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A free boratriptycene-type Lewis superacid

By exploiting the facile self-assembly of the pyrazabole scaffold, authors have devised a straightforward route to boratriptycene-type precursors that have two pyrazole bridges and one 1,1'-ferrocenylene linker between two bridgehead BH moieties. Single hydride abstraction generates ferrocene-stabilized borenium cations with an unprecedentedly large dip angle and exceptional Lewis acidity that can nevertheless be isolated in free form. Exceptional acidity of the prepared borenium salts stems from the structural strain imparted by the bridging rigid pyrazabole moieties, while weak Fe(3d)→B(2p) bonding prevents the planar borenium center from interaction with weakly-coordinated counterions.

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A free boratriptycene-type Lewis superacid†

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Bicyclic pyrazabole-bridged ferrocenes with BH groups at their bridgehead positions were prepared from [Li(thf)]₂[1,1'-fc(BH₃)₂] and pyrazole or 3,5-dimethylpyrazole in the presence of Me₃SiCl (**1** or **1Me**, respectively; 1,1'-fc = 1,1'-ferrocenylene); Me₃SiH and H₂ are released as byproducts. Treatment of **1** or **1Me** with 1 eq. of the hydride scavenger [Ph₃C][B(C₆F₅)₄] afforded the borenium salts [**2**][B(C₆F₅)₄] (72%) and [**2Me**][B(C₆F₅)₄] (77%). According to X-ray crystallography, [**2Me**]⁺ contains one trigonal-planar borenium cation, the cyclopentadienyl (Cp) rings of the 1,1'-fc fragment remain parallel to each other, but the Cp–B bond vector is bent out of the Cp plane by an unprecedentedly large dip angle α* of 40.6°. The Fe...B(sp²) distance is very short (2.365(4) Å) and the ¹¹B NMR signal of the cationic B(sp²) center is remarkably upfield shifted (23.4 ppm), suggesting a direct Fe(3d) → B(2p) donor–acceptor interaction. Although this interpretation is confirmed by quantum-chemical calculations, the coupling between the associated orbitals corresponds to an energy of only 12 kJ mol⁻¹. Accordingly, both the experimental (e.g., Gutmann–Beckett acceptor number AN = 111) and theoretical assessment (e.g., Et₃PO and F⁻-ion affinities) of the Lewis acidity proves that [**2**]⁺ is among the strongest boron-based Lewis acids available to date.

Introduction

The rise to prominence of boron-based Lewis acids began when their application potential as activators for metal-catalyzed homogeneous olefin polymerization was recognized.¹ The advent of the ‘Frustrated Lewis Pairs’ led to a further surge of interest, which has remained at a high level ever since.^{1,2} Among all the remarkable developments in the field, we focus here particularly on Lewis acidic organoboranes (‘Lewis superacids’).³

One way to increase the affinity of a triorganylborane (BR₃) for even weak Lewis bases is to introduce electronegative halogen substituents at the periphery.⁴ Classic examples include the compounds B(C₆F₅)₃ of Massey and Park⁵ or B(C₆Cl₅)₃ of Ashley and O’Hare.⁶ As an alternative, mesomerically electron-withdrawing substituents have also been employed.⁷ The affinity of a boron center (in particular) for anionic ligands can

also be increased by the Coulomb attraction of an adjacent positively charged group.⁸ Gabbai *et al.* took advantage of this effect when they used the phosphonium borane ([A]⁺; Fig. 1) to bind F⁻ ions in water despite their high hydration enthalpy.^{9,10} Our group combined a high fluorine load with the positive charge of a phosphonium center to create a Lewis acid [B]⁺, stronger than B(C₆F₅)₃ and suitable as a catalyst for Diels–Alder



Fig. 1 Organoboranes of particularly high Lewis acidity due to introduced positive charges and fluorine substituents ([A]⁺, [B]⁺, [C]⁺) or structurally enforced pyramidalization (D). Mes = 2,4,6-Me₃C₆H₂, Tf = O₂SCF₃.

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X-ray crystallography

Both precursor/borenium-ion pairs, **1**/[2][B(C₆F₅)₄] and **1Me**/[2Me][B(C₆F₅)₄], were studied by X-ray diffraction. Since the crystal lattice of [2][B(C₆F₅)₄] contains three crystallographically independent entities in the asymmetric unit, only the molecular structures of **1Me**/[2Me][B(C₆F₅)₄] are compared here (Fig. 2). We verified that all the conclusions drawn are also valid for the pair **1**/[2][B(C₆F₅)₄] (see the ESI[†]).

The 1,1'-ferrocenylene moieties in **1Me**/[2Me]⁺ adopt almost perfectly staggered conformations with torsion angles C_i – COG – COG' – C_i' close to zero (C_i = B-bonded C atom; COG = cyclopentadienyl-ring centroid). No significant differences are also observed between the B–C (av. 1.596 Å) or B–N (av. 1.567 Å) bond lengths in **1Me** and the B(2)–C (1.613(6) Å) or B(2)–N (av. 1.568 Å) bond lengths in [2Me]⁺. The configuration of the second B atom, however, changes fundamentally from tetrahedral to trigonal-planar upon going from **1Me** to [2Me]⁺ (sum of angles around B(1) = 359.7°). Accordingly, the B(1)–C (1.497(6) Å) and B(1)–N (av. 1.506 Å) bonds of [2Me]⁺ are contracted relative to the corresponding bonds at B(2). This contraction is about twice as pronounced for B(1)–C (Δ = 0.116 Å) as for B(1)–N (Δ = 0.062 Å). The B(1)–C bond of [2Me]⁺ is also considerably shorter than the exocyclic B–C bond between the orthogonally positioned planes in 9-Mes-9-borafluorene (1.562 Å), which we take as an archetypal B(sp²)–C(sp²) single bond.²⁸ The B(1)–N bonds of [2Me]⁺ are still longer than the average B–N bond in propeller-shaped B(pyrMe₂)₃ (1.443 Å; pyrMe₂ = 2,5-dimethylpyrrolyl), for which B=N π bonding is negligible.²⁹ The most important structural features of [2Me]⁺ are the pronounced dip angle α* = 40.6° and the short

Fe⋯B(sp²) contact of 2.365(4) Å (α* = 180° – α; α = COG–C_i–B(1)). Corresponding distortions have already been observed for other ferrocenylboranes, but the dip angles are much smaller even in the most extreme cases, *i.e.*, FcBBr₂: α* = 18.9°,^{20a} 9-Fc-9-borafluorene: α* = 25.5°,^{20d} FcBC₄Ph₄: α* = 29.4° (Fc = ferrocenyl).^{20f} The planarization of one bridgehead B atom does not result in a substantial tilting of the ferrocenylene unit: **1Me**/[2Me]⁺ show largely coplanar cyclopentadienyl rings with Cp//Cp' angles of 5.2(2)/5.4(2)°. The 'hinge-effect' of the 1,1'-fc bridge, which was assumed in the design of the molecular framework, obviously does not play a major role. Considerable differences are observed for the pyrazole moieties of **1Me** vs. [2Me]⁺: the gap between the two pyrazol-1-yl (pz) rings is significantly wider in **1Me** than in [2Me]⁺ (pz//pz' = 146.8(1)° vs. 118.7(2)°) and the dihedral angle between the best plane through the four N atoms and the B(2)-bonded Cp ring amounts to a value of 88.3° in **1Me**, but only to 71.6° in [2Me]⁺.

NMR spectroscopy

NMR spectra were recorded in CDCl₃ or CD₂Cl₂. The changes in the ¹H, ¹¹B, and ¹³C{¹H} NMR spectra upon going from **1** to [2]⁺ or **1Me** to [2Me]⁺ are very similar and will be discussed here exemplarily for the **1Me**/[2Me]⁺ pair.

The ¹¹B NMR spectrum of the precursor molecule **1Me** shows a resonance in the typical region of tetracoordinated boron nuclei (–7.6 ppm).³⁰ After H[–] abstraction, the spectral parameters of the residual BH moiety of [2Me]⁺ remain largely the same, whereas the newly generated cationic B center gives rise to a signal at 23.4 ppm. Its chemical shift is highly unusual for tricoordinated B sites, which should be much less shielded.³⁰ Since the formation of adduct equilibria with the weakly coordinating solvent molecules CD₂Cl₂ is unlikely (as also supported by our DFT simulations), we attribute the peculiar NMR feature either to a true Fe⋯B bonding interaction or to a magnetic anisotropy effect of the Fe d-electrons in close proximity to the B cation. We note in this context that upfield shifts of the ¹¹B resonances have also been observed for FcBBr₂ vs. PhBBr₂ (46.7 vs. 56.6 ppm),³¹ 9-Fc-9-borafluorene vs. 9-Ph-9-borafluorene (53.0 vs. 64.5 ppm),^{20d} and FcBC₄Ph₄ vs. PhBC₄Ph₄ (47.4 vs. 65.4 ppm);^{20f} along this series, the shift difference increases as the dip angle α* increases.

H[–] ion abstraction leads to a symmetry breaking that renders the two Cp rings of [2Me]⁺ chemically inequivalent. The assignment of resonances to Cp'–B⁺ or Cp–B(H) was achieved by means of a NOESY spectrum (*cf.* Scheme 1 for the atom labeling): an intense cross peak was observed between a pzCH₃ signal at δ(¹H) = 2.56 and a CpH resonance at δ(¹H) = 4.11 ppm; a second, significantly weaker, cross peak was detected between the second pzCH₃ signal (2.48 ppm) and a CpH resonance at 3.31 ppm (pz = pyrazol-1-yl). Through-space interactions of two nuclear spins that are in closer proximity to each other tend to result in a more pronounced NOE. Since we know from the solid-state structure of [2Me][B(C₆F₅)₄] that the average distance between CpH-2' and pzCH₃-3' is 2.94 Å and thus approximately 30% shorter than the distance between CpH-2 and pzCH₃-3 (4.19 Å), we assign the proton signals at 4.11/3.31 ppm to



parameter	1Me	[2Me][B(C ₆ F ₅) ₄]
B(1)–C [Å]	1.593(3)	1.497(6)
B(2)–C [Å]	1.598(3)	1.613(6)
B(1)–N [Å]	1.565(2)	1.505(5)
	1.568(2)	1.506(5)
B(2)–N [Å]	1.562(2)	1.566(6)
	1.570(2)	1.569(6)
Fe⋯B(1) [Å]	3.241(2)	2.365(4)
α* [°]	1.6	40.6

Fig. 2 Molecular structures of **1Me** (left) and [2Me][B(C₆F₅)₄] (right) in the solid state. C-bonded H atoms and the [B(C₆F₅)₄][–] anion are omitted for clarity. Selected structural parameters are compiled in the table.



CpH-2'/CpH-2 and those at 2.56/2.48 to pzCH₃-3'/pzCH₃-3. The proton and carbon nuclei in the Cp' ring of [2Me]⁺ are considerably deshielded relative to those of 1Me due to the electron-withdrawing effect of the attached borenium cation ($\Delta\delta$: CpH-3' = 1.40, CpH-2' = 0.78 ppm; CpC-3' = 15.5, CpC-2' = 9.3 ppm). A qualitatively similar, albeit less marked, effect is also visible for the Cp ring of [2Me]⁺ vs. 1Me. Also all ¹H and ¹³C NMR resonances of the pyrazolyl rings of [2Me]⁺ experience downfield shifts compared to the corresponding signals of 1Me.

Dynamic hydride-exchange equilibrium between 1 and [2]⁺

On one occasion, in the attempt to synthesize the borenium-cation salt [2][B(C₆F₅)₄], we inadvertently added only about 0.8 eq. of [Ph₃C][B(C₆F₅)₄] to 1 (NMR-scale experiment; CD₂Cl₂). A subsequent ¹H NMR spectroscopic investigation of the sample revealed well-resolved resonances of the byproduct Ph₃CH, but extremely broad signals of the ferrocene-containing species. We attributed this effect to a dynamic exchange equilibrium of hydride ions between tetracoordinated BH and tricoordinated B⁺ sites. To test this assumption, we intentionally prepared a mixture of 1 (1.0 eq.) and [Ph₃C][B(C₆F₅)₄] (0.9 eq.) in CD₂Cl₂ and were able to reproduce the previous observation. After addition of [nBu₄N][BH₄] (1.0 eq. of the [BH₄]⁻ ion) to the sample, sharp proton resonances of 1 reappeared. The hydride abstraction/addition sequence was accompanied by only little decomposition (mainly producing ferrocene), and the proton-integral ratios of the re-generated 1 and Ph₃CH conformed to an almost equimolar distribution (see the ESI[†] for plots of the spectra). In a second experiment, we prepared a 1 : 1 mixture of 1 and [2][B(C₆F₅)₄] (CD₂Cl₂); the observed ¹H and ¹¹B NMR resonances were broadened almost beyond detection (except for the [B(C₆F₅)₄]⁻ anion signal). Upon cooling from room temperature to 243 K, the resonances became slightly sharper and the number of distinguishable signals increased as the exchange equilibrium was slowed down. We finally repeated the latter experiment with the 3,5-dimethylpyrazolyl derivatives 1Me and [2Me][B(C₆F₅)₄]. Here, the line-broadening was much less pronounced and we were still able to identify all proton resonances of the two species in the NMR spectrum of the mixture. This result clearly shows that the introduced methyl groups provide considerable steric shielding of the boron centers, further confirming our hypothesis of a 'hydride jump' as the origin of the line-broadening effect.

Electronic structures of [2]⁺/[2Me]⁺ and quantum-chemical calculations

Our experimental results consistently point toward the existence of a donor-acceptor Fe(3d) → B(2p) interaction in the borenium ions [2]⁺/[2Me]⁺, similar to the Fe → Si⁺ interaction in ferrocene-stabilized silylium ions.³² Comparable interactions have been also found for complexes of so-called Z-type ligands, in which Lewis-basic metal atoms donate charge density to Lewis-acidic boron sites located in the ligand backbones.³³ Closely related examples to our system are certain metallaboratranes, *i.e.*, complexes containing κ⁴-tris(2-mercaptoimidazolyl)borane ligands that interact with the coordinated metal atom *via* three dative S → M σ bonds and one retrodative M → B σ bond.³⁴

The experimentally determined very short Fe...B⁺ contacts in [2]⁺ and [2Me]⁺ (Fig. 2) are well reproduced at the DFT level (PBE-D3(BJ)/def2-TZVPP), which provides optimized Fe...B⁺ distances of 2.34 Å and 2.38 Å for [2]⁺ and [2Me]⁺, respectively; these values are practically unaffected by considering/neglecting corrections for dispersion forces. It was also theoretically confirmed that the dip angles α* are the largest among all ferrocene-stabilized boranes or borenium ions and that they are comparable to the corresponding dip angles in [Fc-SiR₂]⁺ cations³² (α* = 41.9° for [2]⁺ and 40.0° for [2Me]⁺; Table S4[†]). Moreover, we found an excellent agreement between the computed and experimental ¹¹B NMR chemical shift values (Table S5 and Fig. S66[†]), demonstrating that the optimized/solid-state structures prevail in solution (elongated Fe...B⁺ distances would result in downfield-shifted ¹¹B(sp²) resonances).

The question now arises, to what extent the short Fe...B⁺ contacts in [2]⁺ and [2Me]⁺ can be attributed to a 'through-space' Fe(3d) → B(2p) donor-acceptor interaction. Structural strain imparted by the bridging rigid pyrazole moieties and the avoidance of a pyramidalized tricoordinated B(sp²) center probably also play a role. According to an NBO second-order perturbation energy analysis, the stabilization energy E⁽²⁾ for the coupling between the occupied 'lone-pair' orbital on Fe and the vacant B(2p) orbital corresponds to only 12 kJ mol⁻¹, which is about eight times less than the stabilization energy found for the Fe → Si⁺ interaction in [Fc-SiR₂]⁺ ions.³² The relative weakness of the Fe(3d) → B(2p) interaction in [2]⁺/[2Me]⁺ is further indicated by the following facts: (i) the B(sp²) center is trigonal planar rather than inwardly pyramidalized. (ii) An optimization of the model system Fc-BpZ₂, formally obtained from [2]⁺ by removing the B(sp³)H tether to the second Cp ring, leads to a notably longer Fe...B contact of 2.70 Å, even after protonation of the pyrazole moieties or N,N'-chelation of a [BH₂]⁺ fragment to introduce the overall positive charge (Fig. S63[†]). The impact of structural strain on the Fe...B⁺ distance is also evident from a comparison of the energies of [2]⁺ in its optimized geometry and in a hypothetical geometry with outwardly pyramidalized borenium center and diminished Fe(3d) → B(2p) interaction ([2^{pyram}]⁺; the structure was obtained from that of 1 by hydride abstraction while keeping the dihedral angle θ(N-B-N-C_i) fixed during the optimization; Fig. S64[†]). Relative to [2]⁺, [2^{pyram}]⁺ is energetically disfavored by 117 kJ mol⁻¹, which is much more than the stabilization energy of the Fe(3d) → B(2p) interaction. Mayer bond orders (MBO = 0.43 for [2]⁺, 0.40 for [2Me]⁺) and QTAIM delocalization indices (DI = 0.21 for [2]⁺, 0.18 for [2Me]⁺) suggest a small covalency for the 'through-space' Fe(3d) → B(2p) interaction in [2]⁺ and [2Me]⁺, where these parameters are about twice as large as those found for previously reported Fc-B analogues (Table S4[†]). The partial covalency of the Fe(3d) → B(2p) interaction in [2]⁺ and [2Me]⁺ is also seen in ELI-D and NLMO analyses (Fig. 3), both revealing a three-center two-electron (3c2e) bond between the Fe(II) center, the B(sp²) cation, and the attached C_i atom of the Cp ring. In the simplified Lewis structure notation, the 3c2e bond in [2]⁺ and [2Me]⁺ results from a sharing of the respective Fe-C_i electron bonding pair, which has a large Fe(3d) character,



with the vacant B(2p) orbital. The 3c2e bond thus can be viewed as a donor–acceptor interaction (see Fig. 3b for the composition of corresponding NLMO orbitals). In contrast, the corresponding 3c2e bond in structurally related $[\text{Fc-SiR}_2]^+$ ions is formed with the C_i atom of the other Cp ring. This difference might be attributed to the larger covalent/ionic radii of tricoordinated Si⁺ compared to tricoordinated B⁺ ions.

The metal \rightarrow B interaction found for $[2]^+$ is computed to become significantly stronger when the Fe(II) center in the metallocene scaffold is replaced by heavier Ru(II) or Os(II) ions with more diffuse 4d or 5d valence orbitals, respectively. This is concluded mainly from the shorter $M\cdots B^+$ contacts ($M = \text{Ru}, \text{Os}$) despite the larger ionic radii of these M(II) centers, and also from the larger $M\cdots B^+$ covalency revealed by the larger QTAIM delocalization indices and Mayer bond orders (Table S4†).

Despite the existing Fe(3d) \rightarrow B(2p) interaction and a hence conceivable charge transfer leading to the generation of Fe(III)/B[•] radical pairs, the electronic ground states of $[2]^+$ and $[2\text{Me}]^+$ remain diamagnetic with Fe(II) and B⁺ centers, which is confirmed by computed and experimental NMR shifts as well as ⁵⁷Fe Mössbauer spectral parameters (Fig. S51, S52 and Tables S1, S6†). The electron-spin density in the lowest-lying triplet state of $[2]^+$ (147 kJ mol⁻¹ above the singlet ground state) resides almost exclusively on the Fe(II) center, with just small positive/negative fractions at the C atoms of both Cp rings (Fig. S65†). The same holds for higher-lying triplet excited states and thus,



Fig. 3 (a) Electron localizability indicator (ELI-D) analysis of bonding in $[2]^+$. The selected plane includes the Fe and two B atoms. The gray-white regions represent ELF maxima (bonding attractors), showing a donor–acceptor Fe \cdots B interaction. (b) Natural localized molecular orbital (NLMO) corresponding to a 3c2e bond between Fe(II), B(sp²), and the adjacent C_i atom in $[2]^+$ (isosurface plot: ± 0.05 au). NLMO composition is as follows: 51% Fe (99% d), 15% B (10% s, 90% p), 26% C (99% p). A similar NLMO picture was obtained for $[2\text{Me}]^+$ with the following composition: 50% Fe (99% d), 14% B (10% s, 90% p), 28% C (99% p).

even upon singlet-triplet excitation, the Fe(3d) \rightarrow B(2p) interaction would not be expected to promote the formation of an Fe(III)/B[•] radical pair. A qualitatively similar picture, but with notably larger energy gap between singlet and triplet states, is obtained for the ruthenocene analogue of $[2]^+$ ($\Delta E = 280$ kJ mol⁻¹). In striking contrast, the osmocene congener (which is also predicted to feature a singlet ground state with Os(II) and B⁺ centers) is computed to display a distinct Os(III)/B[•] character in its relaxed triplet excited state ($\Delta E = 238$ kJ mol⁻¹).

Finally, we propose that the Fe(3d) \rightarrow B(2p) interaction in $[2]^+/[2\text{Me}]^+$, while not significantly reducing the Lewis acidity of the ferrocenyl borenium ions (see below), may nevertheless provide the very extra stability needed to isolate the free Lewis acids (compare the case of the $[\text{D-NTf}_2]^- \leftrightarrow \text{D} + [\text{NTf}_2]^-$ equilibrium shown in Fig. 1).

Assessment of the Lewis acidity of the borenium cation $[2]^+$ by the Gutmann–Beckett NMR method, competition experiments with $\text{B}(\text{C}_6\text{F}_5)_3$ and computational studies

The sterically less encumbered borenium-ion derivative $[2]^+$ was selected for a comparative assessment of Lewis acidities. We first determined the acceptor number (AN) of $[2]^+$ on the scale developed by Gutmann and Beckett.³⁵ To this end, mixtures of $[2][\text{B}(\text{C}_6\text{F}_5)_4]$ and Et_3PO were prepared in CD_2Cl_2 and $^{31}\text{P}\{^1\text{H}\}$ NMR spectra were recorded (see the ESI† for full details). We consistently observed a resonance at $\delta(^{31}\text{P}) = 91.0$ ppm for the adduct $[2\cdot\text{OPEt}_3][\text{B}(\text{C}_6\text{F}_5)_4]$. The signal is shifted to lower field by 40.7 ppm and 50.0 ppm, compared to the resonance of pure Et_3PO in CD_2Cl_2 (50.3 ppm) or *n*-hexane (41.0 ppm), respectively. From these data, an acceptor number $\text{AN}([2]^+) = 111$ was calculated, which is significantly higher than the acceptor number of $\text{B}(\text{C}_6\text{F}_5)_3$ ($\text{AN} = 77\text{--}82$; CD_2Cl_2), higher than the acceptor numbers of so far reported Fc-borenium ions (*cf.* Table S7 in ESI†), and close to that of neat BBR_3 ($\text{AN} = 109$) or BI_3 ($\text{AN} = 115$).³⁶

The pyridine adduct $[2\cdot\text{py}][\text{B}(\text{C}_6\text{F}_5)_4]$ was synthesized on a preparative scale and characterized by NMR-spectroscopy and X-ray crystallography (Scheme 2). Five ¹H and five ¹³C resonances are observed for the pyridine ligand in the corresponding room-temperature NMR spectra, demonstrating a sterically restricted rotation about the B–N(py) bond on the NMR time scale (CD_2Cl_2). The *p*-CH group of the coordinated pyridine molecule should be least affected by magnetic anisotropy effects originating from the surrounding π -electron clouds. Its continuous deshielding upon going from free pyridine ($\delta(^1\text{H})/\delta(^{13}\text{C}) = 7.67/136.1$ ppm)^{11b} to $\text{B}(\text{C}_6\text{F}_5)_3\cdot\text{py}$ (8.21/143.2 ppm)^{11b} and $[2\cdot\text{py}][\text{B}(\text{C}_6\text{F}_5)_4]$ (8.56/147.8 ppm) therefore indicates increasing charge polarization induced by increasingly strong N–B donor–acceptor binding (*cf.* $[\text{Hpy}]\text{Cl}$: 8.51/146.1 ppm (ref. 11b)). Consistent with this, the N(py)–B bond in $[2\cdot\text{py}][\text{B}(\text{C}_6\text{F}_5)_4]$ (1.603(3) Å) is shorter than that in $\text{B}(\text{C}_6\text{F}_5)_3\cdot\text{py}$ (1.614(2) Å,³⁷ 1.628(2) Å (ref. 38)), but identical to the N–B bond in the adducts $[\text{B}\cdot\text{py}][\text{O}_3\text{SCF}_3]$ (1.599(4) Å (ref. 11b)) and $\text{B}(\text{C}_6\text{F}_5)_3\cdot\text{DMAP}$, which contains the stronger donor *p*-dimethylaminopyridine (1.602(6) Å (ref. 39)).

We also performed competition experiments using the combinations $[2\cdot\text{Do}][\text{B}(\text{C}_6\text{F}_5)_4]/\text{B}(\text{C}_6\text{F}_5)_3$ and $[2][\text{B}(\text{C}_6\text{F}_5)_4]/\text{B}(\text{C}_6\text{F}_5)_3\cdot\text{Do}$





Fig. 4 Top: experimentally determined UV/vis absorption spectrum of $[2][\text{B}(\text{C}_6\text{F}_5)_4]$ in CH_2Cl_2 . Bottom: computed key molecular orbitals of $[2]^+$ and lowest energy electronic transitions (TD-DFT PBE0-10HF/def2-TZVP/ CH_2Cl_2).

Conclusions

By exploiting the facile self-assembly of the pyrazabole scaffold, we have devised a straightforward route to boratriptycene-type precursors that have two pyrazole bridges and one 1,1'-ferrocenylene linker between two bridgehead BH moieties (**1**, **1Me**). H^- abstraction with the $[\text{Ph}_3\text{C}]^+$ cation generates bridgehead borenium cations of exceptional Lewis acidity that can nevertheless be isolated in free form ($[2][\text{B}(\text{C}_6\text{F}_5)_4]$, $[2\text{Me}][\text{B}(\text{C}_6\text{F}_5)_4]$). A weak Fe-B(sp^2) through-space interaction likely assists in stabilizing the systems without appreciably diminishing their electron-pair affinities. Although the borenium centers of $[2]^+$ and $[2\text{Me}]^+$ adopt trigonal-planar configurations (X-ray crystallography, DFT calculations), huge dips of the B atoms with respect to their attached Cp rings indicate pretensioned 'entatic' states of the molecules,⁴⁶ which should significantly promote Lewis acid-base pairing. Since a plethora of pyrazole derivatives are available, the degree of steric protection of the electrophilic borenium center can be varied easily (cf. $[2]^+$ with pyrazole bridges vs. $[2\text{Me}]^+$ with bulky 3,5-dimethylpyrazole

bridges). By using chiral substituents in the 3,5-positions of the pyrazole rings, even chiral Lewis acids should be within reach. As an outlook, we note that an exchange of Fe for Os would lead to a related Lewis acid that is computed to exhibit a distinct $\text{Os}(\text{III})/\text{B}^+$ character in its relaxed triplet excited state and thus could open new avenues for exploring the evolving chemistry of *in situ*-generated boron radicals.⁴⁷

Data availability

Experimental and computational data associated with this article have been provided in the ESI.†

Author contributions

M. H. synthesized and characterized all compounds. J. N. and P. H. performed all quantum-chemical calculations. A. O. and V. S. recorded and interpreted the Mössbauer spectra. M. B. performed the X-ray crystal structure analyses. H.-W. L. and M. W. supervised the project. The manuscript was written by M. W. and P. H. and edited by all the co-authors.

Conflicts of interest

There are no conflicts of interest to declare.

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