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Author(s): Konu, Jari; Tuononen, Heikki; Chivers, Tristram

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Syntheses, X-ray structures and redox behaviour of the group 14 bis-boraamidinates $M[\text{PhB}(\mu-\text{N-t-Bu})_2]_2$ ($M = \text{Ge, Sn}$) and $\text{Li}_2M[\text{PhB}(\mu-\text{N-t-Bu})_2]_2$ ($M = \text{Ge, Sn, Pb}$)

Jari Konu, Heikki M. Tuononen, and Tristram Chivers

Jari Konu,1 Heikki M. Tuononen2 and Tristram Chivers3,3

1 Department of Chemistry, University of Calgary, Calgary, Alberta T2N 1N4, Canada
2 Department of Chemistry, University of Jyväskylä, P.O. Box 35, Jyväskylä, FI-40014, Finland
3 Corresponding author (e-mail: chivers@ucalgary.ca)
**Abstract:** The solid-state structures of the complexes \( \text{M[PhB(\mu-N-t-Bu)_2]}_2 \) (1a, M = Ge; 1b, M = Sn) were determined to be spirocyclic with two orthogonal boraamidinate \((\text{bam})\) ligands \(N,N'\)-chelated to the group 14 centre. Oxidation of 1b with \(\text{SO}_2\text{Cl}_2\) afforded the thermally unstable, blue radical cation \(\{\text{Sn[PhB(\mu-N-t-Bu)_2]}_2\}^+\), identified by EPR spectroscopy supported by DFT calculations, whereas the germanium analogue 1a was inert towards \(\text{SO}_2\text{Cl}_2\). The reaction between \(\text{Li}_2[\text{PhB(\mu-N-t-Bu)_2]}_2 \) and \(\text{SnCl}_2 \) or \(\text{PbI}_2\) in 2:1 molar ratio in diethyl ether produced the novel heterotrimetallic complexes \(\text{Li}_2\text{Sn[PhB(\mu-N-t-Bu)_2]}_2\) (2b) and \((\text{Et}_2\text{O} \cdot \text{Li})\text{LiPb[PhB(\mu-N-t-Bu)_2]}_2\) (2c \(\cdot \text{OEt}_2\)), respectively. By contrast, treatment of \(\text{Li}_2[\text{PhB(\mu-N-t-Bu)_2]}_2 \) with \(\text{C}_4\text{H}_8\text{O}_2\cdot\text{GeCl}_2\) yielded the germanium(IV) complex 1a via a redox process. The X-ray structures of 2b and 2c \(\cdot\) THF revealed polycyclic arrangements in which one \(\text{bam}\) ligand is \(N,N'\)-chelated to the Sn(II) or Pb(II) atom and one of the Li\(^+\) cations, while the second \(\text{bam}\) ligand exhibits a unique bonding mode, bridging all three metal centres. The fluctional behaviour of 2b was investigated by variable temperature, multinuclear NMR spectroscopy.
Introduction

The dianionic boraamidinate (bam) ligand, \([\text{RB(NR')}_2]^2-\) (B), is formally isoelectronic with the extensively studied monoanionic amidinate (am) ligand \([\text{RC(NR')}_2]^1-\), (A). A wide range of main-group element and transition-metal complexes have been structurally characterized and a variety of bonding modes have been established for the \(\text{bam}\) ligand (1-3).

The most intriguing consequence of the 2- charge is the facile tendency for redox transformations to occur in which the dianion \(\text{B}\) is oxidized to the corresponding monoanion radical \([\text{bam}]^\cdot\) (C). This paramagnetic ligand can be stabilized through chelation, e.g., to early main-group metals (4, 5). In the case of group 13 metals it has been possible to isolate stable neutral radicals. For example, the intensely coloured paramagnetic species \([\text{MPhB(\mu-N-t-Bu)}_2]^\cdot\) (M = Al, dark red; M = Ga, Dark green) are produced by one-electron oxidation of the corresponding anions with iodine, and the X-ray structures of these spirocyclic complexes have been determined (Scheme 1) (4). The SOMO of these neutral radicals is located primarily and equally in p-orbitals on the four nitrogen atoms of the two \(\text{bam}\) ligands; there is very little electron density on the group 13 centres.

Scheme 1. Synthesis of spirocyclic \([\text{MPhB(\mu-N-t-Bu)}_2]^\cdot\) radicals
The corresponding boron and indium-containing radicals \( \{ \text{M} \text{[PhB(\mu-N-t-Bu)₂]₂} \} \) \(^\ast\) \((\text{M} = \text{B, In})\) were characterized in solution by EPR spectroscopy (5). However, the green indium-containing radical is not sufficiently stable to be isolated in the solid state. The boron analogue, although it is thermally very stable, could not be obtained in a pure form owing to the formation of other products via a competing reaction pathway (5). Thallium(I) mono-bam complexes have also been structurally characterized; they form aggregated chains incorporating metallophilic Tl···Tl interactions in the solid state (6).

The synthesis and characterization of the group 13 complexes \( \{ \text{M} \text{[PhB(\mu-N-t-Bu)₂]₂} \} \) \(^\ast\) \((\text{M} = \text{Al, Ga, In})\) raises the question of whether the isoelectronic group 14 cation radicals \( \{ \text{M} \text{[PhB(\mu-N-t-Bu)₂]₂} \} \)\(^{\ast+}\) \((\text{M} = \text{Si, Ge, Sn})\) will be accessible by mild oxidation of the corresponding neutral precursors. Several bam complexes of group 14 elements (Si, Ge, Sn, Pb) have been reported (1). Although the metathesis reactions of two equivalents of Li₂bam reagents with MCl₄ \((\text{M} = \text{Ge, Sn})\) afford the corresponding M(bam)₂ complexes (7, 8), the synthesis of a silicon analogue \((\text{M} = \text{Si})\) by this method has not been reported. The known silicon complexes have only one bam ligand chelated to silicon in complexes of the type RR'Si(bam); they were prepared by indirect approaches rather than metathesis (9, 10). The solid-state structures of M(bam)₂ complexes \((\text{M} = \text{Ge, Sn})\) have not been determined. Interestingly, the reaction of Li₂[PhB(\mu-N-t-Bu)₂] with PbCl₄ produces the dimeric lead(II) complex \( \{ \text{Pb}[\text{PhB(\mu- \text{N-t-Bu})₂]\}_{2} \} \), which is preferably prepared by using PbCl₂ as a source of lead(II) (11). There are no reports of complexes in which two bam ligands are chelated to a group 14 metal in the formal +2 oxidation state, i.e. \( \{ \text{M} \text{[bam]₂} \} \)\(^{-2}\) \((\text{M} = \text{Ge, Sn, Pb})\). These dianions are isoelectronic with the corresponding group 15 monoanions of the type \( \{ \text{M} \text{[bam]₂} \} \)\(^{-1}\) \((\text{M} = \text{As, Sb, Bi})\), which exhibit interesting polycyclic structures in the solid state and fluctional behaviour in solution (12). The synthesis of dilithio derivatives of the group 14 dianions \( \{ \text{M} \text{[bam]₂} \} \)\(^{-2}\) \((\text{M} = \text{Ge, Sn, Pb})\) is, therefore, of interest for comparison with their group 15 analogues.
In this contribution we report (a) the X-ray structures of the complexes M[PhB(μ-N-t-Bu)₂]₂ (1a, M = Ge; 1b, M = Sn), (b) oxidation of 1b with SO₂Cl₂ to give the radical cation {Sn[PhB(μ-N-t-Bu)₂]₂}⁺, which was identified by EPR spectroscopy supported by DFT calculations, (c) the synthesis and X-ray structures of the new heterotrime
tallic complexes Li₂Sn[PhB(μ-N-t-Bu)₂]₂ (2b) and (THF·Li)LiPb[PhB(μ-N-t-Bu)₂]₂ (2c·THF), and (d) variable temperature, multinuclear (¹H, ¹³C, ⁷Li, ¹¹B and ¹¹⁹Sn) NMR investigations of the fluctional behaviour of 2b.

**Experimental section**

**Reagents and general procedures**  
All reactions and the manipulations of products were performed under an argon atmosphere by using standard Schlenk techniques or an inert atmosphere glove box. The compounds PhBCl₂ (Aldrich, 97%), GeCl₄ (Strem, 99.99%), C₄H₈O₂·GeCl₂ (Aldrich, 99%), SnCl₄ (Aldrich, 1.0 M sol. in heptane), SnCl₂ (Aldrich, 98%), PbI₂ (Strem, 99.999%) and t-BuNH₂ (Aldrich, 98%) were used as received. SO₂Cl₂ (Aldrich, 97%) was distilled prior to use. LiN(H)-t-Bu was prepared by the addition of n-BuLi to a solution of anhydrous t-BuNH₂ in n-hexane at -10 °C and its purity was checked by ¹H NMR spectroscopy. The compounds PhB[N(H)-t-Bu]₂ and Li₂[PhB(μ-N-t-Bu)₂] were prepared as described earlier (13). The solvents n-hexane, toluene, Et₂O and THF were dried by distillation over Na/benzophenone under an argon atmosphere prior to use. Elemental analyses were performed by Analytical Services, Department of Chemistry, University of Calgary.

**Spectroscopic methods**  
The ¹H, ⁷Li, ¹¹B, ¹³C and ¹¹⁹Sn NMR spectra were obtained in d₈-toluene at 23 °C on a Bruker DRX 400 spectrometer operating at 399.59, 155.30, 128.20, 100.49 and 149.00 MHz, respectively. ¹H and ¹³C spectra are referenced to the solvent signal and the chemical shifts are reported relative to (CH₃)₄Si. ⁷Li and ¹¹B NMR spectra are referenced externally and the chemical
shifts are reported relative to a 1.0 M solution of LiCl in D_2O and to a solution of BF_3·Et_2O in C_6D_6, respectively. Similarly, the ^119Sn NMR spectra are referenced externally and the chemical shifts are reported relative to (CH_3)_4Sn.

The X-band EPR spectra were recorded on a Bruker EMX 113 spectrometer equipped with a variable-temperature accessory. EPR spectral simulations were carried out by using WINEPR SimFonia (version 1.25, 1996) and PEST WinSim (version 0.98, 2002) softwares (14).

**X-ray crystallography**

Crystallographic data for 1a, 1b, 2b and 2c·THF are summarized in Table 1. Crystals of Ge[PhB(μ-N-t-Bu)_2]_2 (1a), Sn[PhB(μ-N-t-Bu)_2]_2 (1b), Li_2Sn[PhB(μ-N-t-Bu)_2]_2 (2b) and (THF·Li)LiPb[PhB(μ-N-t-Bu)_2]_2 (2c·THF) were coated with Paratone 8277 oil and mounted on a glass fibre. Diffraction data were collected on a Nonius KappaCCD diffractometer using monochromated MoKα radiation (λ = 0.71073 Å) at -100 °C. The data sets were corrected for Lorentz and polarization effects, and empirical absorption correction was applied to the net intensities. The structures were solved by direct methods using SHELXS-97 (15) and refined using SHELXL-97 (16). After full-matrix least-squares refinement of the non-hydrogen atoms with anisotropic thermal parameters, the hydrogen atoms were placed in calculated positions [C-H = 0.98 Å for C(CH_3)_3 and 0.95 Å for phenyl hydrogens]. The isotropic thermal parameters of the hydrogen atoms were fixed at 1.2 times to that of the corresponding carbon for phenyl hydrogens, and 1.5 times for C(CH_3)_3. In the final refinement the hydrogen atoms were riding on their respective carbon atoms.

In the structure of 2b, the Li_2 and Sn_1 atoms were disordered with the atoms statistically distributed over the two atomic sites. The two atoms were constrained to locate in the same position and the anisotropic thermal parameters were restricted to be equal. In the final refinement, the site occupation factors were ca. 93 and 7%, respectively. The scattering factors for the neutral atoms
were those incorporated with the programmes.

**Computational Details**

All calculations were done with the Gaussian 03 program using density functional theory (17). Molecular structures were optimized using the hybrid PBE1PBE exchange-correlation functional (18) together with the Ahlrichs' TZVP basis sets (19); an effective core potential basis set of similar valence quality was used for the heavy tin nuclei (20). Hyperfine coupling constants were then calculated by single-point calculations employing the optimized geometries and the basis set combination used for optimizations. The orbital plot was obtained by the program gOpenMol (21).

**Synthesis of Ge[PhB(μ-N-t-Bu)$_2$]$_2$ (1a)**

A solution of Li$_2$[PhB(μ-N-t-Bu)$_2$] (0.366 g, 1.50 mmol) in 30 mL of diethyl ether was added to a solution of GeCl$_4$ (0.161 g, 0.75 mmol) in 30 mL of diethyl ether at -80 °C. The reaction mixture was allowed to reach room temperature in 30 min and it was then heated to 35 °C for 15 h. The precipitate of LiCl was removed by filtration and the solvent was evaporated under vacuum giving Ge[PhB(μ-N-t-Bu)$_2$]$_2$ (1a) as a white powder (0.442 g, 83%). C$_{28}$H$_{46}$B$_2$N$_4$Ge: C 63.10; H 8.70; N 10.51. Found: C 62.85; H 8.94; N 10.71. $^1$H NMR (d$_8$-toluene, 23 °C): δ 7.20-7.49 [m, 10H, C$_6$H$_5$], 1.30 [s, 36H, C(CH$_3$)$_3$]. $^{13}$C NMR: δ 139.1-126.7 [C$_6$H$_5$], 51.3 [s, C(CH$_3$)$_3$], 33.7 [s, C(CH$_3$)$_3$]. $^{11}$B NMR: δ 35.2. Crystallization from n-hexane afforded colourless X-ray quality crystals of Ge[PhB(μ-N-t-Bu)$_2$]$_2$ (1a).

**Synthesis of Sn[PhB(μ-N-t-Bu)$_2$]$_2$ (1b)**

A solution of Li$_2$[PhB(μ-N-t-Bu)$_2$] (0.244 g, 1.00 mmol) in 25 mL of diethyl ether was added to a solution of SnCl$_4$ (0.5 mL of a 1.0 M solution in heptane, 0.50 mmol) in 25 mL of diethyl
ether at -80 °C. The reaction mixture was stirred for 30 min at -80 °C and 6 h at 23 °C. The precipitate of LiCl was removed by filtration and the solvent was evaporated under vacuum giving Sn[PhB(μ-N-t-Bu)2]2 (1b) as a white powder (0.257 g, 87%). C28H46B2N4Sn: C 58.08; H 8.01; N 9.68. Found: C 58.30; H 7.93; N 9.03. 1H NMR (d8-toluene, 23 °C): δ 7.12-7.49 [m, 10H, C6H5], 1.23 [s, 36H, C(CH3)3]. 13C NMR: δ 135.1-126.8 [C6H5], 51.7 [s, C(CH3)3], 35.0 [s, C(CH3)3]. 11B NMR: δ 35.0. 119Sn NMR: δ -83.0 (cf. -117.8 ppm for Sn[(2,4,6-i-Pr3C6H2)B(μ-N-t-Bu)2]2 in CDCl3) (8). Crystallization from n-hexane afforded colourless X-ray quality crystals of Sn[PhB(μ-N-t-Bu)2]2 (1b).

Oxidation of Sn[PhB(μ-N-t-Bu)2]2 (1b) with SO2Cl2

A solution of SO2Cl2 (0.040 mL, 0.067 g, 0.50 mmol) was dissolved in 10.0 mL of diethyl ether; 1.0 mL (0.05 mmol) of this solution was added to a solution of 1b (0.058g, 0.10 mmol) in 80 mL of diethyl ether at -80 °C. The reaction mixture was allowed to warm up to ca. -40 °C at which point the colourless solution became bright blue and a small amount of white powder (LiCl) appeared. An aliquot of the reaction solution was used for EPR spectroscopic measurements. The remaining reaction solution was allowed to reach room temperature, which resulted in the decomposition of the paramagnetic species at ca. 0 °C as indicated by disappearance of the blue colour.

Synthesis of Li2Sn[PhB(μ-N-t-Bu)2]2 (2b)

A solution of Li2[PhB(μ-N-t-Bu)2] (0.366 g, 1.50 mmol) in 25 mL of diethyl ether was added to a suspension of SnCl2 (0.142 g, 0.75 mmol) in 25 mL of diethyl ether at -80 °C. The reaction mixture was stirred for 30 min at -80 °C and 5 h at 23 °C. The precipitate of LiCl was removed by filtration and the solvent was evaporated under vacuum. The product was then washed
with cold $n$-hexane (*ca.* 10 mL) to give 2b as a white powder (0.364 g, 75%). Anal. Calcd for C$_{32}$H$_{50}$B$_2$Li$_2$NaSn: C 56.72; H 7.82; N 9.45. Found: C 55.45; H 7.99; N 9.18. $^1$H NMR (d$_8$-toluene, 23 °C): $\delta$ 6.98-7.72 [m, 10H, C$_6$H$_5$], 1.39 [shoulder, br, 9H, C(CH$_3$)$_3$], 1.19 [s, br, 27H, C(CH$_3$)$_3$]. $^1$H NMR (0 °C): $\delta$ 6.96-7.72 [m, 10H, C$_6$H$_5$], 1.44 [s, 9H, C(CH$_3$)$_3$], 1.21 [s, 27H, C(CH$_3$)$_3$]. $^1$H NMR (-20 °C): $\delta$ 6.92-7.70 [m, 10H, C$_6$H$_5$], 1.46 [s, 9H, C(CH$_3$)$_3$], 1.24 [s, 9H, C(CH$_3$)$_3$], 1.21 [s, 18H, C(CH$_3$)$_3$]. $^{13}$C NMR (-20 °C): $\delta$ 133.9-125.8 [C$_6$H$_5$], 54.4 [s, C(CH$_3$)$_3$], 52.1 [s, C(CH$_3$)$_3$], 51.1 [s, C(CH$_3$)$_3$], 37.0 [s, C(CH$_3$)$_3$], 36.6 [s, C(CH$_3$)$_3$], 36.1 [s, C(CH$_3$)$_3$]. $^{11}$B NMR (-20 °C): $\delta$ 36.6. $^7$Li NMR (-20 °C): $\delta$ 1.10. $^{119}$Sn NMR (d$_8$-toluene, 23 °C): $\delta$ -167.9 ppm. X-ray quality crystals of 2b were obtained by dissolving the white powder in boiling $n$-hexane and then allowing the solution to cool down to room temperature in *ca.* 3 h.

**Synthesis of (Et$_2$O·Li)LiPb[PhB(μ-N-t-Bu)$_2$]$_2$ (2c·OEt$_2$)**

**Method A.** A solution of Li$_2$[PhB(μ-N-t-Bu)$_2$] (0.244 g, 1.00 mmol) in 30 mL of diethyl ether was added to a suspension of PbI$_2$ (0.231 g, 0.50 mmol) in 30 mL of diethyl ether at -80 °C. The reaction mixture was allowed to reach room temperature in 30 min and it was then heated to 35 °C for 12 h. The precipitate of LiI was removed by filtration and the solvent was evaporated under vacuum giving a pale yellow, amorphous powder (0.294 g). $^1$H NMR spectroscopy revealed a mixture of products among which the lead(II) complex, [Pb[PhB(μ-N-t-Bu)$_2$]]$_2$, was identified ($\delta$ 1.15 ppm, d$_8$-toluene, 23 °C; lit. value (11): $\delta$ 1.19 in C$_6$D$_6$) in addition to the resonances of 2c·OEt$_2$ (see discussion of the VT NMR experiments). 2c·OEt$_2$: $^1$H NMR (d$_8$-toluene, 23 °C): $\delta$ 7.02-7.78 [m, C$_6$H$_5$], 3.40 [q, 6H, (CH$_3$CH$_2$)$_2$O], 1.27 [s, br, 36H, C(CH$_3$)$_3$], 1.00 [t, 6H, (CH$_3$CH$_2$)$_2$O]. $^1$H NMR (0 °C): $\delta$ 7.08-7.82 [m, C$_6$H$_5$], 3.34 [q, 6H, (CH$_3$CH$_2$)$_2$O], 1.35 [shoulder, 9H, C(CH$_3$)$_3$], 1.29 [s, 18H, C(CH$_3$)$_3$], 1.25 [shoulder, 9H, C(CH$_3$)$_3$], 0.97 [t, 6H, (CH$_3$CH$_2$)$_2$O]. $^1$H NMR (-10 °C): $\delta$ 7.10-7.83 [m, C$_6$H$_5$], 3.34 [q, 6H, (CH$_3$CH$_2$)$_2$O], 1.36 [s, 9H, C(CH$_3$)$_3$], 1.30 [s, 18H, C(CH$_3$)$_3$], 1.25
[s, 9H, C(CH₃)₃], 0.96 [t, 6H, (CH₂CH₂)₂O]. ⁷Li NMR (-20 °C): δ 0.87. Crystallization from THF afforded a few colourless crystals of (THF·Li)LiPb[PhB(μ-N-t-Bu)₂]₂ (2c·THF).

Method B. The Pb(II) complex {Pb[PhB(μ-N-t-Bu)₂]}₂ was prepared by a modification of the procedure reported earlier (11) from the reaction of PbI₂ (0.461 g, 1.00 mmol) and Li₂[PhB(μ-N-t-Bu)₂] (0.244 g, 1.00 mmol) in diethyl ether. The purity of the compound was checked by ¹H NMR spectroscopy. A solution of Li₂[PhB(μ-N-t-Bu)₂] (0.244 g, 1.00 mmol) in 30 ml of diethyl ether was added to a solution of {Pb[PhB(μ-N-t-Bu)₂]}₂ (0.437 g, 0.50 mmol) in 30 mL of diethyl ether at -80 °C. The reaction mixture was allowed to reach room temperature in 30 min and it was then heated to 35 °C for 18 h. The precipitate of LiI was removed by filtration and the solvent was evaporated under vacuum giving a pale yellow, amorphous powder (0.546 g). The ¹H NMR spectrum of this powder in d₈-toluene revealed a complex mixture of products. The reactions described in methods A and B were also carried out in THF at 55 °C without significant improvement in the yield of 2c.

Reaction of Li₂[PhB(μ-N-t-Bu)₂] with C₄H₈O₂·GeCl₂

A solution of Li₂[PhB(μ-N-t-Bu)₂] (0.183 g, 0.75 mmol) in 25 mL of diethyl ether was added to a solution of C₄H₈O₂·GeCl₂ (0.174 g, 0.75 mmol) in 25 mL of diethyl ether at -80 °C. The reaction mixture was stirred for 30 min at -80 °C and 16 h at 23 °C. The precipitate of LiCl was removed by filtration and the solvent was evaporated under vacuum giving a pale yellow, amorphous powder (0.185 g, 78% calculated as a 1:2 mixture of 1a and {Ge[PhB(μ-N-t-Bu)₂]}₂, see discussion). ¹H NMR (d₈-toluene, 23 °C): δ 7.02-7.96 [m, 30H, C₆H₅], 1.41 [s, 36H, C(CH₃)₃], 1.39 [s, 36H, C(CH₃)₃], 1.30 [s, 36H, C(CH₃)₃]. ¹¹B NMR (-20 °C): δ ca. 36.5 (br). Crystallization from n-hexane afforded a few colourless crystals of Ge[PhB(μ-N-t-Bu)₂]₂ (1a).

Results and discussion
X-ray structures of $\text{M}[	ext{PhB(µ-N-t-Bu)}_2]_2$ (1a, $\text{M} = \text{Ge}$; 1b, $\text{M} = \text{Sn}$)

The germanium(IV) and tin(IV) complexes 1a and 1b were obtained in excellent yields (ca. 85 %) by a modification of the literature synthesis in which the dilithium reagent Li$_2$[PhB(µ-N-t-Bu)$_2$] was isolated and purified prior to reaction with MCl$_4$ ($\text{M} = \text{Ge, Sn}$) in a 2:1 molar ratio in diethyl ether. The NMR spectroscopic data (see Experimental Section) showed minor variations compared with the literature values (7). Attempts to make the silicon analogue Si[PhB(µ-N-t-Bu)$_2$]$_2$ by a similar procedure were unsuccessful.

The X-ray structural determinations of 1a and 1b confirmed the expected spirocyclic structures with two orthogonal $\text{bam}$ ligands $\text{N,N'}$-chelated to the distorted tetrahedral metal centres (Fig. 1). In both complexes the molecule lies on a crystallographic two-fold axis that imposes equivalence on the two $\text{bam}$ ligands. The diamagnetic complexes 1a and 1b are isostructural with the paramagnetic group 13 analogues {M[PhB(µ-N-t-Bu)$_2$]$_2$}$^-$ ($\text{M} = \text{Al, Ga}$) (4). The centrosymmetric germanium(IV) complex 1a represents the first structurally characterized germanium $\text{bam}$ complex (1).

Selected bond lengths and bond angles for 1a and 1b are summarized in Table 2. The distorted tetrahedral germanium centre in 1a exhibits equal Ge-N bond lengths, which are noticeably shorter (by ca. 0.20 Å) than the corresponding M-N bonds in the heavier tin analogue 1b. Somewhat surprisingly, the Ge-N bonds in 1a are also significantly shorter than the Ga-N bond lengths of 1.922(2) Å observed in the neutral radical Ga[PhB(µ-N-t-Bu)$_2$]$_2$ (4), despite the difference of only one electron between the two centres (Ge and Ga). The Ge-N bond lengths are, however, equal within estimated standard deviation with the Al-N bond lengths of 1.842(2) and 1.852(2) Å reported for {Al[PhB(µ-N-t-Bu)$_2$]$_2$}$^-$ (4), for which the difference between the two metal centers (Ge and Al) is nine electrons. These trends in bond lengths may be attributed to the weaker Coulomb interaction in the paramagnetic group 13 complexes where the total charge on the ligands is formally 3-
compared to the diamagnetic group 14 complexes for which the formal charge is 4-. Interestingly, the Ge-N bonds in 1a are also ca. 0.04 Å longer than the As-N bond lengths of 1.797(4)-1.811(4) Å observed in the isostructural, and isoelectronic, group 15 cation As[PhB(μ-N-t-Bu)2]2⁺ (in the GaCl4⁻ salt) (22). Since the single bond covalent radius is the same for Ge and As (1.22 Å) (23), the shorter As-N bonds are probably due to the stronger electrostatic interaction between the positively charged arsenic centre and the two dianionic bam ligands. In the tin(IV) complex 1b the Sn-N bonds within each bam ligand are equal in length and are close to the values of 2.043(3)-2.066(3) Å observed in the eight-membered rings {Me₂Sn[μ-N(Me)B(R)NMe]₂SnMe₂} (R = 2,4,6-i-Pr₃C₆H₂, 2,4,6-t-Bu₃C₆H₂), which also involve Sn(IV) centres (8, 24), but they are somewhat shorter than the value of 2.105(1) Å found for the Sn-N bond involving a three-coordinate nitrogen atom in the dimeric Sn(II) complex, {Sn[MeB(μ-NSiMe₃)₂]}₂ (25). The B-N bond lengths in both 1a and 1b are equal and represent typical values for the bam ligand (1).

The M-N-B angles in 1a and 1b are close to 90° and the geometry about boron atom is trigonal planar as indicated by the sum of bond angles (360°). The N-B-N and all N-Ge-N angles in 1a are close to the corresponding bond angles observed in {Al[PhB(μ-N-t-Bu)₂]}⁺ (4) due to the identical Ge-N/Al-N and B-N bond lengths, whereas the longer Sn-N bonds result in a narrower N-Sn-N angle by ca. 7 and 3° within the bam ligands in 1b. The GeBN₂ four-membered rings in 1a are planar with torsion angles of 0.5(2) and 0.6(2)° for ∠N2-Ge1-N1-B1 and Ge1-N1-B1-N2, respectively, while the corresponding torsion angles for the slightly puckered SnBN₂ four-membered rings in 1b are 4.6(2) and 6.5(3)°.

Although all four isostructural compounds (1a, 1b and M[PhB(μ-N-t-Bu)₂])⁺ (M = Al, Ga) exhibit a centre of symmetry at the group 13 or 14 atom, the tin complex 1b exhibits different crystal packing from the other three complexes as indicated by the crystal system and space group [monoclinic C2/c for 1b vs. orthorhombic Pbcn for 1a and M[PhB(μ-N-t-Bu)₂])⁺ (M = Al, Ga)].
EPR spectra and DFT calculations of the radical cation \( \text{Sn}[^\mu\text{PhB}(\mu-\text{N-t-Bu})_2]^+ \)

The intensely coloured spirocyclic group 13 radicals \( \{\text{M}[\text{PhB}(\mu-\text{N-t-Bu})_2]\}^+ \) (\( \text{M} = \text{Al, Ga} \)) (Scheme 1) are stable in the solid state (4), while the indium analogue \( \{\text{In}[\text{PhB}(\mu-\text{N-t-Bu})_2]\}^+ \) has only been characterized in solution by EPR spectroscopy (5). In an attempt to generate the isoelectronic radical cations with a group 14 metal centre, \( \{\text{M}[\text{PhB}(\mu-\text{N-t-Bu})_2]\}^+ \) (\( \text{M} = \text{Ge, Sn} \)), we have investigated the reactions of 1a and 1b with various oxidizing agents (Scheme 2).

**Scheme 2.** One-electron oxidation of \( \{\text{M}[\text{PhB}(\mu-\text{N-t-Bu})_2]\} \) (\( \text{M} = \text{Ge, Sn} \))

The attempted one-electron oxidation of 1a or 1b to the corresponding radical cation by one-half equivalent of I\(_2\) in diethyl ether or THF resulted in no reaction even at elevated temperatures. The tin(IV) complex 1b was also inert towards [NO][SbF\(_6\)] and, surprisingly, the germanium(IV) complex 1a showed no indication of a reaction with SO\(_2\)Cl\(_2\). However, the treatment of 1b with one-half equivalent of SO\(_2\)Cl\(_2\) in diethyl ether at low temperatures produced a bright blue solution of \( \{\text{Sn}[\text{PhB}(\mu-\text{N-t-Bu})_2]\}^+ \) \((\text{vide infra})\), which was persistent below -40 °C, but decomposed above 0 °C, \( cf. \) the thermal instability of the isoelectronic indium-containing neutral radical \( \{\text{In}[\text{PhB}(\mu-\text{N-t-Bu})_2]\}^+ \) (5).

The EPR spectrum of the blue solution in diethyl ether displays an eight-line pattern and a highly broadened lineshape (Fig. 2); the g-value of this radical is 2.0055. Several attempts to resolve additional fine structure in the EPR spectrum by variations in the solvent, concentration of the solution and temperature, as well as changes in the measurement parameters, were unsuccessful. A reasonable simulation of the observed spectrum is obtained by using a line width of 2.85 G (95%
Gaussian shape) and by including hyperfine coupling constants to one boron atom ($^{11}$B, $I = 3/2$, 9.88 G) and two equivalent nitrogen centers ($^{14}$N, $I = 1$, 9.18 G) (Fig. 2) thus suggesting localization of the unpaired electron in only one of the *bam* units, in contrast to the delocalization over both *bam* ligands observed for the neutral group 13 radicals \{M[PhB(μ-N-t-Bu)$_2$]$^\cdot$ (M = Al, Ga, In) (4, 5). This electron distribution is, however, reminiscent of the behaviour noted for the persistent radicals \{(Et$_2$O)Li[PhB(μ-N-t-Bu)$_2$]$^\star$M\} ($M$ = Mg, Zn), which exhibit localization of the unpaired electron on the spin-active nuclei in only one of the *bam* ligands as a consequence of the coordination of the additional lithium counter-cation to the second *bam* unit (5).

The apparent localization of the unpaired electron in only one of the *bam* ligands, and the strong coordinating nature of the Cl$^-$ counter-anion, raised the possibility of the formation of neutral radicals, \{Sn[PhB(μ-N-t-Bu)$_2$]Cl\}$^\star$, comprising a Sn-Cl or B-Cl contact instead of the ion-separated radical cation, \{Sn[PhB(μ-N-t-Bu)$_2$]$^\cdot$\} ($^\cdot$ (Scheme 3), cf. the Zwitterionic arsenic(V) complex, \{[PhB(μ-N-t-Bu)$_2$]As[(μ-N-t-Bu)$_2$B(Cl)Ph]\}, with a covalent B-Cl bond (22). Consequently, the replacement of the Cl$^-$ anion by the weakly coordinating SbF$_6^-$ was performed by an *in situ* reaction with AgSbF$_6$. The thermal stability of the radical cation was not improved, but a colour change from blue to purple was observed along with the formation of AgCl. The EPR spectrum of the purple solution, however, was unaffected by the change of the counter-anion, suggesting that the one-electron oxidation product of 1b is present in very dilute diethyl ether solutions as the ion-separated radical cation I rather than the “contact ion-pairs” II or III.

**Scheme 3.** Possible structures of the product of one-electron oxidation of 1b with SO$_2$Cl$_2$. 
Density functional theory calculations conducted for the cation radical \{\text{Sn[PhB(μ-N-t-Bu)]}_{2}\}_2^{*+}\ predict a \(C_{2v}\)-symmetric minimum structure and localized spin density on only one \textit{bam}-ligand (Fig. 3). A \(D_{2d}\)-symmetric structure, analogous to that observed for the neutral group 13 radicals \{\text{M[PhB(μ-N-t-Bu)]}_{2}\}_2^-(M = \text{Al, Ga}) (Scheme 1), is a transition state with respect to Sn-N stretching vibrations and only 5 kJ mol\(^{-1}\) higher in energy. Hence, it appears that the spiroconjugative interactions in \textbf{1b} are not sufficiently strong to give rise to a fully delocalized electron distribution in the corresponding cation,\(^5\) and the system adopts a structure with the two \textit{bam}-ligands bearing different formal charges, i.e. Sn(IV)(\textit{bam})^{2-}(\textit{bam})^*\). This is consistent with the finding that optimizations carried out for the lighter group 14 congeners of \{\text{M[PhB(μ-N-t-Bu)]}_{2}\}_2^{*+}\ (M = \text{Si, Ge}) give minima with significantly shorter N⋯N separations and, consequently, only \(D_{2d}\)-symmetric structures are found.

The hyperfine coupling constants calculated for \text{Sn[PhB(μ-N-t-Bu)]}_{2}\}_2^{*+}\ (2 \times ^{14}\text{N}, 7.35 \text{G}; 2 \times ^{14}\text{N}, 0.05 \text{G}; ^{11}\text{B}, -10.96 \text{G}; ^{11}\text{B}, -0.32 \text{G}) are in good agreement with the values determined from the experimental spectrum. Similar to the previous observations for the persistent radicals \{(\text{Et}_2\text{O})\text{Li[PhB(μ-N-t-Bu)]}_{2}\}_2\text{M}^*\ (M = \text{Mg, Zn}) (5), the calculated nitrogen couplings are too small, whereas the coupling to the boron nuclei is slightly larger than the value inferred from the simulation; there is an apparent tendency of this functional basis set combination to underestimate
couplings that result from the spin density of the unpaired electron while overestimating those which arise from spin-polarization effects (4, 5). The undulating baseline of the EPR spectrum and the low intensity humps visible at both ends of the spectrum most likely arise from the presence of small amounts of isotopomers which contain the spin-active tin nuclei \(^{(117}\text{Sn}, I = \frac{1}{2}, 7.6 \%; \ 119}\text{Sn}, I = \frac{1}{2}, 8.6 \%)\). The magnitudes of the two Sn couplings cannot, however, be obtained with the current computational method due to the indirect treatment of relativistic effects via effective core potential basis sets. The observed broad lineshape can, at least in part, be attributed to the numerous smaller couplings to the hydrogen atoms of the \(t\)-Bu groups.\(^6\)

**Synthesis of Li\(_2\)Sn[PhB(\(\mu\)-N-\(t\)-Bu)\(_2\)]\(_2\) (2b) and (THF-Li)LiPb[PhB(\(\mu\)-N-\(t\)-Bu)\(_2\)]\(_2\) (2c·THF)**

The reactions of Li\(_2\)[PhB(\(\mu\)-N-\(t\)-Bu)\(_2\)] with group 14 dihalides in a 2:1 molar ratio were investigated with a view to isolating and structurally characterizing complexes of the type Li\(_2\)M[PhB(\(\mu\)-N-\(t\)-Bu)\(_2\)]\(_2\) in which the dianions M[PhB(\(\mu\)-N-\(t\)-Bu)\(_2\)]\(_2\)\(^{2-}\) (M = Ge, Sn, Pb) are isoelectronic with the previously reported group 15 anions M[PhB(\(\mu\)-N-\(t\)-Bu)\(_2\)]\(^{-}\) (M = As, Sb, Bi), which were obtained as monolithium derivatives (12). The outcome of these reactions was markedly dependent on the nature of the group 14 metal.

The reaction between Li\(_2\)[PhB(\(\mu\)-N-\(t\)-Bu)\(_2\)] and SnCl\(_2\) in a 2:1 molar ratio in diethyl ether proceeded cleanly to produce Li\(_2\)Sn[PhB(\(\mu\)-N-\(t\)-Bu)\(_2\)]\(_2\) (2b) in 75 % yield (eq. [1]). The unsolvated heterotrinuclear complex 2b was characterized in solution by multinuclear NMR spectroscopy and in the solid state by single crystal X-ray crystallography.

\[ 2 \text{Li}_2[\text{PhB}(\mu\text{-N-}t\text{-Bu})_2] + \text{SnCl}_2 \rightarrow \text{Li}_2\text{Sn}[\text{PhB}(\mu\text{-N-}t\text{-Bu})_2]_2 + 2 \text{LiCl} \]

(2b)
The reaction of Li$_2$[PhB(μ-N-t-Bu)$_2$] with PbI$_2$ in 2:1 molar ratio was conducted under various conditions in an effort to produce the analogous lead(II) complex Li$_2$Pb[PhB(μ-N-t-Bu)$_2$]$_2$ (2c). The $^1$H NMR spectrum of the reaction mixture, however, revealed several products, one of which was identified as the previously reported mononuclear lead(II) complex, {Pb[PhB(μ$_3$-N-t-Bu)$_2$]}$_2$ (11). In an alternative synthetic approach, this dimeric Pb(II) complex was prepared and isolated prior to treatment with two equivalents of Li$_2$[PhB(μ-N-t-Bu)$_2$]. However, this two-step method also afforded a mixture of products from which only a few crystals of 2c were isolated as the tetrahydrofuran solvate, (THF·Li)LiPb[PhB(μ-N-t-Bu)$_2$]$_2$ (2c·THF).

The reaction of Li$_2$[PhB(μ-N-t-Bu)$_2$] with C$_4$H$_8$O$_2$·GeCl$_2$ in 2:1 molar ratio in diethyl ether produced several products ($^1$H NMR). Consequently, the reaction was repeated in 1:1 molar ratio in an attempt to form the unknown germanium(II) complex, Ge[PhB(μ-N-t-Bu)$_2$], for subsequent reaction with Li$_2$[PhB(μ-N-t-Bu)$_2$]; this two-step approach was previously found to be necessary for the successful synthesis of the aluminum complex (Et$_2$O·Li)Al[PhB(μ-N-t-Bu)$_2$]$_2$ (4). The $^1$H NMR spectrum of the product(s) showed three equally intense resonances for N-t-Bu groups at 1.41, 1.39 and 1.30 ppm (d$_8$-toluene, 23 °C). The chemical shift of 1.30 ppm is identical with the value observed for the t-Bu groups in the germanium(IV) complex Ge[PhB(μ-N-t-Bu)$_2$]$_2$ (1a) (8), suggesting that a redox process has occurred. The resonances at 1.41 and 1.39 are tentatively assigned to the t-Bu groups attached to the three- and four-coordinate nitrogen atoms of the dimeric complex germanium(II) complex {Ge[PhB(μ-N-t-Bu)$_2$]}$_2$; however, attempts to isolate this second product were unsuccessful.

**X-ray structures of Li$_2$Sn[PhB(μ-N-t-Bu)$_2$]$_2$ (2b) and (THF·Li)LiPb[PhB(μ-N-t-Bu)$_2$]$_2$ (2c·THF)**

Crystals of 2b and 2c·THF were obtained by recrystallization from boiling n-hexane and THF, respectively. The crystal structures of 2b and 2c·THF with the atomic numbering scheme are depicted in Fig. 4 and the pertinent bond parameters are summarized in Table 3. The structures
reveal novel polycyclic arrangements, which bear a close similarity with each other despite the introduction of a solvent molecule in 2c·THF. In both frameworks one of the bam ligands is N,N'-chelated to both the M(II) atom (M = Sn, Pb) and one of the Li+ ions while the second bam ligand exhibits a unique bonding motif by bridging all three metal centers (1). While one of the Li+ ions (Li1) in both structures is coordinated to three nitrogens, the second lithium in 2c·THF is coordinated to two nitrogen atoms and the solvent molecule. The absence of the solvent molecule in 2b affords a third, albeit relatively weak, Li···N close contact [2.557(6) Å] for the second lithium cation that results in a formal coordination number of five for the N4 atom (Fig. 4a).

Lithium salts of the group 15 monoanions M[PhB(μ-N-t-Bu)2]2− (3, M = Sb; 4, M = Bi) (12), which are isoelectronic with the group 14 dianions M[PhB(μ-N-t-Bu)2]22− (M = Sn, Pb), provide an interesting benchmark for comparison with the structures of 2b and 2c·THF (Scheme 4) Curiously, the lighter complexes in both group 14 (M = Sn) and group 15 (M = Sb) seem to favour unsolvated structures, whereas solvation of the Li+ cation is observed for the heavier congeners (M = Pb, Bi). The molecular structure of the antimony complex 3 is comprised of two four-membered rings, BN2Li and BN2Sb, connected by Li-N and Sb-N bonds to form a tricyclic compound with both three and four-coordinate nitrogens (12). The introduction of a second Li+ ion in 2b has a surprisingly small effect on the overall structure; the molecule retains the ladder-like backbone and cisoid arrangement of the PhBN-t-Bu -units. Most significantly, however, the Li2···N4 contact in 2b (Fig. 4a, dashed line in Scheme 4) is elongated by ca. 0.28 Å compared to the analogous bond in the antimony complex due to the pseudo-five-coordination of the nitrogen atom. The lithium cation in the bismuth complex 4·OEt2 (Scheme 4) is four-coordinate, being N,N'-chelated by one bam ligand and bonded to one nitrogen of the second bam ligand; the fourth coordination site is occupied by a Et2O molecule (12). The introduction of a second Li+ ion in 2c·THF ruptures the bond between the solvated Li+ ion and the second bam ligand, and cleaves the fourth M-N bond (M = Bi) that exists in the structure of 4·OEt2, although it is elongated compared to the other three Bi-N bonds (by ca. 0.18
Å) (12). As a result, both Li$^+$ ions are three-coordinate and all four nitrogen atoms are four-coordinate in 2c·THF.

**Scheme 4.** Comparison of the structures of Li$_2$M[PhB(μ-N-t-Bu)$_2$]$_2$ (M = Sn, Pb) and LiM[PhB(μ-N-t-Bu)$_2$]$_2$ (M = Sb, Bi)

The average Sn-N bond length of 2.187(4) Å in 2b (Fig. 4a, Table 3) is significantly longer than the values of 2.043(3)-2.066(3) Å observed in 1b and in the Sn(IV) complexes {Me$_2$Sn[μ-N(Me)B(R)NMe]$_2$SnMe$_2$} (R = 2,4,6-Pr$_3$C$_6$H$_2$, 2,4,6-t-Bu$_3$C$_6$H$_2$) (8, 24), but slightly shorter than the distance of 2.254(13) Å found for the Sn-N bonds involving four-coordinate nitrogen atoms in the dimeric Sn(II) complex [Sn[MeB(μ$_2$-NSiMe$_3$)$_2$]]$_2$ (25). Expectedly, the Sn-N bond lengths are also close to the values of 2.145(5) and 2.198(5) Å observed for the Sb-N bonds to the four-coordinate nitrogens in 3 (the single bond covalent radii for Sn and Sb are 1.40 and 1.43 Å, respectively) (23). The Li1-N distance to the bridging bam ligand is ca. 0.18 Å shorter than the two Li1-N bonds to the chelating bam ligand. To compensate for the long Li2···N4 contact, the two Li2-N bonds of 1.869(5) and 1.884(5) Å are among the shortest lithium-nitrogen bonds observed for this ligand system (1).
The introduction of a second Li\(^+\) ion in 2b results in opening the angle between BN\(_2\)Sn and LiN\(_2\)Sn four-membered rings as illustrated by the N1-Sn1-N3 and Li2-N4-B2 angles, which are ca. 4 and 9\(^\circ\) wider, respectively, than the corresponding angles in the related antimony complex, 3 (12). Widening of these angles and elongation of the Sn1-N1 and Li2-N4 contacts in 2b compared to the analogous Sb-N and Li-N bonds, however, allows B1 and N2 atoms to incline towards the central SnLiN\(_2\) four-membered ring and, consequently, the Sn1-N1-B1 and N4-Li2-N2 angles are ca. 4 and 5\(^\circ\) narrower than the comparable angles in 3. The N-Sn-N angle within the chelating bam ligand in 2b is ca. 5.7\(^\circ\) smaller than the corresponding angle in 1b owing to the slightly longer Sn-N bonds in 2b.

The average Pb-N bond length in 2c·THF (Fig. 4b, Table 3) of 2.330(3) Å is identical to the value of 2.329(6) Å observed for the Pb-N bond involving a four-coordinate nitrogen atom in the dimeric lead(II) complex \{Pb[PhB(\mu-3-N-t-Bu)\(_2\)]\}\(_2\) (10). The Pb-N bonds are ca. 0.06 Å longer than the three Bi-N bonds in 4·OEt\(_2\) (cf. the single bond covalent radii of 1.54 and 1.52 Å for Pb and Bi) (23), but they are ca. 0.11 Å shorter than the fourth, elongated, Bi-N bond in the bismuth complex (12). The Li-N distances to the N2 atom in the bridging ligand in 2c·THF are somewhat shorter than the remaining three Li-N interactions (ca. 0.12 and 0.07 Å for Li1-N2 and Li2-N2, respectively). All these distances are consistent with, for example, those in the group 13 and 15 complexes (Et\(_2\)O·Li)M[PhB(\mu-N-t-Bu)\(_2\)]\(_2\), which show two (M = Ga, In, As) or three (M = Bi) Li-N interactions (3, 12). The N-Pb-N angle in the chelating ligand is ca. 10\(^\circ\) narrower than the N-Li-N angle at the unsolvated Li\(^+\) ion due to the longer Pb-N bonds.

The bridging bam ligand in both 2b and 2c·THF exhibits a significant disparity in the B-N bond lengths (ca. 0.12 and 0.08 Å, respectively), presumably as a result of the different environments of N1 and N2, whereas the equality of the B-N bonds in the chelating bam ligand is not significantly perturbed by the weak Li2···N4 contact. The N-B-N angle in the chelating ligand in both 2b and 2c·THF is somewhat smaller (by 7.1 and 6.4\(^\circ\), respectively) than the analogous bond.
angle in the bridging *bam* ligand. Nevertheless, the boron atom assumes trigonal planar geometry in the *bam* ligands in both complexes. The bond angles at the nitrogen atoms in the chelating ligand are close to 90°, whereas the loss of the fourth M-N bond results in a wider M1-N1-B1 angle by *ca.* 32° (*M* = Sn) and 30° (*M* = Pb).

**NMR spectra and fluctional behaviour of Li₂Sn[PhB(μ-N-t-Bu)₂]₂ (2b)**

The \(^1\)H NMR spectrum of 2b in d₈-toluene at 23 °C exhibits a broad, poorly resolved signal for t-Bu groups, in addition to typical resonances for the phenyl groups. When the temperature is lowered to 0 °C, this broad resonance resolves into two well-separated signals at 1.44 and 1.21 ppm in a 1:3 intensity ratio. Cooling the solution to -20 °C results in resolution of the latter resonance to give three singlets at 1.46, 1.24 and 1.21 ppm in a 1:1:2 intensity ratio.\(^8\) No further changes are apparent at lower temperatures. Consistently, the \(^{13}\)C NMR spectrum of 2b at -20 °C exhibits three singlets at 54.4, 52.1 and 51.1 ppm for the α-carbon atoms of the t-Bu groups; three singlets are also observed for the methyl carbons at 37.0, 36.6 and 36.1 ppm, in addition to the phenyl resonances. Throughout the temperature range (from -80 to +23 °C) only one broad singlet is observed in both the \(^{11}\)B and \(^7\)Li NMR spectrum (at 36.6 and 1.10 ppm, respectively, at -20 °C in d₈-toluene). The \(^{119}\)Sn NMR spectrum of 2b shows a single resonance at -167.9 ppm, which exhibits a significant shift to higher field from the value of 120 ppm reported for the dimeric tin(II) complex, {Sn[MeB(μ₃-NSiMe₃)]₂}₂ (25). However, chemical shift values of -151.8 to -158.1 ppm have been reported for the related tin(II) complexes {Sn[RSi(μ₃-N-t-Bu)]₂}₂ (R = C₃H₆, C₄H₆, C₄H₈ and C₅H₁₀) (26), which exhibit a coordination environment around the tin(II) centres similar to that in 2b. The three resonances with a 1:1:2 intensity ratio observed at -20 °C in the \(^1\)H NMR spectrum of 2b are assigned to the *tert*-butyl groups attached to N1, N2 and N3/N4, respectively (Fig. 4a). The observation of only one broad resonance for the inequivalent boron and lithium atoms in the structure of 2b even at low temperatures is attributed to overlap of these resonances.
The fluctional behaviour observed for 2b is reminiscent of the exchange processes exhibited by the related group 15 complexes, 3 and 4·OEt₂, which both showed only a single \( t\)-Bu resonance at room temperature (12). These types of fluctional processes in lithium derivatives of polyimido anions of p-block elements are known to have low activation energies (27). In the case of 3 and 4·OEt₂, the fluctionality was determined to originate from a Berry pseudorotation (12). In a similar manner, the single resonance observed at room temperature in the \(^1\)H NMR spectra of 2b can be attributed to a rapid exchange in which each of the four nitrogens, in turn, occupy the site that is not coordinated to the tin centre.

Conclusions

Comparison of the properties of the cation radicals \{\( M[\text{PhB}(\mu-\text{N-}t\text{-Bu})_2]_2 \})^+ (M = Si, Ge, Sn) with those of the isoelectronic neutral radicals \( M[\text{PhB}(\mu-\text{N-}t\text{-Bu})_2]_2 \})^+ (M = Al, Ga, In) was limited to the tin derivative as a result of the inertness of Ge[\( \text{PhB}(\mu-\text{N-}t\text{-Bu})_2]_2 \) towards oxidizing agents and the inaccessibility of Si[\( \text{PhB}(\mu-\text{N-}t\text{-Bu})_2]_2 \). The blue radical cation \{Sn[\( \text{PhB}(\mu-\text{N-}t\text{-Bu})_2]_2 \})^{++}, which exhibits thermal instability similar to that of the neutral group 13 analogue In[\( \text{PhB}(\mu-\text{N-}t\text{-Bu})_2]_2 \}), was characterized at low temperatures by EPR spectroscopy. In contrast to the isoelectronic, \( D_{2h} \)-symmetric indium bis-bam radical, DFT calculations predict a \( C_{2v} \) symmetry for the radical cation \{Sn[\( \text{PhB}(\mu-\text{N-}t\text{-Bu})_2]_2 \})^{++} with spin density localized on only one of the bam ligands owing to the weak spiroconjugative N···N interactions that, presumably, prevent the delocalization of the unpaired electron over both ligands.

In the heterotrimetallic complexes Li₂M[\( \text{PhB}(\mu-\text{N-}t\text{-Bu})_2]_2 \) [M = Sn, Pb (THF omitted)], one of the bam ligands exhibits a novel bonding mode in which it bridges all three metal centres (1). The solid-state structures of these group 14 complexes are comparable with those of the previously reported group 15 complexes Li₅[\( \text{PhB}(\mu-\text{N-}t\text{-Bu})_2]_2 \) [M = Sb, Bi (OEt₂ omitted)] (12). Despite the introduction of a second Li⁺ ion, the tin complex maintains the ladder-like backbone and cisoid...
arrangement of the *bam* ligands found in the antimony analogue. The intrusion of a second Li$^+$ ion in the lead complex results in rupture of the bond between the solvated Li$^+$ ion and one of the *bam* ligands, as well as cleavage of the fourth M-N bond (M = Bi, Pb) that exists in the structure of (Et$_2$O-Li)Bi[PhB($\mu$-N-t-Bu)$_2$]$_2$. In view of these structural similarities it is, perhaps, not surprising that the variable temperature NMR spectra of Li$_2$Sn[PhB($\mu$-N-t-Bu)$_2$]$_2$ show trends comparable to those previously observed for the group 15 complex LiSb[PhB($\mu$-N-t-Bu)$_2$]$_2$ (12), implying that the flucational processes are also similar.

**Acknowledgements**

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**Footnotes**

1 Department of Chemistry, University of Calgary, Calgary, Alberta T2N 1N4, Canada.
2 Department of Chemistry, University of Jyväskylä, P.O. Box 35, Jyväskylä, FI-40014, Finland.
3 Corresponding author (e-mail: chivers@ucalgary.ca).
4 Supplementary data for this article are available on the journal Web site (canjchem.nrc.ca) or may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Ottawa, ON K1A 0R6, Canada. DUD 3672. For more information on obtaining material, refer to cisti-icist.nrc-cnrc.gc.ca/irm/unpub_e.shtml. CCDCXXXXXXX-XXXXXXX contain the crystallographic data for this article. These data can be obtained, free of charge, via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax +44 1223 336033; or deposit@ccdc.cam.ac.uk).
Spiroconjugation is thought to contribute to the stability of the neutral group 13 radicals \( \{M[PhB(μ-N-t-Bu)₂]₂\}^\bullet \) (\( M = \text{Al, Ga} \)) (see ref. 4, and references cited therein).

DFT calculations were also performed for the neutral (\( C_1 \) symmetric) systems II and III (Scheme 3), which comprise a Sn-Cl or a B-Cl bond, respectively. The paramagnetic species II is \( \text{ca.} 80 \text{ kJ mol}^{-1} \) lower in energy, but the calculated hyperfine coupling constants for II and III are in poor agreement with those obtained from the experimental spectrum. The Sn-Cl bonded radical II exhibits a large (-11.56 G) coupling to the \(^{11}\text{B} \) centre but, due to the lack of symmetry, the hfc couplings to the two nitrogen atoms are not equal (9.15 G and 5.56 G). The B-Cl bonded system III displays a coupling of -7.37 G to the \(^{11}\text{B} \) isotope, and two inequivalent couplings of 11.24 and 2.26 G to the \(^{14}\text{N} \) nuclei.

Crystals of 2b could not be obtained from diethyl ether. The attempted recrystallization of 2b from THF resulted in a yellow solution, which contained the tin(IV) complex 1b \( [^1\text{H} \text{NMR spectrum (in } d_8-\text{THF})] \) as one component.

The variable temperature \(^1\text{H} \) NMR spectra of the lead complex 2c exhibit similar trends; the broad singlet observed for \( t-\text{Bu} \) groups at 1.27 ppm at 23 °C resolves into three resonances at 1.36, 1.30 and 1.25 ppm (with a 1:2:1 intensity ratio) at -10 °C. However, these and other NMR data for 2c were obtained on a reaction mixture and, consequently, any conclusions are necessarily tentative.

References


21. (a) L. J. Laaksonen Mol. Graph. 33, 10 (1992); (b) D. L. Bergman, L. Laaksonen and A. Laaksonen J. Mol. Graph. Model. 15, 301 (1997).


Table 1. Crystallographic data for 1a, 1b, 2b, and 2c·THF.\

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<td>$a$, Å</td>
<td>17.259(4)</td>
<td>24.846(5)</td>
<td>13.544(3)</td>
<td>9.188(2)</td>
</tr>
<tr>
<td>$b$, Å</td>
<td>8.917(2)</td>
<td>8.738(2)</td>
<td>11.828(2)</td>
<td>10.201(2)</td>
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<tr>
<td>$c$, Å</td>
<td>20.256(4)</td>
<td>18.065(4)</td>
<td>20.059(4)</td>
<td>20.649(4)</td>
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<tr>
<td>$\alpha$, deg.</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>79.05(3)</td>
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<td>$\beta$, deg.</td>
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<td>128.29(3)</td>
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<tr>
<td>$\gamma$, deg.</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
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<tr>
<td>$V$, Å$^3$</td>
<td>3117(1)</td>
<td>3078(2)</td>
<td>3108(1)</td>
<td>1801.1(7)</td>
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<tr>
<td>$Z$</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>$T$, °C</td>
<td>-100</td>
<td>-100</td>
<td>-100</td>
<td>-100</td>
</tr>
<tr>
<td>$\rho$$_{\text{calc}}$, g/cm$^3$</td>
<td>1.135</td>
<td>1.249</td>
<td>1.267</td>
<td>1.389</td>
</tr>
<tr>
<td>$\mu$(Mo Kα), mm$^{-1}$</td>
<td>1.004</td>
<td>0.851</td>
<td>0.844</td>
<td>4.712</td>
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<tr>
<td>crystal size, mm$^3$</td>
<td>0.20x0.16x0.12</td>
<td>0.44x0.36x0.06</td>
<td>0.40x0.06x0.02</td>
<td>0.24x0.20x0.08</td>
</tr>
<tr>
<td>$F$(000)</td>
<td>1136</td>
<td>1208</td>
<td>1232</td>
<td>760</td>
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<tr>
<td>$\Theta$ range, deg</td>
<td>2.57-25.02</td>
<td>3.23-25.02</td>
<td>3.38-25.03</td>
<td>3.57-25.03</td>
</tr>
<tr>
<td>reflns collected</td>
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<td>9846</td>
<td>12174</td>
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<td>unique reflns</td>
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<td>2709</td>
<td>5430</td>
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<tr>
<td>$R$$_{\text{int}}$</td>
<td>0.0213</td>
<td>0.0236</td>
<td>0.0457</td>
<td>0.0282</td>
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<tr>
<td>reflns [$I&gt;2\sigma(I)$]</td>
<td>2066</td>
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<td>$R$$_1$ [$I&gt;2\sigma(I)$]</td>
<td>0.0360</td>
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<tr>
<td>$wR$$_2$ (all data) $^c$</td>
<td>0.0901</td>
<td>0.0808</td>
<td>0.0993</td>
<td>0.0555</td>
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<tr>
<td>GOF on $F^2$</td>
<td>1.059</td>
<td>1.033</td>
<td>1.103</td>
<td>1.032</td>
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<tr>
<td>completeness</td>
<td>0.990</td>
<td>0.996</td>
<td>0.991</td>
<td>0.996</td>
</tr>
</tbody>
</table>

$^a\lambda$(MoKα) = 0.71073 Å. $^bR_1 = \Sigma |F_o| - |F_c|/\Sigma |F_o|$. $^c wR_2 = (\Sigma w(F_o^2 - F_c^2)^2/\Sigma wF_o^4)^{1/2}$. 
Table 2. Selected bond lengths (Å) and angles (°) in 1a and 1b

<table>
<thead>
<tr>
<th></th>
<th>1a&lt;sup&gt;a&lt;/sup&gt;</th>
<th>1b&lt;sup&gt;b&lt;/sup&gt;</th>
<th>1a&lt;sup&gt;a&lt;/sup&gt;</th>
<th>1b&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1-N1</td>
<td>1.846(2)</td>
<td>2.047(2)</td>
<td>B1-N1</td>
<td>1.438(3)</td>
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<tr>
<td>M1-N2</td>
<td>1.842(2)</td>
<td>2.047(2)</td>
<td>B1-N2</td>
<td>1.439(4)</td>
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<tr>
<td>N1-M1-N2</td>
<td>75.9(1)</td>
<td>69.2(1)</td>
<td>M1-N2-B1</td>
<td>90.2(2)</td>
</tr>
<tr>
<td>N1-M1-N1’</td>
<td>128.6(1)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>129.2(2)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>N1-B1-N2</td>
<td>104.0(2)</td>
</tr>
<tr>
<td>N1-M1-N2’</td>
<td>127.8(1)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>132.8(1)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>N1-B1-C9</td>
<td>127.3(2)</td>
</tr>
<tr>
<td>N2’-M1-N2’</td>
<td>129.8(1)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>135.5(1)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>N2-B1-C9</td>
<td>128.7(2)</td>
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<td>M1-N1-B1</td>
<td>90.0(2)</td>
<td>91.2(2)</td>
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</tbody>
</table>

<sup>a</sup> M = Ge, <sup>b</sup> M = Sn. Symmetry operation for the atoms marked with a single quote (‘); <sup>c</sup> x, y, 0.5-z.; <sup>d</sup> 1-x, y, 1.5-z.
Table 3. Selected bond lengths (Å) and angles (°) in 2b and 2c-THF.

<table>
<thead>
<tr>
<th></th>
<th>2b(^a)</th>
<th>2c-THF(^b)</th>
<th>2b(^a)</th>
<th>2c-THF(^b)</th>
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</thead>
<tbody>
<tr>
<td>M1-N1</td>
<td>2.194(4)</td>
<td>2.346(3)</td>
<td>Li2-N2</td>
<td>1.884(5)</td>
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<tr>
<td>M1-N3</td>
<td>2.189(3)</td>
<td>2.335(3)</td>
<td>Li2-N4</td>
<td>2.557(6)</td>
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<tr>
<td>M1-N4</td>
<td>2.179(4)</td>
<td>2.309(2)</td>
<td>B1-N1</td>
<td>1.520(6)</td>
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<tr>
<td>Li1-N2</td>
<td>1.915(9)</td>
<td>1.921(6)</td>
<td>B1-N2</td>
<td>1.408(7)</td>
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<tr>
<td>Li1-N3</td>
<td>2.075(9)</td>
<td>2.039(6)</td>
<td>B2-N3</td>
<td>1.434(7)</td>
</tr>
<tr>
<td>Li1-N4</td>
<td>2.115(9)</td>
<td>2.030(6)</td>
<td>B2-N4</td>
<td>1.466(6)</td>
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<tr>
<td>Li2-N1</td>
<td>1.869(5)</td>
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</tr>
<tr>
<td>N1-M1-N3</td>
<td>108.3(1)</td>
<td>99.5(1)</td>
<td>Li1-N3-B2</td>
<td>76.4(4)</td>
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<tr>
<td>N1-M1-N4</td>
<td>99.1(1)</td>
<td>105.2(1)</td>
<td>M1-N3-Li1</td>
<td>84.7(3)</td>
</tr>
<tr>
<td>N3-M1-N4</td>
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<td>59.8(1)</td>
<td>M1-N4-B2</td>
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<td>N1-B1-N2</td>
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<td>84.0(3)</td>
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<tr>
<td>N3-B2-N4</td>
<td>104.9(4)</td>
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<td>Li1-N4-B2</td>
<td>74.5(3)</td>
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<tr>
<td>M1-N1-B1</td>
<td>122.3(3)</td>
<td>120.1(2)</td>
<td>Li2-N4-B2</td>
<td>131.3(3)</td>
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<tr>
<td>Li2-N1-B1</td>
<td>80.5(3)</td>
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<td>N2-Li1-N3</td>
<td>132.7(5)</td>
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<td>M1-N1-Li2</td>
<td>89.5(2)</td>
<td>103.1(2)</td>
<td>N2-Li1-N4</td>
<td>121.9(4)</td>
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<tr>
<td>Li1-N2-B1</td>
<td>108.2(4)</td>
<td>109.5(3)</td>
<td>N3-Li1-N4</td>
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<tr>
<td>Li2-N2-B1</td>
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<td>N1-Li2-N2</td>
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<td>Li1-N2-Li2</td>
<td>75.2(3)</td>
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<td>N4-Li2-N2</td>
<td>104.0(2)</td>
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<tr>
<td>M1-N3-B2</td>
<td>90.1(3)</td>
<td>88.8(2)</td>
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</tbody>
</table>

\(^a\) M = Sn, \(^b\) M = Pb
**Figure Captions**

**Fig. 1.** Molecular structure of Ge[PhB(μ-N-t-Bu)₂]₂ (1a) with the atomic numbering scheme. Hydrogen atoms have been omitted for clarity. The tin complex 1b is isostructural with 1a. Symmetry operation: a- x, y, 0.5-z (M = Ge); 1-x, y, 1.5-z (M = Sn).

**Fig. 2.** (a) Simulated and (b) experimental EPR spectra of {Sn[PhB(μ-N-t-Bu)₂]₂}⁺Cl⁻ measured in diethyl ether at -20 °C.

**Fig. 3.** SOMO of the radical cation {Sn[PhB(μ-N'Bu)₂]₂}²⁺ (±0.05 isodensity surfaces).

**Fig. 4.** Crystal structures of (a) Li₂Sn[PhB(μ-N-t-Bu)₂]₂ (2b) and (b) (THF·Li)LiPb[PhB(μ-N-t-Bu)₂]₂ (2c·THF) with the atomic numbering scheme. Hydrogen atoms have been omitted for clarity.
Fig. 1.
Fig. 2.
Fig. 3.
Fig. 4.