

pH-Selective Hydrogenation of Water-Soluble Carbonyl Compounds and Alkenes with $[\text{Cp}^*\text{Ir}^{\text{III}}(\text{H}_2\text{O})_3]^{2+}$ ($\text{Cp}^* = \eta^5\text{-C}_5\text{Me}_5$) as a Catalyst Precursor in Very Acidic Media

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The organometallic aqua complex $[\text{Cp}^*\text{Ir}^{\text{III}}(\text{H}_2\text{O})_3]^{2+}$ (**1**) acts as a catalyst precursor for hydrogenation of water-soluble carbonyl compounds and alkenes in water (5–20 mM of **1**, 100 mM of the substrates) in a pH range of about –1 to 4 under H_2 at a pressure of 0.1–0.7 MPa at 25 °C. The solution pH was adjusted by using 0.1–10 M $\text{HClO}_4/\text{H}_2\text{O}$ and 0.1 M $\text{NaOH}/\text{H}_2\text{O}$. The aqueous hydrogenation shows unique pH-selectivity to be governed by the following three factors: (i) pH-dependent structural change of the catalyst precursor **1**, which is deprotonated to form a catalytically inactive dinuclear complex, $[(\text{Cp}^*\text{Ir}^{\text{III}})_2(\mu\text{-OH})_3]^+$ (**2**), above pH 4, (ii) stability of a putative iridium hydride active catalyst depending upon pH, and (iii) difference in the proton affinity of the substrates, i.e., Lewis basicity of the carbonyl oxygen atoms of the carbonyl compounds and the C=C moieties of the alkenes. Turnover frequencies of the hydrogenations are also discussed on the basis of Lewis acidity of the carbocations that accept a hydride ion from the active catalyst.

Introduction

Development of water-soluble organometallic catalysts is a worthy endeavor because of potential advantages such as reaction-specific pH selectivity, introduction of new biphasic processes, and alleviation of environmental problems associated with the use of organic solvents.¹ Although the majority of these studies have been carried out with water-soluble organometallic complexes containing water-soluble phosphine ligands,² few have utilized organometallic complexes containing water molecules as ligands (i.e., organometallic aqua complexes).³ These organometallic aqua complexes are promising new pH-selective catalysts since their structures drastically change as a function of pH due to deprotonation of the aqua ligands.

By using the organometallic aqua complex $[\text{Cp}^*\text{Ir}^{\text{III}}(\text{H}_2\text{O})_3]^{2+}$ (**1**, $\text{Cp}^* = \eta^5\text{-C}_5\text{Me}_5$, Scheme 1) as a catalyst

precursor, we have investigated aqueous hydrogenation of water-soluble substrates as a function of pH.^{3a} Herein, we report pH-selective hydrogenation of water-soluble carbonyl compounds and alkenes by utilizing **1** as the catalyst precursor in a pH range of about –1 to 4. The pH-selectivity is discussed on the basis of (i) pH-dependent structural change of **1**, (ii) stability of a putative iridium hydride active catalyst (abbreviated as $[\text{Ir-H}]$) in these acidic media, and (iii) Lewis basicity of the carbonyl oxygen atoms of the carbonyl compounds and the C=C moieties of the alkenes. Turnover frequencies (TOF: number of moles of product formed per mole

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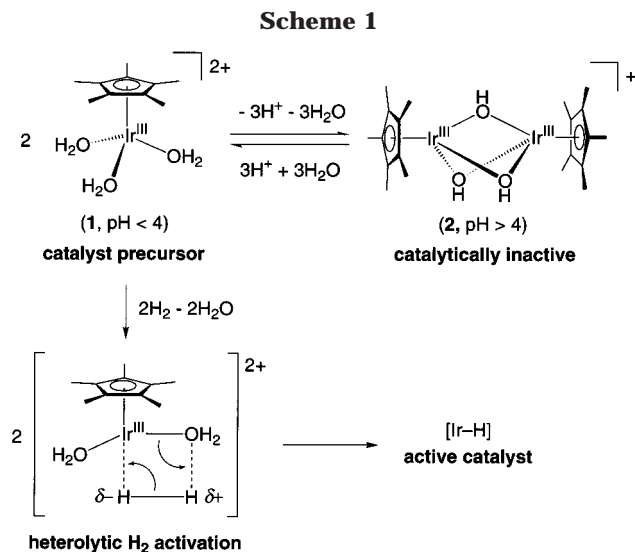


Table 1. Substrates and its Corresponding Products

entry	substrate	product
a	<chem>CCCC=O</chem>	<chem>CCCCO</chem>
b	<chem>CCC(=O)C</chem>	<chem>CCC(O)C</chem>
c	<chem>C=C(C)CO</chem>	<chem>CC(C)CO</chem>
d	<chem>C=CCO</chem>	<chem>CCC(O)O</chem>
e	<chem>C=C(C)Cl</chem>	no reaction

of catalyst per 30 min) of the hydrogenations are also discussed on the basis of the Lewis acidity of the carbocations that accept a hydride ion from the active catalyst. A series of water-soluble substrates having C=O or C=C bonds include *n*-butyraldehyde (entry a in Table 1), 2-butanone (b), 2-methyl-2-propen-1-ol (c), allyl alcohol (d), and 2-chloro-2-propen-1-ol (e).

Results and Discussion

Solution pH. The solution pH was adjusted by using 0.1–10 M HClO₄/H₂O and 0.1 M NaOH/H₂O. In a pH range of 2–10, the solution pH was determined by a pH meter, but below pH 1, it was estimated by the concentration of the solution; for example, pH values of 0.1, 1.0, and 10 M HClO₄/H₂O were estimated to be 1, 0, and –1, respectively. Buffer was not used to control pH since the solution pH did not change during the hydrogenation under the conditions of this study. To determine the exact pH values of the ¹H NMR samples, the ¹H NMR experiments were performed by dissolving the samples in H₂O in an NMR tube (diameter = 5.0 mm) with a sealed capillary tube (diameter = 1.5 mm) containing TSP (100 mM)⁴ dissolved in D₂O (for deuterium lock).

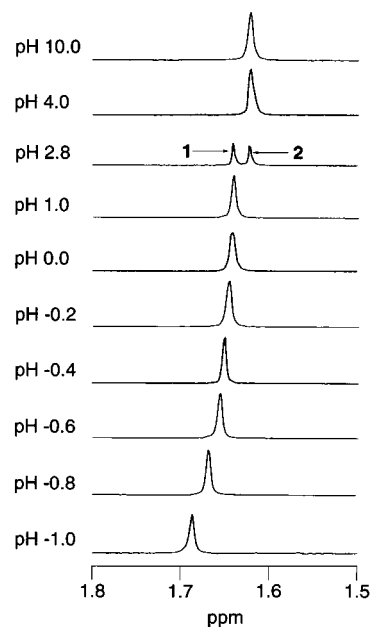


Figure 1. pH-dependent ¹H NMR spectra of **1** in a pH range of about –1.0 to 10.0. Experiments were performed by dissolving **1**·SO₄ (20 μmol) in H₂O (1 mL) in an NMR tube (diameter = 5.0 mm) with a sealed capillary tube (diameter = 1.5 mm) containing TSP (100 mM) dissolved in D₂O (for deuterium lock) at 25 °C. The solution pH was adjusted by using 0.1–10 M HClO₄/H₂O and 0.1 M NaOH/H₂O.

Catalyst Precursor and Active Catalyst. The catalyst precursor [Cp*Ir^{III}(H₂O)₃]²⁺ (**1**) was prepared by a method described previously.^{3a} ¹H NMR experiments (Figure 1) show that at pH 2.8 the mononuclear complex **1** is reversibly converted to a well-known dinuclear complex, [(Cp*Ir^{III})₂(μ-OH)₃]⁺ (**2**),^{3a,j,5} which is the predominant species above pH 4. It is important to note that complex **2** does not catalyze the hydrogenation. Thus, we have performed the hydrogenation with **1** below pH 4. The stability of **1** in the acidic media has been investigated by ¹H NMR as shown in Figure 1. We propose that the downfield shifts of the Cp* signal of **1** are due to further protonation(s) of **1** in the pH range of about 0 to –1.

At this stage, we have no definite structural information on the active catalyst in this hydrogenation. We propose that the H₂O ligands in **1** could act as a base and accelerate the heterolytic activation of dihydrogen to form a putative iridium hydride active catalyst under these acidic conditions (Scheme 1) since it has been known that polar solvents accelerate the heterolytic activation of dihydrogen.⁶ The stability of the active catalyst in these acidic media should be low compared with in neutral solution because of hydride protonation.

Hydrogenation in Acidic Media. There are examples of hydrogenation with organometallic complexes containing water-soluble phosphine ligands under acidic conditions.² For example, Joo et al. have shown that

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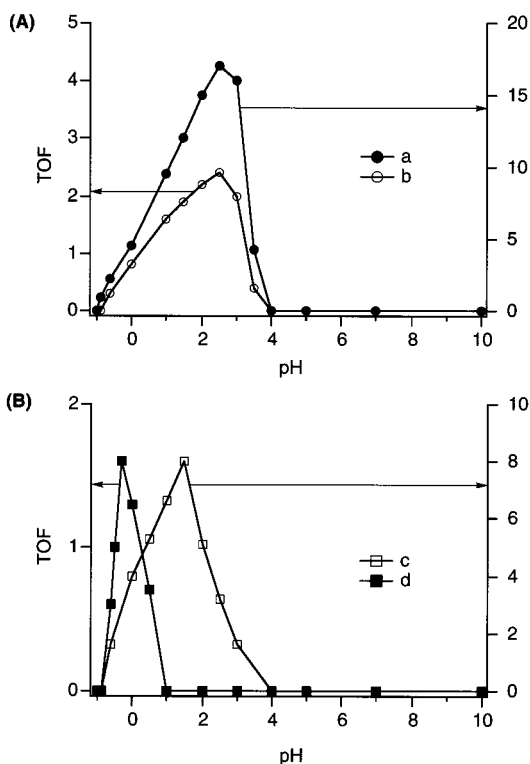
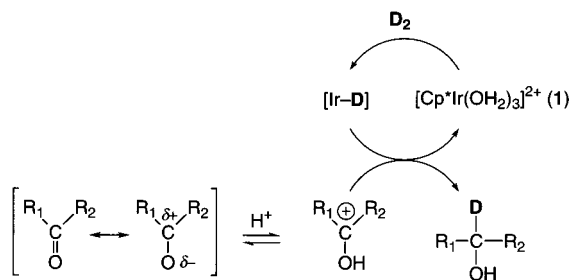


Figure 2. (A) pH-selective hydrogenation of water-soluble carbonyl compounds: *n*-butyraldehyde (a) and 2-butanone (b). (B) pH-selective hydrogenation of water-soluble alkenes: 2-methyl-2-propen-1-ol (c) and allyl alcohol (d). Conditions: $\mathbf{1}\cdot\text{SO}_4$ (5 μmol for a and c, 20 μmol for b and d), substrates (100 μmol), H_2 (0.5 MPa), H_2O (1 mL), 25 $^\circ\text{C}$. TOF: (mol of products/mol of $\mathbf{1}\cdot\text{SO}_4$)/30 min.

Scheme 2



$[\text{HRuCl}(\text{TPPMS})_3]$ (TPPMS = *m*-sulfo phenyl diphenylphosphine sodium salt) acts as a catalyst for hydrogenation of several unsaturated compounds in 0.1 M $\text{HCl}/\text{H}_2\text{O}$ (estimated $\text{pH} \approx 1$).^{2a,b}

We here demonstrate the hydrogenation of water-soluble substrates (100 μmol) with $\mathbf{1}$ (5–20 μmol) in H_2O (1 mL) in the pH range of about –1 to 4. The solution was vigorously stirred (1000 rpm) under H_2 at a pressure of 0.1–0.7 MPa at 25 $^\circ\text{C}$.⁷ Products were determined by ^1H NMR. It has been confirmed that the hydrogenation does not occur without $\mathbf{1}$, and it also has been confirmed that $\text{IrCl}_3\cdot n\text{H}_2\text{O}$ does not catalyze the hydrogenation. Under the conditions of this study, water-soluble amides, sulfoxides, and alkynes cannot be reduced.

Hydrogenation of Compounds Having C=O Bonds. As shown in Figure 2A, hydrogenations of the

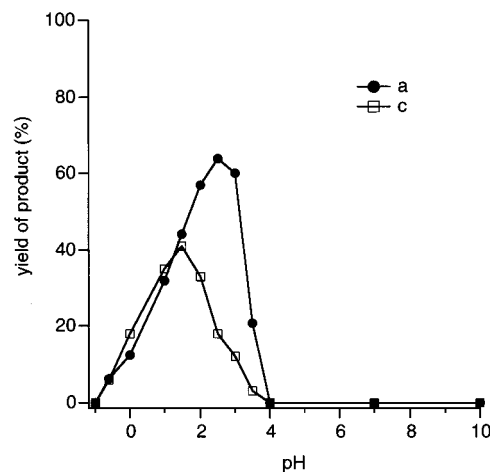
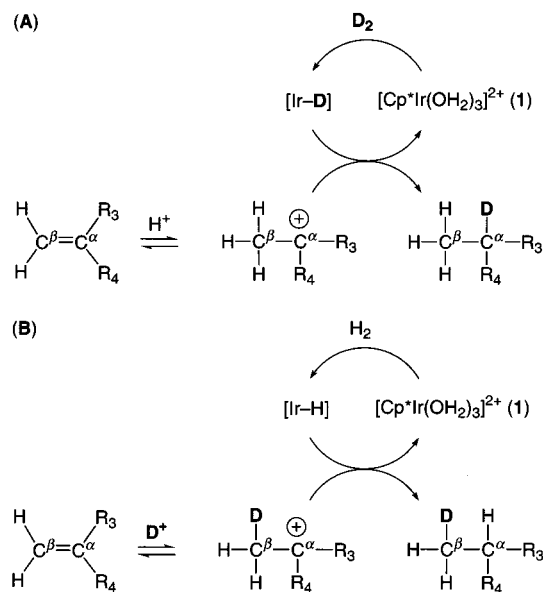


Figure 3. Hydrogenation of a mixture of *n*-butyraldehyde (a) and 2-methyl-2-propen-1-ol (c). Conditions: $\mathbf{1}\cdot\text{SO}_4$ (10 μmol), substrates (a: 100 μmol , c: 100 μmol), H_2 (0.5 MPa), H_2O (1 mL), 25 $^\circ\text{C}$. Yield: based on substrate/30 min.

Scheme 3



aldehyde (a) and the ketone (b) show a very similar pH-selectivity; that is, the TOFs of the hydrogenation of a and b show a maximum (TOF_{max}) at pH 2.5. This could indicate that there is no significant difference in the Lewis basicity of the carbonyl oxygen atoms of a and b that react with a proton. In the acidic media, the carbonyl oxygen atoms could be protonated because of polar resonance structures of the carbonyl group, as shown in Scheme 2.⁸ Figure 2A also shows that the hydrogenation of a (whose $\text{TOF}_{\text{max}} = 17$) proceeds more efficiently than that of b (whose $\text{TOF}_{\text{max}} = 2.4$) at pH 2.5. This could be due to the difference in the Lewis acidity of the carbocations that accept a hydride ion from the putative iridium hydride active catalyst. In addition, it was confirmed by ^1H NMR and electrospray ionization mass spectrometry (ESI-MS) that the labeled hydrogen atom is incorporated into the product when D_2 is used as shown in Scheme 2, where the active catalyst formed by the reaction of $\mathbf{1}$ with D_2 is abbreviated as $[\text{Ir}-\text{D}]$.

(7) Solubility of hydrogen gas in 1 mL of water at 0.1 MPa at 25 $^\circ\text{C}$ is determined as 0.01754 mL. In *Lange's Handbook of Chemistry*, 14th ed.; Dean, J. A., Ed.; McGraw-Hill: New York, 1992; Section 5.1.

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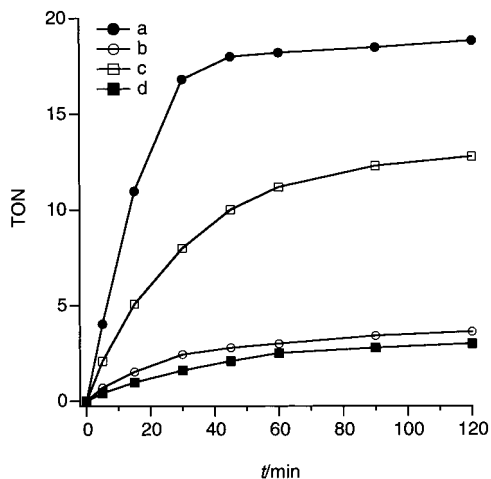


Figure 4. Time course of turnover numbers (TONs) of the hydrogenations. Conditions: $1 \cdot \text{SO}_4$ ($5 \mu\text{mol}$ for **a** and **c**, $20 \mu\text{mol}$ for **b** and **d**), substrates ($100 \mu\text{mol}$), H_2 (0.5 MPa), H_2O (1 mL), pH 2.5 for **a** and **b**, pH 1.5 for **c**, and pH -0.3 for **d**, $25 \text{ }^\circ\text{C}$. TON: mol of products/mol of $1 \cdot \text{SO}_4$.

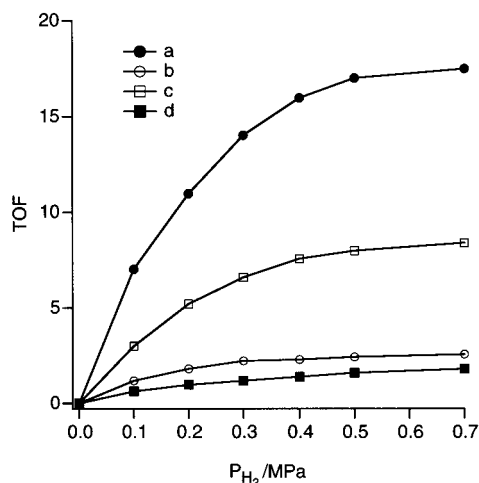


Figure 5. H_2 pressure-dependent turnover frequencies (TOFs) of the hydrogenations. Conditions: $1 \cdot \text{SO}_4$ ($5 \mu\text{mol}$ for **a** and **c**, $20 \mu\text{mol}$ for **b** and **d**), substrates ($100 \mu\text{mol}$), H_2O (1 mL), pH 2.5 for **a** and **b**, pH 1.5 for **c**, and pH -0.3 for **d**, $25 \text{ }^\circ\text{C}$. TOF: (mol of products/mol of $1 \cdot \text{SO}_4$)/30 min.

Hydrogenation of Compounds Having C=C Bonds. The hydrogenation of alkenes shows unique pH-selectivity depending upon their substituents. The TOF_{max} of the hydrogenation of 2-methyl-2-propen-1-ol (**c**) having an electron-donating substituent (Me group) and allyl alcohol (**d**) having nonsubstituent at the same position is observed at about pH 1.5 and -0.3 , respectively as shown in Figure 2B. The hydrogenation of 2-chloro-2-propen-1-ol (**e**) having an electron-withdrawing substituent (Cl group) does not take place in the pH range of -1 to 4. These results indicate that the pH-selectivity of the hydrogenation of alkenes should be controlled by Lewis basicity of the C=C moiety.

Intriguingly, despite higher Lewis acidity of the carbocation of **d** than that of **c**, the TOF of the hydrogenation of **d** ($\text{TOF}_{\text{max}} = 1.6$ at pH -0.3) is lower than that of **c** ($\text{TOF}_{\text{max}} = 8.0$ at pH 1.5), as shown in Figure 2B. One explanation for this result is that the low TOF of **d** in the acidic pH range is attributed to the stability of the active catalyst. ^1H NMR and ESI-MS

experiments have revealed that the labeled hydrogen atom is introduced on the C^α (Scheme 3A) or C^β (Scheme 3B) when D_2 or D_2O is used, respectively, based on Markovnikov rule.

Control Experiments. It is important to note that hydrogenation of mixtures of the carbonyl compounds and the alkenes shows a pH-selectivity similar to that observed in the independent hydrogenations of the carbonyl compounds or the alkenes; for example, the TOFs of the hydrogenation of a mixture of **a** and **c** reveal maximums at pH 2.5 and 1.5, respectively, as shown in Figure 3. Figure 4 shows the time course of turnover numbers (TON) of these hydrogenations, indicating that, after 30 min, the reduction of **a** is almost completed. As shown in Figure 5, the TOFs of these hydrogenations are dependent on the pressure of H_2 in the range from 0.1 to 0.7 MPa.

Conclusions

We have demonstrated the organometallic aqua complex **1** to be a pH-selective catalyst precursor for the hydrogenation of water-soluble carbonyl compounds and alkenes in a pH range of about -1 to 4. The hydrogenation shows unique pH-selectivity depending upon the substrates under these acidic conditions. The pH-selectivity could be rationalized as follows: (i) Above pH 4, the catalyst precursor **1** is predominantly deprotonated to form a catalytically inactive dinuclear complex $[(\text{Cp}^*\text{Ir}^{\text{III}})_2(\mu\text{-OH})_3]^+$ (**2**); therefore, this aqueous hydrogenation is possible only below pH 4. (ii) Stability of the active catalyst in these acidic media should be low compared with in a neutral pH solution because of hydride protonation. (iii) There is a difference in the proton affinity of the substrates; that is, protonation of the carbonyl oxygen atom in the carbonyl compounds proceeds more easily than the protonation of the C=C moieties of the alkenes in these acidic media. We have also discussed the difference in the TOFs of the hydrogenations on the basis of the Lewis acidity of the carbocations that accept a hydride from the active catalyst.

Experimental Section

Materials and Methods. All chemicals (highest purity available) were purchased from Aldrich Chemicals Co. and used without further purification. The ^1H NMR spectra were recorded on a JEOL JNM-EX 270 spectrometer. The potentiometric titration experiments were performed on a TOA pH meter (model HM-18E) with a TOA pH combination electrode (model GS-5015C). A Nissin magnetic stirrer (model SW-R700) was used. The titration experiments were carried out without an inert supporting electrolyte to maintain the constant ionic strength because the addition of a large excess of the electrolyte prevents dimerization of the aqua complex **1**. Mass data were obtained by an API 300 triple quadrupole mass spectrometer (PE-Sciex) equipped with an ESI interface.

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