DOI: 10.1002/ejoc.200701080

Lewis Acid Catalyzed Intermolecular Olefin Hydroamination: Scope, Limitation, and Mechanism

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Keywords: Hydroamination / Lewis acids / Amines / Catalysis / Mechanisms

Intermolecular olefin hydroamination was studied by various Lewis acids. The results of $ZrCl_4$, $FeCl_3$, $BiCl_3$, and $AlCl_3$ catalyzed reactions of norbornene with aromatic amines were compared, and $BiCl_3$ was found to be the most effective catalyst to give high yields for various amines, whereas $ZrCl_4$ could promote the reactions at relatively low temperatures. The $FeCl_3$ catalyzed reactions were the most chemoselective and excellent yields could be achieved for certain amines by using $AlCl_3$. A carbocation mechanism was proposed, and the controllable syntheses of allylamine and tetrahydroquinoline from isoprene and 2,5-dichloroaniline were achieved by application of this mechanism.

Introduction

The synthesis of amines is of great academic and industrial importance. Among the methods used for the generation of C–N bonds, hydroamination of unsaturated C–C bonds has both the advantages of atom economy and thermodynamic feasibility, and it was pursued by many research groups worldwide.[1] Because of the high activation barrier of the hydroamination reaction, the development of catalytic transformations is necessary and has been the focus of numerous studies.

Depending on different catalysts used, the activation of C–C and N–H bonds are the two major strategies in catalytic reactions. So as to achieve efficient transformation, the late transition metals such as Rh, Ru, Ir, Pd, Ni, and Pt have been long used as catalysts for intra- and intermolecular olefin hydroamination.[2] Recent work by He and Che found that gold complexes are capable of catalyzing intramolecular olefin hydroamination reactions through C=C activation.[3] Later on, gold-catalyzed intermolecular hydroaminations of allenes and 1,3-dienes were also achieved by the Yamamoto and He groups.[4] Olefin hydroaminations catalyzed by early transition-metal complexes have also been long investigated. Since the early works of Livinghouse and Bergman,[5] many reports of titanium- and zirconium-catalyzed hydroamination have been reported in the literature, and the M=NR species was proposed as the key intermediate in these reactions.[6]

Organolanthanides have been used as effective catalysts for both intra- and intermolecular olefin hydroaminations since the pioneering work of Marks and coworkers in 1989.[7] The hydroamination reactions catalyzed by organolanthanides possess the features of very high turnover frequencies and excellent stereoselectivities, which makes this methodology quite practical for the concise synthesis of naturally occurring alkaloids and other polycyclic azacycles, as exemplified by the successful total synthesis of (+)-xenovenine, (+)-pyrrolidine 197B,[8] as well as other azacycle natural products.[9] The general accepted mechanism for the organolanthanide-catalyzed hydroamination reactions involves the insertion of the C–C multiple bond into the Ln–N bond, followed by rapid protonolysis by other amine substrates, and the insertion step is defined as the rate-determining step. Because of the importance of stereoselectivity control in natural product synthesis, the asymmetric olefin hydroamination reaction was also studied with other metal catalysts, such as Ni, Rh, and Zn, by exploiting various chiral ancillary ligands.[1c,10]

In an attempt to find a cheap and ecofriendly hydroamination catalyst, many new catalytic processes have been developed in recent years.[11] The scope of the catalyst was greatly expanded by using main-group metals as catalysts. The Hill group found that a calcium complex is an efficient catalyst for both intra- and intermolecular olefin hydroaminations.[12] By using $Bi(OTf)_3$, Shibasaki and coworkers found that allylic amides could be formed in high yields

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from the hydroamination of 1,3-dienes with various amides;[13] later on, the vinylarene hydroamination reaction was also accomplished with the same catalytic system.[14]

Brønsted acid catalyzed hydroaminations are also quite remarkable. By using proton catalysts such as triflic acid, sulfuric acid, proton-exchanged montmorillonite, HI, and other forms of proton catalysts,[15] the intra- and intermolecular hydroamination reaction can be accomplished under relatively mild conditions.

The Lewis acid catalyzed hydroamination reaction was firstly reported by Ackermann and coworkers in 2004.[16] By using $TiCl_4$, the intermolecular hydroamination of norbornene and vinylarene with aromatic amines can be achieved in excellent yields. The work of Komeyama et al. found that the $FeCl_3$ catalyst is quite efficient for the intramolecular hydroamination of unactivated olefins, and both five- and six-membered nitrogen heterocycles are accessible under ambient conditions.[17] On expanding the catalyst scope, previous results of our group found that the reusable, air- and moisture-tolerable $BiCl_3$ catalyst is capable of catalyzing the intermolecular hydroamination of norbornene with aromatic amines.[18]

These newly developed Lewis acid catalytic systems have the advantages of being readily available and easy to handle and they are also ecofriendly. However, the reactions have so far only been applied to a limited number of olefin substrates.[16–18] Another problem with these reactions is that the mechanism is still unknown. Whereas the oxidative-addition/reductive-elimination mechanism was defined for most of the late-transition-metal catalysts, a metal amide was the key intermediate in organolanthanide-catalyzed reactions, and a metal imido species was proposed as the active intermediate for the early transition-metal-catalyzed reactions. Little attention has been paid to the pathway of the reaction catalyzed by commonly used Lewis acids. Mechanistic understanding of these reactions would be crucial to further improve and expand the Lewis acid catalyzed olefin hydroamination reaction.

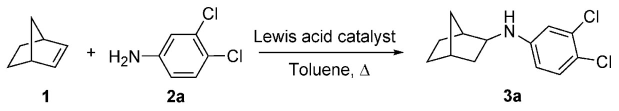
As a continuation of our previous study,[18] the current report aims at revealing the scope, limitation, and mechanism of the intermolecular hydroamination of olefins catalyzed by various Lewis acids. By conducting the hydroamination reactions of norbornene with aromatic amines, the optimal reaction conditions for different Lewis acid catalysts ($FeCl_3$, $ZrCl_4$, $BiCl_3$, and $AlCl_3$) are presented, and the catalytic performances of these catalysts are compared. The possible pathways for these reactions are discussed, and a carbocation mechanism is most favorable, as supported by the experimental results. This mechanistic insight further leads to the controllable synthesis of allylamine and tetrahydroquinoline from isoprene and aromatic amines.

Results and Discussion

Optimization of the Conditions for Various Lewis Acid Catalysts

The hydroamination of norbornene (**1**) with 3,4-dichloroaniline (**2a**) was investigated with different kinds of Lewis acids, and the results are summarized in Table 1 (see Experimental Section for details).

Table 1. Optimization of conditions for different Lewis acid catalysts.



Catalyst	Cat. [mol-%]	Temp. [°C]	Time [h]	Yield [%][a]
$FeCl_3$	5	100	8	38
	5	135	8	45
	5	150	8	49
	5	169	8	48
	10	150	8	54
	15	150	8	72
	20	150	8	71
$ZrCl_4$	10	169	24	trace
	50	169	4	60
	20	110	24	61
	10	110	24	trace
$BiCl_3$	10	169	4	61
	10	150	4	71
	10	110	8	50
$AlCl_3$	10	110	8	42
	10	150	8	67
	10	169	8	28
	20	150	8	65

[a] Isolated yields.

Optimization of the conditions revealed that the catalyst loading, reaction temperature, and reaction time are different for different catalysts to achieve efficient transformation. When $FeCl_3$ was used, a higher catalyst loading and a higher temperature were needed to get a desirable yield, and the optimal conditions of 15 mol-% catalyst loading at 150 °C gave 72% of hydroamination product **3a** within 8 h.

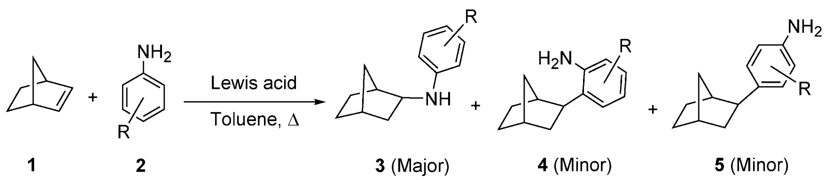
However, the $ZrCl_4$ catalyst was found to be less active: 10 mol-% catalyst loading at 169 °C only gave trace amounts of **3a** after 24 h. The reaction time was shortened when the catalyst loading was increased to 50 mol-%, and a moderate yield of **3a** was obtained within 4 h at 169 °C. A catalyst loading of 20 mol-% at 110 °C gave similar results, but a reaction time of 24 h was necessary. The higher catalyst loading and low reaction rate of the $ZrCl_4$-catalyzed reaction may be attributed to the dimerization of $ZrCl_4$ when coordinated with aniline.[19] When the reaction was catalyzed by $BiCl_3$ and $AlCl_3$, a catalyst loading of 10 mol-% at 150 °C gave moderate yield of the product, and increased catalyst loading and/or higher temperature showed no superiority.

Scope and Limitations of the Lewis Acid Catalyzed Hydroamination Reaction

With the optimized conditions for different catalysts, we next expanded the reactions to various amines with different substituents on the phenyl ring, and the results are shown in Table 2.

For unsubstituted aniline (Table 2, Entry 1), it is interesting that $FeCl_3$ showed no catalytic activity at all, whereas

Table 2. Lewis acid catalyzed hydroamination of norbornene with various aromatic amines.



Entry	Amine	Product	FeCl$_3$		ZrCl$_4$		BiCl$_3$		AlCl$_3$	
			Selectivity[a]	Yield[b]	Selectivity[a]	Yield[b]	Selectivity[a]	Yield[b]	Selectivity[a]	Yield[b]
1	aniline	**3b**	0:0:0	0	72:28:0	43	58:42:0	45	76:24:0	52
2	4-nitroaniline	**3c**	100:0:0	88	100:0:0	61	100:0:0	68	100:0:0	Trace
3	2-nitroaniline	**3d**	100:0:0	93	100:0:0	67	100:0:0	68	100:0:0	69
4	3-nitroaniline	**3e**	100:0:0	86	100:0:0	69	98:2:0	80	100:0:0	44
5	2-chloroaniline	**3f**	97:3:0	82	94:5:1	72	83:13:4	84	82:15:4	75
6	3-chloroaniline	**3g**	94:6:0	26	82:8:10	66	82:8:10	68	91:4:5	49
7	4-chloroaniline	**3h**	100:0:0	18	100:0:0	55	100:0:0	57	100:0:0	30
8	2,5-dichloroaniline	**3i**	100:0:0	88	100:0:0	86	100:0:0	92	100:0:0	82
9	4-bromoaniline	**3j**	100:0:0	39	100:0:0	63	100:0:0	70	92:8:0	70
10	2-fluoroaniline	**3k**	98:2:0	30	87:10:3	74	87:10:3	81	90:9:1	44
11	4-fluoroaniline	**3l**	100:0:0	Trace	78:22:0	59	78:22:0	64	87:13:0	66
12	2,4-dichloroaniline	**3m**	100:0:0	71	100:0:0	67	100:0:0	81	100:0:0	82
13	4-methoxyaniline	**3n**	0:0:0	0	0:0:0	0	0:0:0	0	0:0:0	0

[a] Ratio of **3**/**4**/**5** determined by GC–MS. [b] Isolated yield of **3**.

the other three catalysts gave hydroamination product **3b** in ~50% yield and hydroarylation byproduct **4** in comparable yield.

Without regard of the catalyst, enhanced selectivity and yield were found for most of the substituted anilines. When the aniline is monosubstituted with an NO$_2$ group, only the hydroamination products were obtained (Table 2, Entries 2, 3, and 4). The reactions of 4-chloroaniline, 4-bromoaniline, as well as the dichloro-substituted anilines, were also quite selective (Table 2, Entries 7, 9, 8, and 12); the major products of type **3** were formed exclusively for all these substrates. However, a chlorine atom at C-2 or C-3, as well as a fluorine atom at C-2 or C-4, of the phenyl ring of the aniline (Table 2, Entries 5, 6, 10, and 11), resulted in lower chemoselectivities relative to those of the above-mentioned reactions, but higher chemoselectivities than those obtained with the unsubstituted substrate.

The catalytic performances of the Lewis acids were found to be different. The highest chemoselectivity was found in FeCl$_3$ catalyzed reactions. Only the hydroamination product was formed in almost all the FeCl$_3$ catalyzed reactions, and only one hydroarylation byproduct was formed in quite low yield in limited cases. The FeCl$_3$ catalyst was also found to be quite substrate-dependent. Excellent yields were obtained with substrates containing an NO$_2$ group or a C-2 chloride atom and dichloride-substituted anilines also gave good yields; however, the yields were lower than 40% when other halogen-substituted anilines were used as the nitrogen source. Particularly for 2-fluoroaniline, as no reaction occurred when FeCl$_3$ was used as the catalyst.

The results show that the ZrCl$_4$ and BiCl$_3$ catalysts can be applied to a wide range of amine substrates. Relative to the results of FeCl$_3$ and AlCl$_3$ catalyzed reactions, higher yields were obtained for the reactions catalyzed by ZrCl$_4$ and BiCl$_3$. In almost all cases, the yields of the AlCl$_3$ catalyzed reactions were not as good as those obtained by ZrCl$_4$ and BiCl$_3$ catalysis, and only a trace amount of the hydroamination product was detected for the 4-NO$_2$ aniline substrate. The poorer activity of AlCl$_3$ in these reactions may be the result of rapid hydrolysis, as all the reactions were conducted under ambient conditions. High yields of the reactions and the recoverable and reusable properties of BiCl$_3$ make it the best catalyst choice for the current transformation.[18]

It is interesting to find that no hydroamination or hydroarylation occurred for 4-methoxyaniline, no matter which Lewis acid was used under various conditions (Table 2, Entry 13). These results indicate that the electronic structure of the phenyl ring influences the reactivity of the aniline most. Although all the electron-poor anilines proved to be effective nitrogen sources, we proposed that increased acidity of the amine hydrogen atom would be crucial for the occurrence of the reaction.[20] To test this idea, we conducted more reactions of electron-donating-group-containing anilines by using BiCl$_3$ as a catalyst. No reaction was detected with the use of 4-methylaniline; reaction of 2-methylaniline with norbornene only gave 15% yield of hydroamination product **3o**. However, introduction of an additional NO$_2$ group onto 4-methylaniline, namely, 4-methyl-2-nitroaniline, greatly improved the yield of hydroamination product **3p** to 73%.

Mechanistic Insight

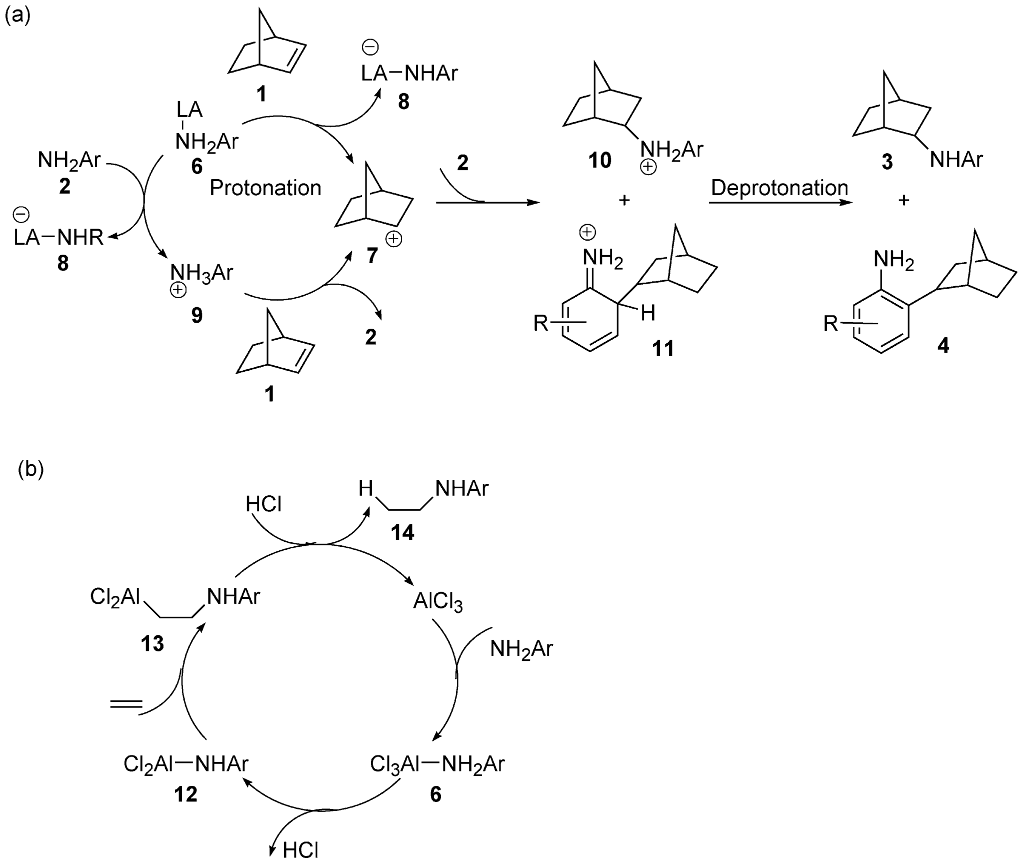
The mechanism of these reactions has not been explored. The metal–imido complex was proposed for the hydroamination reaction catalyzed by TiCl$_4$.[16] However, the formation of metal–imido species from $TiCl_4$ and aniline is questionable, and it is also difficult to use this mechanism for the explanation of reactions catalyzed by various Lewis acids.[21]

The involvement of a proton catalyst in the reaction is possible, as the metal chlorides used in the reactions would be easily hydrolyzed under the ambient conditions. The results are consistent with previous hydroamination reactions catalyzed by acidic zeolites, from which electron-poor anilines were found to be more reactive.[15i] It should be noted that the results of these Lewis acid catalyzed reactions are different from those of the proton-catalyzed ones in two ways. The first one is that only trace amounts of product was detected when HCl was used as the catalyst.[18] Another difference is that relative to the HI catalyzed reactions of norbornene with aromatic amines,[15d] the Lewis acid catalyzed reactions are much more chemoselective, and the hydroamination products are formed exclusively in most cases.

Because the reactions can be catalyzed by various Lewis acids, two possible mechanisms are outlined in Scheme 1. Scheme 1a illustrates that the reactions may be initiated by the Lewis acid–base interaction between the catalyst and the amine substrate, and protonation of norbornene by **6** or **9** to form cationic intermediate **7** is the key step of the hydroamination and hydroarylation reaction.[18] By using $AlCl_3$ as a representative Lewis acid, the alternative mechanism postulated in Scheme 1b suggests that intermediate **12** can be afforded by elimination of HCl from $AlCl_3$–amine complex **6**, and insertion of the C=C bond of the olefin into the metal–N bond of this intermediate will finally give **14** as the hydroamination product.[4a]

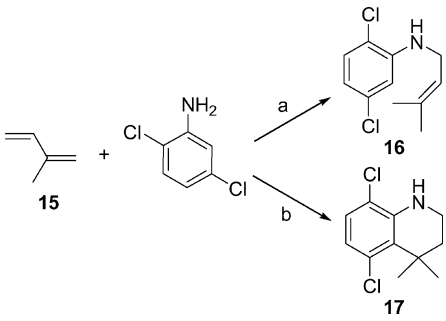
Although both mechanisms are possible, we think the carbocation mechanism is more favorable as supported by the experimental results. Firstly, these Lewis acid catalyzed reactions have only been applied to a limited number of cases so far. Despite the intramolecular hydroamination, the unsaturated species investigated were generally limited to norbornene and styrene, as the generated carbocations from these olefins are stabilized intramolecularly.[15a] Attempts to use other cyclic and acyclic olefins, such as cyclohexene and hex-1-ene, proved unsuccessful. Further support of this mechanism can also be provided by the outcome that the electron-poor anilines are more reactive. It is reasonable to propose that protonation of the olefin is more facile with increased acidity of the amine hydrogen atom.[20]

The carbocation mechanism prompted us to exam other olefins that may generate relatively stable carbocations from protonation.[22] The results of isoprene were quite encouraging. As shown in Scheme 2, the reaction of isoprene (**15**) with 2,5-dichloroaniline could be controlled by using different solvents. When catalyzed by 10 mol-% of $BiCl_3$, allylamine **16** was obtained in 40% yield in dioxane, and



Scheme 1. Plausible mechanisms for the hydroamination and hydroalkylation reactions of norbornene with aromatic amines.

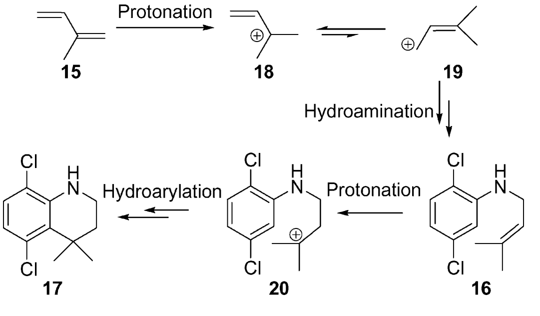
1,2,3,4-tetrahydroquinoline **17** was formed selectively when the reaction was carried out in toluene. The use of other Lewis acids would give similar results.



Scheme 2. Divergent reactions of isoprene with 2,5-dichloroaniline in different solvents: (a) $BiCl_3$ (10 mol-%), 150 °C, dioxane; (b) $BiCl_3$ (10 mol-%), 150 °C, toluene.

Despite the drawback of low yields under the current conditions, the reaction of isoprene with aromatic amines is quite remarkable as a synthetic methodology, as the allylamine derivatives are important synthetic precursors that can be further transformed,[23] and tetrahydroquinoline is the substructure of many naturally occurring substances.[24]

The different results of the isoprene reactions can be well explained by the carbocation mechanism. As illustrated in Scheme 3, the protonation of isoprene (**15**) will firstly give more-stabilized tertiary cation **18**, which may be in its resonance form **19** upon reaction with a nitrogen source to give hydroamination product **16**. In the presence of Lewis acid and amine, the C=C bond of allylamine **16** could be protonated to give tertiary cation **20**. When the reaction is conducted in dioxane, this cation could be stabilized by the polar solvent and further reaction is hindered. However, the polarity of toluene is much lower, which enables more-reactive **20** for the intramolecular hydroarylation reaction to give **17** as the product.



Scheme 3. Mechanism for the formations of **16** and **17** from isoprene and 2,5-dichloroaniline.

Conclusions

By conducting the hydroamination of norbornene with aromatic amines, Lewis acid catalysts were expanded to several commonly used metal halides, and the catalytic performance of these catalysts was compared. Among the catalysts, $BiCl_3$ was the most effective and provided higher yields in short reaction times. Optimization of the reaction conditions found that the $ZrCl_4$ catalyzed reactions could be accomplished at relatively low temperatures, but a higher catalyst loading and a longer reaction time were necessary for desirable yields. The $FeCl_3$ catalyzed reactions were the most chemoselective and excellent yields were achieved for certain amines when $AlCl_3$ was used as the catalyst.

The reactivity of different functional-group-substituted anilines was investigated, and it was found that increased acidity of the amine hydrogen atom was crucial for a high transformation yield. The possible mechanisms were proposed, and a carbocation mechanism was supported by the experiments. This mechanism was taken into consideration in the controllable syntheses of allylamine and tetrahydroquinoline from isoprene and aromatic amines.

Experimental Section

General: All reactions were carried out in pressure tubes (45 mL, 150 psi) equipped with a magnetic stirring bar and capped with a solid PTFE plug. All starting materials were purchased from commercial suppliers and used without further purification. A Varian Unity Plus 400 MHz spectrometer was used to obtain ^1H and ^{13}C NMR spectra. GC–MS spectra were recorded with a GCMS-QP2010 by using dodecane as an internal standard and MS spectra were obtained by TOF-MS.

General Procedure: To a 45-mL pressure tube (ACEGLASS) was added norbornene (0.188 g, 2.00 mmol), $BiCl_3$ (0.0630 g, 0.2 mmol), aniline (8.00 mmol), and anhydrous toluene (4 mL) (the reactions catalyzed by other Lewis acids were conducted with similar procedures according to the conditions optimized in Table 1). The pressure tube was sealed, and the suspension was stirred at 150 °C for 6 h. After the pressure tube was cooled to room temperature, the reaction mixture was transferred to a round-bottomed flask (250 mL) and CH_2Cl_2 (20 mL) and H_2O (20 mL) were added to the flask. The organic layer was collected, and the aqueous phase was extracted with CH_2Cl_2 (3×25 mL). The combined organic layer was dried with $MgSO_4$ and concentrated in vacuo. Pure product was obtained by column chromatography.

***N*-(3,4-Dichlorophenyl)bicyclo[2.2.1]heptan-2-amine (3a):** Product **3a** (0.364 g, 71%, unless mentioned otherwise, all yields given in this section are from the $BiCl_3$ catalyzed reactions, yields of other Lewis acid catalyzed reactions are given in Tables 1 and 2) was obtained as a yellow oil after column chromatography (petroleum ether/ethyl acetate, 100:1). ^1H NMR (400 MHz, $CDCl_3$): δ = 7.17 (dd, J = 5.2, 4.4 Hz, 1 H), 6.61 (m, 1 H), 6.39 (dd, J = 2.8, 2.4 Hz, 1 H), 3.74 (s, 1 H), 3.16 (m, 1 H), 2.30 (s, 1 H), 2.24 (s, 1 H), 1.83 (m, 1 H), 1.61–1.41 (m, 3 H), 1.24–1.14 (m, 4 H) ppm.[25]

***N*-Phenylbicyclo[2.2.1]heptan-2-amine (3b):** Product **3b** (0.169 g, 45%) was obtained as a pale yellow oil after column chromatography (petroleum ether/ethyl acetate, 50:1). ^1H NMR (400 MHz, $CDCl_3$): δ = 7.18–7.14 (m, 2 H), 6.69–6.65 (m, 1 H), 6.58–6.56 (m, 2 H), 3.48 (s, 1 H, NH), 3.23–3.22 (m, 1 H), 2.27 (s, 2 H), 1.84–1.79 (m, 1 H), 1.52–1.43 (m, 3 H),1.22–1.16 (m, 4 H) ppm.

***N*-(4-Nitrophenyl)bicyclo[2.2.1]heptan-2-amine (3c):** Product **3c** (0.316 g, 68%) was obtained as a pale yellow oil after column chromatography (petroleum ether/ethyl acetate, 10:1). ^1H NMR (400 MHz, $CDCl_3$): δ = 7.86 (t, J = 8.8 Hz, 2 H), 6.41 (d, J = 8.8 Hz, 2 H), 4.61 (s, 1 H), 3.21 (s, 1 H), 2.25 (m, 2 H), 1.81–1.76

(dd, J = 8.0, 7.6 Hz, 1 H), 1.50–1.35 (m, 3 H), 1.21–1.09 (m, 4 H) ppm.

***N*-(2-Nitrophenyl)bicyclo[2.2.1]heptan-2-amine (3d):** Product **3d** (0.316 g, 68%) was obtained as a yellow solid after column chromatography (petroleum ether/ethyl acetate, 20:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 8.06 (d, J = 8.4 Hz, 1 H), 7.92 (s, 1 H), 7.35–7.31 (t, J = 7.2 Hz, 1 H), 6.75–6.73 (d, J = 8.8 Hz, 1 H), 6.55–6.51 (t, J = 8.0 Hz, 1 H), 3.33 (m, 1 H), 2.37 (s, 2 H), 1.82 (ddd, J = 2.0, 2.4, 22 Hz, 1 H), 1.58–1.45 (m, 3 H), 1.34–1.30 (m, 1 H), 1.22–1.10 (m, 3 H) ppm.

***N*-(3-Nitrophenyl)bicyclo[2.2.1]heptan-2-amine (3e):** Product **3e** (0.371 g, 80%) was obtained as an orange solid after column chromatography (petroleum ether/ethyl acetate, 20:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.41–7.39 (d, J = 8.0 Hz, 1 H), 7.26 (s, 1 H), 7.19–7.15 (m, 1 H), 6.75–6.72 (m, 1 H), 3.87 (s, 1 H, NH), 3.19 (s, 1 H, CH), 2.19–2.25 (m, 2 H, CH$_2$), 1.82–1.77 (m, 1 H, CH), 1.56–1.36 (m, 3 H), 1.18–1.13 (m, 4 H) ppm.

***N*-(2-Chlorophenyl)bicyclo[2.2.1]heptan-2-amine (3f):** Product **3f** (0.373 g, 84%) was obtained as a colorless oil after column chromatography (petroleum ether/ethyl acetate, 200:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.19–7.15 (m, 1 H), 7.07–7.03 (m, 1 H), 6.65–6.57 (m, 2 H), 4.09 (s, 1 H), 3.19 (m, 1 H), 2.23–2.22 (m, 2 H), 1.78 (m, 1 H), 1.50–1.41 (m, 3 H), 1.23–1.10 (m, 4 H) ppm.

***N*-(3-Chlorophenyl)bicyclo[2.2.1]heptan-2-amine (3g):** Product **3g** (0.302 g, 68%) was obtained as a colorless oil after column chromatography (petroleum ether/ethyl acetate, 50:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.06–7.02 (t, J = 8.0 Hz, 1 H), 6.63–6.61 (d, J = 8.0 Hz, 1 H), 6.52 (s, 1 H), 6.42–6.40 (d, J = 8.4 Hz, 1 H), 3.63 (s, 1 H, NH), 3.20–3.18 (m, 1 H), 2.29–2.26 (m, 2 H), 1.85–1.80 (m, 1 H), 1.53–1.41 (m, 3 H), 1.26–1.18 (m, 4 H) ppm.

***N*-(4-Chlorophenyl)bicyclo[2.2.1]heptan-2-amine (3h):** Product **3h** (0.253 g, 57%) was obtained as a pale yellow oil after column chromatography (petroleum ether/ethyl acetate, 25:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.03–7.01 (m, 2 H), 6.42–6.40 (m, 2 H), 3.65 (s, 1 H), 3.09 (m, 1 H), 2.22 (s, 1 H), 2.18 (s, 1 H), 1.74 (dd, J = 8.0, 7.6, Hz, 1 H), 1.51–1.35 (m, 3 H), 1.18–1.06 (m, 4 H) ppm.

***N*-(2,5-Dichlorophenyl)bicyclo[2.2.1]heptan-2-amine (3i):** Product **3i** (0.471 g, 92%) was obtained as a yellow oil after column chromatography (petroleum ether/ethyl acetate, 60:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.26–7.11 (m, 1 H), 6.57 (s, 2 H), 4.22 (s, 1 H, NH), 3.22 (s, 1 H), 2.33–2.29 (m, 2 H), 1.89–1.84 (m, 1 H), 1.56–1.47 (m, 3 H), 1.26–1.20 (m, 4 H) ppm.

***N*-(4-Bromophenyl)bicyclo[2.2.1]heptan-2-amine (3j):** Product **3j** (0.372 g, 70%) was obtained as an orange oil after column chromatography (petroleum ether/ethyl acetate, 200:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.23–7.21 (d, J = 8.8 Hz, 2 H), 6.44–6.42 (d, J = 8.8 Hz, 2 H), 3.62 (s, 1 H, NH), 3.18–3.16 (m, 1 H, CH), 2.28–2.24 (m, 2 H, CH$_2$), 1.84–1.80 (m, 1 H, CH), 1.53–1.41 (m, 3 H), 1.19–1.17 (m, 4 H) ppm.

***N*-(2-Fluorophenyl)bicyclo[2.2.1]heptan-2-amine (3k):** Product **3k** (0.332 g, 81%) was obtained as a yellow oil after column chromatography (petroleum ether/ethyl acetate, 200:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 6.92–6.84 (m, 2 H), 6.61–6.50 (m, 1 H), 6.49–6.48 (d, J = 1.6 Hz, 1 H), 3.81 (s, 1 H, NH), 3.17–3.15 (t, J = 3.6 Hz, 1 H), 2.21 (s, 2 H), 1.78–1.73 (m, 1 H), 1.53–1.39 (m, 3 H), 1.20–1.06 (m, 4 H) ppm.

***N*-(4-Fluorophenyl)bicyclo[2.2.1]heptan-2-amine (3l):** Product **3l** (0.262 g, 64%) was obtained as an orange oil after column chromatography (petroleum ether/ethyl acetate, 100:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 6.87 (dd, J = 6.4, 8.8 Hz, 2 H), 6.51 (dd, J = 2.4, 4.4 Hz, 2 H), 3.63 (s, 1 H), 3.17 (m, 1 H), 2.32 (s, 1 H), 2.28 (s, 1 H), 1.67–1.43 (m, 3 H), 1.34–1.13 (m, 4 H) ppm.

***N*-(2,4-Dichlorophenyl)bicyclo[2.2.1]heptan-2-amine (3m):** Product **3m** (0.415 g, 81%) was obtained as a yellow oil after column chromatography (petroleum ether/ethyl acetate, 100:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.23–7.22 (d, J = 2.4 Hz, 1 H, 3-C$_6$H$_3$N), 7.09–7.06 (dd, J = 2.4, 2.4 Hz, 1 H, 5-C$_6$H$_3$N), 6.54–6.52 (d, J = 8.8 Hz, 1 H), 4.13 (s, 1 H, NH), 3.22 (s, 1 H, CH), 2.32–2.26 (d, J = 21.6 Hz, 2 H), 1.87–1.82 (m, 1 H), 1.53–1.40 (m, 3 H), 1.22–1.07 (m, 4 H) ppm.

***N*-*o*-Tolybicyclo[2.2.1]heptan-2-amine (3o):** Product **3o** (0.060 g, 15%) was obtained as a pale yellow oil after column chromatography (petroleum ether/ethyl acetate, 100:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.13–7.09 (t, J = 7.6 Hz, 1 H, 6-C$_6$H$_3$N), 7.04–7.02 (d, J = 7.2 Hz, 1 H, 3-C$_6$H$_3$N), 6.65–6.56 (m, 2 H), 3.34 (s, 1 H, NH), 3.28–3.27 (m, 1 H, CH), 2.29 (s, 2 H, CH$_2$), 2.10 (s, CH$_3$), 1.88–1.82 (m, 1 H), 1.55–1.45 (m, 3 H), 1.24–1.17 (m, 4 H) ppm. ^{13}C NMR (100 MHz, CDCl$_3$): δ = 145.75 (C), 130.24 (CH), 127.26 (CH), 121.91 (C), 116.65 (CH), 110.66 (CH), 56.72 (CH), 41.54 (CH), 41.43 (CH$_2$), 35.85 (CH$_2$), 35.62 (CH), 28.72 (CH$_2$), 26.58 (CH$_2$), 17.83 (CH$_3$) ppm. HRMS (EI): calcd. for C$_{14}$H$_{19}$N 201.1517; found 201.1527.

***N*-(4-Methyl-2-nitrophenyl)bicyclo[2.2.1]heptan-2-amine (3p):** Product **3p** (0.359 g, 73%) was obtained as an orange oil after column chromatography (petroleum ether/ethyl acetate, 100:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.97 (s, 1 H), 7.91 (s, 1 H), 6.75–6.73 (d, J = 8.8 Hz, 1 H), 3.40 (s, 1 H, NH), 2.36–2.34 (m, 2 H), 2.26 (s, 3 H, CH$_3$), 1.93–1.87 (m, 1 H, CH), 1.58–1.53 (m, 4 H), 1.41–1.37 (m, 1 H), 1.26–1.20 (m, 3 H) ppm. ^{13}C NMR (100 MHz, CDCl$_3$): δ = 141.99 (CH), 136.59 (C), 130.27 (C), 125.01 (C), 123.46 (CH), 113.69 (CH), 54.98 (CH), 40.66 (CH), 40.07 (CH$_2$), 34.68 (CH$_2$), 34.57 (CH), 27.35 (CH$_2$), 25.28 (CH$_2$), 18.94 (CH$_3$) ppm. HRMS (EI): calcd. for C$_{14}$H$_{18}$N$_2$O$_2$ 246.1368; found 246.1376.

2,5-Dichloro-*N*-(2-methylprop-1-enyl)aniline (16): Product **16** (0.184 g, 40%) was obtained as a yellow oil after column chromatography (petroleum ether/ethyl acetate, 200:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.07–7.05 (d, J = 8.4 Hz, 1 H), 6.52–6.49 (m, 2 H), 5.25–5.22 (t, J = 6.4 Hz, 1 H), 4.2 (s, 1 H, NH), 3.63–3.61 (t, J = 6.4 Hz, 2 H), 1.70–1.65 (d, J = 17.2 Hz, 6 H) ppm. ^{13}C NMR (100 MHz, CDCl$_3$): δ = 145.07 (1-C$_6$H$_3$NCl$_2$), 137.02 (2-C$_6$H$_3$NCl$_2$), 133.74 (5-C$_6$H$_3$NCl$_2$), 129.83 (6-C$_6$H$_3$NCl$_2$), 120.52 (3-C$_6$H$_3$NCl$_2$), 117.38 (4-C$_6$H$_3$NCl$_2$), 116.81 (C$_6$H$_3$NCl$_2$NHCH$_2$CH*C*), 111.28 (C$_6$H$_3$NCl$_2$NHCH$_2$*C*H), 41.78 (C$_6$H$_3$NCl$_2$NH*C*H$_2$), 25.95 (C$_6$H$_3$NCl$_2$NHCH$_2$CHC*C*H$_3$), 18.29 (C$_6$H$_3$NCl$_2$NHCH$_2$CHC*C*H$_3$) ppm. HRMS (EI): calcd. for C$_{11}$H$_{13}$NCl$_2$ 229.0425; found 229.0434.

5,8-Dichloro-1,2,3,4-tetrahydro-4,4-dimethylquinoline (17): Product **17** (0.174 g, 38%) was obtained as a pale yellow oil after column chromatography (petroleum ether/ethyl acetate, 200:1). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 6.94–6.92 (d, J = 8.4 Hz, 1 H), 6.53–6.51 (d, J = 8.4 Hz, 1 H), 4.24 (s, 1 H, NH), 2.74–2.71 (t, J = 6.8 Hz, 2 H), 1.65–1.62 (t, J = 6.8 Hz, 2 H), 1.16 (s, 6 H) ppm. ^{13}C NMR (100 MHz, CDCl$_3$): δ = 141.61 (C-9), 133.36 (C-10), 127.53 (C-5), 119.55 (C-7), 116.91 (C-8), 116.75 (C-6), 49.32 (C-3), 34.06 (C-2), 29.43 (C-4-*C*H$_3$), 23.27 (C-4-*C*H$_3$) ppm. HRMS (EI): calcd. for C$_{11}$H$_{13}$NCl$_2$ 229.0425; found 229.0418.

Supporting Information (see footnote on the first page of this article): Spectroscopic data for the products.

Acknowledgments

The authors appreciate the financial support of the Chinese Academy of Sciences through the Hundreds of Talents Program (2005012), the Natural Science Foundation of Jiangsu Province (BK2005030), and Suzhou University. The authors would like to thank Prof. Aaron L. Odom for editorial comments on a previous version of the manuscript and for helpful scientific discussions.

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Received: November 15, 2007