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COMMUNICATION

Using the FpXylBH$_2$ SMe$_2$ Reagent for the Regioselective Synthesis of Cyclic Bis(alkenyl)boranes

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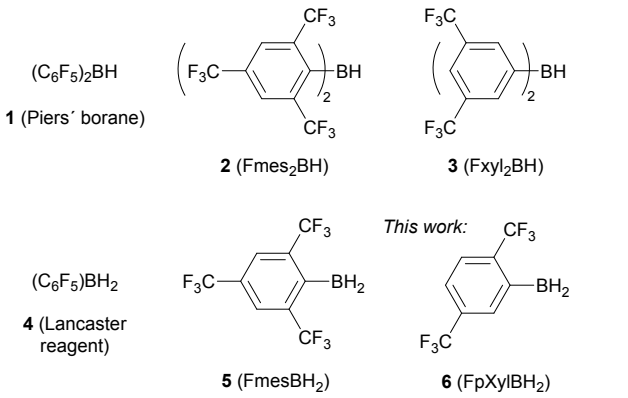
Karel Škoch,[a] Constantin G. Daniliuc,[a] Gerald Kehr[a] and Gerhard Erker*[a]

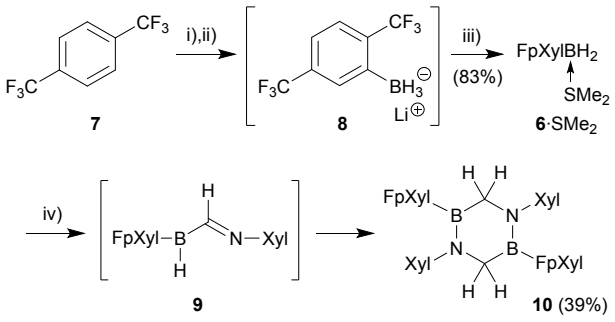
The reactive borane reagent FpXyl-BH$_2$·SMe$_2$ was prepared from 1,4-bis(trifluoromethyl)benzene by treatment with *n*-BuLi, followed by H$_3$B·SMe$_2$ and subsequent removal of hydride. It undergoes a regioseletive hydroboration reaction with 1,2-bis(trimethylsilylethynyl)benzene to give the "dimeric" product 13a featuring a conjugated 14-membered core heterocyclic structure that contains a pair of FpXylB units.

Fluoroarene containing BH boranes are reactive and useful reagents. A prominent example is Piers´ borane [(C$_6$F$_5$)$_2$BH] **1**[1] that has found many interesting synthetic applications, among them the convenient preparations of intramolecular P/B Lewis pairs by respective hydroboration routes.[2] Similar, but less frequently encountered are the corresponding Fmes$_2$BH (**2**)[3] and FXyl$_2$BH (**3**)[4] analogues (Scheme 1). Lancaster´s reagent (C$_6$F$_5$)BH$_2$·SMe$_2$ (**4**·SMe$_2$)[5] is known for some years. (Fxyl)BH$_2$ was mentioned in the literature.[4] Recently, the related FmesBH$_2$ borane was reported, either as dimethyl-sulfide stabilized adduct **5**·SMe$_2$ or the doubly H-bridged donor-free dimer (**5**)$_2$.[6] The aryl boranes **4** and **5** were used in the synthesis of various active FLPs and related systems. FmesBH$_2$ was recently employed as a reagent in multi-component syntheses of rare dihydro-1,3-azaborinine compounds.[7] We have now developed a convenient synthesis of a new member in this series,[8] namely the BH$_2$-borane FpXylBH$_2$ (**6**) and found that it undergoes a series of clean sequential two-fold hydroboration reactions with some bis-alkynyl substrates that led to unusually structured cyclic borane products.

The precursor 1,4-bis(trifluoromethyl)benzene (**7**) was mono-lithiated by treatment with *n*-BuLi. Subsequent addition of H$_3$B·SMe$_2$ was thought to generate the respective borate intermediate **8** *in situ* (Scheme 2). Its treatment with trimethylsilylchloride in the presence of dimethylsulfide in this one pot reaction resulted in the formation of the FpXylBH$_2$·SMe$_2$ adduct (**6**·SMe$_2$) that was isolated as a pale-yellow oil.[9] It shows a pair of ^{19}F NMR resonances (in CD$_2$Cl$_2$) of the inequivalent CF$_3$ groups. There is a broad ca 1:1:1:1 q ^{1}H NMR resonance due to the BH$_2$ moiety with a corresponding ^{11}B NMR feature at δ -9.8 (t, $^1J_{BH}$ ~ 110 Hz). Vacuum sublimation of **6**·SMe$_2$ (80°C) followed by crystallization from CH$_2$Cl$_2$ layered with pentane gave crystals of the SMe$_2$ free FpXylBH$_2$ dimer (Fig. 1). It shows a doubly H-bridged four membered B$_2$H$_2$ core. Each boron atom bears a bulky FpXyl arene substituent, oriented trans to each other in the C$_i$-symmetric molecular arrangement.



Scheme 1 Some fluoroarene BH$_n$ boranes.



Scheme 2 Synthesis of the FpXylBH$_2$ reagent and its reaction with an isonitrile. [i) *n*-BuLi, ii) H$_3$B·SMe$_2$, iii) Me$_3$SiCl, SMe$_2$, iv) XylNC, 80°C].

[a] Organisch-Chemisches Institut, Westfälische Wilhelms-Universität Münster, Corrensstraße 40, 48149; Münster, Germany

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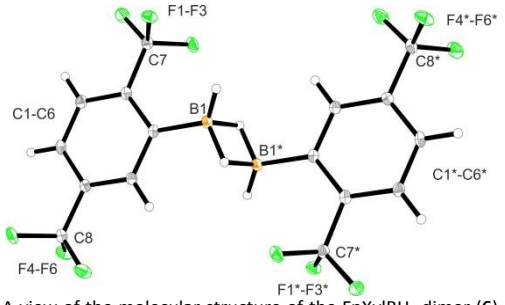


Figure 1 A view of the molecular structure of the $FpXylBH_2$ dimer $(\mathbf{6})_2$ obtained from thermolysis of $\mathbf{6}\cdot SMe_2$ (thermal ellipsoids at 30 % probability).

Compound $\mathbf{6}\cdot SMe_2$ is an active reducing reagent. It slowly reacted with 2,6-dimethylphenyl isocyanide (Xyl-NC, 80°C, heptane, 15h) to give the dimeric [B]-CH_2-[N] containing product **10** that we isolated crystalline at -20°C. Compound **10** is a rare example of this class of compounds.[10] The X-ray crystal structure analysis revealed a dimeric structure with a planar $B_2C_2N_2$ core (B1-N1 1.385(3) Å). Both the boron and the nitrogen atoms show planar tricoordinate geometries. The planes of the N-Xyl substituents are oriented perpendicular to the central core (Fig. 2). In solution we observed decoalescence of some ^1H and ^{19}F NMR signals at low temperature (233 K) that indicated the presence of ca 1:1 mixture of two conformational isomers, probably caused by "freezing" of the B-FpXyl rotation. Both these assumed *syn*- and *anti*-isomers show ^1H NMR AB quartets of their pairs of symmetry-equivalent core CH_2 groups at 253 K (see the ESI for details).

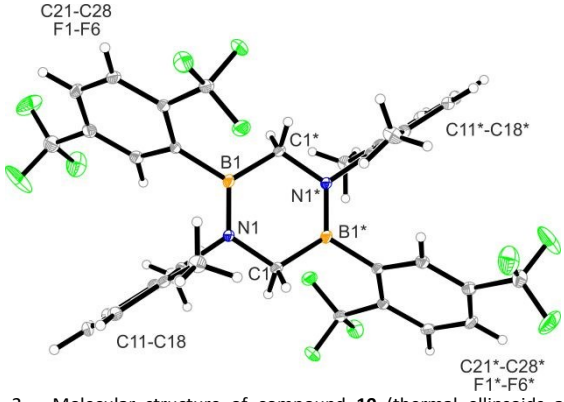
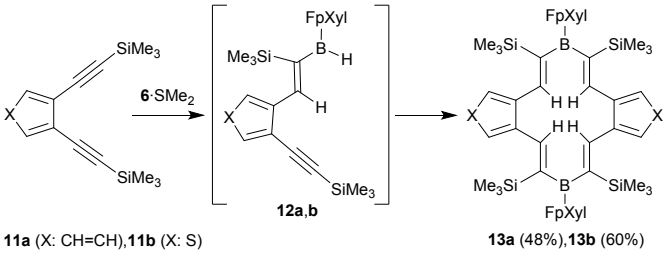


Figure 2 Molecular structure of compound **10** (thermal ellipsoids at 30% probability).

We assume a reaction pathway of the formation of compound **10** that is initiated by formation of a borylated aldimine intermediate **9**[11] that is then subsequently undergoing intermolecular B-H attack to form the final "dimeric" product.

$FpXylBH_2$ is an active hydroboration reagent. It was reacted with 1,2-bis(trimethylsilylethynyl)benzene (**11a**) in a 1:1 molar ratio.[12] The reaction went to completion within 60 min at r.t. in CH_2Cl_2 and we isolated the product **13a** as a solid in 48% yield. We assume a pathway of the formation of compound **13a** as depicted in Scheme 3. Regioselective cis-hydroboration of the trimethylsilylacetylene unit of **11a** would generate the intermediate **12a**. Subsequent intramolecular hydroboration is geometrically precluded, so intermolecular hydroboration with a second equiv. of **12a** (or an analogous unsymmetrical reagent combination) then provides an attractive pathway to the observed macrocyclic product **13a**.



Scheme 3 Formation of macrocyclic products from the reaction of the $FpXylBH_2\cdot SMe_2$ reagent with *vic*-bis-alkynes.

The X-ray crystal structure analysis showed that a 14-membered ring system had been formed. It features twelve sp^2-hybridized carbon atoms with a pair of Lewis acidic planar tri-coordinate boron atoms incorporated. The system is conjugated but not co-planar. It shows a twisted core structure with approximate (but not crystallographically exact) C_2-symmetry. We note that the marked distortion from planarity lets the "inner" olefinic hydrogen atoms become pairwise oriented above and below the mean core plane. The distal pairs of $SiMe_3$ groups become similarly arranged towards positions above and below the twisted ring structure (Fig. 3).

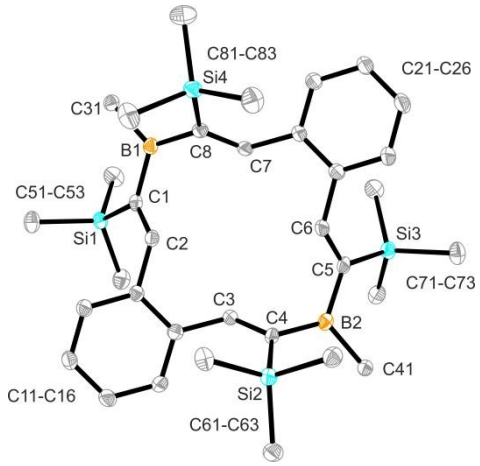


Figure 3 A projection of the molecular structure of the macrocyclic bis-acetylene hydroboration product **13a** (thermal ellipsoids at 30 % probability; for clarity the hydrogen atoms are omitted and only the ipso-carbon atom of the FpXyl substituent at boron is shown).

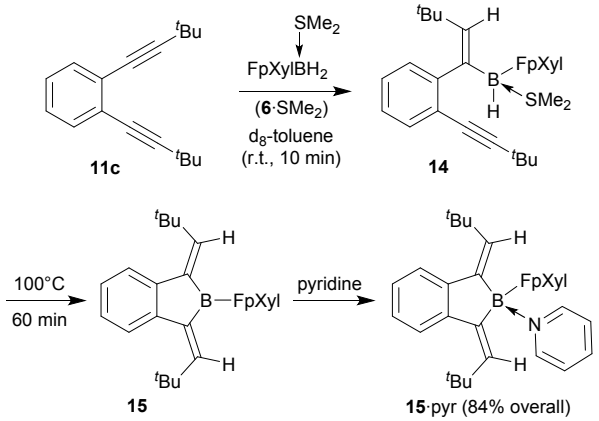
Compound **13a** shows temperature dependent dynamic NMR spectra in solution. At low temperature (233 K, CD_2Cl_2) the olefinic ^1H NMR CH resonance splits into two equal intensity singlets and we observed a similar behaviour for the $SiMe_3$ ^1H NMR signal. This spectroscopic behaviour probably indicates "freezing" of the topomerization process of the 14-membered ring system on the NMR time scale. The ^{11}B NMR signal of compound **13a** occurs at δ 71.2.

The reaction of $FpXyl\text{-}BH_2\cdot SMe_2$ with 3,4-bis(trimethylsilylethynyl)thiophene (**11b**) proceeds analogously. Workup after a reaction time of 60 min at r.t. in dichloromethane involving crystallization at -35°C gave the doubly thiophene-annulated

14-membered macrocyclic product **13b**. It was characterized by X-ray diffraction (see the ESI for details). The NMR spectra in CD_2Cl_2 solution also showed dynamic behaviour. The broad olefinic =CH ^{1}H NMR resonance, averaged at 299K, splits into an equal intensity pair of singlets (δ 8.11 and 7.23). Similarly, we observed a single ^{1}H NMR $SiMe_3$ resonance of compound **13b** at 299K in CD_2Cl_2 at δ -0.21, which slightly shifted upon lowering the measuring temperature and decoalesced to a pair of singlets at δ -0.23 and δ -0.45.

We also examined the reaction of **11a** with the Lancaster reagent **4** and with the $FmesBH_2$ borane **5**. The former reaction gave the macrocycle **13c** (containing a pair of B-C_6F_5 groups); its B-OH hydrolysis product was characterized by X-ray diffraction. The latter reaction stopped at the mono-hydroboration stage; its hydrolysis product was also characterized by an X-ray crystal structure analysis (see the ESI for details).

The favoured reaction course in the $FpXylBH_2$ alkyne hydroboration system is strongly substituent dependent. The reaction of the doubly tert-butyl substituted bis-alkyne **11c** with one molar equivalent of borane **6**·SMe_2 initially (r.t., 10 min) gave a compound which we tentatively assigned the composition of the SMe_2 adduct of the mono-hydroboration product **14** (Scheme 4). Its ^{1}H NMR spectrum shows a pair of tert-butyl singlets, an ABCD like pattern of signals of the phenylene moiety, the typical resonances of the FpXyl substituent and a single =CH-signal (at δ 5.72). The ^{11}B NMR resonance of compound **14** was located at δ 3.4 and there is a broad ^{1}H NMR resonance of the BH unit at δ 3.45.



Scheme 4 Formation of the cycle borane **15** and its pyridine adduct.

Heating the sample (100 °C, 60 min) resulted to a complete conversion to the cyclized product **15**. It was in situ generated and characterized by NMR spectroscopy. It shows a single ^{1}H NMR tert-butyl resonance, a AA´BB´ pattern of four phenylene hydrogen signals and a singlet of rel. intensity two at δ 6.42 of the pair of symmetry-equivalent =CH- moieties. Compound **15** shows a ^{11}B NMR resonance of the Lewis acidic tri-coordinated boron atom at δ 68.7.

We did not isolate compounds **14** or **15**, but trapped **15** by treatment with pyridine on a preparative scale. The pyridine adduct **15**·pyr was isolated in 84% yield. The X-ray crystal structure analysis (Fig. 4) shows the benzo-borole derived framework with a pair of =CH^{t}Bu groups symmetrically arranged at the five-membered heterocyclic substructure.

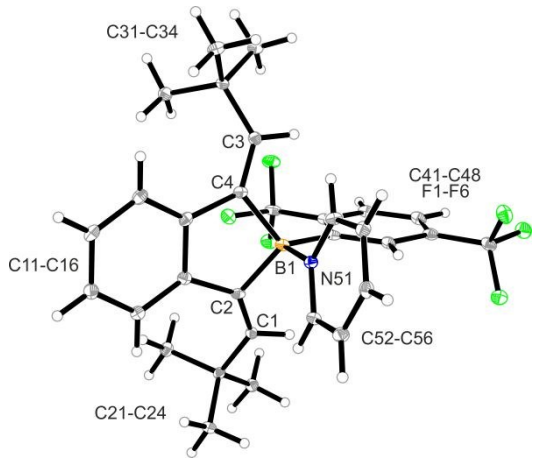
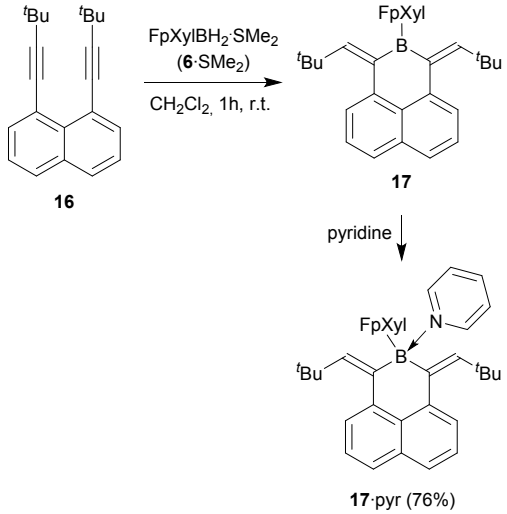


Figure 4 Molecular structure of compound **15**·pyr (thermal ellipsoids at 15 % probability).

The 1:1 reaction of 1,8-bis(tert-butylethynyl)naphthalene (**16**) with the $FpXylBH_2$ reagent **6**·SMe_2 took a similar course. In an NMR experiment (CD_2Cl_2, 60 min, r.t.) we observed the formation of the cyclization product **17**. It showed single sets of NMR signals of the symmetry equivalent halves. The ^{11}B NMR resonance at δ 60.2 indicated the presence of a Lewis acidic tri-coordinate boron atom.

We trapped the cyclization product directly by adding pyridine and isolated compound **17**·pyr as a solid in 76% yield. The X-ray crystal structure analysis (Fig. 5) showed that the hydroboration had again brought the hydrogen atom to the alkynyl β-carbon atoms, that had the tert-butyl groups attached. This resulted in the formation of the planar 1,8-annulated boron-containing six-membered ring in compound **17**·pyr.



Scheme 5 Formation of compound **17**·pyr by the hydroboration route.

In solution (CD_2Cl_2, 299 K) compound **17**·pyr showed a single ^{1}H NMR singlet of the pair symmetry-equivalent tert-butyl substituents (rel. intensity 18) as well as a broad singlet of the adjacent pair of =CH-hydrogen atoms (rel. intensity 2). The

naphthalene nucleus shows a single ABM pattern of the arene CH´s (rel. intensity 6). The ^{11}B NMR signal of compound **17**·pyr was located at δ 2.7.

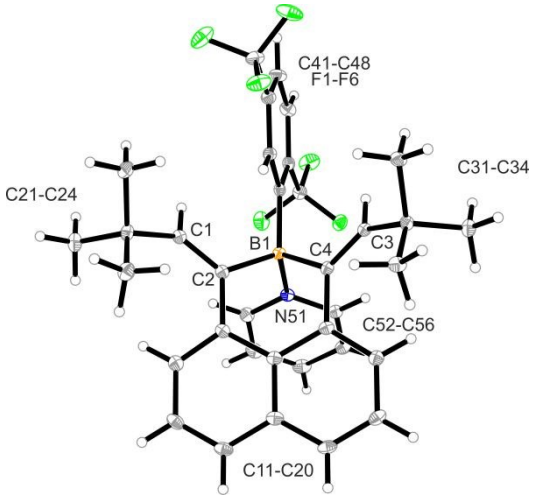


Figure 5 Molecular structure of compound **17**·pyr (thermal ellipsoids at 15 % probability).

We adopted the methodology outlined by Repo, Wagner and others[4,9] for the preparation of the new borane FpXylBH$_2$ that contains the readily available 2,5-bis(trifluoromethyl)phenyl substituent. The reagent was usually generated as the stabilized dimethylsulfide adduct **6**·SMe$_2$. The compound turned out to be a reactive hydroboration reagent. The acetylene hydroboration reactions investigated in this study showed a remarkable dependency on the variation of the bulky substituents at the alkynes. The SiMe$_3$ group in the substrates **11a** and **11b** apparently supported an "anti-Markovnikov" like regioselective cis-1,2-BH addition reaction[13] that resulted in the hydride addition to the α-position to the arene and, consequently, brought the B(H)FpXyl function to the β-carbon. This arrangement geometrically precluded a use of the remaining BH functionality for internal attack on the remaining acetylene and directed the system into an intermolecular pathway toward the formation of the unique fully conjugated 14-membered macrocyclic π-products **13**.

The hydroboration reactions of the FpXylBH$_2$ reagent with the closely related tert-butylethynyl substituted substrates proceeded with the opposite regioselectivity. We assume that steric hinderance here was a sufficient force to overcome any weak electronic preference and, consequently, the -B(H)FpXyl functionality ended up at the α-carbon atom. This enabled the system for an efficient subsequent internal hydroboration reaction with the pendant alkynyl substituent to form the products **15** and **17** with five or six-membered heterocyclic ring formation. The new FpXylBH$_2$ reagent has, thus, shown some interesting initial reaction modes, giving rise to the formation of some unusually composed boron containing heterocycles with hopefully more to come.

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Conflicts of interest

There are no conflicts to declare.

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14 The CCDC numbers of the structures in this paper are 2016810-2016815, 2026639 and 2024709.

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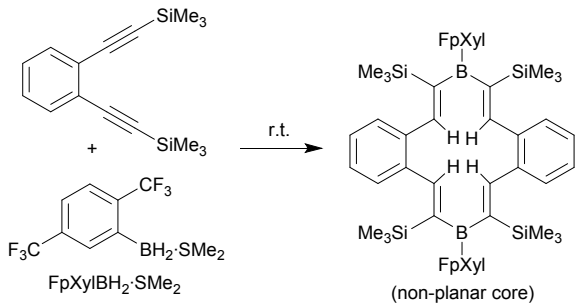

The $FpXylBH_2$ reagent undergoes a twofold hydroboration reaction with 1,2-bis(trimethylsilylethynyl)benzene to give the 14-membered macrocyclic bis-borane product.

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