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New ferrocene-derived hydroxymethylphosphines: $FcP(CH_2OH)_2$ [Fc = (η^5-C_5H_5)Fe(η^5-C_5H_4)] and the dppf analogue 1,1'-Fc'[$P(CH_2OH)_2$] [Fc' = Fe(η^5-C_5H_4)$_2$]

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Abstract

Reactions of the ferrocene-phosphines $FcPH_2$ and 1,1'-Fc'$(PH_2)_2$ with excess formaldehyde gives the new hydroxymethylphosphines $FcP(CH_2OH)_2$ **1** and 1,1'-Fc'$[P(CH_2OH)_2]_2$ respectively. Phosphine **1** is an air-stable crystalline solid, whereas **2** is isolated as an oil. Reaction of **1** with H_2O_2, S_8 or Se gives the chalcogenide derivatives $FcP(E)(CH_2OH)_2$ (E = O, S or Se), whilst reaction of **2** with S_8 gives 1,1'-Fc'$[P(S)(CH_2OH)_2]_2$, which were fully characterized. Phosphine **1** was also characterised by an X-ray crystal structure determination.

Keywords: Ferrocene compounds; Hydroxymethylphosphines; Crystal structure; Phosphine chalcogenides

1. Introduction

Hydroxymethylphosphines, containing PCH_2OH groups, have been known for many years [1] but are attracting recent interest for their versatile reactivity [2] and ability to render metal complexes water-soluble, with uses ranging from catalysis,[2,3] metal complex immobilisation [4] and biomedical applications. [2,5] We have reported the first example of a ferrocene-derived hydroxymethylphosphine, $FcCH_2P(CH_2OH)_2$, and some derivatives thereof. [6] In separate recent reports, cyclophosphazene derivatives of the phosphine sulfide $FcCH_2P(S)(CH_2OH)_2$ [7] and the methyl-substituted derivative $FcCH(Me)P(CH_2OH)_2$ [8] have been studied. In this Communication we report the synthesis of two new ferrocenyl hydroxymethylphosphines, $FcP(CH_2OH)_2$ and 1,1'-Fc'$[P(CH_2OH)_2]_2$. The latter is the hydroxymethyl analogue of dppf, 1,1'-Fc'$(PPh_2)_2$, which has been very extensively investigated. [9]

2. Results and discussion

A general synthesis for the synthesis of hydroxymethylphosphines utilises the ready reactivity of primary phosphines towards formaldehyde. [1,2] Reaction of the known primary phosphines $FcPH_2$ [10] and 1,1'-Fc'$(PH_2)_2$ [11] with excess aqueous formaldehyde gave the hydroxymethylphosphines $FcP(CH_2OH)_2$ **1** and 1,1'-Fc'$[P(CH_2OH)_2]_2$ **2** respectively. Several products were initially obtained in each case, and are presumably the formaldehyde adducts, containing P-$(CH_2O)_nH$ groups [12]; excess formaldehyde was removed by exposure of the crude products to a dynamic vacuum (*ca*. 1 mmHg) for 24 h. Phosphine **1** (δ ^{31}P -24.7) is an orange crystalline solid, soluble in polar organic solvents, and indefinitely stable in air. The ^{1}H NMR spectrum shows that the CH_2 protons are in unique environments, with a geminal coupling of 13 Hz. This effect was not observed in the related compounds $FcCH_2P(CH_2OH)_2$ or $FcCH_2P(S)(CH_2OH)_2$ suggesting that the closer proximity of the bulky Fc group may be causing restricted rotation in the P-CH_2 and/or CH_2-O groups. The positive ion electrospray (ES) mass spectrum of **1** in methanol at a cone voltage of 20 V with added $AgNO_3$ [13] gave a single ion at *m/z* 663 due to the $[2M + Ag]^+$ ion.

The X-ray structure determination of **1**‡ was carried out to unambiguously confirm the formulation of the compound as the bis(hydroxymethyl)phosphine, and the molecular structure is shown in Fig. 1. The network of hydrogen bonding involving the OH groups is very similar to that of $FcCH_2P(CH_2OH)_2$ [6] with the molecules arranged into chains, crosslinked by hydrogen bonds, resulting in each molecule being involved in hydrogen bonding interactions with four other molecules. There are two distinct types of hydrogen bonds, H(4)---O(1), which link two chains together, and H(3)---O(2), which link adjacent molecules in the same chain together, resulting in the formation of linked ten-membered hydrogen bonded rings, Figure 2.

Reaction of **1** with hydrogen peroxide, sulfur or grey selenium under sonication gives the phosphine oxide **3** (δ ^{31}P 47.6), sulfide **4** (δ ^{31}P 38.2) and selenide **5** (δ ^{31}P 39.1, ^{1}J(PSe) 701 Hz) respectively; all are crystalline orange solids. X-ray crystal structure analyses have also been performed on these derivatives, and a detailed comparison of the hydrogen bonding trends will be described elsewhere.

Phosphine **2** was unable to be obtained as a crystalline solid, and unlike **1**, this phosphine is slightly air-sensitive, and a satisfactory elemental analysis was not obtained. The ES mass spectrum of **2** with added $AgNO_3$ showed the $[2M + Ag]^+$ ion (*m/z* 847) at low cone voltages (*ca.* 20V) and $[M + Ag]^+$ (*m/z* 477) at higher cone voltages (e.g. 60 V). Further characterisation was by means of the formation of the disulfide derivative **6**, for which satisfactory microanalytical data were obtained. Like the parent phosphine **1**, the sulfide and selenide derivatives **4** - **6** also show inequivalent CH_2 protons, with geminal ^{2}J(HH) coupling of *ca*. 13 Hz.

In conclusion, we have synthesised mono- and bis-substituted ferrocenyl-hydroxymethylphosphines, where one or both cyclopentadienyl rings are substituted with water-solubilising and reactive $P(CH_2OH)_2$ groups. Given the importance of dppf as a ligand [9], more detailed studies on the coordination chemistry of the related phosphine **2** are clearly warranted.

3. Experimental

General experimental details have been described elsewhere [6] and the atom numbering scheme is given in ref. [14]. The compounds $FcPH_2$ [10] and 1,1'-Fc'$(PH_2)_2$ [11] were prepared by modifications of the literature methods.

*3.1 Preparation of $FcP(CH_2OH)_2$ **1***

Aqueous formaldehyde (0.25 mL, 40% w/v) was added to a solution of $FcPH_2$ (0.26 g, 1.2 mmol) in thf (5 mL) under nitrogen, and the solution stirred for 18 h. The volatiles were removed under vacuum, and the crude product held under vacuum for *ca.* 72 h to remove excess formaldehyde, giving an orange microcrystalline solid (0.33 g, 96%). M.p. 100-106 °C. Found: C, 51.8; H, 5.5. $C_{12}H_{15}FeO_2P$ requires C, 51.8; H, 5.4%. $^{31}P-\{^1H\}$ NMR ($CDCl_3$), δ -24.7. ^1H NMR ($CDCl_3$), δ 2.56 (2H, br s, OH), 4.24 (5H, s, C_5H_5), 4.30 [2H, dd, $^2J(HH)$ 13, $^3J(HH)$ 5, CH_2], 4.40 (2H, s, C_5H_4), 4.45 [2H, br d, $^2J(HH)$ 13, CH_2], 4.50 (2H, s, C_5H_4). $^{13}C-\{^1H\}$ NMR ($CDCl_3$), δ 62.90 [d, J(PC) 17, PCH_2OH], 69.08 s), 70.24 [d, J(PC) 3.8], 73.22 [d, J(PC) 14)].

*3.2 Preparation of 1,1'-Fc'$[P(CH_2OH)_2]_2$ **2***

Following the method for **1**, 40% formaldehyde (0.41 mL) was added to a solution of 1,1'-Fc'$(PH_2)_2$ (0.24 g, 0.97 mol) in thf (5 mL) under nitrogen, and the mixture stirred for 24 h. Workup gave 0.348 g (98%) of **2** as a viscous orange-brown oil. $^{31}P-\{^1H\}$ NMR

(d^6-DMSO), δ -31.0. ^{1}H NMR (d^6-DMSO), δ 4.02 (8H, m, CH_2), 4.34 (4H, br s, C_5H_4), 4.39 [4H, d, ^3J(PH) 1.7, C_5H_4], 4.89 (3.6H, br s, OH). ^{13}C-{^{1}H} NMR (d^6-DMSO), δ 61.02 [d, J(PC) 6.6, PCH_2OH], 72.45 (s, br), 74.56 [d, J(PC) 13], 91.18 [d, J(PC) 9].

3.3 Preparation of phosphine oxide, sulfide and selenide derivatives ***3*** *-* ***6***

The appropriate phosphine was treated with H_2O_2, S_8 or grey Se respectively, followed by standard workup procedures.

3; Yield 97%, m.p. 171-176 °C. Found C, 49.0; H, 5.3. $C_{12}H_{15}FeO_3P$ requires C, 49.0; H, 5.1%. ^{1}H NMR (d^6-DMSO), δ 3.97 (4H, br s, PCH_2OH), 4.39 (5H, s, H4), 4.54 (4H, br s, H2/H3), 5.39 (2H, br s, $PCH_2O\underline{H}$). ^{13}C-{^{1}H} NMR (d^6-DMSO), δ 59.52 [d, ^1J(PC) 84, PCH_2OH], 70.88 (s), 72.61 [d, J(PC) 10], 72.75 [d, J(PC) 11], C1 not observed.

4; Yield 99%, m.p. 122-126 °C. Found C, 46.3; H, 4.9. $C_{12}H_{15}FeO_2PS$ requires C, 46.5; H, 4.9%. ^{1}H NMR ($CDCl_3$), δ 2.76 [2H, dd, ^3J(HH) 6, ^3J(PH) 6, $CH_2O\underline{H}$], 4.05 [2H, ddd, ^2J(HH) 13, ^3J(HH) 4.2, ^2J(PH) 1.6, CH_2], 4.15 [2H, ddd, ^2J(HH) 13, ^3J(HH) 6.3, ^2J(PH) 1.6 CH_2], 4.36 (5H, s, H4), 4.52 [2H, dt, ^3J(HH) 3.6, ^4J(PH) 1.7, H3), 4.56 [2H, dt, ^3J(HH) 3.5, ^3J(PH) 1.7, H2]. ^{13}C-{^{1}H} NMR ($CDCl_3$), δ 61.04 [d, J(PC) 59, PCH_2OH], 70.03 (s), 71.55 [d, J(PC) 12], 72.13 [d, J(PC) 9].

5; Yield 95%, m.p. 116-118 °C. Found C, 40.8; H, 4.5. $C_{12}H_{15}FeO_2PSe$ requires C, 40.4; H, 4.2%. ^{1}H NMR ($CDCl_3$), δ 3.1 (2H, br s, $CH_2O\underline{H}$), 4.08 [2H, d, ^2J(HH) 12, CH_2], 4.20 [2H, d, ^2J(HH) 12, CH_2], 4.36 (5H, s, H4), 4.53 (2H, br s, H2), 4.60 (2H, br s, H3). ^{13}C-{^{1}H} NMR ($CDCl_3$), δ 60.92 [d, J(PC) 51, PCH_2OH], 70.14 (s), 72.16 [d, J(PC) 9], 72.28 [d, J(PC) 8.5], C1 not observed.

6; Yield 83%, m.p. 138-143 °C. Found C, 38.8; H, 4.7. $C_{14}H_{20}FeO_4P_2S_2$ requires C, 38.7; H, 4.6%. ^{1}H NMR (d^6-DMSO), δ 4.05 [4H, dd, ^{2}J(HH) 13.4, ^{3}J(HH) 5.9, CH_2], 4.12 [4H, dd ^{2}J(HH) 13.4, ^{3}J(HH) 4.2, CH_2], 4.72 (4H, m, H3), 4.76, (4H, m, H2), 5.69 (4H, br m, $PCH_2O\underline{H}$). ^{13}C-{^{1}H} NMR (d^6-DMSO), δ 62.65 [d, ^{1}J(PC) 65, PCH_2OH], 73.58 [d, J(PC) 78, C1], 74.80 [d, J(PC) 10], 74.92 [d, J(PC) 9].

4. Supplementary material

Crystallographic data (excluding structure factors) for the structure described in this paper have been deposited with the Cambridge Crystallographic Data Centre (publication number CCDC ######). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CD2 1EZ, UK, e-mail deposit@ccdc.cam.ac.uk.

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Footnotes

‡ Crystals were obtained by diffusion of pentane vapour into a CH_2Cl_2-MeOH (10:1) solution at -20 °C. Crystal data for **1**: $C_{12}H_{14}FeO_2P$, *M* = 278.06, Monoclinic, space group P2$_1$/c, *a* = 12.2386(1), *b* = 6.1101(1), *c* = 16.3344(2) Å, β = 110.941(1) °, *V* = 1140.79(3) Å^3, *Z* = 4, D_{calc} = 1.619 g cm^{-3}, F(000) = 576, Mo-Kα radiation, λ = 0.71073 Å, μ(Mo-Kα) = 1.44 mm^{-1}. Data [10314 reflections, 2357 unique, with R_{int} 0.0327] were collected at 150(2) K on a Siemens SMART CCD diffractometer in the range 1.8 < θ < 26.5°, and corrected for absorption using SADABS [15]. The structure was solved using the direct methods option of SHELXL-97 [16] and developed routinely using full-matrix least-squares refinement based on F_o^2. All non-hydrogen atoms were refined using anisotropic temperature factors and hydrogen atoms were found from peaks of residual electron density in the penultimate electron density map and were refined with isotropic temperature factors. Refinement converged at R_1 [I > 2σ(I)] 0.254, wR_2 0.0659, with the weighting scheme $w = [\sigma^2(F_o)^2 + (0.0422P)^2 + 0.29P]^{-1}$ and $P = (F_o^2 + 2F_c^2)/3$ used in latter stages of refinement. The largest residuals in the final density map were +0.431 and -0.463 e Å^{-3}.

Captions for Figures

Fig. 1 Molecular structure of $FcCH_2P(CH_2OH)_2$ **1**, with ellipsoids at the 50% probability level. Selected bond lengths (Å) and angles (°); C(11)-P(1) 1.809(2), P(1)-C(1) 1.849(2), P(1)-C(2) 1.850(2), C(1)-O(1) 1.425(2), C(2)-O(2) 1.423(2), C(11)-P(1)-C(1) 99.18(8), C(11)-P(1)-C(2) 103.07(9), P(1)-C(1)-O(1) 110.82(13), P(1)-C(2)-O(2) 115.83(13).

Fig. 2. Hydrogen bonding in $FcP(CH_2OH)_2$, showing the formation of linked ten-membered rings.