

Synthesis and C–H Activation Reactions of Cyclometalated Complexes of Ir(III): Cp*(PMe₃)Ir(CH₃)⁺ Does Not Undergo Intermolecular C–H Activation in Solution via a Cyclometalated Intermediate

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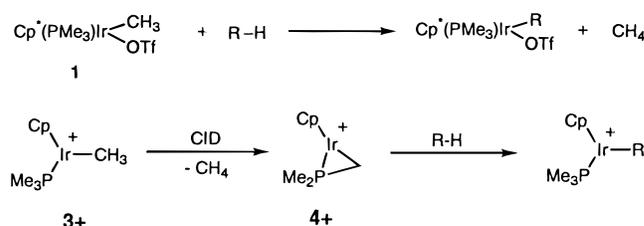
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We recently discovered that the cationic Ir(III) complexes Cp*(L)Ir(CH₃)⁺X⁻ (L = PMe₃, X = OTf (**1**); L = PMe₃, X = BArF₄⁻ (**2**)) and related systems undergo intermolecular C–H bond activation reactions with a wide range of organic molecules, including alkanes, that result in the metathesis of the Ir-bound methyl group with other organic ligands (Scheme 1).^{1–3} While this reaction represents a formal σ -bond metathesis, we have been interested in determining whether the transformation occurs through a four-centered transition state or via a reaction sequence involving oxidative addition and reductive elimination through an Ir(V) intermediate. This issue has been the focus of two recent theoretical studies.^{4,5}

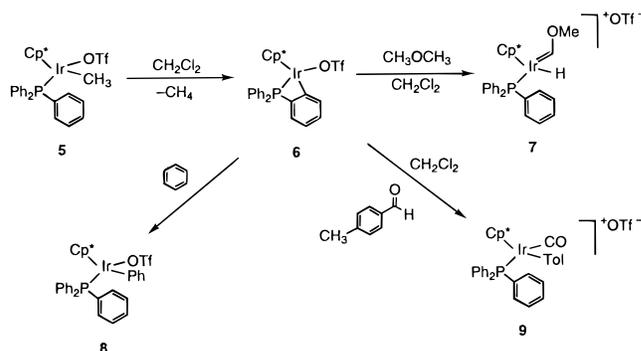
Recently, Chen and co-workers reported the generation of the Cp analog **3+** in the gas phase at very low pressure.⁶ They observed that when subjected to collision-induced dissociation (CID) **3+** undergoes elimination of methane, and they present evidence that the ion formed in this reaction is the cyclometalated species **4+** (Scheme 1). On the basis of this observation they suggest that intermolecular C–H activation reactions under both gas-phase and higher-concentration solution conditions may proceed via a cyclometalated species. They refer to this as a “dissociative” process and suggest that it is a “new mechanism” for the observed C–H activation reaction.⁶

We wish to report ongoing synthetic and mechanistic results that are directly related to this issue. As part of this work we have been able to prepare Cp*-substituted iridium complexes with cyclometalated triphenyl- and trimethylphosphine ligands (the latter had eluded us for some time; cyclometalated PMe₃ complexes are quite rare in the Cp*Ir series), and this has allowed us to generate an intermediate that we believe is the solution analogue of Chen's gas-phase intermediate **4+**. We have found that cyclometalation can take place with iridium(III) complexes in solution, but this depends critically on the phosphine substituents. The cyclometalated complexes undergo intermolecular C–H activation, completing a reaction sequence analogous to the one that Chen observes in the gas phase.^{7–9} Significantly, however, mechanistic studies on the trimethylphosphine-substituted system *conclusively rule out a cyclo-*

Scheme 1



Scheme 2



metalated intermediate in the intermolecular C–H activation process observed with the PMe₃-substituted Ir complexes 1 or 2 in solution.

Complexes **1** and **2** undergo either intermolecular C–H activation or slow decomposition in solution; no cyclometalated product is observed from either complex. The PPh₃ analog **5** does in fact undergo cyclometalation with the release of CH₄ to form **6** (Scheme 2). The extremely high field ³¹P NMR resonance at –51.1 ppm for **6** is especially characteristic of an ortho-metalated PPh₃ complex. Once formed, the cyclometalated complex **6** undergoes reaction with external C–H bonds to give intermolecular C–H activation products. For example, reaction of **6** with dimethyl ether, benzene, and *p*-tolualdehyde proceeds as shown in Scheme 2 to give cationic carbene complex **7** (94%), phenyl triflate **8** (82%) and cationic *p*-tolyl carbonyl complex **9** (89%), respectively. The products of these reactions are directly analogous to those observed in the reactions of these substrates with **1**, and the C–H activation reactivity of **6** is analogous to that seen by Chen in the gas-phase reactions of **4+**.¹⁰ This observation is of particular interest because the cyclometalated complex reacts *faster* with C–H bonds than the noncyclometalated analog Cp*(PPh₃)Ir(Ph)(OTf).^{11,12} For example, **6** reacts with *p*-tolualdehyde at 0 °C instantaneously to form **9**, whereas the reaction between **8** and *p*-tolualdehyde also produces **9**, but the half-life for this reaction is approximately 35 min at 25 °C.

To test the generality of this phenomenon, we were interested in generating complexes containing η^2 -Me₂PCH₂ ligands, based on the prediction that these complexes would display even greater reactivity with external C–H bonds. A successful approach to these materials has now been developed. The

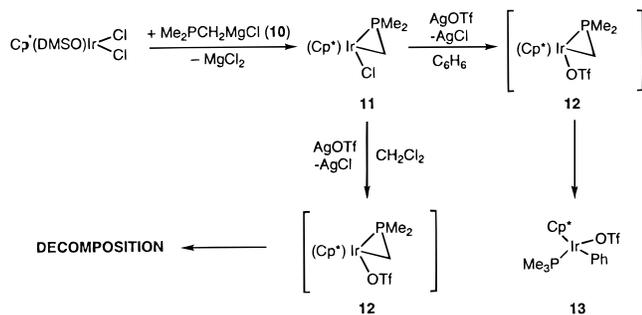
- Arndtsen, B. A.; Bergman, R. G. *Science* **1995**, *115*, 1970.
- Burger, P.; Bergman, R. G. *J. Am. Chem. Soc.* **1993**, *115*, 10462.
- Luecke, H. F.; Arndtsen, B. A.; Burger, P.; Bergman, R. G. *J. Am. Chem. Soc.* **1996**, *118*, 2517.
- Strout, D. L.; Zanic, S.; Niu, S.; Hall, M. B. *J. Am. Chem. Soc.* **1996**, *118*, 6068.
- Su, M.-D.; Chu, S.-Y. *J. Am. Chem. Soc.* **1997**, *119*, 5373.
- (a) Hinderling, C.; Plattner, D. A.; Chen, P. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 243. Similar results have recently been obtained for the Cp* complex in the gas phase: (b) Hinderling, C.; Feichtinger, D.; Plattner, D. A.; Chen, P. *J. Am. Chem. Soc.* In press.
- Ortho-metalated iridium complexes have been shown to react with C–H bonds of arenes following chemical oxidation, presumably to Ir(IV) radical cations; Cf.: Diversi, P.; Iaconi, S.; Ingrosso, G.; Laschi, F.; Lucherini, A.; Zanello, P. *J. Chem. Soc., Dalton Trans.* **1993**, 351.
- Diversi, P.; Iaconi, S.; Ingrosso, G.; Laschi, F.; Lucherini, A.; Pinzino, C.; Uccello-Barretta, G.; Zanello, P. *Organometallics* **1995**, *14*, 3275.
- Diversi, P.; Ferrarini, A.; Ingrosso, G.; Lucherini, A.; Uccello-Barretta, G.; Pinzino, C.; Fabrizi, F. D.; Laschi, F.; Zanello, P. *Gazz. Chim. Ital.* **1996**, *126*, 391.

(10) Complexes **6** and **9** have been characterized spectroscopically, but attempts to recrystallize them have resulted in powdery materials which are not apparently cleaner than the crude product. Additionally, due to the lability of the triflate ligand, observation of a molecular ion for either compound even under low-energy FAB conditions has been impossible.

(11) Hofmann and co-workers have investigated the effect of phosphine chelation on the rate of C–H and Si–H oxidative addition to P₂Pt complexes using both solution and theoretical techniques. They observe that decreasing the phosphine bite angle markedly increases the rate of oxidative addition, which they correlate with an increase in the energy of the HOMO of the P₂Pt fragment. Hofmann, P.; Heiss, H.; Müller, G. *Z. Naturforsch. B* **1987**, *42*, 395.

(12) Hofmann, P.; Heiss, H.; Neiteler, P.; Müller, G. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 880.

Scheme 3



Grignard reagent (Me_2PCH_2) MgCl (**10**) was synthesized by reaction of $\text{LiCH}_2\text{PMe}_2$ ¹³ with MgCl_2 in THF and used as a stock solution. Addition of 1 equiv of this reagent to $\text{Cp}^*(\text{DMSO})\text{IrCl}_2$ at -78°C results in the formation of cyclometalated chloride **11** (Scheme 3) in 30% yield. The ^1H NMR spectrum of **11** in C_6D_6 displays the expected characteristics. The phosphine-bound methyl groups are diastereotopic and resonate at 1.45 and 0.98 ppm. The methylene protons are also diastereotopic and resonate at 1.32 and 0.78 ppm, and the Cp^* methyl resonance is coupled to phosphorus ($J_{\text{P-H}} = 1.6$ Hz). The most compelling spectroscopic characteristic is the ^{31}P resonance at -64.8 ppm. The extremely high field chemical shift is characteristic of phosphametalacyclopropane complexes.^{14,15} A molecular ion is observed in the mass spectrum at m/z 438 with the predicted isotopic pattern and no higher mass peaks are observed.

Treatment of **11** with AgOTf in C_6H_6 results in the formation of $\text{Cp}^*(\text{PMe}_3)\text{Ir}(\text{Ph})(\text{OTf})$ ¹⁶ (**13**) in 90% yield (Scheme 3). This presumably involves initial metathesis of the iridium-bound Cl^- with OTf^- to form iridium triflate **12**, which immediately reacts with C_6H_6 (Scheme 3). The rate of disappearance of **11** under these conditions is extremely rapid ($t_{1/2} = 5$ min at 25°C), and there is no spectroscopic evidence that **12** builds up during the reaction. This indicates that the rate of reaction of **12** with C_6H_6 must be considerably faster than the ligand metathesis reaction, and remarkably faster than the analogous reaction of **1** in neat C_6H_6 ($t_{1/2} = 24$ h at 25°C).¹⁷ In contrast to its behavior in benzene, however, treatment of **11** with AgOTf in CH_2Cl_2 —the solvent normally used for our C–H activation experiments—even in the presence of 20 equiv of C_6H_6 (conditions under which **1** cleanly reacts to give **13**), results in decomposition to unidentifiable products. The fact that no detectable $\text{Cp}^*(\text{PMe}_3)\text{Ir}(\text{Ph})(\text{OTf})$ (**13**) is observed by NMR provides suggestive evidence that **12** is not a viable intermediate in the reaction of **1**.

The following considerations confirm the implication of our observations on the chemistry of **11**. (1) In the reaction of C_6D_6 with **1** no deuterium is incorporated into the phosphine methyl groups, which would be required if the cyclometalation pathway were operative.¹⁸ (2) Additionally, careful monitoring of the reactions of benzene or other organic compounds with **1** or **2** shows that no detectable concentrations of any intermediates build up during the reaction. Therefore, if initial cyclometalation were to occur, it would have to be either the rate-limiting step in the overall reaction or exist in a pre-equilibrium with the starting complex. In the case of benzene as the organic reactant, the rapid pre-equilibrium can be ruled out on the basis of the relative rate of this reaction and that of the reaction between **1**

and $^{13}\text{CH}_4$, which is much slower. The reaction of **1** with $^{13}\text{CH}_4$ results in the incorporation of label into the iridium methyl position,² but the half-life for this reaction at 45°C in CD_2Cl_2 is approximately 6 h, substantially longer than that for which **1** is converted to $\text{Cp}^*(\text{PMe}_3)\text{Ir}(\text{Ph})(\text{OTf})$ ($t_{1/2} = 6$ h at 9.6°C).¹⁷ This establishes that methane extrusion must occur *irreversibly* in the rate determining step of the benzene C–H activation reaction. (3) If intramolecular C–H activation occurred either simultaneously with or immediately following this irreversible methane-elimination step, there could be no dependence of the rate of the reaction on the concentration or nature of the external organic reactant. Exactly the opposite is true: in the reaction of **1** with benzene the rate depends on the concentration of the organic reactant, and in general the C–H activation rate shows wide qualitative variation with different reactants (e.g., benzaldehyde¹⁹ reacts instantaneously with **1** at -60°C). (4) A similar conclusion can be derived from the observed deuterium isotope effect. If irreversible methane elimination/cyclometalation were the first step in the reaction, the rate of disappearance of **1** should be the same for C_6H_6 and C_6D_6 . The contrary is true: there is a large primary isotope effect on the rate of activation of C_6H_6 vs C_6D_6 ($k_{\text{H}}/k_{\text{D}} = 4.0$).¹⁷

We conclude that cyclometalated complexes such as **6** and **12** undergo C–H activation more rapidly than their unstrained analogues. However, the intermolecular C–H activation reactions of **1** in solution *cannot* be proceeding by initial cyclometalation. Since the highly electrophilic species $[\text{Cp}^*(\text{PMe}_3)\text{Ir}(\text{CH}_3)]^+$ is known to coordinate extremely poor donor ligands (i.e., CH_2Cl_2 as shown in the solid-state structure of **2**),¹ we do not find it surprising that in the absence of donor stabilization and at low (or zero, such as in Chen's gas-phase experiments) concentration of substrate, the inherently slower cyclometalation pathway dominates.²⁰

Finally, even in cases where cyclometalation does occur,²¹ we feel it is misleading to characterize this transformation as a new mechanism for the C–H activation process. Cyclometalation can in principle proceed by σ -bond metathesis or oxidative addition/reductive elimination, just as in the intermolecular reaction. Focusing on the intra- rather than the intermolecular reaction does not somehow absolve mechanistic chemists from the need to achieve the resolution of this dichotomy. Theory seems to be strongly favoring the oxidative addition pathway. We plan to continue our work on this problem to confirm this prediction experimentally, and also hope to eventually understand why the cyclometalated complexes, if they are given an opportunity to form, react so readily with external C–H bonds.

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Supporting Information Available: Text giving full experimental details and characterization data for compounds **6–8** and **11** and spectroscopic data for **6**, **8**, and **11** (7 pages). See any current masthead page for ordering and Internet access instructions.

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(19) Arndtsen, B. A.; Bergman, R. G.; Mobley, T. A.; Peterson, T. H. *Acc. Chem. Res.* **1995**, *28*, 154.

(20) Prof. P. Chen has informed us that he, too, has carried out studies on the solution C–H activation reactions of PMe_3 complexes such as the ones described here, and finds results that are in agreement with ours indicating that the intermolecular C–H activation reactions do not proceed by cyclometalation under these conditions. In the manuscript detailing this work (ref 6b), Chen also finds that cyclometalated complexes react more rapidly than their analogous noncyclometalated analogues, and that donor stabilization likely inhibits the cyclometalation reaction in solution. We are grateful to Prof. Chen for providing a draft copy of his full paper describing these results prior to publication.

(21) For a recent example of γ -cyclometalation in $\text{Cp}^*(\text{P}(\text{O}i\text{Pr})_3)\text{Ir}(\text{Me})(\text{OTf})$, see: Simpson, R. D. *Organometallics* **1997**, *16*, 1797.

(13) Karsch, H. H. Z. *Naturforsch. B* **1982**, *37B*, 284.
 (14) Wenzel, T. T.; Bergman, R. G. *J. Am. Chem. Soc.* **1986**, *108*, 4856.
 (15) Bergman, R. G.; Seidler, P. F.; Wenzel, T. T. *J. Am. Chem. Soc.* **1985**, *107*, 4358.
 (16) Woerpel, K. A.; Bergman, R. G. *J. Am. Chem. Soc.* **1993**, *115*, 7888.
 (17) Arndtsen, B. A.; Bergman, R. G. Unpublished results.
 (18) Similarly, the reaction of **1** with CH_3CDO results in exclusive formation of CH_3D . Alaimo, P. J.; Arndtsen, B. A.; Bergman, R. G. *J. Am. Chem. Soc.* **1997**, *119*, 5269.