Studies on Lactone Formation in Vapor Phase. II. Synthesis of ε-Caprolactone

By Shinzaburo OKA

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The results obtained in a previous study[1] of the dehydrogenation of 1, 4-butanediol to γ-butyrolactone prompted this further investigation on ε-caprolactone.

Dehydrogenation of 1, 4-diols or 1, 5-diols with copper chromite catalyst had been studied by several investigators[2-7] to give γ-lactones or δ-lactones, respectively, in good yields.

1) S. Oka, This Bulletin, **34**, 12 (1961).
2) W. Reppe et al., German Pat. 699945 (1940); *Chem. Abstr.*, 35, 6977 (1941).
3) L. P. Kyrides et al., *J. Am. Chem. Soc.*, **68**, 1385 (1946).
4) L. E. Schniepp et al., ibid., **69**, 1545 (1947).
5) Y. Hachihama et al., *Chem. High Polymers (Kobunshi Kagaku)*, **8**, 75 (1951).
6) R. I. Longley et al., *J. Am. Chem. Soc.*, **74**, 2012 (1952).
7) W. Reppe et al., *Ann.*, **596**, 180 (1955).

Studies on dehydrogenation of 1,6-diols to ε-lactones are surprisingly few. Carothers[8] showed that ε-caprolactone was isolated as a by-product from hydrogenation products of ethyl adipate with copper chromite catalyst. Reppe[7] claimed that ε-caprolactone and its polymer were obtained by liquid phase dehydrogenation of 1,6-hexanediol with a copper catalyst. No details on preparation of the catalyst were described. Suitable catalysts for the dehydrogenation of 1,6-diols to ε-lactones are not found in the literature.

Attempts to dehydrogenate 1,6-hexanediol to ε-caprolactone with copper-zinc oxide or copper-magnesium oxide catalyst which gave γ-butyrolactone and δ-valerolactone in good yields, were unsuccessful. Apparently the formation of a seven-membered ring is more difficult as compared with that of the five- or six-membered ring. Examinations of numerous mixed catalysts have resulted in finding a new catalyst, copper chromite-zinc oxide, which gives ε-caprolactone in good yields. The dehydrogenation with this catalyst in vapor phase has an advantage over the liquid phase method which produces the undesirable polymer.

Preparation of 1,6-hexanediol, the starting material for ε-caprolactone, was performed as follows:

(1) $CH{\equiv}CH + HCHO \rightarrow CH{\equiv}CCH_2OH$

(2) $2CH{\equiv}CCH_2OH + 1/2\ O_2 \rightarrow HOCH_2C{\equiv}CC{\equiv}CCH_2OH + H_2O$

(3) $HOCH_2C{\equiv}CC{\equiv}CCH_2OH + 4H_2 \rightarrow HO(CH_2)_6OH$

Since the ethinylation reaction was found by Reppe[9], several investigations[10-12] including the reaction of acetylene with aqueous formaldehyde have been reported. Propargyl alcohol, the initial reaction product, reacts with a second molecule of formaldehyde to give butynediol, which is usually the main product. Murahashi[11] reported the favorable conditions for the propargyl alcohol formation in an aqueous solution. But so far as aqueous formaldehyde is used, isolation of propargyl alcohol from the dilute aqueous reaction mixture is complicated and time-consuming owing to the formation of an azeotropic mixture. It may be, therefore, favorable to carry out the reaction under non-aqueous conditions. For the purpose of raising the yield of propargyl alcohol, it may be preferable to maintain the high concentration of acetylene by using a suitable solvent. Thus, the author studied the reaction of acetylene with anhydrous paraformaldehyde in various solvents.

Experimental

Propargyl Alcohol and Butynediol.—According to Murahashi's procedure[10], a copper acetylide catalyst was prepared from 30 g. of cupric oxide which was obtained by heating basic copper carbonate at 300~350°C. One third of the catalyst was used in each experiment. The reaction was carried out batchwise in a shaking stainless steel autoclave of 300 ml. capacity. The autoclave was charged with paraformaldehyde, solvent and the catalyst. Acetylene was compressed at room temperature. The amount of acetylene compressed was estimated by the pressure drop of the compressor's oil separator which supplied acetylene. After the reaction, the reaction mixture was filtered and about 1 g. of the filtrate was supplied to analytical determination of propargyl alcohol according to Reppe's directions[13]. After removal of the solvent and the propargyl alcohol, the filtrate gave butynediol, b. p. 115~117°C/3 mmHg, m. p. 56~57°C (lit.[10] 57°C).

Hexadiynediol—A shaking stainless steel autoclave of 300 ml. capacity was charged with 56 g. of propargyl alcohol, 6 g. of cuprous chloride, 19 g. of ammonium chloride, and 60 g. of water. Oxygen was filled to 20 kg./cm². The autoclave was heated 55~60°C for one hour. When the pressure fell to 5 kg./cm², oxygen was again changed to 20 kg./cm². The reaction mixture was filtered, and the solid was washed with a minimum amount of water and recrystallized from methanol to yield 51 g. of hexadiynediol, m. p. 112°C (lit.[14] 112°C).

1,6-Hexanediol.—Hexadiynediol (20 g.) in 180 ml. of methanol was hydrogenated under the initial hydrogen pressure of 50 kg./cm² with 2 g. of Raney nickel W-6 at 50~60°C for two hours. The catalyst was filtered off, and the filtrate, after removal of the solvent, was distilled to yield 20 g. of 1,6-hexanediol, b. p. 125°C/3 mmHg, m. p. 40~41°C (lit.[15] 41.5°C).

ε-Caprolactone.—A typical catalyst for the dehydrogenation of 1,6-hexanediol to ε-caprolactone was prepared as follows.

Two solutions, one solution (350 ml.) containing 56 g. of zinc nitrate hexahydrate and 92 g. of cupric nitrate trihydrate, and one solution (350 ml.) containing 24 g. of ammonium dichromate and 56 g. of 28% solution of ammonium hydroxide, were added dropwise into 300 ml. of water with stirring. The orange yellow precipitate formed was filtered and sucked as dry as possible, and dried at 70~80°C for twelve hours. The product was decomposed in a silica tube heated at 260~280°C for

8) W. H. Carothers et al., *J. Am. Chem. Soc.*, **56**, 455 (1934).
9) W. Peppe, Brit. Pat. 508062 (1939); *Chem. Abstr.*, **34**, 447 (1940).
10) S. Murahashi et al., *J. Soc., Chem. Japan, Ind. Chem. Sec.* (*Kogyo Kagaku Zasshi*), **55**, 525 (1952).
11) S. Murahashi et al., ibid., **55**, 567 (1952).
12) K. Yamamoto et al., This Bulletin, **27**, 386 (1954).
13) W. Reppe et al., *Ann.*, **596**, 34 (1955).
14) J. W. Copenhaver and M. H. Bigelow, "Acetylene and Carbon Monoxide Chemistry", Reinhold Publishing Corp. (1949), p. 123.
15) W. Reppe et al., *Ann.*, **596**, 71 (1955).

three hours. The resulting product was washed with fifteen 2 l. portions of water, and dried at 70~80°C for twelve hours. The composition of the catalyst so obtained was about: 50% cupric oxide, 25% chromium oxide and 25% zinc oxide by weight (mol. ratio=2 : 0.5 : 1).

The apparatus and the procedure for the dehydrogenation were essentially the same as those previously described[1]. The dehydrogenation tube (60 cm.×15 mm.) was packed with 50 ml. of tablets of the above catalyst. After activation of the catalyst with hydrogen at 280~300°C, the pressure in the reaction system was reduced to 5~10 mmHg and 1,6-hexanediol (15 g.) was passed in by vacuum distillation in a period of four hours. The reaction temperature was maintained at 210~220°C. The product was fractionated to yield 0.5 g. of forerun, b. p. 50~65°C/2 mmHg, 7.6 g. of ε-caprolactone, b. p. 78~85°C/2 mmHg and 3.4 g. of unreacted hexanediol, b. p. 110~120°C/2 mmHg. Refractionation gave a sample of b. p. 80°C/2 mmHg, n_D^{25} 1.4615, d_4^{25} 1.071, MR_D: Found, 29.3; Calcd., 29.3.

Found: C, 63.22; H, 8.86. Calcd. for $C_6H_{10}O_2$: C, 63.13; H, 8.83%.

ε-Caprolactone gave a hydrazide melting at 115°C (lit.[8] 115°C).

Found: C, 49.16; H, 9.68. Calcd. for $C_6H_{14}O_2 \cdot N_2$: C, 49.30; H, 9.65%.

From the forerun, a 2,4-dinitrophenylhydrazone of 1-cyclopentene-1-carboxaldehyde was obtained, m. p. 209~210°C (lit.[16] 210~211°C), which showed no depression when mixed with an authentic sample.

Found: C, 52.40; H, 4.44. Calcd. for $C_{12}H_{12} \cdot O_4N_4$: C, 52.17; H, 4.38%.

Cyclopentyl Carbinol.—Copper-magnesium oxide tablets (50 ml.) containing 20% copper were used. After activation of the catalyst with hydrogen at 280~300°C, 1,6-hexanediol (17 g.) was passed in with 20 l./hr. of hydrogen at 270°C in a period of three hours. The products consisted of two layers; the upper water-insoluble layer weighed 11 g. and the lower aqueous layer weighed 2 g. By fractionation of the upper layer, 3.5 g. of forerun, b. p. 50~60°C/22 mmHg and 4 g. of cyclopentyl carbinol, b. p. 73~78°C/22 mmHg were obtained. Refractionation gave a sample of b. p. 74°C/20 mmHg, n_D^{20} 1.4540, d_D^{22} 0.926 (lit.[17] b. p. 161~163°C, n_D^{20} 1.4552, d_4^{20} 0.926), MR_D Found, 29.2, Calcd., 29.2.

Found: C, 71,77; H, 12.14. Calcd. for $C_6H_{12}O$: C, 71.95; H, 12.08%.

Cyclopentyl carbinol gave a phenylurethane melting at 108°C (lit.[18] 110°C).

Found: C, 71.30; H, 7.82. Calcd. for $C_{13}H_{17} \cdot O_2N$: C, 71.20; H, 7.82%.

From the forerun, a 2,4-dinitrophenylhydrazone of cyclopentanecarboxaldehyde was obtained, m. p. 149~152°C. (lit.[19] 158°C).

Found: C, 51.63; H, 5.01. Calcd. for $C_{12}H_{14} \cdot O_4N_4$: C, 51.79; H, 5.01%.

16) M. S. Kharash et al., *J. Org. Chem.*, **16**, 150 (1951).
17) N. Turkiewicz, *Ber.*, **72**, 1060 (1939).
18) N. Zelinsky, ibid., **41**, 2628 (1908).
19) H. M. Fales, *J. Am. Chem. Soc.*, **77**, 5118 (1955).

Results and Discussion

Reaction of Paraformaldehyde with Acetylene under Pressure.—The results obtained in various solvents are shown in Table I. Acetylene was compressed to about 15 kg./cm² at room temperature and the amount of acetylene compressed was about 26 g., except in the case of water (35 kg./cm², 14 g.). Obviously chemical structure of the solvent has effects on the relative yields of propargyl alcohol and butynediol to some extents. Methanol, tetrahydrofuran and acetone were suitable solvents for propargyl alcohol formation and benzene for butynediol.

Effects of the reaction temperature are shown in Table II. The relative yields were hardly

Table I. Effects of solvents

Solvent	Reaction pressure kg./cm²	Yield of PA* %	Yield of BD** %
Water	50~33	30	51
Methanol	48~42	52	30
Tetrahydrofuran	47~40	41	38
Acetone	45~40	47	42
Methyl acetate	40~33	36	47
Benzene	45~40	31	60

* Propargyl alcohol ** Butynediol
Reaction temperature: 110°C
Reaction time: 8 hr.
Paraformaldehyde (15 g.) and 100 g. of solvent were used.

Table II. Effects of the reaction temperature

Reaction temp. °C	Reaction pressure kg./cm²	Yield of PA* %	Yield of BD** %
90~100	42~23	28	31
100~110	40~25	32	45
110~120	40~22	36	49

* Propargyl alcohol ** Butynediol
Reaction time: 8 hr.
Paraformaldehyde (20 g.) and 100 g. of methanol were used.

Table III. Effects of reaction pressure

Amount of acetylene charged g.	Reaction pressure kg./cm²	Yield of PA* %	Yield of BD** %
28	40~25	41	37
14	26~15	32	43
8	15~ 2	10	62

* Propargyl alcohol ** Butynediol
Reaction temperature: 110~120°C
Reaction time: 6 hr.
Paraformaldehyde (20 g.) and 100 g. of methanol were used.

affected by the reaction temperature. Under 100°C, the conversion was low.

Results under various pressure are shown in Table III. Similar to the case of aqueous formaldehyde, the distribution of the products depended upon the reaction pressure—the higher the reaction pressure, the higher the yield of propargyl alcohol.

Table IV. Effects of paraformaldehyde concentration

Concn.	Reaction pressure	Yield of PA*	Yield of BD**
%	kg./cm²	%	%
10	50～44	56	26
20	45～35	41	37
30	43～22	32	45
50	50～30	24	52

* Propargyl alcohol ** Butynediol
Reaction temperature: 110～120°C
Reaction time: 8 hr.
A mixture (100 g.) of paraformaldehyde and methanol was used.

Table V. Oxydative coupling of propargyl alcohol

Reaction temp.	Reaction time	PA* : CuCl	Yield of hexadiynediol
°C	hr.	mol. ratio	%
20～25	8	2～4 : 1**	75
25～25	8	16 : 1	58
50～60	1	16 : 1	93
60～70	1	16 : 1	80
75～80	1	32 : 1	71

* Propargyl alcohol
CuCl (6 g.), NH_4Cl (19 g.), H_2O (60 ml.) and propargyl alcohol (56 g.) were used.
** The molar ratio of propargyl alcohol to cuprous chloride was maintained at ratio of 2～4 : 1 by adding propargyl alcohol at intervals.

The effects of paraformaldehyde concentration are shown in Table IV. With increase of the concentration of paraformaldehyde, the relative yield of propargyl alcohol decreased, but the effect was not so noticeable as in the case of aqueous formaldehyde. Therefore, for the purpose of preparing propargyl alcohol batchwise in the laboratory, it is advisable to increase the concentration of paraformaldehyde.

Oxydative Coupling of Propargyl Alcohol.—Hexadiynediol was prepared by the method using air and cuprous chloride catalyst. Reppe[20] described that the molar ratio of propargyl alcohol to cuprous chloride should be maintained at the most favorable ratio of 2 : 1 to 4 : 1 by adding propargyl alcohol at intervals.

The results in Table V show that even at the ratio of 16 : 1, hexadiynediol was easily obtained in a high yield by elevating the reaction temperature to 50～60°C.

Hydrogenation of Hexadiynediol.—Hydrogenation of hexadiynediol in the presence of Raney nickel W-6 proceeded smoothly in methanol solution to give 93% yield of 1, 6-hexanediol. If an unpurified sample containing copper ions is used, a small amount of zinc dust should be added to prevent deactivation of the catalyst.

Dehydrogenation of 1, 6-Hexanediol.—Some of the results obtained in dehydrogenation of 1, 6-hexanediol with numerous mixed catalysts are shown in Table VI. Similar to the previous study[1], a sample was passed in with a steady current of hydrogen. The yields of ε-caprolactone were based upon the amounts of hexanediol consumed. With all the catalysts, the reaction was very slow as compared with that of 1, 4-diols or 1, 5-diols. With the elevation of the reaction temperature, the amount of the forerun increased and the product decreased. With copper-magnesium oxide, it was ascertained

Table VI. Dehydrogenation of 1, 6-hexanediol with mixed catalysts

Catalyst	Reaction temp.	Sample	Product	Forerun	Yield of lactone	Sample recovered	Conversion
	°C	g.	g.	g.	g.	g.	%
Cu-MgO	280	17	11	7.5	0.5	3.0	82
Cu-ZnO	280	12	9	1.2	—	7.0	42
$CuCrO_2$	280	14	10	4.5	2.2	1.0	93
	230	12	10	3.2	2.7	2.3	79
$CuCrO_2$-Al_2O_3	230	14	11	2.5	4.5	3.8	80
$CuCrO_2$-Fe_2O_3	230	12	11	2.0	2.0	5.0	58
$CuCrO_2$-CdO	230	12	9	3.7	0.8	3.0	75
$CuCrO_2$-ZnO	280	14	11	3.0	4.5	2.0	86
	230	13	12	2.3	5.4	3.2	75

Reaction time: 3 hr.

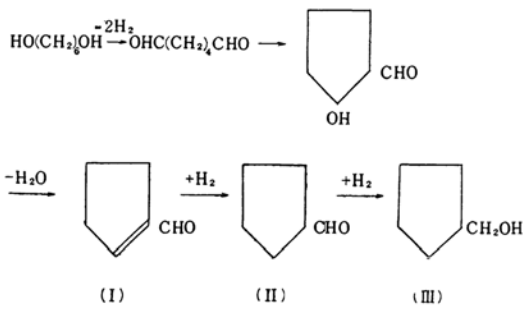
20) W. Reppe et al., *Ann.*, **596**, 51 (1955).

TABLE VII. EFFECTS OF CATALYST COMPOSITION

Catalyst composition (mol. ratio)			Yield of lactone	Sample recovered	Conversion
CuO	Cr_2O_3	ZnO	g.	g.	%
1	0.5	0.5	7.4	2.8	83
1	0.5	1	6.8	4.5	70
1	0.5	2	6.3	4.5	70
1	0.5	3	6.2	3.5	78
2	0.5	1	7.6	3.4	77
3	0.5	1	3.8	4.5	70
1	1	1	Inactive		
1	0.25	1	7.0	4.2	72
1	0.25	2	4.5	5.0	67

The sample (15 g.) was used in each experiment.

that the forerun contained cyclopentyl carbinol (III) and a small amount of cyclopentane carboxyaldehyde (II). This fact suggested the occurrence of the following side reactions.



Copper-chromite catalyst, which had been used for preparing γ-lactones or δ-lactones in the literatures, gave ε-caprolactone in 30% yield in the present work. It was observed that zinc oxide improved the selectivity of copper chromite for the ε-lactone formation.

The relationship between catalytic activity or selectivity and the composition of copper chromite-zinc oxide catalyst was shown in Table VII. In these experiments, the pressure in the reaction system was kept at 5~10 mmHg and the sample was passed in by vacuum distillation. The reaction temperature was maintained at 210~220°C and the reaction time was four hours. The catalysts were prepared by a modification of the procedure for preparing Adkins' copper chromite. The composition of the catalyst has considerable effects on the yield and conversion. The most favorable catalyst giving ε-caprolactone in a 68% yield and in a 78% conversion, had the composition of $CuO : Cr_2O_3 : ZnO = 2 : 0.5 : 1$. The catalysts which contained one of the components excessively lowered both the activity and selectivity. It was also ascertained that the forerun in these experiments contained 1-cyclopentene-1-carboxaldehyde (I).

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Institute for Chemical Research
Kyoto University
Takatsuki, Osaka