Protolytic Reactions of Orthoesters and Ketene Acetals in Ethanol. Mechanistic Implications of Isotope Exchange Studies

A. KANKAANPERÄ, M. KANTANEN, P. ALAKUIJALA and L. OINONEN

Department of Chemistry, University of Turku, SF-205 00 Turku 50, Finland

Protolytic reactions in ethanol of triethyl orthoesters and the corresponding ketene acetals were studied. Firstly, the rate of the exchange of the ethoxy group in different orthoesters was measured using carbon-14 labeling. A linear correlation was observed between the logarithms of the rate coefficients and the σ^* -values of the substituents attached to the reaction center. Secondly, the detritiation of the orthoesters labeled at the α -position of the acid component was studied in ethanol. Thirdly, the acid-catalyzed ethanolysis of ketene acetals was subjected to a kinetic study. On the basis of the kinetic results the energetics of the total reaction from orthoesters to the corresponding ketene acetals is discussed.

In a recent work¹ isotope exchange studies have been found to be an excellent method to study the energetics of the partial reactions between acetals and vinyl ethers. Thus it is reasonable to assume that this method can also be applied to the study of the protolytic reactions of structurally related compounds, the orthoesters (I) and the ketene acetals (II). Although the hydrolytic decomposition of these

compounds has been studied in detail^{2,3} no quantitative data are available on the energetics of the reaction from orthoesters to the corresponding ketene acetals, a reaction which evidently takes place since dioxo-carbenium ions are intermediates in the hydrolysis of both orthoesters and ketene acetals (eqn. 1). In aqueous solution the dioxo-carbenium ion is rapidly decomposed to a carboxylic acid ester and alcohol and thus the interconversion of an orthoester and a ketene acetal through

their common intermediate cannot be studied kinetically. In alcohol solution, however, this interconversion can be investigated by means of isotope labeling. Schroeder⁴ has previously studied in ethanol the hydrogen exchange reactions of orthoesters using NMR and mass-spectral methods. These data show qualitatively that the acid-catalyzed protolysis of an orthoester leads to a hydrogen isotope exchange in the methyl group attached directly to the carbenium ion center of the reaction. Detailed kinetic data are, however, required to get information on the energetics of the process.

The protolytic reactivity of orthoesters² and ketene acetals³ is generally quite high. Therefore, great experimental difficulties are encountered when protolytic reactions of structurally different compounds are studied in water. However, if ethanol is employed as the solvent, the measurements can be extended to temperatures markedly below 0°C and under these conditions even highly reactive compounds can be studied. In the present work the following triethyl orthoesters were subjected to a kinetic study in ethanol: the orthopro-

pionate, the orthoacetate, the orthoformate, the orthobenzoate, the monochloro-orthoacetate, and the dichloro-orthoacetate.

EXPERIMENTAL

Materials. The following orthoesters were commercial products: ethyl orthopropionate (Fluka), ethyl orthoacetate (Fluka), ethyl orthoformate (E. Merck), and ethyl orthobenzoate (Fluka).

1-Chloro-2,2-diethoxyethene was prepared by refluxing 1,1-dichloro-2,2-diethoxyethane with potassium *tert*-butoxide in *tert*-butyl alcohol.^{2c,5} The potassium chloride formed in the reaction was filtered off and the solvent and the ketene acetal were separated by distillation. B.p. 75 °C/35 Torr. NMR spectrum: δ 4.50 (1 H), 4.00 and 3.78 (4 H), and 1.30 (6 H).

1,1,1-Trichloro-2,2-diethoxyethane was prepared from trichloroacetaldehyde and ethanol using a large excess of concentrated sulfuric acid as the catalyst.^{2c,5} B.p. 153 °C/95 Torr. NMR spectrum: δ 4.60 (1 H), 3.80 (4 H) and 1.25 (6 H).

1,1-Dichloro-2,2-diethoxyethene was prepared from the corresponding acetal by refluxing with potassium *tert*-butoxide in *tert*-butyl alcohol.^{2c,5} After potassium chloride had been filtered off, the residue was fractionated. B.p. 85–90 °C/34 Torr. NMR spectrum: δ 3.90 (4 H) and 1.30 (6 H).

Carbon-14 labeling. Two alternative methods were employed in the present work. Most of the orthoesters were labeled through an acid-catalyzed transesterification (eqn. 2). In reaction (2) only the transfer of the carbon-14 labeling from the solvent to the

orthoester took place. This method was applied in the case of the orthopropionate, the orthoacetate, the orthoformate, and the orthobenzoate. About 10 vol. % of ethanol with about 20 μCi of the labeled ethanol (The Radiochemical Centre), and a small amount of *p*-toluenesulfonic acid as catalyst was added to 10 ml of the orthoester. The mixture was refluxed for about 3 h, whereupon the catalyst was neutralized with sodium ethoxide, and the product purified by distillation in vacuum. The purity of the orthoester was checked by NMR spectroscopy. The degree of the carbon-14 labeling was determined with an LKB-81000 liquid scintillation counter. The activity of the labeled orthoesters varied from 2000 to 10 000 cpm per μl .

The monochloro-orthoacetate and dichloro-orthoacetate were labeled by alcoholysing the corresponding ketene acetals in ethanol labeled

with carbon-14 (eqn. 3). In the case of the mono-

chloro derivative the reaction mixture contained 3.3 g of 1-chloro-2,2-diethoxyethene, 1.1 g of absolute ethanol and 15 μCi of carbon-14 labeled ethanol. After refluxing for 15 min the formed 1-chloro-2,2,2-triethoxyethane was purified by distillation. B.p. 85–90 °C/25 Torr. NMR spectrum: δ 3.76 (6 H), 3.46 (2 H), and 1.20 (9 H). The labeled 1,1-dichloro-2,2,2-triethoxyethane was synthesized by refluxing for 15 min a mixture of 2.9 g of 1,1-dichloro-2,2-diethoxyethene, 0.8 g of absolute ethanol, and 15 μCi of the carbon-14 labeled ethanol. A fraction at 100–105 °C/42 Torr was collected. NMR spectrum: δ 5.73 (1 H), 3.78 (6 H), and 1.23 (9 H). The labeled substrates gave from 3000 to 7000 cpm per μl .

Tritium labeling of orthoesters. Two alternative methods were also employed in the tritium labeling of the orthoesters. In the case of the orthoacetate and the orthopropionate the orthoester was sealed in an ampoule with about ten vol. per cent of absolute ethanol and a few μl of tritiated water. *p*-Toluenesulfonic acid was used as the catalyst. The ampoule was kept at 120 °C for about one day whereupon the reaction mixture was neutralized with sodium ethoxide and fractionated. The purity of the product was checked by NMR spectroscopy. In scintillation counting 1 μl of the product gave about 10⁵ cpm.

In the tritiation of monochloro-orthoacetate and dichloro-orthoacetate an alternative route (eqn. 4) was followed. A mixture of 2.5 g

of 1-chloro-2,2-diethoxyethene and 0.8 g of absolute ethanol was refluxed with tritiated water for 15 min. The product, 1-chloro-2,2,2-triethoxyethane, was purified by distillation. In the case of 1,1-dichloro-2,2,2-triethoxyethane, 2.2 g of 1,1-dichloro-2,2-diethoxyethene and 0.6 g of absolute ethanol was employed. The practical performance of the synthesis was identical with that of the monochloro derivative. The purity of the orthoester was checked by NMR spectroscopy.

Kinetic measurements. All the kinetic measurements were performed in absolute ethanol. The commercial alcohol (99.5 %) was dried by a standard method.⁶ Perchloric acid was used as catalyst in the kinetic measurements. If the amount of the added acid was rather low (lower than 10^{−3} M) the oxonium ion concentration of the solution was measured by a kinetic method using as standard reaction the acid-catalyzed exchange of the ethoxy group

of the carbon-14 labeled acetaldehyde diethyl acetal (see Ref. 7). The rate of the carbon-14 exchange of this acetal had been measured previously.¹

The isotope exchange studies were performed as follows: The acid solution (generally 60 ml) was kept in an electronically controlled Lauda thermostat to attain the desired temperature. Depending on the activity of the substrate from 0.05 to 0.5 vol. % of the orthoester was added and after vigorous shaking 5 ml samples were taken from the reaction mixture at suitable intervals. The reaction was stopped by transferring the samples into an aqueous solution (20 ml) which contained sodium hydroxide in sufficient amount to neutralize the catalyst. The progress of the reaction was followed by measuring the activity of the substrate, the orthoester, which was extracted into an organic solvent prior to the scintillation counting. In the case of the acetals¹ the best results were obtained when using a 2/1 mixture of cyclohexane and anisole, and this mixture was also employed in the case of the orthoesters. The extraction was performed immediately after the sample had been taken from the reaction mixture to prevent possible side-reactions. Sodium chloride was added to the aqueous solution to increase the efficiency of the extraction process. Under these conditions most of the orthoester could be extracted into the organic layer and the amount of the solvent, ethanol, transferred into the organic layer was found to be negligible. The amount of the orthoester extracted into the organic phase was found to be quite constant by this procedure, about 95 %. After the two phases had been separated, 5 ml samples were transferred from the organic layer into the vials of the scintillation counter. Before counting 10 ml of the scintillation liquid (4 g of diphenyloxazole and 0.1 g of *p*-bis(*o*-methylstyryl) benzene in 1 l of toluene) was added into the vials. In some cases the increase of the activity in the water solution was also followed. In these measurements permafluor II was used as the scintillation liquid. The measured activities were corrected using the external standardization method.

The alcoholysis of the ketene acetals was followed with a Unicam SP 800 spectrophotometer. In the case of 1,1-dichloro-2,2-diethoxyethene the perchloric acid solution was kept in the cell housing block of the spectrophotometer to attain the desired temperature. After 1 μ l of the ketene acetal had been added, its alcoholysis was followed by measuring the disappearance of the absorption of the carbon-carbon double bond at 245 nm. In the case of 1-chloro-2,2-diethoxyethene direct measurements in the cell could not be performed since, the measurements had to be carried out at temperatures lower than 0 °C due to the high rate of hydrolysis of this ketene acetal. Under these conditions, however, the measurements were difficult to perform since moisture from the air

would condense on the surfaces of the cells. The measurements were therefore performed in separate reaction flasks which had been kept at temperatures between -10 and -30 °C. After the perchloric acid solution (60 ml) had reached the temperature of the thermostat, 3 μ l of the ketene acetal was added. 5 ml samples were withdrawn at suitable intervals from the reaction mixture and transferred immediately into flasks which contained a sufficient amount of sodium ethoxide to neutralize the catalyst. Finally, the samples were analyzed spectrophotometrically at 213 nm.

RESULTS AND DISCUSSION

Rates of formation of dioxo-carbenium ions from orthoesters. Although the acid-catalyzed alcoholysis of orthoesters has not previously been subjected to kinetic studies, it can be concluded on the basis of the kinetic results for the related reaction, the hydrolysis of orthoesters,³ that dioxo-carbenium ions are formed in the rate-determining stage of this reaction. In other words, the rate of the dioxo-carbenium ion formation is equal to that of the formation of the final product. When the transesterification of triethyl orthoesters (eqn. 5) is studied using carbon-14 labeling at the ethoxy group, the isotope effects can be assumed to be negligible.¹

The kinetic data for the acid-catalyzed transesterification (carbon-14 exchange) of different orthoesters are collected in Table 1. Depending on the reaction rate temperatures between 204 and 298 K were used in the measurements and for each compound the measurements were performed at 3 to 5 temperatures. Except in the case of the rate coefficients determined at the lowest temperatures (lower than 230 K) the standard errors of the rate coefficients are lower than two per cent. The larger standard errors of the rate coefficients measured at temperatures lower than 230 K are probably due to experimental difficulties since under these conditions the reaction does not stop immediately after the withdrawal of the sample. Although the pipette had been cooled to the temperature of the reaction mixture, the relatively large temperature

Table 1. Kinetic data for the oxonium ion-catalyzed isotope exchange of triethyl orthoesters $\text{RC}(\text{OEt})_2\text{OEt}^*$ in ethanol at different temperatures. The asterisk denotes the carbon-14 labeling. The activation parameters are calculated at 273.15 K.

R	Tem- perature K	k $\text{M}^{-1} \text{s}^{-1}$	$\Delta H^\ddagger$ kcal mol^{-1}	$\Delta S^\ddagger$ cal $\text{K}^{-1}\text{mol}^{-1}$	$\Delta G^\ddagger$ kcal mol^{-1}	k_{273} $\text{M}^{-1} \text{s}^{-1}$
CH_3CH_2	212.6	7.21 ± 0.18				
	223.7	36.8 ± 1.6				
	223.7	36.8 ± 1.5	12.3 ± 0.3	4.2 ± 1.2	11.17 ± 0.06	6580 ± 680
	253.7	1038 ± 20				
CH_3	204.6	5.27 ± 0.19				
	212.6	19.6 ± 0.5				
	223.7	87.5 ± 3.0	12.2 ± 0.3	5.5 ± 1.5	10.72 ± 0.08	14910 ± 2230
	223.7	78.1 ± 1.0				
H	232.9	245 ± 2				
	232.6	1.530 ± 0.007				
	242.0	5.00 ± 0.18				
	242.0	4.52 ± 0.10	12.8 ± 0.2	-2.3 ± 0.9	13.39 ± 0.02	110.6 ± 5.0
Phenyl	251.9	13.55 ± 0.09				
	251.9	14.21 ± 0.27				
	261.7	38.0 ± 0.2				
	253.2	0.695 ± 0.004				
ClCH_2	263.2	2.27 ± 0.02				
	273.2	7.33 ± 0.04	16.4 ± 0.5	5.6 ± 1.7	14.83 ± 0.02	7.71 ± 0.31
	283.2	24.6 ± 0.2				
	263.2	3.58 ± 0.02				
Cl_2CH	263.2	3.09 ± 0.06				
	273.2	11.96 ± 0.17	16.3 ± 0.9	6.1 ± 3.3	14.64 ± 0.03	10.97 ± 0.57
	283.2	31.7 ± 0.4				
	278.2	0.0620 ± 0.0004				
	283.2	0.1098 ± 0.0011				
	288.2	0.199 ± 0.003				
	293.2	0.302 ± 0.002	15.6 ± 0.8	-7.7 ± 2.9	17.71 ± 0.05	0.0382 ± 0.0033
	298.2	0.431 ± 0.004				

gradient would raise the temperature of the solution in the pipette before its content was added to the quenching solution.

The activation entropies for the transesterification of the studied compounds vary between +6 and -8 cal $\text{K}^{-1} \text{mol}^{-1}$. Correlation with the polar nature of the acid component of the orthoester cannot be observed. The values of this magnitude are in accordance with a mechanism in which the solvent has not taken part in the transition state of the reaction.⁸ Conclusions cannot, however, be drawn with regard to the timing of the proton transfer in the transition state of the reaction; the proton transfer process may be a pre-equilibrium or a rate-determining stage of the reaction.

In order to get an improved understanding of the structural effects in the studied exchange reaction, the rate coefficients were extrapolated

to a certain temperature. To minimize the errors caused by the extrapolation 273 K was used as a reference temperature as it lies in the middle of the temperature range in which the measurements were performed. The logarithms of the rate coefficients at 273 K were plotted against the polar constants of the substituents⁹ attached to the reaction center (Fig. 1). Except in the case of the phenyl substituted derivative there is a satisfactory linear free energy correlation (corr. coeff. 0.995): $\log k_{\text{obs}} = (-2.6 \pm 0.2)\sigma^* + (3.6 \pm 0.2)$. This dependence reveals that the structural effects are comparable with those found in the hydrolysis of structurally related acetals. The only difference is the slightly diminished influence of the structure as shown by the ρ^* -value of -2.6 ± 0.2 , which is somewhat more positive than the value of -3.8 observed for the hydrolysis of acetals.¹⁰

Fig. 1. The logarithms of the rate coefficients for the oxonium ion-catalyzed transesterification of triethyl orthoesters $\text{RC}(\text{OEt})_3$ in ethanol versus the polar constants of the substituents R. The points with filled circles were used in the linear free energy correlation.

This similarity is understandable since it is reasonable to assume that the stabilizing effect of the substituent attached to the carbenium ion center is somewhat similar in oxo-carbenium and dioxo-carbenium ions, the intermediates in the protolytic decomposition of acetals and orthoesters, respectively. In one particular case, in the hydrolysis of diethyl 2,2,2-trichloroethyl orthoesters, structural effects in the orthoester hydrolysis have been studied in detail.⁵ In this series the ρ^* -value was found to be -2.2 , which is only slightly more positive than the one observed in the present work for the alcoholysis of orthoesters.

Of the compounds studied in the present work the phenyl-substituted derivative seems to be an exception since this compound is alcoholysed markedly slower than is expected on the basis

of the linear free energy correlation (Fig. 1). A similar phenomenon has previously⁵ been observed in the hydrolysis of unsymmetrical orthoesters. The exceptional reactivity of the phenyl-substituted derivative is even more marked than shown in Fig. 1 since conjugation effects should be significant in the transition state of this reaction. The relatively low rate of this derivative is understandable if, as a result of steric effects, the conjugation in the dioxo-carbenium like transition state is lower here than in protolytic reactions of aliphatic orthoesters.

Alcoholysis of ketene acetals. Ketene acetals are generally highly reactive and in water the hydronium ion-catalyzed reactions are so fast that the progress of the hydrolysis cannot be followed by conventional methods even at low temperatures.^{2b} When the oxonium ion-catalyzed reaction is performed in ethanol, the ketene diethyl acetals derived from the orthoacetate and the orthopropionate are also too reactive for a study of the oxonium ion-catalyzed reaction. Since ketene acetals derived from the orthoformate and the orthobenzoate do not exist, only the alcoholysis of ketene acetals derived from monochloro- and dichloro-orthoacetate could be subjected to kinetic studies in ethanol. The obtained data are collected in Table 2.

The activation entropies for the alcoholysis of the studied ketene acetals are $+8$ and -15 cal $\text{K}^{-1} \text{mol}^{-1}$. Values of this magnitude are typical of reactions in which the proton transfer to the carbon atom takes place in the rate-determining stage of the reaction, as is the case in the hydrolysis of vinyl ethers¹¹ and

Table 2. Kinetic data for the oxonium ion-catalyzed alcoholysis of ketene diethyl acetals $\text{R}_1\text{R}_2\text{C}=\text{C}(\text{OEt})_2$ in ethanol. Perchloric acid was used as catalyst. The parameters of activation are given at 273.15 K.

$\text{R}_1 \text{ R}_2$	Temperature K	k $\text{M}^{-1} \text{s}^{-1}$	$\Delta H^\ddagger$ kcal mol^{-1}	$\Delta S^\ddagger$ cal $\text{K}^{-1} \text{mol}^{-1}$	$\Delta G^\ddagger$ kcal mol^{-1}	k_{273} $\text{M}^{-1} \text{s}^{-1}$
H Cl	244.2	67.5 ± 2.1	14.1 ± 0.6	8.0 ± 2.4	11.92 ± 0.06	1620 ± 170
	245.2	70.5 ± 1.4				
	253.2	208 ± 5				
	263.2	567 ± 11				
Cl Cl	280.2	0.0382 ± 0.0003	13.9 ± 0.1	-15.3 ± 0.4	18.07 ± 0.01	0.01980 ± 0.0003
	288.2	0.0805 ± 0.0009				
	298.2	0.186 ± 0.002				
	308.2	0.404 ± 0.003				

ketene acetals.² Although the activation entropy is a poor criterion of the reaction mechanism there is no reason to assume that the closely related reactions, the hydrolysis and the alcoholysis of ketene acetals, proceed through different routes.

Detritiation of orthoesters. In these experiments great difficulties were encountered. As first-order kinetics was not strictly obeyed, the kinetic data for reaction (6) are only approximate.

In preliminary experiments reaction (6) could not be observed although the substrate, triethyl orthoacetate, and the solvent, ethanol, were extracted into different phases. The main reason for the apparent lack of reaction appear to be parallel side-reactions. The fact that the solvent contains small amounts of water, although the applied ethanol was carefully dried, hydrolytic decomposition as described in eqn. 7 will occur.

If the substrate decomposes mainly through this route no changes can be observed when the activity of the water layer and the organic layer are followed, since the product of reaction (7) also remains in the organic layer as does the initial substrate. Side-reaction (7) is favored under the conditions employed as the rate of this reaction must be markedly higher than the rate of the triton abstraction from the dioxo-carbenium ion (eqn. 6). Furthermore it can be assumed that the equilibrium of reaction (7) is mainly on the side of the product even in solutions in which the amount of water is relatively low since orthoesters have been found to be excellent agents for quantitative removal of water from reaction mixtures.¹² In the present reaction water could thus be removed from the reaction mixture by using the substrate in

excess. 2–10 vol. % of the unlabeled triethyl orthoacetate was therefore added to the reaction mixture prior to the detritiation reaction. Although the detritiation reaction in this way could be followed, the accuracy of the kinetic results was rather low; the standard errors of the measured rate coefficients varied from 2 to 6 % and the variation in the parallel experiments was relatively high; for instance, at 298 K values of rate coefficients between 10^{-2} and $4 \times 10^{-2} \text{ M}^{-1} \text{ s}^{-1}$ were observed. On the basis of the transition state theory the free energy of activation can be calculated to be of the magnitude of 20 kcal mol⁻¹. For the detritiation of triethyl orthopropionate the values of $\Delta G^\ddagger$ were found to be of the same order of magnitude. The detritiation studies could not be performed on formic acid and benzoic acid derivatives due to the lack of exchangeable α -hydrogen atoms. In the case of triethyl monochloro-orthoacetate and triethyl dichloro-orthoacetate approximate values of 22 and 24 kcal mol⁻¹ were obtained for the free energy of activation, respectively.

Total reaction from orthoester to ketene acetal. The kinetic data in the present work give information on the energetics of the reaction from triethyl orthoesters to the corresponding ketene acetals (Fig. 2) if the possible isotope effects can be excluded. As discussed above in the case of carbon-14 exchange this assumption appears to be justified. In addition it can be

Fig. 2. Free energy profile for the protolytic decomposition of orthoesters to ketene acetals in ethanol. The intermediate I^+ is the dioxo-carbenium ion. Notations: (1) the transacetalization of the orthoester, (2) the detritiation of the orthoester, and (3) the alcoholysis of the ketene acetal.

concluded that in the withdrawal of hydrogen nucleus the primary tritium isotope effect cannot be significant if the uncertainty of the experimental data is taken into consideration.

For the first stage of the total reaction from orthoesters to ketene acetals, the formation of the dioxo-carbenium ion, quantitative kinetic data in ethanol are available (Table 1). It is found that the rate of this partial reaction is relatively high since the second-order rate coefficients at 273 K vary between 0.04 and $15\,000\text{ M}^{-1}\text{ s}^{-1}$.

In the second stage of the total reaction, the proton is abstracted from the methyl group attached directly to the carbenium ion center. When the approximate $\Delta G^\ddagger$ values for the detritiation of the orthoacetate and the mono-chloro-orthoacetate are compared, it is found that $\Delta(\Delta G^\ddagger)$ is of the magnitude of 2 kcal mol^{-1} , which is less than the corresponding difference between the carbon-14 exchange reactions ($\Delta(\Delta G^\ddagger) = 3.92\text{ kcal mol}^{-1}$). This observation may suggest that the chlorine substitution makes the hydrogen atoms attached to the same carbon atom more acidic and thus accelerate the following proton withdrawal although the dioxo-carbenium ion formation is retarded by the chlorine substituent. A similar effect can also be observed when the reactions of triethyl orthoacetate and triethyl dichloro-orthoacetate are compared: $\Delta(\Delta G^\ddagger) = 4\text{ kcal}$ for the detritiation is less than $\Delta(\Delta G^\ddagger) = 6.99\text{ kcal}$ observed for the carbon-14 exchange reaction. The free energy difference between the transition states of the carbon-14 exchange reaction and the detritiation reaction thus appear to decrease with the number of the electronegative substituents attached at the carbon atom adjacent to the carbenium ion. However, in spite of this tendency the energy difference between the different transition states is still about 6 kcal in the case of the dichloro derivative. It is interesting to note that for the related reactions of acetals and vinyl ethers¹ the energy levels of the different transition states are almost equal in the case of the dichloro derivative. In the total reaction from orthoesters to ketene acetals the dioxo-carbenium ion formation seems always to be a pre-equilibrium process. Although the kinetic data discussed above refer to dilute solutions in ethanol the observed energy difference can be

assumed to be of the same magnitude also in other solvent systems.

When discussing the energetics of the total reaction from orthoesters to the corresponding ketene acetals, the kinetic data for the alcoholysis of ketene acetals can also be applied since the proton abstraction from the dioxo-carbenium ion and the proton transfer to the ketene acetal are reverse reactions. For the alcoholysis of 1-chloro-2,2-diethoxyethene the free energy of activation was found to be $11.92\text{ kcal mol}^{-1}$ (Table 2). When this $\Delta G^\ddagger$ value is compared with that of the corresponding detritiation reaction, it can be concluded that the ketene acetal is on an energy level which is approximately 10 kcal higher than that of the corresponding orthoester. In the case of the dichloro derivative the free energy difference between the orthoester, and the ketene acetal is about 6 kcal . This means that in both cases equilibrium concentrations of the ketene acetals are relatively low.

On the basis of the kinetic results of the present work it can be concluded that the route from orthoesters to ketene acetals has limited practical importance and especially when taken into account the facile polymerization of ketene acetals in acid solutions. The reverse reaction, however, the alcoholysis of ketene acetals, appears to be an important synthetic route to the corresponding orthoesters in which they can be obtained in nearly quantitative yield.

Acknowledgement. Grants for support of this work from the Finnish Academy, Division of Sciences, are gratefully acknowledged.

REFERENCES

1. Kankaanperä, A., Salomaa, P., Juhala, P., Aaltonen, R. and Mattsen, M. *J. Amer. Chem. Soc.* **95** (1973) 3618.
2. a. Gold, V. and Waterman, D. *J. Chem. Soc. B* (1968) 839, 849; b. Kankaanperä, A. and Tuominen, H. *Suom. Kemistilehti B* **40** (1967) 271; c. Straub, T. S. *Ph.D. Thesis*, Illinois Institute of Technology, Chicago 1970; d. Kankaanperä, A. and Aaltonen, R. *Acta Chem. Scand.* **26** (1972) 1698.
3. a. Cordes, E. H. *Progr. Phys. Org. Chem.* **4** (1967) 1, and references therein; b. Cordes, E. H. In Patai, S., Ed., *The Chemistry of the Carboxylic Acids and Esters*, Interscience, London 1969, pp. 623–667.

4. Schroeder, L. R. *J. Chem. Soc. B* (1970) 1789.
5. Kankaanperä, A., Lahti, M. and Aaltonen, R. *Acta Chem. Scand.* 27 (1973) 1444.
6. Vogel, A. I. *Practical Organic Chemistry*, 3rd Ed., Longmans, London 1967, p. 167.
7. Kankaanperä, A., Taskinen, E. and Salomaa, P. *Acta Chem. Scand.* 21 (1967) 2487.
8. Schalegar, L. L. and Long, F. A. In Gold, V. *Advances in Physical Organic Chemistry*, Academic, London 1963, pp. 27–29.
9. Taft, Jr., R. W. *J. Amer. Chem. Soc.* 75 (1953) 4231.
10. Kreevoy, M. M. and Taft, Jr., R. W. *J. Amer. Chem. Soc.* 77 (1955) 5590.
11. a. Kresge, A. J. and Chiang, Y. *J. Chem. Soc. B* (1967) 53, 58; b. Salomaa, P., Kankaanperä, A. and Lajunen, M. *Acta Chem. Scand.* 20 (1966) 1790.
12. DeWolfe, R. H. *Carboxylic Acid Ortho Ester Derivatives*, Academic, New York 1970, p. 154.

Received March 27, 1974.