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“Oxidatively Induced” Reductive Elimination of Dioxygen from an η^{2-}Peroxopalladium(II) Complex Promoted by Electron-Deficient Alkenes

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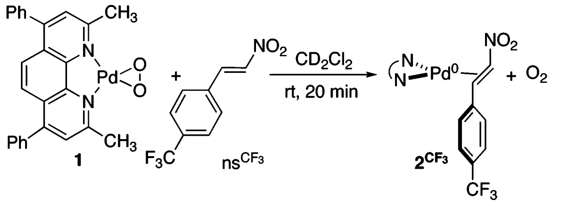
Palladium-catalyzed oxidation reactions employ a variety of stoichiometric oxidants, most commonly, Cu(II) salts and benzoquinone.[1] In some cases, efficient catalytic turnover can be achieved with dioxygen as the sole oxidant.[2] The origin of oxidant specificity for individual reactions is poorly understood. The relationship between benzoquinone and dioxygen is particularly intriguing because these molecules possess different electronic structures (singlet vs triplet), but both react with Pd(0) to produce η^2-adducts that subsequently react with acid to generate catalytically active Pd(II) (Scheme 1).[3,4] In recent mechanistic studies of alkene self-exchange at Pd(0), we speculated about the relationship between reactions of dioxygen and alkenes with well-defined palladium(0) complexes.[5] Here, we report the discovery that electron-deficient alkenes (nitrostyrenes) can displace dioxygen from an η^2-peroxopalladium(II) complex. Mechanistic studies indicate this reaction proceeds by an “oxidatively induced” reductive elimination pathway in which the incoming alkene withdraws electron density from the Pd(II) center in the transition state. These observations amplify the similar reactivity of alkenes and dioxygen with palladium and have direct implications for the use of benzoquinone and dioxygen as oxidants in Pd-catalyzed oxidation reactions.

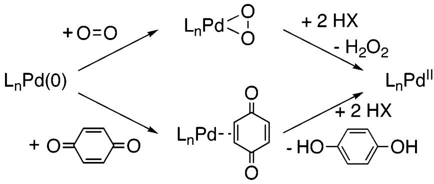
We recently reported the synthesis and characterization of a peroxopalladium(II) complex, **1**, bearing the aromatic diimine ligand bathocuproine (bc).[4a] Shortly thereafter, we began probing whether **1** could effect oxygen-atom transfer to electron-deficient alkenes, such as nitrostyrene.[6] Although no oxygenation products were observed, we obtained a different, unexpected result: nitrostyrene displaces dioxygen from the Pd center. For example, addition of 10 equiv of *p*-CF_3-*trans*-β-nitrostyrene (ns^{CF_3}) to **1** in dichloromethane-d_2 results in nearly complete conversion to the previously characterized alkene adduct, (bc)Pd(ns^{CF_3}) ($\mathbf{2^{CF_3}}$) (eq 1).[5] The identity of $\mathbf{2^{CF_3}}$ was confirmed by comparison of ^1H and ^{19}F NMR spectral data with those from an authentic sample.



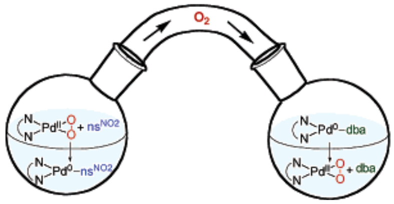
(1)

Other nitrostyrene derivatives (ns^X, X = OCH_3, CH_3, H, F, Br, NO_2) also react with **1**, displacing dioxygen to form the corresponding alkene complex $\mathbf{2}^X$. With the more electron-rich alkenes, ns^{OCH_3} and ns^{CH_3}, a large excess (>100 equiv) is required to achieve quantitative conversion in a sealed reaction vessel. It was possible to characterize and quantify the evolved dioxygen gas by trapping it with (bc)Pd(dba) (dba = dibenzylideneacetone) in a separate flask attached to the reaction vessel (Scheme 2).[7]

Scheme 1. Dioxygen- and Benzoquinone-Mediated Oxidation of Pd(0)



Scheme 2. Quantitative Dioxygen Trapping Experiment



The formation of Pd(η^2-O_2) adducts via Pd(0) oxygenation is generally irreversible, and prior observations in our lab supported this generalization.[4,8,9] The only reported exception is the dissociation of O_2 from (t-$Bu_2PhP)_2Pd(O_2)$, which occurs under vacuum at 60−70 °C over an extended time period (38 h).[10]

The unexpected facility of eq 1 prompted us to investigate the mechanism of this reaction. The kinetics of dioxygen displacement by ns^{CF_3} were studied initially by ^1H NMR spectroscopy. Under pseudo-first-order conditions (12 equiv of ns^{CF_3}) in CD_2Cl_2 at 25 °C, **1** converted cleanly into $\mathbf{2^{CF_3}}$ in ∼20 min with an exponential dependence on [**1**] (Figures S2 and S3). No intermediates were observed during the reaction. UV−visible spectroscopy proved to be a more convenient method to acquire kinetics data. A representative time-course for the reaction of **1** with ns^{NO_2} is shown in Figure 1A, and similar data were acquired for five different ns^X derivatives (X = H, F, Br, CF_3, NO_2). Exponential fits to the time-course data enabled us to obtain k_{obs} values for each alkene over a range of concentrations (Figure 1B). In each case, the k_{obs} values exhibit a linear dependence on [ns^X], and the fit intersects the origin. Activation parameters, obtained by monitoring the temperature dependence of the displacement reaction for four different ns^X derivatives (X = F, Br, CF_3, NO_2), reveal large negative entropies of activation, $\Delta S^\ddagger = -30$ to -36 eu (Figure S4, Table S2). Together, these data indicate that dioxygen displacement by ns^X proceeds exclusively via an *associative* mechanism.

A Hammett plot, derived from the bimolecular rate constants for displacement of dioxygen by the different ns^X derivatives, yields a linear correlation with σ_p parameters (Figure 2). As Figures 1B and 2 reveal, the more electron-deficient alkenes react faster, and the substantial positive slope in the Hammett plot ($\rho = 1.53$) indicates that significant Pd → alkene charge transfer occurs in the transition state of the reaction.

The mechanistic picture that emerges from these data is closely related to that of alkene exchange at Pd(0), which has been characterized experimentally and computationally.[5] The latter reaction proceeds via charge transfer from a palladium-centered

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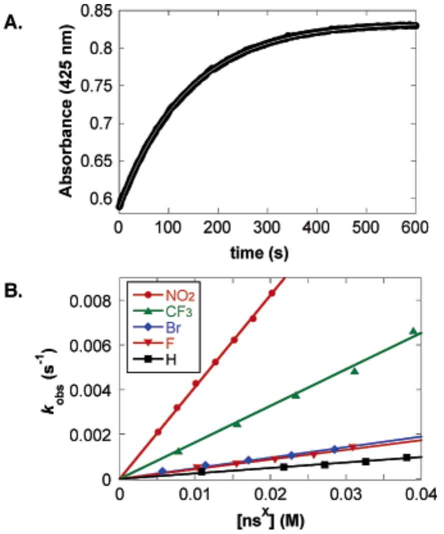


Figure 1. (A) Representative single wavelength (425 nm) UV−visible spectroscopic time-course for the reaction of **1** with ns^{NO_2}. (B) Olefin concentration dependence on the rate of dioxygen displacement from **1** by ns^X to form $\mathbf{2}^X$. Reaction conditions: [Pd] = 0.5 mM, [ns^X] = 5−39 mM, 3 mL of CH_2Cl_2, 298 K.

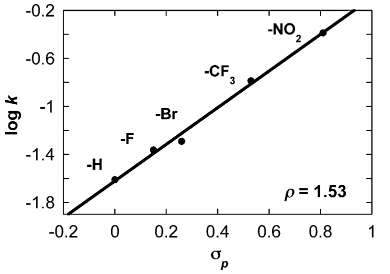


Figure 2. Hammett plot illustrating electronic effects on the rate of dioxygen displacement from **1** by *para*-substituted nitrostyrene derivatives.

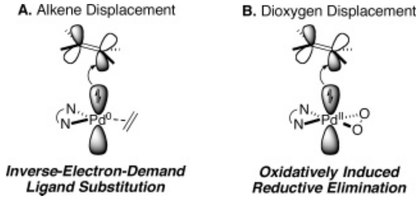
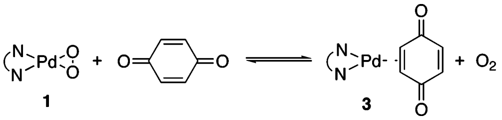


Figure 3. Mechanistic model for associative displacement of alkenes (A) and dioxygen (B) at palladium centers.

lone pair (d_{z^2}) into the π^* orbital of the incoming alkene (Figure 3A), thus reflecting an "oxidative" trajectory.[5b,11] A similar model can be applied to the O_2-displacement reaction (Figure 3B). By analogy to alkene exchange, displacement of dioxygen by an electron-deficient alkene corresponds to an oxidatively induced reductive elimination of O_2 from Pd(II).[12,13]

In summary, we have discovered and characterized an associative pathway for displacement of dioxygen from a Pd(η^2-O_2) complex by electron-deficient alkenes. These observations have important practical and fundamental implications. For example, the challenges encountered in palladium-catalyzed aerobic oxidation of allylic alcohols[14] may reflect their formation of α,β-unsaturated carbonyl compounds. Such products are electron-deficient alkenes that might inhibit catalyst oxidation by competing with dioxygen for coordination to Pd(0). More generally, these results raise fundamental questions concerning the relationship between dioxygen and benzoquinone as oxidants in palladium-catalyzed oxidation reactions. Benzoquinone is an electron-deficient alkene, and in preliminary studies, we find that benzoquinone can displace dioxygen from (bc)Pd(O_2) to form the corresponding alkene adduct **3** (eq 2).[15,16] In future studies, we hope to elucidate the kinetic and thermodynamic factors that differentiate the reactivity of dioxygen and electron-deficient alkenes (including benzoquinone) with palladium centers.



1 **3** (2)

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Supporting Information Available: Experimental details, ^{1}H NMR spectral time-course and concentration traces, Eyring data. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) Heumann, A.; Jens, K.-J.; Réglier, M. *Prog. Inorg. Chem.* **1994**, *42*, 483−576.
(2) (a) Stahl, S. S. *Science* **2005**, *309*, 1824−1826. (b) Stahl, S. S. *Angew. Chem., Int. Ed.* **2004**, *43*, 3400−3420. (c) Sigman, M. S.; Jensen, D. R. *Acc. Chem. Res.* **2006**, *39*, ASAP. (d) Stoltz, B. M. *Chem. Lett.* **2004**, *33*, 362−367. (e) Sheldon, R. A.; Arends, I. W. C. E.; ten Brink, G.-J.; Dijksman, A. *Acc. Chem. Res.* **2002**, *35*, 774−781.
(3) (a) Grennberg, H.; Gogoll, A.; Bäckvall, J.-E. *Organometallics* **1993**, *12*, 1790−1793. (b) Clegg, W.; Eastham, G. R.; Elsegood, M. R. J.; Heaton, B. T.; Iggo, J. A.; Tooze, R. P.; Whyman, R.; Zacchini, S. *J. Chem. Soc., Dalton Trans.* **2002**, 3300−3308.
(4) (a) Stahl, S. S.; Thorman, J. L.; Nelson, R. C.; Kozee, M. A. *J. Am. Chem. Soc.* **2001**, *123*, 7188−7189. (b) Konnick, M. M.; Guzei, I. A.; Stahl, S. S. *J. Am. Chem. Soc.* **2004**, *126*, 10212−10213.
(5) (a) Stahl, S. S.; Thorman, J. L.; de Silva, N.; Guzei, I. A.; Clark, R. W. *J. Am. Chem. Soc.* **2003**, *125*, 12−13. (b) Popp, B. V.; Thorman, J. L.; Morales, C. M.; Landis, C. R.; Stahl, S. S. *J. Am. Chem. Soc.* **2004**, *126*, 14832−14842.
(6) For late-transition-metal peroxo reactions with electrophilic substrates, see: Sheldon, R. A.; Kochi, J. K. *Metal-Catalyzed Oxidations of Organic Compounds*; Academic Press: New York, 1981; pp 81−82.
(7) See Supporting Information for details.
(8) For example, the oxygenation of (bc)Pd(dba) was conducted in the presence of a 10-fold excess of the alkene, dba, and efforts to remove O_2 under vacuum or by sparging solutions of bc- or *N*-heterocyclic-carbene-coordinated Pd(O_2) adducts with an inert gas were unsuccessful.[4]
(9) For additional examples of Pd(O_2) complexes, see: (a) Valentine, J. S. *Chem. Rev.* **1973**, *73*, 235−245. (b) Yamashita, M.; Goto, K.; Kawashima, T. *J. Am. Chem. Soc.* **2005**, *127*, 7294−7295.
(10) Yoshida, T.; Otsuka, S. *J. Am. Chem. Soc.* **1977**, *99*, 2134−2140.
(11) The association of CO at an Ir(I) center is another redox-neutral reaction that proceeds via an oxidative trajectory: Abu-Hasanayn, F.; Krogh-Jespersen, K.; Goldman, A. S. *J. Am. Chem. Soc.* **1994**, *116*, 5979−5980.
(12) This phenomenon has important precedent in organometallic chemistry: Kochi, J. K. *Organometallic Mechanisms and Catalysis*; Academic Press: New York, 1978; pp 466−499.
(13) See also: (a) Yamamoto, T.; Yamamoto, A.; Ikeda, S. *J. Am. Chem. Soc.* **1971**, *93*, 3350−3359. (b) Lau, W.; Huffman, J. C.; Kochi, J. K. *Organometallics* **1982**, *1*, 155−169. (c) Tatsumi, K.; Nakamura, A.; Komiya, S.; Yamamoto, A.; Yamamoto, T. *J. Am. Chem. Soc.* **1984**, *106*, 8181−8188. (d) Komiya, S.; Akai, Y.; Tanaka, K.; Yamamoto, T.; Yamamoto, A. *Organometallics* **1985**, *4*, 1130−1136.
(14) For example, see: (a) Nishimura, T.; Onoue, T.; Ohe, K.; Uemura, S. *J. Org. Chem.* **1999**, *64*, 6750−6755. (b) Schultz, M. J.; Park, C. C.; Sigman, M. S. *Chem. Commun.* **2002**, 3034−3035.
(15) Popp, B. V.; Stahl, S. S. Unpublished results.
(16) For further discussion of the relationship between dioxygen and benzoquinone in palladium-catalyzed oxidation reactions, see: Popp, B. V.; Thorman, J. L.; Stahl, S. S. *J. Mol. Catal. A: Chem* **2006**, in press.

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