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Synthesis and Lewis acid properties of a ferrocene-based planar-chiral borenium cation†

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The first planar chiral ferrocenylborenium species (p*R*)-3$^+$ is obtained in the enantiopure form by halide abstraction from the corresponding chloroborane adduct (p*R*)-2 using Krossing's salt. Competition experiments suggest that the Lewis acidity of (p*R*)-3$^+$ is higher than that of B(C_6F_5)$_3$ towards anions and slightly lower towards neutral Lewis bases. The ferrocenylborenium species (p*R*)-3$^+$ is examined as a catalyst for the stereoselective hydrosilylation of ketones.

Highly Lewis acidic organoboranes continue to attract tremendous interest and current applications range from Lewis acid catalysis of organic transformations[1] and polymerization reactions[2] to small molecule activation,[3,4] sensors for anions,[5] and the development of new and unusual electronic materials.[6] Many of the earlier studies have focused on installing electron withdrawing fluorine substituents onto organoboranes as a means of increasing the electron-deficient character of boron, and B(C_6F_5)$_3$ is nowadays broadly applied not only in academia but has also found its way into a wide range of industrial processes.[7] An alternative approach involves the incorporation of tricoordinate boron into antiaromatic cyclics as in borole and diborabenzene derivatives. In this case, Lewis acid–base adduct formation is energetically favored by conversion to non-aromatic species.[8] Most recently, highly reactive borenium species[9,10] have been introduced, in which the cationic charge further enhances the potency of tricoordinate borane Lewis acids (Chart 1).[11]

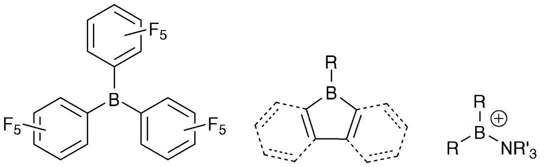
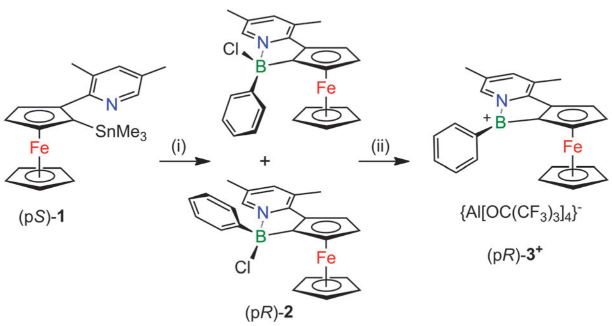


Chart 1 Examples of highly Lewis acidic organoboranes.

Borenium species have proven to be highly advantageous especially in the promotion of electrophilic aromatic substitution chemistries.[10,12] Very recently the first studies of their use in hydrogenation and hydroboration catalysis have also been reported.[13] For broad applications in organic synthesis it is desirable to develop and utilize chiral borenium Lewis acids. Chiral alkyl- and arylboranes, including fluorinated derivatives, are widely applied as reagents and catalysts in stereoselective synthesis.[14–16] We have, over the past several years, pursued planar chiral ferrocene-based Lewis acids.[15,17–19] We have demonstrated, for example, the utility of a bifunctional ferrocene-based Lewis acid as a stereoselective reagent for the allylation of ketones with ee's of up to 80%.[15] We have also introduced fluorinated arylboranes attached to a chiral naphthylferrocenyl framework.[18] Related planar-chiral η^5-1,2-azaborolyl iron complexes have been utilized by Fu and coworkers in Mukayama aldol reactions and in stereoselective additions to imines.[20] Interestingly, planar chiral borenium cations were proposed as intermediates in these processes. We describe herein the first synthesis of an isolable planar-chiral ferrocenylborenium cation, discuss the Lewis acid properties and present a proof-of-principle investigation of its utility in the hydrosilylation of ketones.

The chloroborane adduct (p*R*)-**2** was prepared by treatment of the organotin compound (p*S*)-**1**[21] with an excess of $PhBCl_2$ in a hexanes–toluene mixture (Scheme 1).[22,23] Based on ^{1}H NMR studies (Fig. 1a) two different species (ratio 2.5 : 1) are present in solution, which are attributed to the *exo*-Ph and *endo*-Ph isomers of (p*R*)-**2**.



Scheme 1 Synthesis of (p*R*)-**3**$^+$. (i) 2 $PhBCl_2$, toluene–hexanes, −37 °C to rt. (ii) Method A: [Ag(CH_2Cl_2)]{Al[OC(CF_3)$_3$]$_4$}, $CHCl_3$, −37 °C to rt; Method B: Li{Al[OC(CF_3)$_3$]$_4$}, $CDCl_3$, rt.

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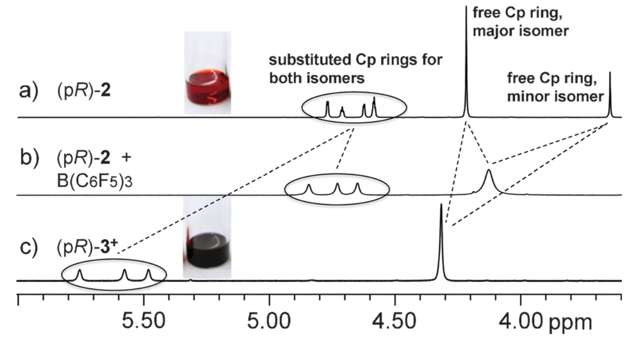


Fig. 1 Expansion of the Cp region of the ^{1}H NMR spectra for (a) (p*R*)-**2** (*exo* and *endo*-isomers), (b) (p*R*)-**2** + $B(C_6F_5)_3$ and (c) (p*R*)-$\mathbf{3}^+$ ($CDCl_3$) and photographs illustrating the associated color change.

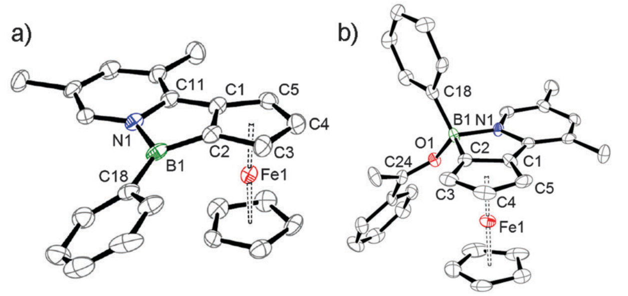


Fig. 2 (a) Ortep plot of (p*R*)-$\mathbf{3}^+$ (50% thermal ellipsoids); counteranions and H atoms are omitted. Selected distances (Å) and angles (°) [2nd independent molecule]: B1–N1 1.544(7) [1.550(9)], B1–C2 1.519(9) [1.539(9)], B1–C18 1.524(9) [1.504(10)], C2–B1–N1 102.2(5) [100.6(5)], C2–B1–C18 131.4(5) [132.2(6)], C18–B1–N1 126.3(5) [127.1(6)]. (b) Ortep plot of (p*R*)-$\mathbf{3}^+$(acetophenone) (50% thermal ellipsoids); counteranions and H atoms are omitted. Selected distances (Å) and angles (°) [2nd independent molecule]: B1–N1 1.603(9) [1.592(9)], B1–O1 1.560(8) [1.577(8)], B1–C2 1.580(11) [1.593(10)], B1–C18 1.603(11) [1.594(10)], O1–C24 1.257(8) [1.255(8)].

According to a 2D NOESY experiment,† the major isomer features the Ph group in the *exo*-position and the minor isomer in the *endo*-position. Coalescence was not observed in the 1D ^{1}H NMR spectra even at temperatures up to 70 °C. This indicates that isomerization is slow on the NMR time scale.

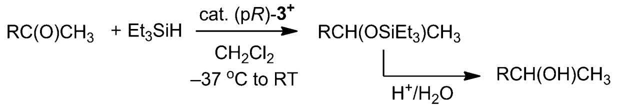
We initially attempted to prepare the corresponding borenium cation by Cl^- abstraction with $B(C_6F_5)_3$. Indeed, when compound (p*R*)-**2** was mixed with one equivalent of $B(C_6F_5)_3$, coalescence into a single set of broad ^{1}H NMR resonances was observed (Fig. 1b). However, the Lewis acid strength of $B(C_6F_5)_3$ proved to be far too low to bring about complete abstraction of Cl^-. In contrast, treatment of (p*R*)-**2** with 1 equiv. of Krossing's salt[24] $[Ag(CH_2Cl_2)]\{Al[OC(CF_3)_3]_4\}$ or $Li\{Al[OC(CF_3)_3]_4\}$ in $CHCl_3$ led to quantitative chloride abstraction with the formation of the tricoordinate borenium cation (p*R*)-$\mathbf{3}^+$ (Scheme 1). The ^{1}H NMR spectrum showed strongly downfield shifted signals at 5.75, 5.58 and 5.48 ppm for the substituted Cp ring, consistent with attachment of a highly electron-deficient borenium cation (Fig. 1c). In the ^{11}B NMR spectrum a broad signal was observed at 45.4 ppm for the cation and in the ^{19}F NMR spectrum a sharp signal at −75.4 ppm for the anion. Another characteristic feature of the borenium cation (p*R*)-$\mathbf{3}^+$ is its deep purple color (Fig. 1, $\lambda_{max} = 566$ nm, $\varepsilon = 2200\ M^{-1}\ cm^{-1}$). This unusual color is likely due to enhanced charge transfer from iron to the more extended and highly electron-deficient π-system of the pyridylborenium heterocycle in (p*R*)-$\mathbf{3}^+$.[25]

A single crystal X-ray diffraction analysis confirmed retention of the planar chirality upon halide abstraction from (p*R*)-**2** to give (p*R*)-$\mathbf{3}^+$ (Fig. 2a). As expected, the highly electron-deficient nature of the borenium moiety results in a strong interaction between B and the electron-rich Fe, which is reflected in pronounced bending of the boryl group out of the Cp plane, towards the iron center. The tilt angles for the boryl groups in two independent cations are 14.1° (Fe···B 2.925 Å) and 14.5° (Fe···B 2.907 Å), respectively, which is similar to Piers' perfluorophenyl-substituted $FcB(C_6F_5)_2$[26] (16°, Fe···B 2.924 Å) and $FcBBr_2$[27] (17.7, 18.9°; Fe···B 2.856/2.840 Å).[28] It is noteworthy that the $Cp_{CENT}\cdots Cp_{CENT}$ distance of 3.316 Å is consistent with a neutral ferrocene,[29] supporting the assignment of (p*R*)-$\mathbf{3}^+$ as a borenium-substituted ferrocene rather than a borane-substituted ferrocenium species.[30] Another interesting aspect is that the planar π-conjugated structure of (p*R*)-$\mathbf{3}^+$ favors formation of inter-molecular π–π dimers that consist of two independent cations.†

A first indication of the high Lewis acidity of (p*R*)-$\mathbf{3}^+$ came from the fact that the reaction of (p*R*)-**2** with an equimolar amount of $B(C_6F_5)_3$ led to only a very modest downfield shift of the Cp resonances (see Fig. 1b). This implies that only partial abstraction (≪50%) of chloride from (p*R*)-**2** occurs and suggests that (p*R*)-$\mathbf{3}^+$ as a cation has a higher affinity than $B(C_6F_5)_3$ towards anionic Lewis bases such as Cl^-. To also explore the Lewis acid properties of (p*R*)-$\mathbf{3}^+$ toward neutral substrates we performed a competitive binding study, in which a mixture of the borenium species (p*R*)-$\mathbf{3}^+$ and $B(C_6F_5)_3$ was treated with an equimolar amount of the neutral Lewis base Et_3PO. The complexes $Et_3PO\cdot$(p*R*)-$\mathbf{3}^+$ and $Et_3PO\cdot B(C_6F_5)_3$ are present in a ratio of 1 : 3.6 at room temperature, which shows that slightly more Et_3PO binds to $B(C_6F_5)_3$ than to (p*R*)-$\mathbf{3}^+$.† We conclude that (p*R*)-$\mathbf{3}^+$ has a higher affinity than $B(C_6F_5)_3$ towards anionic Lewis bases such as Cl^- and is only slightly less Lewis acidic than $B(C_6F_5)_3$ towards neutral Lewis bases such as Et_3PO. In short, (p*R*)-$\mathbf{3}^+$ proved to be a remarkably strong Lewis acid.

An application of Lewis acids in organic synthesis that has attracted considerable interest is the metal-free hydrosilylation of ketones. This process was first studied for $B(C_6F_5)_3$ by Parks and Piers.[31] Piers *et al.* demonstrated that activation of the Si–H functionality in silanes with $B(C_6F_5)_3$ plays a key role[4] and more recent studies by Mewald and Oestreich further support this notion.[32] However, the development of enantioselective versions of this process continues to be a challenge.[14]

We first examined the reactivity of (p*R*)-$\mathbf{3}^+$ toward ketones and silanes, respectively. When (p*R*)-$\mathbf{3}^+$ was mixed with 1 equiv. of $HSiEt_3$ in $CDCl_3$ at RT, the ^{1}H NMR spectra of both components were unchanged. However, at elevated temperatures a loss of *H*–Si–*CH*$_2$ coupling was clearly observed,† which is consistent with an R'_3Si–$H\cdots BR_3$ interaction according to studies by Koller and Bergman[33] on related Al-based systems. Treatment of compound (p*R*)-$\mathbf{3}^+$ with acetophenone resulted in a distinct color change from deep purple to orange-red due to adduct formation.[34] The complex (p*R*)-$\mathbf{3}^+$(acetophenone) can be readily isolated as a crystalline solid and its single crystal X-ray structure shows binding of the acetophenone from the *endo*-side of the ferrocene (B–O = 1.560(8) [1.577(8)] Å, Fig. 2b). When a sample of this complex was treated with an excess of $HSiEt_3$, the acetophenone was reduced and fully converted to the hydrosilylation product. The color of the solution changed back from orange-red to dark purple, and the ^{1}H NMR data were consistent with re-formation of the free borenium ion (p*R*)-$\mathbf{3}^+$. The fact that the lower basicity of the



Scheme 2 Hydrosilylation of ketones catalyzed by (p*R*)-3^+.

product resulted in release from the Lewis acid suggested that a catalytic process is feasible (Scheme 2). Indeed, with a 5% loading of the borenium species (p*R*)-3^+ as the catalyst 60% conversion of acetophenone was achieved over 12 h at RT. Hydrolysis to the corresponding alcohol and subsequent chiral GC-FID analysis revealed a 20% ee for the *R*(+) product in both the stoichiometric and catalytic process.[35]

In conclusion, halide abstraction from the Lewis acid–base pair (p*R*)-**2** was accomplished using the Ag or Li derivative of Krossing's salt, resulting in a novel planar-chiral borenium-type Lewis acid. The Lewis acid strength of chiral (p*R*)-3^+ proved to be comparable to that of $B(C_6F_5)_3$. While modest enantiomeric excess was achieved in the hydrosilylation of ketones with (p*R*)-3^+ as a catalyst, this study represents the first application of a planar-chiral borenium Lewis acid in the stereoselective reduction of ketones. Further modification of the steric demand of the pyridyl ligand and the exocyclic boron substituent is expected to allow for significantly enhanced selectivities, while the activity can likely be optimized through tuning of the electronic effect of the exocyclic B-aryl group.

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