

Anti-Markovnikov Hydroarylation of Unactivated Olefins Catalyzed by a Bis-tropolonato Iridium(III) Organometallic Complex

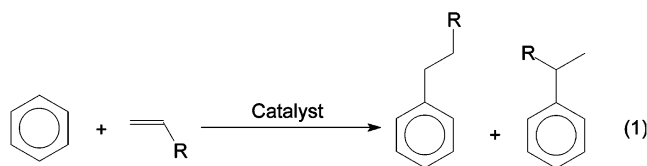
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Recently, we reported the first catalytic, intermolecular, anti-Markovnikov hydroarylation of unactivated olefins by a homogeneous, bis-chelating, O-donor Ir(III) complex, (acac-O,O)₂-Ir(R)(L), based on the simplest β-diketetonate acetylacetonate (acac-O,O). With the ultimate objective of designing more active catalysts for this potentially useful reaction on the basis of structure function studies, we synthesized the related O-donor, bis-tropolonato Ir(III) organometallic analogues. Herein, we report that the new O-donor complex, (trop-O,O)₂-Ir(Ph)(Py), is an active catalyst for the anti-Markovnikov hydroarylation of unactivated olefins and that theoretical calculations are consistent with catalysis proceeding via arene CH activation and olefin insertion.

To date, two homogeneous catalysts^{1,2} have been reported that catalyze the intermolecular hydroarylation of unactivated arenes with unactivated olefins, eq 1, via the CH activation reaction. Catalyzing the hydroarylation of olefins via the CH activation reaction is potentially useful³ because of the possibility for (A) eliminating the use of corrosive Lewis acids, (B) regio- as well as stereocontrol, and (C) compatibility with a wide range of functional groups and reaction solvents such as water.



One reported system that catalyzes the hydroarylation of olefins via CH activation and with anti-Markovnikov regioselectivity is based on the homogeneous, O-donor, late transition metal complex (acac-O,O)₂-Ir(Ph)(Py), **1** (where acac-O,O is the O-bound acetyl-

acetate ligand).¹ To our knowledge, no other O-donor, late transition metal complex has been reported for the CH activation reaction. Given the expected differences of O-donor compared to more typical N-, C-, and P-donor ligands, there is a basis to anticipate different and potentially advantageous properties for O-donor complexes. Consistent with this, we have observed that, in addition to hydroarylation catalysis, **1** is thermally stable to air and protic media and that CH activation with this complex is not severely inhibited by olefins or water.^{1a,4} The key limitation of this initial O-donor catalyst system is an activation barrier of ~37 kcal/mol, which leads to reaction temperatures of ~200 °C.

Given the broad potential utility of efficient catalysts for olefin hydroarylation, the wide availability of O-donor ligands, the unique stability and reactivity properties of this example of an O-donor late transition metal catalyst, and the limited study of O-donor ligands with late transition metals for CH activation reactions, we have begun a systematic study of this class of homogeneous O-donor complexes. The focus has been on structure–function relationships based on variations in the metal center⁵ as well as the O-donor ligands. A short-term, focused objective of these studies is to design additional as well as more active and selective hydroarylation catalysts. A longer term, broader objective is to determine whether the large class of O-donor ligands could be utilized for the generation of stable, active, and selective homogeneous catalysts based on the late transition metals. To begin to address this, it is important to show that (A) the chemistry of **1** is not unique to the O-donor acac-O,O ligands and (B) modi-

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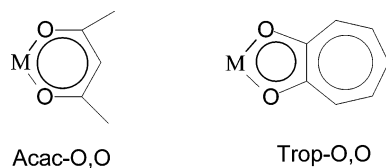


Figure 1. O-Donor bidentate acac-O,O and trop-O,O ligands.

fications of the O-donor ligands of **1** can lead to changes in reactivity.

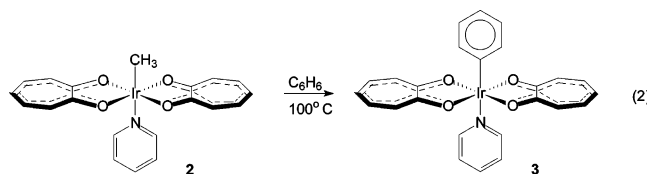
Our experimental^{1,4} and theoretical studies^{6,7} of the initial O-donor complex, **1**, show that the mechanism of catalytic hydroarylation of olefins involves CH activation and olefin insertion and that there is an unexpectedly complex interplay between these steps. Thus, the calculations show that for metals that are good π -donors, increased electron density at the metal center leads to increased barriers for the olefin insertion step but decreased barriers for the C–H activation step. However, preliminary theoretical work⁶ also shows that modifications of various ligand properties, such as σ -donating character, can benefit one of the two steps without overly impairing the other.

The O-donor κ^2 -O,O-tropolonato ligand (trop-O,O) is often considered an analogue of the O-donor κ^2 -O,O-acetylacetonate ligand (acac-O,O) since they are both bidentate, monoanionic, delocalized chelate rings bonded through two oxygen atoms, Figure 1.⁸ Nevertheless, the trop-O,O ligand is significantly different from acac-O,O. Tropolone is more acidic ($pK_a \sim 6.4$ versus ~ 8.9 for acetylacetonate),⁹ and consequently the trop-O,O ligand may be more electron withdrawing within the σ -framework. Additionally, the larger aromatic delocalization could lead to greater polarizability, and perhaps most significantly, the smaller “bite angle”¹⁰ resulting from the five-membered-ring size of the tropolonato ligand (vs six for acac-O,O) could lead to significant differences in sterics and electronics at the metal center.⁸ An interesting possibility, related to the smaller ring size and resulting increase in p-character of the oxygen lone pairs and s-character in the O–Ir σ -bond, is that the trop-O,O ligand could be both a better π -donor and σ -acceptor than the acac-O,O ligand.

Recently, we reported the synthesis of the bis-tropolonato methyl iridium analogue of **1**, the O-donor complex (trop-O,O)₂Ir(CH₃)(Py), **2**, and showed that this complex activates the C–H bond of alkanes and arenes both stoichiometrically and catalytically.¹¹ Significantly, **2** was found to be ~ 50 times more active for catalytic CH activation than the bis-acac-O,O iridium(III) ana-

logue, **1**, and shows that the O-donor, late transition metal complexes are subject to structure–function control through ligand modifications. Herein, we now report that the phenyl analogue of **2**, (trop-O,O)₂Ir(Ph)(Py), **3**, also catalyzes the intermolecular hydroarylation of unactivated olefins with unactivated arenes and is the third example of this class of catalysts.

These trop-O,O catalysts share the thermal stability properties of the acac-O,O complexes, and **3** was synthesized in quantitative yields by thermal CH activation of benzene with **2** at 120 °C for 1 h according to the stoichiometry shown in eq 2.¹¹ The red powder obtained after benzene removal was fully characterized by ¹H and ¹³C NMR spectroscopy and elemental analysis. The complex is both air and water stable, and both the solid and solutions can be handled in the air. Consistent with the reactivity of the methyl analogue, **2**, treatment of **3** with C₆D₆ shows the expected CH activation reaction and quantitative formation of **3-Ph-d₅**, while reaction with mixtures of C₆D₆/C₆H₆ shows rapid H/D exchange.



Having shown that **3** is capable of stoichiometric and catalytic C–H activation of arenes, we examined the CH activation/functionalization activity of **3** by reaction with a mixture of arenes and olefin. As can be seen in Table 1 (entry 1), **3** is active for the intermolecular hydroarylation of olefins. In reactions of benzene with propylene only two products are observed, *n*-propylbenzene and isopropylbenzene in $\sim 61:39$ ratio. As in the case of the acac-O,O complexes,^{1,5} no traces of olefinic products, such as styrenes, are observed. As seen in Table 1, the TOF remains constant with time (entries 2 and 3). Interestingly, despite the higher CH activation activity compared to the analogous acac-O,O complex, **1**, the trop-O,O complex, **3**, is slightly less active (or comparable) than the acac-O,O analogue, **1**, for olefin hydroarylation, Table 1 (entry 4). This is consistent with our earlier proposal^{1,5} and theoretical calculations^{6,7} that olefin insertion is the rate-limiting step in the olefin hydroarylation reactions catalyzed by O-donor Ir(III) organometallic complexes. Significantly, both the acac-O,O and trop-O,O complexes show the same anti-Markovnikov regioselectivity for linear alkyl benzene with propylene and styrene, Table 1.

To provide a basis for the increased reactivity for CH activation but comparable reactivity for olefin hydroarylation, we examined the energy profile by use of DFT calculations assuming a mechanism similar to the acac-O,O complex **1**. Consistent with the experimental observations, the results presented in Figure 1 show that the energy profiles for **1** and **3** are similar, with comparable barriers for rate-determining olefin insertion, **TS2**, and slightly lower barriers for CH activation with the trop-O,O complex, **TS3**.

To access the transition state for cis/trans isomerization (**TS1**), the pyridine ligand must be dissociated (not shown) from **3**, followed by cis/trans isomerization of the five-coordinate intermediate (**TS1**). The resulting five-

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Table 1. Hydroarylation of Olefins by Ir Complexes^a

entry	olefin	complex	time (min)	TON ^b	TOF × 10 ⁻⁴ (s ⁻¹) ^c	L:B ratio ^d
1	ethylene	Ph-Ir(trop) ₂ -Py (3)	30	27	150	
2	propylene	Ph-Ir(trop) ₂ -Py (3)	15	4	44	61:39
3	propylene	Ph-Ir(trop) ₂ -Py (3)	30	8	43	61:39
4	propylene	Ph-Ir(acac) ₂ -Py (1)	30	9	51	61:39
5	styrene	Ph-Ir(trop) ₂ -Py (3)	30	11	62	98:2

^a All reactions were carried out in the presence of 2.96 MPa of nitrogen in neat benzene at 200 °C. ^b TON = (mols of product)/(mols of added catalyst). ^c TOF = (mols of product)/[(mols of added catalyst)·(reaction time)]. ^d Mole ratio of linear to branched products.

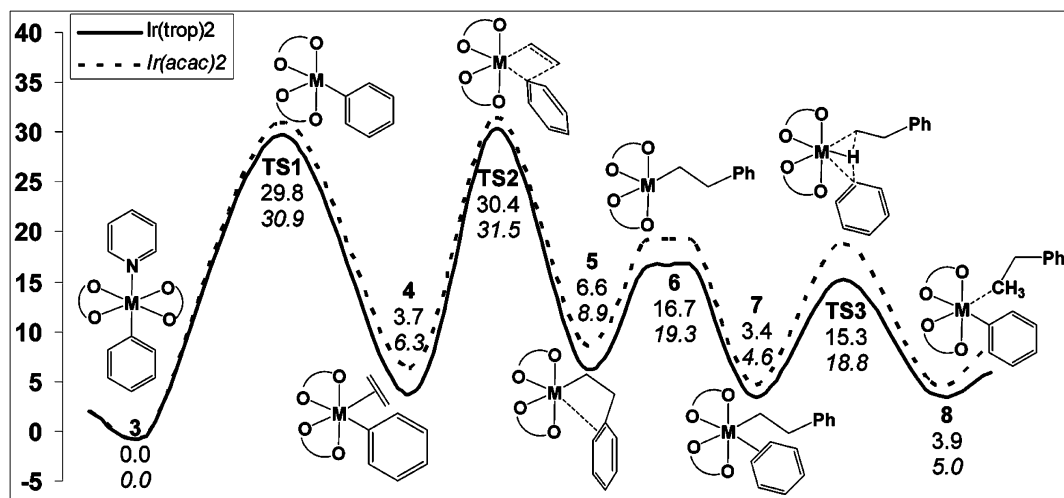


Figure 2. Calculated (B3LYP/LACVP**) energy profile of (trop-O,O)₂Ir(Ph)(Py)-catalyzed hydroarylation with the energy profile of the acac-O,O analogue added for comparison (dashed line).

coordinate cis intermediate (not shown) is very short-lived, and coordination of olefin leads to intermediate 4. The transition state for the insertion, **TS2**, has a calculated activation energy of 30.4 kcal/mol. **TS2** is formally a 1,2-insertion transition state, with the three carbons and the iridium in the plane. It is predicted to be slightly faster for Ir(trop)₂ than for Ir(acac)₂ ($\Delta\Delta H = 1.1$ kcal/mol), which does not correspond to the experimental ratio of 43:51 ($\Delta\Delta G = -0.2$ kcal/mol). However, if only the direct insertion steps are compared, i.e., 4 → **TS2** → 5, the barrier is 26.7 kcal/mol for Ir(trop)₂ and 25.2 kcal/mol for Ir(acac)₂, 1.5 kcal/mol faster for Ir(acac)₂. Thus, depending on whether ground state effects are considered or not, the error in predicted values becomes ± 1.3 kcal/mol, which is within the expected accuracy.

C–H activation occurs through an oxidative hydrogen migration (OHM) mechanism, which features a concerted transition state with oxidative addition character, **TS3**. In this transition state the hydride is covalently bonded to the iridium (Ir–H = 1.56 Å) while forming partial bonds to the arene and aliphatic carbons (2.00 and 1.66 Å, respectively), Figure 3. The energy of **TS3** is 3.5 kcal/mol lower for the (trop-O,O)₂Ir(III) system than for the corresponding acac-O,O analogue, Figure 2, and is consistent with the experimental observations that the CH activation is faster with the trop-O,O system.¹¹ The reason for this higher reactivity of the trop-O,O system is currently not clear. The electron-donating ability of the two ligands seems to be very similar, as the calculated Mulliken charge on the metal center of Ir(trop)₂ and Ir(acac)₂ is 0.23 and 0.27 e⁻ in the transition states, respectively. Furthermore, the lower bite angle in tropolone does not have a perceptible steric effect. The two oxygens in the plane of the reacting

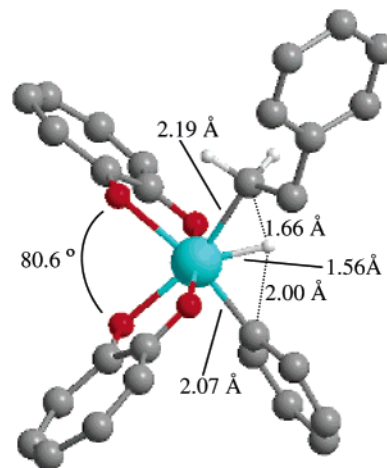


Figure 3. Geometry of calculated **TS3** showing selected bond lengths and angles.

C–H–C have an O–Ir–O angle of 80.6° for Ir(trop)₂, which should be compared to 79.8° for Ir(acac)₂. The lower bite angle was expected to alleviate steric crowding around the metal center in the OHM transition state, but this does not seem to be the case.

However, even though sterics did not change perceptibly, it is possible that the lower bite angle could change the electronic properties of the oxygen ligands. There are several possibilities here: (A) increased ground state destabilization by O– π to Mⁿ– $d\pi$ filled–filled repulsions or so-called “ π -conflict”,¹² (B) increased bonding

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from the filled $O-\pi$ to empty $M^{n+2}-d\pi$ orbitals on the metal center in the oxidized transition state, and/or (C) decreased ground state back-bonding from filled $M^n-d\pi$ orbitals to conjugated ligand π^* orbitals. Computational work is currently underway to determine the extent of these contributions and whether this is the cause of the rate increase.

In conclusion, we have shown that the novel organometallic Ir(III) complex (trop-O,O)₂Ir(Ph)(Py), **3**, is the second example of an O-donor, late transition metal complex that is an active catalyst for the intermolecular hydroarylation of olefins as well as CH activation.

Experimental Section

Reaction Procedure for the Olefin Hydroarylation.

A 3 mL stainless steel autoclave, equipped with a glass insert and a magnetic stir bar, was charged with 1 mL of distilled benzene and 4 mg (5 mmol, ~0.1 mol %) of catalyst. The reactor was degassed with nitrogen and pressurized with 1.96 MPa of ethylene (0.90 MPa of propylene or 0.2 mL of styrene) with an extra 2.96 MPa of nitrogen. The autoclave was heated for 30 min in a well-stirred heating bath maintained at 200 °C. The liquid phase was sampled and the product yields were determined by GC-MS using methylcyclohexane as an internal standard that was introduced into the reaction solution after the reaction.

Computational Section

All calculations were carried out using the hybrid DFT functional B3LYP,^{13,14} as implemented by the Jaguar 5.5 program package.¹⁵ Atoms were described with the LACVP** basis set and effective core potential treatment of Ir (17 explicit electrons).¹⁶ We optimized the geometry for all intermediates and transition states and calculated zero-point energies and solvation corrections for benzene [using the Poisson–Boltzmann continuum solvent method ($\epsilon = 2.284$ and solvent radius = 2.60219 Å)]. All reported energies are solvent-corrected enthalpies at 0 K (including ZPE).

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