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# The First Observation and Kinetic Evaluation of a Single Step Metal Insertion into a C−C Bond

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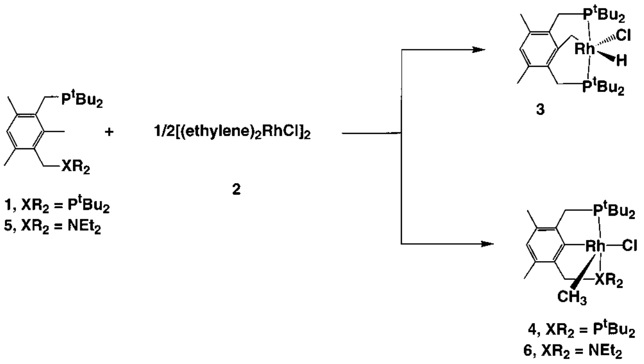
The activation of carbon−carbon and carbon−hydrogen bonds by soluble metal complexes in solution is of much current interest. While metal insertion into C−H bonds is well documented,[1] examples of C−C bond activation by transition metal complexes are by far less common.[2] Moreover, unlike C−H bond cleavage, mechanistic data regarding carbon−carbon bond activation is extremely scarce. In none of the reported examples of C−C bond cleavage by a metal complex has the actual *single insertion step* been studied. In most cases multistep processes were described, often under elevated temperatures.[2−7] Here we present *the first observation* of an apparent *single step* metal insertion into a carbon−carbon bond in solution and the *activation parameters* for this process. The carbon−carbon activation takes place at a temperature as low as −70 °C.

We have reported that the bischelated PCP-type ligand **1** reacts with the olefin Rh(I) complex $[(C_2H_4)_2RhCl]_2$ (**2**) to give the product of metal insertion into carbon−carbon bond **4** at room temperature.[8] Our studies on this ligand system have shown that the C−C activation process is accompanied by a parallel metal insertion into a C−H bond (Scheme 1), with the former being both thermodynamically and slightly kinetically more favorable than the latter. The rate-determining step of the overall process was shown to be the substitution of the olefin ligand at the metal center by the bulky bisphosphine ligand, preventing the direct study of the C−C activation process. Recently, we have reported that the mixed phosphino amine ligand **5** reacts with **2** to give exclusively the C−C insertion product **6**, which was crystallographically characterized.[9] As no parallel formation of the C−H activated product was observed, this system appeared to be ideal for studies of metal insertion into the carbon−carbon bond.

**Scheme 1**



When a solution of **5** in toluene-$d_8$ was mixed with an equivalent amount (per metal) of the rhodium(I) ethylene dimer **2** in $C_6D_5CD_3$ under an argon atmosphere at −80 °C, quantitative formation of the new complex **7** was detected by NMR spectroscopy after 45 min. While complex **7** was stable in solution at −80 °C, at higher temperatures smooth conversion to the C−C activated product **6** was observed. The process took place slowly even at −70 °C with no other products being formed. At −40 °C complete conversion took place within 50 min. The intermediate **7** was characterized by multinuclear NMR at −80 °C. The $^{31}P$ NMR spectrum of **7** exhibits a doublet at 70.5 ppm ($J_{RhP}$ = 183.2 Hz). Unfortunately, the $^1H$ NMR spectrum shows broad multiplet resonances in the aliphatic area, hindering the unambiguous assignment of all the signals. The single proton of the aromatic ring gives rise to a singlet at 6.72 ppm, compared to 6.81 and 6.54 ppm in the ligand **5** and complex **6**, respectively, indicating that the aromatic system is not perturbed.[10] This is supported also by the chemical shifts of the aromatic carbons in the $^{13}C$ NMR spectrum which are in the area expected for nonperturbated aromatics. The Ar−*C*H$_2$−N carbon gives rise to a multiplet due to coupling with phosphorus and rhodium, indicating that the amine group is coordinated to the metal center. This is confirmed by the observation of two sets of signals for the carbon atoms of the NEt$_2$ group, indicating that the ethyl groups are inequivalent. The $^1H-^{15}N$ 2D correlation also shows two sets of ethyl protons bound to the nitrogen atom, indicating the lack of a symmetry plane containing the aromatic ring. The nitrogen signal appears at 61 ppm, 11 ppm downfield from that observed for **5**, and it is broadened compared to the free ligand, probably due to the coupling to rhodium and phosphorus.

To further clarify the nature of the Me group, situated between the P and N "arms" in **7**, the selectively labeled ligand $C_6H(CH_3)_2(^{13}CH_3)CH_2P(t\text{-}Bu)_2CH_2N(Et)_2$ (**5***) was synthesized.[11] The $^{13}CH_3$ group in intermediate **7** gives rise to a singlet at 26 ppm in the $^{13}C$ NMR, which is very characteristic of an unactivated

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(1) For selected reviews see: (a) Shilov, A. E. In *The activation of saturated hydrocarbons by transition metal complexes*; Reidel: Dordrecht, The Netherlands, 1984. (b) Crabtree, R. H. *Chem. Rev.* **1985**, *85*, 245. (c) Ryabov, A. E. *Chem. Rev.* **1990**, *90*, 403. (d) Crabtree, R. H. In *The Chemistry of Alkanes and Cycloalkanes*; Patai, S., Rappoport, Z., Eds.; John Wiley & Sons: New York, 1992; p 653. (e) Arndtsen, B. A.; Bergman, R. G.; Mobley, T. A.; Peterson, T. H. *Acc. Chem. Res.* **1995**, *28*, 154. (f) Shilov, A. E.; Shul'pin, G. B. *Chem. Rev.* **1997**, 97, 2879.

(2) For recent reviews see: (a) Rybtchinski, B.; Milstein, D. *Angew. Chem., Int. Ed.* **1999**, *38*, 870. (b) Murakami, M.; Ito, Y. In *Topics in Organometallic Chemistry*; Murai, S., Ed.; Springer-Verlag: Berlin Heidelberg, 1999; Vol. 3, p 97.

(3) Lu, Z.; Jun, C.-H.; de Gala, S.; Sigalas, M.; Eisenstein, O.; Crabtree, R. *Organometallics* **1995**, *14*, 1168.

(4) (a) Perthuisot, C.; Jones, W. D. *J. Am. Chem. Soc.* **1994**, *116*, 3647. (b) Edelbach, B. L.; Lachicotte, R. J.; Jones, W. D. *J. Am. Chem. Soc.* **1998**, *120*, 2843. (c) Edelbach, B. L.; Vicic, D. A.; Lachicotte, R. J.; Jones, W. D. *Organometallics* **1998**, *17*, 4784.

(5) Yeh, W. Y.; Hsu, S. C. N.; Peng, S. M.; Lee, G. H. *Organometallics* **1998**, *17*, 2477.

(6) (a) Murakami, M.; Amii, H.; Ito, Y. *Nature* **1994**, *370*, 540. (b) Murakami, M.; Amii, H.; Shigeto, K.; Ito, Y. *J. Am. Chem. Soc.* **1996**, *118*, 8285. (c) Murakami, M.; Takahashi, K.; Amii, H.; Ito, Y. *J. Am. Chem. Soc.* **1997**, *119*, 9307.

(7) (a) Gozin, M.; Weisman, A.; Ben-David, Y.; Milstein, D. *Nature* **1993**, *364*, 699. (b) Gozin, M.; Aizenberg, M.; Liou, Sh.-Y.; Weisman, A.; Ben-David, Y.; Milstein, D. *Nature* **1994**, *370*, 42. (c) Liou, Sh.-Y.; Gozin, M.; Milstein, D. *J. Am. Chem. Soc.* **1995**, *117*, 9774. (d) van der Boom, M. E.; Kraatz, H.-B.; Ben-David, Y.; Milstein, D. *J. Chem. Soc., Chem. Commun.* **1996**, 2167. (e) van der Boom, M. E.; Liou, Sh.-Y.; Ben-David, Y.; Milstein, D. *J. Am. Chem. Soc.* **1998**, *120*, 13415. (f) Liou, Sh.-Y.; Gozin, M.; Milstein, D. *J. Chem. Soc., Chem. Commun.* **1995**, 1965. (g) van der Boom, M. E.; Ben-David, Y.; Milstein, D. *J. Chem. Soc., Chem. Commun.* **1998**, 917.

(8) Rybtchinski, B.; Vigalok, A.; Ben-David, Y.; Milstein, D. *J. Am. Chem. Soc.* **1996**, *118*, 12406.

(9) Gandelman, M.; Vigalok, A.; Shimon, L. J. W.; Milstein, D. *Organometallics* **1997**, *16*, 3981.

(10) For upfield-shifted NMR signals of aryl protons in coordinated aromatic systems, see: (a) Tagge, C. D.; Bergman, R. G. *J. Am. Chem. Soc.* **1996**, *118*, 6908. (b) Kolis, S. P.; Kopach, M. E.; Liu, R.; Harman, W. D. *J. Am. Chem. Soc.* **1998**, *120*, 6205. (c) Gunnoe, T. B.; Sabat, M.; Harman, W. D. *J. Am. Chem. Soc.* **1998**, *120*, 8747. (d) Chin, R. M.; Dong, L.; Duckett, S. B.; Jones, W. D. *Organometallics* **1992**, *11*, 871.

(11) The ligand $C_6H(CH_3)_2(^{13}CH_3)CH_2P(t\text{-}Bu)_2CH_2N(Et)_2$ was prepared by reaction of complex **6** with $NaB(C_2H_5)_3H$ to give the Rh(I) complex (PCN)Rh−N$_2$, followed by oxidative addition of $^{13}CH_3I$ to give (PCN)Rh($^{13}CH_3$)I. Treatment of this Rh(III) product with a large excess of trimethylphosphine results in metal displacement and formation, after workup, of the selectively $^{13}C$-labeled ligand **5***.

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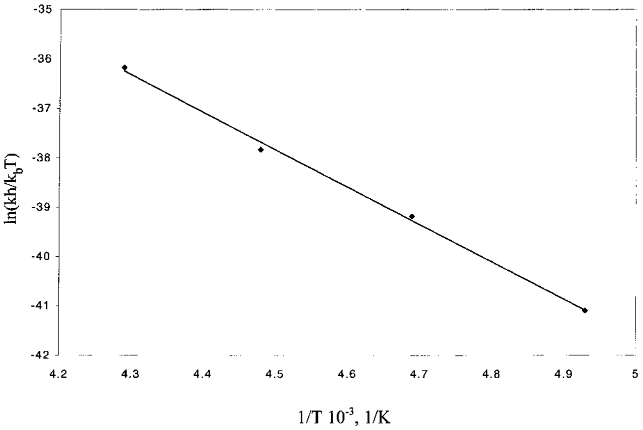
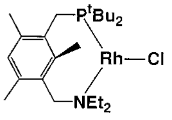


**Figure 1.** Eyring plot for the conversion of complex **7** to **6** in toluene. $\Delta H^{\ddagger} = 15.0(\pm0.4)$ kcal/mol, $\Delta S^{\ddagger} = -7.5(\pm2.0)$ eu, $\Delta G^{\ddagger}(298) = 17.2(\pm1.0)$ kcal/mol.

methyl group bound to an aromatic ring. No coupling to Rh and P was observed. This clearly rules out the possibility that the **7** is the C−H activation product. In addition, no high-field Rh−H signal is observed in $^1$H NMR.[12]

To address the question of solvent coordination, the reaction between ligand **5** and the Rh precursor **2** was carried out in 3-fluorotoluene (stronger binding of this solvent compared to toluene is expected due to a preference of the electron-rich metal center for electron-deficient arenes). The same intermediate **7** was observed at −80 °C by NMR spectroscopy. Moreover, the rate of conversion of **7** to complex **6** in 3-fluorotoluene and in toluene was essentially the same (vide infra). This indicates that, most likely, solvent is not coordinated to complex **7**.



**7**

We found no evidence for alkene coordination in **7**. When a solution of **7** was thoroughly degassed with pure argon at −80 °C and then warmed to −40 °C no appearance of free ethylene upon conversion of **7** into **6** was observed by $^1$H NMR spectroscopy. As there is no coordinated ethylene in **6**, the conversion of **7** into **6** should have resulted in liberation of free ethylene were the latter coordinated to rhodium in **7**. Therefore, based on the NMR data we assign to **7** the structure shown. The aromatic ring is probably rotated out of coplanarity with the P−Rh−N plane due to the steric effects, which can explain the lack of symmetry in **7**.

Complex **7** appears to be unique as it *allows direct investigation of a single-step C−C bond activation*. The conversion of **7** into **6** in toluene and in 3-fluorotoluene was monitored by $^{31}$P NMR spectroscopy, exhibiting first-order kinetics in both solvents. Notably, almost the same rate was observed for both solvents; at −50 °C $k(\text{toluene}) = 2.00 \times 10^{-4}\ \text{s}^{-1}$, $k(\text{3-fluorotoluene}) = 2.14 \times 10^{-4}\ \text{s}^{-1}$. This indicates that the solvent does not have a significant affect on the transition state of the reaction. Measurements at four different temperatures in toluene led to the Eyring plot presented in Figure 1. The derived activation parameters are the following: $\Delta H^{\ddagger} = 15.0(\pm0.4)$ kcal/mol, $\Delta S^{\ddagger} = -7.5(\pm2.0)$ eu., and $\Delta G^{\ddagger}(298) = 17.2(\pm1.0)$ kcal/mol. As expected for a concerted oxidative addition process, the activation entropy is negative. The fact that it is not more negative indicates that the intermediate is already significantly ordered toward the insertion step, although some additional motional restriction is required in the transition state. Our observation support a 3-center nonpolar transition state for Ar−C oxidative addition to Rh(I), in accord with our previous postulate.[8] The obtained activation parameters are *the first data* for an apparent[13] single-step carbon−carbon bond activation by a transition metal complex.[14]

The kinetic data support our hypothesis about a low activation barrier for metal insertion into a strong C−C bond in preoriented systems. However, despite the fact that normally BDEs of C−H bonds are higher than those of C−C bonds (compare $C_6H_5-CH_3$, 100 kcal/mol, $C_6H_5-H$, 110 kcal/mol; $CH_3-CH_3$, 83 kcal/mol, $CH_3CH_2-H$, 99 kcal/mol),[15] examples of metal insertion into carbon−carbon bonds are far less common compared to examples of C−H bond activation. The reason for this fact is mainly kinetic in nature, resulting from steric factors affecting the metal approach to the deep-seated C−C bonds and the statistical preference of the normally more abundant C−H bonds. While orbital directionality also hinders the C−C bond activation compared to the less directed C−H bonds,[16] we see that once the metal center is brought into the proximity of the C−C bond, the actual activation barrier is not high, the reaction taking place even at −70 °C. In our bischelated PCN ligand system the rhodium center is favorably directed toward the $Ar-CH_3$ bond. C−H bond activation concurrent with C−C activation was not observed under our conditions. However, even if this side reaction is fast in the NMR time scale at −70 °C and is not observable, it must be highly reversible and should not significantly affect the C−C bond activation parameters. A possible reason for such fast C−H reductive elimination in an unobserved C−H activated complex may be a rapid, reversible on/off dissociation of the amine "arm". Acceleration of C−H reductive elimination from Rh(III) by ligand dissociation is known.[17] Opening of the amine "arm" in NCN rhodium complexes was reported.[18]

In summary, we have characterized a frozen intermediate in a single-step C−C bond activation by a soluble metal complex and have for the first time obtained the activation parameters for this insertion process. The observed data are compatible with a concerted oxidative addition mechanism of the carbon−carbon bond cleavage by the metal and establish that the activation barrier for this single-step process in a preorganized system is quite low and enthalpy controlled.

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(12) The methylene bound to Rh in the PCP(isopropyl) C−H activation product appears in $^{13}$C NMR as a doublet of triplets ($J_{RhC} = 17.7$ Hz, $J_{PC} = 4.7$ Hz) at 12.0 ppm and the Rh−**H** signal is observed as a multiplet at −18.9 ppm in $^1$H NMR. S.-Y. Liou, Ph.D. Thesis, Weizmann Institute of Science, 1996, p 229.

(13) While the only observed step is the insertion of Rh into the C−C bond in **7**, the unlikely participation of some other unobserved (rapid) processes cannot be totally excluded.

(14) The activation barrier for an overall process involving gas-phase $Fe^+$ insertion into the C−C bond of propane followed by methane elimination was found to be approximately 20 kcal/mol: Schultz, R. H.; Armentrout, P. B. *J. Am. Chem. Soc.* **1991**, *113*, 729.

(15) *CRC Handbook of chemistry and Physics*, 57th ed.; CRC Press: Cleveland, OH, 1976−77.

(16) (a) Siegbahn, P. E. M.; Blomberg, M. A. R. *J. Am. Chem. Soc.* **1992**, *114*, 10548. (b) Low, J. J.; Goddard, W. A., III *J. Am. Chem. Soc.* **1984**, *106*, 8371.

(17) (a) Milstein, D. *J. Am. Chem. Soc.* **1982**, *104*, 5227. (b) Milstein, D. *Acc. Chem. Res.* **1984**, *17*, 221.

(18) van der Zeijden, A. A. H.; van Koten, G.; Nordemann, R. A. *Organometallics* **1988**, *7*, 1957.