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Homogeneous Perdehydrogenation and Perhydrogenation of Fused Bicyclic N-Heterocycles Catalyzed by Iridium Complexes Bearing a Functional Bipyridonate Ligand

Ken-ichi Fujita,* Yui Tanaka, Masato Kobayashi, and Ryohei Yamaguchi*

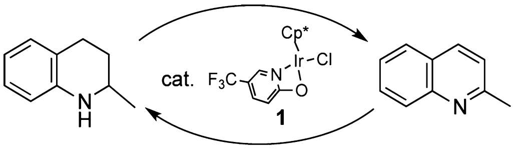
Graduate School of Human and Environmental Studies, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan

Supporting Information

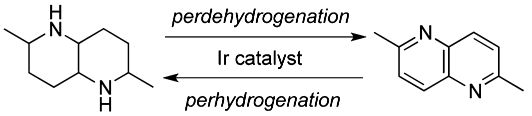
ABSTRACT: Homogeneous perdehydrogenation of saturated bicyclic 2,6-dimethyldecahydro-1,5-naphthyridine and perhydrogenation of aromatic 2,6-dimethyl-1,5-naphthyridine with release and uptake of five molecules of H_2 are efficiently achieved by iridium complexes bearing a functional bipyridonate ligand. Successive perhydrogenation and perdehydrogenation of 2,6-dimethyl-1,5-naphthryridine using a single iridium complex also proceed with the reversible interconversion of the catalytic species, depending on the presence or absence of H_2.

Catalytic dehydrogenation and hydrogenation of N-heterocycles are basic and important organic transformations. In addition, these transformations have recently attracted considerable attention from viewpoints of organic hydrides for hydrogen storage systems,[1,2] because the dehydrogenation of N-heterocycles is more favorable as compared to that of cycloalkanes by decreasing the endothermicity of the reactions.[3−5] Although many catalytic systems using heterogeneous and homogeneous metal catalysts have been reported,[4−8] most of them utilize heterogeneous catalysts and each of the transformations has been carried out by using different metal catalysts. The catalytic dehydrogenation and hydrogenation system using a single metal catalyst is very rare.[9]

We have recently reported that a homogeneous catalytic system for reversible dehydrogenation−hydrogenation between 2-methyl-1,2,3,4-tetrahydroquinoline (2-MeTHQ) and 2-methylquinoline (2-MeQ) with release and uptake of two molecules of H_2 can be achieved by using a Cp*Ir complex (**1**) bearing a 2-pyridonate ligand (Cp* = pentamethylcyclopentadienyl) (eq 1).[7a] However, only the N-heterocyclic part of the bicyclic quinoline system participates in both transformations and, consequently, the hydrogen gravimetric capacity of this system is rather low.[10] Therefore, it is highly desirable to develop a new catalytic system in which a completely saturated N-heterocycle with higher hydrogen capacity is employed. In order to achieve this catalytic system, it is considered essential that perdehydrogenation of saturated N-heterocycles and perhydrogenation of aromatic N-heterocycles are developed, although it is generally very difficult to accomplish these catalytic processes.[11] We report here the efficient homogeneous perdehydrogenation of 2,6-dimethyldecahydro-1,5-naphthyridine and perhydrogenation of 2,6-dimethyl-1,5-naphthyridine with release and uptake of five molecules of H_2[12] catalyzed by Cp*Ir complexes bearing functional bipyridonate ligands as a single precatalyst (eq 2).



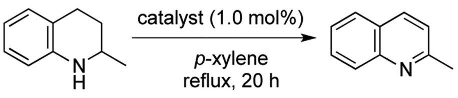
+ $2H_2$ (1)

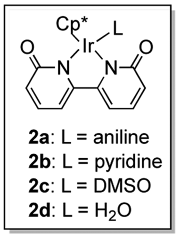


+ $5H_2$ (2)

Quite recently, we have reported the high catalytic activity of Cp*Ir complexes (**2**) bearing a bipyridonate ligand for the dehydrogenative oxidation of a variety of primary and secondary alcohols.[13d] Thus, we first examined the catalytic performance of Cp*Ir complexes **1** and **2a**−**2d** in the dehydrogenation of 2-MeTHQ. The results are shown in Table 1. It was apparent that the new complexes **2** exhibited higher catalytic activities than the previous complex **1**.

Table 1. Dehydrogenation of 2-MeTHQ Catalyzed by Various Ir Complexes[a]





Entry	Catalyst	Conv. (%)[b]	Yield (%)[b]
1	**1**	75	75
2	**2a**	97	96
3	**2b**	100	100
4	**2c**	100	100
5	**2d**	100	100

[a]The reaction was carried out with 2-MeTHQ (2 mmol) and the catalyst (1.0 mol %) under reflux in *p*-xylene for 20 h. [b]Determined by GC.

Having the complexes **2** with high catalytic activity for dehydrogenation of 2-MeTHQ, we next investigated the perdehydrogenation of saturated bicyclic 2,6-dimethyldecahydro-1,5-naphthyridine (**3**) as the substrate, because **3** contains

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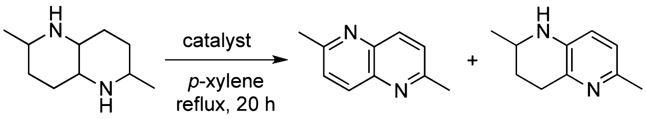
the ring-fused structure of the tetrahydro-N-heterocyclic part of 2-MeTHQ and two nitrogen atoms are apart from each other to prevent the bidentate coordination to the iridium center of the complex. The starting substrate **3** was prepared by hydrogenation of 2,6-dimethyl-1,5-naphthyridine (**4**) as a mixture of two stereoisomers (vide infra, also see Supporting Information). The results are summarized in Table 2. When dehydrogenation of **3** was carried out using **1** as a precatalyst, the perdehydrogenated product **4** was obtained in only 2% yield together with partially dehydrogenated 2,6-dimethyltetrahydro-1,5-naphthyridine (**5**) (23%) (entry 1). However, we were pleased to find that the use of complexes **2** greatly improved the perdehydrogenation process. Thus, dehydrogenation of **3** catalyzed by **2a** gave **4** in 69% yield together with 25% of **5** (entry 2). Furthermore, the yield of **4** increased to 96% without formation of **5** when 5 mol % of **2a** was used (entry 3). Similarly, the reactions using complexes **2b**−**2d** produced **4** in excellent to almost quantitative yields (entries 4−6) and **2b** exhibited the highest catalytic activity (entry 4).[14] Thus, the perdehydrogenation of the saturated fused bicyclic N-heterocycle **3** was achieved by using complexes **2** at relatively low temperature (*p*-xylene reflux, 138 °C) as compared to the analogous reaction of a fused bicyclic cycloalkane, i.e. decalin.[15,16]

Table 2. Perdehydrogenation of 3 Catalyzed by Various Ir Complexes[a]



3 **4** **5**

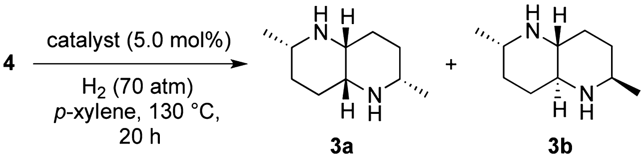
Entry	Catalyst (mol%)	Yield of **4** (%)[b]	Yield of **5** (%)[b]
1	**1** (2.2)	2	23
2	**2a** (2.2)	69	25
3	**2a** (5.0)	96	0
4	**2b** (5.0)	99	0
5	**2c** (5.0)	96	0
6	**2d** (5.0)	97	0

[a] The reaction was carried out with **3** (0.25 mmol) and the catalyst under reflux in *p*-xylene for 20 h. [b] Determined by GC.

Since it was found that the complexes **2** catalyzed the perdehydrogenation of **3** to afford N-heteroaromatic compound **4** in almost quantitative yields, we next examined the reverse reaction, that is, perhydrogenation of **4** to **3** using the same complexes **2**. The results are summarized in Table 3. When hydrogenation of **4** was conducted using **2a** as a precatalyst, a stereoisomeric mixture of 2,6-dimethyldecahydro-1,5-naphthyridines (**3a** and **3b**) was obtained in 82% total yield (entry 1).[17] Among the complexes **2a**−**2d** examined, the perhydrogenation of **4** using **2b** resulted in the best result, giving a mixture of **3a** and **3b** in 92% total yield (entry 2).

Although the perhydrogenation of **4** was accomplished by using **2b** in high yield, it was found that insoluble precipitates were formed when a solution of the catalyst **2a** was kept under H_2 (60 atm) at 100 °C, probably causing a slight deactivation of the catalyst.[18] Then, we turned our attention to the Cp*Ir complexes (**6a** and **6b**)[13d] bearing a rigid functional 1,10-phenanthroline-2,9-dione ligand to prevent the rotation around the pyridyl−pyridyl bond. The results of the perhydrogenation of **4** are summarized in Table 4. Notably, the reactions using complexes **6** under the same conditions as mentioned above gave the perhydrogenated products **3** in almost quantitative yields.[19,20]

Table 3. Perhydrogenation of 4 Catalyzed by 2[a]

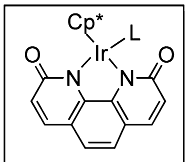


Entry	Catalyst	Yield (%)[b]		Total Yield (%)[b]
		3a	**3b**	**3a** + **3b**
1	**2a**	53	29	82
2	**2b**	55	37	92
3	**2c**	32	28	60
4	**2d**	59	26	85

[a] The reaction was carried out with **4** (1.0 mmol) and **2** (5.0 mol %) under H_2 (70 atm) in *p*-xylene at 130 °C for 20 h. [b] Determined by GC.

Table 4. Perhydrogenation of 4 Catalyzed by 6[a]

$$\mathbf{4} \xrightarrow[\substack{H_2\text{ (70 atm)}\\ p\text{-xylene, 130 °C, 20 h}}]{\text{cat. } \mathbf{6}\text{ (5.0 mol\%)}} \mathbf{3a} + \mathbf{3b}$$



6a: L = pyridine
6b: L = H_2O

Entry	Catalyst	Yield (%)[b]		Total Yield (%)[b]
		3a	**3b**	**3a** + **3b**
1	**6a**	55	44	99
2	**6b**	48	52	100

[a] The reaction was carried out with **4** (1.0 mmol) and **6** (5.0 mol %) under H_2 (70 atm) in *p*-xylene at 130 °C for 20 h. [b] Determined by GC.

The perdehydrogenation of **3** was also successfully conducted by using complexes **6**. Thus, the reactions of a stereoisomeric mixture of **3** catalyzed by **6a** and **6b** proceeded smoothly under the same conditions as previously mentioned to afford fused bicyclic N-heteroaromatic compound **4** in 97% and 98% yields, respectively (Scheme 1), demonstrating the high catalytic performance of complexes **6** for the perdehydrogenation reaction of **3**.

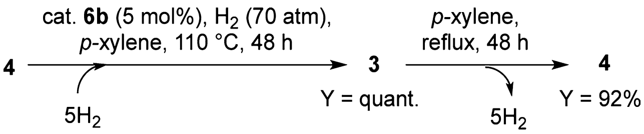
Scheme 1. Perdehydrogenation of 3 Catalyzed by 6

$$\mathbf{3} \xrightarrow[p\text{-xylene, reflux, 20 h}]{\text{cat. } \mathbf{6}\text{ (5.0 mol\%)}} \mathbf{4} + 5H_2$$

6a: Y = 97%
6b: Y = 98%

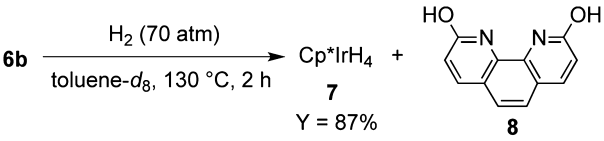
Since it was found that the complex **6b** showed better and the best catalytic performance in the perdehydrogenation and perhydrogenation processes, respectively, the successive interconversion of **4** and **3** was examined by using **6b** (Scheme 2).

Scheme 2. Successive Perhydrogenation and Perdehydrogenation of 4 and 3 Catalyzed by 6b



When a solution of **4** in the presence of **6b** in *p*-xylene was heated at 110 °C under H_2 (70 atm), **3** was produced in quantitative yield. Then, the reaction mixture was transferred to a Schlenk flask and heated at reflux to afford the starting substrate **4** in 92% yield, demonstrating the successive perhydrogenation (uptake of $5H_2$) and perdehydrogenation (release of $5H_2$) of **4** by using **6b** as the single precatalyst.

As mentioned in the reversible dehydrogenation and hydrogenation of 2-MeTHQ catalyzed by **1**, the complex **1** was reversibly interconverted to $[Cp^*IrHCl]_2$, depending on the absence or presence of H_2.[7a] Therefore, it is highly probable that **6b** could be converted to different catalytic species under the perhydrogenation conditions shown above. Then, a solution of **6b** in toluene-d_8 was heated at 130 °C under H_2 (70 atm) for 2 h, and it was revealed by ^1H NMR analysis that **6b** was converted to the tetrahydride Cp*Ir complex, Cp^*IrH_4 (**7**),[21] in 87% yield along with a precipitate, which was identified as the liberated ligand 2,9-dihydroxy-1,10-phenanthroline (**8**) by ^1H NMR analysis in DMSO-d_6 (eq 3). In addition, it was observed that the reaction of equimolar amounts of **7** and **8** in *p*-xylene under reflux for 1 h regenerated the complex **6b** in 76% yield (eq 4).



(3)

$$7 + 8 \xrightarrow[p\text{-xylene, reflux, 1 h}]{} \underset{Y = 76\%}{6b} \qquad (4)$$

Thus, it was apparent that **6b** and **7** were interconverted to each other under the reaction conditions with or without H_2.

Next, we investigated the perhydrogenation of **4** catalyzed by **7** to clarify whether **7** could be a catalytically active species. The results are summarized in Table 5. When a solution of **4** in *p*-xylene was heated at 130 °C in the presence of **7** (5 mol %) under H_2 (70 atm) for 20 h, **3** was obtained in only 19% total yield (entry 1). On the other hand, the addition of phenol (20 mol %) as a proton source improved the yield to 76% (entry 2). Furthermore, it was found that the perhydrogenation of **4** proceeded in 92% total yield when conducted in the presence of **8** (entry 3). These results clearly indicated that protonation of **4** could facilitate the perhydrogenation and that **8** would serve as a proton donor.[22] Thus, the functional ligand **8** could play crucial roles in both perdehydrogenation and perhydrogenation processes.

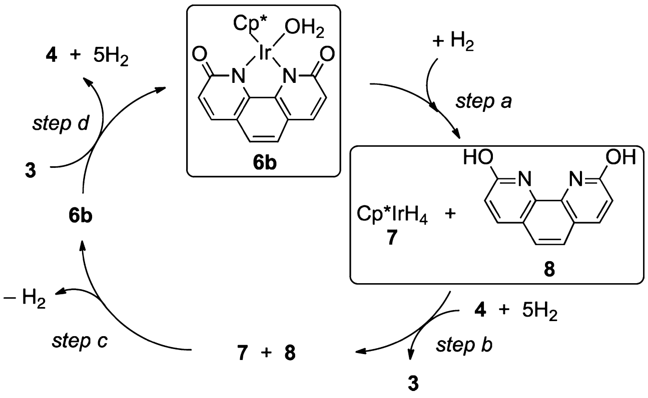
Table 5. Perhydrogenation of 4 Catalyzed by Cp^*IrH_4 (7)[a]

$$4 \xrightarrow[H_2\text{ (70 atm), }p\text{-xylene, 130 °C, 20 h}]{\text{cat. }7\text{ (5.0 mol\%), additive}} 3a + 3b$$

Entry	Additive	Yield (%)[b] 3a	Yield (%)[b] 3b	Total Yield (%)[b] 3a + 3b
1	none	19	0	19
2	PhOH (20 mol%)	67	9	76
3	**8** (10 mol%)	78	14	92

[a]The reaction was carried out with **4** (1.0 mmol) and **7** (5.0 mol %) under H_2 (70 atm) in *p*-xylene at 130 °C for 20 h. [b]Determined by GC.

Scheme 3. Overall Catalytic Processes for Successive Perhydrogenation and Perdehydrogenation Catalyzed by 6b[a]



[a]*Step a*: hydrogenolysis of **6b** to **7** and **8**. *Step b*: perhydrogenation of **4** catalyzed by **7** and **8**. *Step c*: regeneration of **6b** from **7** and **8** releasing H_2. *Step d*: perdehydrogenation of **3** catalyzed by **6b**

Considering the above experimental results, we propose the following overall catalytic processes as shown in Scheme 3. First, hydrogenolysis of **6b** would generate tetrahydride complex **7** along with the liberated ligand **8** under H_2 (70 atm) at 130 °C (*step a*). Then, the complex **7** could catalyze the perhydrogenation of **4** with the aid of the liberated **8** (*step b*). Subsequently, the starting complex **6b** is regenerated by recombination of **7** and **8** when H_2 is removed from the reaction atmosphere (*step c*). Finally, the perdehydrogenation of **3** catalyzed by the complex **6b** could proceed through a similar cooperative catalysis of the iridium center and the functional bipyridonate ligand to that suggested in the dehydrogenative oxidation of alcohols[13d] to afford **4** with concomitant evolution of 5 equiv of H_2 (*step d*), resuming the starting point of the catalytic system.

In conclusion, we have developed for the first time the homogeneous catalytic systems for the perdehydrogenation and perhydrogenation of fused bicyclic N-heterocycles using the Cp*Ir complexes bearing a functional bipyridonate ligand. The perdehydrogenation of saturated **3** gave N-heteroaromatic **4** in excellent yield with the release of five molecules of H_2. The perhydrogenation of **4** was also accomplished by using the same complexes to afford **3** in excellent yield with the uptake of five molecules of H_2. In addition, the successive perhydrogenation and perdehydrogenation process was achieved by using **6b** as a single precatalyst through the reversible interconversion of the catalytic species, depending on the presence or absence of H_2. Further investigations on the more efficient homogeneous catalytic systems for the perdehydrogenation and perhydrogenation of other fused N-heterocycles with high hydrogen content are in progress.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Experimental procedures and X-ray crystallographic data for **2a**, **3a**, and **3b** (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Authors

yamaguchi.ryohei.75s@st.kyoto-u.ac.jp
fujita.kenichi.6a@kyoto-u.ac.jp

Notes

The authors declare no competing financial interest.

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(9) To the best of our knowledge, there have been only two reports.[7a,d]

(10) The hydrogen gravimetric capacity of 2-MeTHQ is 2.7 wt % at a maximum.

(11) All of the perdehydrogenation and perhydrogenation of *N*-ethyldodecahydrocarbazole and *N*-ethylcarbazole have been achieved by using heterogeneous metal catalyst at high temperatures (>150 °C).[4,6a−c] It should be noted that the catalytic dehydrogenation of *N*-ethyldodecahydrocarbazole using homogeneous PCP pincer iridium complexes at 200 °C results in the partial dehydrogenation.[6d]

(12) The hydrogen gravimetric capacity of **3** is 6.0 wt % at a maximum. The DOE 2015 target is 5.5 wt %.

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(14) Evolution of hydrogen was confirmed by dual reactions. See Supporting Information.

(15) The perdehydrogenation of decalin by using heterogeneous catalysts has been generally carried out at >200 °C. Biniwalea, R. B.; Rayalua, S.; Devottaa, S.; Ichikawa, M. *Intl. J. Hydrogen Energy* **2008**, *33*, 360 and references cited therein.

(16) Dehydrogenation of decahydro-1,5-naphthyridine and 2-methylpiperidine under conditions similar to those previously mentioned gave trace amounts of perdehydrogenated products (<4%).

(17) The structures of **3a** and **3b** were determined by X-ray analyses. See Supporting Information.

(18) See Supporting Information for details.

(19) It should be noted that complexes **6** exhibit much lower catalytic activity than complexes **2** in the dehydrogenation of alcohols.[13d]

(20) The perhydrogenation and dehydrogenation were not affected by the addition of mercury at all, supporting the homogeneous catalytic reactions. See Supporting Information for details. We thank the referee for the valuable suggestion.

(21) ^{1}H NMR (toluene-d_8) δ 2.00 (15H), −15.59 (4H). See Supporting Information for details.

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