N-Heterocyclic Carbenes

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Generation and Reactions of an Unsubstituted N-Heterocyclic Carbene Boryl Anion[**]

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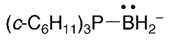
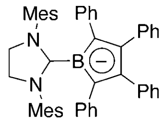
In memory of Marc Julia

Complexation of a boron atom by an N-heterocyclic carbene has been enlisted to make an assortment of unusual low-valent boron compounds[1] and rare boron-containing reactive intermediates including boryl radicals[2,3a] and borenium ions.[3] Such species have interesting fundamental properties and are potentially useful reagents in organic synthesis, among other applications.

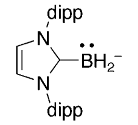
Nucleophilic boron reagents are extremely rare.[4] Recent reviews list only two characterized boryl anions.[5] The tricyclohexylphosphine boryl anion **A** reported by Imamoto and Hikasaka[6] can be considered an analogue of the unknown parent dianion ($:BH_3^{2-}$). Very recently, Braunschweig and co-workers described the generation and characterization of the unusual N-heterocyclic carbene (NHC) borole anion **B**.[7] Theoretical studies suggested that this anion was stabilized by aromaticity; in other words, it is a boron analogue of the tetraphenylcyclopentadienyl anion. Both **A** and **B** were generated by reductive metalation.



A



B



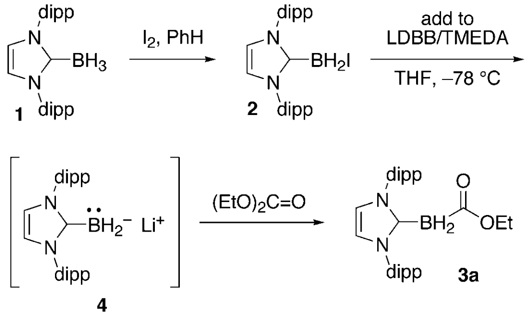
C

dipp = 2,6-diisopropylphenyl

We became interested in the generation and reactions of unsubstituted NHC boryl anions in the context of a program of studying applications of new NHC boranes (NHC–BH_2R) in both small-molecule and polymer synthesis.[8] The usual synthesis of such complexes by complexation of substituted boranes with free NHCs[9] is limited because boranes are reactive towards nucleophiles (whereas NHC boranes are usually stable) and because certain classes of boranes are not easily available by hydroboration or other means. Herein we report that the lithium derivative of the prototypical NHC boryl anion **C** can be generated by reductive lithiation, and trapped by assorted electrophiles to provide new substituted NHC boranes.

Several attempts to deprotonate 1,3-bis-(2,6-diisopropylphenyl)imidazol-2-ylidene borane (**1**; see Scheme 1) with various strong bases did not lead to the desired boryl anion, so we moved quickly to reductive approaches to anion formation. However, precedent from Robinson and co-workers was not necessarily encouraging. They reduced an NHC–BBr_3 complex with potassium graphite to produce novel dimers with boron–boron bonds.[1a] If boryl anions are involved in this process, then they must have reacted rapidly with the starting material or other reaction intermediates.

Boryl iodide **2** can be made rapidly in essentially quantitative yield in situ by reaction of **1** (2 equiv) with iodine (1 equiv) in benzene (Scheme 1). As a prelude to reductive metalations, we studied electrochemical reduction



Scheme 1. Reductive metalation and quenching with diethyl carbonate. TMEDA = N,N,N',N'-tetramethylethylenediamine.

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of **2**. Initial voltammetric measurements were obtained at a millimetric glassy carbon electrode. A single reduction wave was observed at −2.51 V versus a saturated calomel electrode (SCE). The wave current of **2** was comparable to that of oxidation of ferrocene (see the Supporting Information). This suggests that, like ferrocene, complex **2** accepts only one electron to give the corresponding boryl radical NHC–$BH_2^{\bullet}$ (**D**, see Figure 1), which is not reduced under the electrochemical conditions. Again, this precedent is not especially encouraging.

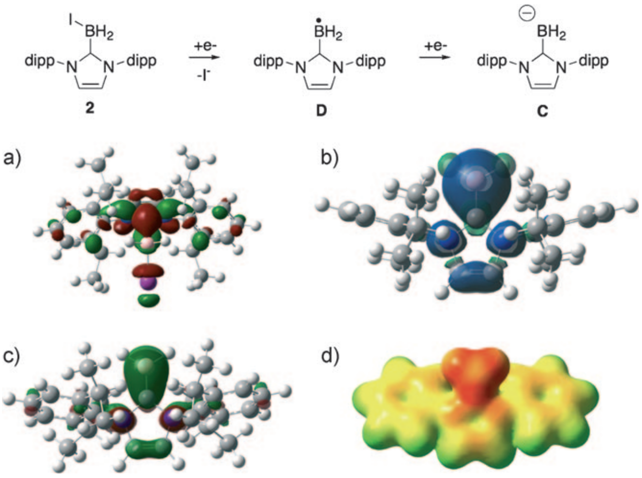


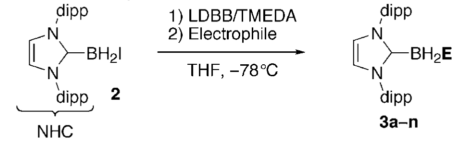
Figure 1. Structures calculated at the B3LYP/SVP level for the species given in the reaction equation. a) HOMO of iodide **2**, b) radical **D** (spin density), c) HOMO of anion **C**, d) the electrostatic potential mapped onto electronic density for anion **C**.

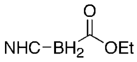
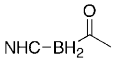
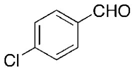
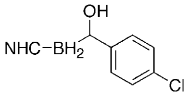
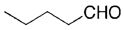
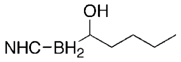
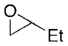
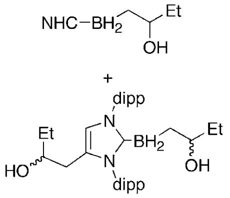
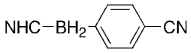
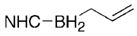
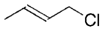
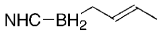
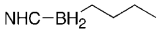
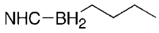
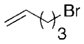
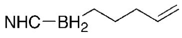
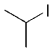
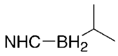
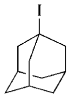
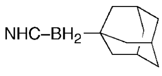
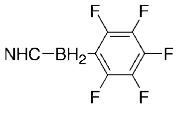
The large negative electrochemical potential of iodide **2** (and presumably the resulting radical) suggested that a very powerful chemical reductant would be needed. Electrochemical measurements with di-*tert*-butylbiphenyl (DBB) indicated that lithium di-*tert*-butylbiphenylide (LDBB) might be suitable since the wave for DBB reduction was less than −2.9 V (see the Supporting Information).[10] Indeed, of the several reductants screened LDBB was the only one to produce significant concentrations of anion as measured by the yields of products isolated by trapping with diethyl carbonate.

In a typical small scale experiment (Scheme 1), **2** (0.075 mmol) was added to excess LDBB (0.17 M THF solution, 4 equiv) in the presence of TMEDA. After 5 minutes at −78 °C, excess diethyl carbonate (12 equiv) was added. Direct flash chromatography on silica gel of the crude reaction mixture provided the stable NHC ethoxycarbonylborane complex **3a** in 61 % yield. In a larger scale experiment, 0.6 mmol of **2** was reacted with a smaller excess of the LDBB (2.5 equiv) and diethyl carbonate (1.5 equiv). This provided **3a** in comparable yield (67 %) after purification. These results suggest the intermediacy of the lithiated boryl anion **4**.[11]

This reductive metalation procedure proved to be surprisingly versatile and the putative boryl anion **C** reacted with a range of electrophiles to provide new diversely substituted borane complexes (NHC–BH_2E). The results of the most successful electrophilic trapping experiments are collected in Table 1. Ethyl acetate provided the acetyl borane complex **3b** resulting from an addition/elimination reaction of the anion **4** (entry 2), whereas 1,2-adducts were isolated from either aromatic (entry 3) or aliphatic aldehydes (entry 4). Crystals were grown from the acyl borane complex **3b** and X-ray analysis confirmed the proposed structure for **3b** (see the Supporting Information). Quenching with an oxirane pro-

Table 1: Formation of functional NHC boranes by reaction of an NHC boryl anion with electrophiles.[a]



Entry	Electrophile	Product	3	Yield [%][b]
1	$(EtO)_2C{=}O$		**3a**	68[c]
2	EtOAc		**3b**	39
3			**3c**	44
4			**3d**	45
5			**3e**	34[d]
6	PhCN		**3f**	51
7	CH_2CHCH_2Br		**3g**	36[e]
8			**3h**	22
9	*n*BuI		**3i**	35
10	*n*BuCl		**3i**	46
11			**3j**	54[e]
12			**3k**	57
13			**3l**	50
14	CH_2Cl_2	NHC−BH_2Me	**3m**	38[f]
15	C_6F_6		**3n**	27

[a] Reaction conditions: **2** (0.075 mmol) was added to excess LDBB (0.17 M THF solution, 4 equiv) in the presence of TMEDA. After 5 minutes at −78 °C, excess electrophile (12 equiv) was added. Where needed, protic quenching by methanol was carried out before workup. The main by-product of most experiments was NHC borane **1**. [b] Yield of isolated product. [c] Used 4 equiv of electrophile. [d] **5** was also isolated (30 %). [e] The reaction was conducted on 0.6 mmol of **2**. [f] Used 2 equiv of electrophile.

vided the expected ring-opened product **3e** (entry 5) along with the double adduct **5** (30%). Compound **5** presumably arises from deprotonation of **3e** on the imidazolyl ring.[12] Accordingly, the imidazolylidene protons on NHC borane complexes must be weakly acidic; a property that merits additional study.

Interestingly, benzonitrile did not give the standard 1,2-addition product expected from highly reactive anions. The *para*-substituted product **3f** (entry 6) was isolated instead. This product resembles those observed by Imamoto in reactions of anion **A**.[6]

Alkyl halides delivered the corresponding B-alkyl derivatives **3g–l** (entries 7–13) in useful yields whereas hexafluorobenzene provided the addition/elimination product **3n** (entry 15). Again, the observations were unusual, with less reactive halides like butyl chloride, isopropyl iodide, and adamantyl iodide (entries 10, 12–13) generally providing better yields than more reactive ones like butyl iodide and crotyl chloride (entries 8–9). Interestingly, the reaction with dichloromethane produced the methylated product **3m**, not the chloromethylated product (entry 14).

Most of the products in Table 1 are members of new classes of substituted NHC boranes that would be difficult to make by the current method of hydroboration and subsequent complexation. The free acyl boranes needed to make **3a** and **3b**, for example, are rare and reactive types of molecules.[13] The unsaturated boranes needed to make **3g**, **3h**, and **3j** would doubtless hydroborate themselves. The α-boryl alcohols **3c** and **3d** and the isopropyl borane **3k** are all formally products of hydroboration with regioselectivity opposite to a classical hydroboration reaction. And products **3e** and **3f** are formally analogous to hydroboration products of an enol and a benzyne, respectively.

To complement the experiments, we conducted DFT calculations on the starting iodide **2** and the intermediate radical **D** and free anion **C**.[14] Figure 1 shows diagrams of the lowest unoccupied molecular orbital (LUMO) of iodide **2** (Figure 1a), the spin density radical on **D** (Figure 1b), the highest occupied molecular orbital (HOMO) of anion **C** (Figure 1c), and the electrostatic potential mapped onto the electronic density on **C** (Figure 1d).

The calculated LUMO of **2** is mostly situated on the NHC fragment (Figure 1a), not the σ* orbital of the B−I bond. The calculations suggest that the radical anion resulting from injection of an electron into the LUMO of **2** does not lead to a stable radical anion. Instead, B−I bond cleavage occurs simultaneously and boryl radical **D** is formed directly. This can also be inferred by the reduction wave width and variation of peak potential with scan rate.[15]

The calculated singly occupied molecular orbital (SOMO) of **D** is similar to that of other NHC boryl radicals (Figure 1b),[2,8d] with a spin density partially on the boron atom and partially delocalized throughout the NHC ring. The radical **D** resists electrochemical reduction but is chemically reduced by LDBB to **C**. The calculated electron affinity for this reduction to the boryl anion is $+42.1\ \mathrm{kcal\,mol^{-1}}$. This may explain why one needs a powerful reducing agent to generate **4**.

The HOMO of free anion **C** shows high electron density on the boron atom delocalized into the NHC ring (Figure 1c,d). Just as the radical **D** is loosely analogous to a benzyl radical, the anion **C** is loosely analogous to a benzyl anion. As such, the anion **C** is structurally different from both the phosphine boryl anion **A**[16] and NHC boryl anion **B**.

In summary, we have generated an unsubstituted NHC boryl anion in situ by reduction of a readily available boryl iodide with LDBB. The anion can be trapped with a diverse range of electrophiles to give an assortment of new types of NHC boranes that would be difficult or impossible to access with existing methods. These compounds form a very small family of tricoordinate boryl anions. Its unusual features in reactions with electrophiles (for example, *para* addition to benzonitrile and substitution of adamantyl iodide) warrant additional mechanistic study, as radical mechanisms might be possible. The availability of the new classes of NHC borane products (acyl boranes, α-boryl alcohols, etc.) opens the door to the study of their properties and chemistry.

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[10] Braunschweig et al. used K/C$_8$ in Et$_2$O to generate anion **B**. See ref. [7].

[11] ^{11}B NMR studies showed the formation of a triplet at $\delta = -18.1$ ppm (at -70 °C) at the expense of the starting material under the reaction conditions. The triplet disappeared upon warming to RT (see the Supporting Information). We attribute these signals to the intermediate lithiated boryl anion **4** (**C** is the cation-free anion).

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[15] The contribution of bond-breaking in the dissociative electron transfer results in a large free enthalpy barrier, leading to a slow reaction and thus to large voltammetric waves (half-peak width of ca. 190 mV typically). See: C. Costentin, M. Robert, J.-M. Savéant, *Chem. Phys.* **2006**, *324*, 40–56.

[16] Imamoto also suggested delocalization of boryl anion to d-orbitals of phosphorus and some double bond character in [(c-C$_6$H$_{11}$)$_3$P=BH$_2$]Li. Presumably, the carbene delocalization is more stabilizing because of the *p*-type conjugation. See ref. [6].