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The First Example of Simple Oxidative Addition of an Aryl Chloride to a Discrete Palladium N-Heterocyclic Carbene Amination Precatalyst

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Summary: Reaction of 4-chlorotoluene with the amination precatalyst [Pd(cyclo-C{N(2,6-^{i}Pr$_2$-C$_6$H$_3$)CH$_2$}$_2$)$_2$] leads to reductive elimination of the arylated imidazolium salt, whereas the analogous reaction with [Pd(cyclo-C{N^{t}BuCH}$_2$)$_2$] affords the structurally characterized oxidative-addition product trans-[Pd(cyclo-C{N^{t}BuCH}$_2$)$_2$-(4-Me-C$_6$H$_4$)Cl].

It has become apparent that the ligating properties of N-heterocyclic carbenes (NHCs) exhibit considerable similarities to those of phosphines and offer an effective ligand environment for transition-metal-mediated organic transformations. A number of reports have successfully demonstrated that a range of such carbene ligands can be incorporated into Pd(II) complexes and offer an alternative class of precatalysts, with improved stability (and potential turnover capacity), for C−C coupling reactions.[1] In particular, recent work by Nolan[2] and Hartwig[3] has demonstrated the use of imidazolinium and imidazolium salts for the in situ generation of catalytically active species from Pd$_2$dba$_3$ for *amination* couplings using aryl chlorides. Both reports suggest formation of a Pd(0) carbene complex via deprotonation of the imidazolium salt to generate carbene followed by subsequent displacement of dba ligands. Hartwig has suggested a mechanism for amination catalyzed by 2-coordinate Pd(0) phosphine species (generated in situ from Pd$_2$(dba)$_3$ and e.g. P^{t}Bu$_3$), in which the key step is dissociation of phosphine from PdL$_2$ to generate a PdL fragment, which then undergoes turnover-limiting oxidative addition (OA) of aryl halide (Figure 1).[3,4]

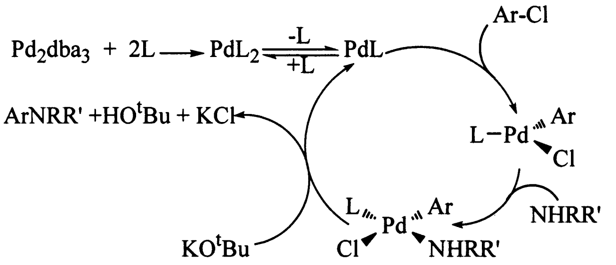
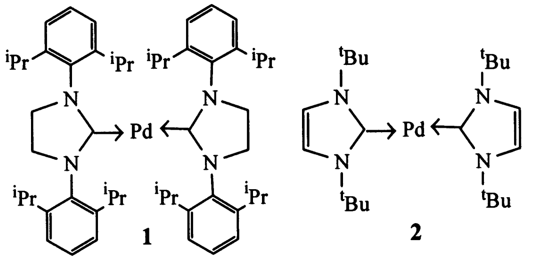


Figure 1. Proposed mechanism for amination.



1

2

Figure 2. Isolated amination precatalysts.

This mechanism is also very likely to be applicable to the case where L is an NHC ligand. In contrast to the in situ approach to presumably generate Pd(NHC)$_2$, we have been exploring the ability of the isolated 2-coordinate NHC complexes of Pd(0) **1** and **2** (Figure 2) to effect amination of aryl chlorides.[5] **1**, in particular, is highly effective for a range of amine couplings with 4-chlorotoluene.

In this paper we report studies on the OA reaction of an aryl chloride with **1** and **2**,[6] which, in the case of **2**, results in isolation of the first example of a stable OA product from a well-defined NHC amination precatalyst.

Attempted OA of 4-chlorotoluene to **1** resulted in the formation of not a four-coordinate complex but rather the arylated imidazolium salt **3** (see Scheme 1), together with the deposition of palladium metal.

The identity of **3** has been confirmed by X-ray crystallography, but the structure will not be reported here. The formation of **3** parallels the report by Cavell on reductive elimination from *trans*-[Pd(carbene)$_2$(Ph)I],[7] in which elimination of such an imidazolium salt is proposed as an important decomposition pathway in palladium−carbene-mediated couplings.[8]

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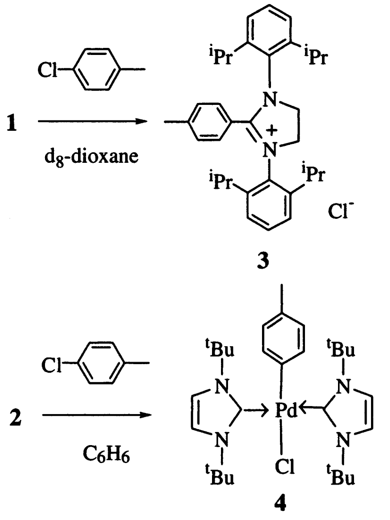
Scheme 1. Reactions of 1 and 2 with 4-Chlorotoluene



In contrast, the reaction between **2** and 4-chlorotoluene proceeded slowly at room temperature, to completion after 1 h at 90 °C, to afford the OA product **4** essentially quantitatively by NMR (see Scheme 1). Reaction of **4** with morpholine and potassium *tert*-butoxide in dioxane at 100 °C afforded the arylated amine in >95% yield, a result identical with that previously obtained for the same coupling using **2**.[5] Single crystals of **4** suitable for X-ray diffraction were grown from benzene at room temperature, and the molecular structure together with selected bond distances and angles is shown in Figure 3.[9]

The geometry around palladium in **4** is virtually perfectly square planar with the carbene ligands mutually trans. Despite the smaller radius of Pd(II) relative to Pd(0), the palladium–carbene bond lengths in **4** (identical within esds at 2.094(4) and 2.091(4) Å) are slightly longer than that found in the parent Pd(0) complex **2** (2.041(6) Å),[10] a reflection of the steric congestion in the 4-coordinate Pd(II) complex. Similarly, in **2** the carbene rings are mutually orthogonal,[10] whereas in **4** they are coplanar in order to sterically accommodate the additional two ligands, with the Cl–Pd-aryl (C23) vector being orthogonal to the carbene ring plane. The Pd–aryl (C23) distance (2.065(4) Å) lies within the range found for related Pd(II) complexes;[11] however, the aryl ring lies in the coordination plane in **4**, atypical for square-planar arylmetal complexes, in which the aryl ring is usually orthogonal to the square plane. CaChe modeling studies on **4** showed the orthogonal arrangement to be ca. 10 kJ mol^{-1} higher in energy than the coplanar case, presumably due to the resultant close contact (3.0 Å) between the ortho carbons of the aryl ring and the carbene *tert*-butyl methyl groups. The distances and angles within the carbene rings in **4** are essentially identical (within esds) with those in **2**.

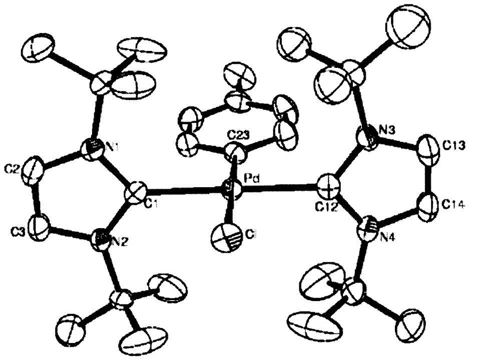


Figure 3. Molecular structure of **4** (thermal ellipsoids at the 50% probability level). Selected bond distances (Å) and angles (deg): Pd–C1 = 2.094(4), Pd–C12 = 2.091(4), Pd–C23 = 2.065(4), Pd–Cl = 2.445(1), C1–N1 = 1.376(5), C1–N2 = 1.376(5), N1–C2 = 1.376(5), N2–C3 = 1.379(5), C2–C3 = 1.335(6), C12–N3 = 1.378(5), C12–N4 = 1.373(5), N3–C13 = 1.383(5), N4–C14 = 1.388(5), C13–C14 = 1.323(6); Cl–Pd–C1 = 88.30(11), C1–Pd–C23 = 91.63(15), C23–Pd–C12 = 90.01(15), C12–Pd–Cl = 90.05(10).

The trans geometry of the carbene ligands in **4** is worthy of comment and suggests (a) concerted OA of 4-chlorotoluene to **2** (perhaps unlikely on steric grounds) and collapse of the resultant tetrahedral intermediate, (b) a nonconcerted OA of 4-chlorotoluene to **2**, or (c) prior dissociation of one carbene ligand from **2** (cf. Figure 1) followed by concerted OA of 4-chlorotoluene and final reattachment of carbene. Detailed kinetic studies are in progress to establish the mechanism of this fundamental step in amination mediated by complexes of types **1** and **2**.

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Supporting Information Available: Text giving details of experimental procedures and characterization data for complexes **3** and **4** and tables giving X-ray data for **4**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(9) Crystal data for **4**: $C_{29}H_{47}ClN_4Pd{\cdot}2C_6D_6$, M_r = 749.77, monoclinic, a = 12.5279(6) Å, b = 13.7541(3) Å, c = 23.2188(11) Å, α = 90°, β = 97.785(2)°, γ = 90°, U = 3964.0(3) Å^3, T = 173(2) K, space group $P2_1/n$ (No. 14), Z = 4, λ(Mo Kα) = 0.710 73 Å, 20 601 reflections measured, 6950 unique (R_{int} = 0.057). The final wR2 value was 0.112 (all data).

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