

compounds with rotations of the order of ten degrees or more were used, because the nature of the function makes too great a percentage error in the answer if the percentage uncertainty in the rotation is too large.

TABLE II
ATOMIC ROTATION CONSTANTS FOR CARBON CALCULATED FROM ACCEPTED ROTATIONS AND A COMPARISON OF THE LATTER WITH ROTATIONS CALCULATED USING AN AVERAGE VALUE OF 2.50 FOR CARBON

Compound, methane	Accepted, (<i>M</i>)	<i>C</i>	Calcd., (<i>M</i>)
Methylethyl- <i>n</i> -butyl-	-11.4	2.50	-11.5
Methylethyl- <i>n</i> -pentyl-	-12.0	2.47	-12.8
Methylethylisobutyl-	-21.3	2.51	-20.8
Methyl- <i>n</i> -propylisobutyl-	-14.9	2.50	-15.0
Methyl- <i>n</i> -butylisobutyl-	-11.9	2.53	-10.8
Methyl- <i>n</i> -pentylisobutyl-	-9.3	2.49	-9.6

Table II also includes a column of rotations calculated by use of Table I and equation 1, employing the average value of 2.50 for carbon. As might be expected from the constancy of the values for carbon, good agreement is found with the accepted rotations. This latter column is not intended as any proof of the method; the consistent values for carbon establish its validity. Rather, it is inserted merely to illustrate the proportional change in the calculated rotation when there is a variation in the value for carbon.

Calculation of Molar Rotation of Alkyl Halides.—The method is also applicable to alkyl halides. Using the same general method and a value of 2.50 for carbon, the contribution of the halogen atom can be found, and once known, the rotations of alkyl halides can then be predicted. Actually, like hydrogen the value for the halogen atom alone need not be found, but rather, the value (*X*-H), the difference in the values for the halogen and hydrogen, is more easily solved for and is sufficient for the calculations.

The following example will illustrate the calculation of the value (*Br*-H). Consider the compound bromoethylethylmethylmethane. Using the following values for the four groups in the order named: $(4/3)C + (8/9)H + (1/9)Br$, $(4/3)C + H$, $C + H$, H , and substituting into equation 1 and simplifying gives

$$(M) = (4C^3/6561)[36C^2(Br-H) + 15C(Br-H)^2 + (Br-H)^3] \quad (4)$$

Using a value of 2.50 for *C*, the equation becomes

$$(M) = 0.009465 [225(Br-H) + 37.5(Br-H)^2 + (Br-H)^3] \quad (5)$$

For this particular compound (*M*) has the value -38.8° . Thus, the quantity (*Br*-H) can be found by solving the cubic equation. A graphical solution yields the value 7.40 for (*Br*-H).

TABLE III
A COMPARISON OF CALCULATED AND ACCEPTED ROTATIONS FOR ALKYL BROMIDES

Compound	Accepted, (<i>M</i>)	Calcd., (<i>M</i>)
1-Bromo-3-methyloctane	14.7	15.2
1-Bromo-5-methylheptane	14.9	15.5
1-Bromo-4-methylhexane	21.9	22.0

Use of this value to calculate rotations for various alkyl bromides yields good agreement with accepted values from the literature as shown in Table III.

Discussion

Though good agreement was obtained between calculated and accepted rotations in the examples presented here and in others not mentioned, notable exceptions were found. Among the alkanes and alkyl halides, these, in all cases, were compounds which, when constructed from Fisher-Hirschfelder-Taylor models, exhibited unavoidable steric hindrance. Compounds which have possible steric hindrance between groups, but which also have configurations which could avoid hindrance, showed good agreement. This seems to indicate that the criterion for applicability of this method is whether or not steric hindrance is *unavoidable*, rather than *possible*. Lack of agreement might thereby indicate unavoidable steric hindrance.

The rotations of compounds with isopropyl groups attached to the asymmetric carbon atom have for some time been known to fall out of line with the rotations of homologous series. Erroneous answers are obtained with this method in such cases. A value other than that given in Table I must be used for the isopropyl group to make the method work. Furthermore, a different value for each case is obtained, showing that the hindrance causing the error depends on the other three groups attached to the asymmetric carbon atom.

It might also be noted that reversing the assignment of groups to the four terms in the equation will result in a change of sign but not of magnitude. The method is thus applicable to predicting the rotation of either isomer and a standardization of method of choosing the order of terms is all that is needed to make the answers conform with absolute configuration.

The particular types of compounds chosen here were those purposely avoiding the many factors complicating the rotation phenomenon, such as association, solvation, hydrogen bonding, chelation, Cotton effect, etc. It is hoped that the method can be extended to include other groups, ring compounds, compounds with more than one asymmetric carbon atom, and even perhaps those with asymmetric atoms other than carbon.

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The Hydrolysis of Some Alkyl Lactates I. Alkaline Hydrolysis¹

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The kinetics of the alkaline hydrolysis of certain normal and branched-chain alkyl acetates² and benzoates³ have been studied, and the effects of lengthening and of branching the alkyl carbon

(1) Abstracted from a thesis submitted by K. H. Vogel to the Committee on Graduate Degrees, Carnegie Institute of Technology, in partial fulfillment of the requirements for the D.Sc. degree.

(2) H. Olsson, *Z. physik. Chem.*, **118**, 107 (1925).

(3) E. Tammila, *Ann. Acad. Sci. Fennicae*, **A59**, No. 3, 3 (1942).

chain on both the activation energy and the frequency factor have been determined. An investigation of the kinetics of the alkaline hydrolysis of some alkyl and substituted alkyl lactates, initiated several years ago,⁴ has now been completed, and the results are given in this paper.

Experiment Method

The hydrolyses of the *n*-alkyl and of the branched-chain and substituted alkyl lactates were carried out in thermostats which held the temperature constant to within ± 0.02 and $\pm 0.01^\circ$, respectively. Temperatures were measured by calibrated Beckmann thermometers.

Each reaction flask for the hydrolyses of the *n*-alkyl lactates consisted of a 500-ml. and a 300-ml. distilling flask with bulbs joined together so that one side of the vessel could hold 200 ml. of solution and the other side 100 ml. Each reaction flask for the other hydrolyses consisted of two 500-ml. wide-mouth Pyrex erlenmeyer flasks with mouths sealed together and with the ends blown out at an angle of 120° . A length of 25-mm. Pyrex tubing was sealed into each 500-ml. erlenmeyer section, in order to provide means for introducing the solution and for tilting the flask while the solutions were mixed.

To start the hydrolyses of the *n*-alkyl lactates, 100 ml. of standard base was introduced into one side of the reaction flask and 100 ml. of standard aqueous ester into the other, the solutions were allowed to reach the temperature of the thermostat, and were then mixed for about three seconds. The electric stop-watch was started when the combined solution reached the larger side of the reaction flask after mixing. The other lactates were charged into dried, weighed Victor Meyer bulbs blown from 8-mm. Pyrex tubing. A bulb was placed in one side of the reaction flask and a measured amount of standard base in the other. Measured amounts of water to give the desired concentrations of aqueous ester and of base (0.005 *M* for both in most cases) were added to each side of the flask. The bulb was broken, the solutions were allowed to come to the temperature of the thermostat and were then mixed for 45 seconds. The electric stop-watch was started at the moment of mixing.

Samples from all hydrolyses were withdrawn at intervals, discharged into stop-solutions containing a measured excess of standard hydrochloric acid, then back-titrated with standard sodium hydroxide solution. Cresol red indicator was used for the *n*-alkyl lactates and brom phenol blue for most of the others. In the *s*- and *t*-butyl lactate runs, fading of the end-point on back-titration could be avoided only by carrying out the reactions in solutions 0.01 *M* in both ester and base and by using phenolphthalein indicator.

Carbon dioxide-free water and base were used in all experiments, and the reaction mixtures were protected from atmospheric carbon dioxide.

The *n*-alkyl lactates (Eastman Kodak Co.) were dried over "Drierite" for several days, then fractionally distilled. The remaining lactic esters were obtained from the Eastern Regional Laboratory of the United States Department of Agriculture.⁵ They were vacuum distilled in an all glass system and stored over anhydrous calcium chloride in a desiccator. The boiling points, refractive indices and saponification equivalents of all esters agreed well with literature values.

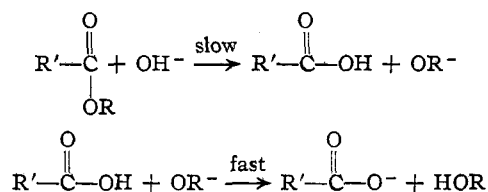
Second-order velocity constants (liters mole⁻¹ min.⁻¹) were determined from the slopes of the best straight-line plots of reciprocal concentration vs. time.

Results and Discussion

Second-order velocity constants were determined at 0 and 15° for the alkaline hydrolyses of the *n*-alkyl lactates, at 10 and 30° for the *t*-butyl ester, and at 3 and 10° for the remaining lactates. The rate of hydrolysis of *n*-alkyl lactates in pure water was investigated and shown to be negligible compared to the velocity of the alkaline hydrolysis of these esters⁶; therefore the average rate constants

shown in Table I cannot contain appreciable contributions from rates of neutral hydrolyses. The activation energies (E_a) and the "frequency factors" (*PZ*) for the alkaline hydrolysis of the lactic esters were calculated and tabulated (Table I). General agreement with the activation energies and frequency factors calculated from some rate constants determined by Krige and Hollow,⁷ Dean⁸ and Salmi and Leino⁹ was observed.

The results of this work are consistent with the mechanism proposed by Hammett¹⁰ and by Day and Ingold,¹¹ termed by the latter investigators "bimolecular basic hydrolysis with acyl-oxygen fission" and labeled B'2:



This process involves a slow attack of hydroxyl ion on the carbonyl carbon, followed by the expulsion of alkoxyl ion, which is converted rapidly and irreversibly to the alcohol by transfer of a proton from the carboxylic acid formed. The nature of the intermediate in the first step has been investigated recently by Bender,¹² but the results of his investigation have no bearing on the work described here or in the two following communications.

TABLE I

Lactic ester	k_{90}	k_{30}	k_{100}	k_{150}	E_a , cal.	$PZ \times 10^{-8}$
Methyl ⁴	21.32			259.2	10,600	67.35
Ethyl ⁴	8.98			24.1	10,300	16.74
<i>n</i> -Propyl ⁴	7.06			19.4	10,500	19.13
Isopropyl					9,400 ^a	0.956 ^a
<i>n</i> -Butyl ⁴	6.79			19.0	10,700	26.10
Isobutyl		9.07	14.67		10,650	24.8
<i>s</i> -Butyl		1.78	2.65		8,750	0.156
<i>t</i> -Butyl ^b			0.251		12,100	5.62
2-Methoxyethyl	27.44	44.30			10,650	71.7
2-Chloroethyl	58.2	96.6			10,900	258.2

^a Calculated from rate constants determined by Salmi and Leino.⁹ ^b $k_{30} = 1.037$.

The energy of activation for the alkaline hydrolysis of *s*-butyl lactate is about 2 kcal./mole lower, and that of the *t*-butyl ester roughly 2 kcal./mole higher, than the essentially constant values observed for the remaining esters (Table I). Except for the case of *s*-butyl lactate, these observations parallel those of Olsson² on the aqueous alkaline hydrolysis of acetone. Neither of the latter investigations revealed a significant deviation of activation energy in the case of the *s*-butyl esters.

Values of *PZ* derived from this work and from studies of the alkaline hydrolysis of alkyl acetates¹ and benzoates³ show a consistent variation; those for isopropyl esters are smaller than those for *n*-

(7) G. J. R. Krige and K. Hollow, *Trans. Faraday Soc.*, **30**, 644 (1934).

(8) E. W. Dean, *Am. J. Sci.*, **35**, 605 (1913).

(9) E. J. Salmi and E. Leino, *Suomen Kemistilehti*, **17B**, 19 (1944).

(10) L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., New York, N. Y., 1940, pp. 355-357.

(11) J. N. E. Day and C. K. Ingold, *Trans. Faraday Soc.*, **37**, 886 (1941).

(12) M. L. Bender, *This Journal*, **73**, 1626 (1951).

(4) A. A. Colon and J. C. Warner, *Bol. oficial. asoc. quim. Puerto Rico*, **2**, No. 2, 15 (1943).

(5) Courtesy of Drs. C. H. Fisher and E. M. Filachione.

(6) K. H. Vogel and J. C. Warner, *This Journal*, **75**, 6074 (1953).

propyl esters, and those for the branched butyl esters are generally lower than those for primary butyl esters. The variations among the isomeric butyl lactates are much greater, however, than are the differences between members of the corresponding butyl acetates and benzoates. Nevertheless, in all cases a pronounced minimum in the *PZ* factor among the butyl esters is encountered with the *s*-butyl compound. Examination of Fisher-Hirschfelder models reveals the possibility that more mechanical interference with the approach of the attacking hydroxyl group to the carbonyl carbon may be offered by a *s*-butyl ester than by other butyl esters and that the low *PZ* factors may be subject to interpretation on this basis.

A comparison of the data for ethyl, *n*-propyl, β -methoxyethyl and β -chloroethyl lactates demonstrates that substitution of a β -hydrogen atom of the ethyl group of ethyl lactate produces no significant effect of E_a . The rate increases resulting from β -methoxy and β -chloro substitution are caused by increased *PZ* factors.

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The Hydrolysis of Some Alkyl Lactates. II. "Neutral" and Acid Hydrolyses¹

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An investigation of the kinetics of the acid hydrolyses of certain alkyl and substituted alkyl lactates, initiated several years ago,² has now been completed, and the effects of lengthening, of branching and of substituting the alkyl carbon chain upon the activation energies and frequency factors are reported in this paper. Studies on the "neutral" hydrolyses of some *n*-alkyl lactates are also reported.

Experimental Method

The sources and methods of purification of the lactic esters, the preparation and care of reagents and solutions and the precision of thermostatic controls were described in the preceding paper.³ To start a hydrolysis a Victor Meyer bulb containing a known amount of ester was placed in a flask together with the amount of standard hydrochloric acid (acid hydrolysis) or water ("neutral" hydrolysis) necessary to give the desired ester concentration. In the case of the *n*-alkyl lactates, each solution was allowed to reach the temperature of the thermostat before the bulb was broken, but with most of the other lactates the bulb was broken in the catalyzing acid before the flask was placed in the thermostat. Aliquot portions of solutions of the *n*-alkyl esters were discharged into sufficient standard sodium hydroxide solution to neutralize just the catalyzing hydrochloric acid. Aliquot portions of solutions of the other lactates were discharged onto washed cracked ice. Excess acid (acid hydrolysis) or total acid ("neutral" hydrolysis) was titrated with standard sodium hydroxide solution using cresol red indicator. Time was measured with an electric stop-watch.

Second-order rate constants for the acid hydrolyses were

(1) Abstracted from theses submitted by A. A. Colon and K. H. Vogel to the Committee on Graduate Degrees, Carnegie Institute of Technology, in partial fulfillment of the requirements for the D.Sc. degree.

(2) A. A. Colon and J. C. Warner, *Bol. oficial asoc. quim. Puerto Rico*, **2**, No. 2, 15 (1943).

(3) K. H. Vogel and J. C. Warner, *THIS JOURNAL*, **75**, 6072 (1953).

evaluated from the slopes of plots of $\log 1/(a - x)$ vs. time in accordance with the pseudo first-order rate equation

$$k = \frac{2.303}{ct} \log \frac{1}{a - x} + \text{constant}$$

in which a represents the initial concentration of ester, x the concentration of lactic acid at time t , and c the essentially constant total acid concentration. Second-order rate constants for the "neutral" hydrolyses were evaluated from the slopes of the plots of $\log (a^{1/2} + x^{1/2})/(a^{1/2} - x^{1/2})$ vs. time in accordance with the rate equation

$$k = \frac{2.303}{(ab)^{1/2}t} \log \frac{a^{1/2} + x^{1/2}}{a^{1/2} - x^{1/2}} + \text{constant}$$

in which a is the initial concentration of ester and x the concentration of acid formed at time t ; the value of b , the ionization constant of lactic acid, was taken from the work of Martin and Tartar.⁴ This rate equation is obtained by integrating: $dx/dt = k(a - x)(bx)^{1/2}$. The units of all rate constants are liters/mole⁻¹ min.⁻¹.

Results and Discussion

In Table I, the second-order rate constants (k), activation energies (E_a), and *PZ* factors for the acid hydrolyses of nine lactic esters are given. Table II shows similar data for the "neutral" hydrolyses of four *n*-alkyl lactates.

TABLE I
ACID HYDROLYSES

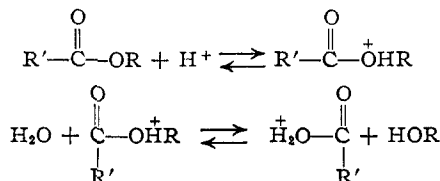
Lactate	10 ³ <i>k</i> _{25°}	10 ³ <i>k</i> _{40°}	10 ³ <i>k</i> _{50°}	<i>E</i> _a , cal.	<i>PZ</i> × 10 ⁻³ (using <i>k</i> _{50°})
Methyl	9.48	20.11		14150	1.55
Ethyl	10.01	20.69		13700	0.77
<i>n</i> -Propyl ^a	9.73	20.35		13700	0.72
<i>n</i> -Butyl	8.70	18.27		14000	1.04
Isobutyl	10.61	23.97	51.13	15300	11.47
<i>s</i> -Butyl	5.41	11.95	26.07	15300	5.66
<i>t</i> -Butyl	6.75	22.46	81.18	24200	1.77 × 10 ⁷
2-Methoxyethyl	8.39	17.69		14050	1.15
2-Chloroethyl	5.63	12.15		14500	1.61

^a *k*_{60°} = 7.899 × 10⁻².

TABLE II
"NEUTRAL" HYDROLYSES

Lactate	10 ³ <i>k</i> _{40°}	10 ³ <i>k</i> _{50°}	<i>E</i> _a , cal.	<i>PZ</i> × 10 ⁻³ (using <i>k</i> _{50°})
Methyl	25.90	118.08	15700	23.10
Ethyl	23.77	113.30	16200	47.49
<i>n</i> -Propyl	22.66	111.50	16500	73.42
<i>n</i> -Butyl	38.28	186.70	16400	105.5

With the exception of the case of *t*-butyl lactate, the pseudo first-order kinetics and the similarity among activation energies and *PZ* factors for the acid hydrolyses of the lactic esters listed in Table I are consistent with the mechanism proposed by Day and Ingold⁵ (termed "bimolecular acid hydrolysis with acyl-oxygen fission" and labeled A'2) and by Roberts⁶ (labeled II).



(4) A. W. Martin and H. V. Tartar, *ibid.*, **59**, 2672 (1937).

(5) J. N. E. Day and C. K. Ingold, *Trans. Faraday Soc.*, **37**, 686 (1941).

(6) I. Roberts, *Ann. N. Y. Acad. Sci.*, **39**, 375 (1940).