There is therefore considerable basis for the generalization that the conversion of an electrically neutral acetic acid derivative to an electrically charged entity, no matter whether this be positively charged or negatively charged, involves a considerably greater decrease in entropy than does the analogous process in the case of a formic acid derivative, whereas the enthalpy effects are likely to be nearly the same for the acetic and formic acid derivatives.

In the gaseous state an acetic acid derivative probably possesses 10 or 11 cal./deg. more entropy than does the corresponding formic acid derivative. (The entropy of gaseous ethanol is 10.6 units greater than that of gaseous methanol, the corresponding difference for acetaldehyde and formaldehyde is 11.2.[12]) This difference can reasonably be assigned to the entropy associated with the internal motions of the methyl group, the mass effect being trivial. A considerable portion of the difference probably disappears on solution in water since the entropy of solution of gaseous ethanol is 6 units more negative than that of gaseous methanol.[13] Some of this effect is no doubt associated with a partial freezing out in solution of the internal motions of the methyl group, but there are indications[13,14] that interference with the freedom of motion of the solvent molecules is also involved. It seems likely therefore that the entropy of a dissolved acetic acid derivative is greater than that of the corresponding formic acid derivative by some 4 to 6 cal./deg. On this basis we may expect that the entropy of acetate ion is approximately the same as that of formate ion, but that the transition state for the alkaline hydrolysis of methyl acetate is several cal./deg. more negative than that for methyl formate.

One could account for equality of the entropies of the charged molecular species derived from acetic acid and from formic acid by supposing merely that all of the internal motion of the methyl group is frozen out by the charge through an effect of the sort suggested by Kirkwood[15] but in order to account for a more negative entropy in the acetic acid derivative, one must certainly assume that some hampering of the motions of the solvent molecules must result from the substitution of methyl for hydrogen in the solute ion. This is of course exactly opposite to what would be expected from the picture in which the two ions are thought of as conducting spheres immersed in a dielectric medium with the acetate having the greater volume, a picture which accounts satisfactorily[16] for the fact that the conversion of methylamine to methylammonium ion involves an entropy change 4.2 cal./deg. more *positive* than does the conversion of ammonia to ammonium ion. It is not however inconsistent with a picture in which the charge is confined to a limited portion of the charged molecule, the COOR structure, but is displaceable within that region. The substitution of a methyl group for hydrogen would then represent the attachment to this conducting region of a region of low dielectric constant. The charge would under such conditions tend to move away from the methyl group and toward the region of high dielectric constant represented by the solvent. This would increase the binding to the ion of the solvent molecules and would thereby decrease the entropy associated with the motions of the solvent molecules.[17]

NEW YORK, N. Y.

[12] "Selected Values of Chemical Thermodynamic Properties," Circular of the National Bureau of Standards 500.

[13] R. E. Powell and W. M. Latimer, *J. Chem. Phys.*, **19**, 1139 (1951).

[14] H. S. Frank and M. W. Evans, *ibid.*, **13**, 507 (1945).

[15] See F. P. Price and L. P. Hammett, THIS JOURNAL, **63**, 2392 (1941).

[16] A. G. Evans and S. D. Hamann, *Trans. Faraday Soc.*, **47**, 34 (1951).

[17] This point of view developed as a result of discussion of this problem with Dr. L. Onsager.

---

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, COLUMBIA UNIVERSITY]

# Structural Studies on Ester Hydrolysis by Strong Base Ion Exchangers[1]

BY HAROLD SAMELSON AND LOUIS P. HAMMETT

RECEIVED SEPTEMBER 8, 1955

The rates of the alkaline hydrolysis in 85% ethanol of three typical esters, ethyl acetate, ethyl *n*-hexanoate and ethyl phenylacetate by seven ion exchangers of the quaternary ammonium hydroxide type which differed in the alkyl groups attached to nitrogen follow the second-order rate law to considerable precision. The hydrolysis rate of hexanoate is materially lower on all the resins studied than it is in homogeneous strong base solution. This effect is presumably to be attributed to the greater loss of entropy which this entropy-rich molecule undergoes in the formation of the transition state of the reaction. Rates of reaction of all esters with the resin in which the functional group is $RN(CH_3)_3^+$ are considerably lower than they are with resins whose functional groups contain ethyl, *n*-hexyl and benzyl groups; the $RN(CH_3)_3^+$ resin is much less swollen by water or aqueous ethanol than are the other resins. In other respects changes in the structure of the functional group have only small effects on the hydrolysis rates.

In an extension of our studies[2] on the catalytic properties of ion exchange resins we have investigated some of the structural factors which affect the rate of hydrolysis of an ester by a resin of the quaternary ammonium hydroxide type. The reaction is

$$\text{-}PCH_2NR_1R_2R_3^+ + OH^- + R_4COOC_2H_5 \longrightarrow \text{-}PCH_2NR_1R_2R_3^+ + R_4COO^- + C_2H_5OH$$

where $\text{-}PCH_2NR_1R_2R_3^+$ is a unit of the structure of a bead-form cross-linked polymer obtained by (1) suspension polymerization of styrene together with

[1] The work reported herewith was carried out as project NR 056-062 under contract N6onr-271 between the Office of Naval Research and Columbia University. Reproduction in whole or in part permitted for any purpose of the United States Government.

[2] (a) V. C. Haskell and L. P. Hammett, THIS JOURNAL, **71**, 1284 (1949); (b) S. A. Bernhard and L. P. Hammett, *ibid.*, **75**, 1798 (1953); (c) **75**, 5834 (1953); (d) S. A. Bernhard, E. Garfield and L. P. Hammett, *ibid.*, **76**, 991 (1954); (e) P. Riesz and L. P. Hammett, *ibid.*, **76**, 992 (1954).

0.5% divinylbenzene, (2) chloromethylation of the resulting product to –PCH$_2$Cl which is a cross-linked polymeric benzyl chloride, (3) "ammination" of –PCH$_2$Cl to –PCH$_2$NR$_1$R$_2$R$_3^+$ + Cl$^-$, (4) exchange of the chloride ion with hydroxyl ion.[3]

## Experimental

**Preparation of the Resins.**—The cross-linked polystyrene beads were prepared from a mix containing 0.5% divinylbenzene.[2d] The chloromethylation process was similar to that described by Pepper, Paisley and Young.[3d] Fifty grams of the polystyrene beads was immersed in 1000 g. of chloromethyl ether and allowed to swell overnight in a closed flask. The mixture was then heated with stirring under reflux to 45° and 15 g. of anhydrous zinc chloride was added. After 60 hours the beads were separated and washed alternately with tetrahydrofurane, ethanol, ethanol–water and water until the color had changed from deep wine-red to light yellow and no chloride could be detected in the washings. A roughly quantitative exploratory study of the ammination reaction was carried out on a sample of –PCH$_2$Cl beads from a commercial source. This behaved similarly to the material we prepared, although it had a lower degree of chloromethylation and was not so largely swollen by tetrahydrofurane.

In a typical preparative ammination 7 g. of the –PCH$_2$Cl polymer, 100 ml. of triethylamine and 100 ml. of acetonitrile were stirred 24 hours at 70°. The resulting beads were washed first with ethanol, then with water, and were subsequently cycled several times between chloride and hydroxyl forms by successive treatments with 1 *M* sodium hydroxide and with 1 *M* hydrochloric acid. The product was stored in the chloride form and converted to the hydroxide form only in amounts which would be used within a period of one week. After conversion to the hydroxide form the resin was kept under 1 *M* sodium hydroxide. The only important variation from this procedure was in the case of trihexylamine where benzonitrile was used instead of acetonitrile because this amine is relatively insoluble in the latter.

The exploratory study of the ammination reaction showed that: (1) the maximum amount of reaction obtained with triethylamine over long periods at either 25 or 78° corresponds to only 72% of the benzene rings calculated to be present from the exchange capacity of the resulting resin on the assumption that no more than one CH$_2$Cl group is present per benzene ring; (2) with bulkier amines containing *n*-hexyl or benzyl groups reaction becomes very slow or ceases when the proportion of amine reacted amounts to from 50 to 70% of the proportion obtained with triethylamine; (3) with a large excess of triethylamine present the rate drops off with time much faster than would be predicted for a first-order reaction; (4) the rate is an order of magnitude or so faster with triethylamine than with amines containing *n*-hexyl or benzyl groups; (5) in the reaction with triethylamine the specific rates are, within 10%, the same in the presence of benzonitrile and of acetonitrile, even though the former solvent is an excellent swelling agent for the –PCH$_2$Cl resin and the latter a poor swelling agent; (6) with triethylamine the reaction is about 90% complete in 1 hour at 78°, while the half time at 25° is of the order of 5 hours. Items 5 and 6 may be taken as evidence of considerable weight in favor of a chemically controlled rather than a diffusion controlled process.

**Other Materials.**—The esters were dried and fractionated from anhydrous sodium carbonate through an effective column. Saponification numbers were within 0.5% of theoretical. The solvent was "85% ethanol," and was prepared by redistilling 95% reagent grade ethanol at 7:1 reflux ratio through a 4 foot column packed with glass helices and diluting with water in the proportion of 460 ml. of alcohol in a total volume of 500 ml. The solvent was always prepared within 24 hours before the kinetic experiments in which it was used.

**Procedure.**—A rather laborious procedure for determining the extent of the ester hydrolysis was dictated by the following considerations: (1) the hydroxyl form of some and probably of all of these resins decomposes seriously on drying even under the most gentle conditions; (2) the resin content of samples of wet resins or of suspensions is not reliably reproducible; (3) the resin must be protected against absorption of carbon dioxide from the air; (4) on lengthy storage of the hydroxyl form of the resin with aqueous ethanol in the presence of air a partial neutralization of the resin occurs, presumably through the formation of acetic acid.

The standard procedure employed was as follows. About 30 milliequivalents of the resin was washed with carbon dioxide-free water until free of sodium hydroxide. Within an hour before use it was washed several times with the 85% ethanol solvent. The sample was then divided into eight roughly equal portions to each of which solvent was added, followed by addition of 1 ml. of an ester solution to each of seven of the flasks. All were diluted to 10 ml. with solvent, stoppered, sealed with paraffin, mixed and brought to temperature in the thermostat. Each flask contained about 0.6 milliequivalent of ester in the case of ethyl acetate and phenyl acetate, and 0.4 in the case of the hexanoate; the final reaction mixture contained 85% by weight of ethanol. Zero time for the reaction was taken as the time of mixing.

The flasks were rotated in the thermostat to produce the requisite mixing.[2a] At suitable time intervals a flask was opened and the resin was washed and transferred as rapidly as possible to a fritted glass funnel, using 95% alcohol. It was then treated on the funnel with 2 *M* sodium chloride solution and washed alternately with this solution and with water until the sodium hydroxide produced by the exchange was completely in the filtrate, where it was titrated. This titration measured the quantity $b - x$, the equivalents of unreacted hydroxide present in the sample at a time defined as that at which the contents of the flask were first poured into the funnel. The resin remaining in the funnel was then reconverted to the hydroxide form with sodium hydroxide solution, washed free of soluble base, and converted to the chloride form as before, the resulting sodium hydroxide again being titrated. This titration measures a quantity $b'$, which should be the number of equivalents of hydroxide in the resin sample at time zero. It was however found that a blank experiment usually showed a loss in titer; this averaged 1.7%. This is to say the first of the two successive titrations was smaller than the second, instead of being equal. This loss in titer was independent of the time during which resin and alcohol solvent had been in contact, and it obviously did not result from absorption of carbon dioxide or the like during the analytical procedure, since this would affect the second titration as much as the first. We have assumed that it resulted from some process connected with the initial preparation of the reaction mixture, that it affected all samples of a given set of eight in the same proportion, and consequently that the quantity $b$ is given by $b = b'r$ where $r$ is the ratio of the first titration of the blank to the second titration.

All measurements were made at 25.00°.

The uncertainties in the values of the quantities $b$ and $b - x$ and in the value of $a$, the number of equivalents of ester present at the start of the reaction are estimated at $3 \times 10^{-6}$ and the uncertainty in the time at 20 sec. The expected scatter in the second-order specific rates resulting from these uncertainties is 2%.

## Results and Discussion

Within the range of reaction studied, from 67 to 84%, the quantity

$$\frac{v}{a - b} \log \frac{b(a - x)}{a(b - x)}$$

in which $a$ = equivalents of ester, and $b$ = equivalents of resin hydroxide present in the sample of total volume $v$ at time zero, and $x$ = equivalents of hydroxide which had reacted in this volume at time $t$, was closely linear in $t$. The probable error in $k$ calculated from the scatter of the experimental points was generally in the range from 1 to 2% with one value of 3%. The intercept of this linear plot was usually a few minutes (in the extreme case 5 minutes) earlier than the estimated zero time of the

---

[3] (a) C. H. McBurney, U. S. Patent 2,591,574 (April 1, 1952); (b) Dow Chemical Company, British Patent 662,314 (Dec. 5, 1951); 677,350 (Aug. 13, 1952); (c) S. L. Thomas, paper presented at the 120th Meeting of the American Chemical Society, New York, Sept., 1951; (d) K. W. Pepper, H. M. Paisley and M. A. Young, *J. Chem. Soc.*, 4097 (1953).

reaction. This corresponds to a reasonable estimate of the uncertainty in the zero time. The deviations from linearity appear to be random and the specific rates calculated from the slopes of the plots agree to about 3% in duplicate measurements, which were made in a number of cases.

In view of our previous experience with catalysis by ion-exchange resins it is not surprising that the equation for a homogeneous reaction may be employed for this kind of heterogeneous reaction. In view of the fact that the actual resin composition changes during the reaction, hydroxyl ion being replaced by the anion produced in the hydrolysis of the ester, and that this replacement presumably alters the solvent content of the resin, one might have expected larger deviations from the simple second-order behavior than are actually observed.

Table I lists the specific rates observed with three esters of characteristically different structures. The resins are denoted by the composition of the functional group; $C_6H_{13}$ refers to *n*-hexyl, $CH_2C_6H_5$ to benzyl. The uncertainties indicated are the probable errors computed in the least squares determination of the specific rates from the experimental data. Table II lists the corresponding efficiencies, defined[2] as the ratio of the specific rate of reaction of ester with the resin to the specific rate of reaction of ester with strong base in homogeneous solution.[4]

TABLE I

SPECIFIC RATES IN $10^3$ L.-MOLE$^{-1}$-SEC.$^{-1}$ FOR ESTER HYDROLYSIS BY STRONG BASE RESINS

| Resin \ Ester | Ethyl acetate | Ethyl *n*-hexanoate | Ethyl phenyl-acetate |
|---|---|---|---|
| $RN(CH_3)_3^+$ | 5.98 ± 0.08 | 0.755 ± 0.01 | 6.59 ± 0.04 |
| $RN(C_2H_5)_3^+$ | 6.70 ± .06 | 1.15 ± .01 | 9.71 ± .11 |
| $RN(C_2H_5)_2(C_6H_{13})^+$ | 6.44 ± .10 | 1.33 ± .02 | 10.4 ± .2 |
| $RN(C_2H_5)(C_6H_{13})_2^+$ | 6.39 ± .08 | 1.45 ± .03 | 10.2 ± .1 |
| $RN(C_6H_{13})_3^+$ | 5.78 ± .07 | 1.40 ± .02 | 10.5 ± .1 |
| $RN(CH_3)_2(CH_2C_6H_5)^+$ | 6.86 ± .1 | 1.27 ± .01 | 11.2 ± .2 |
| $RN(C_2H_5)_2(CH_2C_6H_5)^+$ | 6.57 ± .2 | 1.26 ± .01 | 10.5 ± .1 |

In view of (1) the validity of the second-order rate law, (2) the appearance in the case of ethyl phenylacetate of efficiencies significantly greater than unity, (3) the higher efficiency for phenylacetate than for hexanoate,[5] we conclude that the rate-determining process in the reaction of ester with resin is the chemical reaction, little, if any, modified by the diffusion process from exterior to interior of the bead.

TABLE II

EFFICIENCIES OF STRONG BASE RESINS FOR ESTER HYDROLYSIS

| Resin/Ester | Ethyl acetate | Ethyl *n*-hexanoate | Ethyl phenyl-acetate |
|---|---|---|---|
| $RN(CH_3)_3^+$ | 0.86 | 0.36 | 0.65 |
| $RN(C_2H_5)_3^+$ | .96 | .56 | 0.98 |
| $RN(C_2H_5)_2(C_6H_{13})^+$ | .93 | .64 | 1.03 |
| $RN(C_2H_5)(C_6H_{13})_2^+$ | .92 | .70 | 1.02 |
| $RN(C_6H_{13})_3^+$ | .83 | .68 | 1.04 |
| $RN(CH_3)_2(CH_2C_6H_5)^+$ | .99 | .61 | 1.11 |
| $RN(C_2H_5)_2(CH_2C_6H_5)^+$ | .95 | .61 | 1.04 |

The relatively low efficiency for hexanoate shown by all resins appears to be another example of the entropy effect previously observed[2b] in the acid-catalyzed ester hydrolysis. The transition state for the reaction in the resin is subjected to severe restrictions with respect to the freedom of internal motion. Consequently that ester, the hexanoate, which possesses the most internal entropy loses the most in the formation of the transition state.

Strikingly low efficiencies for all the esters studied are shown by the $RN(CH_3)_3^+$ resin. These are perhaps connected with the fact that this resin in the hydroxide form does not swell perceptibly either in water or in 85% ethanol, whereas all the others do in both solvents. (In the chloride form this resin and the $RN(C_6H_{13})_3^+$ resin fail to swell perceptibly in water while all the others do.) The low swelling and low efficiencies suggest that in some way this resin has become more heavily cross linked than the others. However the experience with acid-catalyzed hydrolysis by ion-exchange resins[2b] would predict that the ester with the highest efficiency, the phenylacetate, would be least affected by an increase in cross linking. In the present case the change from the $RN(C_2H_5)_3^+$ to the $RN(CH_3)_3^+$ resin decreases the efficiency for the hydrolysis of ethyl phenylacetate considerably more than it does for that of ethyl acetate. The effect may therefore belong in the category of the specificities observed by Riesz and Hammett[2e] in the acid-catalyzed hydrolysis of esters by ion-exchange resins. The only other suggestions of this kind of specificity are the relatively high efficiency for the hydrolysis of ethyl phenylacetate shown by the resin $RN(CH_3)_2(CH_2C_6H_5)^+$ and the continuous increase in the ratio of the efficiencies for hexanoate and acetate shown in the sequence from $RN(C_2H_5)_3^+$ to $RN(C_6H_{13})_3^+$.

NEW YORK, N. Y.

---

[4] The specific rate of the alkaline hydrolysis of ethyl acetate in homogeneous 85% ethanol was taken as 6.95 × $10^{-3}$ l.-mole$^{-1}$-sec.$^{-1}$, that of ethyl *n*-hexanoate as 2.07 × $10^{-3}$ (D. P. Evans, J. J. Gordon and H. B. Watson, *J. Chem. Soc.*, 1430 (1937); 1439 (1938); H. A. Smith and H. S. Levenson, THIS JOURNAL, **61**, 1173 (1939)) and that of ethyl phenylacetate as 1.01 × $10^{-2}$ (H. A. Smith and R. R. Myers, *ibid.*, **64**, 2362 (1942)).

[5] *Cf.* ref. 2b, p. 1799.