Effect of Crown Ethers on Rates and Product Distributions in the Oligomerization of Ethylene Oxide in Butanol

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Abstract: The effect of three crown ethers on the rates and product distributions in the oligomerization (1 to 5 mol adduct) of ethylene oxide in 1-butanol was investigated. These reactions were catalyzed by alkali metal hydroxides. With 18-crown-6 the sodium hydroxide catalyzed reaction is accelerated more than tenfold, and the product distribution is shifted to the lower molecular weight adducts. This is interpreted in terms of the disruptive effect of crown ether on the ion pair complexation of higher glycol ether anions with sodium ion. The 12-crown-4 ether appears to form consecutive 1:1 and 2:1 complexes with sodium ion.

Introduction

Since Pederson's first reports on their complexation chemistry,[1,2] macrocyclic polyethers have become recognized as selective complexing agents for alkali metal cations, a class of ions which has heretofore eluded such specific behavior. The parameters which, in general, optimize complexation are a good fit between cation diameter and cavity size of the polyether ring coupled with poor solvating conditions for the cation.[1-3] Generally, the complexes exhibit a 1:1 stoichiometry of macrocycle to cation, but 2:1 complexes are not uncommon and have been observed for both the solid crystalline state and in solution.[1-3] Structures determined by x-ray techniques have shown a variety of conformational preferences in the crystalline complexes. These range from complete envelopment of the cation by the polyether (K^+/30-crown-10) to a situation where the cation sits atop a crown cavity too small to accept it completely (Na^+/benzo-15-crown-5).[4] Two examples of crystalline 2:1 complexes show a sandwich arrangement[5,16] which probably holds (though not necessarily the same exact geometry) for the 2:1 structure in solution. Also, 1:2 (macrocycle to cation) complexes have been found with two cations embedded in one large ring.[13,14]

Aside from investigating the behavior of the complexes themselves (ref 1-3, 7-11, 13), there is interest in their relation to specific problems such as mechanism of ion transport and the action of certain alkali metal complexing macrocyclic antibiotics in biological systems.[15,16] Investigations in solution chemistry have been developing along the lines of use as a probe for determining reaction mechanisms involving ion pairs.[17-21] There are also significant practical aspects for application in preparative chemistry.[22-25] The work reported here arose out of our interest in the effect of cation complexation on the reactivity and product distribution in the alkali metal hydroxide-catalyzed reaction of alcohols with epoxides.

Experimental Section

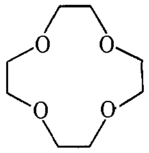
Solutions. Stock solutions for kinetic experiments were made up by dissolving the appropriate amount of reagent grade alkali metal hydroxide in 1-butanol in a volumetric flask at ambient temperature. The solution was then standardized. The kinetic solutions were made by addition of a weighed amount of cyclic ether and an aliquot of stock alkali metal hydroxide in 1-butanol to a volumetric flask and dilution to mark with 1-butanol.

Kinetic Measurements. A small 316 stainless steel pressure vessel of 13-ml volume was connected with ⅛ in. Swagelok fittings to a T-valve. To one side of the valve was connected a pressure transducer with a measuring range of 0-100 psia (Viatran Corp., Model No. PTB 210 C13). The output from the transducer (ca. 30 mV full scale) was fed to a recorder. To the other side of the T-valve was fitted a 13-gauge stainless hypodermic needle extending well down into the reactor cavity, through which reagents were introduced. A Teflon-coated magnetic stirring bar was used for agitation.

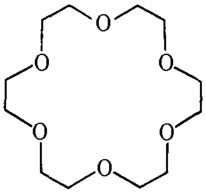
Procedures. To start a kinetic run, exactly 10 ml of alkali metal hydroxide solution in 1-butanol was introduced into the reactor, and the valve was closed. The reactor was clamped into place in a circulated oil bath held at 100.0 ± 0.2 °C. When the solution was up to temperature, exactly 1.0 ml of ethylene oxide in a pressure syringe was introduced into the stirred mixture through the dip pipe well below the liquid level. The pressure was recorded as a function of time. Infinity readings were taken at greater than 20 half-lives and were stable. Pressure data were treated by plotting log $(P_t - P_\infty)$ against time. Good straight-line plots were obtained through 3 half-lives, showing first-order kinetics.

Product Analyses. After being cooled to ambient temperature, the infinity solutions were analyzed by GLC using a 6-ft column of 5% FFAP on Chromosorb W, temperature programmed from 100 to 275 °C at 15 °C/min. Pure standards for each product were used to establish response factors for each product compound. These factors were used to convert computer printouts of area percentages into weight percentages for each product. For each run, the total of the weight response factor multiplied by area percent for all products derived from reaction with ethylene oxide was normalized to 100%. In some cases, the mixture was neutralized prior to GLC analysis by stirring with an alcohol conditioned Dowex 50 H^+ resin. No difference in product distribution was observed when this procedure was followed.

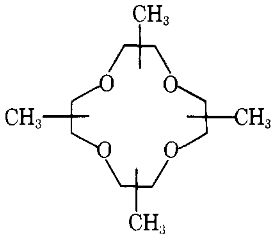
Cyclic Ethers. The macrocyclic ethers investigated in this work were produced by the boron trifluoride catalyzed oligomerization of either ethylene oxide or propylene oxide. The particular cyclic ethers used in this work were selected from their known abilities to complex with alkalic metal cations and their availabilities as the more abundant higher cyclic products from the above reaction. They are, following the nomenclature of Pederson, 12-crown-4 (ethylene oxide cyclic tetramer, I), 18-crown-6 (ethylene oxide cyclic hexamer, II), and tetramethyl-12-crown-4 (or TM-12-crown-4, the cyclic tetramer of propylene oxide, III). The latter is a complex mixture of several isomers due to the various possible head and tail combinations and the resulting complex ring stereochemistry.[26]



I



II



III

Results

Kinetics. Two sets of kinetic data were obtained. The first set describes the effect of I on the rate of reaction of ethylene

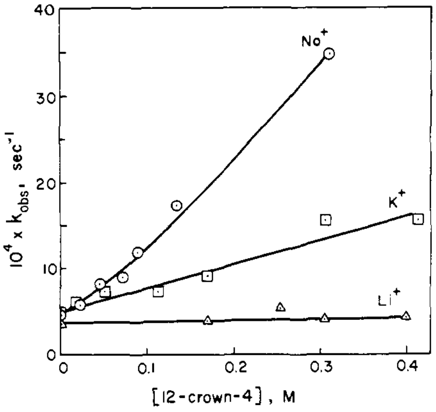


Figure 1. The effect of 12-crown-4 (I) on the rate of reaction of ethylene oxide in 1-butanol catalyzed by alkali metal hydroxide.

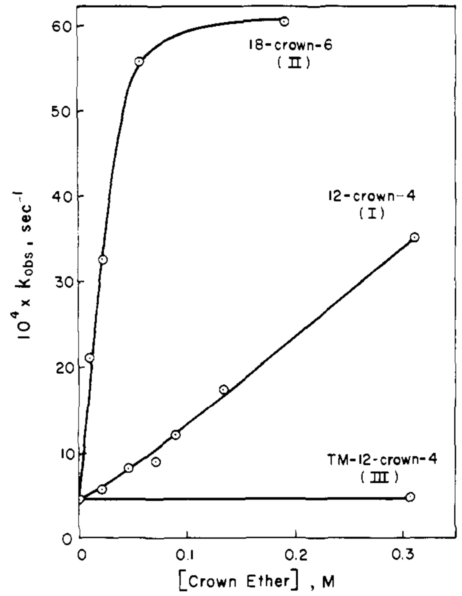


Figure 2. Effect of crown ether structure on the rate of reaction of ethylene oxide in 1-butanol catalyzed by sodium hydroxide.

oxide with 1-butanol catalyzed by lithium, sodium, or potassium hydroxides. These results are shown graphically in Figure 1 and illustrate the selectivity of I as it affects the rates with cations of different size. The other set of kinetic data explores the effects of crown ether structure on the catalytic behavior of sodium hydroxide. Figure 2 shows these results, and here again selectivity is evidenced. In all cases, the concentration of alkali metal hydroxide was 0.0156 M. The observed first-order rate constants are reported directly as such. The related second-order rate constants may be obtained by dividing by 0.0156.

Product Distributions. Under the conditions employed, the products of the base-catalyzed reaction of ethylene oxide in 1-butanol are the mono through penta addition products, i.e., $C_4H_9(OCH_2CH_2)_nOH$ where $n = 1$–5. No hexa ($n = 6$) adduct was ever detected, and no significant amounts of glycols were detected. The quantitative changes in total product distribution as a function of added cyclic polyether for sodium hydroxide with I and II are shown in Figure 3. These are the results of GLC analysis, mostly of the infinity solutions from the kinetic experiments summarized in Figure 2. These results show a clear and consistent trend toward decreasing amounts of the higher addition products as the concentrations of both I and II are increased. In the case of II, however, the maximum effect is reached at a significantly lower concentration than with I. This is in accord with the greater rate-enhancing power of the 6 oxygen crown (Figure 2). A quantitative product distribution for the run with III is not available because of the interference in the GLC elution pattern by the polyisomeric composition of III. However, a qualitatively similar change in product distribution is wrought by the addition of III as by I.

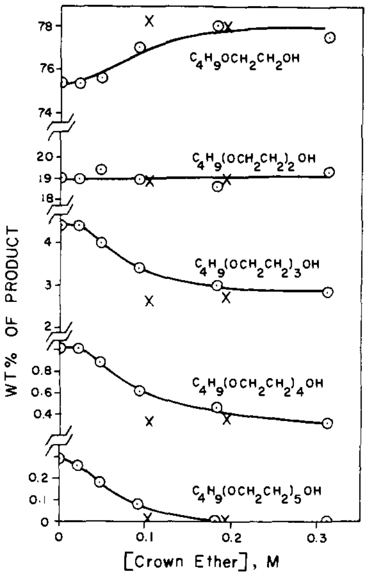


Figure 3. Product distribution from the reaction of ethylene oxide in 1-butanol as a function of crown ether concentration (NaOH catalyst): ⊙, 12-crown-4 (I): X, 18-crown-6 (II).

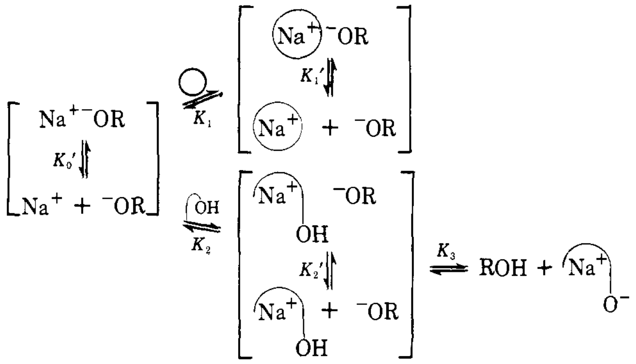
With potassium hydroxide, the product distribution in the absence of crown ether is not substantially different from that with sodium hydroxide in the absence of crown ether. At a level of 0.4 M I, the product distribution with potassium hydroxide is similar to the distribution with sodium hydroxide at about 0.1 to 0.15 M level of I. Thus the changes with potassium are even more subtle than they are for sodium. This is in parallel with the fact of smaller rate enhancements of the I/KOH combination.

The results with lithium hydroxide present a different picture. Firstly, in accord with the lack of rate change, addition of I also produces *no change* in product distribution. Secondly, the product distribution with lithium and no crown ether resembles the product distribution with sodium at *high* levels of crown ether, i.e., right-hand side of Figure 3.

Discussion

The observed changes in rates and the accompanying trends in product distributions can be understood with the aid of the general Scheme I, using sodium as the metal ion.[36] In this

Scheme I



scheme, the equilibrium constant K_1 represents the complexation constant of cyclic polyether (large circle) with the alkali metal ion. The equilibrium denoted by K_2 recognizes the interaction of alkali metal ion with linear oligomeric reaction products [$\frown$OH represents $C_4H_9(OCH_2CH_2)_nOH$, $n = 1-5$]. The strength of this interaction increases as the number of oxygen atoms in the linear glycol ether increases.[27] The equilibrium designated as K_3 represents the extent to which binding to sodium ion would increase the acidity of the sodium-bound alcohol. The driving force for K_3 would be largely due to an increase in entropy upon freeing of ROH, the equilibrium K_2' lying largely toward the ion pair. The equilibrium constants K_0', K_1', and K_2' relate to the dissociation of the ion pairs indicated.

Rate Results. Most important of the factors which promote crown ether-metal ion complexation is the closeness of fit between cation diameter and crown ether hole size. Strength of solvation around the cation may be an important inhibiting factor, especially with the more strongly solvated lithium ion.[3] Based on these considerations and data already in the literature,[3] it is clear that the rate increases directly reflect the relative strengths of complexation. It is also clear that there will be extensive ion pairing under the reaction conditions employed (dielectric constant of 1-butanol = 9 at 100 °C).[28] The reaction pathway can be described adequately by reactions 1-3.

$$M^{+-}OR \overset{K_{dis}}{\rightleftharpoons} M^+ + {}^-OR \qquad (1)$$

$$^-OR + \overset{O}{\triangle} \xrightarrow[slow]{k_-} \text{products} \qquad (2)$$

$$M^{+-}OR + \overset{O}{\triangle} \xrightarrow[slow]{k_\pm} \text{products} \qquad (3)$$

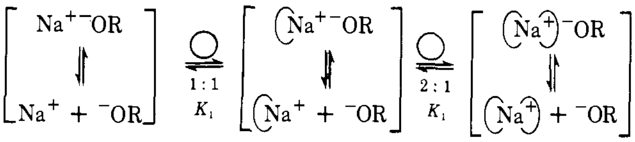
$$k_{obsd} = k_-[OR^-] + k_\pm[M^+OR^-] \qquad (4)$$

Shroder and Acree[30] have investigated the reactions of alkali metal phenoxides and ethoxides with alkyl iodides in ethanol. They show in their cases that the ratios of $k_-/k_\pm$ are in the range of 3-10. Therefore, both terms in the kinetic expression (eq 4) must be considered to contribute significantly to the overall reaction rate of sodium alkoxides with ethylene oxide. Complexation of the metal ion by crown ethers would affect rates in two ways: (i) by increasing K_{dis}, thereby increasing the proportion of free alkoxide ion and (ii) by increasing the reactivity of the ion pair in the direct reaction (eq 3).[31] Underlying these effects is the sterically enforced separation of the charge pair upon complexation. The increase thereby produced in the free energy of the ion pair with respect to the dissociated ions is thus mostly attributable to an increase in the electrostatic energy term.

It is not surprising that the rate constants found with all three alkali metal counterions are nearly the same at the origin of Figure 1 even though there is extensive ion pairing. Alcohols are apparently good "leveling" solvents for the alkali metal cations as indicated by equivalent conductance and ion-pair dissociation data.[32] In such solvents, the cations are all well solvated, and the effect of different "bare" cation size is minimized. This is supported by the work of Exner and Steiner on affects of added alcohol on conductivities and ion pairing of alkali metal alkoxides in dimethyl sulfoxide.[35]

Product Distribution Results. Figure 3 shows how the additions of the cyclic ethers I and II cause a drop-off in the amount of higher adducts formed in the sodium hydroxide catalyzed addition of ethylene oxide to 1-butanol. Recall, however, that with lithium there was no change in product distribution under identical conditions and no rate acceleration. These facts can be understood in terms of Scheme I, wherein introduction of the crown ether is seen to shift the equilibrium K_1 to the right, thereby removing sodium ion from participation in equilibria K_2 and K_3. Under normal circumstances (crown ether not present), the higher adducts tend to be favored in the presence of sodium (but not with lithium which has little tendency to complex) by the operation of K_2 which would cause a shift to the right with increasing molecular weight (greater complexing power) of the glycol ether and K_3 which would shift to the right due to the freeing of ROH, primarily an entropic driving force. This requires the reasonable assumption that K_2' is small, i.e., ion pairing extensive. Although the simple dissociation of the ion pair in the equilibrium K_2' is also formally entropically favored (not withstanding increased solvation of the separated ions which may actually negate the entropy gained upon dissociation), it is at the expense of the increased work of charge separation in the low dielectric medium, whereas in K_3 the entropy is gained without significant change in solvation or charge separation.

Comparing Figure 2 with Figure 3 shows that the profile of kinetic changes produced by introduction of I in the sodium system lags considerably behind the corresponding profile of product distribution changes with respect to the concentration of I. This interesting evidence suggests that in the 12-crown-4/sodium system there occur consecutive 1:1 and 2:1 ligand to ion coordination equilibria. To show this, Scheme I is amplified as shown in eq 5. The difference in the rate and product profiles in the 12-crown-4/I system can be rationalized quite well in terms of the amplified Scheme I with the assumption that the uncomplexed and the monocomplexed ion pairs are both contact ion pairs having equivalent electrostatic energies and therefore equivalent reactivities.[34] Thus, the operation of $K_1^{1:1}$ should not detectably affect the rate of reaction, although it will result in the complexation of sodium strongly enough to remove it from the influence of K_3 (Scheme I), thereby altering the product distribution. The rate increases then are to be associated with the occurrence of formation of the 2:1 complex which can no longer be a contact ion pair, but must be a ligand separated ion pair. The increased electrostatic separation (lower work function) results in greater reactivity and dissociation of the 2:1 ion pair. The maximum effect on product distribution will occur upon complete monocomplexation; dicomplexation should not further affect product distribution. An approximation of the equilibrium constants $K_1^{1:1}$ and $K_1^{2:1}$ (as defined in ref 3) can be made by considering the general shapes of the curves in Figures 2 and 3 to estimate the points of half-conversion. In Figure 3 the half-conversion point ($[\text{-}\frown Na^{+-}OR]/[Na^{+-}OR] \simeq 1$) occurs at $[I] \simeq 0.08$ M. From Figure 2 there is not yet a significant amount of rate acceleration at 0.08 M I, so it is reasonable to simply estimate both $K_1^{1:1}$ and $K_1^{2:1}$ on the basis that the equilibria are sufficiently separated. Using 60×10^{-4} s^{-1} as k_{max} (the experimental value for II/sodium), a value of ~4 M^{-1} for $K_1^{2:1}$ is obtained and a value of ~14 M^{-1} for $K_1^{1:1}$ is calculated. The ratio $K_1^{2:1}/K_1^{1:1}$ is 0.3, which is close to the value reported by Frensdorff[3] for the most favorable case found by him, the dibenzo-18-crown-6/cesium system ($K_1^{2:1}/K_1^{1:1} = 0.23$). In these cases as in others where 2:1 complexing has been demonstrated, the cation is too large to fit within the polyether cavity. With II, on the other hand, both the ring size factor and the stability constants indicate only 1:1 stoichiometry.



(5)

To test the reasonableness of eq 5, the values estimated for $K_1^{1:1}$, $K_1^{2:1}$, and k_{max} were used in a computer simulation of the reaction scheme. The following equations and symbols were

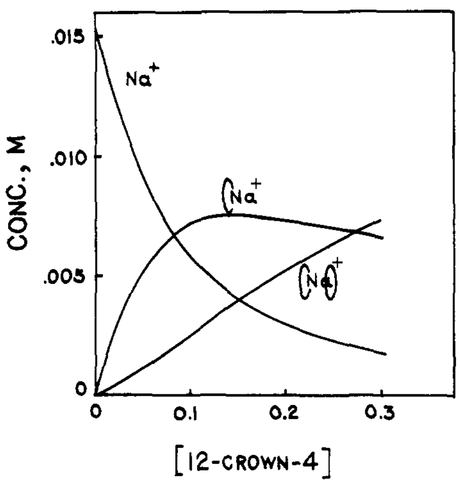


Figure 4. Theoretical curves for mono- and dicomplexes of sodium alkoxide in 1-butanol with 12-crown-4.

set up and evaluated at 12-crown-4 concentrations of 0.1, 0.2, and 0.3 M. Results for the concentration changes in A, C, and D as a function of the concentration of B are shown in Figure 4. According to the preceding analysis of the rate vs. product results, the changes in rate should be proportional to the dicomplex (D), and the changes in product distribution should be proportional to the changes in uncomplexed sodium (A). The curves in Figure 4 verify this analysis bearing in mind that the relative scale of A and D are distorted when related to the actual rate and product percentage changes with which the comparisons are made (see Figures 2 and 3).

$$\mathrm{A} + \mathrm{EO} \xrightarrow{k_0} \text{product} \qquad \mathrm{A} = \mathrm{Na}^{+-}\mathrm{OR}$$

$$\mathrm{A} + \mathrm{B} \underset{}{\overset{K_1^{1\,1}}{\rightleftarrows}} \mathrm{C} \qquad \mathrm{B} = \text{12-crown-4}$$

$$\mathrm{C} + \mathrm{EO} \xrightarrow{k_0} \text{product} \qquad \mathrm{C} = (\mathrm{Na}^+, {}^-\mathrm{OR} \qquad \mathrm{D} = (\mathrm{Na}^+), {}^-\mathrm{OR}$$

$$\mathrm{C} + \mathrm{B} \overset{K_1^{2\,1}}{\rightleftarrows} \mathrm{D} \qquad \mathrm{EO} = \text{ethylene oxide}$$

$$\mathrm{D} + \mathrm{EO} \xrightarrow{k_{\max}} \text{product}$$

$$k_0 = 4.5 \times 10^{-4}\ \mathrm{s}^{-1}$$

$$k_{\max} = 60 \times 10^{-4}\ \mathrm{s}^{-1}$$

$$K_1^{1:1} = 14\mathrm{M}^{-1}$$

$$K_1^{2:1} = 4\mathrm{M}^{-1}$$

The influence of III can be interpreted also by the amplified Scheme I. The value of $K_1{}^{1:1}$ for III must be at least sufficient to account for the effects on product distribution noted in the Results section. However, the lack of rate acceleration indicates an extremely low value for $K_1{}^{2:1}$. This undoubtedly would be due to steric interference of the methyl groups.

The question of the extent to which the rate increases are due to the affect of crown ether on ion pair dissociation or ion pair reactivity cannot be answered without independent ion pair dissociation data.

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References and Notes

(1) C. J. Pedersen, *J. Am. Chem. Soc.*, **89**, 7017 (1967).
(2) C. J. Pedersen, *J. Am. Chem. Soc.*, **92**, 386 (1970).
(3) H. K. Frensdorff, *J. Am. Chem. Soc.*, **93**, 600 (1971).
(4) M. A. Bush and M. R. Truter, *J. Chem. Soc., Chem. Commun.*, 1439 (1970).
(5) Personal communication from F. P. Boer, R. A. Newton, F. P. van Remoortere, and E. C. Steiner; x-ray data show a sandwich structure for $Na^+(12\text{-crown-}4)_2$.
(6) P. R. Mallinson and M. R. Truter, *J. Chem. Soc., Perkin Trans. 2*, 1818 (1972).
(7) N. S. Poonia, *J. Am. Chem. Soc.*, **96**, 1012 (1974).
(8) U. Takaki, T. E. Hogen Esch, and J. Smid, *J. Am. Chem. Soc.*, **93**, 6760 (1971).
(9) K. H. Wong, G. Konizer, and J. Smid, *J. Am. Chem. Soc.*, **92**, 666 (1970).
(10) K. H. Wong, M. Bourgoin, and J. Smid, *J. Chem. Soc., Chem. Commun.*, 715 (1974).
(11) T.-P. I. and E. Grumwald, *J. Am. Chem. Soc.*, **96**, 2879 (1974).
(12) J. M. Timko and D. J. Cram, *J. Am. Chem. Soc.*, **96**, 7159 (1974).
(13) N. S. Poonia and M. R. Truter, *J. Chem. Soc., Dalton Trans.*, 2062 (1973), and references therein.
(14) D. E. Fenton, M. Mercer, N. S. Poonia, and M. R. Truter, *J. Chem. Soc., Chem. Commun.*, 66 (1972).
(15) R. M. Izatt, D. P. Nelson, J. H. Rytting, B. L. Haymore, and J. J. Christensen, *J. Am. Chem. Soc.*, **93**, 1619 (1971), and references therein.
(16) *Fed. Proc., Fed. Am. Soc. Exp. Biol.*, **27**, No. 6 (Nov-Dec 1968).
(17) D. H. Hunter, W. Lee, and S. K. Sim, *J. Chem. Soc., Chem. Commun.*, 1018 (1974).
(18) R. A. Bartsch and R. H. Kayser, *J. Am. Chem. Soc.*, **96**, 4346 (1974).
(19) M. J. Maskornick, *Tetrahedron Lett.*, 1797 (1972).
(20) R. A. Moss and F. G. Pilkiewicz, *J. Am. Chem. Soc.*, **96**, 5632 (1974).
(21) E. A. Noe and M. Rabon, *J. Am. Chem. Soc.*, **96**, 6184 (1974).
(22) D. J. Sam and H. E. Simmons, *J. Am. Chem. Soc.*, **94**, 4024 (1972).
(23) D. J. Sam and H. E. Simmons, *J. Am. Chem. Soc.*, **96**, 2252 (1974).
(24) C. L. Liotta and H. P. Harris, *J. Am. Chem. Soc.*, **96**, 2250 (1974).
(25) D. Landini and F. Montanari, *J. Chem. Soc., Chem. Commun.*, 879 (1974).
(26) (a) R. J. Katnik and J. Schaefer, *J. Org. Chem.*, **33**, 384 (1968); (b) R. J. Kern, *ibid.*, **33**, 388 (1968).
(27) E. M. Arnett, H. C. Ko, and C. C. Chao, *J. Am. Chem. Soc.*, **94**, 4776 (1972).
(28) (a) S. K. Garg and C. P. Smyth, *J. Phys. Chem.*, **69**, 1294 (1965); (b) H. Fellner-Feldegg, *ibid.*, **73**, 616 (1969).
(29) The very occurrence of rate increases with cyclic ethers is in itself diagnostic of significant ion pairing in the demonstrated absence of bulk medium effects.
(30) J. H. Shroder and S. F. Acree, *J. Chem. Soc., Trans.*, **105**, 2582 (1914).
(31) The increase in ion pair reactivity (anion reacting) with increasing cation size is exemplified in N. N. Lichtin and K. N. Rao, *J. Am. Chem. Soc.*, **83**, 2417 (1961), for bromide exchange on *p*-nitrobenzyl bromide in liquid sulfur dioxide.
(32) C. A. Kraus, "The Properties of Electrically Conducting Systems", American Chemical Society Monograph Series, 1922, Chapters III and VII.
(33) T.-P. I. and E. Grunwald, *J. Am. Chem. Soc.*, **96**, 2879 (1974).
(34) The contact ion pair structure for the 1:1 complex is supported by simple inspection according to the Grunwald and I application of the Bottcher dipole treatment (ref 33). Also, molecular models indicate the sodium sits well out atop the 12-crown-4 ring in the monocomplex.
(35) J. H. Exner and E. C. Steiner, *J. Am. Chem. Soc.*, **96**, 1782 (1974).
(36) For discussions of related, interesting chelate effects in polyalkylene oxide chemistry, see (a) E. C. Steiner and R. O. Trucks, *J. Am. Chem. Soc.*, **90**, 720 (1968), and (b) C. C. Price, M. Akkapeddi, B. T. Debone, and B. C. Furie, *ibid.*, **94**, 3964 (1972).