Polymer-Supported Iron Complex as a Catalyst for the Selective Reduction of Diphenylacetylene with Sodium Borohydride

Yoko Nambu,* Masashi Kijima, and Takeshi Endo*

Research Laboratory of Resources Utilization, Tokyo Institute of Technology, Nagatsuta, Midori-ku, Yokohama 227, Japan. *Received August 12, 1986*

ABSTRACT: The polymer-supported lipoamide (LAm)–ferrous chloride system was found to be an effective catalyst for the reduction of diphenylacetylene to *cis*-stilbene with sodium borohydride. From the investigation of the model system, the dithiol–iron(II) (1:1) complex formed in situ was suggested to be an active species for the reduction. Among various insoluble polymers having the lipoamide structure, chitosan–LAm showed the highest activity, even higher than LAm itself, as a result of the inhibition of the formation of an inactive dithiol–iron(II) (2:1) complex in the polymeric catalyst.

Introduction

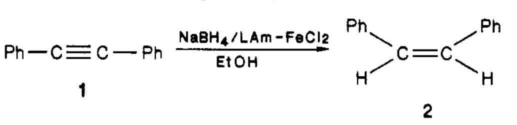
We have previously reported the reduction of hydroxylamines,[1] azobenzene, and nitrobenzenes[2] by dihydrolipoamide (DHLAm) and Fe(II) ion. These reactions are of interest in relation to those nonheme iron proteins such as ferredoxins and their models.

We have also reported the catalytic reduction of hydroxylamine derivatives[3] and nitrobenzenes[4] in the presence of polymer-supported lipoamide (LAm) and ferrous ion (Figure 1). In all cases, the activity of the insoluble polymeric catalysts decreased considerably compared with that of LAm.

In this study, we report the selective reduction of diphenylacetylene to *cis*-stilbene catalyzed by polymer-supported lipoamide–ferrous chloride ($FeCl_2$), in which the polymer-supported iron complex is shown to exhibit a higher activity than the soluble monomeric complex for the first time.

Results and Discussion

Reduction of Diphenylacetylene with the $NaBH_4$/LAm–$FeCl_2$ System. A lipoamide (LAm)–Fe(II) catalyzed reduction of diphenylacetylene (1) was attempted under various conditions (Table I).[5] Acetylene 1 was not reduced at all by the $NaBH_4$/LAm–Fe(II) system in aqueous media, whereas in anhydrous EtOH 1 was reduced with $NaBH_4$ to *cis*-stilbene (2) in 75% yield in the presence of catalytic amounts of LAm and ferrous chloride ($FeCl_2$) for 8 h at 35 °C under argon (eq 1). The reduction hardly occurred in the presence of LAm or $FeCl_2$ alone as a catalyst. $FeCl_3$ was also effective but ferric acetylacetonate showed lower reactivity for the reduction.

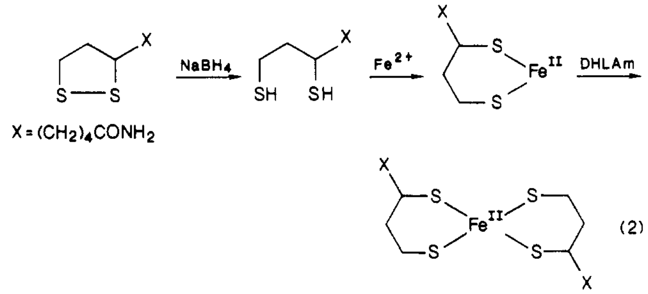


(1)

The ratio of LAm to $FeCl_2$ had an important effect on the product yields. A maximum yield was obtained at nearly equimolar amount of LAm and $FeCl_2$, whereas excess LAm inhibited the reaction (Figure 2). It is presumed from these results that DHLAm, produced in situ by the reduction of LAm with $NaBH_4$, forms an active DHLAm–Fe(II) (1:1) complex to be effective in the reduction of acetylene 1 and further forms an inactive DHLAm–Fe(II) (2:1) complex in the presence of excess LAm (eq 2).

Various thiol–$FeCl_2$ catalyzed reductions of acetylene 1 with $NaBH_4$ were examined (Table II). Dithiols that form stable chelates with metal ions[6] showed higher activity as catalysts, whereas dithiols having carboxyl or hydroxyl groups showed lower activity.

These results suggested that the reduction proceeded by the coordination of acetylene 1 to an active dithiol–Fe(II) (1:1) complex, followed by electron or hydride transfer in the complex. The active complex might be regenerated by $NaBH_4$ to work catalytically. $FeCl_3$ would be easily reduced to ferrous ion by dithiols or $NaBH_4$ to form the active ferrous complex. Excess thiols, other coordinating groups such as carboxyl and hydroxyl groups in the dithiols, acetylacetone, or water might inhibit the coordination of substrate 1 to the active dithiol–Fe(II) (1:1) complexes. It is interesting that such simple thiol–Fe(II), complexes are as active for the reduction of acetylene as other complicated nonheme iron protein model systems.[7]



(2)

Reduction of Acetylene 1 with the $NaBH_4$/(LAm polymer)–$FeCl_2$ System. We have already synthesized several polymers having the LAm structure, such as PVA–LAm (3), chitosan–LAm (4), PAA–LAm (5), and PS–LAm (6), by the reaction of lipoic anhydride with poly(vinylamine) obtained by the Hofmann rearrangement of cross-linked poly(acrylamide), chitosan, and linear poly(allylamine) and aminomethylated polystyrene cross-linked with divinylbenzene (200–400 mesh), respectively (Figure 3).[3,4] The reduction of acetylene 1 with $NaBH_4$ was carried out by using these insoluble LAm polymers and $FeCl_2$ as catalysts under the same conditions as the homogeneous LAm/$FeCl_2$ catalyst system. In every case, the LAm polymer gel dispersed well and was collected easily by filtration. In spite of the heterogeneous reaction, stilbene 2 was obtained as shown in Table III. Polymer 4 showed comparable activity with LAm itself, and polymer 6 also showed a good activity. Polymers 3 and 5 swelled in EtOH better than polymers 4 and 6 but had poor activity. Thus LAm polymers with comparably rigid structures showed higher activity.

The effect of the molar ratio of LAm polymers to $FeCl_2$ on the product yields was investigated to elucidate the correlation of polymer structures to their catalytic efficiencies (Figure 4). Contrary to LAm, polymers 4 and 6 showed high activities for a wide range of polymer/$FeCl_2$ ratio. Polymer 5 with good swelling property and high mobility had poor activities in all ratios.

Further, the effect of the LAm content of polymer 4 on the product yields was investigated. The maximum activity of polymer 4 was with LAm content of 57 mol % and

0024-9297/87/2220-0962$01.50/0

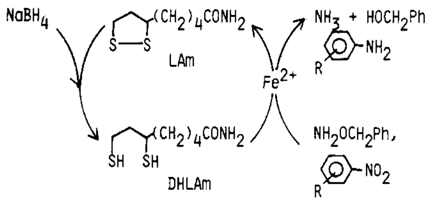


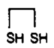
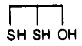
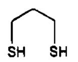
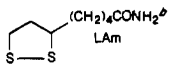
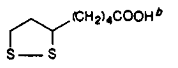
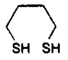
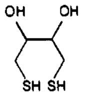
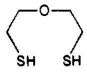
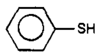
Figure 1. LAm–Fe^{2+} catalyzed reduction.

Table I
Reduction of Acetylene 1 with $NaBH_4$ Catalyzed by LAm–Fe^{n+} [a]

catalyst				yield of *cis*-stilbene
LAm/mM	Fe^{n+}	mM	solvent	(2),[b] %
10	$FeSO_4(NH_4)_2SO_4$	10	buffer[c]–EtOH	0
10	$FeCl_2$	10	buffer[c]–EtOH	0
10	$FeCl_2$	10	EtOH	64
7.5	$FeCl_2$	10	EtOH	75
0	$FeCl_2$	10	EtOH	7
10		0	EtOH	0
10	$FeCl_3$	10	EtOH	73
10	$Fe(acac)_3$	10	EtOH	29

[a] Reaction conditions: [$NaBH_4$] = 500 mM; [1] = 100 mM; 35 °C for 8 h under argon. [b] Determined by GLC. [c] 0.1 M carbonate buffer (pH 9.8).

Table II
Reduction of Acetylene 1 with $NaBH_4$ Catalyzed by Thiol–$FeCl_2$ [a]

thiol	% *cis*-stilbene
	70
	11
	39
	64
	15
	6
	4
	2
	8

[a] Reaction conditions: [thiol] = 10 mM; solvent, EtOH; other conditions are the same as those in Table I. [b] Disulfide was used instead of dithiol.

Table III
Reduction of Acetylene 1 with $NaBH_4$ Catalyzed by (LAm Polymer)–$FeCl_2$ [a]

LAm derivative	DS,[b] mol %	yield of 2, %
PVA–LAm (3)	22	8
chitosan–LAm (4)	43	60
PAA–LAm (5)	46	13
PS–LAm (6)	13	42
LAm		64

[a] Reaction conditions: [LAm derivative] = 10 mM; [$FeCl_2$] = 10 mM; solvent, EtOH; other conditions are the same as those in Table I. [b] Degree of substitution with the LAm structure determined by S analysis.

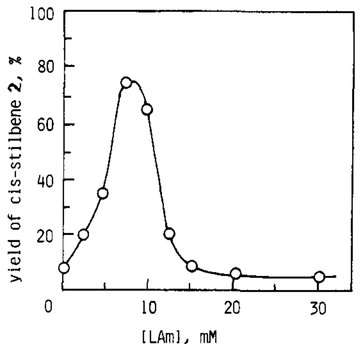


Figure 2. Effect of the concentration of LAm on the reduction of acetylene 1 by $NaBH_4$/LAm–$FeCl_2$ in anhydrous EtOH at 35 °C for 8 h under argon: [$NaBH_4$] = 500 mM, [1] = 100 mM, [$FeCl_2$] = 10 mM.

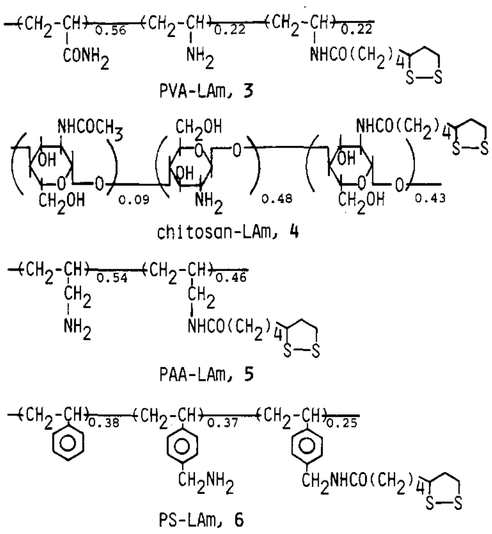


Figure 3. Insoluble polymeric catalysts with the LAm structure.

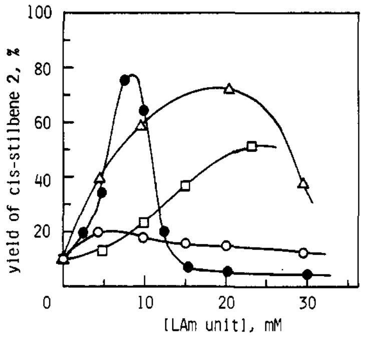


Figure 4. Effect of the concentration of LAm polymers on the reduction of acetylene 1 by $NaBH_4$/(LAm polymer)–$FeCl_2$ with the same conditions as in Figure 2: (●) LAm; (△) 4 (43 mol % LAm); (○) 5 (46 mol % LAm); (□) 6 (13 mol % LAm).

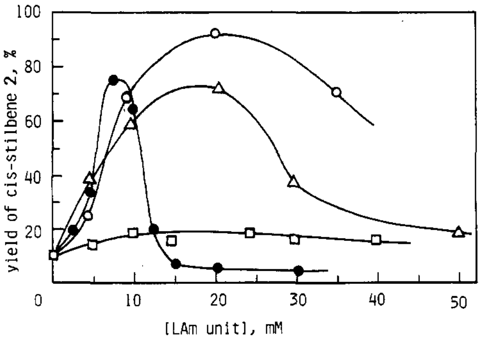


Figure 5. Effect of LAm content in polymer 4 on the reduction of acetylene 1 by $NaBH_4$/(polymer 4)–$FeCl_2$ with the same conditions as in Figure 2: polymer 4 with the LAm content of (□) 7 mol %; (△) 43 mol %; (○) 57 mol %; (●) LAm.

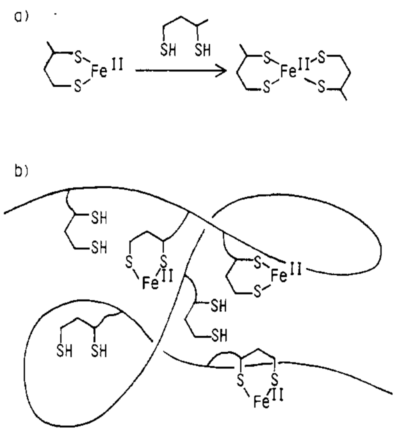
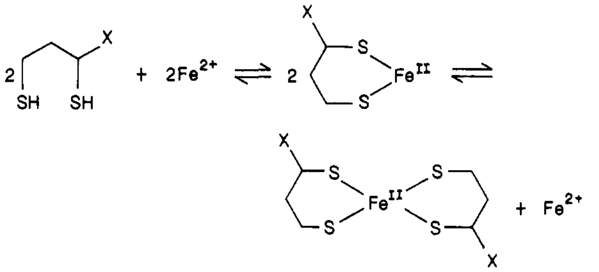


Figure 6. Active complex in (a) a model system and (b) a polymeric system.

exceeded that of LAm as shown in Figure 5. It is noteworthy that higher activity was attained in the insoluble LAm polymer system compared with the LAm system.

In the homogeneous system, as described earlier (eq 2), excess LAm inhibits the reaction by the formation of an inactive DHLAm–Fe(II) (2:1) complex. Even in the presence of an equimolar amount of LAm, ferrous ion may form an inactive 2:1 complex as in eq 3. On the other hand, if a LAm group is attached on the insoluble polymeric support, formation of the inactive dithiol–Fe(II) (2:1) complex by the coordination of two polymer-bound dithiol groups (generated in situ by the $NaBH_4$ reduction) to a ferrous ion would be suppressed. As a result, excess LAm groups in the polymer may not retard the reaction as does LAm (Figure 6). Grubbs reported[8] a similar site isolation in a polymer-bound complex. In addition, chitosan has a rigid pyranose structure, and with an increase in the degree of substitution of a free amino group, the mobility of the polymer backbone is decreased and the coordination of the polymer-bound hydroxyl and dithiol groups to the active dithiol–Fe(II) (1:1) complex is further suppressed. It is reasonable that for these reasons polymer **4** with 57 mol % LAm content forms an active complex most effectively and shows the highest reactivity, even higher than that of LAm.



(3)

In conclusion, insoluble polymers with the lipoamide structure were found to be effective catalysts for the selective reduction of diphenylacetylene with $NaBH_4$ by way of the formation of active polymeric complexes with ferrous ion. Especially chitosan with the lipoamide structure showed a higher activity than that of LAm itself by the suppression of inactive complex formation due to its polymeric effect.

Experimental Section

Materials. Lipoamide (LAm) was supplied by Fujisawa Pharmaceutical Co., Ltd. LAm polymers **3–6** were prepared by the method reported earlier.[3,4] Other chemicals used in this study were reagent grade. Solvents were purified by the usual procedure.

LAm or Polymer–FeCl$_2$ Catalyzed Reduction of Diphenylacetylene 1 by NaBH$_4$. LAm (10.3 mg, 0.05 mmol) or LAm polymer **3–6** (0.05 mmol), $FeCl_2$ (6.4 mg, 0.05 mmol), acetylene **1** (89 mg, 0.05 mmol), and $NaBH_4$ (96 mg, 2.5 mmol) were put into a Schlenk tube which was degassed and replaced with argon gas. To a Schlenk tube was added 5 mL of ethanol previously bubbled with argon gas. The reduction was carried out at 35 °C for 8 h. After the reaction (in the case of polymer catalysts, the polymer was removed by filtration), 10 mL of water was added to the reaction solution and the solution was extracted with dichloromethane several times. The yield of *cis*-stilbene (**2**) was determined by GLC analysis. *trans*-Stilbene was not detected at all. Stilbene **2** was isolated by Kugelrohr distillation and identified by its spectral data.

Dithiol–FeCl$_2$ Catalyzed Reduction of Acetylene 1 by NaBH$_4$. Dithiols (0.05 mmol) were used instead of lipoic acid derivatives and the reduction was carried out in the same manner as above.

Registry No. 1, 501-65-5; LAm, 940-69-2; $FeCl_2$, 7758-94-3.

References and Notes

(1) Nambu, Y.; Kijima, M.; Endo, T.; Okawara, M. *J. Org. Chem.* **1982**, *47*, 3066. Kijima, M.; Nambu, Y.; Endo, T. *Ibid* **1985**, *50*, 1140, 2522.
(2) Kijima, M.; Nambu, Y.; Endo, T.; Okawara, M. *J. Org. Chem.* **1983**, *48*, 2407; **1984**, *49*, 1434.
(3) Nambu, Y.; Kijima, M.; Endo, T.; Okawara, M. *J. Mol. Catal.* **1983**, *18*, 141. Kijima, M.; Nambu, Y.; Endo, T.; Okawara, M. *J. Polym. Sci., Polym. Chem. Ed.* **1984**, *22*, 821.
(4) Kijima, M.; Nambu, Y.; Endo, T. *J. Polym. Sci., Polym. Chem. Ed.* **1985**, *23*, 1723.
(5) For the preliminary communication of the model system: Kijima, M.; Nambu, Y.; Endo, T. *Chem. Lett.* **1985**, 1851.
(6) Jocelyn, P. C. *Biochemistry of the SH Group*; Academic: New York, 1972; p 95.
(7) Itoh, T.; Nagano, T.; Hirobe, M. *Tetrahedron Lett.* **1980**, *21*, 1343.
(8) Grubbs, R.; Lau, C. P.; Cukier, R.; Brubaker, C., Jr. *J. Am. Chem. Soc.* **1977**, *99*, 4517.