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Heterolytic Cleavage of Hydrogen Molecule by Rhodium Thiolate Complexes That Catalyze Chemoselective Hydrogenation of Imines under Ambient Conditions

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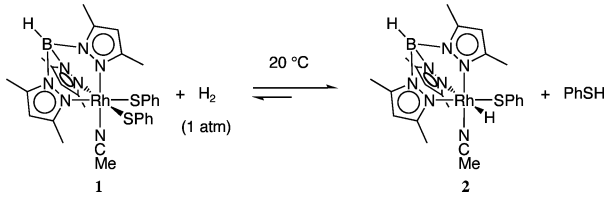
Heterolytic activation of dihydrogen is a key step in catalytic hydrogenation of polar bonds and hydrogen metabolism mediated by hydrogenases. Many transition-metal complexes, especially electron-poor ones, are known to be capable of cleaving H_2 generally in the manner that H^+ is split off from the highly acidic H_2 ligand to leave H^- on the metal center.[1] In this conversion, the proton is accepted by an external Lewis base or more efficiently by an internal ancillary ligand, as is typically observed in metal−ligand bifunctional catalysts represented by organoamide complexes.[2] Anionic S-donor ligands, RS^- and S^{2-}, are also expected to become internal proton acceptors, and some mechanisms proposed for the function of [NiFe]-hydrogenases postulate proton transfer from the coordinated H_2 to the Ni-bound terminal S(Cys) moiety.[3] However, such reactions proceeding on thiolate complexes are uncommon.[4−6] There are only a few cases that clearly confirm the formation of M(H)−S(H)R from M−SR with H_2[5] and scarce applications to catalysis.[6]

We have been engaging in studies involving activation of small molecules by transition-metal thiolate complexes.[7] We herein report that the bis(thiolate)Rh(III) complex having a tris(3,5-dimethylpyrazolyl)borate (Tp^{Me2}) coligand, [$Tp^{Me2}Rh(SPh)_2(MeCN)$] (**1**),[7b] reacts reversibly with H_2 to form the hydridothiolato complex [$Tp^{Me2}RhH(SPh)(MeCN)$] (**2**) and PhSH, as shown in Scheme 1. On the basis of this heterolysis of H_2, a hydrogenation catalyst that operates under ambient temperature and pressure with high chemoselectivity toward imines has been developed.

Scheme 1



Treatment of a 10 mM solution of **1** in C_6D_6 with 1 atm H_2 at 20 °C for 2 h gave an equilibrium mixture containing **1**, **2**, and PhSH in a 1:10:10 ratio. When this mixture was set under a N_2 atmosphere, **1** was slowly regenerated. The ^{1}H NMR spectrum of **2** showed a doublet at δ −13.80 (J_{RhH} = 11.6 Hz) due to the hydrido ligand and 10 singlets corresponding to the three inequivalent pyrazolyl groups (two methyls and one ring proton for each) and MeCN. Although we previously found **2** in the reaction of [$Tp^{Me2}Rh(C_8H_{14})(MeCN)$] with 1 equiv of PhSH, its isolation was hampered by simultaneous production of **1** (**1**/**2** ≈ 1:2).[7e] Here, addition of hexane to an equilibrium mixture prepared from **1** under a H_2 atmosphere gave yellow crystals of pure **2**, with which the structure was fully determined by X-ray crystallography (see the Supporting Information).

As reversible heterolysis of H_2 molecule at the Rh−S bond in **1** was disclosed, catalytic hydrogenation was examined to probe the reactivity of the resulting hydrogen atoms. As shown in Table 1, **1** was found to be effective for the hydrogenation of styrene and *N*-benzylideneaniline under 1 atm H_2 with low to moderate activity at 20−50 °C (entries 1−4). Although higher activity was expected toward the more polarized C═O bond, benzaldehyde and acetophenone were not hydrogenated under these conditions. Isolated **2** showed slightly higher activity than **1** toward styrene, implying that the active species in C═C reduction is close to **2** (entry 5). However, conversion of *N*-benzylideneaniline was much deteriorated when **2** alone was used, and therefore, not only the Rh−H but also the S−H hydrogen are essential for hydrogenating the C═N bond (entry 6). The activity of the diiodo complex [$Tp^{Me2}RhI_2(MeCN)$] (**3**) toward this substrate was also poor (entry 7), but the Se analogue of **1**, [$Tp^{Me2}Rh(SePh)_2(MeCN)$] (**4**),[7c] was found to be much more active than **1**, even at 20 °C (entry 8). Whereas **3** remained almost intact under a H_2 atmosphere at 50 °C, **4** formed the hydrido complex analogously to **1**. These results indicate that catalytic activity for the hydrogenation of C═N bonds sharply depends on the ability to heterolyze H_2 molecules and that this is strongly affected by ligating elements.

Table 1. Hydrogenation of PhCH═Z Catalyzed by [$Tp^{Me2}RhX^1X^2(MeCN)$][a]

entry	catalyst (X^1; X^2)	Z	temp (°C)	time (h)	yield (%)[b]
1	**1** (SPh; SPh)	CH_2	20	20	16
2	**1** (SPh; SPh)	CH_2	50	10	72
3	**1** (SPh; SPh)	NPh	20	20	21
4	**1** (SPh; SPh)	NPh	50	10	63
5	**2** (H; SPh)	CH_2	50	10	86
6	**2** (H; SPh)	NPh	50	10	18
7	**3** (I; I)	NPh	50	10	27
8	**4** (SePh; SePh)	NPh	20	6	99
9	**5** (*o*-$S_2C_6H_4$)	NPh	20	1	98
10[c]	**5** (*o*-$S_2C_6H_4$)	NPh	20	2	48

[a] Conditions: substrate (1.00 mmol), catalyst (0.01 mmol), THF (5 mL), H_2 (1 atm). [b] Yields of ethylbenzene and *N*-benzylaniline were determined by GLC analyses. The sum of the yields of product and remaining substrate was no less than 98% in each reaction. [c] Conducted in benzene (5 mL).

To improve the catalytic efficiency, the benzenedithiolato complex [$Tp^{Me2}Rh$(*o*-$S_2C_6H_4$)(MeCN)] (**5**) was newly synthesized according to Scheme 2. The active intermediate generated from **5** may contain both RhH and SH moieties within the same molecule. As expected, **5** achieved much more rapid hydrogenation of *N*-benzylideneaniline at 20 °C than the other complexes mentioned above (Table 1, entry 9). Moreover, it was found that reduction of the C═C bond is suppressed and inertness toward the C═O bond is still preserved, as shown in Table 2. Thus, the C═N bonds in various aldimines are efficiently hydrogenated under ambient

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temperature and pressure with coexisting C═C or C═O functions unaffected, with the exception that partial reduction occurred for the C═C bond conjugated with the C═N group (entry 3). On behalf of inertness to C═O bonds, reductive amination could be performed by mixing aldehyde and primary amine directly under hydrogenation conditions (entry 5). Conversion of a ternary iminium salt into a tertiary ammonium salt also took place quantitatively (entry 6).

Scheme 2

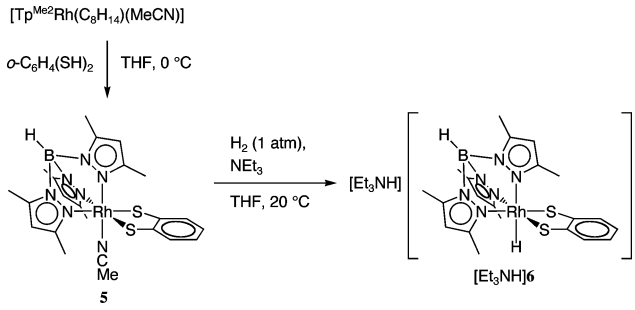
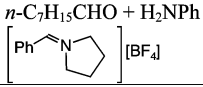
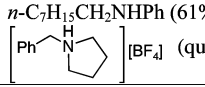


Table 2. Hydrogenation of Various Imines Catalyzed by **5**[a]

entry	substrate	product (yield[b])
1	$PhCH{=}NCH_2Ph$	$PhCH_2NHCH_2Ph$ (97%)
2	$PhCH{=}NCH_2CH{=}CH_2$	$PhCH_2NHCH_2CH{=}CH_2$ (90%)
3	*E*-PhCH=CHCH=NPh	*E*-PhCH=CHCH$_2$NHPh (82%) $PhCH_2CH_2CH_2NHPh$ (15%)
4	*m*-C_6H_4(CHO)(CH=NPh)	*m*-C_6H_4(CHO)(CH_2NHPh) (99%)
5[c]	*n*-$C_7H_{15}CHO + H_2NPh$	*n*-$C_7H_{15}CH_2NHPh$ (61%)
6		 (quant.)

[a] Conditions: substrate (1.00 mmol), **5** (0.01 mmol), THF (5 mL), H_2 (1 atm), 20 °C, 1 h. [b] NMR determination (entries 1−3, 6) or isolated yields (entries 4 and 5). [c] Octanal (1.01 mmol) was added to a solution of aniline (1.02 mmol) and **5** (0.020 mmol) under a H_2 atmosphere.

In contrast to **1**, no observable change in **5** occurred under 1 atm H_2. However, addition of NEt_3 to its THF solution caused rapid formation of an off-white solid, which was characterized as $[Et_3NH][Tp^{Me2}RhH(o\text{-}S_2C_6H_4)]$ ([Et_3NH]**6**). The hydrido ligand in **6**$^-$ exhibited an ^{1}H signal at −18.90 (d, J_{RhH} = 14.8 Hz) and an IR absorption for ν(Rh−H) at 2104 cm^{-1}. Because of the appearance of the ν(N−H) band at 2670 cm^{-1} characteristic of tertiary ammonium cation, **6**$^-$ was identified as a monoanion. From this result, it is plausible that $\{Tp^{Me2}Rh(o\text{-}S_2C_6H_4)\}$ and H_2 form an adduct that may shift H^+ to the imine and also that the resulting **6**$^-$ transfers H^- to this iminium cation. This mechanism, namely, ionic hydrogenation,[8] is supported by the decrease in the catalytic rate in the less-polar benzene medium (Table 1, entry 10).[9] The major catalytic cycle of imine reduction by **1** is also considered to be similar, because the anionic hydrido complex analogous to **6**$^-$ can be prepared from **1** under the same conditions. Such a reaction pathway mediated by formation of an active iminium ion has been proposed in some other catalytic systems.[10] The preferential addition of H_2 to the C═N bond over the C═O bond as observed here is uncommon.[11] Presumably, the H_2 adduct of the Rh species is not acidic enough to protonate O atom, and the nucleophilicity of **6**$^-$ is not strong enough to reduce the nonactivated C═O bond. On the other hand, hydrogenation of acetophenone by a Ru thiolate complex has been proposed to proceed via the concerted transfer of hydride and proton to the C═O bond,[6] as is widely accepted for bifunctional molecular catalysts.[2]

It is still unclear whether deprotonation from the H_2 adducts of Rh thiolate complexes occurs directly at the stage of η^2-H_2 or after formation of Rh(H)−S(H) species. However, their catalytic functions may have some relevance to [Fe]-hydrogenases, which generate a proton and transfer a hydride to an organic molecule at a monoiron site bound to a cysteine residue.[12,13]

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Supporting Information Available: Experimental details and X-ray analysis data for **2** (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) (a) Brothers, P. J. *Prog. Inorg. Chem.* **1981**, *28*, 1. (b) Morris, R. H. *Can. J. Chem.* **1996**, *74*, 1907. (c) Kubas, G. J. *Adv. Inorg. Chem.* **2004**, *56*, 127.
(2) Recent reviews: (a) Noyori, R.; Ohkuma, T. *Angew. Chem., Int. Ed.* **2001**, *40*, 40. (b) Clapham, S. E.; Hadzovic, A.; Morris, R. H. *Coord. Chem. Rev.* **2004**, *248*, 2201. (c) Ito, M.; Ikariya, T. *Chem. Commun.* **2007**, 5134.
(3) Recent reviews: (a) Volbeda, A.; Fontecilla-Camps, J. C. *Dalton Trans.* **2003**, 4030. (b) De Lacey, A. L.; Fernández, V. M.; Rousset, M.; Cammack, R. *Chem. Rev.* **2007**, *107*, 4304. (c) Siegbahn, P. E. M.; Tye, J. W.; Hall, M. B. *Chem. Rev.* **2007**, *107*, 4414. (d) Tard, C.; Pickett, C. J. *Chem. Rev.* **2009**, *109*, 2245. (e) Gloaguen, F.; Rauchfuss, T. B. *Chem. Soc. Rev.* **2009**, *38*, 100.
(4) (a) Sellmann, D.; Käppler, J.; Moll, M. *J. Am. Chem. Soc.* **1993**, *115*, 1830. (b) Jessop, P. G.; Morris, R. H. *Inorg. Chem.* **1993**, *32*, 2236. (c) Sellmann, D.; Gottschalk-Gaudig, T.; Heinemann, F. W. *Inorg. Chem.* **1998**, *37*, 3982. (d) Sellmann, D.; Fürsattel, A. *Angew. Chem., Int. Ed.* **1999**, *38*, 2023. (e) Sellmann, D.; Geipel, F.; Moll, M. *Angew. Chem., Int. Ed.* **2000**, *39*, 561. (f) Sellmann, D.; Prakash, R.; Heinemann, F. W.; Moll, M.; Klimowicz, M. *Angew. Chem., Int. Ed.* **2004**, *43*, 1877. (g) Matsumoto, T.; Nakaya, Y.; Tatsumi, K. *Angew. Chem., Int. Ed.* **2008**, *47*, 1913.
(5) (a) Schlaf, M.; Lough, A. J.; Morris, R. H. *Organometallics* **1996**, *15*, 4423. (b) Sellmann, D.; Rackelmann, G. H.; Heinemann, F. W. *Chem.—Eur. J.* **1997**, *3*, 2071. (c) Ohki, Y.; Sakamoto, M.; Tatsumi, K. *J. Am. Chem. Soc.* **2008**, *130*, 11610.
(6) Ohki, Y.; Takikawa, Y.; Sadohara, H.; Kesenheimer, C.; Engendahl, B.; Kapatina, E.; Tatsumi, K. *Chem.—Asian J.* **2008**, *3*, 1625.
(7) (a) Takagi, F.; Seino, H.; Hidai, M.; Mizobe, Y. *Organometallics* **2003**, *22*, 1065. (b) Seino, H.; Yoshikawa, T.; Hidai, M.; Mizobe, Y. *Dalton Trans.* **2004**, 3593. (c) Nagao, S.; Seino, H.; Hidai, M.; Mizobe, Y. *Dalton Trans.* **2005**, 3166. (d) Kajitani, H.; Seino, H.; Mizobe, Y. *Organometallics* **2005**, *24*, 6260. (e) Misumi, Y.; Seino, H.; Mizobe, Y. *J. Organomet. Chem.* **2006**, *691*, 3157. (f) Saito, A.; Seino, H.; Kajitani, H.; Takagi, F.; Yashiro, A.; Ohnishi, T.; Mizobe, Y. *J. Organomet. Chem.* **2006**, *691*, 5746.
(8) (a) Bullock, R. M.; Voges, M. H. *J. Am. Chem. Soc.* **2000**, *122*, 12594. (b) Magee, M. P.; Norton, J. R. *J. Am. Chem. Soc.* **2001**, *123*, 1778. (c) Bullock, R. M. *Chem.—Eur. J.* **2004**, *10*, 2366. (d) Guan, H.; Iimura, M.; Magee, M. P.; Norton, J. R.; Zhu, G. *J. Am. Chem. Soc.* **2005**, *127*, 7805. (e) Namorado, S.; Antunes, M. A.; Veiros, L. F.; Ascenso, J. R.; Duarte, M. T.; Martins, A. M. *Organometallics* **2008**, *27*, 4589.
(9) Addition of MeCN also retarded the catalysis by **5**.
(10) (a) Casey, C. P.; Singer, S. W.; Powell, D. R.; Hayashi, R. K.; Kavana, M. *J. Am. Chem. Soc.* **2001**, *123*, 1090. (b) Åberg, J. B.; Samec, J. S. M.; Bäckvall, J.-E. *Chem. Commun.* **2006**, 2771. (c) Shirai, S.; Nara, H.; Kayaki, Y.; Ikariya, T. *Organometallics* **2009**, *28*, 802.
(11) (a) Ng Cheong Chan, Y.; Meyer, D.; Osborn, J. A. *J. Chem. Soc., Chem. Commun.* **1990**, 869. (b) Ng Cheong Chan, Y.; Osborn, J. A. *J. Am. Chem. Soc.* **1990**, *112*, 9400. (c) Gross, T.; Seayad, A. M.; Ahmad, M.; Beller, M. *Org. Lett.* **2002**, *4*, 2055.
(12) (a) Shima, S.; Thauer, R. K. *Chem. Rec.* **2007**, *7*, 37. (b) Shima, S.; Pilak, O.; Vogt, S.; Schick, M.; Stagni, M. S.; Meyer-Klaucke, W.; Warkentin, E.; Thauer, R. K.; Ermler, U. *Science* **2008**, *321*, 572. (c) Hiromoto, T.; Ataka, K.; Pilak, O.; Vogt, S.; Stagni, M. S.; Meyer-Klaucke, W.; Warkentin, E.; Thauer, R. K.; Shima, S.; Ermler, U. *FEBS Lett.* **2009**, *583*, 585.
(13) (a) Royer, A. M.; Rauchfuss, T. B.; Gray, D. L. *Organometallics* **2009**, *28*, 3618. (b) Yang, X.; Hall, M. B. *J. Am. Chem. Soc.* **2009**, *131*, 10901.

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