.7, 33.5, 28.7, 27.5, 25.4, 22.0, 20.9, 20.8. Spectral data was consistent with the known 3-methyl-2-oxa-spiro[5.5]undecan-1-one.[52]

3-Ethyl-2-oxa-spiro[4.5]decan-1-one 7f. Compound **7f** was prepared according to the general procedure and isolated as a yellow oil (130 mg, 72% yield) after flash chromatography (EtOAc/petroleum 5%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.30–4.23 (m, 1H), 2.29 (dd, $J = 12.9$, 6.2 Hz, 1H), 1.73–1.18 (m, 13H), 0.93 (t, $J = 7.4$ Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 181.6, 78.6, 44.9, 39.0, 34.3, 31.6, 28.9, 25.3, 22.1, 22.1, 9.5. Spectral data was consistent with the known 3-ethyl-2-oxa-spiro[4.5]decan-1-one.[52]

3-Isopropyl-2-oxa-spiro[4.5]decan-1-one 7g. Compound **7g** was prepared according to the general procedure and isolated as a white solid (70 mg, 35% yield) after flash chromatography (EtOAc/petroleum 5%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.04–3.98 (m, 1H), 2.22 (dd, $J = 12.8$, 6.2 Hz, 1H), 1.75–1.69 (m, 4H), 1.58–1.52 (m, 4H), 1.44–1.16 (m, 4H), 0.96 (d, $J = 6.6$ Hz, 3H), 0.86 (d, $J = 6.8$ Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 181.8, 82.7, 45.0, 37.2, 34.3, 33.3, 31.5, 25.3, 22.2, 22.1, 18.7, 17.3. IR: 2930, 2857, 1764, 1468, 1348, 1279, 1001 cm^{-1}. $[M + H]^+$ calcd for $C_{12}H_{21}O_2$, 197.1542; found: 197.1540.

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