[CONTRIBUTION FROM THE EASTERN REGIONAL RESEARCH LABORATORY[1] AND THE FATTY ACID DIVISION OF THE ASSOCIATION OF AMERICAN SOAP AND GLYCERINE PRODUCERS, INC.]

Phosphorus Derivatives of Fatty Acids. I. Preparation and Properties of Diethyl Acylphosphonates[2]

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Diethyl acylphosphonates have been prepared by the reaction of acyl chlorides with triethyl phosphite. These were derived from the even-numbered C_4–C_{18} saturated fatty acids and oleic acid. Boiling point, density and refractive index were determined for each compound. The diethyl acylphosphonates are unstable to moisture, the rate of hydrolysis decreasing with increase in size of acyl chain and phosphorus ester groups. The ease of hydrolysis suggested the possibility that the new compounds do not have an acylphosphonate bond $(-\overset{\overset{O}{\|}}{C}-\overset{\overset{O}{\uparrow}}{P}<)$ but rather a mixed anhydride bond $(-\overset{\overset{O}{\|}}{C}-O-P<)$. Molar refraction, infrared spectroscopy and polarographic studies, however, demonstrate that the acylphosphonate structure is the correct one.

The "isomerization" reaction of trialkyl phosphites with alkyl halides (equation 1) has been used to prepare a large variety of alkylphosphonates.[4] The preparation of acylphosphonates (1-ketophosphonates) by the reaction of acyl halides with trialkyl phosphites (equation 2) has been used to only a limited extent.[5-8]

$$RX + (R'O)_3P \longrightarrow RP(O)(OR')_2 + R'X \quad (1)$$

$$RC(O)X + (R'O)_3P \longrightarrow RC(O)P(O)(OR')_2 + R'X \quad (2)$$

Examples of aliphatic acylphosphonates derived from acids higher than acetic could not be found in the literature. This paper describes the preparation and characterization of the diethyl acylphosphonates obtained from the acid chlorides of the even-numbered saturated fatty acids from butyric to stearic plus that derived from oleic acid. The diethyl esters were prepared because of their structural similarity to other types of phosphorus derivatives being investigated at our laboratory. In this paper, the acid radicals will be referred to by their common names except in the case of C_6, C_8 and C_{10} fatty acids, where the Geneva system will be used for the purpose of clarity.

The reaction between acyl chloride and triethyl phosphite proceeded smoothly in all cases with no apparent decrease in rate with increasing length of acyl chain. The diethyl acylphosphonates obtained on distillation were colorless, essentially odorless liquids, except for diethyl stearoylphosphonate, which was a white solid at room temperature.

It was difficult to determine accurately the percentage conversion of the acid chlorides to the acylphosphonates because of the heat lability of the latter compounds. However, from the amounts of distillate of fairly high purity, yields could be estimated to range from 45 to 60%. Many of the products were distilled a second time in order to obtain samples of very high purity for characterization.

The boiling ranges, refractive indices and densities of the series of diethyl acylphosphonates are shown in Table I.

The acylphosphonates are quite unstable to moisture. Samples of highly purified diethyl myristoylphosphonate, left open to the atmosphere for seven days, contained a crystalline solid after one day; the samples were completely solidified in two days. The solid material on recrystallization was found to be myristic acid. Acid value was determined daily and found to reach a maximum slightly below that expected from the formation of one acid group. Apparently under these conditions the C–P bond is cleaved with the formation of the fatty acid and diethyl phosphite.

The knowledge that the acylphosphonates are unstable to moisture prompted a study of the rate of hydrolysis of these compounds. We were interested in the effect on the hydrolysis rate of the following variables: acyl chain length, size of ester groups and type of phosphonate (acyl or alkyl). To effect solution, an aqueous dioxane system was used.

Figure 1 shows the rates of the hydrolysis of several different types of acyl- and alkylphosphonates. The results were calculated as percentage of expected total hydrolysis, in order to compensate for differences in molecular weight.

Figure 1 also shows that the rate of hydrolysis decreases with both increased acyl chain length and increased size of ester groups. The two alkylphosphonates are much more resistant to hydrolysis than are acylphosphonates of the same molecular weight. In diethyl dodecylphosphonate, the only source of acid formation is hydrolysis of the ethyl ester groups. Since this occurs at such a relatively slow rate, there is good indication that the diethyl acylphosphonates are first attacked at the C–P linkage with subsequent hydrolysis of the ethyl groups from the smaller diethyl phosphite fragment. Kabachnik[9] has shown that the C–P bond splits after adduct formation with alcohols, the

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(2) Presented in part at the Delaware Valley Meeting of the American Chemical Society, February 16, 1956, Philadelphia, Pa., and the Spring Meeting of the American Chemical Society, Dallas, Texas, April 8–13, 1956.

(3) Fellow of the Fatty Acid Division of the Association of American Soap and Glycerine Producers, Inc.

(4) G. M. Kosolapoff, in "Organic Reactions," Vol. 6, John Wiley and Sons, Inc., New York, N. Y., 1951, p. 273.

(5) M. I. Kabachnik and P. A. Rossiiskaya, *Bull. Acad. Sci. U.R.S.S. Classe sci. chim.*, 364 (1945); *C. A.*, **40**, 4688[6] (1946).

(6) M. I. Kabachnik and P. A. Rossiiskaya, *ibid.*, 597 (1945); *C. A.*, **41**, 88d (1947).

(7) M. I. Kabachnik, P. A. Rossiiskaya and E. S. Shepeleva, *ibid.*, 163 (1947); *C. A.*, **42**, 4132i (1948).

(8) A. E. Arbuzov, V. M. Zoroastrova and N. I. Rizpolozhenskii, *ibid.*, 208 (1948); *C. A.*, **42**, 4932g (1948).

(9) M. I. Kabachnik, *Bull. acad. sci. U.R.S.S., Classe Sci. chim.*, 219 (1947); *C. A.*, **42**, 573g (1948).

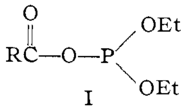
TABLE I

CHARACTERIZATION OF DIETHYL ACYLPHOSPHONATES

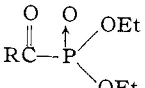
Acyl	B.p. °C.	Mm.	$n^{30}D$	^{8}	Phosphorus, % Calcd.	Found	[M.R.] Calcd.[9]	Found
Butyryl	51–53	0.2	1.4244	1.0498	14.88	14.86	50.04	50.65
Hexanoyl	83–85	.1	1.4301	1.0175	13.12	13.09	59.28	59.98
Octanoyl	98–101	.1	1.4344	0.9936	11.72	11.92	68.52	69.33
Decanoyl	125–132	.3	1.4368	.9747	10.59	10.86	77.76	78.55
Lauroyl	151–155	.3	1.4400	.9636	9.67	9.66	87.00	87.62
Myristoyl	144–151	.1	1.4425	.9514	8.89	8.97	96.24	97.01
Palmitoyl	160–166	.1	1.4452	.9453	8.23	8.42	105.48	106.04
Stearoyl	176–182	.2	1.4463	.9376	7.66	7.78	114.72	115.13
Oleoyl	168–175	.2	1.4531	.9447	7.70	7.62	114.25	115.18
Alkyl phosphonates								
Dodecyl							86.99	86.95
Lauroxyethyl							97.88	97.92

ester groups on the phosphorus atom remaining intact.

In view of the ease of hydrolysis of acylphosphonates the question arose as to whether they might not exist in the form of a mixed anhydride I rather than a true phosphonate II.


I

$RC(=O)-O-P(OEt)_2$


II

$RC(=O)-P(\rightarrow O)(OEt)_2$

The analogous reaction of trialkyl phosphites with alkyl halides (equation 1) and the structure proof of Kabachnik[5] suggest that form II, the true phosphonate structure, is the more likely. In the course of certain physical studies, we have found additional evidence that such is the case.

The observed values of molar refraction (Table I) were found to agree much more closely with the values calculated on the basis of a phosphonate structure than with those based on an anhydride structure. The latter values can be obtained by the addition of 2.20 to the calculated acylphosphonate values appearing in Table I.

The observed [M.R.] values are higher than the calculated ones by a constant increment. Exaltation of the molar refraction is known to occur in compounds having conjugated systems; it is likely that conjugation of the carbonyl and phosphonyl linkages accounts for the exaltation in this case. That the increment cannot be traced to the phosphonate group alone is shown by the observed [M.R.] values for the alkylphosphonates, which agree almost exactly with the calculated values.

The diethyl acylphosphonates exhibited well-defined polarographic waves having half-wave potentials of −1.4 v. *vs.* the saturated calomel electrode. On the other hand, diethyl dodecylphosphonate showed no polarographic reduction. It was assumed, therefore, that reduction of the acylphosphonates was due to the presence of the carbonyl group. Since the isolated carbonyl is not reducible in the applied voltage range of the electrolyte used (0 to −2.0 v.),[10] it is likely that reduction is effected because of conjugation between the carbonyl and phosphonyl groups. The anhydride structure is not conjugated; thus polarographic reduction is additional evidence for the phosphonate form.

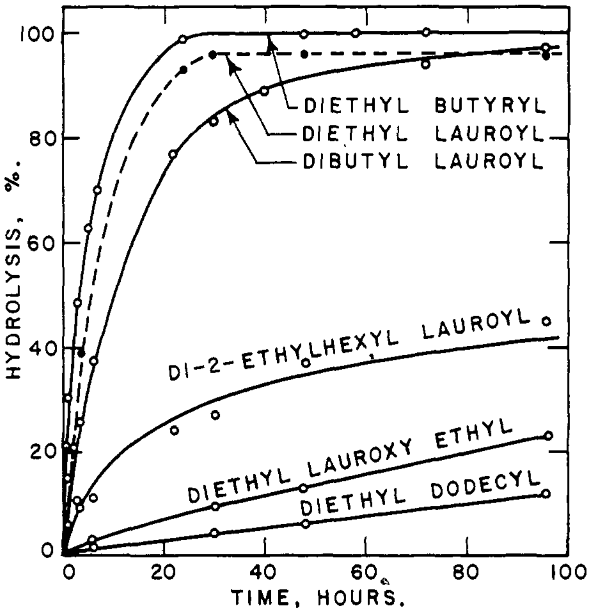


Fig. 1.—Rates of hydrolysis of dialkyl acyl- and alkylphosphonates in dioxane–water at 93 ± 1°.

Ultraviolet absorption spectra were obtained for diethyl octanoyl- and palmitoylphosphonates. Both samples showed a double peak at 333 and 341 mμ. The molar absorptivities were 59.04 and 62.81 for the C_8 and C_{16} derivatives, respectively.

Infrared spectra were obtained on the diethyl acylphosphonates having 10, 12, 14 and 16 carbon atoms in the acyl groups. All of these were liquids and had spectra very similar to that shown in Fig. 2. Differences among these four spectra were only those minor variations which would be expected from the differences in chain length. Table II lists the absorption bands which may be associated with the phosphorus-containing part of the molecule, showing the degree of variation of band positions among these four compounds. The assignments are based on those of Bellamy.[11] The 794 cm.$^{-1}$ band is also tentatively assigned to P–O–C

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[10] C. O. Willits, C. Ricciuti, H. B. Knight and D. Swern, *Anal. Chem.*, **24**, 785 (1952).

[11] L. J. Bellamy, "The Infrared Spectra of Complex Molecules," John Wiley and Sons, Inc., New York, N. Y., 1954.

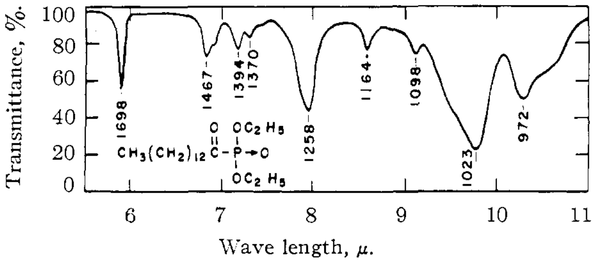

Fig. 2.—Infrared absorption spectrum for diethyl myristoylphosphonate, in liquid state, 0.02 mm. thick, 98–100% pure. Numbers beneath the bands indicate wave numbers, in cm.$^{-1}$. In addition to the bands shown, the spectrum contains strong, sharp bands at 2854 and 2925 cm.$^{-1}$ and broad, weak bands at 723 and 794 cm.$^{-1}$.

vibration in accordance with the suggestion of Meyrick and Thompson.[12]

Presence of the strong band at 1258 cm.$^{-1}$ is evidence that the compounds prepared have the phosphonate structure, with a P→O group, rather than the mixed anhydride structure, which would not contain a P→O group. The low frequency of the carbonyl vibration at 1698 cm.$^{-1}$ is also suggestive of conjugation between the C=O and P→O, providing further evidence that there is no oxygen atom between the acyl group and the phosphorus atom.

Table II

Assignment of Absorption Bands of Diethyl Acylphosphonates, Cm.$^{-1}$

794	P-O-C
972–973	P-O (pentavalent phosphorus)
1023–1025	P-O-C (aliphatic)
1164	P-O-Ethyl
1258	P → O
1697–1698	C=O

Experimental

Trialkyl Phosphites.—Triethyl phosphite was obtained from the Eastman Kodak Company and the Virginia–Carolina Corporation. Before use, it was distilled at atmospheric pressure, the portion distilling at 151–155° being retained. Tri-*n*-butyl phosphite was the Eastman Kodak Company Yellow label grade. Tri-2-ethylhexyl phosphite, obtained from the Virginia–Carolina Corporation, was distilled, the portion boiling at 148–150° (0.25 mm.) being retained.

Acyl Chlorides.—The acyl chlorides, with the exception of decanoyl, oleoyl and stearoyl, were Eastman Kodak Co. organic chemicals. Decanoyl chloride was prepared by reacting highly purified decanoic acid with an excess of oxalyl chloride. Oleoyl chloride was prepared similarly, using oleic acid prepared from olive oil fatty acids by low temperature crystallization and fractional distillation.[13] Stearoyl chloride was prepared by treating highly purified stearic acid (m.p. 68–69°) with an excess of thionyl chloride. In each of these cases, the reaction mixture, after removal of excess chlorinating agent, was used without further purification for the preparation of the corresponding acylphosphonate.

Alkyl Halides.—2-Bromoethyl laurate was prepared by refluxing 40 g. (0.2 mole) of lauric acid, 75 g. (0.6 mole) of 2-bromoethanol and 2.3 g. of concentrated sulfuric acid in 100 ml. of toluene for 3.5 hours, with azeotropic removal of water. After cooling, the dark-colored reaction mixture was washed with water, dried by azeotropic distillation and the residual solvent was evaporated under vacuum. The residue was distilled under high vacuum yielding 52.3 g. (85%) of 2-bromoethyl laurate, b.p. 114–119° (0.5 mm.) and n^{30}D 1.4564. Dodecyl chloride (Hooker Electro-Chemical Company) was fractionally distilled, and the portion distilling at 134–135° (11 mm.) was retained.

Diethyl Acylphosphonates.—The preparation of diethyl lauroylphosphonate is typical; to lauroyl chloride (43.8 g., 0.20 mole) 39.8 g. (0.24 mole) of triethyl phosphite was added dropwise over a period of about one hour, while a stream of dry nitrogen was passed through the solution for agitation and to sweep out the ethyl chloride which formed. The reaction was exothermic and temperature was controlled simply by the rate of addition of the triethyl phosphite. The temperature was not allowed to exceed 45°. After an additional hour, the reaction mixture was vacuum-distilled through a heated Claisen head, yielding 26.2 g. of diethyl lauroylphosphonate, b.p. 151–155° (0.1 mm.) and n^{30}D 1.4388–90, as a colorless liquid. This product was later redistilled with the main portion having an n^{30}D of 1.4399–1.4401.

Diethyl acylphosphonates with molecular weights higher than that of the lauroyl derivative were distilled in an alembic apparatus. In every case a considerable quantity of unidentified high-boiling residue remained in the distillation flask.

The physical properties of the diethyl acylphosphonates are summarized in Table I.

Dibutyl Lauroylphosphonate.—Fifty grams (0.2 mole) of tributyl phosphite was added dropwise to 43.8 g. (0.2 mole) of lauroyl chloride in about one hour. The reaction mixture was held at 80–90° and dry nitrogen was passed through the mixture in order to remove the butyl chloride which formed as a by-product. After an additional hour the reaction mixture was vacuum-distilled and 34.2 g. of crude dibutyl lauroylphosphonate, b.p. 168–182° (0.3 mm.) and n^{30}D 1.4430–35, was obtained. This was redistilled in an alembic still, yielding about 20 g. of product of much higher purity, b.p. 150–155° (0.14 mm.) and n^{30}D 1.4432.

Anal. Calcd. for $C_{20}H_{41}O_4P$: P, 8.23. Found: P, 8.36.

Di-2-ethylhexyl Lauroylphosphonate.—Ninety-two grams (0.22 mole) of tri-2-ethylhexyl phosphite was added dropwise in one hour to 43.8 g. (0.2 mole) of lauroyl chloride through which dry nitrogen was being passed. The reaction was run at room temperature, since raising the temperature to aid in the removal of 2-ethylhexyl chloride might have caused this by-product to react with the tri-2-ethylhexylphosphite. At room temperature the reactivity of the by-product was assumed to be negligible relative to that of the lauroyl chloride. After an additional reaction time of one hour, the reaction mixture was distilled in an alembic still. Only 11.2 g. of di-2-ethylhexyl lauroylphosphonate, b.p. 165–185° (0.1 mm.) and n^{30}D 1.4468, was obtained. The high boiling residue was present in much greater than usual amounts.

Anal. Calcd. for $C_{28}H_{57}O_4P$: P, 6.34. Found: P, 6.83.

Alkyl Phosphonates. Diethyl Dodecylphosphonate.—Dodecyl chloride (61.4 g., 0.3 mole) and triethyl phosphite (52.4 g., 0.315 mole) were mixed in a flask fitted with an air condenser and the mixture was heated to reflux (175°). Refluxing was continued intermittently for 27 hours, during which time the temperature rose slowly to 225°. At this time, there was no evidence of any material refluxing and the heating was discontinued. The mixture was vacuum distilled and 53.9 g. (57%) of diethyl dodecylphosphonate, b.p. 137–139° (0.3 mm.) and n^{25}D 1.4389–91, was obtained.

Anal. Calcd. for $C_{16}H_{35}O_3P$: P, 10.11. Found: P, 9.77.

Diethyl Lauroxyethylphosphonate.—Fifty-two grams (0.17 mole) of 2-bromoethyl laurate was mixed with 58 g. (0.35 mole) of triethyl phosphite and the solution was refluxed (155°). The n^{30}D of the mixture increased from an original value of 1.4292 to 1.4316 after 4 hours of refluxing and then remained constant for an additional 10 hours. The reaction mixture was then vacuum distilled, yielding 35.2 g. (57%) of diethyl lauroxyethylphosphonate, b.p. 162–164° (0.3 mm.) and n^{30}D 1.4419.

Anal. Calcd. for $C_{18}H_{37}O_5P$: P, 8.50. Found: P, 8.63.

Hydrolysis Experiments.—One to two grams of the phosphonate was weighed accurately into a 100-ml. volumetric flask. A hot solution of water:dioxane (30:70) was added

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(12) C. I. Meyrick and H. W. Thompson, *J. Chem. Soc.*, 225 (1950).

(13) H. B. Knight, E. F. Jordan, Jr., E. T. Roe and D. Swern, *Biochemical Preparations*, **2**, 100 (1952).

to the mark and the contents mixed thoroughly.[14] The solution was transferred to a reaction flask and heated to reflux (93 ± 1°) as quickly as possible. Refluxing was continued for 3–4 days (7 days in the case of di-2-ethylhexyl lauroylphosphonate). Ten-milliliter aliquots were removed by pipet frequently during the first 8 hours, then once a day until hydrolysis was complete. The aliquot was transferred to 60–70 ml. of absolute ethanol and titrated immediately with 0.1 *N* NaOH.

Polarographic Studies.—Details of the polarographic procedure and the solvent system have been reported in previous publications.[10,15] Methanol–benzene was the only solvent system used.

Infrared Studies.—Infrared absorption spectra were obtained with a Beckman IR-3 spectrophotometer, using sodium chloride prisms. For the pure liquid samples a spacer approximately 0.02 mm. thick was used between two sodium chloride windows. A single sodium chloride window was used for the tape-recorded blank.

Ultraviolet Studies.—The instrument was the Carey Model 11 recording spectrophotometer. Samples were dissolved in isoöctane at levels of 1 and 0.1%, and measured in a cell of 1 cm. thickness.

Acknowledgment.—The authors wish to thank Dr. Constantine Ricciuti for the polarographic studies, Mrs. Ruth B. Kelly, Mrs. Katherine M. Zbinden and Dr. Clyde L. Ogg for the analytical work, and Miss Anne M. Smith and Dr. George C. Nutting for the ultraviolet spectroscopy. The authors also wish to thank Mr. E. T. Roe for helpful discussions.

PHILADELPHIA, PA.

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(14) Twenty ml. additional dioxane was necessary in the case of di-2-ethylhexyl lauroylphosphonate because of incomplete solubility in the above solution.

(15) W. E. Parker, C. Ricciuti, C. L. Ogg and D. Swern, THIS JOURNAL, **77**, 4037 (1955).

[CONTRIBUTION FROM THE CHEMICAL RESEARCH LABORATORIES, THE LUBRIZOL CORPORATION]

Aromatic Phosphinic Acids and Derivatives. II. Direct Esterification of Diphenylphosphinodithioic Acid[1]

BY T. ROBERT HOPKINS AND PAUL W. VOGEL

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Alkyl diphenylphosphinodithioates have been prepared in good yields by the direct esterification of diphenylphosphinodithioic acid with certain alcohols in the absence of a catalyst. The reaction proceeds readily with primary alcohols, higher boiling secondary alcohols and tertiary alcohols. Phenol yields a monothioester.

Very little work has been reported on the chemistry of the diarylphosphinodithioic acids and their derivatives. The first member of this series, diphenylphosphinodithioic acid, can now be conveniently prepared by the reaction of benzene with phosphorus pentasulfide in the presence of anhydrous aluminum chloride.[2] Esters of this acid have not been reported previously.

In the present investigation it was found that diphenylphosphinodithioic acid can be esterified directly either by addition of the thiol group to an olefin or by reaction with certain alcohols in the absence of a catalyst. The latter is a novel reaction in that water, rather than hydrogen sulfide, is eliminated and a dithioester is formed.

Esters possessing primary alkyl groups are obtained from primary alcohols. An 85% yield of the *n*-octyl ester was obtained from the reaction of *n*-octyl alcohol with the acid at 180°. The alcohol was not first dehydrated since, if this were the case, the 2-octyl ester would result. This was demonstrated by the reaction of diphenylphosphinodithioic acid with 1-octene to give a 90% yield of the 2-octyl ester as shown in reaction (2). The addition of the thiol group to the olefin followed Markownikoff's rule. The structures of the esters were proven by saponification to the corresponding mercaptan and diphenylphosphinothioic acid. The mercaptans were identified by their 2,4-dinitrophenyl thioethers prepared by the procedure of Bost.[3]

$$\mathrm{Ph_2PSSH} + n\text{-}\mathrm{C_8H_{17}OH} \longrightarrow \mathrm{Ph_2PSS{-}C_8H_{17}} + \mathrm{H_2O} \quad (1)$$

$$\mathrm{Ph_2PSSH} + \text{1-octene} \longrightarrow \mathrm{Ph_2PSS{-}CH(CH_3){-}C_6H_{13}} \quad (2)$$

$$\mathrm{Ph_2PSSR} + \mathrm{H_2O} \xrightarrow{\mathrm{NaOH}} \mathrm{Ph_2POSNa} + \mathrm{RSNa} \quad (3)$$

The esterification of carboxylic acids requires the removal of a hydroxyl group from the acid. The relative order of reactivity of alcohols in this type of esterification is $R^{\mathrm{I}} > R^{\mathrm{II}} > R^{\mathrm{III}}$. When a strong acid is esterified, the hydroxyl group is believed to be removed from the alcohol. No definite proof of this is known except in the case of the hydrogen halide acids where there is no alternative. The relative reactivity rates for alcohols in the "esterification" of these acids are in the order $R^{\mathrm{III}} > R^{\mathrm{II}} > R^{\mathrm{I}}$. Diphenylphosphinodithioic acid may be classified as a strong acid, and as such it removes the hydroxyl group from the alcohol during esterification. One would, therefore, expect the relative reactivity rates of the alcohols to be $R^{\mathrm{III}} > R^{\mathrm{II}} > R^{\mathrm{I}}$. Actually, the order seems to be $R^{\mathrm{III}} \gtrsim R^{\mathrm{I}} > R^{\mathrm{II}}$. Primary alcohols react readily while the lower secondary alcohols give little or no reaction at their boiling points. Only one tertiary alcohol, *t*-butyl alcohol, has been studied.

The reactivity rates of primary, secondary and tertiary alcohols were compared by the esterification of a series of butyl alcohols. *n*-Butyl alcohol reacted with the acid at 117° for 28 hr. to give a 63% yield of the *n*-butyl ester. When *sec*-butyl alcohol was employed, little or no reaction occurred after 30 hr. at the reflux temperature (100°), and 90% of the starting acid was recovered unchanged. The fact that *t*-butyl alcohol gave a 66% yield of the

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(1) Presented before the Division of Organic Chemistry at the 125th A.C.S. Meeting, Kansas City, Mo., March, 1954.

(2) W. Higgins, P. Vogel and W. Craig, THIS JOURNAL, **77**, 1864 (1955).

(3) R. W. Bost, J. D. Turner and R. D. Norton, *ibid.*, **54**, 1985 (1932).