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Spontaneous dehydrocoupling in *peri*-substituted phosphine–borane adducts†

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Bis(borane) adducts Acenap(PiPr₂-BH₃)(PRH-BH₃) (Acenap = acenaphthene-5,6-diyl; **4a**, R = Ph; **4b**, R = ferrocenyl, Fc; **4c**, R = H) were synthesised by the reaction of excess H₃B-SMe₂ with either phosphino-phosphonium salts [Acenap(PiPr₂)(PR)]⁺Cl⁻ (**1a**, R = Ph; **1b**, R = Fc), or bis(phosphine) Acenap(PiPr₂)(PH)₂ (**3**). Bis(borane) adducts **4a–c** were found to undergo dihydrogen elimination at room temperature, this spontaneous catalyst-free phosphine-borane dehydrocoupling yields BH₂ bridged species Acenap(PiPr₂)(μ-BH₂)(PR-BH₃) (**5a**, R = Ph; **5b**, R = Fc; **5c**, R = H). Thermolysis of **5c** results in loss of the terminal borane moiety to afford Acenap(PiPr₂)(μ-BH₂)(PH) (**14**). Single crystal X-ray structures of **3**, **4b** and **5a–c** are reported.

Introduction

Dehydrocoupling reactions (E–H + E'–H → E–E' + H₂) are an interesting and effective way of generating bonds between main-group elements, with concomitant evolution of H₂. Reactions of this type show applications not only in inorganic synthesis, but also in hydrogen storage, transfer hydrogenation and polymer synthesis.^{1–6}

Although dehydrocoupling reactions that occur by thermal or autocatalytic routes are known,^{7,8} the vast majority of recent work has focused on catalysis, particularly with transition metals.^{6,9–11} In particular, amine–borane adducts have attracted considerable interest as potential hydrogen storage molecules.^{12,13} However, dehydrocoupling reactions in the chemically related phosphine–boranes have received far less attention.^{11,14}

Dehydrocoupling of phosphine–boranes to form poly(phosphinoboranes) was first reported in the 1950s. Early work in this area is limited, with polymerisations yielding low molecular weight polymers which were often poorly characterised.^{15,16} In 1999 the Manners' group pioneered the use of transition metal catalysts in the synthesis of poly(phosphinoboranes)^{17–20} and more recently B(C₆F₅)₃ has been used as a metal-free dehydrocoupling catalyst.²¹ Thus formed inorganic polymers have interesting and unusual physical properties, which set them apart from the more traditional carbon-based polymers.^{17,18}

While catalysts are incredibly useful, they are often expensive, especially when they contain precious transition metals such as Rh or Ir. As such, it would be helpful to develop systems which undergo dehydrocoupling without the addition of an external catalyst, but while still under mild conditions. The work of our group has focused on *peri*-substitution, which is useful in thermodynamically stabilising bonding motifs which are typically unstable at room temperature.^{22,23} However, lately we have been intrigued by the possibility of using *peri*-substitution to promote reactivity that would typically require the addition of a catalyst. Due to the unique constraints of the *peri*-geometry, atoms in the *peri*-position (E) are forced into close proximity. Strain from the overlap of occupied orbitals can be relieved by, either, the formation of a direct E–E bonding interaction or a bridging motif between the two *peri*-atoms (E–X–E). As such, it was postulated that if two potentially reactive groups were placed in the *peri*-positions, the rigid scaffold could lower the kinetic barrier of the coupling reaction, promoting the formation of a direct bond or a bridging motif and hence emulating the role of an external catalyst.

This was indeed found to be the case, as a series of *peri*-substituted phosphine–borane adducts were synthesised and observed to undergo spontaneous intramolecular dehydrocoupling in solution at room temperature. The results of these investigations are detailed below.

Results and discussion

Bis(borane) Adducts 4a–c

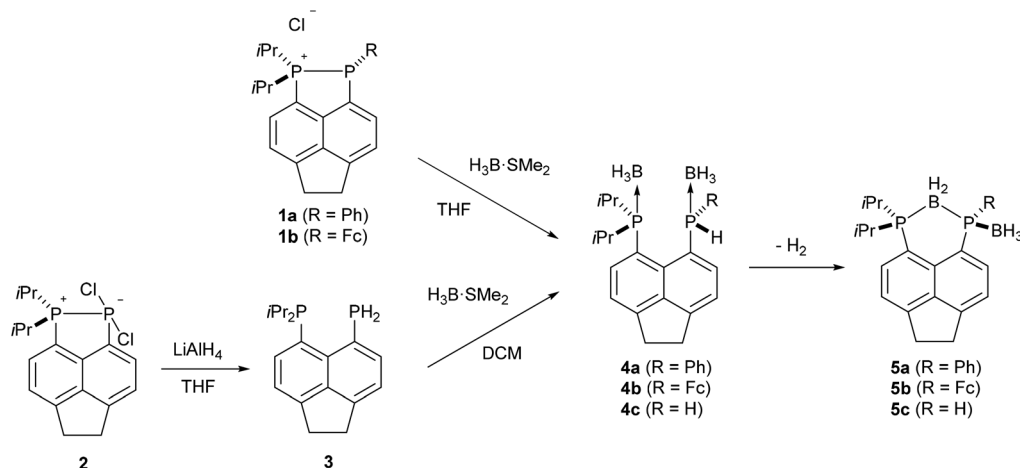
Compounds **1a–b** and **2** were used as the starting points for all of the reactions presented in this work. Compound **2** was

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Scheme 1 Synthesis of bis(borane) adducts **4a–c** and BH₂ bridged compounds **5a–c**.

Table 1 Selected bond lengths (Å) and angles (°) for **3**, **4b**, **5a–c**

| | | | |
|-----------------------|-----------------------|-----------|-----------------------|
| 3 | | | |
| C1–P1 | 1.849(4) | C9–P9 | 1.850(4) |
| C1–P1–H1a | 99(1) | C1–P1–H1b | 94(1) |
| H1a–P1–H1b | 90(2) | | |
| 4b | | | |
| C1–P1 | 1.817(3) | C9–P9 | 1.842(3) |
| B1–P1 | 1.929(4) | B9–P9 | 1.980(4) |
| C1–P1–B1 | 109.7(2) | B1–P1–H1 | 117(2) |
| C1–P1–H1 | 105(2) | C9–P9–B9 | 113.6(2) |
| 5a | | | |
| C1–P1 | 1.818(2) | C9–P9 | 1.812(2) |
| B1–P1 | 1.932(2) | B9–P9 | 1.927(2) |
| B9–P1 | 1.928(2) | | |
| C1–P1–B1 | 112.21(8) | C9–P9–B9 | 110.95(8) |
| C1–P1–B9 | 106.33(8) | P9–B9–P1 | 108.55(9) |
| B9–P1–B1 | 117.28(9) | | |
| 5b^a | | | |
| C1–P1 | 1.82(1) [1.85(1)] | C9–P9 | 1.82(1) [1.80(2)] |
| B1–P1 | 1.94(2) [1.94(2)] | B9–P9 | 1.92(2) [1.90(2)] |
| B9–P1 | 1.94(2) [1.94(2)] | | |
| C1–P1–B1 | 111.6(7) [108.6(7)] | C9–P9–B9 | 114.1(7) [108.3(7)] |
| C1–P1–B9 | 111.3(7) [107.4(7)] | P9–B9–P1 | 110.9(9) [106.6(8)] |
| B9–P1–B1 | 114.0(9) [118.2(8)] | | |
| 5c^a | | | |
| C1–P1 | 1.820(2) [1.821(2)] | C9–P9 | 1.808(2) [1.807(2)] |
| B1–P1 | 1.937(2) [1.930(2)] | B9–P9 | 1.910(2) [1.911(2)] |
| B9–P1 | 1.922(2) [1.914(2)] | | |
| C1–P1–B1 | 111.90(9) [112.48(9)] | C9–P9–B9 | 110.15(8) [109.62(8)] |
| C1–P1–B9 | 107.56(8) [107.54(8)] | P9–B9–P1 | 109.1(1) [109.0(1)] |
| B9–P1–B1 | 118.16(9) [117.60(9)] | | |

^a Measurements for second molecule in asymmetric unit shown in square brackets.

Table 2 *Peri*-distances (Å), splay angles (°) and out-of-plane displacements for **3**, **4b**, **5a–c**

| | 3 | 4b | 5a | 5b^a | 5c^a |
|--------------------------------|----------|-----------|-----------|-----------------------|-----------------------|
| P1...P9 | 3.143(1) | 3.521(1) | 3.1295(8) | 3.181(5) [3.081(5)] | 3.1214(6) [3.1145(6)] |
| splay angle | +16.4(7) | +21.2(7) | +15.1(4) | +16(3) [+15(3)] | +16.5(3) [+16.3(3)] |
| Out-of-plane displacement (P1) | 0.148 | 0.706 | 0.338 | 0.332 [0.213] | 0.050 [0.042] |
| Out-of-plane displacement (P9) | 0.068 | 0.546 | 0.327 | 0.450 [0.296] | 0.068 [0.101] |

^a Measurements for second molecule in asymmetric unit shown in square brackets.

synthesised according to a previously published procedure,²⁴ while compounds **1a–b** were synthesised *via* a modified version of the literature procedure.²⁵

The synthesis and characterisation of the bis(borane) adduct **4a** were recently reported by our group.²⁶ In its preparation, treatment of the phosphino-phosphonium salt **1a** with excess H₃B-SMe₂ resulted in borane mediated reduction to afford **4a** as a yellow oil in quantitative yield (Scheme 1). An analogous procedure was employed to obtain adduct **4b** from the corresponding phosphino-phosphonium salt **1b**. The adduct **4b** was isolated as an orange solid, which was contaminated with the bridged compound **5b** (≈20% as judged by ¹H and ³¹P NMR). Pure **4b** was obtained by recrystallisation from acetonitrile.

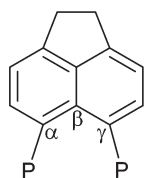
The ³¹P{¹H} NMR spectrum of **4b** exhibits broad singlets at δ_p 36.3 (*i*Pr₂P) and –7.7 (PF₆H), and in the ³¹P NMR spectrum the signal at δ_p –7.7 is split into a broad doublet (¹J_{PH} = 395 Hz). Crystals of **4b** suitable for X-ray diffraction were grown from acetonitrile, the structure is shown in Fig. 2 and Tables 1–3. The structure of **4b** is similar to the previously reported structure of **4a**,²⁶ with a P...P distance of 3.521(1) Å and a large positive splay angle of +21.2(7)° (see Fig. 1 for a definition), indicating significant repulsion between the two *peri*-groups. Additionally, both phosphorus atoms show significant displacement from the mean plane of the acenaphthene ring (0.706 Å for P1, 0.546 Å for P9).



Table 3 Crystallographic data for 3, 4b, 5a–c

| | 3 | 4b | 5a | 5b | 5c |
|--|--|---|---|---|---|
| Chemical formula | C ₁₈ H ₂₄ P ₂ | C ₂₈ H ₃₈ B ₂ FeP ₂ | C ₂₄ H ₃₂ B ₂ P ₂ | C ₂₈ H ₃₆ B ₂ FeP ₂ | C ₁₈ H ₂₈ B ₂ P ₂ |
| Formula weight | 302.34 | 514.02 | 404.08 | 512.01 | 327.99 |
| Crystal dimensions (mm) | 0.12 × 0.10 × 0.03 | 0.10 × 0.10 × 0.01 | 0.10 × 0.06 × 0.06 | 0.20 × 0.03 × 0.01 | 0.18 × 0.12 × 0.08 |
| Crystal system | Triclinic | Monoclinic | Triclinic | Monoclinic | Monoclinic |
| Space group | <i>P</i> 1̄ | <i>P</i> 2 ₁ / <i>c</i> | <i>P</i> 1̄ | <i>P</i> 2 ₁ | <i>P</i> 2 ₁ / <i>c</i> |
| <i>a</i> (Å) | 7.4543(19) | 15.806(5) | 8.3375(11) | 15.409(5) | 14.0458(16) |
| <i>b</i> (Å) | 8.4923(15) | 13.022(4) | 9.4724(14) | 11.059(3) | 18.841(2) |
| <i>c</i> (Å) | 14.361(5) | 12.835(4) | 16.108(2) | 16.712(6) | 14.4671(14) |
| α (°) | 79.88(3) | 90.0000 | 101.8880(17) | 90.0000 | 90.0000 |
| β (°) | 82.10(3) | 94.825(6) | 93.165(3) | 114.651(5) | 101.176(3) |
| γ (°) | 66.47(2) | 90.0000 | 112.772(3) | 90.0000 | 90.0000 |
| <i>V</i> (Å ³) | 818.3(4) | 2632.4(14) | 1134.9(3) | 2588.3(14) | 3768.3(7) |
| <i>Z</i> | 2 | 4 | 2 | 4 | 8 |
| <i>D</i> _{calc} (g cm ⁻³) | 1.227 | 1.297 | 1.182 | 1.314 | 1.156 |
| μ (cm ⁻¹) | 2.546 | 7.088 | 1.989 | 7.207 | 2.244 |
| No. rflns measured (unique) | 5176 (2878) | 27 526 (4765) | 14 052 (4112) | 34 241 (9417) | 45 236 (6914) |
| <i>R</i> ₁ ^a | 0.0643 | 0.0513 | 0.0362 | 0.0948 | 0.0360 |
| <i>wR</i> ₂ ^b | 0.1599 | 0.1533 | 0.1041 | 0.2647 | 0.1045 |

$$^a I > 2\sigma(I), R_1 = \sum(|F_o| - |F_c|) / \sum|F_o|. \quad ^b wR_2 = [\sum[w(F_o^2 - F_c^2)^2] / \sum[w(F_o^2)^2]]^{1/2}, w = 1/[\sigma^2(F_o^2) + [(ap)^2 + bp]], \text{ where } p = [(F_o^2) + 2F_c^2]/3.$$

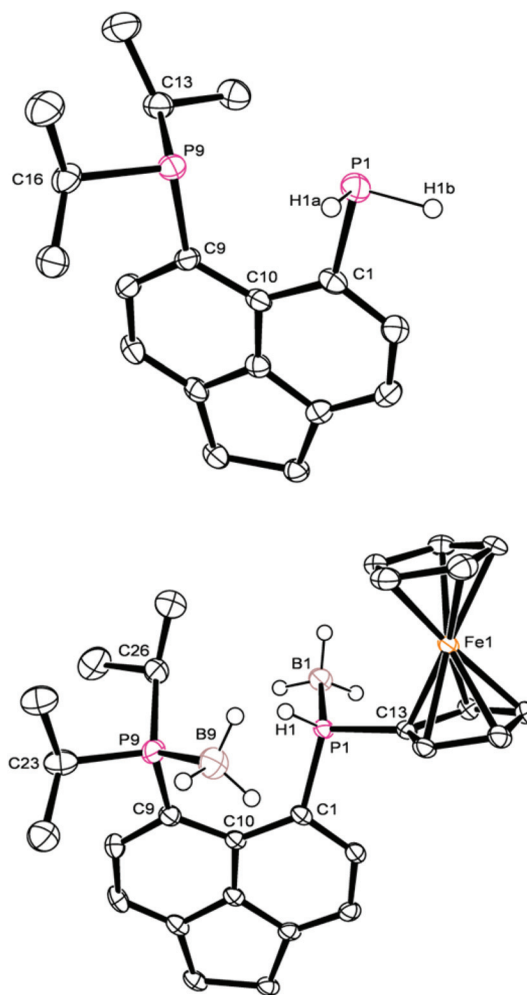


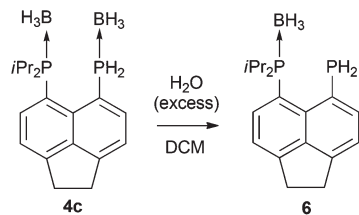
$$\text{splay angle} = \alpha + \beta + \gamma - 360$$

Fig. 1 Definition of a splay angle.

The bis(borane) adduct **4c** was synthesised from the novel primary phosphine **3** (Scheme 1), which was obtained by clean reduction of the phosphonium-phosphoranide **2** with LiAlH₄. The ³¹P{¹H} NMR spectrum of compound **3** displays two doublets at δ_P -11.3 (*i*Pr₂P) and -101.2 (PH₂), with a substantial through-space coupling of ⁴*J*_{PP} = 205 Hz. In the ³¹P NMR spectrum, the signal for the PH₂ group is split into a pseudo-quartet due to ¹*J*_{PH} = 204 Hz being very similar to that of ⁴*J*_{PP}. The ¹H NMR spectrum of **3** displays a doublet of doublets for the PH₂ protons (δ_H 4.98, ¹*J*_{HP} = 204 Hz, ⁵*J*_{HP} = 48 Hz). This long range ⁵*J*_{HP} interaction, in addition to the large ⁴*J*_{PP} coupling, indicates a significant through space contribution to coupling operates in this compound.²⁷ Crystals of compound **3** suitable for single crystal X-ray diffraction were grown from THF, the structure is shown in Fig. 2 and Tables 1–3. The structure indicates a clear repulsive interaction between the two phosphorus moieties, with a P...P distance of 3.143(1) Å and a positive splay angle of 16.4(7)°. The purity of **3** as obtained from the reaction was established by ³¹P, ¹H and ¹³C NMR and was found to be sufficient for further syntheses.

Treatment of primary bis(phosphine) **3** with excess H₃B-SME₂ afforded bis(borane) adduct **4c** as the major product (δ_P 38.0 (br s, *i*Pr₂P), -40.8 (br s, PH₂)), although the reaction was not clean. Even with a large excess (12 equivalents) of

Fig. 2 Structures of **3** (top) and **4b** (bottom) in the solid state. Carbon-bound hydrogen atoms omitted for clarity.



Scheme 2 Synthesis of monoborane adduct 6.

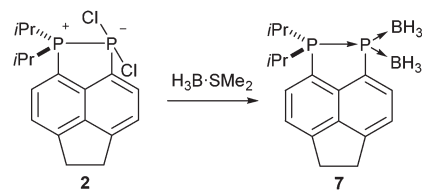
$\text{H}_3\text{B}\cdot\text{SMe}_2$, traces of starting material were found in the $^{31}\text{P}\{^1\text{H}\}$ NMR spectra of the crude mixture after the reaction. In addition, a broad singlet at δ_{p} 44.0 along with a sharp singlet at δ_{p} -101.4 were observed in this spectrum. Rather revealingly, the signal at δ_{p} -101.4 splits into a triplet ($^1J_{\text{PH}} = 207$ Hz) in the ^{31}P NMR spectrum which, together with the chemical shift values, allowed these signals to be assigned to the monoborane adduct 6 (Scheme 2). In the crude mixture, 4c and 6 were present in a ratio of approximately 5 : 1. A number of minor, unidentified P containing side products were also formed.

In sharp contrast to compounds 4a and 4b, which are stable towards both air and moisture, compound 4c is rather moisture sensitive. On a preparative scale, treatment of a dichloromethane solution of 4c with degassed water afforded 6 as a yellow solid in near quantitative yield (Scheme 2). The new compound was characterised by ^1H , ^{31}P , $^{31}\text{P}\{^1\text{H}\}$, $^{13}\text{C}\{^1\text{H}\}$, ^{11}B , and $^{11}\text{B}\{^1\text{H}\}$ NMR spectroscopy.

Primary phosphine–borane adducts have been less extensively studied than secondary or tertiary phosphine–boranes, and are known to be generally less stable.²⁸ In addition, steric hindrance arising from the *peri*-geometry is likely to further destabilise the bis(borane) adduct 4c with respect to the monoborane adduct 6. This corresponds well with our observations of the instability of 4c towards moisture, as well as the difficulty in getting complete conversion to the bis(borane) adduct. Compound 4c could not be isolated in analytically pure form due to its crystallisation being extremely difficult, whilst its sensitivity to air and moisture prevented chromatographic purification.

Compound 4c exhibits two broad singlets in the $^{31}\text{P}\{^1\text{H}\}$ NMR spectrum at δ_{p} 38.0 ($i\text{Pr}_2\text{P}$) and δ_{p} -40.8 (PH_2). In the ^{31}P NMR spectrum, the signal at δ_{p} -40.8 splits into a broad triplet ($^1J_{\text{PH}} = 379$ Hz). One particularly distinctive signal is observed for the PH_2 group in the ^1H NMR spectrum, which is split into a doublet of quartets (δ_{H} 6.14, $^1J_{\text{HP}} = 377$ Hz, $^3J_{\text{HH}} = 7.1$ Hz) due to coupling to the adjacent BH_3 hydrogen atoms. This, therefore, provides strong evidence that BH_3 is bound to PH_2 in this molecule. In contrast, the PH_2 signal in the ^1H NMR spectrum of compound 6 appears as a sharp doublet (δ_{H} 4.48, $^1J_{\text{HP}} = 207$ Hz), indicating the absence of a co-ordinated borane.

It should be noted that, unlike compounds 1a–b, treatment of the phosphonium–phosphoranide 2 with $\text{H}_3\text{B}\cdot\text{SMe}_2$ does not result in borane mediated reduction to give 4c, but



Scheme 3 Synthesis of the “push–double pull” bis(borane) adduct 7.

instead yields the “push–double pull” bis(borane) adduct 7 (Scheme 3).²⁹

Spontaneous intramolecular dehydrocoupling of 4a–c to give 5a–c

When compound 4a was allowed to stand in solution in DCM, the signals corresponding to the bis(borane) adduct (δ_{p} 39.4 (br s, $i\text{Pr}_2\text{P}$) and -6.6 (br s, PhPH)²⁶ were gradually replaced by a broad doublet (δ_{p} 13.9, $\text{P}i\text{Pr}_2$, $^2J_{\text{PP}} \approx 84.0$ Hz) and a very broad signal in which coupling could not be resolved (δ_{p} -26.3, PPh),³⁰ corresponding with the formation of 5a (Fig. 3). Complete conversion to 5a was achieved after 8 days at room temperature (Scheme 1). ^1H and ^{31}P NMR spectroscopy confirmed that the H atom directly bonded to phosphorus had been lost. Additionally, $^{11}\text{B}\{^1\text{H}\}$ NMR spectroscopy revealed a broad pseudo-triplet (δ_{B} -39.4, $^1J_{\text{BP}} \approx 69$ Hz) and a broad doublet (δ_{B} -33.6, $^1J_{\text{BP}} \approx 46$ Hz), consistent with the presence of one bridging P–B–P motif and one terminal B–P motif (Fig. 4).

Crystals of 5a suitable for single crystal X-ray diffraction were grown from d_6 -DMSO. The structure confirmed 5a to contain one bridging BH_2 and one terminal BH_3 motif (Fig. 5, Tables 1–3). A significant reduction of strain is observed in 5a in comparison to 4a, with a reduced P...P distance of 3.1295(8) Å and smaller splay angle of +15.1(4) $^\circ$ (*cf.* 3.61 Å and +24.4(4) $^\circ$ in 4a),²⁶ as well as decreased displacements of the P atoms from the mean plane of the acenaphthene ring (0.338 Å for P1, 0.327 Å for P9; *cf.* 0.478 and 0.816 Å in 4a).²⁶

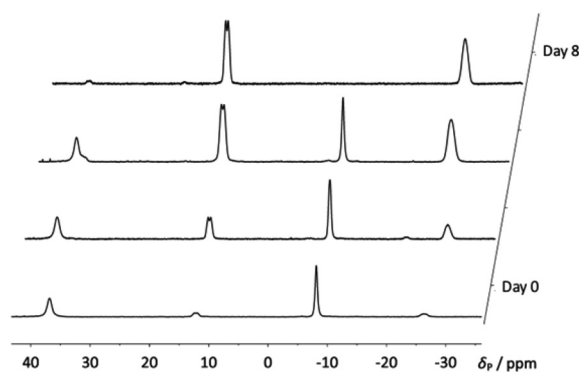


Fig. 3 Stacked $^{31}\text{P}\{^1\text{H}\}$ NMR spectra showing the gradual formation of compound 5a from 4a over 8 days.



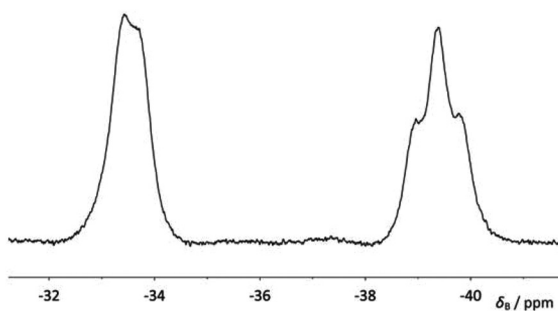


Fig. 4 $^{11}\text{B}\{^1\text{H}\}$ NMR of compound **5a**.

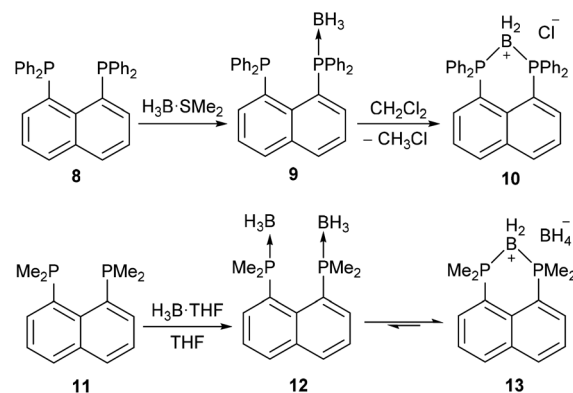
Based on the identity of compound **5a**, it seemed likely that the bis(borane) adduct **4a** had undergone a phosphine–borane dehydrocoupling reaction. In order to confirm the evolution of hydrogen, a solution of **4a** in C_6D_6 was prepared and left to stand in a sealed NMR tube. After 1 day, some conversion to compound **5a** was observed by $^{31}\text{P}\{^1\text{H}\}$ NMR, and a sharp singlet of dissolved H_2 was observed in the ^1H NMR (δ_{H} 4.47).³¹ In another experiment, the conversion of **4a** to **5a** (in CDCl_3) was followed over several days at room temperature by ^1H NMR spectroscopy.³² The reaction was found to follow simple first order kinetics, with an approximate rate constant of 0.04 h^{-1} . It is likely that the driving force for this reaction is the reduction in strain on going from **4a** to **5a**, coupled with the entropic gain from hydrogen evolution.

Spontaneous dehydrocoupling reactions occurring at room temperature are rather rare, with a few examples involving very reactive precursors such as primary/secondary stibines or bismuthines.⁷ In recent work by the Manners' group, a series of primary arylamine–borane adducts were found to undergo spontaneous dehydrocoupling at room temperature, with the rate of dehydrocoupling increasing with decreasing electron density on the aryl substituent.⁸ This reactivity was attributed to weak B–N bonding and the increased acidity of the N–H bonds in arylamine–boranes. By contrast, while dehydrocoupling of phosphine–boranes has been observed in the pres-

ence of catalysts^{17–19,33} or at very high temperatures,^{15,16} spontaneous, room temperature dehydrocoupling of a phosphine–borane adduct is without precedent in the literature.

The compound **5a** bears some similarities to two cyclic boronium salts, **10** and **13**, reported by Mikołajczyk *et al.*³⁴ and Costa and Schmidbauer³⁵ (Scheme 4). Compounds **5a**, **10** and **13** are all formed by the treatment of *peri*-substituted precursors with borane, and all consist of two *peri*-phosphorus atoms bridged by a BH_2 unit. However, compounds **10** and **13** are ionic species; **10** is thought to form *via* the mono(borane) adduct **9**, which then reduces the halogenated solvent to form **10**.³⁴ Compound **13** exists in equilibrium with the bis(borane) adduct **12** and forms *via* hydride transfer to give a BH_2 bridge and a BH_4^- counterion.³⁵ Although these reactions are significantly different from the dehydrocoupling observed in **4a**, in all cases the driving force for the formation of the BH_2 bridge is most likely the same – reduction of strain resulting from the *peri*-substitution geometry. In compound **4a** this is achieved *via* hydrogen evolution, while for **9** and **12** (which contain no P–H bonds) the formation of the boronium salts is preferred.

The ferrocenyl substituted bis(borane) adduct (**4b**) was also found to undergo spontaneous dehydrocoupling in solution,



Scheme 4 Formation of the cyclic boronium salts **10** and **13**.

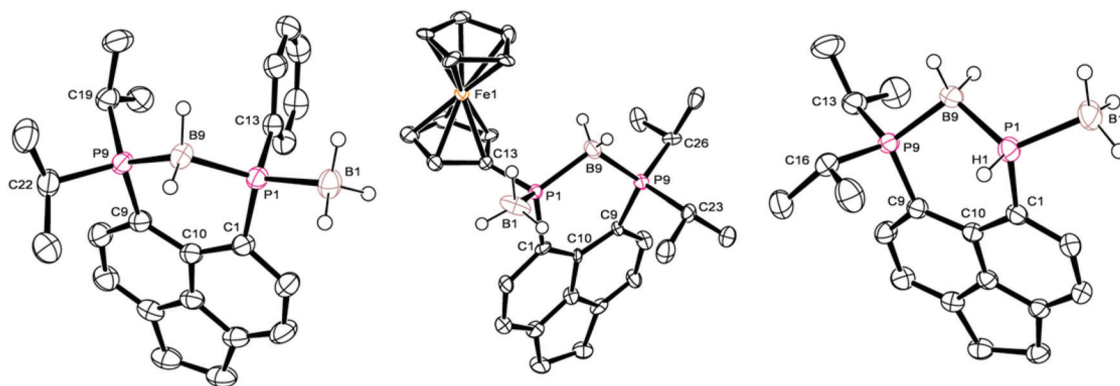


Fig. 5 Structures of **5a** (left), **5b** (centre), and **5c** (right) in the solid state. Carbon-bound hydrogen atoms and second molecule in asymmetric unit (for **5b** and **5c**) omitted for clarity.



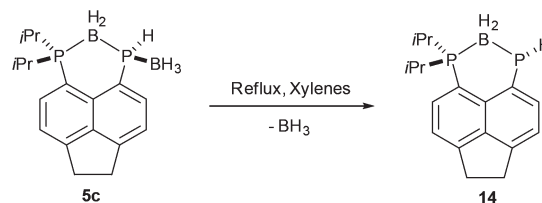
albeit at a slower rate than **4a**. A solution of **4b** left standing in CDCl₃ achieved approximately 80% conversion to **5b** after 2 weeks. Owing to the slow rate of reaction, **5b** was more conveniently synthesised by refluxing **4b** in THF for 4 days. The observed trend in dehydrocoupling rates (**4a** > **4b**) correlates with the acidity of the P–H hydrogen, which is higher in **4a** due to the more electron withdrawing nature of the phenyl substituent as compared to the ferrocenyl substituent.

Compound **5b** demonstrates a similar ³¹P{¹H} NMR spectrum to **5a**, displaying a broad doublet (δ_P 16.1, $^1J_{PP} = 92.6$ Hz, *i*Pr₂P) and a very broad unresolved signal (δ_P –32.0, PFc) located upfield of the corresponding signals for **4b** ($\Delta\delta_P \approx 20$ –25). Once again, ¹H and ³¹P NMR spectroscopy confirmed the loss of H directly bonded to phosphorus, and the ¹¹B NMR spectrum displayed two distinct boron environments. Crystals of **5b** suitable for single crystal X-ray diffraction were grown from acetonitrile. Obtained data is of somewhat poor quality, but is sufficient to demonstrate the connectivity of the molecule. The crystal structure is shown in Fig. 5 with data in Tables 1–3 and is broadly similar to that seen for **5a**.

The dehydrocoupled product of the primary bis(borane) adduct **4c** was obtained by treating **3** with excess H₃B–SME₂ in DCM and then, without isolating **4c**, allowing the reaction mixture to stir at room temperature for 11 days. After this time, no peaks for **4c** could be observed in the ³¹P{¹H} NMR spectrum of the reaction mixture. The resultant bridged compound **5c** is significantly more inert than the corresponding bis(borane) adduct, and was stable enough to be purified by flash column chromatography. As with the previous compounds, **5c** displays peaks in the ³¹P{¹H} NMR spectrum with $\Delta\delta_P \approx 25$ –30 upfield of the corresponding resonances for the parent bis(borane) adduct **4c**. Additionally, in the ³¹P NMR spectrum of **5c**, the signal for the PH group (δ_P –69.5) appears as a doublet ($^1J_{PH} = 339$ Hz) as opposed to the triplet seen for **4c**.

Crystals of **5c** suitable for single crystal X-ray diffraction were grown from slow diffusion of hexane into its concentrated solution in DCM. The structure is presented in Fig. 5, with data in Tables 1–3. One interesting point of note is that, in contrast to **5a–b**, compound **5c** displays almost no out-of-plane displacement of the *peri*-phosphorus atoms (0.050 Å [0.042 Å] for P1, 0.068 Å [0.101 Å] for P8, values in square brackets are for the second molecule in the asymmetric unit). This can be attributed to the significantly reduced steric demands of the hydrogen substituent.

Given the presence of vicinal P–H and B–H bonds in compound **5c**, the thermal decomposition of this compound was investigated to verify whether a further molecule of dihydrogen could be eliminated. After refluxing **5c** in xylenes for 3 days, partial conversion ($\approx 26\%$ by ³¹P NMR) to a new compound, compound **14**, was observed. Compound **14** shows two resonances in its ³¹P{¹H} NMR spectrum, a broad multiplet (δ_P 11.0, *Pi*Pr₂) and a sharp singlet (δ_P –136.9, PH). The low frequency chemical shift of the singlet suggests that **14** forms by loss of BH₃ from **5c** (Scheme 5). Furthermore, the ³¹P NMR spectrum shows a significant reduction in the $^1J_{PH}$ coupling constant (**5c**, $^1J_{PH} = 339$ Hz; **14**, $^1J_{PH} = 185$ Hz), consistent with



Scheme 5 Proposed initial product of thermal decomposition of **5c**.

an increase in electron density on phosphorus due to loss of the Lewis acidic BH₃.³⁶ Due to the slow rate of the reaction, complete conversion to **14** was not achieved and this compound was not isolated pure. Attempts to drive the reaction to completion by prolonged heating resulted in decomposition.

Conclusion

Bis(borane) adducts **4a–c** were formed by either borane mediated reduction of phosphino-phosphonium salts **1a–b**, or by treatment of the bis(phosphine) **3** with excess H₃B–SME₂. All three adducts were found to undergo spontaneous intramolecular dehydrocoupling in solution, resulting in the formation of a P–B bond to afford the novel BH₂ bridged compounds **5a–c**. This reaction is surprisingly facile, occurring at room temperature and in the absence of a catalyst (albeit in some cases at a slow rate). The ease with which the reaction proceeds can be attributed to the unique constraints of the *peri*-geometry; the two reactive moieties are held in close proximity and the repulsive interaction between them introduces considerable strain into the system, which is reduced on formation of a bridging P–B–P motif.

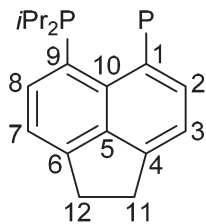
This interesting reaction serves as a demonstration of the utility of *peri*-substitution for promoting unusual or unexpected reactivity. Furthermore, it highlights how manipulation of the steric properties of a molecule can eliminate the need for a catalyst, which could be a potentially interesting alternative approach to developing compounds for hydrogen storage.

Experimental

General procedures

All experiments were carried out using standard Schlenk technique or glove box unless otherwise stated. Solvents were dried on an MBraun solvent purification system and stored over molecular sieves prior to use. 5-Bromo-6-diisopropylphosphinoacene and phosphonium-phosphoranide **2** were synthesised according to literature procedures.²⁴ Where possible, new compounds were fully characterized by ³¹P, ³¹P{¹H}, ¹H and ¹³C{¹H} NMR, including measurement of ¹H{³¹P}, H–H DQF COSY, H–P HMQC, H–C HSQC, and H–C HMBC experiments. The NMR numbering scheme for all compounds discussed is shown in Scheme 6.





Scheme 6 NMR numbering scheme for all compounds discussed.

Instrumentation

All NMR spectra were recorded using a JEOL GSX Delta 270, a Bruker Avance 300, Bruker Avance 400, Bruker Avance 500 or Bruker Avance III 500 spectrometer. 85% H_3PO_4 was used as an external standard in ^{31}P , $\text{BF}_3\cdot\text{OEt}_2$ in CDCl_3 was used as an external standard in ^{11}B , and TMS was used as an internal standard in ^1H and ^{13}C NMR. Measurements were performed at 25 °C unless otherwise indicated. All IR and Raman spectra were obtained in the range 4000–300 cm^{-1} on a Perkin-Elmer System 2000 NIR Fourier transform spectrometer. Mass spectra were acquired by Mrs Caroline Horseburgh at the University of St Andrews on a Micromass LCT. Elemental analysis (C, H and N) was performed by Mr Stephen Boyer at London Metropolitan University.

X-ray experimental

Table 3 lists details of data collections and refinements. Data for compound **3** were collected at $-180(1)$ °C by using a Rigaku Mercury70 diffractometer. Data for compounds **4b** and **5b** were collected at $-180(1)$ °C by using a Rigaku XtaLAB P200 diffractometer. Data for compounds **5a** and **5c** were collected at $-100(1)$ °C by using a Rigaku XtaLAB P200 diffractometer. All instruments use Mo $\text{K}\alpha$ radiation ($\lambda = 0.71075$ Å). Intensities were corrected for Lorentz polarization and for absorption. The structures were solved by direct methods. Refinements were done by full-matrix least-squares based on F^2 using SHELXTL.³⁷ CCDC 1410480–1410484 contain the supplementary crystallographic data for this article.

[Acenap(PiPr₂)(PPh)][Cl] phosphino-phosphonium **1a**

Synthesis adapted from method published by Kilian *et al.*²⁵ 5-Bromo-6-diisopropylphosphinoacenaphthene (4.00 g, 11.45 mmol) was dissolved in diethyl ether (100 mL) and cooled to -78 °C. *n*BuLi (4.58 mL of a 2.5 M solution in hexanes, 11.45 mmol) was added dropwise with stirring. The solution was stirred for 2 hours at -78 °C. A solution of dichlorophenylphosphine (1.55 mL, 2.05 g, 11.45 mmol) in diethyl ether (10 mL) was added dropwise over 30 minutes at -78 °C and the solution left to warm to room temperature overnight. The white precipitate was collected by filtration, washed with diethyl ether (3×10 mL) and dried *in vacuo* to yield **1a** as a fine white powder (4.109 g). Accurate yield could not be determined due to contamination with LiCl, which however poses no problems for further syntheses. The ^1H and

$^{31}\text{P}\{^1\text{H}\}$ NMR of the product were in good agreement with previously published data.²⁵

^1H NMR δ_{H} (270 MHz; CDCl_3) 8.80 (1H, dd, $^3J_{\text{HP}} = 9.2$ Hz, $^3J_{\text{HH}} = 7.3$ Hz, 2-H), 7.84 (1H, \approx $^3J_{\text{HH}} = 6.8$ Hz $^3J_{\text{HP}} = 6.8$ Hz, 8-H), 7.72 (1H, dd, $^3J_{\text{HH}} = 7.3$ Hz, $^4J_{\text{HP}} = 2.9$ Hz, 3-H), 7.58 (1H, dd, $^3J_{\text{HH}} = 7.2$ Hz, $^4J_{\text{HP}} = 2.6$ Hz, 7-H), 7.49–7.22 (5H, m, 5 \times Ph CH), 3.94–3.75 (1H, m, *i*Pr CH), 3.75–3.61 (1H, m, *i*Pr CH), 3.58 (4H, br s, 11-H, 12-H), 1.39 (3H, dd, $^3J_{\text{HP}} = 19.3$ Hz, $^3J_{\text{HH}} = 6.9$ Hz, *i*Pr CH_3), 1.14 (3H, dd, $^3J_{\text{HP}} = 18.9$ Hz, $^3J_{\text{HH}} = 7.0$ Hz, *i*Pr CH_3), 1.03 (3H, dd, $^3J_{\text{HH}} = 7.1$ Hz, $^3J_{\text{HP}} = 3.8$ Hz, *i*Pr CH_3), 0.95 (3H, dd, $^3J_{\text{HH}} = 7.1$ Hz, $^3J_{\text{HP}} = 3.8$ Hz, *i*Pr CH_3).

$^{31}\text{P}\{^1\text{H}\}$ NMR δ_{P} (109 MHz; CDCl_3) 61.3 (d, *i*Pr₂P), -35.3 (d, PPh), $^1J_{\text{PP}} = 304$ Hz.

[Acenap(PiPr₂)(PFc)][Cl] phosphino-phosphonium **1b**

Synthesis adapted from method published by Kilian *et al.*²⁵ 5-Bromo-6-diisopropylphosphinoacenaphthene (1.00 g, 2.86 mmol) was dissolved in diethyl ether (20 mL) and cooled to -78 °C. *n*BuLi (1.14 mL of a 2.5 M solution in hexanes, 2.86 mmol) was added dropwise with stirring. The solution was stirred for 2 hours at -78 °C. A suspension of dichloroferrocenyphosphine (0.82 g, 2.86 mmol) in diethyl ether (20 mL) was added dropwise over 30 minutes at -78 °C and the solution left to warm to room temperature overnight. The orange precipitate was collected by filtration, washed with diethyl ether (3×5 mL) and dried *in vacuo* to yield **1a** as a fine orange powder (1.480 g). Accurate yield could not be determined due to contamination with LiCl, which however poses no problems for further syntheses. The ^1H and $^{31}\text{P}\{^1\text{H}\}$ NMR of the product were in good agreement with previously published data.²⁵

^1H NMR δ_{H} (270 MHz; CDCl_3) 8.62 (1H, dd, $^3J_{\text{HP}} = 9.0$ Hz, $^3J_{\text{HH}} = 7.3$ Hz, 2-H), 8.10–8.01 (1H, m, 8-H), 7.67 (1H, dd, $^3J_{\text{HH}} = 7.2$ Hz, $^4J_{\text{HP}} = 2.7$ Hz, 3-H), 7.62 (1H, dd, $^3J_{\text{HH}} = 7.0$ Hz, $^4J_{\text{HP}} = 2.2$ Hz, 7-H), 4.75–4.71 (1H, m, CpH), 4.65–4.55 (1H, m, CpH), 4.34 (5H, s, CpH), 4.30–4.25 (2H, m, $2 \times$ CpH), 3.56 (4H, s, 11-H, 12-H), 3.21–3.19 (2H, m, $2 \times$ *i*Pr CH), 1.35–0.92 (12H, m, $4 \times$ *i*Pr CH_3).

$^{31}\text{P}\{^1\text{H}\}$ NMR δ_{P} (109 MHz; CDCl_3) 56.1 (d, *i*Pr₂P), -37.3 (d, PFc), $^1J_{\text{PP}} = 313$ Hz.

Acenap(PiPr₂)(PH₂) bis(phosphine) **3**

To a stirred suspension of LiAlH_4 (0.334 g, 8.8 mmol) in THF (15 mL) cooled to -78 °C, a suspension of **2** (0.50 g, 1.35 mmol) in THF (20 mL) was added slowly *via* cannula. The resultant bright pink solution was allowed to warm to room temperature, with stirring, overnight. The solution was cooled to 0 °C and degassed water (2.5 mL) was added dropwise with stirring. The mixture was then filtered to remove insoluble impurities. Volatiles were removed *in vacuo* to give **3** as a pink solid (0.298 g, 0.986 mmol, 73%). The compound is highly soluble in most organic solvents, a small amount of crystals of **3** suitable for single crystal X-ray diffraction were grown from THF.

mp 140–144 °C.



IR (nujol mull) $\nu_{\max}/\text{cm}^{-1}$ 2293w, 2240m (PH), 1604w, 840m, 790m.

Raman (glass capillary) $\nu_{\max}/\text{cm}^{-1}$ 3058s (ArH), 2948s and 2929s and 2866s (CH), 2294m and 2241s (PH), 1605m, 1567s, 1331vs, 585s.

^1H NMR δ_{H} (400 MHz; C_6D_6) 7.79–7.72 (1H, m, 2-H), 7.60 (1H, dd, $^3J_{\text{HH}} = 7.1$ Hz, $^3J_{\text{HP}} = 3.3$ Hz, 8-H), 7.12 (1H, dt, $^3J_{\text{HH}} = 7.2$ Hz, $^4J_{\text{HH}} = 1.3$ Hz, 7-H), 6.93 (1H, d, $^3J_{\text{HH}} = 7.1$ Hz, 3-H), 4.98 (2H, dd, $^1J_{\text{HP}} = 204$ Hz, $^5J_{\text{HP}} = 47.8$ Hz, PH_2), 3.04–2.83 (4H, m, 11-H, 12-H), 2.12–1.99 (2H, m, $2 \times i\text{Pr}$ CH), 1.17 (6H, dd, $^3J_{\text{HP}} = 14.3$ Hz, $^3J_{\text{HH}} = 6.9$ Hz, $2 \times i\text{Pr}$ CH_3), 1.00 (6H, dd, $^3J_{\text{HP}} = 12.3$ Hz, $^3J_{\text{HH}} = 7.0$ Hz, $2 \times i\text{Pr}$ CH_3).

$^{13}\text{C}\{^1\text{H}\}$ NMR δ_{C} (101 MHz; C_6D_6) 148.8 (s, qC-6), 147.7 (d, $^4J_{\text{CP}} = 1.9$ Hz, qC-4), 140.4 (m, qC-5, qC-10), 139.7 (s, C-2), 134.5 (d, $^2J_{\text{CP}} = 2.3$ Hz, C-8), 131.0 (dd, $^1J_{\text{CP}} = 23.9$ Hz, $^3J_{\text{CP}} = 7.4$ Hz, qC-9), 125.9 (d, $^1J_{\text{CP}} = 19.8$ Hz, qC-1), 119.8 (s, C-3), 119.4 (s, C-7), 30.3 (s, C-11/C-12), 29.9 (s, C-11/C-12), 26.4 (d, $^1J_{\text{CP}} = 15.9$ Hz, $i\text{Pr}$ CH), 26.4 (d, $^1J_{\text{CP}} = 15.8$ Hz, $i\text{Pr}$ CH), 20.4 (s, $i\text{Pr}$ CH_3), 20.3 (s, $i\text{Pr}$ CH_3), 20.2 (s, $2 \times i\text{Pr}$ CH_3).

^{31}P NMR δ_{P} (162 MHz; C_6D_6) –11.3 (dm, $^1J_{\text{PP}} = 205$ Hz, $i\text{Pr}_2\text{P}$), –101.2 ($\approx\text{q}$, $^1J_{\text{PP}} = 205$, $^1J_{\text{PH}} = 204$ Hz, PH_2).

$^{31}\text{P}\{^1\text{H}\}$ NMR δ_{P} (162 MHz; C_6D_6) –11.3 (d, $i\text{Pr}_2\text{P}$), –101.2 (d, PH_2), $^1J_{\text{PP}} = 205$ Hz.

MS (ES^+) m/z 301.1 (100%, M – H).

HRMS (ES^+) Found: 301.1278. Calc. for $\text{C}_{18}\text{H}_{23}\text{P}_2$ (M – H): 301.1275.

Acenap($\text{PiPr}_2\text{-BH}_3$)(PFcH-BH₃) bis(borane) 4b

Borane dimethylsulfide (0.10 mL, 94%, 0.99 mmol) was added to a stirred suspension of **1b** (120 mg, 0.23 mmol) in THF (30 mL) at –78 °C. The reaction was stirred for 2 hours at –78 °C, then allowed to warm to RT and stirred overnight. Volatiles were removed *in vacuo* to afford **4b** as an orange solid. The crude product contained the bridged compound **5b** as a minor byproduct (approximately 20%). Analytically pure material, as well as crystals suitable for single crystal X-ray diffraction, was obtained from acetonitrile at 5 °C (50 mg, 0.10 mmol, 42%).

mp 154–155 °C.

Found: C 65.56; H 7.56. Calc. for $\text{C}_{28}\text{H}_{38}\text{FeB}_2\text{P}_2$: C 65.43; H 7.45.

IR (KBr disk) $\nu_{\max}/\text{cm}^{-1}$ 2966m and 2928m (CH), 2374vs (PH), 2345s (BH), 1638m, 1604m, 1460m, 1414m, 1387m, 1316m, 1256m, 1182m, 1071s, 1028s, 929m, 831s, 671m, 643m, 492m, 446m.

^1H NMR δ_{H} (400 MHz; CDCl_3) 8.09 (1H, dd, $^3J_{\text{HP}} = 13.2$ Hz, $^3J_{\text{HH}} = 7.4$ Hz, 2-H), 7.81 (1H, dd, $^3J_{\text{HP}} = 16.4$ Hz, $^3J_{\text{HH}} = 7.3$ Hz, 8-H), 7.70 (1H, dq, $^1J_{\text{HP}} = 393$ Hz, $^3J_{\text{HH}} = 6.1$ Hz, P-H), 7.39 (1H, d, $^3J_{\text{HH}} = 7.4$ Hz, 3-H), 7.31 (1H, d, $^3J_{\text{HH}} = 7.3$ Hz, 7-H), 4.59–4.55 (2H, m, $2 \times \text{CpH}$), 4.48–4.43 (2H, m, $2 \times \text{CpH}$), 4.32 (5H, s, $5 \times \text{CpH}$), 3.38 (4H, s, 11-H, 12-H), 3.16–3.06 (1H, m, $i\text{Pr}$ CH), 3.06–2.95 (1H, m, $i\text{Pr}$ CH), 1.60–0.40 (6H, br m, $2 \times \text{BH}_3$), 1.48–1.37 (9H, m, $3 \times i\text{Pr}$ CH_3), 0.99 (3H, dd, $^3J_{\text{HP}} = 15.2$ Hz, $^3J_{\text{HH}} = 6.8$ Hz, $i\text{Pr}$ CH_3).

$^{13}\text{C}\{^1\text{H}\}$ NMR δ_{C} (101 MHz; CDCl_3) 152.3 (s, qC-6), 151.9 (s, qC-4), 140.8 ($\approx\text{t}$, $^3J_{\text{CP}} = 7.9$ Hz, qC-5), 140.1 (d, $^2J_{\text{CP}} = 7.5$ Hz,

C-2), 136.9 (d, $^2J_{\text{CP}} = 14.3$ Hz, C-8), 133.1–132.9 (m, qC-10), 123.5 (d, $^1J_{\text{CP}} = 53.0$ Hz, qC-9), 120.3 (d, $^3J_{\text{CP}} = 12.9$ Hz, C-7), 119.5 (d, $^1J_{\text{CP}} = 43.4$ Hz, qC-1), 119.5 (d, $^3J_{\text{CP}} = 10.6$ Hz, C-3), 74.3 (d, $J_{\text{CP}} = 15.9$ Hz, Cp CH), 72.7 (d, $J_{\text{CP}} = 6.6$ Hz, Cp CH), 72.4 (d, $J_{\text{CP}} = 3.6$ Hz, Cp CH), 71.4 (d, $J_{\text{CP}} = 9.0$ Hz, Cp CH), 70.2 (s, $5 \times \text{Cp}$ CH), 66.2 (d, $^1J_{\text{CP}} = 68.3$ Hz, Cp qC), 30.2 (s, C-11/C-12), 30.0 (s, C-11/C-12), 25.5 (dd, $^1J_{\text{CP}} = 29.1$ Hz, $^3J_{\text{CP}} = 2.1$ Hz, $i\text{Pr}$ CH), 23.7 (d, $^1J_{\text{CP}} = 33.3$ Hz, $i\text{Pr}$ CH), 19.4 (s, $i\text{Pr}$ CH_3), 18.3 (s, $i\text{Pr}$ CH_3), 17.9–17.3 (m, $i\text{Pr}$ CH_3), 17.5 (s, $i\text{Pr}$ CH_3).

^{31}P NMR δ_{P} (162 MHz; CDCl_3) 36.2 (br s, $i\text{Pr}_2\text{P}$), –7.7 (d, $^1J_{\text{PH}} = 395$ Hz, PFcH).

$^{31}\text{P}\{^1\text{H}\}$ NMR δ_{P} (162 MHz; CDCl_3) 36.3 (br s, $i\text{Pr}_2\text{P}$), –7.7 (br s, PFcH).

^{11}B NMR δ_{B} (160 MHz; CDCl_3) –39.2 (br m, $2 \times \text{BH}_3$).

$^{11}\text{B}\{^1\text{H}\}$ NMR δ_{B} (160 MHz; CDCl_3) –38.7 (br m, BH_3), –39.4 (br m, BH_3).

MS (ES^-) m/z 485.1 (12%, M – 2BH_3 – H), 499.2 (86, M – BH_3 – H), 513.2 (100, M – H).

HRMS (ES^-) Found: 513.1919. Calc. for $\text{C}_{28}\text{H}_{37}\text{P}_2\text{FeB}_2$ (M + H): 513.1906.

Acenap($\text{PiPr}_2\text{-BH}_3$)($\text{PH}_2\text{-BH}_3$) Bis(borane) 4c

Borane dimethylsulfide (0.40 mL, 94%, 3.98 mmol) was added to a stirred solution of **3** (100 mg, 0.33 mmol) in DCM (5 mL) at –78 °C. The reaction was allowed to warm to room temperature over 1 h, then stirred for 30 minutes. Volatiles were removed *in vacuo* to afford crude **4c** as an off-white sticky solid (105 mg). Compound was not purified due to its high sensitivity towards moisture and oxygen, which prevented chromatographic separation. NMR data was assigned from the crude product mixture.

^1H NMR δ_{H} (400 MHz; CDCl_3) 8.26 (1H, dd, $^3J_{\text{HP}} = 14.1$ Hz, $^3J_{\text{HH}} = 7.5$ Hz, 2-H), 8.19 (1H, dd, $^3J_{\text{HP}} = 19.3$ Hz, $^3J_{\text{HH}} = 7.3$ Hz, 8-H), 7.49–7.42 (2H, m, 3-H, 7-H), 6.14 (2H, dq, $^1J_{\text{HP}} = 377$ Hz, $^3J_{\text{HH}} = 7.1$ Hz, PH_2), 3.44 (4H, s, 11-H, 12-H), 2.90–2.77 (2H, m, $2 \times i\text{Pr}$ CH), 1.50–0.30 (6H, br m, $2 \times \text{BH}_3$), 1.38 (6H, dd, $^3J_{\text{HP}} = 14.6$ Hz, $^3J_{\text{HH}} = 6.9$ Hz, $2 \times i\text{Pr}$ CH_3), 1.06 (6H, dd, $^3J_{\text{HP}} = 15.6$ Hz, $^3J_{\text{HH}} = 7.1$ Hz, $2 \times i\text{Pr}$ CH_3).

^{31}P NMR δ_{P} (162 MHz; CDCl_3) 38.0 (br s, $i\text{Pr}_2\text{P}$), –40.8 (br s, PH_2).

$^{31}\text{P}\{^1\text{H}\}$ NMR δ_{P} (162 MHz; CDCl_3) 38.0 (br s, $i\text{Pr}_2\text{P}$), –40.8 (t, $^1J_{\text{PH}} = 379$ Hz, PH_2).

^{11}B NMR δ_{B} (96 MHz; CDCl_3) –40.1 (br m, $2 \times \text{BH}_3$).

$^{11}\text{B}\{^1\text{H}\}$ NMR δ_{B} (96 MHz; CDCl_3) –40.1 (br m, $2 \times \text{BH}_3$).

Acenap(PiPr_2)($\mu\text{-BH}_2$)(PPh-BH₃) 5a

Borane dimethylsulfide (0.15 mL, 94%, 1.49 mmol) was added to a stirred solution of **1a** (150 mg, 0.363 mmol) in THF (5 mL) at –78 °C. The reaction was stirred for 2 hours at –78 °C, then allowed to warm to room temperature and stirred overnight. Volatiles were removed *in vacuo* to afford the bis(borane) adduct **4a**, which was re-dissolved in DCM (5 mL) and stirred at room temperature for 8 days. Volatiles were removed *in vacuo* to afford **5a** as an off-white solid in near quantitative yield (0.145 g, 0.359 mmol, 99%). Crystals suitable for single



crystal X-ray diffraction were grown from d_6 -DMSO at room temperature.

mp 230 °C (decomp).

Found: C 71.23; H 8.05. Calc. for $C_{24}H_{32}B_2P_2$: C 71.34; H 7.98.

IR (KBr disk) $\nu_{\max}/\text{cm}^{-1}$ 3030w (ArH), 2970m and 2934m and 2872m (CH), 2449m, 2364vs (BH), 2258m, 1597s, 1488m, 1453s, 1436s, 1388m, 1340m, 1248m, 1139m, 1111m, 1057vs, 882m, 847s, 829m, 739s, 699vs, 666m, 614m, 472m, 402m.

Raman (glass capillary) $\nu_{\max}/\text{cm}^{-1}$ 3060 (s, Ar-H), 2942 (s, ν C-H), 2895 (m), 2453 (m), 2388 (m), 2340 (m, ν B-H), 1599 (s), 1578 (s), 1444 (s), 1419 (s), 1343 (vs), 1002 (s), 832 (m), 739 (m), 573 (s).

^1H NMR δ_{H} (500 MHz; CDCl_3) 8.01 (1H, dd, $^3J_{\text{HP}} = 12.2$ Hz, $^3J_{\text{HH}} = 7.2$ Hz, 2-H), 7.67 (1H, dd, $^3J_{\text{HP}} = 10.3$ Hz, $^3J_{\text{HH}} = 7.2$ Hz, 8-H), 7.59–7.51 (2H, m, *o*-Ph CH), 7.42 (1H, d, $^3J_{\text{HH}} = 7.5$ Hz, 7-H), 7.40 (1H, d, $^3J_{\text{HH}} = 7.3$ Hz, 3-H), 7.30–7.23 (3H, m, *m/p*-Ph CH), 3.50–3.39 (4H, m, 11-H, 12-H), 2.76–2.64 (1H, m, *iPr* CH), 2.38–2.26 (1H, m, *iPr* CH), 2.10–0.70 (5H, br m, BH_2 and BH_3), 1.28 (3H, dd, $^3J_{\text{HP}} = 14.9$ Hz, $^3J_{\text{HH}} = 7.1$ Hz, *iPr* CH_3), 1.25 (3H, dd, $^3J_{\text{HP}} = 16.0$ Hz, $^3J_{\text{HH}} = 7.2$ Hz, *iPr* CH_3), 1.17 (3H, dd, $^3J_{\text{HP}} = 15.7$ Hz, $^3J_{\text{HH}} = 7.0$ Hz, *iPr* CH_3), 0.93 (3H, dd, $^3J_{\text{HP}} = 15.9$ Hz, $^3J_{\text{HH}} = 7.2$ Hz, *iPr* CH_3).

$^{13}\text{C}\{^1\text{H}\}$ NMR δ_{C} (126 MHz; CDCl_3) 153.0 (m, qC-6), 149.7 (s, qC-4), 139.8 (dd, $^3J_{\text{CP}} = 8.6$ Hz, $^3J_{\text{CP}} = 6.5$ Hz, qC-5), 138.5 (d, $^2J_{\text{CP}} = 8.1$ Hz, C-2), 137.6 (dd, $^1J_{\text{CP}} = 42.1$ Hz, $^3J_{\text{CP}} = 7.0$ Hz, *i*-Ph qC), 135.2 (dd, $^2J_{\text{CP}} = 9.1$ Hz, $^2J_{\text{CP}} = 5.3$ Hz, qC-10), 134.2 (s, C-8), 132.5 (d, $^2J_{\text{CP}} = 8.7$ Hz, *o*-Ph CH), 128.9 (d, $^4J_{\text{CP}} = 2.1$ Hz, *p*-Ph CH), 128.1 (d, $^3J_{\text{CP}} = 9.2$ Hz, *m*-Ph CH), 124.6 (dd, $^1J_{\text{CP}} = 41.4$ Hz, $^3J_{\text{CP}} = 5.0$ Hz, qC-1), 121.0 (d, $^3J_{\text{CP}} = 9.6$ Hz, C-3), 118.8 (d, $^3J_{\text{CP}} = 8.9$ Hz, C-7), 114.5 (dd, $^1J_{\text{CP}} = 56.2$ Hz, $^3J_{\text{CP}} = 3.5$ Hz, C-9), 30.6 (s, C-11/C-12), 30.2 (s, C-11/C-12), 24.3 (dd, $^1J_{\text{CP}} = 35.0$ Hz, $^3J_{\text{CP}} = 1.8$ Hz, *iPr* CH), 23.0 (dd, $^1J_{\text{CP}} = 35.3$ Hz, $^3J_{\text{CP}} = 4.7$ Hz, *iPr* CH), 18.4 (s, *iPr* CH_3), 17.8 (s, *iPr* CH_3), 16.7 (s, *iPr* CH_3), 16.6 (s, *iPr* CH_3).

^{31}P NMR δ_{P} (202 MHz; CDCl_3) 13.7 (br s, *iPr* $_2$ P), –26.4 (br s, PPh).

$^{31}\text{P}\{^1\text{H}\}$ NMR δ_{P} (202 MHz; CDCl_3) 13.9 (br d, $^1J_{\text{PP}} = 84.0$ Hz, *iPr* $_2$ P), –26.3 (br m, PPh).

^{11}B NMR δ_{B} (160 MHz; CDCl_3) –33.6 (br m, BH_3), –39.4 (br m, BH_2).

$^{11}\text{B}\{^1\text{H}\}$ NMR δ_{B} (160 MHz; CDCl_3) –33.6 (br d, $^1J_{\text{BP}} = 46.2$ Hz, BH_3), –39.4 (br \approx t, $^1J_{\text{BP}} = 69.3$ Hz, BH_2).

MS (ES+) m/z 391.2 (28%, M – BH_3 + H), 427.2 (100, M + Na).

HRMS (ES+) Found: 427.2052. Calc. for $C_{24}H_{32}P_2B_2Na$ (M + Na): 427.2058.

Acenap(*PiPr* $_2$)(μ - BH_2)(PFc- BH_3) **5b**

Borane dimethylsulfide (0.10 mL, 94%, 0.99 mmol) was added to a stirred suspension of **1b** (120 mg, 0.23 mmol) in THF (30 mL) at –78 °C. The reaction was stirred for 2 hours at –78 °C, then allowed to warm to RT and stirred overnight to afford **4b**, which was not isolated. The reaction mixture was heated under reflux for 4 days. Volatiles were removed *in vacuo* to afford **5b** as an orange oil. Analytically pure material was

obtained by filtering through silica gel, eluting with DCM (102 mg, 0.20 mmol, 87%). Crystals of **5b** suitable for single crystal X-ray diffraction were grown by slow evaporation from acetonitrile.

mp 180 °C (decomp).

Found: C 65.76; H 6.93. Calc. for $C_{28}H_{36}\text{FeB}_2P_2$: C 65.68; H 7.09.

IR (KBr disk) $\nu_{\max}/\text{cm}^{-1}$ 2967m and 2932m (CH), 2437s, 2362vs (BH), 1598s, 1448m, 1387m, 1332m, 1255m, 1169s, 1105m, 1059s, 1025s, 828s, 670s, 492s, 453m.

Raman (glass capillary) $\nu_{\max}/\text{cm}^{-1}$ 3110s (ArH), 2929s (CH), 2440w, 2381m (BH), 1601s, 1575s, 1447s, 1417s, 1335vs, 1173s, 1107vs, 1060m, 830m, 729m, 552m, 402m, 368m, 321s.

^1H NMR δ_{H} (500 MHz; CDCl_3) 7.71 (1H, dd, $^3J_{\text{HP}} = 11.5$ Hz, $^3J_{\text{HH}} = 7.2$ Hz, 2-H), 7.64 (1H, dd, $^3J_{\text{HP}} = 10.3$ Hz, $^3J_{\text{HH}} = 7.2$ Hz, 8-H), 7.35 (1H, d, $^3J_{\text{HH}} = 7.1$ Hz, 7-H), 7.27–7.23 (1H, m, 3-H), 4.94 (1H, s, CpH), 4.43 (2H, s, 2 \times CpH), 4.39 (5H, s, 5 \times CpH), 4.32 (1H, s, CpH), 3.43–3.27 (4H, m, 11-H, 12-H), 2.90–2.80 (1H, m, *iPr* CH), 2.80–2.70 (1H, m, *iPr* CH), 2.20–0.60 (5H, br m, BH_2 and BH_3), 1.52 (3H, dd, $^3J_{\text{HP}} = 16.6$ Hz, $^3J_{\text{HH}} = 7.3$ Hz, *iPr* CH_3), 1.42 (3H, dd, $^3J_{\text{HP}} = 16.3$ Hz, $^3J_{\text{HH}} = 6.9$ Hz, *iPr* CH_3), 1.32 (3H, dd, $^3J_{\text{HP}} = 14.4$ Hz, $^3J_{\text{HH}} = 7.1$ Hz, *iPr* CH_3), 1.11 (3H, dd, $^3J_{\text{HP}} = 15.5$ Hz, $^3J_{\text{HH}} = 7.0$ Hz, *iPr* CH_3).

$^{13}\text{C}\{^1\text{H}\}$ NMR δ_{C} (101 MHz; CDCl_3) 152.7 (s, qC-6), 148.1 (s, qC-4), 139.6 (dd, $^3J_{\text{CP}} = 9.1$ Hz, $^3J_{\text{CP}} = 6.4$ Hz, qC-5), 135.9 (d, $^2J_{\text{CP}} = 5.7$ Hz, C-2), 133.8 (m, qC-10), 133.5 (s, C-8), 130.2 (dd, $^1J_{\text{CP}} = 38.6$ Hz, $^3J_{\text{CP}} = 3.2$ Hz, qC-1), 120.8 (d, $^3J_{\text{CP}} = 8.5$ Hz, C-3), 118.4 (d, $^3J_{\text{CP}} = 8.8$ Hz, C-7), 114.6 (dd, $^1J_{\text{CP}} = 55.7$ Hz, $^3J_{\text{CP}} = 2.7$ Hz, qC-9), 75.1 (dd, $^1J_{\text{CP}} = 53.3$ Hz, $^2J_{\text{CP}} = 12.2$ Hz, Cp qC), 74.2 (d, $J_{\text{CP}} = 10.4$ Hz, Cp CH), 71.7 (d, $J_{\text{CP}} = 5.9$ Hz, Cp CH), 71.0 (d, $J_{\text{CP}} = 6.1$ Hz, Cp CH), 70.6 (d, $J_{\text{CP}} = 6.8$ Hz, Cp CH), 69.8 (s, 5 \times Cp CH), 30.6 (s, C-11/C-12), 30.0 (s, C-11/C-12), 25.9 (d, $^1J_{\text{CP}} = 34.6$ Hz, *iPr* CH), 21.4 (dd, $^1J_{\text{CP}} = 36.0$ Hz, $^2J_{\text{CP}} = 9.0$ Hz, *iPr* CH), 19.2 (s, *iPr* CH_3), 17.8 (s, *iPr* CH_3), 17.4 (d, $^2J_{\text{CP}} = 2.7$ Hz, *iPr* CH_3), 16.1 (d, $^2J_{\text{CP}} = 3.8$ Hz, *iPr* CH_3).

^{31}P NMR δ_{P} (202 MHz; CDCl_3) 16.1 (br s, *iPr* $_2$ P), –32.0 (br s, PFc).

$^{31}\text{P}\{^1\text{H}\}$ NMR δ_{P} (202 MHz; CDCl_3) 16.1 (br d, $^1J_{\text{PP}} = 92.6$ Hz, *iPr* $_2$ P), –32.0 (br m, PFc).

^{11}B NMR δ_{B} (160 MHz; CDCl_3) –33.9 (br m, BH_3), –41.0 (br m, BH_2).

$^{11}\text{B}\{^1\text{H}\}$ NMR δ_{B} (160 MHz; CDCl_3) δ –33.7 (br m, BH_3), –41.1 (br m, BH_2).

MS (ES+) m/z 498.1 (100%, M – BH_3), 512.2 (38, M).

HRMS (ES+) Found: 498.1483. Calc. for $C_{28}H_{33}\text{FeP}_2\text{B}$ (M – BH_3): 498.1500.

Acenap(*PiPr* $_2$)(μ - BH_2)(PH- BH_3) **5c**

Borane dimethylsulfide (0.40 mL, 94%, 3.98 mmol) was added to a stirred solution of **3** (100 mg, 0.33 mmol) in DCM (5 mL) at –78 °C. The reaction was allowed to warm to room temperature over 1 h, then left to stir at room temperature for 11 days. Distilled water (10 mL) was added and the reaction stirred for 1 h at room temperature. The product was extracted with DCM (3 \times 10 mL) in air and the combined washings were dried over MgSO_4 . Volatiles were removed *in vacuo* and the crude product



was purified by flash column chromatography on silica, eluting with DCM, to yield **5c** as a white crystalline solid (45 mg, 0.137 mmol, 41%). Crystals of **5c** suitable for single crystal X-ray diffraction were grown by diffusion of hexane into a concentrated solution of **5c** in DCM.

mp 140 °C (decomp).

Found: C 65.89; H 8.70. Calc. for C₁₈H₂₈B₂P₂: C 65.92; H 8.61.

IR (KBr disk) $\nu_{\max}/\text{cm}^{-1}$ 2975m and 2959s (CH), 2930m, 2872m, 2444s (BH), 2368vs (PH), 2259w, 1710w, 1597s, 1492m, 1461s, 1418m, 1387m, 1367w, 1333m, 1257m, 1217w, 1139m, 1103m, 1065vs, 1040m, 909s, 883m, 849s, 715s, 629m, 395w.

Raman (glass capillary) $\nu_{\max}/\text{cm}^{-1}$ 3064m, 2962s, 2934vs (CH), 2901vs, 2462m (BH), 2392m, 2351vs (PH), 1599s, 1575s, 1441s, 1420m, 1337vs, 1054m, 883m, 830m, 735m, 585m, 571s.

¹H NMR δ_{H} (500 MHz; CDCl₃) 8.37 (1H, dd, ³J_{HP} = 13.4 Hz, ³J_{HH} = 7.1 Hz, 2-H), 7.67 (1H, dd, ³J_{HP} = 10.3 Hz, ³J_{HH} = 7.2 Hz, 8-H), 7.46 (1H, d, ³J_{HH} = 7.1 Hz, 3-H), 7.42 (1H, d, ³J_{HH} = 7.2 Hz, 7-H), 4.89 (1H, br d, ¹J_{HP} = 328 Hz, PH), 3.45 (4H, s, 11-H, 12-H), 2.78–2.64 (1H, m, *i*Pr CH), 2.55–2.41 (1H, m, *i*Pr CH), 1.90–0.60 (5H, br m, BH₂ and BH₃), 1.32 (3H, dd, ³J_{HP} = 16.6 Hz, ³J_{HH} = 6.9 Hz, *i*Pr CH₃), 1.29–1.23 (6H, m, 2 × *i*Pr CH₃), 1.07 (3H, dd, ³J_{HP} = 16.0 Hz, ³J_{HH} = 7.0 Hz, *i*Pr CH₃).

¹³C{¹H} NMR δ_{C} (126 MHz; CDCl₃) 153.1 (d, ⁴J_{CP} = 2.0 Hz, qC-4), 150.1 (s, qC-6), 139.5 (dd, ³J_{CP} = 8.2 Hz, ³J_{CP} = 5.9 Hz, qC-5), 138.4 (d, ²J_{CP} = 10.9 Hz, C-2), 135.8 (dd, ²J_{CP} = 8.6, ²J_{CP} = 2.2 Hz, qC-10), 134.4 (s, C-8), 120.6 (d, ³J_{CP} = 10.7 Hz, C-3), 119.1 (d, ³J_{CP} = 8.9 Hz, C-7), 118.8 (dd, ¹J_{CP} = 41.0 Hz, ³J_{CP} = 6.8 Hz, qC-1), 112.6 (dd, ¹J_{CP} = 55.9 Hz, ³J_{CP} = 4.1 Hz, qC-9), 30.5 (s, C-11/C-12), 30.0 (s, C-11/C-12), 25.1 (d, ¹J_{CP} = 36.1 Hz, *i*Pr CH), 22.4 (dd, ¹J_{CP} = 36.4, ³J_{CP} = 4.5 Hz, *i*Pr CH), 17.7 (d, ²J_{CP} = 2.2 Hz, *i*Pr CH₃), 17.2 (s, *i*Pr CH₃), 17.1 (s, *i*Pr CH₃), 16.6 (d, ²J_{CP} = 1.8 Hz, *i*Pr CH₃).

³¹P NMR δ_{P} (202 MHz; CDCl₃) 12.8 (br s, *i*Pr₂P), –69.5 (br d, ¹J_{PH} = 339 Hz, PH).

³¹P{¹H} NMR δ_{P} (202 MHz; CDCl₃) 12.8 (br d, ¹J_{PP} = 79.9 Hz, *i*Pr₂P), –69.5 (br m, PH).

¹¹B NMR δ_{B} (160 MHz; CDCl₃) –37.2 (br m, BH₃), –41.9 (br m, BH₂).

¹¹B{¹H} NMR δ_{B} (160 MHz; CDCl₃) –37.1 (br m, BH₃), –41.9 (br \approx t, ¹J_{BP} = 63.0 Hz, BH₂).

MS (ES+) *m/z* 351.2 (100%, M + Na).

HRMS (ES+) Found: 351.1753. Calc. for C₁₈H₂₈P₂B₂Na (M + Na): 351.1750.

Acenap(P*i*Pr₂-BH₃)(PH)₂ **6**

Borane dimethylsulfide (0.72 mL, 94%, 7.6 mmol) was added to a stirred solution of **3** (180 mg, 0.60 mmol) in DCM (10 mL) at 0 °C. The reaction was stirred for 2 hours at room temperature, then cooled to 0 °C and degassed water (10 mL) was added cautiously. The reaction mixture was stirred for a further 2 hours at room temperature, the organic layer was separated and volatiles removed *in vacuo* to afford **6** as a yellow solid in quantitative yield (188 mg, 0.59 mmol, 99%).

¹H NMR δ_{H} (400 MHz; CDCl₃) 8.54 (1H, dd, ³J_{HP} = 17.4 Hz, ³J_{HH} = 7.4 Hz, 8-H), 8.04–8.00 (1H, m, 2-H), 7.33 (1H, d, ³J_{HH} =

7.3 Hz, 7-H), 7.27 (1H, d, ³J_{HH} = 7.2 Hz, 3-H), 4.48 (2H, d, ¹J_{HP} = 207 Hz, PH₂), 3.63–3.49 (2H, m, 2 × *i*Pr CH), 3.38 (4H, s, 11-H, 12-H), 1.70–0.30 (3H, br m, BH₃), 1.42 (6H, dd, ³J_{HP} = 15.0 Hz, ³J_{HH} = 7.0 Hz, 2 × *i*Pr CH₃), 0.88 (6H, dd, ³J_{HP} = 16.2 Hz, ³J_{HH} = 7.1 Hz, 2 × *i*Pr CH₃).

¹³C{¹H} NMR δ_{C} (75 MHz; CDCl₃) 152.3 (s, qC-6), 150.1 (s, qC-4), 143.8 (d, ²J_{CP} = 4.6 Hz, C-8), 143.5 (br d, ²J_{CP} = 20.0 Hz, C-2), 140.9 (\approx t, ³J_{CP} = 7.1 Hz, ³J_{CP} = 7.1 Hz, qC-5), 137.0 (d, ²J_{CP} = 26.6 Hz, qC-10), 120.5 (d, ¹J_{CP} = 43.7, qC-9), 119.8 (s, C-3), 119.2 (d, ³J_{CP} = 14.7 Hz, C-7), 117.8 (d, ¹J_{CP} = 16.0 Hz, qC-1), 30.0 (s, C-11/C-12), 29.9 (s, C-11/C-12), 25.2 (d, ¹J_{CP} = 28.4 Hz, *i*Pr CH), 24.8 (d, ¹J_{CP} = 28.3 Hz, *i*Pr CH), 19.1 (s, 2 × *i*Pr CH₃), 18.9 (s, 2 × *i*Pr CH₃).

³¹P NMR δ_{P} (109 MHz; CDCl₃) 44.5 (m, *i*Pr₂P), –101.3 (t, ¹J_{PH} = 207 Hz, PH₂).

³¹P{¹H} NMR δ_{P} (109 MHz; CDCl₃) 44.0 (m, *i*Pr₂P), –101.4 (s, PH₂).

¹¹B NMR δ_{B} (96 MHz; CDCl₃) –41.9 (br m, BH₃).

¹¹B{¹H} NMR δ_{B} (96 MHz; CDCl₃) –41.9 (br d, ¹J_{BP} = 66.4 Hz, BH₃).

Acenap(P*i*Pr₂)(μ -BH₂)(PH) **14**

A suspension of **5c** (0.100 g, 0.304 mmol) in xylenes (20 mL) was heated under reflux. At high temperatures, all solid dissolved to give a yellow solution. After 3 days volatiles were removed *in vacuo* to give a yellow solid (0.098 g) containing \approx 74% **5c** and \approx 26% **14**. Compound **14** was not isolated pure due to its instability to air and moisture and NMR data was assigned from the mixture. Attempts to bring the reaction to completion *via* prolonged heating under reflux resulted in decomposition to a complex mixture of products.

¹H NMR δ_{H} (400 MHz; CDCl₃) 7.98 (1H, dd, ³J_{HP} = 12.1 Hz, ³J_{HH} = 7.0 Hz, 2-H), 7.61 (1H, dd, ³J_{HP} = 9.9 Hz, ³J_{HH} = 7.2 Hz, 8-H), 7.35 (1H, d, ³J_{HH} = 7.2 Hz, 7-H), 7.25 (1H, d, ³J_{HH} = 7.0 Hz, 3-H), 3.40–3.33 (4H, m, 11-H, 12-H). Signals for H directly bound to phosphorus/boron and *i*Pr groups were obscured by signals from **5c** or were too weak to be seen.

³¹P NMR δ_{P} (162 MHz; CDCl₃) 11.1 (br s, *i*Pr₂P), –137.0 (br d, ¹J_{PH} = 185 Hz, PH).

³¹P{¹H} NMR δ_{P} (162 MHz; CDCl₃) 11.0 (m, *i*Pr₂P), –136.9 (s, PH).

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