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C–H Bond Activation

The Unexpected Role of CO in C–H Oxidative Addition by a Cationic Rhodium(I) Complex**

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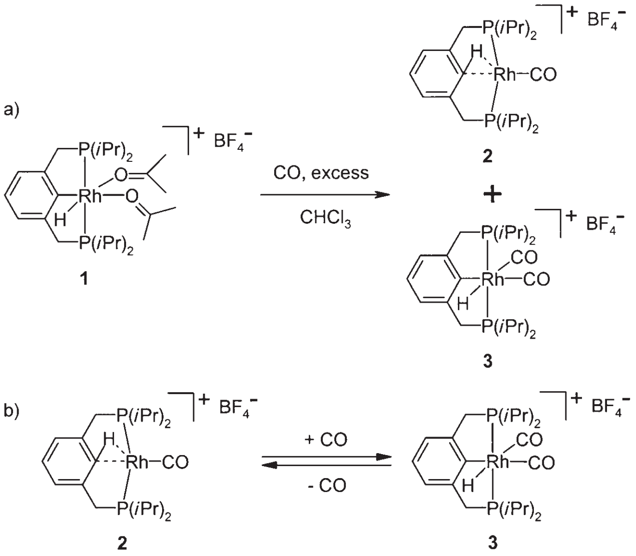
The activation of strong carbon–hydrogen bonds by transition metals is one of the fundamental fields of current organometallic chemistry. This process occurs by one of several possible pathways that are generally dependant on the electron density at the metal center.[1] For electron-rich, low-valent transition metals the typical pathway for C–H cleavage is oxidative addition, which leads to the corresponding alkyl or aryl hydride complexes and is accompanied by a formal two-electron oxidation of the metal. Transition metals that lack the electron density necessary for oxidative addition, such as early transition metals or high-valent late transition metals, can activate C–H bonds by alternative routes, namely σ-bond metathesis, radical activation, 1,2-addition, and electrophilic substitution.[1] It is widely accepted that both σ-bond metathesis and oxidative addition processes take place via σ-complexes or agostic intermediates.[2]

As far as the oxidative addition of C–H bonds is concerned, the requirement for high electron density means that strong π-acceptor ligands, such as carbon monoxide, are normally expected to inhibit oxidative addition processes by drawing electron density away from the metal center. Herein, however, we describe an electron-poor cationic Rh^I system in which addition of a CO ligand can actually promote oxidative addition of a strong C–H bond. This unique reaction pathway is supported by both experimental and theoretical evidence.

The new system was discovered during an attempt to convert the Rh^{III} complex **1**[3] into the C–H agostic Rh^I complex **2**[4] by bubbling excess CO through a chloroform solution of **1** (see Scheme 1 a; crystal structures are shown in Figure 1). After drying the resulting solution and re-dissolving the product in $CDCl_3$ we found that instead of obtaining **2** as the sole product,[5] a mixture of products was obtained which gave extremely broad ^1H and ^{31}P NMR signals at room temperature. Cooling the solution to −55 °C provided well-resolved signals and revealed the existence of only two products: complex **2** and the new aryl hydride dicarbonyl Rh^{III} complex **3**. Complex **3** can also be obtained directly from pure **2** (rather than **1**) simply by treating it with CO.[6] Both complexes **2** and **3** have been fully characterized by solution NMR techniques, which included the use of ^{13}C-labeled CO.[7]



Scheme 1. a) Synthesis of complexes **2** and **3**; b) the equilibrium between **2** and **3** under CO.

A $CDCl_3$ solution of complex **2** at −55 °C exhibits a doublet in the $^{31}P\{^1H\}$ NMR spectrum at $\delta = 18.95$ ppm ($^1J_{Rh,P} = 99.3$ Hz), whereas complex **3** gives rise to a doublet at $\delta = 83.10$ ppm ($^1J_{Rh,P} = 88.7$ Hz). The difference in both the chemical shift and Rh,P coupling constant is indicative of a decrease in electron density at the metal center on going from **2** to **3**. The difference in the ^1H NMR spectra is also pronounced, with the agostic proton of **2** giving rise to a doublet at $\delta = 4.07$ ppm ($^1J_{Rh,H} = 17.3$ Hz), while complex **3** exhibits a hydride signal at $\delta = -8.97$ ppm (m, $^1J_{Rh,H} = 14.5$ Hz), consistent with a hydride *trans* to a carbonyl ligand. The $^{13}C\{^1H\}$ NMR spectrum of **2** exhibits a carbonyl signal at $\delta = 186.54$ ppm (dt, $^1J_{Rh,C} = 89.6$, $^2J_{P,C} = 12.5$ Hz), whereas **3** features two carbonyl signals at $\delta = 184.54$ (dt, $^1J_{Rh,C} = 41.3$, $^2J_{P,C} = 6.3$ Hz; CO *trans* to hydride) and 183.53 ppm (dt, $^1J_{Rh,C} = 42.5$, $^2J_{P,C} = 7.6$ Hz; CO *trans* to aryl). The precise configuration of the carbonyl groups in **3** was verified by using ^{13}C-labeled CO and noting the large C,H coupling constant (58.8 Hz) between the hydride ligand and the CO carbon at $\delta = 184.54$ ppm, consistent with a *trans*

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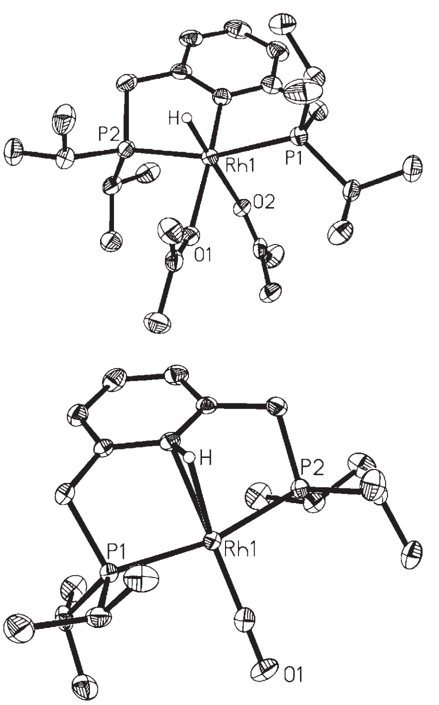


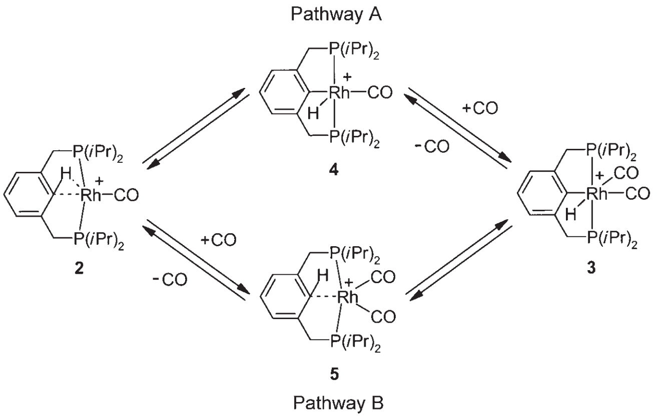
Figure 1. Crystal structures of complexes **1** (top) and **2** (below). Hydrogen atoms (except hydride) and BF_4 have been omitted for clarity. Selected bond lengths [Å] and angles [°] for complex **1**: Rh1–C_{ipso} 2.011(3), Rh1–H 1.51(3), Rh1–P1 2.3181(12), Rh1–P2 2.2997(12), Rh1–O1 2.195(2), Rh1–O2 2.276(2), C_{ipso}–Rh1–P1 81.70(9), C_{ipso}–Rh1–P2 82.41(9), C_{ipso}–Rh1–H 88.7(10), C_{ipso}–Rh1–O1 168.62(10), C_{ipso}–Rh1–O2 88.26(10); complex **2**: Rh1–C_{ipso} 2.267(3), Rh1–H 1.97(3), Rh1–P1 2.3207(10), Rh1–P2 2.3271(10), Rh1–CO 1.816(4), C–O 1.153(4), C_{ipso}–Rh1–P1 83.49(10), C_{ipso}–Rh1–P2 83.78(10), C_{ipso}–Rh1–H 23.90(11), C_{CO}–Rh1–P1 96.09(14), C_{CO}–Rh1–P2 96.61(14).

configuration.[8] $^{13}C,^{13}C$ coupling between the two CO ligands was not observed, but this is probably due to the very small $^2J_{C,C}$ value expected for the *cis* configuration.[9] The use of ^{13}CO also gave rise to a triplet splitting in the $^{31}P\{^1H\}$ signals of **3** ($^2J_{P,C} = 7.6$ Hz), consistent with the presence of two carbonyl ligands at the metal center.

The isolation of complex **3**, let alone the fact that it can be obtained directly from complex **2** upon treatment with CO, was an unexpected observation. Agostic complex **2** is itself an electron-poor system, as judged by the low Rh,P coupling constant (99.3 Hz),[10] and its very structure highlights the role of CO as a strong π-acceptor that inhibits oxidative addition of the arene C–H bond. It is therefore quite surprising that the addition of a second equivalent of CO to **2** actually results in the oxidative addition of the same C–H bond. Nevertheless, this reaction was found to be highly reversible and CO-dependent (Scheme 1b).

The reversibility of the reaction of **2** with CO to yield **3** was clearly evident. Firstly, the very observation that a mixture of **2** and **3** exhibits extremely broad NMR signals at room temperature, and that these signals become resolved upon cooling, indicates a fluxional process involving both complexes. This situation is supported by the fact that pure complex **2** shows no fluxionality whatsoever. Secondly, when a solution of **2** is treated with excess CO and then kept under a CO atmosphere, only complex **3** is observed (also giving very broad NMR signals at room temperature that become resolved upon cooling), but once excess CO is removed, either under vacuum or by bubbling with argon, complex **2** is regenerated.[11] In fact, the instability of **3** under vacuum prevented its isolation in pure solid form. Thirdly, when unlabeled complex **2** is exposed to excess ^{13}CO,[12] complex **3** is obtained with both its carbonyl ligands labeled with^{13}C, thereby implying CO scrambling. Finally, employing the spin saturation transfer (SST) technique, with specific irradiation of the hydride ligand of **3** while monitoring the change in intensity of the agostic proton of **2** (or vice versa),[13] unequivocally shows that complexes **2** and **3** are in dynamic equilibrium and that this equilibrium takes place at temperatures as low as −50 °C.

In light of the above observations it is reasonable to assume that the reaction leading from **2** to **3** involves two elementary steps, namely C–H cleavage and CO coordination. Consequently, two alternative mechanistic pathways can be proposed, as shown in Scheme 2.[14] Pathway A involves direct oxidative addition of the agostic C–H bond to yield square-pyramidal intermediate **4**, which then undergoes trapping by CO to afford complex **3**. Pathway B initially involves coordination of a CO ligand to complex **2** to yield trigonal-bipyramidal (TBP) intermediate **5**,[15] followed by cleavage of the arene C–H bond. No significant coordination of either solvent or counterion was detected by variable-temperature ^1H and ^{19}F NMR experiments, thus implying that their involvement in either of the reaction pathways is unlikely.



Scheme 2. Proposed reaction pathways for the agostic/aryl hydride equilibrium. The BF_4 counterion has been omitted for clarity.

The unknown complexes **4** and **5** could not be detected,[16] therefore density functional theory (DFT) calculations were employed, at the PBE0/SDB-cc-pVDZ//PBE0/SDD level of theory as the primary platform,[17] to investigate the cationic model systems shown in Scheme 2 (excluding the BF_4^- ion for simplicity). Bulk solvent effects were approximated by using a conductor-like screening model (COSMO) with chloroform as the solvent. Basis set superposition errors (BSSE) were corrected for complexes **3** and **5** and their respective transition state (**TS[3-5]**) by means of the Counterpoise method at the PBE0/SDB-cc-pVDZ level of theory.[18] The optimized geometries (including *xyz* coordinates) of the complexes and transition states are given in the Supporting Information.

Pathway A was initially assumed to be more probable than B since monocarbonyl complex **2** is expected to be more electron-rich than dicarbonyl intermediate **5** and hence appears more likely to undergo oxidative addition of the C–H bond (**2**→**4**). Moreover, the fact that **2** is an agostic complex made it a very reasonable candidate for C–H bond cleavage, since such complexes are widely accepted as precursors of C–H activation.[19] Therefore, it was rather surprising to learn that the DFT calculations yielded very different results. Thus, not only did they suggest that both pathways are possible, but the CO-promoted oxidative addition (pathway B) was found to be more favorable.

The calculations found dicarbonyl complex **3** to be more stable than agostic complex **2** by 1.6 kcal mol^{-1},[20] which is compatible with the experimental results (complex **3** is the only observed species under CO atmosphere).[21] However, contrary to our expectations, intermediate **5** was found to be 9.0 kcal mol^{-1} more stable than **4**, and even more stable than **2** by 1.2 kcal mol^{-1}.[22] In addition, two transition states were located along the reaction pathways, namely **TS[2-4]** (11.1 kcal mol^{-1} vs. complex **2**) for the C–H activation in complex **2** to yield **4** (pathway A), and **TS[5-3]** (7.8 kcal mol^{-1} vs. complex **2**) for the C–H activation in intermediate **5** to yield **3** (pathway B). We could not locate the transition states for CO coordination to the rhodium centers of **2** and **4**, but this type of reaction is usually regarded as being barrierless.[23] The overall energy profiles are shown in Figure 2 (see Supporting Information for optimized geometries). It can be seen that the overall free-energy barrier for pathway B (9.0 kcal mol^{-1} vs. complex **5**) is slightly lower than for pathway A (11.1 kcal mol^{-1} vs. complex **2**), hence C–H activation in the model system is more likely to take place by pathway B than pathway A.

The computed structure of **5** exhibits intriguing structural characteristics (see Supporting Information). Firstly, it is stabilized by weak η^1-C coordination between the metal center and the aromatic ring, an interaction which appears redundant for a 16-electron Rh^{I} system. Secondly, intermediate **5** features CO ligands that are slightly bent ($\sphericalangle$ Rh–C–O = 166–168°), thereby suggesting that these ligands exhibit a stronger π-acceptor character than those of complex **3** ($\sphericalangle$ Rh–C–O = 175–179°). Furthermore, complex **5** features a C–O bond length of about 1.18 Å (compared with 1.16 Å in **3**) and a C–O natural bond order (NBO) of 2.07–2.09 (2.17–2.20 for **3**),[24] which suggests that the CO ligands of **5** have more double-bond character than those of **3**.[25]

Strong experimental support for the involvement of intermediate **5** in the formation of complex **3** came from observing the reaction between the cationic Rh^{I} precursor [Rh(CO)$_2$(acetone)$_2$]BF$_4$[26] and the PCP ligand 1,3-bis((diisopropylphosphino)methyl)benzene. When these two reactants were mixed in a 1:1 ratio in acetone,[27] complex **3** was obtained (as determined by NMR spectroscopy at −55 °C), with no significant amounts of complex **2** being observed.[28] The eventual outcome was identical irrespective of whether the reactants were mixed at room temperature or at −70 °C. These results show that complex **3** can be produced by a direct reaction between the PCP ligand and a cationic Rh^{I}-dicarbonyl fragment and lend strong support to the role of intermediate **5**.

In conclusion, we have shown both experimentally and theoretically that CO can promote oxidative addition of a C–H bond in a cationic Rh^{I} system, in addition to its ability to function as a trapping agent. In fact, we have shown that while the first CO ligand inhibits C–H activation by locking the system in an agostic interaction, the second CO ligand facilitates this activation. DFT calculations support the involvement of a trigonal-bipyramidal, Rh^{I}-dicarbonyl intermediate in the C–H activation step. Further work is currently under way to assess the potential of this mechanistic insight regarding C–H oxidative addition processes.

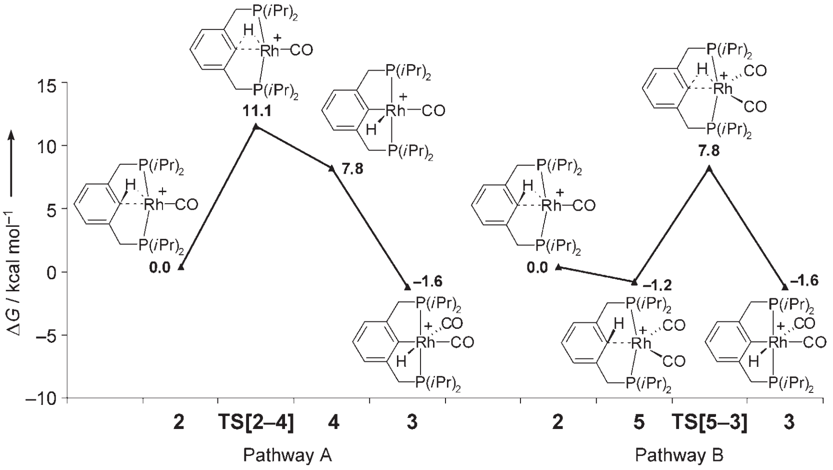


Figure 2. Energy profiles for the proposed reaction pathways (complex **2** is taken as the reference energy point with $\Delta G = 0.0$ kcal mol^{-1}; energy values for monocarbonyl complexes also include one molecule of free CO). See Supporting Information for the optimized complex geometries.

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[3] Obtained by reaction of the PCP ligand 1,3-bis((diisopropylphosphino)methyl)benzene with one equivalent of the cationic Rh^{I} precursor [Rh(coe)$_2$(acetone)$_2$]BF$_4$ (coe = cyclooctene). See Supporting Information for synthesis and characterization.

[4] Complex **2** is a close analogue of an agostic complex previously reported by our group that has *tert*-butyl instead of isopropyl substituents at the phosphine donor groups. For further details, see: A. Vigalok, O. Uzan, L. J. W. Shimon, Y. Ben-David, J. M. L. Martin, D. Milstein, *J. Am. Chem. Soc.* **1998**, *120*, 12539–12544.

[5] The reaction of excess CO with an analogue of complex **1** that has *tert*-butyl instead of isopropyl substituents leads to only one product, namely the agostic complex discussed in ref. [4]. The nature of this apparent steric effect is unclear, but will be investigated as a continuation of this work.

[6] Pure complex **2** was synthesized by treating the neutral complex [{1,3-bis((diisopropylphosphino)methyl)benzene-κ^3-P,C_{ipso},P}$Rh^{I}CO$] with one equivalent of HBF_4. See Supporting Information for further details.

[7] See Supporting Information for the full synthetic procedures and characterization.

[8] A value for the $^{2}J_{C,H}$ coupling constant of 58.8 Hz is consistent with a *trans* configuration, as reported for octahedral Rh^{III} hydrido-carbonyl complexes similar to complex **3**. For further details, see: M. G. Partridge, B. A. Messerle, L. D. Field, *Organometallics* **1995**, *14*, 3527–3530.

[9] A. Silvio, O. Domenico, *J. Chem. Soc. Chem. Commun.* **1981**, 300–302.

[10] For comparison, the neutral complex [{1,3-bis((diisopropylphosphino)methyl)benzene-κ^3-P,C_{ipso},P}$Rh^{I}CO$] features a much larger Rh,P coupling constant of 143.9 Hz (C_6D_6).

[11] The regeneration of **2** is relatively slow. Even after argon bubbling (for about 5 min) or drying under vacuum (several hours) the conversion of **3** into **2** was only partial.

[12] ^{13}CO gas was bubbled through a $CDCl_3$ solution of complex **2** for 1 min. Complete labeling was confirmed by both the ^{1}H and ^{31}P NMR spectra, which show the expected $^{1}H,^{13}C$ and $^{31}P,^{13}C$ coupling.

[13] See Supporting Information for further details, including a typical SST difference spectrum.

[14] A third reaction pathway, involving dissociation of one “arm” of the pincer ligand, was investigated computationally and found to be much higher in energy (more than 16 $kcal\,mol^{-1}$) than pathways A and B and was therefore disregarded.

[15] Pentacoordinate dicarbonyl complexes of rhodium(I) have been reported. See: a) T. E. Nappier, D. W. Meek, *J. Am. Chem. Soc.* **1972**, *94*, 306–307; b) C. M. Beck, S. E. Rathmill, Y. J. Park, J. Chen, R. H. Crabtree, L. M. Liable-Sands, A. L. Rheingold, *Organometallics* **1999**, *18*, 5311–5317; c) I. O. Koshevoy, O. V. Sizova, S. P. Tunik, A. Lough, A. J. Poë, *Eur. J. Inorg. Chem.* **2005**, *22*, 4516–4520.

[16] The room-temperature NMR spectra were too broad to allow any identification, whereas the low-temperature spectra showed signals associated only with **2**, **3**, and unrelated impurities.

[17] The PBE0 functional has been shown to yield more reliable reaction barrier heights than B3LYP or other exchange-correlation functionals without sacrificing performance in other aspects. To validate the general computational method used we carried out comparative calculations using two additional density functionals, namely B3LYP and mPW1k. We found that the PBE0 and mPW1k calculations are qualitatively consistent while B3LYP fails to describe the system correctly. See Supporting Information for further details.

[18] a) S. Simon, M. Duran, J. J. Dannenberg, *J. Chem. Phys.* **1996**, *105*, 11024–11031; b) S. F. Boys, F. Bernardi, *Mol. Phys.* **1970**, *19*, 553–566.

[19] The central role of agostic interactions in C–H activation has been strongly emphasized. See, for example, ref. [2b] and a) M. Brookhart, M. L. H. Green, *J. Organomet. Chem.* **1983**, *250*, 395–408; b) M. Brookhart, M. L. H. Green, L. L. Wong, *Prog. Inorg. Chem.* **1988**, *36*, 1–124; c) B. Rybtchinski, R. Cohen, Y. Ben-David, J. M. L. Martin, D. Milstein, *J. Am. Chem. Soc.* **2003**, *125*, 11041–11050; d) W. D. Jones, *Inorg. Chem.* **2005**, *44*, 4475–4484.

[20] All free-energy values calculated for the monocarbonyl complexes also include a free CO molecule.

[21] The experimental result is unequivocal at −55 °C. At room temperature, however, one of the reaction intermediates may also be present (see below), although this is inconclusive due to the extremely broad NMR signals.

[22] The fact that **5** was not observed experimentally may indicate that it is actually less stable than **2**. However, such a small energy difference may be within the error of the DFT method and hence cannot be resolved.

[23] Free-energy curves for CO dissociation were calculated for **3H** and **5H**, which are simplified models of **3** and **5** that have hydrogen atoms instead of isopropyl groups on the phosphine centers. These curves allowed us to estimate the barriers for CO coordination to **4H** and **2H** and the results suggest that the reaction **4H**→**3H** has no significant barrier, while **2H**→**5H** has only a small barrier (3–7 $kcal\,mol^{-1}$) that does not change the overall energy balance. See Supporting Information for further details.

[24] It is important to stress that calculated NBO values should not be considered quantitatively but rather as qualitative tools for comparison.

[25] Experimental infrared measurements at room temperature yielded several CO absorption peaks (2087, 2104, 2126, and 2134 cm^{-1}). However, these peaks could not be specifically assigned to either **3** or **5** since they could not be fully characterized at room temperature (see above). This situation impeded experimental comparison of the CO bond orders. Nonetheless, it is evident that these complexes have a higher CO bond order than **2** as the latter has a significantly lower CO stretching frequency (1995 cm^{-1}).

[26] Prepared by treating the dimeric complex [{$Rh(CO)_2Cl$}$_2$] with two equivalents of $AgBF_4$ in acetone.[4] See Supporting Information for further details.

[27] The precursor $[Rh(CO)_2(acetone)_2]BF_4$ is unstable in noncoordinating solvents and therefore acetone was used.

[28] Unidentified minor products were also observed.