General Synthesis and Catalytic Applications of Di(1-adamantyl)alkylphosphines and their Phosphonium Salts

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Abstract: An improved synthesis of di(1-adamantyl)alkylphosphines by alkylation of di(1-adamantyl)phosphine followed by deprotonation of the resulting phosphonium halide is described. Compared to previous protocols for the synthesis of this class of compounds, the procedure does not require chlorination of the secondary phosphine by phosgene, or formation of sensitive lithium di(1-adamantyl)phosphide. Selected examples of the prepared phosphonium salts and phosphines are shown to be excellent ligands for the palladium-catalyzed cross-coupling reaction of chloroarenes with arylboronic acids.

Key words: adamantylphosphines, aryl chlorides, palladium, phosphine ligands, Suzuki reaction

Palladium-catalyzed coupling reactions of aryl halides have become a standard tool for carbon–carbon and carbon–heteroatom bond forming reactions.[1] Almost all of these modern catalytic reactions require ligands to stabilize and activate the central metal atom, and to tune the selectivity of the desired transformation. Clearly, until to date phosphines constitute the most important class of ligands for cross-coupling reactions.

In recent years, we and others have developed new efficient ligands and metal complexes for palladium-catalyzed Suzuki,[2] Heck,[3] and Buchwald–Hartwig amination reactions[4] of aryl halides, especially aryl chlorides.[5] In general, improvements in this area have been made possible by the use of in situ [Pd]/L catalysts consisting of a Pd(II) or Pd(0) source and sterically hindered basic ligands. It is commonly agreed on that these in situ catalysts are reduced under reaction conditions to afford coordinatively unsaturated complexes such as 16e PdL_3, 14e PdL_2, and 12e PdL, which constitute the 'real' active catalysts.

In the year 2000, we first have introduced di(1-adamantyl)alkylphosphines as sterically demanding and electron-rich ligands for aryl halide activation.[6] More specifically, we discovered that di(1-adamantyl)-*n*-butylphosphine ($BuPAd_2$) is an excellent ligand for Heck[7] and Suzuki[6] coupling reactions, for Buchwald–Hartwig aminations[8] and α-arylation reactions of ketones.[9]

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In addition to our work, Hartwig and co-workers,[10] Plenio and co-workers[11] and other groups[12] demonstrated elegantly the usefulness of 1-adamantylphosphines in various palladium-catalyzed coupling reactions.

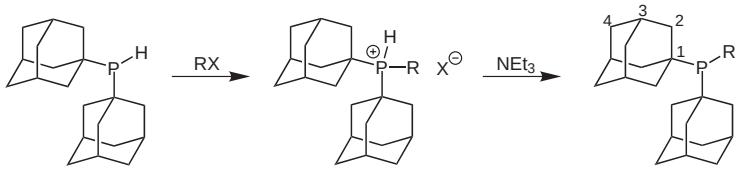
So far our typical preparation of $BuPAd_2$ and related ligands started from adamantane and phosphorous trichloride, yielding di(1-adamantyl)phosphinic chloride after hydrolysis. The resulting phosphorous(V) compound was then reduced by means of lithium aluminum hydride to give di(1-adamantyl)phosphine and subsequently chlorinated with phosgene. Afterwards the desired alkyl group was introduced by a classical nucleophilic substitution reaction of the corresponding chlorophosphine with *n*-butyllithium.[7]

Advantageously, di(1-adamantyl)phosphine can be alkylated with *n*-butyl bromide after deprotonation with *n*-butyllithium at high temperature. However, due to the harsh reaction conditions this nucleophilic substitution was not always reproducible in our hands and led to products of varying purity. To overcome these problems and to access also new adamantyl ligands, which contain more sensitive functional groups, we were attracted by alternative preparations of this type of ligands.

Interestingly, Schmutzler and co-workers described the synthesis of di(1-adamantyl)methylphosphine by quarternization of di(1-adamantyl)phosphine with methyl iodide, followed by triethylamine mediated deprotonation of the resulting phosphonium salt.[13] Obviously this procedure omits the use of an excess of *n*-butyllithium leading to the desired tertiary phosphine under much milder conditions compared to our previous protocol. Based on Schmutzler's procedure, we describe herein a straightforward synthesis of 13 different di(1-adamantyl)alkylphosphine derivatives and their use as ligands in the palladium-catalyzed Suzuki coupling of various aryl chlorides with arylboronic acids.[14]

As shown in Scheme 1 and Table 1, di(1-adamantyl)phosphine reacts readily with different alkyl and benzyl halides to give the corresponding di(1-adamantyl)alkylphosphonium salts in moderate to good yield. Initially, as a model reaction we tested the alkylation using *n*-butyl iodide in different solvents between room temperature and 130 °C.

The successful synthesis of di(1-adamantyl)butylphosphonium iodide depends mainly on the stability of the



1a R= $CH_2CH_2CH_2CH_3$, X= I
1b R= $CH_2CH(CH_3)_2$, X= I
1c R= $CH_2CH{=}CH_2$, X= Br
1d R= CH_2Ph, X= Br
1e R= CH_3, X= I
1f R= $CH(CH_3)_2$, X= I
1g R= $CH_2CH_2OCH_3$, X= Br
1h R= $CH_2CH_2CH_2Cl$, X= I

2a R= $CH_2CH_2CH_2CH_3$
2b R= $CH_2CH(CH_3)_2$
2c R= $CH_2CH{=}CH_2$
2d R= CH_2Ph
2e R= CH_3

Scheme 1 Synthesis of phosphonium salts and free phosphine ligands from di(1-adamantyl)phosphine

product under the selected reaction conditions. In case of significant dissociation to give di(1-adamantyl)butylphosphine ($BuPAd_2$) and HI in situ further alkylation to the corresponding tetraalkylphosphonium salt easily takes place. In general, we observed that polar and basic solvents favor dissociation of the phosphonium salt. Hence, successful reactions were carried out using either less polar solvents like di-*n*-butyl ether (Table 1, entries 1, 5) or without solvent (Table 1, entries 2–4, 6–8). In addition to the synthesis of simple di(1-adamantyl)alkylphosphonium salts **1a**,**b**, **1d**–**f** (Table 1, entries 1, 2, 4–6), the method is also applicable for the preparation of salts with additional functional groups.

Hence, compounds **1c** and **1g**,**h** were obtained by the reaction of alkyl halides having allyl, methoxy or chloro substituents (Table 1, entries 3, 7, 8). Clearly, the resulting functionalized phosphine derivatives constitute interesting building blocks for the preparation of further modified di(1-adamantyl)alkylphosphine derivatives.

Highly reactive α-halo esters or nitriles did not give the desired products. Here, complex mixtures of different phosphorous-containing products were obtained. Although isobutyl iodide and isopropyl iodide reacted well to give the desired products **1b** and **1f**, the sterically more hindered *tert*-butyl iodide did not give satisfactory coupling results (Table 1, entry 9). Furthermore, in one experiment a mesylate was used instead of the corresponding bromide or iodide, but no product formation was observed (Table 1, entry 10).

Next, treatment of the air stable salts **1a**–**h** with triethylamine led to the free di(1-adamantyl)alkylphosphines **2a**–**e** in good yields (Scheme 1, Table 2). In contrast to our previous procedure, the resulting phosphines were isolated without contamination by phosphine oxides or other impurities! Advantageously, this preparation does not need the use of strong bases and is easily performed on a 10 g-scale. However, applying phosphonium salts **1f**,

Table 1 Reaction of Diadamantyl Phosphine with Alkyl and Aryl Halides under Various Conditions

Entry	Alkyl Halide	Solvent	Temp. (°C)	Time (h)	Product	Yield (%)	^{31}P NMR ($CDCl_3$) δ
1	$CH_3CH_2CH_2CH_2I$	*n*-Bu_2O	130	8	**1a**	93	21.5
2	$(CH_3)_2CHCH_2I$	neat	100	12	**1b**	63	12.9
3	$CH_2{=}CHCH_2Br$	neat	r.t.	3	**1c**	79	19.6
4	$PhCH_2Br$	neat	r.t.	1	**1d**	77	22.2
5	CH_3I	*n*-Bu_2O	r.t.	24	**1e**	90	20.1
6	$(CH_3)_2CHI$	neat	100	12	**1f**	43	25.3
7	$CH_3OCH_2CH_2Br$	neat	80	8	**1g**	95	23.1
8	$ClCH_2CH_2CH_2I$	neat	70	5	**1h**	60	19.8
9	$(CH_3)_3CI$	–[a]	–[b]	12–24	no reaction	–	–
10	$CH_3CH_2OSO_2CH_3$	–[a]	–[b]	12–24	no reaction	–	–

[a] Reactions were carried out in di-*n*-butyl ether, NMP and neat.
[b] Reactions were carried out at different temperatures (r.t. and reflux).

1g and **1h** (Table 2, entries 6–8) deprotonation with triethylamine failed due to unwanted side reactions.

Table 2 Deprotonation of Phosphonium Salts **1a–h**

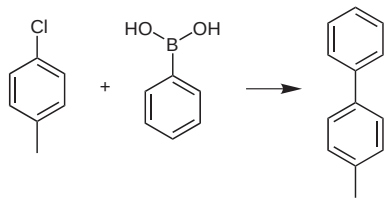
Entry	Salt	Phosphine	Yield (%)	^{31}P NMR (C_6D_6)δ
1	**1a**	**2a**	90	24.9
2	**1b**	**2b**	80	19.5
3	**1c**	**2c**	60	24.0
4	**1d**	**2d**	70	31.1
5	**1e**	**2e**	65	8.2
6	**1f**	no reaction	–	–
7	**1g**	–[a]	–	–
8	**1h**	–[a]	–	–

[a] Desired product was not obtained.

Unfortunately, also the reaction with sodium hydroxide in water did not lead to the desired products. Nevertheless, the resulting phosphonium salts **1f–h** seem to be useful ligand precursors due to the possibility of in situ deprotonation of the phosphonium salts under catalytic conditions.[15]

All products described in Tables 1 and 2 were fully characterized by ^{1}H, ^{13}C, and ^{31}P NMR, IR, and MS data. Correct elemental analyses were obtained in case of the phosphonium salts, but not for the free phosphines because of their oxygen sensitivity.

In order to test the catalytic activity of phosphonium salts **1a–h** and phosphines **2a–e**, we have used the different ligands in the Suzuki coupling reaction of 4-chlorotoluene with phenylboronic acid (Scheme 2). This is a useful benchmark reaction to test new ligands because in the presence of 'standard' aromatic phosphines, which are most often applied for Suzuki reactions of aryl halides, no significant conversion takes place. In addition, catalyst-free Suzuki reactions[16] do not proceed with these substrates.



Conditions: 0.1 mol% $Pd(OAc)_2$
0.2 mol% Ad_2PR or $[Ad_2PRH]X$
2 equiv. K_3PO_4
toluene, 100 °C, 20 h

Scheme 2 Suzuki coupling reaction of 4-chlorotoluene with phenylboronic acid in the presence of different catalysts

In general, the test reaction was performed in toluene using K_3PO_4 as base at 100 °C at low catalyst loading (0.1 mol% of palladium acetate and 0.2 mol% of the respective ligand or ligand precursor). As shown in Table 3, both phosphonium salts and free phosphines lead to active catalyst systems. Hence, at least partial deprotonation of the phosphonium salts seems to occur under the applied reaction conditions. Among the different phosphonium salts the butyl derivative **1a**, the allylated ligand **1c** and the 2-methoxyethyl derivative **1g** (Table 3, entries 1, 3 and 7) showed significant better catalytic activity (yield 79–82%) compared to the other di(1-adamantyl)alkylphosphonium salts. All ligand precursors gave a high selectivity (typically >95%), except for the di(1-adamantyl)-3-chloropropylphosphonium salt **1h**, which might react itself under these conditions.

A comparison of the catalytic activity of the phosphonium salts (Table 3, entries 1–5) and their corresponding free phosphines (Table 3, entries 9–13) shows that in general the free phosphines give better results in catalysis compared to their phosphonium salts. An exception is the isobutyl ligand **1b**, **2b**, where better yields were obtained with the salt. In agreement with the phosphonium salts the best results (84–95% yield) are observed with the *n*-butyl- and allylphosphines **2a** and **2c**.

Nevertheless, with regard to a general use the combinations of di(1-adamantyl)alkylphosphonium salts and $Pd(OAc)_2$ constitute interesting catalyst systems due to the high stability of all components towards air and water and thus the easy handling of the catalyst.

Table 3 Suzuki Cross-Coupling using $[Ad_2PRH]X$ and Ad_2PR

Entry	Ligand	Conversion (%)	Yield (%)[a]
1	**1a**	83	82
2	**1b**	51	51
3	**1c**	80	79
4	**1d**	53	47
5	**1e**	25	19
6	**1f**	55	55
7	**1g**	80	80
8	**1h**	38	28
9	**2a**	100	95
10	**2b**	39	30
11	**2c**	84	84
12	**2d**	68	67
13	**2e**	46	37

[a] GC yield.

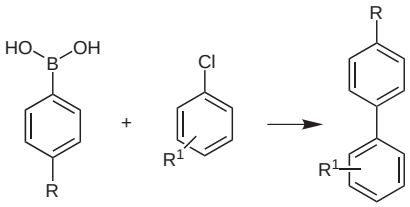
Table 4 Comparison of Free Phosphine Ligands with Their Salt Forms in Different Suzuki Reactions

Entry	R	R^1	Phosphonium Salt **1c**		Phosphine **2c**		Phosphonium Salt **1a**		Phosphine **2a**	
			Conv. (%)	Yield (%)	Conv. (%)	Yield (%)	Conv. (%)	Yield (%)	Conv. (%)	Yield (%)
1	H	2-CN	100	98	100	96	100	97	100	99
2	H	4-CN	100	97	100	96	96	96	100	96
3	H	4-$COCH_3$	100	98	100	98	96	96	100	100
4	H	-[a]	89	87	93	86	88	87	100	97
5	H	2,6-$(CH_3)_2$	44	43	62	62	30	30	94	93
6	H	4-OCH_3	14	6	76	73	12	6	67	65
7[b]	OH	4-CN	94	92	89	87	100	99	100	99

[a] 3-Chloropyridine was used as substrate.
[b] Reaction was carried out at 0.75 mmol scale with DMF as solvent, 1 M HCl was used instead of sodium hydroxide in the work-up procedure (see experimental section).

Next, the best two phosphines and phosphonium salts **1/2a** and **1/2c** were used for Suzuki reactions of various activated and deactivated aryl halides (Scheme 3, Table 4). For electron-deficient aryl chlorides, e.g., cyano or acetyl substituted chlorobenzene, excellent yields are obtained both in the presence of phosphonium salts and phosphines (Table 4, entries 1–3 and 7). In the case of more challenging substrates, e.g. 2,6-dimethylchlorobenzene and 4-chloroanisole (Table 4, entries 5, 6) the use of free phosphines gives superior results. This is probably due to the low solubility of the phosphonium salts in toluene resulting in a somewhat lower catalyst concentration, which is, however, no problem for the coupling of activated substrates. This explanation is also supported by the finding, that substituting toluene as the solvent for the more polar DMF leads to significantly improved yields of the desired biaryls: 91% (**1a** or **1c**) vs. 30% (**1a**)/43% (**1c**) for 2,6-dimethylchlorobenzene, and 78% vs. 6% (**1a** or **1c**) yield for 4-chloroanisole.

In summary, we have described an easy way for preparing various di(1-adamantyl)alkylphosphines and the corresponding phosphonium salts by nucleophilic substitution of alkyl or benzyl halides with di(1-adamantyl)phosphine. The interesting catalytic potential of this class of ligands is shown in the Suzuki reaction of various aryl chlorides. For the first time it has been demonstrated that also adamantylphosphonium salts lead to highly active palladium catalysts. Obviously, the described ligands should be useful for various other palladium-catalyzed coupling reactions, too.



Conditions: 0.1 mol% $Pd(OAc)_2$
0.2 mol% Ad_2PR or $[Ad_2PRH]X$
2 equiv. K_3PO_4
toluene, 100 °C, 20 h

Scheme 3 Suzuki reaction of aryl chlorides with arylboronic acids

Phosphonium Salts; General Procedure

Di(1-adamantyl)phosphine (906 mg, 3 mmol) and alkyl halide (4.5 mmol) were dissolved in di-*n*-butyl ether (20 mL). In the case of neat reactions, a larger excess of alkyl or benzyl halide (12–15 mmol) was used. After stirring the reaction at the given temperature (see Table 1), the mixture was cooled down to r.t., and diluted with di-*n*-butyl ether (10 mL). The precipitated phosphonium salts were filtered off and dried in vacuum. In most cases the obtained salts were sufficiently pure for further catalytic or deprotonation reactions. Otherwise further purification can be done by recrystallization from Et_2O.

Di(1-adamantyl)-*n*-butylphosphonium Iodide (1a)

IR (KBr): 3425 (m, br), 2904 (s), 2852 (s), 2257 (m), 1451 (m), 1345 cm^{-1} (m).

^1H NMR (250 MHz, $CDCl_3$): δ = 0.95 (3 H, t, ^3J = 7.3 Hz, CH_3), 1.45–1.57 (2 H, m, butyl-2H), 1.75–2.22 (34 H, m, adamantyl-30H, butyl-4H), 7.71 (1 H, dt, $^1J_{H,P}$ = 470.6 Hz, $^3J_{H,H}$ = 3.9 Hz, PH).

^{13}C NMR (62 MHz, $CDCl_3$): δ = 38.0 (d, $^2J_{C,P}$ = 2.4 Hz, C-2), 37.4 (C-1), 35.6 (C-4), 28.4 (d, $^2J_{C,P}$ = 5.5 Hz, butyl-β-CH_2), 27.4 (d, $^3J_{C,P}$ = 9.3, C-3), 24.4 (d, $^3J_{C,P}$ = 11.9 Hz, butyl-γ-CH_2), 13.3 (butyl-CH_3), 11.7 (d, $^1J_{C,P}$ = 38.8, butyl-α-CH_2).

MS (EI, 70 eV): *m*/*z* (%) = 358 (M^+, 14.5), 135 (Ad^+, 100).

Anal. Calcd for $C_{24}H_{40}IP$ (486.46): C, 59.26; H, 8.23. Found: C, 59.53; H, 8.39.

Di(1-adamantyl)isobutylphosphonium Iodide (1b)

IR (KBr): 3420 (s, br), 2905 (s), 2852 (s), 2806 (w), 2330 (w), 1450 (m), 1388 cm^{-1} (m).

^1H NMR (250 MHz, $CDCl_3$): δ = 1.21 (6 H, d, $^3J_{H,H}$ = 6.6 Hz, 2 CH_3), 1.76–2.24 (31 H, m, adamantyl-30H, isobutyl-CH), 8.00 (1 H, dt, $^1J_{H,P}$ = 472.5 Hz, $^3J_{H,H}$ = 4.4 Hz, PH),

^{13}C NMR (62 MHz, $CDCl_3$): δ = 37.8 (d, $^2J_{C,P}$ = 2.8 Hz, C-2), 37.2 (C-1), 35.6 (d, $^4J_{C,P}$ = 1.8 Hz, C-4), 27.4 (d, $^3J_{C,P}$ = 9.4 Hz, C-3),

27.0 (d, $^2J_{C,P}$ = 4.7 Hz, isobutyl-CH), 24.2 (d, $^3J_{C,P}$ = 8.5 Hz, isobutyl-CH_3), 20.1 (d, $^1J_{C,P}$ = 37.6, PCH_2).

MS (EI, 70 eV): *m*/*z* (%) = 358 (M^+, 48), 135 (Ad^+, 100).

Anal. Calcd for $C_{24}H_{40}IP$ (486.46): C, 59.26; H, 8.23. Found: C, 59.42; H, 8.33.

Di(1-adamantyl)allylphosphonium Bromide (1c)
IR (KBr): 3420 (s, br), 2904 (s), 2852 (s), 2682 (w), 2301 (w), 1634 (w), 1451 cm^{-1} (m).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.77–2.33 (30 H, m, adamantyl-30H), 3.11–3.21 (2 H, m, PCH_2), 5.34–5.49 (2 H, m, allyl-CH_2), 5.91–6.10 (1 H, m, allyl-CH), 8.0 (1 H, dt, $^1J_{H,P}$ = 481.9 Hz, $^3J_{H,H}$ = 4.0 Hz, PH).

^{13}C NMR (62 MHz, $CDCl_3$): δ = 126.9 (d, $^2J_{C,P}$ = 8.5 Hz, allyl-CH), 123.0 (d, $^3J_{C,P}$ = 12.2 Hz, allyl-CH_2), 38.3 (d, $^2J_{C,P}$ = 2.8 Hz, C-2), 37.9 (d, $^1J_{C,P}$ = 31.0 Hz, C-1), 35.4 (C-4), 27.4 (d, $^3J_{C,P}$ = 9.4 Hz, C-3), 18.6 (d, $^1J_{C,P}$ = 39.5 Hz, PCH_2).

MS (EI, 70 eV): *m*/*z* (%) = 342 (M^+, 30.6), 135 (Ad^+, 100).

Anal. Calcd for $C_{23}H_{36}BrP$ (423.42): C, 65.25; H, 8.51. Found: C, 65.12; H, 8.51.

Di(1-adamantyl)benzylphosphonium Bromide (1d)
IR (KBr): 3420 (s, br), 2903 (s) 2852 (s), 2796 (w), 2224 (m), 1497 (m), 1347 cm^{-1} (m).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.7–2.29 (30 H, m, adamantyl-H), 3.67–3.76 (2 H, m, PCH_2), 7.34–7.4 (3 H, m, aromatic-3H), 7.63 (2 H, d, $^3J_{H,H}$ = 7.9 Hz, aromatic-2H), 8.2 (1 H, dt, $^1J_{H,P}$ = 480.4 Hz, $^3J_{H,H}$ = 6.1 Hz, PH).

^{13}C NMR (62 MHz, $CDCl_3$): δ = 130.3 (d, $^2J_{C,P}$ = 7.5 Hz, aromatic C), 130.1 (d, $J_{C,P}$ = 6.0 Hz, 2 aromatic CH), 129.5 (d, $J_{C,P}$ = 1.5 Hz, 2 aromatic CH), 128.2 (d, $^5J_{C,P}$ = 2.3 Hz, aromatic CH), 38.3 (d, $^1J_{C,P}$ = 30.8 Hz, C-1), 38.1 (d, $^2J_{C,P}$ = 2.8 Hz, C-2), 35.5 (d, $^4J_{C,P}$ = 1.9 Hz, C-4), 27.6 (d, $^3J_{C,P}$ = 9.4 Hz, C-3), 19.6 (d, $^1J_{C,P}$ = 36.6 Hz, PCH_2).

MS (EI, 70 eV): *m*/*z* (%) = 392 (M^+, 25.8), 135 (Ad^+, 100).

Di(1-adamantyl)methylphosphonium Iodide (1e)
IR (KBr): 3410 (s, br), 2908 (s) 2851 (s), 2802 (w), 2320 (w), 1452 (m), 1345 cm^{-1} (m).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.75–2.30 (33 H, m, adamantyl-30H, PCH_3), 7.45 (1 H, dq, $^1J_{H,P}$ = 473.7 Hz, $^3J_{H,H}$ = 5.9 Hz, PH).

^{13}C NMR (62 MHz, $CDCl_3$): δ = 37.9 (d, $^2J_{C,P}$ = 1.8 Hz, C-2), 36.0 (d, $^1J_{C,P}$ = 34.8 Hz, C-1), 35.5 (C-4), 27.3 (d, $^3J_{C,P}$ = 9.4 Hz, C-3), –3.8 (d, $^1J_{C,P}$ = 47.0 Hz, PCH_3).

MS (EI, 70 eV): *m*/*z* (%) = 316 (M^+, 43.5), 135 (Ad^+, 100).

Anal. Calcd for $C_{21}H_{34}IP$ (444.38): C, 56.75; H, 7.65. Found: C, 56.58; H, 7.76.

Di(1-adamantyl)isopropylphosphonium Iodide (1f)
IR (KBr): 3420 (m, br), 2909 (s) 2851 (s), 2676 (w), 2268 (w), 1454 (m), 1342 cm^{-1} (m).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.63 (6 H, dd, $^3J_{H,H}$ = 7.3 Hz, $^3J_{P,H}$ = 15.9 Hz, 2 CH_3), 1.74–2.30 (30 H, m, adamantyl-30H), 2.90–3.10 (1 H, m, PCH), 7.62 (1 H, d, $^1J_{H,P}$ = 465.1 Hz, PH).

^{13}C NMR (62 MHz, $CDCl_3$): δ = 40.3 (d, $^1J_{C,P}$ = 29.1 Hz, C-1), 38.8 (d, $^2J_{C,P}$ = 2.8 Hz, C-2), 35.5 (d, $^4J_{C,P}$ = 1.8 Hz, C-4), 27.6 (d, $^3J_{C,P}$ = 9.4 Hz, C-3), 20.2 (d, $^1J_{C,P}$ = 34.8 Hz, isopropyl-CH), 20.2 (d, $^2J_{C,P}$ = 3.7 Hz, isopropyl-CH_3).

MS (EI, 70 eV): *m*/*z* (%) = 344 (M^+, 33.8), 135 (Ad^+, 100).

Anal. Calcd for $C_{23}H_{38}IP$ (472.43): C, 58.47; H, 8.05. Found: C, 58.92; H, 8.16.

Di(1-adamantyl)-2-methoxyethylphosphonium Bromide (1g)
IR (KBr): 3400 (m, br), 2930 (s), 2853 (s), 2823 (m), 2682 (w), 1451 (m), 1345 cm^{-1} (m).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.80–2.21 (30 H, m, adamantyl-30H), 2.58–2.69 (2 H, m, P-CH_2), 3.41 (3 H, s, OCH_3), 3.75–3.91 (2 H, m, OCH_2), 7.31 (1 H, d, $^1J_{H,P}$ = 472.8 Hz, PH).

^{13}C NMR (62 MHz, $CDCl_3$): δ = 66.6 (d, $^2J_{C,P}$ = 4.7 Hz, OCH_2), 59.1 (OCH_3), 38.2 (d, $^2J_{C,P}$ = 2.8 Hz, C-2), 37.4 (d, $^1J_{C,P}$ = 31.9 Hz, C-1), 35.6 (d, $^4J_{C,P}$ = 1.9 Hz, C-4), 27.5 (d, $^3J_{C,P}$ = 9.4 Hz, C-3), 14.4 (d, $^1J_{C,P}$ = 42.4 Hz, PCH_2).

MS (EI, 70 eV): *m*/*z* (%) = 360 (M^+, 16), 135 (Ad^+, 100).

Anal. Calcd for $C_{23}H_{38}BrOP$ (441.43): C, 62.58; H, 8.62. Found: C, 62.50; H, 8.72.

Di(1-adamantyl)-3-chloropropylphosphonium Iodide (1h)
IR (KBr): 3420 (s, br), 2914 (s) 2853 (s), 2284 (m), 1453 (m), 1343 cm^{-1} (m).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.75–2.41 (34 H, m, adamantyl-30H, 3-chloropropyl-4H), 3.79 (2 H, t, ^3J = 5.18 Hz, 3-chloropropyl-CH_2), 7.88 (1 H, d, $^1J_{H,P}$ = 468.5 Hz, PH).

^{13}C NMR (62 MHz, $CDCl_3$): δ = 45.3 (d, $^3J_{C,P}$ = 12.2 Hz, 3-chloropropyl-γ-CH_2), 37.9 (d, $^2J_{C,P}$ = 1.9 Hz, C-2), 37.9 (d, $^1J_{C,P}$ = 31.9 Hz, C-1), 35.6 (C-4), 29.1 (d, $^2J_{C,P}$ = 4.7 Hz, 3-chloropropyl-β-CH_2), 27.5 (d, $^3J_{C,P}$ = 9.4 Hz, C-3), 9.1 (d, $^1J_{C,P}$ = 40.4 Hz, 3-chloropropyl-α-CH_2).

MS (EI, 70 eV): *m*/*z* (%) = 378 (M^+, 35.5), 135(Ad^+, 100).

Anal. Calcd for $C_{27}H_{37}ClIP$ (506.88): C, 54.49; H, 7.31. Found: C, 54.06; H, 7.37.

Phosphines from Phosphonium Salts; General Procedure
Phosphonium salt (2.2 mmol) was added to a cooled solution (–78 °C) of Et_3N (4.44 g, 44 mmol) in di-*n*-butyl ether (20 mL). The reaction mixture was stirred at –78 °C for 5 h and then allowed to warm gradually to r.t. The solvent was removed under vacuum and the residue was dissolved in degassed EtOH (5 mL). After stirring for 15 min, the solid was filtered off and dried to yield the desired phosphine, which can be further purified by crystallization from EtOH.

Di(1-adamantyl)-*n*-butylphosphine (2a)
Mp 108–110 °C.

IR (KBr): 3425 (m, br), 2952 (s), 2847 (s), 2847 (s), 2675 (w), 1446 cm^{-1} (m).

^{1}H NMR (250 MHz, C_6D_6): δ = 0.96 (3 H, t, $^3J_{H,H}$ = 7.3 Hz, CH_3), 1.35–2.03 (36 H, m, adamantyl-30H, butyl-6H).

^{13}C NMR (62 MHz, C_6D_6): δ = 41.3 (d, $^2J_{C,P}$ = 11.3 Hz, C-2), 37.4 (C-4), 36.1 (d, $^1J_{C,P}$ = 23.5 Hz, C-1), 33.9 (d, $^1J_{C,P}$ = 26.2 Hz, butyl-α-CH_2), 29.1 (d, $^3J_{C,P}$ = 7.6 Hz, C-3), 24.9 (d, $^2J_{C,P}$ = 13.1 Hz, butyl-β-CH_2), 17.1 (d, $^3J_{C,P}$ = 21.6 Hz, butyl-γ-CH_2), 14.3 (butyl-CH_3).

MS (EI, 70 eV): *m*/*z* (%) = 358 (M^+, 60), 135 (Ad^+, 100).

Di(1-adamantyl)isobutylphosphine (2b)
Mp 150–152 °C.

IR (KBr): 3420 (m, br), 2947 (s), 2908 (s), 2886 (s), 2847 (s), 2677 (w), 1448 (m), 1344 cm^{-1} (m).

^{1}H NMR (250 MHz, C_6D_6): δ = 1.10 (6 H d, $^3J_{H,H}$ = 6.4 Hz, 2 isobutyl-CH_3), 1.20–1.30 (2 H, m, isobutyl-H), 1.60–2.00 (31 H, m, adamantyl-30H, isobutyl-1H).

^{13}C NMR (62 MHz, C_6D_6): δ = 41.3 (d, $^2J_{C,P}$ = 11.3 Hz, C-2), 37.4 (C-4), 36.1 (d, $^1J_{C,P}$ = 23.5 Hz, C-1), 29.5 (d, $^2J_{C,P}$ = 23.0 Hz, isobutyl-CH), 29.1 (d, $^3J_{C,P}$ = 7.5 Hz, C-3), 27.4 (d, $^1J_{C,P}$ = 22.6 Hz, PCH_2), 24.2 (d, $^3J_{C,P}$ = 9.4 Hz, 2 isobutyl-CH_3).

MS (EI, 70 eV): *m*/*z* (%) = 358 (M^+, 67.7), 135 (Ad^+, 100).

Di(1-adamantyl)allylphosphine (2c)
Mp 126–130 °C.

IR (KBr): 3400 (s, br), 2902 (s), 2676 (w), 1632 (w), 1449 (m), 1342 cm^{-1} (m).

^1H NMR (250 MHz, C_6D_6): δ = 1.46–2.00 (30 H, m, adamantyl-30H), 2.20–2.30 (2 H, m, PCH_2), 5.00–5.20 (2 H, m, allylic-CH_2), 5.90–6.10 (1 H, m, allylic-CH).

^{13}C NMR (62 MHz, C_6D_6): δ = 139.9 (d, $^3J_{C,P}$ = 18.8 Hz, allylic-CH_2), 114.8 (d, $^2J_{C,P}$ = 11.3 Hz, allylic-CH), 41.2 (d, $^2J_{C,P}$ = 11.3 Hz, C-2), 37.3 (C-4), 36.6 (d, $^1J_{C,P}$ = 33.8 Hz, C-1), 29.0 (d, $^3J_{C,P}$ = 8.4 Hz, C-3), 23.3 (d, $^1J_{C,P}$ = 22.6 Hz, PCH_2).

MS (EI, 70 eV): *m*/*z* = 342 (M^+, 33), 135 (Ad^+, 100).

Di(1-adamantyl)benzylphosphine (2d)
Mp 238–240 °C.

IR (KBr): 3424 (m, br), 2901 (s), 2848 (s), 2677 (w), 1493 (m), 1450 (m), 1342 cm^{-1} (m).

^1H NMR (250 MHz, C_6D_6): δ = 1.54–1.98 (30 H, m, adamantyl-30H), 2.75 (2 H, d, $^2J_{H,P}$ = 2.8 Hz, PCH_2), 7.02–7.24 (3 H, m, aromatic-3H), 7.51 (2 H, d, $^3J_{H,H}$ = 7.9 Hz, aromatic-2H).

^{13}C NMR (62 MHz, C_6D_6): δ = 130.2 (d, $J_{C,P}$ = 9.4 Hz, 2 aromatic-CH), 128.4 (s, 2 aromatic-CH), 125.5 (d, $^5J_{C,P}$ = 2.3 Hz, aromatic-CH), 41.3 (d, $^2J_{C,P}$ = 11.2 Hz, C-2), 37.3 (C-4), 36.7 (d, $^1J_{C,P}$ = 21.6 Hz, C-1), 29.0 (d, $^3J_{C,P}$ = 8.5 Hz, C-3), 24.9 (d, $^1J_{C,P}$ = 24.4 Hz, P-CH_2).

MS (EI, 70 eV): *m*/*z* = 392 (M^+, 32), 135 (Ad^+, 100).

Di(1-adamantyl)methylphosphine (2e)
Mp 159–160 °C.

IR (KBr): 3420 (m, br), 2909 (s), 2899 (s), 2847 (s), 2676 (w), 1447 cm^{-1} (m).

^1H NMR (250 MHz, C_6D_6): δ = 0.87 (3 H, d, $^2J_{H,P}$ = 4.6 Hz, CH_3), 1.58–1.98 (30 H, m, adamantyl-30H).

^{13}C NMR (62 MHz, C_6D_6): δ = 40.9 (d, $^2J_{C,P}$ = 11.1 Hz, C-2), 37.4 (C-4), 34.9 (d, $^1J_{C,P}$ = 21.7 Hz, C-1), 29.1 (d, $^3J_{C,P}$ = 7.6 Hz, C-3), 0.14 (d, $^1J_{C,P}$ = 11.1 Hz, P-CH_3).

MS (EI, 70 eV): *m*/*z* (%) = 316 (M^+, 25.8), 135 (Ad^+, 100).

Suzuki Reaction of 4-Chlorotoluene with Phenylboronic Acid; Typical Procedure
An *ACE* pressure tube (Aldrich) was evacuated, flushed with argon and charged with phenylboronic acid (487 mg, 4.0 mmol), potassium phosphate (636 mg, 3.0 mmol), $Pd(OAc)_2$ (0.1 mol%) and the corresponding ligand (0.2 mol%), and hexadecane (100 μL, internal standard). The tube was evacuated and flushed with argon and 4-chlorotoluene (379 mg, 3.0 mmol) and toluene (8 mL) were added and the mixture was stirred under argon at 100 °C for 20 h. After cooling to r.t., the reaction mixture was diluted with CH_2Cl_2 and washed with 1 N aq NaOH (3 ×). The organic phase was dried ($MgSO_4$) and analyzed by GC. Alternatively, 4-methylbiphenyl can be purified by column chromatography.

4-Methylbiphenyl
^1H NMR (400 MHz, $CDCl_3$): δ = 2.44 (3 H, s, CH_3), 7.29 (2 H, m), 7.36 (1 H, m), 7.47 (2 H, m), 7.54 (2 H, m), 7.63 (2 H, m).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 141.1, 138.1 137.0, 129.5, 128.7, 127.0, 126.9, 126.9, 21.1.

MS (EI, 70 eV): *m*/*z* (%) = 168 (M^+, 100), 152 ($M^+ - CH_3$, 15).

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