

Hydrogen Tunneling in Protonolysis of Platinum(II) and Palladium(II) Methyl Complexes: Mechanistic Implications

John E. Bercaw,* George S. Chen, Jay A. Labinger,* and Bo-Lin Lin

Arnold and Mabel Beckman Laboratories of Chemical Synthesis, California Institute of Technology, Pasadena, California 91125

Received September 25, 2008; E-mail: bercaw@caltech.edu; jal@caltech.edu

The selective transformation of C–H bonds is an important area of current research; over the past several decades, numerous examples of C–H activation by transition metals have appeared in the literature.¹ Of particular significance is the development of a number of homogeneous catalytic systems based on late transition metals, especially platinum² and palladium.³ Several general mechanisms for C–H activation by transition metal complexes have been identified, including (1) electrophilic activation, (2) oxidative addition, (3) σ -bond metathesis, (4) 1,2-addition to metal–ligand multiple bonds, (5) H-atom abstraction by metal-oxo complexes, and (6) metalloradical activation.⁴ Kinetic hydrogen/deuterium isotope effects (KIEs) have been used extensively by many groups to probe the nature of these reactions and to gain key mechanistic insights.⁵

Abnormally large KIEs at room temperature or higher have been observed for C–H activations involving the latter four mechanisms.^{5,6} To the best of our knowledge, though, reactions involving electrophilic activation or oxidative addition as well as their corresponding microscopic reverse processes, protonolysis of a metal alkyl or reductive elimination, have been reported to exhibit only normal or inverse KIEs at similar temperatures.^{5,7} These are the two mechanisms generally proposed for C–H activation by Pd^{II} and Pt^{II}.^{2,3,8} Herein, we report experimental observations of abnormally large KIEs at room temperature and higher for the protonolysis of several dimethylpalladium(II) complexes as well as a dimethylplatinum(II) complex and offer evidence for the occurrence of proton tunneling in these reactions.

Deuterolysis of dimethylpalladium(II) complexes **1**⁹ with excess TFE-*d*₃ (TFE-*d*₃ = CF₃CD₂OD) at room temperature (Scheme 1) results in the liberation of methane and the corresponding (methyl)(trifluoroethoxy)Pd^{II} species **2**.¹⁰ A surprisingly large amount of CH₄ (~20%, determined by integration of the two methane isotopologue ¹H NMR signals) is generated along with the expected CH₃D, considering the isotopic purity of the TFE-*d*₃ (>99%, estimated by ¹H NMR); no significant deuterium incorporation is observed in either the Pd-methyl or ligand (¹H NMR) for **2**. Thus, the small amount of residual H⁺ in the solvent must be responsible for the CH₄ formed. If a 20:1 mixture of TFE-*d*₃/TFE-*d*₀ is used instead, the ratio of CH₄/CH₃D increases to ~1 for all cases, indicating abnormally large kinetic isotope effects ($k_H/k_D \sim 20$ at room temperature) are operating. For **1a–c**, a competing reaction involving reductive elimination of ethane complicates determination of precise KIE values. However, this side reaction is virtually absent (<1%, estimated by ¹H NMR) in the case of **1d**, for which k_H/k_D is found to be 21.4 ± 0.7 at 21 °C in dichloroethane-*d*₄.

Based on these observations, abnormally large KIEs at room temperature appear to be fairly general for the protonolysis of dimethylpalladium(II) complexes. In sharp contrast, inverse or normal KIEs have generally been observed for the corresponding platinum(II) analogues; but (COD)Pt^{II}(CH₃)₂ **3** (COD = 1,5-cyclooctadiene) is found to be an exception. A k_H/k_D of 17.5 ± 0.3

Scheme 1

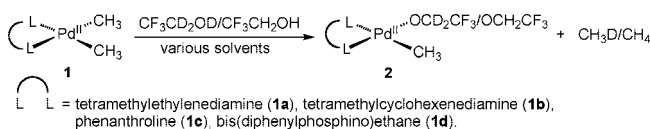
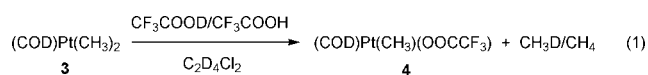


Table 1. KIEs^a for the Protonolysis/Deuterolysis of **1d** and **3** by TFE and TFA in DCE-*d*₄ at Various Temperatures

Complex 1d		Complex 3	
Temperature K	k_H/k_D	Temperature K	k_H/k_D
273	30.3 ± 1.0	273	25.9 ± 0.3
294	21.4 ± 0.7	294	17.5 ± 0.3
311	16.9 ± 0.4	313	12.1 ± 0.3
331	13.9 ± 0.1	333	9.2 ± 0.3
		353	6.9 ± 0.3
$A_H/A_D = 0.34 \pm 0.06$		$A_H/A_D = 0.075 \pm 0.007$	
$E_a^D - E_a^H = 2.4 \pm 0.1 \text{ kcal mol}^{-1}$		$E_a^D - E_a^H = 3.2 \pm 0.1 \text{ kcal mol}^{-1}$	

^a KIEs determined by average of 3 runs for each temperature.

at 21 °C was determined for the competitive protonolysis of **3** with trifluoroacetic acid (TFA-*d*₁ and TFA-*d*₀) in dichloroethane-*d*₄ (eq 1). No products of side reactions are detectable by NMR, nor is deuterium incorporation into **4** observed.



KIE values greater than 10 at room temperature are generally taken to indicate significant contribution of quantum mechanical tunneling in proton transfer reactions.¹¹ The presence or absence of tunneling can also be determined from the temperature dependence of the KIE.^{11,12} Values for the Arrhenius parameters outside the ranges $0.5 < A_H/A_D < 2^{1/2}$ (calculations on model systems suggest $0.7\text{--}1.2$ is a more realistic range¹³) and $(E_a^D - E_a^H) < 1.2$ kcal/mol are generally taken to demonstrate unambiguously the involvement of tunneling. The temperature dependences of k_H/k_D for the protonolysis of **1d** and **3** are shown in Table 1 and Figure 1; the values indicate a tunneling pathway for the protonolysis of the corresponding metal–carbon bonds.

Relatively few systematic studies of the temperature dependence of k_H/k_D for C–H activation or the microscopic reverse have been carried out, aside from enzymatic C–H activations.¹⁴ Temperature-dependent KIEs typical of tunneling have been found for the intramolecular aromatic C–H activation of Cp*₂ZrPh₂ via σ -bond metathesis¹⁵ as well as in a recent study on C–H activation by an oxoiron(IV) porphyrin radical cation.¹⁶ KIEs have been measured for methane C–H activation by Rh^{II} porphyrin via the metalloradical mechanism at two different temperatures,^{6c} and parameters calcu-

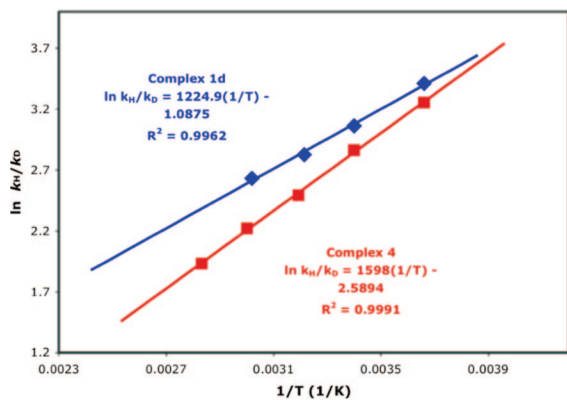
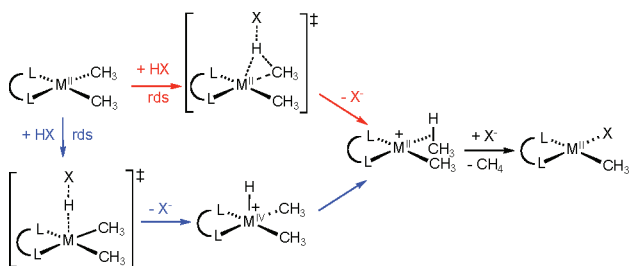


Figure 1. Plot of $\ln(k_{\text{H}}/k_{\text{D}})$ vs $1/T$

Scheme 2



lated from those data indicate tunneling ($k_{\text{H}}/k_{\text{D}} = 8.2$ at 296 K and 5.1 at 353 K, $A_{\text{H}}/A_{\text{D}} = 0.43$, $E_{\text{a}}^{\text{D}} - E_{\text{a}}^{\text{H}} = 1.7$ kcal mol⁻¹). It has been proposed, based on analysis of equilibrium isotope effects (EIEs), that factors such as partition quotients and zero-point energy differences can account for the large KIEs observed in the 1,2-addition of the C–H bond across Ti–N multiple bonds,^{6a} so that tunneling does not necessarily need to be invoked; a similar argument was offered for the above-cited metalloradical C–H activation.^{6c} In light of the temperature parameters, we would suggest that tunneling may be a more reasonable explanation for all of these large KIE values.

The abnormally large KIEs and proton tunneling in the protonolysis of (L–L)Pd^{II}(CH₃)₂ and (COD)Pt^{II}(CH₃)₂ suggest a unifying mechanism. Two alternate routes have been proposed for protonolysis of M–C bonds (and the corresponding microscopic reverse reaction, C–H activation): direct protonation of the M^{II}–C bond or protonation at M (oxidative addition) followed by reductive elimination (Scheme 2). Platinum(IV) hydride intermediates have been observed at low temperatures for the protonolysis of several diamine and diimine ligated platinum dimethyl systems, supporting the oxidative addition mechanism.^{7,8} In contrast, no [Pt^{IV}–H] is observed by ¹H NMR in the protonolysis of **3** at –80 °C in CD₂Cl₂; one might expect the electron-withdrawing COD ligand to disfavor the formation of a Pt(IV) intermediate. [Pd^{IV}–H] is also relatively unfavorable. It is also notable that no scrambling of H/D between methyl/methane positions is observed in the systems studied (unlike the diimine-Pt analogues¹⁷), further suggesting that [M^{IV}–H] intermediates are not involved.

While the possibility of the oxidative addition route cannot be firmly excluded for the cases studied here, we suggest that they proceed instead by direct protonation at the M–C bond and that there is a connection between that mechanism and the observed tunneling. We would also expect to see evidence for proton tunneling (high KIEs at room temperature or higher) in electrophilic C–H activation by Pd^{II} and Pt^{II} when the microscopic reverse of this process (direct proton loss from the sigma complex) is

operating.¹⁸ Given the importance of C–H activation in Pd^{II} and Pt^{II} systems, more studies (both experimental and theoretical) are underway to investigate the correlation between proton tunneling and the mechanisms involved.

Acknowledgment. This work was supported by BP through the MC² program. An NSF Graduate Research Fellowship to GSC is gratefully acknowledged. We thank Drs. Michael W. Day and Lawrence M. Henling for assistance with X-ray crystallography and Dr. Jonathan S. Owen for suggestions in the preparation of complex **1b**.

Supporting Information Available: Detailed experimental data. This material is available free of charge via the Internet at <http://pubs.acs.org>.

References

- (1) Dyker, G. Ed. *Handbook of C-H Transformations*; Wiley-VCH: Weinheim, Germany, 2005, and references therein.
- (2) Lersch, M.; Tilset, M. *Chem. Rev.* **2005**, *105*, 2471–2526, and references therein.
- (3) (a) Kao, L. C.; Hutson, A. C.; Sen, A. *J. Am. Chem. Soc.* **1991**, *113*, 700–701. (b) Lin, M. R.; Shen, C. Y.; Garcia-Zayas, E. A.; Sen, A. *J. Am. Chem. Soc.* **2001**, *123*, 1000–1001. (c) Periana, R. A.; Mironov, O.; Taube, D.; Bhalla, G.; Jones, C. J. *Science* **2003**, *301*, 814–818. (d) An, Z. J.; Pan, X. L.; Liu, X. M.; Han, X. W.; Bao, X. H. *J. Am. Chem. Soc.* **2006**, *128*, 16028–16029.
- (4) Labinger, J. A.; Bercaw, J. E. *Nature* **2002**, *417*, 507–514.
- (5) (a) Ryabov, A. D. *Chem. Rev.* **1990**, *90*, 403–424. (b) Jones, W. D. *Acc. Chem. Res.* **2003**, *36*, 140–146, and references therein.
- (6) (a) Slaughter, L. M.; Wolczanski, P. T.; Klinckman, T. R.; Cundari, T. R. *J. Am. Chem. Soc.* **2000**, *122*, 7953–7975. (b) Yoshizawa, K. *Coord. Chem. Rev.* **2002**, *226*, 251–259, and references therein. (c) Cui, W.; Wayland, B. B. *J. Am. Chem. Soc.* **2004**, *126*, 8266–8274.
- (7) (a) Stahl, S. S.; Labinger, J. A.; Bercaw, J. E. *J. Am. Chem. Soc.* **1996**, *118*, 5961–5976. (b) Romeo, R.; D'Amico, G. *Organometallics* **2006**, *25*, 3435–3446, and references therein. Large KIEs have been previously observed for other types of hydrogen transfer reactions involving inorganic or organometallic complexes; for examples, see: (c) Whitesides, T. H.; Neiland, J. P. *J. Am. Chem. Soc.* **1975**, *97*, 907–908. (d) Huynh, M. H. V.; Meyer, T. J. *Angew. Chem., Int. Ed.* **2002**, *21*, 1395–1398.
- (8) (a) Hill, G. S.; Rendina, L. M.; Puddephatt, R. J. *Organometallics* **1995**, *14*, 4966–4968. (b) Stahl, S. S.; Labinger, J. A.; Bercaw, J. E. *J. Am. Chem. Soc.* **1995**, *117*, 9371–9372. (c) Romeo, R.; Plutino, M. R.; Elding, L. I. *Inorg. Chem.* **1997**, *36*, 5909–5916. (d) Stahl, S. S.; Labinger, J. A.; Bercaw, J. E. *Angew. Chem., Int. Ed.* **1998**, *37*, 2180–2192. (e) Bartlett, K. L.; Goldberg, K. I.; Borden, W. T. *J. Am. Chem. Soc.* **2000**, *122*, 1456–1465. (f) Bartlett, K. L.; Goldberg, K. I.; Borden, W. T. *Organometallics* **2001**, *20*, 2669–2678. (g) Wik, B. J.; Lersch, M.; Tilset, M. *J. Am. Chem. Soc.* **2002**, *124*, 12116–12117.
- (9) Experimental details including syntheses and the X-ray crystal structure of **1b** (CCDC 263612) are provided in the Supporting Information.
- (10) Protonolysis of dimethylpalladium(II) complexes by various alcohols has been previously reported: (a) Kim, Y. J.; Osakada, K.; Sugita, K.; Yamamoto, T.; Yamamoto, A. *Organometallics* **1988**, *7*, 2182–2188. (b) Kim, Y. J.; Osakada, K.; Takenaka, A.; Yamamoto, A. *J. Am. Chem. Soc.* **1990**, *112*, 1096–1104. (c) Kapteijn, G. M.; Dervisi, A.; Grove, D. M.; Kooijman, H.; Lakin, M. T.; Spek, A. L.; van Koten, G. *J. Am. Chem. Soc.* **1995**, *117*, 10939–10949.
- (11) (a) Bell, R. P. *Chem. Soc. Rev.* **1974**, *4*, 513–544. (b) Bell, R. P. *The Proton in Chemistry*; Cornell University Press: Ithaca, NY, 1973. (c) Bell, R. P. *The Tunnel Effect in Chemistry*; Chapman and Hall: London, 1980.
- (12) (a) Caldin, E. F. *Chem. Rev.* **1969**, *69*, 135–156. (b) Kwart, H. *Acc. Chem. Res.* **1982**, *15*, 401–408. (c) Melander, L.; Saunders, W. H. *Reaction Rates of Isotopic Molecules*; Krieger: Malabar, FL, 1987. (d) Limbach, H.; Lopez, J. M.; Kohen, A. *Philos. Trans. R. Soc. London, Ser. B* **2006**, *361*, 1399–1415.
- (13) Schneider, M. E.; Stern, M. J. *J. Am. Chem. Soc.* **1972**, *95*, 1517–1522.
- (14) Kohen, A. In *Hydrogen-Transfer Reactions*; Hynes, J. T.; Klinman, J. P.; Limbach, H. H.; Schowen, R. L. Eds.; Wiley-VCH: Weinheim, Germany, 2007; Vol. 4, pp 1311–1340.
- (15) Schock, L. E.; Brock, C. P.; Marks, T. J. *Organometallics* **1987**, *6*, 232–241.
- (16) Pan, Z.; Horner, J. H.; Newcomb, M. *J. Am. Chem. Soc.* **2008**, *130*, 7776–7777.
- (17) Owen, J. S.; Labinger, J. A.; Bercaw, J. E. *J. Am. Chem. Soc.* **2006**, *128*, 2005.
- (18) Computational studies on oxidative addition of methane C–H bond to Pd⁰ and Pt⁰ and their microscopic reverse have suggested a significant contribution of proton tunneling only at low temperature: Datta, A.; Hrovat, D. A.; Borden, W. T. *J. Am. Chem. Soc.* **2008**, *130*, 2726–2727. Mamaev, V. M.; Glorizov, I. P.; Ishchenko, S. Y.; Simonyan, V. V.; Myshakin, E. M.; Prisyajnyuk, A. V.; Ustynyuk, Y. A. *J. Chem. Soc., Faraday Trans.* **1995**, *91*, 3779–3782.

JA807427D