Proton sponge phosphines: electrospray-active ligands†‡

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Attachment of a proton sponge to a phosphine ligand renders neutral complexes of the ligand highly amenable to analysis by electrospray ionisation mass spectrometry (ESI-MS). The ligand 1,8-bis(dimethylamino)naphthyldiphenylphosphine (**3**) is extremely efficient and highly selective in forming exclusively $[M + H]^+$ ions, which may be detected at very low concentration. Ionisation efficiency of **3** in the presence of H^+ approached 100%. The bis-substituted ligand bis{1,8-bis(dimethylamino)naphthyl}phenylphosphine (**4**) was also prepared and characterised, as were $Fe(CO)_4$- (**5c**), $Mn(\eta^5\text{-}C_5H_4Me)(CO)_2$- (**6**) and $W(CO)_5$- (**7**) complexes of **3**. Compounds **3**, **3**·HBr·EtOH, **4** and **5c** were all structurally characterised.

Introduction

Electrospray ionisation mass spectrometry (ESI-MS) is an increasingly common tool for the direct analysis of catalytically active species.[1] The majority of analyses of this type have employed catalysts which themselves carry a charge, *i.e.* are cations or anions. These species are transported directly into the gas phase with very high efficiency and hence are ideally suited to analysis by ESI-MS. High m/z relative to ions derived from solvent and substrates also assists the efficient detection of catalysts based on organometallic complexes. However, a sizable proportion of organometallic catalysts are neutral complexes, and hence rely on one of the various ionisation pathways that generate detectable ions.[2] Numerous such pathways exist, most well-known being protonation to form $[M + H]^+$ ions, and related ions such as $[M + Na]^+$, $[M + K]^+$ or $[M + NH_4]^+$ (depending on which ions are added or the presence of adventitious ions). Loss of halide from metal halide complexes, L_nMX_m, to form $[L_nMX_{m-1}]^+$ ions is another common ionisation pathway.[3] Complexes with acidic protons may undergo loss of H^+ to generate $[M - H]^-$ ions.[4] Particularly electron-rich complexes may undergo electrochemical oxidation to generate $[M]^+$ radical cations, most notably those based on ferrocene.[5] In certain cases, addition of an ionisation agent can result in highly efficient production of charged derivatives, such as the addition of alkoxy ions, RO^-, to metal carbonyl complexes to generate $[M + OR]^-$ ions,[6] or of Ag^+ to metal–metal bonded species to form $[M + Ag]^+$ ions.[7]

Henderson and co-workers introduced the idea of using the commercially available phosphines $P(p\text{-}C_6H_4OMe)_3$ and $P(p\text{-}C_6H_4NMe_2)_3$ in place of triphenylphosphine as "electrospray-friendly" ligands.[8] This approach allowed the observance of $[M + H]^+$ and $[M + Na]^+$ ions for most of the complexes of these ligands; similarly, cobalt carbonyl clusters with $\{\mu_3\text{-}Si(p\text{-}C_6H_4OMe)\}$ and $\{\mu_3\text{-}Si(p\text{-}C_6H_4NMe_2)\}$ ligands provided ESI mass spectra by protonation.[9] However, aryl amines and aryl ethers are not especially basic and the efficiency with which these sites are protonated is low. As such, these ligands are not well suited to the demands of direct ESI-MS analysis of complexes under non-ideal circumstances, *e.g.* in a catalytic reaction, a complex mixture, or in the presence of other compounds that provide very strong spectra, such as a complex dissolved in an ionic liquid. The ideal functional group would have high basicity, be selective for a single ion, and be non-nucleophilic (to minimise interference in reactions). The group should also not greatly affect the electronic properties of the electrospray-inactive ligand it replaces. Aromatic proton sponges fit these requirements rather well.[10] We selected 1,8-bis(dimethylamino)naphthalene (**1**), introduced by Alder[11] and sold by Aldrich as "Proton Sponge®"; it is not only the best-known compound of its type but is inexpensive and straightforward to derivatise. Its pK_{aH} of 12.1 (in water) is a million-fold higher than most aromatic amines, due to relief of steric strain in the neutral base upon protonation.[12] **1** is non-nucleophilic; it may be recovered unchanged after four days at reflux with ethyl iodide in acetonitrile,[11] and it has been utilised in organic chemistry as a non-nucleophilic base.[13]

Some examples of reactivity of **1** apart from routine protonation include, somewhat surprisingly, its role as a hydride donor in its reaction with *mer*-$RhCl_3(dmso)_3$ or $[RuCl(dppb)]_2(\mu\text{-}Cl)_3$,[14] with fluoroalkyl complexes of iridium,[15] or with $B(C_6F_5)_3$[16] to form the 1,1,3-trimethyl-2,3-dihydroperimidinium cation (TMP^+). There is also a single example of a metal complex coordinating (directly) to **1** (*via* the amino groups); the reaction with $Pd(hfac)_2$ immediately generates a poorly-characterised charge-transfer product, which after standing for a week forms the cationic complex $[Pd(hfac)(\mathbf{1})]^+$.[17] The hfac ligand may be substituted for β-diketones and one of these complexes was structurally characterised; coordination causes severe distortion of the proton sponge, the N···N distance opening to 2.94 Å from 2.51 Å. The proton sponge ligand is easily displaced in this complex, even by water. **1** can also act as a weak *carbon* nucleophile, but only in the presence of exceptionally reactive electrophiles.[18]

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† This paper is dedicated to the memory of Dr Alex Hopkins (1975–2006).
‡ The HTML version of this article has been enhanced with colour images.

An additional advantage of a proton sponge-substituted ligand is that the proton sponge confers pH-dependent solubility properties: in neutral or basic media, the sponge is soluble in organic solvents; in acidic media, it carries a charge and is soluble in polar solvents, including water (depending on the counterion involved). These characteristics are passed on to the ligand and hence also to metal complexes of the ligand.

Herein we report the syntheses of {1,8-bis(dimethylamino)-naphthalen-2-yl}diphenylphosphine (**3**) and bis{1,8-bis(dimethylamino)naphthalen-2-yl}phenylphosphine (**4**), metal complexes of ligand **3** and a comparison of its performance as an ESI-MS handle in organometallic complexes with the PPh_3 ligand and the "electrospray-friendly" ligand P(*p*-$C_6H_4OMe)_3$.

Experimental

Materials

Dry solvents were obtained by distillation or from a solvent purification system. Unless indicated, solvents were HPLC grade. Reagents were purchased from Strem and Aldrich and used without further purification except for Proton Sponge® (**1**), which was recrystallised from hot MeOH before use. **5a** was prepared using a published method. Unless indicated otherwise, reactions were performed under nitrogen using standard Schlenk techniques. Electrospray ionisation mass spectra were collected using either a Micromass *Quattro* LC or a Micromass QTof *micro* instrument. Relative intensities (%) were determined by integration (using Origin 7.5®). Capillary voltage was set at 2900 V, source and desolvation gas temperatures were at 80 and 150 °C, respectively. Samples were infused *via* syringe pump at 5–10 μL min^{-1}. NMR spectra were recorded on one of the following Bruker spectrometers: DPX-400, DRX-500, AV-500, AC-300 and AMX-360. Chemical shifts are quoted in δ (ppm) using internal references, where appropriate, of $CDCl_3$ (^1H δ 7.26 ppm), CD_3CN (^1H δ 1.94 ppm), acetone (^1H δ 2.05 ppm) and external references of TMS (^1H, ^{13}C) and 85% aqueous H_3PO_4 (^{31}P). All coupling constants (*J*) are given in Hz. Where required, assignments were determined through use of $^1H\{^{31}P\}$, ^1H-NOESY, ^1H-COSY, ^{13}C-DEPT, ^1H–^{13}C HSQC and ^1H–^{13}C HMBC NMR experiments. ^{13}C assignments were consolidated by running ^{13}C NMR experiments on both the AV-500 and AC-300 instruments and determining ^{31}P–^{13}C coupling constants by comparing the spectra obtained on the different instruments. Melting points were recorded on a Gallenkamp Melting Point Apparatus and are uncorrected. IR spectra were recorded using a solution cell in a Perkin-Elmer 1000 FTIR spectrometer. Microanalyses were carried out by the Analytical Laboratory in the Cambridge Chemical Laboratory.

Preparations

Proton Sponge®, 1. **1** (10 g) was recrystallised from hot methanol (50 ml) (9.29 g, 93%). ^1H NMR (300 MHz, CD_3CN) δ_H (**1**): 7.35 (dd, 2H, $^3J_{H4–H3}$ 8, $^4J_{H4–H2}$ 2, H^4) 7.30 (dd, 2H, $^3J_{H3–H4}$ 7, $^3J_{H3–H2}$ 7, H^3) 6.97 (dd, 2H, $^3J_{H2–H3}$ 7, $^4J_{H2–H4}$ 2, H^2), 2.77 (s, 12H, $N(CH_3)$).

Proton Sponge® hydrofluoroborate, 1·HBF_4. **1** (5 g) was dissolved in ethanol (100%, 60 ml). $HBF_{4(aq)}$ (3.05 ml, 48%, 23.4 mmol) was added dropwise to the solution with stirring. The white precipitate (6.62 g, 94%) was isolated by suction filtration, washed with cold EtOH and dried under vacuum. ^1H NMR (300 MHz, CD_3CN) δ_H (**1**·HBF_4): 18.67 (s, $1H^+$) 8.05 (d, 2H, $^3J_{H2–H3}$ 8, H^2) 7.90 (d, 2H, $^3J_{H4–H3}$ 8, H^4) 7.71 (dd, 2H, $^3J_{H3–H4}$ 8, $^3J_{H3–H2}$ 8, H^3), 3.11 (d, 12H, *J* 3, $N(CH_3)$).

{1,8-Bis(dimethylamino)naphthalen-2-yl} bromide, 2. A solution of **1** (10 g, 46.7 mmol) in dry THF (40 ml) was cooled to −78 °C. A solution of *N*-bromosuccinimide (NBS) (8.5 g, 48 mmol) in dry THF (280 ml) was cooled to −78 °C and added dropwise to the stirring solution. The solution was stirred and allowed to warm to room temperature overnight. The solvent was removed under reduced pressure and the oil repeatedly filtered to remove the succinimide precipitate and washed with portions of cold dry ether. The ether was removed from the filtrate and the resultant orange oil vacuum distilled. **2** came over at 152–160 °C (~1 mm Hg) as a yellow oil (12.13 g, 41.4 mmol, 89%). ^1H NMR (400 MHz, $CDCl_3$) δ_H (**2**) : 7.50 (d, 1H, ^2J 8.7, H^3), 7.38 (dd, 1H, ^2J 7.9, ^3J 1.2 Hz, H^5), 7.30 (dd, 1H, ^2J 7.5, ^2J 7.9, H^6), 7.29 (d, 1H, ^2J 8.7, H^4), 7.06 (dd, 1H, ^2J 7.4, ^3J 1.2, H^7), 3.00 (s, 6H, $(N(CH_3)_2)_2$ on C^1), 2.75 (s, 6H, $(N(CH_3)_2)_2$ on C^8). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ_C (**2**): 151.6 (C^1), 146.8 (C^8), 136.8 (C^{10}), 131.1 (C^3), 126.6 (C^9), 125.7 (C^6), 124.9 (C^4), 122.8 (C^5), 120.8 (C^2), 115.0 (C^7), 43.4 (2C, $N(CH_3)_2$ on C^8), 45.7 (2C, $N(CH_3)_2$ on C^1). ESI-MS (MeOH) *m*/*z*: 293.1 [**2** + H]$^+$.

{1,8-Bis(dimethylamino)naphthalen-2-yl}diphenylphosphine, 3. Dry THF (150 ml) was added to **2** (12.13 g, 41.3 mmol) and the resulting solution degassed and cooled to −78 °C. *n*BuLi (25.8 ml of a 1.6 M solution in hexanes, 41.3 mmol) was added dropwise. After stirring for 30 min at −78 °C PPh_2Cl (9.5 ml, 43.4 mmol, 5% excess) was added *via* syringe. After addition was complete the reaction mixture was stirred at −78 °C for 2 h and allowed to warm to room temperature overnight (a small amount of white solid **3**·HBr precipitated which could be isolated by filtration). The solvent was removed and addition of minimal CH_2Cl_2 to the residue followed by addition of hexane precipitated **3** which was recrystallised twice to give yellow crystals (9.2 g, 23.1 mmol, 56%). Crystallisation could also be effected from hot minimal ether or hot minimal MeCN. Mp (**3**) 108–110 °C. ^1H NMR (500 MHz, $CDCl_3$) δ_H (**3**): 7.45 (dd, 1H, $^3J_{H5–H6}$ 8.0, $^3J_{H5–H7}$ 1.5, H^5), 7.40 (d, 1H, $^3J_{H4–H3}$ 8.5, H^4), 7.33 (dd, 1H, $^3J_{H6–H7}$ 7.5, $^3J_{H6–H5}$ 8.0, H^6), 7.27–7.31 (m, 10H, 2 Ph), 7.18 (dd, 1H, $^3J_{H7–H6}$ 7.5, $^3J_{H7–H5}$ 1.5, H^7), 6.88 (dd, 1H, $^3J_{H3–P}$ 2.5, $^3J_{H3–H4}$ 8.5, H^3), 2.80 (d, 6H, $^4J_{H–P}$ 1.0, $N(CH_3)_2$ on C^1), 2.73 (s, 6H, $N(CH_3)_2$ on C^8). $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ_C (**3**): 153.5 (d, $^2J_{C–P}$ 23, C^1), 152.5 (d, $^4J_{C–P}$ 1, C^8),139.4 (d, $^1J_{C–P}$ 13, C^{11}) 138.4 (C^{10}), 135.5 ($^1J_{C–P}$ 6, C^2), 134.0 (d, $^2J_{C–P}$ 20, C^{12}), 130.6 (C^3), 128.5 (d, $^3J_{C–P}$ 6, C^{13}), 128.4 (C^{14}), 126.6 (d, $^3J_{C–P}$ 4, C^9), 126.2 (C^6), 125.1 (C^4), 124.1 (C^5), 116.1 (C^7), 46.9 ($N(CH_3)_2$ on C^8), 44.4 (d, $^4J_{C–P}$ 8, $N(CH_3)_2$ on C^1). $^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$) δ_P (**3**): −10.8, δ_P (**3**(O)): 26.6. ESI-MS (MeOH) *m*/*z*: 399.5 [**3** + H]$^+$. Anal. Calc. for $C_{26}N_2H_{27}P$: C, 78.37; H, 6.83; N, 7.03; P, 7.77. Found: C, 77.99; H, 6.83; N, 7.02; P 7.72%.

The HBr salt **3**·HBr was obtained as detailed above from the crude reaction mixture and crystallised from hot EtOH. **3**·HBr crystallised with one molecule of EtOH in the unit cell, Mp (**3**·HBr) 189–191 °C. $^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$) δ_P (**3**·HBr): −17.7, δ_P (**3**(O)·HBr): 32.6. Anal. Calc. for $C_{28}H_{40}BrN_2O_3P$: (**3**·EtOH): C, 64.00; H, 6.52; N, 5.33; P, 5.89. Found C, 63.52; H, 6.46; N, 5.12; P, 5.88%.

3·HBF_4 showed greater solubility in organic solvents (moderately soluble in MeCN, sparingly soluble in $CDCl_3$) than **3**·HBr and could be obtained by adding 48% HBF_4 (aq) to an ethanolic suspension of crude **3** from the synthesis described earlier. The solution was heated to reflux under N_2 and cooled, the white solid which precipitated on standing was isolated by suction filtration and recrystallised from hot EtOH to give **3**·HBF_4 as a white crystalline solid (14.8 g, 30.4 mmol, 74%), mp (**3**·HBF_4) 236–238 °C. ^{1}H NMR (500 MHz, CD_3CN) δ_H (**3**·HBF_4): 19.67 (1H, H^+), 8.02 (dd, 1H, *J* 8, 1, H^5), 7.96 (dd, 1H, *J* 1, *J* 8, H^7), 7.93 (d, 1H, *J* 9, H^4), 7.77 (dd, 1H, *J* 8, H^6), 7.30–7.40 Hz (m, 11H: H^3, 2Ph), 3.49 (dd, 6H, *J* 3, *J* 0.6, $N(CH_3)_2$ on C^1), 3.20 (d, 6H, *J* 3, $N(CH_3)_2$ on C^8). $^{13}C\{^1H\}$ NMR (126 MHz, CD_3CN) δ_C (**3**·HBF_4): 150.4 (d, *J* 24, C^1), 144.9 (s, C^8), 137.2 (s, C^{10}), 136.4 (d, *J* 11, C^2), 135.4 (d, *J* 28, C^{11}), 134.9 (s, C^{13}), 134.3 (d, *J* 19, C^{12}), 130.8 (s, C^5), 130.5 (s, C^4), 130.4 (s, C^{14}), 130.1 (d, *J* 7, C^3), 129.3 (s, C^6), 123.3 (s, C^7), 121.7 (d, *J* 8, C^9), 47.1 (s, CH_3, $N(CH_3)_2$ on C^8), 46.1 (d, CH_3, *J* 17, $N(CH_3)_2$ on C^1), ^{31}P NMR (202 MHz, CD_3CN) δ_P (**3**·HBF_4): −17.3, δ_P (**3**(O)·HBF_4): 32.9. ESI-MS (MeOH) *m*/*z*: 399.5 [**3** + H]$^+$

Di{1,8-bis(dimethylamino)naphthalen-2-yl}phenylphosphine, 4. Dry THF (35 ml) was added to **2** (3 g, 10.2 mmol), the resulting solution degassed and cooled to −78 °C. *n*BuLi (6.8 ml of a 1.6 M solution in hexanes, 10.2 mmol) was added dropwise. After stirring for 30 min at −78 °C $PPhCl_2$ (0.74 ml, 5.4 mmol, 5% excess) was added *via* syringe. After addition was complete the reaction mixture was stirred at −78 °C for 2 h and allowed to warm to room temperature overnight. The solvent was removed under vacuum, CH_3CN was added, the solution filtered and the filtrate reduced. Dark yellow crystals of **4** were obtained by repeated precipitation and eventually crystallisation from hot minimal MeCN (0.53 g, 1 mmol, 10%). ^{1}H NMR (500 MHz, $CDCl_3$) δ_H (**4**): 7.40 (dd, 1H, $^3J_{H5-H6}$ 8.0, $^3J_{H5-H7}$ 1.5, H^5), 7.31 (d, 2H, $^3J_{H4-H3}$ 8, H^4), 7.29 (dd, 2H, $^3J_{H6-H7}$ 7.5, $^3J_{H6-H5}$ 8.0, H^6), 7.22–7.27 (m, 5H, Ph), 7.14 (dd, 2H, $^3J_{H7-H6}$ 7.5, $^3J_{H7-H5}$ 1.5, H^7), 6.78 (dd, 2H, $^3J_{H3-P}$ 2.5, $^3J_{H3-H4}$ 8.5, H^3), 2.83 (s, 12H, $N(CH_3)_2$ on C^1), 2.72 (s, 6H, $N(CH_3)_2$ on C^8), 2.70 (s, 6H, $N(CH_3)_2$ on C^8). $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ_C (**4**): 153.4 (d, $^1J_{C-P}$ 23.6, C^1), 152.5 (d, $^4J_{C-P}$ 1.6, C^8), 141.8 (d, $^1J_{C-P}$ 17.9, C^{11}), 138.2 (C^{10}), 137.2 (d, $^2J_{C-P}$ 10, C^2), 134.3 (d, J_{C-P} 21.6, C^{12}), 131.3 (s, C^3), 128.3 (d, J_{C-P} 5.9, C^{13}), 127.9 (s, C^{14}), 126.4 (d, $^5J_{C-P}$ 3.0, C^9), 125.9 (C^6), 124.7 (C^4), 124.0 (C^5), 115.8 (C^7), 46.6, 47.1 ($N(CH_3)_2$ on C^8), 44.6 (d, $^4J_{C-P}$ 8, $N(CH_3)_2$ on C^1). $^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$) δ_P (**4**): −17.4. ESI-MS (CH_2Cl_2) *m*/*z*: 535.2 [**4** + H]$^+$, 268.1 [**4** + 2H]$^{2+}$.

4·2HBF$_4$. Obtained by addition of $HBF_{4\,(aq)}$ to a suspension of **4** in CH_3CN.

^{1}H NMR (CD_3CN, 500 MHz) δ_H (**4**·2HBF_4): 19.32 (H^+, 2H), 8.04 (dd, *J* 9, 1, 2H, H^5), 7.96 (dd, *J* 7, 1, 2H, H^7), 7.94 (d, *J* 9, 2H, H^4), 7.75 (dd, *J* 8, 2H, H^6), 7.42–7.46 (m, 1H, H^{14}), 7.40 (ddd, *J* 8, 7, 2, 2H, H^{13}), 7.28 (dd, 2H, *J* 9, H^3), 7.22 (ddd, *J* 8, 8, 1, 2H, H^{12}), 3.34 (d, *J* 1.4, 6H, $N(CH_3)_2$ on C^1), 3.30 (d, *J* 1.5, 6H, $N(CH_3)_2$ on C^1), 3.21 (d, *J* 3.4, 6H, $N(CH_3)_2$ on C^8), 3.19 (d, *J* 3.4, 6H, $N(CH_3)_2$ on C^8). $^{13}C\{^1H\}$ NMR (CD_3CN, 500 MHz) δ_C (**4**·2HBF_4): 149.9 (d, *J* 24, C^1), 144.4 (C^8), 137.5 (C^{10}), 136.6 (d, *J* 6, C^9), 135.0 (d, *J* 21, C^{12}), 134.5 (C^3), 133.4 (d, *J* 28, C^{11}), 131.3 (C^5), 131.2 (C^{14}), 130.8 (C^4), 130.6 (d, *J* 8, C^{13}), 129.5 (C^6), 123.5 (C^7), 122.4 (d, *J* 9, C^2), 47.4 ($N(CH_3)_2$ on C^8), 47.3 ($N(CH_3)_2$ on C^8), 45.7 (d, *J* 16, $N(CH_3)_2$ on C^1), 45.0 (d, *J* 13, $N(CH_3)_2$ on C^1), $^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$) δ_P (**4**·2HBF_4): −26.4, ESI-MS (CH_2Cl_2) *m*/*z*: 535.2 [**4** + H]$^+$, 268.1 [**4** + 2H]$^{2+}$

First pK_{aH} of 3: ^{1}H NMR transprotonation experiments[19]. Compounds **1**, **1**·HBF_4, **3** and **3**·HBF_4 were prepared as described in the previous section.

Equimolar amounts of **1** (13.2 mg, 0.062 mmol) and **3**·HBF_4 (30.0 mg, 0.062 mmol) were dissolved together in dry, N_2-saturated CD_3CN (0.75 ml) and ^{1}H NMR spectra recorded. Equimolar amounts of **1**·HBF_4 (7.8 mg, 0.026 mmol) and **3** (10.3 mg, 0.026 mmol) were dissolved together in dry, N_2-saturated CD_3CN (0.75 ml) and ^{1}H NMR spectra were recorded. Both experiments was repeated. The average integral ratios for the coordinated H^+ of the two protonated species over the four experiments were (CD_3CN, 360 MHz) δ_H: 19.7 (**3**·H, $\int$1), 18.7 (**1**·H, $\int$0.93) (1 std. dev. = 0.02). The pK_{aH} of **3** was determined by calculation using this ratio and the known pK_{aH} of **1** in CD_3CN, given as 18.18.[20] Analysis of the equilibrium gave $K_{a2} = K_{a1}/K_{eq}$ where K_{a1} (known) = [**1**][H^+]/[**1**·H^+], K_{a2} = [**3**][H^+]/[**3**·H^+] and K_{eq} (known) = ($\int$**3**·H/$\int$**1**·H).[2]

First and second pK_{aH} of 4: ^{1}H NMR transprotonation experiments. Equimolar amounts of **4** (1.18 mg, 0.0022 mmol) and **1**·HBF_4 (0.67 mg, 0.0022 mmol) were dissolved together in dry, N_2-saturated CD_3CN (3 ml), the solution mixed thoroughly and a ^{1}H NMR spectrum recorded of 1 ml of the solution over several hours (15000 scans). This was repeated and the results averaged. The average integral ratios for the coordinated H^+ of the two protonated species were (CD_3CN, 360 MHz) δ_H: 19.9 (**4**·H and **4**·2H, $\int$1), 18.7 (**1**·H, $\int$0.58) (1 std dev. = 0.04).

Synthesis of iron carbonyl phosphine complexes. CAUTION: $Fe_2(CO)_9$ is pyrophoric.[21] These syntheses release $Fe(CO)_5$ and the initial workups should be carried out in a fumehood.

Fe(CO)$_4$(PPh$_3$), 5a. A solution of PPh_3 (0.7 g, 2.52 mmol) in dry diethyl ether (20 ml) was degassed and added to a flask containing a magnetic stirring bar and $Fe_2(CO)_9$ (0.99 g, 2.52 mmol). The mixture was vigorously refluxed for 90 min, with stirring. Filtration of the solution gave a brown precipitate which was washed with THF, the filtrate and washings were pooled and reduced under vacuum. The reaction formed both **5a** and $Fe(CO)_3(PPh_3)_2$ as evidenced by $^{31}P\{^1H\}$ NMR: (146 MHz, CH_2Cl_2, d_6-acetone lock) δ_P (crude): 81.32 ($Fe(CO)_3(PPh_3)_2$), 70.67 (**5a**) (both peaks equal intensity). The *mono*substituted product (**5a**) was crystallised from minimal hot methanol (0.42 g, 1 mmol, 39%), mp (**5a**) 189–190 °C (decomp.), lit: 201–203 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ_H (**5a**): 7.46–7.50 (m, 9H, $6H_3$ and $3H_4$), 7.41–7.44 (m, 6H, $6H_2$); ^{13}C NMR (126 MHz, $CDCl_3$) δ_C (**5a**): 213.6 (d, *J* 19, CO), 134.2 (d, *J* 49, C_1), 133.4 (d, *J* 10, C_3), 131.1 (d, *J* 3, C_4), 128.9 (d, *J* 11, C_2); $^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$) δ_P (**5a**): 72.51; IR : *ν*(CO) (hexane) 2051 (s), 1978, 1945 (s, br).

Fe(CO)$_4$(PC$_6$H$_4$OMe)$_3$, 5b. A solution of $P(C_6H_4OMe)_3$ (1.00 g, 2.84 mmol) in dry THF (20 ml) was degassed and added to a flask containing a magnetic stirring bar and $Fe_2(CO)_9$ (1.03 g, 2.84 mmol). The mixture was heated to ~55 °C with stirring, and monitored over time with ^{31}P NMR (146 MHz, THF, D_2O lock). Conversion of the free ligand (−9.7 ppm) *via* an intermediate (23.6 ppm) gave *mono* and *di*substituted iron complexes, giving rise to resonances at 66.01 ppm, (relative integral = 1, **5b**) and

78.06 ppm (relative integral = 0.4, $Fe(CO)_3\{P(C_6H_4OMe)_3\}_2$), respectively. The reaction was judged to be complete after 60 min, when the signal at −9.7 ppm had disappeared.

The brown solution was filtered through cotton wool and the residue washed with dry THF (20 ml) to give a green-brown filtrate. The solvent was removed under vacuum, 20 ml of dry MeCN was added to the residue and the solution filtered to leave a cream precipitate (crude $Fe(CO)_3\{P(C_6H_4OMe)_3\}_2$, see below for purification). The MeCN solution was washed repeatedly with hexane (6 × 10 ml) to remove $Fe_3(CO)_{12}$ and the solvent volume was reduced on a vacuum line. Crude yellow **5b** precipitated from the cold minimal MeCN. Dissolving the precipitate in CH_2Cl_2 (5 ml) and filtering into ice-cold MeOH (10 ml) before leaving for 12 h in the fridge gave yellow crystals of **5b** (0.27 g, 18%, 0.5 mmol), mp (**5b**) 151–153 °C.

^{1}H NMR (500 MHz, $CDCl_3$) δ_H (**5b**): 3.82 (s, 9H, $3CH_3$), 6.91 (dd, 6H, $^3J_{H3-H2}$ 8.8, $^4J_{H3-P}$ 1.8, H_3), 7.38 (dd, 6H, $^3J_{H2-H3}$ 8.8, $^3J_{H2-P}$ 8.0, H_2), ^{13}C NMR (125 MHz, $CDCl_3$) δ_C (**5b**): 55.5 (s, CH_3), 114.3 (d, $^3J_{C3-P}$ 11.3, C_3), 126.0 (d, $^1J_{C1-P}$ 55.3, C_1), 134.8 (d, $^3J_{C3-P}$ 11.3, C_2), 161.6 (d, $^1J_{C4-P}$ 2.5 C_4), 213.9 (d, $^1J_{OC-P}$ 18.9, 4CO). $^{31}P\{^1H\}$ NMR: (202 MHz, $CDCl_3$) δ_P (**5b**): 67.06 IR : ν(CO) (50 : 50 hexane–CH_2Cl_2) 2047 (sh), 1972, 1938 (s, br). ESI-MS (MeOH) 542 [**5b** + Na]$^+$, ESI-MS (CH_2Cl_2–HBF_4) 521.1 (87%) [**5b** + H$^+$], 369.2 (59%) $[PO(C_6H_4OMe)_3 + H]^+$, 353.2 (100%) $[P(C_6H_4OMe)_3 + H]^+$.

The cream-coloured residue of $Fe(CO)_3\{P(C_6H_4OMe)_3\}_2$ was dissolved in minimal CH_2Cl_2 and precipitated from the pale green solution by addition of hexane. Dissolving in CH_2Cl_2 (5 ml), filtering into ice-cold MeOH (10 ml) and leaving for 3 h at 4 °C gave $Fe(CO)_3\{P(C_6H_4OMe)_3\}_2$ as flaky pale yellow crystals (13%, 0.313 g, 0.37 mmol). mp ($Fe(CO)_3\{P(C_6H_4OMe)_3\}_2$) 217–218 °C. $^{31}P\{^1H\}$ NMR (146 MHz, CH_2Cl_2, d_6-acetone lock) δ_P: 74.8. ESI-MS (CH_2Cl_2–HBF_4) m/z: 845.3 (100%) $[Fe(CO)_3\{P(C_6H_4OMe)_3\}_2 + H]^+$, 353.2 (7%) $[P(C_6H_4OMe)_3 + H]^+$.

$Fe(CO)_4$(3) (5c). A solution of **3** (1 g, 2.52 mmol) in dry diethyl ether (20 ml) was degassed and added to a flask containing a magnetic stirring bar and $Fe_2(CO)_9$ (0.99 g, 2.52 mmol). The mixture was vigorously refluxed for 90 min, with stirring. The reaction formed both $Fe(CO)_4$(**3**) (**5c**) and $Fe(CO)_3$(**3**)$_2$ as evidenced by $^{31}P\{^1H\}$ NMR (146 MHz, CH_2Cl_2, d_6-acetone lock) δ_P (crude): 83.47 ($Fe\{CO\}_3$(**3**)$_2$), 67.85 (**5c**). Suction filtration of the solution through a glass frit isolated a cream-coloured precipitate from the red supernatant. The precipitate was rinsed with small portions of cold (0 °C) diethyl ether. The precipitate was rinsed with CH_2Cl_2 to leave a brown paramagnetic residue, the orange filtrate was collected, saturated with nitrogen and reduced under vacuum until the product began to precipitate from the dichloromethane.

The *mono*substituted product, **5c**, was obtained as fine yellow crystals from CH_2Cl_2–hexane (0.36 g, 27%, 0.7 mmol), mp (**5c**) 190–191 °C (decomp.). ^{1}H NMR (500 MHz, $CDCl_3$) δ_H (**5c**): 7.60 (dd, 4H, ^2J 10, ^3J 8, 4H^{12}), 7.55 (d, 1H, J 8, H^5), 7.51 (d, 1H, J 8.5, H^4), 7.43 (m, 7H, 4H^{13}, 2H^{14} and H^6), 7.35 (d, 1H, J 7, H^7), 7.06 (dd, 1H, J 8.5, J 10, H^3), 2.58 (6H, H^8), 2.41 (6H, H^1); ^{13}C NMR (126 MHz, $CDCl_3$) δ_C (**5c**): 214.6 (d, $^2J_{C-P}$ 19, 4CO), 154.2 (d, $^2J_{C-P}$ 7, C^1), 153.4 (C^8), 139.8 (C^{10}), 136.6 (d, $^1J_{C-P}$ 47, C^{11}), 134.1 (d, $^2J_{C-P}$ 10, 4C^{12}), 133.3 (d, $^1J_{C-P}$ 58, C^2), 130.4 (2C^{14}), 130.1 (d, $^2J_{C-P}$ 10, C^3), 129.5 (d, $^3J_{C-P}$ 6, C^9), 128.4 (d, $^2J_{C-P}$ 10, 4C^{13}), 127.6 (C^6), 126.5 (d, $^3J_{C-P}$ 11.3, C^4), 125.9 (s, C^5), 118.8 (s, C^7), 47.8 (s, $N(CH_3)_2$ on 2C^8), 43.9 (s, $N(CH_3)_2$ on 2C^1). $^{31}P\{^1H\}$ NMR (146 MHz, $CDCl_3$) δ_P (**5c**): 64.22. IR (hexane) cm^{-1} : 2046 (sharp), 1971 (m, br), 1944 (s, br), 1935 (s, br). ESI-MS (MeCN, formic acid) m/z: 399.1 [**3** + H]$^+$, 567.1 [**5c** + H]$^+$.

ESI-MS comparison of complexes 5a–5c. The metal complex **5** (0.004 mmol) was dissolved in 0.8 ml CH_2Cl_2 and 0.2 ml (0.02 equiv) of a solution (0.0035 g in 10 ml CH_2Cl_2) of the ionic liquid (tetradecyltrihexyl phosphonium bis(trifluromethylsulfonyl)amide was added. The sample was serially diluted in CH_2Cl_2 and a drop of acid (diluted in MeOH) was added (HBF_4 for **5a** and **5b**, HCl for **5c**).

ESI-MS (**5a**; CH_2Cl_2–HBF_4) 483 (100%) $[PC_{32}H_{68}]^+$, (**5b**; CH_2Cl_2–HBF_4) 521 (23%) [**5b** + H]$^+$, 483 (100%) $[PC_{32}H_{68}]^+$, 369 (51%) $[PO(C_6H_4OMe)_3H]^+$, 353 (23%) $[P(C_6H_4OMe)_3 + H]^+$, (**5c**; CH_2Cl_2–HCl) 567 (100%) [**5c** + H]$^+$, 483 (20%) $[PC_{32}H_{68}]^+$, 415 10% [**3**O + H]$^+$, 399 5% [**3** + H]$^+$.

Mn(η^5-MeC$_5$H$_4$)(CO)$_2$(3), (6). A large sublimation apparatus cooled with dry ice was charged with a magnetic stirrer, dry THF (50 ml) and Mn(η^5-MeC_5H_4)$(CO)_3$ (0.215 g, 0.98 mmol) so that the solution was in contact with the cold finger. The solution was degassed, placed under nitrogen and the apparatus placed in a cold water-bath. The solution was irradiated (UV) for 4 h with stirring. During the irradiation the internal temperature of the solution was maintained between −32 and +40 °C and over the course of the irradiation the pale yellow solution deepened in colour to wine-red, indicating formation of Mn(η^5-MeC_5H_4)$(CO)_2$(THF). The apparatus was removed from the water bath and cooled to −78 °C. A chilled degassed solution of **3** (0.39 g, 0.98 mmol) in THF (8 ml) was slowly added *via* syringe to the apparatus. The resulting solution was stirred at −78 °C for 2.5 h and then at 0 °C overnight. The now-orange solution was stirred at room temperature for 24 h to give a yellow solution. Yellow platelet crystals of **6** were obtained by diffusion of pentane into a CH_2Cl_2 solution of **6** (0.17 g, 30%, 0.3 mmol), mp (**6**): 170–171 °C. **6** readily decomposed in air or in solution if exposed to air, to give a paramagnetic brown compound. ^{1}H NMR (500 MHz, $CDCl_3$) δ_H (**6**): 1.94 (s, 3H, CH_3 on Cp), 2.22 (s, 6H, $N(CH_3)_2$ on C^8), 2.58 (s, 6H, $N(CH_3)_2$ on C^1), 4.00, 4.07, (4H, Cp), 7.13–7.65 (m, 15H, Ar); $^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$) δ_P (**6**): 92.6; IR ν(CO) (hexane) cm^{-1}: 2014 (w), 1937 (s), 1877 (s); ESI-MS (CH_2Cl_2–formic acid) m/z: 589.2 [**6** + H)]$^+$, 399.1 [**3** + H]$^+$; ESI-MS/MS (589, **6** + H$^+$); 589.1, 399.1.

$W(CO)_5$(3), (7). $W(CO)_6$ (253 mg, 0.72 mmol), **3** (287 mg, 0.72 mmol) and $Me_3NO{\cdot}2H_2O$ (0.24 mg, 2.16 mg) were dissolved in CH_2Cl_2 (25 ml) and stirred at room temperature for 3 h. Additional $Me_3NO{\cdot}2H_2O$ was added (0.24 mg, 2.16 mg) and the solution refluxed overnight to give a transparent yellow solution and a black oil. The reaction was monitored by IR and TLC. The yellow solution was decanted and the solvent removed by evaporation, the residue was purified by preparative TLC (5 : 1 hexane–thf plus a drop of triethylamine) and the product, **7**, was obtained by precipitation from CH_2Cl_2–pentane in 30% yield.

ESI-MS (CH_2Cl_2–formic acid) 723 [**7** + H]$^+$, 399 [**3** + H]$^+$. IR ν(CO) (CH_2Cl_2–hexane) (cm^{-1}) 2070 (s), 1978, 1920 (br), 1860 (w).

Crystal structure determinations

X-Ray crystallographic data for **3** and **3**·HBr·C_2H_5OH were collected in the X-ray Laboratory of the Cambridge University Chemical Laboratory. Measurements were made on a Nonius Kappa CCD diffractometer at −93 °C with graphite-monochromated Mo-Kα radiation ($\lambda = 0.71073$ Å). Data for **4** and **5c** were collected at −80 °C on a Bruker PLATFORM/SMART 1000 CCD diffractometer with graphite-monochromated Mo-Kα radiation ($\lambda = 0.71073$ Å), at the X-ray Crystallography Laboratory of the University of Alberta. The structures were solved by direct methods, except for **5c** (Patterson search/structure expansion)[22] and refined by full-matrix least-squares on F^2.[23] A Flack parameter[24] of 0.14 (11) for **4** indicated a small degree of racemic twinning, which was accommodated during the refinement. ORTEP diagrams were generated using ORTEP 3[25] and POV-Ray 3.5.[26]

Crystal data and selected details of structure determinations are given in Table 1.

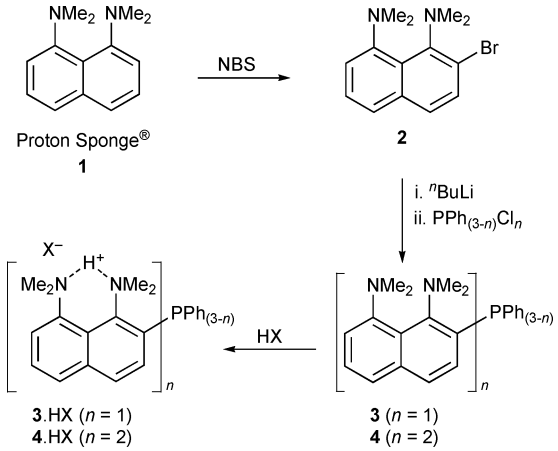
CCDC reference numbers 611411–611414.

For crystallographic data in CIF or other electronic format see DOI: 10.1039/b609561e

Results and discussion

Several groups including those of Alder,[27] Staab,[28] Pozharskii[29] and Lloyd-Jones[30] have investigated and derivatised **1**. Numerous kinetic,[31] structural,[32] spectroscopic[33] and theoretical investigations[34] of **1** and its derivatives have also been carried out. We investigated a variety of bromination methods as a route to functionalisation of **1**; nearly all gave mixtures of *mono* and *di*brominated products; HBr (48%, aq.) in AcOH–DMSO,[35] Br_2 in CCl_4[36] or H_2SO_4,[37] TBABr_3 in CH_2Cl_2[38] and 2,4,4,6-tetrabromo-2,5-cyclohexadien-1-one in CH_2Cl_2.[39] In our hands, the best brominating system proved to be *N*-bromosuccinimide (NBS) in THF at −78 °C, being regiospecific for *mono*bromination at the 2-position, producing 1,8-bis(dimethylamino)-2-bromonaphthalene (**2**) in good yield.[40] Little polybromination was observed under these conditions, indicating either that the system is under kinetic control or that the NMe_2 group *ortho*- to the position of bromination participates in the bromination through an unknown mechanism.

Syntheses of **3** and **4** from **2** were straightforward *via* lithiation followed by treatment with $PPh_{(3-n)}Cl_n$ ($n = 1$ or 2, see Scheme 1) but purification proved to be more complicated. Proton sponge derivatives adhered strongly to both silica and sand and smeared on neutral activated alumina. Low loadings of these compounds could be partially purified by alumina column chromatography, a general method involved loading the compound in CH_2Cl_2 and



Scheme 1 Syntheses of **2**–**4** from Proton Sponge® (**1**).

Table 1 Crystallographic experimental details for **3**, **3**·HBr·C_2H_5OH, **4** and **5c**

	3	**3**·HBr·C_2H_5OH	**4**	**5c**
Formula	$C_{26}H_{27}N_2P$	$C_{28}H_{33}BrN_2OP$	$C_{34}H_{39}N_4P$	$C_{30}H_{27}FeN_2O_4P$
M_r	398.47	524.44	534.66	566.36
Crystal dimensions/mm	0.46 × 0.21 × 0.12	0.46 × 0.10 × 0.05	0.64 × 0.24 × 0.15	0.62 × 0.41 × 0.37
Crystal system	Monoclinic	Monoclinic	Orthorhombic	Monoclinic
Space group	$P2_1/n$	$P2_1/c$	$Pna2_1$	$P2_1/n$
a/Å	17.1220(3)	16.0283(3)	15.4223(12)	10.5700(9)
b/Å	10.1292(2)	7.18140(10)	10.8193(8)	15.0412(13)
c/Å	25.3141(5)	22.5380(6)	17.8969(14)	17.6505(16)
β/°	93.8090(10)	98.9630(10)	90	104.2580(11)
V/Å^3	4380.58(14)	2562.57(9)	2986.3(4)	2719.7(4)
Z	8	4	4	4
D_c/g cm^{-3}	1.208	1.359	1.189	1.383
μ/mm^{-1}	0.140	1.690	0.121	0.652
T/°C	−93(2)	−93(2)	−80	−80
θ Range/°	3.58 to 27.51	3.66 to 27.51	2.20 to 25.85	2.46 to 26.37
Total data	32696	23406	22819	16008
hkl Ranges	−22 to 22, −13 to 13, −32 to 32	−20 to 20, −9 to 9, −29 to 29	−19 to 19, −13 to 13, −22 to 22	−13 to 13, −18 to 18, −22 to 21
Independent reflections	10020	5838	6154	5553
R_{int}	0.0831	0.0613	0.0504	0.0224
Range transmission factors	0.984–0.848	0.990–0.884	0.9821–0.9265	0.7945–0.6881
Data/restraints/parameters	10020/0/523	5838/0/299	6154/0/353	5553/0/343
Goodness-of-fit (S)	1.023	1.038	1.023	1.021
R_1 [$F_o^2 \geq 2\sigma(F_o^2)$]	0.0547	0.0546	0.0503	0.0368
wR_2 [$F_o^2 \geq 3\sigma(F_o^2)$]	0.1137	0.1170	0.1374	0.1085
Largest diff. peak, hole/e Å^{-3}	0.265, −0.343	0.684, −0.542	0.234, −0.248	0.549, −0.595

using 19 : 1 hexane–THF with trace triethylamine (TEA) to elute. Distillation proved to be the method of choice to purify multigram quantities of **2** but could not be easily used to separate different (*ortho*/*para*) isomers of **2**. In general, separation of different proton sponge derivatives from each other was difficult—for example, **1** and **3** are both soluble in **2**—and therefore clean reactions were important. The nature of the compounds meant that incidental protonation during workup procedures had to be considered since this altered the physical properties of the compounds. Intentional protonation/deprotonation could however be used to aid purification. Standard organic workup techniques (extractions, washing, drying with $MgSO_4$) and chromatography were used initially but eventually avoided where possible as they greatly reduced yields. The bulky phosphines **3** and **4** proved to be fairly air stable when solid, and were stable in deoxygenated solution under N_2. They could be reversibly protonated/deprotonated with strong acid and base multiple times without decomposition. The phosphine oxides (which were also yellow) could be removed by stirring the impure phosphine in minimal EtOH under N_2, cooling on ice and filtering, thus removing the soluble oxide.

X-Ray crystal structures of both **3** and its hydrobromide, **3**·HBr (along with an ethanol of crystallisation) were obtained (Fig. 1 and 2). Protonation of **3** to give **3**·HBr significantly increases the planarity of the naphthalene; the average deviation from the best-fit plane defined by the ten naphthalene carbon atoms is 0.102 Å for **3** but only 0.007 Å for **3**·HBr. The deviation from planarity is also manifested by the N–C(1)–C(8)–N torsion angles, 37.4° for **3** but just 1.2° for **3**·HBr. The twisting of the naphthalene is consistent with co-repulsion of the lone pairs, relief of this strain being the suggested driving force for protonation.[12] The position of the nitrogen lone pairs can be estimated from the orientation of the NMe_2 methyl groups. Upon protonation the N···N distance is reduced from 2.90 to 2.56 Å (*cf*. 2.55–2.62 Å in protonated

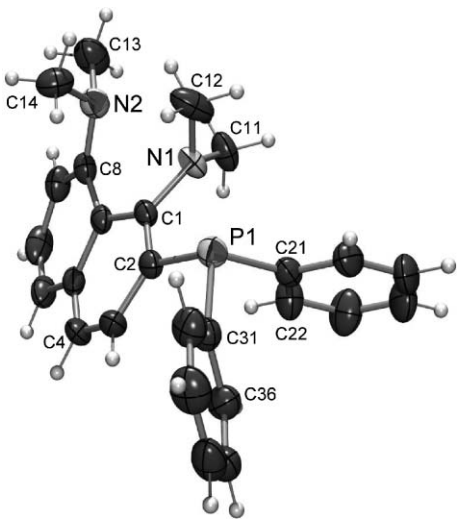


Fig. 1 ORTEP plot of **3** (one of the two independent molecules in the unit cell; bond lengths and angles do not vary significantly between the two). Non-hydrogen atoms are represented by Gaussian ellipsoids at the 50% probability level. Hydrogen atoms are shown with arbitrarily small thermal parameters. Key bond lengths (Å) and angles (°): P1–C2 1.842(2), N1–C1 1.428(2), N2–C8 1.430(3); C2–P1–C21 100.54(9), C2–P1–C31 100.62(9), C21–P1–C31 104.15(10).

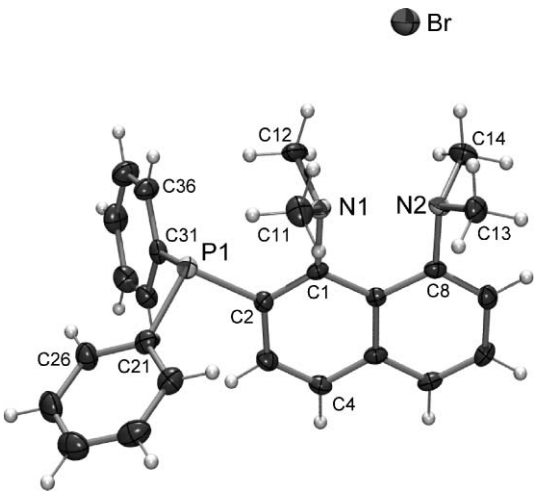


Fig. 2 ORTEP plot of **3**·HBr (ethanol of crystallisation not shown). Non-hydrogen atoms are represented by Gaussian ellipsoids at the 50% probability level. Hydrogen atoms are shown with arbitrarily small thermal parameters. Key bond lengths (Å) and angles (°): P1–C2 1.857(3), N1–C1 1.459(3), N2–C8 1.468(4); C2–P1–C31 100.79(13), C2–P1–C31 101.70(14), C21–P1–C31 104.64(14).

1[41]) and as the nitrogen lone pairs coordinate to the proton there is less involvement with the naphthalene π system resulting in longer C(1)–N(1) and C(8)–N(2) bonds. The average length of these bonds is 1.46 Å in **3**·HBr and 1.43 Å in **3**. The sum of angles around N(1) and N(2) in **3** are 355° (~98% sp^2 character) and 338° (~94% sp^2 character), respectively. In **3**·HBr the nitrogen atoms become marginally more sp^3 like, as the angles reduce to 343° (95%) and 337° (93%). The anisotropic displacement parameters for N(1) and N(2) are smaller in **3**·HBr than in **3**, reflecting the increased bonding and reduced freedom of the nitrogen atoms.

The diproton sponge phosphine ligand **4** was also examined structurally (Fig. 3). One of the proton sponge groups on **4** has similar geometry to its counterpart in **3**; an $N–C^1–C^8–N$ torsion angle of 36.6°, an average deviation from the best-fit plane defined by the ten naphthalene carbon atoms of 0.098 Å, and an N–N distance of 2.91 Å. However, the other proton sponge group

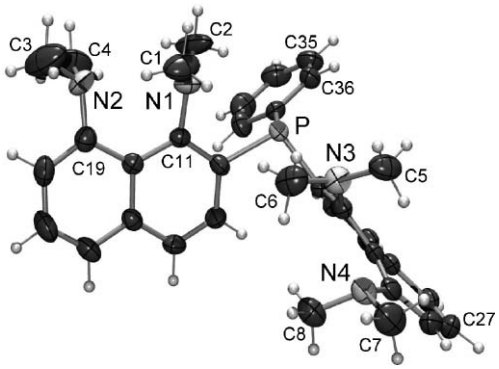


Fig. 3 ORTEP plot of **4**. Non-hydrogen atoms are represented by Gaussian ellipsoids at the 50% probability level. Hydrogen atoms are shown with arbitrarily small thermal parameters. Key bond lengths (Å) and angles (°): P–C12 1.843(3), P–C22 1.850(3), N1–C11 1.413(5), N2–C19 1.432(4), N3–C21 1.423(4), N4–C29 1.410(4); C12–P–C32 100.45(12), C12–P–C31 100.67(12), C22–P–C31 101.30(12).

attached to the phosphorus (containing N1 and N2) is much less distorted from planarity, with the respective torsion angle, deviation from planarity and N–N distance being 16.55°, 0.057 Å and 2.84 Å. The reason for the difference is not immediately obvious, but presumably can be attributed to crystal packing forces and suggests a reasonable degree of flexibility of the proton sponge unit.

Ligands **3** and **4** both display pH-dependent solubility. In their unprotonated form they dissolve readily in organic solvents such as CH_2Cl_2 or THF, but addition of acid greatly increases solubility in polar solvents; **3**·HBF_4 is water-soluble, for example. Neutralisation with a strong base such as NaOH results in the ligand moving back into the organic phase. Ligands that confer water-solubility to their complexes, such as the well-known 1,3,5-triaza-7-phosphaadamantane (PTA),[42] have numerous applications in aqueous phase or biphasic homogeneous catalysis.

Transprotonation experiments

The high basicity of proton sponges has made determining their pK_a values challenging, the pK_a of the solvent in which the study is conducted being a constraining factor. Temperature-jump[43] or NMR methods[44] have been used by other groups. We adopted the latter approach, albeit less accurate, due to the very clear signal of the coordinated proton in the ^{1}H NMR spectra at high chemical shifts (~20 ppm) for all derivatives of **1**. Solubility of all four compounds (the two protonated/unprotonated pairs) in the deuterated solvent was a critical issue since any insolubility would affect the equilibrium and therefore the determined value. HBF_4 and CD_3CN proved to be the best combination. Equimolar amounts of **1** and **3**·HBF_4 were dissolved in CD_3CN and the ^{1}H NMR spectrum was recorded. The same experiment was conducted with equimolar amounts of **1**·HBF_4 and **3**. In both cases, equilibrium between **3**·HBF_4 and **1**·HBF_4 was quickly reached and the ratio of these species remained roughly constant from within 5 min of sample mixing. ^{1}H NMR signals in the low-field region corresponded to the proton coordinated by the different proton sponges, δ 19.7 ppm corresponding to **3**·HBF_4 and δ 18.7 ppm to **1**·HBF_4. The ratios of the protonated species were averaged over 4 samples and the first pK_{aH} of **3** (CD_3CN) was calculated as 18.24 ± 0.02 (1 std) units at 297 K, demonstrating a slight increase in basicity when compared to the value for **1** (18.18 in CH_3CN).[20] Fig. 4 shows the relative ratios of the two peaks.

The slightly higher pK_{aH} is in agreement with the observation that proton sponges with "buttressing" substituents in the 2- and 7-positions demonstrate increased pK_{aH} values as the lone pairs are forced closer together in the unprotonated state, the relief of strain upon protonation being correspondingly higher.[12,45]

After determining that the equilibrium set up was identical from either starting point, the experiment was repeated using equimolar quantities of **4** and **1**·HBF_4. The low solubility of **4** in CD_3CN necessitated very dilute solutions to ensure total dissolution and no precipitation of any species during the experiment, ^{1}H NMR experiments were run overnight (15000 scans). **4**·HBF_4 showed a single peak in the ^{1}H NMR spectra at 19.9 ppm (relative integral 1). The proton coordinated by **1** gave a peak at 18.7 ppm (relative integral 0.6). Due to the structural similarity between **3** and **4** it is anticipated that their first pK_{aH} will be approximately equal. Since the combined coordination by both proton sponge sites of

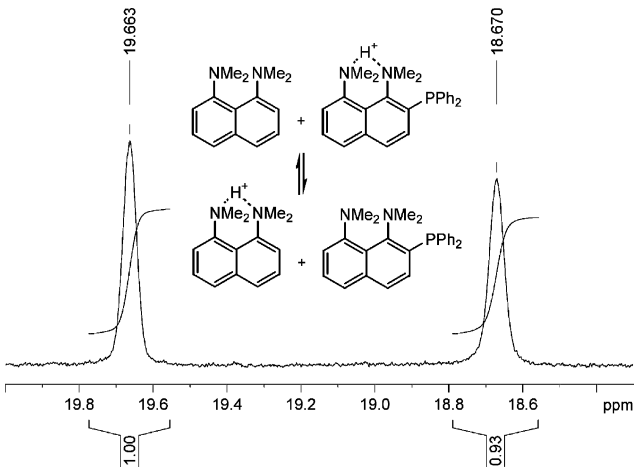


Fig. 4 ^{1}H NMR spectra of an equimolar mixture of **1** and **3**·HBF_4 (an identical spectrum is obtained for an equimolar mixture of **1**·HBF_4 and **3**) in the low-field region.

4 is demonstrated by the integrals to be less than two-thirds, this implies that the second pK_{aH} of **4** is significantly less than the first pK_{aH} of **1**. This is not unexpected, as the second pK_{aH} of **4** corresponds to the protonation of a formally charged compound, **4**·HBF_4, to form **4**·2HBF_4.

ESI-MS of the proton sponge derivatives

Throughout this work we have observed that ESI-MS of proton sponge derivatives generally show no sign of cationisation by species other than H^+, even in the presence of excess Li^+, Na^+, K^+ or NH_4^+. The exception is the spectrum of **5c**, which like **5a** and **5b**, provides an $[M + Na]^+$ signal, though this is certainly due to interactions with the carbonyl ligands rather than the with the proton sponge.[6b] ESI-MS of a solution of a 1 : 1 molar ratio of tetradecyltrihexylphosphonium bis(trifluromethylsulfonyl)amide and the ligand **3** showed that the ionisation efficiency of **3** approaches that of the formally charged phosphonium ion (in CH_2Cl_2, CH_3CN or MeOH in presence of a H^+ source). This has important implications with the use of the ligand to identify catalytic intermediates; reactions typically employ catalysts at a 1–10 mol% concentration[1a] and so the concentration of catalytic intermediates can be expected to be very much lower. Therefore the ionisation efficiency of the ligand must be as high as possible for the ligand to reveal these low concentration reactive intermediates in the ESI mass spectrum. Even without added H^+, the ligand **3** provides a very strong signal from a dichloromethane solution, approximately 50% of the intensity of the phosphonium ion (Fig. 5).

Metal complexes

Several organometallic complexes incorporating **3** as a ligand were prepared by standard methods (Scheme 2).

The preparations of **5c**, **6** and **7** were adapted from syntheses of $Fe(CO)_4(PPh_3)$,[46] $Mn(\eta^5\text{-}C_5H_4Me)(CO)_2(PPh_3)$,[47] and $W(CO)_5(PPh_3)$,[48] respectively. For the sake of comparison, the known complexes $Fe(CO)_4(PR_3)$ (R = Ph, **5a**; R = *p*-C_6H_4OMe, **5b**) were also prepared.

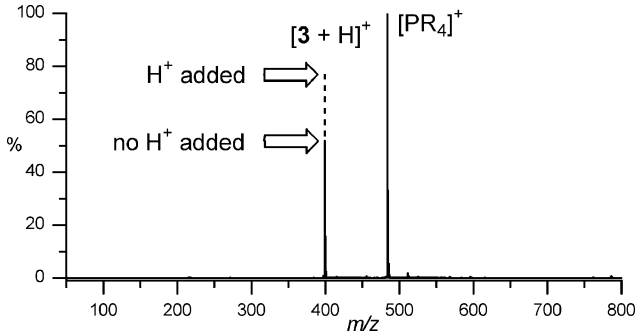
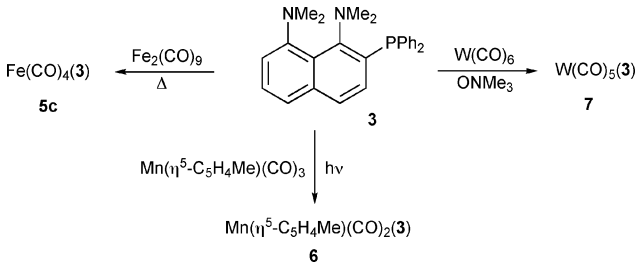


Fig. 5 Positive-ion ESI-MS of an equimolar mixture of **3** and an internal reference, $[P(C_6H_{13})_3(C_{14}H_{29})]^+$, in CH_2Cl_2. The dotted line indicates the change in intensity of the $[3 + H]^+$ signal observed when excess H^+ (a drop of formic acid) is deliberately added to the solution.



Scheme 2 Syntheses of **5c**, **6** and **7** from **3**.

5c readily crystallised and an X-ray crystal structure was obtained of this complex (Fig. 6). It revealed a slightly distorted trigonal-bipyramidal geometry about iron with the phosphine in an axial position, as is seen in the analogous compound $Fe(CO)_4(PPh_3)$ (**5a**).[49] Although it is often assumed that in trigonal bipyramidal organometallic complexes the better π-acceptor ligand adopts an equatorial position,[50] evidence points to the σ-donation also being important[51] with the weaker σ-donor ligand favouring the equatorial position (where CO < PPh_3 in terms of σ-donation).[52] Steric effects would also be expected to encourage the largest ligand in the complex to occupy the equatorial position (with only two groups at 90° *cf*. three for substituents in an axial position). The orientation of the N(1) methyl groups suggests that there may be a weak interaction between the N(1) lone pair and the Fe centre, but in fact the intramolecular distance of 3.58 Å is substantially longer than the sum of van der Waals radii.

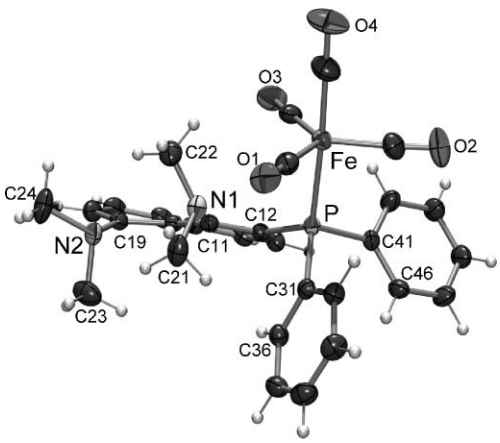


Fig. 6 ORTEP plot of **5c**. Non-hydrogen atoms are represented by Gaussian ellipsoids at the 50% probability level. Hydrogen atoms are shown with arbitrarily small thermal parameters. Key bond lengths (Å) and angles (°): Fe–P 2.2739(6), Fe–C1 1.791(2), Fe–C4 1.776(3), P–C12 1.8416(19), N1–C11 1.428(2), N2–C19 1.429(3); Fe–P–C12 117.46(6), C31–P–C41 101.38(9), C12–P–C41 103.95(9).

Complexes **5a**, **5b** and **5c** exhibited carbonyl stretches in the IR region in the order of PPh_3 > $P(C_6H_4OMe)_3$ ~ **3** (2051, 2047, 2046 cm^{-1} as highest-frequency A′ band) indicating that the net electron density donated to the iron by **3** is greater than for the other ligands, with back-donation to the CO ligands in this complex being correspondingly greater, weakening the CO bond.

Just as is the case for the other unprotonated sponges, the 1,8-bis(dimethylamino)naphthyl group is significantly distorted from planarity, with an N–C^1–C^8–N torsion angle of 28.1°, an average deviation from the best-fit plane defined by the ten naphthalene carbon atoms of 0.078 Å, and an N–N distance of 2.948 Å. These parameters are middle-of-the-range compared to **3** and **4**, with the exception of the N–N distance, which is significantly longer than the other examples. Again, this appears to point to a reasonable degree of flexibility in the 1,8-bis(dimethylamino)naphthyl group and to the participation of crystal packing forces in the structure. The phosphine ligand in **5c** has a cone angle[53] of 168° taking into account the surfaces of the van der Waals spheres in the substituents,[54] with measurements taken directly from the crystal structure. The cone angle of PPh_3 in the triphenylphosphine analogue $Fe(CO)_4PPh_3$ (**5a**) is 151° when calculated by the same method.[55]

Comparison of electrospray activity of 5a, 5b and 5c

Using $[P(C_6H_{13})_3(C_{14}H_{29})]^+$ as an internal reference or in competition experiments it was shown that the ionisation efficiency of **5c** is approximately 20x that of **5b** in acidic CH_2Cl_2, despite **5c** having just one site for protonation compared to three for **5c**. **5a** was not detectable under these conditions. The 20x improvement in signal intensity for **5c** over **5b** is probably conservative; the mass spectra of **5c** were greatly superior under nearly all conditions but less pronounced under the relatively high concentrations used in the competition and internal reference experiments. It certainly appears that the primary advantage of the proton sponge phosphine will be under conditions that are marginal, and those in which the speciation is complicated. Other circumstances in which ESI-MS analysis is challenging and where proton sponge phosphines may provide useful handles include the characterisation of complexes in ionic liquids[56] or in non-polar solvents such as toluene or hexane (in which lipophilic ionic liquids are required to assist the formation of a stable spray).[57]

The proton sponge ligand is also more selective, always providing only $[M + H]^+$ ions except in neutral or basic solutions containing added Na^+, which presumably associates with the complex *via* an interaction with the carbonyl ligands. Both **5b** and **5c** showed the appearance of the free ligand in all spectra; the presence of phosphine oxide suggests that the ligand is not appearing as a fragment generated by the ionisation process, but rather is dissociated to a reasonable degree in solution (Fig. 7). Its appearance suggests a degree of decomposition; this is not unusual in ESI mass spectra, as the concentration of sample used

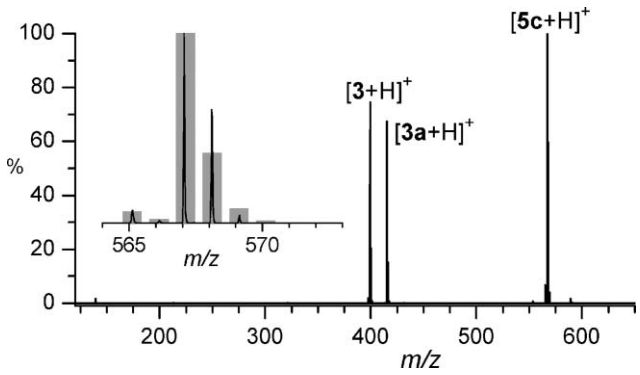


Fig. 7 Positive-ion ESI-MS of **5c** in CH_2Cl_2–trace formic acid. The inset shows the experimental and calculated isotope patterns. Free ligand **3** and free oxidised ligand **3a** were always present in spectra of metal complexes to at least some degree.

is very low (micromolar) and so the presence of small amounts of air and moisture in the solvent becomes significant. The ^{31}P NMR spectrum, collected at much higher concentration, showed insignificant levels of decomposition (in the form of free phosphine or phosphine oxide).

The syntheses of the manganese and tungsten complexes **6** and **7** further demonstrated the ability of this proton sponge derivative **3** to act as a conventional phosphine ligand, with bonding *via* phosphorus and the $–NMe_2$ groups of the proton sponge uninvolved in bonding to the metal. Both complexes displayed strong $[M + H]^+$ ions in their ESI mass spectra. MS/MS studies on these compounds (and of **5c**) revealed that the primary fragmentation process was loss of the protonated ligand from the metal core (see Fig. 8). For **6**, a small amount of $[\mathbf{6} - 2CO + H]^+$ is present, indicating competition between CO and phosphine loss; this process is not observed at all for **5c** or **7**.

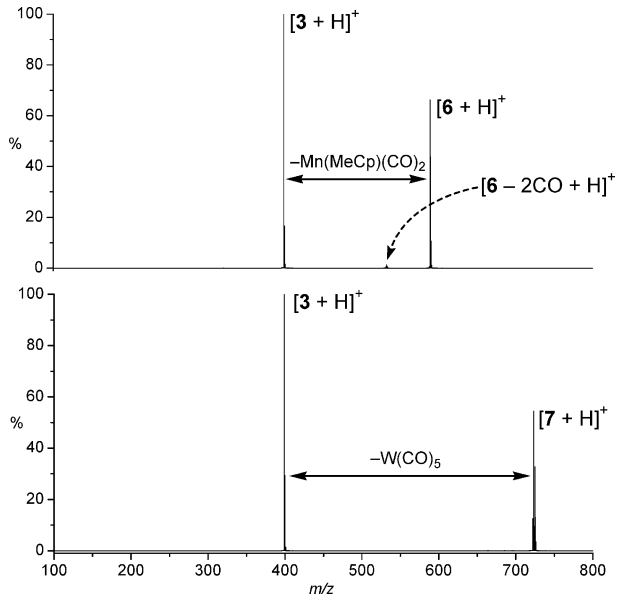


Fig. 8 Positive-ion ESI-MS/MS of $[\mathbf{6} + H]^+$ (top) and $[\mathbf{7} + H]^+$ (bottom) in CH_2Cl_2/trace formic acid. Collision voltage was set to reduce the parent ion intensity to ~50%. In both cases, fragmentation involves loss of the protonated ligand from the metal; the ligand retains the charge.

Conclusions

In order to detect neutral complexes by ESI-MS under challenging conditions of low concentration or in the presence of abundant competing species-circumstances common when wishing to study catalytic systems, for example—the complex must possess functionality capable of selective ionisation with high efficiency. Proton sponges confer exactly these properties to a ligand, and the ligand in turn confers them to the complexes to which they are bound. Absolute selectivity for H^+ means simple spectra uncomplicated by multiple signals derived from different ionisation mechanisms. Complexes incorporating proton sponge phosphines provide strong $[M + H]^+$ ions even in solutions free of added H^+ or protic solvents, making the ligands ideal for facilitating direct ESI-MS analysis of catalytic reactions involving neutral complexes and phosphine ligands.

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