J|A|C|S
COMMUNICATIONS

Oxidatively Induced Reductive Elimination from (^{t}Bu$_2$bpy)Pd(Me)$_2$: Palladium(IV) Intermediates in a One-Electron Oxidation Reaction

Michael P. Lanci,[†] Matthew S. Remy,[‡] Werner Kaminsky,[†] James M. Mayer,*[,†] and
Melanie S. Sanford*[,‡]

Department of Chemistry, University of Washington, Box 351700, Seattle, Washington 98195-1700, and Department of Chemistry, University of Michigan, 930 North University Avenue, Ann Arbor, Michigan 48109

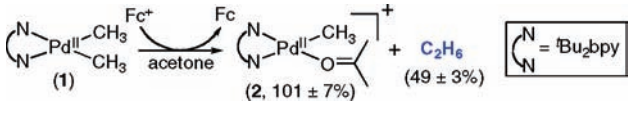
Received July 14, 2009; E-mail: mayer@chem.washington.edu; mssanfor@umich.edu

Carbon−carbon bond formation at palladium centers is one of the most important transformations in organometallic chemistry, as it serves as the product forming step in Pd-catalyzed cross-couplings, allylic substitutions, C−H functionalizations, and numerous other processes.[1] There are two general pathways for Pd-mediated C−C bond formation from Pd^{II}(R)$_2$ intermediates (R = alkyl or aryl): direct C−C bond-forming reductive elimination or oxidatively induced C−C coupling. While direct reductive elimination has been the subject of extensive investigations,[2] the corresponding oxidatively induced transformations remain poorly understood.

Oxidatively induced reductive elimination from Pd^{II}(R)$_2$ is known to occur in the presence of 1e^- chemical oxidants such as Ag$^+$ salts,[3] which are common additives in Pd-catalyzed transformations.[4,5d,6] C−C coupling can also be promoted by potentially oxidizing electron-deficient alkenes such as benzoquinone (BQ).[5] However, it is not currently known whether these different promoters operate by similar mechanisms, whether these reactions occur via coordination to Pd or outer-sphere electron transfer, or whether organic free radical intermediates are involved. As part of a program aimed at developing catalysts for the conversion of methane to ethane, we initiated investigations of oxidatively induced CH$_3$−CH$_3$ coupling from (^{t}Bu$_2$bpy)Pd^{II}(CH$_3$)$_2$ (**1**).[7] This report describes our mechanistic studies of ferrocenium-promoted reductive elimination from **1**, along with a preliminary comparison to related reactions with silver(I) salts and benzoquinone.

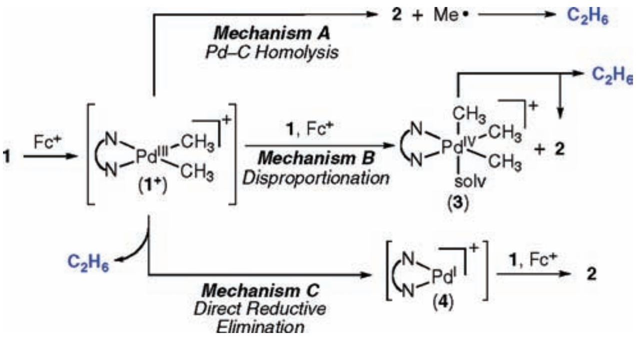
Our first experiments focused on the reaction of (^{t}Bu$_2$bpy)-Pd^{II}(CH$_3$)$_2$ (**1**) with 1.1 equiv of ferrocenium hexafluorophosphate (Cp$_2$Fe$^+$PF$_6^-$, Fc$^+$) in acetone-d_6 at 25 °C. Fc$^+$ was selected for initial study because it should unambiguously serve as a 1e^- outer sphere oxidant in this system. By ^{1}H NMR spectroscopy, the reaction is complete within minutes and affords [(^{t}Bu$_2$bpy)-Pd(CH$_3$)(acetone)]$^+$ (**2**) and ethane, in 101 ± 7% and 49 ± 3% yields, respectively (Scheme 1).[8,9]

Scheme 1. Reaction of Complex **1** with [Cp$_2$Fe]PF$_6$ (Fc$^+$)



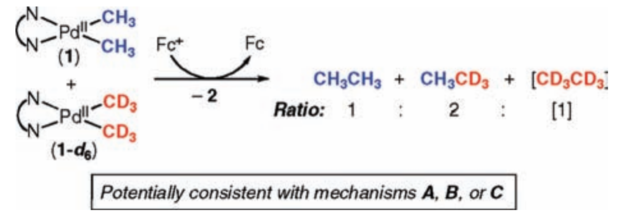
There are at least three potential mechanisms for this C−C coupling process, all of which start with 1e^- oxidation of **1** to the Pd^{III} cation **1**$^+$ (Scheme 2).[10−12] In mechanism **A**, **1**$^+$ undergoes Pd−C bond homolysis to give **2** and CH$_3$•, which then dimerizes to afford ethane. A similar mechanism has been proposed for oxidatively induced reductive elimination from (dmpe)Pd^{II}(R)$_2$ (R = CH$_3$, CH$_2$SiMe$_3$; dmpe = Me$_2$PCH$_2$CH$_2$PMe$_2$)[3a] and from a number of other metal dialkyl complexes.[13,14] In mechanism **B**, **1**$^+$ reacts with **1** and another equivalent of Fc$^+$ to produce 1 equiv of **2** and a Pd^{IV} trimethyl intermediate, **3**. Complex **3** then undergoes C−C bond-forming reductive elimination to afford ethane and a second equivalent of **2**. A similar net disproportionation has been reported for the oxidation of (diimine)Pt^{II}(CH$_3$)$_2$ complexes.[15] Finally, mechanism **C** involves direct C−C reductive elimination from **1**$^+$. Reaction of the resulting transient Pd^I intermediate (**4**) with Fc$^+$ and **1** (a net conproportionation) would then afford **2**.[16] Notably, C−C bond formation from related Ni^{III} intermediates has been proposed as a key step in Ni-catalyzed aryl halide coupling reactions.[17]

Scheme 2. Possible Mechanisms for Reaction of **1** with Fc$^+$



A crossover experiment was conducted by adding 1 equiv of Fc$^+$ to a 1:1 mixture of **1** and (^{t}Bu$_2$bpy)Pd^{II}(CD$_3$)$_2$ (**1-*d*$_6$**) in the dark.[18] This led to rapid formation of **2**, **2-*d*$_3$**, and an essentially statistical 1:1.9 mixture of CH$_3$CH$_3$/CH$_3$CD$_3$, as determined by ^{1}H NMR spectroscopy (Scheme 3). This result is required by mechanisms **A** and **B** but is also consistent with mechanism **C** if **1**$^+$ undergoes rapid scrambling of its methyl groups prior to reductive elimination.

Scheme 3. Crossover Experiment between **1** and **1-*d*$_6$**



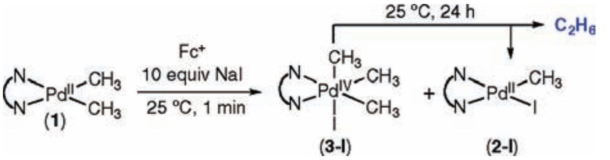
To gain insights into the possibility of methyl radical intermediates (mechanism **A**), we next examined the reaction of **1** with Fc$^+$

[†] University of Washington.
[‡] University of Michigan.

10.1021/ja905816q CCC: $40.75

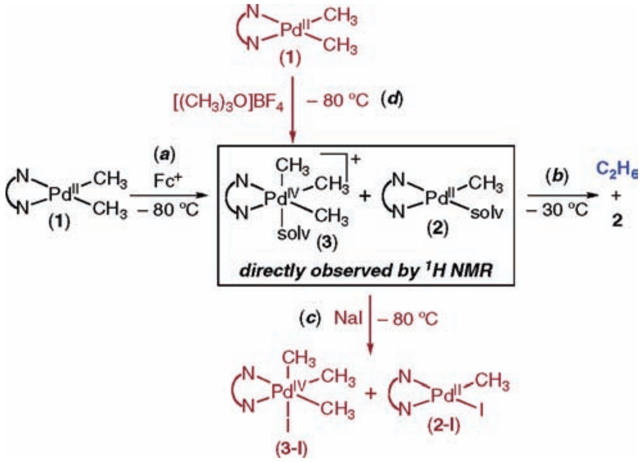
in the presence of 0.1 M of the H• donor 1,4-cyclohexadiene (CHD). In this reaction, the yield of ethane was essentially unchanged (43 ± 3%) and only trace (<1%) methane was formed. Given the rate constant for CHD trapping CH_3• to form CH_4, $k = 1.3 \times 10^5$ M^{-1} s^{-1},[19] this result is not consistent with the formation of ethane from methyl radical dimerization (see Supporting Information for the complete kinetic analysis). Similarly, reactions in the presence of 1 equiv of styrene, another good trap for CH_3•, gave high yields of ethane (55 ± 4%). The absence of observable CH_4 from the reaction in Scheme 1 is also inconsistent with a mechanism involving methyl radicals, since CH_3• in acetone-d_6 has been shown to react to afford both methane and ethane.[20] These results are in interesting contrast to the homolysis pathway indicated for the related complex (dmpe)$\mathrm{Pd^{II}(R)_2}$.[3a]

Scheme 4. Trapping of the $[(^t\mathrm{Bu_2bpy})\mathrm{Pd^{IV}Me_3}]^+$ Intermediate with NaI



The experiments described above suggested that either mechanism **B** or **C** is operating. In an effort to distinguish between these two possibilities, we next examined the reaction of **1** with 1.1 equiv of Fc^+ in the presence of 10 equiv of NaI.[21] The first ^{1}H NMR spectrum after mixing at 25 °C revealed the presence of 0.5 equiv each of the known[22] $(^t\mathrm{Bu_2bpy})\mathrm{Pd^{IV}(CH_3)_3(I)}$ (**3-I**) and $(^t\mathrm{Bu_2bpy})\mathrm{Pd^{II}(CH_3)(I)}$ (**2-I**) (Scheme 4). Over 24 h, the signals associated with complex **3-I** slowly decreased with concomitant appearance of ethane and an additional 0.5 equiv of **2-I**. A crossover experiment under these conditions (**1** + **1-*d*₆** + Fc^+ + NaI) yielded a statistical mixture of isotopologues of **3-I** as determined by ^{1}H NMR spectroscopy, indicating that CH_3 scrambling occurs prior to reductive elimination.[22b] All of these results are required by mechanism **B** but are difficult to rationalize on the basis of mechanism **C**.

Scheme 5. Direct Observation of the $[(^t\mathrm{Bu_2bpy})\mathrm{Pd^{IV}Me_3}]^+$ Intermediate at −80 °C

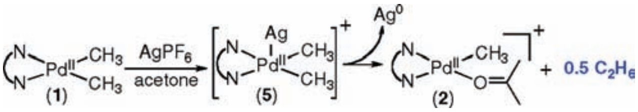


To directly observe the key cationic intermediate **3** that is expected in mechanism **B**, the reaction of **1** with 1.1 equiv of Fc^+ was monitored at low temperature. After mixing at −80 °C in acetone-d_6, an initial ^{1}H NMR spectrum showed the presence of 0.5 equiv of **2** along with 0.5 equiv of a new species assigned as complex **3** (Scheme 5, (a)).[23] These compounds are stable at −80 °C, but upon warming to −30 °C, **3** disappears over ~40 min concomitant with the formation of ethane and an additional 0.5 equiv of **2** (Scheme 5, (b)). The identity of this new species as complex **3** was confirmed by two additional experiments. First, NaI was added to the reaction mixture at −80 °C, which resulted in instantaneous conversion to 0.5 equiv each of **2-I** and **3-I** (Scheme 5, (c)). Second, the reaction between **1** and $[(CH_3)_3O]BF_4$ in acetone-d_6 was conducted at −80 °C and afforded **3** as the sole new inorganic product (as determined by ^{1}H NMR spectroscopy) (Scheme 5, (d)).[22]

In sum, all of the data for the reaction between **1** and Fc^+ are consistent with mechanism **B**, involving (*i*) one-electron oxidation of $(^t\mathrm{Bu_2bpy})\mathrm{Pd^{II}Me_2}$ (**1**), (*ii*) net disproportionation[15] of the transient $\mathrm{Pd^{III}}$ intermediate $\mathbf{1}^+$ to **2** and **3**, and then (*iii*) C−C coupling from **3** to yield ethane in 50% yield.[12] Several radical trapping experiments provide strong evidence against the involvement of CH_3• in these transformations (mechanism **A**). In addition, the direct observation of $\mathrm{Pd^{IV}}$ intermediates at low temperatures is inconsistent with direct C−C bond-forming reductive elimination from either monomeric or dimeric $\mathrm{Pd^{III}}$ intermediates (mechanism **C**).[24−26]

We next examined the reactivity of **1** with Ag^+ and benzoquinone (BQ), which are more common additives in organic transformations.[4,5] Interestingly, ^{1}H NMR spectroscopic analysis of the reaction between **1** and 1.1 equiv of $AgPF_6$ at 25 °C showed rapid and quantitative formation of an intermediate (**5**), which exhibits the same pattern of resonances as that for **1** but different chemical shifts. At longer reaction times (0.5−3 h), a silver mirror was observed along with ethane (51 ± 3%) and **2** (88 ± 6%) (Scheme 6).

Scheme 6. Reaction of Complex **1** with $AgPF_6$



While intermediate **5** proved challenging to characterize due to its thermal instability, a stable analogue (**5-Tl**) with a very similar ^{1}H NMR spectrum was formed upon reaction of **1** with 1 equiv of $TlPF_6$ under identical conditions. An X-ray structure of crystals obtained from this solution revealed a sandwich complex containing three molecules of **1** and two Tl^+ cations (Figure 1). Similar cationic adducts of $\mathrm{Pt^{II}}$ have been reported previously.[15b,27] The enhanced stability of **5-Tl** is likely due to Tl^+ being a weaker oxidant than Ag^+.[28] The reaction of $AgPF_6$ with a 1:1 mixture of **1** and **1-*d*₆** afforded a statistical 1:2 mixture of CH_3CH_3/CH_3CD_3 (similar to

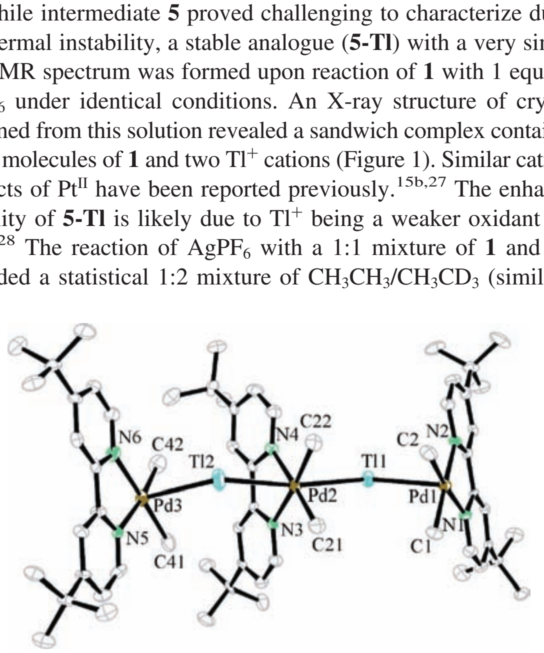
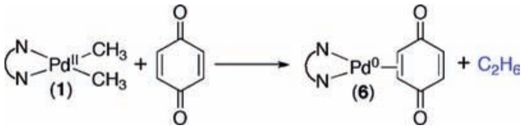


Figure 1. ORTEP of the cation, $\mathrm{Tl_2[(^tBu_2bpy)Pd^{II}Me_2]_3}^{2+}$, in the structure of **5-Tl** (hydrogen atoms, PF_6^- counterions, and solvent molecules excluded for clarity). Bond lengths (Å) and angles (deg): Tl1−Pd1, 2.7963(6); Tl1−Pd2, 2.9320(6); Tl2−Pd2, 2.9942(6); Tl2−Pd3, 2.8299(7); Pd1−Tl1−Pd2, 132.93; Tl1−Pd2−Tl2, 170.92; Pd2−Tl2−Pd3, 131.39.

the analogous crossover experiment with Fc$^+$, Scheme 3).[29] On the basis of all of this data, we propose that Ag$^+$ reacts with **1** via an inner sphere mechanism where Ag$^+$ initially binds to **1** followed by inner sphere electron transfer, generating Ag^0 and **1**$^+$. The Pd^{III} complex **1**$^+$ then likely undergoes net disproportionation via a pathway analogous to the Fc$^+$ reactions (mechanism **B**).[15c]

In marked contrast, the reaction of **1** with 1.1 equiv of benzoquinone (BQ) proceeds much more slowly than the Fc$^+$ and Ag$^+$ reactions under analogous conditions ($t_{1/2} \approx 4.5$ h) and releases nearly a full equivalent of ethane (89 ± 6%; Scheme 7). In this case, the palladium product is the benzoquinone adduct (^{t}Bu$_2$bpy)Pd^0(BQ) (**6**, 94 ± 6%).[30,31] A crossover experiment reacting BQ with a 1:1 mixture of **1** and **1-*d*$_6$** in the dark afforded CH_3CH_3 selectively at initial reaction times (as determined by ^{1}H NMR spectroscopy). CH_3CD_3 only appeared later as the starting material scrambled. These preliminary experiments show that BQ-promoted reductive elimination from **1** occurs by a mechanism distinct from that for Fc$^+$ and Ag$^+$, and further studies of this process are ongoing.[32]

Scheme 7. Reaction of Complex **1** with Benzoquinone



In conclusion, a variety of oxidants induce reductive elimination of ethane from (^{t}Bu$_2$bpy)Pd^{II}(CH$_3$)$_2$ (**1**). With the outer-sphere oxidant ferrocenium, the data are consistent with a mechanism involving Pd^{III} and Pd^{IV} intermediates, with C−C bond formation occurring from the latter. The reaction with Ag$^+$ appears to proceed via a Ag$^+$ adduct (**5**), which undergoes inner sphere electron transfer before following the analogous mechanism for Fc$^+$. In contrast, the slower reaction between **1** and benzoquinone forms ethane by a different pathway that does not involve methyl group scrambling and that generates Pd^0 products. These studies suggest that oxidatively induced C−C bond-forming reductive elimination may be relevant to Pd-catalyzed reactions containing Ag$^+$ additives.[4] Furthermore, this work provides a new mechanistic understanding of 1e^- chemistry at Pd^{II} centers that should assist the development of novel catalytic transformations, including our ongoing efforts toward the oxidative dimerization of methane.

Acknowledgment. We thank the National Science Foundation for support through the NSF Center for Enabling New Technologies through Catalysis (CENTC).

Supporting Information Available: Experimental details, ^{1}H NMR spectra and characterization, and X-ray crystallographic data. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) Crabtree, R. H. *The Organometallic Chemistry of the Transition Metals*; Wiley Interscience: Hoboken, NJ, 1995.
(2) Hartwig, J. F. *Inorg. Chem.* **2007**, *46*, 1936.
(3) (a) Seligson, A. L.; Trogler, W. C. *J. Am. Chem. Soc.* **1992**, *114*, 7085. (b) Kraatz, H. B.; van der Boom, M. E.; Ben-David, Y.; Milstein, D. *Isr. J. Chem.* **2001**, *41*, 163.
(4) For recent examples, see: (a) Takahashi, M.; Masui, K.; Sekiguchi, H.; Kobayashi, N.; Mori, A.; Funahashi, M.; Tamaoki, N. *J. Am. Chem. Soc.* **2006**, *128*, 10930. (b) Chen, X.; Goodhue, C. E.; Yu, J. Q. *J. Am. Chem. Soc.* **2006**, *128*, 12634. (c) Stuart, D. R.; Villemure, E.; Fagnou, K. *J. Am. Chem. Soc.* **2007**, *129*, 12072. (d) Chi, S. H.; Hwang, S. J.; Chang, S. *J. Am. Chem. Soc.* **2008**, *130*, 9254. (e) Potavathri, S.; Dumas, A. S.; Dwight, T. A.; Naumiec, G. R.; Hammann, J. M.; DeBoef, B. *Tetrahedron Lett.* **2008**, *49*, 4050.
(5) For representative examples, see: (a) Temple, J. S.; Riediker, M.; Schwartz, J. *J. Am. Chem. Soc.* **1982**, *104*, 1310. (b) Albeniz, A. C.; Espinet, P.; Martin-Ruiz, B. *Chem. Eur. J.* **2001**, *7*, 2481. (c) Chen, X.; Li, J.-J.; Hao, X.-S.; Goodhue, C. E.; Yu, J.-Q. *J. Am. Chem. Soc.* **2006**, *128*, 78. (d) Hull, K. L.; Sanford, M. S. *J. Am. Chem. Soc.* **2007**, *129*, 11904. (e) Perez-Rodriquez, M.; Braga, A. A. C.; Garcia-Melchor, M.; Perez-Temprano, M. H.; Casares, J. A.; Ujaque, G.; de Lera, A. R.; Alvarez, R.; Maseras, F.; Espinet, P. *J. Am. Chem. Soc.* **2009**, *131*, 3650. (f) Hull, K. L.; Sanford, M. S. *J. Am. Chem. Soc.* **2009**, *131*, 9651.
(6) Palladium-catalyzed C−N bond-forming reactions promoted by 1e^- chemical oxidants such as Ce(IV) have also been recently reported: Mei, T.-S.; Wang, X.; Yu, J.-Q. *J. Am. Chem. Soc.* **2009**, *131*, 10806.
(7) Liu, G. X.; Puddephatt, R. J. *Inorg. Chim. Acta* **1996**, *251*, 319^{t}Bu$_2$bpy = 4,4′-di-*tert*-butyl-2,2′-bipyridine.
(8) Ethane is also formed upon treatment of **1** with other outer sphere 1e^- oxidants such as $(C_5Me_5)_2Fe^+$ and the tri-*p*-tolyl-aminium radical cation $[N(tol)_3]^{\bullet+}$. See Supporting Information for details.
(9) The yield of C_2H_6 remained ≤50% in the presence of up to 10 equiv of Fc$^+$.
(10) Cyclic voltammograms of **1** show a completely irreversible oxidation at $E_{p,a} = +0.58$ V vs Fc$^{+/0}$ in acetone, even at $n = 10$ V/s. For Ag$^{+/0}$, $E°' = +0.18$ V vs Fc$^{+/0}$ in acetone. See Supporting Information.
(11) Klein, A. *Niemeyer Z. Anorg. Allg. Chem.* **2000**, *626*, 1191.
(12) A previous report described the oxidation of Pd(II) to Pd(IV) with 2 equiv of Fc$^+$. However, the electron-rich, rigid nature of the starting material in this report and the presence of a pendant pyrazolyl arm and a chelating alkyl/aryl ligand are expected to render this example mechanistically very different from the current system. Campora, J.; Palma, P.; del Rio, D.; Lopez, J. A.; Alvarez, E.; Connelly, N. G. *Organometallics* **2005**, *24*, 3624.
(13) (a) Hager, E.; Sivaramakrishna, A.; Clayton, H. S.; Mogorosi, M. M.; Moss, J. R. *Coord. Chem. Rev.* **2008**, *252*, 1668. (b) Fooladi, E.; Graham, T.; Turner, M. L.; Dalhus, B.; Maitlis, P. M.; Tilset, M. *J. Chem. Soc., Dalton Trans.* **2002**, 975. (c) Wik, B. J.; Tilset, M. *J. Organomet. Chem.* **2007**, *692*, 3223. (d) Tsou, T. T.; Kochi, J. K. *J. Am. Chem. Soc.* **1978**, *100*, 1634. (e) Lau, W.; Huffman, J. C.; Kochi, J. K. *Organometallics* **1982**, *1*, 155.
(14) Chen, J. Y.; Kochi, J. K. *J. Am. Chem. Soc.* **1977**, *99*, 1450.
(15) (a) Johansson, L.; Ryan, O. B.; Romming, C.; Tilset, M. *Organometallics* **1998**, *17*, 3957. (b) Moret, M.-E.; Chen, P. *J. Am. Chem. Soc.* **2009**, *131*, 5675. (c) In ref 15a, it is shown that net disproportionation of the Pt^{III} intermediate is unlikely to occur by direct reaction of two Pt^{III} species, given their low concentration (p 3963). It is proposed instead that there is transfer of a methyl ligand from L_2PtMe_2 to $L_2PtMe_2^{\bullet+}$. The same argument likely applies to the disproportionation in Scheme 2, mechanism **B**.
(16) Complex **2** could be formed by either (*i*) direct conproportionation of **4** with **1**$^+$ or (*ii*) rapid oxidation of **4** by Fc$^+$ and then conproportionation of the resulting bis-solvento complex with **1**.
(17) Tsou, T. T.; Kochi, J. K. *J. Am. Chem. Soc.* **1979**, *101*, 7547.
(18) This reaction was conducted in the dark because the methyl groups of **1** and **1-*d*$_6$** scramble in room light.
(19) Hawari, J. A.; Engel, P. S.; Griller, D. *Int. J. Chem. Kin.* **1985**, *17*, 1215.
(20) Peick, R.; Steacie, E. W. R. *Can. J. Chem.* **1955**, *33*, 1304.
(21) Fc$^+$ oxidizes I$^-$ significantly more slowly than it does **1** under these conditions.
(22) For related 2,2′-bipyridyl complexes, see: (a) Byers, P. K.; Canty, A. J.; Crespo, M.; Puddephatt, R. J.; Scott, J. D. *Organometallics* **1988**, *7*, 1363. (b) Aye, K.-T.; Canty, A. J.; Crespo, M.; Puddephatt, R. J.; Scott, J. D.; Watson, A. A. *Organometallics* **1989**, *8*, 1518. (c) Byers, P. K.; Canty, A. J.; Skelton, B. W.; Traill, P. R.; Watson, A. A.; White, A. H. *Organometallics* **1992**, *11*, 3085. (d) Canty, A. J. *Acc. Chem. Res.* **1992**, *25*, 83. (e) Dücker-Benfer, C.; van Eldik, R.; Canty, A. J. *Organometallics* **1994**, *13*, 2412.
(23) Two sets of resonances are observed for **3** at−80 °C (possibly due to solv = acetone vs H_2O), and the peaks coalesce at−40 °C. In addition, traces (<9%) of additional Pd−Me species were observed in the Fc$^+$ reaction at−80 °C. See Supporting Information for details.
(24) For a closely related dimeric Pt(III) complex, see: Canty, A. J.; Gardiner, M. G.; Jones, R. C.; Rodemann, T.; Sharma, M. *J. Am. Chem. Soc.* **2009**, *131*, 7236.
(25) For examples of dimeric Pd(III) species, see: (a) Cotton, F. A.; Koshevoy, I. O.; Lahuerta, P.; Murillo, C. A.; Sanau, M.; Ubeda, M. A.; Zhao, Q. *J. Am. Chem. Soc.* **2006**, *128*, 13674. (b) Deprez, N. R.; Sanford, M. S. *J. Am. Chem. Soc.* **2009**, *131*, 11234. (c) Powers, D. C.; Ritter, T. *Nat. Chem.* **2009**, *1*, 302.
(26) The data do not exclude mechanism **C** at > −30 °C where **3** is not observed; however there is no evidence for a change in mechanism with temperature.
(27) Arsenault, G. L.; Anderson, C. M.; Puddephatt, R. J. *Organometallics* **1988**, *7*, 2094.
(28) Skoog, D. A.; West, D. M.; Holler, F. J. *Fundamentals of Analytical Chemistry*, 7th ed.; Saunders: Philadelphia, 1996; p A14.
(29) At ≤ −30 °C, intermediate **5** is stable so it is not possible to directly observe **3** in this system.
(30) Milani, B.; Anzilutti, A.; Vicentini, L.; Santi, A. S.; Zangrando, E.; Geremia, S.; Mestroni, G. *Organometallics* **1997**, *16*, 5064.
(31) A small amount of hydroquinone (3.5 ± 1.7%) was also formed, presumably by protonation of **6** with trace acid. (Similar observations have been reported for the bpy analogue, ref 30.).
(32) Preliminary kinetic studies by ^{1}H NMR revealed an induction period, indicating a complex mechanistic pathway.

JA905816Q