C–H Activation Catalysis

C–H Activation of Alkanes and Arenes Catalyzed by an O-Donor Bis(tropolonato)iridium(III) Complex**

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Catalysts based on the C–H activation reaction show potential for the development of selective hydrocarbon-oxidation reactions.[1] One of the key challenges in this field is developing catalysts based on C–H activation that yield functionalized products such as alcohols.[1g] We have been interested in O-ligated late-transition-metal complexes as a starting point for the development of new hydrocarbon-oxidation catalysts. Although O-donor ligands have been investigated with early and late transition metals,[2] to our knowledge, the only well-defined O-ligated late-transition-metal complexes that activate alkane and arene C–H bonds have been reported recently by our group.[3–5] Compared to the N-, C-, or P-donor ligands generally utilized for homogeneous catalysts,[6] O-donor ligated complexes may have the potential for higher stability under thermal, protic, and oxidation conditions given the lower basicity and higher electronegativity of O atoms. Another important reason for the study of this class of complex is that the unique combination of the higher electronegativity with the π-donor[7] and "hard" properties of O-donor ligands could allow access to higher oxidation states during catalysis that may be required for the C–H activation as well as for the generation of functionalized products.[1g]

Recently, we demonstrated that the bis-bidentate O-donor complex $[Ir(CH_3)(py)(acac\text{-}O,O)_2]$ (acac-O,O = κ^2-O,O-acetylacetonate, py = pyridine) catalyzes the C–H activation of alkanes[3] and functionalization of arenes by the intermolecular anti-Markovnikov hydroarylation of olefins to selectively generate *n*-alkyl benzene derivatives.[4] Experiments and theoretical[5] calculations reveal that this O-donor octahedral d^6 late-transition-metal complex is stable to air and protic media under thermal conditions and activates the C–H bonds of alkanes and arenes by a transition state that has oxidative-addition or insertion character. This transition state is intriguing as the use of ligands with electronegative O-donor atoms to facilitate this mode of C–H activation may

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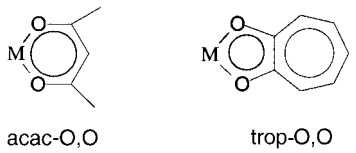
[**] This work was supported by NSF Grant CHE-0328121 and by the ChevronTexaco Energy Technology Co. We thank Dr. William Schinski of ChevronTexaco for helpful discussions. We also acknowledge Dr. Jonas Oxgaard and Prof. W. A. Goddard III for their useful insight.

Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

  DOI: 10.1002/anie.200462065

seem contrary to the common guiding principle that such reactions require electron-rich metal centers.[8] However, one possibility is that the π-donor properties of O-donor ligands may facilitate this mode of C–H activation, whereas the σ-acceptor properties could help to stabilize the complex. This combination of stability and C–H bond reactivity is very attractive for the development of oxidation catalysts based on C–H activation and we are currentlx exploring the extension of this chemistry to other readily available O-donor ligands such as aryloxides,[9] tropolones,[10] catechols,[11] and hydroxyacetophenones,[11c].

The O-donor ligand, trop-O,O (trop-O,O = κ^2-O,O-tropolonato) has often been speculated to be an analogue of the acac-O,O ligand as they share many common features. Both



ligands are bidentate, mono-anionic, and both bond through delocalized chelate rings that are formed through two oxygen atoms. Importantly, however, significant differences in reactivity could be anticipated from the smaller bite angle[12] as well as increased delocalization over the larger tropolonato aromatic system. Thus, for example, trop-O,O complexes may more readily accommodate an increase in the coordination number at the metal center[10] or potentially—because of changes in the extent of π donation that results from the differences in bite angle—change the reactivity of the metal center. Rate changes related to differences in ligand bite angle have been reported.[12a,13] Herein, we report the synthesis and chemistry of the bis-bidentate, O-donor tropolonato iridium complex **2-Me** [Ir(CH$_3$)(py)(trop-O,O)$_2$]. Importantly, we find that this O-donor complex is more active for the C–H activation of alkanes and arenes than is the analogous bis-acac-O,O iridium complex.

To obtain the bis trop-O,O complex of iridium, the original synthesis of the tris complex [Ir(trop-O,O)$_3$] was reinvestigated in anticipation that the bis trop-O,O complex could be isolated as an intermediate in this synthesis.[14] As reported by Griffith et al.,[14] heating IrCl$_3$ with an excess of tropolone and sodium acetate in water resulted in the formation of [Ir(trop-O,O)$_3$] in 40% yield (Scheme 1). However, in addition to this material a red–black solid (**1**) was also isolated, which was insoluble in dichloromethane. Attempts to purify **1** or obtain reproducible analytical data for this material were unsuccessful and we presume that the material is polymeric.[15] The solid **1** is soluble in coordinating solvents such as THF, CH$_3$CN, DMSO, and pyridine, but NMR spectroscopic studies suggest that multiple species are present. Attempted separation of these species by chromatography was also unsuccessful.[16] However, the addition of [Zn(CH$_3$)$_2$] to a solution of **1** in THF followed by the addition of pyridine, resulted in a black organometallic complex [Ir(CH$_3$)(py)(trop-O,O)$_2$] (**2-Me**), which could be obtained in 10% overall yield after column chromatography (Scheme 1). This material has been fully characterized by ^{1}H and ^{13}C NMR spectroscopy, elemental analysis, and single-crystal X-ray diffraction.[17] An ORTEP drawing of **2-Me** is shown in Figure 1.

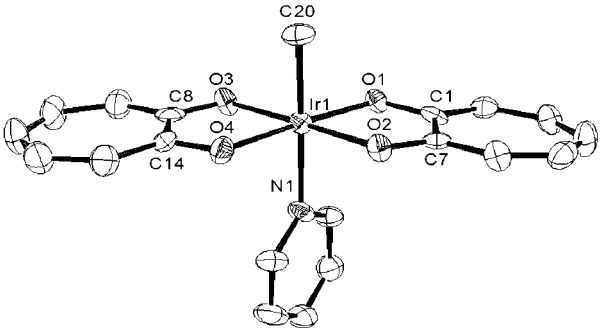
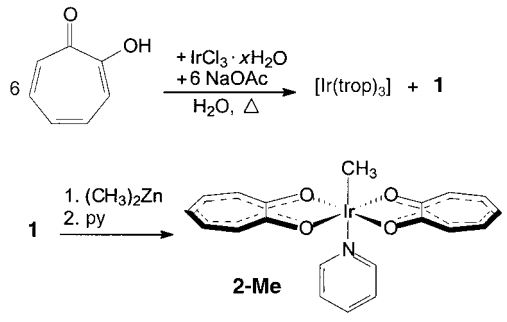


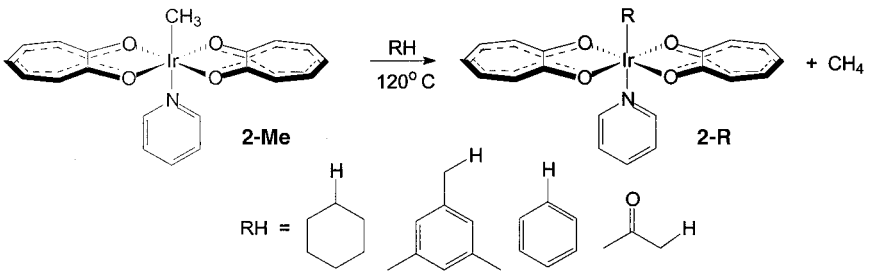
Figure 1. ORTEP drawing of **2-Me**. Thermal ellipsoids are at the 50% probability level. Hydrogen atoms omitted for clarity. Selected bond lengths [Å] and angles [°]: Ir1-C20 2.046(10), Ir1-N1 2.180(8); O1-Ir1-O2 78.4(3).

We find from ^{1}H NMR spectroscopic studies that the methyl group bound to the iridium center in **2-Me** (2.08 ppm, Ir–CH$_3$) is located downfield compared to that in the acac-O,O analogue [Ir(CH$_3$)(py)(acac-O,O)$_2$] (1.65 ppm, Ir–CH$_3$),[18] which suggests possible significant electronic differences at the metal centers. A similar trend is also observed in the ^{13}C NMR spectrum, with the chemical shift of the Ir–CH$_3$ group at −23.3 ppm for **2-Me** compared to −27.1 ppm for the acac-O,O analogue. However, the most significant difference between the two complexes can be seen in the crystal structures of these complexes. As anticipated, the bite angle O1-Ir-O2 in **2-Me** (78.4(3)°) is much smaller than that in the acac-O,O analogue (95.17(16)°). The Ir–N bond length (2.180(8) Å) is comparable to that in the analogous acac complex (2.181(4) Å).

To investigate the stoichiometric C–H activation chemistry of this new O-donor complex we examined the reaction of the complex in various hydrocarbon solvents. Thus, heating **2-Me** in neat mesitylene at 130 °C for 1 h cleanly yielded the corresponding mesityl complex **2-Mes** and methane as shown in Scheme 2. ^{1}H NMR spectroscopic analysis of the crude reaction mixture, after solvent removal and dissolution in CDCl$_3$, showed that the reaction was essentially quantitative, as in the case of the acac-O,O analogue,[3] and only the



Scheme 1. Synthesis of **2-Me**.



Scheme 2. Stoichiometric C–H activation reactions of **2-Me** with RH to generate **2-R**.

benzylic C–H bond of mesitylene was activated. Other hydrocarbon substrates that react by C–H activation with **2-Me** are shown in Scheme 2. Thus, heating a solution of **2-Me** in benzene or acetone at 120 °C for 1 h results in the formation of the corresponding hydrocarbyliridium derivatives, **2-Ph** and **2-Ace**, respectively, in almost quantitative yield. Similarly, heating **2-Me** in cyclohexane resulted in the corresponding cyclohexyliridium complex **2-Cy**, which was purified by flash chromatography and isolated in 35 % yield. All these hydrocarbyliridium derivatives, **2-R** (R = Cy, Mes, Ph, and Ace) were fully characterized by ^{1}H and ^{13}C NMR spectroscopy as well as by elemental analysis. Importantly, as was the case for the acac-O,O analogues, these hydrocarbyl O-donor iridium derivatives are all air, water, and thermally stable. Significantly, the stoichiometric C–H activation reactions of **2-Me** are faster than those of the acac-O,O analogue. Thus, the half-life ($t_{1/2}$) for the reaction of **2-Me** with benzene at 120 °C is less than 5 minutes versus about 50 minutes for the acac-O,O analogue.

Having established that **2-Me** can stoichiometrically activate the C–H bonds of alkanes and arenes, we examined the catalytic C–H activation of this complex as a first step towards attempting to develop stable hydrocarbon-oxidation catalysts. The relative rates of the H/D exchange reaction with a C_6H_6/[D_8]toluene mixture (1:1 v/v),[19] catalyzed at 120 °C by **2-Me** (0.1 mol %) and the acac-O,O analogue were used to compare these complexes. As can be seen in Figure 2, the trop-O,O complex, **2-Me**, is at least 50 times faster than the acac-O,O analogue. Critically, both complexes are stable over the time period studied (ca. 5 h; turnover number (TON) ca. 140 and turnover frequency (TOF) = 80×10^{-4} s^{-1} for **2-Me**, and TON ca. 2 and TOF = 1×10^{-4} s^{-1} for the acac-O,O analogue). This is an important result as it shows that: 1) the

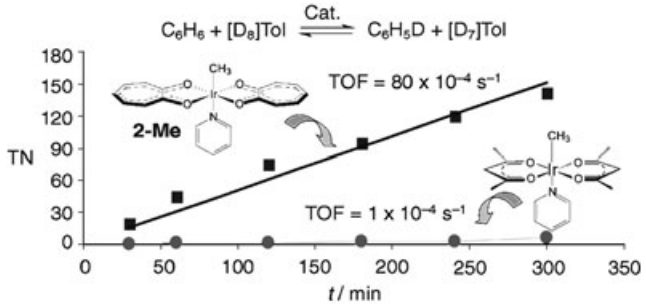


Figure 2. Comparison of catalytic C–H activation of trop-O,O and acac-O,O complexes.

C–H activation chemistry as well as the thermal stability to air and protic media of O-donor late-transition-metal complexes are not unique to the acac-O,O complex and 2) the chemistry of O-donor late-transition-metal complexes can be significantly changed by ligand modification. This observation of ligand-dependent reactivity is an important requirement for this class of O-donor ligand–metal complex to be useful. These results raise the expectation that further investigation of O-donor complexes of late-transition-metal complexes could lead to a broad class of complex with desirable stability, reactivity, and ligand control properties.

In conclusion, we have synthesized a stable O-donor late-transition-metal complex that activates the C–H bonds of alkanes and arenes more rapidly than does the only previously reported O-donor metal complex. Theoretical calculations and further experimental study of these complexes are underway to understand the basis for the increased reactivity and to determine its scope.

Received: September 21, 2004
Published online: January 26, 2005

Keywords: C–H activation · homogeneous catalysis · iridium · O ligands

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[17] Crystal data for $C_{20}H_{18}IrNO_4$: $M_r = 528.55$, monoclinic, space group $P2(1)$, $a = 8.463(2)$, $b = 11.060(3)$, $c = 9.924(3)$ A, $\alpha = 90$, $\beta = 94.721(4)$, $\gamma = 90°$, $V = 925.6(4)$ A^3, $F(000) = 508$, ρ_{calcd} ($Z = 2$) $= 1.896$ mg m^{-3}, $\mu = 0.7236$ mm^{-1}, approximate crystal dimensions $0.28 \times 0.06 \times 0.01$ mm^3, θ range $= 2.06$–$27.50°$, $Mo_{K\alpha}$ ($\lambda = 0.71073$ A), $T = 153$ K, 5610 measured data (Bruker 3-circle, SMART APEX CCD with χ axis fixed at 54.74° by using the SMART V 5.625 program, Bruker AXS: Madison, WI, 2001), of which 3120 ($R_{int} = 0.0436$) unique. Lorentz and polarization correction (SAINT V 6.22 program, Bruker AXS: Madison, WI, 2001), absorption correction (SADABS program, Bruker AXS: Madison, WI, 2001). Structure solution by direct methods (SHELXTL 5.10, Bruker AXS: Madison, WI, 2000), full-matrix least-squares refinement on F^2, data to parameters ratio: 13.2:1, final R indices [$I > 2\sigma(I)$] : $R1 = 0.0396$, $wR2 = 0.0676$, $R1 = 0.0511$, $wR2 = 0.0698$ (all data), GOF on $F^2 = 1.008$. CCDC 250327 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB21EZ, UK; fax: (+44) 1223-336-033; or deposit@ccdc.cam.ac.uk).

[18] G. Bhalla, R. A. Periana, unpublished results.

[19] The H/D exchange rates were quantified by GC/MS analyses. This was achieved by deconvoluting the mass fragmentation pattern obtained from mass spectroscopy by using a program developed with Microsoft EXCEL. See the Supporting Information for details.

