J. Am. Chem. Soc. **1986**, *108*, 943-947

Catalytic Reactions of Metalloporphyrins. 1. Catalytic Modification of Borane Reduction of Ketone with Rhodium(III) Porphyrin as Catalyst[1]

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Abstract: (Octaethyl- or tetraphenylporphyrinato)rhodium(III) chloride shows an efficient catalysis in the aerobic reduction of ketone with $NaBH_4$ in THF, $BH_4^- + 2R_1R_2C{=}O + O_2 \rightarrow 2R_1R_2CHOH + BO_2^-$. The initial step in the catalytic cycle is the rate-determining complexation of BH_4^- with Rh^{III} porphyrin ($Rh^{III} + BH_4^- \rightarrow Rh^{III}{-}BH_4$) followed by a rapid borane transfer from the adduct to ketone to give dialkoxyborane and hydridorhodium species ($Rh^{III}{-}BH_4 + 2R_1R_2C{=}O \rightarrow Rh{-}H + HB(O{-}CHR_1R_2)_2$). In the subsequent step, the Rh-H species undergoes oxidation with O_2 back to Rh^{III} with concomitant "hydrolysis" of dialkoxyborane to alcohol ($Rh{-}H + O_2 + HB(O{-}CHR_1R_2)_2 \rightarrow Rh^{III} + 2R_1R_2CHOH + BO_2^-$). Essentially, autorecycling Rh^{III} and Rh-H act as a "borane" generator and proton source, respectively, in a catalytic manner. Furthermore, the Rh^{III}-BH_4 complex capable of transferring borane to ketone lacks what is characteristic of free borane, i.e., facile oxidation with O_2 and ready hydrolysis with H_2O. Thus, the present system provides a highly efficient, catalytic modification of synthetic reactions of borane in the presence of oxygen.

The combination of a reductant, dioxygen, and a metal ion, metalloporphyrin in particular, constitutes a number of potential, catalytic systems for redox transformation of organic substrates. The cytochrome P_{450} models composed of $NaBH_4$ or H_2/Pt, O_2, and manganese or iron porphyrins have been shown to be effective in oxygenation of hydrocarbon substrates,[2] while a similar system with cobalt complexes has been demonstrated to give organocobalt derivatives, which undergo oxidative C-Co bond cleavage by O_2 in a subsequent step.[3,4] An essential feature of these reactions lies in the reductive activation of oxidants (O_2 or central metals). In the present work, we have studied a different type of catalysis of rhodium porphyrin in the aerobic reduction of ketone with $NaBH_4$ in THF.

Sodium tetrahydroborate(III) is a hydride or 2-electron reductant often used in the reduction of metal complexes, where mass balance suggests that borane might be generated (eq 1). The resulting hydridometal species ($M^{n+}{-}H^-$) or its conjugate base ($M^{(n-2)+}$) is expected to undergo ready reaction with O_2 to regenerate M^{n+} (eq 2).[5] Combination of eq 1 and 2 indicates that aerial oxidation of BH_4^- mediated by metal complex might lead to catalytic generation of borane, which has been proved to be such an important reagent in organic synthesis and is prepared

$$M^{n+} + BH_4^- \rightarrow M^{n+}{-}H^- \ (\leftrightarrow M^{(n-2)+} + H^+) + \text{“}BH_3\text{”} \qquad (1)$$

$$M^{n+}{-}H^- \ (\leftrightarrow M^{(n-2)+} + H^+) + O_2 \rightarrow M^{n+} + \text{“}HO_2^-\text{”} \qquad (2)$$

by stoichiometric reactions of $NaBH_4$ and Lewis acid under inert atmosphere.[6] The catalytic borane generation based on eq 1 and 2, however, has never been reported, although borane generation upon anaerobic oxidation of BH_4^- is not without precedents.[7] A serious dilemma here is that borane, if it is free, undergoes quite ready oxidation with O_2, which is an essential component for the recycling of catalyst (eq 2). We report here that the use of rhodium porphyrin makes it possible to remove this dilemma and consequently to construct a complete, catalytic modification of synthetic reactions of borane.[8] The novel catalysis of rhodium porphyrin lies in the *moderate* oxidative-activation of the reductant.

Results

General Aspects, Stoichiometry, and Rate-Determining Step. The borohydride reduction of acetophenone in tetrahydrofuran (THF) is very slow but is accelerated considerably by a catalytic amount of (octaethylporphyrinato)rhodium(III) chloride, $(OEP)Rh^{III}$- Cl, under otherwise identical conditions, ketone (0.17-1.67 mmol), $NaBH_4$ (0.2-7.9 mmol), and rhodium porphyrin (6.0 μmol) in dry THF (10 mL) exposed to dry air at 20 °C. The reaction took place in completely homogeneous solutions, and typical time courses with and without catalyst are shown in Figure 1, where the acceleration factor is approximately 30 times. Many runs were carried out with $NaBH_4$ in large excess (7.9 mmol) just to keep solutions always saturated with it; the solubility of $NaBH_4$ in THF (10 mL) being ca. 0.2 mmol at 25 °C).[9] The visible spectrum of the solutions did not change during catalytic reactions and was that of a Rh^{III} porphyrin, readily distinguished from those of Rh^{II}, Rh^{I}, and its conjugate acid (hydridorhodium species).[10] There was no indication of decomposition or deactivation of the metalloporphyrin catalyst during reactions. The yield of the reduction product, 1-phenylethanol, was quantitative (>99%) in each run. The present catalytic reduction was also applicable to ketones other than acetophenone such as cyclohexanone, methylcyclohexanones, cyclopentanone, 3-heptanone, and norcamphor.

Dioxygen was found to be an essential component. Under conditions where $NaBH_4$ was the limiting material, 1 mol of O_2 was absorbed and 2 mol of alcohol formed per mol of $NaBH_4$, together with amorphous powders of inorganic borate. On the other hand, hydrogen evolution, if any, was negligible. These

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(1) Presented at the 1984 International Chemical Congress of Pacific Basin Societies, Honolulu, Hawaii, 1984, Abstracts 07H25.

(2) (a) Tabushi, I.; Koga, N. *J. Am. Chem. Soc.* **1979**, *101*, 6456-6458. (b) Tabushi, I.; Yazaki, A. *Ibid.* **1981**, *103*, 7371-7373. (c) Tabushi, I.; Morimitsu, K. *Ibid.* **1984**, *106*, 6871-6872.

(3) (a) Okamoto, T.; Oka, S., presented at the 46th Annual Meeting of the Chemical Society of Japan, Niigata, Japan, 1982, Abstracts p 456. (b) Ohno, N.; Ohkatsu, Y.; Inoue, S., presented at the 46th Annual Meeting of the Chemical Society of Japan, Niigata, Japan, 1982, Abstracts p 457.

(4) (a) Okamoto, T.; Oka, S. *Tetrahedron Lett.* **1981**, *22*, 2191-2194. (b) Okamoto, T.; Oka, S. *J. Chem. Soc., Chem. Commun.* **1984**, 289-290.

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(7) (a) Reference 6a. (b) Biswas, K. M.; Jackson, A. H. *J. Chem. Soc. C* **1970**, 1667-1674.

(8) This system has been applied to the catalytic oxygenation of olefins giving rise to anti-Markownikoff alcohols: Aoyama, Y.; Watanabe, T.; Onda, H.; Ogoshi, H. *Tetrahedron Lett.* **1983**, *24*, 1183-1186.

(9) Reference 6b, p 258.

(10) (a) Ogoshi, H.; Setsune, J.; Omura, T.; Yoshida, Z. *J. Am. Chem. Soc.* **1975**, *97*, 6461-6466. (b) Ogoshi, H.; Setsune, J.; Yoshida, J. *Ibid.* **1977**, *99*, 3869-3870. (c) Setsune, J.; Yoshida, Z.; Ogoshi, H. *J. Chem. Soc., Perkin Trans. 1* **1982**, 983-987.

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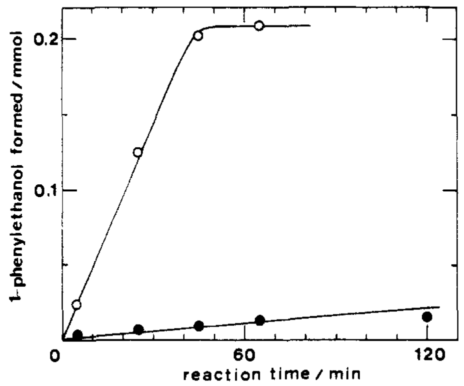


Figure 1. Time courses of the reduction of acetophenone (25 mg, 0.21 mmol) with $NaBH_4$ (10 mg, 0.29 mmol) at 20 °C in THF (10 mL) exposed to air in the presence (6.0 μmol) (○) and absence (●) of $(OEP)Rh^{III}-Cl$.

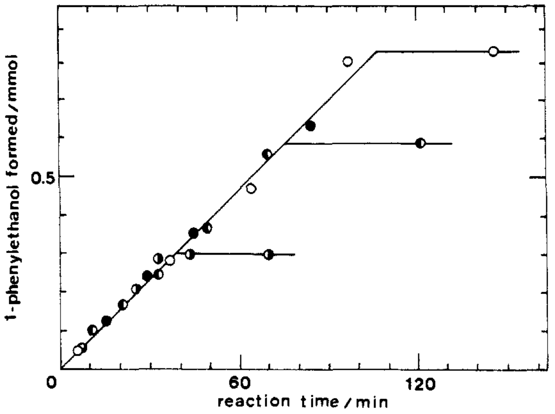


Figure 2. Time courses of the reduction of acetophenone with $NaBH_4$ (300 mg, 7.9 mmol) at 20 °C in THF (10 mL) in the presence of $(OEP)Rh^{III}-Cl$ (6.0 μmol): ketone (36 mg, 0.30 mmol) under air (◑); ketone (70 mg, 0.58 mmol) under air (◐); ketone (100 mg, 0.83 mmol) under air (○); ketone (100 mg, 0.83 mmol) under 1 atm of O_2 (●).

findings lead to the stoichiometry of the reaction as shown in eq 3.

$$2C_6H_5C(O)CH_3 + BH_4^- + O_2 \rightarrow 2C_6H_5 + CH(OH)CH_3 + BO_2^- \quad (3)$$

A survey of solvent effects indicated that THF is the best solvent for the present reaction. Interestingly, addition of water (5% by volume) as a cosolvent resulted in no significant change in the time-course of alcohol formation, although its yield based on mol of $NaBH_4$ consumed was lowered to 150% from 200% for a run in dry THF. When the reaction was carried out in a strongly coordinating solvent such as pyridine, $(OEP)Rh^{III}-Cl$ showed no catalysis, while, in noncoordinating solvent such as dichloromethane or benzene with a crown ether, the reduction of ketone was accelerated by the rhodium complex, but its catalysis was far less effective compared with that in THF. (Tetraphenylporphyrinato)rhodium(III) chloride, $(TPP)Rh^{III}-Cl$, exhibited a similar catalysis as $(OEP)Rh^{III}-Cl$. When $NaBH(OCH_3)_3$ was used instead of $NaBH_4$, the rhodium porphyrin was readily reduced but showed no catalytic activity at all for the reduction of ketone.[11]

Attempting to identify the rate-determining step, the rate-concentration relationships for the substrate, O_2, and $NaBH_4$ were investigated. Three runs were carried out with different amounts of acetophenone (0.30, 0.58, and 0.83 mmol), keeping the amounts of $(OEP)Rh^{III}-Cl$ and $NaBH_4$ constant at 6.0 μmol and 7.9 mmol, respectively, so as to maintain $[NaBH_4]$ in solution constant at its saturation level. In every case was observed a linear time course of alcohol formation up to the completion of the reaction, having the same slope (0.46 mmol/h) in common (Figure 2). The rate of reaction does not depend on the amount of ketone, nor its identity. All the ketones as referred to above were reduced with similar rates, e.g., cyclohexanone with 0.49 mmol/h and 3-heptanone with 0.47 mmol/h. Clearly, the present catalytic reaction is zero order with respect to ketone, which is not involved in the rate-determining step. In Figure 2 is also included the time course of the run carried out under dioxygen (P_{O_2} = 1 atm), which exhibits no deviation from that of the corresponding run carried out under air (P_{O_2} = 0.2 atm). Dioxygen also is concluded not to be involved in the rate-determining step. On the other hand, $NaBH_4$ affects the rate. When $[NaBH_4]$ was within solubility limit, the time course of alcohol formation was not linear but of the usual exponential type (Figure 3), showing that the reaction rate is first order with respect to $[NaBH_4]$ (Figure 3, insertion).[12] Furthermore, an increase in the solubility of $NaBH_4$ via complexation with 18-crown-6 resulted in the corresponding increase in the rate of ketone reduction. Thus, the rate-determining step of the catalytic cycle that determines the overall turnover rate is the reaction between rhodium complex and $NaBH_4$.

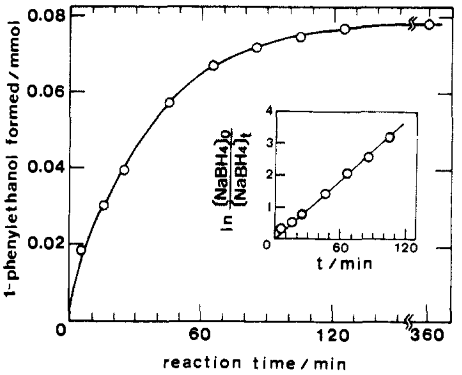
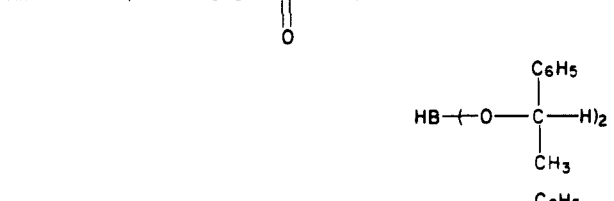
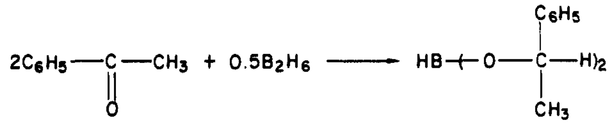


Figure 3. Time course of the reduction of acetophenone in large excess (197 mg, 1.64 mmol) with $NaBH_4$ (0.039 mmol) in THF (10 mL) exposed to air in the presence of $(OEP)Rh^{III}-Cl$ (6.0 μmol). Insertion: analysis of the data according to the first-order kinetics for disappearance of $NaBH_4$.[12]

Borane Transfer and Hydride Transfer. Stoichiometric reactions of $(OEP)Rh^{III}-Cl$, acetophenone, and $NaBH_4$ in the absence of O_2 either in THF or dichloromethane gave bis(1-phenylethoxy)borane and hydridorhodium porphyrin as a result of concomitant borane and hydride transfers from BH_4^- to ketone and Rh^{III} porphyrin, respectively (eq 4, where and hereafter OEP ligand is omitted). Authentic dialkoxyborane was prepared by the reaction of ketone and borane (eq 5).[13]


$$Rh^{III} + BH_4^- + 2C_6H_5C(=O)CH_3 \rightarrow Rh{-}H + HB{+}O{-}C(C_6H_5)(CH_3){-}H)_2 \quad (4)$$


$$2C_6H_5C(=O)CH_3 + 0.5B_2H_6 \rightarrow HB{+}O{-}C(C_6H_5)(CH_3){-}H)_2 \quad (5)$$

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[11] $(OEP)Rh^{III}-Cl$ is readily reduced with $BH(OCH_3)_3^-$ to (OEP)Rh–H (↔ $[(OEP)Rh^I]^- + H^+$) but fails to catalyze the reduction of ketone. This is the clearest evidence ruling out the possibility of direct reduction of ketone with (OEP)Rh–H. For the reaction of (OEP)Rh–H with aldehyde and CO, see: (a) Wayland, B. B.; Woods, B. A.; Minda, V. M. *J. Chem. Soc., Chem. Commun.* **1982**, 634–635. (b) Wayland, B. B.; Woods, B. A. *Ibid.* **1981**, 700–701. (c) Wayland, B. B.; Duttaahmed, A.; Woods, B. A. *Ibid.* **1983**, 142–143. (d) Wayland, B. B.; Woods, B. A.; Pierce, R. *J. Am. Chem. Soc.* **1982**, *104*, 302–303.

[12] The data in Figure 3 are consistent with the first-order kinetics for the disappearance of $NaBH_4$, i.e., $-d[NaBH_4]/dt = k[NaBH_4]$ (Figure 3, insertion), where $[NaBH_4] = 1/2\cdot([alcohol]_\infty - [alcohol])$. Thus, the rate of reaction (d[alcohol]/dt = $-2d[NaBH_4]/dt$) is first order with respect to $NaBH_4$.

Table I. Stereochemistry of Reduction of Ketone with Various Reagents

reagent [solvent]	2-methylcyclohexanone % cis	2-methylcyclohexanone % trans	3-methylcyclohexanone % cis	3-methylcyclohexanone % trans	4-methylcyclohexanone % cis	4-methylcyclohexanone % trans	norcamphor % exo	norcamphor % endo	ref
$(OEP)Rh^{III}$–Cl–$NaBH_4$–O_2 [THF]	66	34	89	11	15	85	9	91	this work
$LiAlH_4$ [THF]	24	76	84	16	17	83	11	89	*a, b*
$NaBH_4$ [CH_3OH]	31	69	83	17	19	81	11	89	*c, d*
B_2H_6 [THF]	26	74	77	23	21	79	2	98	16, *e*
Sia_2BH^f [THF]	79	21	92	8	13	87	8	92	16, *e*

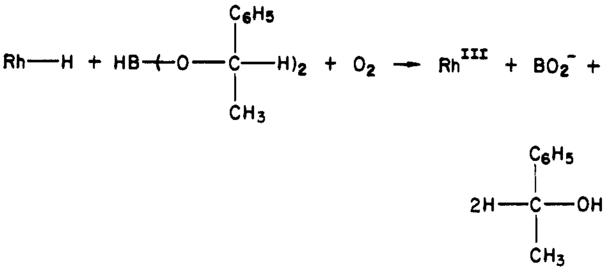
[a] Brown, H. C.; Deck, H. R. *J. Am. Chem. Soc.* **1965**, *87*, 5620–5625. [b] Brown, H. C.; Dickason, W. C. *Ibid.* **1970**, *92*, 709–710. [c] Dauben, W. G.; Fonken, G. J.; Noyce, D. S. *Ibid.* **1956**, *78*, 2579–2582. [d] Combe, M. G.; Henbest, H. B. *Tetrahedron Lett.* **1961**, 404–409. [e] Brown, H. C.; Varma, V. *J. Org. Chem.* **1974**, *39*, 1631–1636. [f] Disiamylborane.

Involvement of borane transfer as a key step is consistent with the lack of any catalysis of rhodium porphyrin in the reduction of ketone with $NaBH(OCH_3)_3$ instead of $NaBH_4$. Triethylamine also served as a borane acceptor. In geneal, amine–borane adducts are rather stable to O_2 and protic compounds so that borane transfer to amine can be carried out aerobically in a catalytic manner without destroying the initial product of borane transfer; a reaction of triethylamine (0.97 mmol), $NaBH_4$ (3.2 mmol), and $(OEP)Rh^{III}$–Cl (6.0 μmol) in THF under air gave borane–triethylamine[14] (0.92 mmol, 95% based on the amine) in a reaction time of 66 h. On the contrary, pyridine failed to accept borane.

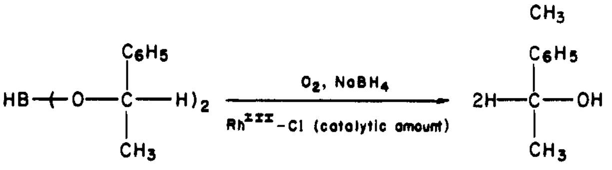
Electronic absorption spectroscopy revealed an interesting solvent dependence of the reduction behavior of $(OEP)Rh^{III}$–Cl with $NaBH_4$ in the absence of O_2. In dichloromethane or benzene a facile reaction took place and gave (OEP)Rh–H, while in pyridine no reaction was observed. In THF, a weakly coordinating solvent, a rather slow reaction took place. Careful examinations revealed that it was biphasic; $(OEP)Rh^{III}$–Cl (λ_{max} 400, 515, and 551 nm) being first converted to an intermediate species (λ_{max} 397, 516, and 548 nm), and then to $(OEP)Rh^{III}$–H (λ_{max} 395, 514, and 545 nm), unambiguously identified by the ^1H NMR spectrum taken for a THF-d_8 solution showing the characteristic signal for the hydrogen bonded to Rh at −39.18 ppm. On the other hand, in the presence of acetophenone $(OEP)Rh^{III}$–Cl was directly converted to Rh–H species without accumulation of the intermediate. Furthermore, addition of ketone to a solution of the intermediate led to a rapid generation of (OEP)Rh–H. These results suggest a rapid borane transfer from the intermediate[15] formed from $(OEP)Rh^{III}$ and BH_4^- to ketone. The intermediate seemed to be stable only in dilute solutions and it was converted to (OEP)Rh–H on most of the attempted isolations.

In Table I are summarized the stereoisomer distributions in the reduction of methylcyclohexanones and norcamphor by the present catalytic system together with those by $LiAlH_4$, $NaBH_4$, diborane, and disiamylborane (Sia_2BH, bis(3-methyl-2-butyl)borane) as a representative of hindered borane derivatives. In particular, the reduction of 2-methylcyclohexanone with less bulky reagents such as B_2H_6 and $NaBH_4$ results in predominant formation of the more stable *trans* isomer, while the thermodynamically less stable cis isomer predominates with a bulky reagent, Sia_2BH.[16] This holds true also for the present system. Furthermore, these two systems show a close similarity in the stereoselectivities of ketone reduction. The borane-transfer step from the intermediate to ketone is also sensitive to the structure of ketone. For example, in a competitive reduction of cyclohexanone and cyclopentanone the reactivity difference was so greater that almost exclusive reduction of the six-membered ketone took place at early stages of reaction, although these two ketones showed nearly the same rate of reduction when separately subjected to the catalytic reduction (vide supra).

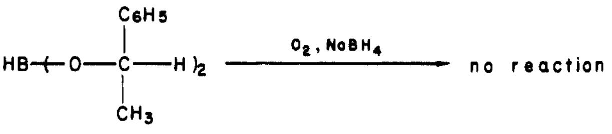
Oxidative "Hydrolysis". The mixture of hydridorhodium porphyrin and dialkoxyborane prepared in THF as above (eq 4) was stable in the absence of O_2, but when exposed to air, a facile reaction took place giving a Rh^{III} complex and 1-phenylethanol, where Rh–H (Rh^I–H^+ ↔ Rh^{III}–H^-) and dialkoxyborane underwent oxidation with O_2 and formal "hydrolysis", respectively (eq 6). This dialkoxyborane to alcohol conversion required the essential Rh–H species either in a stoichiometric amount (eq 6) or in a catalytic amount if it was continuously regenerated by reduction of Rh^{III} porphyrin with $NaBH_4$ (eq 7). In the absence of Rh–H no reaction of dialkoxyborane was observed in the present *dry* THF exposed to air with or without $NaBH_4$ (eq 8). These results indicate a coupling of Rh–H oxidation (Rh–H + O_2 → Rh–OOH)[17] and "acid hydrolysis" of B–O bonds.



$$Rh{-}H + HB{\left(O{-}C(C_6H_5)(CH_3){-}H\right)}_2 + O_2 \rightarrow Rh^{III} + BO_2^- + 2H{-}C(C_6H_5)(CH_3){-}OH \quad (6)$$



$$HB{\left(O{-}C(C_6H_5)(CH_3){-}H\right)}_2 \xrightarrow[Rh^{III}\text{-Cl (catalytic amount)}]{O_2,\ NaBH_4} 2H{-}C(C_6H_5)(CH_3){-}OH \quad (7)$$



$$HB{\left(O{-}C(C_6H_5)(CH_3){-}H\right)}_2 \xrightarrow{O_2,\ NaBH_4} \text{no reaction} \quad (8)$$

Discussion

We have demonstrated the occurrence of two stoichiometric reactions (eq 4 and 6) which when combined give the observed

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(13) (a) Brown, H. C.; Schlesinger, H. I.; Burg, A. B. *J. Am. Chem. Soc.* **1939**, *61*, 673–680. (b) Brown, H. C.; Korytnyk, W. *Ibid.* **1960**, *82*, 3866–3869.

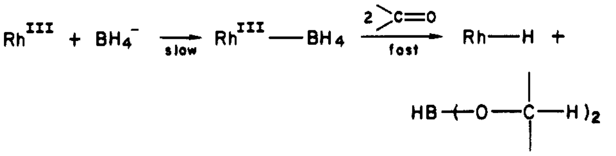
(14) Matsumura, S.; Tokura, N. *Tetrahedron Lett.* **1968**, 4703–4705.

(15) A number of borohydrido complexes of transition-metal species are known. For example: (a) Wong, K. S.; Scheidt, W. P.; Fehlner, T. P. *J. Am. Chem. Soc.* **1982**, *104*, 1111–1113. (b) Letts, J. B.; Mazanec, T. J.; Meek, D. W. *Ibid.* **1982**, *104*, 3898–3905. (c) Vites, J. C.; Eigenbrot, C.; Fehlner, T. P. *Ibid.* **1984**, *106*, 4633–4635. (d) Behnken, P. E.; Marder, T. B.; Baker, R. T.; Knobler, C. B.; Thompson, M. R.; Hawthorne, M. F. *Ibid.* **1985**, *107*, 932–940. (e) Wasserman, H. J.; Moody, D. C.; Ryan, R. R. *J. Chem. Soc., Chem. Commun.* **1984**, 532–533. (f) Wasserman, H. J.; Moody, D. C.; Paine, R. T.; Ryan, R. R.; Salazar, K. V. *Ibid.* **1984**, 533–534. (g) Baker, M. V.; Field, L. D. *Ibid.* **1984**, 996–997. (h) Vites, J. C.; Housecroft, C. E.; Jacobsen, G. B.; Fehlner, Y. P. *Organometallics* **1984**, *3*, 1591–1593. For a discussion of reactions of Lewis acids with metal hydrides, see: Richmond, T. G.; Basolo, F.; Shriver, D. F. *Organometallic* **1982**, *1*, 1624–1628.

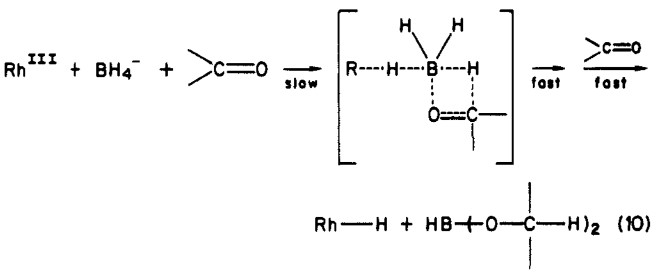
(16) Brown, H. C.; Varma, V. *J. Am. Chem. Soc.* **1966**, *88*, 2871.

(17) The product of the reaction of (OEP)Rh–H and O_2 has been assigned to (OEP)Rh–OOH: James, B. R., personal communication. For the formation of hydroperoxorhodium (Rh–OOH) complexes from the reaction of other hydridorhodium(III) species and O_2, see (a) James, B. R. In "Biomimetic Chemistry"; Dolphin, D., McKenna, C., Murakami, Y., Tabushi, I. Eds.; American Chemical Society: Washington D.C., 1980; Adv. Chem. Ser. 191, Chapter 14. (b) Thomas, K.; Osborn, J. A.; Powell, A. R.; Wilkinson, G. *J. Chem. Soc. A* **1968**, 1801–1806. (c) Johnston, L. E.; Page, J. A. *Can. J. Chem.* **1969**, *47*, 4241–4246. (d) Roberts, H. L.; Symes, W. R. *J. Chem. Soc. A* **1968**, 1450–1453.

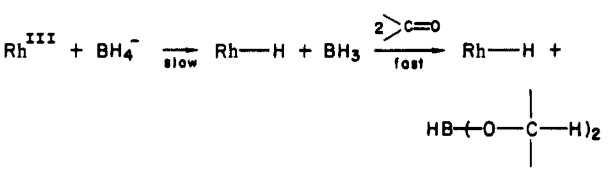
stoichiometry of the catalyzed reaction (eq 3). The mechanism of catalysis can also be speculated. The spectroscopic and kinetic results indicate that eq 4 is a biphasic process (eq 9) with the actual borane-transferring intermediate, $(OEP)Rh^{III}$–BH_4, which seems to be an association complex of $(OEP)Rh^{III}$ and BH_4^-.[15] The mechanism that involves a termolecular reaction (eq 10) is not consistent with the kinetic results. Rate-determining hydride transfer leaving free borane (eq 11) can also be ruled out from the evidence that ketone accelerates the formation of Rh–H from the reaction of Rh^{III} and BH_4^-; this mechanism, however, is likely to be what is operative when the solvent is noncoordinating, where oxidation of free borane with O_2 may be responsible for the poor efficiency of the catalytic reaction. Pyridine as solvent seems to be too strongly coordinating to allow coordination of BH_4^- with $(OEP)Rh^{III}$–pyridine. Significant in this respect is the choice of THF of intermediate coordination ability. The combination of $NaBH_4$ and metal salts or complexes has been used for the reduction of a variety of functional groups[18] and oxygenative transformation of olefins possibly via organoborane intermediates.[19,20] However, the mechanism of these reactions is not clear. A recent study on the mechanism of $NaBH_4$-$CoCl_2$ reduction indicates that cobalt boride (Co_2B), by coordinating to functional groups, catalyzes their heterogeneous reduction by $NaBH_4$.[18] An interesting possibility of surface-generated borane has been suggested. Recently, on the other hand, Brown and Narasimhan[21] have shown that the BH_4^- reduction of esters is catalyzed by olefins, amines, and boron compounds. It was suggested that the hydride transfer could be facilitated by a concurrent reaction of the leaving group, borane, with the catalysts as borane acceptors (eq 12, X = olefin, amine, or boron compound). This mechanism is essentially the same as that for the present reaction involving concurrent borane and hydride transfers (eq 9).



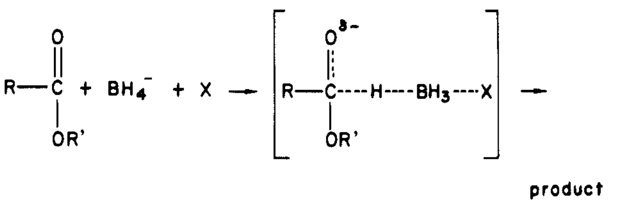
$$\mathrm{Rh^{III} + BH_4^- \xrightarrow[slow]{} Rh^{III}{-}BH_4 \xrightarrow[fast]{2\,>C{=}O} Rh{-}H + HB\!\left(O{-}\overset{|}{\underset{|}{C}}{-}H\right)_2} \quad (9)$$



$$\mathrm{Rh^{III} + BH_4^- + >C{=}O \xrightarrow[slow]{} \left[\begin{array}{c} H\quad H \\ R{\cdots}H{\cdots}B{\cdots}H \\ O{=}C{-} \end{array}\right] \xrightarrow[fast]{} \xrightarrow[fast]{>C{=}O} Rh{-}H + HB\!\left(O{-}\overset{|}{\underset{|}{C}}{-}H\right)_2} \quad (10)$$

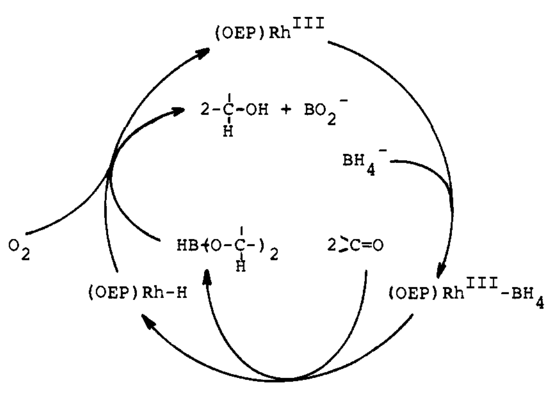


$$\mathrm{Rh^{III} + BH_4^- \xrightarrow[slow]{} Rh{-}H + BH_3 \xrightarrow[fast]{2\,>C{=}O} Rh{-}H + HB\!\left(O{-}\overset{|}{\underset{|}{C}}{-}H\right)_2} \quad (11)$$



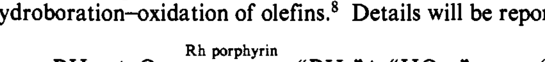
$$\mathrm{R{-}\overset{\overset{O}{\|}}{\underset{\underset{OR'}{|}}{C}} + BH_4^- + X \longrightarrow \left[R{-}\overset{\overset{O^{\delta-}}{\vdots}}{\underset{\underset{OR'}{|}}{C}}{\cdots}H{\cdots}BH_3{\cdots}X\right] \longrightarrow product} \quad (12)$$

Scheme I

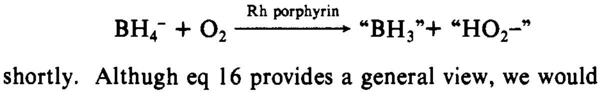


The stereoselectivity of ketone reduction by the present system (Table I) indicates that the effective, local bulkiness of $(OEP)Rh^{III}$–BH_4 is similar to that of Sia_2BH. Another important point about $(OEP)Rh^{III}$–BH_4 is that it preserves much of the properties of $NaBH_4$ which is rather resistant to oxidation with O_2 and hydrolysis with H_2O. In fact, there is no oxidative degradation of "borane" in the present catalytic reduction of ketone in THF under air judging from the observed 200% yield of alcohol based on mol of $NaBH_4$, which indicates a 2:1 (ketone to BH_4^- and hence borane) stoichiometry (eq 3) as in anaerobic reduction of ketone with borane (eq 5). A *moderate* oxidative activation of BH_4^- in $(OEP)Rh^{III}$–BH_4 may control its reactivities toward ketone and O_2. Because of this, the present system constitutes a complete, catalytic modification of borane reduction of ketone in the presence of oxygen, where auto-cycling Rh^{III} and Rh–H act as borane generator and proton source, respectively (Scheme I).[22] The catalytic reaction is thus step-saving and material-saving, generating only alcohol and inorganic borate. On the other hand, the conventional borane reduction of ketone involves three stoichiometric reactions, borane generation (eq 13), borane transfer (eq 14), and hydrolysis of dialkoxyborane (eq 15).

$$\mathrm{3NaBH_4 + 4BF_3{\cdot}OEt_2 \longrightarrow 2B_2H_6 + 3NaBF_4 + 4Et_2O} \quad (13)$$



$$\mathrm{0.5B_2H_6 + 2\,>C{=}O \longrightarrow HB\!\left(O{-}\overset{|}{\underset{|}{C}}{-}H\right)_2} \quad (14)$$



$$\mathrm{HB\!\left(O{-}\overset{|}{\underset{|}{C}}{-}H\right)_2 + 3H_2O \longrightarrow 2H{-}\overset{|}{\underset{|}{C}}{-}OH + H_2 + B(OH)_3} \quad (15)$$

The essential reaction of the ternary system of $NaBH_4$, O_2, and rhodium porphyrin can be regarded as borane generation with concomitant reduction of O_2 upon metal-coontrolled aerial oxidation of BH_4^- (eq 16). The present system is also applicable to the hydroboration–oxidation of olefins.[8] Details will be reported shortly. Althugh eq 16 provides a general view, we would like to make another comment on the overall chemistry of the present reaction, i.e., addition of two hydrogens to a C═O double bond (eq 3). The usual concept in organic chemistry indicates that hydrogen attached to carbon comes as a hydride and that attached to oxygen comes as a proton. Then, a simple analogue to eq 3 is eq 17 or more simply eq 18, i.e., 4-electron oxidation of four hydrides leaving two hydrides intact and two protons.

$$BH_4^- + O_2 \xrightarrow{\text{Rh porphyrin}} \text{“}BH_3\text{”} + \text{“}HO_2\text{-”} \quad (16)$$

$$BH_4^- + O_2 \xrightarrow{\text{Rh porphyrin}} 2H^- + 2H^+ + BO_2^- \quad (17)$$

$$4H^- + O_2 \xrightarrow{\text{Rh porphyrin}} 2H^- + 2H^+ + O_2^{4-} \quad (18)$$

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(22) The turnover rate is 0.5 times 0.46 mmol of alcohol per 6.0 μmol of catalyst per 60 min = 0.64 cycle/min.

Experimental Section

General. Rhodium complexes[10,23] and $NaBH(OCH_3)_3$[24] were prepared according to published procedures. THF was dried with sodium benzophenone ketyl and fractionally distilled. Benzene, dichloromethane, and pyridine were dried with sodium benzophenone ketyl, P_2O_5, and KOH, respectively, and fractionally distilled. $NaBH_4$ was dried in vacuo prior to use. Ketones and 18-crown-6 were commercial products of the highest grade. Solutions for measurements of ^1H NMR spectra were degassed by freeze–pump–thaw cycles. Solutions for measurements of electronic spectra were prepared by the stepwise addition of a degassed solution of $(OEP)Rh^{III}–Cl$ and acetophenone to 3 mL of a nitrogen-purged, saturated solution of $NaBH_4$ with or without acetophenone (30 mg, 0.25 mmol) in a cell sealed with a rubber septum; the final concentration of the rhodium complex was 5×10^{-6} M. When the solvent was benzene, dichloromethane, or pyridine, 10 mg of 18-crown-6 was added to solubilize $NaBH_4$. The air used was dried by passing it through a calcium chloride tube. Transfers of liquids were carried out by means of a syringe.[25] The identification of organic products and determination of their yields were performed by gas chromatography with a column of poly(ethylene glycol) 20 M, unless otherwise indicated, and durene as an internal standard.

Reduction of Ketone: With Limiting Amounts of $NaBH_4$. A completely homogeneous THF solution (10 mL) containing $NaBH_4$ (0.039 mmol) was prepared by a volumetric method. To this was added a solution of acetophenone (in a large excess, 1.64 mmol), $(OEP)Rh^{III}–Cl$ (6.0 μmol), and durene (appropriate amount) in a small amount of THF. Gas chromatography showed a smooth increase in the amount of 1-phenylethanol as the sole product (Figure 3) and its yield was 0.078 mmol (200% based on mol of $NaBH_4$ consumed). A mixture of approximately 1 mmol (0.89–0.96 mmol) of $NaBH_4$ in THF (10 mL) under air or an O_2–N_2 mixture of an appropriate ratio equilibrated with atmospheric pressure was sealed with a rubber septum. To this was added a degassed solution of acetophenone (large excess) and rhodium porphyrin catalyst (6.0 μmol)in a small amount of THF to initiate the reaction. The O_2 absorption was followed by gas chromatographic analysis of the gas phase on a column of molecular sieve 5A, where N_2 served as an internal standard. Inorganic materials which precipitated during the reaction was filtered, washed with THF, and dried to afford amorphous powders. These were dissolved in a minimum amount of water and crystallized to give sodium borate decahydrate, identified by powder X-ray diffraction analysis.

Reduction of Ketone: With Excess Amounts of $NaBH_4$. A mixture of $NaBH_4$ (300 mg, 7.9 mmol), ketone (acetophenone, cyclohexanone, 2-methylcyclohexanone, cyclopentanone, or 3-heptanone, approximately 0.8 mmol), $(OEP)Rh^{III}–Cl$ (6.0 μmol), and an appropriate amount of durene in THF (10 mL) was stirred under air, and the progress of reaction was monitored by gas chromatography. The yield of the corresponding alcohol was nearly quantitative and a linear time course of its formation, similar to that shown in Figure 2, was observed in every case. The reduction of acetophenone was carried out with varying amounts of $NaBH_4$. No significant change in the slope of the time course was observed when the amount of $NaBH_4$ was lowered, provided it was in a sufficiently excess amount so as to maintain saturation of THF with it. In the presence of 18-crown-6 (0.46 mmol), on the other hand, the slope was 1.1 mmol/h, ca. 2.3 times as large as that in its absence (0.46 mmol/h). Stereoisomer distributions in the reduction of methylcyclohexanones and norcamphor catalyzed by $(OEP)Rh^{III}–Cl$ (6.0 μmol) were determined by gas chromatographic peak areas; the columns used were silicone DC QF-1 (for 2-methylcyclohexanol), poly(ethylene glycol) 20 M (for 3- and 4-methylcyclohexanols), and poly(ethylene glycol) 6000 M (for norbornanol). Similarly were carried out the following control runs with acetophenone as substrate: (1) under O_2 (1 atm) instead of air, (2) without O_2, (3) without porphyrin catalyst, (4) with $NaBH(OCH_3)_3$ in place of $NaBH_4$, (5) with $(TPP)Rh^{III}–Cl$ in place of $(OEP)Rh^{III}–Cl$, and (6) in benzene, dichloromethane, or pyridine as a solvent and with crown ether assistance.

Borane Transfer and Oxidative "Hydrolysis". A mixture of $(OEP)Rh^{III}–Cl$ (20 mg), $NaBH_4$ (50 mg), and THF (2 mL) or dichloromethane (2 mL) with added crown ether was degassed several times by freeze–pump–thaw cycles. Acetophenone (10 μL) was added with a syringe through the septum. The mixture was stirred for 30 min and then analyzed by gas chromatography. A rather broad peak (relative retention time, ~2.6) was detected together with a sharper one for the unreacted ketone (retention time, 1). The product was clearly not 1-phenylethanol having the retention time of 1.65 and was identified as bis(1-phenylethoxy)borane by comparison with an authentic sample. The reaction mixture was exposed to air and quickly analyzed, the formation of alcohol at the sacrifice of dialkoxyborane being acertained. Similarly, stoichiometric amounts of authentic bis(1-phenylethoxy)borane and (OEP)Rh–H in THF was mixed and exposed to air. The formation of 1-phenylethanol as the sole organic product was confirmed. In another run, a mixture of dialkoxyborane (0.4 mmol), $NaBH_4$ (0.5 mmol), and $(OEP)Rh^{III}–Cl$ (6.0 μmol) was prepared anaerobically. Aliquots were taken occasionally and analyzed to show no hydrolysis of dialkoxyborane taking place. Then, the mixture was exposed to air. Gas chromatography indicated a gradual conversion of dialkoxyborane to alcohol.

Amine–Borane Adduct. A mixture of $NaBH_4$ (120 mg, 3.2 mmol), triethylamine (98 mg, 0.97 mmol), and $(OEP)Rh^{III}–Cl$ (6.0 μmol) in THF (10 mL) was stirred for 15 h at room temperature under air. Ether (30 mL) was added and inorganic materials were filtered and washed with ether. The ether extract and washing were combined and evaporated in vacuo to give triethylamine–borane complex (73 mg, 67% based on triethylamine), which showed the identical IR spectrum with that of the authentic specimen. When the reaction time was prolonged to 66 h, the yield was enhanced to 103 mg (95%). On the other hand, a control run without $(OEP)Rh^{III}–Cl$ under otherwise identical conditions gave only 4 mg (3.7%) of the amine–borane complex after 15 h. A similar reaction with pyridine in place of triethylamine gave only a trace of pyridine–borane[26] even in the presence of rhodium complex.

Acknowledgment. This work was supported by a Grany-in-Aid for Scientific Research from the Ministry of Education, Science, and Culture (Subject No. 57550533). We are grateful to Dr. T. Yano for powder X-ray diffraction analysis.

Registry No. $(OEP)Rh^{III}Cl$, 36670-30-1; $NaBH_4$, 16940-66-2; 2-methylcyclohexanone, 583-60-8; 3-methylcyclohexanone, 591-24-2; 4-methylcyclohexanone, 589-92-4; norcamphor, 497-38-1.

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