Activation of Hydrogen and Hydrogenation Catalysis by a Borenium Cation

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S Supporting Information

ABSTRACT: The readily prepared borenium salt $[(IiPr_2)(BC_8H_{14})][B(C_6F_5)_4]$ (2) $[IiPr_2 = C_3H_2(NiPr)_2]$ is shown to activate H_2 heterolytically in the presence of tBu_3P. Compound 2 also acts as a catalyst for the metal-free hydrogenation of imines and enamines at room temperature.

The addition of H_2 to unsaturated molecules is without question the most used transformation in chemical industry.[1] This process must be facilitated by a catalyst. Despite the fact that both heterogeneous and homogeneous hydrogenation catalysts are firmly established technologies, research continues to uncover new ways to effect this important reaction. For example, recent efforts from several research groups[2] have exploited iron catalysts, while Harder and co-workers[3] have utilized calcium complexes for hydrogenation catalysis. In addition, we[4] and others[5] have focused on main-group catalysts derived from "frustrated Lewis pairs" (FLPs) for metal-free hydrogenations. While the latter discovery has provided an unprecedented role for main-group chemistry in hydrogenation catalysis, all of the FLP hydrogenation catalysts known to date require neutral boron species with highly electron-withdrawing fluorinated substituents.[4a] The presence of such electron-withdrawing substituents deters hydride delivery and thus slows the catalysis. In addition, synthetic challenges associated with such air- and moisture-sensitive boranes preclude facile access to families of catalysts for process optimization and selectivity control.

A lesser studied, but important, class of boron-based Lewis acids are borenium cations.[6] Considerable electrophilicity is imparted to these boron species by their cationic charge. Nevertheless, a number of research groups[6c,7] have shown that borenium cations can be readily stabilized by a variety of bulky or electron-donating substituents. A number of these compounds have been exploited as electrophiles in aromatic and aliphatic borylations and borylations of arylsilanes,[7a,d,e,n−p,8] and a recent report from Curran, Lacôte, Vedejs, and co-workers describes the borenium ion-catalyzed hydroboration of alkenes.[9] Chiral oxazaborolidinium ions have also been extensively studied in enantioselective catalysis.[10] A number of borenium cations have been prepared from N-heterocyclic carbene (NHC)−borane adducts.[11] Also, NHC−borane adducts have been demonstrated to be potent reductants.[12] Thus, while NHC−borenium cations are electrophilic, the corresponding NHC−borane adducts are effective hydride donors. These complementary features augur well for

the potential of borenium cation-based FLP hydrogenation catalysts. In this work, a carbene-stabilized borenium cation derived from the ubiquitous borane reagent 9-borabicyclo[3.3.1]nonane (9-BBN) has been prepared and shown to effect the stoichiometric heterolytic activation of H_2 in combination with a bulky base. Moreover, this borenium cation-based FLP has been demonstrated to be a highly effective and functional-group-tolerant catalyst for the rapid hydrogenation of imines and enamines at room temperature.

The NHC adduct of 9-BBN, $(IiPr_2)(HBC_8H_{14})$ (1) $[IiPr_2 = C_3H_2(NiPr)_2]$, was readily prepared via the stoichiometric combination of 1,3-diisopropylimidazol-2-ylidene and 9-BBN dimer in toluene at room temperature and recrystallized in 76% yield. While a B−H resonance was not observed at room temperature in the ^1H NMR spectrum of 1, the ^{11}B NMR spectrum showed a doublet resonance at −16.64 ppm ($^1J_{BH} = 80$ Hz). The formulation of 1 as a pseudotetrahedral molecule was confirmed by X-ray crystallography (Figure 1a).

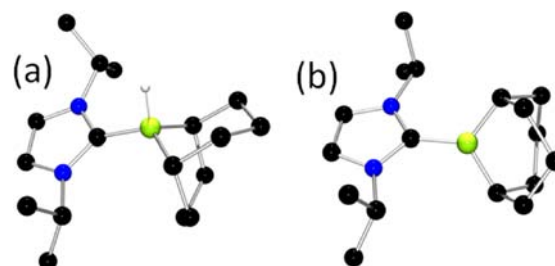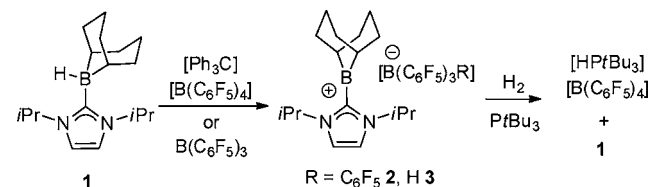**Figure 1.** POV-ray drawings of (a) 1 and (b) the cation of 2 (C, black; N, blue; B, yellow-green; H, gray). H atoms except for BH have been omitted for clarity.

Compound 1 reacted with $[Ph_3C][B(C_6F_5)_4]$ in toluene to give the borenium salt $[(IiPr_2)(BC_8H_{14})][B(C_6F_5)_4]$ (2) (Scheme 1). Recrystallization from chlorobenzene of 2 afforded

Scheme 1. Synthesis and Activation of H_2 by 2

an 81% yield of **2**·0.66 C$_6$H$_5$Cl, which showed the expected ^{11}B and ^{19}F NMR resonances for the [B(C$_6$F$_5$)$_4$]$^-$ anion. In addition, the ^{11}B NMR spectrum also showed a broad resonance at 83.8 ppm, consistent with the generation of a borenium center.[7m] The crystallographic data for **2** (Figure 1b) confirmed a trigonal-planar geometry with a B−C$_{NHC}$ bond length of 1.580(3) Å, analogous to the value of 1.579(7) Å for [(C$_6$H$_2$Me$_3$)$_2$B(IMe$_2$)][OTf] as reported by Matsumoto and Gabbai.[7f]
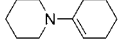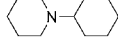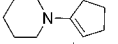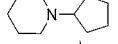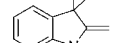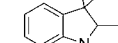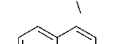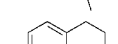
An alternative strategy for obtaining the same cation was derived from the reaction of **1** with B(C$_6$F$_5$)$_3$.[13] This afforded the salt [(I*i*Pr$_2$)(BC$_8$H$_{14}$)][HB(C$_6$F$_5$)$_3$] (**3**) (Scheme 1), which is directly analogous to **2**, as evidenced by ^{1}H, ^{11}B, and ^{19}F NMR spectroscopy. The formation of **3** illustrates the considerably higher hydricity of **1** relative to [HB(C$_6$F$_5$)$_3$]$^-$; alternatively, viewed in terms of Lewis acidity, B(C$_6$F$_5$)$_3$ is a stronger Lewis acid than the borenium cations in **2** and **3**.

The combination of Lewis acid **2** with the Lewis base *t*Bu$_3$P or H$_2$ independently showed no evidence of reaction as determined by multinuclear NMR spectroscopy. Nonetheless, exposure of **2**/*t*Bu$_3$P to H$_2$ (4 atm) at room temperature for 48 h revealed the formation of **1** and the generation of the known salt [*t*Bu$_3$PH][B(C$_6$F$_5$)$_4$] in 68% yield, as evidenced by ^{1}H, ^{11}B, ^{19}F, and ^{31}P NMR spectroscopy (Scheme 1). The analogous experiment with D$_2$ afforded the corresponding deuterium split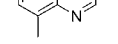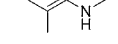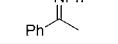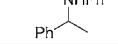ting products. A 1:1:1 triplet resonance was observed in the ^{31}P NMR spectrum at 59.8 ppm with P−D coupling of 66 Hz, while a broad resonance at −16.90 ppm was seen in the ^{11}B NMR spectrum. These observations confirmed that the borenium cation and phosphine acted in concert to effect the FLP heterolytic activation of H$_2$ and D$_2$, respectively. On the other hand, treatment of PhCH=N*t*Bu with [*t*Bu$_3$PH][B(C$_6$F$_5$)$_4$] and **1** resulted in stoichiometric conversion to the corresponding amine and the generation of *t*Bu$_3$P and **2**, as evidenced by NMR spectroscopy.

The above stoichiometric reactions in which H$_2$ is activated and subsequently delivered to a substrate represent the complementary reactivity required for catalytic hydrogenation. Indeed, treatment of PhCH=N*t*Bu with **2** (1 mol%) under H$_2$ (102 atm) in CH$_2$Cl$_2$ at room temperature resulted in quantitative reduction to the corresponding amine in 2 h. No phosphine was employed in this case, as the imine functioned as the base in the FLP activation.[4f] Performing the reaction in C$_6$H$_5$Cl or toluene resulted in slightly diminished yields. This was attributed to the decreased solubility of **2** in these solvents. The ketimine *N*-(1-phenylethylidene)aniline, the aldimines *N*-benzylidene-*tert*-butylamine and *N*-(*m*-methoxybenzylidene)-*tert*-butylamine, and the enamines *N*-(1-cyclohexenyl)-piperidine, *N*-(1-cyclopentenyl)piperidine, and 1,3,3-trimethyl-2-methyleneindoline were also reduced quantitatively in 2−4 h using 1−5 mol% catalyst (Table 1). The product amines were isolated in 79−94% yield. These reductions were generally faster and higher-yielding than those previously reported employing electrophilic borane catalysts.[4a−g,5] In contrast, the N-heterocycle 8-methylquinoline was reduced by **2** in only 27% yield in C$_6$H$_5$Cl and not at all in CH$_2$Cl$_2$. This latter result stands in contrast to previously reported reductions[4e] of this and related heterocycles using B(C$_6$F$_5$)$_3$ and H$_2$.

This difference in reactivity led us to further explore the functional group tolerance and selectivity of catalyst **2**. To this end, a stoichiometric quantity of a surrogate containing a functional group was included in catalytic mixtures of the hydrogenation of *N*-benzylidene-*tert*-butylamine.[4h] Using **2** (5

Table 1. Hydrogenation Catalyzed by a Borenium Ion

substrate $\xrightarrow[\text{102 atm. H}_2\text{, r.t.}]{\text{1-5\% 1 or 2}}$ amine

entry	substrate	cat.(mol%)	t (h)	product	%yield[d] (isolated)
1		**1**[a] 1	4		0
2	Ph, N*t*Bu	**2**[b] 1	2	Ph, NH*t*Bu	100(79)
3		**2**[a] 1	2		71
4		**2**[c] 1	2		30
5	MeO, NtBu	**2**[b] 1	2	MeO, NHtBu	100(88)
6	(N-cyclohexenyl)piperidine	**2**[b] 5	4	(N-cyclohexyl)piperidine	100 (85)
7	(N-cyclopentenyl)piperidine	**2**[b] 5	4	(N-cyclopentyl)piperidine	100 (94)
8	(methyleneindoline)	**2**[b] 5	4	(methylindoline)	60
9		**2**[a] 5	4		100 (94)
10	8-methylquinoline	**2**[b] 5	4	tetrahydroquinoline	0
11		**2**[a] 5	4		27
12	Ph, NPh	**2**[b] 5	4	Ph, NHPh	100 (90)

^{a}C$_6$H$_5$Cl, ^{b}CH$_2$Cl$_2$, ^{c}C$_6$H$_5$Me, ^{d}Yield based on ^{1}H NMR data, isolated yields in parentheses.

mol%) at room temperature in CH$_2$Cl$_2$ under H$_2$ (102 atm), *N*-benzylidene-*tert*-butylamine was selectively reduced in the presence of fenchone, 4,4′-dimethylbenzophenone, 8-methylquinoline, 2-phenylpyridine, and ethyl-4-bromobenzoate. However, the catalytic reductions were inhibited in the presence of acetophenone, 2′,4′,6′-triisopropylacetophenone, and 2,2,2-trifluoroacetophenone. In no case was hydrogenation of the functional-group-containing surrogate observed. These results demonstrate that the borenium cation-based FLP catalyst is significantly more functional group tolerant than metal-free reductions based on B(C$_6$F$_5$)$_3$.[4h]

On the basis of the above observations, the mechanism of action operative in these hydrogenations is thought to involve heterolytic cleavage of H$_2$ by the **2**/imine (or product amine)[4f]-based FLP, generating **1** and an iminium [B(C$_6$F$_5$)$_4$]$^-$ salt (Scheme 2). This is consistent with the observation that the independent combination of **1** and imine gave no reaction. Subsequent hydride transfer from **1** affords the amine and regenerates **2** for further catalysis. In support of this mechanism, we note that the use of **1** in place of **2** under catalytic conditions gave no reduction. This is consistent with

Scheme 2. Proposed Catalytic Cycle for the Hydrogenation of Imines by 2
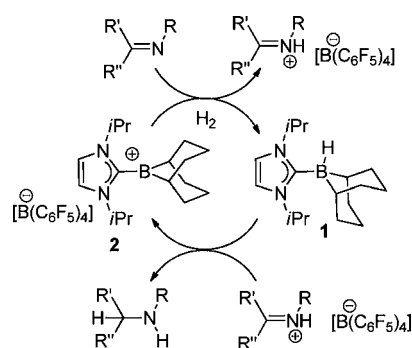
the inability of **1** to transfer hydride to the imine and demonstrates that initial iminium generation is essential. Moreover, this observation implies that the mechanism of H_2 activation does not involve hydride migration from B to the C_{NHC} of **1** to generate a neutral boron−nitrogen FLP, but it is consistent with a mechanism that necessitates the generation of a Lewis acidic borenium ion. The activation of H_2 proceeds slowly, while the reaction of **1** and the iminium salt $[PhCH= NHtBu][B(C_6F_5)_4]$ results in immediate hydride transfer. These preliminary data imply that H_2 activation is rate-determining, although a detailed mechanistic study is ongoing.

In summary, we have demonstrated that a borenium cation can be employed as a Lewis acid in an FLP to activate H_2. This borenium cation, which is readily obtained from an air-stable precursor, is a new, highly active metal-free catalyst for the hydrogenation of imines and enamines at room temperature. Moreover, the borenium cation hydrogenation catalyst exhibits improved selectivity and functional group tolerance relative to existing FLP catalysts. The required Lewis acidity for hydrogen activation is derived from the cationic charge at boron rather than the incorporation of fluorinated substituents. This finding provides a new family of readily accessible Lewis acids for FLP chemistry and catalysis. Accordingly, systematic modifications of the borenium cation catalysts for chemo-, regio-, and stereoselectivity are currently under intense study.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Experimental and crystallographic data. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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