Table I

Yields of 1-Nitro-2-alkanones from 1-Alkenes

Starting olefin	1-Nitro-2-alkanone (mp)	Yield,[a] %
1-Octene	1-Nitro-2-octanone (47°)	79
1-Octadecene	1-Nitro-2-octadecanone (94°)	84
1-Docosene	1-Nitro-2-docosanone (101–100.5°)	96

[a] The yield of isolated crude product was calculated on the starting olefin; the melting points as isolated were depressed by a few degrees.

methyl group at 53 cps, all in the appropriate proton ratios.

Experimental Section

Nitrogen dioxide was obtained from the Matheson Co. and oxygen was obtained from the Linde Co. 1-Dodecene (minimum purity 95%, Columbia Organic Chemicals Co.) was distilled before use. 1-Docosene (Humphrey Chemical Co.) and 1-octene (minimum purity 99%, Phillips Petroleum Co.) were used as received. Dimethylformamide (Eastman White Label) and dimethyl sulfoxide (Crown Zellerbach) were used without purification. Infrared spectra were obtained with a Beckman IR-4 or a Perkin-Elmer Model 137 spectrophotometer. Nmr spectra were obtained in chloroform-*d* with a Varian Associates Model V-4311 spectrometer operated at 60 Mc using tetramethylsilane as an internal standard. All melting points are uncorrected.

1-Nitro-2-Dodecyl Peroxynitrate.—The preparation of 1-nitro-2-dodecyl peroxynitrate is typical of all of the nitroalkyl peroxynitrate preparations and was carried out as follows. An oxygen stream was conducted over liquid dinitrogen tetroxide at a rate of 56.5 cc/min and the resultant oxygen–dinitrogen tetroxide mixture was bubbled into a stirred solution of 1-dodecene (5.00 ml, 2.27×10^{-2} mole) in 50 ml of *n*-hexane. The reaction was allowed to proceed until 1.5 ml (2.4×10^{-2} mole) of liquid dinitrogen tetroxide had been thus transferred to the reaction solution. The process took about 4 hr. The reaction solution was stirred with a magnetic stirring bar and its temperature was maintained at about 0° with an ice bath. The crude nitroalkyl peroxynitrate was isolated by removal of volatiles from the reaction solution *in vacuo* at about 0°. The estimated minimum purity (by nmr) was 80%.

1-Nitro-2-dodecanone from the Thermal Decomposition of 1-Nitro-2-dodecyl Peroxynitrate.—A *n*-hexane solution of 1-nitro-2-dodecyl peroxynitrate at 0° was allowed to warm to ambient temperature overnight resulting in the formation of a crystalline precipitate and a bright yellow solution. The colorless solid (mp 73–74°) was isolated by filtration in 13% yield. Repeated recrystallization from *n*-hexane increased its melting point to 75–75.5°.

Anal. Calcd for $C_{12}H_{23}NO_3$: C, 62.9; H, 10.0; N, 6.1; O, 21.0; mol wt, 229. Found: C, 63.2; H, 10.1; N, 5.9; O, 20.8; mol wt, 231.

The infrared spectrum (Nujol mull) exhibited strong absorption bands at 5.8 μ (characteristic of a carbonyl function) and at 6.40–6.45 μ (characteristic of an aliphatic nitro function). The nmr spectrum showed a two-proton singlet at 315 cps (assigned to the C-1 methylene protons) and a two-proton triplet centered at 153 cps (assigned to the C-3 methylene protons) as well as peaks for the chain methylene and the methyl group protons at 76 and 53 cps, respectively.

Reactions of Nitroalkyl Peroxynitrates.—Reactions of the unpurified peroxynitrate were generally carried out by adding it to a reaction solution. When a water-soluble solvent was employed, the reaction mixture was worked up by mixing with a large amount of ice water. Water-insoluble solvents, when used, were removed from the reaction mixture under vacuum. The nitro ketones, all of which were solids, were isolated by filtration. Analytical samples were prepared by recrystallization from an appropriate hydrocarbon solvent. A typical run was carried out in the following manner. Crude 1-nitro-2-dodecyl peroxynitrate (prepared from 2.27×10^{-2} mole of 1-dodecene) was added dropwise to a reaction flask containing 25 ml of dimethyl sulfoxide, stirred by a magnetic stirring bar. The temperature was maintained at 12–18° by an ice bath and the rate of addition. When the addition was completed, the reaction mixture was added to 150 ml of ice water. A colorless precipitate was isolated by filtration which melted at 69–72° and weighed 4.5 g (86% yield from 1-dodecene). After repeated recrystallization from *n*-hexane the product melted at 75–75.5°. Its infrared spectrum was identical with that of 1-nitro-2-dodecanone.

The following analyses were obtained for 1-nitro-2-octanone, 1-nitro-2-octadecanone, and 1-nitro-2-docosanone.

Anal. Calcd for $C_8H_{15}NO_3$: C, 55.5; H, 8.67; N, 8.09; O, 27.8; mol wt, 173. Found: C, 55.6; H, 8.8; N, 7.9; O, 28.1; mol wt, 182.

Anal. Calcd for $C_{18}H_{35}NO_3$: C, 69.0; H, 11.27; N, 4.47; O, 15.3; mol wt, 314. Found: C, 68.9; H, 11.3; N, 4.3; O, 15.2; mol wt, 315.

Anal. Calcd for $C_{22}H_{43}NO_3$: C, 71.3; H, 11.7; N, 3.79; O, 13.0; mol wt, 370. Found: C, 71.3; H, 11.7; N, 3.7; O, 13.3; mol wt, 366.

Carbomethoxylation of Epichlorohydrin with Cobalt Carbonyl and Glycidyltrimethylammonium Halide Cocatalysts. New Synthesis of Alkali-Sensitive Epoxides

James D. McClure

Shell Development Company, Emeryville, California

Received May 31, 1967

Reaction of epichlorohydrin with carbon monoxide and methanol in the presence of dicobalt octacarbonyl and glycidyltrimethylammonium halide (II or III) cocatalysts gives methyl 4-chloro-3-hydroxybutyrate (I) in 53% yield. In the absence of II (or III) the rate of formation of I is reduced and the yield of I is only 20%. A mechanism whose first step is the attack of the cobalt tetracarbonyl anion on II (or III) is proposed to account for the catalytic activity of II. Reaction of I with sodium methoxide at 0° affords methyl 4-hydroxycrotonate in 64% yield by rearrangement of the intermediate methyl 3,4-epoxybutyrate (VII). However, treatment of I with silver oxide in refluxing dimethoxyethane gives the alkali sensitive VII in 75% yield. Several other alkali-sensitive epoxides that hitherto have been available in only low yield have also been prepared from their chlorohydrins by the use of silver oxide.

In contrast to ethylenic compounds, whose reactions with carbon monoxide (metal carbonyl catalysts) have been extensively studied[1] during the past 25 years, the reactions of epoxides with carbon monoxide have only recently received the attention of organic chemists. In 1961, Eisenmann and co-workers[2] reported that propylene oxide reacts with carbon monoxide and methanol

---

[1] C. W. Bird, *Chem. Rev.*, **62**, 283 (1962).

[2] J. L. Eisenmann, R. L. Yamartino, and J. F. Howard, Jr., *J. Org. Chem.*, **26**, 2102 (1961).

in the presence of dicobalt octacarbonyl catalyst to give methyl 3-hydroxybutyrate in 40% yield when carried out at 130° and 3500 psi of pressure. Heck[3] later observed that ethylene oxide affords methyl 3-hydroxypropionate in 55% yield when treated with carbon monoxide and sodium cobalt carbonyl catalyst in methanol solution at 65° and 2000 psi of pressure.

The latter author[3] also established, by isolating β-hydroxyacylcobalt tricarbonyl triphenylphosphine derivatives, that β-hydroxyacylcobalt tetracarbonyls are the primary products formed on reaction of epoxides with cobalt hydrocarbonyl in ether solution. More recently the reaction[4] of epichlorohydrin with cobalt hydrocarbonyl and ethanol in toluene solution has been reported by Japanese workers to give ethyl 4-chloro-3-hydroxybutyrate in 55–60% yield. It was also found that the reaction rate[4] with epichlorohydrin was one-fortieth as fast as that observed with propylene oxide. No attempt was made to prepare the epichlorohydrin carbonylation product using only catalytic amounts of cobalt apparently because the rate of carbonylation was so much slower than that found with propylene oxide. The appearance of the latter publication prompts us to report the results of our own studies[5] carried out in 1961 on the carbomethoxylation of epichlorohydrin using catalytic amounts of dicobalt octacarbonyl. It has been found by us that only when the carbonylation is carried out in the presence of a cocatalyst are the yields of methyl 4-chloro-3-hydroxybutyrate satisfactory.

Attempts[6] to carry out carbonylation reactions using cobalt carbonyl catalysts with aliphatic halides containing an ethylenic group have not given organic products which retained the halogen. Indeed, in most cases the halogen quantitatively destroyed the cobalt carbonyl catalyst by converting it to cobalt halide and no significant amount of any carbonylation product was observed. Of particular interest, then, are the results of our studies with epichlorohydrin employing only catalytic amounts of cobalt and resulting in the retention of halogen in the product.

Results

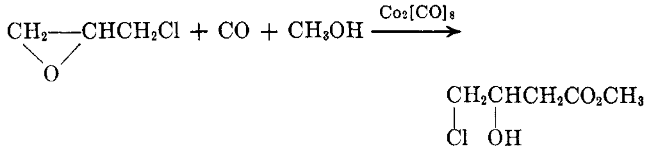
Epichlorohydrin reacts with carbon monoxide in a methanol–hexane solvent in the presence of a dicobalt octacarbonyl catalyst to give methyl-4-chloro-3-hydroxybutyrate (I) in 6–21% yield. The compound was identified by comparison of its spectral properties with those of an authentic sample.[7] None of the isomeric ester, methyl 2-(chloromethyl)-3-hydroxypropionate, could be detected. In Table I are summarized the results of some experiments in which pressure, temperature, and catalyst concentration all were varied. The recorded temperature was maintained for 4–6 hr during which time the initial pressure generally fell 300–700 psi. It is noteworthy that increasing the initial carbon monoxide pressure increased the yield of I even at the highest pressures examined. This observation differs from that reported with propylene oxide[2] where either increasing or decreasing the carbon monoxide pressure from 3500 psi reduced the yield of methyl 3-hydroxybutyrate. The results in Table I also indicate that higher yields of ester are obtained by increasing the concentration of catalyst up to about 2 mole %; any increase in concentration beyond that point does not change the yield of ester. Finally, maximum yields occur at temperatures of 100 ± 5°.

TABLE I

REACTION OF EPICHLOROHYDRIN WITH CARBON MONOXIDE AND METHANOL

Amount of dicobalt octacarbonyl, mole %	Temp, °C	Initial pressure, psi	Methyl 4-chloro-3-hydroxybutyrate, %
2.0	105	1600	2[a]
2.0	105	3500	10
2.0	105	9000	20
2.0	130	3500	7
1.0	95	9000	18
1.0	75	9000	6[a]
0.4	95	9000	4
0.7	95	9000	13
2.0	95	9000	21
4.0	95	9000	20

[a] About 50% of the epichlorohydrin was recovered in each of these two experiments; in all other experiments over 75% of the epichlorohydrin was consumed.



In Table II are presented the results of several experiments in which the reaction of epichlorohydrin with carbon monoxide (2–4-hr duration) was carried out in the presence of several cocatalysts (1 mole %) used in conjunction with dicobalt octacarbonyl (1.5 mole %). The most striking feature of these experiments is that the yield of I is increased two- to threefold by the presence of glycidyltrimethylammonium chloride (II) or bromide (III) in the reaction mixture. Glycidyltrimethylammonium chloride (II) may be either added preformed[8,9] or may be generated "*in situ*" from trimethylamine which reacts rapidly with epichlorohydrin to give II at temperatures as low as 25°. The corresponding bromide III may be prepared in crude form by the procedure reported[8] for preparing II. The preparation of pure II and III in high yield will be the subject of a subsequent publication. Best results

TABLE II

METHYL 4-CHLORO-3-HYDROXYBUTYRATE FROM EPICHLOROHYDRIN

Cocatalyst, 1 mole %	Temp, °C	Pressure, psi	% yield
None	95	9000	18–20
Glycidyltrimethylammonium chloride	80	8500	48
Trimethylamine	80	8500	47
Glycidyltrimethylammonium bromide	70	8500	53
Glycidyltrimethylammonium bromide	75	4500	43
None	105	3500	11

---

(3) R. F. Heck, *J. Am. Chem. Soc.*, **85**, 1460 (1963).

(4) Y. Takegami, C. Yokokawa, Y. Watanabe, and H. Masada, *Bull. Chem. Soc. Japan*, **37**, 672, 935 (1964).

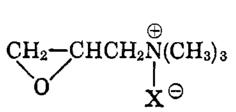
(5) J. D. McClure (Shell Development Co.), U. S. Patent 3,259,649 (1966).

(6) Unpublished work, Shell Development Co.

(7) R. Rambaud, S. Ducher, A. Broche, M. Brini-Fritz, and M. Vessière, *Bull. Soc. Chim. France*, 880 (1955).

(8) E. F. Paschall, U. S. Patent 2,876,217 (1959).

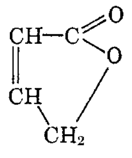
(9) D. M. Burness, *J. Org. Chem.*, **28**, 1862 (1964).



II, X = Cl
III, X = Br

(53% yield) in the carbomethoxylation of epichlorohydrin are obtained using III as cocatalyst at 70° and 8500 psi of pressure. Under these conditions only 5% of the epichlorohydrin is recovered unchanged after a 2-hr reaction time. In the absence of III, 50–60% of the epichlorohydrin is recovered after this reaction period.

The principal by-product formed in the carbomethoxylation of epichlorohydrin is 1,3-dichloro-2-propanol[10] isolated in 22% yield in the experiment in which I was obtained in 53% yield. In those experiments which were conducted in the absence of II or III, 1,3-dichloro-2-propanol was the main product (45–55%) isolated. The formation of this compound is minimized by effecting reaction at as low a temperature (70–80°) as possible. 1-Choro-3-methoxy-2-propanol[11] is obtained as a minor by-product (2–3% yield) under the best reaction conditions described above. Both of these products were identified by comparison of their gas–liquid partition chromatograms and infrared spectra with those of authentic samples prepared by independent routes. Careful work-up of the reaction mixture is necessary in order to avoid the formation of considerable amounts of $\Delta^{\alpha,\beta}$-butenolide[12] (IV). Using the procedure described in the Experimental Section, the yield of IV is less than 2%.



IV

Reaction of epichlorohydrin with carbon monoxide and excess ethanol (used as solvent) in the presence of dicobalt octacarbonyl and glycidyltrimethylammonium bromide at 8500 psi of pressure and 80° affords ethyl 4-chloro-3-hydroxybutyrate[7] in 30% yield. No effort was made to maximum the yield of this compound.

Discussion

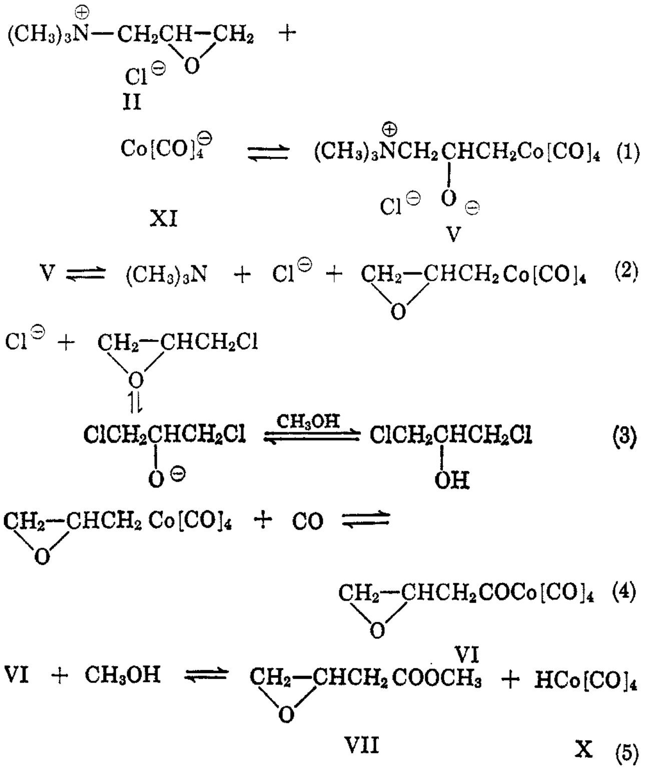
In the absence of a complete kinetic and catalyst study, the results of the experiments on the carbomethoxylation of epichlorohydrin in the presence of cobalt carbonyl are subject to several mechanistic interpretations. Any effort to explain them should be consistent with the following observations.

1. Glycidyltrimethylammonium halides are highly effective cocatalysts for the reaction, improving both the yield and the rate of formation of I. Although tertiary amines and quaternary ammonium halides have been reported[13,14] to be effective in catalyzing the reactions of epichlorohydrin with several nucleophilic reagents, it does not appear to have been recognized[14] previously that glycidyltrimethylammonium halides may be the actual catalytic species involved. The epoxide moiety of glycidyltrimethylammonium chloride (II) has been found by us to be ten times more reactive than that of epichlorohydrin toward nucleophilic attack by thiosulfate anion[15] in aqueous solution. On the other hand, the perchloric acid catalyzed hydrolysis[16] of II proceeds at a slightly slower rate than that observed with epichlorohydrin. Accordingly the rate enhancement produced by the presence of II (or III) in the carbonylation reaction is believed to be due to the greater susceptibility of II to nucleophilic reaction.

2. Both the yield and the rate of formation of I increase as the initial carbon monoxide pressure is increased. This observation stands in contrast to results encountered in the hydroformylation of olefins[17] with cobalt carbonyl catalysts. There, the rate of formation of carbonylation product was found to be inversely proportional to the carbon monoxide pressure[18] at constant hydrogen pressure. Accordingly, it is not necessary to postulate a step in the reaction mechanism which is inhibited by carbon monoxide as has been done in the mechanism[17] for the hydroformylation of olefins.

3. 1,3-Dichloro-2-propanol is a major by-product of the carbomethoxylation under all reaction conditions.

In view of these observations, the course of the carbomethoxylation of epichlorohydrin in the presence of dicobalt octacarbonyl and glycidyltrimethylammonium chloride cocatalysts may be represented[19] by the eq 1–7.



---

[10] P. B. D. De La Mare and J. G. Pritchard, *J. Chem. Soc.*, 1644 (1954).

[11] K. E. Marple, E. C. Shokal, and T. W. Evans, U. S. Patent 2,327,053 (1943).

[12] W. A. Jacobs and A. B. Scott, *J. Biol. Chem.*, **93**, 150 (1931).

[13] W. Bradley, J. Forrest, and O. Stephenson, *J. Chem. Soc.*, 1589 (1951).

[14] P. Edwards, U. S. Patent 2,537,291 (1949).

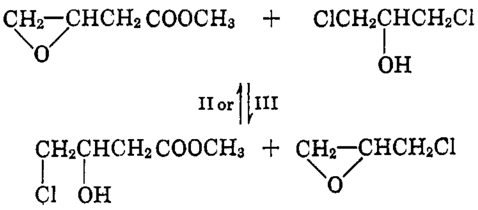
[15] W. C. J. Ross, *J. Chem. Soc.*, 2257 (1950).

[16] J. G. Pritchard and F. A. Long, *J. Am. Chem. Soc.*, **78**, 2667 (1956).

[17] R. F. Heck and P. S. Breslow, *Chem. Ind.*, 467 (1960); *J. Am. Chem. Soc.*, **83**, 4023 (1961).

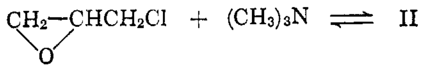
[18] Similar results have been observed in the carboxylation of cyclohexene with aqueous dicobalt octacarbonyl where the rate was found to be inversely proportional to carbon monoxide pressure above 300 atm: R. Ercoli, G. Sighorini, and E. Santambrogio, *Chim. Ind.* (Milan), **42**, 587 (1960).

[19] In view of its more reactive nature, glycidyltrimethylammonium halide is shown as being the substrate involved in step 1, although reaction could certainly proceed with epichlorohydrin, if more slowly.



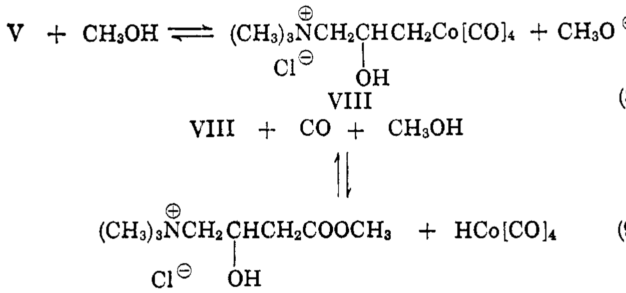
(6)

I



(7)

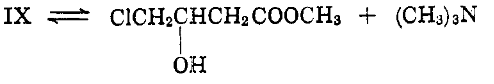
The proposed mechanism infers that methyl 3,4-epoxybutyrate (VII) is involved as an intermediate in the formation of I. To test the validity of this interpretation equimolar amounts of VII and 1,3-dichloro-2-propanol were let react[13] in methanolic solution at 75° in the presence of 1 mole % of II. The isolation of I as a reaction product from this experiment in 35% yield supports the conclusion that VII may be an intermediate in the carbomethoxylation reaction. However, since the yield of I was less than that obtained from the carbomethoxylation (50%) of epichlorohydrin, the result also suggests that I may arise from epichlorohydrin by another reaction path. An alternative mechanism for the formation of I from V appears in eq 8–11.



$$V + CH_3OH \rightleftharpoons \underset{Cl^{\ominus}}{(CH_3)_3\overset{\oplus}{N}}CH_2\underset{OH}{CH}CH_2Co[CO]_4 + CH_3O^{\ominus} \quad \text{VIII} \qquad (8)$$

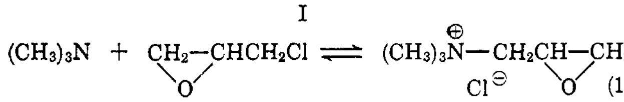
$$\text{VIII} + CO + CH_3OH \rightleftharpoons \underset{Cl^{\ominus}}{(CH_3)_3\overset{\oplus}{N}}CH_2\underset{OH}{CH}CH_2COOCH_3 + HCo[CO]_4 \qquad (9)$$

IX



$$\text{IX} \rightleftharpoons ClCH_2\underset{OH}{CH}CH_2COOCH_3 + (CH_3)_3N \qquad (10)$$

I



(11)

Both of the proposed reaction mechanisms differ in one respect from the mechanism[3] proposed to explain the carbomethoxylations of ethylene and propylene oxides. Heck[3] has suggested that it is cobalt hydrocarbonyl (X) that may be reacting with the epoxide in reactions employing cobalt octacarbonyl or cobalt salts as catalysts. It is our view, however, that the principal species involved in reaction with epichlorohydrin (or II) under the conditions described above is the cobalt tetracarbonyl anion (XI) (step 1) rather than X. The anion XI can be formed initially by the known[8] disproportionation of dicobalt octacarbonyl into cobalt(II)–cobalt tetracarbonyl and carbon monoxide that takes place in hydroxylic solvents (eq 12). Once

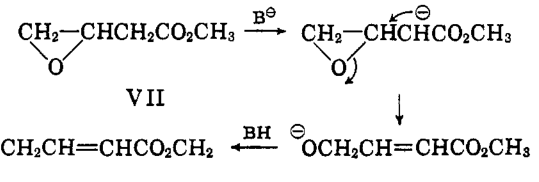
$$Co_2[CO]_8 + 6CH_3OH \rightleftharpoons Co(CH_3OH)_6^{2+}(Co[CO]_4)_2^- + 4CO \qquad (12)$$

formed, XI is regenerated by reaction of cobalt hydrocarbonyl with any base present. Part of the strong catalytic effect which II exerts may be due to the additional fact[20] that it can function as a controlled source of trimethylamine which is capable of converting X into XI. Cobalt hydrocarbonyl (X) is present, being formed by the cleavage of the acylcobalt complex with methanol in step 5. It is also probably formed initially from dicobalt octacarbonyl and methanol as has been suggested by Natta and co-workers.[21]

Our belief that reaction of cobalt hydrocarbonyl (X) with epoxide is not a principal reaction pathway in this carbonylation of epichlorohydrin is based on the following reasoning. $HCo[CO]_4$ is a poor nucleophile as it has been found by Heck[3] not to react with methyl iodide under the conditions that it reacts with epoxides. Furthermore, it has been observed[4] that the relative reactivity of propylene oxide and epichlorohydrin toward cobalt hydrocarbonyl is similar to the relative reactivity of these epoxides toward perchloric acid. Thus, cobalt hydrocarbonyl (X) appears to react not as a nucleophile, but as an acid[3,4] in its reactions with epoxides, but, if X reacts as an acid and is the principal species attacking the epoxide, then it is difficult to explain the catalytic activity of glycidyltrimethylammonium halide (greater susceptibility to nucleophilic reaction) in the carbonylation of epichlorohydrin.

To our knowledge[1] the carbomethoxylation of epichlorohydrin represents the first example of a carbonylation of an aliphatic halide with catalytic amounts of cobalt in which the halogen is retained in the product. The success of this reaction is attributed to the fact that epichlorohydrin can function as a base and trap any hydrogen chloride formed. This is evidenced by the isolation of 1,3-dichloro-2-propanol in considerable quantity. In the absence of an effective trap, large amounts of hydrogen chloride might be expected to destroy the cobalt carbonyl catalyst.[6]

Previous efforts to convert methyl 4-chloro-3-hydroxybutyrate (I) to methyl 3,4-epoxybutyrate (VII) using either mild or strong alkalies have resulted in very low yields of the desired product. Rambaud and co-workers[7] reported that VII was obtained in only 6% yield when I was treated with aqueous sodium carbonate. Our own experiments have shown that use of powdered sodium hydroxide in refluxing (42°) methylene chloride affords VII in only 15% yield at 60–65% conversion of I. The low yield is due to the tendency of VII to undergo base-catalyzed isomerization to methyl 4-hydroxycrotonate (33% yield under these conditions). This allylic alcohol can undergo further alkali-catalyzed condensation with itself or with epoxide. Culvenor and co-workers[22] have already commented on the instability to base of epoxy systems which contain a strong electrophilic group on the carbon atom attached to the ethylene oxide ring.



However, we have found that it is possible to obtain VII in 75% yield at nearly quantitative conversion of

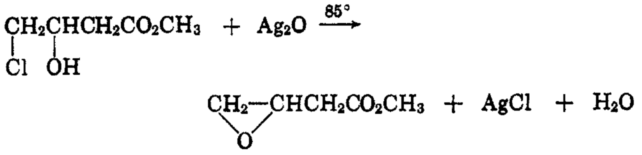
---

[20] Glycidyltrimethylammonium chloride decomposes slowly on heating to 70° with the evolution of trimethylamine.

[21] G. Natta, P. Pino, and R. Ercoli, *J. Am. Chem. Soc.*, **74**, 4496 (1952).

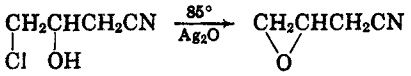
[22] C. C. J. Culvenor, W. Davies, and F. G. Haley, *J. Chem. Soc.*, 3123 (1950).

I by treatment with dry silver oxide[23] in refluxing (85°) dimethoxyethane. Silver oxide has been previously used[24] to convert chlorohydrins to epoxides but only to epoxides whose preparation can also be achieved by conventional treatment of the chlorohydrin with alkali. Thus, Hawkins[24] has reported that *trans*-4-chloro-3-tetrahydrofuranol affords 3,4-epoxytetrahydrofuran in 67% yield by treatment with either silver oxide or cuprous oxide at 150° but the epoxide is also obtained in 80% yield from the reaction[24] of the chlorohydrin with aqueous sodium hydroxide (25°).

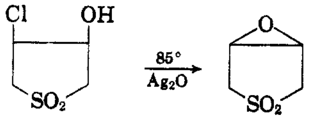


VII, 75%

The silver oxide reagent appears to offer a new way of preparing alkali-sensitive epoxides that hitherto have been either inaccessible or available in only low yield. As a notable example, the heretofore unknown[25] 3,4-epoxybutyronitrile has been obtained in 20% yield by reaction of 4-chloro-3-hydroxybutyronitrile with the reagent. All previous attempts[22,26,27] to prepare this epoxide by treatment of the chlorohydrin with either strong or mild alkali have resulted in the formation of 4-hydroxycrotononitrile (isolated here in 23% yield) or in products derived from this allylic alcohol. Similarly, *trans*-4-chloro-3-sulfolanol is converted to 3,4-epoxysulfolane in 90% yield on reaction with silver oxide at 85°. The latter epoxide has been obtained in only 44% yield from the chlorohydrin and aqueous barium carbonate.[28]



20%



90%

The mechanism of the silver oxide epoxidation has not been investigated extensively; however, certain experimental observations give some clues about the nature of the reaction. The solubility of silver oxide in dimethoxyethane is very low, so that the basicity of the solution is negligible. Rates of epoxidation appear to depend upon the efficiency of stirring of the reaction mixture. These facts indicate that reaction occurs predominately by a heterogeneous pathway. Kornblum[29] has already established that reactions involving silver (*e.g.*, silver nitrite) and alkyl halides can proceed readily on crystal surfaces. It seems possible that the epoxide arises from a transition state in which silver oxide, halogen, and hydroxyl are oriented so as to permit reaction to proceed by a "pull-push" mechanism. Silver contributes a significant pull to break the carbon-halogen bond and hydroxyl (or its anion) contributes a push as it simultaneously attacks the electron-deficient carbon partially bonded to the halogen. The hydroxy group must be in a position *trans* to the halogen for epoxide formation to occur as a *cis*-chlorohydrin, 2-chloro-1-methylcyclopentanol,[30] fails to yield any epoxide. From this reaction, 2-methylcyclopentanone, the same product as is obtained from treatment of the chlorohydrin with sodium hydroxide,[30] is isolated in 70% yield. The anion of the hydroxyl group thus appears to be implicated as a possible reacting species in the silver oxide epoxidation.

The conversion of methyl 4-chloro-3-hydroxybutyrate (I) to methyl 4-hydroxycrotonate is best carried out with sodium methoxide in methanol solution at 0°. Using this procedure, a product of 95% purity is obtained in 64% yield at 95% conversion of chlorohydrin. The purity of the alcohol may be improved to 99% by treatment of the crude product with silver oxide to remove small amounts of chlorohydrin. 2,5-Bis(carbomethoxymethyl)-1,4-dioxane[31] is obtained as a by-product in 16% yield from the reaction of I with sodium methoxide. Rambaud[7] has reported on the formation of methyl 4-hydroxycrotonate from I by treatment with aqueous sodium carbonate but did not specify the yield. In a subsequent publication[32] he described the isolation of the corresponding ethyl compound in 20% yield by similar reaction with ethyl 4-chloro-3-hydroxybutyrate.

Experimental Section

Carbomethoxylation of Epichlorohydrin.—The reactor used for all the high-pressure experiments was a Hasteloy B rocker-type autoclave having a 1600-ml capacity and equipped with automatic temperature and pressure recorder. Epichlorohydrin (92.5 g, 1 mole), dicobalt octacarbonyl (5.1 g, 0.15 mole), glycidyltrimethylammonium chloride or bromide (0.01 mole), methanol (400 ml) and *n*-hexane (100 ml) were charged to the autoclave which was sealed and flushed several times with nitrogen. Carbon monoxide was then introduced to a pressure of 6000 psi (20°) and rocking started. The gas pressure always dropped 200–300 psi at this point but the reactor was repressured to 6000 psi, heated to 70°, and maintained there for 2–3 hr.

The uptake of carbon monoxide varied from 400 to 1200 psi and was not a true indication of the yield of desired product. The reactor was cooled, carefully vented, and flushed with nitrogen. Unchanged epichlorohydrin (3–5 g), methanol, and *n*-hexane were removed by fractional distillation *in vacuo*. Analysis of the distillate for epichlorohydrin was performed by gas–liquid partition chromatography at 110° on a column packed with Carbowax on Fluoropak. Distillation of the residual liquid through a Vigreux column (kettle temperature not allowed to exceed 90° during most of distillation) afforded 99 g, bp 40–80° (3–0.3 mm), along with 6–7 g, bp 85–120° (0.3 mm), and 20 g of nonvolatile residue.

Analysis of the main fraction by gas–liquid partition chromatography at 180° on a column packed with neopentyl glycol sebacate on Chromosorb W showed the presence of I (76 g, 53% yield), 1,3-dichloro-2-propanol (14 g, 22% yield), 1-chloro-3-methoxy-2-propanol (3 g, 2% yield), and an unknown higher

---

(23) Cuprous oxide may also be used to effect conversion of I to VII at 150° in diglyme solvent but the yield is only half that obtained with silver oxide.

(24) E. G. E. Hawkins, *J. Chem. Soc.*, 248 (1959); J. Schmidlin and A. Wettstein, *Helv. Chim. Acta*, **36**, 1241 (1953).

(25) R. R. Rambaud and M. Vessiere, *Bull. Soc. Chim. France*, 1114 (1960).

(26) R. Van Dormael, *Bull. Soc. Chim. Belg.*, **52**, 100 (1943).

(27) F. Johnson, J. P. Panella, and A. A. Carlson, *J. Org. Chem.*, **27**, 2241 (1962), F. Johnson and J. P. Heeschen, *ibid.*, **29**, 3252 (1964).

(28) B. Loev, *ibid.*, **26**, 4394 (1961).

(29) N. Kornblum, R. A. Smiley, R. K. Blackwood, and D. C. Iffland, *J. Am. Chem. Soc.*, **77**, 6269 (1955).

(30) P. D. Bartlett, and R. V. White, *ibid.*, **57**, 224 (1935); **56**, 2785 (1934).

(31) R. Rambaud, S. Ducher, and R. Boudet, *Bull. Soc. Chim. France*, 1419 (1956).

(32) R. Rambaud and S. Ducher, *ibid.*, 466 (1956).

boiling constituent (4–5 g). The distillate also contained 1–2% of dicobalt octacarbonyl as was evidenced by its orange color. The distillate was stirred at 125° (50 mm) for 1 hr and then diluted with 500 ml of ether. The blue solid (0.7 g) which formed was removed by filtration and the ether was removed by evaporation. Fractional distillation of the residual liquid through a spinning band column at 10 mm of pressure afforded the following: fraction 1, 16 g, bp 66–69°; fraction 2, 3 g, bp 70–103°; and fraction 3, 69 g, bp 103–104°. Fraction 3 was analyzed as 98% I and 2% IV. The infrared spectrum and the chromatographic retention time of fraction 3 were identical with that of authentic methyl 4-chloro-3-hydroxybutyrate.[7]

Fraction 1 contained 85% 1,3-dichloro-2-propanol and 15% 1-chloro-3-methoxy-2-propanol. The chromatographic retention times of both of these compounds were the same as those of authentic samples.[10,11]

Anal. Calcd for $C_5H_9O_3Cl$: C, 39.3; H, 5.95; C, 23.3. Found (fraction 3): C, 39.6; H, 6.02; Cl, 23.5.

Carbethoxylation of Epichlorohydrin.—Epichlorohydrin (92.5 g, 1 mole), dicobalt octacarbonyl (5.1 g, 0.015 mole), glycidyltrimethylammonium bromide (2.0 g, 0.01 mole), and ethanol (500 ml) were charged to the autoclave. After flushing with nitrogen, carbon monoxide was introduced to a pressure of 6000 psi (20°), and the autoclave was maintained at 80° for 4 hr.

Unchanged epichlorohydrin (4.0 g) and ethanol were removed by fractional distillation in vacuo. Distillation of the residual liquid through a Vigreux column gave 74 g, bp 50–90° (3–0.3 mm) and 14 g of nonvolatile residue. Analysis by gas–liquid partition chromatography showed the presence of 48.5 g (30% yield) of ethyl 4-chloro-3-hydroxybutyrate, 18.0 g of 1,3-dichloro-2-propanol, and three other minor components. Fractional distillation through a spinning-band column at 5 mm of pressure afforded a central fraction, 43.5 g (bp 98–100°), of ethyl 4-chloro-3-hydroxybutyrate.

Anal. Calcd for $C_6H_{11}ClO_3$: C, 43.3; H, 6.67; Cl, 21.3. Found: C, 43.5; H, 6.80; Cl, 21.1.

Methyl 4-Chloro-3-hydroxybutyrate (I) with Sodium Hydroxide.—Powdered sodium hydroxide (7.1 g, 0.18 mole) was added in small portions over an 8-hr period to a refluxing solution of I (30.4 g, 0.2 mole) in 200 ml of methylene chloride. The water formed was removed by azeotropic distillation with the solvent. Distillation was continued for 2 hr after the addition of sodium hydroxide was complete. Solids were removed by filtration and washed with methylene chloride. After evaporation of methylene chloride, the filtrate was distilled through a Vigreux column to give 18 g, bp 50–80° (5–0.3 mm). Analysis by gas–liquid partition chromatography at 180° on a column packed with neopentyl glycol sebacate on Chromosorb W showed the presence of methyl 3,4-epoxybutyrate (2.3 g, 15% yield), methyl 4-hydroxycrotonate (5 g, 33% yield), and I (10.5 g, 63% conversion).

Methyl 3,4-Epoxybutyrate from I.—A solution of I (84 g, 0.55 mole) in 650 ml of dry dimethoxyethane was stirred under nitrogen with silver oxide (231 g, 1 mole) at 85° for 16 hr. Solids were removed by filtration and extensively washed with warm (50°) solvent. The filtrate was dried and dimethoxyethane was removed by fractional distillation under reduced pressure. Distillation of the residual liquid gave 52 g, bp 55–70° (7–3 mm) and 4.0 g of nonvolatile residue. Analysis by gas–liquid partition chromatography at 180° on a column packed with neopentyl glycol sebacate on Chromosorb W showed the presence of methyl 3,4-epoxybutyrate (46 g, 75% yield), I (3 g, 96.5% conversion), and an unknown product (3 g).

Fractional distillation through a spinning-band column affored 44 g of methyl 3,4-epoxybutyrate, bp 62–63° (10 mm) in addition to a higher boiling fraction. The purity of the epoxide was 98–99% as was indicated by oxirane oxygen content (titration with hydrogen chloride in dioxane).

Anal. Calcd for $C_5H_8O_3$: C, 51.8; H, 7.0; epoxide value, 0.86 equiv/100 g; mol wt, 116. Found: C, 51.7; H, 7.0; epoxide value, 0.84 equiv/100 g; mol wt, 116 (mass spectroscopy).

Methyl 4-Hydroxycrotonate from I.—A solution of sodium methoxide (0.56 mole) in 425 ml of methanol was added dropwise over a 3-hr period to a stirred solution of I (84 g, 0.55 mole) in 400 ml of methanol maintained at 0°. Stirring was continued at 0° for 24 hr. The mixture was neutralized with acetic acid and diluted with 3000 ml of ether. Solids were collected by filtration and washed extensively with ether. After removal of the solvent by distillation, the residual liquid was distilled through a Vigreux column to give the following: fraction 1, 46 g, bp 50–75° (5–0.5 mm); fraction 2, 1.0 g, bp 76–126° (0.5 mm); fraction 3, 10 g, bp 127–129° (0.3 mm); and 6.0 g of nonvolatile residue.

Fraction 1, analyzed by gas–liquid partition chromatography, contained 39 g (64% yield) of methyl 4-hydroxycrotonate, 4 g (95% conversion) of I, and 2 g (3.5% yield) of XI. Fraction 1 was diluted with 250 ml of dimethoxyethane and stirred under nitrogen with 100 g of silver oxide at 85° for 24 hr. After filtration and removal of solvent, fractional distillation through a spinning band column afforded 35 g of 99% pure methyl 4-hydroxycrotonate, bp 98–100° (5 mm) in addition to a lower boiling fraction.

Anal. Calcd for $C_6H_8O_3$: C, 51.8; H, 7.0; saponification value, 0.86 equiv/100 g. Found: C, 51.3; H, 6.9; saponification value, 0.87 equiv/100 g.

Fraction 3 (16% yield) which crystallized on cooling, was recrystallized from aqueous ethanol to give 2,5-bis(carbomethoxymethyl)-1,4-dioxane[31] as white plates, mp 126–128°.

Anal. Calcd for $C_{10}H_{16}O_6$: C, 51.8; H, 7.0; mol wt, 232. Found: C, 51.9; H, 7.0; mol wt, 235 (ebullioscopic).

3,4-Epoxybutyronitrile from 4-Chloro-3-hydroxybutyronitrile.—A solution of 4-chloro-3-hydroxybutyronitrile[33] (60 g, 0.5 mole) in 450 ml of dry dimethoxyethane was stirred under nitrogen with silver oxide (231 g, 1 mole) at 85° for 16 hr. Solids were removed by filtration and washed extensively with warm solvent. After drying, the dimethoxyethane was removed by fractional distillation under reduced pressure. The residual liquid was distilled to give 25 g, bp 50–100° (5–1 mm). Analysis by gas–liquid partition chromatography at 190° on a column packed with neopentyl glycol sebacate on Chromosorb W showed that the distillate contained 3,4-epoxybutyronitrile (7 g, 20% yield), 4-hydroxycrotonitrile (8 g, 23% yield), and 4-chloro-3-hydroxybutyronitrile (10 g, 84% conversion).

Fractional distillation through a spinning-band column at 5 mm of pressure afforded the following: fraction 1, 6.0 g, bp 51–53°, $n^{20}\text{D}$ 1.4262; fraction 2, 1.8 g, bp 54–117°; fraction 3, 16.5 g, bp 118–123°. Fraction 1 was 3,4-epoxybutyronitrile of about 98% purity as was indicated by the infrared spectrum ($C\equiv N$ band at 4.41) and the oxirane oxygen content (titration with hydrogen chloride in dioxane).

Anal. Calcd for C_4H_5ON: C, 57.8; H, 6.1; N, 16.9; epoxide value, 1.20 equiv/100 g; mol wt, 83. Found (fraction 1): C, 57.6; H, 6.0; N, 17.1; epoxide value, 1.18 equiv/100 g; mol wt, 83 (mass spectroscopy).

3,4-Epoxysulfolane from *trans*-4-Chloro-3-Sulfolanol.—A solution of 4-chloro-3-sulfolanol[28] (34.2 g, 0.2 mole) in 500 ml of dimethoxyethane was stirred under nitrogen with silver oxide (93 g, 0.4 mole) at 85° for 24 hr. The solids which were removed by filtration were extensively washed with hot acetone. After drying, removal of the dimethoxyethane and acetone was accomplished by distillation under reduced pressure. The crystalline residue (23.2 g, 90% yield) melted at 150–154° and had an epoxide value that was 95% of theory. Recrystallization from acetone afforded white plates, mp 157–159°, of 3,4-epoxysulfolane.[28]

Anal. Calcd for $C_4H_6SO_3$: C, 35.8; H, 4.48; epoxide value, 0.745 equiv/100 g. Found: C, 36.1; H, 4.70; epoxide value, 0.735 equiv/100 g (hydrochloric acid–magnesium chloride method).

***cis*-2-Chloro-1-methylcyclopentanol with Silver Oxide.**—A solution of 2-chloro-1-methylcyclopentanol[30] (39 g, 0.28 mole) in 350 ml of dimethoxyethane was stirred under nitrogen with silver oxide (130 g, 0.55 mole) at 85° for 18 hr. Work-up in the usual manner gave on distillation 25 g, bp 50–60° (50–30 mm), along with 3.5 g, bp 82–95° (0.3 mm). The main distillate analyzed by gas–liquid partition chromatography at 125° on a column packed with Carbowax on Fluoropak as 76% 2-methylcyclopentanone (70% yield), 20% dimethoxyethane, 1% 2-chloro-1-methylcyclopentanol, and 3% unknown compound. Fractional distillation through a spinning-band column gave 16 g of 99% pure 2-methylcyclopentanone,[30] bp 62–63° (60 mm).

Anal. Calcd for $C_6H_{10}O$: C, 73.5; H, 10.3; carbonyl value, 1.02 equiv/100 g. Found: C, 73.2; H, 10.3; carbonyl value, 0.99 equiv/100 g.

Registry No.—I, 10488-68-3; II, 3033-77-0; III, 13895-77-7; epichlorohydrin, 106-89-8; dicobalt octa-

---

(33) R. Rambaud, *Bull. Soc. Chim. France*, 138 (1936).

carbonyl, 14638-72-3; ethyl 4-chloro-3-hydroxybutyrate, 10488-69-4; methyl 3,4-epoxybutyrate, 4509-09-5; methyl 4-hydroxycrotonate, 4508-99-0; 2,5-bis(carbomethoxymethyl)-1,4-dioxane, 14310-02-2; 3,4-epoxybutyronitrile, 624-58-8; 2-methylcyclopentanone, 1120-72-5.

Acknowledgment.—The author wishes to thank Dr. R. F. Fischer for some helpful discussions.

Linear Free-Energy Relationships in Heterogeneous Catalysis. VI.[1] Catalytic Elimination Reaction of Hydrogen Chloride from Chloroethanes on Solid Acids and Bases

ISAO MOCHIDA, JUN-ICHIRO TAKE, YASUKAZU SAITO, AND YUKIO YONEDA

Department of Synthetic Chemistry, Faculty of Engineering, University of Tokyo, Bunkyo-ku, Tokyo, Japan

Received March 15, 1967

The elimination reaction of hydrogen chloride from chloroethanes on solid acids and bases was studied at 300° with the pulse technique in order to obtain the information about an acid–base nature of the various oxides. The relative reactivities of several reactants on the solid bases were different from those on solid acids. The reactivities on solid bases such as strontium oxide were found in the following order: (f) $CHCl{=}CCl_2$ from $CHCl_2CHCl_2$ > (d) $CCl_2{=}CH_2$ from $CHCl_2CH_2Cl$ > (c) $CCl_2{=}CH_2$ from CCl_3CH_3 > (e) $CHCl{=}CHCl$ from $CHCl_2CH_2Cl$ > (b) $CHCl{=}CH_2$ from CH_2ClCH_2Cl > (a) $CHCl{=}CH_2$ from $CHCl_2CH_3$, whereas they were in the order c > a > e > f > b > d on solid acids such as silica–alumina and alumina–boria. Alumina had a quite different reactivity order of c > f > a > e > b > d. The reactivity orders on strontium oxide and calcium oxide can be correlated with a reactivity index of the delocalizability, $D_r^N(H)$, and on alumina with $D_r^R(Cl) + D_r^R(H)$. The product distributions, $CH_2{=}CCl_2$, *trans*- and *cis*-$CHCl{=}CHCl$, from $CHCl_2CH_2Cl$ were 1,1 > *trans* > *cis* on solid bases, *cis* > *trans* > 1,1 on solid acids, and *cis* > 1,1 > *trans* on alumina. The selectivity variation can be understood if the reaction mechanism is a concerted E2 on the strong acids and varies gradually into a stepwise E2, where the proton-abstraction step is rate determining, as the basicity of the catalyst increases.

It is worthy of attention that the catalytic behaviors of some solid acids like silica–alumina and alumina–boria are not necessarily similar, but even contradictory, to those of alumina. The present authors found that alumina had an exceedingly high reactivity with methylene chloride to produce methyl chloride,[1] whereas it has a low catalytic activity in comparison with silica–alumina in typical solid acid-catalyzed reactions like dealkylation of alkylbenzenes.[2] This fact may indicate that surface hydroxyl groups on alumina have different chemical properties from those on silica–alumina. The surface hydroxyl protons on silica–alumina usually behave as the Brønsted acid sites and produce carbonium ions. However, the surface hydroxyl group on alumina was concluded to behave as a radical reactant for its reaction with methylene chloride.[1]

In the present work, the elimination of hydrogen chloride from chloroethanes to give chloroethylenes on various oxides was studied with the aid of the LFER (linear free-energy relationships) regarding the reactant effect;[2] the main intention is to obtain information about the differences in the catalytic properties of the oxides which may be caused by their acid–base characters.

Both the order of the reactivities in this elimination reaction among five chloroethanes and the stereoselectivity from 1,1,2-trichloroethane were also observed on solid acids and bases. They will be discussed with the aid of the reactivity indices derived from the molecular orbital theory.

Experimental Section

Reagents.—Chloroethanes used are listed in Table I. They were all of GR or EP grade (Tokyo Kasei Co.) and were not purified further, since no impurities were detected by gas chromatography.

TABLE I

REAGENTS AND THEIR REACTIONS

Reagent	Reaction	Reaction products
1,1-Dichloroethane (I)	a	$CHCl{=}CH_2$
1,2-Dichloroethane (II)	b	$CHCl{=}CH_2$
1,1,1-Trichloroethane (III)	c	$CCl_2{=}CH_2$
1,1,2-Trichloroethane (IV)	d	$CCl_2{=}CH_2$
	e	*trans*-$CHCl{=}CHCl$ and *cis*-$CHCl{=}CHCl$
1,1,2,2-Tetrachloroethane (V)	f	$CCl_2{=}CHCl$

Catalysts.—Catalysts used are listed in Table II, together with some of their properties. They were all calcined for 8 hr in the atmosphere.

Apparatus and Procedures.—The pulse technique was adopted.[2–4] The hydrogen carrier gas was purified by removing water and oxygen with a Dry Ice–ethanol trap and activated copper on kieselguhr, respectively. Tricresyl phosphate (Japan Chromato Co.) was used for the analytical column (4 m, 70°).[5] The reaction temperature was 300 ± 2°. After the catalyst was pretreated for 1 to 3 hr in the hydrogen flow at 450°, 2 μl of the reactant was injected into the gas flow at the top of the reactor through a silicone serum cap with a microsyringe. Chloroethylenes and chloroethanes, the elimination products and the reactants, respectively, were analyzed with a gas chromatograph directly connected to the reactor. The elimination reaction was nearly first order under experimental conditions for all reactants, and the conversion was verified to be a linear function of the reciprocal space velocity under low conversions; thus the slope is the apparent rate constant, k (ml/g min).[4] This unit of the rate constant is converted into the usual one, mole/min atm g of catalyst, by the multiplication of a factor, 4.16×10^{-5}. Reactivities of the catalysts decreased remarkably by each pulse; therefore, the rate constant was calculated from the conversion

---

(1) Part V: I. Mochida and Y. Yoneda, *J. Catalysis*, in press.

(2) I. Mochida and Y. Yoneda, *ibid.*, **7**, 386, 393 (1967).

(3) R. J. Kokes, H. Tobin, and P. H. Emmett, *J. Am. Chem. Soc.*, **77**, 5860 (1955).

(4) D. W. Bassett and H. W. Habgood, *J. Phys. Chem.*, **64**, 769 (1960).

(5) W. Funasaka and K. Ikegami, "Gas Chromatography," Hirokawa Shoten Co., Tokyo, 1965, p 583.