

phenylhydrazinium salt (m.p. 178–180°, lit.<sup>13</sup> m.p. 170°). (d) Carbon dioxide was determined by the infrared technique of Pobiner<sup>14</sup> which is both qualitative and quantitative. (e) Methanesulfonic acid was identified by its infrared spectrum and by g.c. comparison of retention times using an authentic sample (2-ft. silicone rubber column, 30 wt. % on Chromosorb W, 0.25-

in. stainless steel tubing, temperature programmed at 9°/min. on an F & M Model 609 flame-ionization gas chromatograph). (f) Formic Acid was identified by g.c. comparison with an authentic sample.

**Acknowledgment.**—The author wishes to acknowledge the technical assistance of Mr. H. Pobiner on several of the analytical techniques employed.

(13) W. Davis and J. H. Dick, *J. Chem. Soc.*, 2104 (1931).

(14) H. Pobiner, *Anal. Chem.*, **34**, 878 (1962).

## The Reaction of Trialkyl Phosphites with Maleate Esters

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The reaction of trialkyl phosphites with monomethyl maleate at temperatures below 100° has been investigated and a mechanism has been suggested to account for the products of the reaction. Tetraalkylphosphonosuccinates were the main reaction product. Dialkyl maleates and/or fumarates, carbon dioxide, and trialkylphosphonopropionates were found in equivalent amounts as major by-products. Changes in the nature of the alkyl group of the phosphorous ester has been shown to affect the rate of the reaction but not to change the nature of the products appreciably. The suggested mechanism involves a simultaneous 1,4 nucleophilic substitution by the tertiary phosphite at both electrophilic carbon atoms of the  $\alpha,\beta$ -unsaturated maleate system followed by an Arbuzov-like rearrangement of the intermediate adduct. Substitution  $\beta$  to the carboxylic acid group is suggested to result in the formation of the tetraalkylphosphonosuccinate while the by-products result from alternate substitution  $\beta$  to the carbomethoxy group with simultaneous esterification of the monomethyl maleate and decarboxylation of the resulting intermediate  $\beta$ -dialkylphosphono- $\beta$ -carboxypropionic ester. Experimental evidence is presented to support the suggested mechanism.

The first report of the reaction of trialkyl phosphites with acrylic and methacrylic acids, by Kamai and Kukhtin,<sup>2</sup> was subsequently followed by the disclosure of similar reactions with other  $\alpha,\beta$ -unsaturated systems.<sup>3</sup> Attempts to extend the reaction to maleic acid and to monoalkyl maleates were unsuccessful, however.<sup>4</sup> During this period, the mechanism for the reaction has been the subject of discussion.<sup>5</sup>

An investigation of the reaction of trialkyl phosphites with monoalkyl maleates was subsequently undertaken in these laboratories during the preparation of phosphorus-containing unsaturated polyesters.<sup>6</sup> These initial investigations have now been extended with the objective of studying the mechanism of the reaction. Although this report deals primarily with the reaction of trimethyl phosphite (I) and monomethyl maleate (II), the effect of various phosphite substituents on the reaction has also been investigated.

**Reaction of Trimethyl Phosphite with Monomethyl Maleate.**—The identification of trimethyl phosphonopropionate (III) as a by-product of this reaction by gas chromatography has already been reported.<sup>6</sup> The detailed analysis of the crude reaction mixture using a recently reported gas chromatographic procedure<sup>7</sup> is now summarized in Table I. It can be seen from these data that tetramethyl phosphonosuccinate (IV) is confirmed as the main reaction product, while the

TABLE I  
G.C. ANALYSIS OF THE REACTION MIXTURE FROM  
MONOMETHYL MALEATE AND TRIMETHYL PHOSPHITE

	%
Trimethyl phosphite	0.7
Dimethyl phosphonate	1.6
Dimethyl methylphosphonate	7.4
Dimethyl fumarate and/or maleate <sup>a</sup>	16.5
Trimethyl phosphonopropionate	18.7
Tetramethyl phosphonosuccinate	64.0
Unknown	0.7
Carbon dioxide <sup>b</sup>	17.8

<sup>a</sup> This method does not distinguish between fumarate or maleate since both compounds appear at the same place in the chromatogram. <sup>b</sup> The carbon dioxide was determined by absorption in aqueous sodium hydroxide during the reaction followed by back titration with acid.

phosphonopropionate III composes 18.7% of the crude reaction mixture. Dimethyl fumarate (V), and/or maleate (VI), and carbon dioxide (VII) were also products of the reaction as previously reported,<sup>6</sup> in yields almost equivalent to that of III. It is interesting to note that three reaction products, III, IV, and V, quantitatively account for all the maleate II originally charged to the reaction mixture.

The presence of the phosphonopropionate III in the chromatogram was determined by the usual technique of adding known amounts of authentic III to a previously analyzed crude reaction mixture and noting a corresponding increase in the g.c. peak. The yield of the fumarate V was found to be in good agreement with the yield reported<sup>6</sup> by simple distillation of the reaction mixture. The reaction and reaction products are summarized in Chart I.

**Isomerization of Dimethyl Maleate.**—Initial attempts to suggest a mechanism to account for the experimental facts were centered around a logical explanation for the formation of dimethyl fumarate.

(1) To whom inquiries should be directed.

(2) G. Kamai and V. A. Kukhtin, *J. Gen. Chem. USSR*, **27**, 2431 (1957).

(3) (a) G. Kamai and V. A. Kukhtin, *ibid.*, **27**, 2436 (1957); (b) V. A. Kukhtin and K. M. Orekhova, *ibid.*, **30**, 1539 (1960); (c) B. A. Arbuzov and V. M. Zorostrava, *Bull. Acad. Sci. USSR*, 962 (1960); (d) V. A. Ginsberg and A. Ya. Yakubovich, *J. Gen. Chem. USSR*, **30**, 3936 (1960).

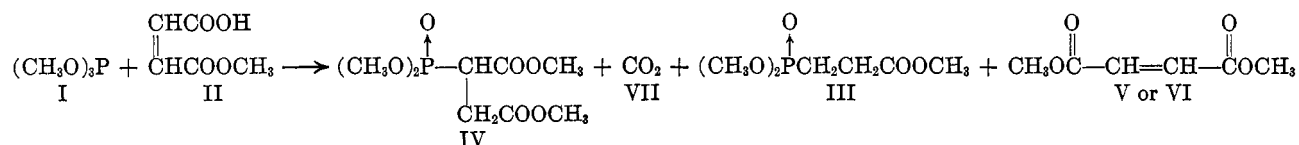
(4) G. Kamai and V. A. Kukhtin, *Tr. Kazansk. Khim.-Tekhnol. Inst.*, **23**, 133 (1957); *Chem. Abstr.*, **52**, 9948 (1958).

(5) (a) V. A. Ginsberg and A. Ya. Yakubovich, *J. Gen. Chem. USSR*, **30**, 3944 (1960); (b) G. Kamai and V. A. Kukhtin, *ibid.*, **31**, 1621 (1961).

(6) R. R. Hindersinn and N. E. Boyer, *Ind. Eng. Chem. Prod. Res. Develop.*, **3**, 141 (1964).

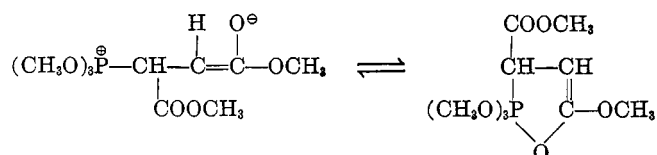
(7) A. Davis, A. Roaldi, J. Michalovic, and H. M. Joseph, *J. Gas Chromatog.*, **1** (8), 23 (1963).

CHART I  
 PRODUCTS FROM THE REACTION OF TRIMETHYL PHOSPHITE AND MONOMETHYL MALEATE



Since the esterification of carboxylic acids by trialkyl phosphites is well known,<sup>8</sup> the formation of some maleate ester VI during the phosphonation was anticipated. The isolation of the fumarate V by direct crystallization from the crude reaction mixture under the relatively mild conditions of the phosphonation,<sup>6</sup> however, made such a simple explanation untenable. In addition, the formation of fumarate V and carbon dioxide (VII) in amounts roughly equivalent to the amounts of phosphonopropionate III made it seem very likely that the formation of these three products was related mechanistically.

The observations<sup>6b</sup> that no appreciable reaction occurred between triethyl phosphite and methyl acrylate at temperatures up to 120° would, by analogy, indicate that the phosphonosuccinate IV could not be a product of the reaction of the maleate ester VI and I under these conditions. In agreement with this conclusion, no phosphonosuccinate IV could be isolated from the reaction mixture when equivalent amounts of I and VI were allowed to react under the same conditions used for reaction of phosphite I and monomaleate II. A quantitative yield of the fumarate V was recovered from the reaction mixture by simple filtration, however. This result could best be explained by postulating the reversible addition of phosphite to the conjugated maleate system to form the addition complexes shown below. The more stable fumarate would be formed on reversion of the complexes to the reactants.



One consequence of the postulated mechanism is that catalytic amounts of phosphite should suffice for complete isomerization of the maleate VI. An attempt to confirm this postulate by repeating the isomerization experiment using catalytic amounts of phosphite I (5 mole % based on the amount of VI used) generated a greater than 83% yield of fumarate V. It was necessary, however, to use a sealed tube as a reaction vessel in order to obtain a high yield of fumarate. Carrying out the reaction in an open system under an inert gas stream resulted only in traces of fumarate. The substitution of 5% tributyl phosphite (VIII) as the isomerization catalyst resulted in a 52% yield of V during a 4-hr. period at 80–100°. The loss of phosphite during the reaction was indicated by analysis of the reaction mixtures for trialkyl phosphite after removal of the fumarate by filtration. The results showed a very pronounced reduction in the original phosphite concentration in most of the reaction mix-

tures, while no phosphite could be detected at the end of the sealed-tube isomerization.

Although these results confirm the postulated mechanism, they also indicate that loss of the original phosphite by entrainment in the inert gas stream or by isomerization to the corresponding dimethyl methylphosphonate (IX) under the reaction conditions are important variables affecting the isomerization rate. The high yield of fumarate V observed using equivalent quantities of phosphite can be attributed to a rapid isomerization rate with the high catalyst concentration and the relatively small percentage of phosphite isomerized under the reaction conditions. The prevention of entrainment losses by the use of a sealed tube allowed high conversion of maleate at a relatively slow reaction rate in contrast to the same reaction in an open system. The extended reaction time, however, eventually resulted in the complete consumption of the trialkyl phosphite, most likely by an Arbuzov-type isomerization to the corresponding phosphonate. These conclusions are substantiated by the pronounced increase in reaction rate and conversion observed when the relatively high-boiling phosphite VIII was substituted for the methyl ester I.

Support for this isomerization mechanism has recently been supplied by Hands<sup>9</sup> who suggested a similar mechanism for the isomerization of the maleate VI by triphenyl phosphine at 150°. In this latter isomerization, it was also noted that the rate of isomerization decreased rapidly with a decrease in catalyst concentration and that appreciable amounts of phosphine were necessary for the complete isomerization of VI. Additional support for the nucleophilic attack of trialkyl phosphites to electrophilic  $\beta$ -carbon atoms of  $\alpha,\beta$ -unsaturated systems is also supplied by the work of DeSombre, Harvey, and Jensen.<sup>10</sup>

The effect of phosphite concentration on the products of the reaction of I with the monoester II was also investigated and supplies additional support for the isomerization reaction postulated. When II was reacted with a carefully measured equivalent of I, only traces of the fumarate V could be isolated by fractional distillation of the reaction products at reduced pressure, while a 14% yield of the maleate VI was isolated. When the reaction was repeated with a 20% excess of phosphite, direct fractional distillation of the reaction mixture resulted in a 14% yield of fumarate V, while no maleate VI could be isolated.

These experiments, therefore, show conclusively that appreciable amounts of fumarate V are not produced during the phosphonation in the absence of an excess of phosphite and that trialkyl phosphites are extremely good catalysts for the isomerization of maleate esters to the corresponding fumarate.

(9) A. R. Hands, *J. Chem. Soc.*, 1181 (1964).

(10) E. R. DeSombre, R. G. Harvey, and E. V. Jensen, Abstracts, 146th National Meeting of the American Chemical Society, Denver, Colo., Jan. 1964, p. 21C.

(8) G. Kamai, V. A. Kukhtin, and O. A. Strogova, *Tr. Kozansk. Khim.-Tekhnol. Inst.*, **21**, 155 (1956); *Chem. Abstr.*, **51**, 11994 (1957).

**Carbon Dioxide Formation.**—The fact that the yield of the diesters V and/or VI during the preparation of the phosphonosuccinate IV is more than 10 times as large as the amount of dimethyl phosphonate IX found in the reaction mixture, coupled with the inertness of IX in the reaction medium, indicates that the diesters must be produced by some reaction other than the direct esterification of monomaleate II by the phosphite. This is true since such a direct esterification would require the formation of IX in amounts equivalent to the ester formed.<sup>8</sup>

The investigation into the mechanism whereby the phosphonopropionate III and carbon dioxide (VII) were generated led to some interesting observations concerning the reaction mechanism. The most logical explanation for the presence of III and VII required that they be generated simultaneously by the decarboxylation of an  $\alpha$ -phosphonocarboxylic acid derivative formed during the reaction. This conclusion was supported by the observations of Kamai and Kukhtin,<sup>4</sup> who noted the evolution of considerable amounts of carbon dioxide when triethyl phosphite was treated with maleic acid, and the reported decarboxylation tendency of carboxylic acids substituted in the  $\alpha$  position by a phosphorus-containing group.<sup>11</sup> The  $\beta$ -dialkylphosphono- $\beta$ -carboxypropionic ester XIV would be the most logical intermediate and would yield the observed products on decarboxylation; this is shown in Chart II. Such an intermediate would be expected to be formed by nucleophilic attack of the phosphite on the carbon atom  $\beta$  to the carboxylic ester group in the monomaleate II.<sup>12</sup>

The likelihood of such nucleophilic attack has already been confirmed by the isomerization experiments just described. In fact, the greater electronegativity of the carbomethoxy group would actually lead to the conclusion that the carbon atom  $\beta$  to the carboxylic ester group of II would be the most electrophilic site available for nucleophilic attack. The two possible reaction paths have been summarized in Chart II.

It can be seen from this chart that the main reaction products (path A) are postulated as being produced by a Michael-type addition of the phosphite to form an enolic addition product which ketonizes to the alternate intermediates XIa and XIb. The formation of the succinate IV then results from an Arbuzov-like nucleophilic attack of the carboxylate ion on the alkyl group of the phosphite.<sup>13-17</sup> A similar Michael addi-

tion to the  $\alpha,\beta$ -unsaturated ester system of the reactant II results in the intermediates XIIa and XIIb. The isomerization of maleate esters just described indicates that the reversible formation of intermediates XIIa and XIIb under the reaction conditions is very probable. The fact that path B does not proceed to completion is most likely a result of the lack of a suitable rearrangement mechanism which is considered to be a necessary driving force for the completion of the reaction.<sup>18,19</sup>

intermediate. A similar argument can be made to substantiate the formation of the pentacovalent intermediate XIIb.

The presence of such a pentacovalent intermediate as XIb, however, does not preclude the possibility of a subsequent reaction proceeding by way of the ionic intermediate XIa, since cleavage of the phosphorus-oxygen bond prior to any nucleophilic attack would then convert XIb into XIa. Thus, the two reaction paths are indistinguishable in the light of the present experimental evidence.

(14) G. Birum and J. Dever, Abstracts, 134th National Meeting of the American Chemical Society, Chicago, Ill., Sept. 1958, p. 101P.

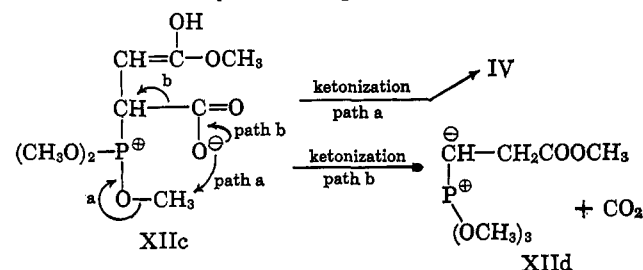
(15) F. Ramirez and N. B. Desai, *J. Am. Chem. Soc.*, **82**, 2652 (1960).

(16) V. A. Kukhtin, K. M. Kirillova, R. R. Shagidullin, Yu. Yu. Samilov, N. A. Lyazina, and N. F. Rakova, *J. Gen. Chem. USSR*, **32**, 2020 (1962).

(17) An alternate mechanism for the formation of the tetramethyl phosphonosuccinate (IV) was originally considered and discarded for the reasons given below. This possible mechanism could involve the initial esterification of the monomaleate ester II by the phosphite I to yield equivalent amounts of dimethyl phosphonate IX and maleate VI; addition of the dimethyl phosphonate to the dimethyl maleate, catalyzed by the phosphite I, would then yield IV. This latter reaction has been shown to proceed in good yield [A. N. Pudovic, *Izv. Akad. Nauk SSSR, Otd. Khim. Nauk*, 026 (1952); *Chem. Abstr.*, **47**, 10467 (1953)] when sodium ethoxide was used as a catalyst. The mechanism was tested by subjecting equivalent amounts of the maleate VI and phosphonate IX, in the presence of 8 mole % of I, to the reaction conditions used in the formation of the phosphonosuccinate IV from I and II. That no IV was produced under these conditions was indicated when the n.m.r. spectra of samples of the mixture before heating, after 1.5 hr. of heating, and after 4 hr. of heating were compared with those of the pure components of the reaction mixture and phosphonosuccinate IV. The spectra of all three samples of the reaction mixture were found to be identical. The absence of appreciable amounts of IV in the mixture was indicated by the lack of absorption at 3.72 p.p.m. This peak is a member of a complex multiplet centered at 3.8 p.p.m. and is readily discernible when superimposed on the multiplet centered at 3.8 p.p.m. characteristic of the reaction mixture.

(18) It is very unlikely that decarboxylation proceeds directly from the ionic intermediate XIIa. Such a decarboxylation would lead one to expect methyl acrylate as one of the reaction products because of the demonstrated reversibility of the initial reaction complex.

(19) A modification of the postulated mechanism which was suggested by one of the referees is also worthy of consideration. In this modification, the intermediate XIIa would be converted to the isomeric structure XIIc via an internal or external proton exchange. Ketonization and an Arbuzov



(11) F. F. Blicke and S. Raines, *J. Org. Chem.*, **29**, 204 (1964).

(12) An alternate method for the formation of XIV by a transesterification of the phosphonosuccinate IV and the monoalkyl ester II was also considered. That this reaction is not important under the conditions used was shown when no carbon dioxide could be detected during a prolonged heating of IV and II at 97°. The addition of trimethyl phosphite to the same reaction mixture under these conditions resulted in an immediate evolution of carbon dioxide.

(13) Although the formation of IV must proceed from the open-chain intermediate XIa as shown in path A, there is a considerable body of evidence to support the presence of the pentacovalent cyclic intermediate XIb as a reaction intermediate. In the reaction of trialkyl phosphites with acrylic acid,<sup>2</sup> it was shown that the addition of an alcohol different from that contained in the phosphite adduct initially formed at room temperature resulted in an exotherm and the isolation of mixed trialkylphosphonobutyrate. The authors took this as evidence for the formation of the cyclic intermediate such as XIb.

Even more convincing evidence for the formation of a cyclic intermediate was the isolation of stable pentacovalent five-membered cyclic phosphorus compounds originally by Birum and Dever<sup>14</sup> and subsequently by Ramirez and Desai<sup>15</sup> and Kukhtin and co-workers.<sup>16</sup> This evidence strongly suggests the formation of the pentacovalent phosphorane XIb as the preferred in-

rearrangement denoted by path a was then suggested to convert XIIc directly to the phosphonosuccinate IV.

An alternate rearrangement path for XIIc not considered in the suggestion is the direct decarboxylation of XIIc via path b as shown to produce the unstable ylide XIIId. One possible mode of decomposition for XIIId is indicated to yield trimethyl phosphonopropionate (III) and a carboxylic ester by a proton-transfer mechanism. In this manner all the main reaction products could then be produced by nucleophilic attack at either electrophilic carbon atom.

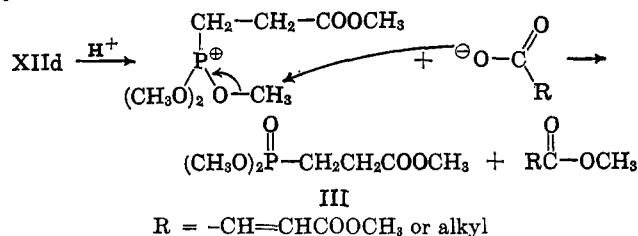
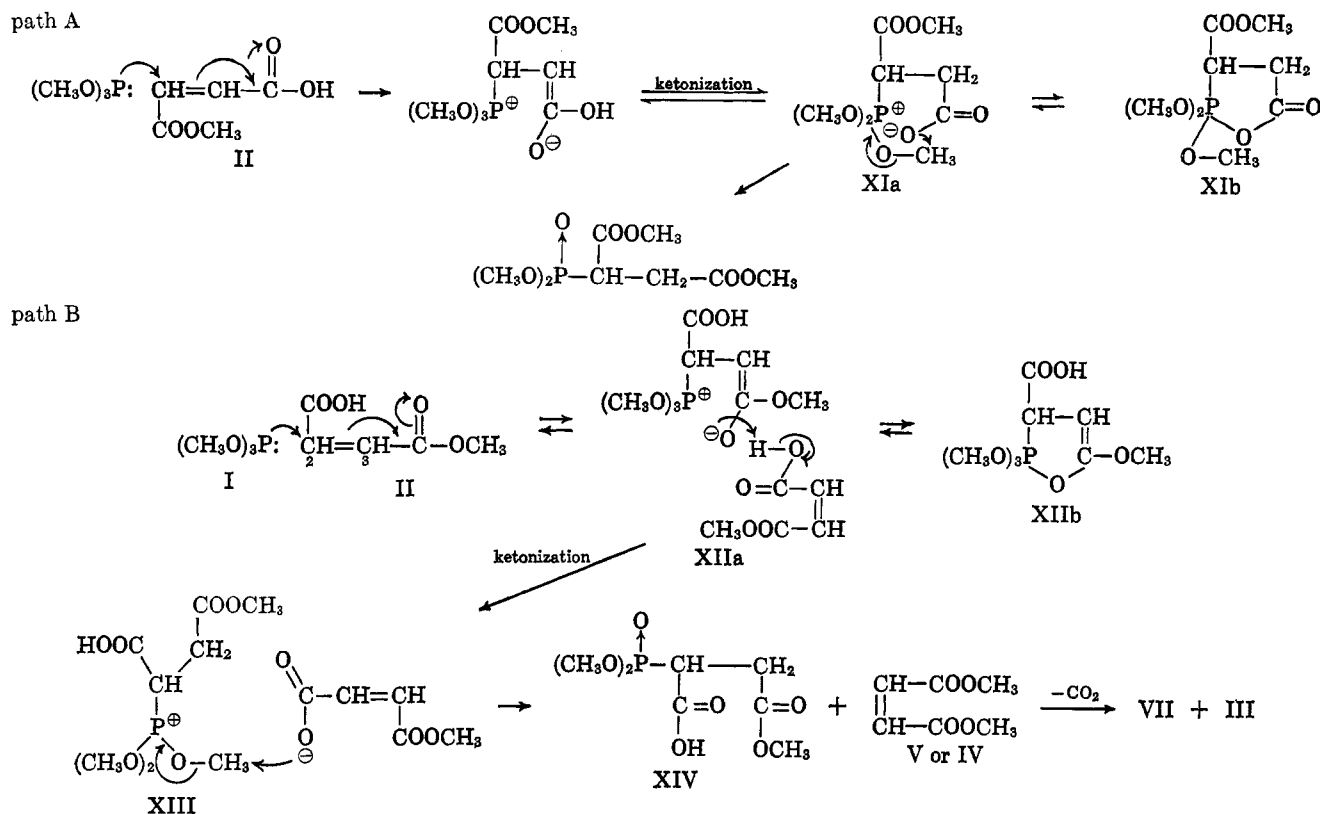


CHART II

## MECHANISM FOR THE REACTION OF TRIALKYL PHOSPHITES WITH MONOETHYL MALEATE



**Reaction of Trialkyl Phosphites with Dialkyl Maleates in the Presence of Acetic Acid.**—That monoester II could act as a carboxylic acid in initial stages of the reaction with phosphite I in addition to its role as an  $\alpha,\beta$ -unsaturated system led to the investigation of the effect of carboxylic acids on the reaction path. When equivalent amounts of the phosphite I were allowed to react with the diester VI in the presence of slightly more than 1 equiv. of glacial acetic acid (XV) at  $80^\circ$ , the result was a smooth elimination of an equivalent amount of methyl acetate (XVI). Subsequent fractionation of the reaction mixture resulted in an 87% yield of phosphonosuccinate IV. Repetition of this reaction with triallyl phosphite (XVII) resulted in the isolation of allyl acetate and diallyl dimethylphosphonosuccinate indicating that the alkyl group originally contained in the phosphite was that being transferred to the carboxylic acid. These experimental facts provide a logical explanation for the formation of the  $\alpha$ -carboxyphosphonopropionate XIV with simultaneous production of the dialkyl maleate as indicated in Chart II.

Acetic acid as an alkyl acceptor was also shown to behave similarly in the reaction of the tertiary phosphite I and methyl acrylate. The main product was a 68% yield of the propionate III, indicating that the use of a carboxylic acid as an alkyl acceptor is not limited to the maleate system and may be a general preparative method for the addition of trialkyl phosphites to  $\alpha,\beta$ -unsaturated carbonyl systems. No additional evidence is currently available, however, to substantiate this viewpoint. The mechanism then accounting for all the experimental observations as shown in Chart II is a simultaneous production of succinate IV by way of path A while the by-prod-

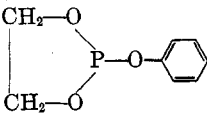
ucts are produced by completion of path B in a bimolecular reaction as shown with I as an example. The postulated mechanism is also supported by the work of Harvey and Jensen,<sup>20</sup> who have recently disclosed the role of phenol and ethyl alcohol as alkyl acceptors in the reaction of trialkyl phosphites with dialkyl maleates.

**Effect of Phosphite Substituents on the Phosphite Reactivity.**—In order to get some insight into the effect of phosphite substituents on the rate of the reaction, a wide variety of phosphites were treated with an equivalent amount of monomaleate II under a standard set of reaction conditions. The amount of gaseous VII and, therefore, the amount of phosphonopropionate produced during the reaction was determined by absorption of the inert gas stream in standard sodium hydroxide followed by titration with acid at the end of the reaction. The conversion of the maleate II to phosphonosuccinate was determined by direct titration of the unreacted carboxylic acid in the final reaction mixture and subtraction of twice the molar equivalent of carbon dioxide produced to correct for carboxylic acid consumed in the decarboxylation and esterification reactions. The carboxylic acid consumption can be taken as a crude measure of reactivity of the phosphite used. The data collected are summarized in Table II.

It can be seen from the first five reactions that the reaction rate remained relatively constant over a wide range of alkyl substituents in spite of the fact that the increased steric requirements of the highly branched substituents would have been expected to have resulted in a reduced reaction rate. This is most likely owing

(20) R. G. Harvey and E. V. Jensen, Abstracts, 144th National Meeting of the American Chemical Society, Los Angeles, Calif., April 1963, p. 61M.

TABLE II  
 REACTION OF VARIOUS PHOSPHITES WITH MONOMETHYL MALEATE

Phosphite	Mole % of CO <sub>2</sub> produced	% of COOH reacted	% of COOH reacted to form phosphonosuccinate	Ratio of phosphonosuccinate to CO <sub>2</sub>
(CH <sub>3</sub> O) <sub>3</sub> P	17.8	92.1	56.5	3.2
(CH <sub>3</sub> CH <sub>2</sub> O) <sub>3</sub> P	17.4	97.3	62.5	3.6
( <i>i</i> -PrO) <sub>3</sub> P	14.6	95.9	66.7	4.6
( <i>i</i> -BuO) <sub>3</sub> P	17.6	97.3	62.1	2.5
(CH <sub>2</sub> =CH-CH <sub>2</sub> O) <sub>3</sub> P	15.2	93.0	62.6	4.1
	8.7	69.6	52.2	6.0
[(ClCH <sub>2</sub> ) <sub>2</sub> CHO] <sub>2</sub> P <sup>a</sup>	7.5	51.7	36.7	4.9
(C <sub>6</sub> H <sub>5</sub> O) <sub>3</sub> P	4.3	24.2	15.6	3.6

<sup>a</sup> The reaction product of epichlorohydrin and phosphorus trichloride has been formulated with the structure shown by N. I. Rizpolozhenski and A. A. Muslinkin [*Bull. Acad. Sci. USSR*, 1493 (1961)] by analogy to the product produced by the reaction of ethyl-dichlorophosphine and epichlorohydrin. The 1,3-dichloropropyl derivative was also shown to result from a similar reaction of epichlorohydrin with dialkylphosphorochloridites [A. N. Pudovic and E. M. Laizullin, *J. Gen. Chem. USSR*, 32, 224 (1962)].

to the fact that the reaction of these phosphites had essentially proceeded to completion under the reaction conditions used and that the test was not sensitive enough to distinguish the relatively small differences in these reaction rates. A reduction in the reaction time or temperature, however, would be expected to reveal differences in the reactivity of these trialkyl phosphites.

That the bulkiness of the alkyl substituent does indeed affect the reaction rate is confirmed by the significant reduction in reaction rate exhibited in the reaction of tris(1,3-dichloro-2-propyl) phosphite. Apparently, the large bulk of the chlorine atom is sufficient to show a very significant reduction in the measured reaction rate. The slightly lower reactivity of phenylethylene phosphite, on the other hand, is most likely due to the decreased number of alkyl groups available for rearrangement in the latter stages of the reaction, since the difficulty of phenyl group migration in the Arbuzov reaction is well known. This conclusion is confirmed by the very slow reaction rate exhibited by triphenyl phosphite. The fact that triphenyl phosphite reacts at all under the reaction conditions is surprising and suggests an unusually facile migration of the phenyl group.

The relatively constant ratio of carbon dioxide (VII) produced relative to the carboxylic acid consumed is interesting, considering the wide reactivity of the phosphites used, and indicates that the phosphite substituents have little effect on the products of the reaction despite very substantial changes shown on the reaction rate. This fact can be explained by the proposed reaction mechanism if the assumption is made that the first-stage adduction to form the intermediates XI and XII shown in Chart II is the rate-determining step. Since the free carboxylic acid concentration remained constant with no change in its reactivity throughout the reaction series, such an assumption would mean that the reaction rate for both reaction paths would be equally affected by any change in the susceptibility of the phosphite substituent to nucleophilic attack in the reaction intermediates XI and XII. This assumption not only allows a ready explanation for the observed experimental data, but is also in agreement with the known facts of the Arbuzov reaction mechanism.<sup>21</sup>

## Experimental Section

**Materials.**—The phosphites used in this work, with the exception of tris(1,3-dichloro-2-propyl) phosphite, were prepared in the conventional manner by reaction of phosphorus trichloride with the alcohol in the presence of an amine as an acid acceptor or by transesterification of trimethyl phosphite with the alcohol in the presence of a basic catalyst. The products were fractionated, with the exception of triallyl phosphite, to yield materials with purities of greater than 95% as determined by iodometric analysis.<sup>22</sup> Tris(1,3-dichloro-2-propyl)phosphite was prepared by the direct reaction of 3 molecular equiv. of epichlorohydrin and an equivalent of phosphorus trichloride under an inert atmosphere at maximum temperatures of 35–40°. The reaction product, which was shown to be 93–94% pure iodometrically, was used directly without distillation. The methyl acrylate was a commercial sample from the Celanese Chemical Corp. with a purity of 99.5% and stabilized with 0.02% of 1,4-dimethoxybenzene. The dimethyl maleate was a commercial sample which was redistilled and the fraction boiling at 105–106° (23 mm.) was used in the experimentation.

Monomethyl maleate was prepared by dissolving commercial maleic anhydride in an equimolar quantity of methanol and allowing the mixture to stand overnight to yield material with a neutralization equivalent of 128–136 (calcd. 130).

All infrared determinations were performed on a Perkin-Elmer Model 21 spectrophotometer. The gas chromatograms were carried out on a Burrell K-2 gas chromatograph.

Melting points are corrected and were carried out on a Nalge-Axelrod micro hot stage. N.m.r. spectra were performed on a Varian A-60 spectrometer.

**Reaction of Trimethyl Phosphite (I) with Monomethyl Maleate (II).**—The reaction vessel consisted of a 250-ml. round-bottom flask equipped with a stirrer, thermometer, N<sub>2</sub> inlet tube, dropping funnel, and a reflux condenser. A tube led from the top of the condenser to two gas-washing bottles connected in series containing a total of 475 ml. of standard sodium hydroxide solution.

To the flask was then added 65.0 g. (0.5 mole) of II, and 75.0 g. (0.6 mole) of I was placed in the dropping funnel. Nitrogen was introduced slowly into the system, stirring was begun, and the temperature was raised to 60°. The addition of I caused a rise in temperature and an ice bath was applied to the flask to maintain the temperature below 80°. After the addition was complete (about 20 min.), the ice bath was removed and heating was resumed. The temperature was maintained at 80° for a total of 2 hr. The nitrogen purge was continued until the reaction had cooled to room temperature. During this time, crystals separated from the reaction mixture. These were removed by suction filtration, washed with cold ether, and dried.

(21) (a) A. Y. Garner, E. C. Chapin, and P. M. Scanlon, *J. Org. Chem.*, 24, 532 (1959); (b) H. I. Jacobson, R. G. Harvey, and E. V. Jensen, *J. Am. Chem. Soc.*, 77, 6064 (1955).

(22) The iodometric method used for the determination of the trialkyl phosphite concentration was a modification of that described by Thompson.<sup>23</sup>

(23) Q. E. Thompson, *J. Am. Chem. Soc.*, 83, 548 (1961).

The yield was 7.0 g., m.p. 100–101, showing no depression with an authentic sample of dimethyl fumarate (V) (lit.<sup>24</sup> m.p. 102°).

Of the 119.0 g. of filtrate recovered, 110.0 g. was distilled under reduced pressure. The following fractions were collected: (1) traces, b.p. 25° (10 mm.),  $n_D^{20}$  1.4151; (2) 5.8 g., b.p. 43° (0.65 mm.) to 95° (0.45 mm.),  $n_D^{20}$  1.4221; (3) 24.7 g., b.p. 98° (0.45 mm.) to 124° (0.55 mm.),  $n_D^{20}$  1.4407; and (4) 51.4 g., b.p. 124–127° (0.55 mm.),  $n_D^{20}$  1.4462. During the distillation of the second fraction a considerable amount of material crystallized in the condenser. At this point, the apparatus was disassembled, and the condenser was carefully washed with acetone. This acetone solution was evaporated to dryness giving 3.2 g. of additional V melting at 97–99°. The total yield of V was 14%.

A titration of the caustic solution in the wash bottles indicated that a total of 91.2 mequiv. of CO<sub>2</sub> had been evolved.

Analysis of fraction 3 by gas chromatography indicated 1.6% dimethyl fumarate (V) or maleate (VI), 62.8% trimethyl phosphonopropionate (III), 15.5 g. (15.8% yield), and 33.8% tetramethyl phosphonosuccinate (IV).

Fraction 4 was shown to be almost pure tetramethyl phosphonosuccinate by comparison of its infrared spectrum with an authentic sample prepared by the method of Pudovic<sup>17</sup> [(b.p. 142° (2 mm.),  $n_D^{20}$  1.4435)].

The total yield of tetramethyl phosphonosuccinate was 59.7 g. or 51.0%. In various experiments, yields of tetramethyl phosphonosuccinate were as high as 65% while the yield of trimethyl phosphonopropionate was generally in the range of 17%.

When an equivalent amount of trimethyl phosphite was used, only traces of dimethyl fumarate could be isolated, while a 14% yield of dimethyl maleate (VI) was obtained (identified by infrared and n.m.r. spectra). A portion of a similar reaction mixture was analyzed by vapor phase chromatography and is summarized in Table I.

**Isomerization of Dimethyl Maleate (VI) with Trimethyl Phosphite (I).**—A mixture of 12.4 g. (0.1 mole) of I and 14.4 g. (0.1 mole) of VI were heated for 1.5 hr. at 80° in a 250-ml. round-bottom flask equipped with a stirrer, thermometer, nitrogen inlet tube, and reflux condenser. At the end of this period, the reaction mixture was cooled and the crystals which separated were filtered and washed once with cold ether. The filtrate was analyzed for phosphite. The crystalline product, which was identified as V (m.p. 102°, m.m.p. 102°), was obtained in quantitative yield. The filtrate was shown to contain 84% I, by iodine titration, with a small amount of dimethyl phosphonate.

**Isomerization using Catalytic Amounts of Trimethyl Phosphite (I).** A. Standard Procedure.—Repetition of the above experiment using only 5 mole % of trimethyl phosphite yielded only a small amount of V. Iodometric titration of the reaction mixture indicated a dimethyl phosphonate concentration of 0.1% and a trimethyl phosphite concentration of 0.9% by weight.

The substitution of tributyl phosphite (VIII) in the above procedure with the exception that the reaction time was extended to 4 hr. at 80–100° yielded 18.8 g. (52% yield) of V (m.p. 100–101°). The filtrate was found to contain 3.0% of VIII and 2.6% of dibutyl phosphonate by iodometric titration.

B. Isomerization in a Sealed Tube.—In a Carius tube were sealed 72.0 g. (0.5 mole) of freshly distilled VI (b.p. 105–106° at 23 mm.) and 3.0 g. (0.025 mole) of I (97.4% pure). The tube was placed in an oven at 80° for a total of 99 hr. During this time, the amount of crystalline product observed after cooling to room temperature was found to increase slowly with time. At the end of this time, the tube was opened and a sample of the material was analyzed by gas chromatography. No trimethyl phosphite (I) could be detected but dimethyl methylphosphonate was found to compose 4.1% of the mixture.

The contents of the tube were recrystallized from chloroform and 58.0 g. of V was obtained (83%, m.p. 101–103°, m.m.p. 103° with dimethyl fumarate).

**Reaction of Trimethyl Phosphite (I) with Dimethyl Maleate (VI) in the Presence of Acetic Acid.**—In a 500-ml. round-bottom flask equipped with stirrer, nitrogen inlet, thermometer, dropping funnel, and distillation head were placed 144.0 g. (1.0 mole) of VI and 66.0 g. (1.1 moles) of glacial acetic acid. The mixture

was heated with stirring to 55°, and the heater was removed. I (124 g., 1.0 mole) was added dropwise at such a rate to keep the temperature below 80°. During the addition, a liquid started to distil from the reaction mixture. After the addition of I was complete, external heat was applied until the distillation of low-boiling material ceased. A total yield of 51.6 g. of material was collected with b.p. 56°,  $n_D^{20}$  1.3618.

After removal of the low-boiling fraction, the reaction mixture was fractionally distilled under reduced pressure. The following fractions were collected: (1) 7.8 g., b.p. to 44° (0.2 mm.),  $n_D^{20}$  1.4208; (2) 4.9 g., b.p. 44° (0.20 mm.) to 121° (0.25 mm.),  $n_D^{20}$  1.4319; (3) 203.5 g., b.p. 122° (0.25 mm.) to 116° (0.2 mm.),  $n_D^{20}$  1.4442 (*Anal.* Calcd. for C<sub>8</sub>H<sub>16</sub>O<sub>7</sub>P: P, 12.19. Found: P, 12.14.); and (4) 17.1 g., b.p. 118° (0.2 mm.) to 121° (0.2 mm.),  $n_D^{20}$  1.4442. A total of 11.9 g. of liquid collected in the cold trap,  $n_D^{20}$  1.3881.

Fraction 1 was redistilled under atmospheric pressure, b.p. 56–57°,  $n_D^{20}$  1.3603, and gave an infrared spectrum identical with that of methyl acetate (lit.<sup>25</sup> b.p. 57.5°,  $n_D^{20}$  1.3593).

Fraction 3 was identified as tetramethyl phosphonosuccinate (lit.<sup>17</sup>  $n_D^{20}$  1.4435) by comparison of its infrared spectrum with that of an authentic sample prepared by the method of Pudovic.<sup>17</sup> The yield of combined fractions 3 and 4 was 87%.

**Reaction of Triallyl Phosphite (XVII) and Dimethyl Maleate (VI) in the Presence of Acetic Acid.**—The above reaction was repeated substituting XVII for I. From 14.4 g. (0.1 mole) of VI and 20.2 g. (0.1 mole) of XVII in 6.0 g. of glacial acetic acid were obtained the following fractions: (1) 4.3 g., b.p. 98–100°,  $n_D^{20}$  1.4048; (2) 1.5 g., b.p. 32–135° (0.18 mm.); (3) 4.4 g., b.p. 135–144° (0.18 mm.); (4) 12.9 g., b.p. 144–148° (0.18 mm.),  $n_D^{20}$  1.4642; and (5) 7.0 g., b.p. 148° (0.18 mm.),  $n_D^{20}$  1.4647. Fraction 1 was identified as allyl acetate from its boiling point and refractive index (lit.<sup>26</sup> b.p. 103–104°;  $n_D^{20}$  1.40488).

The infrared spectra and phosphorus analysis of fractions 4 and 5 indicated the product to be dimethyl diallylphosphonosuccinate (*Anal.* Calcd. for C<sub>12</sub>H<sub>18</sub>O<sub>7</sub>P: P, 10.11. Found: P, 9.94.). The infrared spectrum, showing bands at 3.41 (m), 5.75 (s), 6.09 (w), 6.96 (m), 7.55 (m), 1.94 (s), 8.22 (s), 8.61 (s), 9.19 (s), 9.3–10.1 (s), and 11.63  $\mu$  (m), was consistent with the assigned structure. The combined fraction represents a yield of 65% of theory.

No product was obtained from the attempt to treat triphenyl phosphite with dimethyl maleate under the above conditions.

**Reaction of Methyl Acrylate with Trimethyl Phosphite (I) and Acetic Acid.**—By the same procedure described above, 26.8 g. of trimethyl phosphonopropionate, b.p. 94–98° (0.35 mm.),  $n_D^{20}$  1.4373 [lit.<sup>1</sup> b.p. 122° (3 mm.),  $n_D^{20}$  1.4370], was obtained from 17.2 g. (0.2 mole) of methyl acrylate, 12.0 g. (0.2 mole) of glacial acetic acid, and 24.8 g. (0.2 mole) of trimethyl phosphite. This represents a yield of 68%.

**Reaction of Various Phosphites with Monomethyl Maleate (II).**—The standard procedure used for measuring the reactivity of the phosphites was identical with that described for the preparation of IV with the exception that 0.1-molar amounts of II and the various phosphites were used and added to the reaction flask over a 10–15 min. period at 20°. The reaction was heated at 80° for 1.5 hr. after the addition of the phosphite, and 0.1 N sodium hydroxide was used in the gas absorption bottles. After cooling to room temperature, an aliquot of the combined solution from the gas absorption bottles was titrated to determine the amount of carbon dioxide evolved. The amount of trialkyl phosphonopropionate and the carboxylic acid content were determined by titration with methanolic sodium hydroxide using phenolphthalein as an indicator. The results are summarized in Table II.

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(24) J. R. A. Pollock and R. Stevens, "Dictionary of Organic Compounds," Vol. 3, 4th Ed., Oxford University Press, New York, N. Y., 1965, p. 1473.

(25) See ref. 24, Vol. 4, p. 2114.

(26) See ref. 24, Vol. 1, p. 66.