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# Synthesis and Characterization of $R_2PN{=}P(^iBuNCH_2CH_2)_3N$: A New Bulky Electron-Rich Phosphine for Efficient Pd-Assisted Suzuki−Miyaura Cross-Coupling Reactions

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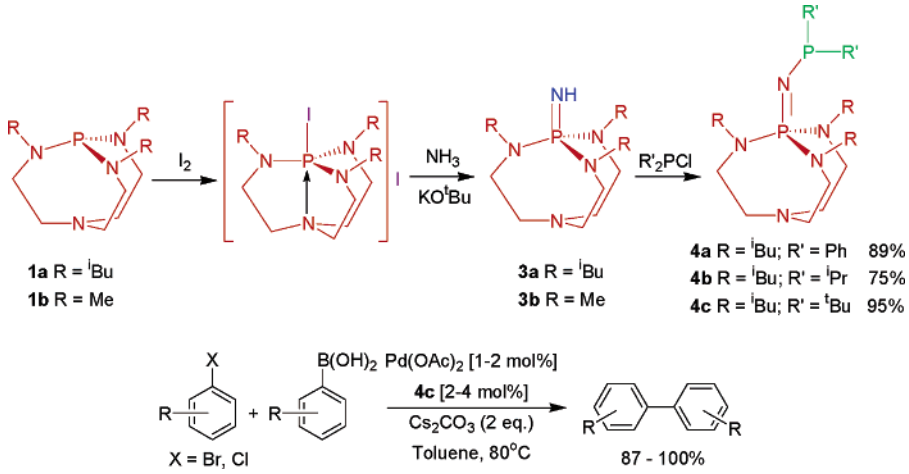


Pro-azaphosphatrane **1a** [$P(^iBuNCH_2CH_2)_3N$] reacts with iodine under mild conditions to give [$IP(^iBuNCH_2CH_2)_3N$]I in excellent yield, which on subsequent reaction with ammonia followed by deprotonation with $KO^tBu$ provided $HN{=}P(^iBuNCH_2CH_2)_3N$ (**3a**) in quantitative yield. Reaction of **3a** with $R'_2PCl$ afforded sterically bulky electron-rich phosphines of the type $R'_2PN{=}P(^iBuNCH_2CH_2)_3N$ (**4**) [R′ = Ph (**4a**), $^i$Pr (**4b**), $^t$Bu (**4c**)]. The $Pd(OAc)_2$/**4c** catalyst system was particularly efficient for the coupling of arylboronic acids with aryl bromides as well as aryl chlorides to give biaryls in excellent yields.

## Introduction

Impressive advances have been made in palladium-catalyzed cross-coupling reactions during the last 20 years, including their use on an industrial scale.[1] Among such transformations, the Suzuki−Miyaura reaction,[2,3] has emerged as a practical approach to synthesizing biaryls; moieties that are found in a wide variety of natural products,[4] chiral reagents,[5] chiral phases for chromatography,[6] chiral liquid crystals,[7] and pharmaceutical drugs.[8,9] An added advantage of the Suzuki−Miyaura reaction is that the organoboron reagents used are fairly insensitive to water and oxygen, generally stable thermally, and tolerant toward a

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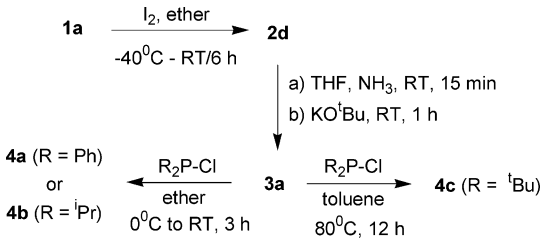
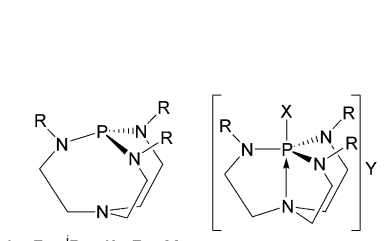
variety of functional groups. In addition, both the boron-containing reagents and byproducts of the Suzuki−Miyaura reaction display low toxicity.[10]

For achieving high efficiency in cross-coupling reactions, past studies have focused mainly on the development of new ligands, particularly phosphorus-containing ligands that can couple aryl chlorides as well as bromides. Even though ligandless catalyst systems are known,[11] an ancillary ligand greatly enhances catalytic performance.[12] The long list of very efficient ligands developed for Pd-catalyzed cross-coupling reactions includes bulky electron-rich phosphines such as aryldialkylphosphines[13] and P(t-Bu)$_3$.[14] There are also reports of efficient catalyst systems containing non-phosphine ligands, such as *N*-heterocyclic carbenes[15] among other ligands[16] for the synthesis of biaryls.

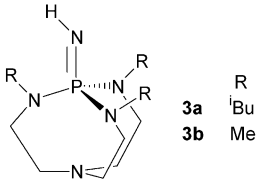
Pro-azaphosphatranes of type **1** developed in our laboratories are very useful as organo-catalysts and promoters, and as efficient ligands for a variety of metal-catalyzed organic transformations, including Suzuki−Miyaura cross-coupling reactions.[17,18] Herein we report the synthesis and structural characterization of a new generation of bulky electron-rich phosphines of type **4**, where in the pro-azaphosphatrane unit is one of the three bulky electron-rich substituents. Recently, we showed that the phosphorus in pro-azaphosphatranes derives enhanced electron richness via two unusual processes.[19] One derives from the planarity of all three equatorial P−N nitrogens, which allows lone pair density from these atoms in their unhybridized 2p orbital lying tangential to the molecular axis to be donated to the phosphorus; a structural feature that is present in only two of the nitrogens in acyclic analogs such as P(NMe$_2$)$_3$. The second process is a lone pair donation from the planar basal nitrogen to the phosphorus in the event of transannulation during a catalytic transformation, leading to the formation of structures modeled by **2a** and **2b**. We also report herein the efficacy of **4c** as a ligand for Pd-assisted Suzuki−Miyaura cross-coupling reactions of aryl bromides and chlorides.

**SCHEME 1**

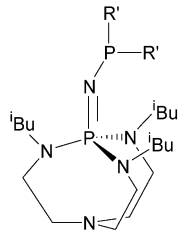



| | X | Y | R |
|---|---|---|---|
| **2a** | H | Cl | $^i$Bu |
| **2b** | H | Cl | Me |
| **2c** | Br | Br | $^i$Bu |
| **2d** | I | I | $^i$Bu |
| **2e** | Br | Br | Me |
| **2f** | Cl | Cl | Me |
| **2g** | CN | Br | $^i$Bu |
| **2h** | NC | Br | $^i$Bu |
| **2i** | $NH_2$ | Br | Me |



| | R |
|---|---|
| **3a** | $^i$Bu |
| **3b** | Me |



| | R' |
|---|---|
| **4a** | Ph |
| **4b** | $^i$Pr |
| **4c** | $^t$Bu |

## Results and Discussion

The new sterically bulky electron-rich phosphines **4a**−**c** were constructed from pro-azaphosphatrane **1a** as depicted in Scheme 1. Earlier, we reported the room-temperature reaction of **1a** with bromine to give **2c** as a pale-yellow solid[20] and the synthesis of the chloro-substituted salt **2f** via the reaction of **1b** with hexachloroethane.[21] Since it has been reported that the nature of the product from the reaction of phosphines with iodine (ionic or covalent) depends on the type of the solvent employed for the reaction,[22] it was of interest to characterize the product from the reaction of pro-azaphosphatrane **1a** with iodine. Upon treatment of a solution of iodine in dry ether with one equivalent of **1a** at −40 °C, the first example of an iodo-substituted azaphosphatranium cation **2d** was isolated in quantitative yield as a white solid (Scheme 1).

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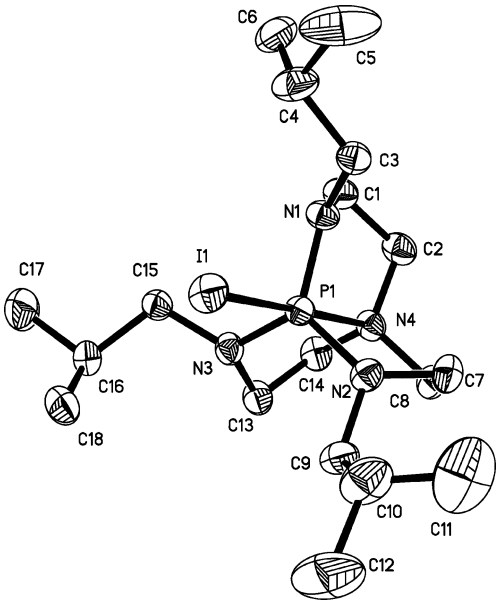


**FIGURE 1.** Computer drawing of the molecular structure of **2d** at the 50% probability level. Hydrogen atoms are omitted for clarity.

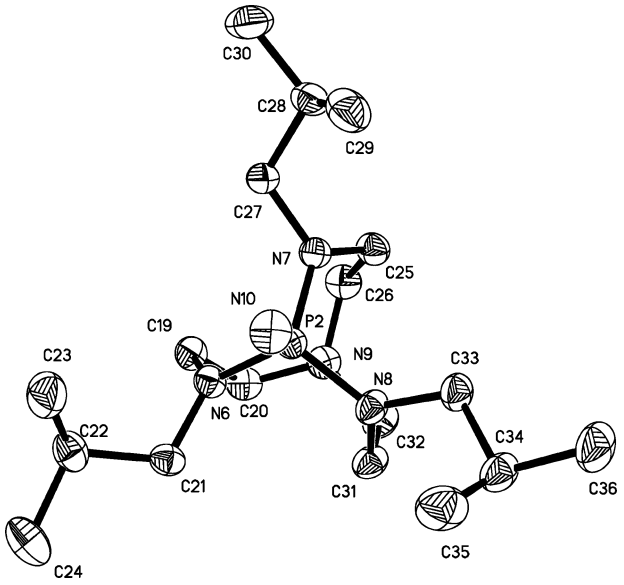


**FIGURE 2.** Computer drawing of the molecular structure of **3a** at the 50% probability level. Hydrogen atoms are omitted for clarity.

Although solutions of **2d** in polar solvents are highly air and moisture sensitive, **2d** can be safely stored at room temperature either as a solid or in solution under inert atmosphere. $^{1}$H and $^{13}$C NMR spectra showed characteristic peaks for the $C_3$ symmetric azaphosphatranium cage structure (see Experimental section). The $^{31}$P NMR spectrum of **2d** featured a downfield singlet at 15.5 ppm suggesting the presence of a weak transannular N→P interaction compared with **2f**, **2g**, and **2h**, which possess strong transannular interactions, displaying strongly upfield $^{31}$P NMR signals at −20.2, −35.3, and −40.3 ppm, respectively.[20,21] A single crystal of **2d** suitable for X-ray crystallographic study was obtained by cooling an acetonitrile solution in a refrigerator for 2 days. Its molecular structure revealed a cationic iodo-azaphosphatranium moiety with trigonal-bipyramidal geometry around the phosphorus, showing a P−$N_{ax}$ bond length of 2.219(2) Å (which is 34% less than the sum of the P and N van der Waals radii of 3.35 Å) and an apical P−I bond length of 2.581(8) Å (Figure 1). A near-planar geometry around the equatorial nitrogens is apparent from the sum of angles around N(1), N(2), and N(3) [356.46, 351.32, and 351.61°, respectively], and the P(1)−N(4) bond distance of 2.219(2) Å indicates a rather weak transannular interaction.

Although cation **2f** failed to react with ammonia owing to decreased reactivity of the strong P−Cl bond as we discussed earlier,[21] compounds **2c** and **2d** possessing relatively weak P−Br and P−I bonds, respectively, readily reacted. Subsequent addition of two equivalents of KO$^{t}$Bu at room temperature provided the corresponding neutral imino-pro-azaphosphatrane **3a** in quantitative yield after simple workup (Scheme 1).

The $^{1}$H and $^{13}$C NMR spectra of **3a** are consistent with $C_3$ symmetry for this molecule (see Experimental section). A moderately broad $^{1}$H NMR signal, well separated from other signals, was observed at 0.48 ppm in benzene-$d_6$. We assign this peak to the imino ═NH proton. The $^{31}$P NMR spectrum of **3a** displayed a single signal at 38.9 ppm [close to 36.9 ppm reported for its analogue **3b**[21]], which is significantly downfield, compared with other azaphosphatranium salts **2a**−**i**, indicating the lack of a transannular N→P interaction in **3a** and **3b**.[17,20,21,23] These NMR features for **3a** were consistent with results obtained from a single-crystal X-ray study of this compound. Two chemically equivalent but crystallographically independent molecules of **3a** were found in the asymmetric unit of its monoclinic cell. The molecular structure of **3a** (Figure 2) revealed a pyramidal phosphorus geometry with a P═N bond length of 1.547(12) Å, which as expected, is shorter than the average of three equatorial P−$N_{eq}$ bonds [1.661(13) Å] and the P−N distance of 1.626(2) Å determined for the previously known protonated analog **2i**.[23] The sums of angles around N(1), N(2), and N(3) are 358.41, 359.03, and 358.83°, respectively, which suggest a near-planar geometry around these P−N nitrogens. The P(1)−N(4) distance of 3.288 Å is consistent with a lack of transannular interactions in **3a**.

The presence of the NH functionality in **3a** permitted an investigation of its reactivity with reagents such as $R_{3-n}PX_n$ ($n$ = 1−3; R = Ph, $^{i}$Pr, $^{t}$Bu) to form sterically hindered phosphines of type **5**. Bulky ligands for metal-assisted cross coupling reactions are known for their role in promoting stereoelectronically driven coordinative unsaturation at the metal center.[24] It is noteworthy that steric shielding by bulky phosphines facilitate the formation of low-coordinate main group and transition metal compounds.[25] Recent reports from several research groups[26] indicate that sterically modified phosphines such as di-*tert*-butyl or dicyclohexyl substituted phosphines are also efficient ancillary

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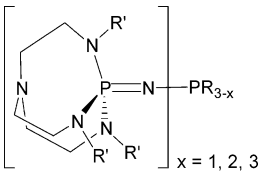
ligands for metal-mediated organic transformations, as may also be the case for ligands of type **5**.




**5**

Although efforts to synthesize analogues of Schwesinger bases, such as $^tBuN{=}P[N{=}P(NMe_2)_3]_3$,[27] by attaching an $=N^tBu$ group, for example, to the $PR_{3-x}$ moiety in **5** are ongoing in our laboratory, our focus here is the reaction of **3a** with monochloro phosphines such as $Ph_2PCl$ or $^iPr_2PCl$. Such reactions at 0 °C in dry ether in the presence of **1a** as an HCl scavenger readily afforded the first examples of $R_2P$-imino-proazaphosphatranes, namely, **4a** and **4b** in 89 and 75% yield, respectively (Scheme 1). These compounds are moderately air stable and are highly soluble in a variety of organic solvents. The $^{31}P$ NMR spectrum of **4a** in benzene-$d_6$ featured two characteristic doublets (38.4 and 24.8 ppm, $^2J_{P-P} = 105.9$ Hz) as did **4b** (66.4 and 18.8 ppm, $^2J_{P-P} = 64.2$ Hz), which are attributable to the presence of a P−N−P′ linkage. The $^1H$ and $^{13}C$ NMR spectra of **4a** and **4b** were also consistent with their formulations (see Experimental section).

Under reaction conditions analogous to those for the synthesis of **4a** and **4b**, **3a** also reacted with $(^tBu)_2PCl$, although rather slowly at room temperature. When the reaction was carried out in toluene at 80 °C for 12 h in the presence of **1a** as a base, however, the corresponding substituted phosphine **4c** was isolated in excellent yield (95%, Scheme 1). The $^{31}P$ NMR spectrum of **4c** exhibited two doublets (83.0 and 21.7 ppm, $^2J_{P-P} = 73.8$ Hz), which are indicative of the formation of a P−N−P′ linkage. The molecular structure of **4c** depicted in Figure 3 confirms its formulation as proposed in the Introduction. The P=N and N−P bond distances are 1.548(15) and 1.673(16) Å, respectively. The average of the three $P-N_{eq}$ bond distances is 1.666(15) Å and the bond angle at the imino-nitrogen [P(1)−N(5)−P(2)] is 137.36(11)°.

To evaluate the usefulness of this new class of bulky electron-rich phosphines **4** in organic synthesis, we investigated its application to Suzuki−Miyaura cross-coupling reactions of aryl bromides and chlorides. The results are tabulated in Tables 1−3. Compared with data in our earlier report on Pd-mediated Suzuki−Miyaura cross-coupling reactions employing the proazaphosphatrane ligand **1a**,[18] the analogous catalyst system using ligand **4c** was found to be twice as active. Thus, in Table 1 containing condition optimization data, for example, only 1 mol % of $Pd(OAc)_2$ and 2 mol % of **4c** was needed to effectively couple aryl bromides with arylboronic acids (Table 1, entry 4), and only 2 mol % of $Pd(OAc)_2$ and 4 mol % of **4c** was necessary for the coupling of aryl chlorides (Table 1, entry 11). Among the bases employed, $Cs_2CO_3$ was found to be the best in the present protocol (Table 1, entry 4). Excellent yields of the biaryl products were isolated by carrying out the reaction in toluene at 80 °C.

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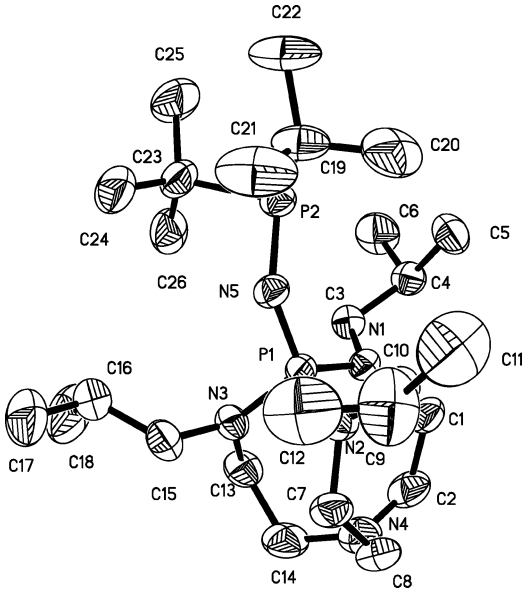


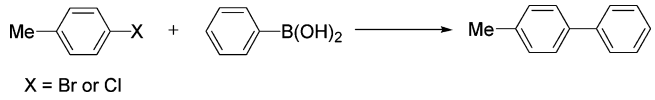

**FIGURE 3.** Computer drawing of the molecular structure of **4c** at the 50% probability level. Hydrogen atoms are omitted for clarity.

It is clear from Table 2 that aryl bromides containing electron-withdrawing groups such as trifluoromethyl, cyano, fluoro, ester, and keto groups are coupled in excellent yields (Table 2, entries 1−8). The $Pd(OAc)_2$/**4c** catalyst system also proved to be highly efficient for electron rich (Table 2, entry 9−14) aryl bromides. Coupling of 1-naphthyl boronic acid with 3-bromo-methylbenzoate proceeded efficiently to afford the corresponding biaryl product in 96% yield (Table 2, entry 6). It should be noted that this is the first time this compound has been made via a Suzuki coupling approach. Previously, this compound was made via a six-step synthesis affording only a 41.6% of overall yield of desired product.[28] Similarly, in the case of economically attractive but notoriously unreactive aryl chlorides,[29] impressive yields of the biaryl products were isolated for substrates possessing electron-withdrawing (Table 3, entries 1−6) and electron-donating (Table 3, entries 7−8) functional groups. Perhaps not surprisingly, heteroaryl chlorides are apparently also efficient coupling partners under our conditions (Table 3, entry 9). Another advantage of the present protocol is that the new phosphine ligand **4c** is air stable and can be easily handled under atmospheric conditions. Gratifyingly, a tetrahydrofuran solution containing **4c** (0.04 mmol), KOH (0.08 mmol), and $H_2O$ (5.6 mmol) in an NMR tube showed no detectable decomposition after heating at 80 °C for 24 h according to $^{31}P$ NMR spectroscopy. Moreover, when **4c** was exposed to air for 24 h before use, impressive yields of biaryl products were isolated (Table 2, entries 1, 5, and 7). Varying yields of cross-coupled biaryl products have been reported in the literature under a variety of reaction conditions employing different palladium sources and ancillary ligands. These results are cited in Tables 2 and 3.

(28) House, H. O.; Bashe, R. W., II. *J. Org. Chem.* **1967**, *32*, 784.

(29) The low reactivity of aryl chlorides in cross-coupling reactions is generally ascribed to their reluctance to oxidatively add to Pd(0). Aryl halides that bear an electron-withdrawing group oxidatively add to Pd(0) more readily than do the corresponding unsubstituted aryl halides. For discussions, see: (a) Grushin, V. V.; Alper, H. *Chem. Rev.* **1994**, *94*, 1047. (b) Grushin, V. V.; Alper, H. In *Activation of Unreactive Bonds and Organic Synthesis*; Murai, S., Ed.; Springer, Berlin, 1999, pp 193−226. (c) Herrmann, W. A. In *Applied Homogeneous Catalysis with Organometallic Compounds, A Comprehensive Handbook*; Cornils, B., Herrmann, W. A., Eds.; VCH: Weinheim, 1996; Vol. 1, p 722.

**TABLE 1. Reaction Optimization on the $Pd(OAc)_2$/4c Catalyzed Suzuki−Miyaura Cross Coupling of Aryl Halides with Arylboronic Acids**[a]




| entry | aryl halide | solvent | base | $Pd(OAc)_2$ (mol %) | **4c** (mol %) | *T* (°C) | time (h) | yield (%)[b] |
|---|---|---|---|---|---|---|---|---|
| 1 | Br | THF | $Cs_2CO_3$ | 2.0 | 4.0 | RT | 24 | 17 (23) |
| 2 | Br | THF | $Cs_2CO_3$ | 2.0 | 4.0 | 80 | 24 | 38 (49) |
| 3 | Br | toluene | $Cs_2CO_3$ | 2.0 | 4.0 | 80 | 4 | 93 (98) |
| 4 | Br | toluene | $Cs_2CO_3$ | 1.0 | 2.0 | 80 | 8 | 96 (98) |
| 5 | Br | toluene | KOtBu | 1.0 | 2.0 | 80 | 12 | 53 (67) |
| 6 | Br | toluene | $K_3PO_4$ | 2.0 | 4.0 | 80 | 16 | 69 (74) |
| 7 | Br | xylene | $K_3PO_4$ | 2.0 | 4.0 | 110 | 16 | 73 (79) |
| 8 | Br | $^i$PrOH | KOtBu | 1.0 | 2.0 | RT | 12 | 43 (53) |
| 9 | Br | DME | $Cs_2CO_3$ | 2.0 | 4.0 | RT | 24 | 57 (66) |
| 10 | Cl | toluene | $Cs_2CO_3$ | 1.0 | 2.0 | 80 | 12 | 82 (88) |
| 11 | Cl | toluene | $Cs_2CO_3$ | 2.0 | 4.0 | 80 | 12 | 96 (99) |

[a] Reaction conditions: 2.0 mmol of aryl halide, 3.0 mmol of arylboronic acid, 4.0 mmol of base, $Pd(OAc)_2$ and ligand **4c**, 5 mL of solvent. [b] Isolated yields. Yields in parenthesis refer to gas chromatography conversions.

**TABLE 2. $Pd(OAc)_2$/4c-Catalyzed Suzuki Cross Coupling of Aryl Bromides with Arylboronic Acids**[a]

| Entry | Arylhalide | Arylboronic acid | Time (h) | Product | Yield (%)[b] |
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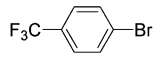
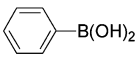
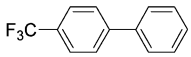
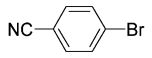
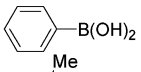
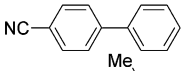
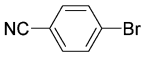
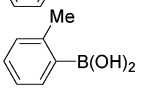
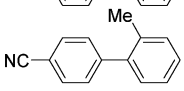
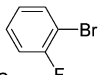
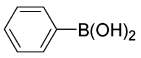
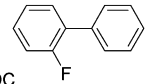
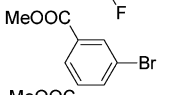
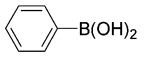
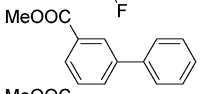
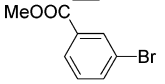
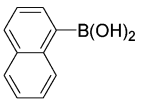
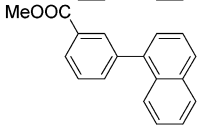
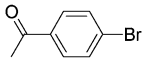
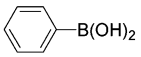
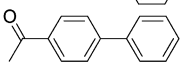
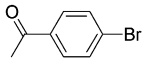
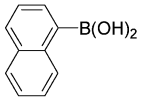
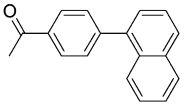
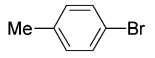
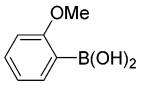
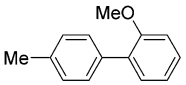
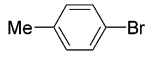
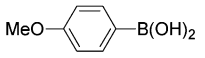
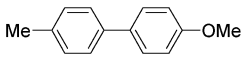
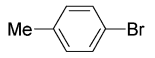
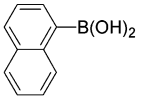
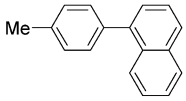
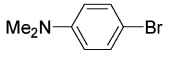
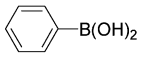
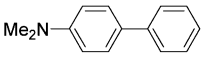
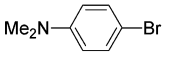
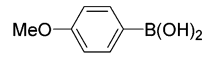
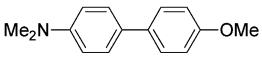
| 1 |  |  | 8 |  | 97 (Lit: 15-99)<br>89[c] |
| 2 |  |  | 16 |  | 98 (Lit: 87-100) |
| 3 |  |  | 16 |  | 93 (Lit: 85-94) |
| 4 |  |  | 10 |  | 98 (Lit: 87-94) |
| 5 |  |  | 8 |  | 99 (Lit: 87-99)<br>91[c] |
| 6 |  |  | 12 |  | 96 (Lit: 42) |
| 7 |  |  | 8 |  | 94 (Lit: 72-100)<br>87[c] |
| 8 |  |  | 10 |  | 100 (Lit: 82-99) |
| 9 |  |  | 16 |  | 97 (Lit: 93) |
| 10 |  |  | 14 |  | 91 (Lit: 83-97) |
| 11 |  |  | 16 |  | 99 (Lit 86-91) |
| 12 |  |  | 14 |  | 96 (Lit: 73-96) |
| 13 |  |  | 14 |  | 92 (Lit: 26-96) |
| 14 |  |  | 16 |  | 95 (Lit:46-98) |

[a] Reaction conditions: 2.0 mmol of aryl halide, 3.0 mmol of arylboronic acid, 4.0 mmol of $Cs_2CO_3$, 1.0 mol % $Pd(OAc)_2$, 2.0 mol % ligand **4c**, 5 mL of toluene, 80 °C, 8−16 h. [b] Isolated yields. Yields in parenthesis refer to literature reports (see ref 3). [c] Reaction using ligand **4c** pre-exposed to the atmosphere.

**TABLE 3. $Pd(OAc)_2$/4c-Catalyzed Suzuki Cross Coupling of Aryl Chlorides with Arylboronic Acids**[a]

| Entry | Arylhalide | Arylboronic acid | Time (h) | Product | Yield (%)[b] |
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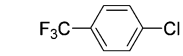
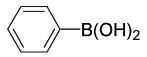
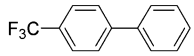
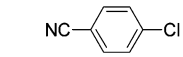
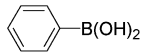
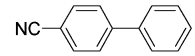
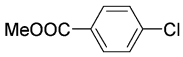
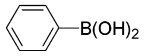
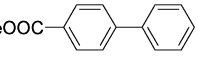
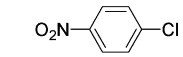
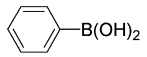
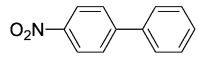
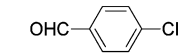
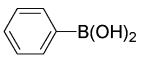
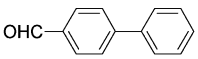
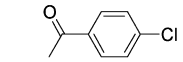
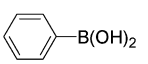
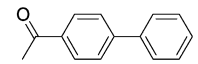
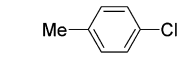
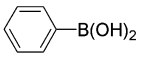
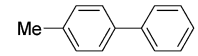
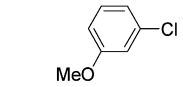
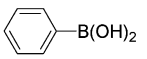
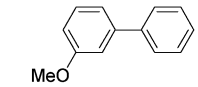
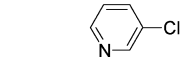
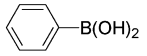
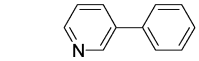
| 1 |  |  | 10 |  | 98 (Lit: 24-96) |
| 2 |  |  | 12 |  | 96 (Lit: 42-99) |
| 3 |  |  | 10 |  | 98 (Lit: 66-100) |
| 4 |  |  | 12 |  | 97 (Lit: 92-100) |
| 5 |  |  | 16 |  | 95 (Lit: 62-99) |
| 6 |  |  | 12 |  | 92 (Lit: 22-100) |
| 7 |  |  | 16 |  | 96 (Lit: 48-100) |
| 8 |  |  | 18 |  | 97 (Lit: 64-98) |
| 9 |  |  | 18 |  | 93 (Lit: 65-99) |

[a] Reaction conditions: 2.0 mmol of aryl halide, 3.0 mmol of arylboronic acid, 4.0 mmol of $Cs_2CO_3$, 2.0 mol % $Pd(OAc)_2$, 4.0 mol % ligand **4c**, 5 mL of toluene, 80 °C, 10−18 h. [b] Isolated yields. Yields in parenthesis refer to literature reports (see ref 3).

## Conclusions

We have shown that proazaphosphatrane **1a** can be structurally modified to provide new phosphines with tunable steric bulkiness and electron richness for metal-mediated cross-coupling reactions. The $Pd(OAc)_2$/**4a** system utilized herein efficiently catalyzes Suzuki−Miyaura cross couplings of aryl bromides and chlorides at relatively low catalyst loadings with good tolerance of functional groups such as methoxy, ester, amino, aldehyde, keto, fluoro, cyano, and nitro substituents. Explorations of the synthesis and chemistry of phosphines with up to three imino-pro-azaphosphatrane substituents and their chalcogeno and imino derivatives, including chiral versions of **4** in which the $PR_2$ moieties are PRR′, are in progress. Expanding the scope of the present methodology to other synthetically useful substrates (e.g., vinyl halides/triflates and alkylboronic acids) as well as employing ligands of type **5** in other important Pd-assisted cross-coupling reactions are underway.

## Experimental Section

**Synthesis of 2d.** To a stirred solution of **1a** (2.76 g, 8.05 mmol) in dry ether (30 mL) at −40 °C was added dropwise a solution of iodine (2.00 g, 7.87 mmol) in dry ether (40 mL) over 15 min, resulting in the immediate formation of a yellow precipitate. The reaction mixture was then slowly brought to room temperature, and after further stirring for 6 h, the pale-yellow solid was filtered and was dried under reduced pressure (4.42 g, 94%). A single crystal suitable for X-ray structural study was obtained by cooling a concentrated acetonitrile solution of **2d** in a refrigerator for 2 days. Mp. (°C): 115−116 (dec). $^{31}P$ NMR (161.8 MHz, $CD_3CN$): $\delta$ = 15.5 ppm. $^1H$ NMR (400 MHz, $CD_3CN$, 25 °C): $\delta$ = 0.98 (d, 18H), 2.21 (sep, 3H), 2.91 (t, 6H), 3.00 (dd, 6H), and 3.21 ppm (dt, 6H). $^{13}C$ NMR (100.6 MHz, $CD_3CN$, 25 °C): $\delta$ = 55.4, 51.2, 46.3, 27.9, and 19.7 ppm. Elemental analysis calculated for $C_{18}H_{39}I_2N_4P$: C, 36.25; H, 6.59; N, 9.40. Found: C, 36.63; H, 7.27; N, 9.36.

**Synthesis of 3a.** Dry ammonia gas was bubbled into stirred slurry of **2d** (1.00 g, 1.68 mmol) in dry THF (30 mL) for 15 min at room temperature. The reaction mixture was further stirred for an additional hour under an argon atmosphere and then solid KO$^t$Bu (0.41 g, 3.7 mmol) was slowly added. After stirring for 1 h at room temperature, volatiles were removed under reduced pressure. The solid residue was then extracted with dry hexanes (2 × 20 mL). Evaporation of volatiles from the hexane filtrate under reduced pressure gave **3a** as a creamy white solid in near quantitative yield (0.59 g, 99%). A single crystal suitable for X-ray study was obtained by cooling a concentrated hexane solution of **3a** in a refrigerator for 2 days. Mp. (°C): 80−81. $^{31}P$ NMR (161.8 MHz, $C_6D_6$, 25 °C): $\delta$ = 38.94 ppm. $^1H$ NMR (400 MHz, $C_6D_6$, 25 °C): $\delta$ = 0.48 (br, 1H), 0.96 (d, 18H), 2.09 (sep, 3H), 2.48 (t, 6H), 2.65 (br, 6H), and 2.75 ppm (br, 6H). $^{13}C$ NMR (100.6 MHz, $C_6D_6$ 25 °C): $\delta$ = 58.6, 50.1, 48.1, 29.2, and 21.1 ppm. Elemental analysis calculated for $C_{18}H_{40}N_5P$: C, 60.47; H, 11.28; N, 19.59. Found: C, 60.32; H, 11.46; N, 19.77.

Compound **3a** can also be prepared analogously starting with azaphosphatranium salt **2c**.

**Synthesis of 4a.** To a stirred solution of **3a** (1.00 g, 2.80 mmol) in dry diethylether (20 mL) cooled to 0 °C was added **1a** (0.96 g, 2.8 mmol) followed by $Ph_2PCl$ (0.62 g, 2.8 mmol). A white precipitate formed almost immediately. The reaction mixture was brought to room temperature over 3 h and stirring was continued for an additional 6 h, after which it was filtered to remove salt **2a**. Evaporation of volatiles from the filtrate under reduced pressure left a slightly sticky solid. Addition of about 2 mL of dry acetonitrile resulted in the formation of a white solid that was quickly filtered under an argon atmosphere. The white solid was then dried under reduced pressure (1.35 g, 89%). Mp. (°C): 154−156. $^{31}P$ NMR (161.8 MHz, $C_6D_6$, 25 °C): $\delta$ = 38.40 (d, $^2J_{P-P}$ = 105.9 Hz) and 24.78 ppm (d, $^2J_{P-P}$ = 105.9 Hz). $^1H$ NMR (400 MHz, $C_6D_6$, 25 °C): $\delta$ = 0.88 (d, 18H), 2.18 (sep, 3H), 2.40 (t, 6H), 2.60−2.90 (br m, 12H), 7.07 (t, 2H), 7.25 (t, 4H), and 8.01 ppm (t, 4H). $^{13}C$ NMR (100.6 MHz, $C_6D_6$ 25 °C): $\delta$ = 132.5, 129.9, 128.4, 126.8, 54.1, 49.4, 48.6, 28.6, and 20.5 ppm. Elemental analysis calculated for $C_{30}H_{49}N_5P_2$: C, 66.52; H, 9.12; N, 12.93. Found: C, 66.58; H, 9.21; N, 12.46.

**Synthesis of 4b.** This compound was synthesized from **3a** and $^{i}Pr_2PCl$ by employing the analogous procedure described above for the synthesis of **4a**. Yield: 75%. Mp. (°C): 132−134. $^{31}P$ NMR (161.8 MHz, $C_6D_6$, 25 °C): $\delta = 66.41$ (d, $^{2}J_{P-P} = 64.2$ Hz) and 18.77 ppm (d, $^{2}J_{P-P} = 64.2$ Hz). $^{1}H$ NMR (400 MHz, $C_6D_6$, 25 °C): $\delta = 0.80$ (d, 18H), 1.01 (m, 12H), 1.45 (m, 2H), 1.85 (sep, 3H), 2.98 (m, 6H), 3.15 (m, 6H), and 3.75 ppm (br, 6H). $^{13}C$ NMR (100.6 MHz, $C_6D_6$ 25 °C): $\delta = 59.0$, 52.1, 47.2, 29.2, 21.2, 20.6, and 17.9 ppm. Elemental analysis calculated for $C_{24}H_{53}N_5P_2$: C, 60.86; H, 11.28; N, 14.79. Found: C, 60.49; H, 11.37; N, 14.68.

**Synthesis of 4c.** To a stirred solution of **3a** (1.00 g, 2.80 mmol) in dry toluene (20 mL) at room temperature was added **1a** (0.96 g, 2.8 mmol) followed by $^{t}Bu_2PCl$ (0.51 g, 2.8 mmol). The reaction mixture was then heated at 80 °C for 12 h. Evaporation of the solvent and other volatiles under reduced pressure left a colorless sticky solid residue, which was extracted into dry diethylether (30 mL) leaving salt **2a** behind. Volatiles were removed under reduced pressure, which provided a sticky solid residue. Addition of about 2 mL of dry acetonitrile quickly resulted in the formation of a white solid that was filtered and dried under reduced pressure (1.34 g, 95%). A single crystal suitable for X-ray study was obtained by cooling a concentrated hexane solution of **4c** in a refrigerator for 2 days. Mp. (°C): 106−108. $^{31}P$ NMR (161.8 MHz, $C_6D_6$, 25 °C): $\delta = 83.01$ (d, $^{2}J_{P-P} = 73.8$ Hz) and 21.72 ppm (d, $^{2}J_{P-P} = 73.8$ Hz). $^{1}H$ NMR (400 MHz, $C_6D_6$, 25 °C): $\delta = 1.05$ (d, 18H), 1.39 (d, 18H), 2.17 (sep, 3H), 2.51 (t, 6H), 2.79 (br, 6H), and 3.02 ppm (br, 6H). $^{13}C$ NMR (100.6 MHz, $C_6D_6$ 25 °C): $\delta = 55.1$, 50.2, 48.8, 30.0, 28.9, and 21.6 ppm. Elemental analysis calculated for $C_{26}H_{57}N_5P_2$: C, 62.24; H, 11.45; N, 13.96. Found: C, 62.28; H, 11.49; N, 13.83.

**Alternative Method for the Synthesis of 4a−c.** Instead of using proazaphosphatrane **1a**, an amine such as $Et_3N$ could also be used as a base, although lower yields and longer reaction times were encountered. $^{n}BuLi$ used as a base, generated the lithium salt of **3a** in situ and subsequent addition of $R_2PCl$ gave the corresponding phosphines. In a typical procedure using $^{n}BuLi$, 1.0 equiv of $^{n}$-BuLi was added to **3a** in 15 mL of dry THF at −45 °C. The reaction mixture was slowly brought to room temperature and stirred for an additional 3 h. The mixture was cooled to 0 °C, and 1.0 equiv of $R_2PCl$ was added followed by stirring for another 12 h at room temperature. After removing the volatiles under reduced pressure, the residue was extracted with hexanes (2 × 15 mL). Evaporation of the extracts gave **4a−c** in 50−60% yield.

**General Procedure for Suzuki−Miyaura Cross Coupling.** An oven-dried Schlenk tube equipped with a magnetic stir bar was charged with aryl halide (2.0 mmol), arylboronic acid (3.0 mmol), base (4.0 mmol), Pd(OAc)2 (1 mol % for aryl bromide and 2 mol % for aryl chloride), ligand **4c** (2.0 mol % for aryl bromide and 4 mol % for aryl chloride), and 5 mL of solvent. The tube was capped with a rubber septum and immersed in an oil bath at 80 °C. Upon complete consumption of starting material as judged by thin-layer chromatography analysis and/or gas chromatography mass spectrometry, the reaction mixture was adsorbed onto silica and the biaryl product was isolated by column chromatography (hexanes/EtOAc). All the biphenyl products reported in Tables 2 and 3 are known compounds and were characterized by favorable comparison of their $^{1}H$ and $^{13}C$ NMR to the previously reported data in the literature (see Supporting Information).

**Acknowledgment.** We thank the National Science Foundation for financial support and we thank Dr. Arkady Ellern of Iowa State University Molecular Structure Laboratory for the single-crystal X-ray results.

**Supporting Information Available:** Tables of detailed structural and refinement data, CIF files, references to known compounds, $^{1}H$ and $^{13}C$ NMR spectra for cross-coupled products. This material is available free of charge via the Internet at http://pubs.acs.org.

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