It is a pleasure to acknowledge the assistance of Mr. George Manning who made up most of the preparations and also took some of the X-ray diagrams.

Summary

1. In the equilibrium diagram Cr_2O_3–NiO the spinel $NiO \cdot Cr_2O_3$ is the only compound present.
2. At 1000° the solubility of nickel and chromium oxide in the spinel is small.
3. Nickel oxide does not dissolve chromium oxide.

ANN ARBOR, MICH. RECEIVED MARCH 4, 1940

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

The Acid Catalyzed Esterification of Aliphatic Acids

BY HILTON A. SMITH

In two previous papers the effect of the alkyl chain of an aliphatic organic acid on its velocity of esterification in methanol was discussed. The first[1] dealt with normal acids only, and the second included simple methyl substituted acids.[2] The present paper reports a study of the velocity of esterification of certain other branched-chain aliphatic acids, together with a discussion of the general effect of alkyl substitution on reaction velocity.

Experimental

Methanol was obtained in a pure dry state, as in previously reported work, by careful fractionation of 99.5% methyl alcohol using a 5-foot (1.5-meter) spiral column. The material used distilled at a constant head temperature.

Trimethylacetic acid and **diethylacetic acid** were obtained by fractionation of the Eastman Kodak Co. acids in a 5-ft. (1.5-meter) Vigreux type column. The former analyzed 99.5% by titration with standard base and melted at 35.4°. The latter analyzed 99.9%.

β-Methylvaleric acid[3] was prepared by the malonic ester synthesis from diethyl malonate, *s*-butyl bromide and sodium ethylate. Ethyl *s*-butylmalonate was prepared by the method indicated in "Organic Syntheses" for its normal isomer,[4] and this ester converted to *β*-methylvaleric acid by hydrolysis and decarboxylation. The crude acid was purified by fractionation in a 5-ft. Vigreux type column. The sample used for esterification purposes distilled at constant head temperature (±0.05°) and analyzed 100.0% by titration with standard base.

Dipropylacetic acid, dibutylacetic acid, and **di-isobutylacetic acid** were prepared in a manner similar to that used for *β*-methylvaleric acid. The di-alkyl substituted ethyl malonates were prepared by introducing two alkyl groups into the ester using sodium ethylate and the necessary alkyl iodide. The substituted malonic ester was hydrolyzed and decarboxylated, and the crude acids purified by reduced pressure distillation in a 5-ft. Vigreux column. Each of the samples used in the esterification studies analyzed at least 99.6% by titration with standard base.

The method employed to obtain the rate constants for the hydrion-catalyzed esterification of these acids was similar to that previously described[1] with the exception that the glass-stoppered bottles were replaced by small Pyrex vials the openings of which were fitted with a glass plug. A rubber sleeve around the opening and the plug prevented possible loss of solvent by evaporation. This was necessary because of the slowness of the runs, some of them lasting for several weeks.

Experimental Results and Calculations

The rate constants were calculated from Goldschmidt's 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 hydrogen chloride. The values of the constant r used were those obtained in earlier work for normal aliphatic acids.[1]

The values of the reaction velocity constant, k, were quite constant for reactions run at the lower temperatures. This is illustrated in Table I for the esterification of trimethylacetic acid at 20°.

TABLE I

ESTERIFICATION OF CH_3OH AND $(CH_3)_3CCOOH$ AT 20°

$a = 0.500$, $(HCl) = 0.005$

t, min.	$(a - x)$	k (liters × moles^{-1} × sec.$^{-1}$)
190	0.465	0.00139
1047	.361	.00141
1897	.298	.00140
3304	.227	.00141
5611	.157	.00139
11593	.073	.00133

For the slower runs at elevated temperatures, the rate constants fall off consistently with increasing reaction. The greatest falling off oc-

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(1) Smith, THIS JOURNAL, **61**, 254 (1939).

(2) Smith, *ibid.*, **61**, 1176 (1939).

(3) The author is greatly indebted to Mr. A. S. Raff for his aid in the preparation of this compound.

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

curred with di-isobutylacetic acid at 50°, this being the slowest high temperature run. The results of such a run are presented in Table II.

TABLE II

ESTERIFICATION OF CH_3OH AND DI-ISOBUTYLACETIC ACID AT 50°

$a = 0.500$, $(HCl) = 0.005$

t, min.	$(a - x)$	k (liters × moles^{-1} × sec.$^{-1}$) k (simple)	k (correct)
407	0.436	0.00121	0.00123
1130	.370	.00103	.00108
1842	.323	.000970	.00104
3376	.255	.000882	.00099
5415	.193	.000834	.00100
7130	.159	.000794	.00100
11297	.106	.000726	.00103

Inspection of column three of this table shows the extent of the falling off of the reaction velocity constant. The value of r at this temperature is 0.42. The falling off of the rate constants might be prevented by changing the value of r for the slow reactions, but this is not permissible since r is theoretically defined by the equation

$$r = \frac{(CH_3OH_2^+)(H_2O)}{(H_3O^+)}$$

and at any given temperature should be the same for all acids.

Hinshelwood[5] already has demonstrated that, at elevated temperatures, the reaction of methanol with hydrogen chloride is appreciable. For the purpose of correcting the rate constants for reaction of the catalyst with the solvent, the rate of reaction of a 0.005 N solution of hydrogen chloride in methanol was studied. The solution was placed in a thermostat in one of the reaction vials, and the disappearance of the acid followed by titration with dilute (0.00229 N) base. Figure 1 gives the results obtained at 30, 40 and 50°. It demonstrates the fact that, while this reaction is negligible in the study of esterification of normal or simple substituted aliphatic acids (80% reaction in a few hours), it must be taken into account for the slower reactions under consideration here.

The rate of reaction of hydrogen chloride with methanol as shown in Fig. 1 is somewhat faster than that found by Hinshelwood.[5] The reason for this difference is not apparent, but may be due to the different concentrations used.

Unfortunately it is impossible to make an absolute correction for the reaction of the catalyst with solvent since one cannot predict the effect of the acid and ester present on its rate. The corrected values of k in column 4 of Table II were calculated by substituting in equation (1) not the original concentration of hydrogen chloride for (catalyst) but rather the concentration present at time t, thus assuming the reaction of hydrogen chloride and methanol in the reaction mixture to proceed at the same rate as that found for the pure solutions. This correction results in reasonably constant values of the reaction velocity constants. Such a correction was applied for studies involving diethyl-, dipropyl-, dibutyl-, and di-isobutylacetic acids at temperatures of 30, 40, and 50°. With the exception of di-isobutylacetic acid at 50°, these corrections are not more than some 10% at as much as 80% reaction, and are usually considerably less.

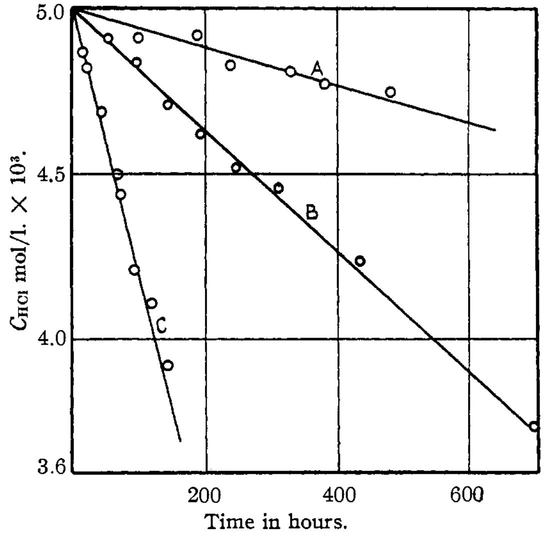

Fig. 1.—Rate of reaction of HCl with CH_3OH in 0.005 N solution: A, T = 30°; B, T = 40°; C, T = 50°.

The values of the specific reaction rate constants for esterification of the acids studied are given in Table III. They represent averages of the individual values of k over the range covered by 20 to 80% reaction. The ± deviations are generally of the order of 2–3%.

Figure 2 shows the plot of log k against inverse temperature for the acids studied. The activation energy for each acid is given in the last column of Table III. These were calculated from the slopes of the lines in the figure, and were checked by the method of least squares.

Discussion

The effect of the length of an alkyl chain of an aliphatic acid on its esterification velocity

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(5) Hinshelwood, *J. Chem. Soc.*, 599 (1935).

TABLE III

REACTION RATE CONSTANTS FOR ESTERIFICATION OF ALIPHATIC ACIDS IN METHYL ALCOHOL CATALYZED BY H^+ IONS

In all cases a = 0.500,[a] (HCl) = 0.005[b]

Acid	k (liters × moles^{-1} × sec.$^{-1}$) t = 20°	t = 30°	t = 40°	t = 50°	E
β-Methylvaleric	0.00461	0.00808	0.0142	0.0239	
	.00465	.00802	.0144	.0242	
Av.	.00463	.00805	.0143	.0240	10,400
Trimethylacetic	.00141	.00267	.00488	.00867	
	.00140	.00269	.00497	.00849	
Av.	.00140	.00268	.00493	.00858	11,400
Diethylacetic	.000348	.000699	.00132	.00254	
	.000354	.000722	.00132	.00252	
Av.	.000351	.000711	.00132	.00253	12,400
Dipropylacetic	.000297	.000630	.00122	.00227	
	.000296	.000632	.00122	.00227	
Av.	.000297	.000631	.00122	.00227	12,400
Dibutylacetic	.000272	.000547	.00111	.00203	
	.000262	.000558	.00108	.00210	
Av.	.000267	.000553	.00110	.00207	12,900
Di-isobutylacetic	.000141	.000282	.000550	.00102	
	.000140	.000278	.000547	.00105	
Av.	.000140	.000280	.000547	.00105	12,600

[a] For trimethylacetic acid at 50°, a = 0.486, (HCl) = 0.00486. [b] For β-methylvaleric acid at 20°, (HCl) = 0.00386.

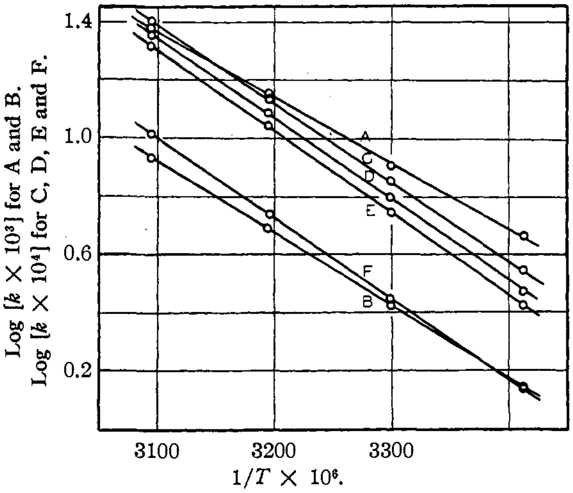

Fig. 2.—Temperature coefficients of hydrogen ion catalyzed esterification of substituted alkyl acids in methanol: A, β-methylvaleric acid; B, trimethylacetic acid; C, diethylacetic acid; D, dipropylacetic acid; E, dibutylacetic acid; F, di-isobutylacetic acid.

already has been discussed.[1,6] It was demonstrated that the velocity constants decreased from formic to butyric acids, and thereafter remained constant with increasing chain length. It was also demonstrated that the activation energy was constant throughout the series. It is now possible to consider the results of lengthening two chains simultaneously. Table IV gives a summary of the pertinent data.

TABLE IV

Acid	$k_{20°}$	E
Acetic[1]	0.0440	10,000
Isobutyric[2]	.0147	9,800
Diethylacetic	.000351	12,400
Dipropylacetic	.000297	12,400
Dibutylacetic	.000267	12,900

The results shown in this table are quite parallel with those found when the length of a single chain is increased. In each case a relatively small drop in the reaction velocity constant occurs on the first methyl substitution, a much larger one on an ethyl substitution, and little change occurs as the chain length is subsequently increased. For the disubstituted acids, some falling off does occur beyond diethylacetic acid, but this change is insignificant when compared to previous changes. In contrast to the normal acids, the change from dimethylacetic to diethylacetic acid is accompanied by a large change in activation energy.

The results of increasing the chain length of a normal aliphatic acid on its velocity of esterification were explained by postulating ring formation in butyric and higher acids. Similar rings have been postulated by Palomaa and co-workers in

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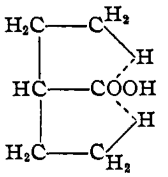
(6) Smith and McReynolds, THIS JOURNAL, 61, 1963 (1939).

their studies of the ether-type linkage.[7] The results for disubstituted acids which are presented here are not readily explainable either by inductive effect[8] or by the mechanical model studies of Fairclough and Hinshelwood.[9] They are, however, readily explainable by the ring theory. The postulated ring structure of diethylacetic acid is



A similar structure might be expected even were no chelation to occur, since from stereochemical considerations alone the zig-zag structure usually assigned to a hydrocarbon chain is improbable for both chains of this acid. The slow esterification of diethylacetic acid is in accord with the explanation already advanced[6] for its high dissociation constant.[10] The fact that only minor changes in esterification rate are found when the alkyl chains are lengthened to form dipropyl and dibutylacetic acids is also expected from the ring theory.

The slow esterification of β-methylvaleric acid was predicted from previous results with impure isocaproic acid.[2] These predictions are now confirmed. The rate of esterification of this acid ($k_{20°} = 0.00463$) compared with that of isovaleric acid ($k_{20°} = 0.00488$) gives further evidence that substitution in the γ position ordinarily has little effect.

The results with di-isobutylacetic acid are interesting since *k* for this acid is considerably lower than those for diethyl, dipropyl and dibutylacetic acids. In the single chain series, the corresponding compound, isocaproic acid, esterified at the same rate as the corresponding normal acids. The slower rate for di-isobutylacetic acid is in line with the fact that some falling off of the esterification rate does occur when the chains in the di-substituted acids are longer than those in diethylacetic acid, and with the fact that β-methylvaleric acid esterifies a little slower than isovaleric acid.

Complete data are now available for discussing the effect of substitution of methyl groups in the α position of acetic acid. This material is summarized in Table V.

TABLE V

Acid	$k_{20°}$	E
Acetic[1]	0.0440	10,000
Propionic[1]	.0400	9,800
Isobutyric[2]	.0147	9,800
Trimethylacetic	.00140	11,400

From this table it is evident that successive methyl substitution in the α position of acetic acid causes a decrease in the velocity of esterification of the acid, the decrease per methyl group becoming greater with increased substitution. This is in accord with the idea of geometrical steric hindrance. The activation energy is changed only when the third methyl group is introduced, in which case a considerable increase occurs. The high activation energy for trimethylacetic acid corresponds with the results of Hinshelwood and Legard[11] for the catalyzed esterification of this acid in ethanol. The increase in activation energy accompanying considerable substitution already has been discussed.[6]

In general, the results of the esterification studies with alkyl substituted acetic acids may be summed up as follows.

Substitution must ordinarily take place in the α or β position from the carboxyl group if the reaction velocity is to be affected, and substitution in either of these positions has approximately the same net effect. The so-called "ethyl effect" is the result of simultaneous substitution in the α and β positions.

One substituent in these positions has little effect on the esterification velocity and none on the activation energy, *e. g.*, propionic acid.

Two substituents have a considerably greater effect on the reaction velocity, but none on the activation energy, *e. g.*, isobutyric acid, butyric and higher normal acids.

Three substituents have a still greater effect on the esterification velocity, and result in a somewhat increased value of *E*, *e. g.*, methylethylacetic acid, isovaleric acid, β-methylvaleric acid, and trimethylacetic acid.

Four substituents have a large effect on the reaction velocity, and result in a greatly increased activation energy, *e. g.*, diethylacetic acid, dipropylacetic acid, etc.

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(7) *Cf.* Palomaa and Siitonen, *Ber.*, **69B**, 1338 (1936).

(8) *Cf.* Evans, Gordon and Watson, *J. Chem. Soc.*, 1439 (1938); see also Smith and Levenson, THIS JOURNAL, **61**, 1172 (1939).

(9) Fairclough and Hinshelwood, *J. Chem. Soc.*, 593 (1939).

(10) Dippy, *ibid*, 1222 (1938). In this connection the attention of the author has been called to the fact that direct credit was not given to Dippy for the form of Fig. 3 in the publication of Smith and McReynolds.[6] A similar figure was presented by Dippy.

(11) Hinshelwood and Legard, *ibid*, 1588 (1935).

Acids which have more than four substituents in the α or β positions should be practically unesterifiable under ordinary conditions.[12]

Finally, if considerable substitution in the α or β positions has already been made, substitution in the γ position may have some effect on esterification rate.

It has been demonstrated already that the effect of lengthening the alkyl chain of the acid portion of ethyl esters on the rate of saponification of these esters is the same as that observed in esterification.[8] In a subsequent paper it will be shown that the general effect of α and β substitution is the same for these two processes.

Summary

The kinetics of the hydrogen ion catalyzed esterification of the following organic acids have been studied: β-methylvaleric acid, trimethylacetic acid, diethylacetic acid, dipropylacetic acid, dibutylacetic acid and di-isobutylacetic acid.

The velocity of esterification of β-methylvaleric acid is similar to that of isovaleric acid. Trimethylacetic acid esterifies slowly, and has a greater activation energy than normal acids. The other four acids esterify very slowly, and have a considerably increased activation energy.

The general results of esterification studies of alkyl substituted acetic acids have been discussed

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(12) *Cf.* Braun and Fischer, *Ber.*, **66B**, 101 (1933).

[CONTRIBUTION FROM THE METCALF RESEARCH LABORATORY OF BROWN UNIVERSITY]

Some Unusual Hydrates of Quaternary Ammonium Salts

BY D. L. FOWLER, W. V. LOEBENSTEIN, D. B. PALL AND CHARLES A. KRAUS

Introduction

In concentrating a solution of tetra-*n*-butylammonium hydroxide for the purpose of preparing as nearly anhydrous a product as possible, it was observed that crystals appeared at room temperature in comparatively dilute solutions and that the entire mass solidified at this temperature while a large quantity of water was still present. On investigating this phenomenon further, it was found that tetra-*n*-butylammonium hydroxide forms a hydrate, containing 31 molecules of water, which melts at 30.2°. On examining solutions of tetra-*n*-butylammonium fluoride, a similar hydrate was found containing 18 molecules of water and melting at 37°. Somewhat later, tetramethyl-, tetra-*n*-propyl-, tetra-*n*-amyl- and tetraisoamylammonium hydroxides were investigated. It was found that only tetraisoamylammonium hydroxide forms a high hydrate. More recently, a considerable number of quaternary ammonium salts has been investigated in a preliminary fashion in order to determine whether they form hydrates and approximately of what composition. All the tetra-*n*-butylammonium salts having a high solubility in water were found to form hydrates, as did also tetraisoamylammonium formate, the one tetraisoamylammonium salt investigated. No salts of ions other than tetra-*n*-butylammonium and tetraisoamylammonium have been found that form high hydrates.[1]

Experimental

Method.—In determining the composition of these salt hydrates, a weighed sample of solution, which had previously been analyzed, was introduced into a suitable cell which was either cylindrical or of Erlenmeyer form and which was provided with a stopcock. The weight of the cell was known so that the composition of the solution could be obtained at any time by weighing the cell and its contents. The cell was attached to a vacuum system which was provided with a mercury manometer; an oil manometer, which had a higher sensitivity than the mercury manometer; a flask, containing water; a small pipet, graduated to 0.1 cubic centimeter; and a closed, drying tube for absorbing water vapor as desired. In most cases, the cell was attached to the apparatus by means of a short length of pressure tubing so that the contents of the cell could be shaken conveniently in determining melting points or in adjusting for pressure equilibrium. The entire apparatus was carefully exhausted so as to remove the permanent gases.

Most of the salts were prepared by titrating acids with solutions of the desired quaternary bases. The bases were prepared from the corresponding iodides by means of silver oxide. In preparing these bases, it is very essential to guard against carbon dioxide. All solutions must be made up with carbon dioxide-free water and the apparatus must

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(1) The experimental work in connection with tetra-*n*-butylammonium hydroxide and fluoride was carried out by D. L. Fowler; that of the other hydroxides by W. V. Loebenstein; that of the remaining salts by David B. Pall. Since it is not planned to continue the investigation of these hydrates at this time, the results are presented as far as they have been obtained.