

[CONTRIBUTION FROM THE WILLIAM H. CHANDLER CHEMISTRY LABORATORY OF LEHIGH UNIVERSITY]

**Kinetics of the Catalyzed Esterification of Methyl and Phenyl Substituted Aliphatic Acids in Methyl Alcohol**

BY HILTON A. SMITH

In a preceding paper<sup>1</sup> the study of the effect of the length of the carbon chain on the rate of the catalyzed esterification of normal aliphatic acids in methyl alcohol was reported. It was demonstrated that an increase in the chain length of the acid from one to four carbon atoms caused a lowering of the value of the specific rate constant, while still further increase in the number of carbon atoms had no effect. It was suggested that these results might be explained if butyric and higher acids were assigned a ring structure involving the first four carbon atoms rather than a straight chain structure. In order to test this idea, the esterification kinetics of certain substituted acids have been studied. This paper reports the results of these investigations.

**Experimental**

**Methanol** was obtained in a pure dry state, as in the case of the previous work, by careful fractionation of 99.5% methyl alcohol using a five-foot (1.5-meter) spiral column. The material used came over at a constant head temperature.

**Isobutyric acid, methylethylacetic acid, and isovaleric acid** were obtained by fractionation of the Eastman acids in a 5-ft. (1.5-m.) Vigreux type column. The resulting products analyzed 99.7, 99.5 and 99.6%, respectively, by titration with standard base.

**Isocaproic acid** was obtained in two ways. Sample A was procured by attempted fractionation of Eastman isocaproic acid in a 5-ft. Vigreux type column. The fractionation was quite unsatisfactory, the middle 50-ml. portion of a 100-ml. sample boiling over a range of 2.1°. A second fractionation gave no better results. The acid was then neutralized and any possible non-acidic impurities were extracted from the aqueous salt solution with benzene. The solution was then acidified and extracted with benzene. The solvent was distilled off, and the acid fractionated. The fractionation of the material treated in this manner was no better than that of the untreated material. The acid analyzed 99.9% by titration with standard base.

Sample B was prepared by the malonic ester synthesis from diethyl malonate, isobutyl bromide and sodium ethylate. Ethyl isobutylmalonate was prepared by the method indicated in organic synthesis for its normal isomer<sup>2</sup> and this ester converted to isocaproic acid by hydrolysis and decarboxylation.<sup>3</sup> The crude isocaproic acid was neutralized, a large excess of water added, and in-

soluble, non-acidic impurities were removed by steam distillation. The solution was then acidified, the acid extracted with benzene, the solvent distilled off, and the isocaproic acid fractionated in a 5-ft. Vigreux type column. The middle 25 ml. of a 50-ml. sample was used in the esterification studies. This fraction came over at a constant head temperature ( $\pm 0.05^\circ$ ), and analyzed 99.8% by titration methods.

**Phenylacetic acid and hydrocinnamic acid** were purchased from the Eastman Kodak Company. The former analyzed 99.9% and melted at 76.7°. The hydrocinnamic acid analyzed 100.0% by titration with standard base, and melted at 48.8°. These acids were used directly as they were obtained from Eastman Kodak Co.

$\gamma$ -**Phenylbutyric acid**<sup>4</sup> was prepared from  $\gamma$ -phenylpropyl bromide by carbonation of the corresponding Grignard reagent.<sup>5</sup> The bromide was prepared by treatment of  $\gamma$ -phenylpropanol with phosphorus tribromide. The Grignard reagent was treated with solid carbon dioxide, and the resulting mixture acidified to give the  $\gamma$ -phenylbutyric acid. The crude acid was obtained as an ether extract which was converted to the sodium salt. The aqueous solution of this salt was extracted with ether to remove non-acidic impurities. The acid was recovered by acidifying the basic solution and was finally recrystallized from benzene. This material analyzed 98% acid.

The  $\gamma$ -phenylbutyric acid was neutralized, a large excess of water added and distilled off. A considerable amount of impurity came over with the steam. The residue was then extracted with benzene to remove any non-acidic impurities. It was then acidified, and the acid extracted with benzene, and distilled in a 5-ft. Vigreux column at a pressure of 10 mm. The acid used analyzed 99.8% by titration with standard base, and melted at 51.2°. Previously reported melting points are 51°, 50.5°<sup>7</sup> and 52°.<sup>8</sup> "Organic Syntheses" gives 46-48°.<sup>9</sup>

The method employed to obtain the rate constants for the acid-catalyzed esterification of these acids in methanol was the same as that described in a previous paper.<sup>1</sup>

**Experimental Results and Calculations**

The rate constants were calculated by means of the equation

$$k = \frac{(r + a) \ln a/(a - x) - x}{(\text{catalyst})rt}$$

where  $a$  is the original concentration of organic acid,  $x$  is the concentration of ester formed after time  $t$ , and the catalyst is hydrochloric acid.

(4) The author is greatly indebted to Mr. H. S. Levenson for his aid in the preparation of this compound.

(5) Rupe, *Ber.*, **43**, 177 and 1233 (1910).

(6) Fischer and Schmitz, *ibid.*, **39**, 2212 (1906).

(7) Dippy, *J. Chem. Soc.*, 1010 (1937).

(8) Rupe, *Ber.*, **43**, 1233 (1910).

(9) *Org. Syntheses*, **15**, 64 (1935).

(1) Smith, *This Journal*, **61**, 254 (1939).

(2) "Organic Syntheses," Coll. Vol. I, p. 245.

(3) Bentley and Perkin, *J. Chem. Soc.*, **73**, 48 (1898).

TABLE I  
REACTION RATE CONSTANTS FOR ESTERIFICATION OF METHYL AND PHENYL SUBSTITUTED ALIPHATIC ACIDS IN METHYL ALCOHOL CATALYZED BY H<sup>+</sup> IONS  
In all cases,  $a = 0.500$ , (HCl) = 0.005

Acid	$t = 20^\circ$	$t = 30^\circ$	$t = 40^\circ$	$t = 50^\circ$
Isobutyric	0.0145 ± 0.0003 .0149 ± .0001	0.0261 ± 0.0003 .0265 ± .0005	0.0440 ± 0.0006 .0439 ± .0006	0.0723 ± 0.0017 .0730 ± .0017
Av.	.0147	.0263	.0440	.0727
Isovaleric	.00485 ± .00004 .00491 ± .00005	.00879 ± .00030 .00874 ± .00019	.0155 ± .0004 .0152 ± .0003	.0246 ± .0005 .0248 ± .0005 .0246 ± .0005 .0251 ± .0004
Av.	.00488	.00877	.0154	.0248
Methylethylacetic	.00407 ± .00003 .00403 ± .00005	.00720 ± .00006 .00724 ± .00008	.0128 ± .0004 .0131 ± .0003	.0219 ± .0006 .0219 ± .0006
Av.	.00405	.00720	.0131	.0219
Isocaproic	.0225 ± .0005 .0224 ± .0004	.0382 ± .0006 .0383 ± .0008	.0629 ± .0009 .0640 ± .0017	.105 ± .003 .104 ± .003
Av.	.0224	.0383	.0634	.104
Phenylacetic	.0198 ± .0003 .0196 ± .0002	.0347 ± .0004 .0341 ± .0007	.0582 ± .0006 .0586 ± .0018	.0954 ± .0016 .0910 ± .0012 .0967 ± .0016
Av.	.0197	.0344	.0584	.0944
Hydrocinnamic	.0199 ± .0004 .0201 ± .0006	.0354 ± .0021 .0359 ± .0014	.0585 ± .0009 .0593 ± .0014	.0928 ± .0012 .0930 ± .0017 .0902 ± .0022
Av.	.0200	.0356	.0589	.0920
Phenylbutyric	.0202 ± .0004 .0199 ± .0002	.0352 ± .0005 .0352 ± .0007	.0609 ± .0013 .0607 ± .0009	.0967 ± .0009 .102 ± .003 .101 ± .001
Av.	.0201	.0352	.0608	.100

$r$  is a constant, and theoretically is given by the equation

$$r = \frac{(\text{CH}_3\text{OH}_2^+)(\text{H}_2\text{O})}{(\text{H}_3\text{O}^+)}$$

The values of  $r$  used in the calculation were the same as those used in calculating the rate constants for the normal acids.<sup>1</sup> In all cases but one the values of  $k$  were constant up to about 80% reaction when they started to fall off. The individual figures from 20 to 80% reaction were averaged to get the values of  $k$  (liters/mole x sec.) given in Table I. The  $\pm$  errors are given to indicate that in no case was the falling off of  $k$  very appreciable.

The one acid which did not give constant values of  $k$  was isocaproic acid, Sample A. A comparison of the results obtained using Sample A and Sample B of this acid is shown in Table II. One may observe readily that the values of  $k$  for Sample A start at a lower value than those for the second sample, and also show a continuous falling off, this decrease becoming greater as the reaction proceeds. The reason for this difference is apparently due to isomeric impurities in Sample

A. This will be discussed more fully further on. At all temperatures this same difference between the  $k$  values for the two samples was observed. The values for isocaproic acid given in Table I are those for sample B only.

TABLE II  
ESTERIFICATION OF CH<sub>3</sub>OH AND ISOCAPROIC ACID AT 50°  
 $a = (0.5)$ , (HCl catalyst) = 0.005

$t$ , min.	$(a - x)$	$k$
Sample B		
4	0.443	0.107
8	.398	.107
17	.320	.108
30	.244	.107
50	.173	.103
80	.110	.100
Sample A		
3.75	0.459	0.0801
9	.408	.0839
23	.315	.0829
41	.240	.0800
75	.166	.0720
128	.110	.0622

Figure 1 shows the plot of  $\log k$  against  $1/T$  for the acids studied. For the purpose of clarity,

the values for the three phenyl-substituted acids have been averaged in making this plot. The slopes of all but one of the lines in the figure are the same within experimental error, and are also the same as the slopes obtained from a similar plot using values of  $k$  for straight chain acids. The value of  $E$  calculated from these slopes is 9800 cal. (The value reported for the normal acids was 10,000 cal. The individual values vary from 9600 to 10,000, and the figure 9800 is probably a better representation. An error of  $\pm 200$  cal. is easily attributable to experimental error.) The one acid which gives a different slope is methylethylacetic acid. The activation energy in this case is 10,400 cal. per mole. This is more than 400 calories larger than any other value obtained, and the difference is probably real.

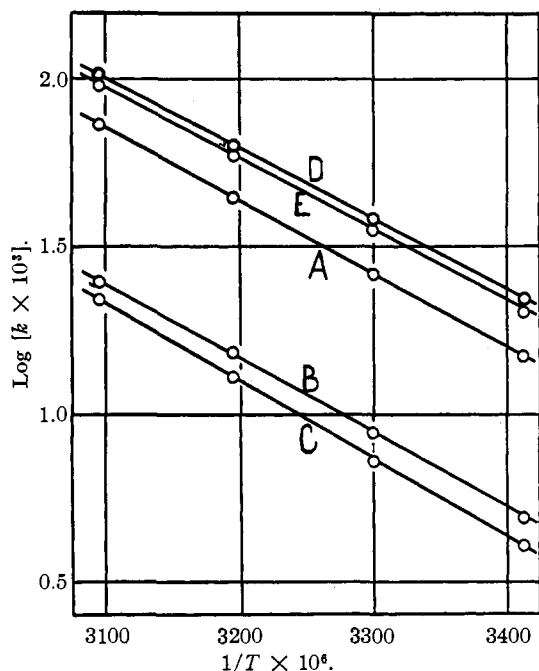


Fig. 1.—Temperature coefficients of hydrogen ion catalyzed esterification of methyl and phenyl substituted  $n$ -alkyl acids in methyl alcohol: A, isobutyric acid; B, isovaleric acid; C, methylethylacetic acid; D, isocaproic acid; E, phenyl substituted acid.

### Discussion

A consideration of the reaction velocity constants for the catalyzed reactions of the methyl-substituted acids with methyl alcohol shows a number of significant facts. In the first place, a comparison of these values with the constants obtained when straight chain acids were used<sup>1</sup> shows that the substitution of a methyl group for

a hydrogen atom causes a considerable lowering of the reaction velocity if this substitution occurs on either the first or second carbons next to the carboxyl group. If, however, the substitution occurs farther away from the acid group, the value of the reaction velocity constant is unchanged. This is evidenced by the fact that the constants for isobutyric and isovaleric acids are lower than the corresponding constants for propionic and butyric acids, while the values of  $k$  for isocaproic acid (4-methylvaleric acid) are the same as those for normal valeric acid. Furthermore, this effect does not decrease as one goes farther from the carboxyl group, as one would ordinarily expect. The lowering of the  $k$  values for the substitution of a methyl group on the carbon atom farthest from the carboxyl group is as follows

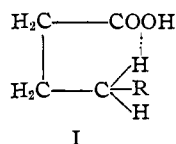
First carbon (propionic → isobutyric)	62%
Second carbon (butyric → isovaleric)	76%
Third carbon (valeric → isocaproic)	0%

Not only is the lowering greatest in the case of substitution on the carbon atom second from the carboxyl group, but the increase in the total number of carbon atoms in a continuous chain to a total of four has a considerable effect on the values of  $k$  even though the position of substitution of a methyl group for a hydrogen atom remains unchanged. Thus, changing isobutyric acid to methylethylacetic acid by addition of a methyl group on the end of the chain causes a diminution in  $k$  considerably greater than that caused by the original change from propionic to isobutyric acid. Further evidence of the effect of substitution on the first two carbons from the carboxyl group is evidenced by the values of  $k$  obtained with the two samples of isocaproic acid used. On correspondence with the Eastman Kodak Company, it was learned that the starting material used for the preparation of their acid was isoamyl alcohol. Since this alcohol as usually obtained (from fusel oil) is a mixture of some 85% 3-methylbutanol-1 and 15% 2-methylbutanol-1,<sup>10</sup> there is a good chance that the isocaproic acid of Sample A was actually a mixture of 4-methylvaleric and 3-methylvaleric acids in the ratio of approximately seven to one. The unsatisfactory distillation of this sample indicates that it was such a mixture, while the analysis indicates that it was a mixture of isomeric caproic acids. The method of preparation of Sample B, on the other

(10) Whitmore ("Organic Chemistry," p. 125) states that the ratio of these two alcohols in fusel oil is about seven to one.

hand, is one which should give no caproic acids except 4-methylvaleric acid. The satisfactory fractionation of this sample plus its analysis indicates that it did consist of this material only. If this is true, then the lower  $k$  values for Sample A and also the falling off of such values in the course of a run, indicate that the esterification of the 3-methylvaleric acid is much slower than that of the 4-methylvaleric acid. This again shows that substitution must take place on the first two carbon atoms from the carboxyl group if the reaction velocity is to be materially affected.

Thus, the results obtained with methyl-substituted aliphatic acids are in complete accord with the ring structure idea for fatty acids. I shows in general what this structure must be like.

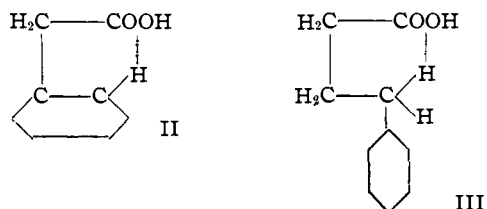


The fact that the activation energies are constant means that the  $s$  factor in the equation  $k = sZe^{E/RT}$  must be the part of this equation which changes with the value of  $k$ . (The value of  $Z$  was shown to change but little with increasing chain length as compared to the change in  $k$ .<sup>1</sup>) It is quite probable that the diminution in  $k$  with substitution is due almost wholly to true steric considerations, as was suggested for the case of the straight chain acids. Hinshelwood and Legard<sup>11</sup> demonstrated the fact that in a series of  $\alpha$ -substituted acids, the activation energy increased. It is interesting to note that the substitution of a methyl group in the  $\alpha$ -position does not appear to increase the activation energy in the case of propionic  $\rightarrow$  isobutyric acid, while the activation is increased for butyric  $\rightarrow$  methylethylacetic acid. In the latter case, the ring would be complete, while in the former, there are not enough carbon atoms in the chain to form a ring of the type postulated.

One ordinarily would expect to find a greater effect when a phenyl group is substituted for a hydrogen than when a methyl group is in a corresponding position. The results with the phenyl-substituted acids show that this is decidedly not the case. The  $k$  values for the esterification of phenylacetic, phenylpropionic, and phenylbutyric acids are the same, almost within experimental error, and, furthermore, are almost the same as the

(11) Hinshelwood and Legard, *J. Chem. Soc.*, 587 (1935).

corresponding values for normal butyric acid. On the basis of the postulated ring structure, these results are easily explained in the case of phenylacetic and phenylbutyric acids. The ring structure for phenylacetic acid is shown in II, and gives a very similar picture to that for normal butyric acid. The fact that phenylacetic acid and normal butyric acid have the same values of  $k$  was also found by Goldschmidt<sup>12</sup> at 25°. The ring structure for phenylbutyric acid is shown in III, and is



quite analogous to that of isocaproic acid. Both of these have values of  $k$  which within experimental error are the same as the corresponding values for normal acids higher than propionic acid.

In the case of hydrocinnamic acid, a very interesting situation arises. Here a four-membered ring of the type suggested for other acids is impossible due to the fact that there is no hydrogen on the carbon atom with which this ring is usually formed. However, there is a good possibility that such a bond would be formed with the next hydrogen atom, thus including  $\text{H}_2\text{C}-\text{COOH}$  five carbons in the ring instead of the usual four. This is illustrated in IV. If this does happen, the values of  $k$  for this acid should be essentially the same as the corresponding values for phenylacetic and phenylbutyric acids. This is found experimentally.

The esterification of diphenylacetic acid was studied by Hinshelwood and Legard.<sup>11</sup> This acid esterifies considerably slower than phenylacetic acid, and also has a higher activation energy (10,800). In this case, both of the phenyl groups are oriented in such a manner as to allow ring formation with the carboxyl group. This would give a much slower reaction rate constant. The higher activation energy is in line with the increase in the activation energy for methylethylacetic acid over that for the normal acids and isobutyric acid. It probably can be predicted with assurance that diethylacetic acid will behave in a manner similar to that found for diphenylacetic acid.

(12) Goldschmidt and Thuesen, *Z. Physik. Chem.*, 81, 30 (1912).

Additional confirmation of the ring theory is found in the work of Hartman and Borders.<sup>13</sup> These authors studied the rate of the acid catalyzed esterification in methyl alcohol of several ortho, meta, and para substituted benzoic acids. They discuss their results with the meta and para compounds on the basis of Hammett's equation for the effect of substituent groups in the meta and para position on the velocity constants of the unsubstituted reactant,<sup>14</sup> but make little mention of the ortho compounds.

The values of the reaction velocity constants for ortho, meta, and para toluic acids show that the latter two esterify with a velocity almost exactly equal to that for benzoic acid, while the ortho-toluic acid esterifies at a slower rate. This is explained readily by the fact that ring formation is possible in the ortho form, but impossible in the meta and para forms.

It would thus appear that the explanation of a ring structure for butyric and higher normal aliphatic acids explains not only the reaction rates

(13) Hartman and Borders, *THIS JOURNAL*, **59**, 2107 (1937).

(14) Hammett, *ibid.*, **59**, 97 (1937).

for the normal acids, but also those obtained with methyl- and phenyl-substituted acids.

### Summary

The kinetics of the hydrogen ion catalyzed esterification of the following seven organic acids have been studied: isobutyric, isovaleric, methyl-ethylacetic, isocaproic, phenylacetic, hydrocinnamic, and phenylbutyric.

The results indicate that substitution of a methyl group must take place in the  $\alpha$ - or  $\beta$ -position if the reaction velocity is to be affected. Furthermore, the combined effect of completion of a row of four carbon atoms plus substitution of a methyl group on one of these atoms is much greater than that of the substitution alone.

The rate constants for the catalyzed esterification of phenylacetic, hydrocinnamic, and phenylbutyric acids are essentially the same, and but slightly different from those of butyric and higher acids. These are discussed in the light of the postulated ring structure.

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## Pressure-Area Relations of Fatty Acid and Alcohol Monolayers

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### 1. Introduction

This investigation was initiated in order to determine the effect of variations in the length of the hydrocarbon chain upon the pressure-area relations of monolayers. In similar earlier work the temperature of the surface was not controlled with sufficient accuracy because the purity of the compounds was in doubt. Since, however, a considerable number of very pure saturated fatty acids and alcohols have been donated for this purpose by Professor E. E. Reid, it seems worth while to increase the accuracy of the measurements and to include new compounds. Seven acids with fourteen to twenty carbon atoms per molecule, and five alcohols with fourteen to eighteen carbon atoms per molecule, were studied. In order to decrease the solubility of the acid films and to avoid salt formation with multivalent positive ions accidentally present in the subsolution, all of the films were spread on 0.01 *N* sulfuric acid. Measurements of the fatty acids were made

at 25.0° and of the alcohols at 20.0°. At these temperatures myristic and pentadecylic acid films are fully expanded and all the rest of the acids and the alcohols are wholly condensed.

### 2. Apparatus, Materials and Methods

The film balance used was modelled rather closely after the one described in detail by Harkins and Myers.<sup>1</sup> A few differences may, however, be noted. The accurately threaded rod which moves the barrier which prevents further spreading of the film on the subsolution was usually turned by a hand-operated worm gear of 30 to 1 ratio. The mounting of the worm gear was such that it could be very quickly disengaged from the pinion gear fitted on the threaded rod, when rapid movement of the barrier was desired. A circle divided into 720 parts was mounted on the end of the rod and by means of a counting device whole revolutions of the shaft were indicated.

In order to give better control of the temperature of the surface a new type of trough was constructed. This was machined from a strip of stainless steel, and the inside dimensions were approximately 80 × 25 × 0.5 cm. Attached to the trough was a false bottom through which

(1) W. D. Harkins and R. J. Myers, *J. Chem Phys.*, **4**, 716 (1936).