Air-Stable Trialkylphosphonium Salts: Simple, Practical, and Versatile Replacements for Air-Sensitive Trialkylphosphines. Applications in Stoichiometric and Catalytic Processes

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Supporting Information

General. CH_2Cl_2 and THF were purified by passing them through a neutral alumina column under argon. DMF (anhydrous, Sure-Seal; Aldrich), 1,4-dioxane (anhydrous, Sure-Seal; Aldrich), and NMP (anhydrous; Aldrich) were used as received. P(*n*-Bu)$_3$ (Sigma), P(*t*-Bu)$_3$ (Alfa-Aesar), HBF_4 (48 wt% aqueous; Aldrich), diphenyl disulfide (Aldrich), TsCl (Fluka), PhOH (Aldrich), PhONa (anhydrous; Gelest), 2-octanol (Aldrich), Bz_2O (98+%; Avocado), NaOBz (Aldrich), $Pd_2(dba)_3$ (Strem), KF (spray-dried; Aldrich), 4-bromo-*N*,*N*-dimethylaniline (Aldrich), CsF (Strem), $Pd(PhCN)_2Cl_2$ (Strem), CuI (99.999%; Aldrich), and HN(*i*-Pr)$_2$ (anhydrous, Sure-Seal; Aldrich) were used as received. 2-Cyclopenten-1-one (Aldrich), 4-chloroacetophenone (Aldrich), hydrocinnamaldehyde (Acros), 2-bromo-*m*-xylene (Aldrich), Cy_2NMe (Aldrich), 4-chloroanisole (Aldrich), 2-bromotoluene (Aldrich), 2-chloro-*m*-xylene (Aldrich), styrene (Aldrich), Bu_3SnPh (Gelest), (1-ethoxyvinyl)tributylstannane (Aldrich), and 4-bromoanisole (Aldrich) were sparged with argon before use. (*i*-Pr)$_2$NEt (Aldrich), Ac_2O (Alfa-Aesar), 1-chlorocyclopentene (Aldrich), methyl methacrylate (Aldrich), and phenylacetylene (Aldrich) were distilled prior to use and stored under an inert atmosphere. 4-Iodoanisole (Aldrich) was recrystallized from hexanes. All boronic acids [4-methoxyphenylboronic acid (Aldrich), 2-tolylboronic acid (Frontier Scientific), and 4-tolylboronic acid (Frontier

Scientific)] were recrystallized from water prior to use.[1] *n*-Octyl azide was prepared according to a literature procedure.[2]

Elemental analyses were performed by Atlantic Microlabs, Inc. (Norcross, GA).

Preparation of [(*n*-Bu)$_3$PH]BF$_4$ [113978-91-9]. HBF_4 (48 wt% aqueous solution; 4.0 mL, 31 mmol) was added to a solution of P(*n*-Bu)$_3$ (5.0 mL, 20 mmol) in CH_2Cl_2 (50 mL), and the resulting mixture was stirred vigorously for 5 min. The organic layer was then separated from the aqueous layer, dried over $MgSO_4$, and filtered. Removal of the solvent provided the title compound (5.8 g, 98%) as an analytically pure colorless solid.

^{1}H NMR ($CDCl_3$, 500 MHz): δ 6.07 (dm, $^1J_{PH}$ = 484 Hz, 1H), 2.30-2.23 (m, 6H), 1.64-1.56 (m, 6H), 1.50 (sextet, *J* = 7.3 Hz, 6H), 0.96 (t, *J* = 7.0 Hz, 9H). ^{13}C NMR ($CDCl_3$, 125 MHz): δ 24.9 (d, $^3J_{PC}$ = 4.6 Hz), 23.9 (d, $^2J_{PC}$ = 15.0 Hz), 16.5 (d, $^1J_{PC}$ = 47.2 Hz), 13.5. ^{31}P{^{1}H} NMR ($CDCl_3$, 202 MHz): δ 14.1. IR (KBr) 2960, 2932, 2874, 1464, 1084 (br) cm^{-1}. Anal. Calcd for $C_{12}H_{28}BF_4P$: C, 49.68; H, 9.73. Found: C, 49.76; H, 9.83. mp 51-52 °C.

Preparation of [(*t*-Bu)$_3$PH]BF$_4$ [131274-22-1]. HBF_4 (48 wt% aqueous solution; 1.0 mL, 7.6 mmol) was added to a solution of P(*t*-Bu)$_3$ (225 mg, 1.11 mmol) in CH_2Cl_2 (15 mL), and the resulting mixture was stirred vigorously for 5 min. The organic layer was then separated from the aqueous layer, dried over $MgSO_4$, and filtered. Removal of the solvent provided the title compound (302 mg, 94%) as an analytically pure white powder.

^{1}H NMR ($CDCl_3$, 400 MHz): δ 6.07 (d, $^1J_{PH}$ = 465 Hz, 1H), 1.65 (d, $^3J_{PH}$ = 15.3 Hz, 27H). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 37.0 (d, $^1J_{PC}$ = 29 Hz), 30.1. ^{31}P{^{1}H} NMR ($CDCl_3$, 121 MHz): δ 51.7. IR (KBr) 3002, 2217, 1478, 1405. 1381, 1181, 1059, 886 (br) cm^{-1}. Anal. Calcd for $C_{12}H_{28}BF_4P$: C, 49.68; H, 9.73. Found: C, 49.58; H, 9.86. mp 261 °C (dec.).

Because the yields reported in the text represent the average of two runs, the yields reported below for a specific reaction may differ from those values. Both runs of reactions that involve [(*n*-Bu)$_3$PH]BF$_4$ were conducted without the use of a glove

box. Reactions that involve $[(t\text{-Bu})_3PH]BF_4$ were conducted once without the use of a glove box and once with the use of a glove box.

***S*-Phenyl thioacetate (eq 1) [934-87-2].**[3] DMF (20 mL), and then a solution of $[(n\text{-Bu})_3PH]BF_4$ (2.0 g, 6.8 mmol) in DMF (5 mL), was added to a round-bottomed flask under argon that had been charged with diphenyl disulfide (1.0 g, 4.6 mmol). $(i\text{-Pr})_2NEt$ (1.2 mL, 6.8 mmol) and water (84 μL, 4.7 mmol) were added, and the reaction mixture was stirred at r.t. for 1 h. Acetic anhydride (1.3 mL, 4.7 mmol) was then introduced, and stirring was continued for 1 h. The reaction mixture was then taken up in EtOAc (50 mL), washed with 1 M HCl (3 × 30 mL) and brine (50 mL), dried with $MgSO_4$, concentrated, and purified by column chromatography (2% EtOAc in hexanes), which afforded the title compound as a colorless liquid (1.29 g, 92%).

***N*-Octyl-4-toluenesulfonamide (eq 2) [1150-31-8].**[4] *n*-Octyl azide (500 mg, 3.22 mmol) and $[(n\text{-Bu})_3PH]BF_4$ (981 mg, 3.38 mmol) were weighed in air into a round-bottomed flask. The flask was sealed with a septum and purged with argon. THF (20 mL) and $(i\text{-Pr})_2NEt$ (1.6 mL, 9.2 mmol) were added, and the reaction mixture was stirred at r.t. for 2 h, during which time evolution of a gas (N_2) was observed. Water (178 μL, 9.90 mmol) was introduced, and the reaction mixture was stirred for 3 h. 4-Toluenesulfonyl chloride (921 mg, 4.83 mmol) in THF (3 mL) was then added, and stirring was continued for 2 h. Saturated aq $NaHCO_3$ (5 mL) was introduced, and the reaction mixture was stirred for 1 h. Then, it was extracted with Et_2O (2 × 100 mL), and the combined organic extracts were washed with brine (50 mL), dried ($MgSO_4$), and concentrated. Column chromatography (Et_2O / hexanes 1:1) provided the title compound as a pale-yellow solid (723 mg, 79%).

2-(1-Hydroxy-3-phenylpropyl)-2-cyclopenten-1-one (eq 3) [273219-46-8]. Sodium phenoxide (23 mg, 0.20 mmol) and $[(n\text{-Bu})_3PH]BF_4$ (58 mg, 0.20 mmol) were weighed in air and transferred to a round-bottomed flask. The flask was fitted with a septum

and purged with argon for 15 min. THF (1 mL), 2-cyclopenten-1-one (84 μL, 1.0 mmol), and hydrocinnamaldehyde (198 μL, 1.50 mmol) were added, and the reaction mixture was stirred at r.t. for 1 h, during which time a white precipitate ($NaBF_4$) appeared. Hexane (1 mL) was added, and the product was purified by column chromatography (Et_2O / hexanes 1:1), which furnished the title compound as a colorless liquid (205 mg, 95%).

^1H NMR ($CDCl_3$, 500 MHz): δ 7.45-7.43 (m, 1H), 7.30-7.27 (m, 2H), 7.22-7.17 (m, 3H), 4.80 (t, J = 6.1 Hz, 1H), 3.30 (br s, 1H), 2.86-2.80 (m, 1H), 2.74-2.68 (m, 1H), 2.61-2.58 (m, 2H), 2.44-2.42 (m, 2H), 2.03-1.99 (m, 2H). ^{13}C NMR ($CDCl_3$, 125 MHz): δ 210.3, 158.3, 147.7, 141.8, 128.7, 128.6, 126.0, 67.3, 37.3, 35.4, 31.8, 26.8.

2-Octyl benzoate (eq 4) [34881-29-3].[5] Finely ground sodium benzoate (22 mg, 0.15 mmol) and [(*n*-Bu)$_3$PH]BF_4 (44 mg, 0.15 mmol) were weighed in air and transferred to a round-bottomed flask. The flask was fitted with a septum and purged with argon for 15 min. CH_2Cl_2 (5 mL), 2-octanol (239 μL, 1.50 mmol), and a solution of benzoic anhydride (679 mg, 3.00 mmol) in CH_2Cl_2 (3 mL) were then added. The reaction mixture was stirred at r.t. for 3 h, during which time a fine white precipitate ($NaBF_4$) was observed. The mixture was quenched with water (5 mL) and stirred for 15 min. The organic layer was separated, washed successively with 10% HCl (10 mL) and a saturated solution of $NaHCO_3$ (10 mL), dried ($MgSO_4$), and concentrated. The product was purified by column chromatography (4% EtOAc in hexanes), which afforded the title compound as a colorless liquid (346 mg, 98%).

The above procedure was also followed using (*i*-Pr)$_2$NEt (27 μL, 0.15 mmol) in place of sodium benzoate. Yield: 347 mg (98%).

Table 1 (Suzuki cross-coupling): Procedure A. $Pd_2(dba)_3$, the boronic acid, [(*t*-Bu)$_3$PH]BF_4, and then KF were weighed in air and transferred to a Schlenk tube,[6] which was evacuated and then refilled with argon (five cycles). The solvent and the aryl / vinyl halide (in the case of 4-iodoanisole, which is a solid, the halide was added

with the other solid reagents) were added, and the Schlenk tube was closed and stirred at the indicated temperature for the indicated amount of time. At the conclusion of the reaction, the mixture was diluted with Et_2O, filtered through a plug of silica gel with copious washings (Et_2O), and purified by column chromatography.

4-Acetyl-4'-methoxybiphenyl (Table 1, entry 1) [13021-18-6].[7,8] Procedure A was followed: $Pd_2(dba)_3$ (4.4 mg, 0.0048 mmol), [(*t*-Bu)$_3$PH]BF_4 (2.9 mg, 0.0010 mmol), 4-methoxyphenylboronic acid (158 mg, 1.04 mmol), KF (184 mg, 3.16 mmol), THF (1.8 mL), and 4-chloroacteophenone (123 µL, 0.950 mmol). After 21 h at r.t., workup and column chromatography (CH_2Cl_2 / hexanes 3:2) yielded the title compound as an off-white solid (188 mg, 87%).

1-(4-Tolyl)cyclopentene (Table 1, entry 2) [827-56-5].[7,9] Procedure A was followed: $Pd_2(dba)_3$ (12 mg, 0.013 mmol), [(*t*-Bu)$_3$PH]BF_4 (9.3 mg, 0.0032 mmol), 4-tolylboronic acid (138 mg, 1.02 mmol), KF (174 mg, 3.00 mmol), THF (1.8 mL), and 1-chlorocyclopentene (88 µL, 0.89 mmol). After stirring at r.t. for 1 h, followed by heating at 50 °C for 52 h, workup and column chromatography (hexanes) yielded the title compound as a white solid (114 mg, 81%).

2,2',6-Trimethylbiphenyl (Table 1, entry 3) [10273-87-7].[7] Procedure A was followed: $Pd_2(dba)_3$ (4.6 mg, 0.0050 mmol), [(*t*-Bu)$_3$PH]BF_4 (3.5 mg, 0.0012 mmol), 2-tolylboronic acid (150 mg, 1.10 mmol), KF (192 mg, 3.30 mmol), THF (2.0 mL), and 2-bromo-*m* -xylene (133 µL, 1.00 mmol). After 2 h at r.t., workup and column chromatography (hexanes) yielded the title compound as a colorless liquid (177 mg, 90%).

4'-Methoxy-2-methylbiphenyl (Table 1, entry 4) [92495-54-0].[7,8] Procedure A was followed: $Pd_2(dba)_3$ (4.6 mg, 0.0050 mmol), [(*t*-Bu)$_3$PH]BF_4 (3.5 mg, 0.0012 mmol), 2-tolylboronic acid (150 mg, 1.10 mmol), KF (192 mg, 3.30 mmol), THF (2.0 mL), and 4-iodoanisole (234 mg, 1.00 mmol). After 4.5 h at r.t., workup and column

chromatography (5% Et_2O in hexanes) yielded the title compound as a purple liquid (195 mg, 98%).

Table 2 (Heck reaction): Procedure B. $Pd_2(dba)_3$ and $[(t\text{-}Bu)_3PH]BF_4$ were weighed in air and transferred to a Schlenk tube, which was evacuated and then refilled with argon (five cycles). The dioxane, aryl halide, olefin, and Cy_2NMe were added, and the Schlenk tube was closed and stirred at the indicated temperature for the indicated amount of time. At the conclusion of the reaction, the mixture was diluted with Et_2O, filtered through a plug of silica gel with copious washings (Et_2O), and purified by column chromatography.

(*E*)-4-Acetylstilbene (Table 2, entry 1) [20488-42-0].[10,11] Procedure B was followed: $Pd_2(dba)_3$ (14 mg, 0.015 mmol), $[(t\text{-}Bu)_3PH]BF_4$ (8.7 mg, 0.030 mmol), dioxane (0.9 mL), 4-chloroacetophenone (130 µL, 1.00 mmol), styrene (126 µL, 1.10 mmol), and Cy_2NMe (236 µL, 1.10 mmol). After 94 h at r.t., workup and column chromatography (15% Et_2O in hexanes) provided the title compound as an off-white solid (177 mg, 80%).

(*E*)-Methyl 3-(2,6-dimethylphenyl)-2-methylacrylate (Table 2, entry 2) [124317-09-5].[10] Procedure B was followed: $Pd_2(dba)_3$ (12 mg, 0.013 mmol), $[(t\text{-}Bu)_3PH]BF_4$ (16 mg, 0.054 mmol), dioxane (0.9 mL), 2-chloro-*m*-xylene (120 µL, 0.905 mmol), methyl methacrylate (110 µL, 1.03 mmol), and Cy_2NMe (210 µL, 0.980 mmol). After stirring at r.t. for 1 h, then heating at 120 °C for 42 h, workup and column chromatography (5% Et_2O in hexanes) provided the title compound as a colorless liquid (175 mg, 87%).

(*E*)-Methyl 3-(4-dimethylaminophenyl)-2-methylacrylate (Table 2, entry 3) [50704-04-6].[10] Procedure B was followed: $Pd_2(dba)_3$ (4.4 mg, 0.0048 mmol), $[(t\text{-}Bu)_3PH]BF_4$ (2.8 mg, 0.0098 mmol), 4-bromo-*N*,*N*-dimethylaniline (191 mg, 0.956 mmol), dioxane (0.9 mL), methyl methacrylate (205 µL, 1.92 mmol), and Cy_2NMe (230 µL, 1.07 mmol). After 24 h at r.t., workup and column chromatography (20% Et_2O in

hexanes) provided the title compound as a yellow solid (196 mg, 93%).

Table 3 (Stille cross-coupling): Procedure C. $Pd_2(dba)_3$, $[(t\text{-}Bu)_3PH]BF_4$, and then CsF were weighed in air and transferred to a Schlenk tube,[6] which was evacuated and then refilled with argon (five cycles). The solvent (dioxane for aryl chlorides; NMP for aryl bromides), the aryl halide, and the organostannane were added, and the Schlenk tube was closed and stirred at the indicated temperature for the indicated amount of time. At the conclusion of the reaction, the mixture was diluted with Et_2O (aryl chlorides) or EtOAc (aryl bromides), filtered through a plug of silica gel with copious washings, and purified by column chromatography [for the coupling of aryl bromides, for which NMP is used as the solvent, an initial column chromatography (pentane / Et_2O 2:1) is performed in order to remove the NMP].

4-Methoxybiphenyl (Table 3, entry 1) [613-37-6].[12] Procedure C was followed: $Pd_2(dba)_3$ (14 mg, 0.015 mmol), $[(t\text{-}Bu)_3PH]BF_4$ (17 mg, 0.060 mmol), CsF (334 mg, 2.20 mmol), dioxane (1.0 mL), 4-chloroanisole (123 µL, 1.00 mmol), and phenyltributylstannane (343 µL, 1.05 mmol). After stirring at r.t. for 1 h, then heating at 100 °C for 52 h, workup and column chromatography (EtOAc / hexanes 1:30) afforded the title compound as a white solid (163 mg, 88%; identical to authentic material (Aldrich) by GC and ^1H NMR).

1-(1-Ethoxyvinyl)-4-acetylbenzene (Table 3, entry 2).[12] Procedure C was followed: $Pd_2(dba)_3$ (13 mg, 0.043 mmol), $[(t\text{-}Bu)_3PH]BF_4$ (7.9 mg, 0.027 mmol), CsF (309 mg, 2.04 mmol), dioxane (0.95 mL), 4-chloroacetophenone (120 µL, 0.925 mmol), and (1-ethoxyvinyl)tributylstannane (330 µL, 0.977 mmol). After stirring for 6 days at r.t., workup (the silica gel was first deactivated by flushing with NEt_3 and then Et_2O) and column chromatography (7% NEt_3 in hexanes) afforded the title compound as a colorless liquid (161 mg, 91%).

^1H NMR (300 MHz, C_6D_6): δ 7.79 (d, J = 8.7 Hz, 2H), 7.66 (d, J = 8.7 Hz, 2H), 4.68 (d, J = 2.7 Hz, 1H), 4.11 (d, J = 2.7 Hz, 1H), 3.51 (q, J = 6.9 Hz, 2H), 2.08 (s, 3H), 1.11 (t, J = 6.9

Hz, 3H). ^{13}C NMR (C_6D_6, 75 MHz): δ 196.4, 159.6, 141.3, 137.7, 128.8, 126.0, 84.5, 63.8, 26.5, 14.8. IR (thin film): 2981, 2931, 2883, 1684, 1607, 1404, 1359, 1311, 1267, 1128, 1056, 974, 846, 808, 591 cm^{-1}. HRMS (EI) calcd. for $C_{12}H_{14}O_2$: 190.0988. Found: 190.0981.

2-Methylbiphenyl (Table 3, entry 3) [643-58-3].[12] Procedure C was followed: $Pd_2(dba)_3$ (14 mg, 0.015 mmol), [(*t*-Bu)$_3$PH]BF_4 (9.6 mg, 0.033 mmol), CsF (320 mg, 2.10 mmol), NMP (1.0 mL), 2-bromotoluene (120 µL, 1.00 mmol), and phenyltributylstannane (343 µL, 1.05 mmol). After stirring for 3.5 h at r.t., workup and column chromatography (hexanes) afforded the title compound as a colorless liquid (143 mg, 85%; identical to authentic material (Aldrich) by GC and ^{1}H NMR).

(4-Methoxyphenyl)phenylacetylene (eq 5) [7380-78-1].[13,14] $Pd(PhCN)_2Cl_2$ (12 mg, 0.030 mmol), CuI (3.9 mg, 0.020 mmol), and [(*t*-Bu)$_3$PH]BF_4 (19 mg, 0.065 mmol) were weighed in air and transferred to a Schlenk tube, which was evacuated and then refilled with argon (five cycles). Dioxane (1.0 mL), HN(*i*-Pr)$_2$ (166 mL, 1.20 mmol), 4-bromoanisole (127 mL, 1.00 mmol), and phenylacetylene (131 mL, 1.20 mmol) were added, and the Schlenk tube was closed and stirred at r.t. for 2 h. Then, the reaction mixture was diluted with EtOAc (5 mL), filtered through a plug of silica gel with copious washings (EtOAc), and purified by column chromatography (1% Et_2O in hexanes), which furnished the title compound as a brown solid (201 mg, 96%).

References

(1) If the boronic acid was not recrystallized, low conversion was sometimes observed.

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