Cyclization Kinetics of N-(β-Haloalkyl)benzenesulfonamides

WALTER J. GENSLER AND BARRY A. BROOKS

Department of Chemistry, Boston University, Boston, Massachusetts 02215

Received September 21, 1965

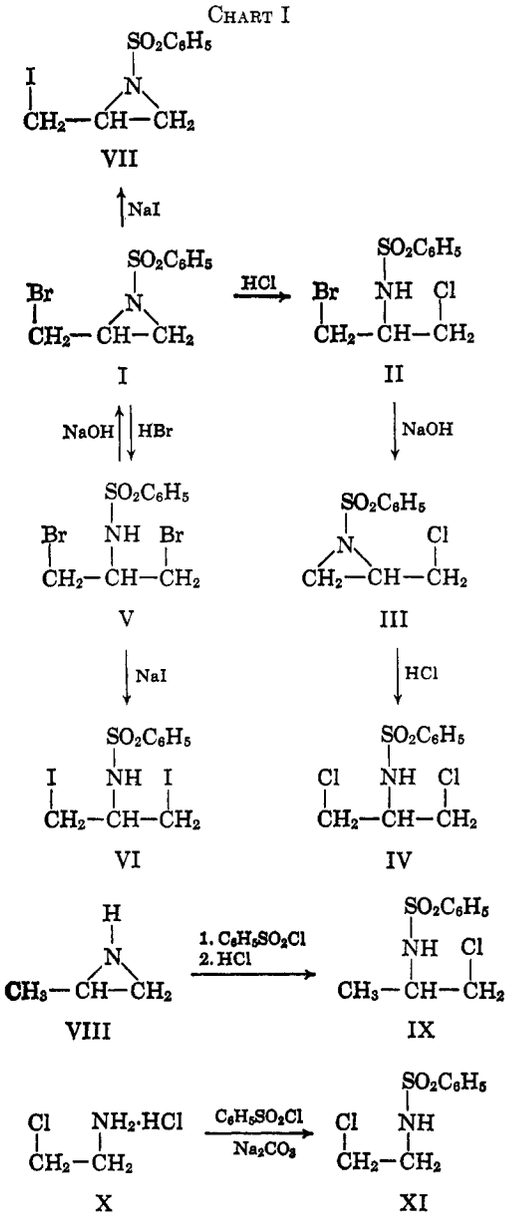
The preparation of several β-haloalkylsulfonamides is described. 1-Benzenesulfonyl-2-chloromethylethylenimine reacts with hydrochloric acid to give 1,3-dichloro-2-benzenesulfonamidopropane. Benzenesulfonylation of propylenimine, followed by hydrochloric acid cleavage of the resulting 1-benzenesulfonyl-2-methylethylenimine, produces 1-chloro-2-benzenesulfonamidopropane. Treatment of β-chloro- and of β-bromoethylamine with benzenesulfonyl chloride in carbonate solution gives the 1-halo-2-benzenesulfonamidoethane. Sodium iodide in acetone converts 1,3-dibromo-2-benzenesulfonamidopropane and 1-benzenesulfonyl-2-bromomethylethylenimine to the corresponding iodo analogs. The cyclization kinetics of the β-chloroethylsulfonamides to ethylenimines have been examined. With excess alkali present, the kinetics show first-order dependence on organic substrate and zero-order dependence on alkali. The first-order rate constants, determined in 95 wt % ethanol and at 0.04°, are as follows: for 1-chloro-2-benzenesulfonamidopropane, 3.74×10^{-4} sec^{-1}; for 1,3-dichloro-2-benzenesulfonamidopropane, 2.75×10^{-4} sec^{-1}; and for 1-chloro-2-benzenesulfonamidoethane, 2.51×10^{-5} sec^{-1}. Raising the temperature increases the rate approximately fourfold per 10° rise. The enthalpies of activation, determined in the 0–20° range, fall close to 21 kcal. The entropies of activation are small. In the cyclization of 1-chloro-2-benzenesulfonamidoethane to 1-benzenesulfonylethylenimine, changing the cation in the series Li^+, Na^+, K^+, and Cs^+ has no effect on the rate. There is also no effect when sodium perchlorate is added. However, increasing the proportion of water in the solvent increases the rate; in 47.5 wt % ethanol, for example, $k_{0.04}$ is 5.61×10^{-5} sec^{-1}. These effects are discussed in terms of a preliminary acid–base equilibrium lying essentially completely to the side of the sulfonamido anion, followed by internal nucleophilic displacement of halogen by the neighboring nitrogen.

β-Haloalkylamines can react intramolecularly to give ethylenimmonium products (eq 1, R = H or alkyl). The generally accepted mechanism has nitrogen displacing the neighboring halogen by an intramolecular SN2 process. The first-order dependence on organic substrate and zero-order dependence on alkali are in accord with this picture.[1-5] Where the nucleophilicity of the nitrogen is reduced, as in β-anilinoethyl bromide,[6] this mechanism is supplemented by another closely related one (eq 2). Here, in a preliminary equilibrium, alkali removes a proton from nitrogen and, instead of the neutral molecule, now the resulting amino anion undergoes cyclization. For compounds with nitrogen of still lower nucleophilicity, as for example in eq 2 with R = CH_3OOC,[7] the first mechanism is no longer operative, and cyclization occurs entirely according to eq 2. In the examples reported so far, the position of the equilibrium is dependent on alkali concentration. Accordingly, the experimental second-order rate constant depends on the equilibrium constant; that is, $k_{obsd} = kK_{equil}$. If the equilibrium lies far enough over to the side of the amino anion (*i.e.*, if the NH is acidic enough), the kinetics should be independent of alkali, and the process actually observed should be cleanly separated from the equilibrium phase and refer only to the anion cyclization. With this in mind, we have now prepared several β-sulfonamidoalkyl halides, notably, 1-chloro-2-benzenesulfonamidopropane (IX), 1,3-dichloro-2-benzenesulfonamidopropane (IV), and 1-chloro-2-benzenesulfonamidoethane (XI), and have studied their cyclization behavior.

Preparation of Sulfonamidoalkyl Halides (Chart I).—Warming 1-benzenesulfonyl-2-bromomethylethylenimine (I)[8] with hydrochloric acid opens the ring and forms 1-bromo-2-benzenesulfonamido-3-chloropropane (II).[9] Treatment with alkali cyclizes II to 1-benzenesulfonamido-2-chloromethylethylenimine (III), which can again react with hydrochloric acid, this time to give 1,3-dichloro-2-benzenesulfonamidopropane (IV). The 1,3-dichloro instead of the 1,2-dichloro structure was assigned to IV by analogy with the proved mode of addition of hydrogen chloride[9] and of hydrogen bromide[8] to 1-benzenesulfonyl-2-bromomethylethylenimine (I) as well as by the fact that 1,2-dichloro-3-benzenesulfonamidopropane, produced by adding chlorine to N-allylbenzenesulfonamide, is different from IV. Benzenesulfonylation of propylenimine (VIII) gave 1-benzenesulfonyl-2-methylethylenimine, which reacted with hydrochloric acid to form 1-chloro-2-benzenesulfonamidopropane (IX). The primary chloride structure was assigned by analogy with the other ring openings. 1-Chloro-2-benzenesulfonamidoethane (XI), obtained before by cleavage of 1-benzenesulfonylethylenimine with hydrogen chloride,[10] was more con-

(1) H. Freundlich and W. Neumann, *Z. Physik. Chem.*, **87**, 69 (1914).
(2) H. Freundlich and H. Kroepelin, *ibid.*, **122**, 39 (1926).
(3) H. Freundlich and G. Salomon, *ibid.*, **A166**, 161 (1933).
(4) G. Salomon, *Helv. Chim. Acta*, **16**, 1361 (1933); **17**, 851 (1934).
(5) (a) P. D. Bartlett, J. W. Davis, S. D. Ross, and C. G. Swain, *J. Am. Chem. Soc.*, **69**, 2977 (1947); (b) P. D. Bartlett, S. D. Ross, and C. G. Swain, *ibid.*, **71**, 1415 (1949); (c) A. L. Thompson, T. J. Hardwick, and C. A. Winkler, *Can. J. Res.*, **B26**, 181 (1948); N. B. Chapman and D. J. Triggle, *J. Chem. Soc.*, 1385 (1963); P. L. Lewis and Z. B. Papanastassiou, *J. Am. Chem. Soc.*, **87**, 826 (1965); (d) M. Simonetta, N. Visconti di Modrone, and G. Favini, *Gazz. Chim. Ital.*, **80**, 129 (1950) [*Chem. Abstr.*, **44**, 9222 (1950)]; (e) B. Cohen, E. R. Van Artsdalen, and J. Harris, *J. Am. Chem. Soc.*, **70**, 281 (1948).
(6) H. W. Heine and B. L. Kapur, *ibid.*, **77**, 4892 (1955).
(7) A. Hassner and C. Heathcock, *J. Org. Chem.*, **29**, 3640 (1964).
(8) W. J. Gensler, *J. Am. Chem. Soc.*, **70**, 1843 (1948).
(9) W. J. Gensler, B. A. Brooks, and W. R. Koehler, *J. Org. Chem.*, **30**, 4365 (1965).
(10) H. Bestian, *Ann.*, **566**, 210 (1950).

CHART I



veniently prepared by the action of benzenesulfonyl chloride with β-chloroethylamine hydrochloride (X) in the presence of carbonate.

Several other compounds were prepared but, because they reacted too rapidly with alkali, were not investigated kinetically. These include 1-bromo-2-benzenesulfonamidoethane from β-bromoethylamine hydrobromide and benzenesulfonyl chloride, and the iodo derivatives, 1-benzenesulfonyl-2-iodomethylethylenimine (VII) and 1,3-diiodo-2-benzenesulfonamidopropane (VI), from the bromo analogs (I and V) with sodium iodide.[11] 1-Benzenesulfonyl-2-iodomethylethylenimine (VII) was intended to serve as the precursor to 1-chloro-3-iodo- and 1-bromo-3-iodo-2-benzenesulfonamidopropane, but the preparations were not pursued when it became clear that the ring closures would be too fast.

Kinetic Results

The β-sulfonamidoalkyl halides, in the form of their anions, were cyclized in 95 wt % ethanol containing excess sodium hydroxide. The reactions were followed

(11) *Cf.* H. Finkelstein, *Ber.*, **43**, 1528 (1910).

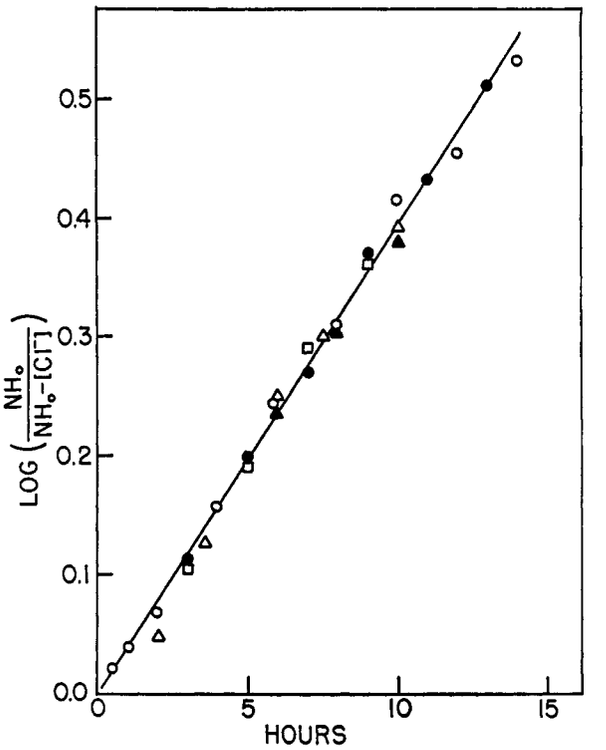


Figure 1.—First-order logarithmic plot for the cyclization of 1-chloro-2-benzenesulfonamidoethane (XI) at 0.04°. The solvent, 95 wt % ethanol, contains excess alkali. The points are taken from runs in which different initial concentrations of substrate were used: ○, 1.005×10^{-2} *M*; ●, 1.003×10^{-2} *M*; □, 0.752×10^{-2} *M*; △, 0.503×10^{-2} *M*; and ▲, 0.1005×10^{-2} *M*.

by determining the liberated halide ion. The first-order logarithmic plots were linear from 0 to 60–90% conversion, the range over which most of the runs were carried. Figure 1 shows a representative plot for 1-chloro-2-benzenesulfonamidoethane (XI), which includes experimental points from runs with different starting concentrations. The rate constants at 0.04° were found to be 3.70×10^{-4} sec^{-1} for 1-chloro-2-benzenesulfonamidopropane (IX), 2.75×10^{-4} sec^{-1} for 1,3-dichloro-2-benzenesulfonamidopropane (IV), and 2.51×10^{-5} sec^{-1} for 1-chloro-2-benzenesulfonamidoethane (XI). Reference to Figure 1 and Table I shows that the rate constants are insensitive to 10-fold variation in initial substrate concentration.

The effect of alkali was tested with 1-chloro-2-benzenesulfonamidoethane (Table II). When the initial alkali:sulfonamide concentration ratio was 1:1, first-order kinetics were not observed. However, when the ratio was 1.5:1 or greater, the process became first order and the rate constants became independent of alkali concentration. In the experiments described below, the initial alkali:substrate concentration ratios were always kept in the order of 2:1. Carbonate, a likely contaminant in the reaction mixtures, did not influence the reaction. Thus, when a mixture of 0.019 *M* alkali plus 0.001 *N* sodium carbonate was used in place of 0.02 *M* alkali, the rate constant was 2.49 instead of 2.51×10^{-5} sec^{-1}. Accordingly, no special precautions were taken to exclude carbon dioxide.

Table III shows that the identity of the alkali metal cation has no effect on the ring closure. The rate constants obtained with lithium, sodium, potassium, and

TABLE I

EFFECT OF INITIAL SUBSTRATE CONCENTRATION ON THE FIRST-ORDER RATE CONSTANTS[a]

Benzenesulfonamide	Concn × 10^2, M	Conversion,[b] %	k, sec^{-1} [c]
1-Chloro-2-benzenesulfonamidopropane (IX)	0.703	82	3.70×10^{-4}
	0.469	64	3.82×10^{-4}
	0.0703	44	3.68×10^{-4}
			Av. $3.74 (\pm 0.14) \times 10^{-4}$
1,3-Dichloro-2-benzenesulfonamidopropane (IV)	1.015	94	2.77×10^{-4}
	1.002	95	2.72×10^{-4}
	0.6681	94	2.78×10^{-4}
	0.1015	91	2.71×10^{-4}
			Av. $2.75 (\pm 0.04) \times 10^{-4}$
1-Chloro-2-benzenesulfonamidoethane (XI)	1.005	70	2.55×10^{-5}
	1.003	69	2.53×10^{-5}
	0.7519	57	2.44×10^{-5}
	0.5027	59	2.50×10^{-5}
	0.1005	59	2.48×10^{-5}
			Av. $2.51 (\pm 0.02) \times 10^{-5}$

[a] In every case, the temperature was 0.04°, the solvent was 95 wt % ethanol, and the total added alkali corresponded to a solution 2.00×10^{-2} M in sodium hydroxide. [b] The percentage of the theoretical amount of chloride released at the last kinetic point. [c] The values for the dichloro compound are the experimental values divided by 2. The quantity in parentheses is the standard deviation of the mean.

TABLE II

EFFECT OF INITIAL ALKALI CONCENTRATION ON THE CYCLIZATION OF 1-CHLORO-2-BENZENESULFONAMIDOETHANE (XI)[a]

Initial alkali concn[b] × 10^2, M	10^5 k, sec^{-1} [c]
2.00	2.55 (±0.02)
1.75	2.52 (±0.04)
1.50	2.47 (±0.03)
1.00	*d*
1.90[e]	2.49 (±0.04)

[a] These data refer to 1.005×10^{-2} M solutions of substrate in 95% ethanol at 0.04°. The runs were followed to 60% completion. [b] Total alkali (sodium hydroxide) added. [c] The quantity in parentheses is the standard deviation. [d] The run did not follow first-order kinetics. [e] In addition to the sodium hydroxide, the reaction mixture contained 0.001 N sodium carbonate.

TABLE III

EFFECT OF CATION ON THE CYCLIZATION OF 1-CHLORO-2-BENZENESULFONAMIDOETHANE (XI)[a]

Alkali	Alkali added × 10^2, M	Conversion,[b] %	10^5 k, sec^{-1} [c]
LiOH	1.85	60	2.56 (±0.03)
NaOH	2	70	2.51 (±0.02)
KOH	1.55	63	2.52 (±0.02)
CsOH	1.73	66	2.46 (±0.03)

[a] In every case, the temperature was 0.04°, the solvent was 95% ethanol, and the initial substrate concentration was 1×10^{-2} M. [b] The percentage of the theoretical amount of chloride released at the last kinetic point. [c] The quantity in parentheses is the standard deviation.

TABLE IV

EFFECT OF SODIUM PERCHLORATE ON THE CYCLIZATION OF 1-CHLORO-2-BENZENESULFONAMIDOETHANE (XI)[a]

Sodium perchlorate concn × 10^2, M	Conversion,[b] %	10^5 k, sec^{-1} [c]
0.0	*Ca.* 60	2.51 (±0.02)
3.3	63	2.45 (±0.06)
6.6	61	2.56 (±0.04)
13.3	60	2.46 (±0.02)

[a] All runs were in 95 wt % alcohol at 0.04°. The initial sulfonamide concentration was 6.68×10^{-3} M; the total added sodium hydroxide corresponded to 13.3×10^{-3} M. [b] The percentage of the theoretical amount of chloride ion released at the last kinetic point. [c] The uncertainties are standard deviations.

TABLE V

CYCLIZATION OF 1-CHLORO-2-BENZENESULFONAMIDOETHANE (XI) IN VARIOUS ETHANOL–WATER MIXTURES[a]

Wt % of ethanol	Dielectric[b] constant	Conversion,[c] %	10^5 k, sec^{-1}
95	30.4	70	2.51
85	35.2	68	3.22
75	40.7	67	4.00
65	46.7	63	4.75
47.5	58.5	83	5.61

[a] In every case, the temperature was 0.04°, the initial substrate concentration was 1×10^{-2} M, and the sodium hydroxide concentration was 2×10^{-2} M. [b] Interpolations from the values given for ethanol–water mixtures at 0° by J. Wyman, Jr., *J. Am. Chem. Soc.*, **53**, 3292 (1931). [c] The percentage of the theoretical amount of chloride released at the last kinetic point.

cesium hydroxides differ by no more than 4% and may be considered to be identical. Adding sodium perchlorate to the reaction mixture also has little effect (Table IV). However, increasing the proportion of water in the solvent increases the rate of reaction (Table V). For example, when the weight percentage of ethanol is halved, the rate constant is more than doubled.

Temperature dependence was studied in the 0.04–21.0° range (Table VI). In all cases, clean-cut first-order kinetics were observed. The rates were found to increase fourfold per 10° rise in temperature. Similar results were obtained when 1-chloro-2-benzenesulfonamidoethane (XI) was examined in 47.5 wt % instead of 95 wt % ethanol (Table VII). For each series, the Arrhenius plot gave a straight line with little scatter. Derived activation constants are collected in Table VIII.

Some preliminary work was done with the bromo and iodo compounds. The reaction of 1,3-dibromo-2-benzenesulfonamidopropane (V) with excess alkali in 95% ethanol was found to be essentially complete in 2 min at 0.04°; the rate constant was approximately 0.05 sec^{-1}. At the same temperature, the reaction of the corresponding diiodo compound VI was complete in less than 60 sec. At −11°, the dibromo compound cyclized completely within 5 min, the diiodo compound within 2. No precise rate constants were obtained.

TABLE VI

RATE CONSTANTS AT DIFFERENT TEMPERATURES[a]

Benzenesulfonamide	Temp, °C	Conversion,[b] %	k, sec^{-1} [c]
1-Chloro-2-benzenesulfonamidopropane[d] (IX)	0.04	Av. 80	$3.74 (\pm 0.14) \times 10^{-4}$
	10.30	92	$11.09 (\pm 0.27) \times 10^{-4}$
	15.10	85	$25.03 (\pm 0.46) \times 10^{-4}$
	21.0	84	$61.17 (\pm 0.39) \times 10^{-4}$
1,3-Dichloro-2-benzenesulfonamidopropane[e] (IV)	0.04	Av. 90	$2.75 (\pm 0.04) \times 10^{-4}$
	10.30	90	$10.26 (\pm 0.22) \times 10^{-4}$
	15.10	89	$23.18 (\pm 0.38) \times 10^{-4}$
	21.0	78	$43.03 (\pm 0.26) \times 10^{-4}$
1-Chloro-2-benzenesulfonamidoethane[e] (XI)	0.04	Av. 70	$2.51 (\pm 0.02) \times 10^{-5}$
	10.30	73	$10.79 (\pm 0.90) \times 10^{-5}$
	15.10	55	$22.54 (\pm 0.40) \times 10^{-5}$
	21.0	76	$40.23 (\pm 1.50) \times 10^{-5}$

[a] The 0.04° data are the average values from Table I. In all cases, the solvent was 95% ethanol, and the initial alkali concentration was 2×10^{-2} M. [b] The percentage of the theoretical amount of chloride ion released at the last kinetic point. [c] The values for the dichloro compound are the experimental values divided by 2. The quantity in parentheses is the standard deviation. [d] With the exception of the 0.04° run, the initial substrate concentration was 0.703×10^{-2} M. [e] With the exception of the 0.04° run, the initial substrate concentration was 1×10^{-2} M.

Discussion

Equation 2 is appropriate for the N-(β-chloroalkyl)-sulfonamide reactions. Thus, without alkali, these compounds are stable, but, with alkali, they cyclize smoothly to the corresponding ethylenimines. Since the amido anion (N^-) is the entity undergoing ring closure, the rate is given by eq 3. If the equilibrium

$$\frac{d[Cl^-]}{dt} = k[N^-] \quad (3)$$

reaction in eq 2 converts the sulfonamide (NH) virtually completely to its anion, the concentration of anion at any time will be given by $[N^-] = [NH]_0 - [Cl^-]$, and rate expressions 3 and 4 become equivalent. Equation 4, which predicts that the release of chloride ion accompanying cyclization should be first order in organic substrate and zero order in alkali, has been

$$\frac{d[Cl^-]}{dt} = k([NH]_0 - [Cl^-]) \quad (4)$$

found, in fact, to correspond to the experimental results.

We have carried through a more detailed analysis in order to determine whether the assumption of complete conversion to the sulfonamido anion is plausible *a priori* and to examine the significance of the alkali concentration more closely. The following relationships hold in the aqueous–alcoholic reaction mixtures.

$$NH + OH^- \rightleftharpoons N^- + HOH \quad K_1 = \frac{[N^-][HOH]}{[NH][OH^-]} \quad (5)$$

$$NH + OC_2H_5^- \rightleftharpoons N^- + HOC_2H_5 \quad K_2 = \frac{[N^-][HOC_2H_5]}{[NH][OC_2H_5^-]} \quad (6)$$

TABLE VII

RATE CONSTANTS FOR CYCLIZATION OF 1-CHLORO-2-BENZENESULFONAMIDOETHANE (XI) IN 47.5 WT % ETHANOL AT DIFFERENT TEMPERATURES[a]

Temp, °C	Conversion,[b] %	$10^5 k$, sec^{-1} [c]
0.04	83	$5.61 (\pm 0.05)$
10.30	89	$20.2 (\pm 1.2)$
15.10	73	$49.4 (\pm 1.9)$
21.0	64	$95.1 (\pm 1.7)$

[a] In all cases, the initial substrate concentration was 1×10^{-2} M and the initial alkali concentration was 2×10^{-2} M. [b] The percentage of the theoretical amount of chloride ion released at the last kinetic point. [c] The quantity in parentheses is the standard deviation.

TABLE VIII

ACTIVATION CONSTANTS[a]

Compound	E_a, kcal[b]	ΔH^*, kcal[c]	ΔS^*, eu[d]
1-Chloro-2-benzenesulfonamidopropane (IX)	21.42 ± 0.91	20.88 ± 0.91	2.37 ± 1.53
1,3-Dichloro-2-benzenesulfonamidopropane (IV)	21.65 ± 0.97	21.10 ± 0.97	0.53 ± 1.65
1-Chloro-2-benzenesulfonamidoethane (XI)	21.54 ± 1.02	21.00 ± 1.02	-2.54 ± 1.72
1-Chloro-2-benzenesulfonamidoethane (XI)	22.01 ± 1.11[e]	21.46 ± 1.11[e]	0.74 ± 1.88[e]

[a] All uncertainties are standard deviations. [b] The Arrhenius activation energy, E_a, was obtained from the plot of log k *vs.* the reciprocal of the temperature by multiplying the least-square slope by $-2.303R$. The data come from Tables VI and VII. [c] Calculated for 0.04° from $\Delta H^* = E_a - RT$. [d] Calculated for 0.04° from $e^{\Delta S^*/R} = hkNe^{\Delta H^*/RT}/RT$. [e] Refers to 47.5 wt % instead of 95 wt % ethanol–water solvent.

$[NH]_0$ = initial substrate concentration = $[NH] + [N^-] + [Cl^-]$ (7)

B = free alkali = $[OH^-] + [OC_2H_5^-]$ (8)

From eq 5 through 8, the concentration of sulfonamido anion at any time can be obtained (eq 9), so that eq 3 may now be expanded to the full rate expression 10.

$$[N^-] = \left\{ \frac{B}{\frac{[HOH]}{K_1} + \frac{[HOC_2H_5]}{K_2} + B} \right\} ([NH]_0 - [Cl^-]) \quad (9)$$

$$\frac{d[Cl^-]}{dt} = k \left\{ \frac{B}{\frac{[HOH]}{K_1} + \frac{[HOC_2H_5]}{K_2} + B} \right\} ([NH]_0 - [Cl^-]) \quad (10)$$

Note that B is not a constant, but is a function of sulfonamido and chloride ion concentrations; *i.e.*, $B = B_0 - [N^-] - [Cl^-]$. Therefore, as it stands, rate expression 10 does not predict a first-order liberation of chloride. This expression will reduce to first order,

however, if the quantity between the braces changes only slightly during the course of a run. Accordingly, the magnitude of, and the variation in, this quantity becomes important. A rough but reasonable estimate[12] shows that, with excess alkali in the reaction mixture, the braced quantity has an essentially constant value and that this value is 1. Thus, the full rate expression 10 reduces to eq 4, and the assumption of complete conversion of the sulfonamide to its anion—the basis for eq 4—is justified. Equation 10 agrees with the observation that increasing the concentration of excess alkali does not influence the kinetics; it also predicts that, when B is small enough, deviations from first-order kinetics must be expected.

The rate constants for cyclization to 1-benzenesulfonyl-2-methylethylenimine, 1-benzenesulfonyl-2-chloromethylethylenimine, and 1-benzenesulfonylethylenimine are in the ratios of 15:11:1 (Table I). Thus, the 1,2-disubstituted ethylenimines are formed at least 10 times as fast as the 1-monosubstituted ethylenimine. Enhanced rates of small-ring cyclization with increasing substitution have been noted before. For example, the above 15:1 ratio may be compared with the 21:1 ratio for cyclization of 1-chloro-2-hydroxypropane and 1-chloro-2-hydroxyethane to the corresponding ethylene oxides,[16] and with the 30:1 ratio for cyclization of 1-chloro-2-aminopropane and 1-chloro-2-aminoethane to the corresponding ethylenimines.[3] Several explanations and interpretations have been suggested for this kind of effect.[17]

The enthalpies of activation for the ring closures examined here (Table VIII) are the same within experimental error, so that the observed rate differences must be the result of entropy differences. Although the uncertainties in the ΔS^* values are relatively large, there is still a significant difference between the least favorable value (−2.54 eu) for 1-chloro-2-benzenesulfonamidoethane (XI) and the most favorable value (+2.37 eu) for 1-chloro-2-benzenesulfonamidopropane (IX) (*cf.* Table VIII). We suggest that this entropy effect arises largely as the result of a more crowded propane molecule IX and a less crowded ethane molecule XI, so that the entropy of the propane is more negative than that of the ethane. In the transition state, with the methyl group somewhat spread away from the neighboring groups, crowding is less important; as a result there is less differences in the transition-state entropies than in the ground-state entropies. Consequently, in agreement with the experimental result, ΔS^* for 1-chloro-2-benzenesulfonamidopropane (IX) is more positive than ΔS^* for 1-chloro-2-benzenesulfonamidoethane (XI).

With a dielectric constant of 30, 95 wt % ethanol is not a particularly effective ion-dissociating solvent, so that ion pairing must be considered.[18] If the free sulfonamido ion as well as its ion pair are present and both can cyclize, the experimental first-order rate constant is actually a composite quantity. Equation 11[19] relates the observed constant to the values for the

$$k_{obsd} = \alpha k_{ion} + (1 - \alpha)k_{ion\ pair} \qquad (11)$$

free ion and the ion pair as well as to the degree of dissociation (α) of the ion pair. Several lines of evidence, however, indicate that ion pairing may not be a complicating feature in our experiments. For example, since the degree of dissociation is a function of concentration, k_{obsd} would be expected to show some change with changing sodium and sulfonamido ion concentrations. The fact is that k_{obsd} was found to be independent of alkali concentration (1.3-fold variation; see Table II) as well as of sulfonamido concentration (10-fold variation; see Table I). Attempts to change α—and thereby also k_{obsd}—by adding a common ion were fruitless. Thus, mixtures made up of 6.7×10^{-3} M 1-chloro-2-benzenesulfonamidoethane (XI) and 13.3×10^{-3} M sodium hydroxide reacted at the same rate either with or without sodium perchlorate (13.3×10^{-3} M) (Table IV). Although the free ion generally reacts faster than the ion pair, considerable variation has been found,[19,20] and conceivably the two rate constants might have approximately the same value. If so, k_{obsd} of eq 11 would remain constant no matter what the degree of dissociation would be. Experiments designed to check this possibility by changing the ion pair again gave negative results. Thus, the rate constants remained the same although the cation varied through the series lithium, sodium, potassium, and cesium (Table III). All these results can be accommodated by a single assumption—namely,

(12) A minimum value for the quantity in braces may be arrived at as follows. In typical runs, 0.01 M substrate is treated with 0.02 M alkali. To arrive at the lowest value of the braced quantity, let us assign the smallest possible value for the concentration of free alkali to B, namely, 0.01. The acid dissociation constant for 1-chloro-2-benzenesulfonamidoethane (XI) may be estimated from the dissociation constant of N¹-(β-hydroxyethyl)-sulfanilamide, $K_a = 1.2 \times 10^{-11}$.[13] In other nonconjugated systems, replacing a β-hydroxyethyl with a β-chloroethyl increases acidity by at least one order of magnitude.[14] Replacing the p-amino group of the sulfanilamide with hydrogen should also work in the direction of increasing acidity. Accordingly, $K_a = 1.2 \times 10^{-10}$ may be taken as a safe estimate for XI. At 0°, the ion product for water, K_w, is 0.113×10^{-14}. With these two constants and with $[H_2O] = 55.5$, the K_1 of eq 5 comes out to be 6.6×10^5. Since ions of the same charge type occur on both sides of the equilibrium in eq 5, the equilibrium constant should be relatively insensitive to changes in solvent,[15] and, as a first approximation, the same K_1 may be used for alcohol–water solvent as for water alone. Ethoxide is a stronger base than hydroxide, so that K_2 of eq 6 must be greater than K_1. Let us take a low value and set $K_2 = K_1$. In 95 wt % ethanol, the concentrations of water and ethanol are 2.3 and 16.5 M, respectively. When these numbers are inserted into the braced expression of eq 10, a value of 0.999 is obtained as the minimum value. Increasing B can only increase this quantity, but no higher than the maximum, which is 1. Accordingly, setting the braced quantity equal to 1 is validated.

(13) P. H. Bell and R. O. Roblin, Jr., *J. Am. Chem. Soc.*, **64**, 2905 (1942). Actually, very little quantitative information on the acid dissociation of sulfonamides is available. *Cf.* C. M. Suter, "The Organic Chemistry of Sulfur," John Wiley and Sons, Inc., New York, N. Y., 1944, p. 580.

(14) *Cf.* H. C. Brown, D. H. McDaniel, and O. Hoflinger, "Determination of Organic Structures by Physical Methods," E. A. Braude and F. C. Nachod, Ed., Academic Press Inc., New York, N. Y., 1955, p. 567, as well as ref 5a and 5e.

(15) *Cf.* S. Glasstone, "An Introduction to Electrochemistry," D. Van Nostrand Co., Inc., Princeton, N. J., 1942 (ammonium ion dissociation; acetate ion solvation). Also note the dissociation behavior of methylammonium and of N,N-dimethylanilinum ions [H. C. Brown, *et al.*, ref. 14].

(16) H. Nilsson and L. Smith, *Z. Physik. Chem.*, **A166**, 136 (1933).

(17) *Cf.* A. Streitwieser, Jr., *Chem. Rev.*, **56**, 571 (1956); E. S. Gould, "Mechanism and Structure in Organic Chemistry," Holt, Rinehart and Winston, New York, N. Y., 1959, p 567. B. Capon presents a recent summary and discussion in *Quart Rev.* (London), **18**, 45 (1964).

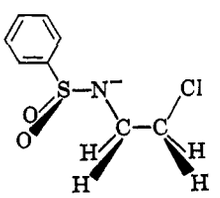
(18) *Cf.*, *inter alia*, C. W. Davies, "Ion Association," Butterworth, Inc., Washington, D. C., 1962, especially p 88; C. A. Kraus, *J. Phys. Chem.*, **60**, 129 (1956); *J. Chem. Educ.*, **35**, 324 (1958); F. Assascina, A. D'Aprano, and R. M. Fuoss, *J. Am. Chem. Soc.*, **81**, 1058 (1959); A. L. Jacobsen and J. B. Hyne, *ibid.*, **82**, 2418 (1960); I. Forsblad, *Arkiv Kemi*, **13**, 343 (1958).

(19) *Cf.* S. F. Acree, *J. Am. Chem. Soc.*, **37**, 1909 (1915).

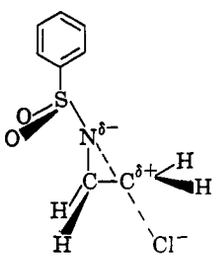
(20) See M. Bruce, M. Kahn, and J. A. Leary, *ibid.*, **87**, 2800 (1965), for pertinent references. Also compare R. C. Petersen, M. Finkelstein, and S. D. Ross, *ibid.*, **84**, 2222 (1962); J. D. Reinheimer, W. F. Kieffer, S. W. Frey, J. C. Cochran, and E. W. Barr, *ibid.*, **80**, 164 (1958); S. S. Woolf, *J. Chem. Soc.*, 1172 (1937); A. Brändström, *Arkiv Kemi*, **11**, 567 (1957); I. Forsblad, *ibid.*, **15**, 403 (1960); E. K. Marshall, Jr., and S. F. Acree, *J. Phys. Chem.*, **19**, 589 (1915); H. C. Robertson, Jr., and S. F. Acree, *J. Am. Chem. Soc.*, **37**, 1902 (1915).

that, under the conditions employed, the sulfonamido salts are largely dissociated (*i.e.*, $K_{\text{dissocn}} > 0.1$) so that only free sulfonamido ions are involved in the ring closures. We have adopted this simplifying assumption.

Increasing the proportion of water in the aqueous–alcoholic solvent monotonically increases the rate of cyclization[21] (Table V). This trend can be interpreted satisfactorily by noting that the dielectric constant goes up as the solvent becomes richer in water and by examining the effect of this increasing dielectric constant on the starting ion (*cf.* XII) and on the transitions state (*cf.* XIII).



XII



XIII

There should be little hindrance to rotation in any of the bonds of the starting material XII. Accordingly, on the average, the negative charge (already diffused to some extent over the sulfonamido oxygens) may be considered to be on the inside of a molecule that assumes many conformations, some partially enveloping the charge. In the transition state XIII, the dotted lines indicate stretched developing and breaking covalencies. A considerable fraction, possibly most, of the negative charge now resides in the leaving chloro group[22] which, being fixed on one side of the structure, cannot be shielded in any way. In other words, when the transition state develops, a large fraction of the negative charge shifts from the middle to the exposed periphery of the ion. This kind of shift is tantamount to a reduction in size and an increase in charge density of the transition state.[24] Accordingly, increasing the solvent dielectric constant will stabilize the transition state more than the starting ion and, in agreement with the data in Table V, will increase the rate.

Examining these data more closely with the help of eq 12, a relation developed for ion–molecule reactions in general,[25] lends support to this argument. In eq 12, k is the rate constant, k' is a constant, D is the

$$\ln k = \ln k' + \frac{Z^2e^2}{2DRT}\left(\frac{1}{r} - \frac{1}{r^*}\right) \qquad (12)$$

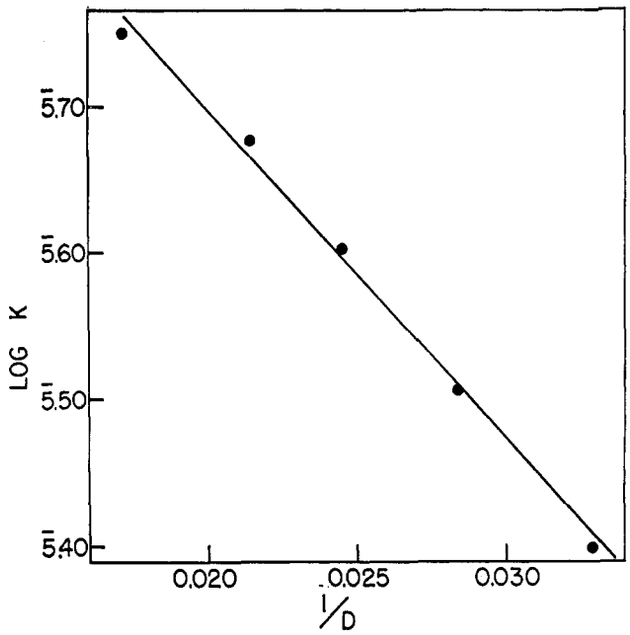


Figure 2.—Plot of logarithm of the rate constants for cyclization of 1-chloro-2-benzenesulfonamidoethane (XI) in different ethanol–water solvents *vs.* reciprocal of the dielectric constant, D (*cf.* Table V).

dielectric constant, and r and r^* are the "radii" of reactant and transition state, respectively. Equation 12 predicts that a plot of log k *vs.* $1/D$ will be a straight line with a slope given by eq 13. Actually when the experimental values given in Table V are handled in this way, a good straight line is obtained (*cf.* Figure 2). Inserting appropriate values into eq 13 establishes a numerical relation between r and r^* (eq 14). Although

$$\text{slope} = \frac{Z^2e^2}{2 \times 2.303 \times RT}\left(\frac{1}{r} - \frac{1}{r^*}\right) \qquad (13)$$

$$\left(\frac{1}{r_A} - \frac{1}{r_A{}^*}\right) = -0.17 \qquad (14)$$

for our purpose eq 14 (where r_A is the radius in angstroms) is quantitatively not significant, qualitatively, it says that the transition state for ring closure is appreciably smaller than the reactant, which conclusion is the same as that reached before.

We had hoped to break down the effect of solvent in terms of enthalpies and entropies of activation. However, the precision of the data (Table VIII) makes such attempts of questionable value, and we have not gone ahead in this direction.

All the enthalpies in Table VIII are close to 21 kcal and, accordingly, compare well with the corresponding values for bimolecular nucleophilic displacements involving an anion and a neutral molecule.[26] This value also agrees reasonably well with the activation energies for the cyclizations covered by eq 1.[1-4,5e,5d] All the entropies of activation in Table VIII fall close to zero. This was surprising since, in general, ring closures might be expected to show negative and appreciable entropies of activation. Presumably, in the transition state (*cf.* XIII), the weak carbon-to-chlorine bond and the still incomplete carbon-to-nitrogen bond allow for considerable vibrational freedom and thereby tend

(21) Specific solvation effects related to those described by J. B. Hyne [*J. Am. Chem. Soc.*, **82**, 5129 (1960)] evidently are not involved here. This may reflect the fact that the range of solvent composition in our work—*i.e.*, 0.12–0.74 mole fraction of water—avoids the extremes.

(22) Preliminary work in our laboratory by Dr. E. A. Roth has shown that the Hammett ρ constant for the cyclization of substituted benzenesulfonamido derivatives is in the order of -1. Accordingly, transfer of the negative charge in the transition state away from nitrogen (and, therefore, to chlorine) must be well advanced. In this connection, Swain and Thornton[23] have concluded that, in the transition state for the analogous cyclization of β-chloroethoxide ion to ethylene oxide, the carbon-to-chlorine bond is long and the chlorine carries most of the net negative charge.

(23) C. G. Swain and E. R. Thornton, *J. Am. Chem. Soc.*, **83**, 3890 (1961).

(24) J. E. Leffler and E. Grunwald, "Rates and Equilibria of Organic Reactions," John Wiley and Sons, Inc., New York, N. Y., 1963, p 267.

(25) A. A. Frost and R. G. Pearson, "Kinetics and Mechanism," 2nd ed, John Wiley and Sons, Inc., New York, N. Y., 1961, p 149.

(26) See p 148 of ref 25. Also, E. A. Moelwyn-Hughes, "Kinetics of Reactions in Solution," 2nd ed, Oxford University Press, London, 1947, p 71.

to compensate for the loss of rotational freedom in the substrate and the loss of translational freedom in the solvation molecules.

Experimental Section[27]

1-Chloro-2-benzenesulfonamidopropane (IX).—Benzenesulfonyl chloride (36 g, 0.20 mole) was added over a period of 2 hr to a vigorously stirred mixture of propylenimine (10 g, 0.18 mole) and aqueous 10% sodium hydroxide (200 ml) at ice-bath temperature. After the mixture was warmed on the steam bath for 15 min, it was allowed to stand overnight. The product was collected by repeated ether extraction. After washing the ether solution with dilute hydrochloric acid, it was dried with sodium sulfate and then stripped of solvent at room temperature and under reduced pressure. The residual yellow oil (21 g), when brought out of acetone, afforded crystalline 1-benzenesulfonyl-2-methylethylenimine, mp 56–61°. This material, which showed no infrared absorption peak at 3.1 μ and which was insoluble in aqueous sodium hydroxide, was used without further purification.

A stirred mixture of the ethylenimine (3.0 g, 0.015 mole) and 33 g of 37% hydrochloric acid was kept at 100° for 3.5 hr. After dilution with 75 ml of water, the cooled mixture was extracted thoroughly with ether. The ether solution was washed twice with water, dried over sodium sulfate, and concentrated at room temperature under reduced pressure. The residue was brought out of aqueous methanol to give 1.7 g of white, crystalline 1-chloro-2-benzenesulfonamidopropane (IX), mp 44–48°. (An amorphous fraction weighing 0.6 g was discarded.) Two crystallizations from the same solvent gave analytically pure material, mp 75–76.5°.

Anal. Calcd for $C_9H_{12}ClNO_2S$: C, 46.26; H, 5.29; N, 5.99. Found: C, 46.38; H, 5.47; N, 6.02.

1-Chloro-2-benzenesulfonamidoethane (XI).—Benzenesulfonyl chloride (40 ml, 0.31 mole) was added in one portion to a stirred mixture of β-chloroethylamine hydrochloride (30 g, 0.26 mole) in 80 ml of water. This was followed immediately by sodium carbonate (80 g, 0.76 mole) dissolved in 300 ml of water. After 3 hr of stirring at room temperature, the three-phase mixture was diluted with enough water to dissolve the solids and then extracted thoroughly with ether. Almost all the ether was removed from the extract, and the residue, dissolved in 100 ml of methanol, was filtered through decolorizing carbon. The product, 1-chloro-2-benzenesulfonamidoethane (XI), on crystallization from aqueous methanol, melted at 66–70° and weighed 43.5 g (77%). Two recrystallizations furnished material with a constant melting point of 69–70.5°.

Anal. Calcd for $C_8H_{10}ClNO_2S$: C, 43.73; H, 4.59; N, 6.38. Found: C, 43.75; H, 4.25; N, 6.37.

Brought out of carbon tetrachloride, the same compound XI has been reported before with mp 70°.[10]

1,3-Dichloro-2-benzenesulfonamidopropane (IV).—The hydrochloric acid ring opening of 1-benzenesulfonyl-2-bromomethylethylenimine (I) to 1-bromo-2-benzenesulfonamido-3-chloropropane (II), and the alkaline cyclization to 1-benzenesulfonyl-2-chloromethyethylenimine (III) were performed as described elsewhere.[9] A mixture of ethylenimine III (0.5 g, 0.0015 mole) and 6.5 ml of 37% hydrochloric acid was warmed on the steam bath for 3.5 hr. The reaction mixture, diluted with 15 ml of water and cooled at 0°, deposited crystals, which were collected on the funnel. A solution of the crystals in methanol, after filtration through a layer of decolorizing carbon, was diluted with water and cooled. The white, crystalline precipitate was recrystallized from aqueous methanol to give 0.5 g (86%) of 1,3-dichloro-2-benzenesulfonamidopropane (IV), mp 75.5–76.5°. Further recrystallization did not change the melting point.

Anal. Calcd for $C_9H_{11}Cl_2NO_2S$: C, 40.30; H, 4.13; Cl, 26.40; N, 5.20. Found: C, 40.24; H, 4.13; Cl, 26.38; N, 5.15.

1,2-Dichloro-3-benzenesulfonamidopropane from N-Allylbenzenesulfonamide.—An ice-cold saturated solution (25 ml) of chlorine in chloroform was added over a period of 2 hr to a vigorously stirred. ice-cold solution of N-allylbenzenesulfonamide[8] (5.0 g, 0.025 mole) in 50 ml of chloroform. All volatile material was then removed under water-aspirator pressures The oily residue was dissolved in methanol, and the solution was filtered. Three crystallizations from water–methanol furnished 4.0 g (61%) of 1,2-dichloro-3-benzenesulfonamidopropane, mp 64.5–66°.

1-Bromo-2-benzenesulfonamidoethane.—Benzenesulfonylchloride (5.0 ml, 0.039 mole) was added in one portion to a stirred mixture of β-bromoethylamine hydrobromide (6.48 g, 0.032 mole) in 20 ml of water. This was followed directly by a solution of sodium carbonate (10 g, 0.095 mole) in 40 ml of water. Thereafter, the procedure was essentially the same as that described above for the chloro analog XI. The first crystallization gave 5.0 g (65%) of white product, mp 55–60°. Two additional recrystallizations from methanol–water furnished crystalline 1-bromo-2-benzenesulfonamidoethane, mp 59.5–61°.

Anal. Calcd for $C_8H_{10}BrNO_2S$: C, 37.37; H, 3.82; N, 5.30. Found: C, 37.90; H, 3.68; N, 5.27.

1,3-Diiodo-2-benzenesulfonamidopropane (VI).[11]—A solution of 0.36 g (0.001 mole) of 1.3-dibromo-2-benzenesulfonamidopropane (V)[8] in 10 ml of acetone containing 0.30 g (0.002 mole) of sodium iodide was boiled for 1 hr. After standing overnight at room temperature, the mixture was first treated with enough water to dissolve precipitated sodium bromide and then shaken vigorously with several drops of mercury until the dark red color became light yellow. Adding more water precipitated the product, which was collected on the funnel and dissolved in methanol. Filtration removed excess mercury. The desired 1,3-diiodo-2-benzenesulfonamidopropane (VI), after crystallization from aqueous methanol, weighed 0.45 g (84%) and showed mp 85–87°. A second crystallization brought the melting point to 85.5–87°.

Anal. Calcd for $C_9H_{11}I_2NO_2S$: C, 23.96; H, 2.46; N, 3.10. Found: C, 24.01; H, 2.53; N, 2.94.

A mixture of the diodo product VI with the dibromo starting material V (mp 93–94.5°) melted at 75–86°.

1-Benzenesulfonyl-2-iodomethylethylenimine (VII).[11]—A solution of 0.57 g (0.002 mole) of 1-benzenesulfonyl-2-bromomethylethylenimine (I)[8] and 0.30 g (0.002 mole) of sodium iodide in 10 ml of acetone was treated as described directly above. The white, crystalline product, 1-benzenesulfonyl-2-iodomethylethylenimine (VII), weighed 0.55 g (85%) and melted at 66–70°. Recrystallization from methanol–water brought the melting point to 69.5–71°.

Anal. Calcd for $C_9H_{10}INO_2S$: C, 33.45; H, 3.12; N, 4.33. Found: C, 33.31; H, 3.21; N, 4.44.

The mixture melting point with the starting material I, mp 87.5–88.5°, was depressed to 55–70°.

Kinetic Procedure.—A 4-ml aliquot of a solution of 0.02 *M* sulfonamidoalkyl halide in 95 wt % ethanol was added to a 125-ml glass-stoppered erlenmeyer flask. The aliquot was cooled for 1 hr in a water–ice slurry or in the constant-temperature bath. At the same time, a 0.04 *M* solution of alkali, prepared by dissolving solid sodium hydroxide in 95 wt % ethanol, was also cooled. The reaction was started by introducing 4 ml of the alcoholic alkali and swirling the flask vigorously. After the homogeneous reaction mixtures had been allowed to remain in the bath for the desired period, the reaction was stopped by adding 4 ml of cold 0.1 *N* nitric acid in a single portion. Free halide ion was then determined by the Volhard method.

This procedure provided one kinetic point. A series of reaction flasks could be handled conveniently at one time, so that a collection of points for each run could be obtained without trouble. In all cases, the first-order plot using $\log \{[\text{substrate}]_0/([\text{substrate}]_0 - [X^-])\}$ as ordinate was a good straight line. The slope, found by a least-squares calculation, was multiplied by 2.303 and the appropriate time-unit conversion factor to get the first-order rate constant in reciprocal seconds.

Two stock solutions of each substrate were prepared by separate weighings, and the solutions were used as checks against each other.

Temperatures in the ice slurry as well as in the thermostated bath used for the higher temperatures were constant to ±0.02°.

Some preliminary tests were made with the 1,3-dihalo-2-benzenesulfonamidopropanes, IV and V. The absence of side reactions was shown by allowing the dibromide V in 0.02 *N* ethanolic alkali to stand at room temperature until cyclization was complete (about 0.5 hr.). Volhard analysis indicated a quantitative yield of bromide ion (101, 100%), while isolation of the organic product afforded 1-benzenesulfonyl-2-bromomethylethylenimine (I), mp 85–87°, in 95% yield.

(27) Microanalyses were performed by S. M. Nagy, Microchemical Laboratory, Massachusetts Institute of Technology, Cambridge, Mass. The melting points, taken in open capillaries, are uncorrected.

When 1,3-dichloro-2-benzenesulfonamidopropane (IV) was treated with alkali at 21°, determination of both chloride ion liberated *and* base consumed showed constant values of 1 equiv for each after 5–10 min of reaction. After 30 min, 1.07 equiv of chloride ion and 1.1 equiv of alkali were observed, an indication that the halide in the 1-benzenesulfonyl-2-chloromethylethylenimine cyclization product was not altogether inert to substitution or elimination. However, this process is slow relative to cyclization. Thus, at the same temperature (21°) cyclization was 78% complete in 3 min; at 15°, cyclization was 89% complete in 8 min.

The analytical procedure did not affect the 1,3-dibromo substrate V. After a mixture of the 1,3-dibromo compound, mp 93–94.5°, with aqueous-alcoholic silver bromide, silver nitrate, and nitric acid had been allowed to stand at room temperature for 0.5 hr, 95% of the starting material (mp 92–94°) could be recovered.

Under the conditions used for ring closure, the process was irreversible. Thus, solutions of 1×10^{-2} *M* 1-benzenesulfonyl-2-bromomethylethylenimine (I) and sodium bromide in 95% ethanol were allowed to stand for 30 min at 0°. Bromide ion was determined in the usual way to give the results in Table IX. The fact that 97, 100, and 99% of the added bromide remained uncombined showed that, once formed, the ring does not consume bromide ion. Whether this indicates a failure to react with bromide ion or whether it is the result of a favorable equilibrium remains to be seen.

TABLE IX

$10^2 \times$ NaBr added, *M*	$10^2 \times$ bromide found, *M*
2.45	2.38
2.14	2.13
2.02	1.99

The Structure of Couper's Compound. Chemical Studies and P^{31} Nuclear Magnetic Resonance Spectra on Couper's Compound and Related Structures[1]

A. G. PINKUS[2] AND P. G. WALDREP

Department of Chemistry, Baylor University, Waco, Texas 76703

Received July 20, 1965

Couper's compound, obtained from the reaction of salicylic acid and phosphorus pentachloride, has the phosphorodichloridate structure Ib rather than the cyclic structure Ia originally proposed by Couper. The structural evidence consists of the following: P^{31} nmr chemical shifts are in the general range found for other phenyl phosphorodichloridates; the infrared spectrum shows absorption bands in the regions expected for benzoyl chloride and phosphorodichloridates. The reaction of Couper's compound with 3 equiv of phenol forms a triphenylphosphate (VIIb) which is also produced in unambiguous fashion from the reaction of the phosphorodichloridate VIII with 2 equiv of phenol. Structure VIIb for this product is confirmed by the closeness of the P^{31} nmr shift to that of triphenylphosphate. Further chemical evidence for Couper's compound as Ib was obtained by the straightforward synthesis of Ib by the reaction of salicyloyl chloride and phosphorus oxychloride in the presence of an equivalent of pyridine. The interrelationships between Couper's compound and various related structures are clarified. The ring-opening and -closing reactions involved, as well as the formation of structure Ib, are rationalized. The infrared spectrum confirms structure XVIa for salicyl phosphate.

The compound obtained from the reaction of salicylic acid and phosphorus pentachloride[3] was designated as a cyclic structure Ia by Couper in his brilliant formulation of a structural theory of organic chemistry[4] in 1858. This structure is one of the first three[5] cyclic structures ever published; however, the correct structure has been a subject of controversy for over 100 years. Anschütz,[9] in 1885, proposed an open structure (Ib). Subsequently,[10] he also independently proposed the cyclic structure in 1887; he did not become aware[11] of Couper's neglected papers on the structural theory of organic chemistry until 1906. In his final paper[11] on the subject after a series of investigations extending over 20 years, Anschütz stated that structure Ib was probably correct, although he could not obtain conclusive evidence to support this structure. More recently, Atherton[7] considered this problem and also favored structure Ib but again furnished no conclusive evidence. In a recent paper,[8] the cyclic structure seemed the most probable on the basis of the available evidence. In the present paper, further chemical evidence and P^{31} nmr spectra of Couper's compound, *meta* and *para* analogs of structure Ib, cyclic structures related to structure Ia, and appropriate reference compounds are reported, enabling a definitive assignment of structure.

Results

P^{31} Nmr and Infrared Spectra.—The results are listed in Table I along with data on pertinent compounds for which P^{31} shifts have been published. The listing is in order of increasing magnitude of the chemical shift. The negative value of −2.3 ppm for Couper's compound (I) leaves no doubt of its identity as an *ortho*-substituted phenyl phosphorodichloridate (Ib). This value lies between the figures, −2.6 for the *meta* derivative II and −1.5 and −1.4 for phenyl phosphorodichloridate[12,13] (III) and the *para* derivative IV, respectively. Cyclic structures analogous to Ia are not possible for the *meta* and *para* derivatives. Large positive values would be expected[12] for structure Ia

(1) Based on Ph.D. Dissertation of P. G. W., Baylor University, 1965.

(2) To whom correspondence should be addressed.

(3) A. S. Couper, *Compt. Rend.*, **46**, 1157 (1858); *Ann.*, **109**, 369 (1859).

(4) A. S. Couper, *Edinburgh New Philosophical Journal*, New Series, **8**, 213 (1858); republished in Alembic Club Reprints, No. 21, "On a New Chemical Theory and Researches on Salicylic Acid," Edinburgh, 1933; *Phil. Mag.*, [4] **16**, 104 (1858).

(5) The other two are[4,6-8] cyanuric acid and 1,2-benzoylene phosphorochloridate (Xa).

(6) O. T. Benfey in "Great Chemists," E. Farber, Ed., Interscience Publishers, Inc., New York, N. Y., 1961, pp 705 ff.

(7) F. R. Atherton in "Phosphoric Esters and Related Compounds," Special Publication No. 8, The Chemical Society, London, 1957, pp 475 ff (report of a Symposium held at the Chemical Society Anniversary Meeting, Cambridge, April 9–12, 1957).

(8) A. G. Pinkus, P. G. Waldrep, and W. J. Collier, *J. Org. Chem.*, **26**, 682 (1961).

(9) R. Anschütz, *Ann.*, **228**, 308 (1885).

(10) R. Anschütz and W. O. Emery, *ibid.*, **239**, 301 (1887).

(11) R. Anschütz, *ibid.*, **346**, 286 (1906).

(12) R. A. Y. Jones and A. R. Katritzky, *Angew. Chem. Intern. Ed. Engl.*, **1**, 32 (1962).

(13) E. Schwarzmann and J. R. Van Wazer, *J. Am. Chem. Soc.*, **81**, 6366 (1959).