INFORMATION TO USERS

This material was produced from a microfilm copy of the original document. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the original submitted.

The following explanation of techniques is provided to help you understand markings or patterns which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting thru an image and duplicating adjacent pages to insure you complete continuity.
2. When an image on the film is obliterated with a large round black mark, it is an indication that the photographer suspected that the copy may have moved during exposure and thus cause a blurred image. You will find a good image of the page in the adjacent frame.
3. When a map, drawing or chart, etc., was part of the material being photographed the photographer followed a definite method in "sectioning" the material. It is customary to begin photoing at the upper left hand corner of a large sheet and to continue photoing from left to right in equal sections with a small overlap. If necessary, sectioning is continued again — beginning below the first row and continuing on until complete.
4. The majority of users indicate that the textual content is of greatest value, however, a somewhat higher quality reproduction could be made from "photographs" if essential to the understanding of the dissertation. Silver prints of "photographs" may be ordered at additional charge by writing the Order Department, giving the catalog number, title, author and specific pages you wish reproduced.
5. PLEASE NOTE: Some pages may have indistinct print. Filmed as received.

Xerox University Microfilms
300 North Zeeb Road
Ann Arbor, Michigan 48106

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

76-30,414

JUNG, Alfred Karl, 1946-
THE HYDROGENOLYSIS-REDUCTION OF UNSATURATED
PHOSPHATE ESTERS.

City University of New York, Ph.D., 1976
Chemistry, organic

Xerox University Microfilms, Ann Arbor, Michigan 48106

THE HYDROGENOLYSIS-REDUCTION
OF UNSATURATED PHOSPHATE ESTERS

BY

Alfred K. Jung

A dissertion submitted to the
Graduate Faculty in Chemistry
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy, The City
University of New York.

1976

This manuscript has been read and accepted for the Graduate Faculty in Chemistry in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

1 June 1976.
date

Robert Engel
Chairman of Examining Committee

6/15/76
date

Leonard H. Schwartz
Executive Officer

Howard H. Haubenstock

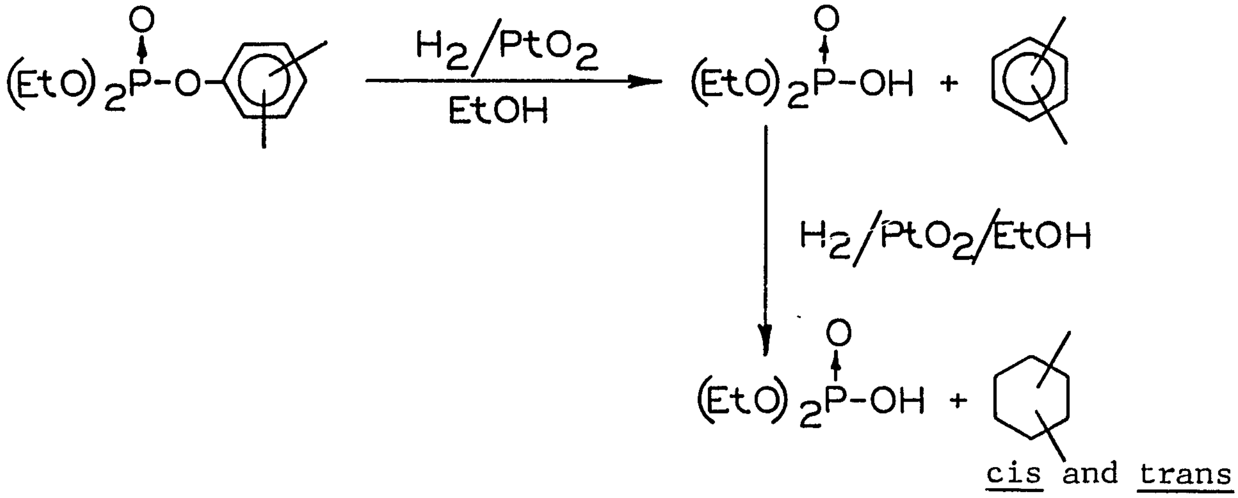
Klaus G. Grohmann

David C. Locke
Supervisory Committee

The City University of New York

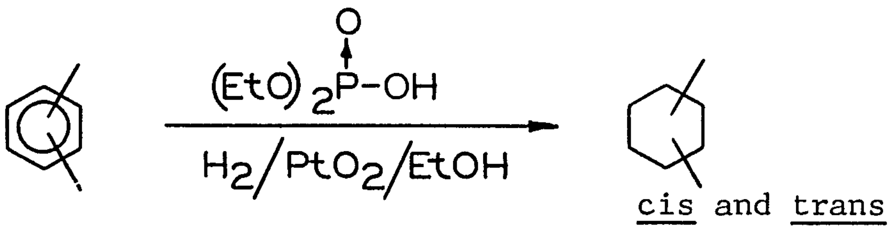
ABSTRACT

The platinum catalysed hydrogenolysis reduction of both aryl and enol phosphate esters has been investigated in order to determine the sequence of steps leading to formation of saturated hydrocarbon and phosphoric acid products. It was found that the catalysed reaction of aryl phosphates proceeded by initial formation of arene and phosphoric acid, followed by reduction of the arene to saturated hydrocarbon. (Scheme I)



Scheme I

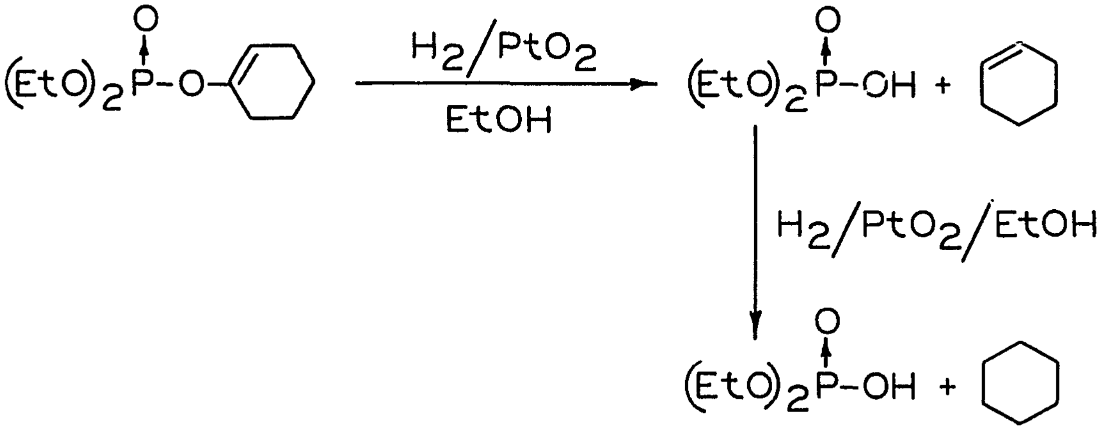
The course of intermediate formation of arene, followed by decay yielding saturated hydrocarbon has been followed and the stereoregularity of the reduction process has been investigated and compared to the reduction of arene when subjected to facilitated reaction conditions. (Scheme II)



Scheme II

The products obtained from the facilitated reduction are in the same proportion as those products obtained from the hydrogenolysis-reduction of aryl phosphates. The isolation of aromatic intermediate from the hydrogenolysis reaction is significant, not only for elucidation of the reaction mechanism, but also for synthetic utility of the reaction; that is, since aryl phosphates are usually synthesized <u>via</u> the phenol,[1] the platinum catalysed hydrogenolysis permits removal of hydroxyl functions from aromatic rings under mild conditions, leaving the rings intact.

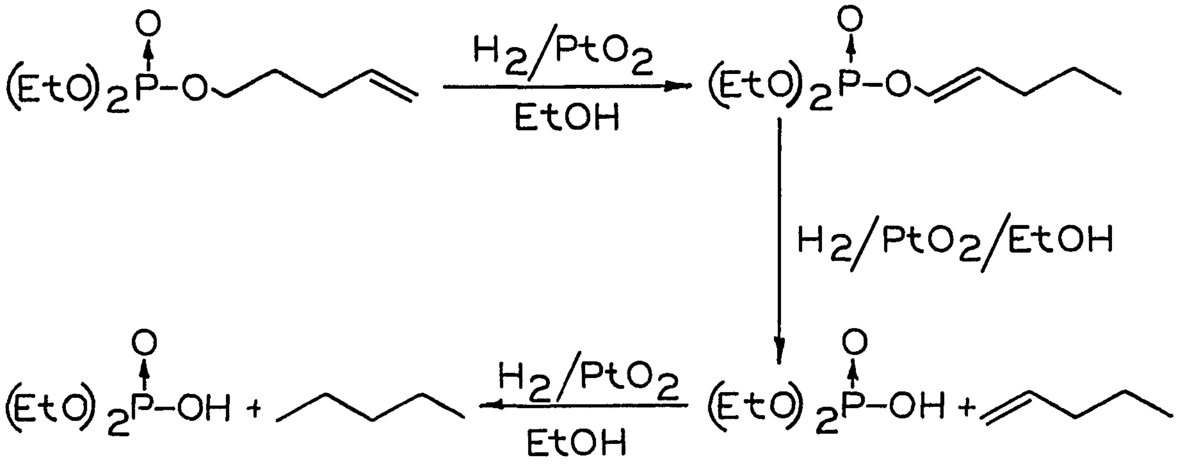
Investigation of the platinum catalysed reaction of enol phosphate esters, revealed, as in the case of aryl phosphate esters, that hydrogenolysis, liberating alkene and phosphoric acid, preceeded reduction of the unsaturated linkage. (Scheme III)



Scheme III

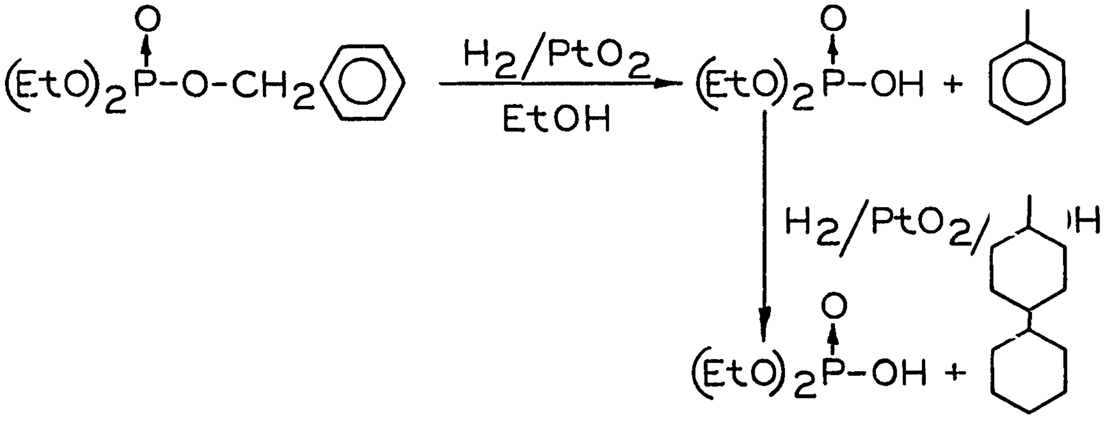
Since enol phosphates are synthesized <u>via</u> ketones or aldehydes,[2,3] it was thought that the reaction would be synthetically useful for the transformation of carbonyl function to olefins. However, olefinic products could not be isolated from the reaction mixture, presumably because the rate of olefin reduction significantly exceeds the rate of hydrogenolysis.

It has also been demonstrated that Adams catalyst promotes migration of "distant" olefinic linkages to sites subject to hydrogenolysis; (Scheme IV)



Scheme IV

benzylic phosphate esters are also hydrogenolysed over platinum oxide, but not homobenzylic esters. (Scheme V)



Scheme V

ACKNOWLEDGEMENTS

I wish to thank Professor Robert Engel whose patience, understanding, guidance, and continued faith in me, made my successful completion of the program of study possible.

Special thanks to the City University of New York for financial support.

TABLE OF CONTENTS

Page

History and Introduction

Results and Discussion

Experimental

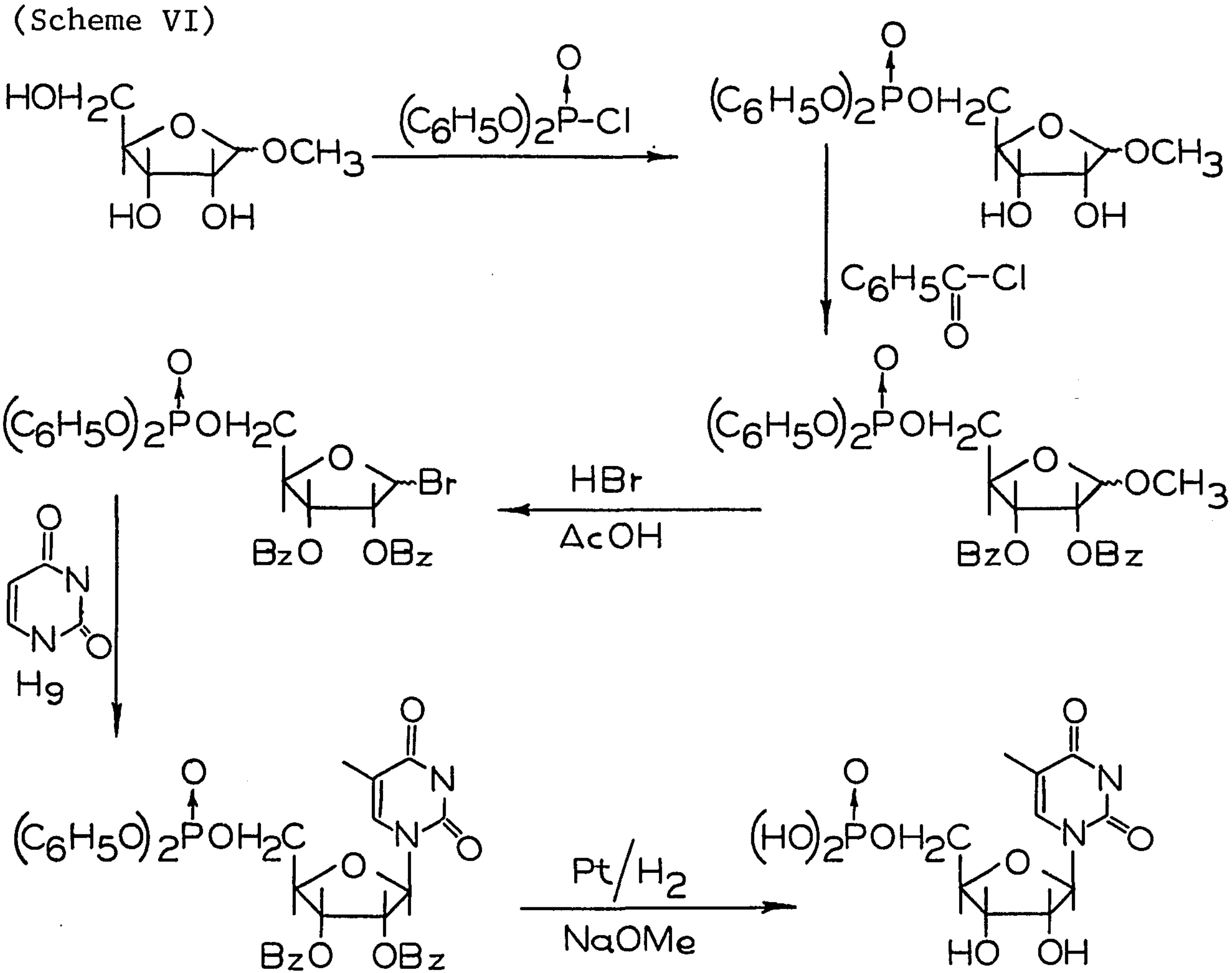
Synthesis

LIST OF FIGURES

LIST OF TABLES

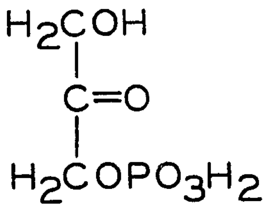
HISTORY AND INTRODUCTION

The use of phenyl and benzyl esters of phosphoric acid has been widely employed in the synthesis of complex phosphoric acid derivatives.[3,9] These groups protect potential acidic sites at phosphorus, while suitable transformations are performed to derivatize the molecule in other regions. When the necessary transformations are complete, the protecting phenyl or benzyl functions are removed by hydrogenolysis liberating the phosphoric acid. An example by Utika showing the utility of phenyl protecting groups with concommitant hydrogenolysis is in the synthesis of nucleotides.[10] (Scheme VI)



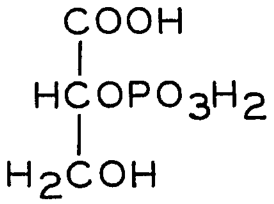
Scheme VI

Other examples involving the hydrogenolysis of phenyl protecting groups on phosphoric acids are found in the synthesis of dihydroxyacetone phosphate,[11] 2-phosphoryl D-glyceric acid,[12] glucosamine 3-phosphate[13] and saturated phosphatidic acids.[14] (Figure I)



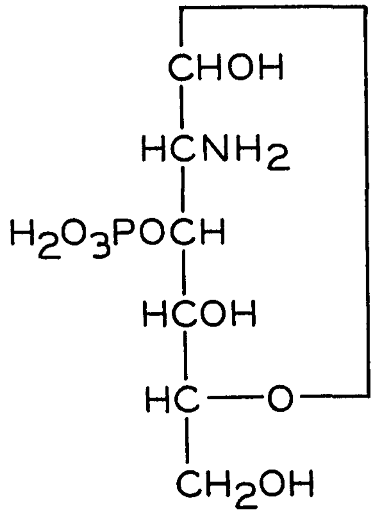
$$\begin{array}{c} H_2COH \\ | \\ C{=}O \\ | \\ H_2COPO_3H_2 \end{array}$$

Dihydroxyacetone
phosphate



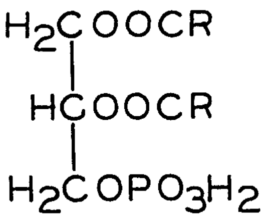
$$\begin{array}{c} COOH \\ | \\ HCOPO_3H_2 \\ | \\ H_2COH \end{array}$$

2-Phosphoryl-
D-glyceric acid



$$\begin{array}{c} CHOH \\ | \\ HCNH_2 \\ | \\ H_2O_3POCH \\ | \\ HCOH \\ | \\ HC{-}O \\ | \\ CH_2OH \end{array}$$

Glucosamine
3-phosphate



$$\begin{array}{c} H_2COOCR \\ | \\ HCOOCR \\ | \\ H_2COPO_3H_2 \end{array}$$

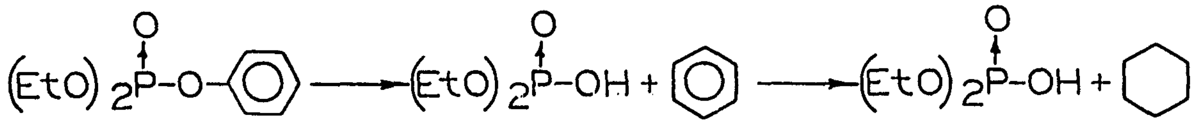
Phosphatidic
acid

Figure I

Despite the importance and utility of the hydrogenolysis reaction in phosphate synthesis, little attention has been given to the study of the mechanism by which hydrogenolysis of aryl phosphates occur, or to the hydrocarbon products which result from hydrogenolysis-reduction. From a review of the literature it appears that aside from phenyl phosphates, only m-acetamidophenyl[15] and p-nitrophenyl[16] esters have been used in this reaction. In the latter case it was presumed that hydrogenolysis-reduction yielded cyclohexylamine, although this was not definitively shown; upon hydrogenolysis-reduction, phenyl phosphates are reported to yield phosphoric acid and cyclohexane.

To rationalize the observed products of hydrogenolysis-reduction of phenyl phosphates (phosphoric acid and cyclohexane) several mechanisms might be envisioned.

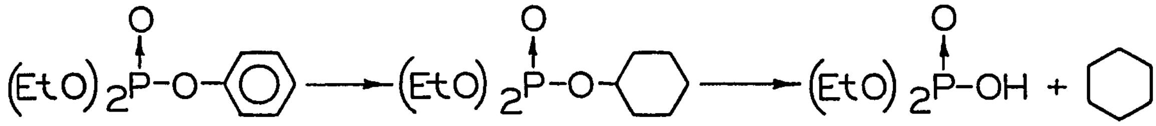
1) Initial cleavage of the aryl ester, yielding phosphoric acid and benzene, followed by reduction of the arene to cyclohexane. (Scheme VII)



Scheme VII

Cleavage without aromatic ring reduction is plausible as it is known that benzyl esters of carboxylic acids can be hydrogenolysed to carboxylic acids and toluene.[17] Moreover, aromatic hydrocarbons undergo facile reduction over Adams catalyst at low hydrogen pressures if a strong acid is present.[18,19]

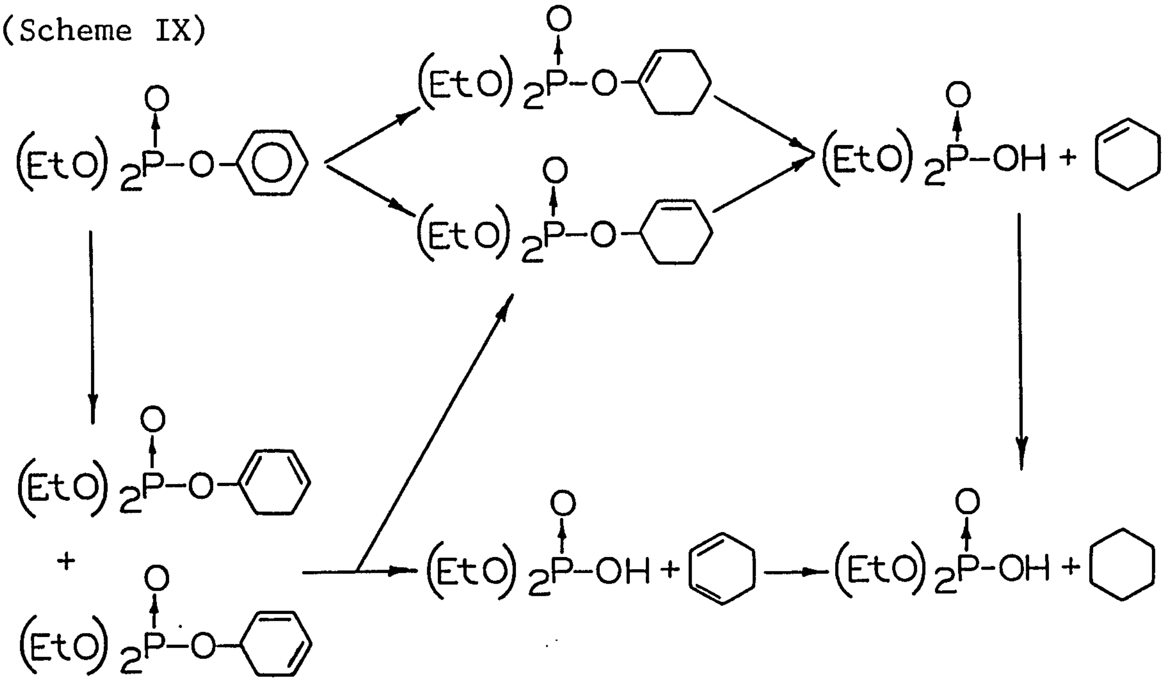
2) Prior reduction of the aromatic nucleus yielding a saturated phosphate ester, followed by hydrogenolysis liberating phosphoric acid and alkane. (Scheme VIII)



Scheme VIII

From the work of Brigl and Muller,[15] it was presumed by Kenner and Williams,[20] that the above mechanism accounted, at least in part, for the observed products of hydrogenolysis. It has subsequently been shown however, that aliphatic phosphate esters do not readily undergo the catalysed hydrogenolysis reaction.[21]

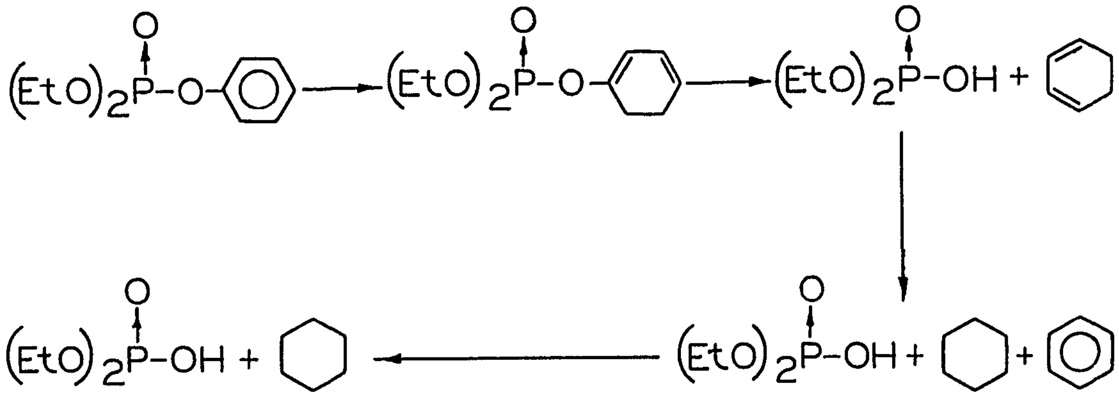
3) Prior partial reduction of the aromatic nucleus, followed by hydrogenolysis before complete reduction occurs. (Scheme IX)



Scheme IX

In addition to hydrogenolysis via the fully saturated ester, Kenner and Williams,[20] presumed that hydrogenolysis also took place by the above route. It is known that the reductive cleavage of aryl phosphates with sodium or lithium in liquid ammonia leads to olefin and phosphoric acid,[20,22] and enol phosphates are cleaved as well under similar conditions to yield olefin and phosphoric acid.[23] There is no precedence however, for the formation of cyclohexadiene from the cleavage of phenyl phosphate esters.

4) Prior partial reduction of the aromatic nucleus, followed by hydrogenolysis, rearomatization via disproportionation and finally reduction to saturated hydrocarbon. (Scheme X)



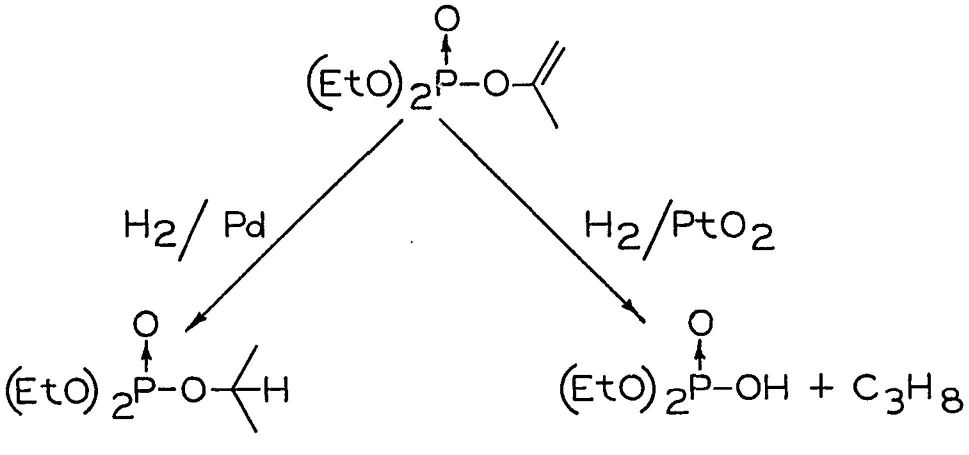
Scheme X

In studies on the disproportionation properties of various catalysts Freidlin observed that platinum promoted hydrogenation of cyclohexadiene to cyclohexane, whereas palladium favored disproportionation to benzene and cyclohexane.[24]

To gain information as to the sequence of steps involved in the mechanism, a complete series of diethyl xylyl phosphate esters was synthesized and subjected to hydrogenolysis over Adams catalyst, followed by identification and determination of the *cis* to *trans* ratios of the various dimethyl cyclohexanes produced. The product ratios from the two xylyl esters with methyl groups in an *ortho*-relationship were compared with one another as were the three xylyl esters with methyl groups in a *meta*-relationship. Similarly, two diethyl naphthyl phosphate esters were synthesized, subjected to hydrogenolysis and the ratios of *cis* to *trans* decalins measured. Comparison of the product ratios from each of the two sets of xylyl esters and the naphthyl esters provided information concerning the possibility of a common intermediate, which could only be accommodated by the first mechanism, Scheme VII. Comparison of the *cis* to *trans* ratios of the dimethyl cyclohexanes resulting from the facilitated hydrogenation of the xylenes was then made with the *cis* to *trans* ratios of the dimethyl cyclohexanes produced from hydrogenolysis-reduction of the corresponding diethyl xylyl phosphate esters, The diethyl naphthyl esters were similarly compared to the facilitated reduction of naphthalene. Close comparison of the product ratio data indicate that free xylene (naphthalene) is an intermediate in the hydrogenolysis of the aryl phosphate esters. Finally, direct evidence for the presence of xylene (naphthalene) was obtained by intercepting the reaction at various stages prior to completion, followed by analysis of the reaction mixture.

A more intensive examination of the conditions under which hydrogenolysis occurs revealed that the reaction may be useful in the synthesis of substituted aromatics with substitution pattern corresponding to the parent phenols (naphthols, etc.) from which the aryl phosphates are synthesized, but without the phenolic linkage.

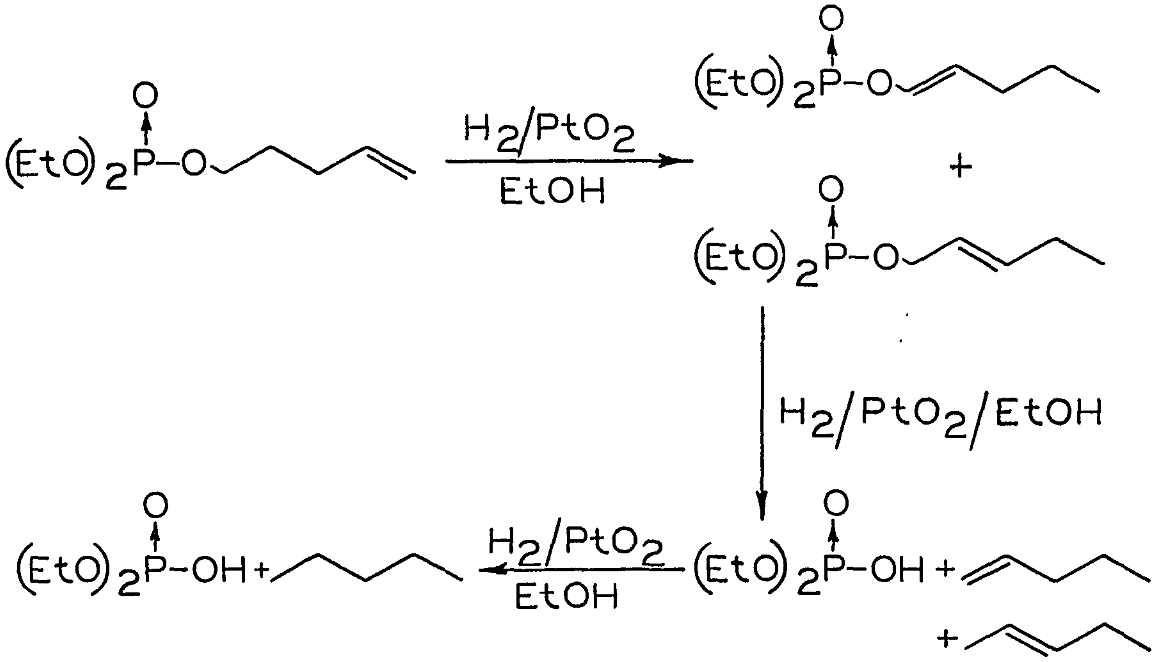
In contrast to the general use of phenyl phosphates in the hydrogenolysis scheme, only one example of enol phosphate hydrogenolysis could be found in the literature. Jacobsen reported that diethyl isopropenyl phosphate undergoes hydrogenolysis over platinum oxide yielding diethyl phosphate.[25] The hydrocarbon product, presumably propane was not identified; it was reported though that two moles of hydrogen were consumed in the reaction. When palladium was used as the catalyst, only one mole of hydrogen was absorbed and diethyl isopropyl phosphate was the observed product. (Scheme XI)



Scheme XI

In view of the cleavage of enol phosphate esters in sodium and liquid ammonia yielding olefin and phosphoric acid,[23] a reasonable extension for the hydrogenolysis with Adams catalyst would involve cleavage of the vinylic ester, yielding olefin and phosphoric acid followed by reduction of the double bond. Further, if the double bond were first reduced, an aliphatic phosphate ester would result, and aliphatic esters do not readily undergo the hydrogenolysis reaction.[21] It was of interest to pursue the study of hydrogenolysis of enol phosphates since this reaction could be of value in the synthesis of olefins or alkanes from carbonyl compounds, which are used in the preparation of enol phosphates, and if the generality of the reaction could be established, it would extend the already well-known scheme of aryl and benzyl phosphate hydrogenolysis. The reaction of enol phosphates is further discussed in the Results and Discussion section.

The migration of double bonds during catalytic hydrogenation is known to occur but difficult to detect unless isotopic tracers are used or special products result. Several workers have attempted to assess the activity of various catalysts to promote double bond migration,[26] and Bond and Wells have offered a mechanistic interpretation.[27] It was of interest to determine whether double bond migration would result under the conditions employed for aryl or enol phosphate hydrogenolysis, as this might aid in the determination of the site at which hydrogenolysis occurs. The migration of a "distant" olefinic linkage in phosphate esters could be assessed, since new products would be formed by hydrogenolysis as a result of migration. (Scheme XII)



Scheme XII

It should be noted, that the site of hydrogenolysis (vinylic or allylic ester) could not be determined. The hydrogenolysis of both vinylic and allylic oxygen is thought to occur, but because of double bond migration, difficult to determine. Attempts to prepare unsaturated tertiary esters of the type illustrated in Figure II proved fruitless.

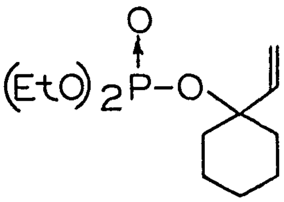


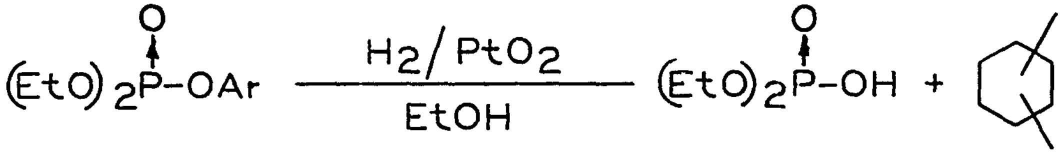
Figure II

It was noted however, that diethyl benzyl phosphate is readily hydrogenolysed, but not the homobenzylic ester.

RESULTS AND DISCUSSION

To determine the sequence of steps in the hydrogenolysis-reduction of aryl phosphates, the six isomeric diethyl xylyl phosphate esters and two naphthyl esters were synthesized and subjected to hydrogenolysis over Adams catalyst in absolute ethanol at pressures of one and four atmospheres of hydrogen. After 24 hours, the reaction was stopped, the reaction mixture filtered through Celite and the filtrate analysed by gas-liquid-chromatography (glc). The overall yield and hydrocarbon product distribution data for these reactions are summarized in Table I. Evidence for a common intermediate in the hydrogenolysis-reduction for each of the two sets of xylyl esters, compounds (I and II) having methyl groups in an ortho-relationship, compounds (III - V) having methyl groups in a meta-relationship, and for the two naphthyl esters, compounds (VII - VIII), arises from the close correlation of product distribution data within each set of compounds under both sets of reaction conditions. The selectivity and specificity, as a function of substrate structure, shown in catalytic hydrogenations, is well documented; it is not likely then, that this close correlation of data within each set of compounds, under each reaction pressure, would exist if different intermediates were involved in the hydrogenolysis-reduction. Moreover, the above product distribution data are in agreement with the data obtained from the facilitated reduction of the

TABLE I



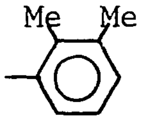
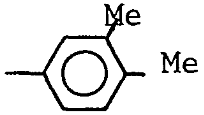
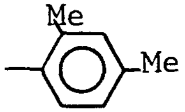
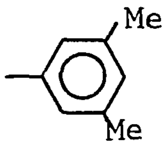
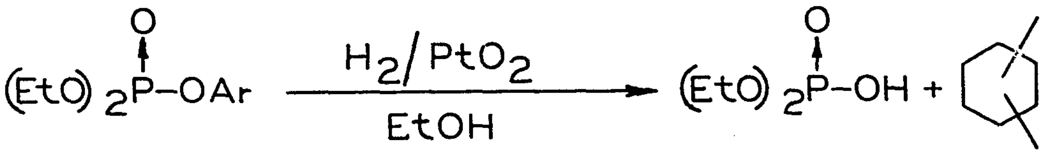
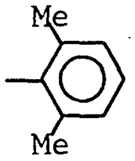
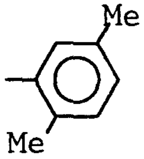
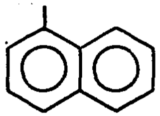
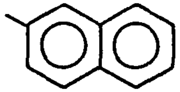
Ar	Compd	Rel % cis-HC[a]		Rel % trans-HC[a]		Overall HC yield,[b] %	
		1 atm H_2	4 atm H_2	1 atm H_2	4 atm H_2	1 atm H_2	4 atm H_2
	I	84.2	90.5	15.8	9.5	71.8	36.2
	II	83.2	90.0	16.8	10.0	75.2	27.8
	III	73.0	78.4	27.0	21.6	90.1	31.9
	IV	75.6	79.3	24.4	20.7	93.8	68.3

TABLE I (Cont.)



Ar	Compd	Rel % cis-HC[a]		Rel % trans-HC[a]		Overall HC yield,[b] %	
		1 atm H_2	4 atm H_2	1 atm H_2	4 atm H_2	1 atm H_2	4 atm H_2
	V	75.9	81.0	24.1	19.0	57.8	24.3
	VI	69.2	72.7	30.8	27.3	76.3	67.4
	VII	83.6	87.8	16.4	12.2	89.0	65.0
	VIII	82.3	85.0	17.7	15.0	76.6	65.3

[a] Dimethylcyclohexane for xylene reactions and decalin for naphthalene reactions.

[b] Average value for a reaction time of 24 hr

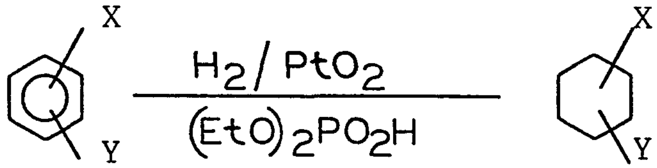
corresponding xylenes (naphthalene) over Adams catalyst. (Table II) This agreement between the hydrocarbon product distribution obtained from the hydrogenolysis-reduction of the diethyl xylyl (naphthyl) phosphate esters, with the product distribution obtained from the facilitated reduction of the free xylenes (naphthalene), is indicative of the intermediacy of free arene in the catalysed reaction of aryl phosphates. It should also be noted that the relative yields of reduced hydrocarbon are in agreement with the work of Shuetz and Caswell [19] on xylene reductions over Adams catalyst, and the distribution trends, as a function of pressure, are in accord with those observed by Siegel, *et al.*[28]

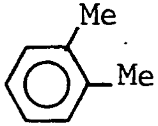
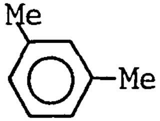
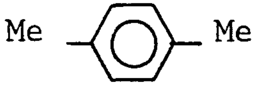
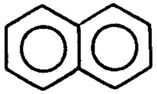
While the above data may be suggestive of the intermediacy of free arene in the hydrogenolysis of the diethyl aryl phosphates, the data do not definitively prove their existence. Definitive proof was obtained from the detection and isolation of the intermediates themselves in all cases except for diethyl 2,6-dimethylphenyl phosphate, Compound V. (The reaction of this compound is discussed later.)

The detection and isolation of xylene and naphthalene from hydrogenolysis of the aryl phosphates examined was accomplished by withdrawing samples from the medium during the course of the reaction *via* a syringe through a serum cap attached to a side arm of the reaction flask. Samples were immediately analysed by glc.

Analysis consisted of collection and identification of the intermediates, separated *via* glc, by comparison of their

TABLE II



	Rel % cis-HC[a]		Rel % trans-HC[a]		Overall yield[b], %	
	1 atm H_2	4 atm H_2	1 atm H_2	4 atm H_2	1 atm H_2	4 atm H_2
	87.4	89.1	12.6	10.9	100.0	98.4
	75.2	79.8	24.8	20.2	97.4	89.3
	67.4	74.9	32.6	25.1	100.0	100.0
		86.4		13.6		100.0

[a] Dimethylcyclohexane for xylene reactions and decalin for naphthalene reactions. [b] Average value for a reaction time of 24 hr.

spectral properties with the spectral properties of authentic samples, in addition to comparison of the retention times of authentic samples. Figures III - VIII graphically represent the formation and decay of intermediate arene, along with the formation of reduced hydrocarbon. As observed in each figure, maxima in arene concentration were obtained within 1-2 hours of commencement of the hydrogenolysis. For the xylyl esters these maxima ranged between 8 and 30% of the initial concentration of reactant; for the naphthyl esters the maxima were about 8% of initial concentration of reactant.

The diethyl 2,6-dimethylphenyl phosphate, exhibited anomalous behavior in the catalytic reduction scheme in that intermediate xylene was never observed, although its intermediacy was indicated by the stereochemical data from the 1,3-dimethyl cyclohexane produced. That is, the product ratio data for the diethyl 2,6-dimethylphenyl phosphate system correlates well with the data obtained from the two other xylyl phosphate esters with methyl groups in a meta-relationship and with the product ratio data obtained from the reduction of meta-xylene. (See Tables I and II). The anomalous behavior of Compound V, can be rationalized if it is presumed that hydrogenolysis of the ester linkage is slow compared to that for other esters investigated due to steric crowding by the two adjacent methyl groups. The meta-xylene once formed, reduces at

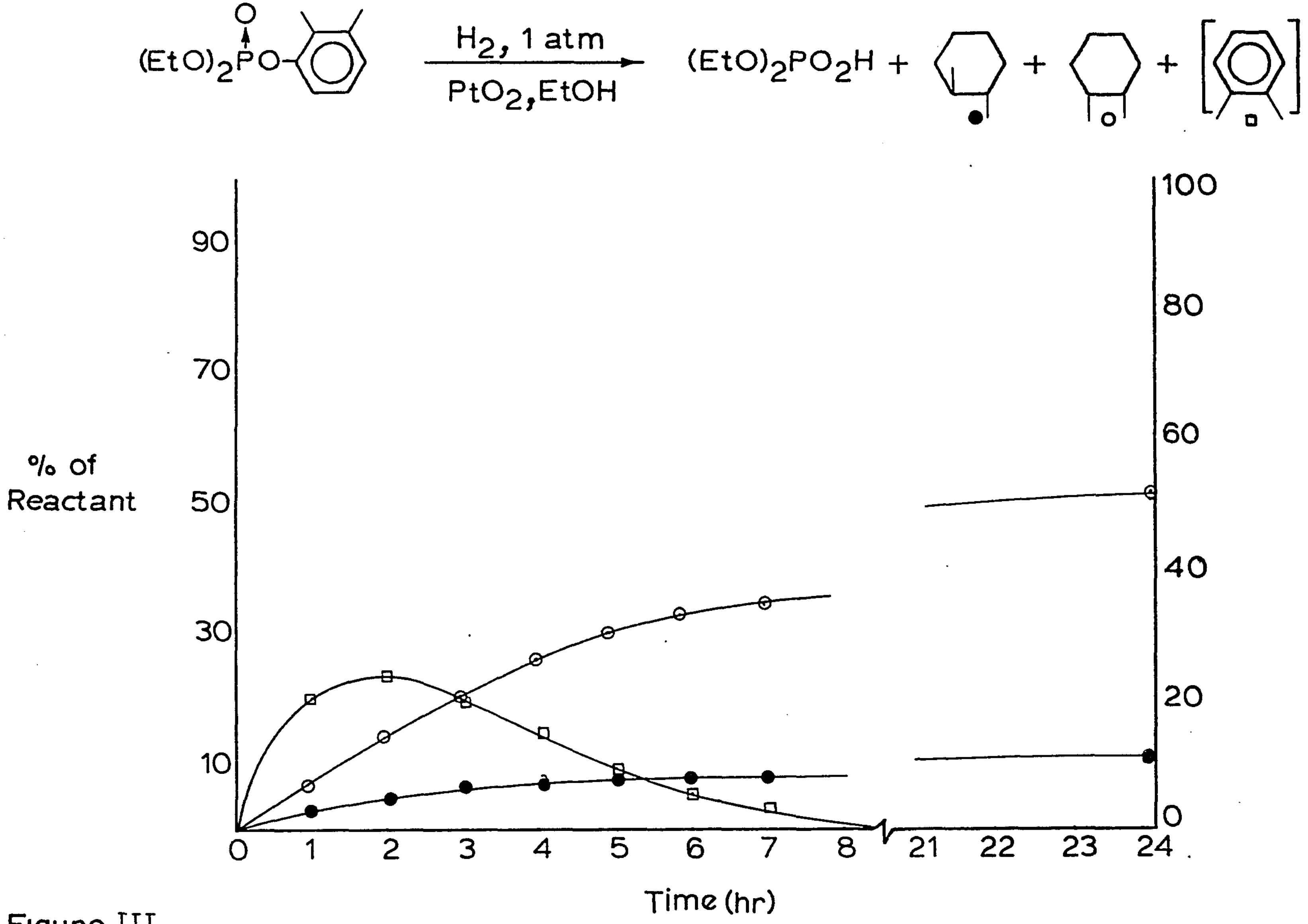

(EtO)2PO(→O)-
H2, 1 atm
PtO2, EtOH
(EtO)2PO2H +
+
+
% of Reactant
90
70
50
30
10
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
21
22
23
24
Time (hr)

Figure III

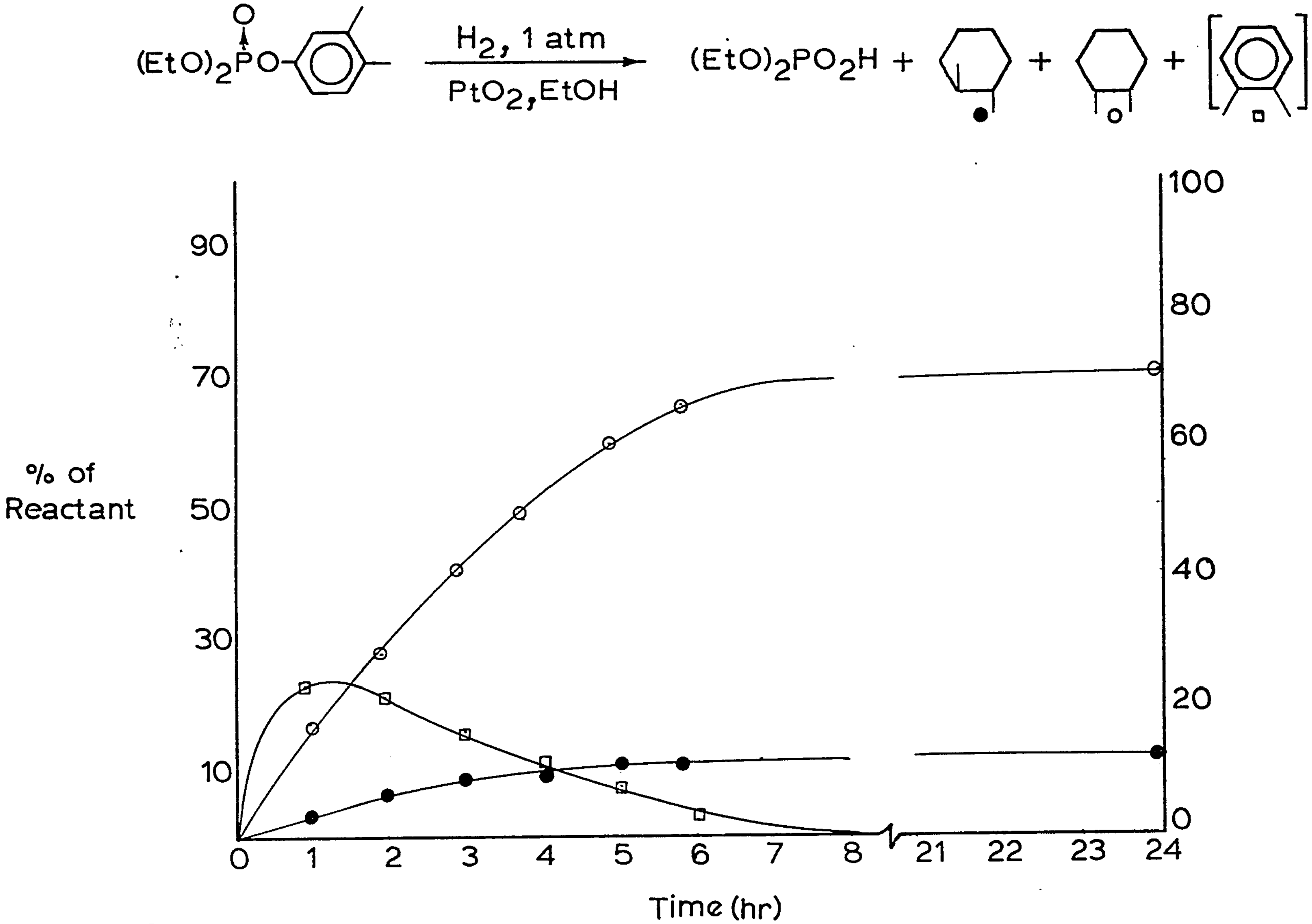

(EtO)$_2$P(O)O–
H$_2$, 1 atm
PtO$_2$, EtOH
(EtO)$_2$PO$_2$H +
+
+
●
○
□
% of Reactant
90
70
50
30
10
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
21
22
23
24
Time (hr)

Figure IV

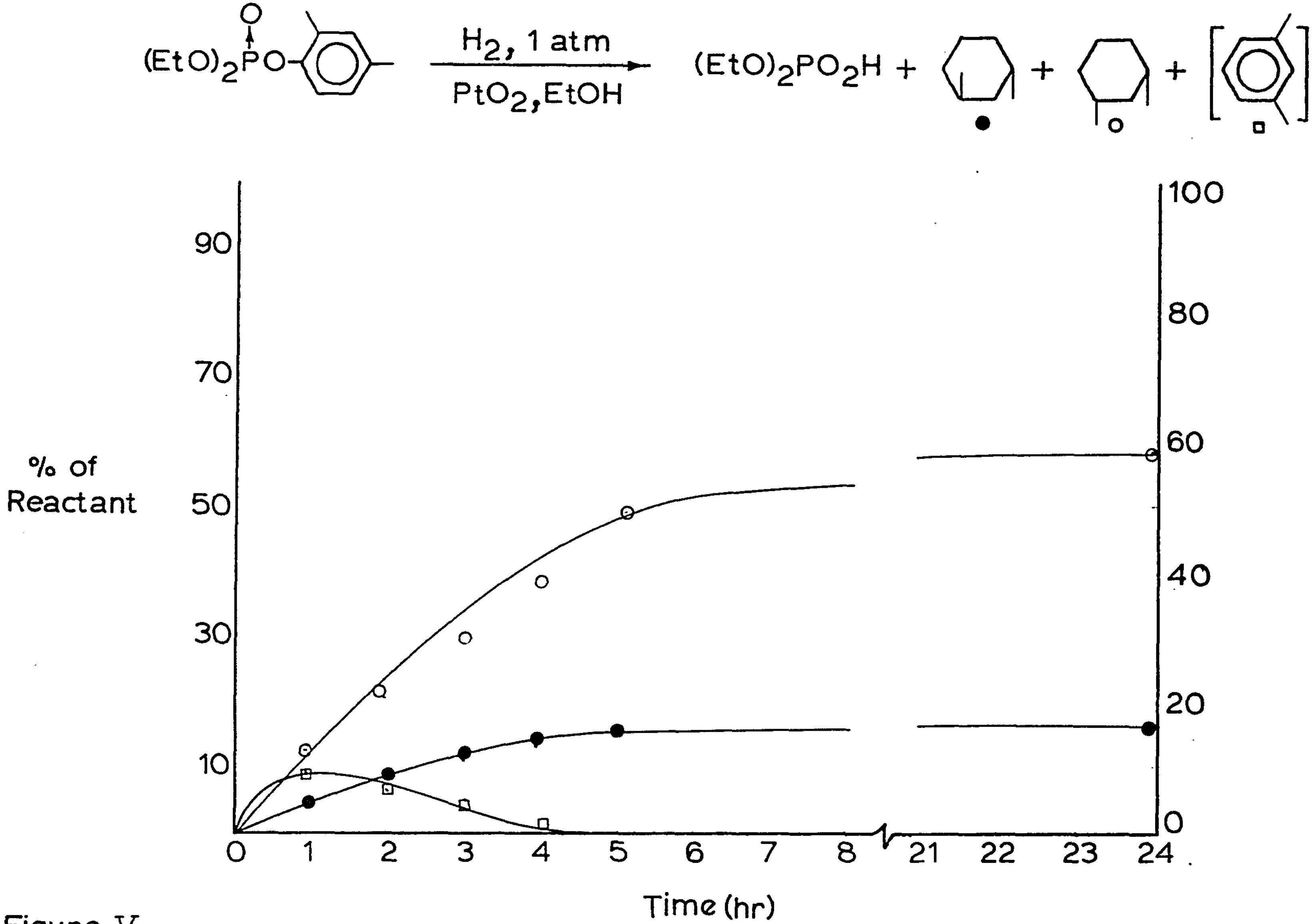

(EtO)$_2$PO-
H$_2$, 1 atm
PtO$_2$, EtOH
(EtO)$_2$PO$_2$H +
+
+
●
○
□
% of Reactant
90
70
50
30
10
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
21
22
23
24
Time (hr)

Figure V

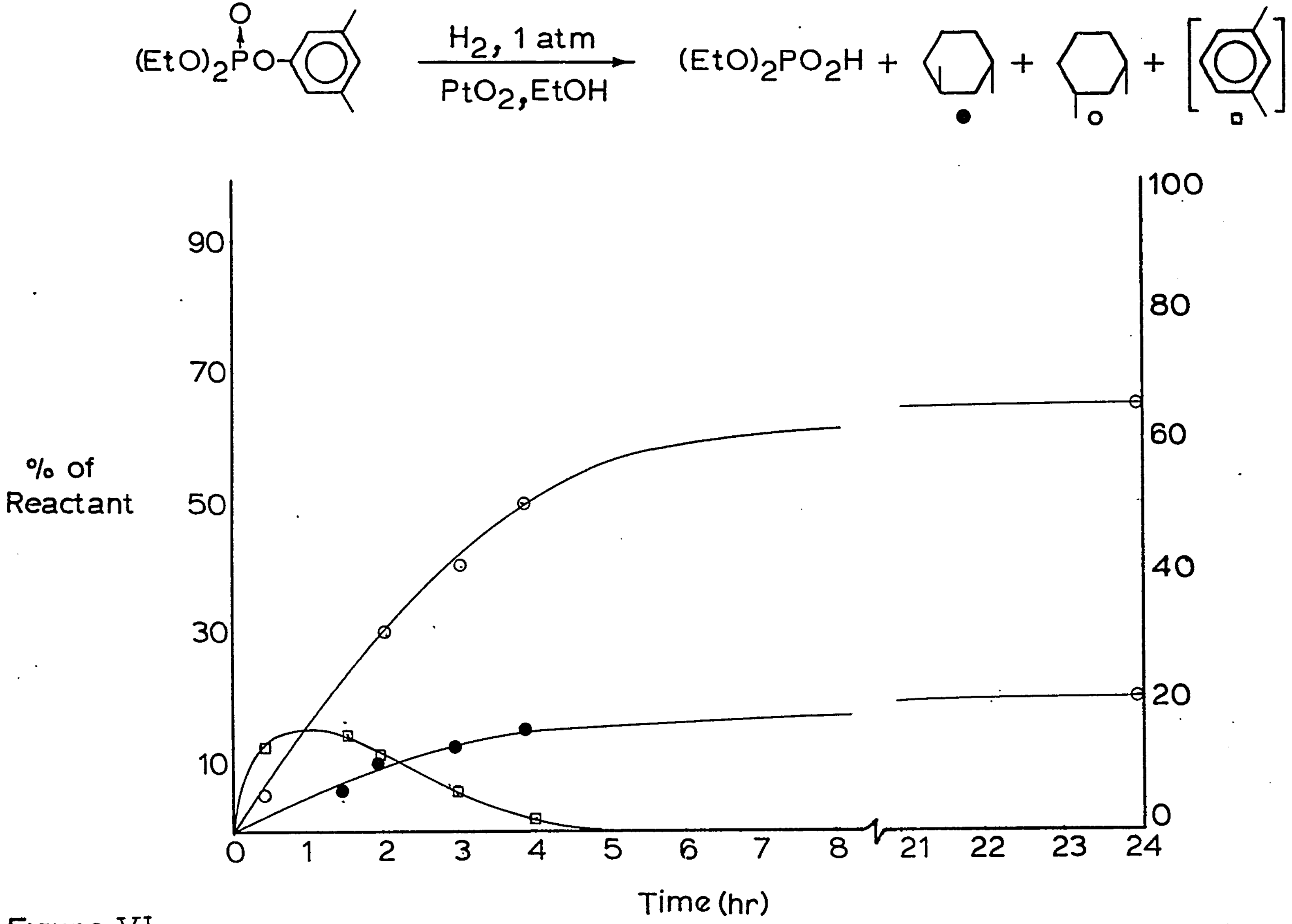

(EtO)2PO
O
H2, 1 atm
PtO2, EtOH
(EtO)2PO2H +
+
+
% of
Reactant
90
70
50
30
10
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
21
22
23
24
Time (hr)

Figure VI

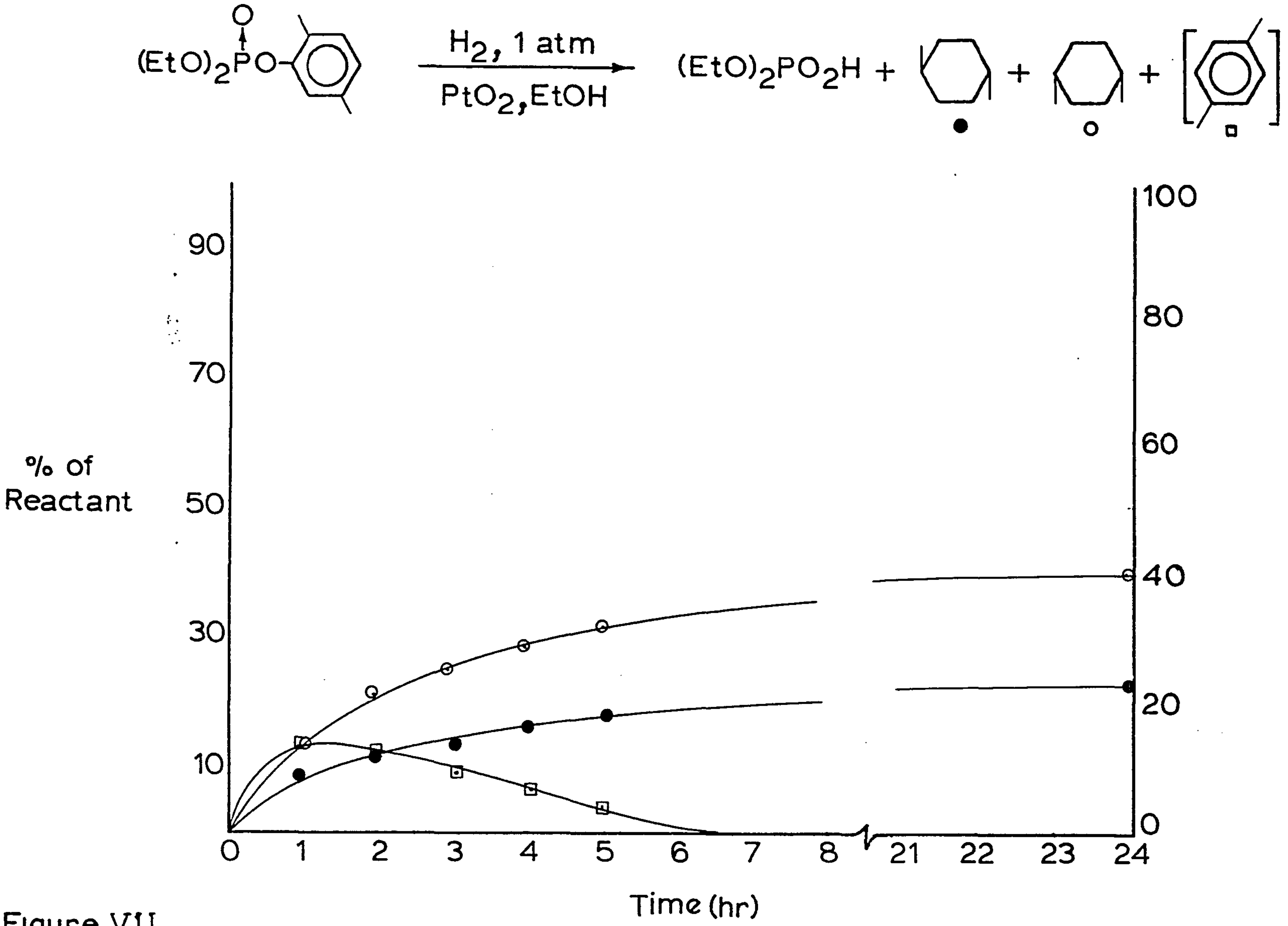
(EtO)$_2$P(O)O-
H_2, 1 atm
PtO_2, EtOH
$(EtO)_2PO_2H$ +
●
○
□
% of Reactant
90
70
50
30
10
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
21
22
23
24
Time (hr)

Figure VII

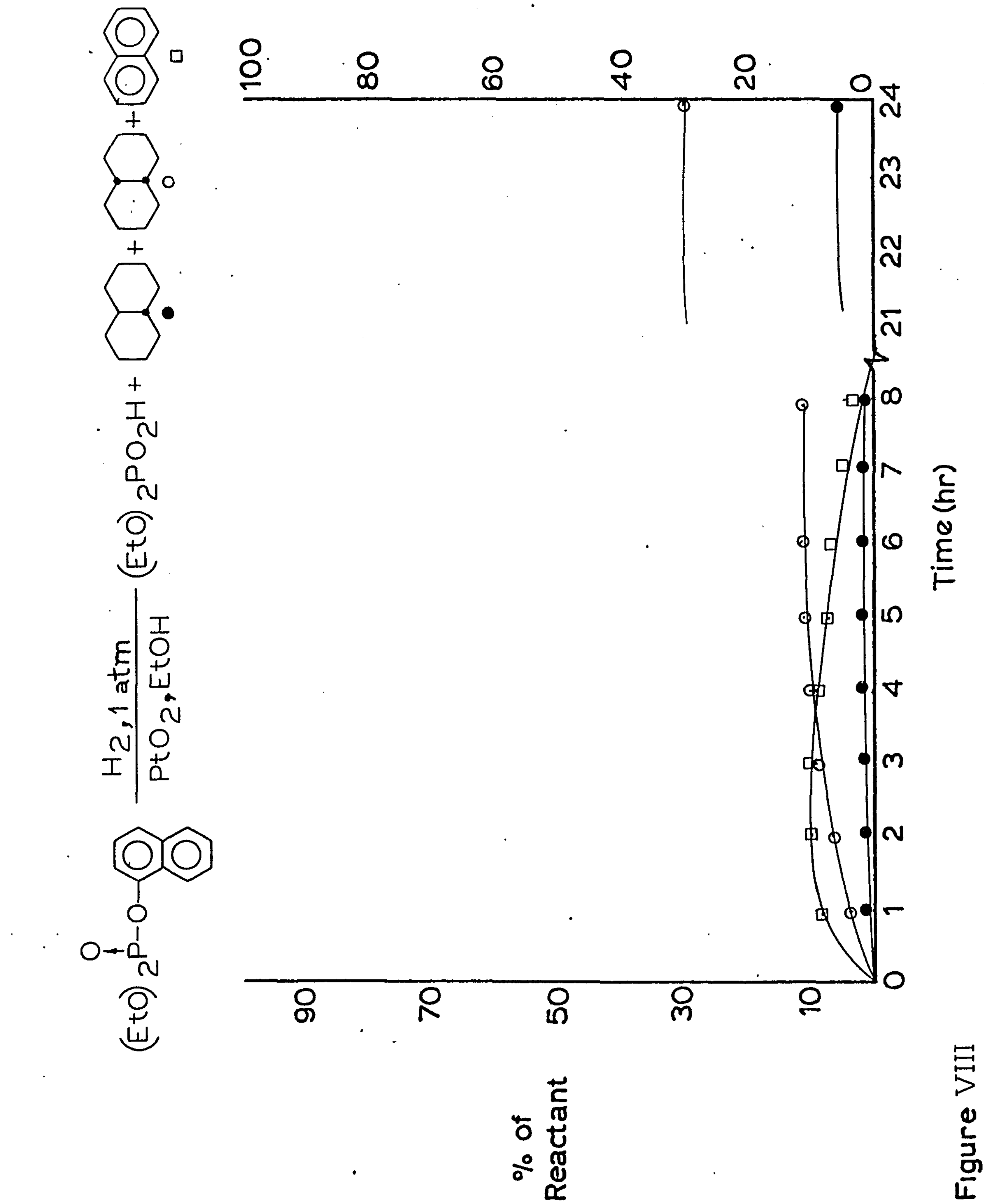

(EtO)2P(O)–O–naphthyl
H2, 1 atm
PtO2, EtOH
(EtO)2PO2H +
●
+
○
+
□
% of Reactant
90
70
50
30
10
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
21
22
23
24
Time (hr)

Figure VIII

the same rate as meta-xylene derived from any other source. Apparently, the rate limiting step for all other systems investigated is reduction of arene; for Compound V, the opposite situation holds. Thus a detectable concentration of xylene is never present; the overall low yield of saturated hydrocarbon for this system is also in agreement with these conclusions. Here, reduction of the aromatic ring of the ester is in competition with hydrogenolysis and evidence for the reduced ester, diethyl 2,6-dimethyl cyclohexyl phosphate has been observed. When Compound V was hydrogenolysed using cyclohexane as solvent, meta-xylene was obtained in significant quantity. Evidently, in cyclohexane solvent, hydrogenolysis proceeds smoothly, but reduction is retarded. This makes cyclohexane an interesting solvent for use when hydrogenolysis is desired but when reduction is to be avoided.

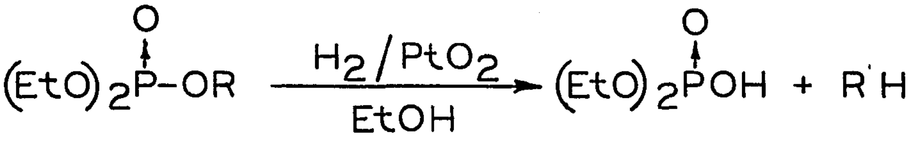
Observations made on the physical appearance of the catalyst in ethanol and cyclohexane solvents during the hydrogenolysis provided a clue to the understanding of this behavior. In ethanol, the finely dispersed catalyst initially coagulates as arene is formed, but upon completion of the reduction the finely dispersed catalyst is regenerated. In cyclohexane solvent, the finely dispersed catalyst again initially coagulates as arene is formed. However, upon completion of the reduction, the catalyst congeals to an oil, which adheres to the sides of the flask and the finely dispersed catalyst is not regenerated.

This oil retains activity for hydrogenolysis but not for arene reduction, which makes it potentially useful for isolation of arenes.

During the investigation of aryl phosphate hydrogenolysis, diethyl 1-cyclohexenyl phosphate was synthesized and subjected to hydrogenolysis over Adams catalyst. The compound underwent facile hydrogenolysis-reduction yielding cyclohexane and diethyl phosphoric acid. It has previously been reported that diethyl 2-propenyl phosphate absorbed two moles of hydrogen over Adams catalyst yielding diethyl phosphoric acid.[25]

To test the generality of this reaction and to help in elucidating the sequence of steps leading to saturated hydrocarbon, a series of vinylic esters (Compounds IX - XIII) was prepared and subjected to hydrogenolysis over Adams catalyst at one and four atmospheres of hydrogen. The products and yields of the hydrogenolysis-reduction are given in Table III. With the exception of Compound IX, where a quantitative determination could not be made due to the volatilization of the product from the reaction mixture, quantitative or near quantitative cleavage of the vinylic ester group was observed, indicating the facile nature of the hydrogenolysis process as compared to other possible reactions, such as olefin reduction. Generalizing from the catalytic hydrogenolysis-reduction scheme of aryl phosphate esters, it might be presumed that hydrogenolysis of the vinylic ester linkage preceeded

TABLE III



$$(EtO)_2\overset{O}{\overset{\uparrow}{P}}\text{-}OR \xrightarrow[EtOH]{H_2/PtO_2} (EtO)_2\overset{O}{\overset{\uparrow}{P}}OH + R'H$$

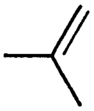
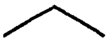
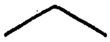
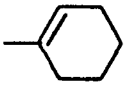
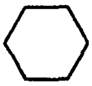
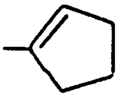
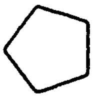
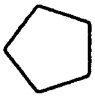
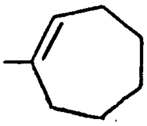
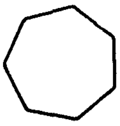
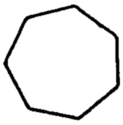
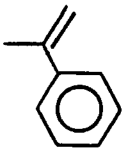
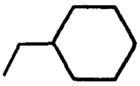
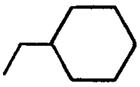
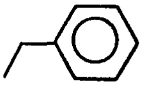
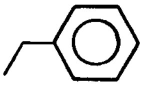
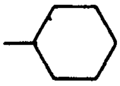
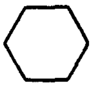
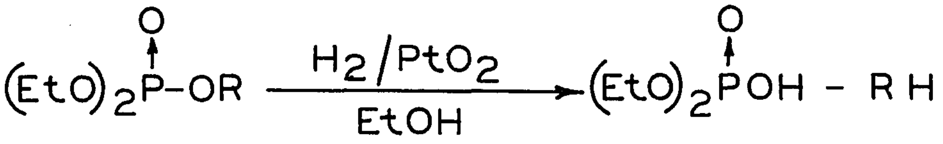
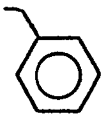
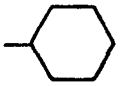
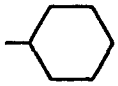
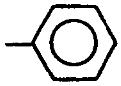
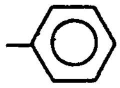
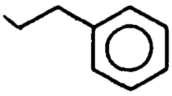
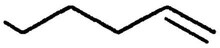
R	Compd	Yield RH (24 hr. reaction time),[a]%			
		1 atm H_2		4 atm H_2	
	IX		15[b]		6[b]
	X		97.6		100.0
	XI		97.3		100.0
	XII		96.7		100.0
	XIII		5.6		100.0
			94.4		0
	XIV		0[c]		5[c]

TABLE III



$$(EtO)_2\overset{O}{\overset{\uparrow}{P}}\text{-OR} \xrightarrow[EtOH]{H_2/PtO_2} (EtO)_2\overset{O}{\overset{\uparrow}{P}}OH - RH$$

R	Compd	Yield RH (24 hr. reaction time),[a]%			
		1 atm H_2		4 atm H_2	
	XV		8.6		86.0
			60.0		1
	XVI	No hydrocarbon product			
	XVII		5.0		1

[a] Yields as measured by glc using a calibrated internal reference. [b] Quantities as determined by glc; these represent minimum values as significant amounts of material are lost due to volatilization of product during isolation. [c] One week reaction time.

saturation of the olefin, and attempts were made to observe and isolate any olefinic hydrocarbon intermediate. Collection of the entire region of expected glc elution was performed, and the collected effluent was subjected to mass spectral analysis; no olefinic material could be observed. Changing the solvent to a saturated hydrocarbon, useful in slowing the reduction of aromatics, again proved unsuccessful. The conclusion was, that either the olefin was not an intermediate, or it was formed in only low concentration and reduced to alkane at a high rate. Several experiments were performed to consider these possibilities.

First, in consideration of the possibility of initial reduction of the vinylic phosphate, followed by hydrogenolysis, diethyl cyclohexyl phosphate XIV, was prepared and subjected to identical reaction conditions as used for the other vinylic compounds. After one week, at one atmosphere of hydrogen, no cleavage product could be detected and the ester was recovered unchanged; after one week at four atmospheres of hydrogen pressure only 5 percent cleavage to cyclohexane could be observed. From this result it was concluded that initial reduction of the vinylic ester followed by hydrogenolysis does not occur.

Second, in consideration of the possibility that free alkene is an intermediate, but present in low concentration during the reaction, several experiments were performed using deuterium in deuterated alcohol (CH_3OD, CD_3OD, CH_3CH_2OD) and cyclohexane solvents.

Evidence of an indirect nature was gathered. With these solvents, in the presence of Adams catalyst, it was observed that the alkenes considered as intermediates undergo deuterium exchange in excess of that expected by saturation of the double bond. This observation correlates with the work of Pearlman, et al.[29] and Fukershima, et al.[30] where excess deuterium incorporation is accounted for by double bond migration via exchange with allylic hydrogens. When saturated hydrocarbon (cyclohexane) was subjected to the conditions of hydrogenolysis, with deuterium in deuterated solvents, no deuterium incorporation could be observed using mass spectral analysis.* Were the hydrocarbon product of hydrogenolysis-reduction of the vinylic esters to show deuterium incorporation of more than three atoms, it could be indicative of alkene intermediacy. For Compound X studied in CH_3OD and CD_3OD solution, use of deuterium resulted in cyclohexane product exhibiting up to seven atoms of deuterium in significant amount. Similarly, with Compound XII, studied in cyclohexane solution, incorporation of up to seven atoms of deuterium in significant amount was observed in the cycloheptane product.

---

*This result is also of significance in the reduction of xylenes to cis-trans-dimethyl cyclohexanes, since it precludes the possibility of isomerization in saturated hydrocarbons. That isomerization does not occur in the dimethyl cyclohexane products is also inferred by the large deviation of cis to trans product ratio data obtained from the reduction to the calculated thermodynamic equilibrium values.[42]

It is critical to note that excess deuterium incorporation can only arise with the alkene itself or a "cleaved alkene-catalyst" complex, since mass spectral analysis of unreacted vinyl phosphate ester, after hydrogenolysis was allowed to proceed to 20% completion, exhibited no deuterium incorporation. These data indicate that the overall mechanism of reaction involves first hydrogenolysis of the vinyl ester linkage, unaccompanied by hydrogen exchange, yielding alkene and the phosphoric acid. The alkene, accompanied by catalyst mediated hydrogen exchange, is then reduced to alkane.

The absence of deuterium incorporation into the vinylic ester is worthy of note; the ester undergoes facile hydrogenolysis, but is stable to both reduction and hydrogen exchange. Since catalyst mediated hydrogen exchange occurs with ordinary olefinic linkages, it was thought that a "distant" olefinic linkage in an alkenyl phosphate ester might be induced to migrate to a position from which cleavage would occur. To test this possibility, diethyl 5-pent-1-eneyl phosphate (XVII) was synthesized and subjected to the standard hydrogenolysis conditions. It was found that cleavage, yielding pentane does occur, although only to a low extent, the remaining material being the reduced phosphate ester; migration is competitive with reduction. The question arises as to the location of the site of unsaturation if cleavage is to occur. That vinyl phosphate esters undergo hydrogenolysis without isomerization is shown by the cleavage of diethyl isopropenyl phosphate and by the absence of deuterium incorporation into unreacted vinyl phosphate ester. However, this does not eliminate the possibility that a more distant olefinic site may also be subject to hydrogenolysis; compounds containing allylic or benzylic linkages are subject to hydrogenolysis over palladium catalysts.[31-37] Efforts to investigate the hydrogenolysis of primary and secondary allylic phosphate ester over platinum oxide seemed rather pointless since these esters are capable of both hydrogen exchange and isomerization prior to and after hydrogenolysis, giving no significant data. Tertiary allylic esters, which would be of value in these experiments, are exceedingly susceptible to both acid catalysed fragmentation and thermal rearrangements.[38-41] Both the fragmentation and rearrangement products are the same as the products of hydrogenolysis, and thus the two routes would be indistinguishable from one another.

Palladium has been shown to be an effective catalyst for hydrogenolysis of benzylic ester linkages, but platinum has only rarely been used. When diethyl benzyl phosphate was subjected to hydrogenolysis conditions over Adams catalyst, rapid hydrogenolysis leading to toluene and methyl cyclohexane was observed. The homobenzylic ester however did not cleave to any measurable extent and only ring reduced ester could be found. As with tertiary allylic phosphate esters, attempts to investigate tertiary benzylic phosphate esters again proved fruitless, due to their thermal and acid catalysed instability.

EXPERIMENTAL

Reagents

1,2-Dimethyl phenol, 1,3-Dimethyl phenol, 1,4-Dimethyl phenol, 2,3-Dimethyl phenol, 2,4-Dimethyl phenol, 2,6-Dimethyl phenol, 1-Hydroxy-naphthalene, 2-Hydroxy-naphthalene, 4-Pentene-1-ol, 2-Phenyl ethanol, o-Xylene, m-Xylene, p-Xylene, 1,2-Dimethyl cyclohexane, 1,3-Dimethyl cyclohexane, 1,4-Dimethyl cyclohexane (Aldrich Chemical Co.) were used without further purification.

Diethyl chlorophosphate (Aldrich Chemical Co.) was distilled prior to use bp. 59-61°/2 Torr

Chloroacetone (Aldrich Chemical Co.) was distilled prior to use bp. 119-120°/760 Torr

Cyclopentanone, Cyclohexanone, Cycloheptanone, Cyclohexanol, Benzyl alcohol (J.T. Baker Chemical Co.) were used without further purification.

Benzene, Diethyl ether (J.T. Baker Chemical Co.) were stored over sodium ribbon prior to use.

α-Chloroacetophenone (Pfaltz and Bauer, Inc.) was used without further purification.

Triethyl phosphite (Pfaltz and Bauer, Inc.) was distilled prior to use bp. 65°/3 Torr.

Cyclohexane, Toluene, Methyl cyclohexane (Matheson, Coleman and Bell) were used without further purification.

Chlorine, Deuterium (Matheson Corp.) were used without further purification.

Cycloheptane, Cyclopentane (Chem. Service Inc.) were used without further purification.

Deuterio Methanol - (d_4), Deuterium Oxide (Stohler Isotope Chemicals) were used without further purification.

Hydrogen (Union Carbide Corp.) prepurified grade was used without further purification.

Absolute Ethanol (Commercial Solvents Corp., "Gold Shield") was used without further purification.

Sodium hydride (Alfa Inorganics) 57% oil dispersion was washed three times with anhydrous ether and then dispersed in anhydrous benzene.

Platinum oxide (83±0.5% Lot No. 98 and 104) Engelhard Minerals and Chemical Corp.) was used without further purification.

Instrumentation

Gas-liquid chromatography was performed with a Varian Aerograph Model 90-P instrument equipped with a thermal conductivity detector. Columns were prepared from ¼ inch (O.D.) copper tubing and were 5 feet in length unless otherwise specified. Two different packing materials were used:

1. 20% Apiezon L on Chromosorb W (60/80 mesh)
2. 20% Carbowax 20M on Chromosorb W (60/80 mesh)

Conditions for gas-liquid chromatography will be presented in the following abbreviated form. (5 ft. column, 20% Apiezon L/Chromosorb W, 180°/80°, 100 ml./min); indicating that a 5 foot x ¼ inch (O.D.) copper column packed with 20% Apiezon L on Chromosorb W (60/80 mesh), at an injection temperature of 180°, a furnace temperature of 80° and helium flow rate of 100 ml/min. was used.

NMR spectra were measured using Varian EM-360 and Varian A 60-A spectrometers. Spectra were obtained on either neat samples or in carbon tetrachloride solution at a probe temperature of 37°C.

Infrared spectra were measured on 2-5% solutions in carbon tetrachloride using a Perkin Elmer Model 237B or Beckman Model 20 spectrometer. Polystyrene film was used for calibration.

Mass spectra were measured using a Varian MAT CH-7 instrument and calibrated against perfluorokerosene.

One atmosphere hydrogenation apparatus was a standard

Fieser-Hershberg apparatus, equipped with manually operated leveling bulbs to maintain atmospheric pressure. A reaction flask bearing a side arm fitted with a serum cap was used in order that samples could be removed for analysis during the course of the reaction. The reaction mixture was stirred throughout the reduction using a magnetic stirrer.

Four atmosphere hydrogenations were performed using a standard Parr apparatus equipped with a mechanical shaker. The pressure was adjusted manually to maintain four atmospheres of pressure.

Integration of glc peak areas was accomplished using a compensating polar planimeter (Gelman Instrument Co. Model 39231) by making three consecutive passes over each chart peak and averaging the values obtained.

Elemental analyses were performed by Schwar zkopf Microanalytical Laboratories, Woodside, N.Y.

Quantitative Analysis of Reaction Mixtures:

Gas-liquid chromatography was employed as the method of quantitative analysis. All products and intermediates were compared for relative response to an internal standard; chart areas were measured using a compensating planimeter. The following example demonstrates the method of quantitation.

Response Factor Determination:

A known weight of internal standard (ca. 0.01 M) and reaction product (ca. 0.01 M) obtained from an external source, were brought up in 25 ml of absolute ethanol. Approximately four microliters were injected into the gas chromatograph and the area under the peaks measured. A response ratio factor was determined according to the following:

$$\text{Response Factor} = \frac{\text{Area of Standard}}{\text{Area of Rx Product}} \times \frac{\text{Weight of Rx Product}}{\text{Weight of Standard}}$$

A response factor was determined for every intermediate and product obtained from the reaction mixtures.

Product Ratio Data: The relative quantity of each product obtained from the reaction mixture was compared to an internal standard as follows:

$$\text{Weight of Product} = \frac{\text{Area of Product}}{\text{Area of Standard}} \times \text{Weight of Standard} \times \text{Response Factor}$$

All products obtained from a single reaction were related to the same internal standard.

Procedure

Atmospheric Pressure Hydrogenation of Aryl Phosphates. (Identification and Isolation of Products)

A reaction flask, fitted with a serum cap over a side arm, was charged with 25 ml absolute ethanol, a known amount of the phosphate ester (ca. 0.020 M) to be investigated and a known amount of internal standard (ca.0.020 M). To this was added 50 mg of Adams catalyst and magnetic stirring bar. After placing the flask on the hydrogenation apparatus, the entire system was evacuated followed by filling with hydrogen. This flushing procedure was performed three times before finally filling the system with hydrogen to one atmosphere and starting the magnetic stirrer. As the reaction proceeded and hydrogen was consumed, the system was maintained at one atmosphere of pressure by manual adjustment of the leveling bulbs attached to the Fieser-Hershberg apparatus. After 24 hrs., the total volume of hydrogen consumed was noted, the system evacuated and then opened to the atmosphere. The reaction solution was filtered through Celite prior to analysis.

Analysis consisted of:

1) separation and collection of the products by glc (5 ft. column, 20% Apiezon L/ Chromosorb W, 170°/72° 120 ml/min.) followed by NMR, infrared, and mass spectral analysis for each of the materials collected, and comparison of this data with that obtained from authentic samples.

2) comparison of the retention times of the products from the reaction with the retention times of authentic samples.

The products and product ratios, along with the percentage yields for the reaction of aryl phosphates are summarized in Table I.

Atmospheric Pressure Hydrogenations of Aryl Phosphates. (Formation and Decay of Intermediates)

A reaction flask bearing a side arm fitted with a serum cap was charged with 25 ml of absolute ethanol, a known amount of the phosphate ester (ca. 1M) under investigation and known amount of internal standard (ca. 0.020 M). To this solution was added 50 mg. of Adams catalyst and a magnetic stirring bar. After placing the flask on the hydrogenation apparatus the entire system was evacuated followed by filling with hydrogen. This flushing procedure was performed three times before finally filling the system to one atmosphere of hydrogen and starting the magnetic stirrer. Samples (70 μl) of the reaction mixture were withdrawn through the serum cap *via* a syringe every hour after commencement of the reaction and immediately injected into the gas-liquid chromatograph for analysis. This procedure of withdrawing samples from the reaction mixture was continued until, upon glc analysis, only end product was observed. A final sample was then withdrawn 24 hrs. after commencement of the reaction and analysed.

Analysis consisted of:

1) separation and collection of the intermediates and the products of the reaction by glc (5 ft. column, 20% Apiezon L/ Chromosorb W, 170°/70°, 120 ml/min.) followed

by NMR, infrared and mass spectral analysis for each of the materials collected and comparison of this data with the data of authentic samples.

2) comparison of the retention times of the intermediates and products of the reaction with the retention times of authentic samples.

The rates of formation and decay of both intermediates and products from the hydrogenolysis-reduction of aryl phosphates are shown in Figures III - VIII.

Atmospheric Hydrogenation of Xylenes. (Identification and Isolation of Products)

A reaction flask was charged with 25 ml absolute ethanol, a known amount of the xylene to be hydrogenated (ca. 0.020M), a known amount of internal standard (ca. 0.020M), and 0.010M in diethyl phosphoric acid. To this solution was added 50 mg platinum oxide and a magnetic stirring bar. After placing the flask on the hydrogenation apparatus, the entire system was evacuated.followed by filling with hydrogen. This flushing procedure was performed three times before finally filling the system with hydrogen to one atmosphere of pressure and starting the magnetic stirrer. As the reaction proceeded and hydrogen was consumed, the system was maintained at one atmosphere pressure by manual adjustment of the leveling bulbs attached to the Fieser-Hershberg apparatus. After 24 hrs., the total volume of hydrogen consumed was noted, the system evacuated and then opened to the atmosphere. The reaction solution was filtered through Celite prior to analysis.

Analysis consisted of:

1) separation and collection of the products of reduction by glc (5 ft. column, 20% Apiezon L/ Chromosorb W, 170°/70°, 120 ml/min.) followed by NMR, infrared and mass spectral analysis for each product collected and comparison of this data with the data of authentic samples.

2) comparison of the retention times of the products of reduction with the retention times of authentic samples. Products and product ratio data are listed in Table II.

Four Atmosphere Hydrogenation of Aryl Phosphates. (Identification and Isolation of Products)

A Parr reaction flask was charged with 25 ml absolute ethanol, a known amount of the phosphate ester (ca. 0.020 M) under investigation and known amount of internal standard (ca. 0.020 M). To this solution was added 50 mg of Adams catalyst. After positioning the flask on the Parr apparatus, the entire system was evacuated, followed by filling with hydrogen to four atmospheres of pressure. This flushing procedure was performed three times before finally filling the system to four atmospheres of hydrogen and starting the mechanical shaker. The pressure was manually adjusted to maintain four atmospheres of hydrogen. After 24 hrs., the system was evacuated and then opened to the atmosphere. The reaction mixture was filtered through Celite prior to analysis.

Analysis consisted of:

1) separation and collection of the products of the reaction by glc (5 ft. column, 20% Apiezon L/ Chromosorb W, 170°/70°, 120 ml/min.), followed by NMR, infrared and mass spectral analysis for each product collected and comparison of this data with the data of authentic samples.

2) comparison of the retention times of the products of the reaction with the retention times of authentic samples. Products and product ratio data, along with percentage yields are shown in Table I.

Four Atmosphere hydrogenation of Xylenes. (Identification and Isolation of Products)

A Parr reaction flask was charged with 25 ml absolute ethanol, a known amount of the xylene to be hydrogenated (ca. 0.020 M), a known amount of internal standard (ca. 0.020 M), and a known amount of diethyl phosphoric acid (ca. 0.010 M). To this solution was added 50 mg of Adams catalyst. After placing the flask on the Parr apparatus, the entire system was evacuated followed by filling with hydrogen to four atmospheres. This flushing procedure was performed three times before finally filling the system to four atmospheres of hydrogen and starting the mechanical shaker. The pressure was adjusted manually to maintain four atmospheres of pressure throughout the reduction. After 24 hrs., the system was evacuated and then opened to the atmosphere. The reaction mixture was filtered through Celite prior to analysis.

Analysis consisted of:

1) separation and isolation of the products of reduction by glc (5 ft. column, 20% Apiezon L/ Chromosorb W, 170°/70°, 120 ml/min.) followed by NMR, infrared and mass spectral analysis for each product collected and comparison of this data with the data of authentic samples.

2) comparison of the retention times of the products of reduction with the retention times of authentic samples. Product and product ratio data along with percentage yields are listed in Table II.

Atmospheric Hydrogenation of Enol Phosphates. (Identification and Isolation of Products)

A reaction flask was charged with 25 ml absolute ethanol, a known amount of the enol phosphate (ca. 0.020 M) under investigation and of the internal standard (ca. 0.020 M). To this solution was added 50 mg of Adams catalyst and a magnetic stirrer. After placing the flask on the hydrogenation apparatus, the entire system was evacuated followed by filling with hydrogen, This flushing procedure was performed three times before finally filling the system with hydrogen to one atmosphere of pressure and starting the magnetic stirrer. As the reaction proceeded and hydrogen was consumed, the system was maintained at one atmosphere of pressure by manual adjustment of the leveling bulbs attached to the apparatus. After 24 hrs., the total volume of hydrogen consumed was noted and the system evacuated prior to opening to the atmosphere. The reaction solution was filtered through Celite before analysis.

Analysis consisted of:

1) separation and isolation of the products of the reaction by glc (5 ft. column, 20% Apiezon L/ Chromosorb W, 170°/60°, 200 ml/min.) followed by NMR, infrared and mass spectral analysis for each product collected and comparison of this data with the data of authentic samples. In the case of the analysis of the products obtained from the reaction of diethyl 2-propenyl phosphate different glc conditions were used (10 ft. column, 20% Carbowax 20M/ Chromosorb W, 170°/35°, 60 ml/min.)

2) comparison of the retention times of the products of the reaction with the retention times of authentic samples. Products along with percentage yields are summarized in Table III.

Four Atmosphere Hydrogenation of Enol Phosphates (Isolation and Identification of Products)

A Parr reaction flask was charged with 25 ml absolute ethanol, a known amount of the enol phosphate (ca. 0.020 M) to be hydrogenated and a known amount of internal standard (ca. 0.020 M). To this was added 50 mg platinum oxide. After placing the flask on the Parr apparatus the entire system was evacuated followed by filling with hydrogen to four atmospheres. This flushing procedure was performed three times before finally filling the system to four atmospheres of hydrogen and starting the mechanical shaker. Pressure was adjusted manually to maintain four atmospheres of hydrogen throughout the reaction. After 24 hrs., the system was evacuated and then slowly opened to the atmosphere. The reaction mixture was filtered through Celite to remove the catalyst prior to analysis.

Analysis consisted of:

1) separation and isolation of the products of the reaction by glc (5 ft. column, 20% Apiezon L/ Chromosorb W, 170°/60°, 200 ml/min.) followed by NMR, infrared and mass spectral analysis for each product collected and comparison of this data with the data of authentic samples. In the case of the analysis of the products obtained from the reaction of diethyl 2-propenyl phosphate different glc conditions were used. (10 ft. column, 20% Carbowax 20M/ Chromosorb W, 170°/35°, 60 ml/min.)

Deuterium Incorporation Studies (Atmospheric Reactions of Enol Phosphates)

Identical procedures were used for these studies as were used in the atmospheric hydrogenations of enol phosphates except that solutions were 1M in phosphate ester and that D_2 was substituted for H_2, CH_3CH_2OD, CH_3OD, or CD_3OD for CH_3CH_2OH. Analysis of reaction mixtures was performed as previously described.

Diethyl 1-cyclohexenyl phosphate was studied using D_2 in CH_3OD, CD_3OD and CH_3CH_2OD solvents.

Diethyl 1-cycloheptenyl phosphate was studied using D_2 in cyclohexane solvent. Hydrogenolysis-reduction of diethyl styryl phosphate, diethyl cyclohexyl phosphate, diethyl benzyl phosphate, diethyl 2-phenylethyl phosphate and diethyl 4-pent-1-eneyl phosphate were performed as described previously for aryl and enol phosphate hydrogenations at both one and four atmospheres of hydrogen pressure. Analysis was as previously described.

Synthesis

Diethyl 2,3-dimethylphenyl phosphate:

To a solution of 12.2g (0.10 mol) of 2,3-dimethyl phenol in 400 ml of sodium-dried benzene was added 3.2g (0.13 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for approximately 24 hrs. as hydrogen was evolved and salt formed. To the stirred slurry of phenolic salt was added dropwise 17.2g (0.10 mol) of diethyl chlorophosphate. Upon dissolution of the salt, the reaction mixture was washed three times with 150 ml of water. The organic layer was separated and dried over anhydrous magnesium sulfate and the benzene was distilled at reduced pressure. The residue was then vacuum distilled to yield 13.9g (54%) diethyl 2,3-dimethylphenyl phosphate (I), bp 104°/0.12 Torr. Anal. Calcd for $C_{12}H_{19}O_4P$: C, 55.81; H, 7.36. Found: C, 55.65; H, 7.44.

Diethyl 3,4-dimethylphenyl phosphate:

To a solution of 12.2g (0.10 mol) of 3,4-dimethyl phenol in 400 ml of sodium-dried benzene was added 3.2g (0.13 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for approximately 24 hrs. as hydrogen was evolved and salt formed. To the stirred slurry of phenolic salt was added dropwise 17.2g (0.10 mol) of diethyl chlorophosphate. Upon dissolution of the salt, the reaction mixture was washed three times with 150 ml of water. The organic layer was separated and dried over anhydrous magnesium sulfate and the benzene was distilled at reduced pressure. The residue was then vacuum distilled to yield 19.4g (75%) diethyl 3,4-dimethylphenyl phosphate (II), bp 109°/0.17 Torr. Anal. Calcd for $C_{12}H_{19}O_4P$: C, 55.81; H, 7.36. Found: C, 55.48; H, 7.58.

Diethyl 2,4-dimethylphenyl phosphate:

To a solution of 12.2g (0.10 mol) of 2,3-dimethyl phenol in 400 ml of sodium-dried benzene was added 3.2g (0.13 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for approximately 24 hrs. as hydrogen was evolved and salt formed. To the stirred slurry of phenolic salt was added dropwise 17.2g (0.10 mol) of diethyl chlorophosphate. Upon dissolution of the salt, the reaction mixture was washed three times with 150 ml of water. The organic layer was separated and dried over anhydrous magnesium sulfate and the benzene was distilled at reduced pressure. The residue was then vacuum distilled to yield 7g (27%) diethyl 2,4-dimethylphenyl phosphate (III), bp 101°/0.10 Torr. Anal. Calcd for $C_{12}H_{19}O_4P$: C, 55.81; H, 7.36. Found: C, 55.41; H, 7.47.

Diethyl 3,5-dimethylphenyl phosphate:

To a solution of 12.2g (0.10 mol) of 3,5-dimethyl phenol in 400 ml of sodium-dried benzene was added 3.2g (0.13 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for approximately 24 hrs. as hydrogen was evolved and salt formed. To the stirred slurry of phenolic salt was added dropwise

17.2g (0.10 mol) of diethyl chlorophosphate. Upon dissolution of the salt, the reaction mixture was washed three times with 150 ml of water. The organic layer was separated and dried over anhydrous magnesium sulfate and the benzene was distilled at reduced pressure. The residue was then vacuum distilled to yield 9.7g (38%) of diethyl 3,5-dimethylphenyl phosphate (IV) , bp 97°/0.14 Torr. Anal. Calcd for $C_{12}H_{19}O_4P$: C, 55.81; H, 7.36. Found: C, 55.89; H, 7.50.

Diethyl 2,6-dimethylphenyl phosphate:

To a solution of 12.2g (0.10 mol) of 2,6-dimethyl phenol in 400 ml of sodium dried benzene was added 3.2g (0.13 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for approximately 24 hrs. as hydrogen was evolved and salt formed. To the stirred slurry of phenolic salt was added dropwise 17.2g (0.10 mol) of diethyl chlorophosphate. Upon dissolution of the salt, the reaction mixture was washed three times with 150 ml of water. The organic layer was separated and dried over anhydrous magnesium sulfate and the benzene was distilled at reduced pressure. The residue was then vacuum distilled to yield 11g (43%) of diethyl 2,6-dimethylphenyl phosphate (V), bp 107°/0.45 Torr. Anal. Calcd for $C_{12}H_{19}O_4P$: C, 55.81; H, 7.36. Found: C, 55.99; H, 7.25.

Diethyl 2,5-dimethylphenyl phosphate:

To a solution of 12.2g (0.10 mol) of 2,5-dimethyl phenol in 400 ml of sodium-dried benzene was added 3.2g (0.13 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for approximately 24 hrs. as hydrogen was evolved and salt formed. To the stirred slurry of phenolic salt was added dropwise 17.2g (0.10 mol) of diethyl chlorophosphate. Upon dissolution of the salt, the reaction mixture was washed three times with 150 ml of water. The organic layer was separated and dried over anhydrous magnesium sulfate and the benzene was distilled at reduced pressure. The residue was then vacuum distilled to yield 21g (81%) diethyl 2,5 dimethylphenyl phosphate (VI), bp 99°/0.05 Torr. Anal. Calcd for $C_{21}H_{19}O_4P$: C, 55.81; H, 7.36. Found: C, 56.12; H, 7.66.

Diethyl 1-naphthyl phosphate:

To a solution of 28.8g (0.20 mol) of 1-hydroxy naphthalene in 400 ml of sodium dried benzene was added 6.4g (0.26 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for approximately 24 hrs. as hydrogen was evolved and salt formed. To the stirred slurry of sodium naphthoxide was added dropwise 34.4g (0.20 mol) of diethyl chlorophosphate. Upon dissolution of the salt, the reaction mixture was washed three times with 150 ml of water. The organic layer was separated and dried over anhydrous magnesium sulfate and the benzene was distilled at reduced pressure. The residue was then vacuum distilled to yield 23g (41%) diethyl 1-naphthyl phosphate (VII), bp 129°/0.05 Torr.

Diethyl 2-naphthyl phosphate:

To a solution of 28.8g (0.20 mol) of 2-hydroxy naphthalene in 400 ml of sodium dried benzene was added 6.4g (0.26 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for approximately 24 hrs. as hydrogen was evolved and salt formed. To the stirred slurry of the sodium naphthoxide was added dropwise 34.4g (0.20 mol) of diethyl chlorophosphate. Upon dissolution of the salt, the reaction mixture was washed three times with 150 ml of water. The organic layer was separated and dried over anhydrous magnesium sulfate and benzene was distilled at reduced pressure. The residue was then vacuum distilled to yield 2.2g (4%) of diethyl 2-naphthyl phosphate (VIII), bp 127°/0.07 Torr.

Diethyl cyclohexyl phosphate:

To a solution of 12g (0.12 mol) of cyclohexanol in 100 ml of sodium dried benzene was added 2.4g (0.1 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for 48 hrs. as salt slowly formed. To this salt slurry was added dropwise 17.2g (0.10 mol) of diethyl chlorophosphate and the reaction stirred for two hours, at which time, 50 ml of pentane was added to the reaction medium, causing precipitation of the salt which was then filtered with suction. The solvent was distilled at reduced pressure and the residue was vacuum distilled yielding 10.6g (45%) of diethyl cyclohexyl phosphate, bp 103°/0.65 Torr.

Diethyl benzyl phosphate:

To a solution of 12.9g (0.12 mol) of benzyl alcohol in 100 ml of sodium dried benzene was added 2.4g (0.1 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for 24 hrs. as hydrogen was evolved and salt formed. To this salt slurry was added dropwise 17.2g (0.10 mol) of diethyl chlorophosphate and the reaction stirred for two hours, at which time, 50 ml of pentane was added to the reaction medium, causing precipitation of the salt which was then filtered with suction. The solvent was distilled at reduced pressure and the residue was vacuum distilled yielding 16.3g (67%) of diethyl benzyl phosphate, bp 101°/0.8 Torr.

Diethyl 2-phenylethyl phosphate:

To a solution of 14.6 (0.12 mol) of 2-phenylethanol in 100 ml of sodium dried benzene was added 2.4g (0.1 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for 24 hrs. as salt formed. To this salt slurry was added dropwise 17.2g (0.10 mol) of diethyl chlorophosphate and the reaction was stirred an additional two hours before 50 ml of pentane was added to the reaction medium causing precipitation of the salt which was then filtered with suction. The solvent was removed at reduced pressure and the residue was vacuum distilled yielding 7.7g (30%) of diethyl 2-phenyl ethyl phosphate, bp 147°/0.25 Torr.

Diethyl 4-pent-1-eneyl phosphate:

To a solution of 10g (0.12 mol) of 4-penten-1-ol in

100 ml of sodium dried benzene was added 2.4g (0.10 mol) of sodium hydride with constant mechanical stirring. The reaction was stirred for 24 hrs. before the dropwise addition of 17.2g (0.10 mol) diethyl chlorophosphate to the salt slurry. The reaction was stirred for two hours prior to the addition of 50 ml of pentane to the reaction medium causing precipitation of the salt which was then filtered with suction. The solvent was removed at reduced pressure and the residue was vacuum distilled yielding 3g (12%) of diethyl 4-pent-1-eneyl phosphate, bp 85°/0.75 Torr.Anal. Calcd for $C_9H_{19}O_4P$: C, 48.65; H, 8.65. Found: C, 48.93; H, 8.64.

Diethyl 2-propenyl phosphate:

To 36.4g (0.20 mol) of triethyl phosphite heated to 120° was dropwise added 18.5g (0.20 mol) of chloroacetone. The reaction mixture was maintained at 120° for one hour after addition of the phosphite and then raised to 170° for an additional hour at which time the reaction mixture was vacuum distilled yielding 9.3g (25%) of diethyl 2-propenyl phosphate, bp 64°/0.9 Torr.

Diethyl 1-cyclohexenyl phosphate:

To 250 ml of water was added 49g (0.5 mol) of cyclohexanone. The mixture was stirred with a magnetic stirrer and cooled in an ice bath as 26g (0.75 mol) of chlorine gas was bubbled through the mixture over a three hour period. After separation of the product, which appeared as a milky white liquid, the aqueous layer was extracted with three 50 ml portions of ether and the extracts where combined with the product. The resulting solution was then washed with 75 ml of water, followed by washing with 100 ml of a saturated solution of sodium chloride. The organic layer was separated and dried over anhydrous sodium sulfate for 30 minutes. After filtration, the resulting solution was stripped of ether and the residue was vacuum distilled yielding 17.4g (20%) of 2-chloro cyclohexanone, bp 87°/13 Torr. To 18.2g (0.1 mol) of triethyl phosphite heated to 120° was added dropwise 13.2g (0.1 mol) of 2-chloro cyclohexanone. The reaction mixture was maintained at 120° for one hour after completion of addition and then raised to 170° for an additional hour at which time the reaction mixture was vacuum distilled yielding 12.6g (54%) of diethyl cyclohexenyl phosphate, bp 105°/0.15 Torr.

Diethyl 1-cyclopentenyl phosphate:

To 250 ml of water was added 25.2 (0.3 mol) of cyclopentanone. The mixture was stirred with a magnetic stirrer and cooled in an ice bath as 52g (1.5 mol) of chlorine gas was bubbled through the mixture over a three hour period. After separation of the product, which appeared as a milky white liquid, the aqueous layer was extracted with three 50 ml portions of ether and the extracts where combined with the product. The resulting solution was then washed with 75 ml of water, followed by washing with 100 ml of a saturated solution of sodium chloride. The organic layer was separated and dried over anhydrous sodium sulfate for 30 minutes. After filtration, the resulting solution was stripped of ether and the residue was vacuum distilled yielding 15.3g (43%) of 2-chloro cyclopentanone, bp 94°/20 Torr. To 18.2g (0.1 mol) of triethyl phosphite heated to 120° was added dropwise 11.8g (0.1 mol) of 2-chloro cyclopentanone. The reaction mixture was maintained at 120° for one hour after completion of addition and then raised to 170° for an additional hour at which time the reation mixture was cooled to room temperature and vacuum distilled yielding 17.2g (78%) diethyl 1-cyclopentenyl phosphate, bp 83°/0.09 Torr. Anal. Calcd for $C_9H_{17}O_4P$: C, 48.88; H, 7.85. Found: C, 49.09; H, 7.73.

Diethyl 1-cycloheptenyl phosphate:

To 250 ml of water was added 62g (0.5 mol) of cycloheptanone. The mixture was stirred with a magnetic stirrer and cooled in an ice bath as 52g (1.5 mol) of chlorine gas was bubbled through the mixture over a three hour period. After separation of the product, the aqueous layer was extracted with three 50 ml portions of ether and the extracts where combined with the product. The resulting solution was then washed with 75 ml of water, followed by washing with 100 ml of a saturated sodium chloride solution. The organic layer was separated and dried over a anhydrous sodium sulfate for 30 minutes. After filtration, the resulting solution was stripped of ether and the residue was vacuum distilled yielding 44g

(80%) 2-chloro cyclopentanone, bp 45°/.15 Torr. To 51g (0.3 mol) of triethyl phosphite heated to 120° was added dropwise 44g (0.3 mol) of 2-chloro cycloheptanone. The reaction mixture was maintained at 120° for one hour after addition of the phosphite and then raised to 170° for an additional hour at which time the reaction mixture was cooled to room temperature and vacuum distilled yielding 29.8g (40%) of diethyl 1-cycloheptenyl phosphate, bp 80°/0.01 Torr Anal. Calcd for $C_{11}H_{21}O_4P$: C, 53.56; H, 8.53 Found: C, 53.23; H, 8.47.

Diethyl styryl phosphate

To 33g (0.2 mol) of triethyl phosphite heated to 120° was added in small portions 31g (0.2 mol) α-chloro acetophenone. The reaction mixture was maintained at 120° for one hour after the addition and then raised to 170° for an additional hour at which time the reaction mixture was cooled to room temperature and vacuum distilled yielding 20g (37%) diethyl styryl phosphate bp 106°/0.04 Torr Anal. Calcd for $C_{12}H_{17}O_4P$: C, 56.06; H, 6.78. Found: C, 56.21; H, 6.64.

REFERENCES CITED

1. H.D. Orloff, C.J. Worrel and Markley, J. Amer. Chem. Soc., 80, 727 (1958)

2. W. Perkow, K. Ullerich and F. Meyer, Naturwissenschaften, 39, 353 (1952)

3. F.J. Reithel and C.K. Claycomb, J. Amer. Chem Soc., 71, 3669 (1949)

4. F. Maley, G.F. Maley and H.A. Lardy, J. Amer. Chem. Soc., 78, 5303 (1956)

5. C.E. Ballou and H.O.L. Fischer, J. Amer. Chem. Soc., 77, 3329 (1955)

6. G.L. Kilgour and C.E. Ballou, J. Amer. Chem Soc., 80, 3956 (1958)

7. E. Baer and J. Maurukas, J. Amer. Chem. Soc., 74, 158 (1952)

8. B.S. Griffin and A. Burger, J. Amer. Chem. Soc., 78, 2336 (1956)

9. E. Baer and M. Kates, J. Amer. Chem Soc., 72, 942 (1950)

10. T. Utika and H. Hayatser, J. Amer. Chem. Soc., 84, 1879 (1962)

11. C.E. Ballou, Biochem. Prep., 7, 45 (1960)

12. C.E. Ballou and H.O.L. Fischer, J. Amer. Chem. Soc., 76, 3188 (1954)

13. O. Westphal and R. Stadler, Angew. Chem. Intern. Ed., 2, 327 (1963)

14. E. Baer, J. Biol Chem. 189, 235 (1951)

15. P. Brigl and H. Muller, Ber., 72 2121 (1939)

16. J.G. Moffat and H.G. Kharana, J. Amer. Chem. Soc., 79, 3741 (1957)

17. R.W. Meschke and W.H. Hartung, J. Org. Chem., 25, 137 (1960)

18. C.W. Keenan, B.W. Giesemann and H.A. Smith, J. Amer. Chem. Soc., 76, 229 (1954), and references therein.

19. R.D. Shuetz and L.R. Caswell, J. Org. Chem., 27, 486 (1962)

20. G.W. Kenner and N.R. Williams, J. Chem. Soc., 522 (1955)

21. A. Jung and R. Engel, J. Org. Chem., 40, 244 (1975)

22. W.D. Clossen, Abstract presented at the 6th Northeast Regional Meeting of the American Chemical Society, Burlington, Vermont, August 19, 1974

23. R.E. Ireland and G. Pfister, Tetrahedron Letters, No. 26, 2145 (1969)

24. L.Kh. Freidlin, B.D. Polkovnikov and Yu.P. Egorov, Izv. Akad. Nauk. SSSR Otd. Khim. Nauk p910 (1959) C.A. 60: 1355i

25. H.I. Jacobson, M.J. Griffin and E.V. Jensen, J. Amer. Chem. Soc., 79, 2068 (1957)

26. G.C. Bond and J.S. Rank, in"Proceedings of the Third International Congress on Catalysis," Sachtler, W.M.H., etal. (Eds), Wiley, New York, 1965 Vol. II, p.1225

27. G.C. Bond and P.B. Wells, in "Advances in Catalysis," Academic Press, New York, 1964 Vol. 15, p. 91

28. S. Siegel, G.V. Smith, B. Dmuchovsky, D. Dubbell, and W. Halpern, J. Amer. Chem. Soc., 84, 3136 (1962)

29. W.H. Pearlman, M.R.J. Pearlman and S. Elsey, J. Amer. Chem. Soc., 71, 4126 (1949)

30. D.K. Fukushima and T.F. Gallagher, J. Amer. Chem. Soc., 77, 139 (1955)

31. K.B. Wiberg and T.W. Hutton,J. Amer. Chem. Soc., 76, 5367 (1954)

32. R. Adams and M. Gianturco, J. Amer. Chem. Soc., 78, 1922 (1956)

33. V. Boekelheide and M.Y. Chang, J. Org. Chem., 29, 1303 (1964)

34. J.C. Godfrey, D.S. Torbell and V. Boekelheide, J. Amer. Chem. Soc., 77, 3342 (1955)

35. R.J. Stedman, K. Swered and J.R.E. Hoover, J. Med. Chem., 7, 117 (1964)

36. N.K. Richtmyer, J. Amer. Chem. Soc., 56, 1633 (1934)

37. W.H. Hartung and R. Simonoff, Org. Reactions, 7, 263 (1953)

38. C.E. Diebert, Diss. Abstr. B, 27, 3854 (1967)

39. W. Gerrad, J. Chem. Soc., 84, 85 (1944)

40. W.J. Bailey and J.J. Hewitt, J. Org. Chem., 21, 543 (1956)

41. H. Baumgarten and R.A. Setterquist, J. Amer. Chem. Soc., 79, 2605 (1957)

42. E.L. Eliel, Stereochemistry of Carbon Compounds, McGraw-Hill, New York, 1962, p.207ff