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Dialkylammonium *tert*-Butylmethylphosphinites: Stable Intermediates for the Synthesis of P-Stereogenic Ligands

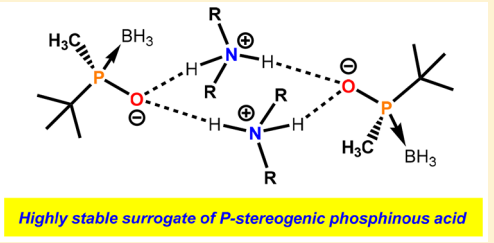
Ernest Salomó,[†] Amparo Prades,[†] Antoni Riera,*[,†,‡] and Xavier Verdaguer*[,†,‡]

[†]Institute for Research in Biomedicine (IRB Barcelona), Barcelona Institute of Science and Technology, Baldiri Reixac 10, 08028 Barcelona, Spain

[‡]Dept. Química Inorgànica i Orgànica, Secció de Química Orgànica, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain

Supporting Information

ABSTRACT: The preparation of shelf-stable crystalline salts of *tert*-butylmethylphosphinous acid borane **1** is described. X-ray analysis of diisopropylammonium *tert*-butylmethylphosphinite borane **6** revealed the presence of a cyclic hydrogen-bond network in the solid state which accounts for an increased melting point and stability. Dialkylammonium phosphinite boranes are convenient precursors of the chiral *tert*-butylmethylphosphine fragment. Compound **6** can be used directly in S_N2@P reactions with various nucleophiles to yield valuable P-stereogenic intermediates and ligands.

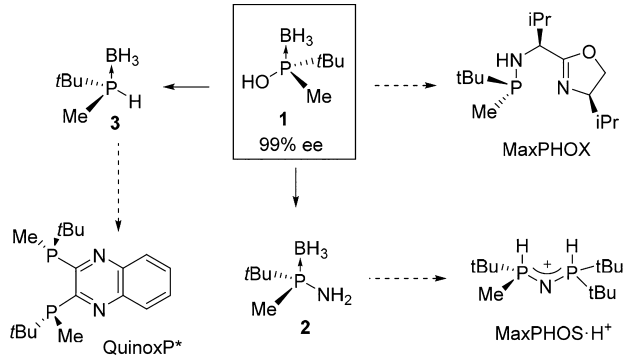


Since the initial seminal work of Knowles and co-workers,[1] P-stereogenic phosphines have emerged as an important group of ligands that are highly proficient in asymmetric hydrogenation and other relevant industrial catalytic transformations.[2,3] However, the assembly of stereogenic phosphorus centers in an optically pure fashion continues to be a hurdle. In this respect, the development of efficient methods for the rapid assembly of this class of compounds and the availability of key intermediates that facilitate the synthesis of P-stereogenic compounds is highly relevant in this field.

Optically pure P-stereogenic phosphinous acid boranes are attractive synthetic intermediates in the synthesis of compounds with chiral phosphorus; however, they have received little attention. Buono and co-workers described the synthesis of several P-stereogenic phosphinous acid boranes via H-menthylphosphinate or H-adamantylphosphinate technology.[4] Taking advantage of the intrinsic acidity of these compounds, Pietrusiewicz reported the resolution of several P-stereogenic phosphinous acid boranes via diastereomeric cinchonine salt formation.[5]

We have recently achieved the efficient synthesis of optically pure *tert*-butylmethylphosphinous acid-borane **1** (Scheme 1).[6] This compound is a key P-stereogenic intermediate in the synthesis of MaxPHOX and other ligands, which have shown excellent results in iridium- and rhodium-catalyzed asymmetric processes.[7] The transformation of phosphinous acid **1** into optically pure *tert*-butylmethylphosphanamine **2** allows its use in the synthesis of ligands, such as MaxPHOS and SIP.[8] It was also used as starting material for the preparation of optically pure *tert*-butylmethylphosphine-borane **3** which is the precursor of Imamoto's Quinox-P*.[9] We firmly believe that phosphinous acid **1** holds promise to become a key intermediate in the synthesis of new and already known P-stereogenic chiral ligands.

Scheme 1. Applications of Optically Pure *tert*-Butylmethylphosphinous Acid Borane 1



The main drawback that hampers the extensive use of **1** is its limited stability. Phosphinous acid **1** is a gummy-solid with a low melting point (54−56 °C), which upon storage decomposes to yield the corresponding secondary phosphine oxide and borane byproducts. ^{1}H NMR analysis revealed 35−40% of decomposition when a pure sample of **1** was stored at room temperature for a week. This limited stability made it necessary to use **1** immediately after its preparation. This is clearly a serious drawback for the large-scale utilization of **1**.

With this scenario in mind, we considered that it would be highly desirable to find a derivative of **1** that could circumvent the stability issues associated with pure phosphinous acid **1**. Here we report on dialkylamonium phosphinites, which are stable and convenient surrogates of **1**. These compounds are highly crystalline and can be utilized in the same fashion as **1** in

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S_N2@P reactions with different nucleophiles to yield mono and bisphosphines in a stereospecific manner.

The acidity of the phosphinous acid boranes is influenced by electronic and steric factors with pK_a values ranging from 5.8 for $Cy_2P(BH_3)OH$ to 3.9 for $Ph_2P(BH_3)OH$.[10] Potentiometric titration revealed that **1** has a pK_a of 4.8 and thus should readily form salts with inorganic and organic bases (Figure 1). An

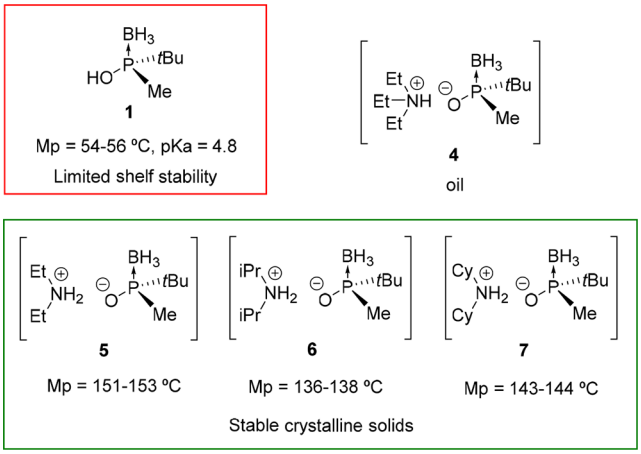


Figure 1. Melting points and stability of **1** and its corresponding ammonium phosphinites.

initial assessment showed that sodium and potassium salts did not fulfill the requirements to become useful surrogates of **1** since they were hygroscopic and not crystalline. We then turned our attention to organic bases and various trialkyl and dialkyl amines, along with DMAP and DBU, were screened as salt formation agents. While triethylamine provided an oily salt (**4**), diethylamine afforded a crystalline solid (**5**) with a melting point of 151−153 °C. Diisopropylamine and dicyclohexylamine also provided crystalline salts **6** and **7** with melting points around 130−140 °C. Most significantly, these saline surrogates proved to be shelf-stable and could be stored indefinitely at room temperature.

To gain further insight into the high crystallinity of dialkylammonium derivatives of **1**, an X-ray analysis of **6** was pursued. With this aim, single crystals were grown by evaporation of a solution of **6** in CH_2Cl_2. The resulting solid state structure of **6** is shown in Figure 2. The resolved structure is pseudosymmetric and holds a C_2 axis of symmetry. The most characteristic feature is the cyclic hydrogen bond network that

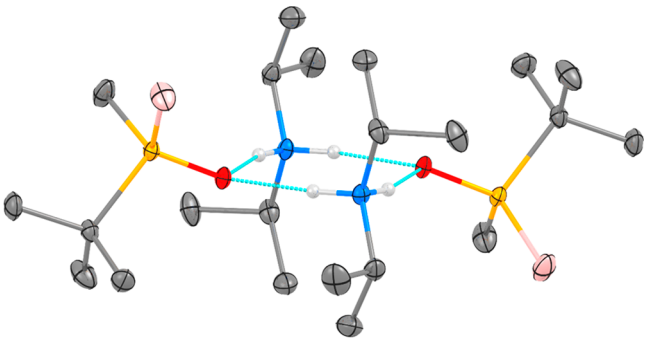
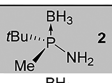
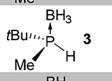
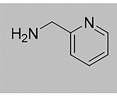
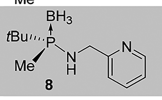
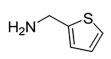
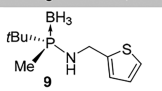
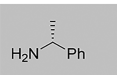
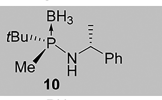
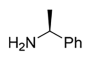
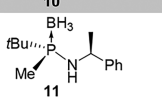
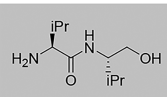
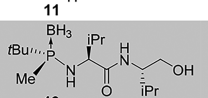
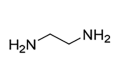
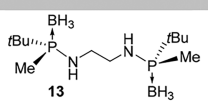
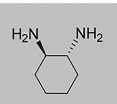
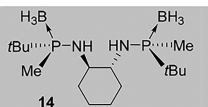
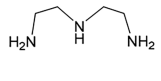
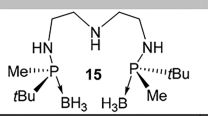


Figure 2. X-ray structure of **6**. Ortep diagram displays ellipsoids at 50% probability. Only hydrogen atoms involved in the H-bond network are depicted.

brings two $tBuMeP(BH_3)O^-$ and two $iPr_2NH_2^+$ units together in a tetrameric assembly. This cyclic H-bond network is completely planar. The two nitrogen and oxygen atoms conform a regular flat square of 2.77 Å sides. This strong hydrogen bond system probably accounts for the observed increased melting point (approximately +100 °C) with respect to the free phosphinous acid **1**.

With the stable dialkylammonium phosphonites in hand, we proceeded to test their ability to participate directly in S_N2@P reactions (Table 1). We have recently developed a protocol for the activation of **1** with mesyl anhydride. This approach provides a mixed anhydride that undergoes inversion of configuration when it reacts with different amine nucleophiles and reducing agents at −20 °C. For this test, we chose the optically pure diisopropylammonium phosphonite **6**, since it contained a bulky amine that was not expected to participate as

Table 1. Reaction of 6 with Various Amine Nucleophiles and Reducing Agents

Entry	NuH	Product	Yield (%)[a]	ee/de
1	NH_3	 **2**	99	98% ee[b]
2	$Bu_4N{\cdot}BH_4$	 **3**	80	99% ee[c]
3		 **8**	84	99% ee[d]
4		 **9**	85	99% ee[d]
5		 **10**	88	98% de[e]
6		 **11**	83	98% de[e]
7		 **12**	93	>95% de[e]
8		 **13**	66	>95% de[e]
9		 **14**	77	>95% de[e]
10		 **15**	84	>95% de[e]

[a]Yield corresponds to isolated product purified by flash chromatography. [b]Enantiomeric excess determined by chiral GC analysis. [c]Enantiomeric excess determined by chiral HPLC of the corresponding benzyl derivative. [d]Enantiomeric excess was determined by chiral HPLC. [e]As determined by ^1H NMR analysis.

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a nucleophile in the substitution reactions on phosphorus and offered the right balance between crystallinity and solubility. In practice, the addition of extra base was necessary to achieve clean activation of **6** with Ms_2O. The use of 2 equiv of NEt_3 at −20 °C afforded the clean and fast formation of the mixed anhydride intermediate, which was then reacted in situ with the nucleophile of choice. Thus, reaction with ammonia afforded the resulting primary aminophosphine **2** in 98% ee (Table 1, entry 1). Compound **2** is an intermediate in the synthesis of MaxPHOS ligand. Reduction of the mixed anhydride with Bu_4NBH_4 provided the secondary phosphine borane **3** in optically pure form and excellent yield (Table 1, entry 2). *tert*-Butylmethylphosphine borane **3** is also a key intermediate in the synthesis of Imamoto's QuinoxP* and BenzP* ligands.[11] Reaction with primary amines provided the resulting S_N2@P products with excellent yields and stereospecificity (Table 1, entries 3−6). Even for α-branched chiral amines like (*R*)- and (*S*)-1-phenylethan-1-amine, the resulting substitution products **10** and **11** were obtained with almost perfect inversion of configuration at the phosphorus (Table 1, entries 5 and 6). Reaction with a highly functionalized amino alcohol produced solely the substitution product at the amine to give **12** in excellent yield as a single diastereomer, as determined by ^{1}H NMR analysis (Table 1, entry 7). Compound **12** is a precursor of P-stereogenic phosphino-oxazoline ligand MaxPHOX. The amenability of **6** for the synthesis of bis-aminophosphines was also studied. Indeed, reaction of **6** with ethylenediamine produced compound **13** in a single step in >95% diastereomeric excess and 66% yield (Table 1, entry 8). Also, using (*R*,*R*)-cyclohexane-1,2-diamine as nucleophile, the corresponding disubstitution product was readily isolated in satisfactory yield and excellent optical and diastereomeric purity (Table 1, entry 9). Finally, **6** was reacted with diethylenetriamine, which bears one secondary and two primary amines (Table 1, entry 10). The S_N2@P reaction proved highly specific for the primary positions and led to compound **15**, which holds great potential as a wide bite-angle pincer ligand.

In summary, we disclosed that diisopropylammonium *tert*-butylmethylphosphonite borane **6** is a convenient highly crystalline and stable surrogate of the corresponding phosphinous acid. X-ray analysis showed that the increased stability of **6** in solid state arises from a tetrameric assembly with a cyclic H-bond network. Moreover, we have demonstrated that **6** can be used directly in S_N2@P reactions with reducing agents and amine nucleophiles. We envisage that the stability of compounds **5**−**7** will foster the preparation and use of optically pure phosphinous acid boranes in large-scale in the synthesis of valuable P-stereogenic compounds.

EXPERIMENTAL SECTION

General Methods. All reactions were carried out in dried solvents under nitrogen atmosphere. Et_2O and CH_2Cl_2 were dried in a purification system. Other commercially available reagents and solvents were used with no further purification. Thin layer chromatography was carried out using TLC-aluminum sheets with silica gel. Flash chromatography was performed by using an automated chromatographic system with hexane/ethyl acetate or hexane/dichloromethane gradients as eluent unless otherwise stated. NMR spectra were recorded at 23 °C on a 400, 500, or 600 MHz apparatus. ^{1}H NMR and ^{13}C{^{1}H}NMR spectra were referenced either to relative internal TMS or to residual solvent peaks. ^{31}P NMR spectra were referenced to phosphoric acid. Optical rotations were measured at room temperature (25 °C) and concentration is expressed in g/100 mL. Melting points were determined using a Büchi apparatus and were not corrected. IR spectra were recorded in a FT-IR apparatus. HRMS were recorded in a LTQ-FT spectrometer using the Nanoelectrospray technique. Compound **1** was prepared from hydrolysis of the corresponding *cis*-hydroxyindan-1-yl derivative.[6,12]

Diethylammonium (*R*)-*tert*-Butyl(methyl)phosphinite Borane (5). Phosphinous acid **1** was placed in a vial (15 mg, 0.11 mmol) and solved in TBME (0.5 mL). Diethylamine (12 μL, 0.11 mmol) was added dropwise via a syringe. The resulting crystalline precipitate was filtered and dried under a stream of nitrogen. White solid. Yield: 87% (20 mg). M_P: 151−153 °C. $[\alpha]_D$: − 22.1 (c 0.50, $CHCl_3$). IR (KBr/NaCl) υ_{max}: 3424, 2966, 2349, 1628, and 997 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ; 9.08 (br s, 2H), 2.97−2.81 (m, 4H), 1.33 (t, J = 7 Hz, 6H), 1.16 (d, J_P = 8 Hz, 3H), 1.06 (d, J_P = 13 Hz, 9H), 0.73−0.03 (m, 3H, BH_3) ppm. ^{13}C{^{1}H}NMR (101 MHz, $CDCl_3$) δ; 42.4 (2 x CH_2), 30.8 (d, J_P = 41 Hz, C), 24.6 (d, J_P = 3 Hz, 3 x CH_3), 13.8 (d, J_P = 33 Hz, CH_3), 12.0 (2 x CH_3) ppm.^{31}P{^{1}H}NMR (202 MHz, $CDCl_3$) δ; 90.1−87.9 (m, P−BH_3). HRMS (ESI-TOF) m/z $[C_4H_{12}N]^+$ Calcd for $C_4H_{12}N$ 74,0964; found 74.0965. HRMS (ESI-TOF) m/z $[C_5H_{15}OBP]^-$ Calcd for $C_5H_{15}OBP$ 133.0959; found 133.0959.

Diisopropylammonium (*R*)-*tert*-Butyl(methyl)phosphinite borane (6). Phosphinous acid **1** was placed in a vial (15 mg, 0.11 mmol) and solved in TBME (0.5 mL). Diisopropylamine (16 μL, 0.11 mmol) was added dropwise via a syringe. The resulting crystalline precipitate was filtered and dried under a stream of nitrogen. White solid. Yield: 81% (21 mg). M_P: 136.5−138.0 °C. $[\alpha]_D$: + 3.2 (c 0.56, $CHCl_3$). IR (KBr/NaCl) υ_{max}: 3439, 2923, 2860, 2388, and 2342 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ; 7.43 (br s, 1H), 3.27−3.16 (m, 2H), 1.29 (d, J = 6 Hz, 12H), 1.22 (d, J_P = 9 Hz, 3H), 1.09 (d, J_P = 13 Hz, 9H), 0.79−0.01 (m, 3H, BH_3) ppm. ^{13}C{^{1}H}NMR (101 MHz, $CDCl_3$) δ 46.6 (2 x CH), 30.9 (d, J_P = 43 Hz, C), 24.6 (3 x CH_3), 21.0 (d, J_P = 11 Hz, 4 x CH_3), 13.3 (d, J_P = 35 Hz, CH_3) ppm. ^{31}P{^{1}H}NMR (202 MHz, $CDCl_3$) δ; 92.4−90.2 (m, P−BH_3) ppm. HRMS (ESI-TOF) m/z $[C_6H_{16}N]^+$ Calcd for $C_6H_{16}N$ 102.1278; found 102.1277. HRMS (ESI-TOF) m/z $[C_5H_{15}OBP]^-$ Calcd for $C_5H_{15}OBP$ 133.0959; found 133.0959.

Dicyclohexylammonium (*R*)-*tert*-Butyl(methyl)phosphinite Borane (7). Phosphinous acid **1** was placed in a vial (15 mg, 0.11 mmol) and solved in TBME (0.5 mL). Dicyclohexylamine (22 μL, 0.11 mmol) was added dropwise via a syringe. The resulting crystalline precipitate was filtered and dried under a stream of nitrogen. White solid. Yield: 87% (32 mg). M_P: 143−144 °C. $[\alpha]_D$: + 8.8 (c 0.34, $CHCl_3$). IR (KBr/NaCl) υ_{max}: 3419, 2939, 2857, 2347, and 1619 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ; 7.57 (br s, 2H), 2.94−2.80 (m, 2H), 2.09−1.95 (m, 4H), 1.85−1.74 (m, 4H), 1.68−1.60 (m, 2H), 1.51−1.33 (m, 4H), 1.31−1.12 (m, 6H), 1.20 (d, J_P = 9 Hz, 3H), 1.08 (d, J_P = 13 Hz, 9H), 0.84−0.03 (m, 3H, BH_3) ppm. ^{13}C{^{1}H}NMR (101 MHz, $CDCl_3$) δ; 53.6 (2 x CH), 31.4−31.2 (4 x CH_2), 30.9 (d, J_P = 43 Hz, C), 25.3−24.9 (6 x CH_2), 24.6 (d, J_P = 3 Hz, 3 x CH_3), 13.4 (d, J_P = 36 Hz, CH_3) ppm. ^{31}P{^{1}H}NMR (202 MHz, $CDCl_3$) δ; 91.4−89.1 (m, P−BH_3) ppm. HRMS (ESI-TOF) m/z $[C_{12}H_{24}N]^+$ Calcd for $C_{12}H_{24}N$ 182.1905; found 182.1903. HRMS (ESI-TOF) m/z $[C_5H_{15}OBP]^-$ Calcd for $C_5H_{15}OBP$ 133.0959; found 133.0959.

General Procedure for the Substitution Reactions with 6. Methanesulfonic anhydride (1.0−1.2 equiv) was solved in CH_2Cl_2 under N_2 atmosphere and cooled to −20 °C. A solution of the phosphinous acid salt **6** in CH_2Cl_2 under N_2 atmosphere was slowly added dropwise. Anhydrous NEt_3 (2.0 equiv) was then added dropwise. The reaction was stirred for 1.5 h at −20 °C. The corresponding amine/reducing agent (0.5−3 equiv) was added and the solution was stirred overnight at −20 °C. NaOH (1 M) was added to quench the reaction and the mixture was allowed to warm to room temperature. The mixture was extracted with CH_2Cl_2. The organic layer was washed with NaOH (1M) and/or HCl (1M) when deemed useful to purify the crude product. The organic layer was dried with $MgSO_4$ and filtered, and the solvent was removed under reduced pressure. When required, the crude product was further purified by flash chromatography (SiO_2, hexanes:EtOAc).

(+)-(*S*)-*tert*-Butyl(methyl)phosphanamine Borane (2).[8a] Following the general procedure, 73 mg of methanesulfonic anhydride

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(0.41 mmol, 1.2 equiv), 80 mg of **6** (0.34 mmol, 1 equiv), 95 μL of NEt_3 (0.68 mmol, 2 equiv), and 5 mL of CH_2Cl_2 were used. NH_3 was bubbled through the solution for 5 min, then the flow was removed and the reaction stirred for 10 min. H_2O was added to quench the reaction. The mixture was extracted with CH_2Cl_2 to afford 46 mg (99%, 0.34 mmol) of a white wax, which was not further purified (*ee* 98%). ^1H NMR (400 MHz, $CDCl_3$) δ; 1.76 (s, 2H), 1.35 (d, J_P = 9 Hz, 3H), 1.14 (d, J_P = 14 Hz, 9H), 0.86−0.08 (m, 3H, BH_3) ppm. GC: β-DEX (30 m), 130 °C, 1 mL/min, t_R(+) = 14.5 min, t_R (−) = 14.9 min.

(−)-(*R*)-*tert*-Butyl(methyl)phosphine Borane (3).[13] Following the general procedure, 128 mg of methanesulfonic anhydride (0.71 mmol, 1.05 equiv), 160 mg of **6** (0.68 mmol, 1 equiv), 150 μL of *N*-methylmorpholine (1.36 mmol, 2 equiv), and 8 mL of CH_2Cl_2 were used. nBu_4NBH_4 (525 mg, 2.04 mmol, 3 equiv) in 2 mL of CH_2Cl_2 were added dropwise and the solution was stirred for 2 h at −20 °C. NaOH (1 M) was added to quench the reaction. The mixture was extracted with CH_2Cl_2. This afforded, after purification by flash chromatography (SiO_2, hexanes/EtOAc), 64 mg (80%, 0.54 mmol) of **3** as a white waxy solid (*ee* = 99%).[14] ^1H NMR (400 MHz, $CDCl_3$) δ; 4.40 (dm, J_P = 355 Hz, 1H), 1.31 (dd, *J* = 11, 6 Hz, 3H), 1.21 (d, J_P = 15 Hz, 9H), 0.48 (br q, J_B = 96 Hz, 3H, BH_3) ppm.

(+)-(*R*)-1-*tert*-Butyl-1-methyl-*N*-(pyridin-2-ylmethyl)-phosphinamine Borane (8).[6] Following the general procedure, 64 mg of methanesulfonic anhydride (0.36 mmol, 1.05 equiv), 80 mg of **6** (0.34 mmol, 1 equiv), 95 μL of NEt_3 (0.68 mmol, 2 equiv) and 4 mL of CH_2Cl_2 were used. 2-Picolylamine (105 μL, 1.02 mmol, 3 equiv) was added and the solution was stirred overnight at −20 °C. This afforded, 64 mg (84%, 0.29 mmol) of **8** as a white solid (*ee* = 99%) after purification by flash chromatography (SiO_2, hexanes/EtOAc). ^1H NMR (400 MHz, $CDCl_3$) δ; 8.56−8.44 (m, 1H), 7.66 (td, *J* = 8, 2 Hz, 1H), 7.30−7.27 (m, 1H), 7.21−7.15 (m, 1H), 4.42−4.30 (m, 1H), 4.30−4.19 (m, 1H), 2.80 (br s, 1H), 1.33 (d, J_P = 9 Hz, 3H), 1.14 (d, J_P = 14 Hz, 9H), 0.96−0.07 (m, 3H, BH_3) ppm. HPLC: CHIRALCEL OJ. Heptane:EtOH: 90:10−0.2% DEA, 0.50 mL/min, λ= 210 nm. t_R (−) = 12.9 min, t_R (+) = 13.6 min.

(−)-(*S*)-1-*tert*-Butyl-1-methyl-*N*-(2-thiophenylmethyl)-phosphinamine Borane (9).[6] Following the general procedure, 64 mg of methanesulfonic anhydride (0.36 mmol, 1.05 equiv), 80 mg of **6** (0.34 mmol, 1 equiv), 95 μL of NEt_3 (0.68 mmol, 2 equiv), and 4 mL of CH_2Cl_2 were used. 2-Thiophenemethylamine (105 μL, 1.02 mmol, 3 equiv) was added and the solution was stirred overnight at −20 °C. After purification by flash chromatography (SiO_2, hexanes/EtOAc), 66 mg (85%, 0.29 mmol) of **9** as a white solid was obtained (*ee* = 99%). ^1H NMR (400 MHz, $CDCl_3$) δ; 7.23−7.20 (m, 1H), 6.96−6.93 (m, 2H), 4.47−4.37 (m, 1H), 4.37−4.23 (m, 1H), 1.86 (br s, 1H), 1.36 (d, J_P = 9 Hz, 3H), 1.15 (d, J_P = 14 Hz, 9H), 0.95−0.13 (m, 3H, BH_3) ppm. HPLC: CHIRALCEL OJ. Heptane:EtOH: 80:20−0.2% DEA, 0.50 mL/min, λ= 210 nm. t_R (−) = 14.7 min, t_R (+) = 15.9 min.

(+)-(*S*)-1-*tert*-Butyl-1-methyl-*N*-((*R*)-1-phenylethyl)-phosphanamine Borane (10).[6] Following the general procedure, 64 mg of methanesulfonic anhydride (0.36 mmol, 1.05 equiv), 80 mg of **6** (0.34 mmol, 1 equiv), 95 μL of NEt_3 (0.68 mmol, 2 equiv), and 4 mL of CH_2Cl_2 were used. (*R*)-(1)-Phenylethylamine (132 μL, 1.02 mmol, 3 equiv) was added and the solution was stirred overnight at −20 °C. After purification by flash chromatography (SiO_2, hexanes/EtOAc), 66 mg (83%, 0.28 mmol) of **10** as a white solid was obtained (*de* 98%, as determined by ^1H NMR). ^1H NMR (400 MHz, $CDCl_3$) δ; 7.37−7.20 (m, 5H), 4.50−4.41 (m, 1H), 1.81 (br d, *J* = 9 Hz, 1H)), 1.46 (d, *J* = 7 Hz. 3H), 1.24 (d, J_P = 9 Hz, 3H), 1.07 (d, J_P = 14 Hz, 9H), 0.96−0.12 (m, 3H, BH_3) ppm.

(−)-(*S*)-1-*tert*-Butyl-1-methyl-*N*-((*S*)-1-phenylethyl)-phosphanamine Borane (11).[6] Following the general procedure, 64 mg of methanesulfonic anhydride (0.36 mmol, 1.05 equiv), 80 mg of **6** (0.34 mmol, 1 equiv), 95 μL of NEt_3 (0.68 mmol, 2 equiv), and 4 mL of CH_2Cl_2 were used. (*S*)-(1)-Phenylethylamine (132 μL, 1.02 mmol, 3 equiv) was added and the solution was stirred overnight at −20 °C. The workup afforded 70 mg (88%, 0.30 mmol) of **11** as a white solid which was not further purified (*de* 98%, as determined by ^1H NMR). ^1H NMR (400 MHz, $CDCl_3$) δ; 7.48−7.14 (m, 5H), 4.53−4.48 (m, 1H), 1.74 (br d, *J* = 9 Hz, 1H)), 1.44 (d, *J* = 7 Hz. 3H), 1.20 (d, J_P = 9 Hz, 3H), 1.11 (d, J_P = 14 Hz, 9H), 0.96−0.11 (m, 3H, BH_3) ppm.

(*S*)-2-(((*S*)-*tert*-Butyl(methyl)phosphanyl)amino)-*N*-((*S*)-1-hydroxy-3-methylbutan-2-yl)-3-methylbutanamide Borane (12).[7a] Following the general procedure, 73 mg of methanesulfonic anhydride (0.41 mmol, 1.2 equiv), 80 mg of **6** (0.34 mmol, 1 equiv), 95 μL of NEt_3 (0.68 mmol, 2 equiv) and 4 mL of CH_2Cl_2 were used. (*S*)-2-Amino-N-((*S*)-1-hydroxy-3-methylbutan-2-yl)-3-methylbutanamide (206 mg, 1.02 mmol, 3 equiv) was added and the solution was stirred overnight at −20 °C. Workup and purification by flash chromatography (SiO_2, hexanes/EtOAc) afforded 96 mg (93%, 0.32 mmol) of **12** as a white solid. (*de* > 95%, as determined by ^1H NMR). ^1H NMR (400 MHz, $CDCl_3$) δ; 6.13 (br s, 1H), 3.77−3.64 (m, 3H), 3.49 (ddd, *J* = 11, 9, 7 Hz, 1H), 2.21 (dd, *J* = 11, 5 Hz, 1H), 2.01−1.84 (m, 2H), 1.27 (d, J_P = 9 Hz, 3H), 1.15 (d, J_P = 14 Hz, 9H), 1.01−0.95 (m, 12H), 0.81−0.06 (m, 3H, BH_3) ppm.

(*S,S*)-N^1,N^2-Bis(*tert*-butyl(methyl)phosphanyl)ethane-1,2-diamine Bisborane (13). Following the general procedure, 128 mg of methanesulfonic anhydride (0.71 mmol, 1.05 equiv), 160 mg of **6** (0.68 mmol, 1 equiv), 189 μL of NEt_3 (1.36 mmol, 2 equiv) and 10 mL of CH_2Cl_2 were used. Ethylenediamine (18 μL, 0.27 mmol, 0.4 equiv) were added and the solution was stirred overnight at −20 °C. This afforded, after purification by flash chromatography (SiO_2, hexanes/EtOAc), 52 mg (66%, 0.18 mmol) of **13** as a white solid. (*de* > 95%, as determined by ^1H NMR). Mp: 123.5−124.5 °C. $[\alpha]_D$: + 6.7 (c 0.23, $CHCl_3$). IR (KBr/NaCl) υ_{max}: 3335, 2970, 2390, 2345, and 1467 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ; 3.16−2.97 (m, 4H), 1.68 (br s, 2H), 1.33 (d, *J* = 9 Hz, 6H), 1.12 (d, *J* = 14 Hz, 18H), 0.86−0.05 (m, 6H, 2 x BH_3) ppm. $^{13}C\{^1H\}$NMR (101 MHz, $CDCl_3$) δ; 45.3 (d, *J* = 5 Hz, 2 x CH_2), 31.2 (d, *J* = 39 Hz, 2 x C), 24.7 (d, *J* = 3 Hz, 6 x CH_3), 9.6 (d, *J* = 40 Hz, 2 x CH_3) ppm. $^{31}P\{^1H\}$NMR (202 MHz, $CDCl_3$) δ; 72.3−70.0 (m, 2 x P−BH_3) ppm. HRMS (ESI-TOF) *m*/*z* $[C_{12}H_{36}B_2N_2P_2 + H]^+$ Calcd for $C_{12}H_{37}B_2N_2P_2$ 293.2609; found 293.2613.

(1*R*,2*R*)-N^1,N^2-Bis((*S*)-*tert*-butyl(methyl)phosphanyl)-cyclohexane-1,2-diamine Bisborane (14). Following the general procedure, 99 mg of methanesulfonic anhydride (0.55 mmol, 1 equiv), 130 mg of **6** (0.55 mmol, 1 equiv), 154 μL of NEt_3 (1.11 mmol, 2 equiv), and 6 mL of CH_2Cl_2 were used. (1*R*,2*R*)-Cyclohexane-1,2-diamine (28 mg, 0.25 mmol, 0.45 equiv) were added dissolved in 3 mL of CH_2Cl_2 and the solution was stirred overnight at −20 °C. This afforded 78 mg (91%, 0.23 mmol) of a very pure solid crude. After further purification by column chromatography (SiO_2, hexanes/EtOAc), 66 mg (77%, 0.19 mmol) of **14** was obtained as a white solid. (*de* > 95%, as determined by ^1H NMR). M_P: 216.5−217.5 °C. $[\alpha]_D$: − 3.9 (c 0.39, $CHCl_3$). IR (KBr/NaCl) υ_{max}: 3305, 2926, 2362, 2339, and 1096 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ; 2.91 (br s, 2H), 2.12 (br d, *J* = 13 Hz, 2H), 1.68−1.52 (m, 4H), 1.36−1.13 (m, 4H), 1.33 (d, *J* = 9 Hz, 6H), 1.16 (d, *J* = 14 Hz, 18H), 0.84−0.03 (m, 6H, 2 x BH_3) ppm. $^{13}C\{^1H\}$NMR (101 MHz, $CDCl_3$) δ; 57.8 (d, *J* = 7 Hz, 2 x CH), 36.1 (CH_2), 30.1 (d, *J* = 44 Hz, C), 24.7 (d, *J* = 3 Hz, 6 x CH_3), 24.4 (4 x CH_2), 11.8 (d, *J* = 32 Hz, 2 x CH_3) ppm. $^{31}P\{^1H\}$NMR (202 MHz, $CDCl_3$) δ; 70.8−69.0 (m, 2 x P−BH_3) ppm. HRMS (ESI-TOF) *m*/*z* $[C_{16}H_{42}B_2N_2P_2 + Na]^+$ Calcd for $C_{16}H_{42}B_2N_2P_2Na$ 369.2907; found 369.2902.

***N*^{1}-((*S*)-*tert*-Butyl(methyl)phosphanyl)-*N*^{2}-(2-(((*S*)-*tert*-butyl-(methyl)phosphanyl) amino) ethyl)ethane-1,2-diamine Bisborane (15).** Following the general procedure, 128 mg of Ms_2O (0.71 mmol, 1 equiv), 168 mg of **6** (0.71 mmol, 1 equiv), 199 μL of NEt_3 (1.42 mmol, 2 equiv), and 10 mL of CH_2Cl_2 were used. Diethylenetriamine (35 μL, 0.32 mmol, 0.45 equiv) was added and the solution was stirred overnight at −20 °C. This afforded, after purification by column chromatography (SiO_2, hexanes/EtOAc), 92 mg (84%) of **15** as a yellow wax. (*de* > 95%, as determined by ^1H NMR). $[\alpha]_D$: + 11.4 (c 0.54, $CHCl_3$). IR (KBr) υ_{max}: 3353, 2928, 2866, 2364, and 2337 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ; 3.15−3.05 (m, 2H), 3.05−2.96 (m, 2H), 2.71−2.66 (m, 4H), 2.03 (br t, *J* = 6 Hz, 2H), 1.95 (br s, 1H), 1.30 (d, *J* = 9 Hz, 6H), 1.11 (d, *J* = 14 Hz, 18H), 0.86−0.03 (m, 6H, 2 x BH_3) ppm. $^{13}C\{^1H\}$NMR (101 MHz, $CDCl_3$) δ; 50.8 (d, *J* = 5 Hz, 4 x CH_2), 42.8 (4 x CH_2), 31.2 (d, *J* = 39

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Hz, C), 24.8 (d, J = 3 Hz, 6 x CH_3), 9.28 (d, J = 39 Hz, 2 x CH_3) ppm. $^{31}P\{^1H\}$NMR (202 MHz, $CDCl_3$) δ; 70.7−68.9 (m, 2 x P−BH_3) ppm. HRMS (ESI-TOF) m/z $[C_{14}H_{41}B_2N_3P_2 + H]^+$ Calcd for $C_{14}H_{42}B_2N_3P_2$ 336.3034; found 336.3035.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.7b01180.

Crystallographic data for **6** (CIF)

Potentiometric titration data for **1**, Ortep diagram of **6** (CCDC 1547434), and NMR spectra for new compounds. (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

*E-mail: antoni.riera@irbbarcelona.org

*E-mail: xavier.verdaguer@irbbarcelona.org

ORCID

Antoni Riera: 0000-0001-7142-7675

Xavier Verdaguer: 0000-0002-9229-969X

Notes

The authors declare no competing financial interest.

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