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## Lead(II) nitrate and hexafluorosilicate complexes with neutral diphosphine coordination†

Jennifer Burt, William Grantham, William Levason\* and Gillian Reid

Rare examples of phosphine complexes of lead(II) are reported. The reaction of  $\text{Pb}(\text{NO}_3)_2$  with  $\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2$ ,  $o\text{-C}_6\text{H}_4(\text{PMe}_2)_2$  or  $\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2$  (L–L) in  $\text{H}_2\text{O}/\text{MeCN}$  gave white  $[\text{Pb}(\text{L}–\text{L})(\text{NO}_3)_2]$ , irrespective of the ratio of reagents used. The X-ray structures of  $[\text{Pb}\{\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2\}(\text{NO}_3)_2]$  and  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{NO}_3)_2]$  reveal chelating diphosphines and  $\kappa^2\text{-NO}_3^-$  groups occupying one hemisphere about the lead centre with single oxygen bridges to two further nitrate groups from neighbouring molecules completing a distorted eight-coordinate geometry. Using  $\text{Pb}(\text{SiF}_6) \cdot 2\text{H}_2\text{O}$  produced  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{H}_2\text{O})(\text{SiF}_6)] \cdot \text{H}_2\text{O}$  which has a chelating diphosphine, the water molecule and a coordinated  $\text{SiF}_6^{2-}$  group (which could be described as either  $\kappa^1\text{-}$  or asymmetric  $\kappa^3\text{-}$  coordinated to the lead), with further Pb–F interactions to neighbouring molecules producing a chain polymer structure. The structure of  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{DMF})_2(\text{SiF}_6)] \cdot \text{DMF}$  was also determined and contains dimers with fluorosilicate bridges. Adventitious oxygen readily form diphosphine dioxide complexes, and the structures of  $[\text{Pb}\{\text{Et}_2\text{O}(\text{P}(\text{CH}_2)_2\text{P}(\text{O})\text{Et}_2)_2(\text{NO}_3)_2\}]$  and  $[\text{Pb}\{\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2\}\{\text{Me}_2\text{O}(\text{P}(\text{CH}_2)_2\text{P}(\text{O})\text{Me}_2)\}[\text{BF}_4]_2 \cdot \frac{1}{2}\text{MeNO}_2]$  produced in this way were determined. The former contains eight-coordinate lead with  $\kappa^2\text{-NO}_3^-$  groups and bridging diphosphine dioxides, which results in an infinite polymer. In the latter the diphosphine is chelated but the diphosphine dioxide bridges between Pb(II) centres, with coordinated  $\text{BF}_4^-$  groups completing a very distorted ten-coordinate moiety. Attempts to isolate similar complexes with  $o\text{-C}_6\text{H}_4(\text{PPh}_2)_2$  or  $o\text{-C}_6\text{H}_4(\text{AsMe}_2)_2$  were unsuccessful.

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## Introduction

Classed as an intermediate Lewis acid by Pearson's hard and soft acid–base concept,<sup>1</sup> lead(II) forms stable complexes with a broad range of neutral and charged donor ligands across Groups 14–17.<sup>2–4</sup> Although the majority of complexes are with hard (oxygen and nitrogen) donor atom ligands,<sup>3</sup> there is also considerable coordination chemistry with softer sulfur and selenium donor ligands.<sup>4</sup> However, whilst phosphine complexes of most heavy main group metals (including Hg(II), In(III), Sn(II), Sn(IV) and Bi(III)) are well established,<sup>5</sup> the coordination chemistry of lead(II) with neutral phosphines is extremely limited.<sup>5</sup> While  $[\text{Pb}\{\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2\}\text{Br}_2]$  and  $[\text{Pb}\{\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2\}_2(\text{ClO}_4)_2]$  were claimed in 1960, characterisation was limited to partial microanalysis,<sup>6</sup> and the only structurally characterised examples of neutral diphosphine complexes are the lead(II) thiolates  $[(2,6\text{-Me}_2\text{C}_6\text{H}_3\text{S})_2\text{Pb}]_2\{\mu\text{-Ph}_2\text{P}(\text{CH}_2)_2\text{PPh}_2\}$  and  $[(2,6\text{-Me}_2\text{C}_6\text{H}_3\text{S})_2\text{Pb}]_3\{\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2\}$ .<sup>7</sup> The latter contains a chain of the three lead centres linked by thiolate

bridges, with the  $\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2$  chelating to the central Pb.<sup>7</sup> Several 1:1 polydentate phosphine complexes of  $\text{Pb}(\text{SbF}_6)_2$  have also been studied by *in situ*  $^{31}\text{P}\{^1\text{H}\}$  and  $^{207}\text{Pb}$  NMR spectroscopy in  $\text{MeNO}_2$ , although no complexes were isolated.<sup>8,9</sup>

One of the major challenges in synthesising lead(II) complexes with neutral diphosphine ligands is in finding a suitable lead precursor. Main group phosphine coordination chemistry has mostly been performed with metal halides,<sup>5</sup> but the insoluble and intractable nature of the lead dihalides precludes easy synthetic access to this area; instead lead(II) oxo-salts such as acetate, nitrate or perchlorate are often used.<sup>2,3</sup> Previously we have investigated crown ether, oxathia- and oxaseleno-macrocyclic complexes of  $\text{Pb}(\text{NO}_3)_2$ ,  $\text{Pb}(\text{BF}_4)_2$  and  $\text{Pb}(\text{PF}_6)_2$ , finding that the weakly coordinating fluoroanions also readily enter the first coordination sphere of the lead.<sup>10</sup> The very stable di- and tri-imine complexes of Pb(II) with  $\text{Pb}(\text{NO}_3)_2$  or  $\text{Pb}(\text{ClO}_4)_2$  exhibit high coordination numbers and irregular geometries,<sup>11</sup> whilst complexes of these ligands with  $\text{Pb}(\text{BF}_4)_2$  and  $\text{Pb}(\text{SiF}_6)$  were shown to exhibit a variety of different fluoroanion coordination modes.<sup>12</sup> Here we report the reactions of  $\text{Pb}(\text{NO}_3)_2$ ,  $\text{Pb}(\text{SiF}_6)$  and  $\text{Pb}(\text{BF}_4)_2$  with the diphosphines  $o\text{-C}_6\text{H}_4(\text{PMe}_2)_2$ ,  $\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2$  and  $\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2$ , focussing on the coordination behaviour of both the diphosphine and

School of Chemistry, University of Southampton, Southampton SO17 1BJ, UK.

E-mail: wxl@soton.ac.uk

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counterion in the complexes formed. Lead is a large metal centre with a covalent radius of 1.46 Å and hence regularly forms complexes with high coordination numbers where the geometry is governed by the number and steric demands of the ligands present, as well as by inter-ligand repulsions. The presence of a formal lone pair on lead(II) will also have an effect on the geometry observed if it is stereochemically active.<sup>2,3</sup>

## Experimental section

All preparations were carried out under a dry dinitrogen atmosphere using standard Schlenk and glove-box techniques. Lead(II) nitrate and lead(II) tetrafluoroborate (the latter as 50% solutions in water) were obtained from Aldrich and used as received. Lead(II) hexafluorosilicate dihydrate was obtained from Alfa Aesar and used as received. Aqueous solutions of the lead salts were degassed before use, by bubbling with N<sub>2</sub>. The ligands were obtained commercially, (Strem) apart from *o*-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub> and *o*-C<sub>6</sub>H<sub>4</sub>(AsMe<sub>2</sub>)<sub>2</sub> which were made by the literature methods.<sup>13</sup> Solvents were dried by distillation from CaH<sub>2</sub> (CH<sub>2</sub>Cl<sub>2</sub>, CH<sub>3</sub>CN) or sodium benzophenone ketyl (hexane, Et<sub>2</sub>O). IR spectra were recorded as Nujol mulls between CsI plates using a Perkin Elmer Spectrum 100 spectrometer over the range 4000–200 cm<sup>-1</sup>. <sup>1</sup>H and <sup>31</sup>P{<sup>1</sup>H} NMR spectra were recorded using a Bruker AV300 or DPX400 spectrometer and referenced to the residual solvent resonance and external 85% H<sub>3</sub>PO<sub>4</sub> respectively. Microanalytical measurements were performed by London Metropolitan University.

### [Pb{*o*-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>]

To *o*-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub> (0.090 g, 0.45 mmol) in CH<sub>3</sub>CN (5 mL) was added a degassed solution of Pb(NO<sub>3</sub>)<sub>2</sub> (0.150 g, 0.45 mmol) in deionised water (3 mL). A white precipitate formed rapidly on stirring; the reaction was stirred for 2 h, then the white powder was isolated by filtration and dried *in vacuo*. Yield: 0.056 g, 23%. Anal. Calc. for C<sub>10</sub>H<sub>16</sub>N<sub>2</sub>O<sub>6</sub>P<sub>2</sub>Pb: (529.4) C, 22.7; H, 3.1; N, 5.3. Found: C, 22.6; H, 3.1; N, 5.2%. IR (Nujol):  $\nu$  = 1314 (s), 1295 (s), 1033 (s), 837 (sh), 818 (m) (NO<sub>3</sub>) cm<sup>-1</sup>.

### [Pb{Me<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PMe<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>]

To Me<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PMe<sub>2</sub> (0.091 g, 0.60 mmol) in CH<sub>3</sub>CN (5 mL) was added a degassed solution of Pb(NO<sub>3</sub>)<sub>2</sub> (0.101 g, 0.30 mmol) in deionised water (5 mL), giving a colourless solution. The reaction was stirred for 1 h, then the solvent was concentrated *in vacuo* and the resulting white powder was filtered and dried *in vacuo*. Yield: 0.071 g, 48% based on Pb. Anal. Calc. for C<sub>6</sub>H<sub>16</sub>N<sub>2</sub>O<sub>6</sub>P<sub>2</sub>Pb: (481.4) C, 15.0; H, 3.4; N, 5.8. Found: C, 15.1; H, 3.3; N, 5.8%. IR (Nujol):  $\nu$  = 1310 (vs, br), 1038 (s), 840 (w), 819 (m) (NO<sub>3</sub>) cm<sup>-1</sup>.

### [Pb{Et<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PEt<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>]

To a degassed solution of Pb(NO<sub>3</sub>)<sub>2</sub> (0.162 g, 0.49 mmol) in deionised water (3 mL) was added Et<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PEt<sub>2</sub> (0.101 g, 0.49 mmol) in CH<sub>3</sub>CN (5 mL) to give a colourless solution. The

reaction was stirred for 2 h, then the solvent volume was reduced to about 3 mL *in vacuo*. The resulting white precipitate was isolated by filtration and dried *in vacuo* to give a white powder. Yield: 0.092 g, 35%. Anal. Calc. for C<sub>10</sub>H<sub>24</sub>N<sub>2</sub>O<sub>6</sub>P<sub>2</sub>Pb: (537.5) C, 22.4; H, 4.5; N, 5.2. Found: C, 22.2; H, 4.6; N, 5.2%. <sup>1</sup>H NMR (CD<sub>2</sub>Cl<sub>2</sub>, 295 K):  $\delta$  = 1.19–1.27 (m, [12H], CH<sub>3</sub>), 1.92–2.02 (m, [4H], CH<sub>2</sub>), 2.20–2.35 (m, [4H], CH<sub>2</sub>), 2.40 (d, [4H], CH<sub>2</sub>). <sup>31</sup>P{<sup>1</sup>H} NMR (CH<sub>2</sub>Cl<sub>2</sub>/CD<sub>2</sub>Cl<sub>2</sub>, 295 K):  $\delta$  = 89.3 (s); (223 K): 89.5 (s, <sup>1</sup>J<sub>PbP</sub> = 2465 Hz); (193 K): 89.6 (s, <sup>1</sup>J<sub>PbP</sub> = 2532 Hz). IR (Nujol):  $\nu$  = 1300 (s, br), 1029 (s), 816 (m) (NO<sub>3</sub>) cm<sup>-1</sup>. Small colourless single crystals of the phosphine oxide complex, [Pb{Et<sub>2</sub>(O)P(CH<sub>2</sub>)<sub>2</sub>P(O)Et<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>], were grown from layering hexane onto a solution of the isolated powder dissolved in the minimal amount of CH<sub>2</sub>Cl<sub>2</sub>.

### [Pb{*o*-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub>}(H<sub>2</sub>O)(SiF<sub>6</sub>)]·H<sub>2</sub>O

To a degassed solution of Pb(SiF<sub>6</sub>)·2H<sub>2</sub>O (0.151 g, 0.39 mmol) in deionised water (10 mL) was added *o*-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub> (0.077 g, 0.39 mmol) in CH<sub>3</sub>CN (5 mL) which caused the precipitation of a small amount of white solid. The reaction was stirred for 1.5 h, then the solid was removed by filtration to leave a colourless solution. The solvent was removed *in vacuo* and the resulting white powder was dried *in vacuo*. Yield: 0.110 g, 48%. IR (Nujol):  $\nu$  = 3500 (br), 1628 (m, br) (H<sub>2</sub>O), 721 (vs, br), 473 (s), 446 (s) (SiF<sub>6</sub>) cm<sup>-1</sup>. Small colourless single crystals of [Pb{*o*-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub>}(H<sub>2</sub>O)(SiF<sub>6</sub>)]·H<sub>2</sub>O were grown by layering Et<sub>2</sub>O onto a solution of the isolated product dissolved in the minimal amount of DMF.

In a similar reaction where the *o*-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub> to Pb(SiF<sub>6</sub>)·2H<sub>2</sub>O ratio used was 2 : 1.

### [Pb{Me<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PMe<sub>2</sub>}{Me<sub>2</sub>(O)P(CH<sub>2</sub>)<sub>2</sub>P(O)Me<sub>2</sub>}] [BF<sub>4</sub>]<sub>2</sub>·<sup>1</sup>/<sub>2</sub> MeNO<sub>2</sub>

To a degassed solution of Me<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PMe<sub>2</sub> (0.087 g, 0.58 mmol) in MeNO<sub>2</sub> (6 mL) was added Pb(BF<sub>4</sub>)<sub>2</sub> as a 50% aqueous solution (0.229 g, 0.30 mmol) that had been degassed (bubbling with N<sub>2</sub>) beforehand. A small amount of white precipitate rapidly formed, which was removed by filtration, then Et<sub>2</sub>O (10 mL) was layered onto the colourless filtrate, giving a few small colourless crystals.

## X-Ray experimental

Details of the crystallographic data collection and refinement parameters are given in Table 1. Crystals suitable for single crystal X-ray analysis were obtained as described above. Data collections used a Rigaku AFC12 goniometer equipped with an enhanced sensitivity (HG) Saturn724+ detector mounted at the window of an FR-E+ SuperBright molybdenum ( $\lambda$  = 0.71073 Å) rotating anode generator with VHF Varimax optics (70 micron focus) with the crystal held at 100 K (N<sub>2</sub> cryostream). Structure solution and refinements were performed with SHELX-(S/L)97<sup>14</sup> and were straightforward, except where detailed below. H atoms bonded to C were placed in calculated positions using the default C–H distance and refined using a riding model. Attempts to improve the absorption correction for both [Pb{*o*-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>] and [Pb{Me<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PMe<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>] failed to eliminate the large residual density electron peaks <1 Å




$$^a \text{Common items: } T = 100 \text{ K; wavelength (Mo-K}\alpha) = 0.71073 \text{ \AA; } \theta(\text{max}) = 27.5^\circ; {}^b R_1 = \sum \|F_o\| / \sum \|F_c\| - \|F_o\| / \sum \|F_c\|; wR_2 = [\sum w(F_o^2 - F_c^2) / \sum wF_o^2]^{1/2}.$$

The reaction of  $\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2$  with  $\text{Pb}(\text{NO}_3)_2$  in  $\text{MeCN}/\text{H}_2\text{O}$  formed only the 1 : 1  $[\text{Pb}\{\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2\}(\text{NO}_3)_2]$ , despite a 2 : 1 molar ratio of reagents being used. Elemental analysis of the bulk powder isolated confirmed the 1 : 1 stoichiometry, while colourless crystals of  $[\text{Pb}\{\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2\}(\text{NO}_3)_2]$  (Fig. 1a) were grown by layering  $\text{Et}_2\text{O}$  onto a DMF solution containing the complex. The structure shows the  $\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2$  ligand chelated symmetrically to the  $\text{Pb}(\text{II})$  centre with  $d(\text{Pb}-\text{P}) = 2.7918(15)$  Å while the nitrate groups are asymmetrically  $\kappa^2$ -coordinated ( $d(\text{Pb}-\text{O}) = 2.621(4), 2.859(5)$  Å), all on one hemi-

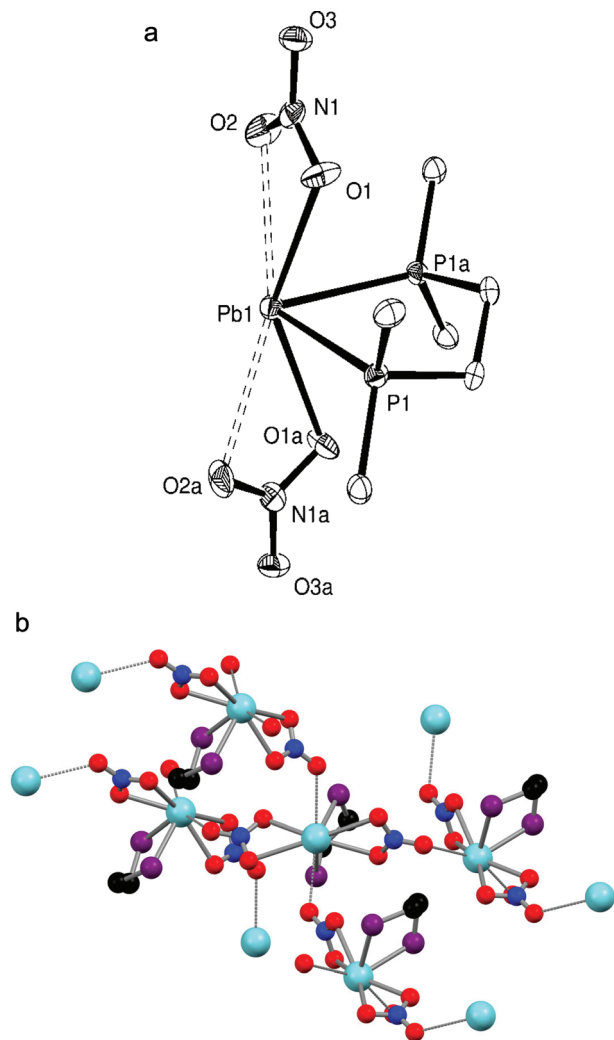
Open Access Article. Published on 21 May 2015. Downloaded on 2/10/2026 11:44:02 PM.  
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sphere of the lead. Two further Pb–O contacts, 2.995(4) Å, well within the Van der Waals radii sum of 3.54 Å for Pb...O<sup>15</sup> from nitrates on neighbouring molecules link the units into an infinite polymer network (Fig. 1b) where the coordination number around the lead(II) centre is eight. The Pb–P bonds are ~0.05 Å shorter than those in [(2,6-Me<sub>2</sub>C<sub>6</sub>H<sub>3</sub>S)<sub>2</sub>Pb]<sub>3</sub>{Me<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PMe<sub>2</sub>} (2.8389(10) Å).<sup>7</sup>

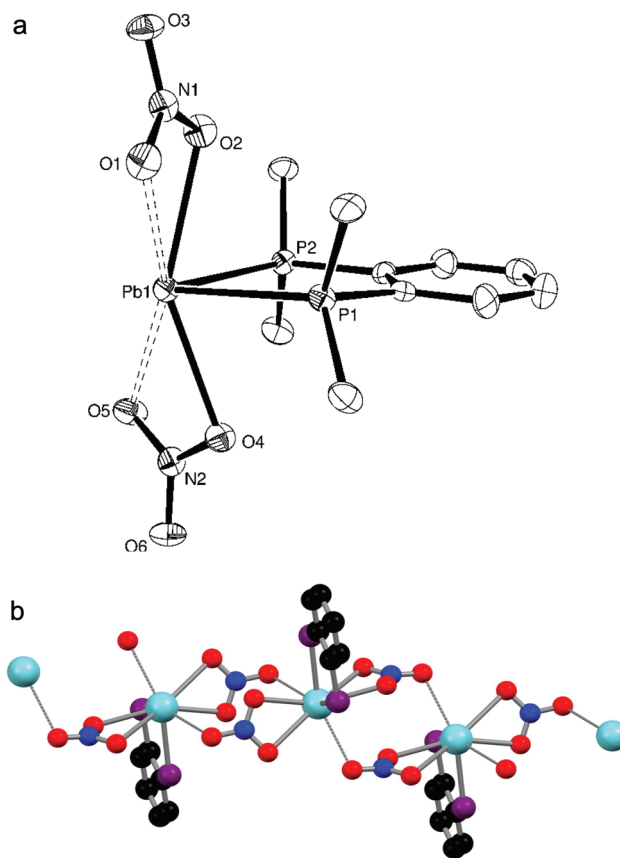
Similarly, [Pb{o-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>] was isolated as a white powder from a 1 : 1 mol. ratio reaction of o-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub> with Pb(NO<sub>3</sub>)<sub>2</sub>. Colourless crystals were obtained from a DMF solution layered with Et<sub>2</sub>O. A crystal structure determination revealed a similar molecular unit (Fig. 2a) to [Pb{Me<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PMe<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>] with the lead(II) centre being eight coordi-

nate. Though no longer symmetrical the Pb–P bond lengths are comparable, while the O–Pb–O angle formed by the nitrate oxygen atoms nearest to the diphosphine is larger in [Pb{o-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>] (147.36(16)° vs. 139.98(19)°). Again the third oxygen of the nitrate groups bridge (*d*(Pb–O) = 2.948(5), 2.959(5) Å) to neighbouring molecules to give an infinite chain structure (Fig. 2b).

The crystallographically identified κ<sup>2</sup>-coordinated nitrate groups can also be seen in the IR spectra of [Pb{Me<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PMe<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>] and [Pb{o-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>]. The approximate C<sub>2v</sub> symmetry of κ<sup>2</sup>-NO<sub>3</sub> groups means three IR active stretching modes (2A<sub>1</sub> + B<sub>2</sub>) are expected;<sup>16</sup> as seen with macrocyclic complexes of Pb(NO<sub>3</sub>)<sub>2</sub> (e.g. [Pb(18-crown-6)-(NO<sub>3</sub>)<sub>2</sub>]), which also exhibit high coordination numbers and κ<sup>2</sup>-NO<sub>3</sub> groups, two stretches are observed at ~1310 and 1030 cm<sup>-1</sup> (the stretch anticipated at ~1470 cm<sup>-1</sup> is obscured by Nujol).<sup>10</sup> A bending mode is also evident at ~815 cm<sup>-1</sup>.<sup>16</sup> Splitting of some of the bands was observed in the IR spec-



**Fig. 1** (a) Crystal structure of [Pb{Me<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PMe<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>] showing the atom labelling scheme. The displacement ellipsoids are drawn at the 50% probability level and H atoms are omitted for clarity. Symmetry operation: *a* = *x*, *y*, *−z*. Selected bond lengths (Å) and angles (°): Pb1–P1 = 2.7918(15), Pb1–O1 = 2.621(4), Pb1–O2 = 2.859(5), P1–Pb1–P1a = 74.19(6), O1–Pb1–O2 = 46.07(13), O1–Pb1–O1a = 139.98(19). (b) The extended structure of [Pb{Me<sub>2</sub>P(CH<sub>2</sub>)<sub>2</sub>PMe<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>]. Methyl groups are omitted for clarity.



**Fig. 2** (a) Crystal structure of [Pb{o-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>] showing the atom labelling scheme. The displacement ellipsoids are drawn at the 50% probability level and H atoms are omitted for clarity. Selected bond lengths (Å) and angles (°): Pb1–P1 = 2.806(2), Pb1–P2 = 2.8088(19), Pb1–O1 = 2.869(6), Pb1–O2 = 2.611(6), Pb1–O4 = 2.595(5), Pb1–O5 = 2.827(6), P1–Pb1–P2 = 71.95(6), O1–Pb1–O2 = 46.56(15), O2–Pb1–O4 = 147.37(16), O4–Pb1–O5 = 46.83(15). (b) The polymeric chain structure of [Pb{o-C<sub>6</sub>H<sub>4</sub>(PMe<sub>2</sub>)<sub>2</sub>}(NO<sub>3</sub>)<sub>2</sub>]. Methyl groups are omitted for clarity.





trum of  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{NO}_3)_2]$ , which is less clearly resolved for  $[\text{Pb}\{\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2\}(\text{NO}_3)_2]$ .

Owing to the unpredictable geometries and the dissociative nature of complexes of Pb(II) in solution<sup>7,11</sup> meaningful NMR spectra can generally only be obtained in non-competitive solvents such as  $\text{CD}_2\text{Cl}_2$ , in which both  $[\text{Pb}\{\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2\}(\text{NO}_3)_2]$  and  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{NO}_3)_2]$  were found to be insoluble. By using  $\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2$  as the ligand with  $\text{Pb}(\text{NO}_3)_2$  under analogous conditions a white powder,  $[\text{Pb}\{\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2\}(\text{NO}_3)_2]$ , was isolated which was found to be freely soluble in  $\text{CD}_2\text{Cl}_2$ . There is a significant high frequency shift in the  $^1\text{H}$  NMR spectrum of this complex confirming that the phosphine is coordinated, while a sharp singlet at  $\delta = 89.3$  is observed in the  $^{31}\text{P}\{^1\text{H}\}$  NMR spectrum. This is a very large, high frequency shift from 'free'  $\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2$  ( $\delta = -18$ ) whose magnitude is mirrored in the shifts seen by Dean *et al.*<sup>8</sup> in their *in situ* NMR studies of phosphine complexes of  $\text{Pb}(\text{SbF}_6)_2$ . Upon cooling the solution to 223 K,  $^{207}\text{Pb}$  satellites were observed, which sharpened upon further cooling to 193 K ( $J_{\text{PbP}} = 2532$  Hz). The appearance of  $^{207}\text{Pb}$  satellites only at low temperatures has been reported before in a study of Pb(II) complexes of 2-phosphinobenzenethiolates,<sup>17</sup> and was attributed to ligand lability. Similarly, no resonances were observed in the  $^{207}\text{Pb}$  NMR spectrum, even at low temperatures. To ensure that the resonances observed were indeed due to coordinated  $\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2$  (*i.e.* that no unwanted oxidation of the ligand had occurred), an NMR spectrum of the complex was taken in  $\text{DMSO}-d_6$ , which displaced the diphosphine and showed the resonance of the uncoordinated  $\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2$ . Despite numerous attempts, no crystals of  $[\text{Pb}\{\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2\}(\text{NO}_3)_2]$  could be grown (instead a few crystals of the phosphine oxide complex  $[\text{Pb}\{\text{Et}_2\text{P}(\text{O})(\text{CH}_2)_2\text{P}(\text{O})\text{Et}_2\}(\text{NO}_3)_2]$  were obtained, discussed below); the IR spectrum of  $[\text{Pb}\{\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2\}(\text{NO}_3)_2]$  indicates that the nitrate groups are again  $\kappa^2$ -coordinated (bands at 1300, 1029 and  $816\text{ cm}^{-1}$ ), which when combined with the NMR spectroscopic evidence suggests that  $[\text{Pb}\{\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2\}(\text{NO}_3)_2]$  has a similar structure to the other bidentate phosphine complexes.

Although  $[\text{Pb}\{\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2\}(\text{NO}_3)_2]$  and  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{NO}_3)_2]$  were found to dissolve completely in DMF, a property exploited in order to grow crystals of these complexes, its relatively strong coordinating nature makes it problematic for NMR studies of these dynamic and labile systems. For both complexes a single resonance was observed in  $^{31}\text{P}\{^1\text{H}\}$  NMR spectra run in  $\text{DMF}-d_7$ , with chemical shifts intermediate between those expected by analogy with the complex  $[\text{Pb}\{\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2\}(\text{NO}_3)_2]$  and the uncoordinated ligand shifts. The chemical shifts varied widely with concentration, indicating partial displacement of the diphosphine and rapidly exchanging systems. The values are not quoted.  $[\text{Pb}\{\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2\}(\text{NO}_3)_2]$  was also found to be partially decomposed by  $\text{DMF}-d_7$ .

Under the same reaction conditions the weaker  $\sigma$ -donor and sterically more crowded ligand  $o\text{-C}_6\text{H}_4(\text{PPh}_2)_2$  did not form a complex with  $\text{Pb}(\text{NO}_3)_2$ . No complex could be isolated with  $o\text{-C}_6\text{H}_4(\text{AsMe}_2)_2$ , suggesting that the alkylphosphines are

better donors in these systems than alkylarsines, an effect also observed with other Group 14 metal acceptors.<sup>5</sup>

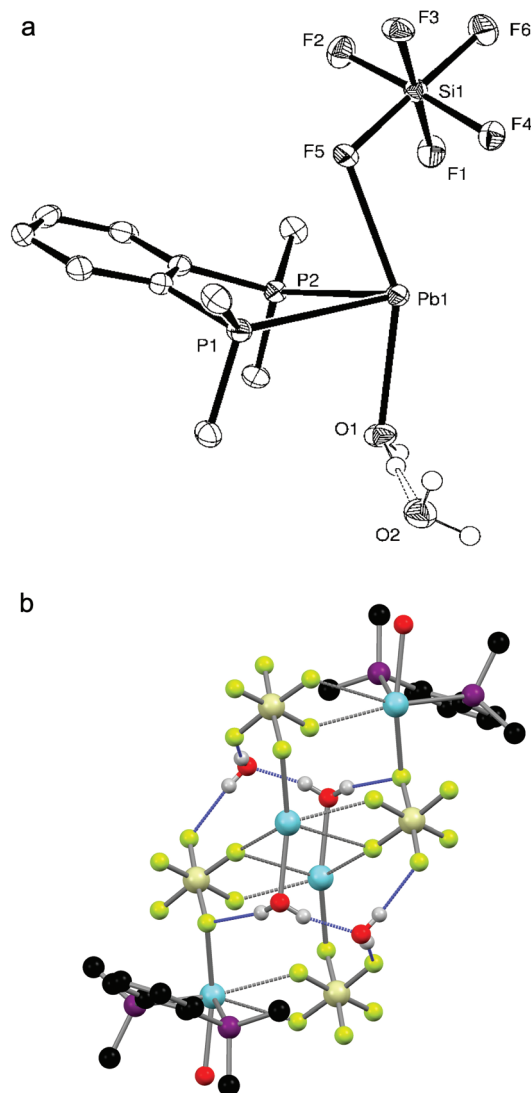
### Lead(II) hexafluorosilicate complexes

The reaction of  $\text{Pb}(\text{SiF}_6) \cdot 2\text{H}_2\text{O}$  with  $o\text{-C}_6\text{H}_4(\text{PMe}_2)_2$  in a 1 : 1 ratio yielded a white powder which, when dissolved in DMF and layered with  $\text{Et}_2\text{O}$ , gave small colourless crystals of  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{H}_2\text{O})(\text{SiF}_6)] \cdot \text{H}_2\text{O}$ . The crystal structure (Fig. 3a) shows the diphosphine to be asymmetrically chelating, with a short Pb–F bond ( $d(\text{Pb1-F5}) = 2.573(3)\text{ \AA}$ ) to a  $\kappa^1$ -coordinated  $\text{SiF}_6^{2-}$  group and a further bond to a water molecule, so that overall the core molecular geometry is very similar to that of  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{NO}_3)_2]$  (Fig. 2a), although the disparity in Pb–P bond lengths is greater ( $\sim 0.03\text{ \AA}$ ) and the F–Pb–O angle is large ( $154.76(11)^\circ$ ). The core geometry is therefore little affected by the anion present, with the primary contacts again covering one hemisphere of the lead. Although two more Pb–F distances ( $d(\text{Pb1-F1}) = 3.201(3)$ ,  $d(\text{Pb1-F4}) = 3.167(3)\text{ \AA}$ ) lie well within the sum of the Van der Waal's radii of  $3.49\text{ \AA}$  for  $\text{Pb} \cdots \text{F}$ ,<sup>14</sup> these long contacts are probably the result of packing within the crystal lattice causing these F atoms to lie close to the Pb(II) centre. Nevertheless, an alternative description for the molecular structure of  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{H}_2\text{O})(\text{SiF}_6)] \cdot \text{H}_2\text{O}$  is that the  $\text{SiF}_6^{2-}$  group is asymmetrically  $\kappa^3$ -coordinated. These units are arranged into infinite strands by a Pb–F interaction from a neighbouring  $\text{SiF}_6^{2-}$  group ( $d(\text{Pb-F}) = 2.815(3)\text{ \AA}$ ); two further Pb–F interactions with a  $\text{SiF}_6^{2-}$  group on a parallel strand ( $d(\text{Pb-F}) = 2.795(3)$ ,  $3.083(3)\text{ \AA}$ ) gives a polymeric chain structure overall (Fig. 3b), where the lead(II) centre is seven coordinate (or nine if the core  $\text{SiF}_6^{2-}$  group is described as  $\kappa^3$ -coordinated). The  $o\text{-C}_6\text{H}_4(\text{PMe}_2)_2$  groups are arranged so that they point outwards from the chain. The coordinated water molecule is also hydrogen bonded to a lattice water molecule ( $\text{HO-H} \cdots \text{OH}_2 = 1.89(7)\text{ \AA}$ ), and together these form a hydrogen-bonding network (Fig. 3b) with F atoms on nearby  $\text{SiF}_6^{2-}$  groups ( $\text{HO-H} \cdots \text{F} = 1.93(2)$ ,  $2.05(6)$ ,  $2.14(3)\text{ \AA}$ ).

The IR spectrum of the bulk solid confirms the presence of the  $\text{SiF}_6^{2-}$  group, although the anion coordination mode cannot be reliably identified.<sup>16</sup> The stretching mode is significantly broadened, indicating that the Pb–F interactions are too weak to lower the symmetry of the fluoroanion sufficiently to give resolved splittings.<sup>121</sup> Water is also visible in the IR spectrum, indicating that the bulk solid is probably also  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{H}_2\text{O})(\text{SiF}_6)] \cdot x\text{H}_2\text{O}$ , though a satisfactory elemental analysis could not be obtained. Poor solubility precluded NMR analysis of this complex.

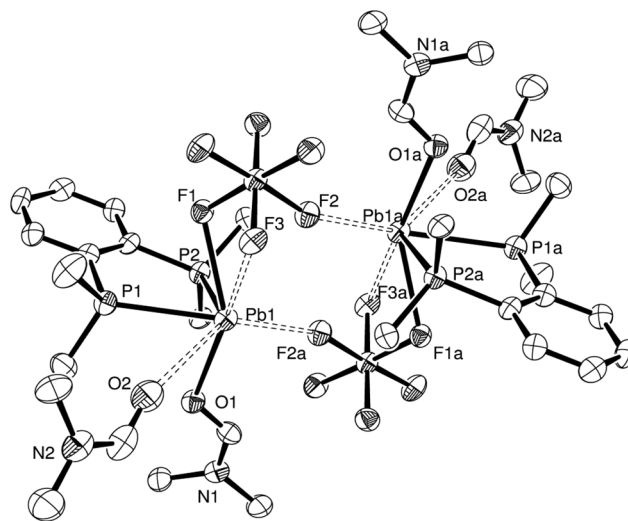
Repetition of the reaction with a 2 : 1 (diphosphine : Pb) ratio yielded a few crystals of  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{DMF})_2(\text{SiF}_6)] \cdot \text{DMF}$ , again demonstrating the preference of the Pb(II) centre to coordinate to just one diphosphine ligand. The asymmetric unit has the expected core bonding environment ( $\text{P}_2\text{FO}$ ) around the lead, with an O-bonded DMF molecule in place of  $\text{H}_2\text{O}$ , giving a F–Pb–O angle of  $140.82(12)^\circ$ . The  $\text{SiF}_6^{2-}$  group is now  $\kappa^2$ - or  $\kappa^3$ -coordinated depending on the viewpoint – the  $d(\text{Pb1-F3})$  is  $\sim 0.3\text{ \AA}$  shorter than the comparable distance in  $[\text{Pb}\{o\text{-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{H}_2\text{O})(\text{SiF}_6)] \cdot \text{H}_2\text{O}$ , while the  $d(\text{Pb1-F2})$





**Fig. 3** (a) Crystal structure of  $[\text{Pb}\{\text{o-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{H}_2\text{O})(\text{SiF}_6)] \cdot \text{H}_2\text{O}$  showing the atom labelling scheme. The displacement ellipsoids are drawn at the 50% probability level and H atoms are omitted for clarity. Selected bond lengths (Å) and angles (°):  $\text{Pb1-P1} = 2.8299(14)$ ,  $\text{Pb1-P2} = 2.7976(13)$ ,  $\text{Pb1-F5} = 2.573(3)$ ,  $\text{Pb1-O1} = 2.496(3)$ ,  $\text{P1-Pb1-P2} = 69.67(4)$ ,  $\text{F5-Pb1-O1} = 154.76(11)$ . (b) The polymeric chain structure of  $[\text{Pb}\{\text{o-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{H}_2\text{O})(\text{SiF}_6)] \cdot \text{H}_2\text{O}$ . The intermolecular H-bonding network is shown in blue and the diphosphines on the two central lead atoms are omitted for clarity.

remains long at  $3.081(4)$  Å. The size of the DMF molecule and the lack of hydrogen bonding are presumably the main reasons the units now dimerise (Fig. 4) with the  $\text{SiF}_6^{2-}$  groups bridging *via* one F atom per fluoroanion. The orientation of a second DMF molecule close to the  $\text{Pb}(\text{II})$  centre suggests that is also interacting with the lead ( $d(\text{Pb-O}) = 3.263(6)$  Å), which gives an overall coordination number of seven or eight for  $\text{Pb}(\text{II})$ . There is also a DMF solvate molecule in the structure. Formation of this complex also shows that DMF will readily coordinate to lead(II), highlighting its unsuitability as a NMR solvent in these systems, but because of the lability of the



**Fig. 4** Crystal structure of the  $\text{SiF}_6$ -bridged dimer present in  $[\text{Pb}\{\text{o-C}_6\text{H}_4(\text{PMe}_2)_2\}(\text{DMF})_2(\text{SiF}_6)] \cdot \text{DMF}$  showing the atom labelling scheme. The displacement ellipsoids are drawn at the 50% probability level. H atoms and DMF solvate molecules are omitted for clarity. Symmetry operation:  $a = 2 - x, 2 - y, 1 - z$ . Selected bond lengths (Å) and angles (°):  $\text{Pb1-P1} = 2.7671(19)$ ,  $\text{Pb1-P2} = 2.7553(16)$ ,  $\text{Pb1-F1} = 2.585(3)$ ,  $\text{Pb1-F3} = 2.894(3)$ ,  $\text{Pb1-F2a} = 2.752(3)$ ,  $\text{Pb1-O1} = 2.463(4)$ ,  $\text{Pb1-O2} = 3.263(6)$ ,  $\text{P1-Pb1-P2} = 72.30(5)$ ,  $\text{F1-Pb1-F3} = 50.67(9)$ ,  $\text{F1-Pb1-F2a} = 110.58(10)$ ,  $\text{F1-Pb1-O1} = 140.82(12)$ ,  $\text{F1-Pb1-O2} = 109.10(12)$ .

complex in solution, the structure obtained is ultimately dependant on which complex crystallises out under the conditions employed.

### Phosphine oxide complexes

When trying to grow crystals of  $[\text{Pb}\{\text{Et}_2\text{P}(\text{CH}_2)_2\text{PEt}_2\}(\text{NO}_3)_2]$  by recrystallisation from  $\text{CH}_2\text{Cl}_2$  and *n*-hexane, a few small colourless crystals of  $[\text{Pb}\{\text{Et}_2(\text{O})\text{P}(\text{CH}_2)_2\text{P}(\text{O})\text{Et}_2\}_2(\text{NO}_3)_2]$  were instead isolated, indicating that *in situ* oxidation of the ligand has occurred, presumably due to adventitious  $\text{O}_2$ . The X-ray structure determination reveals (Fig. 5a) that the  $\text{Et}_2(\text{O})\text{P}(\text{CH}_2)_2\text{P}(\text{O})\text{Et}_2$  ligands each bridge to different  $\text{Pb}(\text{II})$  atoms, and that there are two phosphine oxide ligands per metal centre, despite the parent phosphine complex having a 1 : 1 stoichiometry. This gives a core  $\text{PbO}_4$  geometry, with one  $\text{Pb-O}$  bond  $\sim 0.1$  Å longer than the other three and a  $\text{O1-Pb1-O4}$  angle of  $160.29(9)^\circ$ . Interactions with the nitrate groups are weaker than in  $[\text{Pb}(\text{L-L})(\text{NO}_3)_2]$  ( $\text{L-L} = \text{o-C}_6\text{H}_4(\text{PMe}_2)_2$ ,  $\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2$ ) but they remain  $\kappa^2$ -coordinated (the third oxygen is uncoordinated) and fill the remainder of the coordination sphere, to give eight coordinate lead. Due to the bridging nature of the phosphine oxide groups, the extended structure (Fig. 5b) is an infinite polymer network.

The *in situ* oxidation of diphosphine ligands in the presence of heavy *p*-block metals has been reported before;<sup>5</sup> for example, the oxidation of the 1 : 1 adduct of  $\text{BiCl}_3$  and  $\text{Ph}_2\text{PCH}_2\text{PPh}_2$  to the crystallographically identified  $[\text{BiCl}_3\{\text{Ph}_2\text{P}(\text{O})\text{CH}_2\text{P}(\text{O})\text{Ph}_2\}]_2$  having occurred when trying to grow crystals



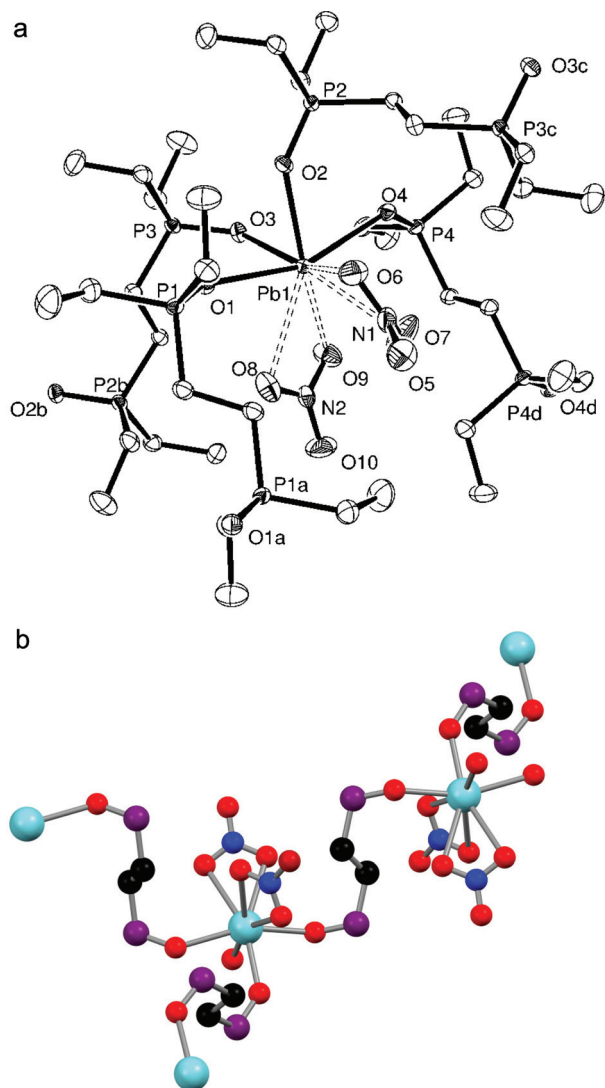


Fig. 5 (a) Crystal structure of  $[\text{Pb}\{\text{Et}_2(\text{O})\text{P}(\text{CH}_2)_2\text{P}(\text{O})\text{Et}_2\}_2(\text{NO}_3)_2]$  showing the atom labelling scheme. The displacement ellipsoids are drawn at the 50% probability level and H atoms are omitted for clarity. Symmetry operations:  $a = -x, 1 - y, 1 - z$ ;  $b = x, 1/2 - y, 1/2 + z$ ;  $c = x, 1/2 - y, -1/2 + z$ ;  $d = 1 - x, 1 - y, 1 - z$ . Selected bond lengths (Å) and angles (°):  $\text{Pb1}-\text{O1} = 2.484(2)$ ,  $\text{Pb1}-\text{O2} = 2.429(2)$ ,  $\text{Pb1}-\text{O3} = 2.418(2)$ ,  $\text{Pb1}-\text{O4} = 2.589(2)$ ,  $\text{Pb1}-\text{O6} = 2.786(2)$ ,  $\text{Pb1}-\text{O7} = 2.912(3)$ ,  $\text{Pb1}-\text{O8} = 2.875(3)$ ,  $\text{Pb1}-\text{O9} = 2.891(3)$ ,  $\text{P1}-\text{O1} = 1.502(3)$ ,  $\text{P2}-\text{O2} = 1.504(2)$ ,  $\text{P3}-\text{O3} = 1.510(3)$ ,  $\text{P4}-\text{O4} = 1.504(3)$ ,  $\text{O1}-\text{Pb}-\text{O2} = 80.24(8)$ ,  $\text{O1}-\text{Pb}-\text{O3} = 83.96(8)$ ,  $\text{O1}-\text{Pb}-\text{O4} = 160.29(9)$ ,  $\text{O2}-\text{Pb}-\text{O3} = 81.05(9)$ ,  $\text{O2}-\text{Pb}-\text{O4} = 81.58(8)$ ,  $\text{O3}-\text{Pb}-\text{O4} = 85.75(8)$ ,  $\text{O6}-\text{Pb}-\text{O7} = 44.41(10)$ ,  $\text{O8}-\text{Pb}-\text{O9} = 43.97(8)$ ,  $\text{Pb1}-\text{O1}-\text{P1} = 144.23(15)$ ,  $\text{Pb1}-\text{O2}-\text{P2} = 137.26(14)$ ,  $\text{Pb1}-\text{O3}-\text{P3} = 132.28(15)$ ,  $\text{Pb1}-\text{O4}-\text{P4} = 131.85(14)$ . (b) The extended structure of  $[\text{Pb}\{\text{Et}_2(\text{O})\text{P}(\text{CH}_2)_2\text{P}(\text{O})\text{Et}_2\}_2(\text{NO}_3)_2]$ . Ethyl groups are omitted for clarity.

of the phosphine complex.<sup>18</sup> Interestingly, the *in situ* oxidation of diphosphine ligands has also been reported with  $\text{Pb}(\text{II})$ , when a few crystals of  $[\{(\text{Pb}_3(\mu\text{-I})_6)(\text{Ph}_2(\text{O})\text{P}(\text{CH}_2)_2\text{P}(\text{O})\text{Ph}_2)_2\}]\cdot\text{EtOH}$  were obtained from the solvothermal reaction of  $\text{PbI}_2$  with  $\text{KI}$ ,  $\text{I}_2$  and  $\text{Ph}_2\text{P}(\text{CH}_2)_2\text{PPh}_2$ . Attempts to increase the yield of the phosphine oxide complex by introducing  $\text{H}_2\text{O}_2$

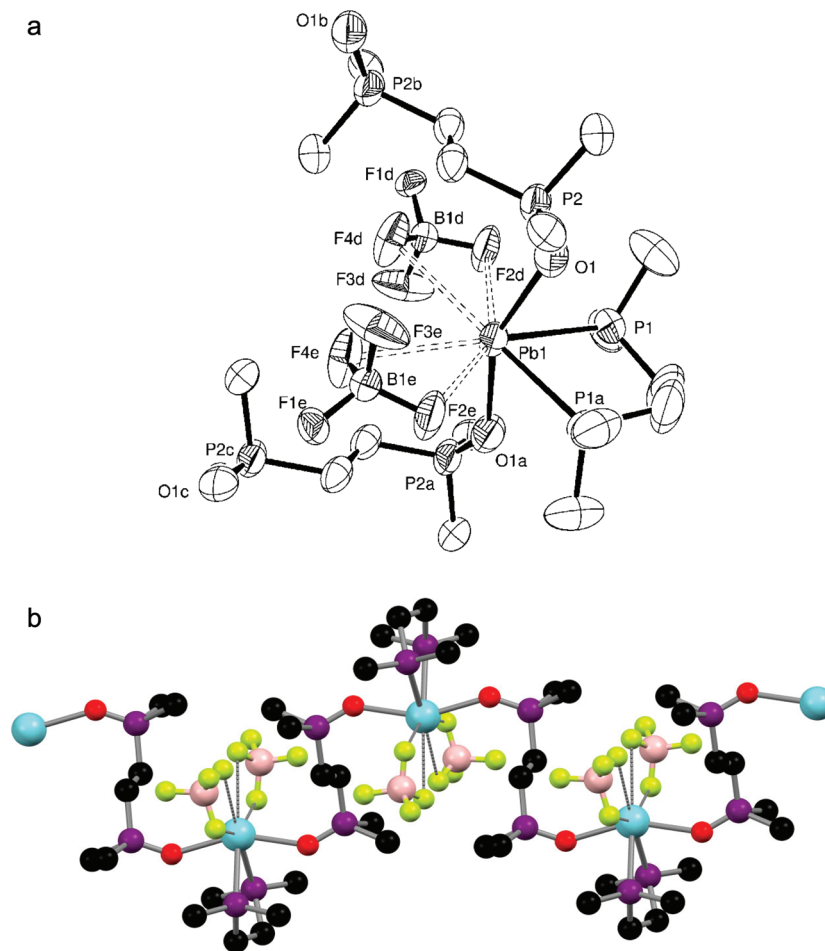
into the reaction generated  $[\{\text{Pb}_2(\mu\text{-I})_2(\mu^3\text{-I})_2\}\{\text{Ph}_2(\text{O})\text{P}(\text{CH}_2)_2\text{-P}(\text{O})\text{Ph}_2\}]$ . Both structures have octahedrally coordinated  $\text{Pb}(\text{II})$  centres with the  $\text{Ph}_2(\text{O})\text{P}(\text{CH}_2)_2\text{P}(\text{O})\text{Ph}_2$  groups bridging between metal centres.<sup>19</sup>

Attempts to form diphosphine complexes with  $\text{Pb}(\text{BF}_4)_2$  (supplied as a 50% aqueous solution) were largely unsuccessful due to the acidity of the solution (which contains some excess acid to prevent hydrolysis), and led to protonation of the phosphine ligands. This tendency towards ligand protonation has been previously observed when crystals of  $[\text{terpyH}_2][\text{BF}_4]_2$  (terpy = 2,2':6',2''-terpyridyl) were obtained from the reaction of aqueous  $\text{Pb}(\text{BF}_4)_2$  and terpy.<sup>12</sup> Despite this, on one occasion small colourless crystals of  $[\text{Pb}\{\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2\}][\text{BF}_4]_2 \cdot \frac{1}{2}\text{MeNO}_2$  were obtained from the reaction of aqueous  $\text{Pb}(\text{BF}_4)_2$  (one mol. equiv.) with two mol. equiv. of  $\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2$  in  $\text{MeNO}_2$ . The complexes crystallises in the unusual orthorhombic  $Fddd$  space group. The preferred coordination mode of both the diphosphine and diphosphine dioxide to lead(II) discussed above is also evident here, as the X-ray structure (Fig. 6a) reveals the  $\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2$  to be symmetrically chelating, while the  $\text{Me}_2(\text{O})\text{P}(\text{CH}_2)_2\text{P}(\text{O})\text{Me}_2$  (from the *in situ* oxidation of the diphosphine ligand) bridges between  $\text{Pb}(\text{II})$  centres, giving an infinite chain structure (Fig. 6b). The symmetry related  $\text{BF}_4^-$  groups are disordered, but seem to adopt two distinct and reasonably well-defined orientations. Although not discussed in detail because of the disorder, the  $\text{Pb}-\text{F}$  distances in the two orientations are similar at  $\sim 3.1$  and  $3.3$  Å, allowing the fluoroanion to be described as either  $\kappa^1$ - or  $\kappa^2$ -coordinated. Overall the  $\text{Pb}(\text{II})$  exhibits the expected core  $(\text{P}_2\text{O}_2)$  geometry. There is also a disordered (the N atom is located on a site with 222 symmetry) fractionally occupied (50%)  $\text{MeNO}_2$  solvate molecule in the asymmetric unit.

## Conclusions

Several new and rare diphosphine complexes of the lead(II) salts  $\text{Pb}(\text{NO}_3)_2$  and  $\text{Pb}(\text{SiF}_6)$  have been isolated and structurally characterised, revealing a clear preference for a single bidentate phosphine ligand to chelate to lead(II). Unexpectedly, there is no evidence that a second diphosphine can be introduced to the  $\text{Pb}(\text{II})$  coordination sphere, in marked contrast to the complexes of diimines where bis-ligand complexes predominate.<sup>11,12</sup> This is unlikely to be due to steric constraints on the large metal centre, and presumably reflects rather limited affinity of the lead(II) for the phosphorus donors. Although the geometries around the  $\text{Pb}(\text{II})$  are highly irregular, a core four-coordinate motif arranged on one hemisphere of the lead is identifiable in every complex, with longer (weaker) contacts to anions from neighbouring molecules occupying much of the remaining coordination sphere, leading to extended polymer chain and network structures. As with the di- and tri-imine complexes of  $\text{Pb}(\text{SiF}_6)$ ,<sup>11</sup> the little studied  $\text{SiF}_6^{2-}$  dianion can bond to a single  $\text{Pb}(\text{II})$  ion *via* one or more  $\text{Pb}-\text{F}$  interaction(s), or can bridge between metal centres. The  $\text{SiF}_6^{2-}$  group is





**Fig. 6** (a) Structure of  $[\text{Pb}(\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2)\{\text{Me}_2(\text{O})\text{P}(\text{CH}_2)_2\text{P}(\text{O})\text{Me}_2\}][\text{BF}_4]_2 \cdot \frac{1}{2}\text{MeNO}_2$  showing the atom labelling scheme. The displacement ellipsoids are drawn at the 50% probability level and H atoms and the fractionally occupied (50%)  $\text{MeNO}_2$  solvate molecule are omitted for clarity. Symmetry operations:  $a = 7/4 - x, 3/4 - y, z$ ;  $b = 2 - x, 1 - y, -z$ ;  $c = -1/4 + x, -1/4 + y, -z$ ;  $d = 2 - x, -1/4 + y, -1/4 + z$ ;  $e = -1/4 + x, 1 - y, -1/4 + z$ . Selected bond lengths (Å) and angles (°):  $\text{Pb1}-\text{P1} = 2.789(2)$ ,  $\text{Pb1}-\text{O1} = 2.454(6)$ ,  $\text{O1}-\text{P2} = 1.478(6)$ ,  $\text{P1}-\text{Pb1}-\text{P1a} = 72.86(9)$ ,  $\text{O1}-\text{Pb1}-\text{O1a} = 154.5(3)$ ,  $\text{Pb1}-\text{O1}-\text{P2} = 139.1(3)$ . The  $\text{BF}_4$  is disordered with two distinct orientations (only one orientation is shown). (b) The extended structure of  $[\text{Pb}(\text{Me}_2\text{P}(\text{CH}_2)_2\text{PMe}_2)\{\text{Me}_2(\text{O})\text{P}(\text{CH}_2)_2\text{P}(\text{O})\text{Me}_2\}][\text{BF}_4]_2 \cdot \frac{1}{2}\text{MeNO}_2$ . Only one orientation of the  $\text{BF}_4$  is shown.

stable in these systems, with no evidence of hydrolysis or fragmentation of the fluoroanion having occurred. This contrasts with the degradation seen for some  $\text{PF}_6^-$  or  $\text{BF}_4^-$  salts with  $\text{Pb}(\text{II})$  and  $\text{Sn}(\text{II})$  macrocyclic species.<sup>10</sup> In some cases adventitious oxygen leads to *in situ* oxidation of diphosphine ligands, yielding the corresponding diphosphine dioxide complexes, where the diphosphine dioxide bridges between lead(II) centres. This remains a challenging area, with poor solubility and the lability of  $\text{Pb}(\text{II})$  in solution limiting the information that can be gathered from spectroscopic characterisation.

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## References

- 1 R. G. Pearson, *J. Am. Chem. Soc.*, 1963, **85**, 3533.
- 2 J. Parr, in *Comprehensive Coordination Chemistry II*, ed. J. A. McCleverty and T. J. Meyer, Elsevier, Oxford, 2004, vol. 3, p. 545.
- 3 E. S. Claudio, H. A. Godwin and J. S. Magyar, *Prog. Inorg. Chem.*, 2003, **51**, 1.
- 4 R. L. Davidovich, V. Stavila and K. H. Whitmire, *Coord. Chem. Rev.*, 2010, **254**, 2193.
- 5 J. Burt, W. Levason and G. Reid, *Coord. Chem. Rev.*, 2014, **260**, 65.





- 6 C. E. Wymore and J. C. Bailar, *J. Inorg. Nucl. Chem.*, 1960, **14**, 42.
- 7 A. J. Rossini, A. W. Macgregor, A. S. Smith, G. Schatte, R. W. Schurko and G. G. Briand, *Dalton Trans.*, 2013, **42**, 9533.
- 8 P. A. W. Dean, D. D. Phillips and L. Polensek, *Can. J. Chem.*, 1981, **59**, 50.
- 9 P. A. W. Dean, *Can. J. Chem.*, 1983, **61**, 1795.
- 10 P. Farina, T. Latter, W. Levason and G. Reid, *Dalton Trans.*, 2013, **42**, 4714; C. Beattie, P. Farina, W. Levason and G. Reid, *Dalton Trans.*, 2013, **42**, 15183.
- 11 M. Kadarkaraisamy, D. P. Engelhart, P. M. Basa and A. G. Sykes, *J. Coord. Chem.*, 2010, **63**, 2261; L. M. Engelhardt, J. M. Harrowfield, H. Miyamae, J. M. Patrick, B. W. Skelton, A. A. Soudi and A. H. White, *Aust. J. Chem.*, 1996, **49**, 1111; I. Bytheway, L. M. Engelhardt, J. M. Harrowfield, D. L. Kepert, H. Miyamae, J. M. Patrick, B. W. Skelton, A. A. Soudi and A. H. White, *Aust. J. Chem.*, 1996, **49**, 1099; L. M. Engelhardt, J. M. Harrowfield, H. Miyamae, J. M. Patrick, B. W. Skelton, A. A. Soudi and A. H. White, *Aust. J. Chem.*, 1996, **49**, 1135.
- 12 J. Burt, W. Grantham, W. Levason, M. E. Light and G. Reid, *Polyhedron*, 2015, **85**, 530.
- 13 E. P. Kyba, S. T. Liu and R. L. Harris, *Organometallics*, 1983, **2**, 1877; R. D. Feltham, A. Kasenally and R. S. Nyholm, *J. Organomet. Chem.*, 1967, **7**, 285.
- 14 G. M. Sheldrick, *Acta Crystallogr., Sect. A: Found. Crystallogr.*, 2008, **64**, 112.
- 15 M. Mantina, A. C. Chamberlain, R. Valero, C. J. Cramer and D. G. Truhlar, *J. Phys. Chem. A*, 2009, **113**, 5806.
- 16 K. Nakamoto, *Infrared and Raman Spectra of Inorganic and Coordination Compounds*, Wiley, NY, 4th edn, 1986.
- 17 B. M. Barry, B. W. Stein, C. A. Larsen, M. N. Wirtz, W. E. Geiger, R. Waterman and R. A. Kemp, *Inorg. Chem.*, 2013, **52**, 9875.
- 18 G. R. Willey, M. D. Rudd, C. J. Samuel and M. G. B. Drew, *J. Chem. Soc., Dalton Trans.*, 1995, 759.
- 19 Z. J. Huang, H. J. Cheng, M. Dai, C. Y. Ni, H. X. Li, K. P. Hou, Z. G. Ren and J. P. Lang, *Inorg. Chem. Commun.*, 2013, **31**, 33.

