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Communication

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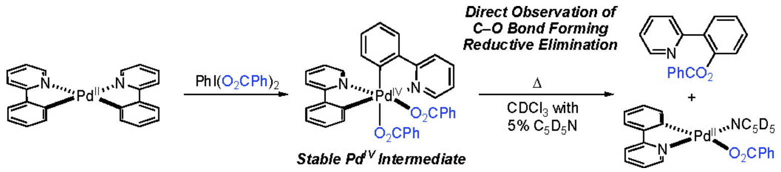

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Unusually Stable Palladium(IV) Complexes: Detailed Mechanistic Investigation of C−O Bond-Forming Reductive Elimination

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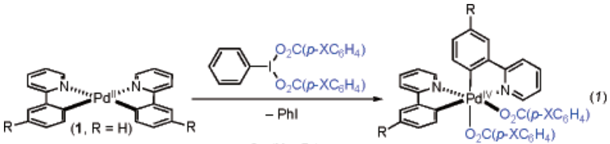
Carbon−oxygen bond-forming reductive elimination is a fundamental organometallic transformation involved in a wide variety of transition metal catalyzed processes.[1] Of particular current relevance, C−O bond-forming reductive elimination from transient Pd^{IV} aryl/acetate intermediates has been implicated as the product release step in Pd^{II}-catalyzed arene oxygenation reactions.[2] Recent elegant studies have probed the mechanisms of related C−O bond-forming processes at Ni^{III},[1d] Pd^{II},[3] and Pt^{IV} [4] centers, uncovering distinctly different pathways in each system. In contrast, a detailed mechanistic picture of C−O bond formation from Pd^{IV} has remained elusive.[5] Attempts to investigate this process have been hampered by the low stability of Pd^{IV} complexes (particularly those containing multiple oxygen donor ligands) as well as by the propensity of Pd^{IV} to undergo undesired side reactions, such as competing C−C bond-forming reductive elimination and/or intermolecular alkyl ligand exchange.[5−7] *We report herein the rational design and synthesis of a series of unusual Pd^{IV} complexes (**2a**−**2o**) that are remarkably stable at ambient temperature but undergo clean C−O bond-forming reductive elimination upon thermolysis*. These complexes have enabled the first detailed mechanistic investigation of C−O bond-forming reductive elimination from Pd^{IV}.

In designing Pd^{IV} model complexes for these studies, we sought to incorporate features that would both stabilize the +4 oxidation state and promote C−O bond formation over competing side reactions. In this regard, our first synthetic target was complex **2a** (eq 1), containing two rigid cyclometalated pyridine ligands (to stabilize Pd^{IV})[5−8] with aryl rather than alkyl groups (to prevent ligand exchange between metal centers).[5−8] These aryl ligands were also placed in independent rigid chelating frameworks, which we reasoned should reduce undesired ligand exchange and C−C bond-forming processes. Finally, benzoate-based O-donors were incorporated to allow facile manipulation of electronic parameters (through variation of the *para*-substituent) as well as to model Pd-catalyzed arene oxygenation reactions.[2]



(1)

2a (X = H)
2b (X = OMe)
2c (X = Me)
2d (X = OPh)
2e (X = F)
2f (X = Cl)
2g (X = Br)
2h (X = Ac)
2i (X = CF_3)
2j (X = CN)
2k (X = NO_2)
2l (X = H, R = Me)
2m (X = Cl, R = Me)
2n (X = Br, R = Me)

Our studies began with complex **1**, which was readily prepared according to a literature procedure.[9] Gratifyingly, we found that **1** undergoes clean oxidation with $PhI(O_2CPh)_2$ to afford the isolable bisbenzoate Pd^{IV} complex **2a** in 77% yield (eq 1). The ^1H NMR spectrum of **2a** shows 22 inequivalent aromatic resonances, consistent with an asymmetric *cis*-geometry with free rotation about the C−Ph bond of the benzoate ligands. The solid-state structure of the *para*-NO_2 analogue (**2k**) was further confirmed by X-ray crystallography (Figure 1).

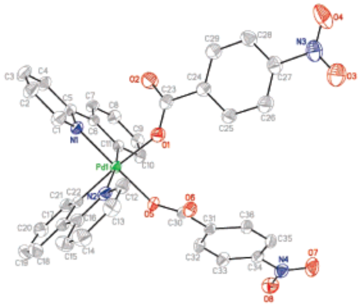
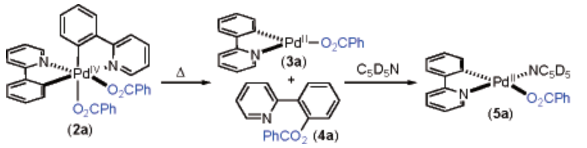


Figure 1. ORTEP diagram of **2k**.

Remarkably, complex **2a** is stable in the solid state for at least a week and shows little decomposition after an hour in $CDCl_3$ solution at 25 °C.[7] (In contrast, analogous $(C_2N_2O_2)Pd^{IV}$ complexes that do not contain cyclometalated ligands have been implicated as reactive intermediates but not detected even at −70 °C.)[5a] However, we were pleased to find that **2a** does undergo smooth C−O bond-forming reductive elimination to afford **4a** when heated for 1 h at 60 °C (eq 2). This reaction proceeds with clean first-order kinetics when conducted in the presence of 5% d_5-pyridine (added to trap putative three-coordinate Pd^{II} intermediate **3a**),[10] facilitating detailed mechanistic studies of this process.



(2)

As summarized in Scheme 1, we considered three distinct mechanistic pathways for reductive elimination from **2a**—(i) pre-equilibrium dissociation of a benzoate ligand followed by either external or intramolecular nucleophilic attack (**A**), (ii) direct reductive elimination from the six-coordinate starting material (**B**), or (iii) dissociation of a pyridyl arm of one cyclometalated ligand followed by internal coupling (**C**). We initially felt that mechanism **A** was most likely, by analogy to related C−O bond-forming reactions at Pt^{IV} (which proceed by pre-equilibrium dissociation of RO^-)[4] and to C−C coupling at Pd^{IV} (which involves pre-equilibrium loss of I^-).[11] As a result, we first examined the effect of solvent on the rate of reductive elimination from **2o** (a more soluble analogue of **2a** containing two $C_9H_{19}CO_2^-$ ligands), expecting a significant acceleration in more polar solvents.[4,11] However, surprisingly, the reaction proceeded at essentially identical rates in polar acetone ($\epsilon = 21$, $k_{rel} = 1.0 \pm 0.1$) and nonpolar benzene ($\epsilon = 2.3$, $k_{rel} = 1.0 \pm 0.1$) at 55 °C ($k_{rel} = k_{obs}/k_{acetone}$). Furthermore, the rate showed no discernible correlation with solvent dielectric constant: DMSO ($\epsilon = 47$, $k_{rel} = 2.0 \pm 0.3$) < $CHCl_3$ ($\epsilon = 4.8$, $k_{rel} = 2.3 \pm 0.2$) < MeCN ($\epsilon = 38$, $k_{rel} = 2.4 \pm 0.1$) < nitrobenzene ($\epsilon = 36$, $k_{rel} = 3.1 \pm 0.3$).[12] In contrast, the rates of

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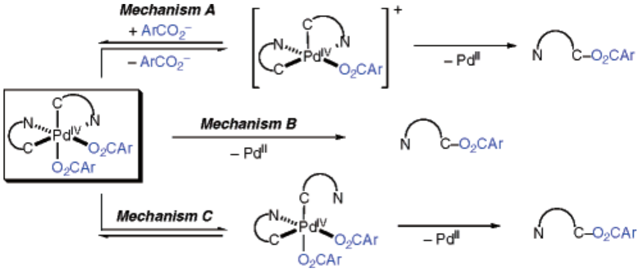
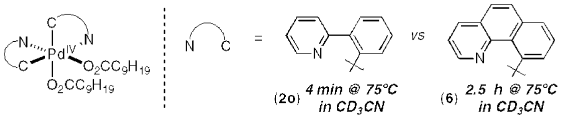
Scheme 1. Possible Mechanisms of C−O Reductive Elimination



ionic reductive elimination from both Pt^{IV} and Pd^{IV} typically show strong dependence on solvent polarity.[4,11]

A series of additional experiments provided further evidence against benzoate dissociation mechanism **A**. First, Eyring analysis of reductive elimination from **2c** afforded $\Delta S^\ddagger$ values of $+4.2 \pm 1.4$ and -1.4 ± 1.9 eu in d_6-DMSO and CDCl$_3$, respectively.[12] In contrast, ionic reductive elimination reactions typically show highly negative values of $\Delta S^\ddagger$ as a result of solvent ordering about the charged transition state. (For example, $\Delta S^\ddagger$ values ranging from −13 to −49 eu are typical of ionic C−C and C−Se reductive elimination from Pd^{IV}.)[6,11] Additionally, the rate of reductive elimination was examined in a series of complexes containing *para*-substituted benzoate ligands (**2b**−**2k**). Electron donor substituents led to moderate rate accelerations [with a Hammett ρ value of -1.36 ± 0.04 ($R^2 = 0.98$)], indicating that the benzoate acts as a nucleophilic partner in these transformations.[12] A comparable ρ value of −1.5 has been reported for C−S coupling at Pd^{II}, which is believed to proceed by a mechanism similar to **B**.[10] In contrast, C−O bond-forming reductive elimination from Pt^{IV} (which proceeds via mechanism **A**) shows a ρ of +1.44, indicative of stabilization of the dissociated RO$^-$ moiety by electron-withdrawing groups.[4] Finally, thermolysis of mixtures of **2l** and **2g** (two differentially substituted Pd^{IV} complexes that reductively eliminate at comparable rates) yielded oxygenated organic products without any observable crossover in CHCl$_3$ or DMSO.[13] Furthermore, thermolysis of **2b** in the presence of 5 equiv of NBu$_4$OAc resulted in ≤5% incorporation of acetate into the organic reductive elimination product in CHCl$_3$ or DMSO. These results provide further evidence against mechanism **A** as the major reaction pathway since extensive exchange between ion pairs and/or free ions would be expected if benzoate dissociation preceded reductive elimination in these systems.

In sum, these studies led us to the surprising conclusion that C−O bond-forming reductive elimination from complex **2a** proceeds predominantly by either direct reductive elimination from the octahedral starting material (a rare process in both Pt^{IV} and Pd^{IV} chemistry)[14,15] or by dissociation of an arm of one of the chelating phenylpyridine ligands (mechanisms **B** and **C**, respectively). These mechanisms are kinetically indistinguishable and cannot be definitively differentiated based on any of the experiments detailed above. However, we reasoned that preliminary evidence to distinguish **B** and **C** might be obtained by comparing the rate of reductive elimination from bisphenylpyridine complex **2o** to that from bisbenzo[*h*]quinoline complex **6** (eq 3). In the case of mechanism **B**, comparable rates of reductive elimination are expected for **2o** and **6**, due to the similar steric and electronic parameters of the ligands. However, in the case of mechanism **C**, the added rigidity of the fused ring system is expected to dramatically decrease the rate of nitrogen dissociation and, therefore, the overall rate of reductive elimination from **6** relative to **2o**.[16] When these complexes were heated at 75 °C in CD$_3$CN, reductive elimination from **2o** was complete in 4 min, while the reaction of **6** took 2.5 h to reach completion. On the basis of this large (approximately 40-fold) difference, we currently favor mechanism **C** for these reactions, and further studies to confirm this hypothesis are underway.



(3)

In summary, we have demonstrated the design and synthesis of a series of remarkably stable Pd^{IV} complexes and have presented the first detailed study of C−O bond-forming reductive elimination from this oxidation state. These experiments indicate that C−O coupling at Pd^{IV} proceeds by a significantly different mechanism than other reductive eliminations from Pd^{IV} or Pt^{IV} centers. Current work in our laboratory aims to exploit these mechanistic insights for the development of new Pd^{IV}-catalyzed reactions.

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Supporting Information Available: Experimental details, crystallographic data for **2k**, spectroscopic and analytical data for new compounds, and detailed discussion of kinetics (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(16) Related experiments have been used to differentiate mechanisms involving dissociation of chelating phosphines (see refs 10 and 14a).

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