

Accepterless Dehydrogenation of C–C Single Bonds Adjacent to Functional Groups by Metal–Ligand Cooperation

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Supporting Information

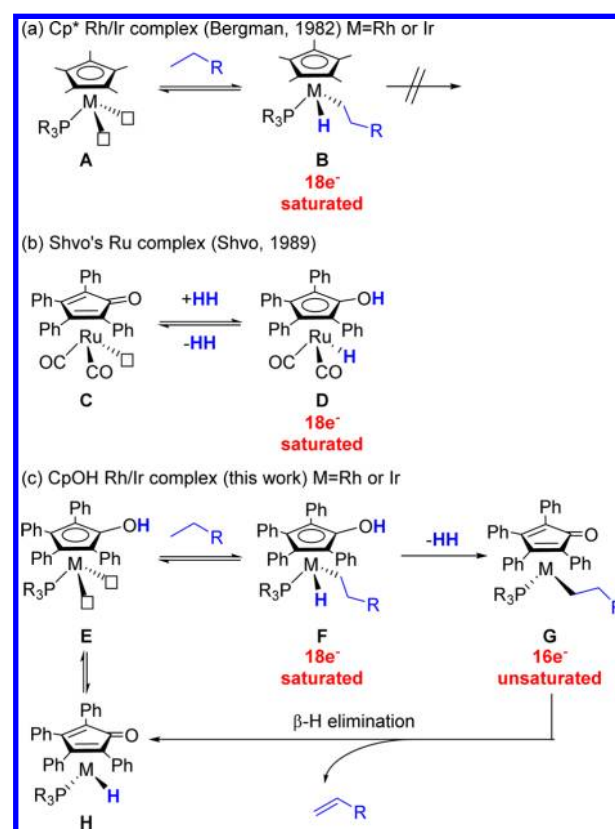
ABSTRACT: Unprecedented direct acceptorless dehydrogenation of C–C single bonds adjacent to functional groups to form α,β -unsaturated compounds has been accomplished by using a new class of group 9 metal complexes. Metal–ligand cooperation operated by the hydroxycyclopentadienyl ligand was proposed to play a major role in the catalytic transformation.

Since the first report by Bergman, Graham, and Jones in the early 1980s, cyclopentadienyl rhodium or iridium phosphine complexes have been known to undergo oxidative addition of unactivated sp^3 C–H bonds to form alkylmetal hydride species.¹ Because the resulting alkylmetal hydride is a coordinatively saturated 18-electron complex (complex B in Scheme 1a), further chemical transformation of the alkyl group was rather limited, and examples have been confined to a few stoichiometric reactions.^{1a} Hence, catalytic functionalization of a sp^3 C–H bond had required photoirradiation to make vacant site(s) except for a few thermal dehydrogenations.^{2,3} In 1996, Jensen reported a PCP-type pincer iridium dihydride 16-electron complex, which shows quite high activity in thermal alkane dehydrogenation reaction.⁴ Intensive efforts have been devoted to further development of pincer-type complexes by Jensen, Goldman and Brookhart in alkane and amine dehydrogenation.^{5–7} As another type of sp^3 C–H functionalization, rhodium-catalyzed alkane borylation via σ -bond metathesis established by Hartwig may be also referred.⁸

In the field of dehydrogenation of alcohols or hydrogenation of carbonyl groups, metal–ligand cooperation has attracted much attention.⁹ A pioneering work by Shvo with cyclopentadienone–hydroxycyclopentadienyl based ruthenium complex established a heterolytic formation of dihydrogen from proton and hydride (from complex D to C in Scheme 1b) and heterolytic cleavage of dihydrogen into proton and hydride (from C to D).¹⁰ As another example of efficient metal–ligand cooperation, highly active acceptorless dehydrogenation of alcohols was reported by Fujita with pyridone–hydroxypyridine based iridium catalyst, which can release hydride on the metal as dihydrogen by the assistance of proton on the hydroxypyridine ligand.^{11,12}

Here in this work, we designed hydroxycyclopentadienyl group 9 metal complexes E in the aim of metal–ligand cooperation in C–H functionalizations (Scheme 1c). While the 18-electron Cp^* complex B does not have a coordination site for further functionalizations (Scheme 1a), we hypothesized the

Scheme 1



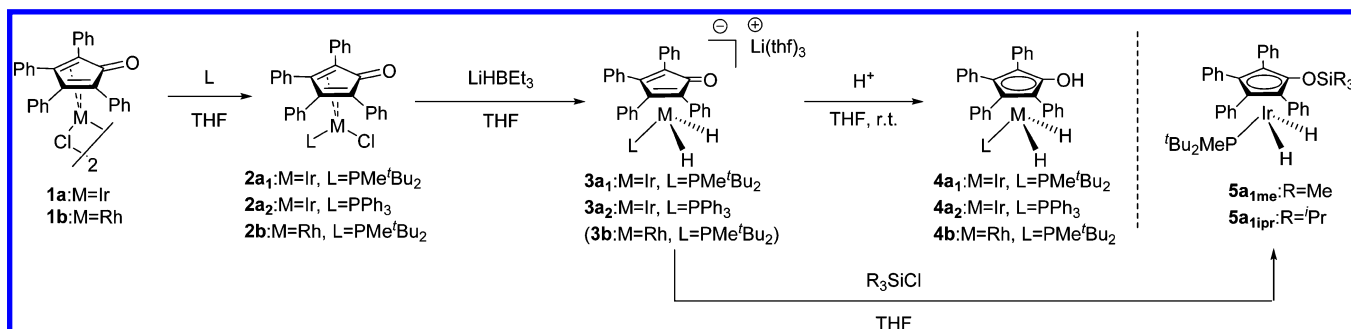
18-electron alkyl hydride complex F having a hydroxyl group on the Cp ring would release dihydrogen via metal–ligand cooperative heterolytic bond formation to form a 16-electron alkyl complex G (Scheme 1c). Coordinatively unsaturated G is expected to be active for further functionalizations, e.g., β -hydride elimination to afford an alkene and hydride complex H, which would exist under equilibrium with E.¹³ By developing these hydroxycyclopentadienyl group 9 metal complexes, we have accomplished the first direct acceptorless dehydrogenation of C–C single bonds adjacent to functional groups with metal–ligand cooperation. In the precedents for α,β -dehydrogenation of carbonyl compounds, stoichiometric oxidants such as DDQ,¹⁴ IBX¹⁵ and O₂^{16,17} for palladium catalysts or alkenes for ruthenium catalysts¹⁸ were indispensable.¹⁹

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Scheme 2



Desired hydroxycyclopentadienyl iridium and rhodium complexes **4a₁**, **4a₂** and **4b** were synthesized in three steps from cyclopentadienone metal(I) chloride dimer **1a** or **1b** (Scheme 2). Reaction of iridium and rhodium chloride dimer **1a** and **1b** with di-*tert*-butylmethylphosphine resulted in the formation of tetracoordinated complexes **2a₁** and **2b**.²⁰ These tetracoordinated complexes were air and moisture stable and could be purified by silica-gel column chromatography. Complex **2a₁** showed a distorted tetrahedral geometry by X-ray crystallography.²¹ Treatment of chloride complexes **2a₁** and **2b** with 2 equiv of lithium triethylborohydride led to clean formation of dihydride complexes **3a₁** and **3b**, confirmed by ³¹P and ¹H NMR spectroscopy. Iridium complex **3a₁** was isolated in a nearly quantitative yield as a rare anionic Ir(I) dihydride complex²² (Figure 1a), while rhodium complex **3b** was too

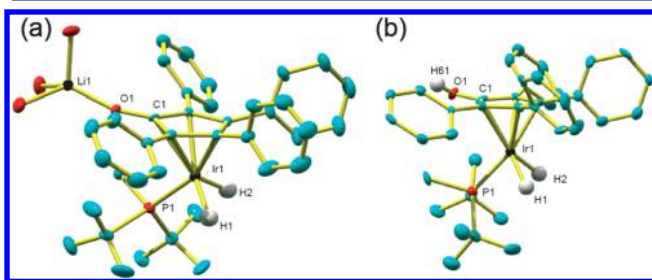


Figure 1. X-ray structures of complex (a) **3a₁** and (b) **4a₁** (thermal ellipsoids are drawn with 10% probability for **3a₁**, 50% for **4a₁**. Hydrogens on carbon atoms and carbon atoms of THFs are omitted for clarity.).

unstable to be fully characterized. This anionic iridium(I) complex **3a₁** readily reacted with a proton source such as moisture, alcohol and triethylaminehydrochloride to afford the desired hydroxyl-substituted cyclopentadienyl iridium(III) dihydride complex **4a₁**.²³ Anionic Iridium(I) complex **3a₁** can be also trapped by trialkylchlorosilane to afford trimethylsilyloxyl- (**5a_{1me}**) or triisopropylsilyloxyl- (**5a_{1ipr}**) substituted complexes. Although anionic complex **3b** could not be isolated because of its instability, the corresponding hydroxycyclopentadienyl rhodium complex **4b** was isolated by flash silica-gel column chromatography. Triphenylphosphine ligated iridium complex **4a₂** was also synthesized by the same procedure as for **4a₁**.

X-ray structures of **3a₁** and **4a₁** are shown in Figure 1. Physical parameters (¹H NMR, IR and bond lengths observed in X-ray analysis) of **3a₁**, **4a₁** and Cp*IrH₂PMe'Bu₂ (**6**) are summarized in Table 1. The short C1–O1 distance in **3a₁** (1.261(10) Å) and the long Ir–C1 length (2.474(9) Å) suggest that **3a₁** is an anionic Ir(I) complex with the cyclopentadienone coordination in an η^4 manner. In sharp contrast, longer C1–O1 bond length (1.382(7)

Table 1. Physical Parameters of Complexes **3a₁**, **4a₁**, and **6**

	3a₁	4a₁	6
IR ν (Ir–H, sym) (cm ^{−1})	2181 ^a	2210 ^a	2162
¹ H NMR (Ir–H) (ppm)	−19.21 ^b	−18.50 ^b	−18.54 ^c
bond length (Ir–C1)	2.479(9)	2.330(6)	—
(C1–O1) (Å)	1.261(10)	1.382(7)	—

^aMeasured by KBr method. ^bIn THF-*d*₈. ^cIn C₆D₆.

Å) and shorter Ir–Cl distance (2.330(6) Å) in **4a₁** correspond to a structure where cyclopentadienone ring is reduced and coordinates to Ir(III) as an η^5 -cyclopentadienyl anion. ¹H NMR signal of hydrides in complex **3a₁** was observed at −19.21 ppm, in a higher field than in **4a₁** (−18.50 ppm), implying stronger anionic feature of the hydrogens in **3a** when compared to **4a₁**. IR absorbance of Ir–H symmetric stretching is slightly weaker in anionic Ir complex **3a₁** (2181 cm^{−1}) than in complex **4a₁** (2210 cm^{−1}), showing weaker Ir–H bond in anionic Ir(I) complex **3a₁** than neutral Ir(III) complex **4a₁**. The Ir–H bond in **4a₁** is stronger in comparison to Cp* complex **6** (2162 cm^{−1}), probably because of the weaker donation from tetraphenylhydroxycyclopentadienyl ring than Cp*.²⁴

Direct acceptorless dehydrogenation of C–C single bonds attached to functional groups were accomplished by using hydroxycyclopentadienyl iridium complex **4a₁** (Table 2).²⁵ First, reactivities of the Ir complexes were compared in the dehydrogenation of a simple cycloalkane, cyclooctane in the presence of a hydrogen acceptor (^{*t*}butylethylene, hereafter abbreviated as TBE). The hydroxycyclopentadienyl complex **4a₁** showed higher activity (TON 24, entry 1) when compared to silyl-protected complexes **5a_{1me}** and **5a_{1ipr}** (TON 5 for each, entries 2 and 3) or Cp* complex **6** (TON 4, entry 4), although the values were lower than the highest record with PCP-type pincer Ir complexes.^{3,5} Dehydrogenation with **4a₁** also proceeded in the absence of TBE (entry 6). Next, we applied the Ir complexes to other substrates. It should be noted that the hydroxycyclopentadienyl complexes **4a₁** and **4a₂** were uniquely active in dehydrogenation of α -tetralone to 1-naphthol in the absence of dihydrogen acceptor. Complexes **4a₁** and **4a₂** showed 19 and 4 turnovers in the dehydrogenation of α -tetralone to 1-naphthol in 30 min (entries 7 and 8), while rhodium complex **4b**, Cp* iridium complex **6** or even PCP-type pincer iridium complex IrH₂(C₆H₃-2,6-(CH₂P^{*t*}Bu₂)₂) (**7**) showed no activity (entries 9, 11 and 12). The reaction is strongly suppressed when the hydroxyl group on the Cp ring was protected by a silyl group (**5a_{1ipr}**), indicating that the free hydroxyl group plays an important role in this metal–ligand cooperation (compare entries 10 with 7). It is worth noting that no oxidant was necessary and evolution of 116 μ mol of dihydrogen (almost

Table 2. Dehydrogenation of C–C Single Bonds Catalyzed by Group 9 Metal Complexes^{a,b}

$\text{R-CH}_2\text{-CH}_2\text{-FG} \xrightarrow[200\text{ }^\circ\text{C}]{\text{catalyst acceptor}} \text{R-CH=CH-FG}$						
entry	substrate	catalyst	acceptor	time(h)	product(s)(μmol)	TON ^c
1	cyclooctane	4a₁	TBE	29	cyclooctene	120
2	cyclooctane	5a_{1me}	TBE	29	cyclooctene	26
3	cyclooctane	5a_{1lpr}	TBE	29	cyclooctene	27
4	cyclooctane	6	TBE	29	cyclooctene	18
5	cyclodecane	4a₁	none	29	cyclodecene	55
6		none	none	0.5		0
7		4a₁	none	0.5		94 ^d
8		4a₂	none	0.5		(85) ^e
9		4b	none	0.5		0
10		5a_{1lpr}	none	0.5		12
11		6	none	0.5		0
12		7	none	0.5		0
13		4a₁	none	29		483 ^f
14		4a₁	none	29		40
15		4a₁	TBE	29		120
16		4a₁	none	29		27
17		4a₁	none	29		31
18		4a₁	none	29		186 ^g
19		4a₁	none	29		19
20		4a₁	none	29		331

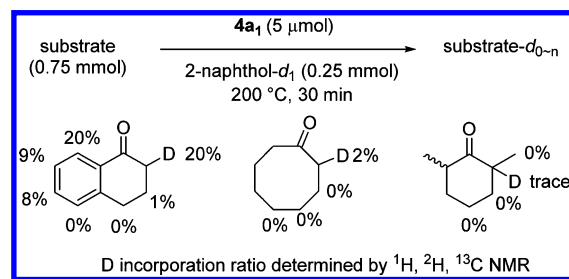
^aReaction condition for entries 1–4 and 15: mixture of complex (**5** μmol), substrate (4.0 mL) and ^tbutylethylene (200 μL) were stirred in a stainless autoclave at 200 $^\circ\text{C}$ for 29 h. ^bReaction condition for other entries: mixture of substrates (200 μL for liquid or 100 mg for solid) and complex (**5** μmol) were stirred in a glass tube connected to an Ar line at 200 $^\circ\text{C}$ for 19 h. ^cDetermined by GV analysis with dodecane as an internal standard. ^d116 μmol of dihydrogen was detected by GC. ^eIsolated yield. ^fTetrahydronaphthalene (107 μmol) and naphthalene (171 μmol) were observed as side products. ^gQuinoline (22.7 μmol) was observed as a sided product.

equimolar to 1-naphthol) was confirmed in entry 7. In longer reaction time, 29 h, turnover number increased up to 97 in entry 13. However, reduction of the carbonyl moiety by evolved dihydrogen took place, and significant amounts of naphthalene and tetrahydronaphthalene were detected as side products. This undesired reduction of the carbonyl moiety could be suppressed by removing the evolved dihydrogen by Ar bubbling.²⁶ Aliphatic ketone, 2,6-dimethylcyclohexanone, can be also dehydrogenated to afford 2,6-dimethylcyclohexenone and 2,6-dimethylphenol as two major products with total TON of 12 (entry 14). The addition of hydrogen acceptor TBE improved the TON by about double (entry 15). The reaction was applicable to cyclic esters, dihydrocoumarin and splitomicin showing 5 and 6 turnovers to afford the corresponding α,β -unsaturated lactone, coumarine

and naphthopiranone, respectively (entries 16 and 17). Cyclic amide, dihydroquinolinone, was also dehydrogenated to quinolinol with 37 turnovers (entry 18). The applicable substrate was not limited to the ones to form α,β -unsaturated carbonyl compounds: Isochromanone was also dehydrogenated to the corresponding alkenyl ester with 4 turnovers (entry 19). To the best of our knowledge, no direct dehydrogenation of alkyl ester to alkenyl ester has been reported even in the presence of stoichiometric oxidant. Dihydrobenzofuran could be applied and showed relatively high activity (TON 66, entry 20). On the other hand, however, the reaction was not applicable to the following substrates: Unsubstituted cyclohexanone resulted in formation of a complex mixture including cyclohexenone, phenol and higher molecular weight compounds originated from the competing aldol type condensation (see Supporting Information). Structurally related cyclooctanone or acyclic esters did not show any activity for the dehydrogenation to result in recovery of the starting materials.²⁶

In the dehydrogenation reaction of cycloketones, β -hydride elimination was suggested to be the turnover limiting step by H/D exchange experiment and DFT calculation. To clarify the reason for the different reactivity of cyclohexanone and cyclooctanone in this reaction, we first examined H/D exchange experiment in the presence of 2-naphthol-*d*₁ (Scheme 3). After

Scheme 3



the reaction with complex **4a₁** in 30 min, α -position of cyclooctanone was deuterated by 2%, while only a trace amount of H/D exchange was observed with 2,6-dimethylcyclohexanone. Because this H/D exchange is thought to undergo via oxidative addition to Ir(I) followed by replacement of the Ir(III) by D⁺, the higher activity observed for cyclooctanone than 2,6-dimethylcyclohexanone suggests that the C–H bond cleavage did take place with cyclooctanone. DFT calculation (B3LYP/LanL2DZ, 6-31G*) was further performed to compare the following β -hydride elimination step for cyclooctanone and cyclohexanone (Figure 2).²⁶ As a result, β -hydride elimination barrier relative to the corresponding α -metallocarbonyl complex **G** is 2.4 kcal/mol higher for cyclooctanone (ΔG_8^\ddagger) than for cyclohexanone (ΔG_6^\ddagger). When these two transition states are compared to the common intermediate **E**, the transition state with cyclooctanone (**TS₈**) was located 9.8 kcal/mol higher than that with cyclohexanone (**TS₆**). The difference of ΔG_8^\ddagger and ΔG_6^\ddagger could be attributed to the larger ring strain of cyclooctanone than cyclohexanone, which caused the larger dihedral angle (Ir–C $_{\alpha}$ –C $_{\beta}$ –H) in the transition state (22.1 $^\circ$ in **TS₈** and 13.6 $^\circ$ in **TS₆**). Also, dehydrogenation to unsaturated ketone is thermodynamically more favored for cyclohexanone than for cyclooctanone by 3 kcal/mol.²⁶

In conclusion, we synthesized novel hydroxycyclopentadienyl group 9 metal complexes. Hydroxycyclopentadienyl iridium complex **4a₁** was found to be active in direct acceptorless

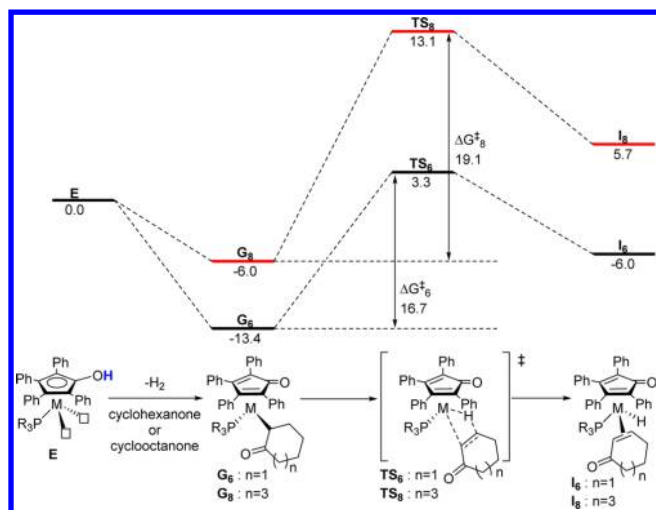


Figure 2. DFT calculation for β -hydride elimination (kcal/mol).

dehydrogenation of C–C single bonds adjacent to functional groups by metal–ligand cooperation. This report provides a new strategy for C–H bond functionalization and synthesis of α,β -unsaturated compounds.

■ ASSOCIATED CONTENT

Supporting Information

Experimental details for the synthesis of complexes and dehydrogenation reactions, crystallographic data (CIF) for complexes **3a**₁, **4a**₁, **5a**_{1me}, and **6**. Optimized geometries for calculated transition states and intermediates. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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(26) See Supporting Information for further experimental details and theoretical calculation results.