Effects of bases and halides on the amination of chloroaarenes catalyzed by $Pd[P(tBu_3)]_2$

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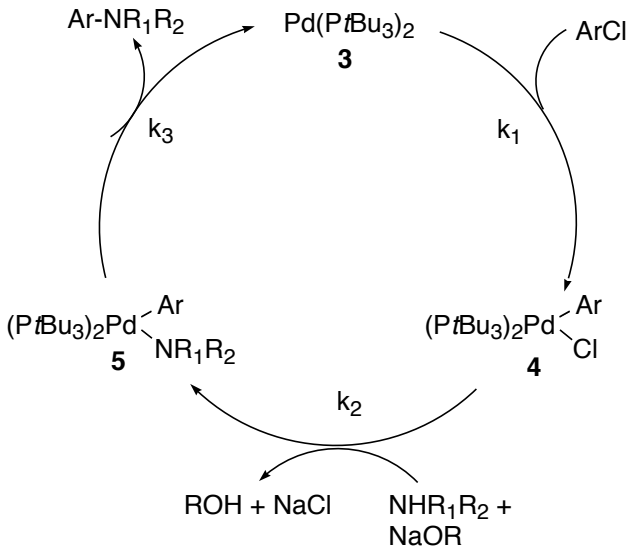
Supporting Information

The full rate equations for the catalytic cycles of Scheme **S1**-**S7** were derived by the schematic method developed for deriving the steady-state concentrations of enzyme-containing species based on the determinant method. [1]

Scheme S1

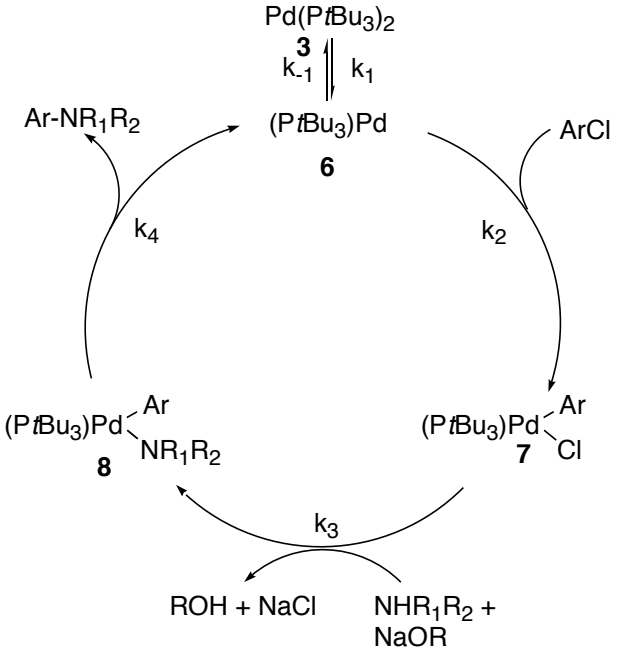


$$rate = \frac{k_1 k_2 k_3[Pd_{tot}][ArCl][NHR_1R_2][NaOR]}{k_2 k_3[NHR_1R_2][NaOR] + k_1 k_3[ArCl] + k_1 k_2[NHR_1R_2][NaOR][ArCl]} \quad \text{(S1)}$$

$$rate = k_1[Pd(PtBu_3)_2][ArCl] \quad \text{(S2)}$$

The simplified equation S2 was based on the following set of assumptions. First, $k_2k_3[NHR_1R_2][NaOR] >> k_1k_3[ArCl]$ because the reaction of the arylpalladium bromide complex with amine and base ($k_2[NHR_1R_2][NaOR]$) is much faster than oxidative addition of chloroarenes to the $L_2Pd(0)$ species ($k_1[ArCl]$) and the k_3 term is present in both terms. The reaction of amine and base with **4** occurs within minutes at room temperature, but oxidative addition of ArCl to **3** requires hours at 50 °C. Second, $k_2k_3[NHR_1R_2][NaOR] >> k_1k_2[NHR_1R_2][NaOR][ArCl]$ because the reductive elimination (k_3) is much faster than oxidative addition ($k_1[ArCl]$) and the $k_2[NHR_1R_2][NaOR]$ terms are present in both terms. The reductive elimination of *N*-alkyl arylamines from P*t*Bu$_3$ complexes occurs rapidly at room temperature. Finally, we approximate $[Pd_{tot}]$ as $[Pd(PtBu_3)_2]$ because $Pd(PtBu_3)_2$ is the only palladium complex observed during the catalytic reaction by NMR spectroscopy.

Scheme S2



$$rate = \frac{k_1 k_2 k_3 k_4 [Pd_{tot}][ArCl][NHR_1R_2][NaOR]}{k_{-1}k_3k_4[NHR_1R_2][NaOR][PtBu_3] + k_1k_3k_4[NHR_1R_2][NaOR] + k_1k_2k_4[ArCl] + k_1k_2k_3[NHR_1R_2][NaOR][ArCl]} \quad \text{(S3)}$$

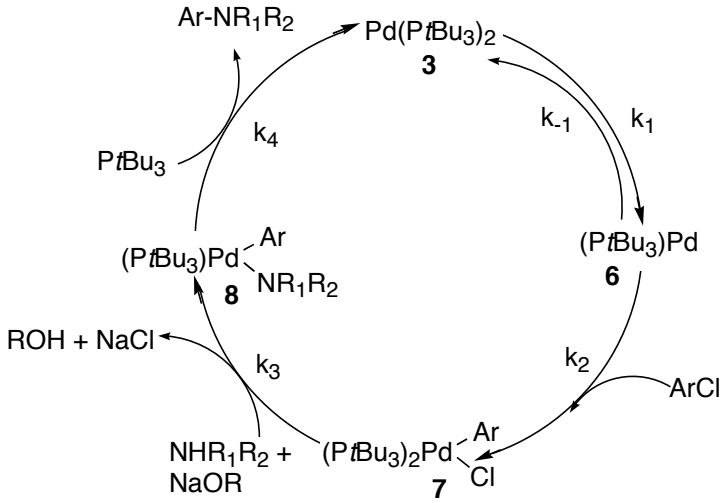
$$rate = \frac{k_1 k_2 [Pd(PtBu_3)_2][ArCl]}{k_{-1}[PtBu_3]} = k_{obs} \quad \text{(S4)}$$

Equation S3 was simplified to equation S4 by making the following approximations. First, $k_{-1}k_3k_4[NHR_1R_2][NaOR][PtBu_3] >> k_1k_2k_4[ArCl]$ because the rate of formation of the amido complex ($k_3[NHR_1R_2][NaOR]$) is much greater than the rate of ligand dissociation (k_1), the rate of ligand reassociation ($k_{-1}[L]$) is approximately equal to the rate of the oxidative addition step ($k_2[ArCl]$),[2] and k_4 is present in both terms. The reaction of amine and base with [Pd(P*t*Bu$_3$)(Ar)(Cl)] occurs rapidly at room temperature, but the dissociation of P*t*Bu$_3$ from Pd(P*t*Bu$_3$)$_2$ requires several hours at 100° C.[3]

Second, we deduced that $k_{-1}k_3k_4[NHR_1R_2][NaOR][PtBu_3] >> k_1k_2k_3[NHR_1R_2][NaOR][ArCl]$ because the reassociation of phosphine is much faster than the dissociation of phosphine ($k_{-1}[PtBu_3] >> k_1$) (*vide supra*), reductive elimination of the amine (k_4) is much faster than oxidative addition of the chloroarene ($k_2[ArCl]$), and k_3 is present in both terms. The equilibrium for dissociation of P*t*Bu$_3$ is known to be very small ($k_{-1}[PtBu_3] >> k_1$) and $k_4 >> k_2[ArCl]$ for the same reason that was stated during the discussion of the mechanism in

Scheme 2. Third, $[Pd_{tot}] = [Pd(PtBu_3)_2]$ because $Pd(PtBu_3)_2$ is the only palladium complex observed by NMR spectroscopy during the catalytic reaction.

Scheme S3



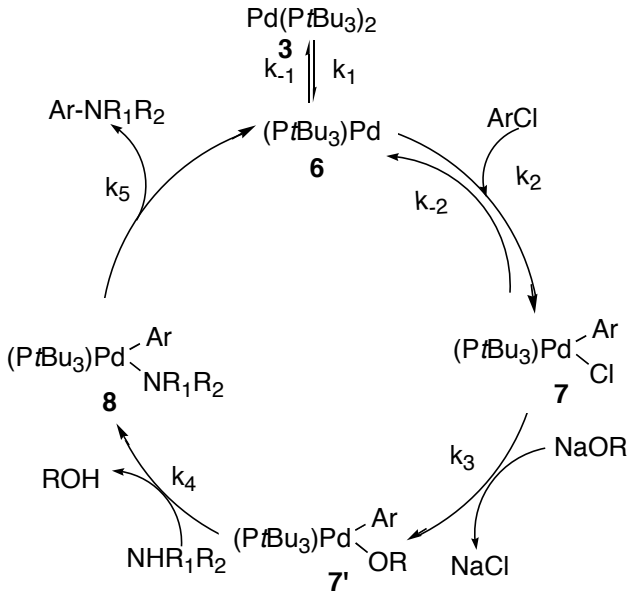
$$rate = \frac{k_1k_2k_3k_4[Pd_{tot}][ArCl][NHR_1R_2][NaOR][PtBu_3]}{k_2k_3k_4[ArCl][NHR_1R_2][NaOR][PtBu_3] + k_{-1}k_3k_4[NHR_1R_2][NaOR][PtBu_3]^2 + k_1k_3k_4[NHR_1R_2][NaOR][PtBu_3] + k_1k_2k_4[ArCl][PtBu_3] + k_1k_2k_3[ArCl][NHR_1R_2][NaOR]} \quad \text{(S5)}$$

$$rate = \frac{k_1k_2k_3[Pd(PtBu_3)_2][ArCl]}{k_2[ArCl] + k_{-1}[PtBu_3]} \quad \text{(S6)}$$

Equation S5 was simplified to equation S6 by making the following approximations. First, $k_2k_3k_4[ArCl][NHR_1R_2][NaOR][PtBu_3] >> k_1k_2k_3[ArCl][NHR_1R_2][NaOR]$ because $k_4[PtBu_3] >> k_1$ and the other terms are present on both sides of the comparison. The associative displacement of amine by $PtBu_3$ from the $(PtBu_3)Pd$(product) will be much faster than the ligand dissociation from **3**. Second, $k_2k_3k_4[ArCl][NHR_1R_2][NaOR][PtBu_3] >> k_1k_2k_4[ArCl][PtBu_3]$ because $k_3[NHR_1R_2][NaOR] >> k_1$ and $k_2k_4[ArCl][PtBu_3]$ is present on both sides of the comparison. The reaction of amine and base with **7** occurs within seconds at room temperature but the dissociation of $PtBu_3$ from $Pd(PtBu_3)_2$ (k_1) is known to be require several hours at 100 °C. (*vide supra*) Third, $k_{-1}k_3k_4[NHR_1R_2][NaOR][PtBu_3]^2 >> k_1k_3k_4[NHR_1R_2][NaOR][PtBu_3]$ because $k_{-1}[PtBu_3] >> k_1$ as noted in discussing mechanisms in Scheme 2 and 3 and $k_3k_4[NHR_1R_2][NaOR][PtBu_3]$ is common to both sides of the comparison. Fourth, $[Pd_{tot}] =$

[Pd(P*t*Bu$_3$)$_2$] because Pd(P*t*Bu$_3$)$_2$ is the only palladium complex observed by NMR spectroscopy during the catalytic reaction.

Scheme S4



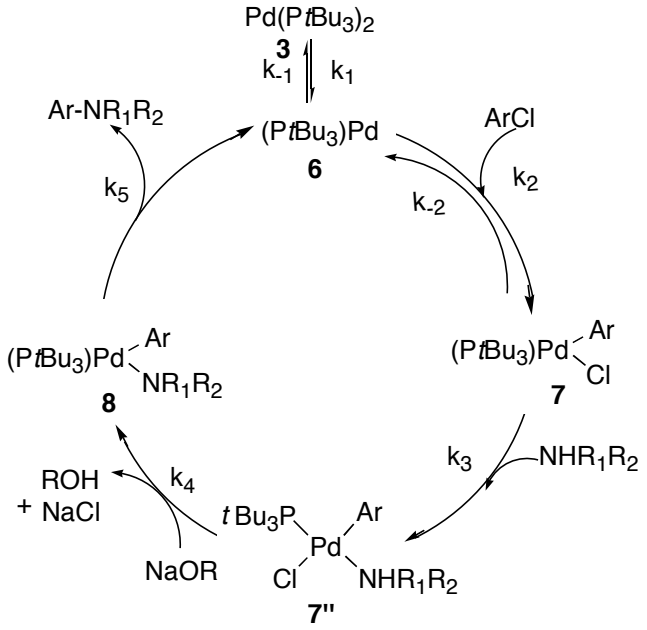
$$rate = \frac{k_1k_2k_3k_4k_5[Pd_{tot}][ArCl][NHR_1R_2][NaOR]}{k_1k_3k_4k_5[NHR_1R_2][NaOR] + k_1k_4k_5k_{-2}[NHR_1R_2] + k_3k_4k_5k_{-1}[NHR_1R_2][NaOR][PtBu_3] + k_4k_5k_{-1}k_{-2}[NHR_1R_2][PtBu_3] + k_1k_2k_4k_5[ArCl][NHR_1R_2] + k_1k_2k_3k_5[ArCl][NaOR] + k_1k_2k_3k_4[ArCl][NHR_1R_2][NaOR]} \quad \text{(S7)}$$

$$rate = \frac{k_1k_2k_3[Pd_{tot}][ArCl][NaOR]}{k_{-1}(k_3[NaOR] + k_{-2})[PtBu_3]} \quad \text{(S8)}$$

Equation S7 was simplified to equation S8 by making the following approximations. First, $k_3k_4k_5k_{-1}[NHR_1R_2][NaOR][PtBu_3] >> k_1k_3k_4k_5[NHR_1R_2][NaOR]$ because the equilibrium constant for dissociation of phosphine from **3** is known to be very small ($k_{-1}[PtBu_3] >> k_1$) (*vide supra*), as explained earlier. Second, $k_1k_2k_4k_5[ArCl][NHR_1R_2] >> k_1k_2k_3k_5[ArCl][NaOR]$ because the reaction of palladium-alkoxide or –aryloxo complex **7'** with amine ($k_4[NHR_1R_2]$) >> the reaction of base with the palladium-aryl halide complex **7** ($k_3[NaOR]$). If this were not the case, then the intermediate **7'** would accumulate during the catalytic reactions. Third, $k_1k_2k_4k_5[ArCl][NHR_1R_2] >> k_1k_2k_3k_4[ArCl][NHR_1R_2][NaOR]$ because $k_5 >> k_3[NaOR]$. The reductive elimination of amine (k_5) must be faster than reaction of the palladium-alkoxide complex **7'** with amine ($k_4[NHR_1R_2]$) to prevent accumulation of the intermediate **8**, and $k_4[NHR_1R_2] >> k_3[NaOR]$ as explained above. This implies that k_5 must be greater than $k_3[NaOR]$. Fourth, $k_4k_5k_{-1}k_{-2}[NHR_1R_2][PtBu_3] >> k_1k_4k_5k_{-2}[NHR_1R_2]$ because $k_{-1}[PtBu_3] >> k_1$, as

explained earlier. Fifth, $k_4k_5k_{-1}k_{-2}[NHR_1R_2][PtBu_3] >> k_1k_2k_4k_5[ArCl][NHR_1R_2]$ because $k_{-1}[PtBu_3] \sim k_2[ArCl]$[50] and $k_{-2} >> k_1$. The approximation $k_{-2} >> k_1$ is valid because the reductive elimination of aryl chlorides from **7** can be observed[4] but free phoshine is never observed in ^{31}P NMR spectra of $Pd(PtBu_3)_2$ even at elevated temperatures. Finally, $[Pd_{tot}] = [Pd(PtBu_3)_2]$ because $Pd(PtBu_3)_2$ is the only palladium complex observed during the catalytic reaction by NMR spectroscopy.

Scheme S5



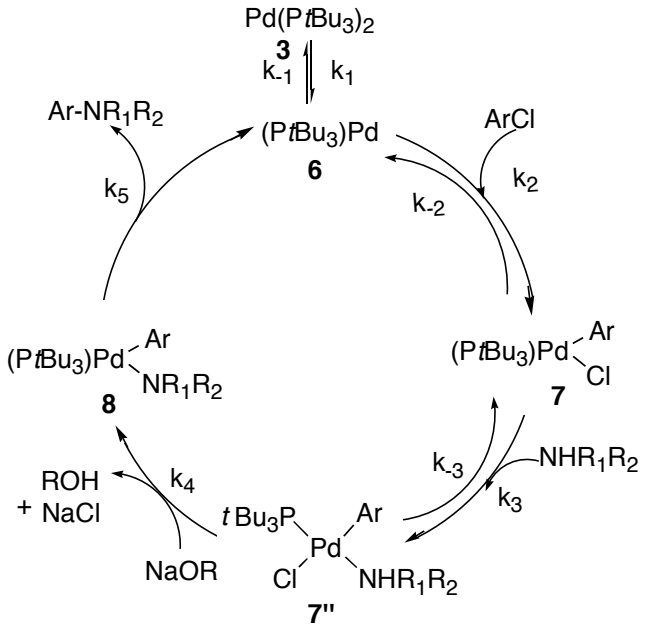
$$rate = \frac{k_1k_2k_3k_4k_5[Pd_{tot}][ArCl][NHR_1R_2][NaOR]}{k_1k_3k_4k_5[NHR_1R_2][NaOR] + k_1k_4k_5k_{-2}[NaOR] + k_3k_4k_5k_{-1}[NHR_1R_2][NaOR][PtBu_3] + k_4k_5k_{-1}k_{-2}[NaOR][PtBu_3] + k_1k_2k_4k_5[ArCl][NaOR] + k_1k_2k_3k_5[ArCl][NHR_1R_2] + k_1k_2k_3k_4[ArCl][NHR_1R_2][NaOR]} \quad (S9)$$

$$rate = \frac{k_1k_2k_3[Pd_{tot}][ArCl][NHR_1R_2]}{k_{-1}(k_3[NHR_1R_2] + k_{-2})[PtBu_3]} \quad (S10)$$

Equation S9 was simplified to equation S10 by making the following approximations. First, $k_3k_4k_5k_{-1}[NHR_1R_2][NaOR][PtBu_3] >> k_1k_3k_4k_5[NHR_1R_2][NaOR]$ because $k_{-1}[PtBu_3] >> k_1$ as noted above for the discussion of mechanims in Schemes 2-5 and $k_3k_4k_5[NHR_1R_2][NaOR]$ is present on both sides of the comparison. Second, $k_1k_2k_4k_5[ArCl][NaOR] >> k_1k_2k_3k_5[ArCl][NHR_1R_2]$ because the deprotonation of amine in **7''** ($k_4[NaOR]$) is much faster than the reaction of **3** with amine ($k_3[NHR_1R_2]$) to form the four coordinate complex **7''**. If this

were not the case, then the intermediate **7''** would accumulate during the catalytic reactions. The term $k_1k_2k_5$[ArCl] is present on both sides of the comparison. Third, $k_1k_2k_4k_5$[ArCl][NaOR] >> $k_1k_2k_3k_4$[ArCl][NHR_1R_2][NaOR] because k_5 >> k_3[NHR_1R_2] and k_4[NaOR] >> k_3[NHR_1R_2] and k_1k_2[ArCl] is common to both sides of the comparison. The reductive elimination of product amine from **8** (k_5) must be much faster than deprotonation of amine in **7''** (k_4[NaOR]) to prevent accumulation of the intermediate **8** during stoichiometric reactions of the arylpalladium halide complex with amine and base. k_4[NaOR] >> k_3[NHR_1R_2] for reasons explained above. Fourth, $k_4k_5k_{-1}k_{-2}$[NaOR][P*t*Bu_3] >> $k_1k_4k_5k_{-2}$[NaOR] because k_{-1}[P*t*Bu_3] >> k_1 as explained above and $k_4k_5k_{-2}$[NaOR] is common to both sides of the comparison. Fifth, $k_4k_5k_{-1}k_{-2}$[NaOR][P*t*Bu_3] >> $k_1k_2k_4k_5$[ArCl][NaOR] because k_{-1}[P*t*Bu_3] ~ k_2[ArCl][50] and k_{-2} >> k_1, as explained for the discussion of mechanism 5 and k_4k_5[NaOR] is present on both sides of the comparison. Sixth, [Pd_{tot}] = [Pd(P*t*Bu_3)$_2$] because Pd(P*t*Bu_3)$_2$ is the only palladium complex observed during the catalytic reaction by NMR spectroscopy.

Scheme S6

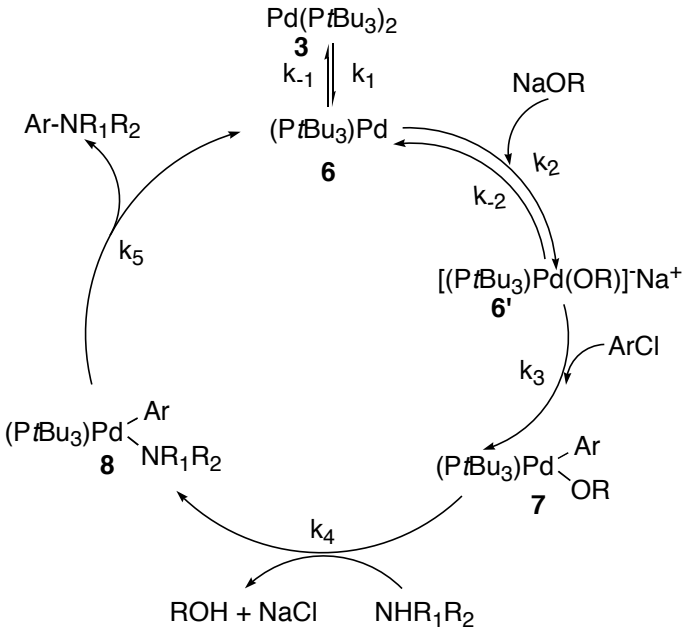


$$rate = \frac{k_1k_2k_3k_4k_5[Pd_{tot}][ArCl][NHR_1R_2][NaOR]}{k_1k_3k_4k_5[NHR_1R_2][NaOR] + k_1k_4k_5k_{-2}[NaOR] + k_1k_5k_{-2}k_{-3} + k_3k_4k_5k_{-1}[NHR_1R_2][NaOR][PtBu_3] + k_4k_5k_{-1}k_{-2}[NaOR][PtBu_3] + k_5k_{-1}k_{-2}k_{-3}[PtBu_3] + k_1k_2k_4k_5[ArCl][NaOR] + k_1k_2k_5k_{-3}[ArCl] + k_1k_2k_3k_5[ArCl][NHR_1R_2] + k_1k_2k_3k_4[ArCl][NHR_1R_2][NaOR]} \quad \text{(S11)}$$

$$rate = \frac{k_1k_2k_3k_4[Pd_{tot}][ArCl][NHR_1R_2][NaOR]}{k_{-1}(k_{-2}k_{-3} + k_3k_4[NHR_1R_2][NaOR] + k_{-2}k_4[NaOR])[PtBu_3]} \quad \text{(S12)}$$

Equation S11 was simplified to equation S12 by making the following approximations. First, $k_3k_4k_5k_{-1}[NHR_1R_2][NaOR][PtBu_3] >> k_1k_3k_4k_5[NHR_1R_2][NaOR]$ because $k_{-1}[PtBu_3] >> k_1$, as noted above for the discussion of mechanism in Schemes 2-6 and $k_3k_4k_5[NHR_1R_2][NaOR]$ is common to both sides of the comparison. Second, $k_1k_2k_4k_5[ArCl][NaOR] >> k_1k_2k_3k_5[ArCl][NHR_1R_2]$ because $k_4[NaOR] >> k_3[NHR_1R_2]$, as noted for the discussion of mechanism in Scheme 6 and $k_1k_2[ArCl]$ is present on both sides of the comparison. Third, $k_1k_2k_4k_5[ArCl][NaOR] >> k_1k_2k_3k_4[ArCl][NHR_1R_2][NaOR]$ because $k_5 >> k_3[NHR_1R_2]$, as noted for the discussion of mechanism in Scheme 6 and $k_1k_2k_4[ArCl][NaOR]$ is present on both sides of the comparison. Fourth, $k_4k_5k_{-1}k_{-2}[NaOR][PtBu_3] >> k_1k_4k_5k_{-2}[NaOR]$ because $k_{-1}[PtBu_3] >> k_1$ as explained earlier in this paper and $k_4k_5k_{-2}[NaOR]$ is present on both sides of the comparison. Fifth, $k_5k_{-1}k_{-2}k_{-3}[PtBu_3] >> k_1k_5k_{-2}k_{-3}$ because $k_{-1}[PtBu_3] >> k_1$ as explained earlier and $k_5k_{-2}k_{-3}$ is common to both sides of the comparison. Sixth, $k_4k_5k_{-1}k_{-2}[NaOR][PtBu_3] >> k_1k_2k_4k_5[ArCl][NaOR]$ because $k_{-1}[PtBu_3] \sim k_2[ArCl]$ and $k_{-2} >> k_1$, as noted for the discussion of mechanisms in Schemes 5 and 6 and $k_4k_5[NaOR]$ is common to both sides of the comparison. Seventh, $[Pd_{tot}] = [Pd(PtBu_3)_2]$ because $Pd(PtBu_3)_2$ is the only palladium complex observed during the catalytic reaction by NMR spectroscopy.

Scheme S7



$$rate = \frac{k_1k_2k_3k_4k_5[Pd_{tot}][ArCl][NHR_1R_2][NaOR]}{k_1k_3k_4k_5[ArCl][NHR_1R_2] + k_1k_4k_5k_{-2}[NHR_1R_2] + k_3k_4k_5k_{-1}[ArCl][NHR_1R_2][PtBu_3] + k_4k_5k_{-1}k_{-2}[NHR_1R_2][PtBu_3] + k_1k_2k_4k_5[NHR_1R_2][NaOR] + k_1k_2k_3k_5[ArCl][NaOR] + k_1k_2k_3k_4[NHR_1R_2][NaOR][ArCl]}$$

(S13)

$$rate = \frac{k_1k_2k_3[Pd(PtBu_3)_2][ArCl][NaOR]}{k_{-1}\,k_{-2}[PtBu_3]} = k_{obs} \qquad \text{(S14)}$$

Equation S13 was simplified by making the following approximations. First, $k_1k_2k_4k_5[NHR_1R_2][NaOR] >> k_1k_2k_3k_4[NHR_1R_2][NaOR][ArCl]$ because $k_5 >> k_3[ArCl]$ and $k_1k_2k_4[NHR_1R_2][NaOR]$ is present on both sides of the comparison. The reductive elimination to form arylamine from Pd(P*t*Bu$_3$)-complexes (k_5) is much faster than oxidative addition of ArCl to Pd(P*t*Bu$_3$)$_2$ (k_3[ArCl]). Second, $k_1k_2k_4k_5[NHR_1R_2][NaOR] >> k_1k_2k_3k_5[ArCl][NaOR]$ because $k_4[NHR_1R_2] >> k_3[ArCl]$ and $k_1k_2k_5[NaOR]$ is present on both sides of the comparison. If the reaction with amine were slower than the oxidative addition, then the intermediate **7** would accumulate during the catalytic reactions. Third, $k_4k_5k_{-1}k_{-2}[NHR_1R_2][PtBu_3] >> k_1k_2k_4k_5[NHR_1R_2][NaOR]$ because $k_{-1}k_{-2}[PtBu_3] >> k_1k_2[NaOR]$ and $k_4k_5[NHR_1R_2]$ is present on

both sides of the comparison. $k_{-1}[P\textit{t}Bu_3] >> k_1$ because the equilibrium for dissociation of $P\textit{t}Bu_3$ from $Pd(P\textit{t}Bu_3)_2$ is known to be very small[51] and $k_{-2} >> k_2[NaOR]$ because no evidence for the accumulation of **6'** was gained by ^{31}P NMR spectroscopy when **3** was treated with various bases. Fourth, $k_3k_4k_5k_{-1}[ArCl][NHR_1R_2][P\textit{t}Bu_3] >> k_1k_3k_4k_5[ArCl][NHR_1R_2]$ because $k_{-1}[P\textit{t}Bu_3] >> k_1$, as for the discussion of mechanims in Schemes 2-7 and $k_3k_4k_5[NHR_1R_2][ArCl]$ is commo to both sides of the comparison. Fifth, $k_4k_5k_{-1}k_{-2}[NHR_1R_2][P\textit{t}Bu_3] >> k_1k_4k_5k_{-2}[NHR_1R_2]$ because $k_{-1}[P\textit{t}Bu_3] >> k_1$, as explained earlier and $k_4k_5k_{-2}[NHR_1R_2]$ is common to both sides of the comparison. Sixth, $k_4k_5k_{-1}k_{-2}[NaOR][P\textit{t}Bu_3] >> k_1k_2k_4k_5[ArCl][NaOR]$ because $k_{-1}[P\textit{t}Bu_3] \sim k_2[ArCl]$[50], $k_{-2} >> k_1$ and $k_4k_5[NaOR]$ is common to both sides of the comparison. The rate constant for dissociaton of anion from **6'** must be greater than the dissociation of ligand from **3**. Seventh, $k_4k_5k_{-1}k_{-2}[NHR_1R_2][P\textit{t}Bu_3] >> k_3k_4k_5k_{-1}[ArCl][NHR_1R_2][P\textit{t}Bu_3]$ because $k_{-2} >> k_3[ArCl]$ and $k_4k_5k_{-}[NHR_1R_2][P\textit{t}Bu_3]$ is common to both sides of the comparison. The rate constant for dissociation of anion from **6'** must be greater than the oxidative addition of chloroarenes to **6'**. If this were not the case ,then **6'** would accumulate during the catalytic reactions. Eight, $[Pd_{tot}] = [Pd(P\textit{t}Bu_3)_2]$ because $Pd(P\textit{t}Bu_3)_2$ is the only palladium complex observed during the catalytic reaction by NMR spectroscopy.

(1) Wong, J. T. *Kinetics of Enzyme Mechanisms*; Academic Press: New York, 1975.
(2) The ratio of $k_2[ArCl]/k_{-1}[L]$ was determined from the studies done on the stoichiometric oxidative additions of PhCl to PdL_2 (L = (1-Ad)$\textit{t}Bu_2P$) by Fabiola Barrios-Landeros and John F. Hartwig. We have used the rate constants from the oxidative additions of PhCl to PdL_2 (L = (1-Ad)$\textit{t}Bu_2P$) instead of oxidative addition of PhCl to $Pd[P\textit{t}Bu_3]_2$ beacuse the rate constants obtained from the oxidative addition to $Pd[P\textit{t}Bu_3]_2$ were not reproducible. These data show that $k_2[ArCl] \sim 5 * k_{-1}[L]$ for the reported set of setcatalytic reactions . If $k_2[ArCl] > k_{-1}[L]$ then the catalytic reactions cannot be first-order in [ArCl], thus we estimate that $k_2[ArCl] \sim k_{-1}[L]$ for our catalytic reactions
(3) Fabiola Barrios-Landeros and John F. Hartwig, unpublished data.
(4) Roy, A. H.; Hartwig, J. F. *Organometallics* **2004**, *23*, 1533.