J|A|C|S COMMUNICATIONS

Published on Web 08/24/2010

Acceleration of Nucleophilic CH Activation by Strongly Basic Solvents

Brian G. Hashiguchi,[‡] Kenneth J. H. Young,[†] Muhammed Yousufuddin,[§] William A. Goddard III,[||] and Roy A. Periana*,[‡]

The Scripps Energy Laboratories, The Scripps Research Institute, Scripps Florida, Jupiter, Florida 33458, Department of Chemistry, University of Southern California, Los Angeles, California 90089, Center for Nanostructured Materials, The University of Texas at Arlington, Arlington, Texas 76019, and Materials and Process Simulation Center, California Institute of Technology, Pasadena, California 91125

Received March 26, 2010; E-mail: rperiana@scripps.edu

Abstract: (IPI)Ru(II)$(OH)_n(H_2O)_m$, **2**, where IPI is the NNN-pincer ligand, 2,6-diimidizoylpyridine, is shown to catalyze H/D exchange between hydrocarbons and strongly basic solvents at higher rates than in the case of the solvent alone. Significantly, catalysis by **2** is accelerated rather than inhibited by increasing solvent basicity. The evidence is consistent with the reaction proceeding by base modulated nucleophilic CH activation.

There is ongoing interest in metal mediated CH activation[1] reactions as a platform for designing hydrocarbon functionalization catalysts. We recently suggested that the various named CH activation reactions can be broadly classified on a continuum of electrophilic, ambiphilic or nucleophilic character depending on the net direction of charge transfer between the CH bond and the metal fragment in the transition state for CH cleavage.[2] The most effective catalysts reported for the selective, facile conversion of alkanes to oxygenates require strongly acidic solvents and operate by electrophilic CH activation followed by functionalization of the M−R intermediates.[1d] An important basis for the efficiency of these systems is that both CH activation and functionalization are compatible with and accelerated by strong acid solvents. The key issue with these electrophilic systems, as with most known CH activation systems, is inhibition by coordinating species (such as H_2O and alcohols) through formation of stabilized ground states that inhibit hydrocarbon coordination.[3]

We have shown that an essential role of the strong acid solvent is ligand protonation that facilitates *both CH activation and functionalization*.[4] In the case of M−R functionalization, this increases the electrophilicity of the R group and facilitates reductive functionalization. In the case of CH activation, ligand protonation facilitates both coordination of the alkane by generating, new, less stable catalyst ground states (e.g., by protonation of coordinated water) and CH cleavage by increasing catalyst electrophilicity.[4] The basis for this increase in electrophilicity is shown conceptually in Figure 1A. Ligand protonation removes electron density at the metal center, leading to a lower energy metal based LUMO that facilitates interaction with the low lying CH HOMO.

Recently, we and others reported the first examples of efficient ambiphilic or nucleophilic CH cleavage[2] by d^6 Ir^{III} and Ru^{II} ligated metal cations with alkoxo[5] and hydroxo[6] ligands. The two key distinguishing features of nucleophilic systems are that (1) the metal centers utilized are both weakly electrophilic and oxidizing and characterized by good π-donor properties that result from high lying,

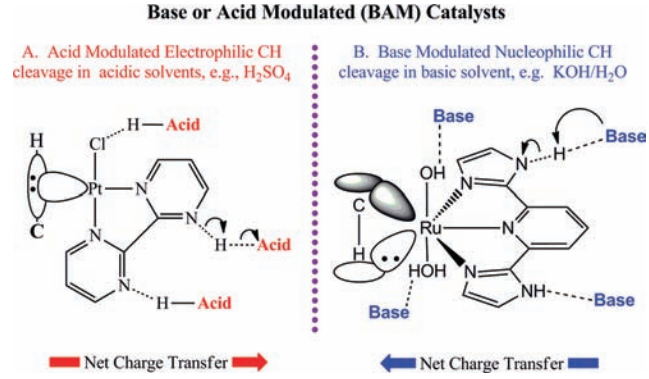
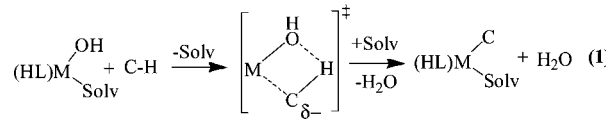
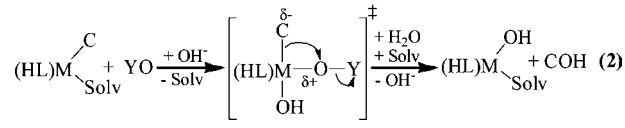


Figure 1. Conceptual diagram showing how ligand *protonation* by acids (A) and *deprotonation* by bases (B) can increase reactivity for electrophilic and nucleophilic CH cleavage reactions, respectively.

high electron count nonbonding orbitals and (2) the ligands are strong electron donors, e.g., OH^-. Significantly, these systems show much less sensitivity to inhibition by coordinating species such as water and could provide a basis for the design of CH conversion catalysts that can directly and efficiently generate coordinating products such as alcohols, amines, carboxylates, etc.



Our theoretical calculations show that these nucleophilic systems can cleave CH bonds by 4-centered transition states involving the basic hydroxide group (eq 1).[7] Recently, we also showed that M−R complexes from this nucleophilic class *cannot* be functionalized by pathways that operate for strongly electrophilic, oxidizing metals.[8] Instead, new functionalization pathways were identified with these (nucleophilic) M−R complexes that, significantly, *require basic aqueous OH^- solvents for high efficiency*.[9] In these pathways, coordination of OH^- to M−R increases the nucleophilicity of R, facilitating the reaction with weakly electrophilic O-atom donors to generate alcohols (eq 2). Consequently, we expect that designing new catalysts by coupling nucleophilic CH activation reactions with base-assisted functionalization of the resulting nucleophilic M-R intermediates will require that the CH activation reaction be compatible and ideally accelerated by basic solvents.

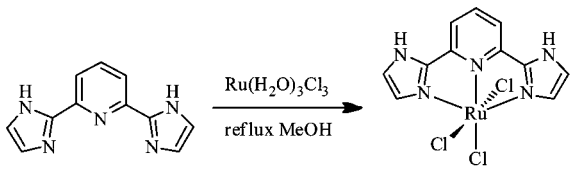


‡ Scripps Florida.
† University of Southern California.
§ The University of Texas at Arlington.
|| California Institute of Technology.

10.1021/ja102518m

Low activation barriers for CH activation to generate M−R intermediates require both low energy transition states for cleavage of the coordinated CH bond and high energy, reactive ground states that are sufficiently labile to facilitate CH coordination. Analogous to how ligand *protonation* by acid solvents accelerates electrophilic CH cleavage (Figure 1A), we considered that *reversible ligand deprotonation of protic ligands by strongly basic solvents* could also accelerate CH cleavage by systems that operate via *nucleophilic* CH activation (Figure 1B).[10] As shown, increasing electron *donation* to the metal center by ligand deprotonation with a basic solvent could enhance the π-nucleophilicity of metal complexes by *raising* the energy of metal-based, filled, nonbonding, π-donor orbitals (the HOMO) and facilitate interaction with the high lying, antibonding orbitals of the CH bond (the LUMO). Significantly, this effect should be exhibited by deprotonation of *any* protic ligand and show a dependence on the basicity of the solvent when the deprotonation is reversible.[11] Aqueous KOH could be an ideal basic solvent and could facilitate *in situ* generation of the active M−OH catalyst.

Key to utilizing this concept is the requirement that KOH should not inhibit substrate coordination by generating highly stable M−OH ground states. Since H_2O is known to inhibit most CH activation systems by generation of stable ground states[3] and OH^- is generally considered to be much more coordinating than H_2O, this may seem to be implausible. However, we reasoned that this type of ground state inhibition could be prevented or minimized with nucleophilic metals since the M−OH complexes of these metals are known to be basic.[12] Thus, a strongly basic M−OH could be *less* stable than the corresponding M−H_2O complex and use of KOH solvent should not lead to inhibition. Indeed, in such systems, along with increasing the π-nucleophilicity (*vide supra*), deprotonation of an aquo complex (e.g., $M(OH_2)_2$) in strongly basic solvents could generate more labile and reactive metal hydroxo (e.g., $M(OH)(H_2O)$) ground states. This expected effect is related to the long known observations by Basolo and others that bases can catalyze ligand substitution by decreasing the electrophilicity of the metal center through reversible deprotonation of protic spectator ligands.[13] These considerations led us to investigate whether $(HL)M(OH)_n(H_2O)_m$ type complexes, where M is a strong π-nucleophile and HL is a *protic*, polydentate ligand, could be compatible with and ideally accelerated by aqueous KOH for nucleophilic CH activation.



(3)

1

We report herein the first observation that aqueous KOH can accelerate, rather than inhibit, nucleophilic CH activation by a d^6 $(HL)Ru^{II}(OH)_n(H_2O)_m$ complex. A key challenge in designing such base modulated catalysts was to identify nucleophlic M−OH complexes that would be soluble and thermally stable in strongly basic aqueous solvents and with protic ligands that could be reversibly deprotonated by strong bases. Among several systems investigated, $(IPI)Ru^{III}Cl_3$, **1**, where IPI is the tridentate, NNN-pincer ligand, 2,6-diimidizoylpyridine (IPI),[14] was selected as a good candidate to observe base modulated catalysis because (1) *in situ* $1e^-$ reduction should generate a desired high electron count d^6, Ru^{II} center; (2) reversible reaction with aqueous KOH should generate a range of highly labile, strong π-donor water-soluble complexes $(L)Ru^{II}(OH)_n(H_2O)_m$ by chloride displacement and deprotonation of the IPI, aquo, and/or hydroxo ligands; and (3) the tridentate IPI could impart catalyst stability. Complex **1** was synthesized as shown in eq 3 and was fully characterized by elemental analysis, X-ray crystallography (Figure 2), IR, and HR-MS. **1** is not soluble in neutral water but is readily soluble in >1 M KOH at room temperature. The chlorides of **1** are quite labile, and recrystallization from wet DMSO can lead to O-bridged species.[15] Treatment of brown-red KOH solutions of **1** at room temperature with Zn dust led to a rapid color change to a deep purple solution. Other reductants such as $NaBH_4$, H_2PO_3, H_2, Al, Mg, etc. showed varying levels of reduction but were not as clean as Zn. As expected ^1H and ^{13}C analysis of the reaction mixture showed that several diamagnetic, IPI coordinated, putative $(IPI)Ru^{II}(OH)_n(H_2O)_m$ species were formed, designated as **2**, presumably due to various levels of ligand deprotonation (*vide supra*) by solvent.

Consistent with **2** as a mixture of labile, equilibrating, $(IPI)Ru^{II}$ species, addition of several equivalents of KCN at room temperature led to an immediate color change and formation of a single diamagnetic, IPI coordinated species. Quantitative ^{13}C NMR analysis of the crude reaction mixture prepared with $K^{13}CN$ shows a single species with a fully coordinated, symmetrical IPI ligand and two distinct cyanides in a 2 to 1 ratio. The material was crystallized from aqueous methanol and identified as $K[(IPI)Ru^{II}(CN)_3]$ on the basis of ^1H and ^{13}C NMR, IR, X-ray crystallography, elemental analysis, and mass spectrometry.

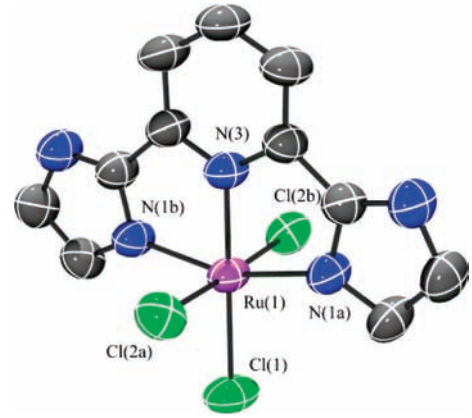


Figure 2. ORTEP representation of **1** (50% ellipsoids; the hydrogens and a DMSO molecule are removed for clarity); see Supporting Information (SI).

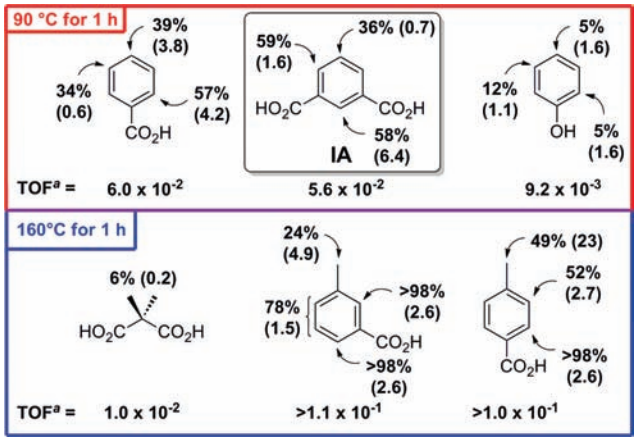
To examine whether **2** would catalyze CH activation in basic solvents, the rates of H/D exchange were examined using a 4 mL total internal volume PTFE-lined reactor equipped with a magnetic stir bar. Varying concentrations of KOD/D_2O with 3.0 mM of **2** prepared by *in situ* reduction of **1** with zinc dust were used at temperatures up to 160 °C. As expected, benzene is immiscible with aqueous KOH but H/D exchange of this two-phase system could be observed if rapidly stirred. To avoid mass transfer issues and simplify kinetic studies, we focused our studies on water-soluble hydrocarbons substrates. Use of phase transfer agents were not examined as these would likely complicate kinetic interpretation. *Importantly*, any H/D exchange due to reversible deprotonation by the basic solvent (hydrocarbons are very weak carbon acids) in the absence of catalyst (background reaction) was subtracted from the reported catalytic rates.

$$R{-}CH + D_2O \xrightarrow[\substack{3.7\ M\ KOD/D_2O,\\ 90\ or\ 160\ ^\circ C,\ 1\ h}]{1\ mol\ \%\ \mathbf{2}} R{-}CD + DHO \qquad (4)$$

As shown in Chart 1, **2** catalyzes the relatively fast H/D exchange between 3.7 M KOD in D_2O and the water-soluble substrates (eq 4).[16] Consistent with the reduced species, **2**, as the active catalyst

control experiments showed that **1** was inactive without reduction. Additionally, neither $RuCl_3$ (without IPI) nor free IPI ligand in the presence or absence of Zn catalyzed the H/D exchange. The IPI ligand is critical to the stability of **2** since addition of $RuCl_3$ to KOD/D_2O in the presence or absence of Zn immediately led to formation of insoluble, inactive, black precipitates (presumably Ru oxides) not observed upon reduction of **1**.

Chart 1. Selected Aromatic and Aliphatic Substrates Showing Relative Percent H/D Exchange with 3.7 M KOD/D_2O at 90 and 160 °C in the Presence and Absence (in brackets) of **1**



[a] TOF = $[product_{total} - background][\mathbf{1}]^{-1}$ $time^{-1}$. See SI for more data and other substrates.

The kinetics of the H/D exchange reactions are well behaved, showing a high degree of reproducibility and clean first order dependence on both **2** and the added substrate (**IA**) (Figure 3). To minimize the possible influence of steric interactions and chelation control on the CH activation reactions, only the CH bonds *meta* to the carboxylate groups of isophthalic acid (**IA**, Chart 1) were used in these kinetics studies. In general, aromatics (Chart 1) are substantially more reactive and were examined at 90 °C, where **2** is stable for at least 4 h. As can be seen, the water-soluble alkyl substrates were less reactive and examined at 160 °C. At this temperature the catalyst is stable for ~1 h. At low substrate conversion only monodeuteration of the methyl groups was observed. As discussed above, H/D exchange is observed in a two-phase system with benzene at 90 °C, but no detectable exchange was observed with methane or soluble long chain alkyl carboxylates at temperatures up to 160 °C for 1 h. We believe this is due to the expected lower reactivity of the alkanes. As noted above, higher temperatures could not be examined due to the thermal instability of **2** above 160 °C.

The emphasis in this communication is neither the absolute rates of H/D exchange nor a comparison to reported systems. The key focus was to determine whether CH activation catalysts could be designed that were not inhibited in basic solvents and whether strongly basic solvents would lead to base modulated catalysis and acceleration. However, some comparison is useful to begin to access the potential of this approach. To our knowledge there are no reports of CH activation systems that benefit from the use of basic solvents and the closest comparisons are with H/D exchange studies in D_2O as the solvent.[17] Of these, the most analogous system is the use of water-soluble $Cp^*Ir(PMe_3)Cl_2$ reported by Bergman[17a] that catalyzes H/D exchange between water-soluble aryl and alkyl carboxylates and D_2O with TOFs of 1.6×10^{-4}–8.8×10^{-4} s^{-1} obtained at 135 °C over 40 h.[18] Figure 3 shows that the rates of H/D exchange for arenes catalyzed by **2** compare favorably to this system and are faster in some cases.

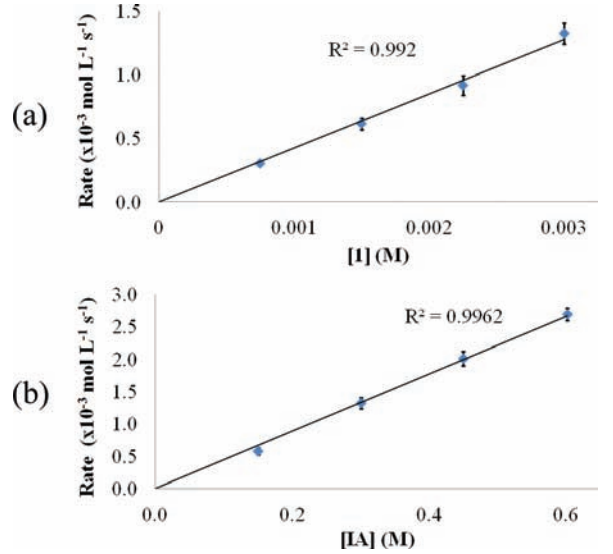


Figure 3. (a) Rate of H/D exchange as a function of [**1**] with [**IA**] = 0.3 M at 80 °C for 1 h in 3.7 M KOD/D_2O (where rate = $([\mathbf{IA}]_0 - [\mathbf{IA}]_{Final})time^{-1}$) and (b) Rate of H/D exchange as a function of [**IA**] with [**2**] = 3.0 mM at 80 °C for 1 h in 3.7 M KOD/D_2O.

To test for the possibility of base modulated catalysis, the rate of H/D exchange was examined as a function of [KOD]. Isophthalic acid (**IA**) was utilized for this study as it was soluble from 1.5 M to a maximum of 8 M [KOH] whereas the other substrates were insoluble above ~4 M [KOH]. Significantly, as shown in Figure 4, the rate of H/D exchange catalyzed by **2** is *accelerated* rather than inhibited by increasing [KOD] over the entire 1.5 to 8 M range.

We consider that this data is consistent with H/D exchange proceeding by reversible CH activation involving coordination of the CH bond and concerted, rate-determining nucleophilic CH cleavage to generate Ru−R intermediates. Consistent with a mechanism involving substrate coordination, addition of 5 equiv of water-souble sodium nicotinate or potassium cyanide (both poor σ-donors and relatively weak π-acids) relative to **2** (~6 mM) inhibits all catalytic H/D exchange at 90 °C even though the solution remains homogeneous. Significantly, as shown in Chart 1, the less acidic, stronger aromatic CH bonds (benzene: $pK_a = 43$, BDE = 110.9 kcal/mol)[19b] are more reactive than the more acidic, weaker benzylic CH bonds (toluene: $pK_a = 41$, BDE = 88.0 kcal/mol).[19b] If the reaction proceeded by simple reversible C−H deprotonation by the Ru^{II}−OH species, as observed with analogous amido complexes by Bergman and others,[12] then the more acidic CH bonds should show higher H/D exhange rates (as observed for the background acid−base reactions, *vide supra*). Higher rates of reaction at the stronger aromatic CH bonds would also rule against free radical, radical cationic, and anionic pathways. The well behaved kinetics, ligand inhibition, good reproducibility, and reaction with water-soluble alkyl substates are also consistent with a CH activation mechanism.

The increase in H/D exchange rate with increasing [KOH] would require that [KOH] is involved in the rate-determining step(s) for CH activation. This would be the case if reversible deprotonation of *any* ligand[20] by OH^- facilitated both substrate coordination (see SI for proposed rate law) and/or CH cleavage by increasing the nucleophilicity of the metal center (*vide supra*). Another possibility is that the outer sphere, solvent OH^-, could facilitate rate-determining cleavage of CH bonds coordinated to the Ru(II) center. A proposed mechanism based on reversible ligand deprotonation is shown in Figure 5.

As discussed above, we could not examine [KOD] above 8 M due to substrate insolubility. However, we anticipate that since reactivity likely correlates with the activity of OH^- (see derived rate law in SI)

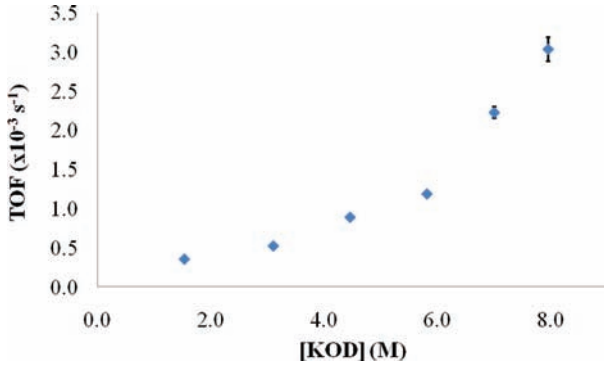


Figure 4. Plot of TOF vs [KOD] for the H/D exchange reaction between the *meta*-position of isophthalic acid and KOD/D_2O at 50 °C for 1 h.

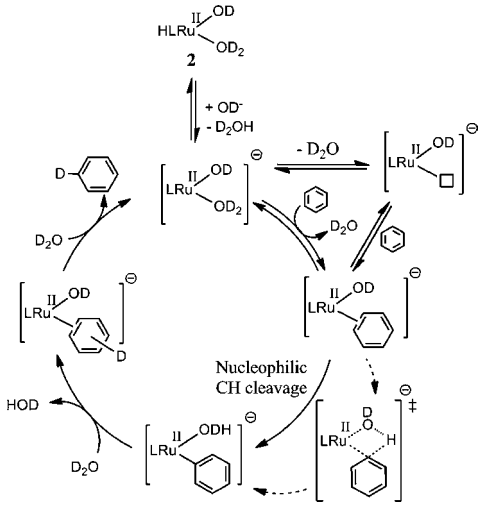


Figure 5. Proposed reaction mechanism for H/D exchange involving reversible ligand deprotonation followed by water loss, substrate coordination, reversible CH activation, and loss of product.

the reactivity could continue to accelerate since the activity of OH^- of concentrated aqueous KOH is known to increase exponentially at higher concentrations.[21] Other possibilities for continued acceleration could be that, as with electrophilic catalysts in neat strong acidic solvents,[4] very concentrated basic solvents might generate, new, less stable, more reactive ground states (e.g., by complete deprotonation of a protic ligand) or open new, lower energy CH cleavage pathways, involving, e.g., Ru−O^- species. These possibilities are being examined theoretically and experimentally.

In summary, (IPI)$Ru^{II}(OH)_n(H_2O)_m$, **2**, catalyzes facile H/D exchange reactions between water-soluble hydrocarbons and strongly basic KOD/D_2O solvent at rates faster than in the case of the solvent alone. We propose that catalysis proceeds via reversible nucleophilic CH activation. Significantly, the reaction is accelerated by increasing the solvent basicity which we propose to result from reversible ligand deprotonation and the resulting increase in ligand lability and π-nucleophilicity of the Ru^{II} catalyst. We are continuing to study this and related systems with the ultimate goal of understanding how to couple base accelerated CH activation with base accelerated functionalization of the M−R intermediates in an effort to design new hydrocarbon functionalization systems that are not inhibited by coordinating substrates. We believe that this concept of base modulated catalysis through ligand deprotonation in strongly basic solvents could be extended to activate other weak π-acceptors (e.g., N_2, CO_3^{2-}, etc.), and these studies are underway.

Acknowledgment. The mechanistic studies were supported as part of the Center for Catalytic Hydrocarbon Functionalization, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Award Number DE-SC0001298. The authors acknowledge helpful discussions with Dr. Daniel H. Ess, Dr. Robert J. Nielsen, Dr. Kapil S. Lokare, and Steven M. Bischof. We thank Chevron Corporation for partial financial support for this research.

Supporting Information Available: Synthetic procedures, spectroscopic details, crystallographic data, and catalysis procedures for **2**. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) We define the CH activation reaction as a coordination reaction that proceeds without the involvement of free radicals, carbocations, or carbanions to generate discrete M−R intermediates. (a) Shilov, A. E.; Shul'pin, G. B. *Chem. Rev.* **1997**, *97*, 2879. (b) Arndtsen, B. A.; Bergman, R. G.; Mobley, T. A.; Peterson, T. H. *Acc. Chem. Res.* **1995**, *28*, 154. and citations therein. (c) Periana, R. A.; Bhalla, G.; Tenn, W. J., III; Young, K. J. H.; Liu, X. Y.; Mironov, O.; Jones, C.; Ziatdinov, V. R. *J. Mol. Catal. A: Chem.* **2004**, *220*, 7. and citations therein. (d) Conley, B. L.; Tenn, W. J., III; Young, K. J. H.; Ganesh, S. K.; Meier, S. K.; Ziatdinov, V. R.; Mironov, O.; Oxgaard, J.; Gonzales, J.; Goddard, W. A., III; Periana, R. A. *J. Mol. Catal. A: Chem.* **2006**, *251*, 8. (e) Crabtree, R. H. *J. Organomet. Chem.* **2004**, *689*, 4083. (f) Lersch, M.; Tilset, M. *Chem. Rev.* **2005**, *105*, 2471.

(2) Ess, D. H.; Nielsen, R. J.; Goddard, W. A., III; Periana, R. A. *J. Am. Chem. Soc.* **2009**, *131*, 11686.

(3) Kua, J.; Xu, X.; Periana, R. A.; Goddard, W. A., III. *Organometallics* **2002**, *21*, 511.

(4) Ahlquist, M.; Periana, R. A.; Goddard, W. A., III. *Chem Commun.* **2009**, 2373.

(5) (a) Tenn, W. J.; Young, K. J. H.; Oxgaard, J.; Nielsen, R. J.; Goddard, W. A., III; Periana, R. A. *Organometallics* **2006**, *25*, 5173. (b) Tenn, W. J., III; Young, K. J. H.; Bhalla, G.; Oxgaard, J.; Goddard, W. A. III; Periana, R. A. *J. Am. Chem. Soc.* **2005**, *127*, 14172. (c) Young, K. J. H.; Oxgaard, J.; Ess, D. H.; Meier, S. K.; Stewart, T.; Goddard, W. A., III; Periana, R. A. *Chem. Commun.* **2009**, 3270.

(6) (a) Foley, N. A.; Lee, J. P.; Ke, Z.; Gunnoe, T. B.; Cundari, T. R. *Acc. Chem. Res.* **2009**, *42*, 585. and citations therein. (b) Meier, S. K.; Young, K. J. H.; Ess, D. H.; Tenn, W. J., III; Oxgaard, J.; Goddard, W. A., III; Periana, R. A. *Organometallics* **2009**, *28*, 5293.

(7) (a) Oxgaard, J.; Muller, R. P.; Goddard, W. A., III; Periana, R. A. *J. Am. Chem. Soc.* **2004**, *126*, 352. (b) Lail, M.; Bell, C. M.; Conner, D.; Cundari, T. R.; Gunnoe, T. B.; Petersen, J. L. *Organometallics* **2004**, *23*, 5007.

(8) (a) 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. (b) Gonzales, J. M.; Distasio, R., Jr.; Periana, R. A.; Goddard, W. A., III; Oxgaard, J. *J. Am. Chem. Soc.* **2007**, *129*, 15794.

(9) Conley, B. L.; Ganesh, S. K.; Gonzales, J. M.; Ess, D. H.; Nielsen, R. J.; Ziatdinov, V. R.; Oxgaard, J.; Goddard, W. A., III; Periana, R. A. *Angew. Chem., Int. Ed.* **2008**, *47*, 7849.

(10) Himeda, Y.; Onozawa-Komatsuzaki, N.; Sugihara, H.; Kasuga, K. *Organometallics* **2007**, *26*, 702.

(11) Irreversible deprotonation of *all* protics ligands will prevent further modulation of the catalysis by ligand deprotonation at higher basicities.

(12) Fulton, J. R.; Holland, A. W.; Fox, D. J.; Bergman, R. G. *Acc. Chem. Res.* **2002**, *35*, 44. and citations therein.

(13) (a) Basolo, F. *Pure Appl. Chem.* **1968**, *17*, 37. (b) Jackson, W. G. *Inorg. React. Mech.* **2002**, *4*, 1. (c) See SI for conjugate mechanism.

(14) (a) Stupka, G.; Gremaud, L.; Bernardinelli, G.; Williams, A. F. *Dalton Trans.* **2004**, *40*, 7–412, and citations therein. (b) Voss, M. E.; Beer, C. M.; Mitchell, S. A.; Blomgren, P. A.; Zhichkin, P. E. *Tetrahedron* **2008**, *64*, 645.

(15) Based upon X-ray analysis, see SI for details.

(16) In a typical experiment a 0.3 M solution of substrate in 3.7 M KOD was heated with 1 mol % of **2** in the presence of excess zinc at 90 °C for 1 h with sp^2 substrates and 160 °C for 1 h with sp^3 substrates. After a cooling step, addition of an internal standard (0.2 mL of 1.05 M CH_3CO_2K/KOD solution) and ^1H NMR analysis were used to monitor the incorporation of deuterium into the substrates. ^2H NMR spectroscopy showed deuterium incorporation into IA.

(17) (a) Klei, S. R.; Golden, J. T.; Tilley, T. D.; Bergman, R. G. *J. Am. Chem. Soc.* **2002**, *124*, 2092. (b) Prechtl, M. H. G.; Hölscher, M.; Ben-David, Y.; Theyseen, N.; Loschen, R.; Milstein, D.; Leitner, W. *Angew. Chem., Int. Ed.* **2007**, *119*, 2319. and citations therein. (c) Meier, S. K.; Young, K. J. H.; Ess, D. H.; Tenn, W. J., III; Oxgaard, J.; Goddard, W. A., III; Periana, R. A. *Organometallics* **2009**, *28*, 5293. and citations therein. (d) Feng, Y.; Jiang, B.; Boyle, P. A.; Ison, E. A. *Organometallics* **2010**, *29*, 2857.

(18) TOF = [product][catalyst]$^{-1}$ time^{-1} is approximated by TON_{total}/time, where TON_{total} = [product][catalyst]$^{-1}$.

(19) (a) Fulton, J. R.; Bouwkamp, M. W.; Bergman, R. G. *J. Am. Chem. Soc.* **2000**, *122*, 8799–8800. (b) Fulton, J. R.; Sklenak, S.; Bouwkamp, M. W.; Bergman, R. G. *J. Am. Chem. Soc.* **2002**, *124*, 4722.

(20) The pK_a of free IPI is ~14, but that of the coordinated IPI will depend on the other species coordination to Ru.

(21) Rochester, C. H. *Q. Rev. Chem. Soc.* **1966**, *20*, 511.

JA102518M