Optimization of Procedures for the Syntheses of Bisphosphinepalladium(0) Precursors for Suzuki−Miyaura and Similar Cross-Coupling Catalysis: Identification of 3:1 Coordination Compounds in Catalyst Mixtures Containing Pd(0), PCy_3, and/or $PMeBu^t{}_2$

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Although $Pd[PCy_3]_2$, $Pd[PMeBu^t{}_2]_2$, $Pd[PBu^t{}_3]_2$, and a large number of similar bisphosphinepalladium(0) compounds are excellent cross-coupling catalysts, most are not readily synthesized and stored, and research involving their utilization generally relies on *in situ* synthetic processes that proceed at unknown rates and in unknown yields. This paper describes, in part, the development of an efficient synthetic route to the representative catalysts $Pd[PCy_3]_2$, $Pd[PMeBu^t{}_2]_2$, and $Pd[PBu^t{}_3]_2$ via reactions of $Pd(\eta^3\text{-}C_3H_5)(\eta^5\text{-}C_5H_5)$ with 2 equiv each of PCy_3, $PMeBu^t{}_2$, or $PBu^t{}_3$. The procedures, which may be generally useful, are optimized such that known concentrations of the bisphosphine catalysts may be generated quickly, reliably, and under mild conditions. That said, the chemistry of the 2:1 compounds can be surprisingly complex; although $Pd[PBu^t{}_3]_2$ shows no inclination to increase its coordination number, $Pd[PCy_3]_2$ and $Pd[PMeBu^t{}_2]_2$ react with added PCy_3 or $PMeBu^t{}_2$ to form 3:1 coordination compounds. Equilibrium constants for dissociation of the compounds PdL_3 to PdL_2 + free L (L = PCy_3, $PMeBu^t{}_2$) were measured over a range of temperatures, and from the resulting linear plots of ln K_D vs $1/T$, ΔH and ΔS values of 21 kJ mol^{-1} and 59 J deg^{-1} mol^{-1}, respectively, were determined for the PCy_3 system, and 23 kJ mol^{-1} and 86 J deg^{-1} mol^{-1}, respectively, for $PMeBu^t{}_2$. The enthalpy values provide a rough measure of the Pd−P bond dissociation energies, which are, as expected, considerably lower than both the single Pd(II)−phosphine and the single Pt(0)−phosphine bond energies that have been reported (both ~55 kJ mol^{-1}). The significant formation of the catalytically less active 3:1 compounds has serious implications for many of the published catalytic cross-coupling processes that involve catalyst formation via the slow reduction of palladium(II) precursors in the presence of excess phosphine; for many such systems, relatively little of the added palladium may actually be present as the catalytically active bisphosphinepalladium(0) compound.

Introduction

The discovery and development of palladium-catalyzed Suzuki−Miyaura cross-coupling reactions have revolutionized methodologies for the formation of carbon−carbon bonds and have thereby profoundly changed the strategies for the construction of many types of complex organic molecules.[1] In the general case, an aryl halide ArX (X = Cl, Br, I) reacts catalytically with an arylborate species $[Ar'BY_3]^-$ (Y = halide, alkoxide, etc.) to form the coupled product Ar−Ar′, although extensions to coupling of alkyl halides are also being explored. The most widely accepted catalytic cycle (Scheme 1) typically involves oxidative addition of ArX to what is believed to be a homoleptic bisphosphine Pd(0) compound PdL_2 (L = tertiary phosphines), followed by transmetalation and reductive elimination steps.[1]

High temperatures and long reaction times are often utilized to obtain good yields of cross-coupling products, and attempts to improve reaction efficiencies have included varying the nature of the phosphines L (sterically demanding phosphines often seem to be best), the L:Pd ratio, the solvent, the temperature, added salts and bases, and Y.[1] Interestingly, a possibly central variable that has not generally been considered is the extent to which the putative catalytic species, PdL_2, is actually present in solution. Bisphosphine Pd(0) compounds not only are extremely air sensitive but also are prone to expand their coordination spheres to form species of the types PdL_2L' and $PdL_2L'_2$ (L′ = CO, alkenes, alkynes, phosphines) and to form clusters containing Pd−Pd bonds.[2] Therefore, because of their delicate and often unpredictable nature, preformed bisphosphine compounds are rarely utilized.

Instead more readily accessible compounds, such as the relatively poor catalyst $Pd(PPh_3)_4$,[2d,g,k,l] are utilized or the phosphine to be used is added to solutions of precursor Pd(0) compounds such as $Pd(dba)_2$ and $Pd_2(dba)_3$ (dba = *trans,trans*-

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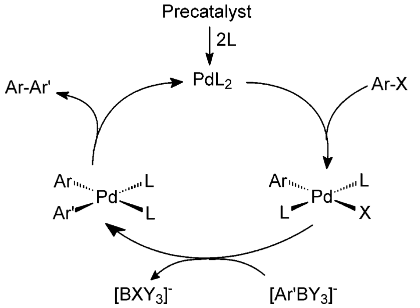
Scheme 1



dibenzylideneacetone).[3] In the case of Pd(dba)$_2$ and Pd$_2$(dba)$_3$, it was at one time generally assumed that the dba is completely displaced or, if not, that it does not impede oxidative addition. However there has now accrued ample evidence that alkenes containing electron-withdrawing groups, including dba, bind very strongly to Pd(0) and are not always fully displaced by tertiary phosphines.[4] Furthermore, for a combination of electronic and steric reasons, dba is found to actually inhibit many oxidative addition reactions.[4]

Catalyst solutions are alternatively generated by adding a phosphine to a suspension or solution of a Pd(II) compound such as Pd(OAc)$_2$ or PdCl$_2$, sometimes in the presence of a base, the assumption made being that the Pd(II) salts are somehow reduced to Pd(0) compounds.[1] Although suggestions of relevance for a number of reducing processes have appeared for a variety of palladium-based catalytic systems, there seems in fact to be a paucity of careful studies establishing the usefulness, general or specific, of any class of reducing agents. Indeed, for most of the phosphine/palladium catalyst systems used, there is little or no evidence that substantial reduction is effected either rapidly or completely.

Indeed, although tertiary phosphines themselves may serve as reducing agents[5] and it has long been known that triarylphosphines in DMF reduce Pd(OAc)$_2$ and Pd(OCOCF$_3$)$_2$ via the corresponding bisphosphine Pd(II) compounds,[4a,5b,d,e,f] the analogous halo compounds PdX$_2$(PPh$_3$)$_2$ (X = Cl, Br, I) are stable with respect to reduction in this way.[5a] On the other hand, unidentified but presumed Pd(0) compounds are formed when Pd(OAc)$_2$ and PdCl$_2$ are treated with PBu$_3$ in benzene and THF,[5c] and reactions of Pd(OAc)$_2$ with PBu$_3$, PMe$_2$Ph, and PMePh$_2$ give similar species in DMF at 60 °C.[5d] Thus reduction to Pd(0) does seem to occur in some instances although the species produced have not in fact been identified. Interestingly, under the particular conditions of the latter study, reduction is inhibited by bulky substituents on the phosphorus[5d] such that reduction of even Pd(OAc)$_2$ by monodentate phosphines becomes disfavored when the phosphine cone angle is $\sim$130°. This corresponds approximately to the size of PEt$_3$,[6] and thus reduction of Pd(OAc)$_2$ by the bulkier phosphines normally utilized in Suzuki cross-coupling reactions[1] is problematic. For instance, the commonly used PCy$_3$, PMeBu$^t_2$, and PBu$^t_3$ have cone angles of 170°,[6] 161°,[7] and 182°,[6] respectively.

The question arises then, if one particular palladium(II)−phosphine cross-coupling catalyst system is found to be more effective than another, does the difference arise because one phosphine is intrinsically superior, as is generally claimed or implied? Or does the difference arise because more of the Pd(II) precursor is reduced in the one case than in the other? Furthermore, in situations where, in spite of the addition of excess phosphine, reduction of the Pd(II) is far from complete such that the ratio L:Pd(0) $\gg$ 1, say 100:1 or 1000:1, might the major palladium(0) species in solution *for some phosphines* be predominantly a less active species PdL$_3$ or PdL$_4$, depending on the steric requirements of L? The importance of and difficulties in identifying the true catalyst(s) in the plethora of processes investigated has been explicitly recognized,[1n,5g] although it *may* be an exaggeration to suggest that the "literature has grown into a morass, with an endless list of hypothesized or claimed true catalytic species".[1n]

However, as mentioned above, high temperatures and long reaction times are often required to obtain good yields in Suzuki−Miyaura aryl−aryl cross-coupling reactions. If one hypothesizes that somewhat extreme conditions may be necessary in order that a Pd(0) catalyst species be formed in catalytically effective concentrations, then a mild and efficient method to produce bisphosphine Pd(0) compounds unambiguously would permit an accurate assessment of the relative merits of various phosphines in the catalytic cycle. It might also result in the realization of much milder reaction conditions for cross-coupling reactions involving otherwise poorly reducible Pd(II) precatalysts, a potentially useful development where thermally sensitive functionality in cross-coupling substrates would preclude the use of high temperatures for prolonged periods of time.

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In order to explore these possibilities, we have begun a study of cross-coupling reaction chemistry in which we have determined initially the mildest conditions under which useful compounds of the specific stoichiometry PdL_2 may be generated unambiguously, quantitatively, quickly, and under mild conditions. The method chosen utilizes $Pd(\eta^3\text{-}C_3H_5)(\eta^5\text{-}C_5H_5)$,[8] which, on heating in the absence of potential ligands, reductively eliminates $C_5H_5-C_3H_5$ (as a mixture of isomers) and deposits palladium metal.[9] It also reacts with phosphines L to give, following reductive elimination of $C_5H_5-C_3H_5$, Pd(0) compounds of the types PdL_n ($n = 2-4$);[2f,h,m,p,10] σ-allyl compounds of the type $\eta^5\text{-}C_5H_5Pd(\eta^1\text{-}C_3H_5)L$ and dinuclear species of the type $Pd_2L_2(\mu\text{-}C_5H_5)(\mu\text{-}C_3H_5)$ are often intermediates.[11]

Although $Pd(\eta^3\text{-}C_3H_5)(\eta^5\text{-}C_5H_5)$ has been used in this way previously to generate Pd(0) cross-coupling catalysts,[2f,h,m,p,10] a systematic study to determine the optimal conditions for catalyst generation has not previously been carried out. We have now determined and herein report the optimum (i.e., minimum temperature, maximum time required) conditions under which the representative, catalytically very important[1a,b,g,h] compounds PdL_2 (L = PCy_3,[2e,g] $PMeBu^t_2$,[2p] PBu^t_3[2f,m,o]) are generated cleanly and essentially quantitatively.

Complementing these findings, and relevant to understanding cross-coupling processes under the commonly occurring circumstances where L:Pd(0) $\gg$ 1 (see above), we have also determined the conditions in which significant proportions of palladium(0) species produced are present as the homoleptic 3:1 compounds PdL_3 (L = PCy_3, $PMeBu^t_2$), in equilibrium with the corresponding 2:1 species PdL_2 (K_D of Scheme 2), and the thermodynamic parameters for dissociation of PdL_3 to PdL_2 + L (L = PCy_3, $PMeBu^t_2$). The heteroleptic species $Pd[PCy_3][PMeBu^t_2]$, $Pd[PMeBu^t_2][PBu^t_3]$, $Pd[PCy_3][PBu^t_3]$, $Pd[PCy_3][PMeBu^t_2]_2$, and $Pd[PCy_3]_2[PMeBu^t_2]$ are also formed in mixed phosphine systems. In a following paper,[12] we shall describe a related kinetics study of the oxidative addition of PhBr to $Pd(PCy_3)_n$ (n = 1, 2, 3), of importance as the first step of the Suzuki-Miyaura cross-coupling catalytic cycles involving this very important, representative catalyst system.

Scheme 2

$$Pd[PCy_3]_3 \overset{K_D}{\rightleftharpoons} Pd[PCy_3]_2 + PCy_3$$

Experimental Section

All syntheses were carried out under a dry, deoxygenated argon atmosphere using standard Schlenk line techniques. Argon was deoxygenated by passage through a heated column of BASF copper catalyst and then dried by passing through a column of 4 Å molecular sieves. Handling and storage of air-sensitive organometallic compounds were done in an MBraun Labmaster glovebox, and NMR spectra were recorded using a Bruker AV 600 spectrometer. ^{31}P NMR spectra were run at 242.95 MHz and are referenced with respect to external 85% H_3PO_4; data are given in Table 1, although it should be noted that the chemical shifts vary somewhat with temperature. ^1H and ^{13}C NMR data are referenced to TMS via the residual proton signals of the deuterated solvents.

Table 1. ^{31}P NMR Data (at 25 °C in toluene-d_8 unless otherwise indicated)

compound	δ (free L)	δ (PCy_3)	δ ($PMeBu^t_2$)	δ (PBu^t_3)	^2J(P−P) (Hz)
$Pd[PCy_3]_2$	9.89	39.2			
$Pd[PCy_3]_3$		25.5[a]			
$Pd[PMeBu^t_2]_2$	11.4		41.9		
$Pd[PMeBu^t_2]_3$			30.3[b]		
$Pd[PBu^t_3]_2$	63.3			84.7	
$Pd[PCy_3][PMeBu^t_2]$		40.3[c]	40.8[c]		300
$Pd[PMeBu^t_2][PBu^t_3]$			41.8	85.4	246
$Pd[PCy_3][PBu^t_3]$		41.4		85.2	241

[a] At −68 °C. [b] At −88 °C. [c] In benzene-d_6 at 25 °C; calc as an AB spin system.

Toluene-d_8 and benzene-d_6 (Cambridge Isotope Laboratories, Inc. or CDN Isotopes) were degassed under vacuum and dried by passage through a small column of activated alumina before being stored over 4 Å molecular sieves. The phosphines PCy_3, $PMeBu^t_2$, and PBu^t_3 were obtained from Strem and used without further purification. Tetraoctylphosphonium bromide (TOPB) was purchasd from Aldrich and dried under vacuum at 45 °C prior to use. The compounds $Pd(\eta^3\text{-}C_3H_5)(\eta^5\text{-}C_5H_5)$,[8] $Pd[PCy_3]_2$,[2m] $Pd[PMeBu^t_2]_2$,[2m] and $Pd[PBu^t_3]_2$[2m] were prepared according to the literature. While the ^{31}P resonances of the three bisphosphine compounds were all sharp singlets at 25 °C and below, the ^{31}P resonances of $Pd[PCy_3]_2$ and $Pd[PMeBu^t_2]_2$ broadened significantly in the presence of free PCy_3 or $PMeBu^t_2$ at 25 °C. The resonances of coordinated PBu^t_3 remained sharp under all circumstances.

***In Situ* Generation of PdL_2 (L = PCy_3, $PMeBu^t_2$, PBu^t_3).** In a typical reaction, 4.5 mg of $Pd(\eta^3\text{-}C_3H_5)(\eta^5\text{-}C_5H_5)$ (0.021 mmol) in 0.18 mL of C_6D_6 was combined with 12 mg of PCy_3 (0.043 mmol) in 0.3 mL of C_6D_6 in an NMR tube, and a ^{31}P NMR spectrum of the solution was run every 10 min for 2 h at 25 °C. Similar experiments were carried out for various periods of time in the temperature range 65−80 °C and using $PMeBu^t_2$ and PBu^t_3 at various temperatures.

***In Situ* Generation of $Pd[PCy_3][PMeBu^t_2]$.** A solution of 4.4 mg of $Pd[PMeBu^t_2]_2$ (0.010 mmol) in 0.5 mL of benzene-d_6 was added to a solution of 7.2 mg of $Pd[PCy_3]_2$ (0.011 mmol) in 0.5 mL of benzene-d_6 at 21 °C, and a ^{31}P NMR spectrum was obtained at 25 °C. In a complementary experiment, 10 mg of $Pd[PCy_3]_2$ (0.015 mmol) in 0.7 mL of toluene-d_8 was treated with 2.5 mg of $PMeBu^t_2$ (0.015 mmol) in 0.3 mL of toluene-d_8 at 21 °C, and ^{31}P NMR spectra were obtained in the temperature range 25 to −93 °C. Similarly 27 mg of $Pd[PCy_3]_2$ (0.04 mmol) in 0.7 mL of toluene-d_8 was treated with 13 mg of $PMeBu^t_2$ (0.082 mmol) in 0.016 mL of toluene-d_8 at 21 °C, and a $^{31}P-^{31}P$ NMR correlation spectrum was obtained at −88 °C.

***In Situ* Generation of $Pd[PCy_3][PBu^t_3]$.** A solution of 7.3 mg of PBu^t_3 (0.036 mmol) in 0.18 mL of toluene-d_8 was added to 10 mg of PCy_3 (0.036 mmol) in 0.25 mL of toluene-d_8 in an NMR tube. The sample was preheated to 77 °C, and 7.6 mg of $Pd(\eta^3\text{-}C_3H_5)(\eta^5\text{-}C_5H_5)$ (0.036 mmol) in 0.25 mL of toluene-d_8 was added. The sample was heated for 1 h at 77 °C, then cooled to 21 °C, and a ^{31}P NMR spectrum was then obtained at 21 °C. Alternatively 7.0 mg of $Pd[PCy_3]_2$ (0.011 mmol) in 0.5 mL of toluene-d_8 was added to 7.3 mg of $Pd[PBu^t_3]_2$ (0.014 mmol) in 0.2 mL of toluene-d_8 at 21 °C, and a ^{31}P NMR spectrum was then obtained.

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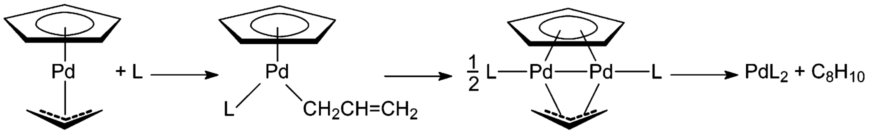

Figure 1. Reaction sequence in the formation of PdL_2.

***In Situ* Generation of Pd[PMeBu$^t_2$][PBu$^t_3$].** A solution of 71 mg of Pd[PMeBu$^t_2$]$_2$ (0.17 mmol) and 89 mg of Pd[PBu$^t_3$]$_2$ (0.17 mmol) was made up in 0.65 mL of toluene-d_8 at 21 °C, and a ^{31}P NMR spectrum was obtained at 25 °C.

Determination of K_D for PdL$_3$ (L = PCy$_3$, PMeBu$^t_2$). In a typical experiment, 6.1 mg of Pd[PCy$_3$]$_2$ (9.8×10^{-3} mmol) in 0.5 mL of toluene-d_8 was added to 2.5 mg of PCy$_3$ (9.0×10^{-3} mmol) in 0.1 mL of toluene-d_8. The resulting solution was diluted with an additional 0.2 mL of toluene-d_8, a glass capillary containing a toluene-d_8 solution of tetraoctylphosphonium bromide (TOPB) (0.046 M, 3.0×10^{-3} mmol) was added ([Pd(PCy$_3$)$_2$]$_o$ = [PCy$_3$] = 0.011 M), and ^{31}P inverse-gated NMR spectra were obtained between −85 and −68 °C with d_1 = 45 s. Similar experiments were carried out using PMeBu$^t_2$.

Results and Discussion

Syntheses of the Homoleptic Compounds PdL$_2$ (L = PCy$_3$, PMeBu$^t_2$, PBu$^t_3$). A small number of Pd(0) compounds PdL$_2$ have been prepared previously via reactions of Pd(η^3-C$_3$H$_5$)(η^5-C$_5$H$_5$) with tertiary phosphines,[2f,h,m,p,10] but there have apparently been no attempts to ascertain the conditions under which 2:1 compounds are best prepared. We have therefore monitored by ^{31}P NMR spectroscopy the reactions of Pd(η^3-C$_3$H$_5$)(η^5-C$_5$H$_5$) with 2 equiv each of the representative phosphines PCy$_3$, PMeBu$^t_2$, and PBu$^t_3$, all of great relevance in the context of catalytic Suzuki−Miyaura cross-coupling reactions.[2p,10h,i,13,14] In this way we have determined the optimal conditions (lowest temperature for quantitative conversion in minimal time) under which specifically the compounds Pd[PCy$_3$]$_2$, Pd[PMeBu$^t_2$]$_2$, and Pd[PBu$^t_3$]$_2$ are obtained in toluene-d_8.

Conversion of Pd(η^3-C$_3$H$_5$)(η^5-C$_5$H$_5$) to the 2:1 compounds is expected to proceed as in Figure 1, via the types of η^1-allyl and dinuclear intermediates shown.[11] Reactions of Pd(η^3-C$_3$H$_5$)(η^5-C$_5$H$_5$) with 2 equiv each of PCy$_3$ or PMeBu$^t_2$ at 25 °C (Figure 2a for L = PCy$_3$) were found to proceed slowly to produce intermediate species exhibiting ^{31}P resonances at δ 27.8 and 35.4, respectively, attributable to the corresponding dinuclear species,[11] in addition to extremely broad resonances at δ 54.6 and 61.0, respectively, attributable to the η^1-allyl intermediates.[11c] After a day at this temperature, there were observed no ^{31}P resonances at δ 39.4 or 41.0, the chemical shifts of the 2:1 compounds Pd[PCy$_3$]$_2$ and Pd[PMeBu$^t_2$]$_2$, respectively.[2p,15]

Supporting these conclusions, the ^{1}H NMR spectrum of the Pd(η^3-C$_3$H$_5$)(η^5-C$_5$H$_5$)/PCy$_3$ reaction mixture in toluene-d_8 at 25 °C exhibited a broadened η^5-C$_5$H$_5$ singlet of Pd(η^3-C$_3$H$_5$)(η^5-C$_5$H$_5$) at δ 5.84 and a new sharp singlet at δ 6.03, attributed to the dinuclear species Pd$_2$(PCy$_3$)$_2$(μ-C$_3$H$_5$)(μ-C$_5$H$_5$). The resonance at δ 6.03 gained in intensity over the course of the reaction and exhibited an HSQC correlation to a ^{13}C resonance at δ 89.9, consistent with a coordinated η^5-C$_5$H$_5$ ligand in a dinuclear species,[11b] while the ^{1}H resonance at δ 5.84 diminished. Concurrently a third broad resonance, attributable to the η^5-C$_5$H$_5$ ligand of an intermediate η^1-allyl species, appeared at δ 6.28. As reported previously for other phosphines,[11c] it seems that Pd(η^3-C$_3$H$_5$)(η^5-C$_5$H$_5$) reacts with PCy$_3$ reversibly to produce the intermediate η^1-allyl species, which in turn forms irreversibly the dinuclear species Pd$_2$(PCy$_3$)$_2$(μ-C$_3$H$_5$)(μ-C$_5$H$_5$). While ^{1}H resonances anticipated for an η^1-allyl intermediate were not observed at 25 °C, such species are fluxional and rapid exchange processes would undoubtedly result in extensive broadening. In addition to the above, new ^{1}H resonances also emerged over the course of the reaction in the regions δ ∼6−6.5, ∼5.7, ∼4.9, and ∼3; these are attributed to the products of reductive elimination, C$_5$H$_5$−C$_3$H$_5$, formed as a mixture of isomers.[11]

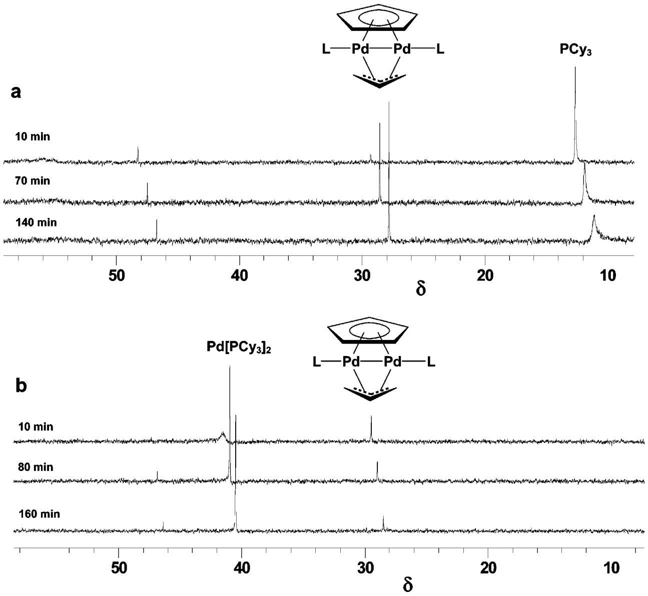

Figure 2. Stacked plots of ^{31}P NMR spectra for reaction of Pd(η^3-C$_3$H$_5$)(η^5-C$_5$H$_5$) with 2 equiv of PCy$_3$ (a) at 25 °C and (b) at 65 °C.

Similarly, the Pd(η^3-C$_3$H$_5$)(η^5-C$_5$H$_5$)/PMeBu$^t_2$ system reacted in toluene-d_8 at 25 °C to produce a new species with a resonance at δ 6.02, consistent with the coordinated η^5-C$_5$H$_5$ ring of a dinuclear species. Two virtual triplets appeared at δ 1.08 (6.3 Hz splitting) and 1.00 (6 Hz splitting) and are attributed respectively to the Bu^t and PMe groups on the mutually trans phosphines of Pd$_2$(PMeBu$^t_2$)$_2$(μ-C$_3$H$_5$)(μ-C$_5$H$_5$). In addition, resonances of the anticipated reductive elimination products C$_5$H$_5$−C$_3$H$_5$ appeared as above.

At 65 °C (Figure 2b for L = PCy$_3$), the dinuclear species Pd$_2$L$_2$(μ-C$_3$H$_5$)(μ-C$_5$H$_5$) (L = PCy$_3$, PMeBu$^t_2$) were slowly consumed to produce the anticipated 2:1 products Pd[PCy$_3$]$_2$ (δ 39.4[15]) and Pd[PMeBu$^t_2$]$_2$ (δ 41.0[2p]). In contrast, and of note, at 77 °C the 2:1 compounds Pd[PCy$_3$]$_2$ (δ 39.5) and Pd[PMeBu$^t_2$]$_2$ (δ 43.9) were both formed quantitatively within 1 h. In both cases, the anticipated resonances for the reductive elimination products C$_5$H$_5$−C$_3$H$_5$ were also observed in the ^{1}H NMR spectra, while for the PMeBu$^t_2$ system broad singlets at δ 1.26 and 1.03 appeared and are attributed to the Bu^t and PMe groups, respectively, of Pd[PMeBu$^t_2$]$_2$.

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In contrast, we find that PBu^t_3 generates neither η^1-allyl nor dinuclear intermediate species at 25 °C in toluene-d_8, as has been noted elsewhere;[11e] only $Pd[PBu^t_3]_2$ is formed in a reaction that is complete within 1 h at 25 °C. The ^{31}P and ^1H NMR spectra (25 °C) exhibit resonances respectively at δ 86.0 (δ 85.2 in C_6D_6[16]) and at δ 1.49 (virtual triplet, 5.6 Hz splitting) (δ 1.53, 5.7 Hz splitting in C_6D_6[16]). The compound $Pd[PBu^t_3]_2$ is also formed quantitatively in about 30 min at 77 °C (^{31}P: δ 88.4; ^1H: δ 1.49, 5.6 Hz splitting). It seems likely in this system that an η^1-allyl species is formed initially but that the steric bulk of the PBu^t_3 ligand induces rapid reductive elimination of $C_5H_5{-}C_3H_5$. The anticipated resonances of the latter are observed in the ^1H NMR spectra of the reaction mixtures at both 25 and 77 °C.

Homoleptic Compounds PdL_3; Equilibria between PdL_2 and PdL_3. The analysis described above inevitably involved on occasion the addition of slight excesses or deficiencies of the phosphines because of the small amounts of materials being reacted, and we became aware of other apparent Pd(0) species that were also being formed. In some cases there was observed exchange broadening that implicated species other than the 2:1 compounds being investigated, while low-temperature spectra sometimes exhibited weak resonances that could not be accounted for.

There is certainly precedent for 3:1 compounds PdL_3 existing in solution in equilibrium with the corresponding 2:1 compounds,[2g,17] as in Scheme 2, but these usually involve sterically undemanding ligands and perhaps would not be expected to be very important in the chemistry of the three relatively large phosphine ligands of interest here. On the other hand, there is considerable speculation in the literature concerning possible equilibria between 2:1 and 1:1 compounds and the possible role(s) of monophosphine compounds PdL in cross-coupling reactions,[1m,18] and it was decided to investigate further the palladium(0) systems being formed. Therefore, for all three phosphines, experiments were carried out in which 1 equiv of the phosphine was added to a solution of the PdL_2 compound in toluene-d_8 and the ^{31}P NMR spectra were obtained at various temperatures.

Although the ^{31}P NMR spectrum of pure $Pd[PCy_3]_2$ at 25 °C exhibits a sharp resonance at δ 39.2 (Table 1), the ^{31}P NMR spectrum of a solution containing equimolar amounts of $Pd[PCy_3]_2$ and PCy_3 at this temperature exhibits only broadened resonances at δ 39.7 and 9.44, respectively, very close to the chemical shifts of $Pd[PCy_3]_2$ and PCy_3 alone and hence attributed to these compounds undergoing exchange. On cooling the solution (Figure 3), the two resonances sharpen somewhat and shift slightly, and at −56 °C a new broad resonance appears at δ 26.3. At −68 °C the latter is clearly apparent and of intensity comparable with that of the 2:1 compound (Figure 3). The resonance is not observed in low-temperature ^{31}P NMR spectra containing just $Pd[PCy_3]_2$, and therefore, consistent with a previous report based on relatively low field spectra (36.43 MHz),[2g] it is attributed to the 3:1 compound $Pd[PCy_3]_3$ rather than the 1:1 analogue $Pd[PCy_3]$.

Since the ^{31}P resonances of all three compounds PCy_3, $Pd[PCy_3]_2$, and $Pd[PCy_3]_3$ are observable over a range of temperatures, the opportunity was presented to measure the equilibrium constant K_D (see Scheme 2) as a function of temperature and hence to obtain thermodynamic data for this system in toluene-d_8. To this end, the concentrations of all three species in a 1:1 mixture of PCy_3 and $Pd[PCy_3]_2$ were determined via integrations in the temperature range −68 to −85 °C, mass balances being ensured by relating all intensity measurements to the constant intensity of a very narrow ^{31}P resonance of a solution of tetraoctylphosphonium bromide (TOPB) standard in toluene-d_8 and contained in a glass capillary inserted into the NMR tube.

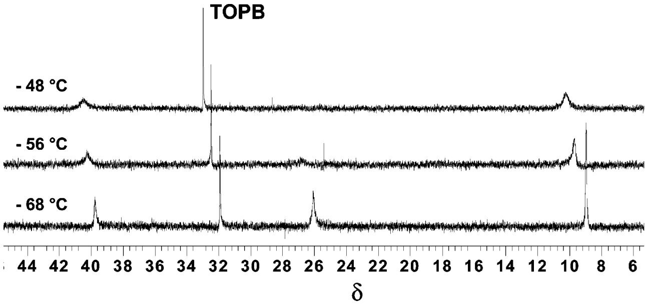

Figure 3. Stacked plots of low-temperature ^{31}P inverse gated NMR spectra for reaction of $Pd[PCy_3]_2$ with 1 equiv of PCy_3 (242.95 MHz).

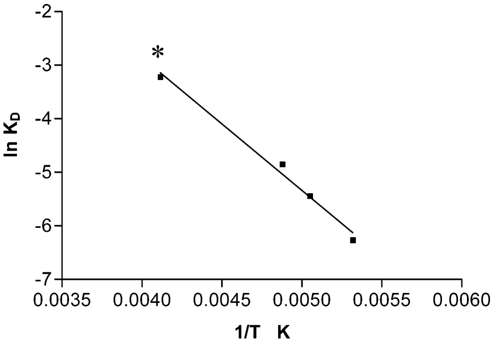

Figure 4. Plot of ln K_D as a function of $1/T$ for the dissociation of $Pd[PCy_3]_3$ ($R^2 = 0.988$) (* point from ref 2g).

A linear plot of ln K_D vs $1/T$ was obtained (Figure 4), from which values of ΔH and ΔS were found to be 21 kJ mol^{-1} and 59 J deg^{-1} mol^{-1}, respectively. Extrapolation of this plot indicates that K_D is 0.3 at 25 °C and 1.5 at 100 °C. Thus, for situations posited in the Introduction in which excess PCy_3 has been added to a Pd(II) precursor and the ratio of PCy_3:Pd(0) in an attempted cross-coupling reaction might be 100:1, the proportion of the total palladium present as $Pd[PCy_3]_3$ could be 84% at 25 °C and 48% at 100 °C. On the other hand, if the ratio of PCy_3:Pd(0) was, say, 1000:1, as might be the case in the very early stages of any cross-coupling reaction involving Pd(II) precatalysts and excess PCy_3, the proportion of the total palladium present as $Pd[PCy_3]_3$ at 25 and 100 °C could be 98% and 90%, respectively.

Similar ^{31}P NMR experiments involving 1:1 mixtures of $Pd[PMeBu^t_2]_2$ and $PMeBu^t_2$ in toluene-d_8 resulted in similar observations, with a resonance attributable to $Pd[PMeBu^t_2]_3$ being observed at δ ~30.3 over a range of temperatures. A linear plot of ln K_D vs $1/T$ was again obtained, from where ΔH and ΔS values 23 kJ mol^{-1} and $\Delta S = 86$ J deg^{-1} mol^{-1}, respectively, were obtained. Extrapolation to 25 and 100 °C yielded K_D values at these temperatures of 3 and 19, respectively. Therefore a 100:1 mixture of $PMeBu^t_2$ and $Pd[MeBu^t_2]_2$ under the conditions decribed above could contain 32% of the total palladium as $Pd(MeBu^t_2)_3$ at 25 °C and 7% at the higher temperature. Similarly, if the $PMeBu^t_2$:Pd(0) ratio was 1000:1, then the total palladium present as $Pd(MeBu^t_2)_3$ at 25 and 100 °C could be 83% and 42% respectively.

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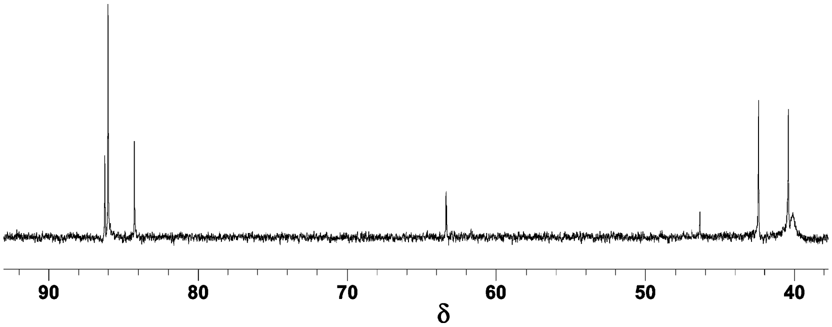

Figure 5. ^{31}P NMR spectrum (25 °C) of the reaction of Pd(η^3-C_3H_5)(η^5-C_5H_5) with 1 equiv of PCy_3 and 1 equiv of PBu^t_3.

In contrast, ^{31}P NMR spectra of a 1:1 solution of PBu^t_3 and Pd[PBu^t_3]$_2$ in toluene-d_8 exhibit two unbroadened resonances for the two compounds over the entire temperature range 0 to −73 °C, implying that any exchange must be slow on the NMR time scale. There is thus no evidence for the formation of Pd[PBu^t_3]$_3$, reasonable in view of the much larger cone angle of this ligand.[6] The great steric requirements of this ligand have been noted elsewhere[10f,13] as being of significance in their effect on cross-coupling reactions using Pd[PBu^t_3]$_2$.

The Δ*H* values presented above, 21 and 23 kJ mol^{-1} for respectively the PCy_3 and $PMeBu^t_2$ systems, presumably provide reasonable approximations of the Pd−P bond dissociation energies. If so, then the Pd(0)−phosphine bond energies of these two 3:1 coordination compounds are considerably lower than are those determined for many other types of phosphine−transition metal complexes.[19a] They are also, as would be anticipated, significantly lower than the only available bond dissociation energy of a Pd(II)−phosphine compound (54 kJ mol^{-1})[19b] and the Pt−PCy_3 bond dissociation energy of the Pt(0) compound Pt[PCy_3]$_3$ (55 kJ mol^{-1}).[19c]

Syntheses of the 2:1 Heteroleptic Compounds PdLL′ (L, L′ = PCy_3, $PMeBu^t_2$, PBu^t_3); Identification of the Corresponding 3:1 Compounds. As indicated above, *in situ* identification of the 2:1 compounds Pd[PCy_3]$_2$, Pd[$PMeBu^t_2$]$_2$, and Pd[PBu^t_3]$_2$ was readily made on the basis of comparisons with spectra of authentic samples in addition to previously published spectroscopic data for these compounds.[2m,p,15,16] Our identification of the 3:1 homoleptic species formed *in situ* on addition of excess PCy_3 or $PMeBu^t_2$ to solutions of Pd[PCy_3]$_2$ or Pd[$PMeBu^t_2$]$_2$, respectively, seems therefore eminently reasonable, but there is a possibility that the resonances of these two compounds were for some reason severely exchange broadened and therefore unobservable. In this case, since the ^{31}P nuclei are expected to remain chemically equivalent regardless of the number of ligands coordinated to the palladium, the resonances observed could conceivably be attributable to the 4:1 adducts, and thus identification of the compounds formed is to this point ambiguous.

Unambiguous determinations of coordination numbers could be made via syntheses of mixed phosphine heteroleptic compounds, since the spin−spin coupling patterns observed in the ^{31}P NMR spectra would provide information concerning the nature of any new species formed. Thus a bis-ligated compound of the type Pd[PR_3][PR'_3] is expected to exhibit the spectrum of an AX or AB spin system, depending on the ratio $\Delta\nu/J$,[20] a compound of the type Pd[PR_3][PR'_3]$_2$ is expected to exhibit the spectrum of an AX_2 or AB_2 spin system, and compounds of the type Pd[PR_3]$_2$[PR'_3]$_2$ or Pd[PR_3][PR'_3]$_3$ are expected to exhibit the spectra of A_2X_2 (A_2B_2) or AX_3 (AB_3) spin systems, respectively.[20] As we had wondered in any case if heteroleptic 2:1 compounds would form as readily and in the same way as the homoleptic compounds described above—such species have not been studied as cross-coupling catalysts—we carried out experiments designed to generate heteroleptic compounds in which different phosphines were bound to palladium.

To this end, Pd(η^3-C_3H_5)(η^5-C_5H_5) was reacted with 1 equiv each of PCy_3 and PBu^t_3 for 1 h at 77 °C in toluene-d_8, and the resulting ^{31}P NMR spectrum, run at 25 °C after brief cooling, is shown in Figure 5. As can be seen, in addition to the resonances of Pd[PCy_3]$_2$ (δ 40.1, exchange broadened), Pd[PBu^t_3]$_2$ (δ 86.0, sharp), unreacted PBu^t_3 (δ 63.3), and a minor amount of impurity (δ 46.3), the spectrum also exhibits an AX pattern with chemical shifts δ 41.4 and 85.2 and coupling constant ^2J(P−P) of 241 Hz ($\Delta\nu/J = 0.182$). An essentially identical ^{31}P NMR spectrum is obtained on reaction of equimolar amounts of Pd[PBu^t_3]$_2$ with Pd[PCy_3]$_2$ in toluene-d_8, and a ^{31}P−^{31}P COSY correlation experiment at 25 °C confirms the mutual coupling of the two doublets and hence supports their assignment to the new heteroleptic compound Pd[PCy_3][PBu^t_3].

Formation of Pd[PCy_3][PBu^t_3] directly from the two 2:1 homoleptic precursors shows that ligand exchange in this system is facile, although exchange broadening is observed for only Pd[PCy_3]$_2$, not for Pd[PCy_3][PBu^t_3] or Pd[PBu^t_3]$_2$. Similar results were noted above where the ^{31}P resonance of Pd[PCy_3]$_2$ broadened in the presence of free PCy_3, while that of Pd[PBu^t_3]$_2$ remained sharp in the presence of free PBu^t_3. Exchange processes are probably associative for compounds PdL_2, with the low coordination number of two,[2g] and it is likely that compounds containing relatively bulky PBu^t_3 are too sterically hindered to participate readily.

A very similar result is obtained on reaction of equimolar amounts of Pd[$PMeBu^t_2$]$_2$ and Pd[PBu^t_3]$_2$ in toluene-d_8. Again an AX spin system with chemical shifts δ 85.4 and 41.8 and ^2J(P−P) 246 Hz, attributable to the heteroleptic compound Pd[$PMeBu^t_2$][PBu^t_3] results, and again the new compound is in equilibrium with its precursors Pd[$PMeBu^t_2$]$_2$ (δ 41.7, exchange broadened) and Pd[PBu^t_3]$_2$ (δ 85.3). As above, a ^{31}P−^{31}P COSY correlation spectrum of Pd[$PMeBu^t_2$][PBu^t_3] confirms the assignments.

The third of the heteroleptic systems involve PCy_3 and $PMeBu^t_2$, both with cone angles significantly smaller than that of PBu^t_3 (see above). Complicating matters, while the ^{31}P chemical shifts of coordinated PBu^t_3 generally lie ~20−40 ppm downfield from the chemical shifts of coordinated PCy_3 and $PMeBu^t_2$ (Table 1), giving rise to first-order ^{31}P NMR spectra,

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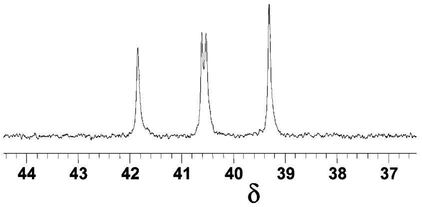

Figure 6. ^{31}P NMR spectrum at 25 °C of a solution containing equimolar quantities of $Pd[PCy_3]_2$ and $Pd[PMeBu^t_2]_2$.

the ^{31}P chemical shifts of $Pd[PCy_3]_2$ and $Pd[PMeBu^t_2]_2$ differ by only ~2 ppm. This (~486 Hz at a probe frequency of ~243 MHz) is comparable in magnitude to the values of $^2J(P-P)$ discussed above for $Pd[PCy_3][PBu^t_3]$, and thus we anticipated that a second-order ^{31}P spectrum would be observed[20] for the compound $Pd[PCy_3][PMeBu^t_2]$, for example.

The Pd(0)/PCy_3/$PMeBu^t_2$ system turned out to be much more complex and interesting than anticipated, and it has been investigated in rather more detail than were the two systems involving PBu^t_3. In the first experiment carried out, a ^{31}P NMR spectrum of a toluene-d_8 solution containing equimolar amounts of $Pd[PMeBu^t_2]_2$ and $Pd[PCy_3]_2$ was run at 25 °C, and as is apparent from Figure 6, there are observed four resonances of comparable intensity at δ 41.8, 40.6, 40.5, and 39.3, very similar to the ^{31}P chemical shifts of the corresponding homoleptic 2:1 compounds. The two apparent $^2J(P-P)$ separations (i.e., the differences in Hz between the resonances at δ 41.8 and 40.6, and between those at δ 40.5 and 39.3) were identically 300 Hz and thus somewhat greater than the values of $^2J(P-P)$ found above for $Pd[PMeBu^t_2][PBu^t_3]$ and $Pd[PCy_3][PBu^t_3]$. Thus $\Delta\nu$ would indeed appear to be comparable to $^2J(P-P)$ for the presumed species $Pd[PCy_3][PMeBu^t_2]$ in solution. However, if the two very closely spaced central lines at δ 40.6 and 40.5 are taken as the two center peaks of an AB quartet, then the two outside peaks should exhibit much lower intensities than are observed[20] and it seems very likely that most of the intensity of each of the resonances at δ 41.8 and 39.3 is a result of the presence in the solution of significant concentrations of the two homoleptic compounds $Pd[PMeBu^t_2]_2$ and $Pd[PCy_3]_2$, respectively. Strengthening this conclusion, a $^{31}P-^{31}P$ COSY NMR experiment shows that the central peaks at δ 40.6 and 40.5 correlate with resonances at δ 41.8 and 39.3, respectively, hidden under the main resonances having these chemical shifts. Furthermore the chemical shifts of the two "outside" resonances are essentially identical to those of $Pd[PMeBu^t_2]_2$ and $Pd[PCy_3]_2$, respectively, and we note that, in Figure 1, the chemical shifts of the two "outside" resonances of the quartet in the spectrum of $Pd[PCy_3][PBu^t_3]$ are very similar to those of the two homoleptic compounds $Pd[PBu^t_3]_2$ and $Pd[PCy_3]_2$.

Consistent with our findings for the $PdPMeBu^t_2/PBu^t_3$ and $PdPCy_3/PBu^t_3$ systems, it is not surprising to find significant amounts of the two homoleptic compounds present in equilibrium with the heteroleptic analogue. The ^{31}P chemical shifts of the AB spin system do not, of course, coincide with any of the four observed resonances, but are calculated to be δ 40.3 and 40.8 (Table 1).[20]

In the second experiment carried out to better understand this system, a solution containing $Pd[PCy_3]_2$ (0.015 mmol) and 1 equiv of $PMeBu^t_2$ was prepared in 0.5 mL of toluene-d_8 at 21 °C, and ^{31}P NMR spectra were obtained over the temperature range +25 to −93 °C (Figure 7). As can be seen, the ^{31}P NMR spectrum at 25 °C exhibits only two very broad resonances at δ ~14 and ~42. On cooling to −40 °C, these narrow somewhat and shift upfield very slightly and, by −63 °C, both have begun to decoalesce (Figure 7c). At −93 °C, the lowest temperature achievable, many better resolved features can be recognized (Figure 7e), although the limiting spectrum may not yet have been reached. Prominent in the spectrum at −93 °C are singlets at δ 7.52 and 7.95, which are assigned respectively to free $PMeBu^t_2$ and PCy_3 shifted somewhat from the room-temperature chemical shifts (Table 1) by temperature effects. There are also strong singlets at δ 25.5 and 30.3, which are readily assigned to the 3:1 homoleptic compounds $Pd[PCy_3]_3$ and $Pd[PMeBu^t_2]_3$, respectively (see above).

Much weaker resonances present in the spectrum at −93 °C include several in the region δ 39−40; these are consistent with the anticipated presence of $Pd[PCy_3]_2$, $Pd[PMeBu^t_2]_2$, and $Pd[PCy_3][PMeBu^t_2]$, although the chemical shifts do not coincide exactly with those listed in Table 1 because of temperature effects. Also observed are two very broad resonances at δ ~23.3 and ~21.6, two less broadened 1:2:1 triplets at δ ~32.2 and ~34.4, and an extremely broad resonance at δ ~35, which is partially obscured by the low-field line of the triplet at δ ~34.4. None of these resonances appears in spectra of solutions containing only PCy_3 or $PMeBu^t_2$, and thus they suggest the presence of various of the possible heteroleptic compounds $Pd[PCy_3][PMeBu^t_2]_2$, $Pd[PCy_3]_2[PMeBu^t_2]$, $Pd[PCy_3]_2[PMeBu^t_2]_2$, $Pd[PCy_3][PMeBu^t_2]_3$, and/or $Pd[PCy_3]_3[PMeBu^t_2]$. Our initial and somewhat surprising interpretation of the pair of 1:2:1 triplets at δ ~32.2 and ~34.4 was that they comprise an A_2X_2 spin system and thus are to be attributed to the 4:1 compound $Pd[PCy_3]_2[PMeBu^t_2]_2$.

In order to obtain better resolved 1D spectra and satisfactory 2D $^{31}P-^{31}P$ correlation spectra, the NMR experiment was repeated utilizing a higher concentration of $Pd[PCy_3]_2$ (0.025 mmol in 0.5 mL of toluene-d_8) and 2 equiv of $PMeBu^t_2$. The spectra obtained at the various temperatures are largely similar to those shown in Figure 7, although the exchange broadening at 25 °C was so severe in the presence of the larger excess of $PMeBu^t_2$ that the two resonances at δ ~14 and ~42 were barely distinguishable from the baseline. A spectrum run at −88 °C (Figure 8) is similar to that shown in Figure 7e except that the resonance of free $PMeBu^t_2$ at δ 7.71 is as expected relatively more intense than that of free PCy_3 (δ 8.14). More importantly, the triplets at δ ~32.2 and ~34.3 are now much more intense than the resonances of the 2:1 compounds in the region δ 39−40, consistent with their being attributed to a species of higher coordination number. In addition they are sufficiently well resolved that the splittings can be reasonably accurately measured: ~90.7 Hz for that centered at δ ~34.3 and ~101.6 Hz for that centered at δ ~32.2. Furthermore, for both, the center lines are also found to be broader than the corresponding outside lines, and thus the two resonance patterns are not coupled 1:2:1 triplets but are more likely pairs of overlapping doublets!

The two broad resonances at δ ~23.6 and ~21.7 have also gained in intensity relative to the resonances at δ 39−40, but while the resonance at δ ~23.6 remains featureless, that at δ ~21.7 has become a broadened apparent triplet, with splittings of ~90.4 Hz, and it also appears to be comprised of overlapping doublets. The resonances at δ ~32.2, ~34.3, ~23.6, and ~21.7 are all of comparable intensities. The extremely broad resonance at δ ~35 remains barely visible.

A $^{31}P-^{31}P$ correlation experiment was carried out on this sample at −88 °C (Figure 9), and several features are notable. For instance the resonances in the region δ 39−40 do not correlate with any resonances at higher field, consistent with their assignment solely to the homo- and heteroleptic 2:1 compounds. Of note, the apparent double doublets at δ ~32.2, ~34.3, and ~21.7 are all mutually coupled, implying that they

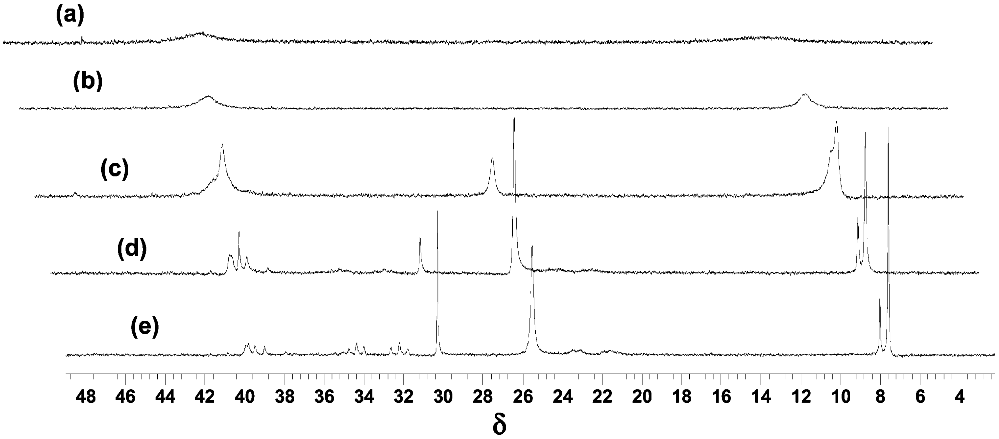

Figure 7. Stacked plots of ^{31}P NMR spectra of the reaction of Pd[PCy$_3$]$_2$ with 1 equiv of PMeBu$^t{}_2$ at (a) 25 °C, (b) −40 °C, (c) −63 °C, (d) −83 °C, and (e) −93 °C.

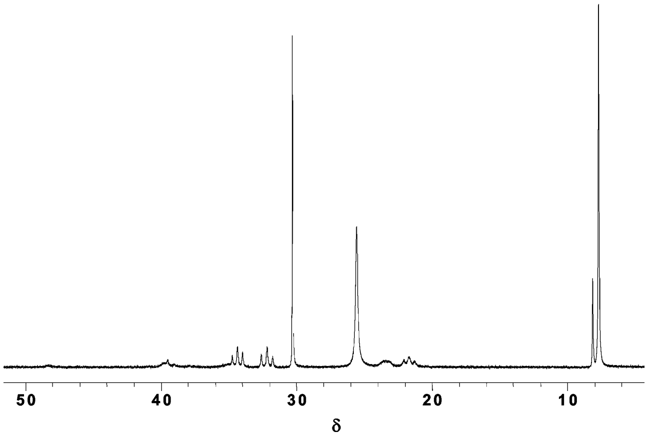

Figure 8. ^{31}P NMR spectra of the reaction of Pd[PCy$_3$]$_2$ with 2 equiv of PMeBu$^t{}_2$ at −88 °C.

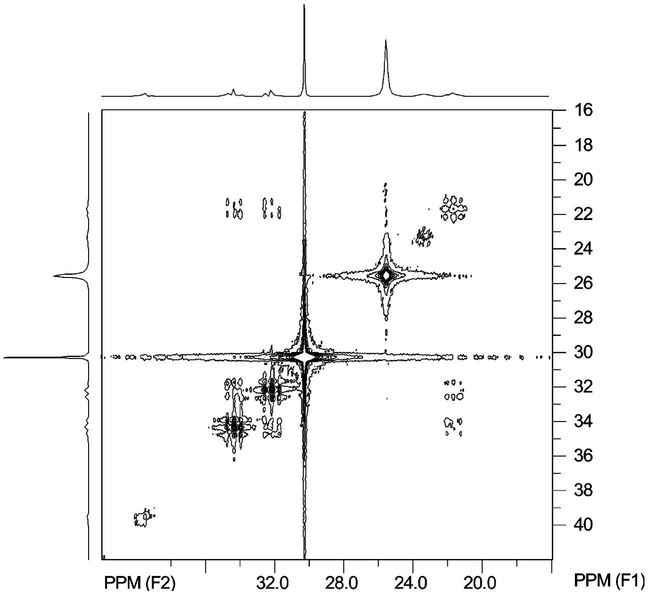

Figure 9. ^{31}P−^{31}P correlation spectrum of a solution containing Pd[PCy$_3$]$_2$ and 2 equiv of PMeBu$^t{}_2$ at −88 °C.

comprise an AMX spin system and are to be attributed to one of the three-coordinate compounds Pd[PCy$_3$]$_2$[PMeBu$^t{}_2$] or Pd[PCy$_3$][PMeBu$^t{}_2$]$_2$.

Since the ^{31}P resonance of Pd[PMeBu$^t{}_2$]$_3$ lies downfield from and is sharper than that of Pd[PCy$_3$]$_3$ (Figure 8), it seems likely that the compound giving rise to the AMX spin system is Pd[PCy$_3$][PMeBu$^t{}_2$]$_2$, with the multiplets at δ ~32.2 and ~34.3 attributed to two PMeBu$^t{}_2$ rendered nonequivalent because they are "frozen" at this low temperature in different rotational conformations relative to the PCy$_3$. In support of this suggestion, we note that the room-temperature ^{31}P NMR spectrum of *trans*-PdCl$_2$(PMeBu$^t{}_2$)$_2$ consists of two singlets of unequal intensity because of the presence of two different rotamers in solution.[21] The two resonances only coalesce at higher temperatures, consistent with the chlorine ligands presenting a significant steric barrier to rotation about the Pd−P bond. It is thus clearly reasonable to suppose that the two PMeBu$^t{}_2$ ligands in Pd[PCy$_3$][PMeBu$^t{}_2$]$_2$ assume different orientations in the most stable conformation, with significant barriers to interconversion. Alternatively, of course, the two PMeBu$^t{}_2$ ligands may be magnetically nonequivalent (diastereotopic) by virtue of the chirality of the coordinated PCy$_3$.[22]

Assuming, as seems reasonable, that the magnitudes of ^2J(P−P) in these palladium(0) compounds are governed largely by the Fermi contact term,[23] the decrease in ^2J(P−P) from 486 Hz for Pd[PCy$_3$][PMeBu$^t{}_2$] to ~96 Hz for Pd[PCy$_3$][PMeBu$^t{}_2$]$_2$ is consistent with the change from the linear sp-hybridized structure to the trigonal sp^2 analogue and supports our suggestion of an increase in the coordination number. Weakening of the Pd−P σ bonds because of greater steric crowding in the 3:1 compound should also result in a decrease in ^2J(P−P).[23] Observation of a near first-order spectral pattern between the resonances at δ ~32.2 and ~34.3 arises from the fact that $\Delta\nu \approx 500$ Hz and $J \approx 90$ Hz and therefore $\Delta\nu/J \approx 5.6$, much larger than was found to be the case with Pd[PCy$_3$][PMeBu$^t{}_2$].

By process of elimination, the very broad resonance at δ ~23.6 is assigned to the PCy$_3$ ligands of the compound Pd[PCy$_3$]$_2$[PMeBu$^t{}_2$], with the PMeBu$^t{}_2$ resonance being the very broad band at δ ~35. These resonances appear not to be correlated, but would not expected to be in view of their extreme breadth.

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Summary and Conclusions

Although reactions of Pd(η^3-C_3H_5)(η^5-C_5H_5) with 2 equiv each of PCy_3, $PMeBu^t_2$, or PBu^t_3 are slow at room temperature and produce η^1-allyl and dinuclear intermediates in the cases of PCy_3 and $PMeBu^t_2$, reactions of all three ligands at 77 °C proceed cleanly and at very useful rates to give Pd[PCy_3]$_2$ and Pd[$PMeBu^t_2$]$_2$ within 1 h and Pd[PBu^t_3]$_2$ within 30 min. While application of this methodology to syntheses of analogous Pd(0) compounds of other phosphines would ideally be preceded by a brief ^{31}P NMR spectroscopic assessment similar to those described above, the known lability of Pd(η^3-C_3H_5)(η^5-C_5H_5)[9] suggests that 1 h at 77 °C will normally suffice. The procedure outlined here appears to provide the only reliable method available to date for generating known concentrations of bisphosphine−palladium(0) compounds quickly, reliably, and under mild conditions.

Interestingly, and consistent with its greater steric bulk, Pd[PBu^t_3]$_2$ is quite disinclined to increase its coordination number, its ^{31}P NMR resonance being completely unaffected by added PCy_3, $PMeBu^t_2$, or PBu^t_3. In contrast, the ^{31}P NMR resonances of Pd[PCy_3]$_2$ and Pd[$PMeBu^t_2$]$_2$ are both broadened significantly by added PCy_3 or $PMeBu^t_2$, and both ligands form 3:1 coordination compounds. Indeed, the homoleptic compounds Pd[PCy_3]$_3$ and Pd[$PMeBu^t_2$]$_3$ are the dominant species in the presence of excess phosphines at low temperatures, and even the heteroleptic compounds Pd[PCy_3]$_2$[$PMeBu^t_2$] and Pd[PCy_3][$PMeBu^t_2$]$_2$ appear to exist.

Equilibrium constants for dissociation of the compounds PdL_3 to PdL_2 and free L (L = PCy_3, $PMeBu^t_2$) were measured over a range of temperatures, and from the resulting linear plots of ln K_D vs 1/T, ΔH, and ΔS values of 21 kJ mol^{-1} and 59 J deg^{-1} mol^{-1}, respectively, were found for the PCy_3 system and 23 kJ mol^{-1} and 86 J deg^{-1} mol^{-1}, respectively, for $PMeBu^t_2$. The enthalpy values are presumably, to a first approximation at least, a measure of the Pd−P bond dissociation energies. If so, then the Pd(0)−phosphine bond energies are, as expected, considerably lower than are those reported previously for both a Pd(II)−PPh_3 bond (54 kJ mol^{-1})[19b] and a Pt(0)−PCy_3 bond (55 kJ mol^{-1}).[19c]

The ready formation of the 3:1 compounds has serious implications for cross-coupling processes involving bisphosphine−palladium(0) catalysts. As outlined in the Introduction, such catalysts are most often presumed to be generated via reductions of palladium(II) precursors in processes that are largely of an unknown nature, proceeding at unknown rates and resulting in unknown yields. Relative catalytic activities are often deduced on the basis of yields of cross-coupling products and then rationalized on the basis of steric and/or electronic properties of the phosphines used. We initiated this research with the notion that relative catalytic activities may rather reflect the relative rates of reduction of palladium(II), but now we must realize also that reactivities may vary because of differing degrees to which the initially very small amounts of generated palladium(0) species may be present as tris-phosphine compounds rather than the generally assumed bisphosphine species.

For example, given the aforementioned temperature variation of the equilibrium constant for dissociation of Pd[PCy_3]$_3$ to Pd[PCy_3]$_2$ + PCy_3, the proportion of palladium(0) present at 25 °C as the tris complex if the PCy_3:Pd ratio lies in the range 100:1 to 1000:1, as it must during the early stages of a cross-coupling reaction involving the use of excess phosphine and Pd(II) precatalysts, varies between 84% and 98%. Even at 100 °C, in the range of temperatures often used for Suzuki−Miyaura cross-coupling reactions,[1] the proportion of palladium(0) present as Pd[PCy_3]$_3$ varies between 48% and 90%. For $PMeBu^t_2$ under the same conditions, the calculated proportions present as the tris species are lower but still in the range 32−83% at 25 °C and 7−42% at 100 °C. Thus the fraction of the total added palladium present as the tris complexes in catalytic solutions can be quite significant.

The relative tendency of a particular phosphine to form the more highly coordinated, presumably much less reactive species may be a determining factor of the overall efficiency of a cross-coupling process, one that should be considered during the optimization of a catalytic cross-coupling protocol. In a paper to follow, we shall describe a kinetics study involving the oxidative addition reactions of bromobenzene to the palladium(0) compounds Pd[PCy_3], Pd[PCy_3]$_2$, and Pd[PCy_3]$_3$.[12]

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