

Small Molecule Activation Using Transfer Hydrogenation Catalysts

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The search for a universal catalyst has led to the recent discovery that catalysts of the type (arene)M(amido-amine) (M = Ru, Rh, Ir), developed by Noyori and coworkers, have been shown to act as both transfer hydrogenation and direct hydrogenation catalysts (Figure 1).^{1,2} The ability of these complexes to effect both transfer hydrogenation and direct hydrogenation dramatically increases the breadth of possible substrates. Although the organic transformations performed by these catalysts have been studied for some time, little is known about their coordination chemistry.³

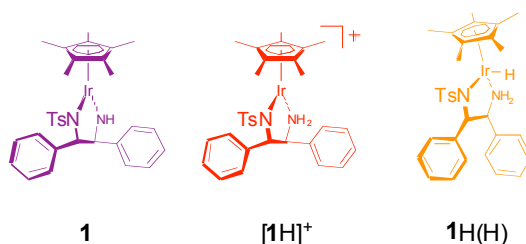


Figure 1. Iridium based transfer hydrogenation complexes of interest. (Ts = SO₂C₆H₄-*p*-Me).

Oxidation of Cp*IrH(TsDPEN), **1H(H)**, with Cp₂FePF₆ resulted in [Cp*Ir(TsDPEN)]PF₆ (**[1H]PF₆**), Cp₂Fe, and a half equivalent of H₂.⁴ Complex **[1H]⁺** was found to be Lewis acidic, and could bind a variety of Lewis bases such as CO, phosphines, and amines.^{4,5} Deprotonation of the Lewis base adduct, **[1H(L)]⁺**, resulted in the formation of Cp*Ir(TsDPEN-H) (**1**) and free ligand (L). Coordination of a Lewis base was found to increase the pK_a of the amine proton by as much as three orders of magnitude. Surprisingly, these complexes are not poisoned by water, which is the key to their recently reported catalytic activity in aqueous solution.² Oxidation of alcohol solutions containing **1H(H)** in the presence of piperidine was found to be catalytic.

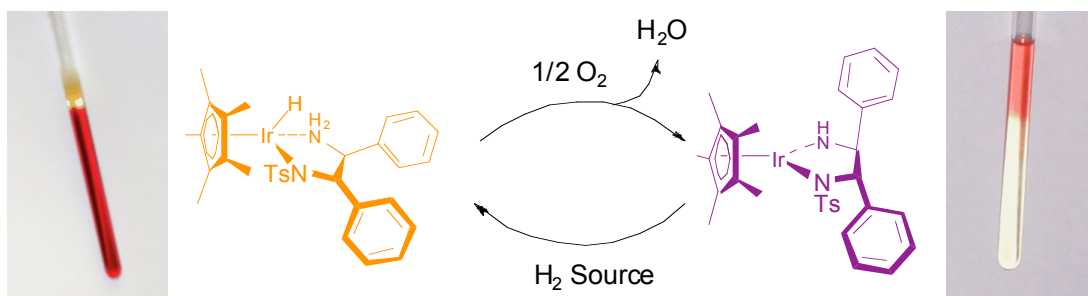
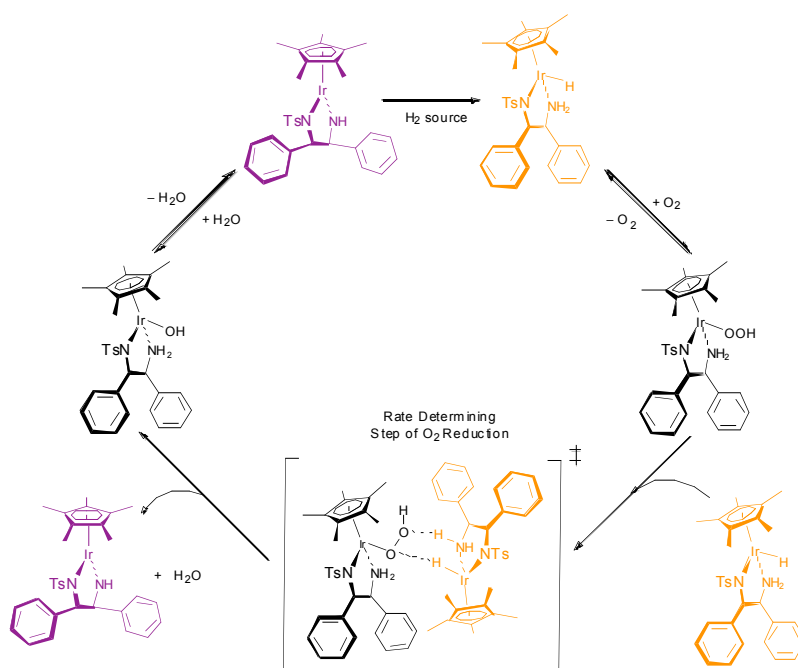


Figure 2. Reactivity of Cp*Ir(TsDPEN) complexes towards H₂ and O₂. (left) NMR tube demonstrating the conversion of **1** to **1H(H)** in the presence of a H₂ atmosphere, (right) NMR tube demonstrating the conversion of **1H(H)** to **1** in the presence of an O₂ atmosphere.

Exposure of a solution of **1H(H)** to oxygen resulted in the generation of **1** and one equivalent of water.⁶ Kinetic analysis showed a second-order dependence on $[\mathbf{1H(H)}]$ and a first-order dependence on $[\text{O}_2]$. Through isotopic labeling, the reaction was found to be localized at the iridium center ($k_{\text{H}}/k_{\text{D}} = 7.1$), indicating that the amine protons ($k_{\text{H}}/k_{\text{D}} = 1.2$) have a secondary effect. The reduction of dioxygen with **1H(H)** was found to be catalytic in the presence of a hydrogen source such as alcohols and ammonia-boranes (Figure 2). This discovery has been recently elaborated on by Ikariya and coworkers in the area of oxidative chiral resolution of secondary alcohols.⁷ The reaction of **1H(H)** with O_2 is proposed to occur through a hydroperoxide intermediate, which is reactive towards **1H(H)** (Scheme 1).⁸ Examination of this reactivity with other transfer hydrogenation complexes illustrated a direct correlation between the relative hydride donor ability of the metal complex⁹ and its reactivity towards O_2 . The more strongly reducing metal hydride complexes exhibited higher reaction rates with O_2 .

Scheme 1. Proposed catalytic cycle for the reduction of O_2 with $\text{Cp}^*\text{IrH}(\text{TsDPEN})$.



Though **1** is not Lewis acidic and does not readily react with H_2 , the addition of a catalytic amount of acid was found to promote the hydrogenation of **1** to **1H(H)**. The rate of hydrogenation of **1** was found to be dependent on the identity of the acid. It was found that acids with a $\text{p}K_{\text{a}}$ three orders of magnitude less ($\text{p}K_{\text{a}} \sim 10$ in MeCN) than $[\text{Cp}^*\text{Ir}(\text{H}_2)(\text{TsDPEN})]^+$ ($\text{p}K_{\text{a}} = 13.88$ in MeCN) resulted in the fastest hydrogenation rate. Kinetic analysis of the hydrogenation of **1** in the presence of acid showed a first order dependence on $[\mathbf{1H}]\text{X}$ ($\text{X}^- = \text{NO}_3^-$, PF_6^- , BF_4^- , and OTf^-), a first order dependence on $[\text{H}_2]$, and a zeroth order dependence on **1**. Solutions containing anions with poor basicity ($\text{X}^- = \text{ClO}_4^-$ or $\text{BAr}_4^{\text{F}-}$ ($\text{B}(\text{C}_6\text{H}_3\text{-}3,5\text{-}(\text{CF}_3)_2)_4^-$)) exhibited an additional dependence on **1**. Using **1** and a catalytic amount of acid, water was produced from an atmosphere containing H_2 and O_2 (Figure 3).

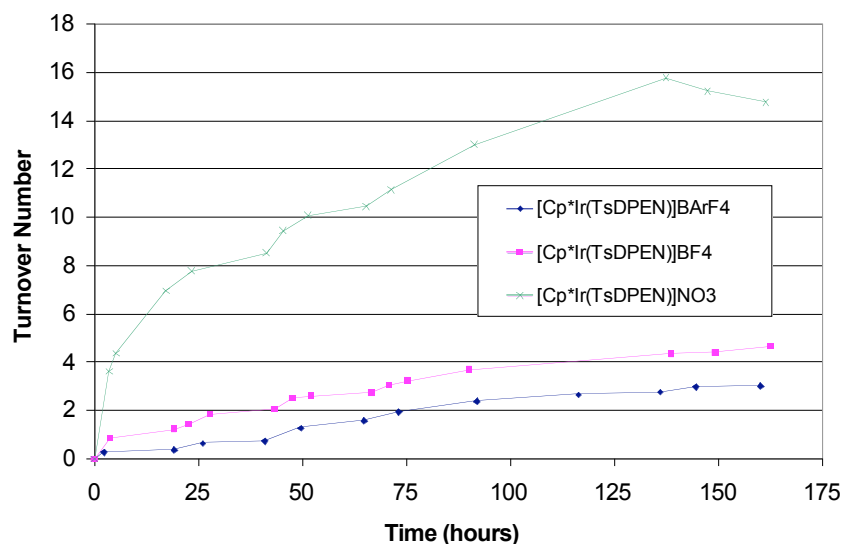


Figure 3. Turnover number for the production of water in CD_2Cl_2 solutions of **1** and 15 mol % of $[\text{1H}]\text{X}$, $\text{X}^- = \text{BARf}_4^-$ ($\text{B}(\text{C}_6\text{H}_3\text{-3,5-(CF}_3)_2)_4^-$), BF_4^- , and NO_3^- and an atmosphere of H_2 and O_2 .

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