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Characterization of Peroxo and Hydroperoxo Intermediates in the Aerobic Oxidation of *N*-Heterocyclic-Carbene-Coordinated Palladium(0)

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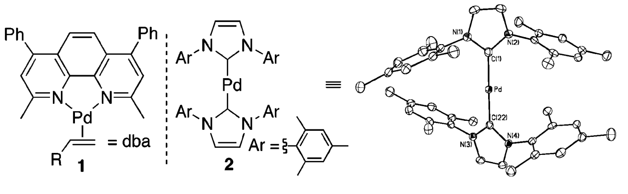
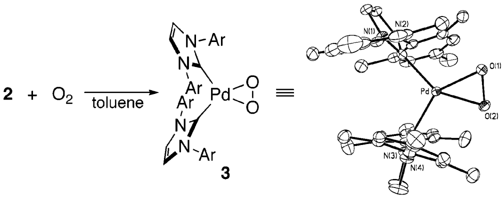
Selective aerobic oxidation of organic substrates represents a key challenge in modern chemistry, and palladium-catalyzed methods (Scheme 1) are emerging as a versatile strategy to achieve this goal.[1] Despite significant recent advances, only a small fraction of the known palladium(II)-mediated oxidation reactions operate effectively with molecular oxygen as the stoichiometric oxidant.[2] We have been investigating the fundamental reaction between palladium(0) and molecular oxygen to facilitate further advances in this area. Both chelating and monodentate ligands have been used in palladium-catalyzed oxidation reactions,[1] and we recently reported the oxygenation of **1**, a palladium(0) complex coordinated by the chelating ligand, bathocuproine (bc), and dibenzylidene acetone (dba).[3] In the present study, we describe the aerobic oxidation of **2**, a palladium(0) complex bearing two *N*-heterocyclic carbene (NHC) ligands, 1,3-di(2,4,6-trimethylphenyl)imidazoline-2-ylidene (IMes).[4] The IMes ligands are stable under the oxidizing reaction conditions and lead to important differences in the reactivity between **1** and **2**. The ability of the monodentate IMes ligands to undergo *cis*−*trans* isomerization has enabled isolation and characterization of the first dioxygen-derived palladium(II)−hydroperoxide complex, which is frequently postulated as an intermediate in palladium-catalyzed oxidation reactions.[1a]



1 **2**

Pd(IMes)$_2$, **2**, was prepared according to a published procedure;[5] however, our spectroscopic data (^{1}H, ^{13}C NMR) differ from those in the original report. The mass spectrum (MALDI-TOF) and X-ray crystal structure of **2** (see above) clearly establish its identity and support our spectral assignments.[6] The discrepancy with the literature data appears to arise from the extreme air sensitivity of **2**, which reacts immediately even in the solid state upon exposure to air. A solution of Pd(IMes)$_2$ in toluene at −78 °C changes color from yellow to brown upon introduction of an atmosphere of oxygen into the reaction vessel. The ^{1}H and ^{13}C NMR spectroscopic data of the new product match the characterization data originally reported for **2**.[5] Further analysis establishes the identity of this product as an η^2-peroxo complex, (IMes)$_2$Pd(O$_2$), **3** (eq 1). Infrared spectroscopy reveals a medium-intensity band at 868 cm^{-1} that shifts to 821 cm^{-1} when **3** is prepared with ^{18}O-labeled dioxygen. The 47 cm^{-1} shift is close to the 52 cm^{-1} shift predicted by a simple diatomic oscillator model for an O−O stretch. MALDI-TOF mass spectrometric data for **3** reveal an ion peak that corresponds to the palladium(0) complex, **2**, at m/z = 714.3 (M)$^+$. A softer ionization technique (electrospray) was required to obtain the corresponding peak for **3** at m/z = 747.1, (M + H)$^+$. The mass fragment for **2** also appears in the electrospray experiment (Figure S4) and suggests dissociation of O$_2$ from **3** may be possible; however, no evidence for reversible oxygenation was obtained under standard preparative conditions.[7] The structure of **3** was definitively established by X-ray crystallography. The η^2-O$_2$ fragment exhibits an O−O bond length of 1.443(2) Å, which supports its formulation as a peroxo complex. The bulky NHC ligands are forced into a cis arrangement to accommodate O$_2$ binding, and their steric crowding is evident from low-temperature ^{1}H NMR spectroscopic studies of **3**, which reveal restricted rotation around the N−Ar bonds. For example, decoalescence of the IMes aryl resonances was detected below −80 °C.



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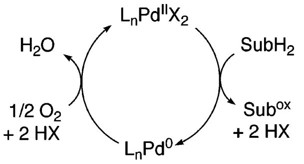
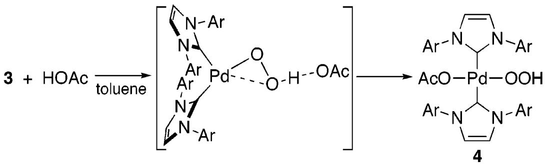
(1)

Scheme 1. Simplified Mechanism for Palladium-Catalyzed Aerobic Oxidation Reactions



The extremely rapid oxygenation of **2** at −78 °C contrasts the reactivity of the (bc)Pd(0) complex, **1**, which requires 20−30 min to form the peroxopalladium(II) complex at room temperature. This rate difference probably reflects the difference in mechanism between the two complexes: associative olefin substitution for **1** versus simple O$_2$ addition for **2**. The reaction between O$_2$ and palladium(0) is formally spin-forbidden, but the rapid rate observed for eq 1 suggests that spin-state changes do not contribute to a large kinetic barrier.[8] Relatively large spin−orbit coupling of palladium should facilitate triplet−singlet surface crossing along the reaction coordinate.[9]

Addition of acetic acid to a toluene solution of **3** at room temperature leads to rapid formation of the hydroperoxopalladium(II) complex, **4** (eq 2). The presence of only one carbene ligand resonance in the ^{1}H and ^{13}C NMR spectra of **4** indicates that protonolysis of a Pd−O bond in **3** occurs with concomitant *cis*−



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(2)

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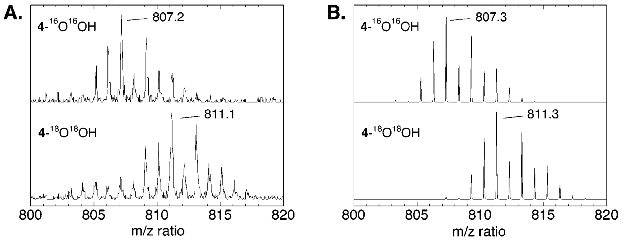
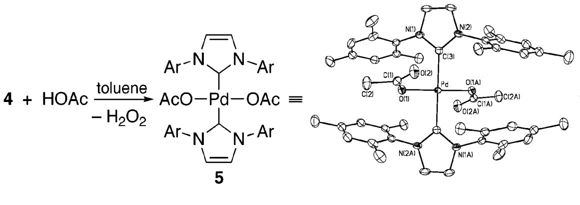


Figure 1. Experimental (A) and simulated (B) electrospray ionization mass spectra of **4** and **4-^{18}O$_2$**. Both major peaks correspond to the ion derived from protonation of the parent molecule, $(M + H)^+$. The **4-^{18}O$_2$** sample also contains small amounts of ^{16}O-labeled compound. The full mass spectrum also reveals ion fragments corresponding to loss of OAc and/or OOH from these compounds (see Supporting Information).

trans isomerization of the carbene ligands. The hydroperoxide proton is evident in the ^{1}H NMR spectrum at 3.87 ppm, (C_6D_6, Figure S6), and the O−H stretch is detected by infrared spectroscopy with a weak band at 3504 cm^{-1}. Upon preparation of the oxygen-18- and deuterium-labeled compounds, **4-^{18}O$_2$** and **4-*d*$_1$**, this infrared band shifts to 3492 and 2591 cm^{-1}, respectively. These observed shifts of 12 and 913 cm^{-1} compare favorably with the predicted shifts of 12 and 955 cm^{-1} (Figure S7). The O−O stretch was not detected by infrared spectroscopy, and strong background fluorescence interfered with the acquisition of resonance Raman data. The proposed identity of **4** was further supported by electrospray ionization mass spectrometry. The spectrum reveals the predicted pattern for the $(M + H)^+$ ion, which shifts as expected for the corresponding ^{18}O-labeled complex (Figure 1).

The isolation and characterization of a dioxygen-derived hydroperoxopalladium(II) complex is unprecedented,[10] although it is frequently proposed as a catalytic intermediate.[1a] No hydroperoxide species was detected in protonation studies of (bc)Pd(O_2), **1**.[3] Addition of <2 equiv of HOAc to **1** yields only unreacted starting material, (bc)Pd(OAc)$_2$, and hydrogen peroxide. In the present system, rapid *cis*−*trans* isomerization of the NHC ligands appears to provide steric protection of the remaining Pd−O bond. The substantially slower second protonolysis step enables the isolation of **4**.

Further protonolysis of **4** to yield hydrogen peroxide (eq 3) proceeds quite slowly, reaching 80% completion after 3 days at room temperature. ^{1}H NMR spectroscopic analysis of this reaction reveals the formation of (IMes)$_2$Pd(OAc)$_2$, **5**, which was prepared independently by the addition of the free NHC ligand to Pd(OAc)$_2$. Protonolysis of **3** was also performed with H_2SO_4 as the acid, and under these conditions, a colorimetric assay[11] revealed a 70% yield of H_2O_2.[12]



(3)

The reactions outlined above (eqs 1−3) provide the most detailed insights to date into the proposed mechanism for palladium(0) oxidation by molecular oxygen. The advantageous features of *N*-heterocyclic carbene ligands are immediately apparent based on comparison with phosphine-coordinated palladium complexes, which undergo rapid ligand oxidation in the presence of molecular oxygen.[13] In fact, Pd(OAc)$_2$ is among the most active homogeneous catalysts for phosphine oxidation by molecular oxygen.[14] This instability limits the use of phosphines in both fundamental studies and catalytic reactions of this kind.[1,4] Finally, in certain palladium-catalyzed oxidation reactions, activated oxygen species, especially hydroperoxides, have been proposed to react directly with organic substrates.[15] The isolation of both **3** and **4** provides us with a unique opportunity to probe these proposals directly.

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Supporting Information Available: Experimental procedures and spectroscopic data. X-ray crystallographic data for complexes **2**, **3**, and **5** in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org

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