Activation of a C−H Bond in Indene by [(COD)Rh(μ_2-OH)]$_2$[†]

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The air- and water-tolerant hydroxy-bridged rhodium dimer [(COD)Rh(μ_2-OH)]$_2$ cleanly activates the aliphatic C−H bond in indene to generate [(COD)Rh(η^3-indenyl)]. The mechanism involves direct coordination of indene to the dimer followed by rate-determining C−H bond cleavage, in contrast to the previously reported analogous reactions of [(diimine)M(μ_2-OH)]$_2^{2+}$ (M = Pd, Pt), for which the dimer must be cleaved before rate-determining displacement of solvent by indene. Another difference is observed in the reactions with indene in the presence of acid: the Rh system generates a stable η^6-indene 18-electron cation, [(COD)Rh(η^6-indene)]$^+$, that is not available for Pd and Pt, which instead form the η^3-indenyl C−H activation products. The crystal structure of [(COD)Rh(η^6-indene)] is reported.

Introduction

The development of practical methods for the selective functionalization of C−H bonds could have a significant environmental and economic impact in areas ranging from fuels and commodity chemicals to pharmaceuticals.[1] As water will usually be a byproduct of oxidative functionalization (especially using O$_2$) and alcohols are often desirable products, the fact that most transition-metal complexes capable of activating C−H bonds are unstable or unreactive in the presence of water or alcohols represents a significant obstacle. Several groups have studied metal alkoxy and hydroxy complexes that effect C−H bond activation reactions even in the presence of free alcohols and, in some cases, water.[2−4]

Recently we have found that the air- and water-stable hydroxy-bridged dimers [(diimine)M(μ_2-OH)]$_2^{2+}$ as well as the bis(aquo) dications [(diimine)M(OH$_2$)]$^{2+}$ (M = Pd, Pt) can react with a variety of C−H bonds, subject to the requirement

that a multidentate ligand can result.[5−7] Mechanistic studies revealed that Pd dimers can react directly with indene in the presence of weakly coordinating solvents, such as 2,2,2-trifluoroethanol (TFE), whereas the Pt dimers require addition of acid to generate the bis(aquo) dication [(diimine)Pt(OH$_2$)$_2$]$^{2+}$, which then activates indene, albeit at higher temperatures than does the Pd dimer. The Pd bis(aquo) dication can also activate indene at elevated temperatures. In all cases displacement of the coordinated solvent by indene appears to be rate-limiting. Since we would expect solvent to be bound more strongly to a positively charged metal center, the rate of ligand displacement−and hence the overall rate of C−H activation−might be faster for neutral Rh analogues, possibly allowing more challenging hydrocarbons to be activated. Here, we report on C−H bond activation of indene by a neutral hydroxy-bridged Rh dimer.

Results and Discussion

The previously synthesized[8] air- and water-tolerant hydroxy-bridged dimer [(COD)Rh(μ_2-OH)]$_2$ (**1**; COD = 1,5-cyclooctadiene) does not appear to react with alkanes or benzene, as even in the presence of acid no H/D exchange could be observed, but it does react cleanly with indene to form an η^3-indenyl species, **2** (eq 1), in quantitative yield as determined by ^{1}H NMR spectroscopy. The kinetics of the reaction were followed by ^{1}H NMR spectroscopy under the conditions shown in eq 1, with varying [indene]; the reaction was found to be first order in [Rh] and [indene].[9] The kinetic isotope effect (KIE) for the reaction (determined from rate constants for parallel reactions between 1,1,3-trideuteroindene[10] and **1** to

[†]This paper is dedicated to Professor Jennifer C Green on the occasion of her retirement.

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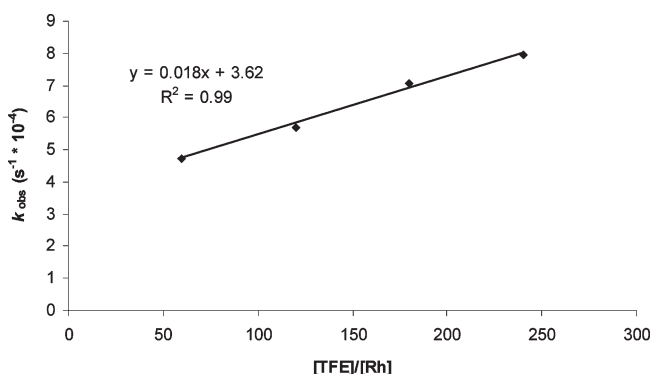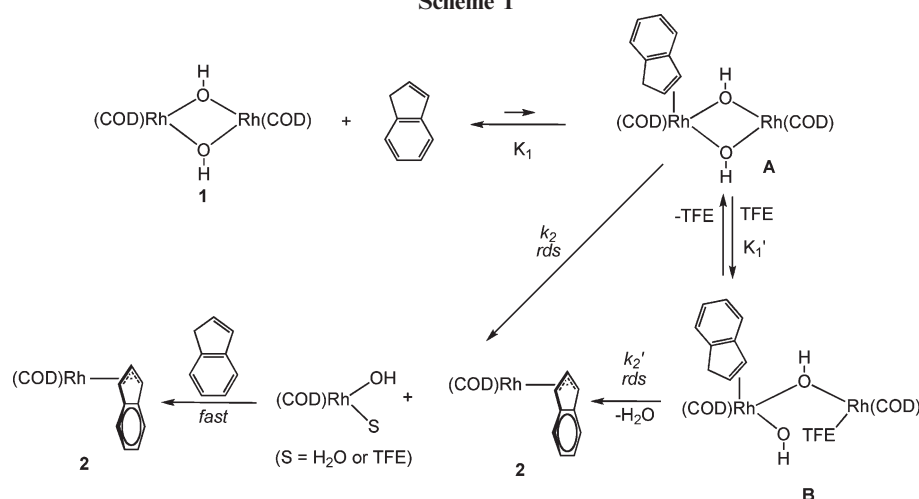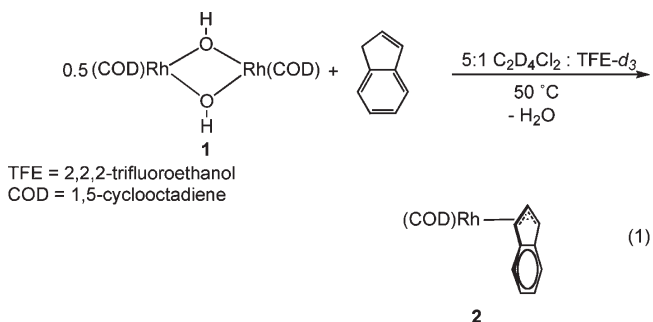
Scheme 1

Figure 1. Dependence of rate on [TFE] in the reaction of $[(COD)Rh(\mu_2\text{-}OH)]_2$ (**1**) with 10 equiv of indene at 50 °C.

form the deuterated indenyl complex **2-d_2** and between indene and **1** to form **2**) is $k_H/k_D = 4.2(2)$, consistent with rate-determining C–H bond cleavage.[11,12]

For comparison to the related Pd system, in which the rate exhibits first-order dependence on coordinating solvent,[6] further experiments were performed with varying [TFE]. The data (Figure 1) imply a two-term rate law, with one pathway showing first-order dependence on [TFE] and the other no dependence.

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(12) A KIE of 4.2 is consistent with a primary isotope effect, which suggests that C–H bond cleavage is involved in the rate-determining step; if the rate-determining step involved indene coordination (as proposed in the Pd systems),[6] then only a secondary isotope effect, less than 1.5, would be expected, by analogy to related arene C–H activations by Pt complexes.[11]

The first-order dependence on Rh and the substantial KIE suggest that reversible coordination of indene to the *intact* dimer is followed by rate-determining C–H bond cleavage, presumably involving abstraction of H^+ by OH^-, to give water, one molecule of indenyl product **2**, and one solvated Rh center, which undergoes rapid reaction with indene to give the second equivalent of **2**. In this scenario the initial pre-equilibrium must lie substantially on the side of starting dimer **1**, as no intermediate is detectable by ^1H NMR spectroscopy. Addition of TFE accelerates formation of **2** but does not change the first-order dependence on **1** and indene; therefore, the mechanism cannot be significantly different.

The mechanism shown in Scheme 1 appears most consistent with these observations. Formation of intermediate **A**, as well as **B** if TFE is present, involves rapid equilibria, with the concentrations of intermediates always very low relative to that of **1**. The acceleration by TFE may result from k_2' being greater than k_2—it seems reasonable that a terminal hydroxy group would be a more reactive hydrogen abstractor than a bridging one—or from the values of the equilibrium constants being such that the concentration of **B** is considerably higher, when TFE is present, than that of **A** in the absence of TFE, or from a combination of both factors. This mechanism may be contrasted with that found for the analogous Pd system, where the half-order dependence on [Pd] implies (solvent-aided) dissociation of the dimer before the rate-determining step.[6,13]

At this stage the detailed mechanism of C–H bond cleavage is unclear; possibilities include a σ-bond metathesis pathway similar to that described for Ru hydroxy complexes by Cundari and Gunnoe,[3] an internal electrophilic substitution analogous to that suggested by Periana and Goddard for Ir systems,[2] or even oxidative addition to generate Rh(III). (A mechanism such as that proposed by Goldberg and Heinekey for H–D exchange between water and benzene effected by (PNP)Rh(OR), which involves dissociation of alkoxide followed by coordination of benzene and subsequent deprotonation,[4] seems unlikely for the dimeric complex here.)

(13) An analogous mechanism involving a dimer–monomer pre-equilibrium followed by rate-determining indene C–H activation would give a half-order dependence on [Rh], whereas a first-order dependence is observed.
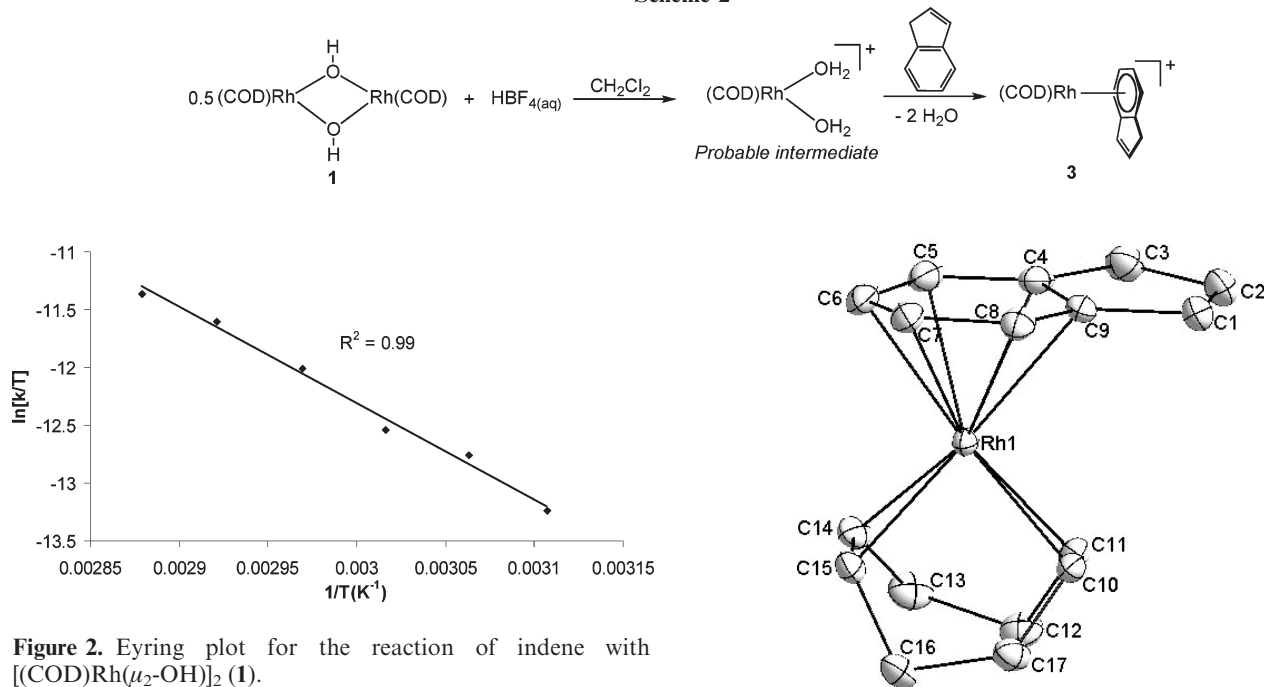
Scheme 2

Figure 2. Eyring plot for the reaction of indene with $[(COD)Rh(\mu_2\text{-}OH)]_2$ (**1**).

It may be noted that extrapolation of the line in Figure 1 to [TFE] = 0 gives a value of $k_{obs} = 3.6 \times 10^{-4}$ s^{-1}, a value which is significantly higher than that obtained under the same conditions, with the same indene concentration, in the absence of added TFE: $k_{obs} = [1.6(1)] \times 10^{-4}$ s^{-1}. We propose that this discrepancy may be explained by solvent effects: even at the lowest ratio of [TFE] to [Rh] employed (60:1), TFE comprises more than 10% of the solvent. Since the solvent polarity could affect the rate of the TFE-free pathway, the extrapolated and measured rates might well differ.

An Eyring analysis of experiments at different temperatures (Figure 2) gave the activation parameters for the reaction: $\Delta H^{\ddagger} = 69.4(2)$ kJ mol^{-1} and $\Delta S^{\ddagger} = -91(5)$ J mol^{-1} K^{-1}. The large entropic barrier is consistent with the proposed transition state, in which indene is coordinated to the Rh dimer but H_2O has not yet been released.

For further comparison to the Pd and Pt analogues, we examined the reactivity of **1** with indene in the presence of acid; as noted above, both of the dimers $[(diimine)M(\mu\text{-}OH)]_2^{2+}$ are protonated to the bis(aquo) dications $[(diimine)M(OH_2)]^{2+}$, which can activate C–H bonds (in the case of Pt, this is the only route to C–H bond activation).[5] Treatment of **1** with 2 equiv of aqueous HBF$_4$ resulted in a new ^{1}H NMR spectrum which exhibited several broad peaks. Most probably these arise from the bis(aquo) cation $[(COD)Rh(OH_2)_2]^+$ (although we were unable to isolate it; on further standing an intractable orange oil precipitated out of solution). Subsequent addition of 10 equiv of indene resulted in the clean formation of $[(COD)Rh(\eta^6\text{-}indene)]^+$ (**3**) (Scheme 2), whose structure was unambiguously confirmed by X-ray diffraction analysis (Figure 3; crystal and refinement data are given in Table 1). Unlike **2**, here the C$_6$ ring in indene is bound to the Rh as a neutral L$_3$-type ligand, in an η^6 fashion, to give a cationic species with 18 valence electrons.

In contrast to the Pd and Pt systems, where indene reacts with $[(diimine)M(OH_2)]^{2+}$ to give indenyl complexes with concomitant generation of H_3O^+, water is apparently unable to deprotonate the coordinated indene in **3**. Two possible

Figure 3. Solid-state structure of $[(COD)Rh(indene)]^+$ (**3**). Hydrogen atoms and the BF$_4^-$ counterion have been omitted for clarity. Selected bond distances of **3** (Å): Rh(1)–C(14) = 2.1296(11), Rh(1)–C(10) = 2.1303(11), Rh(1)–C(15) = 2.1444(11), Rh(1)–C(11) = 2.1474(11), Rh(1)–C(6) = 2.2226(11), Rh(1)–C(9) = 2.2766(10), Rh(1)–C(7) = 2.2979(13), Rh(1)–C(5) = 2.3238(13), Rh(1)–C(8) = 2.3268(12), Rh(1)–C(4) = 2.3431(11), C(10)–C(11) = 1.3926(18), C(14)–C(15) = 1.4070(19).

Table 1. Crystal and Refinement Data for Complex 3

empirical formula	C$_{17}$H$_{20}$Rh·BF$_4$
formula wt	414.05
temp (K)	100(2)
a (Å)	8.2092(4)
b (Å)	13.8314(6)
c (Å)	13.8068(6)
α (deg)	90
β (deg)	95.092(2)
γ (deg)	90
V (Å^3)	1561.50(12)
Z	4
cryst syst	monoclinic
space group	$P2_1/n$
d_{calcd} (Mg/m^3)	1.761
θ range (deg)	2.09–39.26
μ (mm^{-1})	1.130
abs cor	none
GOF	1.988
R1,[a] wR2[b] ($I > 2\sigma(I)$)	0.0289, 0.0649

[a] $R1 = \sum||F_o| - |F_c||/\sum|F_o|$. [b] $wR2 = \sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]^{1/2}$.

explanations for this difference are as follows: (i) there is no low-energy pathway for C–H bond activation from the η^6-coordinated indene observed for Rh, as opposed to the η^2-coordinated intermediate postulated for Pd and Pt;[14] (ii) coordination of indene to monovalent Rh does not lower the pK_a of the methylene group sufficiently to facilitate deprotonation by water, unlike the case for divalent Pd and Pt. Addition of a stronger base, such as tetrabutylammonium

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hydroxide or 2,6-lutidine, to a solution of **3** resulted in rapid formation of **2** at room temperature, strongly supporting the second interpretation. The ability of noncoordinating 2,6-lutidine to effect this transformation suggests that a mechanism involving direct deprotonation of coordinated indene, without any interaction between the base and the metal, is most plausible; an accompanying migration of Rh to change the coordination mode from η^6 to either η^4 (involving the olefin and the bridgehead carbons) or η^2 may be required.

Conclusions

While the reactions of indene with neutral [(COD)Rh(μ_2-OH)]$_2$ and cationic [(diimine)M(μ_2-OH)]$_2$$^{2+}$ (M = Pd, Pt)[5,6] follow the same stoichiometry, the detailed mechanisms are significantly different. For both Pd and Pt the dimer must be cleaved before reaction with indene, and displacement of solvent by indene is rate-determining, whereas in the case of Rh reaction takes place directly from the dimeric species, and C−H bond cleavage is rate-determining. The reason for this switch is not obvious; possibly Rh(I) is better able to stabilize a five-coordinate olefin complex intermediate by back-donation than Pd(II) or Pt(II), thus reducing the barrier to olefin coordination. Another difference between the systems was observed in the reactions with indene in the presence of acid. The Rh system generates a stable η^6-indene 18-electron cation that is not available for Pd and Pt, which instead form the η^3-indenyl C−H activation products.

Unfortunately, our hope of activating more difficult C−H bonds using the Rh system was not realized. It *does* appear that the coordination of substrate, which is rate-limiting for the cationic Pd and Pt complexes, is more facile for neutral Rh, as expected. However, as a consequence of the change in mechanism, a different step has become rate-limiting, so that the overall reaction with indene is actually somewhat *slower* for Rh than for Pd. Nonetheless, we continue to believe that detailed mechanistic investigations of C−H activation will eventually point the way toward more practical methods for functionalization.

Experimental Section

General Considerations. All manipulations were performed in air. The hydroxy-bridged dimer [(COD)Rh(μ_2-OH)]$_2$ (**1**) was synthesized according to literature methods.[8] Indene and HBF$_4$ (48 wt % in water) were reagent-grade commercial samples purchased from Sigma Aldrich and were used without further purification. 1,2-Dichloroethane-d_4 and 2,2,2-trifluoroethanol-d_3 were purchased from Cambridge Isotope Laboratories and used as received. ^{1}H NMR spectra were recorded using a Varian Inova 500 MHz spectrometer using the VNMRJ software program, version 2.2d, at room temperature unless otherwise stated. X-ray crystallographic data were collected on a Bruker KAPPA APEX II instrument, with the crystals mounted on a glass fiber with Paratone-N oil. The structure of **3** was determined using direct methods as implemented in the Bruker AXS software package.

Reaction of Indene with [(COD)Rh(μ_2-OH)]$_2$ (1) To Form [(COD)Rh(indenyl)] (2). [(COD)Rh(μ_2-OH)]$_2$ (**1**; 75 mg, 0.16 mmol) was weighed out in an 20 mL scintillation vial equipped with a stir bar. 1,2-Dichloroethane (10 mL) and 5 equiv of

indene (195 μL, 0.8 mmol) were added to the solid. The reaction mixture was heated at 50 °C for 5 h, during which time the color of the solution darkened. The solution was then filtered and the volume of solvent reduced to 2 mL in vacuo. Pentane (15 mL) was added, precipitating a small amount of a yellow-orange solid, which was collected by filtration and washed with cold pentane to give **2** as a yellow solid (15 mg, 13%). The low isolated yield is attributable to the partial solubility of the complex in pentane, which makes separation from excess indene difficult; when the reaction was followed using ^{1}H NMR spectroscopy, quantitative conversion of **1** to **2** was observed. X-ray diffraction quality crystals were grown from a saturated solution of dichloromethane, and the structure was identical with that previously reported. The ^{1}H NMR data were also consistent with those previously reported for **2**.[15,16]

Reaction of Indene with [(COD)Rh(μ_2-OH)]$_2$ (1) and HBF$_4$ To Form [(COD)Rh(indene)]$^+$ (3). [(COD)Rh(μ_2-OH)]$_2$ (**1**; 75 mg, 0.16 mmol) was weighed out in an 20 mL scintillation vial equipped with a stir bar. Dichloromethane (10 mL) and 48 wt % of HBF$_4$ in water (43 μL, 0.33 mmol) were added to the solid. The reaction mixture was stirred for 10 min, and then 10 equiv of indene (0.39 mL, 1.6 mmol) was added. After 20 min of stirring, the solution was filtered and the volume of solvent reduced to 2 mL in vacuo. Hexane (15 mL) was added, precipitating a yellow solid, which was collected by filtration and washed with hexane to give **3** as a yellow solid (67 mg, 49%). X-ray diffraction quality crystals were grown from a saturated solution of dichloromethane. The ^{1}H NMR data were consistent with those previously reported for **3**.[15]

Standard Reaction Protocol for Kinetics Experiments. For a standard kinetics experiment [(COD)Rh(μ_2-OH)]$_2$ (**1**; 5 mg, 0.01 mmol) was dissolved in 600 μL of 5:1 dichloroethane-d_4 and TFE-d_3 in a J. Young NMR tube. The appropriate amount of indene was then added using a microliter syringe, and the tube was quickly placed into the NMR spectrometer, which had been preheated to the desired temperature. The growth of the product **2** was monitored by integration of a series of ^{1}H NMR spectra recorded at different times using the MestReNova software package. Integration of peaks corresponding to **1** confirmed that the rate of growth of **2** was the same as the rate of loss of **1**. The ^{1}H NMR spectrum of the reaction mixture at the end of the reaction was consistent with that previously reported for **2**. Several reactions were run in duplicate or triplicate to confirm that reactions were reproducible and estimate uncertainties in measurements. The KIE for the reaction of **1** with indene was determined by comparing the rate constants for parallel reactions using 1,1,3-trideuteroindene[10] and **1** to form the deuterated indenyl complex **2-d_2** and between indene and **1** to form **2**. The experiment was run three times, giving $k_{\rm H}/k_{\rm D}$ = 4.2(2).

Supporting Information Available: Text and figures giving further information on the kinetics analyses and a CIF file giving crystal data for the structure of **3**. This material is available free of charge via the Internet at http://pubs.acs.org.

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