1506 BULLETIN OF THE CHEMICAL SOCIETY OF JAPAN, VOL. 48 (5), 1506—1512 (1975) [Vol. 48, No. 5

The Reduction of Enamines with Carbonylhydridoferrates

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(Received December 11, 1974)

Enamines react with an alcoholic solution of $[FeH(CO)_4]^-$ (**1**), $[Fe_2H(CO)_8]^-$ (**2**), and $[Fe_3H(CO)_{11}]^-$ (**3**), with the absorption of carbon monoxide at room temperature, to give the corresponding saturated tertiary amines. The reduction of the pyrrolidine enamine of 2-methylcyclohexanone with **1**, **2**, and **3** gave *cis* and *trans* *N*-(2-methyl-1-cyclohexyl)pyrrolidine. The *cis*/*trans* ratio of the products were characteristic of **1**, **2**, and **3**; the values, 0.67, 1.2, and 2.1 respectively, represent the bulkiness of the hydrides. The mechanism of the reduction was discussed.

Enamines are known to be very useful starting materials for various organic syntheses, particularly for the formation of α-substituted carbonyl compounds and cyclic ones.[1] This reactivity of enamine is mainly due to the polarized carbon-carbon double bond.

On the other hand, only a few reactions of enamines with transition-metal complexes have been reported.[2] Moreover, little attention has been paid to the reaction of enamines with hydridotransition metal complexes. Previously, we briefly mentioned the reduction of enamines with $[FeH(CO)_4]^-$ (**1**).[3] This paper will deal in detail with the reduction of enamines with **1**, $[Fe_2H(CO)_8]^-$ (**2**), and $[Fe_3H(CO)_{11}]^-$ (**3**).

Experimental

The PMR spectra were obtained on a JOEL Model 3H60 NMR spectrometer. The infrared spectra were measured on a Hitachi Model 215 grating infrared spectrometer. The mass spectra were obtained with a JMS-OISG mass spectrometer.

Materials. The *N*-(1-cyclohexenyl)morpholine (**4**),[4] *N*-(2-methyl-1-propenyl) piperidine (**6**),[5] *N*-(1-phenyl-1-vinyl)-morpholine (**5**),[6] and the pyrrolidine enamine of 2-methylcyclohexanone (**7**)[7] were prepared according to the methods described in the literature and were stored in ampoules under an argon atmosphere in a refrigerator. The pentacarbonyliron, morpholine, cyclohexanone, ethyl alcohol, and other compounds employed in this study were all commercial products; their purity were checked and found to be satisfactory for the reaction. The tetrahydrofuran was dried over lithium aluminum hydride.

Preparation of Carbonylferrates. All the reactions were carried out in a 300 ml, three-necked flask equipped with a gas buret and a magnetic stirrer under an carbon monoxide or nitrogen atmosphere. $K[FeH(CO)_4]$ (**1**) and $K_2[Fe(CO)_4]$ (**1′**) were prepared according to the methods described in a previous paper.[8] Eleven mmol of each complex in 50 ml of a solvent was used in each run. The preparation of $K[FeH(CO)_4]$ is accompanied by the formation of an equivalent mole of water:[9]

$$Fe(CO)_5 + 3KOH \longrightarrow \underset{(\mathbf{1})}{K[FeH(CO)_4]} + K_2CO_3 + H_2O \qquad \text{(a)}$$

Therefore, when a dry solution of **1** was required, the solvent of the **1** was once distilled off under a vacuum, and then 50 ml of a new dry solvent was added.

$K_2[Fe_2(CO)_8]$ (**2′**) was prepared by the method described in the literature.[10] $Fe_2(CO)_9$ (2.0 g, 5.5 mmol=11 mg-atom-Fe) was treated with 22 mmol of KOH in 50 ml of ethanol at 30 °C for 2 hr.

$[Et_3NH]$ $[Fe_3H(CO)_{11}]$ (**3**) was prepared according to the published method.[11] In each run, a 2.1 g portion of **3** (3.7 mmol=11 mg-atom-Fe) in 50 ml of ethanol was used.

General Reaction Procedures and Analysis. To the solution of the carbonylferrates described above, 33 mmol of the enamine or an equimolar mixture of a ketone and a secondary amine and an internal standard for gc analysis were added, and the mixture was agitated. After a certain reaction time, a 0.2 ml sample of the solution was taken out, oxidized with air or with an equivalent mole of iodine in ethanol for 20 s to terminate the reaction, and then submitted to gc analysis; column: SE-30 on chromosorb(I), 3 mmϕ × 1.5 m; Diethylene Glycol Adipate Polyester on chromosorb(II), 3 mmϕ × 3 m. *N*-Isobutylpiperidine(**10**), tri(*n*-butyl) amine(**13**), and *N*-propylmorpholine(**14**) were identified by gc analysis by the use of the authentic samples. The amount of $Fe(CO)_5$ was analyzed by TCD-type gas chromatography, using the latter column(II) and with benzene as the internal standard.

The amount of CO_3^{2-} was analyzed as follows. The gas evolved by the acidification of the reaction solution was collected in a gas buret; after standing for 1 hr, the gas was bubbled in aqueous KOH. The volume of the absorbed gas was regarded as the amount of CO_2. This method was verified by gc analysis; column: active carbon(III), 3 mmϕ × 3 m.

Reaction of Enamine (4) with 1. Enamine (**4**) (5.5 g, 33 mmol) was added to an ethanolic solution of (**1**) (11 mmol) under a carbon monoxide atmosphere, and the mixture was agitated for 4 hr at 30 °C, during which time 1.6-mol portion of carbon monoxide was absorbed. The reaction mixture was filtered in a hood and 2.6 g of *N*-cyclohexylmorpholine (**8**) was obtained by distillation (bp 100 °C/6 mmHg; Yield, 1.4 mol/g-atom-Fe). Found: C, 70.99; H, 11.21%; mol wt (Mass) 169. Calcd for $C_{10}H_{17}NO$: C, 70.96; H, 11.32% mol wt 169.26. PMR(acetone-d_6): δ 3.3(m, 4H), 2.3(m, 4H), 1.6(m, 6H), 1.1(m, 5H) ppm.

Reaction of Enamine (5) with 1. Enamine (**5**) (6.2 g, 33 mmol) was treated with an ethanolic solution of **1** (11 mmol) at 30 °C for 24 hr, during which time a 1.6 mol portion of carbon monoxide was absorbed and 3.1 g of *N*-(1-phenylethyl)-morpholine (**9**) was obtained by distillation (bp 80 °C/0.3 mmHg; Yield, 1.6 mol/g-atom-Fe). Found: C, 75.28; H, 8.89%; mol wt (Mass) 191. Calcd for $C_{12}H_{17}NO$: C, 75.35; H, 8.96%; mol wt 191.27. PMR($CDCl_3$): δ 7.0(m, 5H), 3.5 (m, 4H), 3.2(q, 1H, J=6Hz), 2.4(m, 4H), 1.3(d, 3H, J=6Hz) ppm.

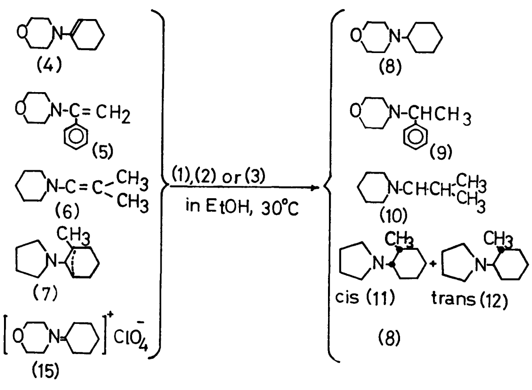
Reaction of Enamine (7) with 1. This reaction was carried out in a manner similar to that described above. Gc analysis showed that two products, (A) and (B), were formed at the retention time of 8.3 and 9.9 min, respectively (Column temperature, 120 °C; carrier gas: N_2, 40 ml/min). The products, (A) and (B), were identified as *N*-(*trans*-2-methyl-1-cyclohexyl)pyrrolidine (**12**) and *N*-(*cis*-2-methyl-1-cyclohexyl)-

pyrrolidine (**11**) respectively by the use of authentic samples prepared by the reduction of enamine (**7**) with atmospheric hydrogen.[12]

Reduction of Enamine (7) with Raney Nickel.[12] Enamine (**7**) (7.6 ml) was reduced catalytically with Raney nickel (1.0 g) in dry ethyl alcohol at 30 °C under 1 atm. of hydrogen. After 2 hr, the reaction mixture was analyzes by gas chromatography. Two peaks, (A′) and (B′), were found at the same retention time of (A) and (B). The ratio of (A′) to (B′) was 27:73, the same ratio as Mitsui has reported. Five grams of the mixture of (A′) and (B′) was separated from the reaction mixture by distillation (bp 82—85 °C/9 mmHg; Yield, 63%; Found: C, 79.00; H, 12.65; N, 8.37%; mol wt (Mass) 167). The separation of (A′) and (B′) by column chromatography (Silica gel) was attempted. Pure (A′) or (B′) could not be obtained, but two mixtures, 1) (A′)/(B′)=90/10 and 2) (A′)/(B′)=14/86, were obtained. The PMR spectra of these mixtures showed that (A′) and (B′) are *trans* and *cis* *N*-(2-methyl-1-cyclohexyl)pyrrolidine, respectively.[13] PMR (CCl_4): (A′) δ 0.94(d, J=6.0 Hz, 3H), 1.4—1.1(m, 5H), 1.9—1.5(m, 8H), 2.0—2.4(m,1H), 2.8—2.4(m, 4H) ppm, (B′) 0.89(d, J=6.8 Hz, 3H), 1.4—1.2(m, 1H), 2.6—2.3(m, 4H) ppm.

Results and Discussion

Reaction of Enamines with 1. Enamines such as *N*-(1-cyclohexenyl)morpholine (**4**), *N*-(1-phenyl-1-vinyl)morpholine (**5**), and *N*-(2-methyl-1-propenyl)-piperidine (**6**) reacted with an alcoholic solution of $[FeH(CO)_4]^-$ (**1**) at 30 °C, with a rapid absorption of carbon monoxide after a certain induction period. However, no carbonylated products were detected; rather the corresponding saturated tertiary amines, *N*-cyclohexylmorpholine (**8**), *N*-(1-phenylethyl)-



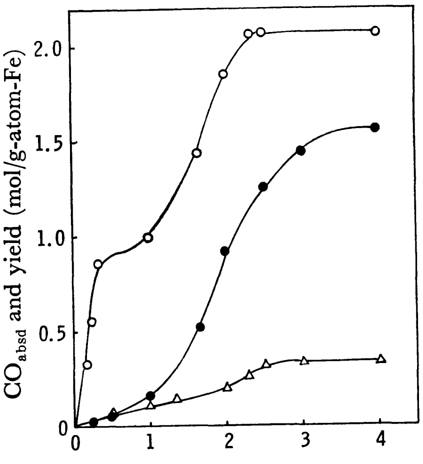


Fig. 1. Reaction of enamine (**4**) with $K[FeH(CO)_4]$ in ethanol at 30 °C. ○: *N*-Cyclohexylmorpholine, ●: CO absorbed, △: $Fe(CO)_5$.

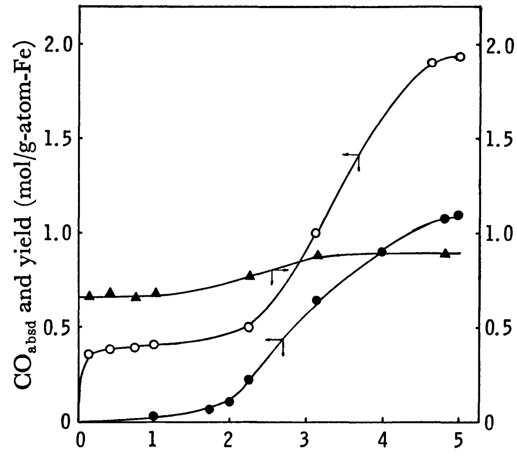


Fig. 2. Reaction of enamine (**7**) with $K[FeH(CO)_4]$ in ethanol at 30 °C. ○: Total yield of *cis* and *trans* N-(2-methylcyclohexyl)pyrrolidine. ●: CO absorbed, ▲: *cis*/*trans*.

Table 1. The reaction of enamines with mononuclear carbonylferrates in ethanol

Exp. No.	Enamine (33 mmol)	Carbonyl Ferrate (11 mmol)	Reaction conditions		CO absd[a]	Product	Yield[a]	*cis*/*trans*
			Temp °C	Time hr				
1	**4**	$KFeH(CO)_4$	30	4	1.6	**8**	2.1	
2	**4**	$KFeH(CO)_4$	30	1.5	N_2	**8**	0.9	
3	**4**	$KFeH(CO)_4$	30	216	N_2	**8**	1.0	
4	**5**	$KFeH(CO)_4$	30	48	1.7	**9**	1.6	
5	**6**	$KFeH(CO)_4$	30	48	1.9	**10**	1.5	
6	**7**	$KFeH(CO)_4$	30	5(min)	0	**11**+**12**	0.4	0.67
7	**7**	$KFeH(CO)_4$	30	5	1.1	**11**+**12**	1.9	0.88
8	**7**	$KFeH(CO)_4$	−60	0.5	0	**11**+**12**	0.16	0.65
9	**4**	$K_2Fe(CO)_4$	30	29	2.0	**8**	2.4	
10	**4**	$KFeH(CO)_4$+5KOH	30	192	4.9	**8**	1.0	
11	**4**	$KFeH(CO)_4$+5H_2O	30	120	1.3	**8**	0.9	
12	**15**	$KFeH(CO)_4$	30	24	1.0	**8**	1.0	

a) mol/g-atom-Fe

Table 2. The reaction of enamines with $K_2Fe_2(CO)_8$[a] in ethanol

Exp. No.	Enamine (33m mol)	Reaction conditions Temp (°C)	Reaction conditions Time (hr)	CO absd[b]	Product	Yield[b]	*cis/trans*
13	**4**	30	4	2.1	**8**	2.2	
14	**4**	45	24	2.1	**8**	1.9	
15	**7**	30	10(min)	0.65	**11**+**12**	0.88	1.2
16	**7**	30	5	1.45	**11**+**12**	1.88	0.94

a) 5.5 mmol of $K_2Fe_2(CO)_8$ was used. b) mol/g-atom-Fe

morpholine (**9**), and *N*-isobutylpiperidine (**10**), were produced in high yields.

The pyrrolidine enamine of 2-methylcyclohexanone (**7**) was also reduced to *cis* (**11**) and *trans* (**12**) *N*-(2-methyl-1-cyclohexyl)pyrrolidine. The results are summarized in Table 1. The periodical change in the yields of the saturated tertiary amines and the absorption of carbon monixide in a typical reaction of **4** and **7** are shown in Figs. 1 and 2. Time plots of the *cis/trans* ratio of the isomers of the products are also shown in Fig. 2. In both cases, the plots of the yields of the products *vs.* the reaction time are very characteristic. They clearly have two steps. At first, the yield of the product increases rapidly, with a very slow absorption of carbon monoxide, and the yield amounts to 0.4—0.9 mol* in 30 min. Then the rate of the formation of the product becomes very slow for about 0.5—2 hr, after which it becomes very fast again, with a rapid absorption of carbon monoxide, and the yield of the product amounts to about 2 mol.

As the reaction proceeded, the color of the reaction solution changed from pale brown to dark red, and $[Fe_3H(CO)_{11}]^-$** and CO_3^{2-}, as well as $Fe(CO)_5$, were detected in the reaction mixture. The amount of $Fe(CO)_5$ formed is also shown in Fig. 1.

The reaction also proceeded under a nitrogen atmosphere, but the yield did not exceed 1.0 mol (Exps. 2, 3).

In the reduction of enamine (**7**), the *cis/trans* ratio of the products was 0.67 at the beginning, and it stayed constant for about 1.5 hr. Then it became large with the progress of the reduction, with a rapid absorption of carbon monoxide, reaching 0.88 at the end of the reaction. The *cis/trans* ratio of the products newly formed with the absorption of cabon monoxide was 1.1, which was easily calculated from the data at 60 min and at 190 min. These results apparently show that there are at least two different ways for the reduction of enamines; the first may be the reduction with **1** itself, while the second is that with the newly produced active species, with an absorption of carbon monoxide.

The Reaction of $K_2[Fe(CO)_4]$ *with Enamine (4).* When $K_2[Fe(CO)_4]$ is used instead of **1**, the rate of the reduction is slower than that in the reaction of **1**. However, the total amount of gas absorbed and the yield of the product were larger than those in the reaction of **1** (Exp. 9). In this system, $K_2[Fe(CO)_4]$ may be hydrolyzed[14] to **1**, which is active in the reduction of enamine, and a 1 mol excess of potassium hydroxide is considered to be effective for the reformation of the new hydride species.

$$K_2Fe(CO)_4 + H_2O \rightleftharpoons \underset{(\mathbf{1})}{K[FeH(CO)_4]} + KOH \qquad (b)$$

However, a large exess of potassium hydroxide disturbed the reduction (Exp. 10). In this case, the concentration of the active hydride (**1**) is low, and the reaction may be highly inhibited.

The Reaction of $K_2[Fe_2(CO)_8]$ *with Enamines.* The enamines **4** and **7** also reacted with an alcoholic solution

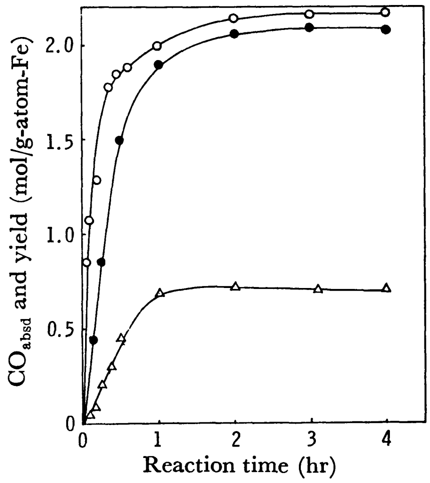


Fig. 3. Reaction of enamine (**4**) with $K_2[Fe_2(CO)_8]$ in ethanol at 30 °C. ○: *N*-Cyclohexylmorpholine, ●: CO absorbed, △: $Fe(CO)_5$.

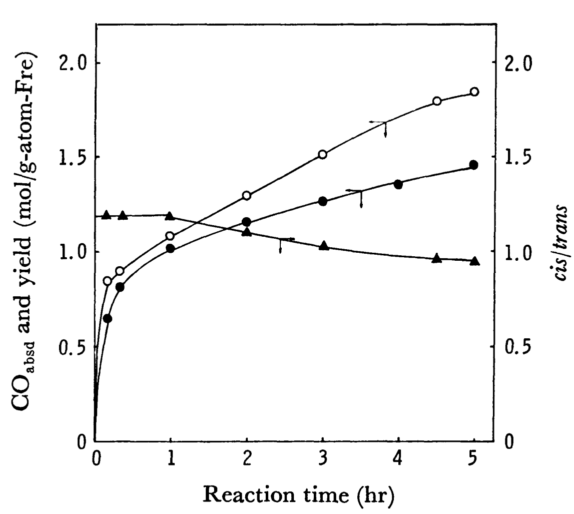


Fig. 4. Reaction of enamine (**7**) with $K_2[Fe_2(CO)_8]$ in ethanol at 30 °C. ○: Total yield of *cis* and *trans* *N*-(2-methylcyclohexyl)pyrrolidine, ●: CO absorbed, ▲: *cis/trans*.

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* "mol" means mol/g-atom-Fe hereafter.

** ~0.06 mol/g-atom-Fe of $[Fe_3H(CO)_{11}]^-$ was detected by means of UV spectra in the reaction mixture of Exp. 1.

Table 3. The reaction of enamines with $[Fe_3H(CO)_{11}]^-$ a) in ethanol

Exp. No.	Enamine (33 mmol)	Reaction conditions		CO_{absd} b)	Product	Yield b)	*cis*/*trans*
		Temp (°C)	Time (hr)				
17	**4**	30	120	1.3	(**8**)	0.46	
18	**4**+KOH (50 mmol)	30	24	1.7	(**8**)	1.2	
19	**7**	30	0.5	0.1	(**11**) + (**12**)	0.11	2.1
20 c)	**7**	30	5	0.6	(**11**) + (**12**)	0.17	1.9
21	**7**+H_2O (11 mmol)	30	5	0.6	(**11**) + (**12**)	0.08	1.9
22	**7**+H_2O (11 mmol)	−60	0.25	0	(**11**) + (**12**)	0.05	1.8

a) 3.7 mmol of $[Fe_3H(CO)_{11}]^-$ was used. b) mol/g-atom-Fe. c) 11 mmol of $[Fe_3H(CO)_{11}]^-$ was used.

of dinuclear carbonylferrate, $K_2[Fe_2(CO)_8]$, with an absorption of carbon monoxide, to give saturated amines. The results are shown in Table 2 and Figs. 3 and 4. The mode of the reaction of $K_2[Fe_2(CO)_8]$ was, however, different from that of **1**. The yield of the product increased smoothly without the step which was observed in the reaction of **1**, and it amounted to 1.9—2.2 mol, *i.e.*, 3.8—4.4 mol/mol-$[Fe_2(CO)_8]^{2-}$. The induction period of the carbon-monoxide absorption was not observed; the rate of the absorption was very rapid in spite of the half concentration of the carbonylferrate complex as compared with the case of **1**, and a large amount of $Fe(CO)_5$ was formed.

The *cis*/*trans* ratio of the product in the reaction of enamine **7** was 1.2 at the beginning of the reaction, and it stayed constant for 1 hr, during which period 2 mol/mol-$[Fe_2(CO)_8]^{2-}$ of the product was formed; thereafter it became smaller, reaching 0.94 in 5 hr. Apparently, an active species is also reproduced during the reaction. The active species formed during the first 1 hr gave the ratio of ~1.2, which is almost the same as that observed in the reduction with the newly formed active species in the reaction of **1**.

Considering the results of the reaction of $K[FeH(CO)_4]$ and $K_2[Fe(CO)_4]$, the dinuclear hydride species, $K[Fe_2H(CO)_8]$ (**2**), which exists in the reaction system in the equilibrium:

$$K_2[Fe_2(CO)_8] + H_2O \rightleftharpoons \underset{(\mathbf{2})}{K[Fe_2H(CO)_8]} + KOH \quad (c)$$

may be the active species at the beginning of the reaction.

Reaction of $[Fe_3H(CO)_{11}]^-$ *(3) with Enamines.* An alcoholic solution of $[Fe_3H(CO)_{11}]^-$ (**3**) also reduce enamines. The results are summarized in Table 3. The mode of the reduction of the enamine (**7**) is shown in Fig. 5. The reduction of the enamine proceeded rapidly and ceased in ten min. The yield of the product was small (0.11 mol, *i. e.*, 0.33 mol/mol.$[Fe_3H(CO)_{11}]^-$), and the *cis*/*trans* ratio of the isomers was 2.1. The ratio stayed constant for more than 4 hr. The addition of 11 mmol of a 1M-ethanolic potassium hydroxide solution to this reaction mixture caused a dramatic change of the mode of the reaction. The yield of the product increased rapidly, with an absorption of carbon monoxide. The *cis*/*trans* ratio of the isomers decreased rapidly to the value of 1.0, and then it reached 0.9 by the end of the reaction. It is calculated that the *cis*/*trans* ratio of the isomers of the newly formed product is about 0.88. The effect of the mole ratio of **3** to the enamine on the *cis*/*trans* ratio of the products which were observed in the reduction with $LiAlH_4$[15] was small (Exp. 20). The effects of the addition of water or of the reaction temperature on the *cis*/*trans* ratio were also small.

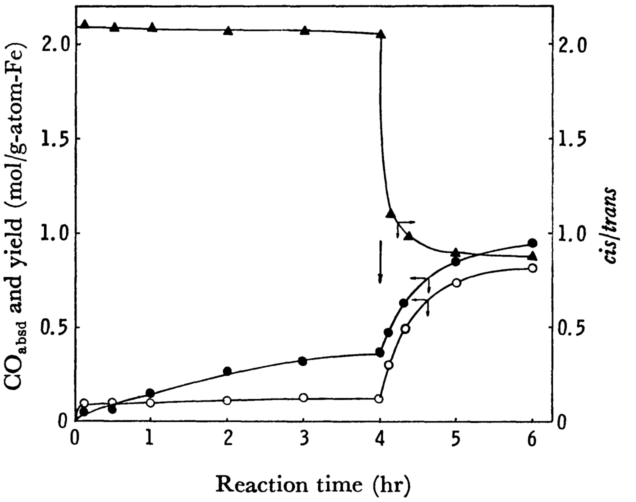


Fig. 5. Reaction of enamine (**7**) with $[Et_3NH][Fe_3H(CO)_{11}]$ in ethanol at 30 °C. ○: Total yield of *cis* and *trans* *N*-(2-methylcyclohexyl)pyrrolidine, ●: CO absorbed, ▲: *cis*/*trans*, ↓ : 11 ml of 1 M-KOH–EtOH was added.

Reaction of Enamine (4) with 1 in Dry THF and the Effect of the Addition of Water. In order to investigate the source of the hydrogen, the enamine (**4**) was treated with **1** in dry THF. As is shown in Fig. 6, no carbon monoxide absorption occurred, and even after a prolonged reaction time only a small amount of the product was formed. The addition of water to this reaction solution caused a rapid carbon monoxide uptake and an increase in the quantity of the product, the yield of which amounted to more than 2 mol. This result shows that the hydrogen source in the reduction of enamines is water and that carbon monoxide and water are indispensable for the reproduction of the active species of the reduction. However, a large excess of water disturbed the reduction (Exp. 11).

The Fate of the Carbon Monoxide Absorbed. The fate of the carbon monoxide absorbed was investigated. The amounts of $Fe(CO)_5$ and carbonate formed in the

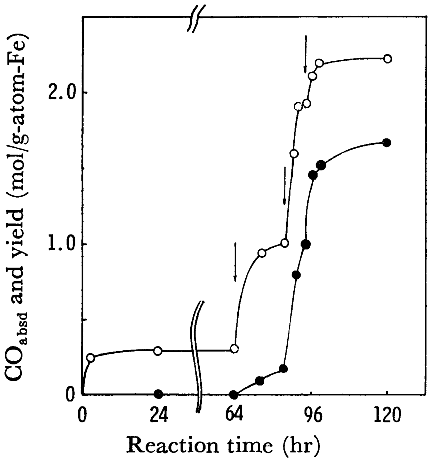


Fig. 6. Reaction of enamine (**4**) with K[FeH(CO)$_4$] in dry THF and the effect of the addition of water. ○: *N*-Cyclohexylmorpholine, ●: CO absorbed, ↓ : 1.0 mol of water was added.

Table 4. Material balance of carbon monoxide absorbed

Exp. No.	Carbonylferrate	CO$_{absd}$	Fe(CO)$_5$ (mol/g-atom-Fe)	CO$_3^{2-}$
1	KFeH(CO)$_4$	1.6	0.32	1.30
13	K$_2$Fe$_2$(CO)$_8$	2.1	0.70	1.42
17	[Fe$_3$H(CO)$_{11}$]$^-$	1.3	1.05	0.11
18	[Fe$_3$H(CO)$_{11}$]$^-$+KOH	1.7	0.41	1.31

reaction solution are summarized in Table 4. These results show that the carbon monoxide absorbed ultimately goes into Fe(CO)$_5$ and carbonate:

$$[\text{CO absorbed}] = [\text{Fe(CO)}_5] + [\text{CO}_3^{3-}] \qquad \text{(d)}$$

Mechanism of the Reduction of Enamines. The mechanism of the reduction of enamines with formic acid[16] and sodium borohydride,[17] and that of the hydrolysis of enamines,[18] have been studied. The first step of both the reaction is shown to be the rapid protonation of the *β*-carbon atom of enamines to form the iminium salts:

$$>\text{N-CH=CHR} + \text{H}^+ \longrightarrow >\overset{+}{\text{N}}\text{=CH-CH}_2\text{R} \qquad \text{(e)}$$

In our reaction, carried out in moist ethanol, it is reasonable to consider that the first step of the reduction is also the formation of iminium salt. In fact, enamine could not be detected in the reaction solution, even 10 min after the beginning of the reaction by means of gas chromatography, but iminium salt was detected by means of the IR spectra. On the other hand, enamine was detected in the reaction solution when the reduction was carried out in a dry solvent.

The fact that the iminium salt, *N*-cyclohexylidenemorpholinium perchlorate (**15**), reacts with **1**, with absorption of carbon monoxide, to give *N*-cyclohexylmorpholine (**8**) (Table 1. Exp. 12) shows that the second step is surely the nucleophilic attack of carbonylhydridoferrates on the iminium cation and the abstraction of a hydride ion from the complex.

$$>\overset{+}{\text{N}}\text{=CHCH}_2\text{R} + [\text{HFe}_m(\text{CO})_n]^- \longrightarrow >\text{N-CH}_2\text{CH}_2\text{R} + \text{Fe}_m(\text{CO})_n \qquad \text{(f)}$$

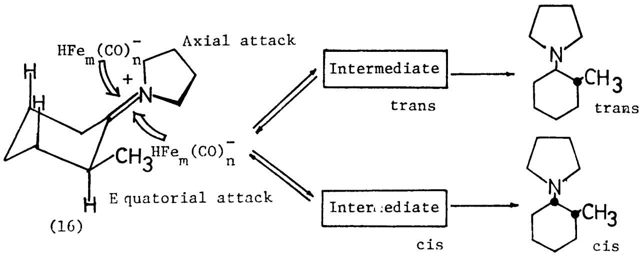
In the reduction of iminium salts with LiAlH$_4$,[19] NaBH$_4$,[17] and formic acid,[1,16] a similar abstraction of a hydride ion has been observed.

Reproduction of Active Species. Alcoholic solutions of **1** and **2** have been known to reduce isoprene[20] and the Shiff base[21] to the corresponding monoolefins and saturated amines respectively, with absorption of carbon monoxide. The yields of the products often exceeded 1.0 mol, and the reproduction of the active species was observed. However, little has been studied on the mechanism of the reformation of the active species. The infrared spectra of the reaction solution showed too complicated absorption to resolve at 2100—1750 cm^{-1}.

In the reduction of enamines with **1** and **2**, the active species is also reproduced, with an absorption of cabon monoxide. The reduction of the enamine (**7**) with **1**, **2**, and **3** gives us some information on the reproduction of the active species. The results show that **1**, **2**, and **3** have their own ability in the reduction of enamine and have characteristic values of the *cis*/*trans* ratio of the products, 0.67, 1.2, and 2.1, respectively. The fact that the *cis*/*trans* ratios of the products stay constant for more than 1 hr in each reaction system shows that the isomerization between these isomers is negligible.

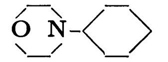
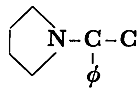
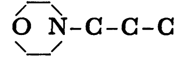
In the reduction with **1**, the *cis*/*trans* ratio of the newly formed product, with a rapid absorption of carbon monoxide, was 1.1, this value shows that the active species mainly reproduced is not **1**, but another active species. Considering the results of the reduction with **2**, we may suppose that the newly formed active species in the reaction of **1** is **2**. Once **2** is formed it may reduce the iminium salt catalytically, with a rapid absorption of carbon monoxide in the presence of the hydroxide ion, which is necessary for the formation of hydride species by the base reaction.[10] In this process, the formation of the carbonate may also occur. The catalytic cycle may be terminated by a lack of hydroxide ion and the formation of some such stable iron carbonyl complexes as Fe(CO)$_5$, which can not reduce the iminium salt by itself. However, to elucidate the mechanism of these reactions further studies will be required.

The Factors Which Determine the cis/trans *Ratio in the Reduction of the Enamine (7).* Considering the mechanism of the reduction of enamines with carbonylhydridoferrates discussed above the factors which determine the *cis*/*trans* ratio in the reduction of the



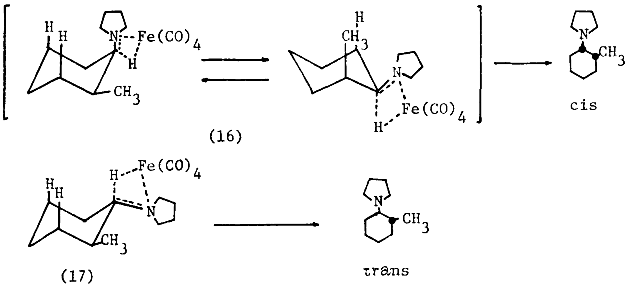
Scheme 1.

TABLE 5. REDUCTIVE ALKYLATION OF *sec*-AMINES WITH $[FeH(CO)_4]^-$ [a]

Exp. No.	Amine (33 mmol)	Carbonyl compounds (33 mmol)	Temp (°C)	Time (hr)	CO absd[b]	Product	Yield[b]
23	Morpholine	Cyclohexanone	30	48	1.7		1.4
24	Dibutylamine	Butyraldehyde	30	24	1.4	$(n\text{-Bu})_3N$	0.50
25	Pyrrolidine	Acetophenone	30	48	1.5		1.1
26	Morpholine	Propionaldehyde	30	24	1.4		0.41
27	Morpholine	Acetophenone	65	48	—	No reaction	
28	Diisopropylamine	Acetone	30	24	—	No reaction	

a) Solvent: EtOH: $[FeH(CO)_4]^-$: 11 mmol. b) mol/mol-$[FeH(CO)_4]^-$

enamine (**7**) are 1) the direction of the attack of the hydride complexes on the iminium salt (**16**); the axial and equatorial attack of the hydrides may give *trans* and *cis* isomers respectively, and 2) the stability of the reaction intermediates (Scheme 1). The ratios of 1.2 and 2.1 for **2** and **3** may be reasonably explained by the direction of the attack of the hydrides. The axial attack of the bulky polynuclear hydrides may be retarded by the axial hydrogens at the 3 and 5 positions, and an equatorial attack may precede. However, to explain the ratio 0.65 for **1**, another factor must be considered. It may be the stability of the intermediates. One of the possible models is a four-centered model, **16** or **17**. As **17**, in which all the axial positions are occupied by hydrogen atom, is considered to be more stable than **16**, the *cis*/*trans* ratio may become less than 1.0.



The Reductive Alkylation of sec-*Amines with 1.* In the course of this investigation, it was found that an equimolar mixture of a secondary amine and ketone or aldehyde reacts with an alcoholic solution of **1** at room temperature, with an absorption of carbon monoxide, to give the corresponding tertiary amine:

$$\rangle N{-}H + O{=}C\langle^{R_1}_{R_2} + (\mathbf{1}) \xrightarrow[\text{in EtOH}]{\text{CO}} \rangle N{-}\underset{H}{C}\langle^{R_1}_{R_2} \qquad (i)$$

The results are summarized in Table 5. Morpholine and cyclohexanone gave 1.4 mol of *N*-cyclohexylmorpholine, with an absorption of 1.7 mol of carbon monoxide. Acetophenone and pyrrolidine gave *N*-(1-phenylethyl)pyrrolidine. This reaction should be compared with the Leuckart-Wallach reaction.[22] The mechanism of the Leuckart-Wallach reaction of a ketone and a secondary amine has been considered to be as follows.[1] In the first step, the ketone and the secondary amine form a 1 : 1 adduct and then an iminium salt (**18**) is formed, which abstracts a hydride ion from formic acid or its derivatives:

$$\rangle C{=}O + H{-}N\langle \longrightarrow \rangle\underset{OH}{C}{-}N\langle \longrightarrow$$

$$\underset{(\mathbf{18})}{\left[\rangle C{=}N\langle\right]^{+}} OH^{-} \xrightarrow{H^{+}} \rangle\underset{H}{C}{-}N\langle \qquad (j)$$

In our reaction, neither ketone nor secondary amine reacts separately with **1**, and the boundary of the reaction is almost the same as that of the Leuckart-Wallach reaction. These facts strongly suggest that, in our reductive alkylation, the iminium salt (**18**) formed by the (j) equation abstracts a hydride ion from **1**; they support the mechanism of the reduction of enamines with **1** presented above.

The reductive alkylation using **1** is characterized by a low reaction temperature and the successful mono-[21] and dimethylation[23] of anilines. A full report on these reactions will be published soon.

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