H_2 Activation

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Metal-Free Catalytic Hydrogenation of Enamines, Imines, and Conjugated Phosphinoalkenylboranes**

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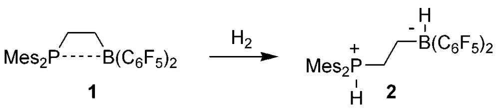
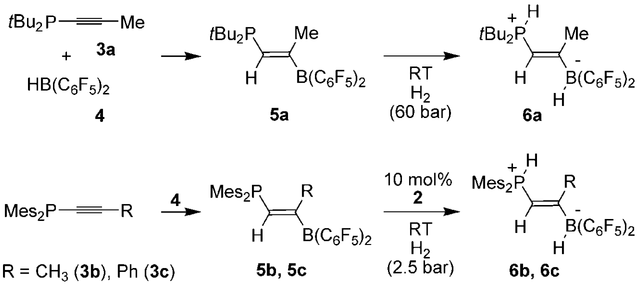
Dedicated to Professor Reinhard W. Hoffmann on the occasion of his 75th birthday

Catalytic heterolytic splitting of dihydrogen had until recently been a domain of metal-containing systems, be it for example in the Fe or Fe/Ni hydrogenase enzymes[1] or the Noyori-type chelate amine ruthenium catalysts and many conceptually related systems.[2] Stephan et al. recently reported the reaction of dihydrogen with frustrated phosphane/borane Lewis pairs, some of which are quite active catalysts for the hydrogenation of bulky imines at elevated temperatures.[3–9] We reported the formation of the ethylene-bridged P/B system **1** (Mes = 2,4,6-trimethylphenyl),[6] a weakly intramolecularly interacting phosphane/borane pair that rapidly activates dihydrogen heterolytically at ambient temperature to form the linked phosphonium/hydridoborate zwitterion **2** [Eq. (1)]. Herein we show that the system **1**/**2** is able to transfer the H^+/H^- pair under mild conditions and can serve as a catalyst for the hydrogenation of bulky imines and of enamines.



(1)

Hydroboration of $tBu_2PC{\equiv}CCH_3$ (**3a**)[10] with $HB(C_6F_5)_2$ (**4**)[11] at 80 °C in benzene gave the bifunctional phosphane/borane system **5a** (Scheme 1). The orange-colored oil reacts slowly with dihydrogen at elevated pressure (60 bar H_2, toluene, 3 h at room temperature) to yield the zwitterionic product **6a** (63 %). Compound **6a** was characterized by elemental analysis and NMR spectroscopy (see the Experimental Section).



Scheme 1. Preparation of the zwitterionic compounds **6**.

The hydroboration of compounds **3b** ($R = CH_3$) and **3c** (R = Ph, Scheme 1) at room temperature in pentane gave the bright-red products **5b** (82 %) and **5c** (93 %), respectively. The NMR spectra are consistent with three-coordinate boron (^{11}B NMR, [D$_6$]benzene: $\delta = 64$ (**5b**), 59 ppm (**5c**);[12] ^{19}F NMR: $\Delta\delta(m/p\text{-}C_6F_5) = 11.7$ (**5b**), 11.4 ppm (**5c**); ^{31}P NMR: $\delta = -27.1$ (**5b**), −22.0 ppm (**5c**)).

In contrast to **5a**, neither compound **5b** nor **5c** reacts with dihydrogen under the reaction conditions used (room temperature, pentane or toluene solution, 2.5 bar H_2), nor with dihydrogen at a pressure of 60 bar. Addition of bulky tri-*tert*-butyl phosphane (15 mol %) to a solution of **5b** led to slow heterolytic dihydrogen splitting at ambient conditions (2.5 bar H_2, 3 d at RT) to eventually yield **6b**. Treatment of **5b** with dihydrogen at 60 bar in the presence of $P(tBu)_3$ (15 mol %) in toluene at room temperature led to a complete conversion into **6b** within 3 h.

Although the $-CH{=}C(CH_3)$-linked P/B system (**5b**) itself proved to be unreactive toward dihydrogen under the reaction conditions used, it accepted the H^+/H^- pair from the H_2 activator system **1**/**2**. Compound **5b** was mixed in [D$_6$]benzene with an equimolar amount of the zwitterion **2**, and the rapid formation of an equilibrium mixture of **1**, **2**, **5b**, and **6b** was observed (Figure 1).

The heterolytic splitting of dihydrogen and its transfer to **5b** was efficiently catalyzed by the **1**/**2** pair. Treatment of a mixture of the unreactive compound **5b** with H_2 (2.5 bar) at RT in toluene solution in the presence of 10 mol % of **2** (either added as the substance, or generated in situ from **1** during the hydrogenation reaction) resulted in a complete conversion into the hydrogen addition product **6b** within 4 h (Scheme 1). Compound **6b** (admixed with some residual **2**) was isolated from the reaction mixture in over 80 % yield as a colorless solid (m.p. 153 °C). It features a characteristic ^{1}H NMR signal

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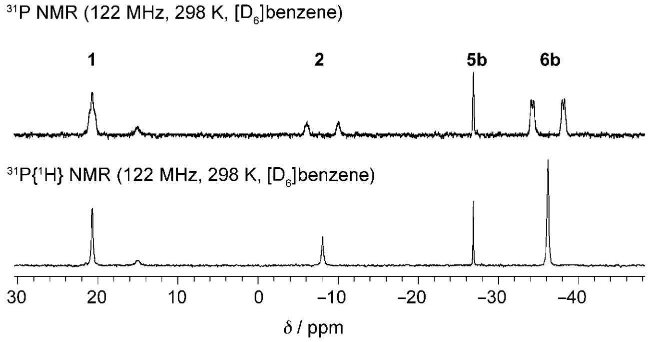


Figure 1. ^{31}P NMR spectra (upper: {^{1}H} coupled, lower: {^{1}H} decoupled) of the equilibrium mixture of **1**, **2**, **5b**, and **6b** after reaction of **2** and **5b** (1:1) after ca. 30 min in [D$_6$]benzene.

at $\delta = 7.58$ ppm (see Experimental Section) for P–H and a corresponding ^{31}P NMR resonance at $\delta = -36.2$ ppm.

The analogous reaction of **5b** with D_2, catalyzed by **1**/[D$_2$]**2** (10 mol%) gave [D$_2$]**6b**. The compound has ^{2}H NMR signals at $\delta = 7.55$ ($^1J_{PD} \approx 70$ Hz, P–D) and 4.1 ppm (br s, B–D). The ^{31}P NMR spectrum of [D$_2$]**6b** has a corresponding 1:1:1 triplet for the P–D unit at $\delta = -36.8$ ppm ($^1J_{PD} \approx 70$ Hz). The weakly interacting P/B pair **1** also catalyzes the P/B hydrogenation of the analogous phenyl derivative **5c** at ambient temperature (**6c** isolated in 80% yield).

The products **6b** and **6c** were characterized by X-ray diffraction. Both the phosphorus and the boron atom have pseudotetrahedral coordination geometries; each carries a hydrogen atom which was located in the structure. The structure of **6b** (single crystals from THF) has bulky $[Mes_2PH]^+$ and $[(C_6F_5)_2BH]^-$ units oriented *trans* to each other at the central bridging -CH=CMe-unit (Figure 2). Compound **6c** has a very similar structure (for details, see the Supporting Information).

The system **1**/**2** catalyzes the hydrogenation of bulky imines under mild conditions. Treatment of *N-tert*-butylbenzaldimine (**7a**) with dihydrogen (2.5 bar) in the presence of 20 mol% of the dihydrogen activation/transfer reagent system **1**/**2** leads to the rapid formation of *tert*-butylbenzylamine (**8a**) at room temperature (87% yield of isolated product; Scheme 2). In the case of the ketimine substrate **7b**, using 5 mol% catalyst was sufficient to achieve complete imine hydrogenation within 180 min (70% amine **8b** isolated).

The **1**/**2** pair is a good metal-free catalyst for the hydrogenation of enamines. We achieved quantitative hydrogenation of the enamine **9** to the tertiary amine **10** at ambient conditions with 10 mol% of the **1**/**2** catalyst system (Scheme 2). Similarly, we were able to hydrogenate the enamines piperidinocyclohexene (**11a**) and morpholinocyclohexene (**11b**) to the respective tertiary amines *N*-cyclohexylpiperidine (**12a**, 88% yield of isolated product) and *N*-cyclohexylmorpholine (**12b**, 78%) at room temperature and H_2 at a pressure of 2.5 bar employing 5 mol% or 3 mol% of the metal-free **1**/**2** hydrogenation catalyst system, respectively.

Our study has revealed some distinctive features of the new hydrogen activation systems that are currently beginning to emerge.[3–9] It seems that a subtle balance of steric and electronic factors is controlling the potential dihydrogen activation ability of the P/B frustrated Lewis pairs. It is remarkable that some of the rather open systems **5** by themselves do not show activity toward dihydrogen. However, these systems accept the H^+/H^- pair readily from the active hydrogen splitting catalyst **1**/**2** to undergo a unique catalytic P/B hydrogenation reaction, as do imines and enamines. The unique pair **1**/**2** seems to be one of the most active metal-free catalytic hydrogenation catalysts described to date. Our observations indicate that the development of new frustrated Lewis pairs is useful for the development of novel catalyst systems for reactions with dihydrogen.

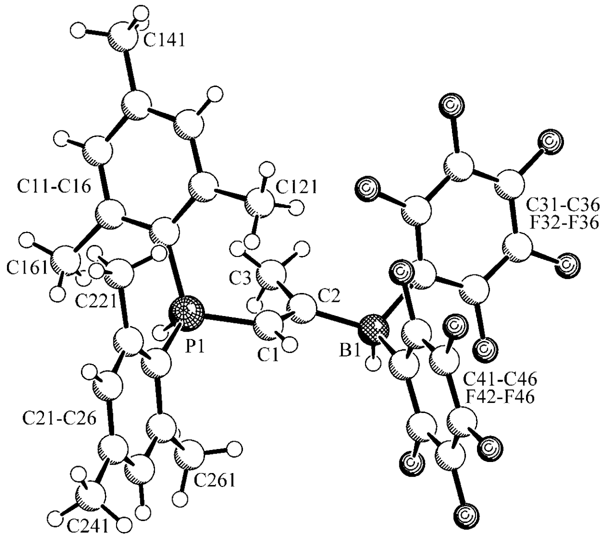
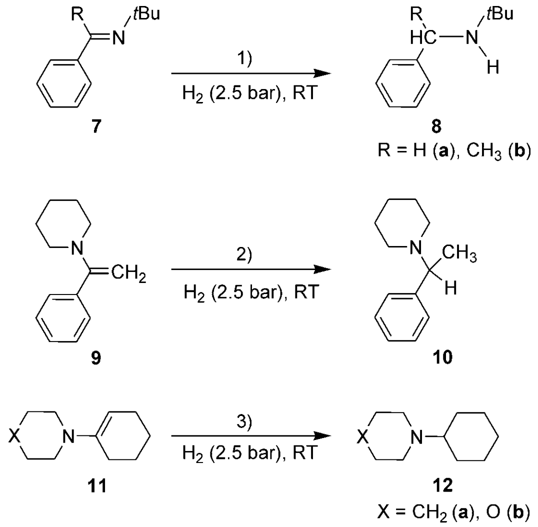


Figure 2. Molecular structure of the zwitterionic product **6b**. Selected bond lengths [Å] and angles [°]: P1–C1 1.775(2), C1–C2 1.340(2), C2–C3 1.506(3), C2–B1 1.616(3), C11-P1-C21 117.7(1), C11-P1-C1 113.5(1), C21-P1-C1 110.0(1), P1-C1-C2 124.4(1), C1-C2-C3 120.7(2), C1-C2-B1 122.6(2), C3-C2-B1 116.3(2), C31-B1-C41 108.3(1), C31-B1-C2 115.3(2), C41-B1-C2 113.7(2).



Scheme 2. 1) **a**: 20 mol% **2**, **b**: 5 mol% **2**; 2) 10 mol% **2**; 3) **a**: 5 mol% **2**, **b**: 3 mol% **2**.

Experimental Section

5a: Reaction of **3a** (32 mg, 0.17 mmol) with HB(C_6F_5)$_2$ (**4**); 59 mg, 0.17 mmol) in benzene at 80 °C (10 min) gave **5a** (90 mg, 100 %). ^{1}H NMR (400 MHz): $\delta = 7.31$ ppm (1 H, dq, $^{2}J_{PH} = 4.5$, $^{4}J_{HH} = 1.3$ Hz, ^{P}CH=); ^{13}C{^{1}H} NMR (101 MHz): $\delta = 161.7$ (br s,=C^{B}), 158.0 ppm (d, $^{1}J_{PC} = 33.7$ Hz, ^{P}C=); ^{19}F NMR (282 MHz): $\delta = -129.8$ (*o*), -147.1 (*p*), -160.6 ppm (*m*); ^{31}P{^{1}H} (122 MHz): $\delta = 3.2$ ppm ($\nu_{1/2} = 4$ Hz); ^{11}B{^{1}H} NMR (96 MHz): $\delta = 62$ ppm ($\nu_{1/2} = 930$ Hz). UV/Vis (pentane): $\lambda_{max}(\varepsilon) = 397$ nm (1500).

5b: Compound **3b** (344 mg, 1.1 mmol) was reacted with HB(C_6F_5)$_2$ (**4**; 386 mg, 1.1 mmol) in pentane (15 mL) at room temperature to give **5b** (591 mg, 82 %). ^{1}H NMR: $\delta = 8.17$ ppm (1 H, d, $^{2}J_{PH} = 8.0$ Hz, ^{P}CH=); ^{13}C{^{1}H} NMR: $\delta = 171.4$ (d, $^{2}J_{PC} = 22.8$ Hz, ^{P}CH=), 151.8 ppm (br s, =C^{B}); ^{31}P{^{1}H} NMR: $\delta = -27.1$ ppm ($\nu_{1/2} = 7$ Hz); ^{19}F NMR: $\delta = -130.8$ (*o*), -149.2 (*p*), -160.9 ppm (*m*). UV/Vis (pentane): $\lambda_{max}(\varepsilon) = 432$ nm (10 500). Elemental analysis (%) calcd for $C_{33}H_{26}BF_{10}P$: C 60.57, H 4.01; found: C 60.13, H 4.04.

6a: Compound **3a** (111 mg, 0.60 mmol) was reacted with HB(C_6F_5)$_2$ (**4**; 208 mg, 0.60 mmol) in toluene (10 mL) at 80 °C for 10 min. Subsequent hydrogenation (3 h, 60 bar H_2) in a steel autoclave gave **6a** (200 mg, 63 %). ^{1}H NMR: $\delta = 5.11$ (1 H, dd, $^{2}J_{PH} = 31.5$, $^{3}J_{HH} = 12.9$ Hz, ^{P}C=), 4.57 (1 H, dd, $^{1}J_{PH} = 435$, $^{3}J_{HH} = 12.9$ Hz, P–H), 4.04 ppm (1 H, br s. 1:1:1:1 q (partially relaxed),[13] $^{1}J_{BH} = 93$ Hz, B–H); ^{13}C{^{1}H} NMR: $\delta = 202.0$ (br s, =C^{B}), 90.2 ppm (d, $^{1}J_{PC} = 65$ Hz, ^{P}C=); ^{31}P NMR: $\delta = 22.0$ ppm (d, $^{1}J_{PH} = 435$ Hz); ^{19}F NMR: $\delta = -131.4$ (*o*), -161.6 (*p*), -165.3 ppm (*m*); ^{11}B NMR: δ–18.0 ppm (d, $^{1}J_{BH} = 91$ Hz). IR (KBr): $\tilde{\nu} = 2345$ cm^{-1} (m, ν_{PH}/ν_{BH}). Elemental analysis (%) calcd for $C_{23}H_{24}BF_{10}P$: C 51.91, H 4.55; found: C 52.05, H 4.89.

6b: Compound **5b** was generated in situ from **3b** (200 mg, 0.65 mmol) and HB(C_6F_5)$_2$ (**4**; 224 mg, 0.65 mmol) in the presence of the catalyst **2** (42 mg, 0.07 mmol). Subsequent hydrogenation (2.5 bar, toluene, RT) gave **6b** (298 mg, 70 %). ^{1}H NMR: $\delta = 7.58$ (1 H, dd, $^{1}J_{PH} = 469$, $^{3}J_{HH} = 7.8$ Hz, P–H), 5.47 (1 H, dd, $^{2}J_{PH} = 38.4$, $^{3}J_{HH} = 7.8$ Hz, ^{P}CH=), 4.11 ppm (1 H, br s, 1:1:1:1 q (partially relaxed), $^{1}J_{BH} = 95$ Hz, B–H); ^{13}C{^{1}H} NMR: $\delta = 201.2$ (br s, =C^{B}), 96.8 ppm (d, $^{1}J_{PC} = 68.3$ Hz, ^{P}CH=); ^{31}P NMR: $\delta = -36.2$ ppm (dd, $^{1}J_{PH} = 469$, $^{2}J_{PH} = 38$ Hz); ^{19}F NMR: $\delta = -131.3$ (*o*), -161.6 (*p*), -165.3 ppm (*m*); ^{11}B NMR: $\delta = -18.0$ ppm (d, $^{1}J_{BH} = 95$ Hz). IR (KBr): $\tilde{\nu} = 2329$ cm^{-1} (s, ν_{PH}/ν_{BH}). Elemental analysis (%) calcd for $C_{33}H_{28}BF_{10}P$: C 60.39, H 4.30; found: C 59.87, H 4.18.

X-ray crystal structure analysis for **6b**: $C_{33}H_{28}BF_{10}P$, $M_r = 656.33$, colorless crystal $0.35 \times 0.20 \times 0.20$ mm^3, $a = 13.0699(4)$, $b = 16.1472(5)$, $c = 15.1163(5)$ Å, $\beta = 100.271(1)°$, $V = 3139.06(17)$ Å^3, $\rho_{calc} = 1.389$ g cm^{-3}, $\mu = 1.515$ mm^{-1}, empirical absorption correction ($0.619 \leq T \leq 0.752$), $Z = 4$, $P2_1/n$ (No. 14), $\lambda = 1.54178$ Å, $T = 223$ K, ω and ϕ scans, 32 792 reflections collected ($\pm h, \pm k, \pm l$), $[(\sin\theta)/\lambda] = 0.60$ Å^{-1}, 5640 independent ($R_{int} = 0.048$) and 5080 observed reflections ($I \geq 2\sigma(I)$), 421 refined parameters, $R = 0.042$, $wR^2 = 0.111$, max. (min.) residual electron density 0.25 (–0.27) e Å^{-3}, hydrogen atoms at P and B from difference Fourier calculations and refined free, others calculated and refined as riding atoms. CCDC-679345 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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[1] Reviews: a) B. J. Lemon, J. W. Peters, *Handbook of Metalloproteins*, *Vol. 2* (Eds.: A. Messerschmidt, R. Huber, T. Poulos, K. Wieghardt), Wiley, New York, **2001**, pp. 738–751; b) M. Frey, J. C. Fontecilla-Camps, A. Volbeda, *Handbook of Metalloproteins*, *Vol. 2* (Eds.: A. Messerschmidt, R. Huber, T. Poulos, K. Wieghardt), Wiley, New York, **2001**, pp. 880–896; c) X. Liu, S. K. Ibrahim, C. Tard, C. J. Pickett, *Coord. Chem. Rev.* **2005**, *249*, 1641–1652; d) E. Bouwman, J. Reedijk, *Coord. Chem. Rev.* **2005**, *249*, 1555–1581; See also: e) M. H. Cheah, C. Tard, S. J. Borg, X. Liu, S. K. Ibrahim, C. J. Pickett, S. P. Best, *J. Am. Chem. Soc.* **2007**, *129*, 11085–11092, and references therein.

[2] a) R. Noyori, S. Hashiguchi, *Acc. Chem. Res.* **1997**, *30*, 97–102; b) R. Noyori, M. Kitamura, T. Ohkuma, *Proc. Natl. Acad. Sci. USA* **2004**, *101*, 5356–5362; c) C. P. Casey, G. A. Bikzhanova, I. A. Guzei, *J. Am. Chem. Soc.* **2006**, *128*, 2286–2293; Review: d) M. Ito, T. Ikariya, *Chem. Commun.* **2007**, 5134–5142.

[3] a) G. C. Welch, R. R. San Juan, J. D. Masuda, D. W. Stephan, *Science* **2006**, *314*, 1124–1126; b) G. C. Welch, D. W. Stephan, *J. Am. Chem. Soc.* **2007**, *129*, 1880–1881.

[4] a) P. A. Chase, G. C. Welch, T. Jurca, D. W. Stephan, *Angew. Chem.* **2007**, *119*, 8196–8199; *Angew. Chem. Int. Ed.* **2007**, *46*, 8050–8053; Corrigendum: P. A. Chase, G. C. Welch, T. Jurca, D. W. Stephan, *Angew. Chem.* **2007**, *119*, 9296; *Angew. Chem. Int. Ed.* **2007**, *46*, 9136, and references therein. b) See also: G. Wittig, E. Bunz, *Chem. Ber.* **1959**, *92*, 1999–2013; c) W. Tochtermann, *Angew. Chem.* **1966**, *78*, 355–375; *Angew. Chem. Int. Ed. Engl.* **1966**, *5*, 351–371, and references therein.

[5] See also: a) C. Walling, L. Bollyky, *J. Am. Chem. Soc.* **1961**, *83*, 2968–2969; b) C. Walling, L. Bollyky, *J. Am. Chem. Soc.* **1964**, *86*, 3750–3752; c) D. Frey, V. Lavallo, B. Donnadieu, W. W. Schoeller, G. Bertrand, *Science* **2007**, *316*, 439–441; Review: d) A. L. Kenward, W. E. Piers, *Angew. Chem.* **2007**, *120*, 38–42; *Angew. Chem. Int. Ed.* **2007**, *47*, 38–41.

[6] P. Spies, G. Erker, G. Kehr, K. Bergander, R. Fröhlich, S. Grimme, D. W. Stephan, *Chem. Commun.* **2007**, 5072–5074.

[7] a) G. C. Welch, L. Cabrera, P. A. Chase, E. Hollink, J. D. Masuda, P. Wei, D. W. Stephan, *Dalton Trans.* **2007**, 3407–3414; b) J. S. J. McCahill, G. C. Welch, D. W. Stephan, *Angew. Chem.* **2007**, *119*, 5056–5059; *Angew. Chem. Int. Ed.* **2007**, *46*, 4968–4971.

[8] a) P. A. Chase, T. Jurca, D. W. Stephan, *Chem. Commun.* **2008**, 1701–1703; b) See also: D. Chen, J. Klankermayer, *Chem. Commun.* **2008**, 2130–2131.

[9] Theoretical analysis: T. A. Rokob, A. Hamza, A. Stirling, T. Soós, I. Pápai, *Angew. Chem.* **2008**, *120*, 2469–2472; *Angew. Chem. Int. Ed.* **2008**, *47*, 2435–2438.

[10] a) W. Drent, A. Hogervorst, *Recl. Trav. Chim. Pays-Bas* **1968**, *87*, 41–44; b) G. Borkent, W. Drent, *Recl. Trav. Chim. Pays-Bas* **1970**, *89*, 1057–1067.

[11] a) R. E. von H. Spence, D. J. Parks, W. E. Piers, M.-A. McDonald, M. J. Zaworotko, S. J. Rettig, *Angew. Chem.* **1995**, *107*, 1337–1340; *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 1230–1233; b) D. J. Parks, R. E. von H. Spence, W. E. Piers, *Angew. Chem.* **1995**, *107*, 895–897; *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 809–811; c) D. J. Parks, W. E. Piers, G. P. A. Yap, *Organometallics* **1998**, *17*, 5492–5503; d) R. E. von H. Spence, W. E. Piers, Y. Sun, M. Parvez, L. R. MacGillivray, M. J. Zaworotko, *Organometallics* **1998**, *17*, 2459–2469; Review: e) W. E. Piers, T. Chivers, *Chem. Soc. Rev.* **1997**, *26*, 345–354.

[12] For examples of remotely related systems, see: a) L. V. Ermolabva, S. G. Vul'fson, B. A. Arbuzov, *Phosphorus Sulfur Silicon Relat. Elem.* **1992**, *645*, 57–60; b) P. Binger, R. Köster, *J. Organomet. Chem.* **1974**, *73*, 205–210; c) R. Köster, L. A. Hagelee, *Synthesis* **1976**, 118–120; d) J. Grobe, R. Martin, *Z. Anorg. Allg. Chem.* **1992**, *607*, 146–152; e) Z. Yuan, N. J. Taylor, T. B. Marder, I. D. Williams, S. K. Kurtz, L.-T. Cheng, *J. Chem. Soc. Chem. Commun.* **1990**, 1489–1492; f) Z. Yuan, N. J. Taylor, Y. Sun, T. B. Marder, I. D. Williams, L.-T. Cheng, *J. Organomet. Chem.* **1993**, *449*, 27–37; g) Z. Yuan, N. J. Taylor, R. Ramachan-

dran, T. B. Marder, *Appl. Organomet. Chem.* **1996**, *10*, 305–316; h) Z. Yuan, J. J. Collings, N. J. Taylor, T. B. Marder, C. Jardin, J.-F. Halet, *J. Solid State Chem.* **2000**, *154*, 5–12; i) S. Sasaki, F. Murakami, M. Murakami, M. Watanabe, K. Kato, K. Sutoh, M. Yoshifuji, *J. Organomet. Chem.* **2005**, *690*, 2664–2672; j) J. Grobe, K. Lütke-Brochtrub, B. Krebs, M. Läge, H.-H. Niemeyer, E.-U. Würthwein, *Z. Naturforsch. B* **2006**, *61*, 882–895; k) S. Bontemps, G. Bouhadir, K. Miqueu, D. Bourissou, *J. Am. Chem. Soc.* **2006**, *128*, 12056–12057; l) S. Bontemps, G. Bouhadir, P. W. Dyer, K. Miqueu, D. Bourissou, *Inorg. Chem.* **2007**, *46*, 5149–5151; m) T. W. Hudnall, F. P. Gabbaï, *J. Am. Chem. Soc.* **2007**, *129*, 11978–11986; n) T. M. Gilbert, S. M. Bachrach, *Organometallics* **2007**, *26*, 2672–2678.

[13] For a detailed discussion, see: "NMR-Spektroskopie von Organobor-Verbindungen": B. Wrackmeyer, R. Köster in *Methoden Org. Chem. (Houben-Weyl)*, Vol. 13, Part 3c, **1984**, pp. 406–408.