was slowly heated to 90° . After standing at room temperature overnight, the solution was added to excess water and the suspension thus produced filtered. This produced (1,2-diphenylethyl)diphenylphosphine oxide by mixed melting point and infrared comparison. Acknowledgment. We would like to acknowledge the financial support given this work by Research Corporation.

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[CONTRIBUTION FROM THE PROCTOR & GAMBLE COMPANY, MIAMI VALLEY LABORATORIES]

The Thermal Reaction between Alkylating Agents and Phosphonate or Phosphate Esters

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The reaction between trimethyl phosphite and dodecyl bromide at $180-200^{\circ}$ has been found to form methyl dodecyl methylphosphonate, I, in addition to the expected product, dimethyl dodecylphosphonate, II. I constitutes about 40% of the mixture. It has been established that I is formed by an alkyl exchange reaction between dodecyl bromide and dimethyl methylphosphonate, which is formed *in situ* by isomerization of trimethyl phosphite.

The alkyl exchange reaction has been shown to occur with phosphate as well as phosphonate esters, and thus appears to be a completely general reaction of aliphatic esters of organophosphorus acids. The reaction offers a new and convenient synthesis of mixed esters of phosphonic or phosphoric acids, of the type exemplified by I.

The relative reactivity of alkyl halides in the alkyl exchange reaction is $\hat{R}I > RBr > RCl$. The relative reactivity of esters is phosphinate > phosphonate > phosphate. This information provides support for the concept that the reaction involves nucleophilic displacement by phosphoryl oxygen on the alkylating agent.

A classical method for the preparation of aliphatic phosphonates, RPO(OR')₂, is the "mixed" Michaelis-Arbuzov reaction between an alkylating agent and a trivalent phosphorus ester¹:

$$RX + (R'O)_{a}P \longrightarrow$$

 $RPO(OR')_{a} + R'X; X = halide, tosylate, etc.$

The permissible structural variations in RX and in the phosphorus ester have been studied extensively, and the generally accepted mechanism involves nucleophilic attack of the phosphorus atom on the alkyl halide as the primary step.

The fact that an alkylating agent can react with *pentavalent* organophosphorus esters is not so generally recognized, although there are a few scattered references to such reactions. Pistschimuka and others² have investigated the reaction between alkyl halides and thiophosphoryl esters. The alkyl halide and the ester exchange substituents according to the general scheme³: The R group of the



halide always attaches to sulfur, and the ether-like oxygen becomes a coordinately bonded oxygen. Related reactions in the oxygen series have been reported only recently. Among these are the reaction of 2-bromoethyl acetate with methyl methylphenylphosphinate, which yields the 2-acetoxyethyl ester of the phosphinic acid,^{4a} and the reactions of 1,3-dibromopropane with phosphite or phosphonite esters,^{4b} which yield cyclic phosphonate or phosphinate esters, respectively. Examples of the alkyl exchange reaction between phosphonate esters and various alkylating agents have also appeared recently in the Russian literature.^{4c} Ref. 4a quotes other examples of thermal reactions of 2-chloroalkyl phosphonate and phosphate esters, which can be viewed as alkyl exchange reactions, and to a copper-catalyzed exchange reaction. The latter, one might guess, would differ mechanistically from the purely thermal reactions considered in this paper.

RESULTS

In this paper it is shown that O-alkyl groups of simple aliphatic phosphonate or phosphate esters react with suitable alkylating agents to undergo an alkyl exchange reaction at high temperatures. This reaction has proved to be a useful synthesis of mixed esters of phosphonic or phosphoric acids, and has also been shown to occur as a side reaction in certain Michaelis-Arbuzov reactions.

Although Harwood and Grisley^{4a} were the first to report a well documented case of the alkyl exchange reaction involving the phosphoryl rather than the thiophosphoryl group, their study was

⁽¹⁾ G. M. Kosolapoff, Organophosphorus Compounds, Wiley, New York, 1950, p. 121.

⁽²⁾ P. Pistschimuka, J. für prakt. Chem. (2), 84, 746
(1911); J. Russ. Phys.-Chem. Soc., 44, 1406 (1912); Chem. Zentr., 84, I, 1581 (1913); A. J. Burn and J. I. G. Cadogan, Chem. & Ind. (London), 591 (1961).

⁽³⁾ The term "alkyl exchange reaction" is used in this paper to describe this general reaction.

^{(4) (}a) H. J. Harwood and D. W. Grisley, Jr., J. Am. Chem. Soc., 82, 423, 6429 (1960). (b) A. Y. Garner, U. S. Patent 2,916,510, December 8, 1959; U. S. Patent 2,953,591, September 20, 1960. (c) A. N. Pudovik, A. A. Muratova, T. I. Konnova, T. Feoktistova, and L. N. Levkova, Zhur. Obshchei, Khim., 30, 2624 (1960); Chem. Abstr., 55, 15332 (1961).

Ester	Conditions	Mole Ratio Ester: RX	Product	Yield
0 			<u>O</u>	
$\mathrm{CH}_{3}\overset{\parallel}{\mathrm{P}}(\mathrm{OCH}_{3})_{2}$	200°/20 hr.	1:1	$\mathrm{CH_3}\overset{ }{\mathrm{P}}(\mathrm{OCH_3})\mathrm{OC_{12}H_{25}}$	35 – 38%
O II			O II	
$\mathrm{C_{2}H_{5}}\overset{\parallel}{\mathrm{P}}(\mathrm{OC_{2}H_{5}})_{2}$	200°/20 hr.	2:1	$\mathrm{C_{2}H_{5}P(OC_{2}H_{\delta})OC_{12}H_{25}}$	58%
			O II	
$(CH_{3}O)_{3}PO$	220°/18 hr.	2:1	$(CH_{3}O)_{2} \overset{ }{P}OC_{12}H_{25}$	$20 extsf{-}54\%$
			O II	
$(C_2H_5O)_3PO$	220°/16 hr.	2:1	$(\mathrm{C_{2}H_{5}O})_{2}\overset{\mathrm{H}}{\mathrm{POC}}_{12}\mathrm{H}_{25}$	47 - 63%

REACTION OF DODECYL BROMIDE WITH VARIOUS PHOSPHORUS ESTERS

limited to phosphinate esters. They recognized that the reactivity of different esters in such a reaction would be expected to decrease in the order phosphinate > phosphonate > phosphate. Hence, as they implied, it does not necessarily follow that phosphonates or phosphates would undergo the same reaction. Independently of their work, we discovered that the reaction does indeed occur, and is useful synthetically, with phosphonates and phosphates.

As was predicted, progressively more vigorous conditions are required to carry out the reaction in the above series of phosphorus esters. Harwood and Grisley treated their phosphinate at 160-175° for five hours: the phosphonates we studied react to a similar degree at $180-200^{\circ}$ for twenty hours, and the phosphates require heating to 220° for sixteen to eighteen hours. The reaction temperatures required of the phosphates is near their pyrolysis temperature.⁵ Nevertheless, reasonable vields of mixed phosphate esters can be obtained. The table summarizes the results of reactions of dodecyl bromide with various esters. Didodecyl esters were usually formed to some extent along with monododecyl esters. The use of higher mole ratios of starting phosphorus ester to dodecyl bromide should give even higher yields of monododecyl ester than are listed in the table. Likewise, didodecyl esters (and tridodecyl in the case of phosphates) should predominate if excess dodecyl bromide is used. The ready availability of the symmetrical phosphonate and phosphate esters makes the exchange reaction a particularly convenient method for obtaining the mixed esters.

Methyl dodecyl methylphosphonate (I) appeared as an unexpected byproduct in the Michaelis-Arbuzov reaction between trimethyl phosphite and dodecyl bromide. Because of this, particular attention was paid to the proof of structure of I, as prepared by the alkyl exchange reaction. Analytical data and infrared spectra were consistent with the proposed structure, and hydrobromic acid degradation established its structure conclusively. The expected products—methylphosphonic acid, methyl bromide, and dodecyl bromide—were isolated and identified. Methylphosphonic acid was characterized as the calcium salt monohydrate, $CH_3PO_3Ca \cdot H_2O$, the isolation of which was greatly facilitated by its insolubility in basic solution.

The Michaelis-Arbuzov reaction with trimethyl phosphite. The alkyl exchange reaction with phosphonate esters was discovered in much the same way that Harwood and Grisley discovered the phosphinate alkyl exchange reaction. In both instances, complications arose in a Michaelis-Arbuzov reaction. The initial objective in this work was the preparation of dimethyl dodecylphosphonate (II) via dodecyl bromide and trimethyl phosphite. The actual sequence of reactions which occurs when these two reactants are heated in a 180-200° bath, however, has now been shown to be as follows:



The symmetrical phosphonate, III, is formed by a Michaelis-Arbuzov isomerization, and reacts with alkyl bromide under the conditions of the reaction to give the exchange reaction product (I). As I and II are isomeric, it is very difficult to separate them. The evidence that the above described scheme represents the actual course of the reaction is: (1) isolation of III from the reaction; (2) demonstration that the exchange reaction between dodecyl bromide and III can be carried out separately to yield pure I; (3) the infrared spectrum and refractive index of the trimethyl phosphite-dodecyl bromide product, which suggest that a mixture of I and II is formed; and (4) hydrobromic acid degradation of the mixture, which yielded the ex-

⁽⁵⁾ C. E. Higgins and W. H. Baldwin, J. Org. Chem., 26, 846 (1961).

pected products: dodecylphosphonic acid, methylphosphonic acid, dodecyl bromide, and methyl bromide. II can be obtained pure by reaction of dodecylphosphonic dichloride with methanol in the presence of tertiary amine. The best value for the composition of the mixture obtained from the trimethyl phosphite-dodecyl bromide reaction was probably obtained from the yield of dodecylphosphonic acid. This composition was consistent with estimates based on relative band intensities ($P = O vs. P--CH_3$) in the infrared spectrum of the mixture compared to relative intensities in pure I.

In view of the course which the Michaelis-Arbuzov reaction between trimethyl phosphite and dodecyl bromide takes, the previously reported triethyl phosphite-dodecyl bromide reaction⁶ was reinvestigated. An exothermic reaction occurred when this phosphite and bromide (2:1 mole ratio) were heated to 170° . Further heating at 170- 180° for a total time of 45 minutes gave, after two distillations, diethyl dodecylphosphonate in 68%yield. Hydrobromic acid hydrolysis of the ester produced 98% of the theoretical yield of dodecylphosphonic acid. No dodecyl bromide or ethylphosphonic acid could be detected.

It seems, therefore, that products of the alkyl exchange reaction do not result when triethylphosphite is used in the Michaelis-Arbuzov reaction, but that they are formed as by-products when trimethyl phosphite is used. The low boiling point of trimethyl phosphite and the high reactivity of methyl esters may account for this difference in behavior. Whereas triethyl phosphite and the high-boiling bromide can be heated directly to a temperature where they will react (170°) , the initial temperature in the trimethyl phosphite reaction is held to $120-130^{\circ}$ by the relatively low reflux temperature of the phosphite. This initial period of 4-5 hr at lower temperatures provides an opportunity for trimethyl phosphite to isomerize to dimethyl methylphosphonate (III). The high concentration of III thus produced promotes the formation of I. The more facile rearrangement of trimethyl phosphite relative to triethyl phosphite has been reported.7

The absence of exchange reaction products with triethyl phosphite is *not* due to the inability of diethyl ethylphosphonate to undergo the reaction (see table). Although this phosphonate is less reactive with dodecyl bromide than is triethyl phosphite, a 58% yield of ethyl dodecyl ethylphosphonate was obtained after heating the two reactants at 200° for 20 hr.

The use of alkylating agents other than bromides. To aid in defining both the utility and the mechanism of the exchange reaction, alkylating agents

other than bromides were investigated. Dodecyl iodide was found to react with dimethyl methylphosphonate (III) to give I in 34% yield. However, the reaction occurred readily at 170°, whereas dodecyl bromide reacts only very slowly at this temperature. Dodecyl iodide is not preferred for the preparation of I because it is more difficult to separate from I than is dodecyl bromide. Didodecyl methylphosphonate, IV, is formed in addition to the monododecyl ester I in appreciable amounts (ca. 55% yield) with both the bromide and the iodide using 1:1 mole ratios of reactants. Tetradecyl chloride did not react with III at a bath temperature of 200° (reaction temperature 195-198°). At reaction temperatures up to ca. 250° no I was formed. Instead, a mixture of terminal and trans-internal tetradecenes (71% yield), plus dimethyl ether, some methyl chloride, and unidentified phosphorus acids resulted.

Dodecyl acetate was similarly unreactive towards III at 200°. When the reactants were heated in an autoclave at 250° for 18 hours, I (19%), IV (12%), and much starting material were obtained. Yields of 9–15% of I were obtained in reactions at atmospheric pressure in a 250° bath. Methyl acetate was isolated from these reactions and identified.

Octadecyl tosylate was also investigated as an alkylating agent in reaction with III. At 200° , pyrolytic elimination to olefins and *p*-toluenesulfonic acid occurred so readily that no exchange reaction was observed. Some methyl tosylate was isolated, but its origin is not clear.

It thus appears that only alkylating agents which are reactive in nucleophilic substitution reactions but are not too prone to undergo thermal elimination reactions will participate in the exchange reaction.

Mechanism of the alkyl exchange reaction. It is reasonable to classify this reaction mechanistically with the Michaelis-Arbuzov reaction. The primary step in both reactions is probably nucleophilic displacement by the phosphorus ester on the alkylating agent, as suggested by Harwood and Grisley.44 This implies that the two reactions have in common the alkoxyphosphonium ion intermediate which is generally accepted for the Michaelis-Arbuzov reaction. The major difference between the two reactions is the nucleophilic atom in the primary interaction. In the Michaelis-Arbuzov reaction the phosphorus in the trivalent ester is the nucleophilic site, whereas in the exchange reaction it is the oxygen atom in the phosphoryl group (or the suffur in the thiophosphoryl group). The ester phosphoryl groups are very weak bases and show no inflection on titration with perchloric acid in acidic organic solvents such as acetic acid or acetic anhydride.⁸ In contrast to phosphites, they show

^{(6) (}a) G. M. Kosolapoff, J. Am. Chem. Soc., 76, 615 (1954). (b) J. Am. Chem. Soc., 67, 1180 (1945).

⁽⁷⁾ J. Cason and W. Baxter, J. Org. Chem., 23, 1302 (1958).

⁽⁸⁾ Unreported observations. The phosphoryl group in phosphine oxides is titratable with perchloric acid [D. C. Wimer, Anal. Chem., **30**, 2060 (1958)].

no tendency to react with heavy metal salts such as mercuric chloride. It would be predicted, therefore, that the pentavalent esters would be less reactive than trivalent esters towards alkylating agents.

The following facts can be mentioned in support of the above mechanism, in addition to the evidence quoted by Harwood and Grisley.^{4a}

1. This work has shown that the reactivity of alkyl halides with a common phosphonate ester, III, is in the order RI > RBr > RCl. This is the expected order of reactivity in nucleophilic substitution reactions.⁹

2. In the case of thiophosphoryl esters such as Pistschimuka studied, the alkyl group of the alkylating agent was attached to the sulfur of the thiophosphoryl group, and an oxygen became the coordinately bonded atom.¹⁰ Such a "migration" is required of the above mechanism.

3. Harwood and Grisley^{4a} predicted that reactivity should decrease in the phosphinate-phosphonate-phosphate series. This is consistent with several types of information which reflect the electron density (hence, nucleophilicity) on the different phosphoryl oxygens. As mentioned earlier the present work confirms this prediction. However, it is now also clear that even the least reactive esters— (*i.e.*, phosphates)—will react under sufficiently vigorous conditions.

4. Triethyl phosphite is appreciably more reactive towards dodecyl bromide than is the isomeric phosphonate. This would be expected on the basis of the above mechanisms.

The reaction between dodecyl acetate and III would seem to deserve comment, as it represents an unusual mode of cleavage of an open chain carboxylate ester.¹¹ A nucleophilic agent usually attacks the carbonyl carbon of esters, although there are known exceptions to this generalization in special cases such as lactones.¹² The distinguishing features of the phosphoryl nucleophilic group which

(10) It would be predicted that in the phosphoryl ester reactions a similar interchange of coordinately and singly bound oxygen atoms could be observed if the phosphoryl oxygen or ether oxygens were labeled with ¹⁸O.

(11) Harwood and Grisley observed a similar reaction, apparently, in the formation of the ethylene diphosphinate via the reaction:



No further comment was made, however.

(12) J. Hine, *Physical Organic Chemistry*, McGraw-Hill, New York, 1956, p. 272.

enable it to cause alkyl-oxygen cleavage of an acyclic ester are not obvious.

EXPERIMENTAL

Materials. Trimethyl phosphite, dimethyl phosphonate, triethyl phosphite, and 1-octadecene were obtained from Matheson, Coleman and Bell. The phosphonates were redistilled prior to use. Dodecyl bromide, dodecyl iodide, tetradecyl chloride, and octadecyl bromide were obtained from Halogen Chemicals, Columbia, S. C., and used as received. Trimethyl phosphate (K & K Laboratories, Jamaica, N. Y.) and triethyl phosphate (Matheson, Coleman and Bell) were purified by stirring with potassium carbonate, filtering, and redistilling. The phosphates, which are hygroscopic, were stored in wax sealed bottles.

Dimethyl methylphosphonate (III) was prepared by the methyl iodide-catalyzed rearrangement of trimethyl phosphite--b.p. $82^{\circ}/76$ mm., n_{D}^{25} 1.4118.

Dodecyl acetate was prepared by acetylation of refractionated dodecanol with excess acetic anhydride and a few drops of pyridine, warming an hour on the steam bath after the reaction subsided, and distilling; b.p. $102-104^{\circ}/0.86$ mm., n_D^{25} 1.4313.

Octadecyl tosylate was prepared from octadecanol and *p*-toluenesulfonyl chloride.¹³

Boiling points are uncorrected. Infrared data reported here was taken from spectra of pure liquids or compensated nitrile mulls recorded with a Perkin-Elmer Model 21 spectrophotometer.

Reaction of trimethyl phosphite with dodecyl bromide and with octadecyl bromide. In a typical experiment 125 g. (0.50 mole) of dodecyl bromide and 124 g. (1.00 mole) of trimethyl phosphite were mixed in a 500 ml. 3 neck flask equipped with a gas inlet tube extending to the bottom of the flask, thermometer, and a reflux condenser. The reaction was heated in an oil bath at approximately 200° for 20 hr., while a slow stream of nitrogen was swept through the reaction. Extremely vigorous reflux of trimethyl phosphite occurred initially. During this period, the reaction temperature was near 130°. In 4-5 hours, refluxing slowed and the reaction temperature rose to 190-195°. Fractionation through a 14" jacketed Vigreux column yielded a forerun which consisted of a mixture of dodecyl bromide and dimethyl methylphosphonate (III). These two compounds are immiscible from room temperature to about 140°, at which temperature they become miscible. Distillation of the higher boiling portion gave a mixture of esters I and II, b.p. ca. 115° at 0.3 mm., $n_{\rm D}^{25}$ 1.442, in 51-69% yields, and a higher boiling residue which was not investigated.

Anal. Calcd. for C14Ha1PO3; P, 11.15. Found; P, 10.7.

The infrared spectrum of the mixture showed the usual aliphatic C—H absorption plus bands at 7.10 μ (w), —CH₂-adjacent to P→O in alkylphosphonate esters; 7.66 μ (m), P—CH₂; 8.04 μ (s), P→O; 8.48 μ (m), P—O—CH₃; 9.4–9.8 μ (s), 10.96 μ (m) (shoulder at 11.20 μ), 12.35 μ (s), and 13.90 μ (m) (tetramethylene band).

Octadecyl bromide reacted similarly with trimethyl phosphite at ca. 200°. After distilling the III which was formed, a mixture of solid esters was left which was not resolved by recrystallization from methanol, and which was ca. 3% high in carbon and ca. 1.5% low in P for $C_{18}H_{37}PO(OCH_3)_2$. The infrared spectrum had the same bands as the C_{12} homolog (above) including the P--CH₄ band at 7.66 μ and the 11.0 μ band. After the existence of isomeric methylphosphonate esters in the reaction product was recognized another attempt was made to obtain dimethyl octadecylphosphonate using lower temperature and rigorous temperature control. However, reaction for 20 hours in a 180 \pm 1° bath controlled by a Therm-O-Watch temperature controller

(13) C. S. Marvel and V. C. Sekera, Org. Syntheses, Coll. Vol. II, 50 (1940).

⁽⁹⁾ C. K. Ingold, Structure and Mechanism in Organic Chemistry, Cornell University Press, Ithaca, N. Y., 1953, p. 338f.

(manufactured by Instruments for Research and Industry, Cheltenham, Pa.), gave a product which still showed a strong $P-CH_3$ peak. The product was indistinguishable in its infrared spectrum from the one obtained at the higher temperature.

Reaction of triethyl phosphite with dodecyl bromide. Triethyl phosphite (66.4 g., 0.40 mole) and dodecyl bromide (49.6 g., 0.20 mole) were heated in a flask equipped with a stirrer, thermometer, and Dean-Stark receiver capped with a reflux condenser, using a 375 watt radiant heater controlled by a Therm-O-Watch. At 140° no reaction was observed; at 170° a vigorous exothermic reaction occurred. The temperature was allowed to go to 180° and was held there for a total reaction time of 45 min. The theoretical weight of ethyl bromide (16.0 g.), identified by its gas phase infrared spectrum¹⁴ was collected. Distillation yielded 32 g. of a forerun consisting mainly of triethyl phosphite, and (after two distillations) 42 g. of diethyl dodecylphosphonate, b.p. 116-120°/0.12 mm., $n_2^{p_5}$ 1.4399 (lit. n_{2p}^{30} 1.4365°).

Attempted resolution of the trimethyl phosphite-dodecyl bromide reaction product. The ester mixture obtained from this reaction was carefully refractionated through a jacketed 14" Vigreux column. A 100-g. sample was divided into ten equal cuts using this column. The boiling point fluctuated during the distillation, but the refractive indices found were as follows:

	n ²⁵ _D
Fraction No. 1	1.4399
Fraction No. 2	1.4412
Fraction No. 3	1,4418
Fraction No. 4-6	1,4419
Fraction No. 7-10	1.4420

It can be seen that, aside from the first fraction and to a lesser extent the second, the refractive index was nearly constant over the distillation.

Fraction No. 8 (above) was chromatographed on silica gel, as described for the dimethyl phosphonate-olefin reaction (below). A single peak appeared in the elution curve, but there were obvious differences in the relative intensities of the P—CH₂ and P—O—CH₂ bands in the leading and trailing fractions, indicating partial resolution of a mixture. The P—CH₃ band was strongest in the trailing fraction.

Gas chromatography of the phosphite-dodecyl bromide ester mixture through a silicone-on-Celite column at 210° using helium carrier gas gave only one major peak (96% of total area) and several minor ones.

Gas chromatography of pure I obtained *via* acid chloride (below) gave a single major peak (98% of total area), with a similar retention volume. No further attempts were made to use different columns or to adjust conditions.

Preparation of dimethyl dodecylphosphonate (II) via dodecylphosphonic dichloride. Dodecylphosphonic acid was prepared by 48% hydrobromic acid hydrolysis of the dibutyl ester, which in turn was prepared from dodecyl bromide and the sodium salt of dibutyl phosphonate.¹⁵ The acid was converted to the acid chloride with a 10% excess of phosphorus pentachloride, and was distilled after decomposition of excess phosphorus pentachloride by passage of sulfur dioxide through the reaction mixture; b.p. ca. 146°/0.1 mm., m.p. ca. 13-14°.

The dodecylphosphonic dichloride was added to a 10-fold excess of methanol containing 2 moles pyridine per mole acid chloride, allowing the temperature to rise to approximately the b.p. of methanol. After removal of excess methanol in a rotating Rinco evaporator, ether was added and pyridine hydrochloride was filtered off. Distillation gave II, b.p. 110–116°/0.03 mm., n_{24}^{24} 1.4431. The infrared spectrum showed no trace of the 7.66 μ (P--CH₃) or 11.0 μ bands, but was otherwise essentially identical to the spectrum of the phosphite-dodecyl bromide product.

Preparation of dimethyl octadecylphosphonate via dimethyl phosphonate and 1-octadecene. A 126-g. sample (0.50 mole) of 1-octadecene, 55 g. (0.50 mole) of dimethyl phosphonate, and 3.2 g. (4 mole %) of α, α' -azo-diisobutyronitrile in 500 ml. benzene were heated at 65° under nitrogen pressure overnight, then at reflux for 4 hr. Benzene and unchanged starting materials were distilled through a 14-in. jacketed Vigreux column, and the pot residue recrystallized once from 30-60° petroleum ether (24.3 g.).

The reaction was repeated at $75-80^{\circ}$, using stirring. A crude yield of 50 g. was obtained. The two reaction products were titrated for acidity and acidic products were removed by precipitation of the potassium salts from isopropyl alcohol solution with the calculated amount of standard potassium hydroxide. The neutral fractions were combined and chromatographed over silica gel containing 5% water. The following fractions were resolved (wt. percent in product given): 1. 1-Octadecene, eluted with hexane, 12%. 2. A nitrile-substituted hydrocarbon, eluted by 1:1 hexanebenzene, 6%. 3. Dimethyl 2-hexadecyleicosylphosphonate¹⁶ eluted with benzene, 26%.

Anal. Calcd. for C₂₈H₇₉PO₃: C, 74.2; H, 12.9; P, 5.0. Found: C, 74.7; H, 13.0; P, 4.6, 4.6.

4. Dimethyl octadecylphosphonate (crystalline) eluted with 1:1 ether-benzene, 50%.

Anal. Caled. for C₂₀H₄₃PO₃: P, 8.55. Found: P, 8.35.

The infrared spectrum of compound 4 taken on a mull showed the P \rightarrow O band near 8.0 μ , on which was superimposed the progression bands characteristic of crystalline long chain compounds. No 7.6- μ or 11.0- μ absorption was present such as is found in the spectra of I and III.

Hydrobromic acid cleavage of esters. (a). Structure Proof of I. A 5.00-g. sample (18.0 millimoles) of I, prepared from III and dodecyl bromide, was refluxed five minutes with 25 ml. 48% hydrobromic acid in a 100 ml. round bottom flask fitted with a reflux condenser which was connected to a small Dry-Ice cooled trap. A volatile material, 0.94 g. (9.5 millimoles; 53% yield calculated as methyl bromide) was obtained in the trap. The material was identified as pure methyl bromide by comparing its gas phase infrared spectrum (10 cm. cell) with that of authentic methyl bromide.¹⁴

On cooling the reaction, an organic phase was present which was separated and distilled. Dodecyl bromide (2.3 g. 9.8 millimoles, 55% yield), b.p. $93-95^{\circ}/0.9$ mm., was obtained. The infrared spectrum was identical with that of authentic dodecyl bromide.

Anal. Calcd. for C₁₂H₂₅Br: Br, 32.1. Found: Br, 31.9.

Another sample of I was refluxed 15 minutes with 48% hydrobromic acid (5 ml./g. ester). The dodecyl bromide layer was separated, and the aqueous layer diluted with five parts of water. An excess of 1*M* calcium chloride over the calculated amount was added, and the pH was adjusted to 9.5 with sodium hydroxide solution. After a few minutes a precipitate was formed, which was filtered, washed with water and acetone, and vacuum dried over phosphorus pentoxide at room temperature. Yield—59%, calculated as $CH_{2}PO_{3}Ca \cdot H_{2}O$.

Dimethyl methylphosphonate (III) was hydrolyzed similarly and the calcium salt was prepared as above, in 84% yield. The m.p. is over 400°.

Anal. Calcd. for CH₃PO₃Ca·H₂O: C, 7.90; H, 3.29; Ca, 26.4; P, 20.4. Found: C, 8.02; H, 3.59; Ca, 26.5; P, 19.9.

The infrared spectrum of the salts show the P-CH₃

⁽¹⁴⁾ R. H. Pierson, A. N. Fletcher, and E. St. Clair Ganz, Anal. Chem., 28, 1218 (1956).

⁽¹⁵⁾ G. M. Kosolapoff, J. Am. Chem. Soc., 67, 1180 (1945).

⁽¹⁶⁾ This structure is assigned on the basis of elemental analyses and by analogy with the work of C. E. Griffin and H. J. Wells, J. Org. Chem., 24, 2049 (1959).

band at 7.60 μ and hydrate bands at 3.05-3.13 μ and 6.02 μ , in addition to bands at 8.93, 9.18, 9.79, 10.06, and 13.00 μ .

The salts obtained from I and from III were shown to be identical in their infrared spectra and x-ray powder patterns. The latter, in contrast to the infrared spectra, are extraordinarily complex. There are at least 65 discernible lines in the patterns.

(b) Cleavage of the trimethyl phosphite-dodecyl bromide reaction product. A sample of the mixed monododecyl esters from the trimethyl phosphite-dodecyl bromide reaction was refluxed for 30 min. with 48% hydrobromic acid. The reaction was diluted with 4 parts water and extracted with ether. The ether layer was extracted with 0.5N sodium hydroxide. The ether was dried over sodium sulfate, then magnesium sulfate, and evaporated. Distillation yielded dodecyl bromide, b.p. 98°/1 mm. The sodium hydroxide layer was made strongly acid with concentrated hydrochloric acid and digested on the steam bath for 30 min.¹⁷ After cooling, the precipitate was filtered, washed with water, and dried in vacuo. Dodecyl phosphonic acid, m.p. 99-100° (lit. 100.5-101.5°6b) was obtained, in 53% yield, whose infrared spectrum was identical with that of authentic acid.

Anal. Calcd. for $C_{12}H_{25}PO_3H_2$: neutralization equivalent, 250. Found: neut. equiv., 248.¹⁸

The hydrobromic acid hydrolysis of the ester mixture was then repeated. The phosphonic acid was filtered off, and washed with 48% hydrobromic acid. The filtrate was distilled to a small volume, at atmospheric pressure, diluted with *ca*. 5 parts water, and again filtered to remove a small amount of dodecyl phosphonic acid which precipitated. Methylphosphonic acid was again isolated and identified as the calcium salt, as above.

(c) Cleavage of diethyl dodecylphosphonate. A 20.0-g. sample of diethyl dodecylphosphonate was cleaved by refluxing with 100 ml. of 48% hydrobromic acid for 30 min. The reaction product was separated into neutral and acidic fractions, approximately as described under section (b) above. Drying and evaporating the ether layer, which should contain neutral materials such as dodecyl bromide, gave a residue of only 7 mg. The basic extracts were acidified with a large excess of concentrated hydrochloric acid and digested on the steam bath about 30 min. Cooling and filtering yielded 15.4 g. (98%) of dodecylphosphonic acid. Mt tetrabutylammonium hydroxide in isopropyl alcohol gave a neutralization equivalent of 253 (calcd. 250).

Reaction of dimethyl methylphosphonate (III) with dodecyl bromide. A 50.0-g. sample (0.40 mole) of III and 100 g. (0.40 mole) of dodecyl bromide were heated in a flask connected to a Dry-Ice trap, using an oil bath controlled by a Therm-O-Watch at 200 \pm 2°. Nitrogen (ca. 1 cu. ft./hr.) was swept over the reaction. After 20 hr., 16.8 ml. of condensate (a 76% yield, calculated as methyl bromide) had

(18) Attempts to titrate both acidic functions of dodecylphosphonic acid with standard sodium hydroxide in aqueous or ethanolic solutions were not successful, quantitatively, because of formation of the earlier mentioned precipitate.¹⁷ It was found that potentiometric titrations using 0.1 Ntetrabutylammonium hydroxide in methanol-benzene, and isopropyl alcohol solvent, gave a homogeneous titration. A glass electrode and a sleeve-type calomel electrode filled with saturated methanolic potassium chloride were used. It was established with authentic phosphonic acid that only one acid function is titratable. been collected in the Dry Ice trap. The gas phase infrared spectrum identified the sample as methyl bromide containing a small amount of methanol.¹⁴

Distillation of the main product yielded a small forerun of dodecyl bromide and III, plus 40.5 g. (36%) of I, b.p. ca. $115^{\circ}/0.03$ mm., $n_{\rm D}^{*5}$ 1.4406, and 49.3 g. of higher boiling esters (57% calculated as didodecyl methylphosphonate). I on standing, even in a capped bottle, showed evidence of undergoing changes such as Harwood and Grisley found with methylphenylphosphinate.^{4a} As obtained from the reaction, I was inert to permanganate test solution in aqueous suspension, but readily reduced permanganate after standing. A redistilled sample had b.p. ca. $120^{\circ}/0.2$ mm., $n_{\rm D}^{*5}$ 1.4400.

Anal. Calcd. for $C_{14}H_{31}PO_3$: C, 60.4; H, 11.2; P, 11.2. Found: C, 60.1; H, 11.3; P, 11.2, 11.0, 10.6.

It showed infrared bands at 7.64 μ (P--CH₃), 8.02 μ (P \rightarrow O), 8.46 μ , (P-O--CH₃), 9.45 to 9.9 μ , (P-O--C), 10.95, 11.17 (shoulder), 12.35, and 13.87 μ , plus aliphatic C--H bands.

The high boiling residue was distilled through a special large bore apparatus; b.p. ca. $150^{\circ}/0.06$ mm. It showed the 7.6 μ P—CH₃ and the 8.0 μ P→O bands, but no 8.4- μ (P—O —CH₃) band. It had a broad 9.5-10 μ band, the 10.8- μ band with 11.0- μ shoulder, and 12.2- and 13.9- μ bands.

Reaction of diethyl ethylphosphonate with dodecyl bromide. An 81.7-g. sample (0.493 mole) of diethyl ethylphosphonate and 61.0 g. (0.246 mole) of dodecyl bromide were heated at 200 \pm 1° for 20 hr. A 15.1-g. sample (56%) of ethyl bromide was collected and identified by infrared spectra and a positive sodium iodide-acetone test. The residue was distilled, and the fraction b.p. 116°/0.23 mm. to 131°/0.16 mm. was redistilled. Ethyl dodecyl ethylphosphonate, b.p. 123°/0.14 mm.-122°/0.13 mm.; n_D^2 1.4383, was obtained in 58% yield.

Anal. Calcd. for C16H35POs; P, 10.1. Found: P, 10.0.

Reaction of III with dodecyl iodide. A 24.8-g. sample (0.20 mole) of III and 59.2 g. (0.20 mole) of dodecyl iodide were allowed to react in an apparatus similar to the bromide-III reaction. In a 160° bath some condensate was observed after 1 hour. The temperature of the bath was raised to 170°, and heating was continued for 19 hours. The condensate in the trap amounted to 19.3 g. (68% calculated as methyl iodide) after redistillation, b.p. 40-42°. The infrared spectrum revealed it was largely methyl iodide, with some dimethyl ether and methyl alcohol present. It gave a yellow precipitate rapidly with silver nitrate reagent.

Distillation of the main reaction product gave an approximately 34% yield of I and a 55% yield of distilled didodecyl ester IV, b.p. ca. 157°/0.04 mm. Reaction of III with tetradecyl chloride. A 24.8-g. sample

Reaction of III with tetradecyl chloride. A 24.8-g. sample (0.20 mole) of III and 46.5 g. (0.20 mole) of tetradecyl chloride were treated in the standard apparatus for 20 hr. in a 200° bath (reaction temperature 195–198°). No condensate appeared in the trap. The bath was then raised to 260° for 20 hours. The reaction temperature rose from 200 to 250°; 9.9 g. of condensate (dimethyl ether containing a small amount of methyl chloride) was obtained. The reaction was two phase at 250° after the reaction, was completed there were two phases at 250 degrees; this is not observed normally. It was established independently that heating III alone at these temperatures in a sealed tube in an autoclave yields dimethyl ether and pyro-derivatives of III.

Distillation of the upper layer from the reaction gave mixed tetradecenes, b.p. $58-65^{\circ}/0.08$ mm., in 71% yield. The olefins were largely terminally substituted, but also contained some internal olefin, according to infrared spectra. A small amount of a higher boiling fraction, b.p. $81-86^{\circ}/$ 0.08 mm., with a sharp 8.9- μ band was obtained. This was probably a mixture of olefins and methyltetradecyl ether, as it gave *ca*. one third the theoretical methoxyl content. The yield of alkyl exchange reaction products, if formed, was less than 1%.

The lower layer is apparently a partially esterified pyro-

⁽¹⁷⁾ If the water-soluble disodium salt of dodecylphosphonic acid is carefully acidified with dilute acid in the cold, a highly insoluble precipitate forms, which appeared to be a partially neutralized phosphonic acid (*vide infra*). Only vigorous treatment such as digestion with concentrated acid or recrystallization from 48% hydrobromic acid will liberate the free acid. One of the referees suggested that this could have been a hemisalt of the composition RPO₃H₂·RPO₃HNa.

derivative of methylphosphonic acid. A 1.12-g. sample of this product was stirred at 10–15° for 30 min. with 50 ml. distilled water and gave, after addition of calcium chloride and neutralization to pH 10, 0.23 g. CaCH₃PO₃·H₂O. However, refluxing 1.03 g. of the lower layer 30 min. with 5 ml. 48% hydrobromic acid, followed by distillation of most of the hydrogen bromide from the reaction gave by the above procedure 1.39 g. of CaCH₃PO₃·H₂O, a much higher yield.

Reaction of III with dodecyl acetate. A 30.1-g. sample (0.24 mole) of III and 55.6 g. (0.243 mole) of dodecyl acetate were reacted in the standard apparatus. After reaction at a bath temperature of 200° for 20 hr., 1.32 g. of material was collected in the trap. Distillation of the high boiling product recovered most of the starting materials, which were recombined and heated in a 250° bath for 20 hr. The reaction temperature rose to 228°. The condensate in the trap was redistilled, yielding 2.95 g. (16%) of methyl acetate, b.p. 54°, which was water soluble and had an infrared spectrum identical with that of authentic material.

Distillation of the high boiling material yielded III (54% recovery), dodecyl acetate (80% recovery), and 6.1 g. of I (9.0%), identified by its infrared spectrum and refractive index. The residue consisted of phosphorus acids containing $P-CH_3$ groups.

III and dodecyl acetate in 1:1 mole ratio were treated in an autoclave for 18 hours at 250° in a glass liner. Distillation gave 28% recovery of III, 56% recovery of dodecyl acetate, and a 19% yield of I. A higher boiling acidic fraction was also obtained. A similar reaction except for 48 hr. gave a 14% yield of I.

Reaction of III with octadecyl tosylate. Equimolar amounts of III and tosylate reacted in the usual apparatus (except that the Dry Ice trap was omitted) at a reaction temperature of 200° (bath slightly higher). The product consisted of two layers. The upper layer was distilled, b.p. mostly 87-94°/0.02 mm., and consisted primarily of trans-octadecenes (almost no CH=CH₂ absorption).

Methyl tosylate was obtained; m.p. after distillation $26-27^{\circ}$; mixture m.p. with authentic methyl tosylate (m.p. $28-28.5^{\circ}$) was $27-28^{\circ}$. The infrared spectra of the two samples were identical.

The lower layer from the reaction was mostly acids. From the weight and neutralization equivalent, 40% more equivalents of acid were formed than could be accounted for by conversion of all the tosylate groups to *p*-toluene-sulfonic acid. Hence, much of the acidic material must have been phosphorus acids.

Examination of the neutral fractions by infrared revealed that none of them contained a phosphonate $P \rightarrow O$ band at 7.9-8.0 μ .

Reaction of trimethyl phosphate with dodecyl bromide. Trimethyl phosphate (70.0 g., 0.50 mole) and dodecyl bromide (62.0 g., 0.25 mole) were heated for 3/4 hr. at 190°. No condensate appeared in the Dry Ice trap. Similarly, no apparent reaction had occurred after an additional $3^{3}/_{4}$ hr in a 200° bath. Finally, the bath was held at 220° for $14^{1}/_{2}$ hr. The condensate (4 ml.) consisted of methyl bromide plus large amounts of methanol and a small amount of dimethyl ether.

Unchanged phosphate and dodecyl bromide were distilled through the 14" Vigreux column, and the residue was distilled through simple large bore apparatus. A 40-g. sample (54%) of dimethyl dodecyl phosphate was obtained, b.p. ca. 120°/0.05 mm. The sample contained a small amount of P—OH which was removed by chromatography over silica gel containing 5% water, eluting with 80:20 benzene-ether. Redistillation gave a pure sample, b.p. 100°/0.02 mm., n_{25}^{25} 1.4345.

Anal. Caled. for C₁₄H₃₁PO₄: C, 57.2; H, 10.5; P, 10.5. Found: C, 57.2; H, 11.0; P, 10.6.

Hydrobromic acid hydrolysis followed by orthophosphate analysis gave the theoretical value for % PO₄. The infrared spectrum showed key bands at 7.80 μ (shoulder at 7.88 μ) (P \rightarrow O), 8.44 μ (P-O-CH₃), 9.6 μ (broad) (P-O-C), and 11.80 μ .

Reaction of triethyl phosphate with dodecyl bromide. A 91.4-g. sample (0.50 mole) of triethyl phosphate and 62.0 g. (0.25 mole) of dodecyl bromide reacted as described for III and dodecyl bromide (above) for 4 hr. in a 210° bath and 16 hr. in a 220° bath. The condensate amounted to 18 ml. The infrared spectrum showed the condensate to be ethyl bromide containing some ethyl ether. It gave an immediate precipitate with sodium iodide-acetone reagent.

Unchanged triethyl phosphate and dodecyl bromide were distilled through the 14-in. Vigreux column and the residue was distilled. Yield—44 g. (63%) of crude diethyl dodecyl phosphate, plus 22 g. higher boiling materials.

The infrared spectrum showed P—OH bands, which were removed by column chromatography. A 68.4-g. sample of combined yields from two reactions in 100 ml. petroleum ether were placed on an approximately 1" I.D. column containing 120 g. silica gel. Elution with 50:50 benzene-ether gave most of the neutral product in an early fraction. This was rechromatographed similarly using 90:10 benzene-ether. The main fractions, which were free of P—OH, were redistilled, b.p. $106^{\circ}/0.02 \text{ mm.}, n_D^{25}$ 1.4330.

were redistilled, b.p. $106^{\circ}/0.02 \text{ mm.}, n_D^{28} 1.4330.$ Anal. Calcd. for $C_{16}H_{35}PO_4$: C, 59.7; H, 10.8; P, 9.63. Found: C, 59.3; H, 10.5; P, 9.69. Hydrobromic acid hydrolysis followed by orthophosphate analysis gave 9.57%orthophosphate P.

The principal infrared bands of the compound are at 7.80 μ (P-O), 8.60 μ (P-O-Et), 9.5-10.3% (P-O-C).

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