

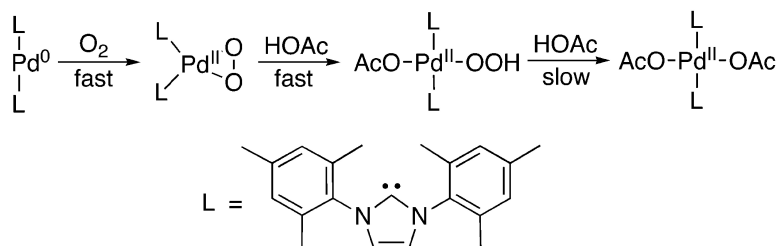
Communication

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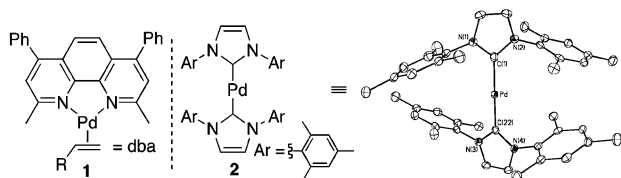
## Characterization of Peroxo and Hydroperoxo Intermediates in the Aerobic Oxidation of *N*-Heterocyclic-Carbene-Coordinated Palladium(0)

Michael M. Konnick, Ilia A. Guzei, and Shannon S. Stahl\*

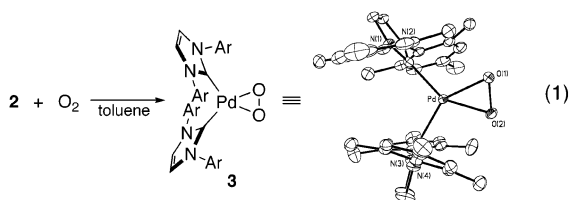
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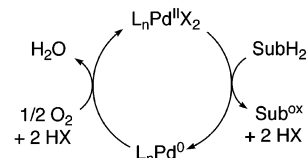
Selective aerobic oxidation of organic substrates represents a key challenge in modern chemistry, and palladium-catalyzed methods (Scheme 1) are emerging as a versatile strategy to achieve this goal.<sup>1</sup> Despite significant recent advances, only a small fraction of the known palladium(II)-mediated oxidation reactions operate effectively with molecular oxygen as the stoichiometric oxidant.<sup>2</sup> 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,<sup>1</sup> and we recently reported the oxygenation of **1**, a palladium(0) complex coordinated by the chelating ligand, bathocuproine (bc), and dibenzylidene acetone (dba).<sup>3</sup> 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).<sup>4</sup> 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.<sup>1a</sup>



$\text{Pd}(\text{IMes})_2$ , **2**, was prepared according to a published procedure;<sup>5</sup> however, our spectroscopic data (<sup>1</sup>H, <sup>13</sup>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.<sup>6</sup> 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  $\text{Pd}(\text{IMes})_2$  in toluene at  $-78^\circ\text{C}$  changes color from yellow to brown upon introduction of an atmosphere of oxygen into the reaction vessel. The <sup>1</sup>H and <sup>13</sup>C NMR spectroscopic data of the new product match the characterization data originally reported for **2**.<sup>5</sup> Further analysis establishes the identity of this product as an  $\eta^2$ -peroxo complex,  $(\text{IMes})_2\text{Pd}(\text{O}_2)$ , **3** (eq 1). Infrared



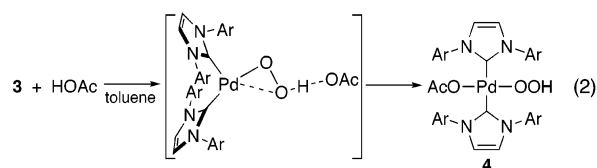
### Scheme 1. Simplified Mechanism for Palladium-Catalyzed Aerobic Oxidation Reactions



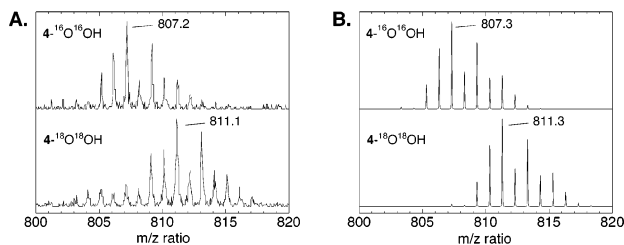
spectroscopy reveals a medium-intensity band at  $868\text{ cm}^{-1}$  that shifts to  $821\text{ cm}^{-1}$  when **3** is prepared with <sup>18</sup>O-labeled dioxygen. The  $47\text{ cm}^{-1}$  shift is close to the  $52\text{ cm}^{-1}$  shift predicted by a simple diatomic oscillator model for an O–O stretch. MALDI-TOF mass spectrometric data for **3** reveal an ion peak that corresponds to the palladium(0) complex, **2**, at  $m/z = 714.3$  ( $\text{M}^+$ ). A softer ionization technique (electrospray) was required to obtain the corresponding peak for **3** at  $m/z = 747.1$  ( $\text{M} + \text{H}^+$ ). The mass fragment for **2** also appears in the electrospray experiment (Figure S4) and suggests dissociation of  $\text{O}_2$  from **3** may be possible; however, no evidence for reversible oxygenation was obtained under standard preparative conditions.<sup>7</sup> The structure of **3** was definitively established by X-ray crystallography. The  $\eta^2$ - $\text{O}_2$  fragment exhibits an O–O bond length of  $1.443(2)\text{ \AA}$ , which supports its formulation as a peroxo complex. The bulky NHC ligands are forced into a *cis* arrangement to accommodate  $\text{O}_2$  binding, and their steric crowding is evident from low-temperature <sup>1</sup>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  $-80^\circ\text{C}$ .

The extremely rapid oxygenation of **2** at  $-78^\circ\text{C}$  contrasts the reactivity of the  $(\text{bc})\text{Pd}(0)$  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  $\text{O}_2$  addition for **2**. The reaction between  $\text{O}_2$  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.<sup>8</sup> Relatively large spin–orbit coupling of palladium should facilitate triplet–singlet surface crossing along the reaction coordinate.<sup>9</sup>

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 <sup>1</sup>H and <sup>13</sup>C NMR spectra of **4** indicates that protonolysis of a Pd–O bond in **3** occurs with concomitant *cis*–

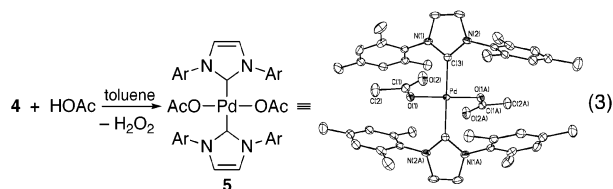


**Figure 1.** Experimental (A) and simulated (B) electrospray ionization mass spectra of **4** and **4-<sup>18</sup>O<sub>2</sub>**. Both major peaks correspond to the ion derived from protonation of the parent molecule, (M + H)<sup>+</sup>. The **4-<sup>18</sup>O<sub>2</sub>** sample also contains small amounts of <sup>16</sup>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 <sup>1</sup>H NMR spectrum at 3.87 ppm, (C<sub>6</sub>D<sub>6</sub>, Figure S6), and the O–H stretch is detected by infrared spectroscopy with a weak band at 3504 cm<sup>-1</sup>. Upon preparation of the oxygen-18- and deuterium-labeled compounds, **4-<sup>18</sup>O<sub>2</sub>** and **4-d<sub>1</sub>**, this infrared band shifts to 3492 and 2591 cm<sup>-1</sup>, respectively. These observed shifts of 12 and 913 cm<sup>-1</sup> compare favorably with the predicted shifts of 12 and 955 cm<sup>-1</sup> (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)<sup>+</sup> ion, which shifts as expected for the corresponding <sup>18</sup>O-labeled complex (Figure 1).

The isolation and characterization of a dioxygen-derived hydroperoxopalladium(II) complex is unprecedented,<sup>10</sup> although it is frequently proposed as a catalytic intermediate.<sup>1a</sup> No hydroperoxide species was detected in protonation studies of (bc)Pd(O<sub>2</sub>), **1**.<sup>3</sup> Addition of <2 equiv of HOAc to **1** yields only unreacted starting material, (bc)Pd(OAc)<sub>2</sub>, 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. <sup>1</sup>H NMR spectroscopic analysis of this reaction reveals the formation of (IMes)<sub>2</sub>Pd(OAc)<sub>2</sub>, **5**, which was prepared independently by the addition of the free NHC ligand to Pd(OAc)<sub>2</sub>. Protonolysis of **3** was also performed with H<sub>2</sub>SO<sub>4</sub> as the acid, and under these conditions, a colorimetric assay<sup>11</sup> revealed a 70% yield of H<sub>2</sub>O<sub>2</sub>.<sup>12</sup>



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.<sup>13</sup> In fact, Pd(OAc)<sub>2</sub> is among the most active homogeneous catalysts for phosphine oxidation by molecular oxygen.<sup>14</sup> This instability limits the use of phosphines in both fundamental studies and catalytic reactions of this kind.<sup>14</sup> Finally, in certain palladium-catalyzed oxidation reactions, activated oxygen species, especially hydroperoxides, have been proposed to react directly with organic substrates.<sup>15</sup> 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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