Oxidatively Resistant Ligands for Palladium-Catalyzed Aerobic Alcohol Oxidation

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Aerobic Alcohol Oxidation with Cationic Palladium Complexes: Insights into Catalyst Design and Decomposition

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Aerobic alcohol oxidation catalyzed by the newly synthesized dimeric [(neocuproine)Pd(μ-OAc)]$_2$-(OTf)$_2$ (**1**; neocuproine = 2,9-dimethyl-1,10-phenanthroline) proceeds under exceptionally mild conditions (room temperature, ambient air) compared to those required for the previously reported monomeric diacetate analogue (neocuproine)Pd(OAc)$_2$ (**2**) and the monomeric ditriflate analogue (neocuproine)Pd-(MeCN)$_2$(OTf)$_2$ (**3**). An unprecedented initial turnover frequency (TOF$_i$) for such mild conditions (78 (Pd atom)$^{-1}$ h^{-1}) is observed with catalyst **1**; however, competitive oxidation of a methyl group on the ligand to a carboxylate group results in catalyst inactivation. During the study of **1**, we isolated for the first time [(neocuproine)Pd(μ-OH)]$_2$(OTf)$_2$ (**4**), a possible intermediate in the catalytic cycle, and we report its crystal structure and catalytic activity herein.

Introduction

The selective, catalytic oxidation of organic molecules remains one of the central challenges in chemical synthesis.[1] Air is an attractive terminal oxidant, as it is abundant and, if reduced completely to water, generates environmentally benign coproducts. Nevertheless, the high overpotential of dioxygen for most oxidative transformations of interest and its kinetic stability and tendency to generate highly reactive partially reduced oxidizing species (PROS) once activated[2] are the major chemical challenges in taming this readily available oxidant for selective oxidation reactions. It is instructive to consider that aerobic organisms have not completely solved this problem, in that a significant component of physical aging is the inability of aerobic organisms to mitigate deleterious free-radical oxidation reactions. To quote accomplished biochemist Bruce Ames, "We're all going rancid."[3]

In an effort to develop highly active oxidation catalysts for potential use in low-temperature fuel cells, we sought active catalyst systems that would mediate oxidative transformations, preferably at ambient temperatures. To this end, we were attracted to recent work which suggested that appropriately ligated Pd(II) complexes could mediate selective oxidative transformations with air as a terminal oxidant.[4,5] In particular, the palladium-catalyzed aerobic oxidation of alcohols to aldehydes and ketones has been the subject of several excellent reviews,[4,6,7] and its mechanism has been studied extensively.[8−25]

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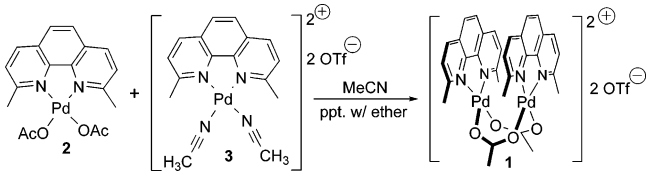
Scheme 1. Preparation of Complex 1



Sigman and co-workers reported that the Pd N-heterocyclic carbene complex (IiPr)Pd(OPiv)$_2$ catalyzes the oxidation of alcohols at room temperature in air.[26] Since the first report of ligand-accelerated catalysis using Pd(OAc)$_2$ and pyridine by Uemura and co-workers,[27] a variety of ligands have been employed, including triethylamine,[20,26,28] substituted phenanthrolines,[11,12,29−31] N-heterocyclic carbenes,[16,26,32,33] and sterically encumbered pyridines.[34,35] While much attention has been given to the effect of ligand modulation on catalyst activity, there are only a few examples of effective catalyst systems that use palladium salts other than Pd(OAc)$_2$.[11,26,32,36,37] Sigman and Jensen[21] attribute the success of acetate to its dual role as an anionic ligand and as a base for intramolecular deprotonation of the palladium-bound alcohol species. However, the use of *noncoordinating* ions to make cationic palladium(II) complexes with an open coordination site has also been shown to dramatically increase the rate of aerobic oxidations.[38] We reasoned that a palladium(II) complex with both a basic, coordinating acetate ion and a noncoordinating triflate counterion should yield a more active alcohol oxidation catalyst.

Herein, we report that cationic neocuproine palladium acetate complexes exhibit very fast initial rates of alcohol oxidation at room temperature in air but undergo competitive ligand oxidation from hydroperoxide intermediates generated from the partial reduction of O_2. Mechanistic studies reveal that the presence of an open coordination site and an internal acetate base are key features that enable the rapid dehydrogenation of alcohols.

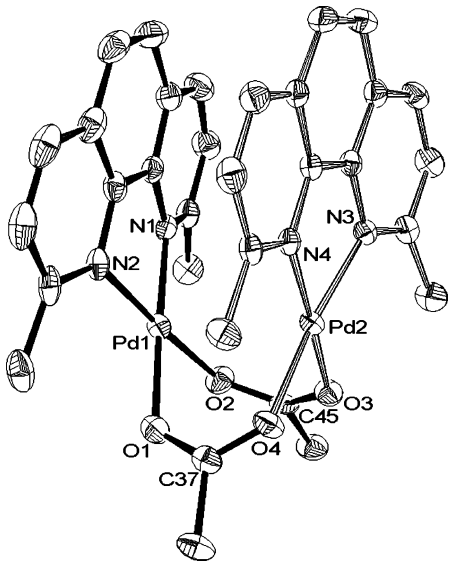


Figure 1. Solid-state structure of **1** with ellipsoids drawn at the 50% probability level. Hydrogen atoms and triflate anions are omitted for clarity. Selected bond lengths (Å) and angles (deg): Pd1−Pd2, 2.9582(4); Pd1−O1, 2.016(2); Pd1−O2, 2.015(2); Pd1−N2, 2.024(2); Pd1−N1, 2.019(3); Pd2−O4, 2.026(2); Pd2−O3, 2.0105(19); Pd2−N4, 2.056(2); Pd2−N3, 2.038(2); O4−C37, 1.272(3); O1−C37, 1.256(4); O3−C45, 1.271(3); O2−C45, 1.262-(3); O1−Pd1−O2, 84.17(9); O4−Pd2−O3, 81.85(8); O4−Pd2−N3, 173.46(9); O3−Pd2−N4, 176.69(9); N3−Pd2−N4, 82.77(9).

Results and Discussion

On the basis of Sheldon's report that substituted (neocuproine)Pd(OAc)$_2$ complexes were active alcohol oxidation catalysts under 30 bar of air at 80 °C,[30,31] we sought a synthetic route to cationic (neocuproine)Pd(OAc)(OTf) complexes. We found that conproportionation of (neocuproine)Pd(OAc)$_2$ (**2**)[30] and the ditriflate analogue (neocuproine)Pd(MeCN)$_2$(OTf)$_2$ (**3**) (prepared by treating **2** with triflic acid)[39] in acetonitrile afforded the dimeric acetate-bridged compound **1**, as shown in Scheme 1. Investigations by ^{1}H NMR spectroscopy in acetonitrile-d_3 as a function of concentration reveal that this complex speciates as a dimer (M_2, **1**) and monomer (M)[40] in fast equilibrium (Scheme 2) with the dissociation constant $K = [M]^2/[M_2] = 5$ mM at 295 K in CD_3CN; the monomer and dimer resonances at 8.59 and 8.24 ppm, respectively, were integrated to determine the equilibrium constant. Thermodynamic parameters for this

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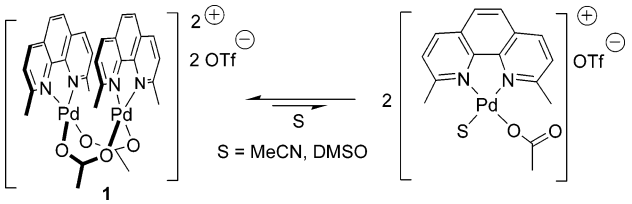
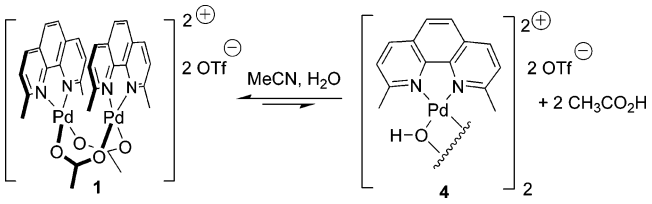
(40) The monomer/dimer equilibrium was studied by ^{1}H NMR in two different coordinating solvents, acetonitrile and DMSO. For a 9.2 mM solution of **1**, the monomer to dimer ratios were determined to be 1.0:1.5 and 1.0:3.3 in acetonitrile and DMSO, respectively. This solvent-dependent equilibrium implies that the monomer exists as a solvate.

Scheme 2. Monomer−Dimer Equilibrium of the Cationic Palladium Complex 1



Scheme 3. Generation of the μ-OH Dimer 4



equilibrium were extracted from a van't Hoff plot, which was constructed using data from variable-temperature ^{1}H NMR spectra from 295 to 345 K ($\Delta H° = 32.1$ kJ mol^{-1}, $\Delta S° = 65.1$ J mol^{-1} K^{-1}). The solid-state structure of **1** (Figure 1) reveals a stacked dimeric structure spanned by bridging acetates, analogous to the structures of a recently reported cationic palladium bis(carbene) dimer[41] and neutral palladacycle dimers.[42,43]

Addition of water to an acetonitrile-d_3 solution of **1** generates an equilibrium mixture of [(neocuproine)Pd(μ-OH)]$_2$(OTf)$_2$ (**4**), acetic acid, and **1**, as shown in Scheme 3. Similar equilibria have been reported for other L_2PdX_2 complexes.[11,44] The μ-hydroxo Pd dimer **4** is only sparingly soluble in acetonitrile and precipitates from solution. The X-ray crystal structure of **4**, shown in Figure 2, indicates that **4** is isostructural with the previously reported platinum analogue[45] and adopts a butterfly structure to minimize nonbonded interactions between the methyl groups of the neocuproine ligands. The structure reveals a hydrogen bond between bridging OH groups and the triflate counterions. Addition of an excess of acetic acid to an isolated sample of **4** in acetonitrile resulted in its clean conversion back to **1**. As the μ-hydroxo Pd dimer **4** is analogous to the resting state of the catalyst system reported by Sheldon et al. for the aerobic oxidation of alcohols,[11,30,31,46] it was also examined as a catalyst precursor for aerobic alcohol oxidation.

Complexes **1**−**4** were investigated for the catalytic oxidation of 2-heptanol to 2-heptanone in acetonitrile[47] at room temperature under an ambient pressure of air. The reaction progress for each complex is plotted in Figure 3. Under these mild conditions, complex **1** (3 mol % Pd) exhibits a fast initial TOF ($TOF_i = 78$ Pd atom^{-1} h^{-1}) for the oxidation of 2-heptanol but the rate slows rapidly to afford a 36% yield of 2-heptanone after 24 h, which corresponds to a turnover number (TON) of 12 (Pd atom)$^{-1}$. The initial rates are the same in the presence of either air or dioxygen, implying that reoxidation of palladium is not rate limiting.

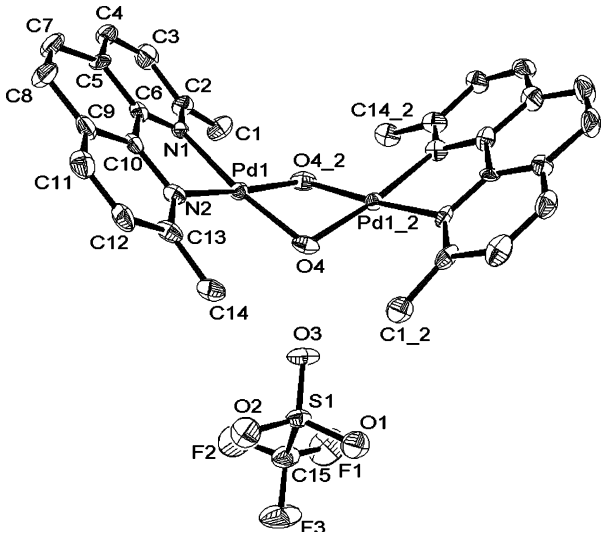


Figure 2. Solid-state structure of **4** on a crystallographic 2-fold axis with ellipsoids drawn at the 50% probability level. Hydrogen atoms, except those corresponding to the μ-OH groups, and one triflate anion are omitted for clarity. Selected bond lengths (Å) and angles (deg): Pd1−N1, 2.038(8); Pd1−N2, 2.047(9); Pd1−O4, 2.014(9); Pd1−O4_2, 2.006(9); O4−Pd1−O4_2, 79.3(3); N1−Pd1−N2, 82.1(3); Pd1−O4_2−Pd1_2, 95.8(3); C14−C13−N2−Pd1, 14.4(3); C1−C2−N1−Pd1, 12.5(5). Nonbonded distances (Å): Pd1−Pd1_2, 2.982(2); O4−O4_2, 2.564(9); C(methyl)−Pd1, 3.44(8) (average); C(methyl)−(μ-O), 2.89(3) (average); O3−O4, 2.74(9).

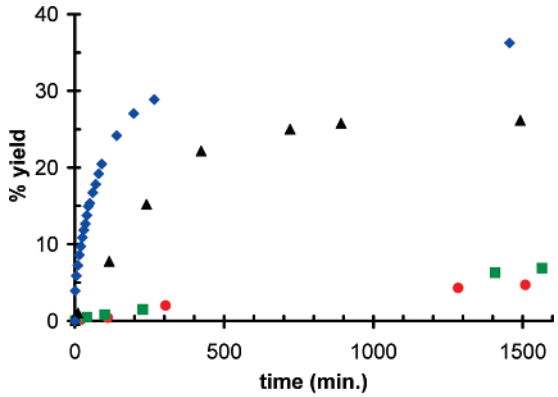


Figure 3. Reaction progress of air oxidation (1 atm) of 2-heptanol (0.5 M) with complexes **1** (◆), **2** (■), **3** (●), and **4** (▲) (3 mol % Pd) in acetonitrile (1:1 acetonitrile/dichloromethane for **2**; 1:1 acetonitrile/dimethyl sulfoxide for **4**) at room temperature.

To assess the role of charge and ligand substitution on catalytic alcohol oxidation, complexes **2**−**4** were investigated for alcohol oxidation under similar conditions (Figure 3). The μ-hydroxo Pd dimer **4** showed behavior similar to that of the mixed acetate/triflate Pd dimer **1** but exhibited lower initial rates ($TOF_i = 2.0$ (Pd atom^{-1}) h^{-1}) and yield.[48] In contrast, under these conditions, both (neocuproine)Pd(OAc)$_2$ (**2**) and (neocuproine)Pd(MeCN)$_2$(OTf)$_2$ (**3**) were ineffective catalysts ($TOF_i = 0.24$ and 0.16 (Pd atom^{-1}) h^{-1}, respectively).

The high initial rates for the aerobic oxidation of 2-heptanol by the palladium acetate triflate dimer **1** under ambient air are remarkable. Of the few reported Pd systems for alcohol oxidation with ambient air,[26,29,34,42,49] only the N-heterocyclic carbene system described by Sigman and co-workers[26] proceeds at room temperature. The high activity of this catalyst under

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such mild conditions[50] was proposed to be due to the low coordination number of (IMes)Pd(OAc)$_2$, which enables facile binding of alcohol, and deprotonation of the bound alcohol by the internal acetate base[21] to yield the Pd alkoxide intermediate.[26,33] We propose that the presence of both triflate and acetate counterions in complex **1** allows for fast alcohol binding and fast deprotonation of the palladium-bound alcohol species, followed by β-hydride elimination.[51] The slow rate observed with the diacetate **2** suggests that an open coordination site for the alcohol is a key feature leading to fast oxidation with **1**.[52] The slow rate observed with the ditriflate **3** implies that the presence of a suitable base to deprotonate the palladium-bound alcohol is also important.[14] We attribute the slower rate of **4** (relative to **1**) to the slow dissociation of the μ-OH dimer[53] in the absence of acetic acid. These data suggest that a weakly coordinating ligand and an intramolecular base are necessary to achieve high TOFs with the neocuproine/palladium(II) system under mild conditions.

Despite the fast initial rates of alcohol oxidation with complexes **1** and **4**, the rates decrease rapidly with conversion, implicating that these catalysts are deactivated, even under these mild reaction conditions. The time course of the reaction reveals that the rate of alcohol oxidation decreases linearly with percent yield of 2-heptanone. Palladium black was not observed in the catalysis with **1** during the time in which the reaction was monitored and, therefore, cannot account for this loss of activity. Furthermore, control experiments indicated that neither water, a byproduct of the oxidation,[54] nor 2-heptanone inhibited the catalyst. The addition of molecular sieves[23] leads to lower initial rates and conversion. While hydrogen peroxide, a possible byproduct of the oxidation,[31] was found to inactivate the catalyst, it could not be detected electrochemically in the reaction mixture during the course of the reaction,[55] and the addition of a variety of hydrogen peroxide disproportionation catalysts into the reaction mixture did not prolong the life of the catalyst **1**.[56]

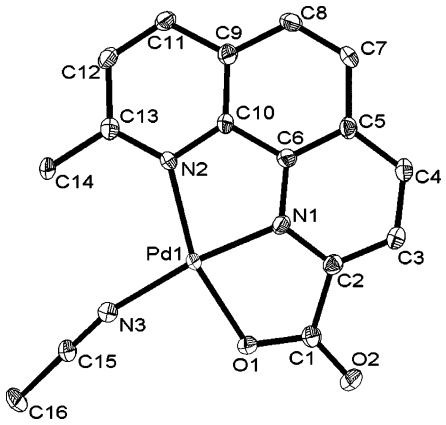

Figure 4. Solid-state structure of **5** with ellipsoids drawn at the 50% probability level. Only one of the three identical cations composing the asymmetric unit is shown, with hydrogen atoms and triflate anions omitted for clarity. Selected bond lengths (Å) and angles (deg): Pd1−N1, 1.917(3); Pd1−N2, 2.095(2); Pd1−N3, 2.021(3); Pd1−O1, 2.020(2); C1−O1, 1.308(4); C1−O2, 1.207-(4); N2−Pd1−N1, 81.24(10); N1−Pd1−O1, 80.22(10).

These observations are inconsistent with reversible catalyst inhibition and implicate a competitive process involving catalyst decomposition to a soluble, inactive palladium complex.

To identify the fate of catalyst **1**, the reaction mixture was precipitated with diethyl ether after 24 h of reaction. Analysis of the palladium-containing products revealed the presence of the cationic palladium carboxylate **5** (see Figure 4), indicating that one of the methyl groups of the 2,9-dimethylphenanthroline ligands is oxidized to the carboxylate. This complex was inactive as a catalyst for alcohol oxidation. Complex **5** was also formed in the aerobic oxidation of 2-heptanol with the μ-hydroxo Pd dimer **4**. The solid-state structure of **5** reveals a square-planar coordination geometry with an intramolecularly bound carboxylate derived from one of the ligand methyl groups and a coordinated acetonitrile ligand.

The formation of the inactive complex **5** during the course of the reaction implies that either oxygen or a PROS degrades the ligand in competition with alcohol oxidation. Given that the dimer **1** is stable to air in the absence of alcohol, we suspected that ligand oxidation was mediated by hydroperoxide intermediates generated during the course of the catalytic cycle. To gain insight into the pathway through which **5** was formed, an acetonitrile solution of dimer **1** was treated with aqueous hydrogen peroxide. Three products were identified from this reaction: the μ-hydroxo palladium dimer **4**, the alkoxide **6**, and the carboxylate **5** (Scheme 4). The formation of the μ-hydroxo dimer **4** is likely due to the presence of water from the aqueous hydrogen peroxide. The formation of the alkoxide **6** and the carboxylate **5** are proposed to derive from the hydroperoxide intermediate **7**. The reaction of palladium(II) complexes with hydrogen peroxide is known to give palladium hydroperoxides.[57] An isolated sample of the alkoxide **6** was converted quantitatively to **5** by stirring in acetonitrile in the presence of air, with no requirement for hydrogen peroxide. In the absence of air, a yellow dimethyl sulfoxide-d_6 solution of alkoxide **6** decomposes to give a deep red solution, the ^{1}H NMR spectrum of which exhibited an aldehyde peak at 11.0 ppm. These data suggest that, in the absence of air, alkoxide **6** undergoes β-hydride elimination to generate the ligand-derived aldehyde that we tentatively assign as being bound to Pd(0), as we could not observe a characteristic palladium hydride chemical shift around

(47) For solubility reasons, **2** and **4** were tested in acetonitrile/dichloromethane (1:1) and acetonitrile/DMSO (1:1), respectively. To demonstrate that the use of acetonitrile/DMSO (1:1) was not responsible for the large difference in activity between **1** and **4**, **1** was also tested in this solvent system and exhibited $TOF_i = 52.4$ (Pd atom^{-1}) h^{-1}.

(48) After 24 h, the rate of aerobic oxidation of 2-heptanol catalyzed by either **1** or **4** was negligible due to complete decomposition of the catalyst. The TON for **1** (~12) was higher than the TON for **4** (~9) because, in addition to decomposing to **5**, complex **4** has a second decomposition pathway; **4** is unstable in solution and decomposes to an unidentified species on the same time scale as the reaction.

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(50) The NHC palladium pivolate system reported by Sigman and coworkers[26] exhibits 97% conversion in the oxidation of 2-decanol in 14 h with 1 mol % catalyst under an ambient atmosphere of air at room temperature. Although no TOF_i value is reported, the average TOF for this catalyst is 6.9 (Pd atom^{-1}) h^{-1}.

(51) Other phenanthroline catalysts[11] are believed to exhibit rate-limiting β-hydride elimination.

(52) Complex **2** has been used as an effective aerobic alcohol oxidation catalyst at 80 °C with 30 bar of air.[30,31]

(53) At room temperature, the ^{1}H NMR spectrum of **4** (7.4 mM in 1:1 acetonitrile-d_3/dimethyl sulfoxide-d_6) indicates that only a single species is present. While we suspect that this species is the dimer **4**, we have not yet ruled out its assignment as monomeric **4**.

(54) Although water does create an equilibrium between **1**, **4**, and acetic acid, a very large excess of water is required to produce appreciable amounts of **4**. Therefore, the formation of **4** (due to the water produced in the reaction) cannot account for the entirety of the rate decrease with time observed for catalysis with **1**.

(55) The limit of detection for hydrogen peroxide by this method was estimated to be 0.5 mM (see the Supporting Information).

(56) These disproportionation catalysts include catalase enzyme (1:1 water/acetonitrile), silver(I) oxide, manganese(II) oxide, and palladium/calcium carbonate. The use of either potassium iodide or sodium thiosulfate resulted in precipitation of a palladium complex.

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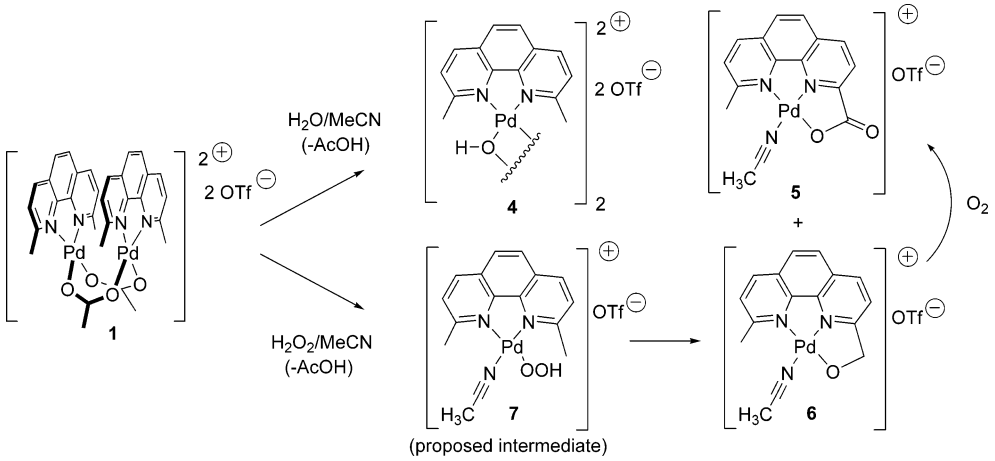
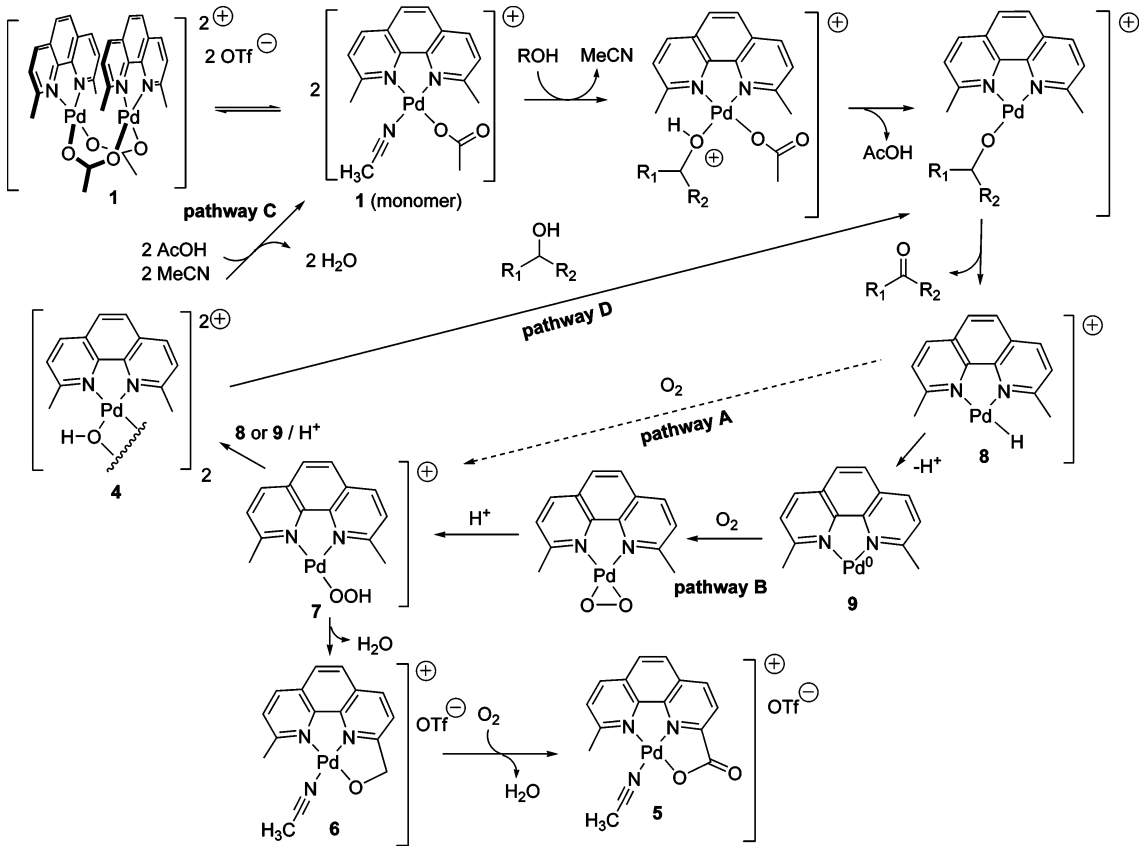
Scheme 4. Reaction of Catalyst 1 with Hydrogen Peroxide in Acetonitrile



Scheme 5. Proposed Mechanism for Aerobic Alcohol Oxidation with Catalyst 1



−18 ppm in the ^{1}H NMR spectrum.[25] As further support for this tentative Pd(0) assignment, we note that a similar red solution is observed when tris(dibenzylideneacetone)dipalladium-(0) is complexed to neocuproine in dichloromethane. The formation of **5** both in aerobic alcohol oxidation with **1** and in treatment of **1** with hydrogen peroxide in acetonitrile implicates the intermediacy of hydroperoxide **7** in the aerobic oxidation of alcohols mediated by **1**.

On the basis of our mechanistic studies and other studies of aerobic alcohol oxidation,[8−25,27] we propose the mechanism illustrated in Scheme 5 (solid line arrows) for the oxidation of 2-heptanol with the dimeric palladium complex **1**. We propose that the alcohol binds to the monomeric form of **1** followed by intramolecular deprotonation to generate the cationic palladium alkoxide (neocuproine)PdOR. β-Hydrogen elimination generates the ketone and cationic (neocuproine)Pd−H (**8**), which is subsequently oxidized to the hydroperoxide **7**.[25,58,59]

Several mechanisms have been proposed for the reoxidation of reduced palladium species, such as **8**, in aerobic alcohol oxidation reactions.[4] Uemura and co-workers proposed that insertion of molecular oxygen into a Pd(II) hydride yields Pd-(II) hydroperoxides directly (Scheme 5, pathway A),[60] a transformation which was later shown to be feasible by the groups of Stahl[25] and Goldberg.[58] However, a Pd(0)/Pd(II) pathway may also be operative, on the basis of Stahl and co-

(58) Denney, M. C.; Smythe, N. A.; Cetto, K. L.; Kemp, R. A.; Goldberg, K. I. *J. Am. Chem. Soc.* **2006**, *128*, 2508.
(59) Popp, B. V.; Wendlandt, J. E.; Landis, C. R.; Stahl, S. S. *Angew. Chem., Int. Ed.* **2007**, *46*, 601.
(60) Nishimura, T.; Onoue, T.; Ohe, K.; Uemura, S. *J. Org. Chem.* **1999**, *64*, 6750.

workers' finding that molecular oxygen reacts readily with a (bathocuproine)Pd(0) complex to give a Pd(II) peroxo complex that can be protonated by 2 equiv of acetic acid to give hydrogen peroxide and (bathocuproine)Pd(OAc)$_2$.[61] Although not reported, addition of 1 equiv of acetic acid to the Pd(II) peroxo complex should yield palladium hydroperoxide **7** (Scheme 5, pathway B). Finally, Sheldon and co-workers have proposed a bimolecular pathway that involves reaction of a Pd(II) peroxo complex with a Pd(0) complex and 2 equiv of Brønsted acid to give the μ-hydroxo Pd(II) dimer **4**.[29]

We favor a variation of the bimolecular pathway whereby the hydroperoxide **7**, formed through pathway B, conproportionates with either the cationic (neocuproine)Pd−H (**8**) or (neocuproine)Pd(0) (**9**)/H$^+$ to generate the μ-hydroxo Pd dimer **4**, which reacts either with acetic acid to generate **1** (pathway C) or directly with the alcohol to regenerate the cationic (neocuproine)PdOR (pathway D). We propose that the rapid drop-off in rate and low turnover numbers observed are due to competitive reactions of the hydroperoxide intermediate **7**. If intramolecular ligand oxidation of **7** is competitive with regeneration of the active catalyst species, then after several cycles all the palladium would speciate to the inactive palladium carboxylate **5**. Evidence for the mechanism shown in Scheme 5 includes the following: (a) no hydrogen peroxide can be detected in the reaction mixture,[55] (b) the μ-hydroxo Pd dimer **4** is observed in the aerobic alcohol oxidation reaction mixture,[62] (c) the μ-hydroxo Pd dimer **4** can be cleanly converted to **1** by action of acetic acid, and (d) a deep red species that does not exhibit the characteristic palladium hydride ^{1}H chemical shift[25] accumulates in the aerobic alcohol oxidation reaction mixture under oxygen-starved conditions.

These observations illustrate one of the potential liabilities of air as a terminal oxidant. Air is certainly a convenient terminal oxidant, but its large overpotential and tendency to generate highly oxidizing species (such as **7**) upon partial reduction illustrates the liabilities of utilizing terminal oxidants more powerful than necessary to carry out oxidative transformations of interest.[63] Nevertheless, the fast initial rates observed suggest that catalysts with readily accessible coordination sites and coordinated internal bases are promising leads for further catalyst development.

Experimental Section

[(2,9-Dimethyl-1,10-phenanthroline)Pd(μ-OAc)]$_2$(OTf)$_2$ (1). To a 25 mL round-bottom flask with a stirbar was added **2** (0.0400 g, 0.0924 mmol), **3** (0.0642 g, 0.0924 mmol), and acetonitrile (10.0 mL). The resulting mixture was stirred until all solids dissolved and then precipitated with diethyl ether to give an orange solid. This solid was isolated by centrifugation, washed with diethyl ether, and dried under vacuum to give **1** as an orange solid (0.0589 g, 0.0563 mmol, 61% yield). ^{1}H NMR (300 MHz, CD_3CN, saturated solution to favor dimer; dimer peaks): δ 2.22 (s, 6H), 2.59 (s, 12H), 7.36 (d, 4H, J = 8.4 Hz), 7.66 (s, 4H), 8.24 (d, 4H, J = 8.4 Hz). ^{1}H NMR (500 MHz, CD_3CN, 7.2 mM solution; monomer peaks): δ 1.98 (s, 3H), 2.80 (s, 6H), 7.71 (d, 2H, J = 9.5 Hz), 8.01 (s, 2H), 8.59 (d, 2H, 8 Hz). ^{13}C NMR (75 MHz, CD_3CN, saturated solution to favor dimer): δ 23.77, 24.73, 128.02, 128.99, 129.10, 141.29, 146.92, 166.68, 188.56, $CF_3SO_3^-$ not observed. ESI-MS: *m*/*z* (relative intensity) [ion] 374 (75%) [0.5M − $CF_3SO_3^-$ + H]$^+$, 314 (47%) [0.5M − $CF_3SO_3^-$ − CH_3COO^-]$^+$, 209 (100%) [0.5M − $CF_3SO_3^-$ − CH_3COO^- − Pd^{2+} + H^+]$^+$. Anal. Calcd for $C_{34}H_{30}N_4O_{10}S_2Pd_2F_6$ (1045.59): C, 39.06; H, 2.89; N, 5.36; Pd, 20.36. Found: C, 39.14; H, 2.87; N, 5.22; Pd, 20.1.

(2,9-Dimethyl-1,10-phenanthroline)Pd(OAc)$_2$ (2). This compound was prepared as previously reported.[30]

(2,9-Dimethyl-1,10-phenanthroline)Pd(MeCN)$_2$(OTf)$_2$ (3). To a slurry of **2** (0.221 g, 0.511 mmol) in acetonitrile (1.0 mL) was added a solution of triflic acid in acetonitrile (0.33 M, 3.8 mL, 2.5 equiv). The solution was stirred briefly and then precipitated with diethyl ether to give a yellow solid. This solid was isolated by centrifugation, precipitated two more times from acetonitrile using diethyl ether, and dried under vacuum to give **3** as a light yellow solid (0.090 g). Additional triflic acid (0.33 M, 1.0 mL) was added to the original supernatant, followed by brief stirring and precipitation with diethyl ether. The resulting yellow solid was subjected to the same workup as described above to give additional **3** (0.021 g). The pure solids were combined (0.111 g, 0.160 mmol, 31% yield). ^{1}H NMR (300 MHz, CD_3CN): δ 2.98 (s, 6H), 7.77 (d, 2H, J = 8.4 Hz), 8.07 (s, 2H), 8.68 (d, 4H, J = 8.4 Hz). ^{1}H NMR (400 MHz, DMSO-d_6): δ 2.06 (s, 6H, CH_3CN), 3.09 (s, 6H), 7.90 (d, 2H, J = 8.4 Hz), 8.17 (s, 2H), 8.80 (d, 2H, J = 8.4 Hz). ^{13}C NMR (125 MHz, DMSO-d_6): δ 1.19, 24.85, 118.15, 120.70 (q, J = 320.1 Hz, $CF_3SO_3^-$), 126.72, 127.42, 128.52, 140.16, 146.40, 164.65. ESI-MS: *m*/*z* (relative intensity) [ion] 209 (100%) [M − Pd^{2+} − $2CF_3SO_3^-$ + H^+]$^+$, 315 (6%) [M − $2CF_3SO_3^-$ + H]$^+$, 149 (100%) [$CF_3SO_3^-$]. Anal. Calcd for $C_{20}H_{18}O_6N_4S_2PdF_6$ (694.92): C, 34.57; H, 2.61; N, 8.06; Pd, 15.3. Found: C, 34.81; H, 2.68; N, 8.77; Pd, 14.6.

Synthesis of (2,9-dimethyl-1,10-phenanthroline)Pd(μ-OH)]$_2$(OTf)$_2$ (4) from 1 and Water. A concentrated solution of **1** (100 mg, 0.095 mmol) in acetonitrile (4 mL) was prepared, and then the solution was diluted by addition of an equal volume of H_2O, causing the orange solution to become yellow and cloudy. The solution was stirred for 1 h, and the precipitate was isolated by centrifugation. The pellet was washed with acetonitrile and dried under vacuum, yielding the dimer **4** as a yellow solid (23.0 mg, 25% yield). ^{1}H NMR (300 MHz, DMSO-d_6): δ 2.13 (s, 2H), 2.87 (s, 12H), 7.86 (d, 4H, J = 8.1 Hz), 8.15 (s, 4H), 8.79 (d, 4H, J = 8.1 Hz). ^{13}C NMR (500 MHz, DMSO-d_6): δ 23.12, 126.72, 127.92, 128.26, 139.86, 146.10, 165.14, $CF_3SO_3^-$ not observed. ESI-MS: *m*/*z* (relative intensity) [ion] 372 (100%) [0.5M − $CF_3SO_3^-$ + CH_3CN]$^+$, 314 (30%) [0.5M − $CF_3SO_3^-$ − OH^-]$^+$, 209 (50%) [0.5M − $CF_3SO_3^-$ − HO^- − Pd^{2+} + H^+]$^+$. Anal. Calcd for $C_{30}H_{26}N_4Pd_2O_8S_2F_6$ (961.51): C, 37.47; H, 2.73; N, 5.83; Pd, 22.1. Found: C, 37.27; H, 2.61; N, 5.89; Pd, 22.0.

Synthesis of (2,9-dimethyl-1,10-phenanthroline)Pd(μ-OH)]$_2$(OTf)$_2$ (4), (9-methyl-1,10-phenanthroline-2-carboxylate)Pd(OTf) (5), and [(9-methyl-1,10-phenanthrolin-2-yl)methanolate]Pd(OTf) (6) from 1 and 30% Hydrogen Peroxide. In a test tube, 9.79 M (∼30%) hydrogen peroxide (73.2 μL, 0.717 mmol, 15.0 equiv) was added to a solution of **1** (0.0500 g, 0.0478 mmol) in acetonitrile (2.0 mL) with stirring. The solution immediately, albeit temporarily, changed color from yellow to deep red, and bubbling was observed. After 15 min of stirring in air, the solution had become bright yellow and contained a light yellow precipitate. This precipitate was isolated from the reaction mixture by centrifugation, washed with acetonitrile, and dried under vacuum to give **4** as a pale yellow solid (0.016 g, 0.017 mmol). The supernatant was then filtered and precipitated with diethyl ether (∼2 mL). The resulting yellow solid was isolated by centrifugation, precipitated a second time from acetonitrile, washed with diethyl ether, and dried under

(61) Stahl, S. S.; Thorman, J. L.; Nelson, R. C.; Kozee, M. A. *J. Am. Chem. Soc.* **2001**, *123*, 7188.

(62) During the course of the aerobic 2-heptanol oxidation, dimer **4** appears as a precipitate in the reaction mixture. Dimer **4** eventually redissolves, presumably by reaction with alcohol or acetic acid, to regenerate **1**.

(63) It is noteworthy that Sheldon, in carrying out similar oxidations with (neocuproine)Pd(OAc)$_2$ (**2**) at higher temperatures (80 °C, 30 bar of air), did not report ligand oxidation. This may be due to the different reaction conditions (presence of sodium acetate) or the faster rate of hydrogen peroxide (or palladium hydroperoxide) disproportionation at these higher temperatures.

vacuum to give **6** as a bright yellow solid (0.010 g, 0.019 mmol). The supernatants from both precipitations of **6** were combined, filtered, and evaporated to give **5** as an orange solid (0.0011 g, 0.0021 mmol).

Alternative Synthesis of (9-methyl-1,10-phenanthroline-2-carboxylate)Pd(OTf) (5) by Aerobic Oxidation of 2-Heptanol. 2-Heptanol (1.14 mL, 8.04 mmol) was added to a solution of **1** (0.1256 g, 0.1201 mmol) in acetonitrile (8.0 mL). The dark orange reaction mixture was stirred vigorously in air overnight and became light yellow-orange. After filtration, a light orange solid was precipitated from the filtrate using diethyl ether. This solid was isolated by centrifugation, precipitated a second time from acetonitrile, washed with diethyl ether, and dried under vacuum to give **5** as a light orange solid (0.027 g, 0.051 mmol, 42% yield).

Characterization of (9-methyl-1,10-phenanthroline-2-carboxylate)Pd(MeCN)(OTf) (5). ^{1}H NMR (300 MHz, CD_3CN): δ 2.87 (s, 3H), 7.91 (d, 1H, $J = 8.4$ Hz), 8.01 (d, 1H, $J = 8.7$ Hz), 8.12 (d, 1H, $J = 9.0$ Hz), 8.21 (d, 1H, $J = 8.7$ Hz), 8.69 (d, 1H, $J = 8.7$ Hz), 8.89 (d, 1H, $J = 8.1$ Hz). ^{13}C NMR (300 MHz, CD_3CN): δ 27.08, 125.58, 126.89, 130.27, 130.41, 131.23, 132.51, 141.69, 142.29, 145.75, 148.08, 150.02, 166.77, 172.16, $CF_3SO_3^-$ not observed. ESI-MS: *m*/*z* (relative intensity) [ion] 384 (10%) $[M - CF_3SO_3^-]^+$, 345 (22%) $[M - CF_3SO_3^- - CH_3CN]^+$, 299 (100%) $[M - CF_3SO_3^- - CH_3CN - COO^-]^+$, 195 (20%) $[M - CF_3SO_3^- - CH_3CN - CO_2 - Pd^{2+}]^+$. Anal. Calcd for $C_{17}H_{12}N_3PdO_5SF_3$ (533.78): C, 38.25; H, 2.27; N, 7.87; Pd, 19.9. Found: C, 38.15; H, 2.19; N, 7.77; Pd, 20.2.

Characterization of [(9-methyl-1,10-phenanthrolin-2-yl)-methanolate]Pd(MeCN)(OTf) (6). ^{1}H NMR (500 MHz, DMSO-d_6): δ 2.06 (s, 3H), 5.24 (s, 2H), 7.67 (d, 1H, $J = 8.5$ Hz), 7.77 (d, 1H, $J = 8.5$ Hz), 7.86 (d, 1H, $J = 9.0$ Hz), 7.88 (d, 1H, $J = 8.5$ Hz), 8.47 (d, 1H, $J = 8.0$ Hz), 8.65 (d, 1H, $J = 8.5$ Hz); ^{1}H NMR (300 MHz, CD_3CN): δ 2.91 (s, 3H), 5.35 (s, 2H), 7.82 (d, 1H, $J = 8.7$ Hz), 7.83 (d, 1H, $J = 8.7$ Hz), 8.10 (d, 2H, $J = 0.9$ Hz), 8.61 (d, 1H, $J = 8.4$ Hz), 8.76 (d, 1H, $J = 8.4$ Hz). ^{13}C NMR (500 MHz, DMSO-d_6): δ 1.18, 23.57, 74.63, 118.14, 120.70 (q, $J = 320.6$ Hz, $CF_3SO_3^-$), 123.81, 126.05, 127.54, 127.67, 128.62, 128.66, 139.21, 140.02, 142.82, 144.84, 150.91, 164.59. ESI-MS: *m*/*z* (relative intensity) [ion] 329 (28%) $[M - CF_3SO_3^- - CH_3CN]^+$, 299 (100%) $[M - CF_3SO_3^- - CH_3CN - CH_2O]^+$, 223 (10%) $[M - CF_3SO_3^- - CH_3CN - Pd^{2+}]^+$. HRMS (ESI) calcd for $C_{14}H_{11}N_2PdO^+$ $[M - CF_3SO_3^- - CH_3CN]^+$, required *m*/*z* 328.9906, found 328.9910.

Conditions for Crystallization of 1, 4, and 5. Crystallization of **1** was achieved by diffusion of ether vapor into a saturated solution of **1** in acetonitrile. High-quality crystals were obtained in less than 30 min. Crystallization of **4** was effected by vapor diffusion of dichloromethane into a solution of **4** in dimethyl sulfoxide. Due to the asymmetry of **5**, its crystallization proved to be much more difficult and a large number of vapor diffusion conditions failed. Suitable crystals were finally obtained by slow evaporation of an acetonitrile solution of **5**.

Protocol for Aerobic Alcohol Oxidation of 2-Heptanol using 1 or 3. To a 25 mL round-bottom flask with a stirbar was added acetonitrile (2.0 mL), 2-heptanol (142.2 μL, 1.000 mmol), and, optionally, *n*-decane (100.0 μL, 0.5130 mmol, internal standard). The mixture was stirred until the *n*-decane dissolved completely, and an aliquot was collected at $t = 0$ for analysis by GC (gas chromatography). The catalyst (0.03 mol % Pd) was added, and the reaction mixture was stirred vigorously at room temperature under a balloon of air. During the reaction, aliquots were collected, quenched by dilution into acetonitrile, and subjected to GC analysis.

Protocol for Aerobic Alcohol Oxidation of 2-Heptanol using 2. The above procedure was followed, with the exception that acetonitrile/dichloromethane (1:1) was used as the solvent (2.0 mL).

Protocol for Aerobic Alcohol Oxidation of 2-Heptanol using 4. The above procedure was followed, with the exception that acetonitrile/dimethyl sulfoxide (1:1) was used as the solvent (2.0 mL).

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Supporting Information Available: Text, tables, and figures providing experimental details, characterization data, ^{1}H and ^{13}C NMR spectra, thermodynamic data, and electrochemistry details for isolated compounds and CIF files giving crystal data for compounds **1**, **4**, and **5**. This material is available free of charge via the Internet at http://pubs.acs.org.

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