Synthesis and reduction chemistry of mixed-Lewis-base-stabilised chloroborylenes†

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The one-electron reduction of (CAAC Me)BCl3 (CAAC Me = 1-(2,6-diisopropylphenyl)-3,3,5,5-tetramethylpyrrolidin-2-ylidene) yields the dichloroboryl radical [(CAAC Me)BCl2]. Furthermore, the twofold reduction of (CAAC Me)BCl3 in the presence of a range of Lewis bases (L = CAAC Me, N-heterocyclic carbene, phosphine) yields a series of doubly base-supported (CAAC Me)LBCl chloroborylenes, all of which were structurally characterised. NMR and UV-vis spectroscopic and electrochemical data for (CAAC Me)LBCl show that the boron centre becomes more electron-rich and the HOMO–LUMO gap widens as L becomes less π-accepting. A [(CAAC Me)BCl2]− boryl anion coordination polymer was isolated as a potential intermediate in these reductions. In most cases the reduction of the chloroborylenes resulted in the formation of the corresponding hydroborylenes or derivatives thereof, as well as ligand C–H activation products.

Introduction

While the field of boron chemistry has long been dominated by the naturally occurring +3 oxidation state of this electron-deficient element, the last decade has seen tremendous advances in the accessibility of lower oxidation state boron species. Among these, borylenes (:BR), which feature a highly reactive boron(i) centre with two empty p orbitals, have attracted a lot of attention owing to their similarities with organic carbenes.1 The parent borylène, :BH, was first generated in the 1930s by exposure of a BCl3/H2 gas stream to an electrical discharge,2 but is so short-lived that it can only be studied spectroscopically. In contrast, boron fluoride (:BF), which calculations have shown to be the most stable diatomic boron species,3 can be generated in over 90% yield from the comproportionation of BF3 with solid boron at 1850 °C4 and trapped with a variety of small molecules, as for example acetylene (Scheme 1a).5 A variety of methods have been used to generate the significantly less stable boron chloride species, :BCl, including plasma discharge or flash photolysis of BCl3 (Scheme 1b),6 reduction of BCl3 with gaseous copper at −196 °C to generate B2Cl4, which decomposes to :BCl and BCl3 at high temperature (Scheme 1c)7 or comproportionation of Cl2(g) with laser-ablated boron(0) in a solid argon matrix (Scheme 1d).8 The even less stable heavier boron halides, :BBr and :BI, have only been studied spectroscopically.9

Like carbenes, borylenes may be stabilised by adduct formation with electron-rich metal centres. Since the report by our group of the first stable metal borylene in 19959 this field has rapidly expanded10 and a number of bridging haloborylene complexes have been structurally characterised,11 while terminal fluoroborylene complexes have only been observed in the matrix at 6 K.12

It was not until 2011 that the first stable metal-free borylene, (CAAC Cy)2BH (CAAC Cy = 3,3-dimethyl-2-(2,6-diisopropylphenyl)-2-azaspiro[4,5]dec-1-ylidene) was isolated by Bertrand...
and co-workers. It's stability is owed to the two strongly donors–π-acidic cyclic (alkyl)(amino)carbene (CAAC) ligands, which compensate for the build-up of electron density at the boron(II) centre by efficient π delocalisation to form two partial B–CAAC π bonds. In recent years the field of metal-free borylenes has greatly expanded, recently culminating in the synthesis of the first bis(borylene)-stabilised borylene (TM)[B(TMP)]2 (TMP = 2,2,6,6-tetramethylpiperidinyl), which may itself undergo carbene borylene of the form (CAAC)LBCl (L = CAAC, NHC, phosphine) and examine the steric and electronic effects of L on the structural and spectroscopic properties of these borylenes. We also present the first stable dichloroboryl radical and a dichloroboryl anion, both likely intermediates in the formation of these borylenes. Finally, we show that further reduction of these species leads to hydrogen abstraction from the solvent, ligand metatation and C–H activation products.

Results and discussion

The reduction of (CAACMe)BCl3 with one mole of Li in THF at room temperature yielded a pale green solution, which displayed no 11B NMR resonance (Scheme 3). Solvent removal and crystallisation of the hexane extract at −25 °C provided a small crop of orange crystals, which X-ray crystallographic analysis showed to be the first stable dichloroboryl radical, compound 2 (Fig. 2a).

The geometry around the boron atom is trigonal planar (Σ = 0.359.96(13)°), while the B1–C1 distance (1.498(3) Å) is indicative of a double bond and significantly shorter than in precursor 1 (1.644(2) Å, see Fig. S41 in the ESI† for the solid-state structure of 1). This has been observed previously for other CAAC-supported boryl radicals and is indicative of the delocalisation of the unpaired electron over the B–C–N π framework. The EPR spectrum of 2 shows a very broad singlet centred at giso = 2.003 (Fig. 2c), unlike its relative [([CAACMe]B(Dur)Cl)]+ which displays a triplet from the hyperfine interaction with the 14N nucleus (a(14N) = 19 MHz). A simulation of bromoborylene, compound V, supported by a complex, chelating carbaborane-bridged bis(silylene) ligand, has been reported thus far and has already shown promising reduction and ligand exchange reactivity, providing access to the first borylene cation, VI (Scheme 2).

In this contribution we present a facile route towards chloroborylenes of the form (CAAC)LBCl (L = CAAC, NHC, phosphine) and examine the steric and electronic effects of L on the structural and spectroscopic properties of these borylenes.

Fig. 1 Selected examples of mixed-base-stabilised (CAAC)LBR borylenes.

Fig. 2 Structures of compounds 1 and 2.

Scheme 2 Halide abstraction at bromoborylene V.

Scheme 3 One-electron reduction of 1.
the EPR spectrum of 2 provided the following hyperfine coupling parameters: $a^{14}N = 17.3$ MHz and $a^{11}B = 6.70$ MHz, the latter being significantly higher than that in the simulated EPR spectrum of [(CAACMe)B(Dur)Cl] $^*$ (ca. 2.7 MHz), which contributes to the strong signal broadening and loss of resolution. The spin density distribution in 2 was further analysed by density functional theory (DFT) calculations. The unpaired electron is delocalised over the B–C–N π system with atomic spin densities of 0.39, 0.33, and 0.24 on C1, B1, and N1, respectively (Fig. 2d). The lower hyperfine coupling with $^{11}B$, as well as the lower spin density at boron for [(CAACMe)B(Dur)Cl] $^*$ compared to that of the chloride ligand.

Removal of volatiles, extraction with hexanes and subsequent solvent removal yielded a crude purple solid displaying a broad $^{11}B$ NMR resonance at 18.7 ppm and a single set of $^1H$ NMR CAAC$^{Me}$ resonances, indicating a symmetrical compound. Crystallisation from pentane at $-25 \degree C$ over a period of one week yielded large purple crystals suitable for X-ray crystallographic analysis, which provided the structure of a doubly CAAC$^{Me}$-stabilised chloroborylene, 3-CAAC$^{Me}$ presenting a trigonal planar boron centre ($\Sigma \angle B_1 359.97(15)^\circ$, Fig. 3). The molecule is $C_2$ symmetric and the two B1–C1 and C1–N1 bonds (1.530(2) and 1.389(2) Å, respectively) are intermediate between typical lengths of $sp^2$–$sp^3$ single (B–C 1.56; C–N 1.47 Å) and double bonds (B=C 1.44; C=N 1.35 Å), suggesting delocalisation of the borylene lone pair over the entire N–C–B–N π framework. The compound is thereby reminiscent of Bertrand’s parent borylene 1, the B–C bonds of which are slightly shorter (1.5175(15) and 1.5165(15) Å) presumably because of the smaller size and lower electronegativity of the hydride compared to that of the chloride ligand.

The analogous reductions of 1 in the presence of one molar equivalent of IMes (1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidine) or SIMes (1,3-bis(2,4,6-trimethylphenyl)-4,5-dihydroimidazol-2-ylidine) with 2.5 molar equivalents of KC$_8$ in benzene similarly yielded deep-pink reaction mixtures from which the corresponding mixed-base chloroborylenes 3-L (L = IMes, SIMes) were extracted in moderate to good yields (58–76%). For smaller L ligands, such as IMe$^{Me}$, PE$_3$ or PMe$_3$ using a 1 : 1 1:1-L ratio for the reduction resulted in mixtures of the desired chloroborylene 3-L and (CAACMe)$_2$BH ($\delta_{11}B$ 12.5 ppm, $vide infra$ compound 5-CAAC$^{Me}$). For PE$_3$ or PMe$_3$, a fivefold excess of the phosphine could be used to obtain the mixed CAAC-phosphate-stabilised chloroborylenes in moderate isolated yields (ca. 50%), with the excess phosphine simply being removed in vacuo prior to extraction of the product. Unlike the bis(CAAC)- or CAAC–NHC-stabilised chloroborylenes, these compounds crystallise as pale yellow solids. Finally, 3-IMe$^{Me}$ was obtained as a bright red compound by quantitative NHC/phosphine ligand exchange with 3-PMe$_3$ at room temperature (Scheme 5). Ligand exchange with the more sterically demanding carbene IMes, SIMes and CAAC$^{Me}$ was also attempted but remained limited to 2–5% conversion.

From the attempted synthesis of the dimethylsulfide-stabilised borylene (CAAC$^{Me}$)$_2$(SMe$_2$)BCl using 20 equivalents SMe$_2$, recrystallisation of the toluene–hexane extract at $-25 \degree C$ yielded a few isolated crystals of a linear coordination polymer of the dichloroboryl anion 4, [(CAAC$^{Me}$)BCl$_2$]$_2$K$_2$(SMe$_2$)$_3$. 

**Scheme 4** Synthesis of doubly base-stabilised chloroborylenes.
The boron atoms in this structure are trigonal planar with respect to their attached chloride and CAACMe ligands ($\Sigma(\angle B1) 359.95(14)^\circ$) and present a relatively short $B-CCAAC$ double bond (1.427(3) Å) compared to other known $[(CAAC)BX_2]^{2-}$ boryl anions ($XY = (CN)_2, H(CN), HCl, H_2B-CCAAC$ 1.432(6) to 1.473(2) Å). Each potassium cation lies in the plane of the sp$^2$-boron atom, coordinating to both chloride ligands and bridging between three adjacent boryl anion units, once via a Cl1–K1–Cl1$^0$ bridge and once via a Cl2–K1–Cl2$^0$ bridge. The adjacent (N1,C1,B1,Cl1) planes form an angle of 75° between each other. The two potassium cations bridging the Cl and Cl$^0$ atoms, K1 and K1$^0$, are further bridged by one SME$_2$ ligand and their coordination sphere is completed by π-interactions with the adjacent Dip residue. Unfortunately, due to its virtual insolubility in hydrocarbon solvents and extreme air- and moisture-sensitivity, no NMR spectroscopic or elemental analysis data could be obtained for 4. It is likely, however, that similar $[(CAACMe)BCl_2]_{\infty}$ coordination oligomers or polymers could be intermediates in the synthesis of the 3-L chloroborylenes shown in Scheme 4.

A comparison of all six 3-L chloroborylenes shows an increasing upfield shift in the $^{11}$B NMR resonances in the following order (Table 2): CAACMe (18.7 ppm) > SIMes (11.9 ppm) > IMes (8.4 ppm) > PEt$_3$ (5.6 ppm) ≈ IMeMe$^{\beta}$ (5.5 ppm) > PMe$_3$ (2.8 ppm). This correlates well with the trend of the overall electron-donating nature of the ligands L, i.e. their combined σ donor and π acceptor abilities, usually determined using the Tolman electronic parameter (TEP),$^{27}$ which is defined as the $ν$(CO) stretching frequency of Ni(CO)$_3$L complexes: the lower the TEP, the less electron-donating L is overall. While the TEP of IMeMe$^{\beta}$ is yet to be determined experimentally,$^{27}$ the trend in this table suggests a value close to 2062 cm$^{-1}$ and similar electronic properties to PEt$_3$.

Moreover, for $L = $ carbene, the $^{11}$B NMR shifts of 3-L decrease with the $^{77}$Se NMR shifts for the corresponding $L=Se$ adducts, which are a measure of the π acidity of the corresponding carbene: the more downfield the $^{77}$Se NMR chemical shift, the more π-accepting the carbene.$^{28}$ Consequently, the $^{11}$B NMR shift of 3-L represents a reliable measure of the relative electron-donating ability of L.

Another measure of the relative σ donor and π acceptor abilities of L is provided by a comparison of the X-ray structural data of 3-L (Fig. 3, Table 1). For the carbene ligands, this is linked to the degree in which the CAACMe$^{\beta}$ and L π frameworks, respectively, are rotated out of the plane of the borylene core, represented by the torsion angles (N1,C1,B1,Cl1) and (N2,C21,B1,Cl1), respectively, as well as the relative B–CAAC and B–Cl bond lengths. In the $C_2$-symmetric 3-CAACMe$^{\beta}$ the (N1,C1,B1,Cl1) torsion angles are only 14.51(16)$^\circ$, which enables

![Fig. 3](image-url)

Crystallographically-derived molecular structures of 3-L, $L = $ (a) CAACMe, (b) IMes, (c) SIMes, (d) PEt$_3$, (e) PMe$_3$, and (f) IMeMe$^{\beta}$. Thermal ellipsoids drawn at 50% probability level. Ellipsoids on the CAACMe$^{\beta}$ ligand periphery and hydrogen atoms omitted for clarity.

![Scheme 5](image-url)

Synthesis of 3-IMeMe$^{\beta}$.
Fig. 4 (Top) Synthesis of polymeric 4 showing the connectivity of adjacent boryl anion units in different colours. (Bottom) Crystallographically-derived molecular structure of 4 showing the connectivity of two boryl anion units. Thermal ellipsoids drawn at 50% probability level. Ellipsoids on the CAAC(Me) ligand periphery and hydrogen atoms omitted for clarity. Selected bond lengths (Å) and angles (°): N1–C1 1.442(2), B1–C1 1.427(3), B1–C1 1.839(2), B1–C1 1.852(2), C1–K1 3.2353(6), C1′–K1 3.1617(8), C1′–K1 3.1866(6), C1′–K1 3.1489(7), K1–K1 3.4032(7), Σ(ΩB1) 359.95(14).

a large overlap between the borylene lone pair and the empty p$_2$ orbitals on both carbene carbon atoms. As a result, the borylene lone pair is fully delocalised over the C–B–C π orbital, which is further confirmed by the B–C bond lengths of 1.530(2) Å, which are intermediate between a single and double bond. While the (N1,C1,B1,C11) torsion angle remains very small for all the other derivatives (<5°), allowing for excellent overlap of CAAC(Me) with the borylene lone pair, the (N2,C21,B1,C11) torsion angle increases in the following order: CAAC(Me) (14.5(2)°) < SIMes (44.4(2)°) < IMes (53.5(6)° = avg. of the two molecules present in the asymmetric unit) < IMe(Me) (79.3(2)°). This is in agreement with the decrease in π acidity in this ligand series (see Table 2). As the (N2,C21,B1,C11) torsion angle grows closer to orthogonality, π overlap decreases until it becomes negligible for L = IMe(Me). This is also apparent in the lengthening of the B–C$_1$ bond from 1.530(2) Å in 3-CAAC(Me) to 1.578(3) Å in 3-IMe(Me), which suggests a typical double bond, concomitant with a shortening of the B–C$_\text{CAAC}$ bond to 1.440(3) Å in the IMe(Me) analogue, indicating a typical B=C double bond, as the entire π electron density from the borylene lone pair is employed in π backbonding from boron to CAAC(Me). A similar trend can also be observed in the structural data from Bertrand’s (CAAC)LBH hydroborylenes, I$^1$ and IV-L (Fig. 1) for which the torsion angles between the borylene plane and π framework of L increase in the order of CAAC$_{\text{Cy}}$ < BI$_{\text{Pr}}$ < BAC$_{\text{Pr}}$, which fits with the decreasing π acidity of L, concomitant with a shortening of the B–C$_\text{CAAC}$ bonds and a lengthening of the B–C$_1$ bonds. For the two 3-PR$_3$ derivatives, in which the phosphines act as pure σ donors, the B–C bond lengths of 1.456(2) (R = Et) and 1.449(2) (R = Me) indicate a B=C double bond, similarly to the 3-IMe$_2$ derivative. In the only structurally characterised CAAC-phosphate-stabilised borylene, compound II-PMe$_3$ (Fig. 1), the B–C bond is slightly longer (1.484(6) Å) due to a small amount of π backbonding to the π-acidic cyano ligand.$^{18}$

DFT calculations by the group of Bertrand have shown that the π-type HOMO of the (CAAC)LBH hydroborylenes I and IV-L is delocalised over the C$_\text{CAAC}$–B–C$_1$ moiety, with the extent of delocalisation increasing with the π acidity of L.$^{13,22}$ Given the structural and electronic similarities of these compounds to our 3-CAAC$_{Me}$ and 3-NHC$_{Me}$ derivatives, we limited our DFT analysis to the bonding and electronic structure of 3-PMe$_3$, in which the phosphine ligand acts as a pure σ donor. As expected, the HOMO of 3-PMe$_3$ corresponds largely to the B–C π bond, with minor C1–N1 and B–C$_1$ π antibonding interactions (Fig. 5b). The calculated B–C$_1$ Wiberg bond index of 1.53 indicates a full B=C double bond (Fig. 5a). This is also borne out by natural resonance theory (NRT), which gives the phosphonium allylborane as the major resonance form (38.3%, see Fig. S45 in the ESI†), as well as natural population analysis (NPA), which places a large positive charge of +1.25 on P1 and small negative charges of −0.07 and −0.19 on B1 and C1, respectively (Fig. 5a).

<table>
<thead>
<tr>
<th>3-L, L =</th>
<th>CAAC(Me)</th>
<th>IMes</th>
<th>SIMes</th>
<th>IMe(Me)</th>
<th>PMe$_3$</th>
<th>PMe$_3$</th>
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<tr>
<td>B1–C1</td>
<td>1.530(2)</td>
<td>1.437(7), 1.450(7)</td>
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<td>1.440(3)</td>
<td>1.456(3)</td>
<td>1.449(2)</td>
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<td>B1–C11</td>
<td>1.843(3)</td>
<td>1.884(5), 1.879(6)</td>
<td>1.854(2)</td>
<td>1.855(2)</td>
<td>1.855(2)</td>
<td>1.8516(17)</td>
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<td>B1–C21</td>
<td>—</td>
<td>1.575(7), 1.570(7)</td>
<td>1.550(3)</td>
<td>1.578(3)</td>
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<td>B1–P1</td>
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<td>—</td>
<td>—</td>
<td>1.912(2)</td>
<td>1.9114(17)</td>
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<td>C1–N1</td>
<td>1.389(2)</td>
<td>1.429(5), 1.428(6)</td>
<td>1.408(2)</td>
<td>1.432(2)</td>
<td>1.421(2)</td>
<td>1.4294(18)</td>
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<td>Σ(ΩB1)</td>
<td>359.95(15)</td>
<td>360(4), 359.9(4)</td>
<td>359.58(15)</td>
<td>359.94(17)</td>
<td>359.56(14)</td>
<td>359.7(11)</td>
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<tr>
<td>C1–B1–C21</td>
<td>133.9(2)$^a$</td>
<td>132.1(4)</td>
<td>128.49(17)</td>
<td>122.96(18)</td>
<td>129.06(16)$^a$</td>
<td>131.54(12)$^ɛ$</td>
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<tr>
<td>(N1,C1,B1,C11)$^a$</td>
<td>14.51(16)</td>
<td>4.9(8), 1.3(7)</td>
<td>3.2(3)</td>
<td>2.8(3)</td>
<td>3.0(3)</td>
<td>0.6(2)</td>
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<tr>
<td>(N2,C21,B1,C11)$^a$</td>
<td>—</td>
<td>57.5(7), 49.2(6)</td>
<td>44.4(2)$^d$</td>
<td>79.3(2)</td>
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$^a$ Torsion angles. $^b$ C1–B1–C1. $^c$ The asymmetric unit contains two structurally distinct borylene molecules. $^d$ Torsion angle (N3,C21,B1,C11). $^e$ C1–B1–P1.
With the exception of the two phosphine derivatives, compounds 3-L were intensely coloured (Fig. 6, top). Furthermore, whereas the NHC and phosphine derivatives were highly air-sensitive, solutions of 3-CAACMe exposed to air retained their colour for several hours at room temperature, thus demonstrating the unusual stability of this species. An overlay of the UV-vis spectra of all 3-L compounds (Fig. 6, bottom) shows that the wavelength of the most red-shifted absorbance maximum decreases in the order of L = CAACMe (556 nm, purple-blue) > IMes (550 nm, purple-pink) > SIMes (538 nm, pink) > IMeMe (470 nm, orange-red) > PMe3 (350 nm, pale yellow) > PET3 (336 nm, pale yellow). A TD-DFT study of our tetrameric cyanoborylene, [(CAACMe)B(CN)]4, had shown that its absorption bands of 3-L are likely correspond to transitions from the four π-bonding borylene-centred molecular orbitals (MOs) to four π*-antibonding MOs centred on the π system of the cyano ligands and the aromatic Dip substituents of the CAAC ligand.18 By analogy, the highest wavelength absorption bands of 3-L likely correspond to π−π* transitions from the borylene-centred HOMO to the LUMO distributed over the π system of the ligands. A red-shift of this transition, i.e. a decrease in the HOMO−LUMO gap, can be correlated with an increase in (a) the σ-donor capacity of L, which can destabilise the HOMO and/or (b) the π-acceptor ability of L and/or (c) the amount of π conjugation within the molecule, where both (b) and (c) can stabilise the LUMO. In this case, from the alkylphosphine derivatives, which present no π system on L (λmax < 350 nm), via the IMeMe derivative with its conjugated imidazole-2-ylidene ring (λmax = 470 nm), to the CAAC and (aryl)NHC derivatives with their extensive π systems (λmax > 530 nm), the red-shift is seen to increase with the extent of the π system on L, as well as the amount of π delocalisation of the borylene lone pair.

Cyclovoltammetric experiments performed on the carbene-supported 3-L borylenes (solvent: THF, supporting electrolyte: [n-Bu4N][PF6]) showed a first semi- or fully reversible oxidation wave between E1/2 = −1.00 V (3-CAACMe) and E1/2 = −1.26 V (3-IMeMe vs. (Fc+/Fc), see Fig. S35−S38 in the ESI†). Although the potential differences are relatively small, it is apparent that E1/2 becomes slightly more negative as L becomes less π-accepting, i.e. as electron density increases at the borylene centre, which is to be expected. Furthermore, 3-CAACMe and 3-SIMes show irreversible reduction waves at Ep = −2.68 V and Ep = −3.17 V, respectively, whereas 3-IMes and 3-IMeMe show no reduction wave down to −3.30 V. Here again, the trend correlates with the overall electron-donating ability of L: the less electron-rich the borylene centre, the more facile its reduction.

These results prompted us to attempt to reduce these compounds chemically. The room temperature reduction of either 3-IMes or 3-IMeMe with KC8 in benzene resulted in conversion to new red-coloured species displaying broad 11B NMR resonances at 1.4 and −3.0 ppm respectively (Scheme 6a).

<table>
<thead>
<tr>
<th>L</th>
<th>11B NMR shift (ppm) of 3-L</th>
<th>TEP of L 17 (cm −1)</th>
<th>77Se NMR shift (ppm) of L = Se 18</th>
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<tbody>
<tr>
<td>CAACMe</td>
<td>18.7</td>
<td>2046.0</td>
<td>492</td>
</tr>
<tr>
<td>IMes</td>
<td>11.9</td>
<td>2051.5</td>
<td>116</td>
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<tr>
<td>IMes</td>
<td>8.4</td>
<td>2050.7</td>
<td>35</td>
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<td>PET3</td>
<td>5.6</td>
<td>2061.7</td>
<td>n.a.</td>
</tr>
<tr>
<td>IMeMe</td>
<td>5.5</td>
<td>—a</td>
<td>3</td>
</tr>
<tr>
<td>PMe3</td>
<td>2.8</td>
<td>2064.1</td>
<td>n.a.</td>
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a Only a calculated TEP of 2051.7 cm −1 has been reported for IMeMe.24

Fig. 5 (a) Optimised structure of 3-PMe3: Wiberg bond indices in blue, NPA charges in red. (b) Plot of the HOMO of 3-PMe3 (isovales ±0.05|q503−0.3/2|).

Fig. 6 (Top) Colours of 1.2 mM benzene solutions of 3-L. (Bottom) Superposition of the UV-vis absorption spectra (highest absorbance normalised to 1) of 3-L.

Table 2 11B NMR shifts (ppm) for 3-L, experimentally determined TEP (cm −1) for L and 77Se NMR shifts (ppm) of L = Se.
identity of 5-CAAC\textsuperscript{Me} was further confirmed by X-ray crystallographic analysis (see Fig. S42 in the ESI\textsuperscript{t}).

The reduction of 3-IMes with excess Li sand in THF also proceeded cleanly to a red-orange compound presenting a broad \(^{11}\text{B}\) NMR resonance at 2.8 ppm (compound 6, Scheme 6b). X-ray crystallographic analysis of 6 revealed a planar hydroborylene (\(\Sigma(\angle B1) 359.8(8)^\circ\)) stabilised on the one side by a strongly \(\pi\)-accepting CAAC\textsuperscript{Me} ligand (B1–C1 1.454(4) Å) and on the other side by a \(\sigma\)-donating IMes ligand (B1–C21 1.583(4) Å) lithiated at the backbone C4 position, the coordination sphere of the lithium atom being completed by three THF residues (Fig. 7, top). Such metatation of unsaturated NHC backbones in the presence of strong, non-nucleophilic bases or reducing agents has been well documented over the last decade.\(^{39}\) Brief exposure of a \(\text{C}_6\text{D}_6\) solution of 6 to air led to an immediate colour change from red to orange and NMR spectra showed clean conversion to 5-IMes (Scheme 6c). Interestingly, this route is more reliable and selective than the reduction of 3-IMes with \(\text{KC}_8\) (Scheme 6b) or the reduction of \((\text{CAACMe})\text{BHX}_2\) (X = Cl, Br) in the presence of one equiv. IMes, which besides 5-IMes also yields the dihydrodiborene \((\text{CAACMe})\text{B}_2\text{H}_2\). The boron-bound hydrides in 5-L and 6 presumably arise from hydrogen abstraction from the reaction solvent by intermediate dicoordinate boron-centred radicals.**

The reduction of 3-SIMes with \(\text{KC}_8\) in benzene or Li in THF or 1,2-dimethoxyethane (DME) did not proceed selectively, as evidenced by the appearance of multiple new \(^{11}\text{B}\) NMR resonances. Recrystallisation of the product mixture of the Li-based reduction in DME, however, yielded a few red crystals of the alkylideneborate 7 with a Li\((\text{dme})_3\) counterion (Scheme 6d, Fig. 7, bottom). The boron centre is planar (\(\Sigma(\angle B1) 359.96(2)^\circ\)) and displays a B1–C1 single bond to the now sp\(^3\)-hybridised C1 atom (B1–C1 1.615(3) Å; C1–N1 1.500(3) Å) and a formal B1–C21 double bond (1.435(3) Å) to the former SIMes ligand. Alkylidene borates are typically generated by \(\pi\)-deprotonation of a suitable sp\(^2\)-borane precursor with a strong, non-nucleophilic base,\(^{25a}\) by nucleophilic quaternisation of a neutral alkylidene borane,\(^{25a}\) or by tautomerisation of intramolecular frustrated Lewis pair systems involving an \(\pi\)-proton transfer from a highly electron-withdrawing \(\text{CH}_2\text{B}(\text{C}_6\text{F}_5)_3\) moiety to the Lewis basic site.\(^{25b}\) In contrast, the formation of 7 presumably results from the 2e\(^{-}\) reduction of 3-SIMes to a highly reactive dicoordinate \([\text{CAAC-Me}]^+(\text{SIMes})\text{B}^-\) anion (proposed intermediate in Scheme 6), which undergoes intramolecular ortho-methyl C–H activation of the mesityl substituent, followed by a 1,2-hydride migration from the boron centre to the adjacent CAAC carbene carbon atom. Similar mesityl-CH\(_2\) activations have been observed previously in the reduction of IMes-stabilised or mesityl-substituted boranes,\(^{30}\) as has the 1,2-hydride migration in...
CAAC-supported hydroboranes. Unfortunately, the other products of this reduction could not be cleanly isolated. No tractable products were obtained from various reduction attempts of the phosphine derivatives 3-PMe$_3$ and 3-PET$_3$.

Conclusions

To conclude, we have described a facile synthetic route towards a series of metal-free haloborylenes, (CAAC)BLCI, by twofold reduction of a (CAAC)BCl$_3$ precursor with KC$_8$ in the presence of a donor ligand L. Two likely intermediates in these reduction reactions were isolated in the form of a [(CAAC)BCl$_3$]$^-$ radical and a [(CAACMe$_3$)BCl$_3$]$^-$ anion, the potassium countercation of which is coordinated by L. Variation of L from a highly π-accepting CAAC ligand via moderately π-accepting NHCS to purely α-donating phosphines provides a series of borylenes displaying more or less sterically shielded and electron-rich boron centres, as determined by X-ray crystallographic analyses, NMR and UV-vis spectroscopy and cyclic voltammetry. The PMe$_3$ derivative undergoes facile phosphine–NHC ligand exchange with a small NHC but not with the more sterically demanding ones. DFT calculations show that in the absence of possible π backbonding to L, the borylene lone pair is stabilised solely by π backbonding to the CAAC ligand. Finally, the room-temperature reduction of the CAAC and NHC derivatives led to the isolation of several hydroborylenes and the product of an intramolecular C–H activation, suggesting the formation of radical and anionic dicooordinate ‘[(CAAC)-(NHC)B]−’ reduction intermediates. We are currently studying the reactivity of these compounds, in particular 3-PMe$_3$, towards Lewis acids and bases, unsaturated small molecules and electrophilic substitution, and will be reporting our results in a follow-up study.

Conflicts of interest

The authors declare no conflict of interest.

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Notes and references

† Geometry optimisations were performed at the wB97XD/DGD* level of density functional theory; bonding analyses reported are based on wave functions obtained from subsequent M06-2X/6-311G(d,p) single-point calculations. See ESI† for full details.

‡ These attempted ligand exchange reactions had to be carried out at room temperature as 3-PMe$_3$ started decomposing in solution at 60 °C.

§ 3-PMe$_3$ and 3-PET$_3$ display near identical solution colours at 0.12 mM.

¶ The cyclovoltammograms of 3-PMe$_3$ and 3-PET$_3$ are virtually identical (see Fig. S19 and S40 in the ESI) and show multiple irreversible redox events, presumably due to rapid phosphine dissociation upon oxidation or reduction.

** NMR-spectroscopic monitoring of the reduction of 3-DMes with Li in THF showed that 3-DMes is an intermediate in the formation of 6. Since the latter is quantitative, hydrogen abstraction from the ligand backbone can be excluded as source of the BH functionality.


2 W. Loche-Holtgreven and E. S. van der Vleugel, Z. Phys., 1931, 70, 188.


