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A simple route to azaborinylphosphines: isoelectronic B-N analogues of arylphosphine ligands†

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Azaborinylphosphines are readily prepared by the reaction of silylphosphines with a chloroborane under mild conditions; they are shown to contain P-B bonds that are sufficiently robust to allow these ligands to be used in homogeneous catalysis.

Phosphorus(III) ligands have been a cornerstone of much coordination chemistry and homogeneous catalysis for half a century. The strength of P-C, P-N and P-O bonds makes ligands based on these bonds robust and amenable to design, in terms of stereoelectronic properties, to an unsurpassed level of finesse. As a result, a cornucopia of applications in catalysis has emerged based on P-donor complexes.

Ligands containing P-F and P-B bonds have been underdeveloped despite the fundamental interest arising from the extremes of electron density that these bonds might be predicted to confer on the P atom. Recently, fluorophosphines (e.g. fluorophobane I)² and fluorophosphites (e.g. II),³ which contain inert P-F bonds, have not only been reported but have been shown to have potentially commercial applications in hydroformylation⁴ or hydrocyanation⁵ catalysis.

The low electronegativity of boron (B: 2.0; P: 2.2; C: 2.5) combined with the electron deficiency of BX_3 compounds makes the coordination chemistry of borylphosphines (phosphinoboranes) fascinating to explore. The reactive P-B bond can be stabilised by: (i) having π -donating NR_2 substituents on the B as in (III);⁶ (ii) having very bulky aryl substituents on the B as in (IV);⁷ (iii) enhancing the P-B π -bonding by having electron-accepting groups on B and electron-donating groups on P as in (V);^{8,9} (iv) incorporating the B into a carborane as in (VI).¹⁰ The proposition that the coordination chemistry of borylphosphines should be academically interesting has been validated by the report of the remarkably strong σ -donor capacity

of $(VI)^{10}$ and the Pt(0) complex of (V) which is the first example of side-on, alkene-like coordination of a phosphinoborane. None of the previously reported phosphinoboranes have been shown to be ligands that support homogeneous catalysis.

We are interested in the preparation of phosphorus ligands in which a BN formally replaces an isoelectronic CC group in an aromatic ring to produce azaborinyl analogues of aryl phosphines and compare their properties. It was predicted that the azaborinylphosphines would be stabilised by the aromaticity of the BN-containing ring and therefore may be potentially useful as ligands. Here we describe a simple, high-yielding route to azaborinylphosphines, compare their structural and electronic properties with the parent arylphosphines, and show that these azaborinylphosphines form stable complexes with Rh which are catalysts for hydrogenation.

The first targets were phosphines L_{1a} and L_{1b} derived from the BN analogue of phenanthrene and these were to be compared with the all-carbon analogues L_{2a} and L_{2b} . The readily prepared^{6,7} chloroborane 1 was the proposed precursor to L_{1a} and L_{1b} . However, 1 did not react with the secondary phosphines HP^iPr_2 or HPPhob in the presence of amine bases (NEt₃ or NEt^iPr_2) and treatment of 1 with LiPR₂ led to the formation of secondary phosphine R_2PH (~70%, by ³¹P NMR spectroscopy) and a mixture of several B-containing products (according to ¹¹B NMR spectroscopy). It was reasoned that a non-basic source of PR_2 was required and so we turned our attention to silylphosphines. The chloroborane 1 reacts with $Me_3SiP^iPr_2$ or $Me_3SiPPhob$ ‡ rapidly and quantitatively under

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$$\begin{array}{c} \text{CI} \\ \text{HN=B} \\ \text{I} \\ \text{I} \\ \text{HN=B} \\ \text{HN=B}$$

Scheme 1 Synthesis of the azaborinylphosphines and their carbon analogues.

mild conditions to give the desired azaborinylphosphines L_{1a} and L_{1b} (Scheme 1). The facility of these reactions was a surprise since it had been reported11 that formation of $[Et_2P-BZ_2]_n$ from the reaction of Et_2PSiMe_3 with $ClBZ_2$ (Z = F, Cl, Br, OⁿBu or ⁿPr) required several hours at high temperatures (120–180 °C) and in the case of $Z = NMe_2$, the route was unsuccessful.

The phenanthryl analogues L_{2a} and L_{2b} are new compounds: which have been prepared from the lithio reagent according to Scheme 1 which is a modification of the method reported for the preparation of the 9-diphenylphosphinophenanthrene. 12 The broad ³¹P NMR signals for the azaborinylphosphines are at -49.1 ppm for L_{1a} and -64.5 ppm for L_{1b} which are both \sim 40 ppm to high field of the phenanthrene analogues L_{2a} (-7.2 ppm) and L_{2b} (-23.8 ppm) but close in chemical shift to the silylphosphine precursors ⁱPr₂PSiMe₃ (-44.0 ppm) and PhobPSiMe₃ (-67.4 ppm). The similarity of the δ_P values for the analogous P-B and P-Si compounds is an NMR manifestation of the B-Si diagonal relationship.

In order to compare the donor properties of ligands L_{1a} and L_{1b} with L_{2a} and L_{2b}, the corresponding trans-[RhCl(CO)L₂] complexes 3a,b and 4a,b were prepared and their crystal structures determined (Fig. 1 and 2). Complexes 3a and 3b are the first examples of rhodium complexes of phosphinoboranes. 13 The structures of azaborinylphosphine complex 3a and its phenanthrylphosphine analogue 4a are isomorphous and all the Rh-ligand bonds are essentially the same lengths (Fig. 1). The conformations of the ligands in complexes 3b and 4b featuring the PhobP group are quite different from their $^{1}\text{Pr}_{2}\text{P}$ analogues **3a** and **3b**. The 90 $^{\circ}$ torsion angles, Rh-P-B-N in **3b** and Rh-P-C-C in **4b**, contrast with the *ca.* 140° for these angles in the analogues 3a and 4a. One plausible explanation for this difference is that the phobane ligands are prevented from adopting a 140° conformation because of unfavourable clashing of the H on the C10 or N10 with the axial protons

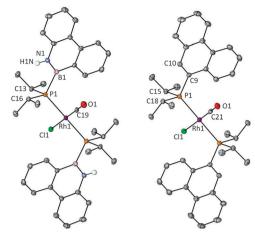


Fig. 1 Thermal ellipsoid (50% probability) plot of 3a (left) and 4a (right), omitting all C-H hydrogen atoms. Selected bond lengths [A] and angles [9] for **3a**: Rh1-P1 2.3407(6), C19-O1 1.171(6), N1-B1 1.406(3), P1-B1 1.957(3), Rh1-P1-B1-N1 143.64. For **4a**: Rh1-P1 2.3369(6), C21-O1 1.147(7), P1-C9 1.843(2), Rh1-P1-C9-C10 142.61.

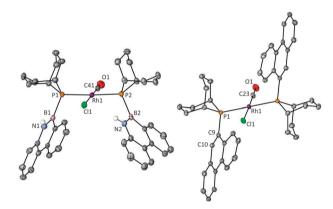
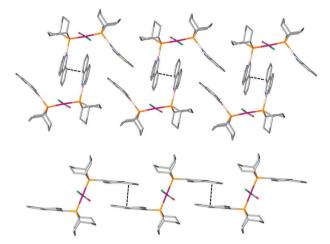


Fig. 2 Thermal ellipsoid (50% probability) plot of 3b (left) and 4b (right), omitting all C-H hydrogens. Selected bond lengths [Å] and angles [°] for **3b**: P1-Rh1 2.3296(5), P2-Rh1 2.3304(5), C41-O1 1.078(3), B1-P1 1.941(2), B2-P2 1.962(3), B1-N1 1.404(3), B2-N2 1.408(4), Rh1-P1-B1-N1 96.50, Rh1-P2-B2-N2 -71.78. For **4b**: Rh1-P1 2.3313(3), O1-C23 1.155(4), P1-C9 1.8281(11), Rh1-P1-C9-C10 98.72.

within the phosphabicycle that would result; the rigidity of the phobane makes these clashes unavoidable whereas the greater rotational freedom of the isopropyl groups of the ⁱPr₂P group allows the 140° conformer to be adopted. Another striking structural difference is that the PhobP complexes 3b and 4b exhibit extensive π -stacking between the aromatic units whereas the ⁱPr₂P analogues 3a and 4a do not; this is illustrated in the crystal packing structures for 3b and 4b shown in Fig. 3.

The $\nu(CO)$ values for **3a,b** and **4a,b** show that the BN ligands L_{1a} and L_{1b} are more electron-donating than their CC counterparts ChemComm Communication



Crystal packing structures of **3b** (top) and **4b** (bottom).

Table 1 IR^a, ³¹P NMR^b and catalytic^c data for the Rh complexes

Complex	ν (CO)/cm ⁻¹	$\delta_{ extsf{P}}/ extsf{ppm}$	$J_{ m RhP}/{ m Hz}$	Rel. TOF
3a	1951	0.8	$\sim 120^d$	_
3b	1946	-17.6	$\sim 120^d$	_
4a	1966	33.8	121	_
4b	1951	15.3	118	_
5a	_	-20.6	129	15
5 b	_	-30.7	130	≥ 30
6a	_	19.3	146	1
6b	_	-2.0	152	12

^a Measured in CH₂Cl₂. ^b Measured in CD₂Cl₂. ^c Cyclohexene hydrogenation carried out in CD_2Cl_2 with ~ 10 mg cyclohexene, 5 mol% catalyst and 2 bar H2. Conversions were monitored by 1H NMR spectroscopy. ^d Estimated from weak NMR signals. ^e Relative TOF were estimated from rates of product formation at low conversion. The value of TOF for 6a

 L_{2a} and L_{2b} (Table 1), as was expected from the prediction that the boryl substituent would make the P-donor electron-rich.¹⁰ It was hoped that the borylphosphines L_{1a} and L_{1b} would be members of a new class of ligands for catalysis. Therefore [Rh(nbd)₂][BF₄] was reacted with 2 equivalents of L_{1a} and L_{1b} to generate single products, assigned the structures 5a and 5b on the basis of their ³¹P NMR spectra (see Table 1 for the data) which were tested for the catalytic hydrogenation of cyclohexene. The catalytic results obtained for 5a and 5b and the phenanthryl analogues 6a and 6b are collected in Table 1. In all cases 100% conversion of the cyclohexene was observed. It is clear from Table 1 that (a) the borylphosphine complexes 5a and 5b are more efficient catalysts than their phenanthrene phosphine counterparts 6a and 6b; (b) the bicyclic phosphine complexes 5b and 6b are more efficient catalysts than their acyclic counterparts 5a and 6a.

Addition of water (ca. 0.1% by volume) to CH₂Cl₂ solutions of the borylphosphines L_{1a} or L_{1b} led to 100% hydrolysis to R₂PH

and 10-hydroxy-9,10-azabora-phenanthrene in less than 5 min. In similar aqueous media, the Rh-coordinated L_{1b} in 5b was significantly more resistant to hydrolysis than the free ligand with 75% of the complex remaining after 5 min. Nevertheless it was possible that the favourable catalytic results given in Table 1 for the borylphosphine complexes were the result of hydrolysis by adventitious water giving a highly active catalyst. To refute this proposition, the hydrogenation was carried out using a sample of 5b which had been deliberately hydrolysed prior to the catalysis. Using this degraded catalyst, after 5 min, only ca. 5% cyclohexene conversion was observed, compared to the 100% conversion when pure 5b was used as the catalyst.

In conclusion, it has been shown that the reaction of silvl phosphines ¹Pr₂PSiMe₃ and PhobPSiMe₃ with 9-aza-10-bora-10chlorophenanthrene afforded the corresponding azaborinyl phosphines under very mild conditions. The generality of this $P-Si \rightarrow P-B$ conversion for the synthesis of BN analogues of arylphosphines is currently under investigation. Moreover azaborinyl phosphines have proved to be competent ligands for rhodium-catalysed hydrogenation and indeed produce more active catalysts than their arylphosphine analogues.

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Notes and references

‡ The crystal structures of PhobPSiMe3, La and L2b (as a mixture with its oxide) are described in the ESI.†

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