

of reflux to yield 11.5 g. (59%) of 4-(*p*-chlorophenyl)thiane, m.p. 70–71°, after recrystallization from ethanol.

Anal. Calcd. for C₁₁H₁₃ClS: C, 62.11; H, 6.16. Found: C, 62.10; H, 6.22.

cis-4-(*p*-Chlorophenyl)thiane 1-Oxide (VIa). Oxidation of 4-(*p*-chlorophenyl)thiane with aqueous sodium metaperiodate provided a quantitative yield of crude sulfoxides consisting of 70% *cis* and 30% *trans* sulfoxide. Recrystallization of the crude sulfoxide mixture from ethyl acetate provided pure *cis*-4-(*p*-chlorophenyl)thiane 1-oxide, m.p. 172.5–173°.

Anal. Calcd. for C₁₁H₁₃ClOS: C, 57.58; H, 5.76; S, 14.04. Found: C, 57.58; H, 5.76; S, 13.81.

Hydrolysis of IXa with dilute alkali provided in crude yield the *cis* sulfoxide VIa, identical (melting point, mixture melting point, and infrared spectrum) after a single recrystallization with that obtained above by the oxidation of the sulfide with periodate.

trans-4-(*p*-Chlorophenyl)thiane 1-Oxide (VIIIa). To 20 ml. of 0.1 *N* aqueous sodium hydroxide was added *cis*-4-(*p*-chlorophenyl)-1-ethoxythioniacyclohexane fluoroborate (VIIa) (650 mg., 1.88 mmoles). Shiny platelets began to precipitate almost immediately. The mixture was cooled in an ice bath and the precipitate was collected by suction filtration. The crude sulfoxide, m.p. 119–121°, was obtained in 93% yield. Recrystallization from ethyl acetate–hexane provided pure *trans*-4-(*p*-chlorophenyl)thiane 1-oxide, m.p. 120–120.5°.

Anal. Calcd. for C₁₁H₁₃ClOS: C, 57.76; H, 5.73. Found: C, 57.55; H, 5.76.

Material identical (melting point, mixture melting point, and infrared spectrum) with VIIIa was obtained by chromatography on neutral alumina of the residue

from evaporation of the ethyl acetate mother liquors from the recrystallization of VIa.

4-(*p*-Chlorophenyl)thiane 1,1-Dioxide. Oxidation of the sulfide Va with potassium permanganate in glacial acetic acid gave 4-(*p*-chlorophenyl)thiane 1,1-dioxide (Xa), m.p. 208–209°, $\nu_{\max}^{\text{CH}_2\text{C}=\text{O}}$ 1300, 1120 cm.⁻¹ (SO₂).

Anal. Calcd. for C₁₁H₁₃ClO₂S: C, 54.07; H, 5.35. Found: C, 53.90; H, 5.58.

The same sulfone was obtained by oxidation of VIa and VIIIa with permanganate.

Vapor Phase Analysis. Percentage compositions were ascertained by planimetric integration of curves obtained from an F and M. Model 720 chromatograph equipped with silicone gum nitrile (GE XE-60) columns. These columns were capable of excellent resolution of sulfide, sulfoxide, and sulfone. For the 4-*t*-butylthianes a 6-ft. column at 240° was employed; the same column at 175° was used for the 4-methylthianes; a 9-in. column at 225° was useful for the 4-*p*-chlorophenylthianes.

Optical Rotatory Dispersion Curves. The spectropolarimetric data were obtained on a Bendix-Ericsson instrument using freshly prepared samples in spectral grade dioxane. Ultraviolet absorption curves on the samples were obtained on a Cary Model 11 spectrophotometer; compounds I and III had λ_{\max} 256 m μ (ϵ 7300) and compounds II and IV had λ_{\max} 248 m μ (ϵ 12,500).

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The Effect of Dimethyl Sulfoxide on Neighboring Group Participation. I. Carboxyl Functions

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Solvolysis data on bromoacetic acid, 3-bromopropionic acid, and meso- and DL-dibromosuccinic acids in water and dimethyl sulfoxide (DMSO) solutions are presented. Anchimeric assistance by carboxylate is thought to become increasingly important as the solvent mixture is enriched in DMSO, although solvolysis proceeds by diverse mechanisms in water. Activation parameters change strikingly in the solvent region in which the anion becomes poorly hydrogen bonded. Solvent isotope effects show a similar change. External ion return is shown to vary considerably with solvent and the charge the substrate bears. The meso-dibromosuccinic acid yields predominately olefinic products. The reaction is not subject to common ion rate depression and the rate is not accelerated by acetate. The DL isomer yields predominately substitution products. The reaction is

subject to common ion rate depression and the rate is accelerated by acetate.

Dipolar aprotic solvents have been found to strongly accelerate the rates of many reactions involving nucleophiles or bases.¹ In general, current thinking seems to favor a mechanism in which the anion is unsolvated in dipolar aprotic media and presumably much more reactive than its highly solvated counterpart in hydroxylic solvents.²

Recently, an attempt was made to focus attention upon one particular segment of the solvation phe-

(1) A. J. Parker, *Quart. Rev.* (London), 16, 163 (1962), and references cited therein.

(2) W. Weaver and J. Hutchison, *J. Am. Chem. Soc.*, 86, 261 (1964).

Table I. Solvolysis of Bromoacetic Acid

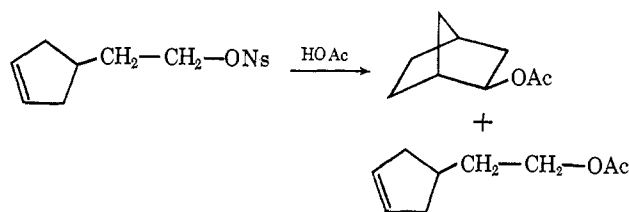
% DMSO (v./v.) in DMSO-H ₂ O	Free acid at 74.7°	Anion, $k \times 10^5$, sec. ⁻¹		ΔH^* , kcal.	ΔS^* , e.u.
		74.7°	90.2°		
0	1.15 ± 0.01	1.89 ± 0.05	10.6 ± 0.2	24.6	-9.5
20	5.81 ± 0.05	4.05 ± 0.10 ^a	18.6 ± 0.1	24.8	-8.1
40		6.31 ± 0.17	30.0 ± 1.1	24.3	-8.2
60		18.6 ± 0.8	71.0 ± 0.6	21.0	-16
80	17.6 ± 0.4	110 ± 2	393 ± 6	19.8	-16

^a At 75.4°.

nomenon, namely, hydrogen bonding.³ In mixed solvents, *i.e.*, dimethyl sulfoxide (DMSO)-alcohol systems, some evidence was presented that the nucleophile, alkoxide, was strongly hydrogen bonded up to high DMSO concentrations in which the nucleophile became insoluble. Specific involvement of a DMSO molecule in the transition state was also considered probable in certain reactions.^{1,3}

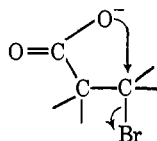
Neighboring group participation, in one sense, may be considered an intramolecular nucleophilic displacement. It seemed desirable to see if dipolar aprotic solvents would catalyze neighboring group displacements to the same extent as these solvents affect intermolecular displacements.

Some previous work on the effect of DMSO on solvolytic ring closures by Bartlett and Trahanovsky is of interest.⁴ In certain cyclopentenylethyl nosylate systems, enriching the solvent mixture in DMSO (of



DMSO-acetic acid solvent mixtures) resulted in less ring closure and more attack by solvent, even though the nucleophile was present in increasingly smaller concentrations.

The present study is concerned with neighboring group displacement by carboxylate. This group, being an anion, is probably more susceptible to DMSO catalysis than an uncharged neighboring group.^{1,3}



Neighboring group participation by carboxylate functions was one of the first and most completely studied instances of this phenomenon.⁵⁻⁸ In particular, stereochemical evidence indicated that carboxylate anions were effective internal nucleophiles yielding products of retained configuration by way of an inter-

mediate lactone. On the other hand, carboxylate esters and the undissociated acids showed little tendency towards participation.

Results and Discussion

In this study, bromoacetic acid, 3-bromopropionic acid, and *meso*- and dibromosuccinic acids were solvolyzed in DMSO-water mixtures.

Bromoacetic Acid. The kinetic data for the free acid and the anion are recorded in Table I. As the solvent mixture is enriched in DMSO it is seen that the free acid solvolyzes more rapidly by a moderate factor (*ca.* 15 going from 0 to 80% DMSO). By comparison, the carboxylate anion reaction rate is much more strongly influenced by DMSO. Going from 0 to 80% DMSO results in a rate increase of *ca.* 60 (74.70°) or *ca.* 40 (90.2°). These rate increases are rather small compared to certain SN₂ reactions in which rate enhancements as high as 10⁶ have been observed, going from protic solvents to pure DMSO.¹

At higher temperature (90.2°) the rate increase per increment DMSO was more shallow than at the lower temperature. This has the effect of giving a decreasing activation enthalpy with increasing DMSO concentration. As Table I shows, the change in activation entropy is particularly dramatic going from 40% DMSO to 60% DMSO; ΔS^* moves from -8 to -16 e.u.

These entropy effects are somewhat reminiscent of the findings of Winstein and co-workers in a study of neighboring group reactions.⁹ The direction of change, however, is opposite. These workers found that attack of substrate by a solvent molecule serving as nucleophile resulted in a high negative entropy, while neighboring group displacement resulted in a more positive entropy.

The reactions of bromoacetate ion are known to be complex.^{10,11} Bimolecular reactions involving two molecules of bromoacetate or bromoacetate ion and a molecule of product acid are important at high substrate concentrations. In this study the substrate concentration was quite low (0.02 *M*), decreasing the probability of bimolecular reaction. Moreover, linear first-order plots were obtained up to as much as 80% reaction. The bimolecular reactions, if indeed important, can account for no more than a small part of the reaction.

Very likely several competing processes exist in the solvolysis of these compounds. One process is nucleo-

(9) S. Winstein, C. Lindgren, H. Marshall, and L. L. Ingraham, *J. Am. Chem. Soc.*, **75**, 147 (1953).

(10) (a) G. Senter, *Proc. Chem. Soc.*, 24, 89 (1908); (b) H. Brook and M. Dawson, *J. Chem. Soc.*, 497 (1936).

(11) H. Robinson and D. Lewis, *ibid.*, 1260 (1933); J. Lane and H. Heine, *J. Am. Chem. Soc.*, **73**, 1348 (1951).

(3) C. A. Kingsbury, *J. Org. Chem.*, **29**, 3262 (1964).
 (4) P. D. Bartlett and W. S. Trahanovsky (private communication by Dr. Trahanovsky).
 (5) (a) S. Winstein, *J. Am. Chem. Soc.*, **61**, 1635 (1939); (b) E. Grunwald and S. Winstein, *ibid.*, **70**, 841 (1948).
 (6) C. Bean, J. Kenyon, and H. Phillips, *J. Chem. Soc.*, 303 (1936).
 (7) W. Cowdrey, E. D. Hughes, and C. K. Ingold, *ibid.*, 1028 (1937).
 (8) C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953, p. 386.

the hydrogen bonding tendencies of various ions.^{14,15,19} It is realized that hydrogen bonding is a part of the all inclusive term, solvation, and also it is realized that semantic difficulties are strongly in evidence in discussing these terms. Nevertheless, if solvent isotope effects are related to hydrogen bonding effects to ions and if these effects disappear upon addition of DMSO, then the rate-increasing effect of DMSO must involve solvent molecules hydrogen bonded to carboxylate. The effect of DMSO on the solvation of ions cannot be assessed by the present data. However, since one part of solvation involves ion-dipole interactions and since DMSO itself is strongly dipolar, it is difficult to believe that anions are weakly solvated in DMSO solutions.

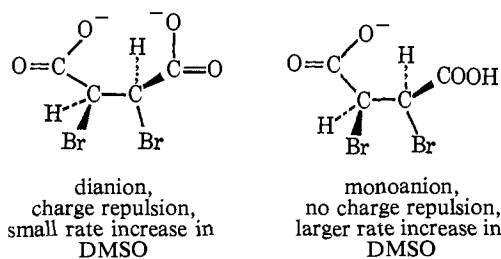
meso- and DL-Dibromosuccinic Acids. The most interesting data, but also the most difficult data to interpret, result for the dibromosuccinic acids. Table IV

Table IV. Solvolysis of *meso*-Dibromosuccinic Acid

% DMSO (v./v.) in DMSO-H ₂ O	$k_1 \times 10^3, \text{sec.}^{-1}$		
	Free acid	Monanion	Dianion ^a
0	0.81 ± 0.08	0.83 ± 0.08	0.47 ± 0.01
20	1.3 ± 0.1 ^b	1.9 ± 0.2	0.80 ± 0.09 ^b
40	2.1 ± 0.2 ^b	3.7 ± 0.3	1.4 ± 0.2
60	5.4 ± 0.4 ^b	15 ± 2 ^b	5.4 ± 0.5 ^b
80		71 ± 5 ^b	

^a At 60.1°. ^b At 60.5°.

lists the kinetic data for the *meso* isomer. Surprisingly the free acid, monoanion, and the dianion show approximately the same reactivity in water. As the solvent mixture is enriched in DMSO, the free acid shows a modest rate increase, the monoanion shows a fairly strong increase, and finally the dianion shows a smaller rate increase (for the *meso* isomer). These rate increases are rather shallow compared to the 3-bromopropionate. Probably these small rate increases are the result of very small concentrations of nonhydrogen-bonded anions even at high DMSO concentrations. Charge-charge and charge-dipole repulsions no doubt are significantly enhanced by the lower dielectric constant medium resulting from removal of hydrogen bonding solvent molecules by DMSO and so this removal tends not to occur. It is significant that the *meso* dianion, where charge-charge repulsion can occur, is less sensitive to DMSO concentration than the *meso* monoanion.



For the DL isomer (Table V), once again the free acid shows a small rate increase with increasing DMSO

(19) C. G. Swain and E. Thornton, *J. Am. Chem. Soc.*, **83**, 3884, 3890 (1961).

Table V. Solvolysis of DL-Dibromosuccinic Acid at 60°

% DMSO (v./v.) in DMSO-H ₂ O	Free acid, $k_1 \times 10^4$ (sec. ⁻¹)	Dianion, $k_1 \times 10^4$ (sec. ⁻¹)
0	1.2 ± 0.1	2.6 ± 0.2
20	1.5 ± 0.2 ^a	4.0 ± 0.2
40		8.9 ± 0.4
60	3.1 ± 0.4 ^a	22 ± 1
80		
100	3.1 ± 0.3	

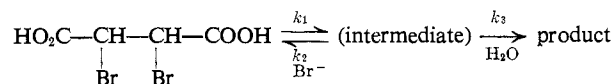
^a At 60.5°.

concentration, while the dianion showed a somewhat larger increase. The data are similar to those from the *meso* isomer. The first-order rate plots tended to be very poor for the DL isomer, curving down after ca. 30% reaction. It was verified that the reaction was indeed first order in substrate by varying concentration.

The poor rate plots are not the result of the buildup of an intermediate. It was possible to monitor the course of the reaction by n.m.r. in D₂O. The two products, DL-tartaric acid and bromofumaric acid, appeared monotonically as substrate disappeared. Although some interference from the HOD absorption is possible, no prominent peak appeared which could be ascribed to an intermediate. It seems likely that the second step of the hydrolysis (to tartaric acid) is probably fairly rapid compared to the initial step (to bromohydroxysuccinic acid).

It seems likely that the drifting rates are due to return of bromide ion to capture a reactive intermediate.^{5,20} This conclusion is corroborated by the data in Table VI. The data shows that the *meso* isomer, which yields mainly olefin products, is not affected a great deal by salts of any kind. The DL isomer, which yields predominately DL-tartaric acid as product, undergoes a common ion rate depression with NaBr and a rate enhancement with massive amounts of potassium acetate (dianion case). The common ion rate depression is quite strong for the DL free acid and is intensified in DMSO solutions. The common ion rate depression is also evident for the DL dianion but is *diminished* in DMSO.

The data may be explained with the help of the following reaction scheme.



For the DL free acid, the intermediate is either neutral or positively charged. No charge repulsion prevents the return of bromide and a strong common ion rate depression is the result. It is well documented¹ that many ions, such as bromide, are stronger nucleophiles in DMSO than in water. It is not surprising that the rate depression due to bromide return is stronger in 60% DMSO.

An attempt was made to treat the rate data in Table V in a similar manner to the treatment of Grunwald and Winstein.⁵ If the rate of appearance of product (x) is diminished as the concentration of product increases,

(20) A. Streitwieser, Jr., "Solvolytic Displacement Reactions," McGraw-Hill Book Co., Inc., New York, N. Y., 1962, p. 54.

Table VI. Salt Effects in Dibromosuccinic Acid Solvolyses

Substrate	Salt	Concn., <i>M</i>	Solvent	$k \times 10^5$, sec. ⁻¹
(1) <i>meso</i> free acid ^a	None		H ₂ O	4.2 ± 0.4
(2) <i>meso</i> free acid ^a	NaBr	0.0265	H ₂ O	4.2 ± 0.2
(3) <i>meso</i> dianion ^a	None		H ₂ O	3.7 ± 0.3
(4) <i>meso</i> dianion ^a	NaBr	0.0204	H ₂ O	3.3 ± 0.2
(5) <i>meso</i> dianion ^a	KOAc	0.204	H ₂ O	3.3 ± 0.3
(6) DL free acid ^a	None		H ₂ O	40 ± 0.2
(7) DL free acid ^a	NaBr	0.0207	H ₂ O	33 ± 0.1
(8) DL dianion ^a	None		H ₂ O	120 ± 10
(9) DL dianion ^a	NaBr	0.0199	H ₂ O	99 ± 9
(10) DL dianion ^a	KOAc	0.203	H ₂ O	160 ± 10
(11) DL free acid ^b	None		60% DMSO	31 ± 2
(12) DL free acid ^b	NaBr	0.0200	60% DMSO	12 ± 1
(13) DL dianion ^b	None		60% DMSO	230 ± 10
(14) DL dianion ^b	NaBr	0.0208	60% DMSO	200 ± 10

^a At 74.9°. ^b At 60.6°

Table VII. Solvent Effects in Dibromosuccinic Acid Systems

	H ₂ O	CH ₃ OH	HCOOH
<i>meso</i>			
Free acid	4.2 × 10 ⁻⁵ (75°)		
Monoanion	5.3 × 10 ⁻⁵ (75°)	6.0 × 10 ⁻⁵ (74.6°)	
Dianion	3.9 × 10 ⁻⁵ (75°)	1.4 × 10 ⁻⁴ (74.6°)	
DL			
Free acid	2.3 × 10 ⁻⁵ (45°)	4.0 × 10 ⁻⁵ (60°) ^a	2.7 × 10 ⁻⁵ (74°)
Monoanion	1.8 × 10 ⁻⁵ (46°)	2.4 × 10 ⁻⁵ (46°)	
Dianion	3.6 × 10 ⁻⁵ (46°)	8.6 × 10 ⁻⁵ (46°)	

^a Estimated.

the following rate equation should be obeyed. The term ($A - x$) is the concentration of substrate.

$$\frac{dx}{dt} = v = \frac{k_3 k_1 (A - x)}{k_2(x) + k_3} \quad (1)$$

By rearranging the above equation, eq. 2 is obtained.

$$\frac{(A - x)}{v} = \frac{1}{k_1} + \frac{k_2(x)}{k_1 k_3} \quad (2)$$

A plot of $(A - x)/v$ vs. x then should yield $k_2/k_1 k_3$ as the slope. Knowing k_1 (from the intercept), k_2/k_3 , or the ratio of rates of capture of the intermediate by bromide or by water, can be calculated. In actuality the data appeared to follow eq. 3 more closely than eq. 2 for both the free acid and for the dianion cases. It is difficult to

$$\frac{A - x}{v} = \frac{1}{k_1} + \frac{k_2(x)^2}{k_1 k_3} \quad (3)$$

attach physical significance to the rate dependence involving x .² This dependence may be an artifact.

Qualitatively, however, the data derived from eq. 2 show the same trends as the common ion rate depression data of Table VI. For the DL free acid, k_2/k_3 , or the relative rate of capture of the intermediate by bromide and solvent, ranges from *ca.* 20 (0% DMSO) to 900 (100% DMSO). The values increase monotonically with each increment of DMSO. Thus bromide seems to intercept the intermediate more effectively as the DMSO concentration increases.

For the DL dianion, the opposite trend is apparent; the k_2/k_3 ratio diminishes from 200 (0% DMSO) to *ca.* 0 (60% DMSO). Thus bromide becomes a less

important nucleophile, relative to solvent, as the DMSO concentration increases.²¹

Solvent Effects. Other factors were investigated in hopes of determining the nature of the reaction intermediates. Table VII lists the effects of methanol and formic acid as well as of water on the reactivity of the *meso* and DL isomers. In water there is not a great deal of difference between the free acid, monoanion, and dianion for each isomer. However, for the DL isomer, the dianion is the most reactive by a factor of *ca.* 2. This difference in reactivity, of course, is accentuated in DMSO solutions. In methanol, a pronounced difference in reactivity exists in the order dianion > monoanion > free acid, for both isomers. For the DL, the dianion is over 10⁴ as reactive as the free acid. In methanol, as in DMSO, it is thought that anchimeric assistance²² by carboxylate is an important phenomenon.²³ In water the situation is not clear-cut. For the DL free acid, the logarithm of the reaction rates roughly follow Winstein's *Y* values.²⁴ On the other hand, the order of solvent nucleophilicity,²⁵ *i.e.*, H₂O > CH₃OH > HCOOH, is not obeyed. Nucleophilic displacement by solvent does not appear important.

(21) A similar treatment of the data is possible for 3-bromopropionic acid and its anion. In this case the k_2/k_3 ratio diminishes for both the free acid and anion. The data for this compound is very similar to the DL-dibromosuccinic acid dianion.

(22) S. Winstein and A. H. Fainberg, *J. Am. Chem. Soc.*, **80**, 457 (1958), and many earlier papers.

(23) A. Streitwieser, Jr., ref. 20, p. 118.

(24) *Y* values are a measure of the ionizing power of a given solvent, compared to 80% EtOH-20% H₂O, which is assigned a zero *Y* value: (a) E. Grunwald and S. Winstein, *J. Am. Chem. Soc.*, **70**, 846 (1948); (b) A. H. Fainberg and S. Winstein, *ibid.*, **78**, 2770 (1956); (c) J. E. Leffer and E. Grunwald, ref. 20, p. 298.

(25) C. G. Swain, R. Mosely, and D. Bown, *J. Am. Chem. Soc.*, **77**, 3731 (1955).

Table VIII. Ion-Pairing Effects in DL-Dibromosuccinic Acid Solvolyses at 60°

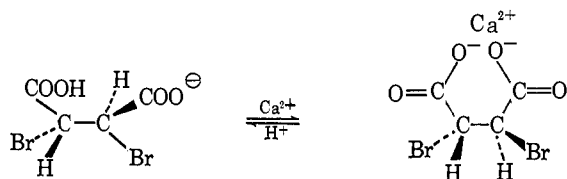
Substrate	Salt	Concn., M	Solvent	$k \times 10^4$, sec. ⁻¹
(1) Monoanion	None		H ₂ O	1.1 ± 0.1
(2) Monoanion	KClO ₄	0.0296	H ₂ O	1.0 ± 0.1 ^a
(3) Monoanion	Ca(NO ₃) ₂	3.11	H ₂ O	2.3 ± 0.2 ^a
(4) Dianion	None		H ₂ O	2.6 ± 0.1
(5) Dianion	KClO ₄	0.0882	H ₂ O	2.6 ± 0.2
(6) Dianion	Ca(NO ₃) ₂	5.83	H ₂ O	2.1 ± 0.2 ^a
(7) Dianion	None		40% DMSO	8.9 ± 0.4
(8) Dianion	Ca(NO ₃) ₂	0.759	40% DMSO	5.1 ± 0.2
(9) Dianion	None		60% DMSO	22 ± 1 ^a
(10) Dianion	Ca(NO ₃) ₂	1.66	60% DMSO	4.4 ± 0.2

^a At 60.50°.

Product studies show that the reaction in water, as in methanol or DMSO solutions, occurs with considerable stereospecificity. Thus the *meso* isomer (free acid, monoanion, or dianion) yields mainly bromomaleic acid plus some *meso*-tartaric acid. The DL isomer yields predominately DL-tartaric acid plus some bromofumaric acid. It is possible that the reaction in water is primarily an ionization phenomenon with the carboxylate coming in at a later time to preserve stereochemistry.⁵

Ion-Pairing Effects. Ion pairing has been found to reduce the reactivity of a carboxylate function in other systems involved in decarboxylation reactions.²⁶ Furthermore, ion pairing is known to occur in the dibromosuccinic acid system readily, particularly with divalent cations such as calcium.^{27,28} The effect of calcium ion on the solvolysis of DL-dibromosuccinic acid is given in Table VIII. It is apparent that massive amounts of calcium ion diminish the reactivity slightly. In concentrated DMSO solutions, where anchimeric assistance by carboxylate is more likely, ion pairing does seem to reduce the reactivity of the substrate by approximately a factor of 5. Again the data seem to indicate that the carboxylate is not involved in the ionization process in water.

Runs 2 and 3 show that calcium ion increases the reactivity of the monoanion by a modest amount in water. This rate increase might be explained by a metathesis wherein the more reactive dianion ion pair is produced from the monoanion.

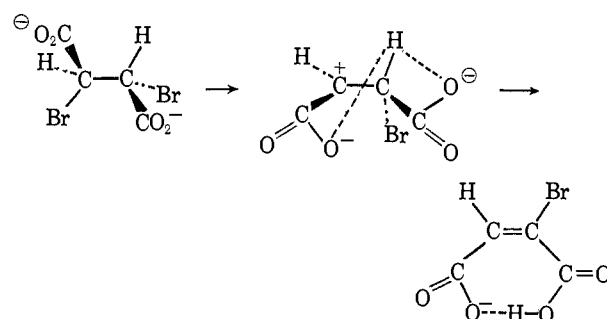


For the *meso* dianion a slight rate increase is observed in the presence of calcium ion.

To summarize, for the *meso* isomer, the order of reactivity is monoanion > free acid > dianion at most temperatures (see the Experimental Section). The product of the solvolysis is mainly bromomaleic acid. An intermediate could not be detected, in our hands. The rate of reaction was insensitive to ion-pairing salts.

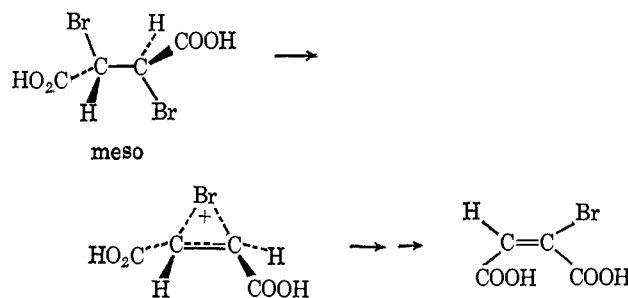
(26) K. Petersen, *Acta. Chem. Scand.*, **3**, 676 (1949).
 (27) C. W. Davies, "Ion Association," Butterworth and Co. (Publishers) Ltd., London, 1962, p. 143.
 (28) B. Holmberg, *Z. Physik. Chem.*, **79**, 147 (1912).

One possible mechanism involves predominantly an ionization process, rapidly followed by the removal of a proton by the carboxylate. Going to the final product



the two carboxyl groups may become hydrogen bonded, thus providing some driving force for the reaction, and counterbalancing steric repulsions between the two carboxyl groups.

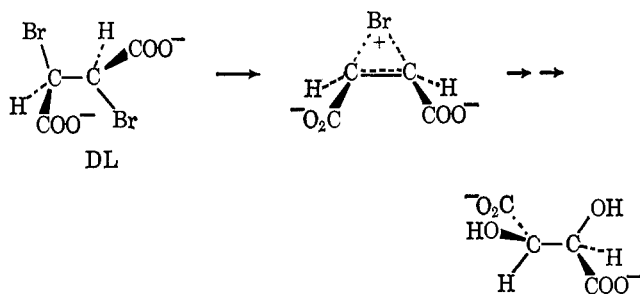
A second possible mechanism appears fairly attractive particularly for the free acid. This mechanism involves a bromonium ion intermediate. In this intermediate the bulky carboxyl groups are on opposite sides



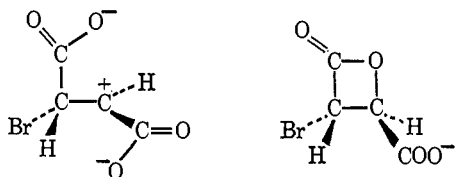
of the molecule, which is an energetically favorable stereochemistry. However, it is difficult to envision the formation of product olefin directly from this intermediate.

For the DL isomer, the order of reactivity is dianion > monoanion > free acid. The product is mainly DL-tartaric acid. External ion return to an intermediate appears probable. Solvent effects favor primarily an ionization process.⁵ Ion-pairing salts have strong effects.

In this case a bromonium ion intermediate would involve eclipsing two large carboxyl groups. Nevertheless, this mechanism cannot be ruled out, particularly for the free acid case.



More likely a lactone intermediate (either α or β) is present. Once again the large groups are *trans* to one another in the β intermediate. The timing of events



would seem to be initial ionization, rapidly followed by participation by carboxylate to preserve stereochemistry.⁵ On the other hand, in methanol and DMSO solutions, anchimeric assistance by carboxylate is considered likely.

The recent, elegant work of Vaughn and co-workers²⁹ showed that rate enhancements occurred for β -bromocarboxylic acid substrates in situations in which carboxyl participation was stereochemically impossible. The rate increases were interpreted in terms of solvation effects. It appears that zwitterionic intermediates may be more important than previously thought, as alternative structures for β -lactones as well as α -lactones. Nevertheless, in open-chain systems, where steric problems are unimportant, the covalent intermediate should still be favored since with the zwitterion considerable electrostatic work is necessary to preserve charge separation.

Experimental Section

Materials were purified as follows. Normal laboratory-distilled water was redistilled from potassium permanganate, although little difference was noted whether single- or double-distilled water was used for rates; methanol (Mallinckrodt reagent grade) was distilled from its alkoxide through a 24-cm. Podbielniak column; formic acid (Matheson) was purified by Winstein and Marshall's procedure³⁰; dimethyl sulfoxide (Crown-Zellerbach) was purified by a method described earlier.³ Deuterium oxide (Columbia Chemical Co., 99.5%) was used without purification. Reagent grade inorganic chemicals were used without further purification.

The substrate bromoacetic acid (Eastman) was purified by distillation from a small quantity of P_2O_5 , yielding a colorless solid; 3-bromopropionic acid was prepared by the method of Kendall and McKenzie,³¹ m.p. 61–62°; *meso*- and DL-dibromosuccinic acids were prepared by the method of Fittig and Petri,³² m.p.

(29) W. Vaughn, R. Caple, J. Csapilla, and P. Scheiner, *J. Am. Chem. Soc.*, **87**, 2204 (1965).

(30) S. Winstein and H. Marshall, *ibid.*, **74**, 1120 (1952).

(31) E. C. Kendall and B. McKenzie, "Organic Synthesis," Coll. Vol. I, A. H. Blatt, Ed., John Wiley and Sons, Inc., New York, N. Y., 1941, p. 131.

(32) R. Fittig and C. Petri, *Ann.*, **195**, 58 (1879).

255–257° (sealed capillary) and 174–175°, respectively. Rates were followed by bromide ion determination by the usual Volhard method.³³

In a typical run, the solvent mixture was added by pipet to a volumetric flask. The flask was thermostated and the substrate was added as a solid to begin the rates. In runs involving volatile solvents it was necessary to use sealed tubes. Initial substrate concentration was 0.01 to 0.02 *M*. Aliquots were withdrawn and added to ice-cold dilute HNO_3 solution. The best procedure was to pretitrate these solutions with standard KSCN to close to the assumed end point. Standard silver nitrate solution was then added and the titration rapidly was completed. In general, duplicate determinations were made. Good first-order kinetics were observed for all substrates except DL-dibromosuccinic acids. With the DL substrate, drifting rate constants were a severe problem past 30% reaction which were unaffected by added salt, although added potassium acetate produced good plots for the dianion case. For the *meso* and DL substrates the data were difficultly reproducible in part due to inconstancy of the infinity titer. These data are not considered as accurate as for the other substrates. A typical run involving the DL substrate is given in Table IX. Rates were calculated using the expression³⁴

$$k = \frac{2.303 \log \left(\frac{[Br]_{\infty}}{[Br]_{\infty} - [Br]_t} \right)}{(t - t_0)}$$

Activation parameters were calculated by standard procedures.³⁴ These are listed in Table X. Arrhenius

Table IX. Solvolysis of DL-Dibromosuccinic Acid in Water (59.40°)^a

No.	Time, sec.	5-ml. aliquot, titer	Concn. (subs.), <i>M</i>	(Bromide), <i>M</i>	$x_{\infty}/(x_{\infty} - x_t)$	k_t , sec. ⁻¹
1	320	2.825	0.02194	0.00139	1.064	1.08
2	710	2.725	0.02154	0.00179	1.083	1.13
3	1407	2.298	0.01983	0.000350	1.175	1.10
4	1980	1.962	0.01849	0.00484	1.261	1.06
5	2662	1.724	0.01753	0.00580	1.330	1.10
6	3505	1.300	0.01584	0.00749	1.472	1.05
7	4647	0.888	0.01419	0.00914	1.643	1.02
8	5663	0.610	0.01308	0.01025	1.783	0.98
9	∞	3.072 (10)		0.02333		

^a Initial concentration, 0.02010 *M*; [KSCN], 0.02000 *M*; [AgNO₃]₀, 0.01781 *M*.

Table X. Activation Parameters for the Dibromosuccinic Acid Hydrolysis^a

	ΔH^* , kcal./mole	ΔS^* , e.u.
DL series		
H ₂ O, free acid	23	-6
Monoanion	26	+1
Dianion	27	+8
<i>meso</i> series		
Free acid	25	-8
Monoanion	27	+5
Dianion	32	+13

^a Determined from lower temperatures of the Arrhenius plots.

(33) H. Diehl and G. F. Smith, "Quantitative Analysis," John Wiley and Sons, Inc., New York, N. Y., 1952, p. 330.

(34) B. Stevens, "Chemical Kinetics," Chapman and Hall, London, 1961, pp. 17, 37.

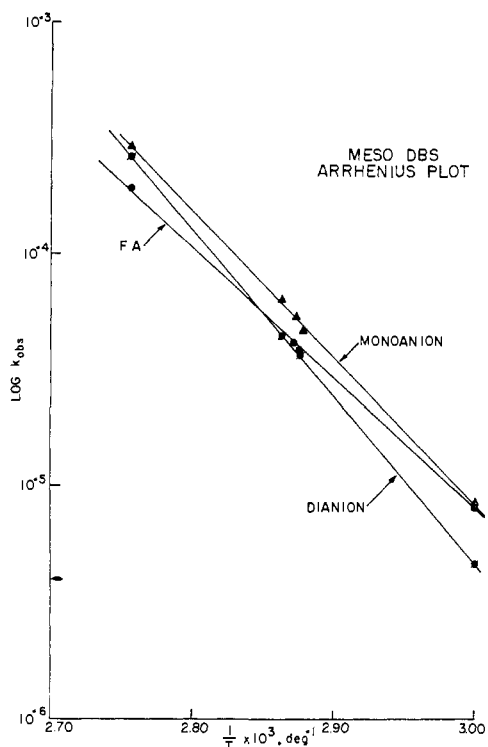


Figure 1. Solvolysis of *meso*-dibromosuccinic acid (DBS), free acid (FA), monoanion, and dianion, in H₂O.

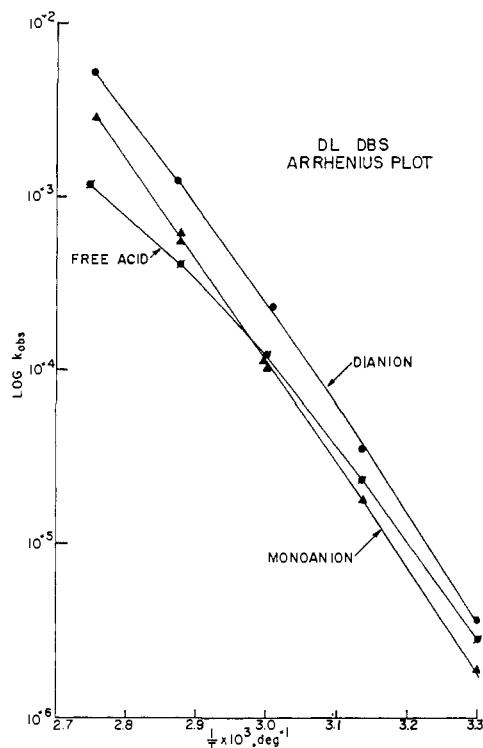


Figure 2. Solvolysis of *DL*-dibromosuccinic acid, free acid, monoanion, and dianion, in H₂O.

plots are given in Figures 1 and 2. Owing to the pronounced curvature, activation energies were calculated from the lower temperature ranges.

Product studies were run, in selected instances, by distilling off the aqueous solvent at reduced pressure, esterifying the residue with methanol and sulfuric acid, working up the product ester by common procedures, and analyzing the product by vapor phase chromatography.

Direct observation of the course of the reaction was possible by running the solvolysis in D₂O and scanning the reaction mixture by n.m.r. at intervals. The products, bromofumaric acid, *ca.* 7.52 p.p.m., and bromomaleic acid, 6.28 p.p.m., were easily distinguished. The substitution products, *DL*-tartaric acid, 4.77 p.p.m., and *meso*-tartaric acid, *ca.* 4.70 p.p.m., were distinguishable but not well separated; interference with the HOD absorption was a problem. In general the

product ratios obtained by these two methods were in fair agreement with the ratios calculated from infinity titers (solvolysis to olefin yields 1 mole of bromide, while solvolysis to tartaric acid yields 2 moles). For the *meso* isomer the ratio of substitution to elimination ranged from *ca.* 1 to 0, usually closer to the latter figure. The *meso* dianion yielded more substitution product than the other forms. The substitution to elimination ratio for the *DL* isomer was temperature dependent as well as dependent upon the anionic form of the substrate. In general, the dianion and monoanion yielded a ratio as high as 7.6. The free acid at low temperature yielded mainly olefin. In 100% DMSO, olefin appeared to be the only product. Product ratios in methanol were similar to ratios in water.

The n.m.r. spectra definitely showed propiolactone to be present in the 3-bromopropionate solvolysis.