

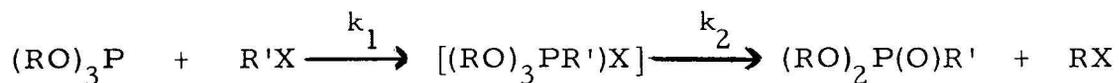
AN ABSTRACT OF THE THESIS OF

LANE JOSEPH GOODELL for the MASTER OF SCIENCE
(Name) (Degree)
in CHEMISTRY presented on March 25, 1968
(Major) (Date)

Title: REACTIONS OF TERTIARY PHOSPHITES WITH ALKYL
IODIDES IN ACETONITRILE

Abstract approved: Redacted for Privacy
Dr. John Thomas Yoke III

The Arbuzov reaction is an important method of synthesis of compounds containing a carbon-phosphorus bond.



The intermediate might have a salt-like or a penta-coordinate type of structure, or both in equilibrium. In many systems, the rate determining step of the reaction is not known. A polar solvent might have a significant influence on these points.

Although the reaction is normally carried out without a solvent, two groups of workers have studied the kinetics of the reaction in acetonitrile. These two groups published conflicting reports, specifically related to the system of tri-n-butyl phosphite with ethyl iodide in acetonitrile at 31°.

The possibilities for the reaction to be considered in the

present work were (1) olefin elimination from the tertiary phosphite to give a dialkyl hydrogen phosphonate, (2) inadvertent hydrolysis to give a dialkyl hydrogen phosphonate and an alcohol, (3) the Arbuzov reaction to give a dialkyl alkylphosphonate, and (4) no reaction. Assuming that it is the Arbuzov reaction which actually occurs for such reactants in acetonitrile, the previous reports were also in conflict as to the rate determining step. In the present work, it was found by qualitative and quantitative analysis of this system that the Arbuzov reaction occurs, but very slowly, contrary to one of the previous reports.

A second system was investigated, in which triisopropyl phosphite and isopropyl iodide were heated in acetonitrile at 50^o. Olefin elimination had previously been reported as probably occurring in this system. It was found that after 13.5 days almost no reaction occurred; apparently the Arbuzov reaction occurred to a very limited extent. It was substantiated that olefin elimination absolutely did not occur.

The rate determining step of the Arbuzov reaction in acetonitrile was of great interest. A third system which was studied was that of trimethyl phosphite and n-butyl iodide in acetonitrile at 50^o. As in the two previous experiments, products and reactants in the reaction mixture were analyzed qualitatively and then quantitatively. The objective of the experiment was to set up competition between

the reactant, n-butyl iodide, and the product, methyl iodide, as reagents for trimethyl phosphite. Because of steric factors, methyl iodide would be expected to react faster than n-butyl iodide. If $k_1 \gg k_2$ and if the first step were not reversible, then very little or no dimethyl methylphosphonate would be produced. The sole or predominant Arbuzov product would be dimethyl n-butylphosphonate. As a result of the experiment, it was found that more dimethyl methylphosphonate than dimethyl n-butylphosphonate was formed. The proposed kinetic assumptions were therefore discounted.

In this latter experiment, hydrolysis of the tertiary phosphite occurred to a minor extent despite rigorous precautions to eliminate moisture. Because of this observation, it appears that the published report of dialkyl hydrogen phosphonate formation in the reaction of triisopropyl phosphite and isopropyl iodide in acetonitrile was due to inadvertent hydrolysis of the tertiary phosphite, rather than to olefin elimination. Qualitative and quantitative analysis had not been undertaken by two previous groups of workers to account for all possible products of the systems investigated.

A major point of the present research was that product isolation and identification were accomplished through the use of a vacuum line, infrared and n. m. r. spectroscopy, and gas liquid chromatography. The reactions were conducted in a vacuum line to eliminate contaminating traces of moisture from the atmosphere and to trap and

identify possible olefin gases being formed. Rigorous precautions were necessitated during synthesis and purifications of materials, during the starting and termination of reactions, and during all analyses to eliminate the presence of moisture.

The general conclusions of this work follow. Olefin elimination involving tertiary phosphites undergoing the Arbuzov reaction in acetonitrile has not occurred in any of the systems studied. It is extremely difficult to eliminate moisture in these systems, and previous reports of the fairly rapid formation of phosphoryl compounds, and of dialkyl hydrogen phosphonate formation by olefin elimination, now shown to be incorrect, are probably due to contamination of the systems by water. The Arbuzov reaction proceeds very slowly in acetonitrile at temperatures in the range 31-50^o for those systems investigated in this study. Steric hindrance is a determining factor for alkyl iodides undergoing the Arbuzov reaction in acetonitrile. Major portions of previous published work were shown to be incorrect.

Reactions of Tertiary Phosphites
with Alkyl Iodides in Acetonitrile

by

Lane Joseph Goodell

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1968

APPROVED:

Redacted for Privacy

Professor of Chemistry
in charge of major

Redacted for Privacy

Chairman of Department of Chemistry

Redacted for Privacy

Dean of Graduate School

Date thesis is presented March 25, 1968

Typed by Donna Olson for Lane Joseph Goodell

ACKNOWLEDGEMENT

The author is grateful to his research advisor, Dr. John T. Yoke III, for his direction, interest, and enthusiasm which were generously given in this investigation.

Acknowledgement is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this work.

Materials supplied by Mobil and Hooker Chemical Companies are very much appreciated.

The author wishes to thank Mr. Donald D. Schmidt for the n. m. r. spectra and Dr. Theran D. Parsons for the use of the spinning band column and accessory equipment.

I wish to thank Dr. Chester A. Schink for encouraging me to enter graduate school.

TABLE OF CONTENTS

<u>Chapter</u>	<u>Page</u>
I. INTRODUCTION	1
II. HISTORICAL	3
III. EXPERIMENTAL	14
Instrumental Methods	14
Infrared Spectroscopy	14
Gas Liquid Chromatography	14
Nuclear Magnetic Resonance	15
Refractive Index	15
Spinning Band Column	15
Distillation Assembly	16
Materials	16
Acetonitrile	17
Methyl Alcohol	17
Isopropyl Alcohol	17
n-Butyl Alcohol	17
Isopropyl Bromide	18
n-Butyl Bromide	18
Methyl Iodide	18
Ethyl Iodide	18
Isopropyl Iodide	19
n-Butyl Iodide	19
Trimethyl Phosphite	19
Triisopropyl Phosphite	20
Tri-n-butyl Phosphite	20
Dimethyl Hydrogen Phosphonate	21
Diisopropyl Hydrogen Phosphonate	21
Di-n-butyl Hydrogen Phosphonate	22
Dimethyl Methylphosphonate	22
Dimethyl n-Butylphosphonate	22
Di-n-butyl Ethylphosphonate	23
Procedure	
Reaction of Tri-n-butyl Phosphite with Ethyl Iodide in Acetonitrile at 31 ^o	26
Starting the Reaction	26
The Reaction Conditions	27
Terminating the Reaction	27
Reaction of Trimethyl Phosphite with n-Butyl Iodide in Acetonitrile at 50 ^o	28

<u>Chapter</u>	<u>Page</u>
Starting the Reaction	29
The Reaction Conditions	30
Terminating the Reaction	31
Reaction of Triisopropyl Phosphite with Isopropyl Iodide in Acetonitrile at 50°	31
Starting the Reaction	31
The Reaction Conditions	32
Terminating the Reaction	32
 IV. RESULTS	 34
Reaction of Tri-n-butyl Phosphite with Ethyl Iodide in Acetonitrile at 31°	34
Pressure Readings	34
Gas Liquid Chromatographic Analysis	34
Infrared Spectroscopic Analysis	37
Nuclear Magnetic Resonance Analysis	40
Reaction of Trimethyl Phosphite with n-Butyl Iodide in Acetonitrile at 50°	42
Gas Liquid Chromatographic Analysis	42
Infrared Spectroscopic Analysis	45
Nuclear Magnetic Resonance Analysis	46
Reaction of Triisopropyl Phosphite with Isopropyl Iodide in Acetonitrile at 50°	47
Pressure Readings	47
Gas Liquid Chromatographic Analysis	48
Compound Y	48
Compound X	51
Attempted Quantitative G. L. C. Analysis of the Reaction Product	52
Infrared Spectroscopic Analysis	53
Nuclear Magnetic Resonance Analysis	56
 V. CONCLUSIONS	 58
 BIBLIOGRAPHY	 63
 APPENDIX	 65

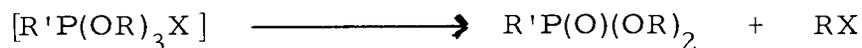
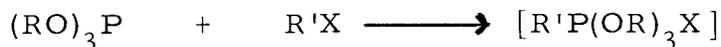
LIST OF TABLES

<u>Table</u>	<u>Page</u>
I. Gas Liquid Chromatographic Data for the Reaction Mixture from Tri-n-butyl Phosphite with Ethyl Iodide in Acetonitrile at 31°.	36
II. Infrared Spectroscopic Data on Standard Tri-n-butyl - Ethyl Iodide Standard Samples.	39
III. Gas Liquid Chromatographic Data for the Reaction Mixture from Trimethyl Phosphite with n-Butyl Iodide in Acetonitrile at 50°.	43
IV. Quantitative Gas Liquid Chromatographic Analysis and Preparation of Standards for the Trimethyl Phosphite - n-Butyl Iodide Reaction Mixture.	45
V. Gas Liquid Chromatographic Data for the Reaction Mixture from Triisopropyl Phosphite with Isopropyl Iodide in Acetonitrile at 50°.	49
VI. Chromatographic Standards for the Analysis of Diisopropyl Hydrogen Phosphonate.	53
VII. Infrared Spectroscopic Data on Triisopropyl Phosphite Concentration Standards.	54

REACTIONS OF TERTIARY PHOSPHITES WITH ALKYL IODIDES IN ACETONITRILE

I. INTRODUCTION

Reaction of a trialkyl phosphite with an alkyl halide is the basis of a well-known method of major synthetic importance for the preparation of compounds containing a carbon-phosphorus bond. The reaction, known as the Arbuzov or Michaelis-Arbuzov reaction, is normally carried out in the absence of a solvent and at elevated temperatures, e. g., above 100°. It is generally accepted to be a two stage process, written as follows:



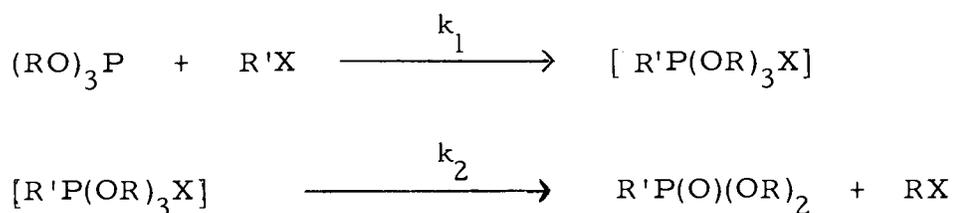
It has not always been clear which of these steps is rate determining. There seem to be major effects due to variations in the groups R and R' and in X. If R and R' are the same, the reaction is an isomerization, and a catalytic amount of alkyl halide may suffice; otherwise a mixture of products might result if a different alkyl halide is generated in the course of the reaction, to compete with the alkyl halide originally present. Solvent effects have been little studied, although they might be expected to influence the rates and especially the structure of the intermediate.

Two previous groups of studies in acetonitrile solvent at temperatures ranging from 30 to 70^o have given contradictory results, and the desire to clarify our knowledge of this system has lead to the present investigation. Specifically, the following possibilities have been suggested and were to be investigated in the present work: various tertiary phosphites and alkyl halides, in acetonitrile at temperatures only slightly in excess of room temperature, give (1) the Arbuzov reaction, (2) no reaction, (3) a dialkyl hydrogen phosphonate hydrolysis product due to unavoidable contamination by traces of water, or (4) olefin elimination from the tertiary phosphite, resulting in a dialkyl hydrogen phosphonate.

II. HISTORICAL

A review of the Arbuzov Reaction from the practical synthetic standpoint has been given by Kosolapoff (21, p. 273-289) and such factors bearing on the mechanism of the reaction as were known prior to about 1950 are mentioned by Kosolapoff in his well known book (20).

There are two matters of practical importance in considering the reaction written as a two step process,



which involve the question of the relative magnitudes of k_1 and k_2 : (1) can the intermediate be isolated? (2) in the case that R and R' are different, does the alkyl halide generated in the second step compete with that reacting in the first step to give a mixture of phosphonic acid esters, $\text{R}'\text{P}(\text{O})(\text{OR})_2$ and $\text{RP}(\text{O})(\text{OR})_2$?

In some cases the intermediate has been isolated. Its isolation would be possible only when $k_1 > k_2$; other practical factors, such as its tendency to be separable from the reaction mixture by crystallization may also play a role. When the reaction involves simple aliphatic groups in both tertiary phosphite and alkyl halide, the

intermediate has not proven isolable. $((C_6H_5O)_3PMeI)$ (29) and Arbuzov intermediates (27) resulting from the reactions of alkyl dialkylphosphinites, $R_2P(OR)$, have been isolated by crystallization and identified, which suggests that steric and electronic effects may have a large influence on the relative magnitudes of k_1 and k_2 .

There is evidence of the substantial formation and subsequent decay of some intermediates even in those cases when the intermediate cannot be isolated. Differential thermal analysis (5) shows two exothermic effects for many reactions including the case where both R and R' are ethyl groups. Conductivity maxima for several examples of the Arbuzov reaction, including the reaction of $(EtO)_3P$ with EtBr, correspond to viscosity and density extrema of other experiments (6). In one study, methyl iodide was added to tri-t-butyl phosphite at $5 \cdot 10^0$. White crystals appeared and then disappeared during the course of the reaction; this was attributed to the formation of the Arbuzov intermediate (23).

The first step of the Arbuzov reaction approximates a second order nucleophilic substitution where the phosphite is the nucleophile. Inductive effects appear to have some effect on reaction rates involving tertiary phosphites, since the reactivity order t-butyl > isopropyl > ethyl appears to be correct (4, 23). Steric factors are also involved since $(EtO)_3P$ reacts faster than $(nBuO)_3P$ (3). Also both steric and inductive effects are suggested,

since reaction rates increase in the order $(RO)PR_2 > (RO)_2PR > (RO)_3P$ when R is ethyl (26).

There are steric factors involved in the nature of R'X; reaction rates decrease in the order primary alkyl > secondary alkyl (15) and methyl > ethyl > propyl > butyl (16). Concerning the leaving group, the normal sequence I > Br > Cl is observed (15).

If R and R' are not the same, two Arbuzov products might occur. First, if $k_1 \gg k_2$ and if the first step is not reversible, the second alkyl halide will not be generated in significant amount until the phosphite has been largely and irreversibly removed. A single product would result. Second, if $k_2 \gg k_1$, then two alkyl halides would compete. A preponderant yield of either $R'P(O)(OR)_2$ or $RP(O)(OR)_2$ is conceivable. Obviously, all intermediate stages are possible, depending on the relative magnitudes of the two rates and the reversibility of the reactions. Past practical experience has little to offer here, since the reaction has most often been conducted as an isomerization, with R and R' the same. Even when different alkyl groups have been involved, and when the alkyl halide being generated would be expected to react more effectively than the initial alkyl halide (e. g. , methyl iodide being formed, with butyl iodide as the starting reagent) synthetic conditions have been chosen so as to give a predominant yield of a single desired product. Thus, the lower boiling alkyl halide has been simply distilled away from the

reaction mixture as it was formed in the course of the reaction (13, 21, p. 276).

The second step of the Arbuzov reaction involves the breaking of a carbon-oxygen bond in the intermediate (15, 29). A mechanism approximating S_N2 appears evident in some cases. Walden inversion occurred when tri-2-octyl phosphite reacted to give 2-octyl halide (14). Steric effects were evident in a study involving mixed phosphite esters, because the ease of removal of alkyl groups followed the order methyl > ethyl > isopropyl (15). In addition to steric effects, the polarity of the carbon-oxygen bond appears to be important: mixed phosphites were prepared that had alkyl groups which were similar in size, but different in electronegativity. It was found that the group displaced had the lowest electronegativity (24).

Several structures may be proposed for the intermediate, including: (a) a penta-coordinate phosphorus (phosphorane) molecule; (b) a halide-bridged dimer of the phosphorane, with six-coordinate phosphorus; (c) a quasi-phosphonium (ionized) salt $R'(RO)_3P^+X^-$; (d) either a solvent-separated or an "intimate" ion pair of the phosphonium salt, i. e., the salt in ionized but non-dissociated condition. Clearly equilibrium between structural forms could occur.

The effect of solvents might well be expected to be significant. The position of an equilibrium, or the identity of a single predominant

form of an intermediate, might well be determined by the dielectric constant of a solvent as well as by specific solvation effects. For example, a solvent of high dielectric constant may promote ionization of a salt and it may also thereby affect the reaction rate. A high dielectric constant solvent may affect the equilibrium of two proposed intermediate structures by causing a shift from a pentavalent type compound to a salt-like compound. The question of isolability of the intermediate seems to be dependent on temperature, substituent effects, etc.; solvents might have an important effect on the isolation of the intermediate because of these factors.

With one exception, past studies of tertiary phosphite-alkyl halide reactions in solution have been limited to a single solvent, acetonitrile, and to two groups of investigators, Buck, Kumli, and Yoke in America, and Aksnes and Aksnes in Norway. Two Russian workers have studied the Arbuzov reaction briefly in ethanol and toluene solutions (11).

Buck and Yoke (7) made a conductometric study of the reaction of ethyl iodide with tri-n-butyl phosphite, each approximately 0.2 molar in acetonitrile at 31°. They observed a rapid increase and then a slow decay of the specific conductance, and interpreted the observations in terms of the formation and consumption of the Arbuzov intermediate. The conductance values were quantitatively interpretable in terms of a second order rate constant for the first

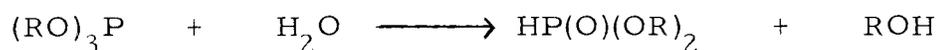
step, and a first order rate constant for the rate-determining second step. The actual maximum conductance observed was very much less than would be expected for a fully dissociated 1:1 electrolyte at a concentration of 0.2 molar; Buck and Yoke supposed that the intermediate was present primarily as a phosphorane or ion pair, slightly dissociated into ions. This would also be in accord with, and required by, the first order kinetics observed for the second step, in that the attack of halide on the carbon-oxygen bond would be effectively intramolecular. After completion of the reaction as indicated by conductivity measurements, the infrared spectrum of the reaction mixture was determined. It was found that a band present in the starting solution at $6.8-7.0\mu$, which was assigned to tertiary phosphite absorption, had disappeared, and that a strong new band at $7.9-8.0\mu$, characteristic of the phosphoryl bond, had appeared. This was taken as evidence that the Arbuzov reaction had occurred. For the measurement of this spectrum, the indicator cell contained 25% (vol) of the reaction mixture in carbon tetrachloride and the reference cell contained 25% (vol) acetonitrile in carbon tetrachloride. Because acetonitrile has a very strong absorption band in the region from $6.1-8.2\mu$, it seems most likely that the absorption band of tri-*n*-butyl phosphite would be obscured by the absorption of the solvent. Incidentally, di-*n*-butyl ethylphosphonate, di-*n*-butyl hydrogen phosphonate, and *n*-butyl alcohol have infrared absorption

bands close to 6.8μ .

Aksnes and Aksnes (1, 3) used quantitative infrared spectroscopic measurements for their kinetic investigation. The phosphoryl absorption band at $7.9-8.0\mu$ ($1250-1256\text{ cm}^{-1}$) and the absorption band of ethyl iodide at 1204 cm^{-1} were measured. They reported that essentially no reaction occurred between tri-n-butyl phosphite and ethyl iodide under the conditions used by Buck and Yoke. After a reaction time of 20.5 hours no phosphoryl band, which would be characteristic of the Arbuzov product, di-n-butyl ethylphosphonate, was observed. The data of Buck and Yoke indicated that the reaction reached completion after 27.8 hours, and that approximately 80% of the product was formed after 20.5 hours. Aksnes and Aksnes then studied reactions of triethyl phosphite and ethyl iodide (a true isomerization), each about 0.2 molar in acetonitrile, at higher temperatures (about 65°). The Arbuzov reaction was observed and the rates were found to be pseudo first order in phosphite. Because the heights of the absorption bands for ethyl iodide were constant during each run, it was concluded that the concentration of ethyl iodide remained constant. If the second step had been rate determining, the concentration of ethyl iodide would have at first decreased, and then returned to its original value. The addition of sodium iodide did not affect the rate. Aksnes and Aksnes concluded that this was confirming evidence that the first step was rate determining.

Aksnes and Aksnes (1) felt that the low absolute magnitude of the conductance observed by Buck and Yoke was unreasonable, and failed to understand that this was taken to signify that the reaction intermediate was supposedly present largely in undissociated form. Thus, they felt that their finding that addition of sodium iodide had no effect on the rate proved that conversion of phosphonium intermediate to products could not be rate determining. They did not realize that the scheme of Buck and Yoke would also predict no influence of sodium iodide. However, the scheme of Buck and Yoke would not call for constancy of ethyl iodide concentration during the reaction, as observed by Aksnes and Aksnes. There is a definite assignment (9) for the ethyl iodide absorption at 1204 cm^{-1} , but the possibility of a coincidence of an absorption band of the intermediate at this wavelength cannot be eliminated.

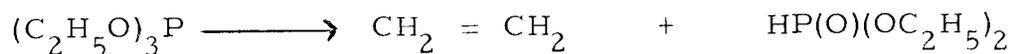
Aksnes and Aksnes criticized Buck and Yoke's experimental method, particularly with reference to the drying of the acetonitrile. They suggested that the small conductivity changes observed were due to the hydrolysis reaction



which they claimed was autocatalytic (3). Formation of the hydrolysis product, a dialkyl hydrogen phosphonate (or secondary phosphite ester) would account for the phosphoryl infrared absorption observed.

The way in which such a hydrolysis would be related to the conductivity effects was not clear. Aksnes and Aksnes also failed to realize that a stoichiometric equivalent of water, rather than just a trace would be required. In a subsequent paper (2), Aksnes and Aksnes reported that the hydrolysis in acetonitrile was in fact not autocatalytic (such apparent catalysis as is observed in the absence of solvent being due to a mutual solubilization phenomenon of reactant and product).

Kumli and Yoke (22) attempted to repeat the previous type of conductometric work, using the triethyl phosphite-ethyl iodide system. Excellent agreement with the previous work was found. A conductivity peak for the hydrolysis reaction (triethyl phosphite plus added water) was found to come later in time and to be much larger than that for the triethyl phosphite-ethyl iodide reaction. However, in the latter reaction, despite rigorous precautions for the exclusion of traces of water, the product seemed to be the hydrolysis product, diethyl hydrogen phosphonate. Kumli postulated that this could result from olefin elimination.



Mark and Van Wazer (23) reported olefin elimination when tri-*t*-butyl phosphite reacts with methyl iodide. Also, when tri-*t*-butyl phosphite was heated in a vacuum, isobutylene and

di-*t*-butyl hydrogen phosphonate were formed.

Aksnes and Aksnes (4) reported a study of the reaction of triisopropyl phosphite with isopropyl iodide in acetonitrile. They concluded that the product of the reaction was not the Arbuzov product, but rather was diisopropyl hydrogen phosphonate. To account for this, elimination of propene was postulated, although it was not isolated nor otherwise identified. Their only experimental evidence was the infrared spectrum of the phosphoryl band of the product, which was compared with that of authentic diisopropyl hydrogen phosphonate. There is uncertainty that the phosphoryl absorption might have been due to diisopropyl isopropylphosphonate, because that compound was not prepared. The authors stated that the reaction proceeds "very slowly", but the reaction time, the molar concentrations of the reactants, and the temperature were not stated in their paper. Because the temperatures of other systems studied by Aksnes and Aksnes were between 50^o and 70^o, it is assumed that this reaction was also studied in this temperature range.

The previous work of Buck and Yoke, and Aksnes and Aksnes, has been characterized by general failure to isolate products, and thus establish the reaction to which kinetic measurements apply. Another criticism of the previous work has been the tendency of the investigators to over-generalize their conclusions. Thus, results found in dilute solution at relatively low temperatures do not

necessarily serve to characterize the mechanism of the Arbuzov reaction as it is run in synthetic practice, with neat reagents and high temperatures. For example, Aksnes and Aksnes concluded that the Arbuzov reaction (including the example of the reaction of an alkyl diarylphosphinite, ethyl diphenylphosphinite) is in general characterized by a rate determining first step (1). In view of the several instances of isolation of the reaction intermediate, this is a patently invalid general conclusion.

III. EXPERIMENTAL

Instrumental Methods

Infrared Spectroscopy

Infrared spectra were taken in the range of 2.5μ (4000 cm^{-1}) to 14.5μ (690 cm^{-1}) using a Beckman Microspec double beam recording infrared spectrophotometer. Demountable cells with sodium chloride windows and 0.025 mm nylon spacers were used for qualitative analysis. A 0.100 mm fixed path length cell was used for quantitative analysis. The reference solution was 100% spectro-quality reagent grade carbon tetrachloride (Matheson Coleman and Bell CX 415) and the samples were prepared as 5% (vol) solute in carbon tetrachloride.

Gas Liquid Chromatography

A F and M Scientific Model 700 Chromatograph with six ft identical dual stainless steel columns and connected to a Sargent Recorder Model SR was used. Helium was the carrier gas. The specifications of the various columns used and the details of the sampling procedures are indicated later. Sargent Recorder Chart paper (catalog No. S-72166) was used. The base line is at 0 and the maximum peak height of any peak would be 100.

Nuclear Magnetic Resonance

A Varian Model A-60 n. m. r. spectrometer was used. Samples were contained in Wilmad 501-GS n. m. r. tubes covered with plastic caps. Calibrants were ethylbenzene and tetramethylsilane. The sample tubes were loaded and capped in a nitrogen-filled dry box. N. m. r. analysis was used to establish the purity of the tri-alkyl phosphites used as reagents, and to test for the presence of dialkyl hydrogen phosphonates in the reaction mixtures. The tests were based on the resonance signals of the protons directly attached to the phosphorus atoms in the hydrogen phosphonates which were absent in the tertiary phosphites and in the dialkyl alkylphosphonates. All chemical shifts reported were relative to tetramethylsilane, a separate tube of which was used to zero the instrument.

Refractive Index

A Bausch and Lomb refractometer was used to measure refractive indices at the sodium D line.

Spinning Band Column

A Nester-Faust NFT-50 Annular Teflon Spinning Band Distillation Column was used in the final stages of purification of some materials. The use of such a column was necessary for the trialkyl

phosphites because of excessive foaming tendencies during vacuum fractionation. The spinning column was connected to a trap, a Cole-Parmer cartesian diver type manostat, a three-way "T" shape stopcock which was connected to a manometer, and a vacuum line. Temperatures were indicated in the still pot by a thermometer and at the column and the still head by thermocouples. However, the thermocouple readings were not considered to be reliable measures of the distillation temperatures of the fractions collected.

Distillation Assembly

A Lab Glass Inc. Model ML-670 Distillation Assembly was also used for distillations under reduced pressure. The tube of a ground joint was drawn to a capillary tip for each distillation. The tip was submerged into the liquid being distilled and nitrogen gas was passed through it to prevent bumping. The assembly was connected to a three-way "T" shape stopcock which was connected to a manometer, a drying tube containing soda lime, an aspirator bottle, and a water aspirator.

Materials

All atmospheric pressure distillations involved in the purification of chemicals for this research were carried out in an atmosphere of dry purified nitrogen. Infrared spectra of all organophosphorus

compounds described in this section are given in the Appendix.

Acetonitrile

Acetonitrile (Matheson Coleman and Bell R 2726) was added to a glass stoppered bottle containing phosphorus pentoxide; after several days it was distilled from phosphorus pentoxide. Various subsequent details of purification, corresponding to different stages of the experimental work, are given in full later.

Methyl Alcohol

Methyl alcohol (Baker and Adamson 1207) was used without purification as a qualitative standard for gas liquid chromatographic analysis.

Isopropyl Alcohol

Isopropyl alcohol (Matheson Coleman and Bell CB 891) was distilled at atmospheric pressure. The fraction collected had a boiling point of 82° , lit. (8) 82.3 (760 mm).

n-Butyl Alcohol

n-Butyl alcohol (Baker and Adamson 1207) was used without purification as a qualitative standard for gas liquid chromatographic analysis.

Isopropyl Bromide

Isopropyl bromide (Matheson Coleman and Bell BX 1450) was distilled at atmospheric pressure. The fraction collected had a boiling point of 59° , lit. (8) 59.6° (760 mm).

n-Butyl Bromide

n-Butyl bromide (Matheson Coleman and Bell BX 1045) was purified by distillation. The fraction boiling in the range of $99-100^{\circ}$ was used, lit. (8) 101.6° (760 mm).

Methyl Iodide

Methyl iodide (Matheson Coleman and Bell IX 185) was used without purification as a qualitative standard for gas liquid chromatographic analysis.

Ethyl Iodide

Ethyl iodide (Matheson Coleman and Bell CB 377) was washed with aqueous sodium thiosulfate, distilled from calcium chloride, and then redistilled. The boiling point of the fraction collected was $69-70^{\circ}$, lit. (8) 72.2° .

Isopropyl Iodide

Isopropyl iodide (Matheson Coleman and Bell IX 215) was treated with aqueous sodium thiosulfate. It was washed three times with distilled water and then distilled from calcium chloride in a flask cooled by ice water into the vacuum line, where the sample was fractionated. Only the middle fraction collected was used for the reaction.

n-Butyl Iodide

n-Butyl iodide (Matheson Coleman and Bell IX 160) was used without purification as a qualitative standard for gas liquid chromatographic analysis.

Trimethyl Phosphite

Trimethyl phosphite (combined samples from the Hooker and Monsanto Chemical Companies) was distilled at atmospheric pressure. The fraction collected had a boiling range of 105-108^o, lit. (17) 112-113^o. No phosphorus-hydrogen absorption (10) was observed in the infrared spectra of this compound, which indicated the absence of hydrolytic impurities.

Triisopropyl Phosphite

Triisopropyl phosphite (sample from the Mobil Chemical Co.) was treated with sodium wires, allowed to stand until hydrogen evolution ceased, and then decanted. The resulting material was distilled under reduced pressure using the spinning band column. The fraction so obtained was distilled again under reduced pressure using the distillation assembly. The middle fraction collected had a boiling point of 57° (8 mm), lit. (20) $60-61^{\circ}$ (8-10 mm). Analysis by gas liquid chromatography, infrared spectroscopy, and nuclear magnetic resonance confirmed the purity of the triisopropyl phosphite. No phosphorus-hydrogen absorption (10) was observed in the infrared spectrum of this compound, which indicated the absence of hydrolytic impurities.

Tri-n-butyl Phosphite

Tri-n-butyl phosphite (Eastman Kodak P 6833) was treated with sodium wires, allowed to stand until hydrogen evolution ceased, and then decanted. The material so obtained was distilled twice in the spinning band column at 5 mm pressure. A pure fraction of tri-n-butyl phosphite was collected under the following conditions: pot $140-150^{\circ}$, column $145-150^{\circ}$, head $125-135^{\circ}$. The boiling point of this material given in the literature (17) is $107-108^{\circ}\text{C}$ (5 mm).

Analysis by gas liquid chromatography, infrared spectroscopy, and nuclear magnetic resonance confirmed the purity of tri-n-butyl phosphite. No phosphorus-hydrogen absorption (10) was observed in the infrared spectra of this compound, which indicated the absence of hydrolytic impurities.

Dimethyl Hydrogen Phosphonate

Dimethyl hydrogen phosphonate (combined samples from the Mobil and Monsanto Chemical Companies) was distilled under reduced pressure using the distillation assembly. The fraction collected had a boiling point of 66-70^o (19-21 mm), lit. (30) b. p. 72-73^oC (25 mm).

Diisopropyl Hydrogen Phosphonate

Diisopropyl hydrogen phosphonate was synthesized by boiling triisopropyl phosphite with water in acetonitrile for twelve hours. 50 ml of triisopropyl phosphite (sample from the Mobil Chemical Co.), 4 ml of distilled water and 100 ml of acetonitrile (Matheson Coleman and Bell R 2726) were added to a 300 ml three neck round bottom flask. The flask was fitted with a thermometer, an Allihn condenser, and a gas inlet tube with a stopcock, for admission of dry purified nitrogen. The condenser was connected first to an empty safety trap and then to a bubbler, through which the nitrogen

gas exited. A heating mantle was used to heat the flask and glass wool was wrapped around the upper part of the flask. After the reaction was terminated, the acetonitrile and unreacted water were then distilled at atmospheric pressure from the reaction mixture. The remaining solution was distilled under reduced pressure using the distillation assembly. The fraction (60% yield) boiling in the range 73-74^o (8-9 mm) was collected, lit. (20) 69.5^oC (9 mm).

Di-n-butyl Hydrogen Phosphonate

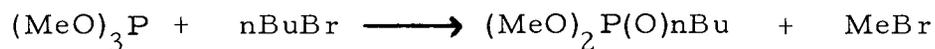
Di-n-butyl phosphonate (sample from the Mobil Chemical Co.) was purified by distillation under reduced pressure. The distillation assembly was used. The fraction collected had a boiling point of 130^o (19 mm), lit. (30) 118-119^o (7 mm).

Dimethyl Methylphosphonate

Dimethyl methylphosphonate (Aldrich D 16, 910) was distilled under reduced pressure using the distillation assembly. The fraction collected had a boiling range of 76-78^o (18-19 mm), lit. (20) 181^o (760 mm).

Dimethyl n-Butylphosphonate

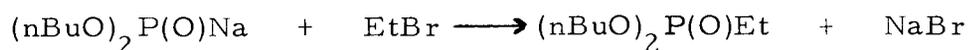
Dimethyl n-butylphosphonate was synthesized by the Arbuzov reaction (19).



One product, methyl bromide, was evolved as a gas during the course of the reaction. The reaction assembly was the same as that described for the synthesis of diisopropyl hydrogen phosphonate, except that a 500 ml three neck round bottom flask was used. An 85 ml quantity of n-butyl bromide and 72 ml of trimethyl phosphite were added to the flask. The time allowed for the reaction was thirty hours and the pot temperature was in the range 105-115°. The un-consumed starting materials were removed by distillation at atmospheric pressure. Dimethyl n-butylphosphonate was purified by vacuum distillation. The distillation assembly was used. The fraction (25% yield) boiling in the range 76-78° (18-19 mm) was collected. This compound has not previous been reported.

Di-n-butyl Ethylphosphonate

Di-n-butyl ethylphosphonate was synthesized from the sodium salt of di-n-butyl hydrogen phosphonate by the Nylen reaction (18).



A 2 l three neck round bottom flask was used for the reaction. The flask was fitted with a three way connecting tube, an Allihn condenser, and a gas inlet tube with a stopcock, for admission of dry

purified nitrogen. The three way connecting tube was attached to a dropping funnel and a thermometer. The flask contained a glass coated magnetic stirring bar. An oil bath, which was heated by a combination hot plate-magnetic stirrer, was used to heat the flask. The condenser was connected first to an empty safety trap and then to a bubbler, through which the nitrogen gas exited. The procedure follows: 9.4 g of small pieces of sodium and approximately 900 ml of n-hexane were placed into the flask. While the liquid was being gently refluxed with agitation, 80 ml of di-n-butyl hydrogen phosphonate was added dropwise during fifty minutes, after which the refluxing and stirring were continued until the sodium was completely dissolved; this lasted sixteen hours. Thirty-three ml of ethyl bromide was then added during fifty minutes and the mixture was stirred and refluxed for twenty four hours. The separation of sodium bromide began after twenty minutes. The di-n-butyl ethylphosphonate was separated from the reaction mixture and purified as follows: After cooling, the reaction mixture was washed thoroughly with distilled water and the organic layer was separated. The solvent was removed from the di-n-butyl ethylphosphonate by distillation under reduced pressure at about room temperature, and then the di-n-butyl ethyl phosphonate was purified by distillation under reduced pressure with heating. The spinning band column was used for the distillations. A middle fraction (60% yield) of the di-n-butyl

ethylphosphonate was collected at a pressure of 5 mm under the following temperature conditions: pot 160-170^o, column 155-160^o, head 135^o. The literature (18) indicates a boiling point of 137-139^o at 17 mm for this material. The refractive index of the synthesized di-n-butyl ethylphosphonate at 25^o was found to be 1.4258, lit. (18)

$$n_D^{25} \quad 1.4258.$$

Procedure

All materials and reaction mixtures were exposed as little as possible to the atmosphere. Throughout all transfer operations, a dry box flushed with dry nitrogen gas and containing phosphorus pentoxide was used. As an added precaution against moisture, all glassware used was previously heated in a drying oven. The reactions were carried out in standard taper apparatus connected to a glass high vacuum system of the type described by Sanderson (28). Dow Corning High Vacuum Silicone grease was used on all joints and stopcocks in the vacuum line. Liquid nitrogen was used to freeze all materials introduced to the vacuum line. The air was removed by pumping, and a cycle of thawing and refreezing was followed to ensure degassing of the samples. Liquid nitrogen was also used for the transfer of all materials within the vacuum line.

Reaction of Tri-n-butyl Phosphite with Ethyl Iodide in Acetonitrile at 31°

Acetonitrile, described on page 17 was distilled from anhydrous potassium carbonate. The fraction boiling in the range 79-80° was used, lit. (8) 82°.

Starting the Reaction. Using the dry box, 1.8 ml of ethyl iodide was transferred, using a 5 ml pipette with 0.1 ml gradations, into a 50 ml one neck round bottom flask. The flask was connected to the vacuum line and the air was removed from the flask. The ethyl iodide was transferred to a tared weighing bulb. After the weight of the ethyl iodide had been determined, the compound was transferred to a trap in the vacuum line. The 50 ml flask and the weighing bulb were removed from the vacuum line.

A magnetic stirring bar was placed in a short neck 250 ml round bottom flask. In the dry box, 5.60 ml of tri-n-butyl phosphite was pipetted into the flask, using a 5 ml pipette and a 1 ml pipette with 0.01 ml gradations. A 50 ml pipette was used for the addition of 100 ml of acetonitrile into the flask. The flask was then connected to the vacuum line and the nitrogen atmosphere was removed from it. The ethyl iodide was transferred to the flask and the frozen mixture was then allowed to warm. When the solution had partly thawed, it was stirred until the temperature of the solution approached room temperature.

Assuming the volumes of acetonitrile, ethyl iodide, and tri-n-butyl phosphite to be additive, the concentration of ethyl iodide was 0.214 M and the concentration of tri-n-butyl phosphite was 0.193 M.

The Reaction Conditions. The stopcock between the vacuum line and the flask, and the mercury float valves between the manifold and the storage bulb, were opened for the reaction.

The flask was submerged to its neck in a constant temperature water bath at $31.0 \pm 0.5^{\circ}$ (uncorrected).

To prevent condensation of the reaction mixture throughout the manifold and storage bulb, it was necessary to maintain these parts of the vacuum system at a temperature greater than 31° . Therefore, the room was heated to a temperature in the range of $32-34^{\circ}$.

The time allowed for the reaction was exactly seven days.

Terminating the Reaction. The reaction flask was immersed in liquid nitrogen to quench the reaction and to recondense all volatile material. The manifold and storage bulb were opened to the high vacuum pumping system briefly. After the manifold was shut from the pumping system, the contents of the reaction flask were allowed to warm to room temperature. To see if olefin elimination had taken place during the reaction, the flask was immersed in a -63.5° bath (chloroform slush), at which temperature the olefin

would be volatile but the other components of the reaction mixture would not. Any volatile material present was then transferred to a trap connected to the storage bulb. The mercury float valves between the storage bulb and the manifold were then closed. The pressure of any volatile material so isolated in the gas storage bulb could subsequently be determined manometrically. To ensure that compounds other than olefin had not transferred, the trap of the storage bulb was cooled to -63.5° and a manometric reading was taken. All material in the storage bulb was then recondensed in the reaction flask. The reaction flask was then allowed to warm to room temperature. Dry nitrogen was admitted, and the flask was removed from the vacuum line and quickly stoppered. It was stored in a Dewar vessel containing dry ice until such time as its contents were sampled for analysis by infrared spectral, gas chromatographic, and nuclear magnetic resonance methods. Such samples were removed in the nitrogen filled dry box.

Reaction of Trimethyl Phosphite with
n-Butyl Iodide in Acetonitrile at 50°

In a preliminary study of the reaction of trimethyl phosphite and n-butyl iodide, each about 0.2 molar in acetonitrile at 31° , it was found by gas liquid chromatographic analysis that hydrolysis had occurred to a large extent. The acetonitrile was purified by first

distilling over phosphorus pentoxide and then distilling over calcium hydride. Pure reagents, the dry box, and the vacuum line were used. Therefore, in the subsequent work in this system, the most rigorous precautions were taken to minimize this problem.

Acetonitrile, described on page 17 was distilled from the phosphorus pentoxide into a flask containing calcium hydride. The boiling point of the fraction collected was in the range $79-80^{\circ}$, lit. (8) 82° . The latter flask was connected to the vacuum line. While it was cooled by a -23° bath (carbon tetrachloride slush), the acetonitrile was transferred into a storage bulb until used.

Starting the Reaction. The reaction assembly consisted of a short neck 250 ml round bottom flask with a magnetic stirring bar and an Allihn condenser which was connected to the vacuum line through a joint with a stopcock. The purpose of the condenser was to prevent condensation of volatile components of the heated reaction mixture at this stopcock; such condensation would be expected to result in attack of the stopcock grease, causing a leak.

In the dry box, 2.20 ml of n-butyl iodide was pipetted, using a 5 ml pipette with 0.1 ml gradations, into a 50 ml one neck round bottom flask. The flask was connected to the vacuum line and the nitrogen atmosphere was removed. The n-butyl iodide was then transferred to a tared weighing bulb. After the weight of the n-butyl iodide had been determined, the compound was transferred

to a trap in the vacuum line. The 50 ml flask and the weighing bulb were removed from the vacuum line.

In the dry box, 2.20 ml of trimethyl phosphite was pipetted into the reaction flask, using a plain 1 ml pipette and a 1 ml pipette with 0.01 ml gradations. The reaction flask was then removed from the dry box and attached to the condenser, which previously had been evacuated and then purged with nitrogen. The nitrogen atmosphere was then removed from the reaction assembly.

A portion of acetonitrile was transferred from the storage bulb to a tared weighing bulb. The weight of acetonitrile was found to be 68.63 g. The acetonitrile was then transferred to the reaction assembly.

The n-butyl iodide was then transferred from its storage trap to the reaction assembly. The frozen mixture was then allowed to warm. When the solution had partly thawed, it was stirred until the temperature of the solution approached room temperature.

Assuming the volumes of acetonitrile, n-butyl iodide, and trimethyl phosphite to be additive, the concentration of n-butyl iodide was 0.215 M and the concentration of trimethyl phosphite was 0.203 M.

The Reaction Conditions. The stopcock between the vacuum line and the condenser was closed. The flask was submerged to its neck in a constant temperature water bath at $52.0 \pm 0.5^{\circ}$

(uncorrected). The temperature of the liquid phase was not accurately measured; it was taken to be approximately 50° since cooler liquid refluxing from the condenser would bring the temperature slightly below that of the water bath. The time allowed for the reaction was exactly seven days.

Terminating the Reaction. The reaction flask was immersed in liquid nitrogen until the contents appeared to be frozen. The mixture was then allowed to warm slightly until it appeared to be just all melted. Then, while a continuous stream of nitrogen gas was passed through the condenser, the flask was disconnected and immediately stoppered. It was stored in a Dewar vessel containing dry ice until such time as its contents were sampled for analysis by infrared spectral, gas chromatographic, and nuclear magnetic resonance methods. Such samples were removed in the nitrogen filled dry box.

Reaction of Triisopropyl Phosphite with
Isopropyl Iodide in Acetonitrile at 50°

Starting the Reaction. The acetonitrile and the reaction assembly were the same as were used for the reaction of trimethyl phosphite and n-butyl iodide, except that the magnetic stirrer was omitted. The same procedure as that given for starting the reaction of trimethyl phosphite and n-butyl iodide was executed. A 10 ml

pipette with 0.1 ml gradations and a 1 ml pipette with 0.01 ml gradations were used to transfer 4.26 ml of triisopropyl phosphite into the flask. The acetonitrile used was found to weigh 63.30 g; it was transferred to the reaction flask through the vacuum system. Isopropyl iodide was transferred from its vacuum line storage trap into a tared weighing bulb. The weight of isopropyl iodide taken was 3.3905 g. The isopropyl iodide was then transferred to the reaction flask. Assuming the volumes of acetonitrile, isopropyl iodide, and triisopropyl phosphite to be additive, the concentration of isopropyl iodide was 0.228 M and the concentration of triisopropyl phosphite was 0.214 M.

The Reaction Conditions. The stopcock between the vacuum line and the flask, and the mercury float valves between the manifold and an evacuated storage bulb, were opened for the reaction. The flask was submerged to its neck in a constant temperature bath at $52.0 \pm 0.5^{\circ}$ (uncorrected). The temperature of the liquid phase was not accurately measured; it was taken to be approximately 50° since cooler liquid refluxing from the condenser would bring the temperature slightly below that of the water bath. The time allowed for the reaction was exactly 13.5 days.

Terminating the Reaction. At the completion of this experiment, any material (e. g., olefin) with a high vapor pressure at -63.5 was transferred to the storage bulb, as in the previous

experiment. Any such highly volatile material was subsequently transferred to a smaller trap plus manometer assembly (total volume about 80 ml), to permit a more sensitive manometric test for olefin elimination. Otherwise, the procedure for terminating this reaction was the same as that followed for the reaction of tri-n-butyl phosphite and ethyl iodide.

IV. RESULTS

Reaction of Tri-n-butyl Phosphite with
Ethyl Iodide in Acetonitrile at 31^oPressure Readings

During the seven day period allowed for the reaction, the pressure inside the vacuum line remained constant at 118 mm. If olefin gas was being formed it is expected that the pressure would have increased during the course of the reaction. This pressure is in excellent agreement with that calculated for the solution on the basis of the original concentrations of the reactants and solvent at 31^o using Raoult's Law. The calculated value was 119 mm. For the calculation, values of the vapor pressures of acetonitrile and ethyl iodide at 31^o were obtained graphically by fitting literature citations of vapor pressure-temperature data to the Clausius-Clapyron equation. The pressure of the phosphite was taken to be negligible.

A test was made for olefin formation as described in the experimental section. The result was completely negative.

Gas Liquid Chromatographic Analysis

Instrumental conditions for all analysis were as follows: the temperature of the injection port was 280^o, the temperature of the detector was greater than 300^o, and the filament current was 150

milliamperes. Chromatographic standards were prepared as 10% (vol) solutions in acetonitrile. All the samples were stored in small vials that were sealed by rubber septa. These were kept in a desiccator containing phosphorus pentoxide. All injections, including those of the reaction mixture, were 2 μ l in volume. Two types of columns used were (methyl vinyl) Silicone Oil W98 (10%) - Chromosorb W 80-100 mesh and (polypropylene glycol adipate) Reoplex 400 (20%) - Chromosorb W (water washed) 30-60 mesh. The outside dimensions were 1/8 in. for the W98 columns and 1/4 in. for the Reoplex 400 columns. These columns were chosen on the basis of literature reports of their satisfactory performance with similar organophosphorus compounds (12, 25). The flow rates were for the W98 column 2 ml/sec, and for the Reoplex 400 column 1 ml/sec. All retention times are in minutes and include the time from the injection of the sample to the elution of the compound at the detector.

The results for the analysis of the reaction mixtures along with the retention times for all standard samples are given in Table I. The elution peak corresponding to the retention time assigned to a decomposition product of tri-n-butyl phosphite decreased in magnitude with decreasing oven temperature in contrast to the main peak assigned to the parent compound; at each set of specified temperatures and column conditions it was smaller than the peak assigned to tri-n-butyl phosphite.

Table I. Gas Liquid Chromatographic Data for the Reaction Mixture from Tri-n-butyl Phosphite with Ethyl Iodide in Acetonitrile at 31°.

Elution Peak Retention Times Observed (min)	Oven Temperature (°C)	Magnitude of Peak Height (chart divisions)	Attenuator Setting	Assignment	Retention Time of Standard Sample (min)
For the W98 Column:					
2.0	40	22.5	32	ethyl iodide	2.0
Not observed in the reaction mixture	40	--	1	n-butyl alcohol	3.2
0.6	70	36.0	1024	acetonitrile	0.6
3.8	70	7.5	8	n-butyl iodide	3.8
0.9	200	--	--	decomposition product of tri-n-butyl phosphite	0.9
Not observed in the reaction mixture	200	--	1	di-n-butyl hydrogen phosphonate	1.3
1.7	200	--	--	tri-n-butyl phosphite	1.7
1.8	200	--	--	di-n-butyl ethylphos- phonate	1.8
For the Reoplex 400 Column:					
0.5	182	24.5	1024	acetonitrile	0.5
1.5	182	5.5	8	decomposition product of tri-n-butyl phosphite	1.5
1.9	182	9.5	8	tri-n-butyl phosphite	1.9
7.5	182	37.5	1	di-n-butyl ethylphos- phonate	7.5

Using the W98 column, the elution peaks of tri-n-butyl phosphite and di-n-butyl ethylphosphonate were not resolved for a 1:1 mixture of the two. The Reoplex 400 (20%) - Chromosorb W column was therefore necessary to analyze for di-n-butyl ethylphosphonate and tri-n-butyl phosphite.

The instrument was set at maximum sensitivity at all oven temperatures with the W98 column to see if peaks other than those expected occurred. No compounds other than those listed were present in the reaction mixture.

Infrared Spectroscopic Analysis

The objective of this analysis was to determine the change in concentration of tri-n-butyl phosphite in the reaction mixture at least semi-quantitatively by applying Beer's law to a characteristic absorption band of tri-n-butyl phosphite, which is at 11.5μ . Tertiary phosphites with alkyl groups larger than ethyl have absorption close to 11.5μ (10). Neither acetonitrile, n-butyl hydrogen phosphonate, di-n-butyl ethylphosphonate, n-butyl alcohol, n-butyl iodide, nor ethyl iodide have an absorption band at this wavelength. Concentration standards of ethyl iodide and tri-n-butyl phosphite were prepared for quantitative analysis in a dry box. A 1 ml pipette with 0.01 ml gradations was used to transfer ethyl iodide and/or tri-n-butyl phosphite and a five ml pipette was used to transfer acetonitrile.

The following samples were taken:

(1) Acetonitrile.

(2) 0.21 M Ethyl Iodide. Ethyl iodide (0.18 ml) was transferred to a 10 ml volumetric flask, which was then filled with acetonitrile. This concentration approximates that originally present in the reaction mixture.

(3) 0.18 M Tri-n-butyl Phosphite. Tri-n-butyl phosphite (0.28 ml) was transferred to 5.00 ml of acetonitrile. Assuming additivity of volumes this concentration approximates 95% of that originally present in the reaction mixture.

(4) 0.20 M Ethyl Iodide and 0.18 M Tri-n-butyl Phosphite. Ethyl iodide (0.09 ml) and tri-n-butyl phosphite (0.28 ml) were transferred to 5.00 ml of acetonitrile. Assuming additivity of volumes this concentration approximates 5% reaction.

(5) 0.15 M Tri-n-butyl Phosphite. Tri-n-butyl phosphite (0.22 ml) was transferred to 5.00 ml of acetonitrile. Assuming additivity of volumes this concentration approximates 79% of that originally present in the reaction mixture.

(6) 0.11 M Tri-n-butyl Phosphite. Tri-n-butyl phosphite (0.17 ml) was transferred to 5.00 ml of acetonitrile. Assuming additivity of volumes this concentration approximates 58% of that originally present in the reaction mixture.

(7) Reaction Mixture. A 2 ml aliquot was taken from the

reaction flask. The spectra of these samples were obtained immediately after their preparation. The samples were contained in a cell with sodium chloride windows and a fixed path length of 0.100 mm; nothing was placed in the reference beam. For test sample (1), pure solvent acetonitrile, the trimmer comb was adjusted at 11.5 μ so that the percent transmittance was one hundred for the base line. The other samples were scanned and the trimmer comb was not readjusted. To ensure that a constant base line was maintained, acetonitrile was scanned last as well as first. It was found not to be necessary for samples (5) and (6) to contain ethyl iodide because ethyl iodide does not contribute to the absorbance at 11.5 μ ; at this wave length samples (1) and (2) had one hundred percent transmittance and samples (3) and (4) had forty nine percent transmittance.

Table II. Infrared Spectroscopic Data on Standard Tri-n-butyl Phosphite-Ethyl Iodide Samples.

Sample	Percent Transmittance	$-\log_{10} T$
0.18 M Tri-n-butyl Phosphite	49	1.69
0.15 M Tri-n-butyl Phosphite	55	1.74
0.11 M Tri-n-butyl Phosphite	64	1.81

By plotting $-\log_{10} T$ vs. percent concentration of tri-n-butyl phosphite a straight line was obtained, indicating that Beer's law may be applied to this system for analysis of the reaction mixture.

The infrared spectrum of the reaction mixture showed 53% transmittance at 11.5μ ; $-\log_{10} T$ was equal to 1.72. From the standard Beer's plot, the concentration of tri-n-butyl phosphite was found to be 0.16 M, corresponding to 84% of that originally present in the reaction mixture. Approximately sixteen percent of the original tri-n-butyl phosphite had reacted. The accuracy of the infrared spectrophotometric analysis was estimated to be within $\pm 5\%$.

There was found a definite phosphoryl absorption (10) at $7.9-8.0 \mu$ for the spectrum of the reaction mixture, by comparing it to the spectrum of the 0.20 M Ethyl Iodide and 0.18 M tri-n-butyl phosphite. This is indicative that either hydrolysis of tertiary phosphite occurred (and di-n-butyl hydrogen phosphonate was formed) or the Arbuzov rearrangement occurred (and di-n-butyl ethylphosphonate was formed).

Nuclear Magnetic Resonance Analysis

The proton resonance of hydrogen attached to phosphorus in di-n-butyl hydrogen phosphonate is split into a doublet by coupling with the phosphorus ($J_{P-H} = 680$ c. p. s.); one component is obscured by the methylene proton signal, while the other component is readily

observed at $\delta = 12.30$ p.p.m.

The reaction flask was attached to the vacuum line and the more volatile components (solvent and alkyl halide) were transferred from the reaction mixture. Di-n-butyl ethylphosphonate, di-n-butyl hydrogen phosphonate, and tri-n-butyl phosphite each have vapor pressures much less than 1 mm at room temperature, and would remain in the reaction flask. The n.m.r. spectrum of the resulting reaction residue was compared with that of the latter three compounds (run as neat liquids). N.m.r. spectra of the three organophosphorus compounds are in the Appendix. The spectrum amplitude of these spectra is less than that for the qualitative analysis so that none of the peaks would be off scale.

The conditions of the Varian Model A-60 n.m.r. spectrometer when analyzing the four samples were: Integral Amplitude, Off; Filter Bandwidth, 4; Spectrum Amplitude, 2.0×1.0 ; R.F. Field, 0.04; Gradient, 21; Sweep Time, 250 sec; Sweep Width 1000 cps.

The height of the n.m.r. peak at 12.30 ppm for di-n-butyl hydrogen phosphonate was two inches. There was no n.m.r. peak at 12.30 ppm for tri-n-butyl phosphite. This indicates the absence of hydrolytic impurities in the starting material. The reaction mixture residue had a peak of 1/8 inch at 12.30 ppm, which indicated that a very small amount of di-n-butyl hydrogen phosphonate was present. This may be attributed to contamination of the reaction mixture by

atmospheric moisture during the period between termination of the reaction and the n. m. r. analysis, rather than to formation of di-n-butyl hydrogen phosphonate during the reaction itself. A storage period of two months was necessitated by the lack of availability of the spectrometer. For the first half of this period, the sample was stored in dry ice; for the rest of the time, it was allowed to stand at room temperature. Attack of the high vacuum grease during this period was apparent.

Reaction of Trimethyl Phosphite with n-Butyl
Iodide in Acetonitrile at 50°

Gas Liquid Chromatographic Analysis

All conditions were the same as that described for analyzing the reaction mixture of the reaction of tri-n-butyl phosphite with ethyl iodide in acetonitrile at 31° except that only one column, (polypropylene glycol adipate) Reoplex 400 (20%) - Chromosorb W (water washed), was used.

The results for the analysis of the reaction mixture along with the retention times for all the standard samples are given in Table III. For the reaction mixture, the magnitude of the peak height for trimethyl phosphite was comparatively small because of considerable tailing. This was the only elution peak that had tailing, using the Reoplex 400 column. The instrument was set at maximum sensitivity

Table III. Gas Liquid Chromatographic Data for the Reaction Mixture from Trimethyl Phosphite with n-Butyl Iodide in Acetonitrile at 50°.

Elution Peak Retention Times Observed (min)	Magnitude of Peak Height	Attenuator Setting	Assignment	Retention time of Standard Sample (min)
At Oven Temperature 75°:				
1.2	5.5	1	methyl iodide	1.2
1.5	2.5	1	methyl alcohol	1.5
3.0	--	--	acetonitrile	3.0
4.0	71.0	2	n-butyl iodide	4.0
5.4	16.5	1	trimethyl phosphite	5.4
At Oven Temperature 158°:				
0.6	19.5	1024	acetonitrile	0.6
2.8	1.0	1	dimethyl hydrogen phosphonate	2.8
4.0	13.0	1	dimethyl methyl-phosphonate	4.0
8.2	2.0	1	dimethyl n-butyl-phosphonate	8.2

at all oven temperatures to see if peaks other than those expected occurred. No compounds other than those listed were present in the reaction mixture.

Concentration standards of dimethyl hydrogen phosphonate, dimethyl methylphosphonate, and dimethyl n-butylphosphonate were prepared for quantitative analysis. The percentages preceding each product in Table IV designate the percent of the original concentration of trimethyl phosphite in the reaction mixture which would have reacted to form such a molar concentration of product. All standard samples were prepared using a 0.005 ml syringe with 0.1 μ l gradations to transfer the compound to a 10 ml volumetric flask, which was then filled with acetonitrile. A 2 μ l volume of each sample was injected into the chromatograph. The attenuator was set at one for the elution of the organophosphorus compounds.

Comparing the magnitudes of the peak heights of the standards to those of the reaction mixture in Table III, it is concluded that 1% of the trimethyl phosphite hydrolyzed to form dimethyl hydrogen phosphonate, 13% of the trimethyl phosphite reacted with methyl iodide to form dimethyl methylphosphonate, and 2% of the trimethyl phosphite reacted with n-butyl iodide to form dimethyl n-butylphosphate.

Table IV. Quantitative Gas Liquid Chromatographic Analysis and Preparation of Standards for the Trimethyl Phosphite - n-Butyl Iodide Reaction Mixture.

Gas Liquid Chromatography			
Percent	Standard	ml of Compound Added to Flask	Magnitude of Peak Height
2.5	0.5×10^{-2} M Dimethyl hydrogen phosphonate	0.0047	2.0
2.5	0.5×10^{-2} M Dimethyl methylphosphonate	0.0050	3.0
5.0	1.0×10^{-2} M Dimethyl methylphosphonate	0.0100	6.0
10.0	2.0×10^{-2} M Dimethyl methylphosphonate	0.0200	13.0
15.0	3.0×10^{-2} M Dimethyl methylphosphonate	0.0300	21.0
1.5	3.1×10^{-3} M Dimethyl n-butylphosphonate	0.0050	1.5
3.0	6.2×10^{-3} M Dimethyl n-butylphosphonate	0.0100	2.5

Infrared Spectroscopic Analysis

The presence of dimethyl hydrogen phosphonate in the reaction mixture was not confirmed. An infrared spectrum was taken of the non-volatile reaction residue (obtained as described in the section on nuclear magnetic resonance analysis). The P-H absorption band of dialkyl hydrogen phosphonates is at approximately 2400 cm^{-1} (10); this band was not observed in the infrared spectrum of the resulting reaction residue. Incidentally there was very strong phosphoryl absorption in this spectrum.

Infrared spectra were taken of acetonitrile, n-butyl iodide, dimethyl n-butylphosphonate, dimethyl hydrogen phosphonate, dimethyl methylphosphonate, methyl alcohol, methyl iodide, and trimethyl phosphite. There were not any absorption bands that were suitable for quantitative analysis in the reaction mixture.

Nuclear Magnetic Resonance Analysis

The proton resonance of hydrogen attached to phosphorus in dimethyl hydrogen phosphonate is split into a doublet by coupling with the phosphorus ($J_{\text{P-H}} = 693$ cps); the components are observed at $\delta = 0.75$ ppm and $\delta = 12.30$ ppm.

The reaction flask was attached to the vacuum line and while the flask was cooled by an ice water bath, the more volatile components (solvent, alcohol, alkyl halides, and trimethyl phosphite) were transferred from the reaction mixture. Dimethyl hydrogen phosphonate, dimethyl methylphosphonate, and dimethyl n-butylphosphonate each have vapor pressures much less than 1 mm in the range 0-5^o, and would remain in the reaction flask. The n.m.r. spectrum of the resulting reaction residue was compared with that of the latter three compounds (run as neat liquids). N.m.r. spectra of the four organophosphorus compounds are in the Appendix. The spectrum amplitude of these spectra is less than that for the qualitative analysis so that none of the peaks would be off scale.

The conditions of the Varian Model A-60 n. m. r. spectrometer when analyzing the four samples were: Integral Amplitude, Off; Filter Band-width, 4; Spectrum Amplitude, 5.0 x 1.0; R. F. Field, 0.015; Gradient, 21; Sweep Time, 250 sec; Sweep Width, 1000 cps.

The height of the peaks at 0.75 ppm and 12.30 ppm were 6.00 inches and 5.75 inches respectively for the n. m. r. spectrum of dimethyl hydrogen phosphonate. There were no peaks at 0.75 ppm and at 12.30 ppm observed for pure trimethyl phosphite. This indicates the absence of hydrolytic impurities in the starting material. For the reaction residue, the component at 0.75 ppm would be obscured by the methylene proton signals of the other products. However, the component at 12.30 ppm was not observed. This indicates that the concentration of dimethyl hydrogen phosphonate in the reaction mixture was less than the minimum amount detectable by this method, i. e. , less than approximately 5%.

Reaction of Triisopropyl Phosphite with
Isopropyl Iodide in Acetonitrile at 50^o

Pressure Readings

A test was made for olefin formation as described in the experimental section. The result was completely negative.

Gas Liquid Chromatographic Analysis

All conditions were the same as that described for analyzing the reaction mixture of the reaction of tri-n-butyl phosphite with ethyl iodide in acetonitrile at 31^o except that only one column, (polypropylene glycol adipate) Reoplex 400 (20%) - Chromosorb W (water washed), was used.

The results for the analysis of the reaction mixture, along with the retention times for all the standard samples, are given in Table V. Because isopropyl alcohol and isopropyl iodide have almost the same retention times, no attempt was made to analyze for isopropyl alcohol in the reaction mixture. The height of the peak attributed to isopropyl iodide in the reaction mixture could also include a contribution due to elution of isopropyl alcohol if hydrolysis of the tertiary phosphite occurred. The instrument was set at maximum sensitivity at oven temperatures of 133^o and 150^o to see if peaks other than those expected occurred. One unexpected peak occurred; it is assigned as the elution of compound X.

Compound Y

A reference sample of this material resulted from an attempted synthesis of the previously unknown compound, diisopropyl isopropylphosphonate. It is not certain if the desired product was

Table V. Gas Liquid Chromatographic Data for the Reaction Mixture from Triisopropyl Phosphite with Isopropyl Iodide in Acetonitrile at 50°.

Elution Peak Retention Times Observed (min)	Magnitude of Peak Height	Attenuator Setting	Assignment	Retention Time of Standard Sample (min)
At Oven Temperature 55°:				
2.6	59.0	2	Isopropyl Iodide	2.6
			Isopropyl Alcohol	2.8
At Oven Temperature 133°:				
0.8	16.0	1024	Acetonitrile	0.8
1.2	53.0	8	Triisopropyl Phosphite	1.2
5.8	3.5	1	Diisopropyl Hydrogen Phosphonate	5.8
5.8	3.5	1	Compound Y*	5.8
7.2	28.0	1	Compound X	

* When reference sample, compound Y, was injected into the chromatograph, there was an elution peak for an impurity at 7.2 minutes with the oven temperature 133°. The heights of the elution peaks with the attenuator at four were 44.0% at 5.8 minutes and 3.5% at 7.2 minutes.

obtained in this attempt to apply the Arbuzov reaction in acetonitrile solvent for practical synthetic purposes.

The reaction assembly was the same as that described for the synthesis of dimethyl n-butylphosphonate. Acetonitrile, described on page 17 was distilled from phosphorus pentoxide into a flask containing calcium hydride. The boiling point of the fraction collected was in the range $79-80^{\circ}$, lit. (8) 82° . The receiving flask was then connected to the vacuum line and immersed in a -23° bath (carbon tetrachloride slush). The acetonitrile was redistilled into a flask cooled by liquid nitrogen (-196°). A 200 ml quantity of this acetonitrile, 50 ml of triisopropyl phosphite, 25 ml of isopropyl bromide, and a trace of iodine were mixed and heated at $78 \pm 1^{\circ}$ for ten days. After the time allowed for the reaction, the solvent and the isopropyl bromide were removed by distillation at atmospheric pressure. Using the distillation assembly, a first fraction (about 45 ml) of unreacted triisopropyl phosphite was distilled in the range $64-69^{\circ}$ (10-13 mm) and then a second fraction (about 3 ml) of compound Y was collected at 92° (11-12 mm). N.m.r. and infrared spectra were obtained of this compound. These spectra are in the Appendix.

In a preliminary experiment, it had been found that no Arbuzov product was obtained when the neat reagents, triisopropyl phosphite and isopropyl bromide, were used. Therefore, the reaction in solvent was attempted for synthesis. It was hoped that the solvent would

promote the reaction; perhaps by affecting the intermediate. For example, the solvent might promote dissociation of a salt-like form of the intermediate.

A second preliminary experiment designed for the synthesis of diisopropyl isopropylphosphonate was also unsuccessful. It was planned to obtain the desired product by ester exchange of dimethyl isopropylphosphonate. Unfortunately, the attempted synthesis of the latter compound by the Arbuzov reaction of trimethyl phosphite with isopropyl bromide was unsuccessful.

The Nylen reaction was not used in the attempted synthesis of diisopropyl isopropylphosphonate for two practical reasons. First, the solubility of the sodium salt of diisopropyl hydrogen phosphonate is very limited in the organic solvents used for this reaction. Second, the procedure would involve the use of water to remove the by-product sodium bromide, and diisopropyl isopropylphosphonate would be expected to be very sensitive to hydrolysis.

Compound X

The elution peak listed in Table V at 7.20 minutes with oven temperature 133° is assigned to compound X. This component is present in both the reaction mixture and as an impurity in the reference sample of compound Y.

Because isopropyl iodide readily decomposes, both

photolytically and thermally, with the liberation of free iodine, it was suspected that compound X might be iodine. However, it was found that iodine did not give a matching elution peak. The identity of compound X remains unknown.

Attempted Quantitative G. L. C. Analysis of the Reaction Product

For calibration purposes a series of standard solutions of diisopropyl hydrogen phosphonate were prepared. In Table VI the percentages preceding each concentration of diisopropyl hydrogen phosphonate designate the percent of the triisopropyl phosphite originally present in the reaction mixture which would have been consumed to form that concentration of the hydrolysis product. All standard samples were prepared using a 0.010 ml syringe with 0.1 μ l gradations to transfer the compound to a 10 ml volumetric flask, which was then filled with acetonitrile. A 2 μ l volume of each sample was injected into the chromatograph. For the elution peaks of the hydrogen phosphonate, the attenuator was set at one.

The magnitude of this peak height for a 2 μ l injection of the reaction mixture was 3.5%. By comparison of this value with the peak heights of the standards, it may be concluded that not more than 3% of the original triisopropyl phosphite reacted to form diisopropyl hydrogen phosphonate. Part or all of this elution peak of the reaction

mixture could be due to compound Y.

Table VI. Chromatographic Standards for the Analysis of Diisopropyl Hydrogen Phosphonate.

Percent	Standard	ml of Compound Added to Flask	Magnitude of Peak Height
2.5	0.5×10^{-2} M Diisopropyl hydrogen phosphonate	0.009	2.5
5.0	1.0×10^{-2} M Diisopropyl hydrogen phosphonate	0.018	6.0
10.0	2.1×10^{-2} M Diisopropyl hydrogen phosphonate	0.036	12.5

Infrared Spectroscopic Analysis

The first objective of this analysis was to determine the change in concentration of triisopropyl phosphite in the reaction mixture at least semi-quantitatively by applying Beer's law to a characteristic absorption band of triisopropyl phosphite. Tertiary phosphites, when the alkyl groups are larger than ethyl, have strong absorption close to 11.5μ (10). The absorption band for triisopropyl phosphite is at 11.6μ . Neither acetonitrile, diisopropyl hydrogen phosphonate, isopropyl alcohol, isopropyl iodide, nor compound Y have an absorption band at this wavelength.

Concentration standards of triisopropyl phosphite, which are described along with infrared spectroscopic data in Table VII, were prepared in a dry box by using a 1 ml pipette with 0.01 ml gradations

Table VII. Infrared Spectroscopic Data of Triisopropyl Phosphite Concentration Standards.

Sample	Vol. (ml) of Triisopropyl Phosphite Added to Volumetric Flask	Approximated Percent of that Triisopropyl Phosphite Present in the Reaction Mixture	Percent Transmittance	$-\log_{10} T$
0.21 M Triisopropyl Phosphite	0.49	100	22	1.342
0.19 M Triisopropyl Phosphite	0.44	90	24	1.380
0.17 M Triisopropyl Phosphite	0.40	80	27	1.432

to transfer triisopropyl phosphite to a 10 ml volumetric flask, which was then filled with acetonitrile. The standard samples were analyzed just as soon as they were prepared. The concentration standards of triisopropyl phosphite, acetonitrile, and an aliquot of the reaction mixture were contained in a cell with sodium chloride windows and a fixed path length of 0.100 mm; nothing was placed in the reference beam.

The pure solvent acetonitrile was first scanned. The trimmer comb was adjusted at 11.6μ so that the percent transmittance was one hundred for the base line. The concentration standards and the reaction mixture were scanned and the trimmer comb was not re-adjusted. To ensure that a constant base line was maintained, acetonitrile was scanned last as well as first.

By plotting $-\log_{10} T$ vs. molar concentration of triisopropyl phosphite a straight line was obtained, indicating that Beer's law may be applied to this system for analysis of the reaction mixture. The infrared spectrum of the reaction mixture showed 22% transmittance at 11.6μ ; $-\log_{10} T$ was equal to 1.342. From the standard Beer's law plot, the concentration of triisopropyl phosphite was found to be 0.21 M, corresponding to that originally present in the reaction mixture. The accuracy of the infrared spectrophotometric analysis is estimated to be within $\pm 5\%$. However, comparing infrared spectra of the 0.21 M triisopropyl phosphite solution and the

reaction mixture, it was found that there was a phosphoryl absorption in the latter sample. This indicates that a small amount of either diisopropyl hydrogen phosphonate or of diisopropyl isopropylphosphonate was formed.

A second objective of this infrared spectroscopic analysis was to test qualitatively for the presence of diisopropyl hydrogen phosphonate in the reaction mixture. An infrared spectrum was taken of the non-volatile residue of the reaction mixture (obtained as described in the section on nuclear magnetic resonance analysis). The P-H absorption band of dialkyl hydrogen phosphonates is at approximately 2400 cm^{-1} ; this band was not observed in the infrared spectrum of the resulting reaction residue. Incidentally there was very strong phosphoryl absorption observed in this spectrum.

Nuclear Magnetic Resonance Analysis

The proton resonance of hydrogen attached to phosphorus in diisopropyl hydrogen phosphonate is split into a doublet by coupling with the phosphorus ($J_{\text{P-H}} = 681\text{ cps}$); the components are observed at $\delta = 0.95\text{ ppm}$ and at $\delta = 12.30\text{ ppm}$.

The reaction flask was attached to the vacuum line and the more volatile components (solvent, alkyl halide and possible alcohol) were transferred from the reaction mixture. The organophosphorus compounds each have vapor pressures much less than 1 mm at room

temperature, and would remain in the reaction flask. The n. m. r. spectrum of the resulting reaction residue was compared with that of diisopropyl hydrogen phosphonate, compound Y, and triisopropyl phosphite (run as neat liquids). N. m. r. spectra of the three organophosphorus compounds are in the Appendix. The spectrum amplitude of these spectra is less than that for the qualitative analysis so that none of the peaks would be off scale.

The conditions of the spectrometer were the same as for the n. m. r. analysis of the reaction residue of trimethyl phosphite with n-butyl iodide in acetonitrile at 50^o, page 47.

The height of the n. m. r. peak at 12.30 ppm for diisopropyl hydrogen phosphonate was 3.25 inches. There were no peaks observed at 12.30 ppm or the n. m. r. spectra of triisopropyl phosphite, the reaction residue, and compound Y. This indicates the absence of hydrolytic residue impurities in the starting material, that during the reaction diisopropyl hydrogen phosphonate was not formed, and that compound Y is not diisopropyl hydrogen phosphonate (despite the coincidence in the retention times of these two compounds).

V. CONCLUSIONS

For the study of the system tri-n-butyl phosphite-ethyl iodide in acetonitrile at 31° , the most careful procedures to eliminate contamination by traces of water were carried out. Thus, the reaction was conducted in a high vacuum line, which also would permit the trapping and analysis of any possible gaseous olefin formed. Although the reactant, tri-n-butyl phosphite, is very difficult to purify, the absence of any hydrolysis impurity was confirmed by its n. m. r. and infrared spectroscopic spectra and by gas liquid chromatographic analysis. The result of the work indicated that the Arbuzov reaction proceeded very slowly in this system. Kumli's hypothesis of olefin elimination was found to be incorrect. After a period of seven days, only 16% of the original phosphite had been consumed, as demonstrated by quantitative infrared spectral analysis. The infrared spectrum of the reaction mixture showed the formation of a compound containing the phosphoryl group, and the only components in addition to the starting materials found by gas liquid chromatographic analysis were the Arbuzov products, di-n-butyl ethylphosphonate and n-butyl iodide. It would seem that the statement by Aksnes and Aksnes (3, p. 212) that "almost no reaction took place" within 20.5 hours under these conditions is essentially correct. The claim of Buck and Yoke (7) that reaction would reach completion within 28

hours is wrong.

Another Arbuzov system in acetonitrile in which olefin elimination had been postulated was that of triisopropyl phosphite with isopropyl iodide, previously studied by Aksnes and Aksnes (4). The experiment was repeated in the present work. After this reaction system had been heated at 50° for 13.5 days, the test for olefin, propylene, in the vacuum line was completely negative. By quantitative infrared spectroscopic analysis, it was found that not more than between 0 and 5% of the original triisopropyl phosphite had reacted. An infrared phosphoryl absorption was observed in the reaction mixture, however, which presumably would be indicative of either diisopropyl hydrogen phosphonate or diisopropyl isopropylphosphonate being formed.

A product, compound Y, was obtained in a separate experiment designed for the purpose of synthesizing the previously unknown compound, diisopropyl isopropylphosphonate, and probably was in fact an impure sample of that compound. However, under the only set of chromatographic conditions investigated, the retention times of compound Y and diisopropyl hydrogen phosphonate were the same. A component found present in the reaction mixture with this retention time could have been either of the latter two compounds. If this compound in the reaction mixture were diisopropyl hydrogen phosphonate and not compound Y, then the quantitative gas liquid

chromatographic results showed that not more than 3% of the triisopropyl phosphite reacted to form the hydrolysis product. Since diisopropyl hydrogen phosphonate was not detected in the reaction mixture by infrared spectroscopic and n. m. r. qualitative analysis, however, it is tentatively concluded that the small amount of starting material consumed was converted to the Arbuzov product, diisopropyl isopropylphosphonate. In addition, the chromatogram of the reaction mixture had an unassigned elution peak, compound X.

The report by Aksnes and Aksnes, that isopropyl iodide and triisopropyl phosphite react extremely slowly in acetonitrile to produce diisopropyl hydrogen phosphonate and probably propylene, was not substantiated. Because of the difficulty in preventing contamination by traces of moisture, it appears that any diisopropyl hydrogen phosphonate was formed by hydrolysis of the tertiary phosphite and not by olefin elimination. For example, in the trimethyl phosphite - n-butyl iodide-acetonitrile system, despite rigorous precautions to eliminate moisture, hydrolysis occurred to a large extent in a preliminary experiment. As described below, in an even more careful study of the same reaction at 50°, 1% of the trimethyl phosphite hydrolyzed.

The object of the study of the remaining Arbuzov system, where trimethyl phosphite reacted with n-butyl iodide in acetonitrile at 50°, was to set up competition between the reactant, n-butyl iodide and the

product, methyl iodide, as potential substrates for nucleophilic attack by the tertiary phosphite. The results would be expected to give some insight on the question of the rate determining step. Because of steric factors, methyl iodide would be expected to react faster than n-butyl iodide. If $k_1 \gg k_2$ and if the first step were not reversible, then very little or no dimethyl methylphosphonate would be produced. To the extent to which the reaction took place, the predominant or sole product would be dimethyl n-butylphosphonate. If the first step were reversible, or if k_2 exceeded k_1 (or were of roughly comparable magnitude), then a significant amount of dimethyl methylphosphonate would be produced in addition to any dimethyl n-butylphosphonate found in the reaction mixture. As a result of the experiment, it was found that, in the period of seven days allowed for the reaction, only 16% of the trimethyl phosphite was consumed. Gas liquid chromatographic analysis showed that 2% of the trimethyl phosphite reacted with n-butyl iodide to form dimethyl n-butylphosphonate, 13% of it reacted with the methyl iodide produced by the Arbuzov reaction, to give dimethyl methyl phosphonate, and 1% of it hydrolyzed to form dimethyl hydrogen phosphonate. In summary, the Arbuzov rearrangement proceeded very slowly, and the hypothesis that $k_1 \gg k_2$ and that the first step was not reversible, was shown to be incorrect. By comparison of the different concentrations of phosphonates found in the reaction mixture, the

presumption that methyl iodide reacts faster than n-butyl iodide with the nucleophile, trimethyl phosphite, in acetonitrile was found to be correct.

The general conclusions of this work follow. Olefin elimination involving tertiary phosphites undergoing the Arbuzov reaction in acetonitrile has not occurred in any of the systems studied. It is extremely difficult to eliminate moisture in these systems, and previous reports of the fairly rapid formation of phosphoryl compounds, and of dialkyl hydrogen phosphonate formation by olefin elimination, now shown to be incorrect, are probably due to contamination of the systems by water. The Arbuzov reaction proceeds very slowly in acetonitrile at temperatures in the range 31-50° for those systems investigated in this study. Steric hindrance is a determining factor for alkyl iodides undergoing the Arbuzov reaction in acetonitrile. Major portions of the work of Buck and Yoke (7), and of Aksnes and Aksnes (4) were shown to be incorrect.

BIBLIOGRAPHY

1. Aksnes, Gunnar and Dagfinn Aksnes. A kinetic study of Michaelis-Arbuzov reactions. *Acta Chemica Scandinavica* 18: 38-46. 1964.
2. Aksnes, Gunnar and Dagfinn Aksnes. Kinetics and mechanism of the reaction of tripropyl phosphite with water in acetonitrile. *Acta Chemica Scandinavica* 18:1623-1628. 1964.
3. Aksnes, Gunnar and Dagfinn Aksnes. On the mechanism of the Michaelis-Arbuzov rearrangement in acetonitrile. *Acta Chemica Scandinavica* 17:2121-2122. 1963.
4. Aksnes, Gunnar and Dagfinn Aksnes. The reactions of isopropyl and ethyl iodides with triisopropyl phosphite in acetonitrile. *Acta Chemica Scandinavica* 19:898-902. 1965.
5. Arbuzov, B. A. and A. V. Fuzhenkova. A study of the A. E. Arbuzov rearrangement by the method of thermography. *Doklady Akademii Nauk SSSR* 114:89-92. 1957. (Abstracted in *Chemical Abstracts* 52:1056d. 1958)
6. Arbuzov, B. A. et al. Intermediate products of the Arbuzov rearrangement. *Khimiya i Primenie Fosfororganicheskikh Soedinenii*, Akademiya Nauk SSR Kazanskii Filial, Trudy 1-oi Konferentsii, 1955. p. 62-70. (Publication 1957) (Abstracted in *Chemical Abstracts* 52:239d. 1958)
7. Buck, Francis C. and John T. Yoke, III. On the mechanism of the Arbuzov rearrangement. *The Journal of Organic Chemistry* 27:3675-3677. 1962.
8. Chemical Rubber Publishing Company. *Handbook of chemistry and physics*. 43d ed. Cleveland, 1962. 3513 p.
9. Cross, Paul C. and Farrington Daniels. Chemical aspects of the infrared spectra of the ethyl halides. *The Journal of Chemical Physics* 1:48-55. 1933.
10. Daasch, L. W. and D. C. Smith. Infrared spectra of phosphorus compounds. *Analytical Chemistry* 23:853-868. 1951.

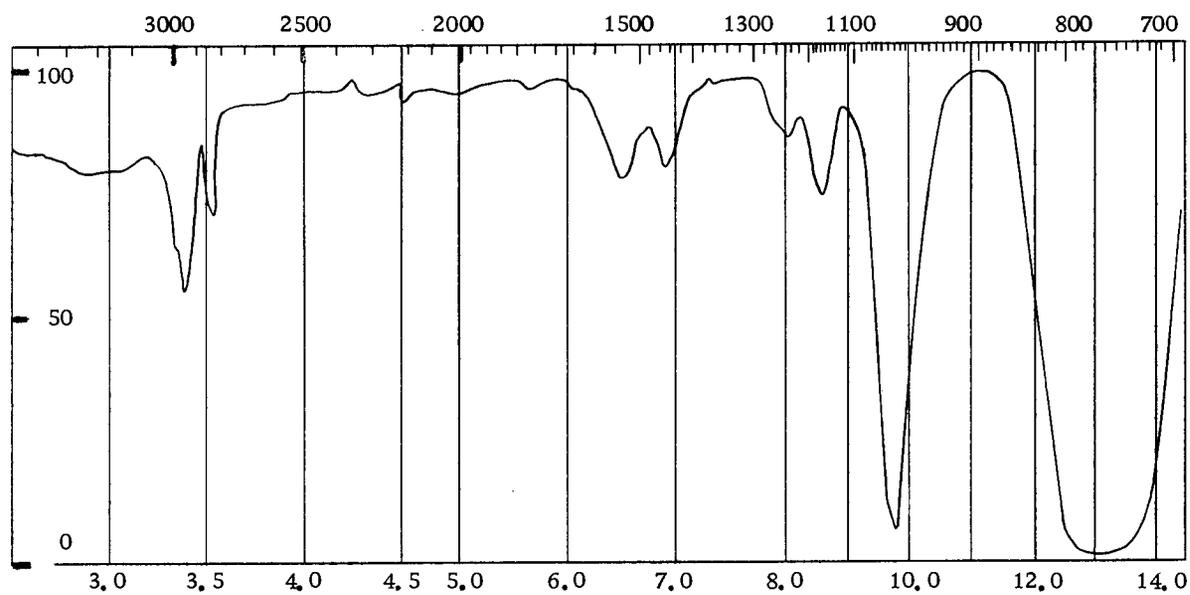
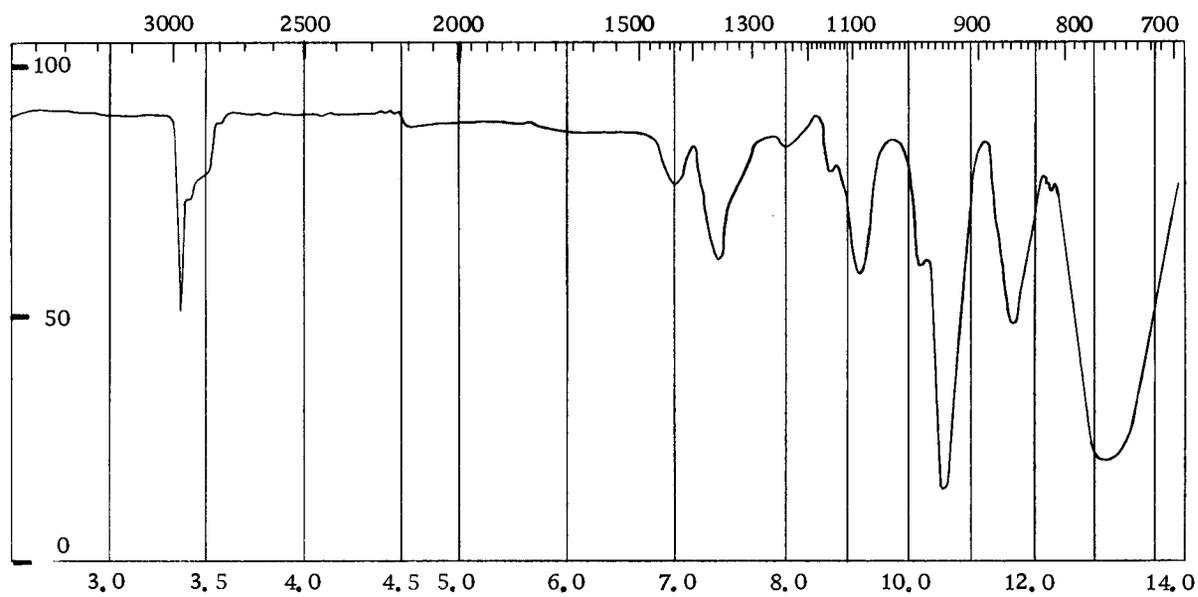
11. Fainshtein, I. Z. and M. G. Gonikberg. Pressure effect on the rate of the Arbuzov rearrangement in solution. *Izvestiya Akademii Nauk SSSR, Seriya Khimiya* 8:1401-1406. 1964. (Abstracted in *Chemical Abstracts* 61:15953d. 1964)
12. Feinland, Raymond, Jeremy Sass and Sheldon A. Buckler. Determination of trialkylphosphines and their oxidation products by gas liquid chromatography. *Analytical Chemistry* 35: 920-921. 1963.
13. Ford-Moore, A. H. and J. Howarth Williams. The reaction between trialkyl phosphites and alkyl halides. *Journal of the Chemical Society*, 1947, p. 1465-1467.
14. Gerrard, W. and W. J. Green. Mechanism of the formation of dialkyl alkylphosphonates. *Journal of the Chemical Society*, 1951, p. 2550-2553.
15. Grayson, Martin and Edward J. Griffith (eds.). *Topics in phosphorus chemistry*. Vol. 1. New York, Interscience, 1964. 262 p.
16. Ingold, Christopher Kelk. *Structure and mechanism in organic chemistry*. Ithaca, New York, Cornell University, 1953. 828 p.
17. Jensen, K. A., et al. Reductions with potassium graphitite. I. Complexes of trialkyl phosphites. *Acta Chemica Scandinavica* 19:768-770. 1965.
18. Kosolapoff, Gennady M. Isomerization of alkylphosphites. III. The synthesis of n-alkylphosphonic acids. *The Journal of the American Chemical Society* 67:1180-1182. 1945.
19. Kosolapoff, Gennady M. Isomerization of tri-alkyl phosphites. *The Journal of the American Chemical Society* 66:109-111. 1944.
20. Kosolapoff, Gennady M. *Organophosphorus compounds*. New York, Wiley, 1950. 376 p.
21. Kosolapoff, Gennady M. The synthesis of phosphonic and phosphinic acids. In: *Organic Reactions*, ed. by Roger Adams et al. 2d ed. New York, Wiley, 1957. p. 273-338.

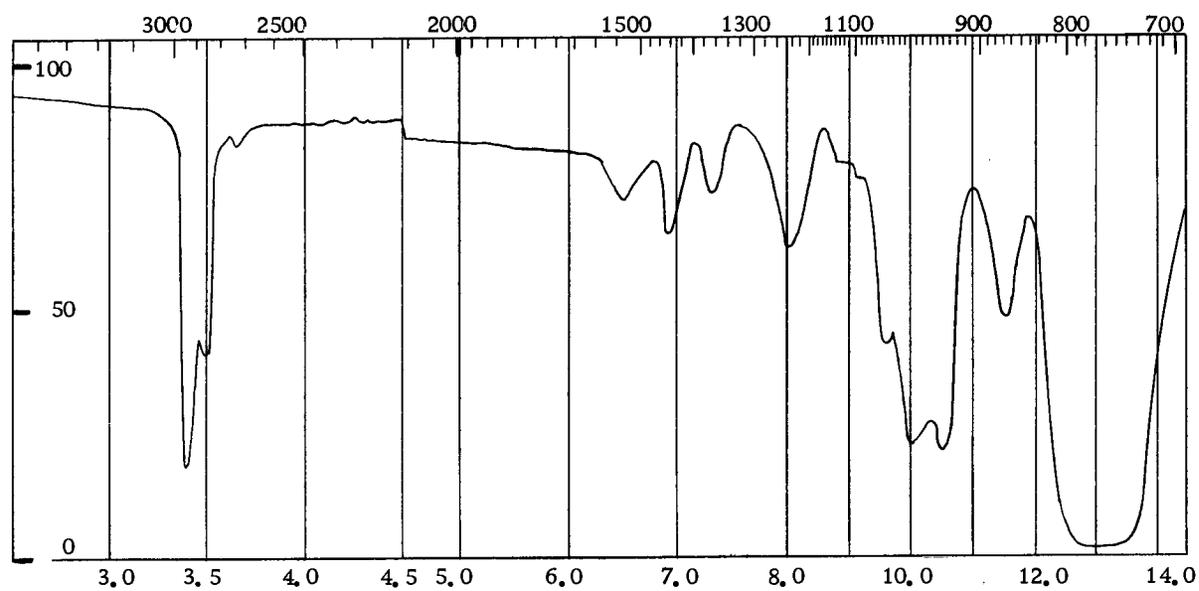
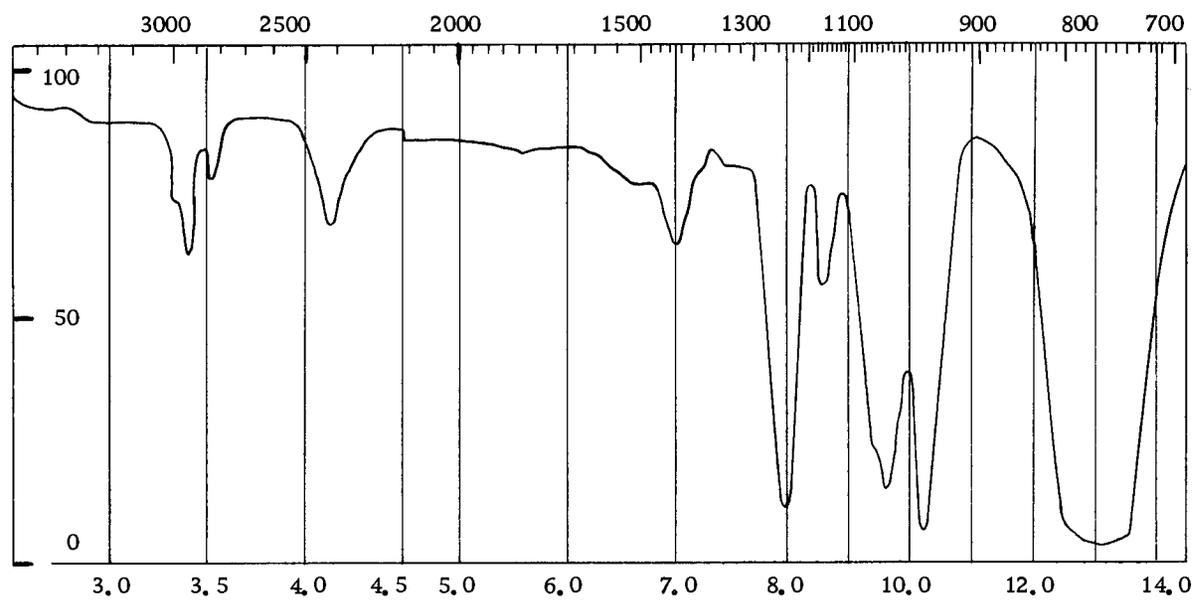
22. Kumli, Karl F. Unpublished research on reaction of trialkyl phosphites with alkyl halides in acetonitrile. Corvallis, Oregon, Oregon State University, Department of Chemistry, 1965.
23. Mark, Victor and John R. Van Wazer. Tri-*t*-butyl phosphite and some of its reactions. *The Journal of Organic Chemistry* 29:1006-1008. 1964.
24. Nesterov, L. V., N. E. Krepysheva and R. I. Mutalapova. Phosphorus acid derivatives. III. Arbuzov reaction with some mixed phosphites. *Zhurnal Obschei Khimii* 35(11):2050-2055. 1965. (Abstracted in *Chemical Abstracts* 64:8019g. 1964)
25. Plumb, J. B. and C. E. Griffin. The photoinitiated oxidation of tertiary phosphites. *The Journal of Organic Chemistry* 28: 2908-2910. 1963.
26. Razumov, A. I. Mechanism of the Arbuzov rearrangement. *Zhurnal Obshchei Khimii* 29:1635-1639. 1959. (Abstracted in *Chemical Abstracts* 54:8608b. 1960)
27. Razumov, A. I. and N. N. Bankovskaya. Preparation and some properties of intermediate products of the Arbuzov rearrangement. *Doklady Akademii Nauk SSR* 116:241-243. 1957. (Abstracted in *Chemical Abstracts* 52:6164i. 1958)
28. Sanderson, Robert Thomas. *Vacuum manipulation of volatile compounds*. New York, Wiley, 1948. 162 p.
29. Van Wazer, John R. *Phosphorus and its compounds*. Vol. I. Chemistry. New York, Interscience, 1958. 954 p.
30. Virginia-Carolina Chemical Corporation. *Alkyl phosphites*. Richmond, Virginia, n.d. 11 p. (Product Information Booklet no. R-1)

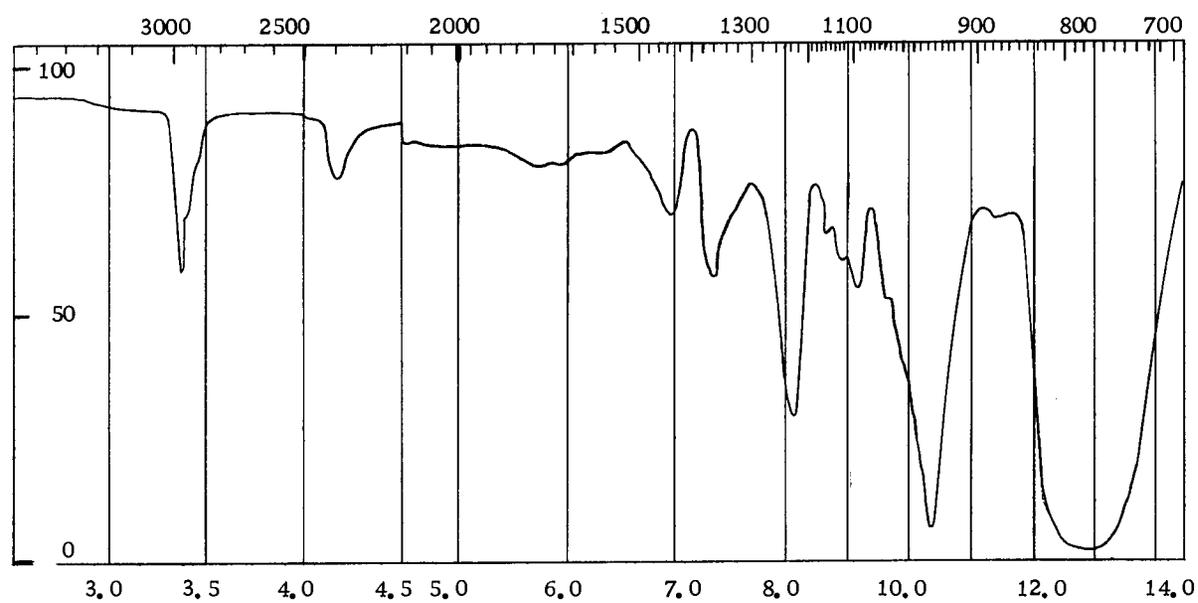
APPENDIX

INFRARED SPECTRA OF
ORGANOPHOSPHORUS COMPOUNDS

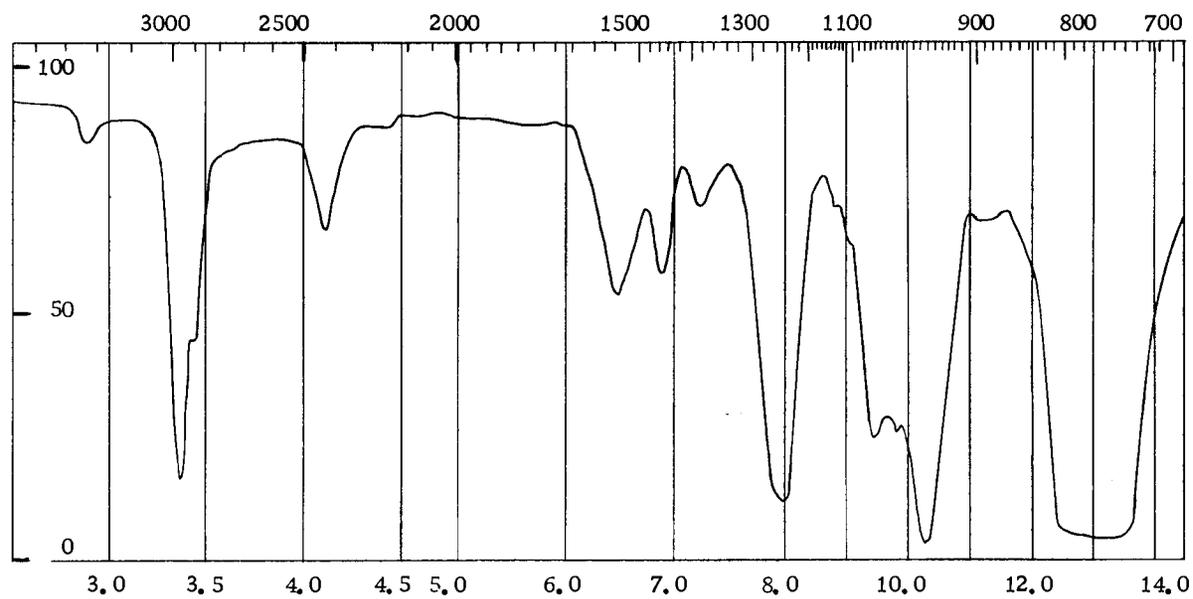
The scale at the top of each chart is in wave number, cm^{-1} ,
and the scale at the bottom of each chart is for wavelength in
microns, μ . Percent transmission is recorded on the vertical axis.

Trimethyl Phosphite $(\text{MeO})_3\text{P}$ Triisopropyl Phosphite $(\text{IsoprO})_3\text{P}$

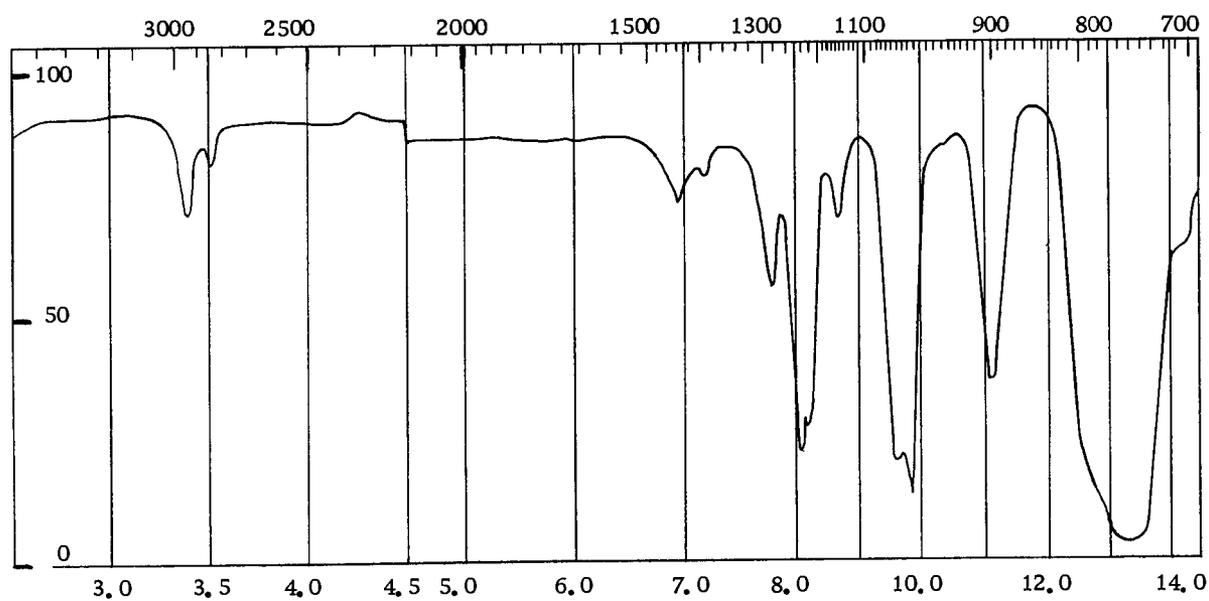
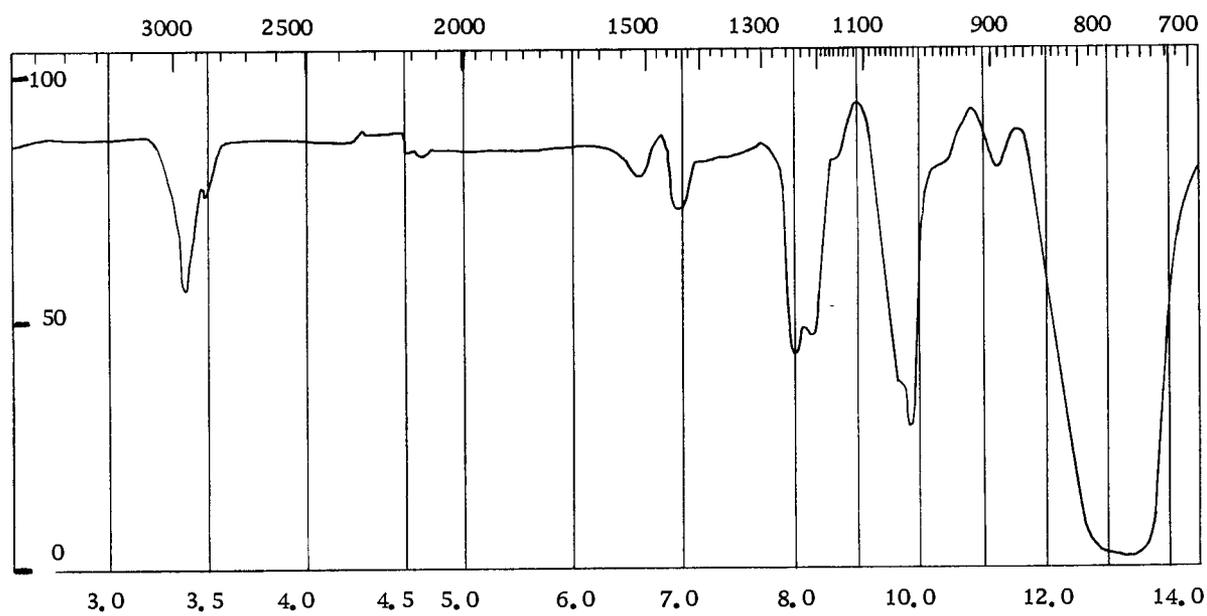
Tri-n-butyl Phosphite $(n\text{BuO})_3\text{P}$ Dimethyl Hydrogen Phosphonate $(\text{MeO})_2\text{P}(\text{O})\text{H}$

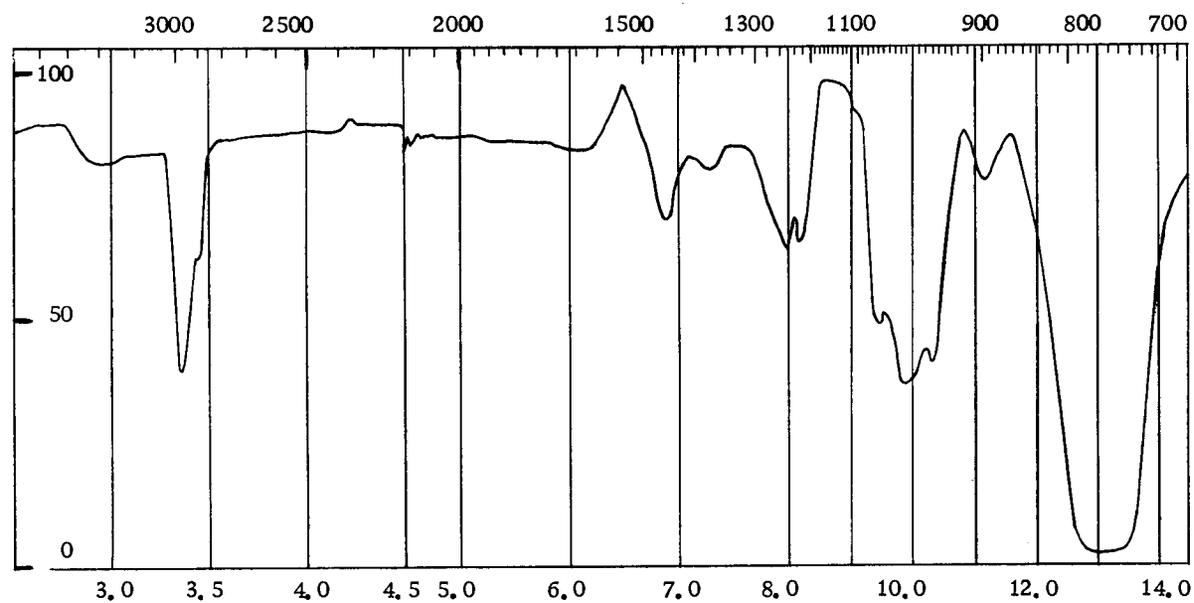
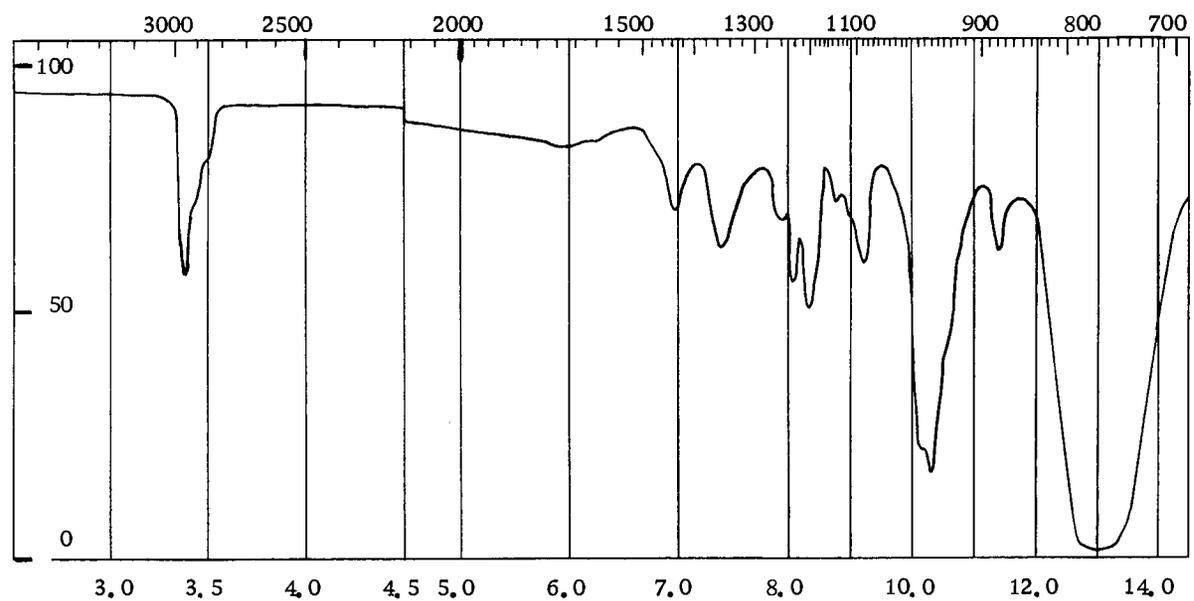


Diisopropyl Hydrogen Phosphonate (IsoprO)₂P(O)H



Di-n-butyl Hydrogen Phosphonate (nBuO)₂P(O)H

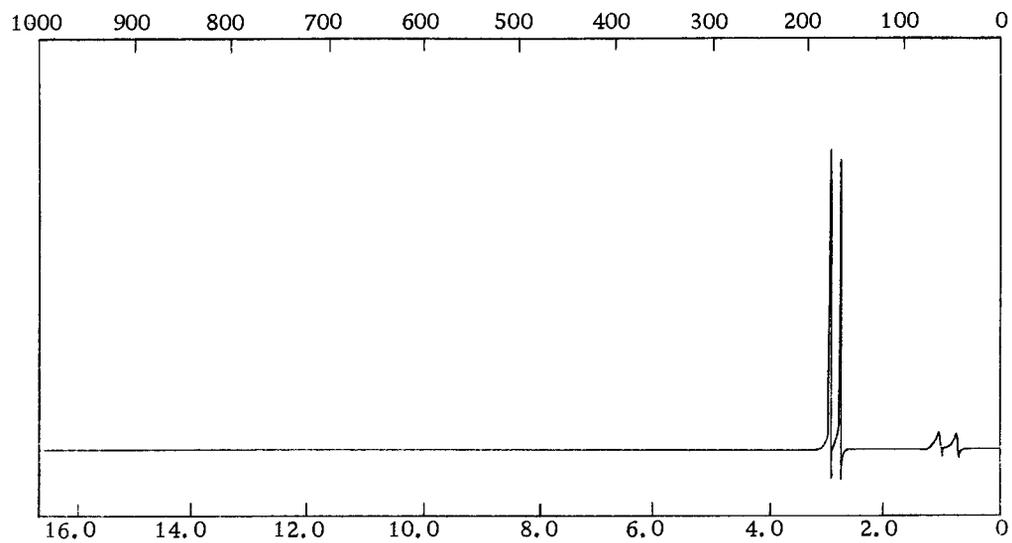
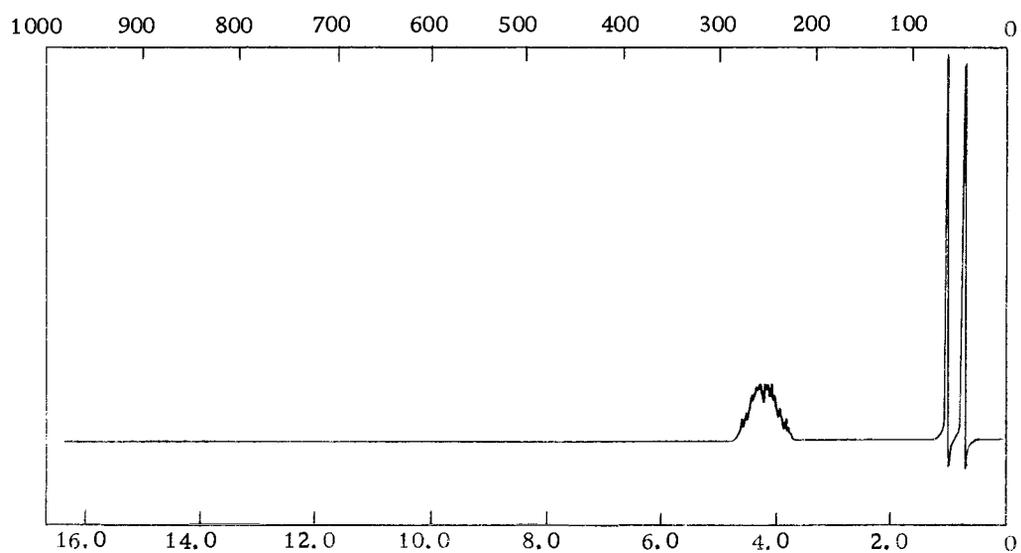
Dimethyl Methylphosphonate $(\text{MeO})_2\text{P}(\text{O})\text{Me}$ Dimethyl n-Butylphosphonate $(\text{MeO})_2\text{P}(\text{O})\text{nBu}$

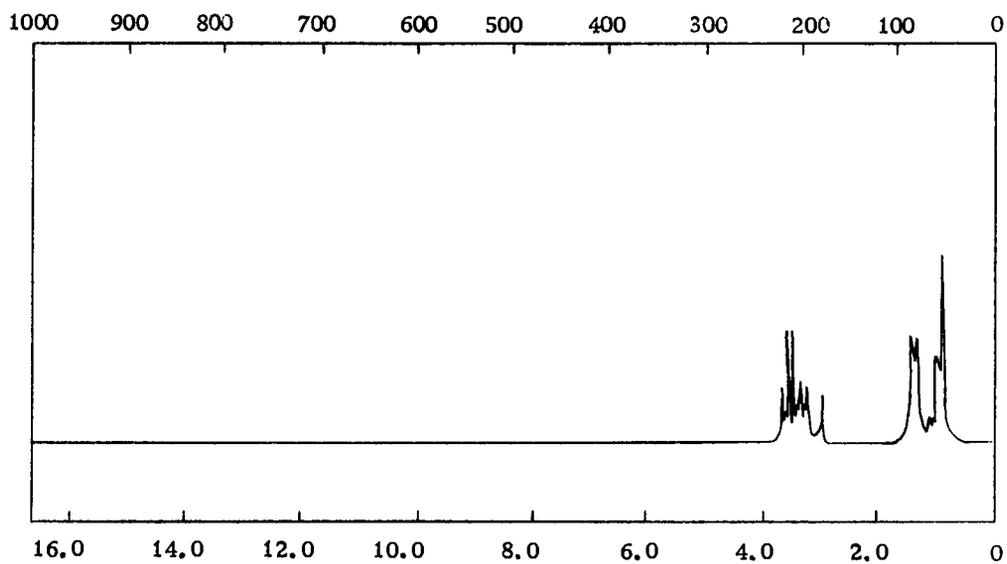
Di-n-butyl Ethylphosphonate ($(n\text{BuO})_2\text{P}(\text{O})\text{Et}$)

Compound Y

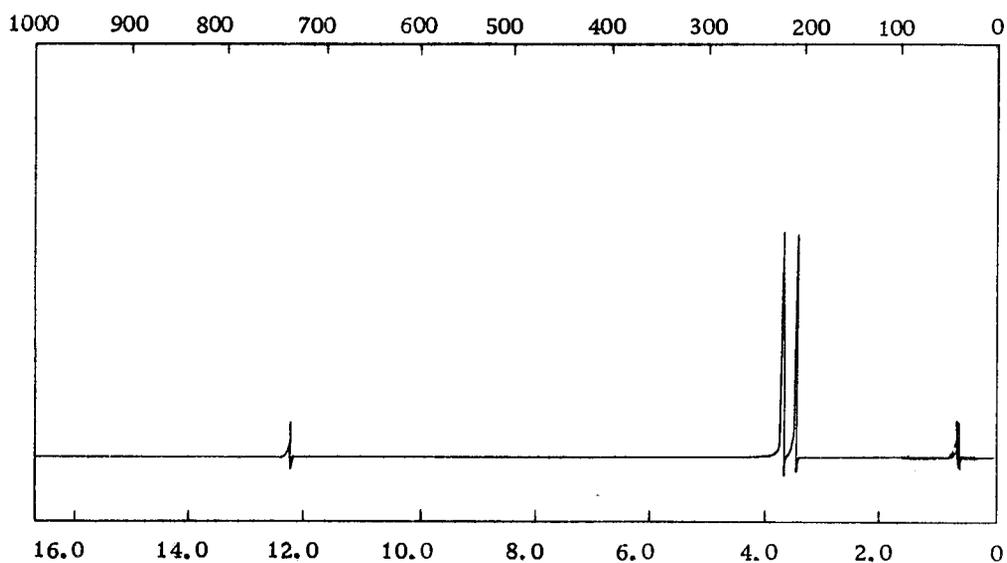
PROTON NUCLEAR MAGNETIC RESONANCE
SPECTRA OF ORGANOPHOSPHORUS COMPOUNDS

The scale at the top of each chart is in cycles per second and the scale at the bottom of each chart is in parts per million. The spectrum amplitude used in analytical work was greater than that for the reference standards shown here.

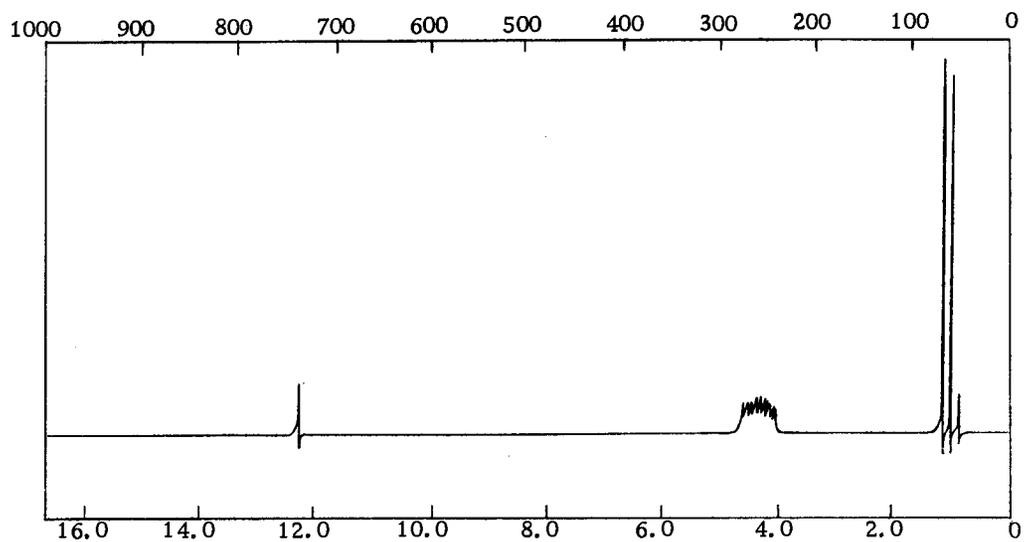
Trimethyl Phosphite $(\text{MeO})_3\text{P}$ Triisopropyl Phosphite $(\text{IsoprO})_3\text{P}$



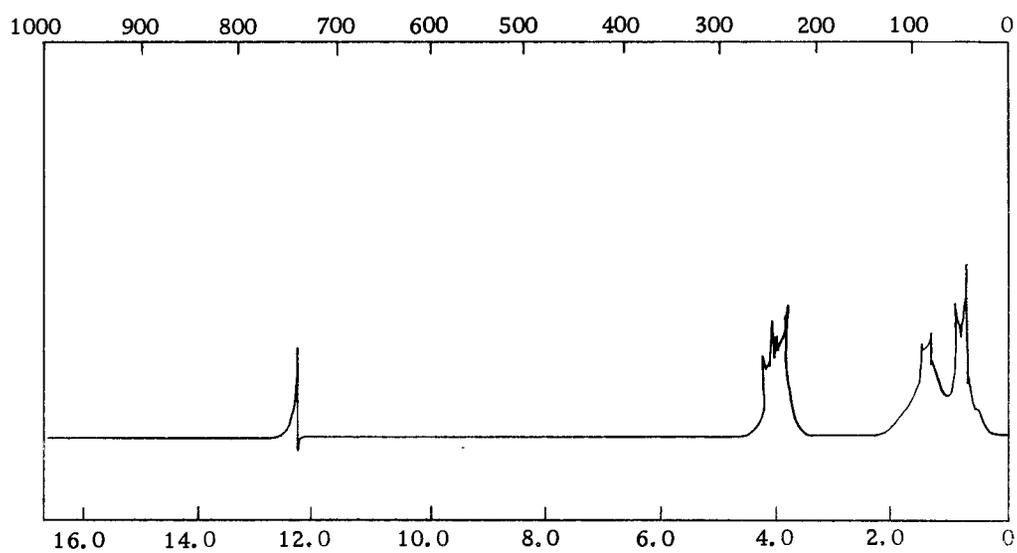
Tri-n-butyl Phosphite $(n\text{BuO})_3\text{P}$



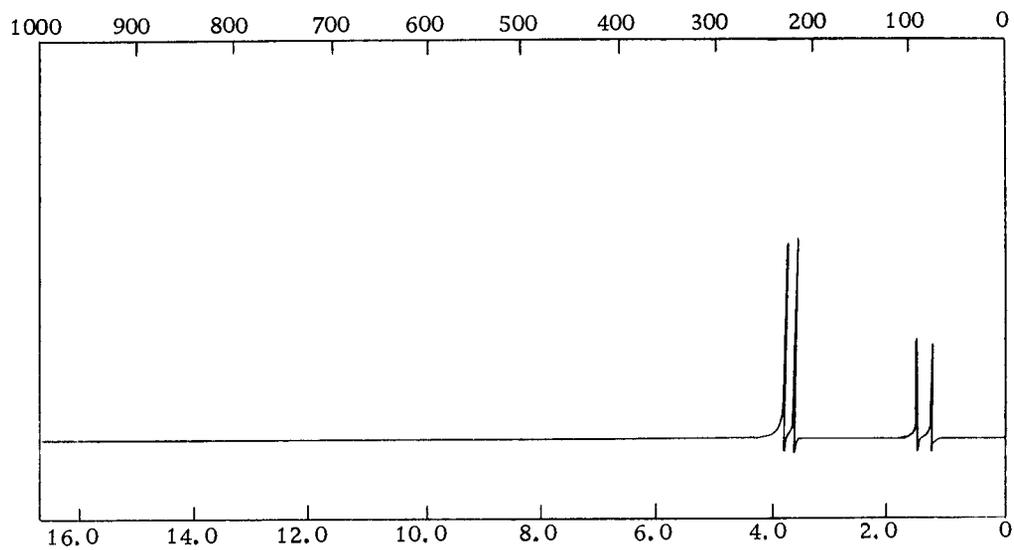
Dimethyl Hydrogen Phosphonate $(\text{MeO})_2\text{P}(\text{O})\text{H}$



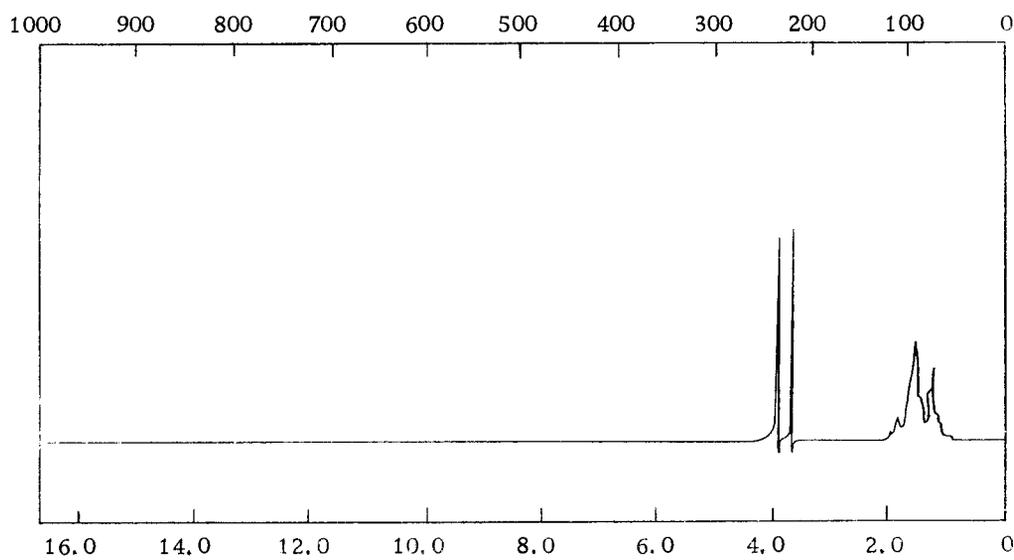
Diisopropyl Hydrogen Phosphonate (IsoprO)₂P(O)H



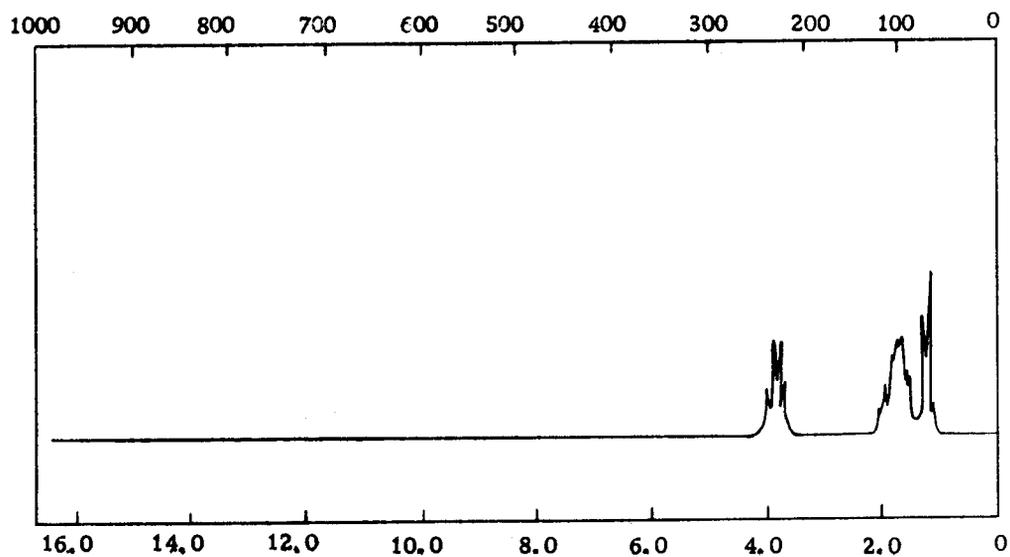
Di-n-butyl Hydrogen Phosphonate (nBuO)₂P(O)H



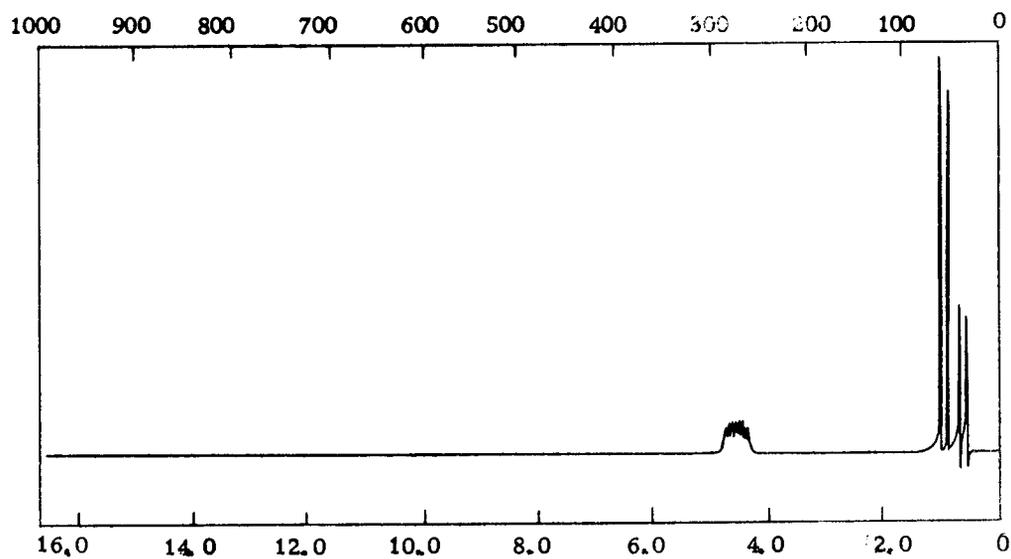
Dimethyl Methylphosphonate $(\text{MeO})_2\text{P}(\text{O})\text{Me}$



Dimethyl n-Butylphosphonate $(\text{MeO})_2\text{P}(\text{O})\text{nBu}$



Di-n-butyl Ethylphosphonate $(n\text{BuO})_2\text{P(O)Et}$



Compound Y