

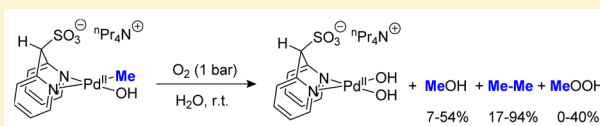
Oxidation of a Monomethylpalladium(II) Complex with O₂ in Water: Tuning Reaction Selectivity to Form Ethane, Methanol, or Methylhydroperoxide

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S Supporting Information

ABSTRACT: Photochemical aerobic oxidation of *n*-Pr₄N-[(dpms)Pd^{II}Me(OH)] (5) and (dpms)Pd^{II}Me(OH₂) (8) (dpms = di(2-pyridyl)methanesulfonate) in water in the pH range of 6–14 at 21 °C was studied and found to produce, in combined high yield, a mixture of MeOH, C₂H₆, and MeOOH along with water-soluble *n*-Pr₄N-[(dpms)Pd^{II}(OH)₂] (9). By changing the reaction pH and concentration of the substrate, the oxidation reaction can be directed toward selective production of ethane (up to 94% selectivity) or methanol (up to 54% selective); the yield of MeOOH can be varied in the range of 0–40%. The source of ethane was found to be an unstable dimethyl Pd^{IV} complex (dpms)Pd^{IV}Me₂(OH) (7), which could be generated from 5 and MeI. For shedding light on the role of MeOOH in the aerobic reaction, oxidation of 5 and 8 with a range of hydroperoxo compounds, including MeOOH, *t*-BuOOH, and H₂O₂, was carried out. The proposed mechanism of aerobic oxidation of 5 or 8 involves predominant direct reaction of excited methylpalladium(II) species with O₂ to produce a highly electrophilic monomethyl Pd^{IV} transient that is involved in subsequent transfer of its methyl group to 5 or 8, H₂O, and other nucleophilic components of the reaction mixture.

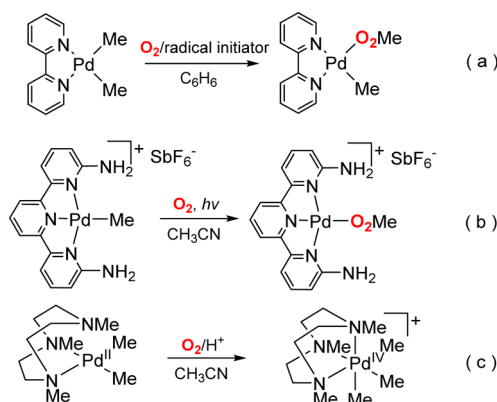


INTRODUCTION

Palladium complexes have received much attention as homogeneous catalysts for selective C–H oxidation of organic substrates.^{1–7} Among such processes, oxidation of methane^{1,7} is one of the least developed and one of the most sought after transformations that can be used, in particular, for the development of economically viable routes for “methane upgrade” to higher hydrocarbons⁸ and value-added oxygenates such as methanol. Taking into account the low cost of some of the simplest methane-derived products, such as MeOH, C₂H₆, and so forth, oxidants that may be practically important in such processes must be very cheap. In this regard, the use of oxygen from the air as a virtually free oxidant is an excellent choice.^{7,9} Although direct oxidation of palladium(0) species with dioxygen has been studied in some detail, thus allowing for substantial advances in aerobic C–H bond oxidations involving Pd⁰/Pd^{II} couple,⁴ direct aerobic oxidation of organopalladium(II) complexes, especially chemistry involving palladium transients in higher oxidation states, is poorly explored. As a result, the use of dioxygen in catalytic mediator-free chemistry of Pd^{II} compounds remains very limited.^{10–12} There are only a few reports on the reactivity of Pd^{II}CH₃ complexes toward O₂.^{13–15} The reported reactions of O₂ insertion into a Pd–C bond produce methylperoxo Pd^{II} complexes and employ either a chain radical (Scheme 1a)¹³ or a nonradical photochemical mechanism (Scheme 1b).¹⁴ Oxidation of Pd^{II} hydrocarbyl complexes with O₂ to generate related Pd^{III} and/or Pd^{IV} species has also been demonstrated (see, e.g., Scheme 1c).^{16–18}

As a guideline for possible further development of aerobic organopalladium(II) chemistry, one can use an analogy with dioxygen–platinum(II) chemistry. There are a number of

Scheme 1. Examples of Reactions between O₂ and Pd^{II}CH₃ Complexes^{13,14,17}

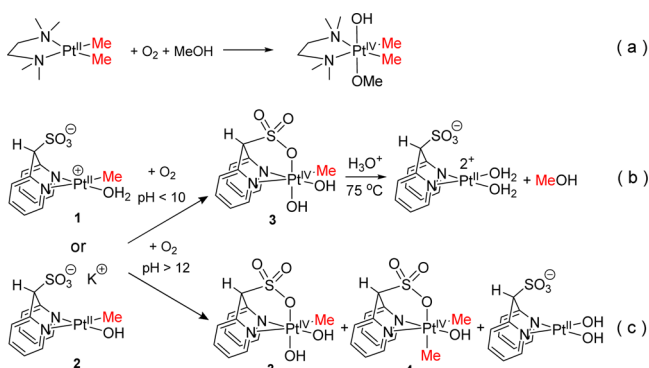


parallels here. For instance, a homolytic¹⁹ or nonradical photochemical^{14,20} dioxygen insertion into a Pt^{II}–CH₃ bond is also known for platinum analogues of complexes shown in Scheme 1a and b. In addition, dimethyl Pt^{II} complexes are known to react with O₂ in protic media to produce corresponding dimethyl Pt^{IV} hydroxo derivatives (Scheme 2a).²¹ It is also known that the range of Pt^{II} complexes that can be involved in aerobic Pt^{II}-to-Pt^{IV} oxidation can be expanded when they are supported by facially chelating ligands such as 1,4,7-triazacyclononane²² or 1,3,5-triaminocyclohex-

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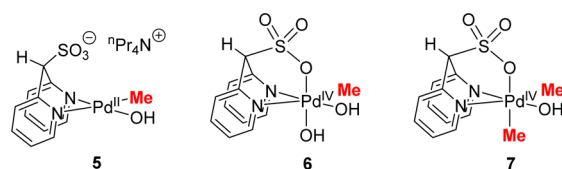
Scheme 2. Aerobic Oxidation of Dimethyl Pt^{II} Complexes (a–c) and Functionalization of Pt^{II}–CH₃ Bond (b)



ane.²³ Importantly, the Pt^{IV}–C bond of the resulting oxidation products can be functionalized. Such reactions are facilitated when the supporting facially chelating ligands contain a good leaving group, as is the case of di(2-pyridyl)methanesulfonate (dpms) (Scheme 2b).^{24–26} The dpms-enabled aerobic Pt^{II}–C(sp³) bond functionalization sequence can be very efficient and selective, e.g., MeOH can be produced in >97% yield along with 3% Me₂O, starting from neutral zwitterionic (dpms)-Pt^{II}Me(OH₂) complex **1** or its anionic derivative **2** and O₂ in water via the intermediacy of methyl Pt^{IV} hydroxo species **3**.²⁴ Hence, considering the Pt chemistry noted above, it would be interesting to see if a similar aerobic Pd^{II}–CH₃ bond oxyfunctionalization is possible for Pd analogues of complexes **1** and **2**. Exploring chemistry of such Pd analogues may be even more intriguing because the selectivity of the oxidation reaction in Scheme 2 is pH-dependent: transformation of **2** to monomethyl Pt^{IV} complex **3** is impeded at pH ≥ 12 and leads to the predominant Pt^{IV}-to-Pt^{II} methyl group transfer resulting in the formation of dimethyl Pt^{IV} hydroxo derivative **4** (Scheme 2c).^{27,28} A similar observation has also been recently made by Goldberg using an analogue of complex **2** supported by a tripod dipyrazolylacetate ligand.²⁹ Though complex **4** is robust and does not eliminate ethane, the knowledge of the mechanism of its formation may be useful for the possible development of similar palladium-based systems for aerobic methane-to-ethane oxidative coupling. In fact, the first examples of oxidative aerobic coupling of dimethyl Pd^{II} complexes to form ethane via intermediacy of Pd^{IV} species were reported recently by Mirica.^{16,18} The same group has described a photochemical elimination of ethane from a monomethyl Pd^{III} complex,³⁰ whereas Canty and Sanford have demonstrated oxidative coupling of monomethyl Pd^{II} species to form ethane using some other oxidants.⁸ Notably, though monomethyl Pd^{II} species are usually considered to be most relevant to methane C–H activation by Pd^{II} complexes,^{1,7} oxidative aerobic coupling of monomethyl Pd^{II} complexes to form ethane so far remain unknown.

It is also important to note that aerobic functionalization of a Pd^{II}–CH₃ bond in either mono- or dimethyl Pd^{II} compounds to form MeOH has never been documented. The only example of the formation of methanol in a low yield in a photochemical reaction of O₂ with a monomethyl Pd^{III} complex was reported by Mirica.³⁰ Hence, the goal of this work was to determine if the aerobic functionalization in water of a Pd^{II} analogue of complex **2**, such as **5** (Chart 1), might lead to Pd^{IV} intermediates **6** and **7**, which are analogues of **3** and **4** and which can be highly reactive at the production of MeOH and

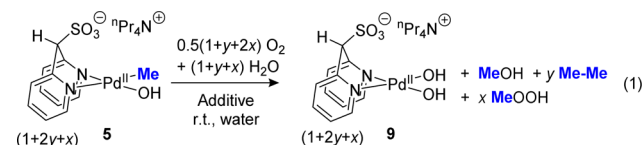
Chart 1. DPMS-Supported Palladium Analogues of Complexes 2–4



ethane, respectively. We were interested to see if this type of reactivity can compete with or complement the insertion of O₂ into the Pd^{II}–C(sp³) bond described in Goldberg or Britovsek's works.^{13,14} In this paper, we report the results of such a study revealing, that the aerobic functionalization of the monomethyl Pd^{II} complex **5** is viable and can lead to selective formation of either ethane or methanol with or without concomitant formation of methylhydroperoxide. We also disclose some means to control the reaction selectivity with respect to each of these three products.

RESULTS AND DISCUSSION

1. Oxidation of *n*-Pr₄N[(dpms)Pd^{II}Me(OH)] with O₂ in Water.
1.1. Product Distribution. The anionic monomethyl Pd^{II} complex [(dpms)Pd^{II}Me(OH)][−] in the form of a water-soluble tetra-*n*-propylammonium salt (**5**) was prepared using standard synthetic protocols (see the Supporting Information (SI)). Similar to the Pt^{II} analogue **2**, aqueous solutions of **5** are basic; the pH of a 4–7 mM solution typically used in our experiments is ~10.6, which translates to approximately a 6% fraction of the corresponding protonated species (dpms)-Pd^{II}Me(OH₂) (**8**) with an estimated pK_a of 9.4. Exposure of such solutions to air or pure O₂ atmosphere at 1 atm of pressure in a Teflon-sealed NMR tube leads to complete consumption of **5** after 5–6 days at 21 °C accompanied by the formation of dihydroxo Pd^{II} complex **9** and ethane as two major products along with small amounts of an unidentified black solid and methanol (eq 1; Table 1, entries 1–2). No transient



Pd complexes were observed in the course of these experiments by means of ¹H NMR spectroscopy. Hence, the dpms ligand enables an unprecedented selective aerobic oxidative coupling of a monomethylpalladium(II) species to form ethane with 80–90% selectivity. Importantly, this tripod ligand also allows for the formation of methanol, albeit in a low yield, a type of reactivity that to the best of our knowledge has never been observed previously in aerobic reactions of methylpalladium(II) compounds.

On the basis of the fact that the rate and selectivity of the oxidation of the Pt^{II} analogue **2** with O₂ are strongly pH dependent,²⁸ we hypothesized that the effect of pH may also be pronounced in aerobic oxidation of **5**. The effect of the reaction pH on the product distribution was probed using 1.0 M KOH (pH ~14.0) and some buffer solutions. The pH change from 10.6 to 14.0 turned out to have the most dramatic effect on the reaction **1** selectivity (Table 1, entry 3 vs 2): the yield of methanol has almost tripled up to 54% after 4 days, and a small

Table 1. Summary of Product Distribution in Complete Oxidation of *n*-Pr₄N[(dpms)Pd^{II}Me(OH)] (5) in NMR Tube under an O₂ Atmosphere and 20 °C^a

entry	conditions	reaction time	C ₂ H ₆ /CH ₄ (%/%)	MeOH (%)	MeO ₂ H (%)	other products (%)
1	air, pH 10.6	5 days	89 ± 3	9 ± 2	0	9, 83 ± 5 ^b
2	O ₂ , pH 10.6	6 days	82 ± 4	16 ± 3	0	9, 83 ± 5 ^b
3	O ₂ , pH 14.0 ^c	4 days	44 ^d	54 ± 2	4 ± 1	9, 83 ± 5 ^b
4	O ₂ , pH 14.0 ^{c,e}	2 days	31 ^d	49 ± 1	20 ± 1	9, 71 ± 1; ^b dpms ⁻ , 21 ± 1
5	Ar, pH 10.6 ^a	7 days	55 ± 3/43 ± 1	0	0	dpms ⁻ , 47 ^b
6	Ar, pH 10.6, TEMPO ^f	13 days	63 ± 9/27 ± 8	0	0	Me-TEMPO, 7 ± 2 ^b

^aAll of the reactions were carried out under standard ambient fluorescent lamp lighting. Yields are based on initial [Pd^{II}Me]. ^bThe formation of small amounts of a black solid was observed, which may be the reason for the approximately 15% lower than expected dpms ligand balance. ^cWith 1.0 M KOH solution. ^dCalculated assuming 100% methyl group balance. Poor solubility of ethane in this solution precluded quantitative determination of ethane yield. ^eIrradiation with 26 W CFL; no stirring. ^fWith 1.9 equiv of TEMPO additive.

Table 2. Effect of Various Factors on the Kinetics of Oxidation of 6 mM Complex 5 at 20 °C^a

entry	conditions	<i>t</i> _{1/2} (h)	MeOH (%)	C ₂ H ₆ ^b (%)	MeO ₂ H (%)	other products (%)
1	air, pH 10.6	31 ± 1	7 ± 2	94	0	9, 55 ± 6 ^c
2	O ₂ , pH 10.6	25 ± 1	12 ± 2	88	0	9, 81 ± 4 ^c
3	O ₂ , pH 10.6, TEMPO ^d	38 ± 1	11 ± 1	80	0	9, 89 ± 4; ^c Me-TEMPO, 9 ± 1
4	O ₂ , pH 6.8 ^e	4.8 ± 0.1	10 ± 1	90	0	11, 70 ± 1 ^c
5	O ₂ , pH 14.0 ^f	16.0 ± 0.2	51 ± 4	44	5 ± 1	9, 99 ± 5
6	O ₂ , pH 10.6, 1.0 M KNO ₃	15.8 ± 0.3	9 ± 2	91	0	9, 69 ± 18
7	O ₂ , pH 14.0, ^f light ^g	4.4 ± 0.1	41 ± 1	45	14 ± 2	9, 98 ± 2 ^c
8	O ₂ , pH 14.0, ^f dark ^h	187	6	94	0	dpms ⁻ , 70 ^c

^aYields are based on the amount of 5; typical concentration [5] = 6–7 mM. ^bCalculated assuming 100% methyl group balance. ^cFormation of black solid was observed. ^dWith 2.4 equiv of TEMPO. ^eKH₂PO₄/K₂HPO₄ buffer. ^fWith 1.0 M KOH solution. ^gReaction mixture was irradiated with 26 W fluorescent lamp. ^hReaction flask wrapped with aluminum foil.

amount of methylhydroperoxide (4%) was detected among the reaction products.

All of the experiments in Table 1 were conducted using standard borosilicate glass vessels under standard lighting conditions employing fluorescent hood lights as the only light source. In the course of these experiments, it was noticed that the reaction rate and selectivity are changed when the mixtures are exposed to more or less light (vide infra). Notably, when the reaction was performed under irradiation with 26 W CFL at pH 14.0, the yield of methylhydroperoxide could be increased up to 20% (entry 4).

Methane was not detected among reaction products in either of our aerobic experiments. By contrast, when argon was used instead of air or oxygen, methane formed in 43% yield after 7 days (entry 5). Notably, in the presence of 1.9 equiv of TEMPO, the formation of the Me-TEMPO adduct was detected by means of ¹H NMR spectroscopy and electro-spray mass-spectrometry (entry 6), thus suggesting that methyl radicals may be involved in the anaerobic reaction. Formation of methane in the course of decomposition of monomethyl Pd^{II} complexes in the absence of any oxidants was also reported by Sanford.⁸

It is important to note that, in all of our closed-vessel experiments where reliable integration of the alkane signals was possible (that is, all experiments except entries 3 and 4 where 1 M KOH was used), the methyl group balance was reasonably close to 100%.

1.2. Factors Affecting Rate of Oxidation of Complex 5 (eq 1) and Possible Mechanisms of O₂ Activation. The effect of various factors on the rate of reaction in eq 1 was analyzed next with the goal of obtaining some insight into the reaction mechanism. For maintaining a steady concentration of the oxidant in the solution, the experiments were carried out with

rapid stirring under ambient pressure of oxygen gas at 20 °C. Under these conditions, the amount of ethane formed could not be quantified. Hence, the yield of ethane was estimated assuming 100% methyl group balance as it was observed in our sealed flask experiments (Table 1). The oxidation was monitored by ¹H NMR spectroscopy for ~3 or 4 reaction half-lives and was found to follow first order kinetics in the complex 5 concentration (Table 2, entries 1–5).

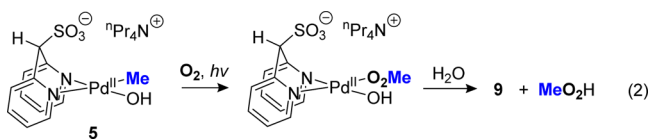
(a) Oxygen partial pressure. A comparison of the experiments performed under air and pure O₂ atmosphere at pH 10.6 (entries 1 and 2, respectively) shows that an ~5-fold increase in the partial pressure of oxygen leads to only ~25% faster rate of the overall reaction (eq 1) and does not significantly change its selectivity. Hence, for most of the contributing processes, the rate-determining step of the reaction does not involve O₂.

(b) TEMPO additives. The reaction rate is moderately inhibited by an additive of 2.4 equiv of TEMPO (entry 3), pointing to a radical-like reactivity of the reaction intermediates. Formation of Me-TEMPO adduct was detected in those experiments by means of ¹H NMR spectroscopy.

(c) Solution pH. The most significant change of the rate and/or selectivity of the reaction between 5 and O₂ could be achieved by changing its pH from the “native” value of 10.6 to either the lower or higher side. A 5-fold acceleration without change in the selectivity of MeOH was observed at a lower pH of 6.3 (entry 4). In turn, a 4-fold increase in selectivity with respect to MeOH with a modest 30% increase of the reaction rate was seen at pH 14.0 (entry 5 vs 2). The effect of the ionic strength of 1.0 M KOH solution may be responsible for the latter reaction rate increase but not its selectivity change, as is seen from the results of oxidation at pH 10.6 in the presence of 1.0 M KNO₃ (entry 6 vs 2).

(d) Effect of light. Finally, the photochemical nature of the reaction in eq 1 was demonstrated by (i) running it in the presence of 26 W CFL bulb placed near the temperature-controlled reaction flask in which the reaction rate increased ~5 fold (entry 7) and (ii) running the oxidation in the dark (aluminum foil wrapping; entry 8). In the latter case, the reaction was slowed by more than 10 fold.

Discussing possible mechanisms of O₂ activation in our system, it is worth noting that the formation of MeOOH and the effects of TEMPO additives and light on the reactivity of complex 5 are reminiscent of a chain radical O₂ insertion into the Pd^{II}-CH₃ bond observed for a bipyridyl dimethyl Pd^{II} complex (Scheme 1a).¹³ The methylhydroperoxide may be released into the reaction mixture as a result of subsequent reaction with the solvent (eq 2).



At the same time, a modest inhibition of reaction 1 by TEMPO and the lack of noticeable changes in its selectivity in the presence of TEMPO (entry 3 vs 2) support the notion that the chain radical O₂ insertion is not the major mechanism of O₂ activation in reaction 1 under ambient-light conditions.

A nonradical photochemical O₂ insertion into Pd^{II}-CH₃ bond described by Britovsek (Scheme 1b)¹⁴ may be considered as another possible mechanism of O₂ activation in reaction 1, also leading to the formation of Pd^{II}-OOMe species via a Pd^{IV} peroxo methyl intermediate. The Britovsek's reaction model suggests the involvement of a dinuclear excited triplet species, which if applied to our system, translates to a second order rate of disappearance in [5]. This mechanism is also unlikely to be predominant in our system because reactions listed in Table 2 (entries 1–5) follow first order kinetics in [5].

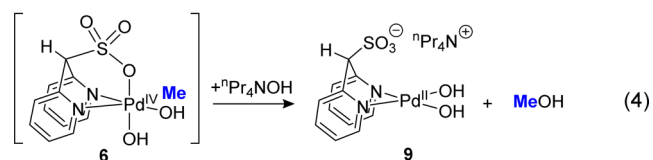
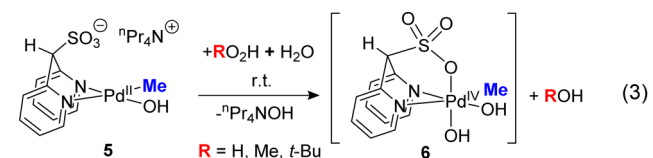
Because none of the reaction models above can account for our experimental observations, we propose that a direct photochemical oxidation of 5 to produce an electrophilic Pd^{IV} complex 6 (Chart 1; see section 6) might constitute a third mechanistic possibility for O₂ activation in reaction 1. In such a case, the aerobic reaction 1 would follow a first order dependence in [5], consistent with our observations. In this mechanism, formation of MeOOH may result from a nucleophilic attack of H₂O₂ at the methyl ligand in complex 6 (vide infra).³¹

2. Oxidation of *n*-Pr₄N[(dpms)Pd^{II}Me(OH)] with ROOH in Water (R = Me, *t*-Bu, H). The fact that methylhydroperoxide is observed as one of the reaction products in our aerobic experiments at pH 14.0 prompted us to consider potential involvement of MeOOH in the oxidation reaction (eq 1) as an intermediate that is more reactive and hence “invisible” at lower pH values. It is worth noting that the ability of H₂O₂³² and

some alkyl hydroperoxides^{16,30} to oxidize organopalladium(II) complexes has been documented previously.

Because MeOOH is not commercially available and is a dangerous compound with which to work, dilute solutions of MeOOH (~0.3 mmol/L) were generated at pH 14.0 using reaction 1 carried out under light. These solutions contained no unreacted complex 5; dihydroxopalladium(II) 9 was the only soluble Pd-containing complex. The content of CH₃OH and CH₃OOH was quantified using ¹H NMR spectroscopy using 1,4-dioxane as an internal standard. The stability of the resulting solutions at pH 14.0 was tested, and no noticeable change in MeOOH concentration was observed over the course of at least 2 days (Table S9). Upon mixing of solutions containing 5 and MeOOH to allow for 2.5:1 MeOOH:5 ratio, the pH of the MeOOH solution was adjusted by the addition of 50% aqueous HBF₄ when necessary, and the mixture was monitored by ¹H NMR spectroscopy.

In the reaction carried out at pH 14.0, complex 5 was consumed over the course of 16 h. Intriguingly, the oxidation produced 1.62 ± 0.05 mol of methanol per mol of 5 (Table 3, entry 1). Assuming that 1 equiv of MeOH is liberated from MeOOH as a result of its reduction with 5 (vide infra), the additional 0.62 ± 0.05 equiv should have originated from the methyl ligands of 5. We propose that MeOH produced beyond the expected 1 equiv is derived from complex 6 (see section 4), as shown in eqs 3 (R = Me) and 4.



Oxidation of 5 with MeOOH at pH 5.7 (Table 3, entry 2) was complete in 5 h, which is noticeably and expectedly²⁸ (using analogy with Pt^{II} complex 1) faster than at pH 14.0. The reaction produced 1.16 ± 0.09 mol of methanol per mol of 5. Importantly, formation of an intermediate dimethyl Pd^{IV} complex 7 along with dihydroxopalladium(II) species 9 (eq 5; R = Me) was also detected. The amount of 7 increased

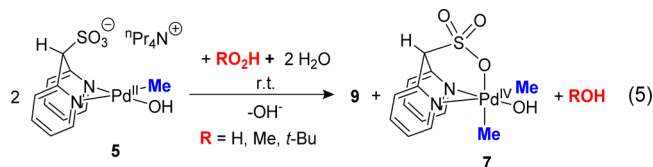


Table 3. Results of the Oxidation of 0.60 mM *n*-Pr₄N[(dpms)Pd^{II}Me(OH)] with MeOOH in Water at 20 °C^a

entry	conditions	conversion (%) / reaction time	MeOH (equiv) ^b	other products (%)
1	pH 14.0, ^c MeOOH (2.5 equiv)	100/16 h	1.62 ± 0.05	
2	pH 5.7, ^d MeOOH (2.0 equiv)	100/5 h	1.16 ± 0.09	LPd ^{IV} Me ₂ (OH), 28 ± 1

^aYields are based on the initial [Pd^{II}Me]. ^bThe amount of MeOH formed with respect to that of 5. ^cWith 1.0 M KOH solution. ^dpH adjusted with aqueous solution of HBF₄.

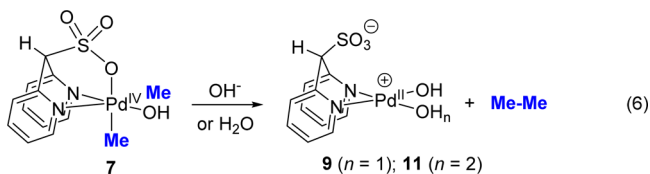
during the initial stages of the reaction, reaching a maximum yield of 28%; the complex disappeared by the end of the reaction.

The reactivity observed in our experiments involving **5** and MeOOH was found to also be common for some other hydroperoxides, *tert*-butylhydroperoxide, and hydrogen peroxide (eqs 3–5, R = H, *t*-Bu; see also SI). When either of these oxidants was used in the reaction with **5** in water at pH 5.7, 10.6, and 14.0, formation of MeOH was detected with the highest MeOH yield of 32% for H₂O₂ and 61 ± 6% for *t*-BuOOH as oxidant at pH 14.0. In the latter case, quantitative formation of *t*-BuOH (99% NMR yield) was also observed. Notably, one more reaction product, MeOOH, was also detected in the oxidation of **5** with H₂O₂ and *t*-BuOOH in the oxidation with *t*-BuOOH when these reactions were carried out at pH 14 and 6 (see SI).

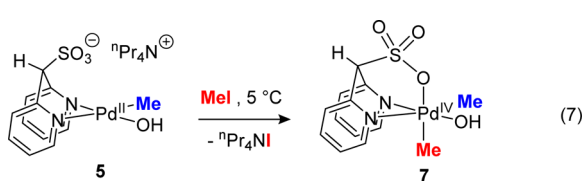
On the basis of these observations and the proposed intermediacy of monomethyl Pd^{IV} complex **6** in the oxidation of **5** with O₂ (eq 1), methanol may result from (i) the reduction of transient MeOOH with **5** (eqs 3 and 5; R = Me) and (ii) from nucleophilic attack by water solvent or OH⁻ at the monomethyl Pd^{IV} complex **6** (eq 4). A similar nucleophilic attack at **6** involving H₂O₂ instead of water would also lead to the formation of MeOOH that we observed at pH 14.0.

As in the case of the reaction with MeOOH, the reaction of **5** with H₂O₂ (except at pH 14.0) was fast and complete in the course of a few minutes at 21 °C. Formation of dimethyl Pd^{IV} intermediate **7** was seen in these experiments in yields ranging from 15 to 50%. The oxidation of **5** with *t*-BuOOH at pH ≤ 14.0 was also fast enough to observe transient formation of **7**.

Production of ethane was detected in all of the oxidation experiments above where MeOOH, *t*-BuOOH, or H₂O₂ were used as oxidants. The source of ethane was found to be dimethyl Pd^{IV} complex **7**. In contrast to its thermally robust dimethyl Pt^{IV} analogue **4** (Scheme 1), Pd^{IV} complex **7** eliminates ethane readily at 21 °C (eq 6). This complex was prepared and characterized independently as described below.



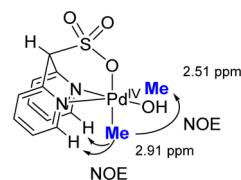
3. Synthesis of (dpms)Pd^{IV}Me₂(OH). Dimethyl Pd^{IV} complex **7** could be generated by stirring aqueous solutions of complex **5** with methyl iodide at 5 °C (eq 7). This reaction



can be viewed as a formal S_N2 attack of the nucleophilic methylpalladium(II) species **5** at the electrophilic MeI.³³ The reaction is relatively slow, and elimination of ethane from the thermally unstable **7** (eq 6) is competitive with the formation of **7**. As a result, the fraction of **7** in the reaction mixtures increases over the course of the first 40 min and then remains steady at 40–47% over the following hour (Chart S4), thus allowing for a reliable NMR characterization of **7**. According to ¹H NMR

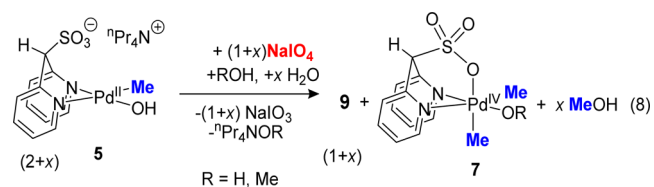
spectroscopy, complex **7** is C₁-symmetric; selective NOE experiments show an interaction between the axial methyl ligand (2.91 ppm) and both *o*-C-H protons of the dpms ligand pyridine rings (Figure S12, Chart 2). An interaction between the axial and equatorial (2.51 ppm) methyl ligands is also observed.

Chart 2. NOE Interaction in DPMS-Supported Palladium Complex **7**

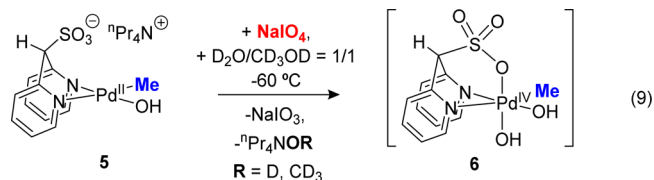


Notably, complex **7** does not produce any MeOH even at pH 14.0. When the temperature of the solution containing **7** is raised to 21 °C, ethane elimination becomes fast with a half-life of 6 min for this first order process (Chart S5). The short reaction half-life suggests that complex **7** can be observed at this temperature only when the rate of its formation is much faster or comparable to that of the ethane elimination. In fact, this condition was never met in our aerobic oxidation experiments or in the oxidation of **5** with H₂O₂ at pH 14.0, which allows us to account for our failure to detect **7** in the corresponding reaction mixtures.

4. Competitive Formation of **7 and Methanol via Proposed Methylpalladium(IV) Transient **6**.** A much faster conversion of **5** to mixtures of dimethyl Pd^{IV} complex **7**, dihydroxo Pd^{II} derivative **9**, and MeOH can be achieved using a more efficient oxidant, NaIO₄ (eq 8; R = H). The oxidation is

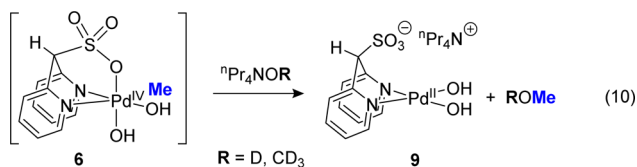


complete after 11 min at pH 10.6 and 21 °C, leading to 27% yield of MeOH, 31% yield of **7**, and free ethane. Overall, this chemistry is reminiscent of the reactions of **5** with hydroperoxides (eqs 3 and 5) and presumably also proceeds via intermediacy of a highly electrophilic monomethyl palladium(IV) complex (**6**, eq 9).



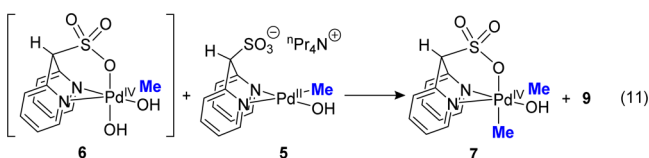
Indirect evidence for the transient formation of intermediate **6** can be obtained from the oxidation of **5** with NaIO₄ in D₂O/CD₃OD (eq 9). Analysis of the products by ¹H NMR spectroscopy shows that CH₃OCD₃ (32% yield) is formed along with CH₃OH (32% yield). These products may result from concurrent reactions of **6** with OCD₃⁻ and OH⁻, respectively (eq 10). Remarkably, the Pt^{IV} analogue of **6**,

complex **3**, is much less electrophilic and is virtually unreactive with respect to such nucleophiles.^{28,31}

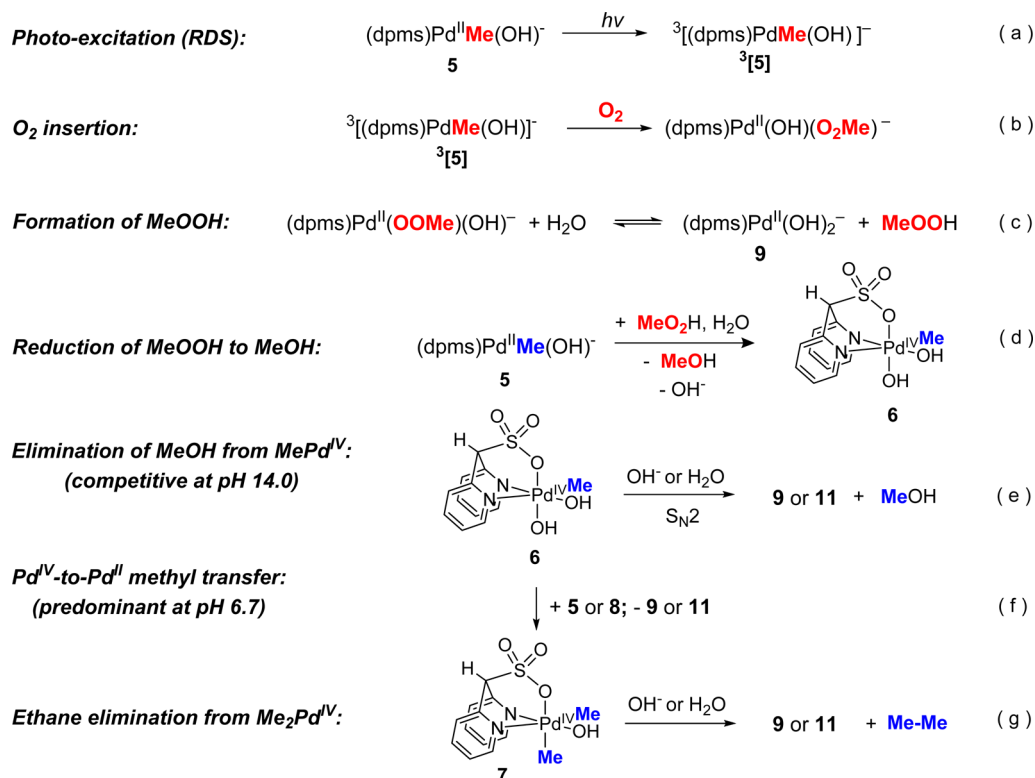


Our attempts to observe the formation of **6** in reactions between **5** and 3 equiv of NaIO₄ were unsuccessful even at temperatures as low as -60 °C using D₂O-CD₃OD mixtures. Complex **5** was fully consumed within the first 5–10 min producing dimethyl Pd^{IV} complex **7** and two more C₁-symmetric dimethylpalladium(IV) species (dpms)PdMe₂X in a 54% combined yield (see SI); here, X was presumed to be OMe (eq 8; R = Me) and IO₄. All three (dpms)PdMe₂X complexes decompose rapidly at 21 °C with the elimination of ethane with a half-life ranging between 3 and 6 min.

It is also apparent that, similar to (dpms)Pt chemistry,²⁸ a Pd^{IV}-to-Pd^{II} methyl transfer from the electrophilic methyl Pd^{IV} complex **6** to a nucleophilic species **5** may be involved (eq 11). The Pd^{IV}-to-Pd^{II} methyl transfer reaction **11** occurs concurrently with reactions **4** and **10**, where **6** reacts with hydroxide and methoxide anions, respectively, acting as nucleophiles.



Scheme 3. Mechanism of MeOOH and MeOH formation in Reaction 1 via Initial Photochemical O₂ Insertion into the Pd^{II}-C Bond



5. Mechanism of Oxidation of Pr₄N[(dpms)Pd^{II}Me(OH)] via O₂ Insertion into the Pd^{II}-C Bond. As discussed in section 2, MeOH and ethane in reaction 1 may form both via intermediacy of MeOOH and monomethylpalladium(IV) transient **6**, respectively. Scheme 3 summarizes the hypotheses concerning a possible mechanism of such photoinduced transformations. The first step is the photoexcitation of **5** to produce, after a spin interconversion, a triplet spin-isomer ³[**5**] (step a). This photoexcitation should be rate-limiting consistent with the observed first order of reaction 1 in complex **5**. Subsequent fast trapping of ³[**5**] with O₂ leads to the O₂ insertion into Pd-CH₃ bond of ³[**5**] to form a palladium(II) methylperoxy species (step b; see section 7 for more detail). Hydrolysis of the palladium(II) methylperoxy species generates free methylhydroperoxide (step c). The MeOOH is then converted to MeOH by another equiv of **5** to produce a highly electrophilic monomethylpalladium(IV) transient **6** (step d). This pH-dependent reaction is fast at pH ≤ 11 so that MeOOH does not accumulate in the mixtures and is undetectable by means of ¹H NMR spectroscopy. By contrast, the reaction is slow enough at pH 14.0 that MeOOH is an observable product of photo-oxidation (1).

Transient **6** may be involved in two concurrent processes: (i) a nucleophilic reaction with the solvent or hydroxide anion (S_N2) leading to a second equivalent of MeOH (step e) and (ii) a Pd^{IV}-to-Pd^{II} methyl transfer reaction leading to a dimethyl Pd^{IV} intermediate **7** (step f) that is responsible for ethane production (step g) in this reaction sequence.

If the step f fully outcompetes e, the MeOH:C₂H₆ ratio is expected to be 1:1, whereas if step e is also competitive, the MeOH:C₂H₆ ratio should be greater than 1:1. In the latter case, this ratio is expected also to grow as pH increases because

greater concentration of the nucleophile OH^- involved in reaction e becomes available. Indeed, when ROOH are used as oxidants ($\text{R} = \text{H}, \text{Me}, t\text{-Bu}$) in their reactions with complex **5** (see Table 3), both pathways e and f are operational and competitive. For instance, when MeOOH is used at pH 14.0, the observed $\text{MeOH}:\text{C}_2\text{H}_6$ ratio is approximately $1.62:0.38 = 80\%:20\%$. This ratio of products points to a $0.62/0.38 = 1.6$ times greater contribution of the reaction e relative to f, such that in 1.0 M KOH solution the hydroxide anion is approximately 1.6 times more competitive than ~ 5 mM **5** in the reaction with **6**. Hence, **5** is $(1.0/0.005)/1.6 \approx 100$ times more nucleophilic than OH^- . In turn, at pH 5.7, the observed $\text{MeOH}:\text{C}_2\text{H}_6$ ratio is $1.16:0.84 = 58\%:42\%$, which suggests that ~ 5 mM complex (dpms) $\text{Pd}^{\text{II}}\text{Me}(\text{OH}_2)$, **8**, is approximately $0.84/0.16 = 5.3$ times more competitive than 55 M H_2O in their reaction with **6**. Hence, **8** is $(55/0.005) \times 5.3 \approx 60000$ times more nucleophilic than H_2O .

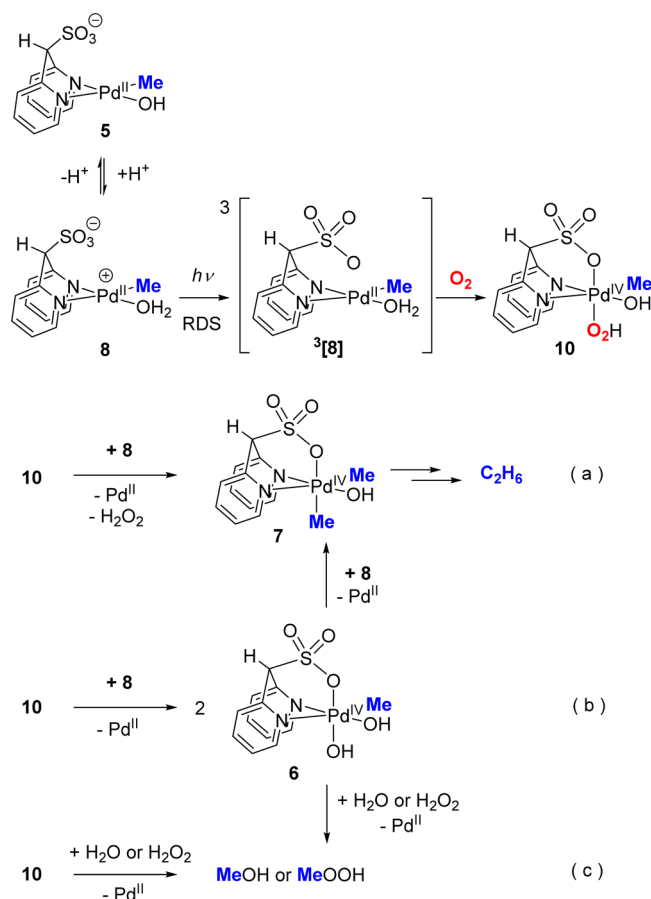
We can now compare $\text{MeOH}:\text{C}_2\text{H}_6$ ratios in reactions of **5** at pH 14.0 when O_2 is the oxidant that ranges from 49:31 to 54:44 (Table 1, entries 4 and 3, respectively) relative to 80:20 (see above) when MeOOH is the oxidant. These ratios at a lower pH of ~ 7 are 10:90 with O_2 as oxidant (Table 2, entry 4) relative to 58:42 when MeOOH is the oxidant. In both cases, in the aerobic reaction, the observed fraction of MeOH is always lower than in the analogous reactions utilizing MeOOH as oxidant. The observed dramatic difference in the reaction selectivity implies that the predominant mechanisms leading to the formation of MeOH and ethane do not involve intermediacy of MeOOH at either pH 14.0 or pH 6–7. Therefore, the mechanism in Scheme 3 can have only a minor contribution to the overall reaction 1. Hence, we propose another mechanism leading to complex **6** as discussed in the following section.

6. Direct Photochemical Formation of Complex 6 with O_2 as Oxidant. The alternative mechanism for the formation of MeOH and ethane is given in Scheme 4 for the methylpalladium(II) aqua complex **8** as an example. A similar reaction sequence can be written for its hydroxo derivative **5**.

Complex **8** is expected to be the predominant (>99%) palladium-containing species in ~ 6 mM solution at pH 6.7; this complex should be a minor ($\sim 6\%$) species at pH 10.6 and a trace component at pH 14. According to the mechanism in Scheme 4, the Pd^{II} complex **8** is photoexcited (a formal rate-determining step of the overall oxidation reaction) to produce, after a spin interconversion, a triplet spin-isomer $^3[\mathbf{8}]$ (vide infra). The triplet transient is trapped by O_2 to form derived hydroperoxo methylpalladium(IV) species **10**. In support of the viability of the formation of Pd^{IV} intermediates in direct aerobic oxidation of palladium(II) methyl species, precedents involving dimethyl Pd^{II} complexes were reported earlier by Mirica.^{16–18} In contrast to these previous observations, the aerobic oxidation in Scheme 4 is photoinduced and involves monomethyl palladium(II) species.

As in the case of the monomethyl hydroxopalladium(IV) **6** (Scheme 3), several competing reactions are possible that involve **10**. Among them are (i) a nucleophilic attack by methylpalladium(II) complex **8** (paths a and b) leading to Pd^{IV} -to- Pd^{II} methyl transfer product **7**; H_2O_2 is another expected product here (path a) and/or an OH-group transfer via O–O cleavage to produce **6** (path b) and (ii) a nucleophilic attack by water and/or H_2O_2 to produce MeOH and/or MeOOH , respectively (path c). Pathway c with H_2O_2 as a nucleophile

Scheme 4. Direct Photochemical Oxidation of **5 or **8** with O_2 to Produce Complex **6****



may serve for the MeOOH production in our reaction mixtures at pH 14.0 besides insertion of O_2 into the $\text{Pd}^{\text{II}}\text{—C}$ bond (eq 2).

7. Time-Dependent DFT Analysis of $^3[\mathbf{5}]$ and $^3[\mathbf{8}]$. To shed light on the anticipated reactivity toward O_2 of the triplet species $^3[\mathbf{5}]$ and $^3[\mathbf{8}]$ that are expected to result from photoexcitation and spin interconversion involving **5** and **8**, respectively, we used methods of time-dependent density functional theory (TDDFT). The geometry optimization for **5** and **8** and calculations of the 30 lowest energy singlet and triplet excited states were done for water as a solvent (see SI for details).

The calculated UV–vis spectrum of anionic complex **5** contains multiple electronic metal-to-ligand charge transfer (MLCT) transitions in the wavelength range 420–600 nm. Most of the excitations correspond to transitions of the metal electrons promoted from its $4d$ orbitals to the π^* orbitals of the pyridine rings (see SI). In particular, the lowest energy excitation at 549 nm leading to a singlet spin-isomer $^1[\mathbf{S}_{549}]$ involves an electron transition from the metal d_{z^2} orbital to a π^* pyridine ring molecular orbital. A higher energy excitation at 355 nm leading to a spin-isomer $^1[\mathbf{S}_{355}]$ corresponds to a transition from the metal d_{z^2} orbital to a predominantly Pd—C σ^* orbital. Analysis of the triplet excitations of **5** allows for finding the triplet excited states with similar spin populations (see SI for details). For instance, the lowest energy triplet excited state $^3[\mathbf{S}_{575}]$ has two singly occupied molecular orbitals, SOMOs, which are predominantly the metal $4d_{z^2}$ orbital and SOMO+1, which is one of the pyridine π^* orbitals (Figure 1, a and b).

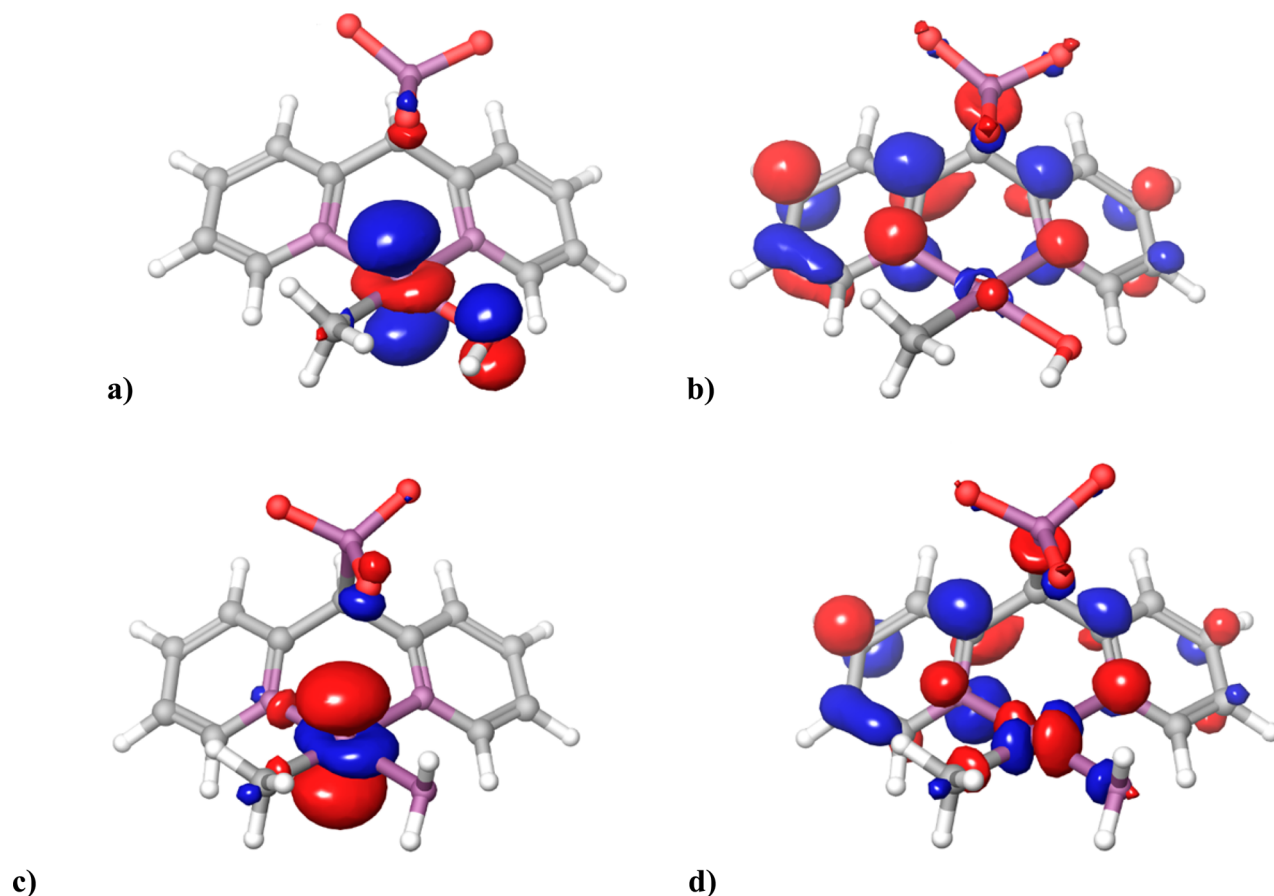
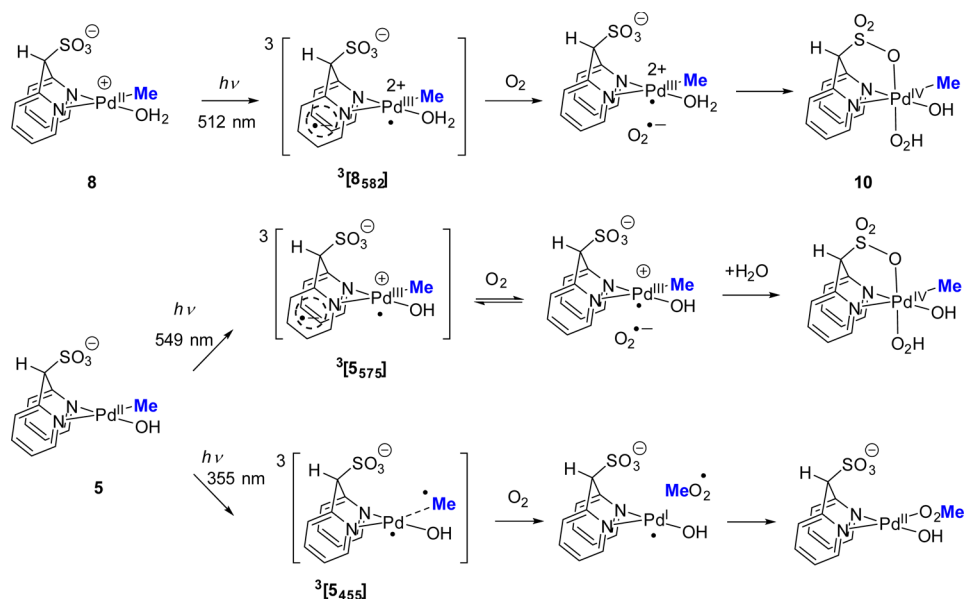


Figure 1. Singly occupied molecular orbitals, SOMO and SOMO+1, corresponding to a triplet excited spin-isomer $^3[5_{75}]$ (a, b) and $^3[8_{82}]$ (c, d).

Scheme 5. Reactivity of $^3[5]$ and $^3[8]$



Similar analysis was performed for aqua complex **8**. Compared to **5**, the absorption bands of the MLCT are blue-shifted spanning from 350–550 nm. The lowest energy excitation at 512 nm leading to a spin-isomer $^1[8_{512}]$ involves an electron transition from the metal d_{z^2} orbital to a π^* pyridine ring orbital (89% contribution) and a Pd–C σ^* orbital (11%).

Because a fluorescent lamp light spectrum has the greatest intensity in the visible range, we may limit our analysis to the MLCT transitions above. For both lowest energy triplet excited states, $^3[5_{75}]$ and $^3[8_{82}]$ (Figure 1), the highest energy SOMO+1 is predominantly one of the pyridine π^* orbitals where the unpaired electron can be “picked up” by an O_2 molecule to produce a superoxide anion radical and a

Table 4. Effect of [Pd^{II}Me] on the Product Distribution in the Oxidation of *n*-Pr₄N[(dpms)Pd^{II}Me(OH)] with O₂ in Water at pH 14.0^a

entry	[5] (mM)	conversion/reaction time	MeOH (%)	MeOOH (%)	C ₂ H ₆ ^b (%)	other products (%)
1	13.2	98%/4 days	54 ± 2	4 ± 1	42	9, 82 ± 5
2	1.3	100%/4 days	44 ± 2	30 ± 1	26	9, 92 ± 6
3	0.7	100%/4 days	43 ± 1	40 ± 3	17	9, 69 ± 2 dpms ⁻ , 27 ± 7

^aYields are calculated based on initial [Pd^{II}Me]; 1.0 M KOH solution. ^bCalculated assuming 100% mass balance.

corresponding Pd^{III} metal radical (Scheme 5). In the case of the reaction sequence involving ³[8₅₈₂], a subsequent radical pair collapse may be assisted with a proton transfer from the nearby aqua ligand to give Pd(IV) intermediate 10. Such a reaction sequence may be less efficient for ³[5₅₇₅] at pH 14.0, and the corresponding spin-isomer ³[5₅₇₅] may decay back to 5.

A higher-energy spin-isomer of ³[5], ³[5₄₅₅], with SOMO+1 being essentially a Pd-CH₃ antibonding orbital, is expected to have a weakly bound Me ligand, which may be abstracted by O₂ to eventually form a Pd^{III} methylperoxo complex. A similar methyl radical abstraction reaction may lead to Me-TEMPO when TEMPO is present in the reaction mixtures. Similar pathways may be considered for ³[8₅₈₂] as well.

We hypothesize that in the absence of O₂ some of the spin-isomeric triplet species ³[5] and ³[8] may be involved in a homolytic Pd^{III}-CH₃ bond cleavage resulting in a hydrogen atom abstraction/methane formation.

h. Controlling the C₂H₆/MeX and MeOH/MeOOH Ratios: Effect of [Pd^{II}] on Product Distribution. Three organic products of aerobic Pd^{II}-CH₃ bond functionalization resulting from reaction 1, MeOH, MeOOH, and ethane, could be produced in different ratios in our experiments. Some results pertinent to control of the reaction selectivity are summarized here. With the goal of maximizing the yield of the oxygenated products MeOH and MeOOH, resulting from reaction 1, one should perform the aerobic oxidation of 5 at pH 14.0 (Table 2, entry 5).

Because the rate of formation of ethane is expected to be second order in [5] (Scheme 4, path a), one would expect that at a lower [5], formation of ethane should become less competitive as compared to MeOH (Scheme 4, path c), which is expected to be first order in [5]. In fact, decreasing concentration of the methylpalladium(II) complex 5 by approximately 10–20-fold from 13.2 mM (Table 4, entry 1) to 1.3 mM (entry 2) and 0.7 mM (entry 3) allows for decreasing the yield of ethane from 42 to 17% while maintaining the yield of MeOH at 43–54%.

Similarly, if the major pathway for the reduction of MeOOH to MeOH involves its reaction with 5 (eq 3), by lowering [5] one can increase the MeOOH:MeOH ratio. Indeed, this ratio could be raised from 0.07 (Table 4, entry 1) to 0.93 (entry 3) as a result of an approximate 20-fold decrease of [5].

CONCLUSIONS

In this work, the first example of aerobic oxidation of monomethyl palladium(II) complexes has been demonstrated. The reaction is photochemical in nature and can lead to the formation of three organic products, ethane, methanol, and methylhydroperoxide. By varying the solution pH and concentration of methylpalladium(II) species, the reaction selectivity can be tuned to favor the formation of predominantly ethane (≤94%) or methanol (≤54%). The fraction of methylhydroperoxide could also be changed from 0 to 40% using solution pH and light as key tools. A reaction mechanism

is proposed that includes photochemical oxidation of monomethyl palladium(II) complexes to their monomethylpalladium(IV) derivatives (major reaction path) and O₂ insertion into the Pd^{II}-C bond (minor path). The methylpalladium(IV) complexes are proposed to be highly electrophilic and responsible for concurrent methyl group transfer to nucleophiles present, e.g., water or hydroxide anion would form methanol, hydrogen peroxide would form methylhydroperoxide, and another methylpalladium(II) species would produce a dimethylpalladium(IV) intermediate. The dimethylpalladium(IV) complex was detected in some reaction mixtures, prepared independently, and shown to be highly reactive in ethane reductive elimination. The knowledge gained in this work may be useful for the development of selective photochemical aerobic oxidation of methane to value-added oxygenates or ethane.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.5b12832.

Crystallographic information for the Pd complex (dpms)Pd^{II}Me(SMe₂) (CIF)

Experimental details regarding the synthesis and characterization of the ligands, metal complexes, and TDDFT calculations (PDF)

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Notes

The authors declare no competing financial interest.

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