Inorganic Chemistry
Cumulative Examination
September 09, 2005


In your answers, be sure to expand beyond what is stated in the paper. If your answer is directly from the paper, or merely a rewording of the text, you will receive little or no credit. When needed, make full use of formulas, equations, schemes, and figures in your answers.

1) Provide a general description of the fundamental step Oxidative Addition by a metal complex and indicate the changes of formal oxidation state and coordination number of the metal center. (10 pt.)

2) For the oxidative addition of chloro-, bromo-, and iodoarenes to a phosphine palladium(0) complex, rank the aryl halides in order of increasing reactivity. Explain. (10 pt.)

3) The first sentence of the paper states “the oxidative addition of aryl halides is the first step in most palladium-catalyzed coupling reactions.” Provide three examples to support the statement. (10 pt.)

4) Explain why palladium(0) complexes of hindered alkylmonophosphines generate highly active catalysts for coupling processes. (10 pt.)

5) Draw the detailed structures of [Pd(Q-phos-tol)2] and [Pd(Q-phos-tol)(Ph)(Br)]. Give their electron counts, coordination numbers, formal oxidation states, and d10 configurations. Explain why they are stable. (10 pt.)

6) What is reductive elimination? Explain why [Pd(PhBu')(o-tol)(I]) undergoes reductive elimination easier than [Pd(Q-phos-tol)(Ph)(I)]. (10 pt.)

7) Predict the peak patterns in 31P{1H} NMR spectra for [Pd(Q-phos-tol)(Ph)(Cl)], [Pd(Q-phos-tol)(Ph)(Br)], and [Pd(Q-phos-tol)(Ph)(I)], respectively. Which complex has the highest 31P chemical shift? Explain. (10 pt.)

8) Predict the relative rates for oxidative addition processes of [Pd(Q-phos-tol)2] with the following aryl bromides and explain: (10 pt.)

9) It is concluded that the reaction between [Pd(Q-phos-tol)2] and PhI occurs by the mechanism Path A. Present evidences that exclude each one of the other four reaction mechanisms (Path B–E) in Scheme 1. (10 pt.)

10) The oxidative addition of fluoroarenes is a challenging process. Explain why. If you are asked to propose a new research project to attack the problem, what might that be? Give a detailed account. (10 pt.)
The oxidative addition of aryl halides is the first step in most palladium-catalyzed coupling reactions. Previous mechanistic studies of this reaction have focused on reactions of iodo- and bromoarenes. Despite the identification of catalysts for mild couplings of chloroarenes, few studies of the mechanism of the oxidative addition of these reagents have been conducted. Studies on the oxidative addition of chloroarenes to PhPd0 complexes of hindered alkylphosphines, which generate highly active catalysts for coupling processes, have not been reported, and, most strikingly, no studies have been reported on the mechanism of the oxidative addition of chloro-, bromo-, and iodoarenes to the same PhPd0 complex. Without such studies, extrapolation of the data on the oxidative addition of iodo- and bromoarenes to the mechanisms of chloroarenes is tenuous.

To compare the mechanisms of oxidative addition of chloro-, bromo-, and iodoarenes, we studied the addition of these reagents to [Pd(Q-phos-tol)]2 (Scheme 1). This complex adds all three types of halogenes in high yields. Moreover, Q-phos[1] generates highly active catalysts for the arylation of anilines and alkylamines, malononitriles, cyanocarbons, azides, and zinc enolates. We report that the addition of iodo-, bromo-, and chloroarenes to the Pd(0) complex of the sterically hindered Q-phos ligands occurs by three different mechanisms.

The oxidative addition of iodo- and bromoarenes to [Pd(Q-phos)2]
(1) generates [Pd(Q-phos)(Ar)(X)] (Scheme 1). Because the low solubility of complex 1 precluded mechanistic studies, analogous Pd(0) complexes, [Pd(Q-phos-tol)]2 (2) and [Pd(Q-phos-CF3)]2 (3), containing p-CH3 or p-CF3 groups on the phenyl rings of the ligand were prepared. These substituted Q-phos complexes were sufficiently soluble in THF for kinetic studies.

The oxidative addition of PhI, PhBr, and PhCl to 2 at 30–65 °C in neat PhX produced [Pd(Q-phos-tol)(PhX)] (X = I, Br, Cl, X = Cl, 6) quantitatively, as determined by 195P NMR spectroscopy (94, 53, and 82% isolated yield). Like the analogous Q-phos complexes, Q-phos-tol complexes 4 and 5 are monomeric. How-

Scheme 1. Possible Mechanisms and Rate Expressions for the Oxidative Addition of ArX to 2

Path B: $k_{o,b} = k_{d,b} + k_{a,b}$

Path C: $k_{o,b} = k_{d,b} + k_{a,b}$

Path D: $k_{o,b} = k_{d,b} + k_{a,b}$

Path E: $k_{o,b} = k_{d,b} + k_{a,b}$

$PhX$ ads by path A, PhI ads by path D and PhCN ads by path E

Figure 1. Plots of $k_{obs}$ vs [PhI] and $k_{obs}$ vs [Q-phos-tol] ([Pd] = 0.95 M) for the oxidative addition of PhI to 2 at 30 °C in THF.

ever, chloride complex 6 is dimeric in the solid state (X-ray diffraction) and in CH2Cl2 solution (Signer method). The difference between the reactivity of the aryl halide complexes does not affect our study because the dimerization occurs after the oxidative addition.

Potential mechanisms of oxidative addition of ArX to 2 and the corresponding rate expressions are shown in Scheme 1. Path A involves, under the conditions of oxidative addition, rate-limiting associative replacement of a phosphine ligand in 2 by PNX to generate a haloarene complex that is either bound $\nu'$ through the halide 1 or $\nu'$ through the arsene. This step is followed by carbon-halogen bond cleavage in the resulting monophosphine complex of the haloarene. The $k_{obs}$ for this route depends on [ArX] and [L]. Path B is similar to path A, but the replacement of ligand by ArX is reversible. The $k_{obs}$ for this route depends on [ArX] and [L]. Path C involves irreversible oxidative addition of ArX directly to 2, followed by ligand dissociation from the resulting four-coordinate arylpalladium halide intermediate. The rate expression for this route is identical to that for path A. Path D involves irreversible, rate-limiting dissociation of L from 2 followed by oxidative addition to the resulting monophosphine Pd(0) complex, which might be stabilized by coordination of solvent. The $k_{obs}$ for this route is independent of [ArX] and [L]. Path E is similar to path D, except that the dissociation of phosphine is reversible. The $k_{obs}$ for this route depends on [ArX] and [L].

Studies of the oxidative addition of iodo-, bromo-, and chloroarenes to palladium(0) complex 2 generate three distinct sets of rate data. The reaction of PhI with [PdI] was 90–4.47 M and [L] = 0.30 M. As illustrated in Figure 1, the oxidative addition of PhI to 2 was first-order in [PdI] and independent of [L]. Reactions between 30 and 60 °C showed that $\Delta S^\circ = 16.8 ± 2.0$ eV. Those data are consistent with reaction of PhI with 2 by associative paths A or C. 13

To differentiate between reaction of PhI by paths A and C, we studied the reductive elimination of iodoarene. If the reductive elimination of iodoarene from 4 or a closely related compound occurred by the reverse of path A, then the reaction would be independent of the concentration of added ligand; however, if the reductive elimination of iodoarene occurred by the reverse of path C, then the reaction would be first-order in added ligand.

Complex 4 did not undergo clean reductive elimination of PhI at even at 70 °C in the presence of 30 equiv of added Q-phos-tol, but the related complex [Pd(PPh3)3(tol)] [7] undergoes reductive elimination of a-tol upon addition of PPh3 (Scheme 2). 14 The rate constants for this reductive elimination were measured by 195P NMR.
spectroscopy with a 0.02 M concentration of the palladium complex and 0.2–0.4 M concentration of added PhBr. Consistent with reaction by the reverse of path A but not by the reverse of path C, k_{lab} was independent of [PhBr] assuming that the addition and elimination of halocarbon to the palladium complexes ligated by PhBr and Q-phen-tol follow the same mechanism. Oxidative addition of PhBr to 2 would follow path A. This finding is consistent with the low stability of four-coordinate arylphosphine halide complexes containing these sterically demanding ligands.

The oxidative addition of PhBr followed a path that was different from that for oxidative addition of PhI. The rates of the oxidative addition of PhBr were measured at 50 °C with [PhBr] between 0.95 and 6.3 M and [L] between 0 and 0.45 M. The values of k_{lab} were independent of the concentration of PhBr and ligand; the value of k_{lab} from experiments with varied [Q-phen-tol] was (6.2 ± 0.8) × 10^{-5} s^{-1}, and the value from experiments with varied [PhBr] was (6.7 ± 0.9) × 10^{-5} s^{-1}. Further, the values of k_{lab} for reactions of RC1H2Br (R = 4-ClC6H4, 4-Me, 2-CH2) were indistinguishable from that for reaction of PhBr, and ∆Δ (9.8 ± 3.8 eu) was small, albeit slightly negative. Among the mechanisms in Scheme 3, these data are consistent with only path D, involving rate-limiting dissociation of L.

If the rate constant for the oxidative addition of PhBr corresponds to that for dissociation of ligand from [Pd(phen-CF3)]2, then an independent measurement of the rate constant for dissociation of ligand from [Pd(phen-CF3)]2 should give the same value. The rate constant for ligand dissociation from Q-phen-CF3 complex 3 was determined by reaction of 3 with Q-phen. The reaction was conducted with a large enough excess of Q-phen (10–50 equiv) that the equilibrium for ligand exchange lay toward Q-phen complex 3 (Scheme 3). This ligand substitution was dissociative, as shown by the lack of dependence of k_{lab} on [Q-phen]. Most important for understanding the mechanism of oxidative addition, the value of k_{lab} for the exchange process in THF at 60 °C was 4.6 ± 0.4 × 10^{-5} s^{-1}, and the value of k_{lab} for the oxidative addition of bromobenzene to the same Q-phen-CF3 complex 3 at 60 °C in THF solvent was 4.0 ± 0.2 × 10^{-5} s^{-1}. Likewise, the value of ∆Δ for the exchange process (−7.4 ± 3.6 eu) was indistinguishable from that for the oxidative addition to 2.

The oxidative addition of PhI to 2 occurred by a third mechanism. The oxidative addition of PdCl to 2 was measured at 60 °C with [PhCl] between 0.76 and 6.8 M and [L] between 0.050 and 0.33 M. As shown by the plots in Figure 2, the rate constant for addition of PhCl depended positively on [PhCl] and inversely on [L]. Of the mechanisms in Scheme 1, these data are consistent with only path E.

The inverse of the y-intercepts of both plots (2.0 ± 0.2 and 1.7 ± 0.1 × 10^{−5}) corresponds to the rate constant for dissociation of Q-phen-tol from 2. These values are nearly identical and match the rate constant for oxidative addition of PhBr to 2 at 60 °C (1.9

References


(3) Amatore, C.; Pfeger, P. Organometallics 1990, 9, 2276.


(12) Supporting Information Available: Experimental procedures and additional kinetic data (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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1) (a) Oxidative Addition:

\[ \text{LnM} + X-Y \rightarrow \text{LnM} \sigma_{X,Y} \]

(b) \( \Delta \text{O.S.} = +2 \)

(c) \( \Delta \text{C.N.} = +2 \)

2) (a) \( \text{LnPd}^0 + \text{Ar}-X \rightarrow \text{LnPd}^{+2} \text{Ar} \sigma_X \) \( (X = Cl, Br, I) \)

(b) Order of Increasing Reactivity:

\( \text{Ar}-Cl < \text{Ar}-Br < \text{Ar}-I \)

(c) Bond Dissociation Energy:

\( \text{Ar}-Cl > \text{Ar}-Br > \text{Ar}-I \)

3) (a) Heck Reaction:

\[ \text{Ar}-X + \text{R} \xrightarrow{\text{Pd/L, base}} \text{Ar} = \text{R} + \text{HX} \]
(b) Suzuki Coupling Reaction:

\[ \text{Ar-} X + \text{RB(OH)}_2 \xrightarrow{\text{Pd/L}} \text{Ar-} R + \text{XB(OH)}_2 \]

(c) Buchwald-Hartwig Reaction:

\[ \text{Ar-} X + \text{R}_2 \text{NH} \xrightarrow{\text{Pd/L}} \text{Ar-NR}_2 + \text{HX} \xrightarrow{\text{base}} \]
4) The use of hindered alkylmonophosphines allows formation of Pd(0) complexes with low coordination number and electron richness.
   (a) Low coordination \implies \text{Facilitation of Oxidative Addition}
   (b) Electron-rich \implies \text{More Active Catalysts}
      for Coupling Processes.

5) (a) $[\text{Pd}(\eta^3-\text{phos-tol})_2]$  
    \begin{align*}
    \text{E.C.: } & 14e \\
    \text{C.N.: } & 2 \\
    \text{O.S.: } & 0 \\
    d^n: & d^{10}
    \end{align*}
6) **(a) Reductive Elimination:**

\[ \text{L}_n \text{M} \xrightarrow{X} \text{L}_n \text{M} + X-Y \quad \Delta \text{O.S.} = -2 \]

\[ \Delta \text{C.N.} = -2 \]

**(b) Steric Hindrance:**

\[ \text{P Bu}_3^- > \text{Q-phos-tol} \]

\[ \text{a-tol} > \text{ph} \]

⇒ Steric hindrance facilitates reductive elimination.

7) **(a)** \[ [\text{Pd}(\text{Q-phos-tol})(\text{Ph})(\text{Cl})]\]: Singlet

**(b)** \[ [\text{Pd}(\text{Q-phos-tol})(\text{Ph})(\text{Br})]\]: Singlet

**(c)** \[ [\text{Pd}(\text{Q-phos-tol})(\text{Ph})(\text{I})]\]: Singlet

**(d)** \[ [\text{Pd}(\text{Q-phos-tol})(\text{Ph})(\text{Cl})]\] has the highest $^{31}P$ chemical shift.

Electron-withdrawing capability: \[ \text{Cl} > \text{Br} > \text{I} \]

⇒ Ejection Density on P: \[ (a) < (b) < (c) \]

⇒ $^{31}P$ Chemical Shift: \[ (a) > (b) > (c) \]
8) Relative Rates:

\[ \text{Me}_2\text{N}-\text{O}^{-}\text{Br} \equiv \text{Et}-\text{O}^{-}\text{Br} = \text{Et}-\text{O}^{-}\text{Br} \]

(b) The oxidative addition of ArBr was found to be consistent with Path D in Scheme 1, involving rate-limiting dissociation of phosphine. As a result, the values of \( k_{obs} \) should be independent of the concentration of ArBr. Consequently, the relative rates should be indistinguishable between different ArBr.

9) The kinetic data obtained for the reaction are consistent with the Path A mechanism, but not the other four mechanisms.

(a) If Path B, the \( k_{obs} \)s would depend on [PPhI] and [L].

It was found that the \( k_{obs} \)s was independent of [L].

(b) If Path C, the reverse reaction, which is the reductive elimination of iodoarene, would be first-order in added ligand. It was found that the \( k_{obs} \)s of the reductive elimination reaction was independent of [L].

(c) If Path D, the \( k_{obs} \)s would be independent on
[PHI] and [IL]. It was found that the oxidative addition of PHI was first-order in [PHI].

d) If Path E, the rate would depend on [PHI] and [IL].
   It was found that the oxidative addition of PHI was independent of [IL].

10) (a) The bond dissociation energy of Co(yz)F is very strong.

     (b) Various answers are expected.