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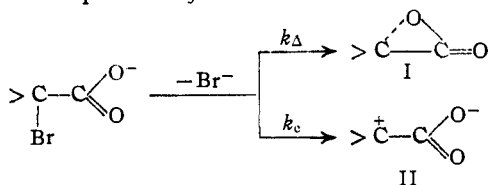
The Role of Neighboring Groups in Replacement Reactions. XV. Rates and Medium Effects in the Alcoholysis and Hydrolysis of α -Bromopropionate Ion. The Carboxylate Ion Group

BY ERNEST GRUNWALD AND S. WINSTEIN

Of the neighboring groups which participate in unimolecular type¹ nucleophilic displacements, one of the more important in organic chemistry is the α -carboxylate ion group. The recognition of retention of configuration as a possible over-all steric result of unimolecular reactions of materials of the type of α -bromopropionate ion has gone far toward clearing up a long-existing confusion attending the stereochemistry of displacement reactions of compounds containing various forms of the α -carboxyl group.²

Hughes and Ingold^{2a} explained the effect of the carboxylate ion group as due to the presence of the negatively charged group in an alkyl cation, thus stabilizing the ion in a pyramidal configuration. We have since shown that the phenomenon of participation of neighboring groups such as OAc, Br, etc., in unimolecular displacement reactions is a general phenomenon, neutral groups being able to bring about retention of configuration. The action of the CO_2^- group is but one illustration of this general phenomenon, a charge being in principle unnecessary.

As in the case of other groups,^{1,3} actual rates and other kinetic features of the unimolecular displacement reactions of α -halocarboxylate ions are of interest for the possible information afforded regarding the intimate mechanism of formation and the nature of the intermediate I, which has been termed an α -lactone⁴ or a zwitterion.^{2a} In principle, the rate determining ionization of the α -carboxylate ion may produce I directly with inversion of configuration (rate constant k_Δ) or it may yield first the more open zwitterion II (rate constant k_c). The first of these descriptions has been used previously.⁴



In connection with neutral neighboring groups, we have previously made some use of the varia-

(1) Winstein, Grunwald, Buckles and Hanson, *THIS JOURNAL*, **70**, 816 (1948).

(2) (a) Cowdrey, Hughes, Ingold, Masterman and Scott, *J. Chem. Soc.*, 1252 (1937); (b) Hughes, *Trans. Faraday Soc.*, **34**, 202 (1938); (c) Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1940, p. 175.

(3) (a) Winstein, Grunwald and Ingraham, *THIS JOURNAL*, **70**, 821 (1948); (b) Winstein and Grunwald, *ibid.*, **70**, 828 (1948); (c) Winstein and Adams, *ibid.*, **70**, 838 (1948).

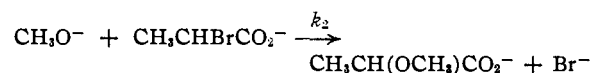
(4) (a) Winstein and Lucas, *ibid.*, **61**, 1576 (1939); (b) Winstein, *ibid.*, **61**, 1635 (1939).

tion of rate with changes in the solvolyzing medium (solvent or salt effects). The case of the CO_2^- group is one where salt effects might prove to be particularly helpful. For the intermolecular analogs of processes with the rate constants k_Δ and k_c , S_N2 and S_N1 type reactions of alkyl halides with a carboxylate ion, the sign of medium effects can be anticipated on the basis of the general theory⁵ of solvent effects with which Hughes, Ingold and co-workers have had considerable success. For the S_N2 reaction, there is subdivision of charge in the transition state so that addition of inert salt or change to a more ionizing solvent will lead to a decrease in rate. In the S_N1 reaction, there is generation of charge in the transition state so the effect of solvent change will be opposite in sign. By analogy, k_c will increase with addition of inert salt or change to a more ionizing solvent. On the other hand, if there is enough involvement of the CO_2^- group with the carbon atom undergoing substitution in the transition state, k_Δ will decrease with such solvent change.

The most recent pertinent work on the solvolysis of α -bromopropionate ion is that of Cowdrey, Hughes and Ingold⁶ and Chadwick and Pacsu.⁷ With regard to salt effects, Cowdrey, Hughes and Ingold⁶ report a large decrease in the first order rate on addition of 0.5 *M* sodium bromide in methanol solution. This they expect on the basis that "the rate-controlling stage is an ionization, in the transition state of which the anionic charge becomes divided between the carboxylate group and the bromine atom." This kind of salt effect would indicate that ionization occurs essentially by the process labelled k_Δ . On the other hand, in water Chadwick and Pacsu⁷ report slight increases in first order rate with increase in ionic strength.

In this article are reported the results of a re-investigation of the alcoholysis and hydrolysis of α -bromopropionate ion, special attention being given to salt effects.

In solvolysis, for example methanolysis, of α -bromopropionate ion, two reactions are prominent, the second order reaction with methoxide ion

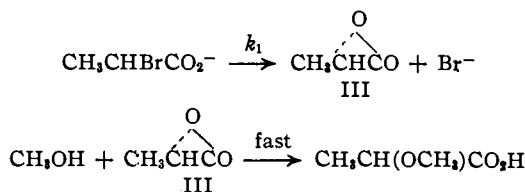


and the first order reaction by way of the so-called α -lactone or zwitterion III

(5) (a) Hughes and Ingold, *J. Chem. Soc.*, 244 (1935); (b) Bateman, Church, Hughes, Ingold and Taher, *ibid.*, 979 (1940); (c) Hughes, *Trans. Faraday Soc.*, **37**, 603 (1941).

(6) Cowdrey, Hughes and Ingold, *J. Chem. Soc.*, 1208 (1937).

(7) Chadwick and Pacsu, *THIS JOURNAL*, **65**, 392 (1943).



either reaction path predominating, depending on conditions. At high concentrations of methoxide ion, κ_2 , an apparent second-order reaction rate constant, is fairly constant, and at low concentrations of methoxide ion, κ_1 , an apparent first-order reaction rate constant, is also quite constant. If one is interested in the first-order reaction rate constant in the low concentration region, a correction still needs to be made for the second-order contribution. Furthermore, if at low methoxide ion concentration the ionic strength is increased, κ_1 increases markedly, but so much of this is due to the increase in the second-order contribution that a careful analysis is necessary to decide whether increase in ionic strength increases or decreases κ_1 .

Kinetic Part

For convenience the symbols we employ are summarized below:

t = time in seconds.

α_0 = concn. in moles/l. of α -bromopropionate ion at zero time.

α = concn. in moles/l. of α -bromopropionate ion at time t .

β_0 = concn. in moles/l. of methoxide or hydroxide ion at zero time.

β = concn. in moles/l. of methoxide or hydroxide ion at time t .

x = concn. in moles/l. of bromide ion from solvolyses at time t .

$$\kappa_2 = \frac{1}{t(\alpha_0 - \beta_0)} \ln \left(\frac{\beta_0(\alpha_0 - x)}{\alpha_0(\beta_0 - x)} \right)$$

$$\kappa_1 = \frac{1}{t} \ln \left(\frac{\alpha_0}{\alpha_0 - x} \right)$$

k_2 = specific reaction rate constant for the second-order reaction.

k_1 = specific reaction rate constant for the first-order reaction.

k' = depressed first order rate constant in presence of bromide ion.

μ = ionic strength in moles/l. at 64.04 \approx 0.04 $^\circ$.

$$\phi = x / \left(\frac{k_1}{k_2} + \beta_0 \right)$$

k_{Br} = specific reaction rate constant for reaction of intermediate with bromide ion.

k_s = specific reaction rate constant for reaction of intermediate with solvent (methanol or water).

Equation 1 is the differential equation applicable in the present case, both k_1 and k_2 being func-

$$dx/dt = k_1\alpha + k_2\alpha\beta = k_1(\alpha_0 - x) + k_2(\alpha_0 - x)(\beta_0 - x) \quad (1)$$

tions of ionic strength.

Values of k_2 at various ionic strengths necessary in evaluating k_1 were derived as follows. A series of experiments with α_0 at ca. 0.03 M and β_0 at 0.25 M to 1.0 M (Table I) gave κ_2 values which were constant within experimental error in each run. Average values in each run, κ_2 , were cor-

rected for first-order contribution according to equation 2 which chooses

$$k_2 = \bar{\kappa}_2 - k_1/(\beta_0 - \alpha_0/3) \quad (2)$$

($\beta_0 - 1/3\alpha_0$) as a good working mean between β_0 and $\beta_0 - \alpha_0$, the extreme values to be considered here. Since $\beta_0 \gg \alpha_0$ in these runs, the accuracy in this empirical procedure is good. In this correction, k_1 is at first an estimate based on data from largely first-order solvolyses. These first values of k_2 which were always within 4% of the final values enable one to obtain better values of k_1 (see below) and second approximations (which are sufficient) become possible for k_2 . The data for the largely second-order runs in both methanol and water are summarized in Table I. In this table, as well as in all subsequent ones, rate-constants and concentrations have been corrected for solvent expansion.

The plot of $\log k_2$ against $\mu^{1/2}$ gives a good straight line. Equation 3, obtained by least squares, fits runs 1 through 5 with a

$$\log k_2 = -4.568 + 1.308\mu^{1/2} \quad (3)$$

mean deviation of 0.006 in $\log k_2$. For the runs 6 and 7 in water as a solvent one can write⁸ equation 4

$$\log k_2 = -3.681 + 0.343\mu^{1/2} \quad (4)$$

The values of k_1 at different ionic strengths were based on runs with low methoxide or hydroxide ion concentrations, sodium perchlorate (or nitrate) being added. The solution of equation 1 is equation 5

$$\frac{1}{t} \left\{ \ln \left[\frac{k_1 + k_2(\beta_0 - x)}{k_1 + k_2\beta_0} \right] \left(\frac{\alpha_0}{\alpha_0 - x} \right) \right\} = k_1 + k_2(\beta_0 - \alpha_0) \quad (5)$$

TABLE I

SECOND ORDER RATE CONSTANTS FOR SOLVOLYSIS OF α -BROMOPROPIONATE ION AT 64.04 $^\circ$

Run	Solvent	μ	$10^4\kappa_2$ (sec. ⁻¹ M ⁻¹)	10^4k_2 (sec. ⁻¹ M ⁻¹)
1	CH ₃ OH	1.019	6.18 \pm 0.16	5.57
2	CH ₃ OH	0.930	5.60 \pm .07	4.94
3	CH ₃ OH	.745	4.35 \pm .05	3.51
4	CH ₃ OH	.462	3.48 \pm .01	2.12
5	CH ₃ OH	.370	3.44 \pm .07	1.69
6	HOH	1.024	6.11 \pm .08	4.63
7	HOH	0.504	6.48 \pm .05	3.65

with which some investigators^{7,9} have worked directly, although this is admittedly laborious. We found it much more convenient to evaluate an apparent first-order constant κ_1 and then, using ϕ as previously defined, equation 6 follows. The expansion of $-\ln(1 - \phi)$ in

(8) The slopes for the variation of $\log k_2$ with $\mu^{1/2}$ in these concentration ranges are roughly one-third the limiting Debye-Hückel-Brønsted values of $1.826 \times 10^4 [2/(\epsilon T)^{1/2}]$. These limiting values are 4.58 for methanol and 1.118 for water at 64.04 $^\circ$ ($T = 337.2$) using values for dielectric constants, ϵ , of 25.52 for methanol and 65.30 for water [Akerlof, THIS JOURNAL, 54, 4125 (1932)].

(9) Meisraheimer and Bentler, *Ann.*, 508, 58 (1933).

TABLE II
FIRST ORDER REACTION RATE CONSTANTS FOR SOLVOLYSIS OF α -BROMOPROPIONATE ION AT 64.04°

Run	Solvent	μ	α_0	β_0	Other salts, <i>M</i>	Ag ⁺	H ⁺	$10^3 \bar{k}_1$ (sec. ⁻¹)	$10^3 \bar{k}_1$ (sec. ⁻¹) av.
8	CH ₃ OH	0.991	0.03	0.03	0.944 NaClO ₄	5.84 ± 0.05	5.83 ± 0.16		5.84
9	CH ₃ OH	.546	.03	.03	.486 NaClO ₄	5.65 ± .05	5.65 ± .14		5.65
10	CH ₃ OH	.539	.03	.03	.482 NaClO ₄	5.73 ± .05	5.69 ± .08		5.71
11	CH ₃ OH	.300	.03	.03	.239 NaClO ₄	5.76 ± .11	5.76 ± .07		5.76
12	CH ₃ OH	.0749	.03	.0460	.....	5.17 ± .01	5.15 ± .02		5.16
13	CH ₃ OH	.0589	.03	.03	.....	5.06 ± .10	4.97 ± .07		5.02
14	CH ₃ OH	.0410	.02	.02	.....	5.19 ± .03	.....		5.19
15	CH ₃ OH	.941	.03	.03	.883 NaBr	.....	1.48 ± .06		1.48
16	CH ₃ OH	.917	.03	.03	.855 NaBr	.....	1.72 ± .04		1.72
17	CH ₃ OH	.475	.03	.03	.415 NaBr	.....	2.66 ± .06		2.66
18	CH ₃ OH	.304	.03	.03	.240 NaBr	.....	3.43 ± .09		3.43
19	HOH	1.053	.03	.03	.992 NaNO ₃	13.25 ± .25	.....		13.25
20	HOH	0.933	.03	.03	.878 NaClO ₄	13.25 ± .10	13.25 ± .10		13.25
21	HOH	.564	.03	.03	.502 NaNO ₃	12.90 ± .20	.....		12.90
22	HOH	.496	.03	.03	.434 NaClO ₄	13.10 ± .15	12.95 ± .20		13.05
23	HOH	.0804	.03	.05	.....	12.55 ± .20	12.45 ± .05		12.50
24	HOH	.0638	.03	.03	.....	12.45 ± .05	12.55 ± .05		12.50
25	HOH	1.040	.03	.03	.976 NaBr	.....	7.48 ± .15		7.48
26	HOH	0.540	.03	.03	.476 NaBr	.....	9.54 ± .32		9.54

$$\kappa_1 - k_1 = k_2(\beta_0 - \alpha_0) - \frac{1}{l} \ln(1 - \phi) \quad (6)$$

$$\kappa_1 - k_1 = k_2(\beta_0 - \alpha_0) + \frac{1}{l} \left(\phi + \frac{\phi^2}{2} + \frac{\phi^3}{3} + \dots \right) \quad (7)$$

a series gives rise to equation 7 which is a convenient working equation since ϕ turns out to be of the order of 0.05, so that ϕ^3 is usually negligible and ϕ^2 and ϕ^3 can be obtained with the slide rule.

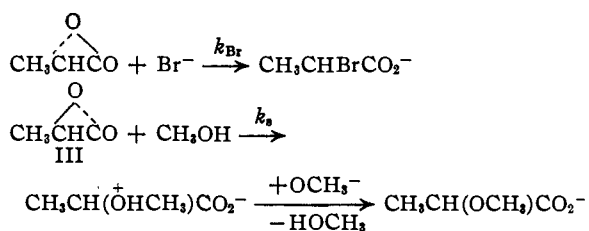
In the rate runs summarized in Table II a value of κ_1 was evaluated for each analytical point. Using κ_1 , the known values of x , β_0 and α_0 , the value of k_2 for the given ionic strength calculated from equation 3 or 4, and guessing a reasonable value for k_1 , the right-hand side of equation 7 was easily evaluated and thus a first value for k_1 at any one analytical point was obtained. A second approximation (usually sufficient) was obtained by substituting this first approximation for k_1 into the right-hand side of equation 7. The values for k_1 at the different analytical points were averaged to give the values shown in Table II. In some cases separate rate constants are listed based on titration for both base and bromide ion and these are averaged for the final values.

Discussion

Inspection of Table II shows, in agreement with the report of Chadwick and Pacsu, that the first order reaction rate constant k_1 for solvolysis rises with ionic strength when sodium perchlorate is the added salt both in water and methanol. In water approximately a 6% increase is produced by a change in ionic strength from 0.06 to 1 *M* while the analogous figure is 17% in methanol. In water, Chadwick and Pacsu⁷ recorded increases of 12 and 5% at 49.2° and 59.7°, respectively, on the addition of 0.95 *M* sodium nitrate to 0.2 *N* sodium bicarbonate solutions of the α -bromopropionate (ca. 0.04 *M*).

The observation of Cowdrey, Hughes and Ingold⁶ with regard to the direction of the salt effect in methanol was due to the choice of the added salt, sodium bromide. The bromide ion competes very well for the intermediate III. This represents a type effect on which Hughes, Ingold and co-workers^{6b} have since done considerable work but which they had not yet discovered at the time of the earlier work. In connection with the hydrolysis of bromomalonate ion Hughes and Taher¹⁰ have reported a similar action of sodium bromide and mention the possibility that some of the effect is a "mass-law" effect.

The effect of bromide ion on the rate constant is very marked and may be treated according to the scheme



which depicts a competition between bromide ion and solvent molecules for the intermediate III, and neglects the competition by methoxide or hydroxide ion. According to this scheme, the first order rate constant k' evaluated by use of equation 7 (putting k' in place of k_1) is given by equation 8. This predicts, as is actually observed, that k' will be satisfactorily constant if the bromide concentration is essentially constant. The latter condi-

$$k' = k_1 \frac{1}{1 + (k_{\text{Br}}/k_s)(\text{Br}^-)} \quad (8)$$

tion is fulfilled if the initial bromide concentration

(10) Hughes and Taher, *J. Chem. Soc.*, 956 (1940).

is large compared to that produced in the reaction. Comparison of the rate constant k' in the presence of sodium bromide with the rate constant k_1 at the corresponding ionic strength in the runs with sodium perchlorate allows one to estimate the ratio k_{Br}/k_s . These are shown in Table III, the values being close to constant at 2.9 in methanol and 0.76 in water.

The value of k_{Br}/k_s would not be expected to be absolutely independent of ionic strength. Actually our values show a slight downward drift with decrease in ionic strength but this is too slight to be sure it is not accidental, especially since we would have expected a reverse trend.

The success of equation 8 indicates that the rate constant for reaction of intermediate III with methoxide ion or hydroxide ion cannot be much greater than k_{Br} . In the course of a run, the methoxide or hydroxide ion concentration decreases markedly and, were these ions competing for intermediate III, bromide ion would show an increasing ability to compete for III and give a decreasing reaction rate constant as the reaction progresses. Instead, solutions containing high bromide ion and low base concentration produce acid in a good first-order fashion after allowance is made for second-order reaction with methoxide ion. The relative inactivity of the base ion for attack on the intermediate recalls the inactivity of hydroxide ion in the case of ethylene oxides.¹¹

TABLE III
RELATIVE RATES OF REACTION OF INTERMEDIATE III
WITH BROMIDE ION AND SOLVENT

Solvent	μ	(Br ⁻)	$10^5 k_1$ (sec. ⁻¹)	$10^5 k'$ (sec. ⁻¹)	k_{Br}/k_s	k_{Br}/k_s av.
CH ₃ OH	1	0.893	5.84	1.48	3.30	2.86 ±
CH ₃ OH	1	.865	5.84	1.72	2.77	
CH ₃ OH	0.5	.425	5.68	2.66	2.67	0.22
CH ₃ OH	0.3	.250	5.76	3.43	2.72	
HOH	1	.986	13.25	7.48	0.78	0.76
HOH	0.5	.486	13.00	9.54	0.75	

Judging by the data obtained following the reactions for both bromide ion and base, either perchlorate ion shows negligible reaction with intermediate III or any ester product is unstable. Nitrate ion does react slightly with III (see experimental).

The information on k_{Br}/k_s adds information of a type which needs to be greatly expanded before the general phenomenon of participation is fully understood. These values for k_{Br}/k_s are listed in Table IV along with some related ones from similar situations. The value for the intermediate from bromomalonate ion is a rough one calculated from the data of Hughes and Taher.¹⁰ The value for the intermediate from phenylbromoacetate ion is calculated from the data of Bulcraig and Dawson.¹² These workers report rate constants of hydrolysis of the 0.025 *M* neutral salt of

(11) Bronsted, Kilpatrick and Kilpatrick, *THIS JOURNAL*, **51**, 428 (1929).

(12) Bulcraig and Dawson, *J. Chem. Soc.*, **80** (1943).

0.0238 (0.975 *M* NaNO₃) and 0.0250 (0.975 *M* NaClO₄) for an average of 0.0244, whereas the rate constant is 0.0184 for 0.975 *M* NaBr. The value for the stilbene bromonium ion is given by Bartlett and Tarbell¹³ and the value for ethylene oxide is from the data of Bronsted, Kilpatrick and Kilpatrick.¹¹ More needs to be known regarding temperature coefficients of these values and, sometimes, effects of ionic strength before the figures are properly comparable.

The small positive salt effect in the unimolecular solvolysis of α -bromopropionate ion indicates generation of charge in the transition state for the rate-determining ionization of the bromide ion. Corresponding to the salt effect is the effect of solvent change, the solvolysis rate in water at 64° being approximately twice that in methanol. Thus the sign of the medium effects does not enable one to choose unambiguously between the two modes (rate constants k_Δ or k_c) of the rate-determining

TABLE IV
COMPETITION FOR INTERMEDIATES

Compound	T, °C.	Solvent	k_{Br}/k_s
CH ₂ CHCOO	64	MeOH	2.9
CH ₃ CHCOO	64	HOH	0.76
O ₂ CCHCOO	100	HOH	2.7
C ₆ H ₅ CHCOO	25	HOH	0.33
C ₆ H ₅ CHBrCHC ₆ H ₅	0	MeOH	1.21
H ₂ COHCH ₂	20	HOH	37

ionization. The intermediate III has very high ionic character^{5b,14} to the new carbon-oxygen bond. Thus, even if it is produced in one stage (k_Δ), the transition state could have increased charge over the reagent α -bromopropionate ion. This possibility gains support from the observation that the effect of neutral salts and of solvent change in the case of β -lactone formation, which more surely proceeds by a concerted ring closure (k_Δ) in the examples available, is the same in sign as for α -bromopropionate ion. This is shown in Table V. On the other hand for the closure of the larger 6-membered ring from CH₂CHBrCONH-CH₂CO₂⁻ Chadwick and Pacsu⁷ observed a salt effect of the sign anticipated for the intermolecular example.

In the case of the other neighboring groups it was useful to compare the unimolecular rate constant k with k_H , the rate constant of the unsubstituted material³. Estimated values of k_c/k_H made it possible to derive estimates of k_Δ/k_c . In the present case k_H is the specific rate of CH₂CHBr-CH₃ if O₂⁻ is considered the neighboring group. With the charged neighboring group, the choice of solvent for the comparison k/k_H is difficult because a change to a more ionizing solvent affects the al-

(13) Bartlett and Tarbell, *THIS JOURNAL*, **58**, 466 (1936).

(14) Winstein and Henderson, *ibid.*, **65**, 2196 (1943).

kyl halide so much more than the α -halocarboxylate ion. Also k_c/k_H is hard to estimate since it may be considered to involve a large rate retardation due to two oxygen atoms which are ordinarily electron-attracting and the very large rate enhancement due to the negative charge of the O_2^- group.

TABLE V
RATES OF UNIMOLECULAR TYPE SOLVOLYSIS OF SOME BROMIDES

Compound	Solvent	Temp., °C.	k_1 (sec. ⁻¹)	Ref.
$CO_2^-CHBrCH_2CO_2^-$	H ₂ O ^a	25.8	4.65×10^{-6}	15
$CO_2^-CHBrCH_2CO_2^-$	H ₂ O, 0.9 M KNO ₃ ^a	25.8	6.34×10^{-6}	15
$CO_2^-CHBrCH_2CO_2^-$	MeOH	25.8	4.06×10^{-6}	16
$CH_3CHBrCH_2CO_2^-$	H ₂ O ^b	45.0	4.5×10^{-4}	17
$CH_3CHBrCH_2CO_2^-$	MeOH ^c	45.0	1.03×10^{-4}	16
$(CH_3)_2CBrCO_2^-$	H ₂ O ^d	44.3	2.13×10^{-3}	18
$(CH_3)_2CBrCO_2^-$	MeOH	44.3	2.6×10^{-4}	16
$(CH_3)_3CBrCH_2$	MeOH ^e	44.3	3.3×10^{-4}	
$CH_3CHBrCO_2^-$	MeOH	64.0	5.12×10^{-3}	Table II
$CH_3CHBrCH_2$	MeOH ^e	64.0	5×10^{-3}	

^a Interpolated between data at 25.00° and 37.39°. ^b Extrapolated from data at 25.0° and 38.0°. ^c At 0.2 M ionic strength, k_1 has the following values¹⁶: $\beta = 0.129 M$, $10^4 k_1 = 2.70$; $\beta = 0.085 M$, $10^4 k_1 = 2.13$. Using $k_1 = k_1 + k_2\beta$, $k_1 = 1.03 \times 10^{-4} \text{ sec.}^{-1}$; $k_2 = 1.30 \times 10^{-3} \text{ sec.}^{-1} M^{-1}$. ^d Values of $10^4 k_1$ (sec.⁻¹) at 25.0° and 35.0° are 1.21 ± 0.04 and 5.59 ± 0.08 , respectively. These values were calculated from the data given by Simpson¹⁸ on the hydrolysis of sodium α -bromoisobutyrate in initially neutral solution, assuming that the ratio of ionization constants of the α -bromo and α -hydroxy acid is 8.0 and using the equations developed by Bulcraig and Dawson.¹² Values of k_1 were satisfactorily constant up to 90% reaction at 25° and 70% reaction at 35°. ^e k_1 for t -butyl bromide at 25.0° is estimated at $3.53 \times 10^{-6} \text{ sec.}^{-1}$ on the basis of solvolysis rates in alcohol-water mixtures¹⁹ by a method to be published soon.²⁰ Taking E^\ddagger as 22.0 kcal.,¹⁹ k_1 is $3.3 \times 10^{-4} \text{ sec.}^{-1}$ at 44.3° and $2.6 \times 10^{-3} \text{ sec.}^{-1}$ at 64.0°. The ratio of specific rates of isopropyl and t -butyl bromide is tentatively taken²⁰ as 2×10^{-5} .

However, it is instructive to choose one solvent throughout and to contrast k/k_H for the α -bromopropionate ion with that for the α -bromoisobutyrate ion, $(CH_3)_2CBrCO_2^-$. Table V lists the necessary first order rate constants in methanol. It is seen that k/k_H for $CH_3CHBrCO_2^-$ is of the order of 10^2 or 10^3 while for $(CH_3)_2CBrCO_2^-$ it is 0.8. In the latter case, the carboxylate ion group is inferior to a methyl group. The data are consistent with a substantial driving force,^{3a} $RT \ln (k_\Delta/k_c)$, due to the O_2^- group in α -bromopropionate ion and at least a much smaller one in the case of the more highly α -substituted α -bromoisobutyrate ion. This decrease in the driving force of a neighboring group with α -methyl substitution has been observed previously.^{3a,b}

Consistent with a lowered interaction between

- (15) Long and Olson, *J. Phys. Chem.*, **41**, 267 (1937).
 (16) Madsen, *Z. physik. Chem.*, **92**, 98 (1918).
 (17) (a) Johansson, *Ber.*, **48**, 1262 (1915); (b) Olson and Miller, *This Journal*, **60**, 2687 (1938).
 (18) Simpson, *ibid.*, **40**, 674 (1918).
 (19) (a) Cooper and Hughes, *J. Chem. Soc.*, 1183 (1937); (b) Bateman, Cooper, Hughes and Ingold, *ibid.*, 925 (1940).
 (20) Winstein and Cruickshank, unpublished work.

the carboxylate ion group and the α -carbon atom in the transition state for ionization of α -bromoisobutyrate ion is the greater effect of solvent change than for α -bromopropionate ion. From the rate constants in Table V it is seen that the factor between water and methanol for α -bromoisobutyrate ion is approximately 8 whereas it is 2.4 for α -bromopropionate ion.

The extent of the superiority of the CO_2^- group over the CO_2R group for participation in unimolecular type displacement reactions is of some interest but not easy to judge. While k_c is high for the CO_2^- group and any positive driving force makes unimolecular reactions even easier to attain, k_c is very low in the case of the CO_2R group. Thus in the latter case even if k_Δ/k_c were appreciable, unimolecular reactions would be hard to attain. In the case of the reaction of ethyl α -bromopropionate with silver oxide in alcohol, one explanation¹⁴ but, as pointed out, not necessarily the unique one, was that the reaction is unimolecular in type but that the carboxy group does not participate. It is probable that the reaction is not unimolecular in type and thus no information is afforded regarding participation of the carboxy group.

Experimental

Solvents.—Commercial synthetic methanol, dried by the method of Bjerrum and Zechmeister,²¹ and containing less than 0.08% water from the miscibility temperature with cyclohexane,²² was used in this work. Conductivity water was used as solvent in the aqueous runs.

α -Bromopropionic Acid.—Eastman Kodak Co. material was redistilled at reduced pressure. The samples used in the course of the work were: I, b. p. 99.0° (13 mm.), n_D^{20} 1.4747, equivalent wt. 152.8 \pm 0.6 (calcd. 153.0), m. p. 24.2°; II, b. p. 98.5–98.8° (13.5 mm.), n_D^{20} 1.4737, equivalent wt. 152.8 \pm 0.6, m. p. 25.3°.

Inorganic Salts.—Sodium nitrate and bromide were Baker and Adamson reagent grade or C. P. materials dried at 120° before use. Sodium perchlorate was prepared halide-free by careful neutralization of J. T. Baker C. P. 70% perchloric acid with C. P. sodium carbonate to the methyl orange endpoint. Concentration of the solution gave crystalline material which was washed with a little ether, and dried to constant weight over sulfuric acid *in vacuo*.

Rate Measurements.—Reaction mixtures were prepared by mixing weighed amounts of α -bromopropionic acid and added salts and measured volumes of aqueous sodium hydroxide or methanolic sodium methoxide (prepared by dissolving sodium in the absolute methanol) in a volumetric flask, the volume being made up at room temperature. As quickly as possible the initial titre of base was determined by titration of an aliquot with standard acid. Aliquot portions (20 ml.) of the reaction mixture were sealed off in tubes and placed in a thermostat at $64.04 \pm 0.04^\circ$ for suitable intervals. On removal from the thermostat, the tubes were chilled in ice and the contents were analyzed for base by adding an excess of standard halide-free nitric acid and back-titrating with standard halide-free base to the phenolphthalein endpoint. The neutral solution was analyzed for bromide ion by titration with standard silver nitrate with eosin or, sometimes, dichlorofluorescein as indicator. Control experiments showed that both titrations were reliable within ordinary experimental error. "Zero" time was called

(21) Bjerrum and Zechmeister, *Ber.*, **56**, 894 (1923).

(22) Jones and Amstell, *J. Chem. Soc.*, 1316 (1930).

the time of removal of the first tube after attainment of temperature.

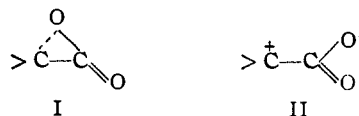
The "infinite" titer of bromide ion agreed well with the expected as indicated by the equivalent weights of the α -bromopropionic acid samples. The "infinite" titer of base was usually unreliable by a few per cent., probably due to reaction of the glass. Soft glass tubes were used in the experiments with methanolic solutions, and Pyrex tubes were employed for the aqueous runs.

In the runs with high base concentration, the reaction was followed chiefly by titration for bromide ion. With the low base concentrations, titration was carried out for both base and bromide ion except where bromide ion was added in large amounts initially. When added sodium perchlorate the rate constants based on the two titrations agreed closely (Table II). With added sodium nitrate, the rate constants from bromide titration were steady but those based on base titration were lower and drifted downward. In run 21 with 0.5 *M* added sodium nitrate, the base consumed during a run averaged $98.8 \pm 0.7\%$ of the bromide ion produced, while the analogous figure was $96.6 \pm 1.5\%$ for run 19 with *M* added sodium nitrate.

Summary

The hydrolysis and methanolysis of sodium α -bromopropionate in the presence of sodium hydroxide or methoxide was investigated in solutions of varying ionic strength at 64.04° . A kinetic analysis reveals that both the bimolecular and unimolecular specific reaction rate constants, k_2 and k_1 , respectively, increase with ionic strength.

The variation of k_1 with change in solvent and ionic strength is discussed in terms of a rate-determining ionization either to the zwitterion II (specific rate k_c), or the α -lactone I (specific rate k_Δ). An unambiguous decision regarding the reaction mechanism is not possible from the salt and solvent effects alone.



However, the sign of these effects and related evidence, particularly the high reactivity of α -bromopropionate ion compared to isopropyl bromide and the contrast with α -bromoisobutyrate ion, are consistent with the rate-determining ionization symbolized by k_Δ .

The ratio of rate constants for reaction of the intermediate in the solvolysis of α -bromopropionate ion with bromide ion and solvent, $k_{\text{Br}}/k_{\text{S}}$, derived from measurements in solutions containing high bromide ion concentrations, is 2.9 in methanol and 0.76 in water.

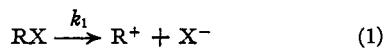
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[CONTRIBUTION FROM THE CHEMISTRY DEPARTMENT OF THE UNIVERSITY OF CALIFORNIA, LOS ANGELES]

The Correlation of Solvolysis Rates

BY ERNEST GRUNWALD AND S. WINSTEIN

One of the important mechanisms (A) for solvolysis^{1,2} of alkyl halides involves more than one stage and is at present best formulated as involving a rate-determining ionization (equation 1) to a cationic intermediate. The rate constant k_1



depends on the so-called ionizing power of the solvent, and it is possible from such rates to arrange solvents in a relative order. For example substitution of the unimolecular type³ proceeds slightly more rapidly in acetic acid than in absolute ethanol.⁴ The rate is increased by addition of water to alcohol or partly aqueous acetone or dioxane.^{1,2} Further, substitution is about as rapid in formic acid as in 50% aqueous ethanol.⁵

The question arises whether it is possible to assign to each solvent a definite number *Y* which is a quantitative measure of its ionizing power in determining k_1 . In this article is reported a scheme for correlating unimolecular solvolysis

rates with the aid of such a set of *Y* values and a simple functional relationship between k_1 and *Y*. Also, the theoretical implications of the method are discussed.

In addition to the solvolysis mechanism A there occurs solvolysis in neutral and acidic solvents by a process or processes (B, rate constant k_x) for which the nucleophilic character as well as the ionizing power of the solvent is important. The best understood concerted process is the so-called bimolecular substitution in which a solvent molecule plays a role such as that of a pyridine molecule in the Menshutkin reaction. One of the important problems for the proper understanding of such subjects as reactivity, stereochemistry of displacements and rearrangements^{1b} is that of sorting out the fractions of solvolysis proceeding by mechanisms A and B.

The scheme for correlating solvolysis rates allows one to make deductions regarding the rate by process A and therefore the fraction of solvolysis by mechanism A. This application of the method is being actively pursued and the procedure is illustrated in the present article for isopropyl *p*-bromobenzenesulfonate.

A Quantitative Measure of Ionizing Power. The *Y* Function.—The specific solvolysis rates k for a number of halides which, the accumulation

(1) (a) Hughes, *Trans. Far. Soc.*, **37**, 611 (1941); (b) Dostrovsky, Hughes and Ingold, *J. Chem. Soc.*, 173 (1946).

(2) Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., New York, N. Y., 1940, pp. 166 ff.

(3) Winstein, Grunwald, Buckles and Hanson, *THIS JOURNAL*, **70**, 816 (1948).

(4) Winstein, Hanson, and Grunwald, *ibid.*, **70**, 812 (1948).

(5) Dostrovsky and Hughes, *J. Chem. Soc.*, 166, 171 (1946).