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Activation of the C−N Bond in Nitromethane by Palladium α-Diimine Complexes

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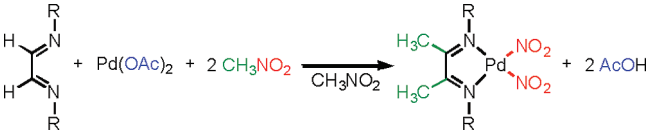
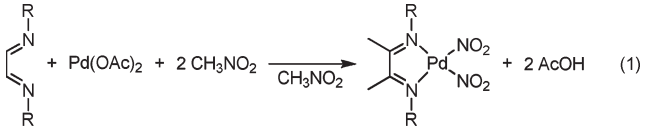


The reaction of glyoxal-derived α-diimines with palladium acetates in nitromethane leads to cleavage of the C−N bond in nitromethane, to give palladium nitro complexes in which the α-diimine ligand has been methylated.

We recently found that a high-throughput screening study, intended to generate a library of complexes of the form $(L_2)PdX_2$, led in several cases to much more complicated palladium products, including one resulting from activation of the solvent, acetone.[1] We report here the unexpected activation of the C−N bond in nitromethane, observed during a similar study using glyoxal-derived α-diimines as bidentate ligands and nitromethane as solvent.

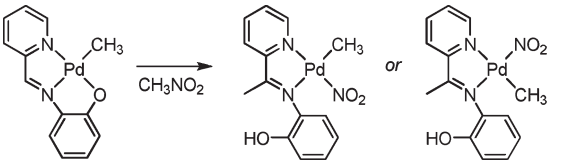
The reaction of palladium acetate ($Pd(OAc)_2$) with either 1,4-bis(2,6-diisopropylphenyl)-1,4-diaza-1,3-butadiene (^{H}diimine-Ar) or 1,4-bis(cyclohexyl)-1,4-diaza-1,3-butadiene (^{H}diimine-Cy) in nitromethane gave (^{Me}diimine)$Pd(NO_2)_2$ (**1a**, **1b**) as orange or gold crystalline solids, respectively (eq 1); the identity of both species was confirmed by ^{1}H NMR and ^{13}C NMR spectroscopy, high resolution mass spectrometry (HRMS), and X-ray crystallography (Figures 1 and 2). These reactions correspond to two C−N bond cleavages of nitromethane, with the methyl groups replacing protons on the backbone of the diimine and the nitro groups displacing acetates on palladium, generating 2 equiv of acetic acid.



(1)

1a R = 2,6-diisopropylphenyl
1b R = cyclohexyl

The very similar transformation shown in eq 2 was recently reported;[2] the proposed mechanism is related to well-known organic reactions (Henry reaction or Michael addition followed by denitration)[3] as well as a couple of earlier examples involving coordination complexes in which nucleophilic addition of the CH_2NO_2 anion to an imine carbon center is followed by loss of nitrite and proton transfer.[4,5]



(2)

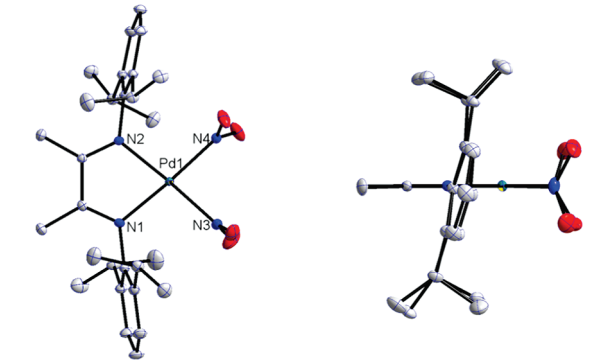


FIGURE 1. The solid state structure of (^{Me}diimine-Ar)$Pd(NO_2)_2$ (**1a**). Selected bond lengths (Å): Pd1−N1 2.044(7), Pd1−N2 2.050(7), Pd1−N3 2.011(8), and Pd1−N4 2.011(7).

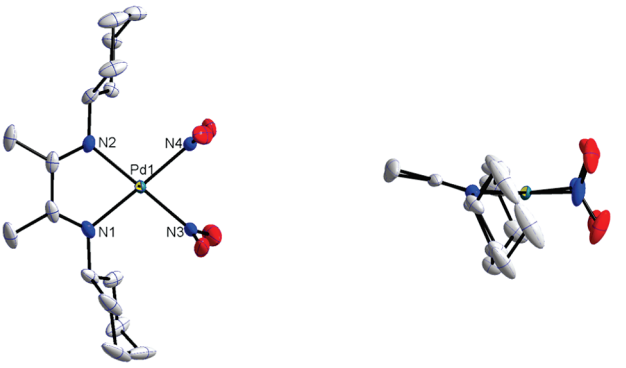


FIGURE 2. The solid state structure of (^{Me}diimine-Cy)$Pd(NO_2)_2$ (**1b**). Selected bond lengths (Å): Pd1−N1 2.058(12), Pd1−N2 2.046(11), Pd1−N3 2.013(14), and Pd1−N4 2.014(12).

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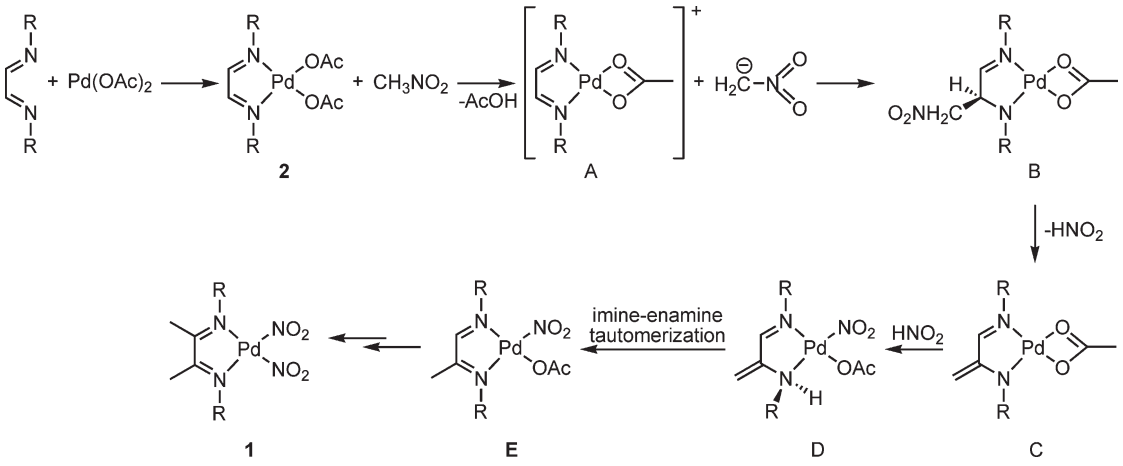
SCHEME 1



A plausible mechanism for the present case, following similar lines, is shown in Scheme 1, which begins with reaction between diimine and $Pd(OAc)_2$ to give **2**. Deprotonation of nitromethane by acetate leads to [(diimine)Pd(η^2-OAc)]$^+$ (**A**) and the carbanion, which adds to the carbon of one imine to give an imine−amide complex (**B**). Elimination of HNO_2 cleaves the C−N bond to give an imine−enamide complex (**C**); readdition of HNO_2 to protonate the amide and attach NO_2 to Pd (**D**) followed by tautomerization generates the singly methylated diimine complex (**E**). (Protonation of **C** at the methylene to give **E** directly is also possible.) Repeating the entire cycle leads to the observed bis-methylated diimine complex (**1**).

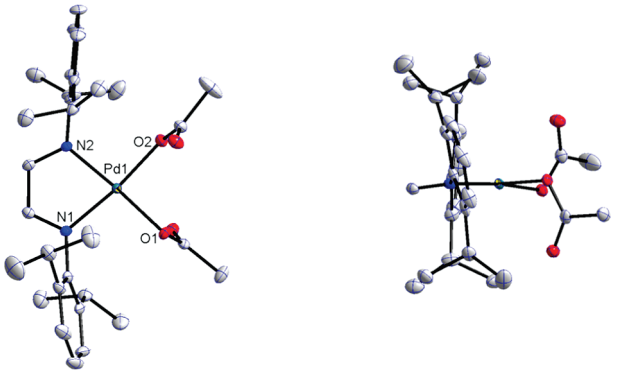


FIGURE 3. The solid state structure of (^{H}diimine-Ar)Pd(OAc)$_2$ (**2a**). Selected bond lengths (Å): Pd1−N1 2.017(11), Pd1−N2 1.995(12), Pd1−O1 2.009(9), and Pd1−O2 2.017(11).

As an initial test of this mechanism, (^{H}diimine-Ar)Pd(OAc)$_2$ (**2a**) was prepared by reacting $Pd(OAc)_2$ with ^{H}diimine-Ar in methylene chloride, as confirmed by ^{1}H NMR and ^{13}C NMR spectroscopy, HRMS, and X-ray crystallography (Figure 3). A dilute (1.5 mM) solution of **2a** in nitromethane, initially dull orange, changes over a few hours to a bright orange solution containing **1a** (by ^{1}H NMR spectroscopy), strongly suggesting that **2a** is a viable reaction intermediate. (A transient yellow color was observed during the course of this reaction, possibly attributable to one or more of the suggested intermediates, but we were unable to isolate or identify this species.)

Attempts to follow kinetics of the transformation of **2a** to **1a** by ^{1}H NMR spectroscopy in nitromethane-d_3 (neat or mixed with other deuterated solvents) were unsuccessful, as the reaction did not proceed cleanly to product. It was noted that the backbone methyl signals exhibited the presence of significant amounts of CH_3 and CH_2D isotopologues. These presumably result from exchange with residual water (solvents were used as received with no further drying); such exchange has been observed previously.[6] When the reaction was performed in the presence of small amounts of D_2O, the ^{1}H NMR signals for the backbone methyls were greatly reduced, demonstrating that the latter do originate from the methyl group of nitromethane.

The direct reaction of eq 1 appears to be quite concentration dependent: with [diimine] and [$Pd(OAc)_2$] greater than about 9 mM intense colors (dark blue and green) appear. With both reagents at 4.4 mM, formation of **1a** takes place over the course of a few hours, with no such coloration. The reaction also proceeds if excess diimine (but not excess $Pd(OAc)_2$) is used, but clean kinetics could not be obtained. Semiquantitative reaction rates in the presence of added bases or acids were estimated by following the appearance of product by ^{1}H NMR spectroscopy, since the proposed mechanism suggests there should be an effect. Addition of nitrogen bases (3,5-lutidine, 2,6-lutidine or 2,6-*cis*-dimethylpiperidine) to the dilute mixture of $Pd(OAc)_2$ in nitromethane-d_3 and ^{H}diimine-Ar in acetone-d_6 gave only base-ligated palladium species (supported by ^{1}H NMR chemical shifts), and no productive chemistry involving the ^{H}diimine-Ar. In contrast, addition of either NaOAc or AcOH had little effect on the rate of formation of **1a**.

Addition of the stronger trifluoroacetic acid (tfa) inhibited nitromethane activation and led instead to (^{H}diimine-Ar)-Pd(tfa)$_2$ (**3a**), which was prepared separately by the reaction of Pd(tfa)$_2$ and ^{H}diimine-Ar in acetone and characterized by ^{1}H NMR and ^{13}C NMR spectroscopy, HRMS, and X-ray crystallography (Figure 4). Dissolution of **3a** in nitromethane did not yield **1a** cleanly under a variety of conditions, including heating; after prolonged stirring (45 days) of **3a** in nitromethane-d_3, approximately 20% of **1a**-d_6 was observed.

It seems reasonable that the reaction should be much slower for trifluoroacetate than for acetate, if deprotonation

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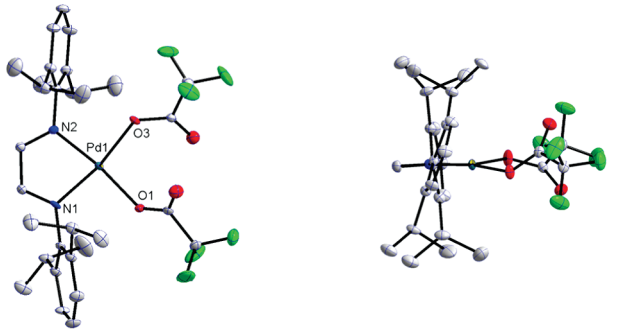
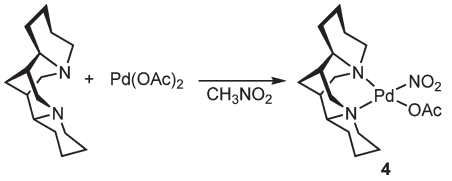


FIGURE 4. The solid state structure of (^{H}diimine-Ar)Pd(tfa)$_2$ (**3a**). Selected bond lengths (Å): Pd1−N1 1.994(11), Pd1−N2 1.996(10), Pd1−O1 2.002(9), and Pd1−O2 2.005(10).

of nitromethane is a required early step; it is less clear why addition of excess acetate or acetic acid has little or no effect on the overall rate. In the absence of any characterizable intermediates, the proposed mechanism, while plausible and consistent with related chemistry, remains speculative; alternative mechanisms (for example, oxidative addition of the C−N bond to give a Pd(IV) intermediate) cannot be ruled out. Indeed, small amounts of a C−N activation product were obtained with a different system (eq 3)[7] for which a mechanism related to that of Scheme 1 appears highly unlikely. The scope of this type of C−N bond cleavage by coordination complexes,[8] as well as the mechanistic relationship to purely organic activations, remains to be explored.



(3)

Experimental Section

General Considerations. All manipulations were performed in air. Palladium(II) acetate and palladium(II) trifluoroacetate (Aldrich) and nitromethane (Acros Organics) were used as received. 1,4-Bis(2,6-diisopropylphenyl)-1,4-diaza-1,3-butadiene[9] (^{H}diimine-Ar) and 1,4-bis(cyclohexyl)-1,4-diaza-1,3-butadiene[10] (^{H}diimine-Cy) were prepared by literature methods. Nitromethane-d_3, acetone-d_6, methylene chloride-d_2, and chloroform-d_1 were purchased from Cambridge Isotopes and used as received. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Varian INOVA 500 MHz instrument, using the VNMRJ software program, version 2.2d, at room temperature. Proton and carbon chemical shifts are reported relative to the residual solvent signal. HRMS were obtained from the California Institute of Technology Mass Spectrometry Facility.

X-ray Crystallography. The crystals were mounted on a glass fiber with Paratone-N oil. Data were collected on a Bruker KAPPA APEX II instrument. Structures were determined by using direct methods or, in some cases, Patterson maps with standard Fourier techniques, using the Bruker AXS software package. Data are shown in Table S1 (Supporting Information).

(^{Me}diimine-Ar)Pd(NO$_2$)$_2$ (1a). A solution of ^{H}diimine-Ar (168 mg, 0.45 mmol) in nitromethane was added to a solution of Pd(OAc)$_2$ (100 mg, 0.45 mmol) in nitromethane. Evaporation of the solvent overnight gave an orange solid (158 mg, 59% yield). ^{1}H NMR (500 MHz, acetone-d_6) δ 1.18 (d, J = 7 Hz, 12H, CH(CH_3)$_2$), 1.54 (d, J = 7 Hz, 12H, CH(CH_3)$_2$), 2.49 (s, 6H, NCCH_3), 3.35 (sept, J = 7 Hz, 4H, CH(CH$_3$)$_2$), 7.24 (d, J = 8 Hz, 4H, m-C$_6H_3$), 7.32 (t, J = 7 Hz, 2H, p-C$_6H_3$); ^{13}C NMR (126 MHz, acetone-d_6) δ 21.57, 23.66, 24.62, 125.03, 129.72, 140.24, 141.44, 181.68; HRMS (FAB+) obsd M − NO$_2$ 556.2172, calcd for C$_{28}$H$_{40}$N$_4$O$_4$Pd − NO$_2$, 556.2166.

(^{Me}diimine-Cy)Pd(NO$_2$)$_2$ (1b). A solution of ^{H}diimine-Cy (49 mg, 0.22 mmol) in nitromethane was added to a solution of Pd(OAc)$_2$ (50 mg, 0.22 mmol) in nitromethane. Evaporation of the solvent overnight gave gold crystals (13 mg, 13% yield). ^{1}H NMR (500 MHz, CDCl$_3$) δ 0.84 (tt, J = 12.5 Hz, 3.5 Hz, 2H, CH), 1.00 (m, 10H, CH_2), 1.47 (dd, J = 13.2 Hz, 1.3 Hz, 5H, CH_2), 1.95 (d, J = 9.5 Hz, 5H, CH_2), 3.58 (s, 6H, NCCH_3); ^{13}C NMR (126 MHz, CDCl$_3$) δ 24.50, 24.64, 34.59, 53.85, 99.48; HRMS (FAB+) obsd M − NO$_2$ 400.1225, calcd for C$_{16}$H$_{28}$N$_4$O$_4$Pd − NO$_2$, 400.1216.

(^{H}diimine-Ar)Pd(OAc)$_2$ (2a). A solution of ^{H}diimine-Ar (335 mg, 0.89 mmol) in CH$_2$Cl$_2$ was added to a solution of Pd(OAc)$_2$ (200 mg, 0.89 mmol) in CH$_2$Cl$_2$. Evaporation of the solvent overnight gave orange needle-like crystals (456 mg, 85% yield). ^{1}H NMR (500 MHz, acetone-d_6) δ 1.16 (s, 6H, OCOCH_3), 1.16 (d, J = 7 Hz, 12H, CH(CH_3)$_2$), 1.48 (d, J = 7 Hz, 12H, CH(CH_3)$_2$), 3.70 (sept, J = 7 Hz, 4H, CH(CH$_3$)$_2$), 7.27 (d, J = 8 Hz, 4H, m-C$_6H_3$), 7.37 (t, J = 7 Hz, 2H, p-C$_6H_3$), 8.45 (s, 2H, NCH); ^{13}C NMR (126 MHz, acetone-d_6) δ 21.98, 23.24, 25.53, 55.05, 124.21, 129.59, 142.18, 143.42, 169.29, 175.50; HRMS (FAB+) obsd M − C$_2$O$_2$H$_3$ 541.2054, calcd for C$_{30}$H$_{42}$N$_2$O$_4$Pd − C$_2$O$_2$H$_3$, 541.2047.

(^{H}diimine-Ar)Pd(tfa)$_2$ (3a). A solution of ^{H}diimine-Ar (340 mg, 0.90 mmol) in acetone was added to a solution of Pd(tfa)$_2$ (300 mg, 0.90 mmol) in acetone. Removal of the solvent in vacuo after 30 m gave a bright orange semicrystalline solid (560 mg, 88% yield). ^{1}H NMR (500 MHz, acetone-d_6) δ 1.21 (d, J = 7 Hz, 12H, CH-(CH_3)$_2$), 1.48 (d, J = 7 Hz, 12H, CH(CH_3)$_2$), 3.67 (sept, J = 7 Hz, 4H, CH(CH$_3$)$_2$), 7.28 (d, J = 8 Hz, 4H, m-C$_6H_3$), 7.41 (t, J = 7 Hz, 2H, p-C$_6H_3$), 8.61 (s, 2H, NCH); ^{13}C NMR (126 MHz, acetone-d_6) δ 22.98, 25.26, 29.83, 124.69, 130.50, 141.89, 142.22, 172.76; HRMS (FAB+) obsd M − C$_2$O$_2$F$_3$ 595.1764, calcd for C$_{30}$H$_{36}$N$_2$O$_4$F$_6$Pd − C$_2$O$_2$F$_3$, 595.1764.

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Supporting Information Available: NMR spectra, crystal and refinement data, details of synthesis, X-ray structure of **4**, and CIFs. This material is available free of charge via the Internet at http://pubs.acs.org.

(7) The structure of [(−)-sparteine]Pd(OAc)(NO$_2$) (**4**) is shown in the Supporting Information (Figure S9). We have as yet been unable to determine what becomes of the methyl group from the nitromethane in this reaction.

(8) Solutions of either ^{H}diimine-Ar plus Pd(OAc)$_2$ or **2a** in nitroethane turn orange and exhibit ^{1}H NMR signals consistent with what would be expected for the ethyl analogue of **1a**, but the reaction is considerably less clean than the nitromethane reactions, as indicated by additional NMR signals and further color changes; no pure product could be isolated.

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