ORGANOMETALLICS

Volume 26, Number 9, April 23, 2007

Communications

Stoichiometric Oxy Functionalization and CH Activation Studies of Cyclometalated Iridium(III) 6-Phenyl-2,2′-Bipyridine Hydrocarbyl Complexes

Kenneth J. H. Young, Oleg A. Mironov, and Roy A. Periana*

Donald P. and Katherine B. Loker Hydrocarbon Research Institute and Department of Chemistry, University of Southern California, Los Angeles, California 90089-1661

Received December 3, 2006

*Summary: A well-defined, thermal-, air-, and protic-stable, bis-bidentate, cyclometalated Ir(III) complex, Ir(NC)(NN^{tBu})CH_3-OTf, (**2-CH_3**; NC = κ^2-6-phenyl-2,2′-bipyridine, NN^{tBu} = κ^2-4,4′-di-tert-butyl-2,2′-bipyridine) has been shown to undergo oxy functionalization with oxidants such as $PhI(X)_2$ (X = OAc, TFA) to generate CH_3X (X = OAc, TFA, OTf) in yields ranging from 36 to 67% in CH_2Cl_2 at ambient temperatures. **2-CH_3** is also competent for CH activation, undergoing stoichiometric CH activation in benzene, and catalyzes the H/D exchange reaction between benzene and acids (acetic and trifluoroacetic acid).*

CH activation[1,2] reactions with more electropositive, less oxidizing metals to the left of Pt in the periodic table, such as iridium, have not been incorporated into catalytic cycles to generate oxy functionalized products. This absence is notable, since Ir(III) complexes are among the most active CH activation systems[3] and are likely to be less inhibited by oxy functionalized products such as methanol or water than the more electrophilic systems[4] that have been shown to efficiently convert methane to methanol. Likely reasons for this are that the Ir complexes examined to date (a) have no facile pathways for oxy functionalization of the Ir−R intermediates generated by CH activation or such pathways have not yet been identified, (b) are unstable to the oxidizing conditions required for the generation of oxy functionalized products, and (c) the CH activation reaction is inhibited under the conditions required for oxy functionalization. To develop new oxidation catalysts based on these more electropositive metals, we have begun to investigate the oxy functionalization chemistry of new thermal-, acid-, and oxidant-stable metal hydrocarbyl complexes (M−R's) of metals to the left of Pt in the periodic table. The objective is to identify efficient oxy functionalization reactions of these M−R's that could be combined with CH activation reactions to generate new, more efficient, selective, low-temperature hydrocarbon oxidation catalysts.

One obvious oxy functionalization reaction that could be considered would involve a reductive functionalization catalytic cycle from Ir^{III}−R, as shown in Figure 1A, that would be analogous to that observed in the Pt^{II}/Pt^{IV} systems.[4] However, to our knowledge there is no precedent for oxy functionalization

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* To whom correspondence should be addressed. E-mail: rperiana@usc.edu.

[1] We define the CH activation reaction as a reaction between the reactive species "M" that proceeds without the involvement of free radicals, carbocations, or carbanions to generate discrete M−R intermediates. (a) Arndtsen, B. A.; Bergman, R. G.; Mobley, T. A.; Peterson, T. H. *Acc. Chem. Res.* **1995**, *28*, 154 and references therein. (b) Periana, R. A.; Bhalla, G.; Tenn, W. J., III; Young, K. J. H.; Liu, X. Y.; Mironov, O.; Jones, C. J.; Ziatdinov, V. R. *J. Mol. Catal. A: Chem.* **2004**, *220*, 7 and references therein.

[2] Crabtree, R. H. *J. Organomet. Chem.* **2004**, *689*, 4083 and references therein.

[3] (a) Klei, S. R.; Tan, K. L.; Golden, J. T.; Yung, C. M.; Thalji, R. K.; Ahrendt, K. A.; Ellman, J. A.; Tilley, T. D.; Bergman, R. G. In *Activation and Functionalization of C-H Bonds*; Goldberg, K. I., Goldman, A. S. Ed., ACS Symposium Series 885; American Chemical Society: Washington, DC, 2004; 46. (b) Bergman, R. G. *Science* **1984**, *223*, 902.

[4] (a) Periana, R. A.; Taube, D. J.; Gamble, S.; Taube, H.; Satoh, T.; Fujii, H. *Science* **1998**, *280*, 560. (b) Shilov, A. E.; Shul'pin, G. B. *Activation and Catalytic Reactions of Saturated Hydrocarbons in the Presence of Metal Complexes*; Kluwer Academic: Dordrecht, The Netherlands, 2000; p 560. (c) Periana, R. A.; Mironov, O.; Taube, D.; Bhalla, G.; Jones, C. J. *Science* **2003**, *301*, 814. (d) Muehlhofer, M.; Strassner, T.; Herrmann, W. A. *Angew. Chem., Int. Ed.* **2002**, *41*, 1745.

10.1021/om0611002 CCC: $37.00

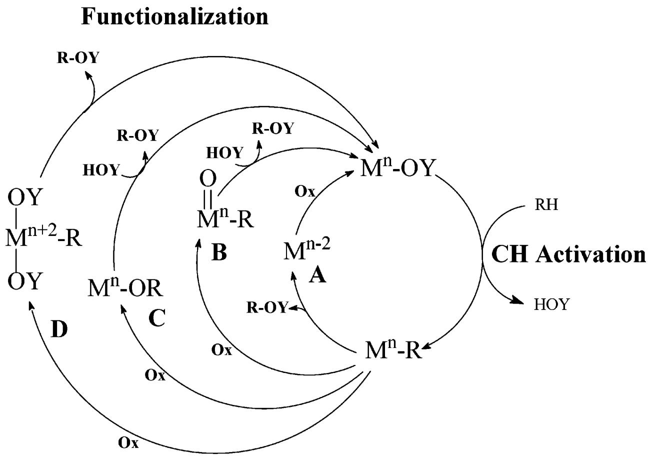


Figure 1. Catalytic sequences for oxy functionalization of hydrocarbons via CH bond activation.

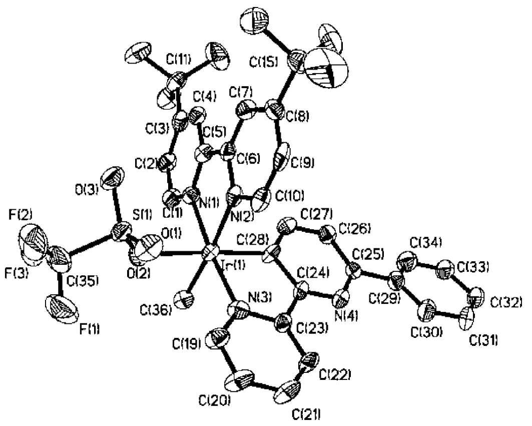


Figure 2. Thermal ellipsoid plot of **2-CH$_3$** at the 50% probability level. Hydrogens and cosolvent water are omitted for clarity.

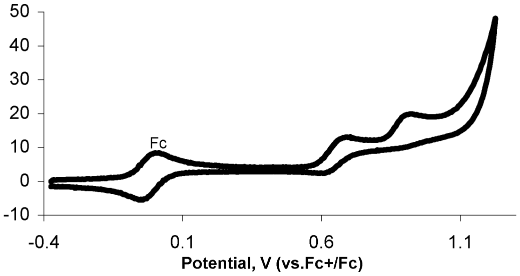
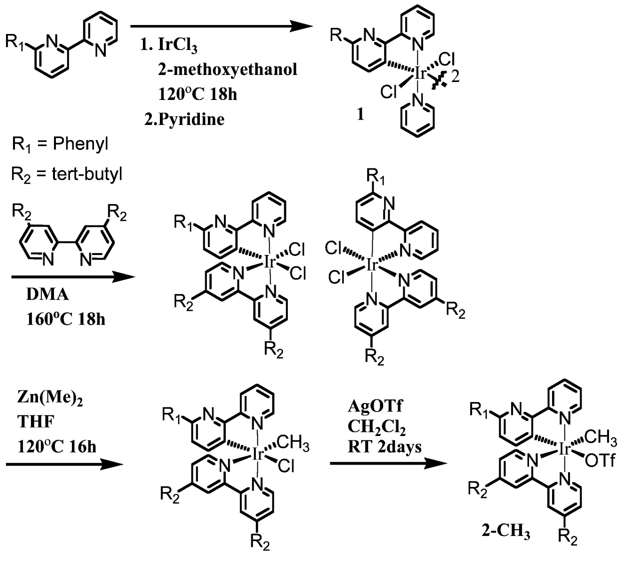


Figure 3. Cyclic voltammogram of **2-CH$_3$**, measured at 25 °C in DMF (scan rate 10 mV/s).

Scheme 1. Synthesis of 2-CH$_3$



of Ir$^{\mathrm{III}}$−alkyl species by this or any other reaction mechanism.[5,6b] This lack of facile reductive oxy functionalization of Ir$^{\mathrm{III}}$−alkyl species[7] is perhaps not unexpected since Ir(III) is a poorer oxidant than more electronegative ions such as Pt(IV), Pd(II), and Au(III), and reductive processes involving formation of carbon−oxygen bonds and Ir(I) (Figure 1A) would be expected to be unfavorable or much less facile. Consequently, more plausible approaches to developing oxidation catalysts based on CH activation with Ir(III) could involve oxidation of Ir$^{\mathrm{III}}$−R to the more oxidizing Ir$^{\mathrm{V}}$−R[8] intermediates that could facilitate oxy functionalization (Figure 1B,D) or use of a non-redox, O-atom insertion type reaction of the type we recently reported[9] (Figure 1C). Herein, we report that the novel air-, thermal-, protic-, and oxidant-stable Ir$^{\mathrm{III}}$−R complex Ir(NC)(NN$^{\mathrm{tBu}}$)CH$_3$-OTf (**2-CH$_3$**) separately undergoes both oxy functionalization and CH activation reactions. To our knowledge this is the first example of efficient oxy functionalization of an iridium alkyl to an oxy functionalized product.

The mononuclear bis-bidentate complex Ir(NC)(NN$^{\mathrm{tBu}}$)CH$_3$-OTf (**2-CH$_3$**) was synthesized in three steps from the monoligated, dinuclear complex [Ir(NC)Cl$_2$Py]$_2$ (**1**) (Scheme 1) and has been fully characterized by ^{1}H, ^{13}C, and ^{19}F NMR spectroscopy, elemental analysis, and mass spectrometry. Crystals of **2-CH$_3$** suitable for single-crystal X-ray diffraction were obtained from a CH$_2$Cl$_2$/ether mixture at −35 °C. As can be seen in the thermal ellipsoid plot shown in Figure 2, the ligand binds in a bis-bidentate fashion in which cyclometalation has occurred at the 3-position of the central pyridine ring and methyl and triflate groups exhibit a cis relationship. The complex **2-CH$_3$** is an air-stable solid,[10] and no decomposition was observed in solution after 2 days under an oxygen atmosphere. Consistent with the lack of facile oxy functionalization of Ir$^{\mathrm{III}}$−alkyl species by reductive processes, heating a mixture of **2-CH$_3$** in solvents such as acetic acid and benzene shows *no* formation of methyl oxy esters or other functionalized methyl products but does lead to formation of new Ir(III) products from loss of methane and CH activation of the benzene, respectively (vide infra).

Cyclic voltammetry (CV) of **2-CH$_3$** was examined in order to gain some insight into the redox chemistry. As can be seen, two one-electron oxidation waves were observed (Figure 3 and Figure S2 (Supporting Information)). The wave at +0.69 V (vs Cp$_2$Fe$^+$/Cp$_2$Fe) was reversible (Figure S2), and we attribute this to an Ir(III)/Ir(IV) couple. At a higher potential, an irreversible oxidation was observed at +0.89 V (vs Cp$_2$Fe$^+$/Cp$_2$Fe). CV analysis of this seems to fit the electrochemical characteristics

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(5) Examples of Ir$^{\mathrm{I}}$OCH$_3$ complexes forming esters: (a) Bernard, K. A.; Atwood, J. D. *Organometallics* **1987**, *6*, 1133. (b) Bernard, K. A.; Atwood, J. D. *Organometallics* **1988**, *7*, 235. (c) Bernard, K. A.; Atwood, J. D. *Organometallics* **1989**, *8*, 795.

(6) (a) Thompson, J. S.; Randall, S. L.; Atwood, J. D. *Organometallics* **1991**, *10*, 3906. (b) Mann, G.; Hartwig, J. F. *J. Am. Chem. Soc.* **1996**, *118*, 13109.

(7) Example of C(sp^3)−C(sp^2) bond formation from Ir$^{\mathrm{III}}$−CH$_3$: Thompson, J. S.; Atwood, J. D. *Organometallics* **1991**, *10*, 3525. Example of C(sp^2)−N(sp^2) bond formation with Ir$^{\mathrm{I}}$−pyrrole through an Ir(III) intermediate: Driver, M. S.; Hartwig, J. F. *Organometallics* **1998**, *17*, 1134.

(8) Jacobi, B. G.; Laitar, D. S.; Pu, L.; Wargocki, M. F.; DiPasquale, A. G.; Fortner, K. C.; Schuck, S. M.; Brown, S. N. *Inorg. Chem.* **2002**, *41*, 4815 and references therein.

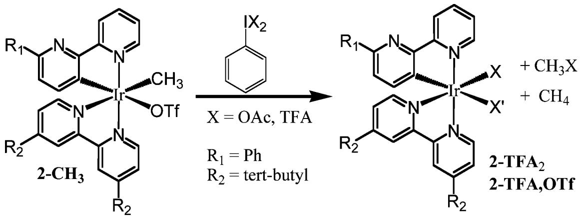
(9) Conley, B. L.; Ganesh, S. K.; Gonzales, J. M.; Tenn, W. J., III; Young, K. J. H.; Oxgaard, J.; Goddard, W. A., III; Periana, R. A. *J. Am. Chem. Soc.* **2006**, *128*, 9018.

(10) Stable to dry air. It slowly reacts with moisture.

of a one-electron-transfer process (possibly involving an Ir(IV)/Ir(V) couple) followed by an irreversible chemical reaction, potentially to generate methyl triflate by a reductive process.[11] To study this possibility in greater detail, we examined the oxidation of **2-CH$_3$** with a variety of chemical oxidants. Details of the experimental procedure and analysis of the CV are given in the Supporting Information.

The complex **2-CH$_3$** does not react with oxygen in the absence or presence of the radical initiator AIBN. However, **2-CH$_3$** does react with strong oxidants such as iodobenzene diacetate (PhI(OAc)$_2$), PhI(TFA)$_2$, I$_2$, and Br$_2$. Thus, treatment of **2-CH$_3$** (0.03 mmol) in CD$_2$Cl$_2$ with 1.1 equiv of PhI(OAc)$_2$ at room temperature generated methyl acetate (0.0108 mmol, 36% yield based on **2-CH$_3$**) and methane slowly over the course of 3 days. Carrying out the reaction at 70 °C increased the reaction rate, and after 5 h a 37% yield of methyl acetate could be obtained. The formation of methyl acetate in these reactions was confirmed by ^{1}H and ^{13}C NMR as well as GC-MS of an authentic sample.

A stronger oxidant, iodobenzene bis(trifluoroacetate) (PhI(TFA)$_2$; 1−3 equiv), generated both methyl triflate and methyl trifluoroacetate in much shorter times (∼3 h) at room temperature in yields as high as 66.8% based on added **2-CH$_3$** with ∼7.8% methane observed as a side product. ^{1}H NMR analysis of the reaction mixture indicated that one main organometallic complex, Ir(NN)(NC)(TFA)$_2$ (**2-TFA$_2$**), was generated in ∼75% yield along with smaller amounts of Ir(NN)(NC)TFA(OTf) (**2-TFA-OTf**) (eq 1).



(1)

To our knowledge, this is the first example of relatively efficient Ir^{III}−alkyl functionalization to generate oxy functionalized products. Consequently, we have begun to examine these reactions in order to elucidate the mechanisms. In situ studies of the reaction of **2-CH$_3$** with PhI(TFA)$_2$ in CD$_2$Cl$_2$ by ^{1}H NMR at 21 °C show that **2-CH$_3$** is essentially completely consumed in ∼30 min. However, the rate of methyl ester formation is slower, and after 30 min only ∼20% CH$_3$X (X = OTf, TFA) is produced. These observations are consistent with formation of an intermediate before generation of the functionalized product. When the reaction was carried out in polar, coordinating solvents such as CD$_3$CN, **2-CH$_3$** reacted immediately to quantitatively generate [Ir(NN)(NC)CH$_3$(CD$_3$CN)](OTf) (**2-CH$_3$-CD$_3$CN**), but the rate of formation of CH$_3$TFA is much slower than the reactions in CD$_2$Cl$_2$. Thus, after 30 min only ∼2.3% CH$_3$TFA is generated in the CD$_3$CN reactions. When the reaction was followed by ^{1}H NMR over 20 h, the rate at which **2-CH$_3$-CD$_3$CN** disappeared (Figure S13, in the Supporting Information) is faster than the rate at which MeTFA is formed, and several other unidentified organometallic products are produced. Since CD$_3$CN is a more coordinating solvent than CD$_2$Cl$_2$, this would seem to suggest that the reaction proceeds via loss of either OTf or the solvent. Consistent with this, when the reaction is carried out in pyridine-d_5 at 21 °C, Ir(NN)(NC)CH$_3$(C$_5$D$_5$N)](OTf) (**2-CH$_3$-Py-d$_5$**) is formed immediately, but the functionalization reactions are completely inhibited and no oxy functionalized methyl products are observed after 11 h with any oxidant.

Plausible mechanisms[12] for this functionalization could involve (a) formation of an Ir(V) intermediate, such as shown in Figure 1B,D,[13] (b) concerted addition of PhIX$_2$ across the Ir−CH$_3$ bond, and (c) one-electron transfer or free radical reactions. Of these, we favor formation of an Ir(V) intermediate, but the data do not allow the other possibilities to be ruled out. To determine if oxygen plays a role, the functionalization reactions were carried out under an atmosphere of pure oxygen at 21 °C. Under these conditions the rate of disappearance of **2-CH$_3$** did not change significantly in either CH$_2$Cl$_2$ or CH$_3$CN ($k = [6.00\ (\pm 0.38)] \times 10^{-5}\ \mathrm{s}^{-1}$ under N$_2$ and $k = [3.90\ (\pm 0.06)] \times 10^{-5}\ \mathrm{s}^{-1}$ under O$_2$ for CH$_3$CN; Figure S13). However, the reaction yield did change. In the case of CH$_3$CN the yield increased from 14.8% to 48.2%, but in CH$_2$Cl$_2$ the yield decreased from 60.9% to 17.2%. Other oxidants such as iodosylbenzene and NOBF$_4$ were also investigated; however, no CH$_3$OTf was observed with these oxidants. When oxidants such as iodine or bromine were used, CH$_3$I and CH$_3$Br were formed on mixing in essentially quantitative yield in acetonitrile at 25 °C.

Iodobenzene dicarboxylates have been shown to react with nucleophiles via both non-radical nucleophilic substitution pathways and cationic radical pathways.[14] While free-radical reactions[15] cannot be ruled out, given the change in reaction yield with O$_2$ we favor a reaction mechanism involving oxidation to Ir^V−R, followed by reductive formation of the methyl ester product. Crabtree has shown that Pd(OAc)$_2$ catalyzes the acetoxylation of benzene with PhI(OAc)$_2$ to form phenyl acetate, which is proposed to go through a Pd(IV) intermediate.[16] Recently, Sanford has shown that iodobenzene diacetate was capable of oxidizing Pd(II) cyclometalated complexes to oxy functionalized products via intermediate formation of Pd(IV).[17]

In an attempt to develop a catalytic process, we also investigated whether **2-CH$_3$** was sufficiently stable and active to catalyze the CH activation reaction with methane or benzene. Initial tests showed that **2-CH$_3$** does not catalyze H/D exchange between CH$_4$ and CF$_3$CO$_2$D or D$_2$SO$_4$ at temperatures up to 208 °C after 21 h. Significantly, however, demonstrating the thermal and protic stability of the complex, ^{1}H NMR of the reaction mixtures showed that, while protonolysis of the Ir−CH$_3$ group occurs in these solvents to generate methane (only CH$_3$D is observed), no loss of the NN and NC spectator ligands is observed. The complex **2-CH$_3$** does undergo stoichiometric

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(11) (a) Novak, F.; Speiser, B.; Mohammad, H. A. Y.; Mayer, H. A. *Electrochim. Acta* **2004**, *49*, 3481. (b) Castillo-Blum, S. E.; Richens, D. T.; Sykes, A. G. *Inorg. Chem.* **1989**, *28*, 954. (c) Diversi, P.; Iacoponi, S.; Ingrosso, G.; Laschi, F.; Lucherini, A.; Pinzino, C.; Uccello-Barretta, G.; Zanello, P. *Organometallics* **1995**, *14*, 3275.

(12) A reviewer has suggested another mechanism that involves nucleophilic attack of acetate (or trifluoroacatate) at the Ir-bound Me group, which might also explain the lack of reactivity of the phenyl complex.

(13) Tamura, H.; Yamazaki, H.; Sato, H.; Sakaki, S. *J. Am. Chem. Soc.* **2003**, *125*, 16114.

(14) (a) Hamamoto, H.; Hata, K.; Nambu, H.; Shiozaki, Y.; Tohma, H.; Kita, Y. *Tetrahedron Lett.* **2004**, *45*, 2293. (b) Moriarty, R. M.; Prakash, O. *Acc. Chem. Res.* **1986**, *19*, 244 and references therein. (c) Kita, Y.; Tohma, H.; Hatanaka, K.; Takada, T.; Fujita, S.; Mitoh, S.; Sakurai, H.; Oka, S. *J. Am. Chem. Soc.* **1994**, *116*, 3684.

(15) An example of alkane oxidation through a cation radical mechanism: In, J.-H.; Park, S.-E.; Song, R.; Nam, W. *Inorg. Chim. Acta* **2003**, *343*, 373.

(16) Yoneyama, T.; Crabtree, R. H. *J. Mol. Catal. A: Chem.* **1996**, *108*, 35.

(17) (a) Dick, A.; Sanford, M. S. *Tetrahedron* **2006**, *62*, 2439. (b) Dick, A. R.; Kampf, J. W.; Sanford, M. S. *J. Am. Chem. Soc.* **2005**, *127*, 12790. (c) Desai, L. V.; Hull, K. L.; Sanford, M. S. *J. Am. Chem. Soc.* **2004**, *126*, 9542.

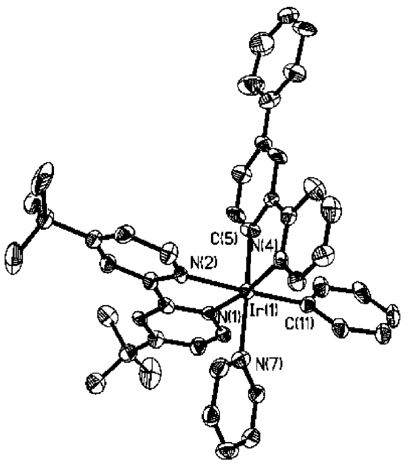
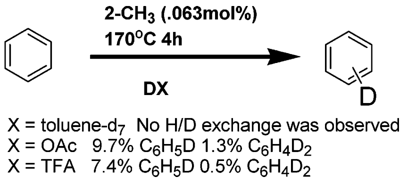
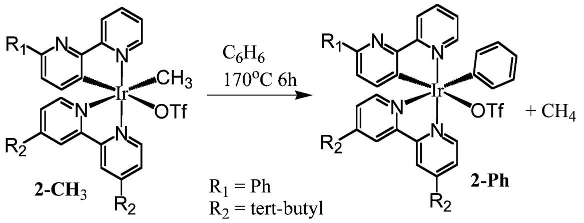


Figure 4. Thermal ellipsoid plot of **2-PhPy** at the 50% probability level. Hydrogens, triflate, $CDCl_3$, and water cosolvent are omitted for clarity.

Scheme 2. Catalytic H/D Exchange between Benzene and Acids with 2-CH_3



CH activation in neat benzene (170 °C, under argon) to quantitatively generate Ir(NC)(NN^{tBu})(Ph)OTf (**2-Ph**) and methane (eq 2). As indicated above, no oxy-functionalized methyl products are formed in these reactions. This phenyl product has been fully characterized by ^1H, ^{13}C, and ^{19}F NMR spectroscopy, elemental analysis, and X-ray crystallography (Figure 4.).



(2)

Complex **2-CH_3** does *not* catalyze H/D exchange between benzene and toluene-d_8, but it is an efficient catalyst for H/D exchange between acetic or trifluoroacetic acids and benzene (Scheme 2), presumably via CH activation reactions that reversibly generate the phenyl complex, **2-Ph**. Thus, when a 3.50 mM solution of **2-CH_3** in a 1:1 mixture of C_6H_6 and acetic acid-d_4 was heated at 170 °C for 4 h, 11% of the benzene (180 turnovers) was converted into a mixture of deuterated isotopologues, which consisted mainly of C_6H_5D. The activity slowly drops over time, and preliminary studies suggest that this could be due to catalyst deactivation by formation of acetate-bridged dinuclear complexes. Interestingly, while H/D exchange is also observed in trifluoroacetic acid, the reaction was slower than in acetic acid. Thus, when a 4.56 mM solution of **2-CH_3** in 1:1 C_6H_6/trifluoroacetic acid-*d* was heated at 170 °C for 4 h, 7.9% of the benzene (97 turnovers, as apposed to 180 in acetic acid) was converted into a mixture of deuterated isotopologues, which consisted mainly of C_6H_5D. Since benzene and trifluoroacetic acid-*d* show a background exchange, the reported values are corrected by subtraction of this non-metal-catalyzed exchange from the total exchange observed in the presence of the metal catalysts.

Since **2-CH_3** efficiently catalyzes the H/D exchange between benzene and acetic acid, presumably via benzene CH activation, and also efficiently generates oxy functionalized products, we explored the possibility that **2-CH_3** could catalyze the acetoxylation of benzene by carrying out the H/D exchange reaction in the presence of $PhI(OAc)_2$. Thus, a 12.9 mM solution of **2-CH_3** in a 1:1 mixture of C_6H_6 and acetic acid-d_4 was heated at 170 °C for 8 h with 19.3 equiv of iodobenzene diacetate. Interestingly, no formation of phenyl acetate was observed. To understand whether it was instability of the catalyst, inhibition of CH activation, or inefficient functionalization that prevented catalytic oxidation, we examined the reaction in greater detail. Significantly, it was found that addition of iodobenzene diacetate did not inhibit the CH activation reaction and H/D exchange between benzene and acetic acid was observed (~42% conversion, ~360 TON) over the reaction period in the presence of this oxidant. These results show that these (NN)(NC)Ir^{III} complexes are stable to the presence of relatively strong oxidants and acidic solvents at elevated temperatures and that neither poor stability nor inhibition of CH activation could explain the lack of oxy functionalization. Importantly, however, while oxy functionalization of the methyl complex **2-CH_3** with $PhI(TFA)_2$ is relatively efficient, preliminary results show that oxy functionalization of the corresponding phenyl complex **2-Ph** does not proceed. Thus, treatment of **2-Ph** with $PhI(X)_2$ (X = OAc, TFA) did not generate PhX, indicating that the phenyl complex **2-Ph** is much less reactive toward functionalization than the methyl complex **2-Me**. Consistent with this, preliminary CV analyses of the phenyl complex **2-Ph** show only one oxidation wave at $E_{1/2} = +0.79$ V (instead of the two observed for the methyl complex **2-CH_3)**. These results would tend to suggest that the lack of acetoxylation of benzene likely results from the lack of efficient functionalization of the phenyl complex **2-Ph**, generated from CH activation. Efforts are underway to understand the requirements for oxy functionalization of this complex and to determine whether these reactions proceed via an Ir^V−R intermediate followed by reductive functionalization.

In summary, we report the synthesis of a new air-, protic-, and thermally-stable bis-bidentate cyclometalated iridium complex, Ir(NN)(NC)CH_3OTf (**2-CH_3**), which reacts in a stoichiometric CH activation reaction with benzene to generate the corresponding phenyl complex **2-Ph**, as well as catalytic benzene CH activation in the presence of acetic or trifluoroacetic acids. When it is treated with oxidants such as iodobenzene bis(trifluoroacetate), **2-CH_3** gives rise to the first example of an Ir(III) alkyl complex undergoing functionalization to oxygenated products.

Acknowledgment. We thank Ken Conklin (UCLA) for running the mass spectra. We thank Mohammad Yousufuddin and Timmothy Stewart for X-ray structure determinations. We thank Prof. William C. Kaska, Dr. Peter Djurovich, and William Tenn III for helpful discussions. We acknowledge the National Science Foundation (Grant No. CHE-0328121) and Chevron Texaco Energy Technology Co. for financial support of this research.

Supporting Information Available: Text, figures, and tables giving details of the synthesis of **2-CH_3**, spectroscopic details, crystallographic data, cyclic voltammetry data, oxidation studies, and H/D exchange experiments for **2-CH_3** and CIF files giving crystal data for **2-CH_3** and **2-PhPy**. This material is available free of charge via the Internet at http://pubs.acs.org.

OM0611002