STUDIES ON THE SYNTHESIS, REACTIVITY AND UTILITY OF CYCLIC PHOSPHORUS(III) COMPOUNDS AND ORGANOPHOSPHONATES

A THESIS

SUBMITTED FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

BY

SATISH KUMAR NUNE

SCHOOL OF CHEMISTRY

UNIVERSITY OF HYDERABAD

HYDERABAD - 500 046

INDIA

April 2004

To

my mother

CONTENTS

PART B

(I) PHOSPHONATES - SYNTHESIS AND UTILITY

(II) HYDROLYSIS OF PHOSPHITES/ PHOSPHORAMIDITES AND ITS INHIBITION

STATEMENT

I hereby declare that the matter embodied in this thesis is the result of investigations carried out by me in the School of Chemistry, University of Hyderabad, Hyderabad, under the supervision of Prof. K. C. Kumara Swamy.

In keeping with the general practice of reporting scientific observations, due acknowledgements have been made wherever the work described is based on the findings of other investigators.

Hyderabad

April 2004

Satish Kumar Nune

CERTIFICATE

This is to certify that the work described in this thesis entitled "Studies on the Synthesis, Reactivity and Utility of Cyclic Phosphorus(III) Compounds and Organophosphonates" has been carried out by Mr. Satish Kumar Nune, under my supervision and the same has not been submitted elsewhere for any degree.

Hyderabad

April 2004

Kumara Swamy

Prof. K. C. Kumara Swamy

(Thesis supervisor)

Dean

School of Chemistry
University of Hyderabad
Hyderabad-500 046, India

Dean
School of Chemistry

University of Hyderabad

Hyderabad 500 046

INDIA

ACKNOWLEDGEMENTS

With high regards and profound respect, 1 wish to express my deep sense of gratitude to **Prof. K. C. Kumara Swamy** for his constant encouragement throughout my research work and introducing me to this fascinating field of research. He has been a source of inspiration throughout with provoking discussions.

I thank present and former Deans, School of Chemistry, for providing all necessary facilities to carry out my research work during my stay here, and all the faculty members for their inspiration.

I thank Prof. M. Periasamy for his encouragement. I thank Prof. Jagadese J. Vittal (National University of Singapore) for providing some of the X-ray data.

I specially thank Dr. Sudha Kumaraswamy for her unique help, useful discussions, encouragement and cooperation. I enjoyed the company of my lab-mates Praveen Kumar, Senthil Kumar, Pavan Kumar, Manab Chakravarty, Balaraman, and Bhuvan Kumar. I particularly thank Bhuvan and Pavan for their help during thesis submission. I am also thankful to former lab-mates Dr. C. Muthiah, Dr. Praveen Kommana and Mr. B. Srinivas for their cooperation in the lab.

I am thankful to Ms. G. Padmaja for her constant encouragement, co-operation. I also thank Alchemie99 friends particularly Suresh, Shekar, Koti-kaka, Narsi, Shyam, Peru, Bharat and Satyanarayana Reddy for creating a cheerful and competitive atmosphere. Thanks are also due to my friends Venu, Vamsi, Basavoju, Chilla-Malla, Gupta, Rajesh, Yadaiah, Sharat and Abhik who made my stay here a pleasant one. I thank Mr. S. Satyanarayana and Mr. V. Bhaskar Rao for patiently recording various NMR spectra, Mr. Ragavaiah for X-ray data collection and all other non-teaching staff for their cooperation.

I particularly thank my school-friend D. Narsing Rao, who encouraged and supported me throughout. I also thank all my friends Bajju, Dora, Srinuraju (CM), Rotte, Hari, Om, Packit, Ravi, Botta, Vijay, Santhosh, Venu and Chilka for their support.

Thanks are due to *S. Mallikarjun Prasad,* whose encouragement made me to take chemistry major at the bachelor's level. I also wish to acknowledge all my teachers in my previous courses of study for their guidance.

1 express my profound gratitude to my mother **N. Krishnaveni;** her sacrifice provided me with a good education and opportunities. Her love provided me with substantive strength to live in this challenging world. I am extremely thankful to my brothers N. Naresh Kumar and N. Chandrashekar for their constant encouragement throughout my academic career. I thank my sister and brother-in-law for their support and encouragement at both the crest and trough periods of my life. I am extremely thankful to my uncle Ch. Bhagavan, who really supported and encouraged me throughout my career.

I thank the Council of Scientific and Industrial Research (CSIR, New Delhi) and Department of Science and Technology (DST, New Delhi) for financial support. I also thank COSIST (UGC), SAP (UGC) and FIST (DST) for various instrumental facilities. Single Crystal X-ray Diffractometer Facility at the University of Hyderabad funded by Department of Science and Technology (New Delhi) is also gratefully acknowledged.

Satish Kumar Nune

LIST OF PUBLICATIONS

1. 4,4,6,6-Tetrachloro-2,2-(2,2-dimethylpropane-1,3-diyldioxy)-1,3,5,2λ^5,4λ^5,6λ^5–triazatriphosphorine.
N. Satish Kumar and K. C. Kumara Swamy.
ActaCrystallogr. Sect. C, 57, **2001,** 1421.

2. Novel reaction of phosphorus (III) azides and isocyanates: unusual modes of cycloaddition with dipolarophiles and an unexpected case of ring expansion.
Sudha Kumaraswamy, Praveen Kommana, **N. Satish Kumar** and K. C. Kumara Swamy.
J. Chem. Soc, Chem. Commun., **2002,** 40.

3. Chemistry of selected cyclic P(III) compounds possessing a P-Cl bond.
K. C. Kumara Swamy, Sudha Kumaraswamy, Praveen Kommana, **N. Satish Kumar** and K. Senthil Kumar.
Proc. Indian. Acad. Sci. (Chem. Sci.J, **2002,** *114,* 367.

4. Pentacoordinate phosphoranes with reversed apicophilicity as stable intermediates in a Mitsubobu-type reaction.
N. Satish Kumar, Praveen Kommana, J. J. Vittal and K. C. Kumara Swamy.
J. Org. Chem., **2002,** *67,* 6653.

5. Hydrolysis of Cyclic Phosphites /Phosphoramidites and its Inhibition - Reversible Cyclization of Acyclic Phosphonate Salts to Cyclic Phosphites.
N. Satish Kumar, Sudha Kumaraswamy, Musa A. Said, and K. C. Kumara Swamy.
Org. Process Res. and Develop., **2003,** 7, 925.

6. Mitsunobu Reagent [triphenylphosphine (TPP) and diethyl azodicarboxylate (DEAD) /diisopropyl azodicarboxylate (DIAD)].
N.Satish Kumar.
Synlett ***(Spotlight),*** **2003,** 1221.

7. Pentacoordinated Phosphorus in Action.
K. C. Kumara Swamy and **N. Satish Kumar.**
Current Science, **2003,** 1258.

8. Synthesis and Structures of Unsymmetrical Bis- and Tris Cyclotriphosphazenes.
N. Satish Kumar and K. C. Kumara Swamy.
Polyhedron, **2004** (in *Press).*

9. Does a sterically bulky group occupy the equatorial site in trigonal bipyramidal phosphorus?
Praveen Kommana, N. **Satish Kumar,** Jagadese J Vittal, E. G. Jayasree, E. D. Jemmis and K. C. Kumara Swamy.
Org. Lett., **2004,** 6, 145.

10. Diverse Modes of Reactivity of Dialkyl azodicarboxylates with P(III) Compounds: Synthesis, Structure and Reactivity of Products Other than the Morrison-Brunn-Huisgen Intermediate in a Mitsunobu-Type Reaction.
N Satish Kumar, K. Praveen Kumar, K. V. P. Pavan Kumar, Praveen Kommana, Jagadese J Vittal and K. C. Kumara Swamy
J. Org. Chem., **2004,** *69,* 1880.

11. Penta and Hexa-coordinate Phosphoranes with a Diisopropyl azodicarboxylate residue.
N.Satish Kumar, K. V. P. Pavan Kumar, K. C. Kumara Swamy *{Manuscript under preparation).*

12. Synthesis and Reactivity of new Vinyl and Allyl phosphonates.
N. Satish Kumar and K. C. Kumara Swamy *{to be submitted).*

13. Unusual Reaction of Heterocycle $[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2PC(COOMe)C(COOMe)C(O)N\text{-}]$ with Chloroform: Synthesis and Structural Characterization of Fuctionalized Vinylphosphonate.N. **Satish Kumar,** K. C. Kumara Swamy *{to be submitted).*

PAPERS PRESENTED IN SYMPOSIA

1. Unusual Modes of Cycloaddition and an Unexpected Case of Ring Expansion Involving Phosphorus(III) Azides and Isocyanates
K. C. Kumara Swamy, Sudha Kumaraswamy, Praveen Kommana, and N. **Satish Kumar.**
Singapore International Chemical Conference II, December, 18-20, **2001.**

2. Novel features in the reaction of cyclic phosphites $[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2]PX$ with diisopropyl azodicarboxylate (DIAD): Comparision to the Mitsunobu intermediate $Ph_3P^+N(COOR)N^-COOR$.
K.C. Kumara Swamy, **N. Satish Kumar,** Praveen Kommana, Sudha Kumaraswamy, and J. J. Vittal.
224th ACS National Meeting, Boston, USA, August 18-22, **2002.**

3. New Synthetically useful phosphonates derived from the Cyclic Phosphite $(OCH_2CMe_2CH_2O)PCl$.
N. Satish Kumar, Manab Chakravarty, K. Senthil Kumar, C. Muthiah, B. Srinivas and K. C. Kumara Swamy.
5 th National Symposium in Chemistry, IIT Chennai, Feb 7-9, 2003.

4. Towards Chiral Cyclotriphosphazenes.
N. Satish Kumar, N. N. Bhuvan Kumar and K. C. Kumara Swamy.
MTIC, IIT Mumbai, Dec 17-19, 2003.

5. Synthesis, Structure and Reactivity of Products Other than the Morrison-Brunn-Huisgen Intermediate in the Mitsunobu type reaction.
K. V. P. Pavan Kumar, **N Satish Kumar,** K. Praveen Kumar and K. C. Kumara Swamy
6 th National Symposium in Chemistry (CRSI), IIT Kanpur, INDIA, Feb 5-7, **2004.**

6. Cycloaddition Reactions of Phosphorus(III) Compounds with Dialkyl Azodicarboxylates (in the context of Mitsunobu reaction).
N. **Satish Kumar** and K. C. Kumara Swamy
Chemfest-2004, School of Chemsitry, University of Hyderabad, Mar 11, 2004.

Synopsis

This thesis divided into two parts: Part-A and Part-B. **Part-A** embodies various cycloaddition and oxidative addition reactions of phosphorus(III) compounds. **Part-B** deals with the synthesis of various phosphites and phosphonates and their utility in organic synthesis.

Each part is subdivided into three chapters: (a) Introduction (Literature Survey), (b) Results and Discussion and (c) Experimental. The compounds obtained in the present study are, in general, characterized by Mp, IR and NMR (^{1}H, ^{13}C & ^{31}P) techniques followed by elemental analysis (of representative compounds). Wherever feasible, X-ray structure determination is undertaken. References are compiled at the end of each part.

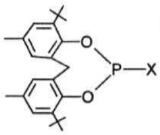
PART-A

A review of literature on aspects relevant to this part [Mitsunobu reaction, cycloaddition reactions of P(III) compounds, pentacoordinate phosphorus compounds etc.] is presented in Chapter 1.

In Chapter 2 the results obtained on the above-mentioned aspects are discussed; these are as outlined below.

(i) Phosphite precursors

The precursors 1-9 used in the present study are prepared by standard procedures available in the literature.



X = Cl [**1**; δ(P): 153.7]
NHMe [**2**; δ(P): 142.6]
NH*t*-Bu [**3**; δ(P): 141.9]
NMe_2 [**4**; δ(P): 142.7]
NCO [**5**; δ(P): 121.1]
NCS [**6**; δ(P): 115.9]

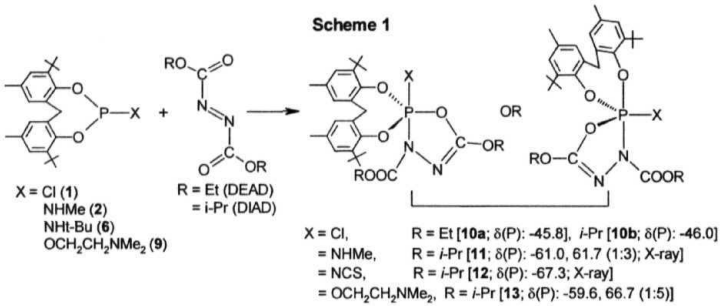
Et [**7**; δ(P): 188.5]
n-Bu [**8**; δ(P): 190.4]
$OCH_2CH_2NMe_2$ [**9**; δ(P): 129.0]

(ii) Reactions of phosphorus(III) compounds with dialkyl azodicarboxylates (in the context of Mitsunobu reaction)

In the reaction of the cyclic phosphites 1, 2, 6 and 9 with diethyl azodicarboxylate (DEAD) and/ or diisopropyl azodicarboxylate (DIAD), novel pentacoordinate phosphoranes **10-13,** rather than the Morrison-Brunn-Huisgen type

intermediate $[Ph_3P^+N(CO_2Et)N^-CO_2Et]$ (I, *cf.* O. Mitsunobu, *Synthesis,* ***1981,*** 1), are obtained (Scheme 1). A possible rationale is provided for this observation.

Scheme 1



From the X-ray structures of **11** and 12 (trigonal bipyramidal geometry at P), it is noted that the nitrogen of the five-membered ring, rather than the oxygen, is at the apical position of the trigonal bipyramidal phosphorus, in spite of the fact that it is less electronegative than oxygen and carries a sterically bulky group. These observations contradict the most often assumed tenet that high apicophilicity is favored by small size and *vice versa* [Corbridge, D. E. C. *Phosphorus: An Outline of its Chemistry, Biochemistry and Technology,* 4th ed.; Elsevier: Amsterdam, 1990; Chapter 14, pp. 994-1007]. Thus, these results add an interesting facet to the reversed apicophilicity phenomenon.

Interestingly, the ^{31}P NMR spectrum of **11** exhibits two peaks at 8 -60.1 and -60.4 and a broad hump at -39.5 in toluene-d_8 at 298 K. The intensity of the downfield peak [8 -39.5] increases at the cost of the up-field peaks (which merge eventually at 8 -60.2) with raise in temperature. At 338 K, the peak at 8 -39.5 is the most predominant one (Fig. 1). The spectra are reversible with respect to temperature. These features are ascribed to the presence of the isomers **11a-11c.** Compound 12 also showed multiple ^{31}P NMR resonances at low temperature.

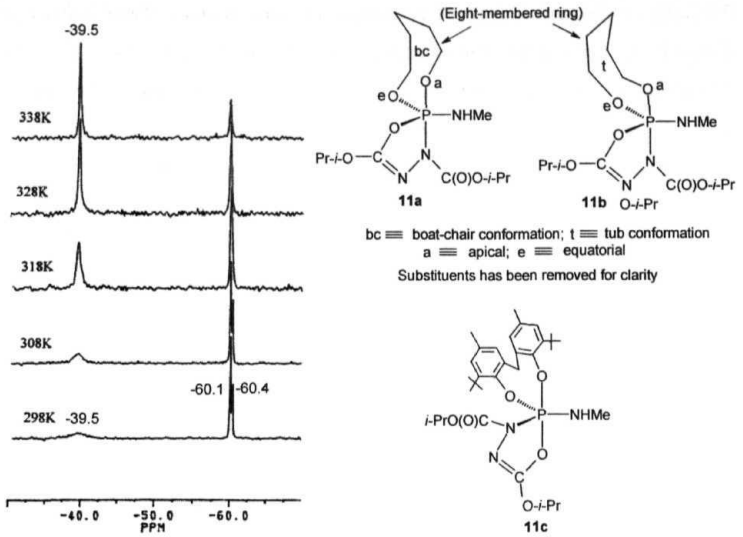


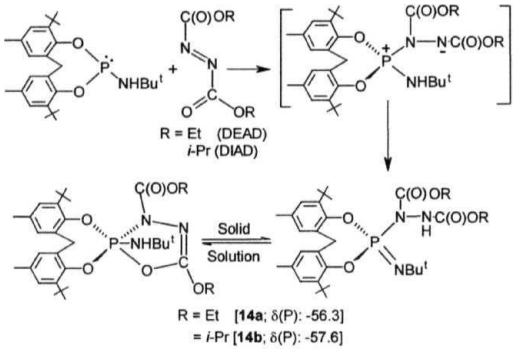
Fig. 1 Variable-temperature ^{31}P NMR spectra of **11.**

The chloro compounds **10a-b** are useful precursors to various substituted derivatives and hence we have reacted **10a-b** with 2,2,2-trifluoroethanol, imidazole, pyrazole and 8-hydroxy quinoline. The imidazolyl or oxinate occupies an apical position with the nitrogen of the five-membered ring equatorial (X-ray structural analysis).

The reaction of *t*-butylamino phosphoramidite $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2PNH\text{-}t\text{-Bu}$ (3) with DEAD and DIAD gave compounds with composition $[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(N\text{-}t\text{-Bu})\{N(CO_2R)NH(CO_2R)\}$; R = Et **(14a), *i*-Pr (14b)]** respectively [^1H and ^{31}P NMR, elemental analysis]. The ^{31}P NMR chemical shifts [solid and solution] of compounds **14a-b** is in the pentacordinate region. However, IR (KBr) spectra showed two v(NH) bands [for **14a** at 3264, 3154 cm^{-1}; **14b** at 3260, 3159 cm^{-1}]. *This is different from a single v(NH) band at 3383 cm^{-1} observed for the pentacoordinate methylamino compound **11.*** There is also a fairly strong band at 1205cm^{-1} ascribable to v(P=N). These features are analogous to that for compound $[S\{6\text{-}t\text{-Bu-4-Me-}C_6H_2O\}_2P\{N\text{-}t\text{-Bu}\}\{N(CO_2Et)NH(CO_2Et)\}]$ (II) prepared in our laboratory by the same route. The latter compound was characterized

by X-ray crystallography, which clearly showed (i) a strong P=N(*t*-Bu) bond [P-N 1.464(4) A], and (ii) the carbamate type linkage –NH-C(O)OR that is a hydrogen bonded dimer through the NH and the C=O moieties. On the basis of above data (IR, NMR and X-ray structure of II) an equilibrium between the tetracoordinate and pentacoordinate forms for **14a-b** as shown in Scheme 2 is proposed.

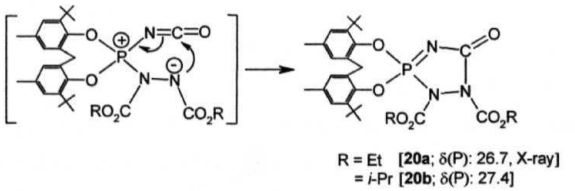
Scheme 2



Thus, the solution and the solid-state ^{31}P NMR spectra of **14a** appear to be *inconsistent* with the X-ray structure of the analogous compound II. A low temperature ^{31}P NMR study on compound **14a** reveals an *unprecedented* solution state behavior wherein *at least four* isomeric phosphoranes are present at 242 K [δ –48.0, -50.3, -53.4, -54.2; all in pentacoordinate region]. Upon warming to 298 K, the original spectrum was obtained. Possible rationale for such behavior in solution is also discussed.

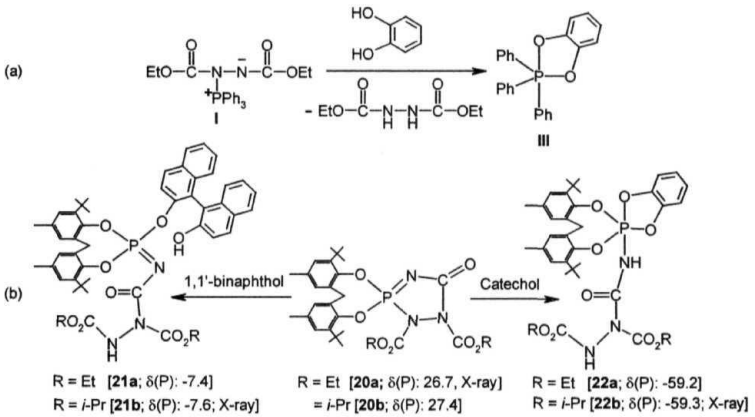
In contrast to the above, the reaction of P(III) isocyanate [CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$]P-NCO (5) with DEAD/ DIAD takes an entirely different turn with the formation of the cyclic products **20a-b,** presumably *via* the betaine (Scheme 3) in a step-wise pathway. The structure of **20a** is proven by X-ray crystallography.

Scheme 3



Reaction of **20a-b** with l,l'-bi-2-naphthol and catechol gave the products **21a-b** and **22a-b** respectively (Scheme 4). The structures of **21b** and **22b** are proven by X-ray crystallography. These products are different from compound **III** obtained by Trippett *et al* in the reaction of betaine $[Ph_3P^+N(CO_2Et)N^-CO_2Et]$ (I) and catechol. Thus, a different set of pentacoordinate phosphoranes can be obtained from our compounds 20a-b.

Scheme 4

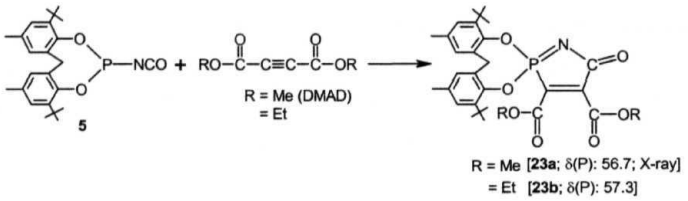


Despite having a structure different from the betaine I, compound **20b** *does participate in the Mitsunobu coupling* between ethanol and benzoic acid, suggesting that the five-membered heterocycle is in equilibrium with the betaine.

(iii) Reaction of phosphorus (III) isocyanates with dipolarophiles

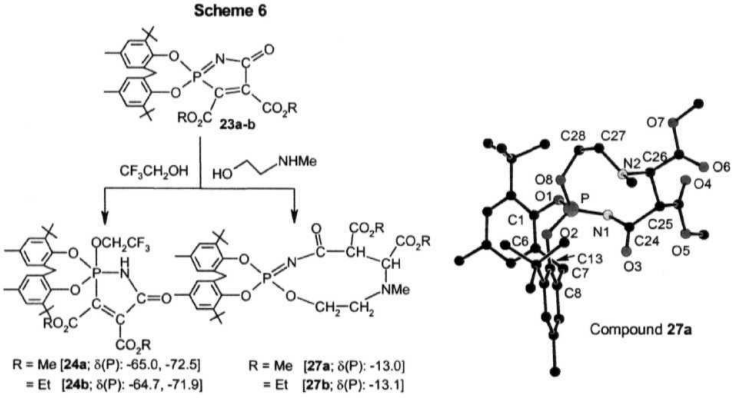
The reaction of $CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2P\text{-}NCO$ (5) with dipolarophiles like DMAD and diethyl acetylenedicarboxylate in toluene yielded products **23a-b** (Scheme 5). This result shows that a P(II1) isocyanate behaves as a 1,3-(P,C) dipole; such a behavior is different from that of an organic isocyanate. The structure of **23a** [for **a** sample prepared by a laboratory colleague] was unambiguously proved by X-ray crystallography.

Scheme 5



An unprecedented ring expansion *(from five* to *nine*-membered) occurs upon addition of 2-(methylamino)ethanol to **23a-b,** to yield **27a-b.** By contrast, 2,2,2-trifluoroethanol adds across the P=N bond of **23a-b,** resulting in the spirocyclic pentacoordinate phosphorane **24a-b** (Scheme 6). Compounds **24a** and **27a** were characterized X-ray crystallography. A possible mechanism for the formation of the heterocycle **27a** from the **23a** is also discussed.

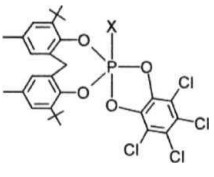
Scheme 6



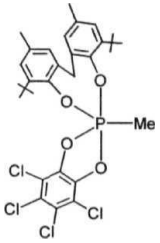
(iv) Pentacoordinate phosphoranes *via* (4+1) cycloaddition reactions of phosphites with *o*-chloranil

Between the pentacoordinate phosphoranes **28-29** synthesized (by reacting the corresponding phosphites 7 and 8 with *o*-chloranil) in the present study, the disposition of ethyl group in **28** is unambiguously proved by X-ray crystallography. This contrasts with the equatorial disposition of methyl group in IV. Thus, we observe

the 'reversed apicophilicity' phenomenon again. The bond parameters clearly show a trigonal bipyramidal geometry around phosphorus in 28.



X = Et [28; δ(P): -18.5, -25.3 (1:7); X-ray]
n-Bu [29; δ(P): -19.6, -22.6 (1:7)]



[IV; δ(P):-21.0; X-ray]

There are three distinct ^{31}P NMR signals in solution at low temperatures (< 242 K) for 28 [δ -14.1, -18.6, -25.3] and **29** [δ -15.3, -20.0, -26.0] in the pentacoordinate region. The solid-state ^{31}P NMR spectra show two peaks for 28 [δ -10.6 (major), -25.0(minor)] and a single peak at for **29** [δ -26.0]. The δ[P(solid, 298 K)] value for the rc-butyl compound **29** is close to the up-field peak seen at low temperatures in solution. Possible rationalization for these results are discussed.

An attempt to prepare the analogous hydridophosphorane $[CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2P(H)(1,2\text{-}O_2C_6Cl_4)]$ (31) by treating $[CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2PH$ (30) with *o*-chloranil was not successful. Treatment of $[CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2P(Cl)(1,2\text{-}O_2C_6Cl_4)]$ (32) with $LiAlH_4$ resulted in the hexacoordinate aluminum compound $[CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2P(O)(OC_6Cl_4O)]_3Al$ (33; X-ray).

Chapter 3 gives details of experimental procedures.

PART-B

A review of literature on the relevant aspects of phosphonates and phosphites chemistry is presented in Chapter 4.

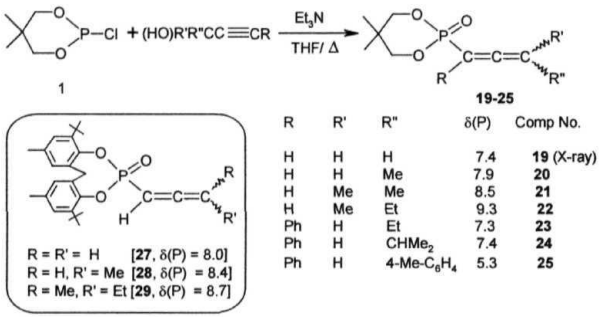
Chapter 5 describes the results obtained in the present study on the above-mentioned aspects, as described below:

(i) Synthesis of Phosphonates

(a) ***Allenylphosphonates:*** Allenylphosphonates **19-25** and **27-19** were prepared by the reaction of $(OCH_2CMe_2CH_2O)PCl$ (1) or $CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2PCl$ (26) with a substituted propargyl alcohol $RC{\equiv}CCR'R''(OH)$ in the presence of triethylamine via

a pseudo-Claisen rearrangement (Scheme 7). Compound 19 is also characterized by X-ray crystallography.

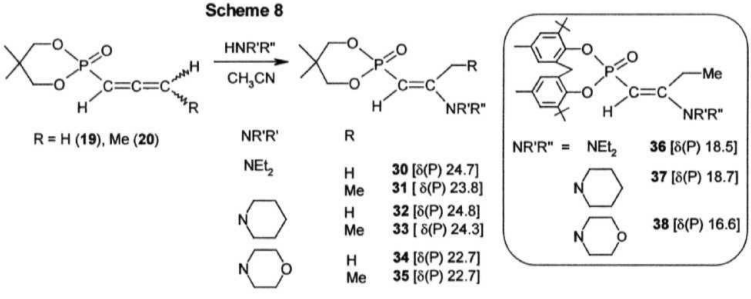
Scheme 7



R	R'	R"	δ(P)	Comp No.
H	H	H	7.4	**19** (X-ray)
H	H	Me	7.9	**20**
H	Me	Me	8.5	**21**
H	Me	Et	9.3	**22**
Ph	H	Et	7.3	**23**
Ph	H	$CHMe_2$	7.4	**24**
Ph	H	4-Me-C_6H_4	5.3	**25**

(b) ***fi-enamino, ally l and*** *fl-keto* ***and*** *fi-hydroxyphosphonates:* The preparation of *β*-enaminophosphonates **30-38** was accomplished very easily and in very high yields by means of simple addition of aliphatic and cyclic amines to allenylphosphonates 19-20 and 28 in acetonitrile (Scheme **8**). An important point to be noted here is the use of mild conditions coupled with high yields of phosphonate products.

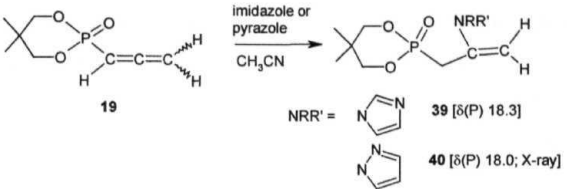
Scheme 8



R	
H	**30** [δ(P) 24.7]
Me	**31** [δ(P) 23.8]
H	**32** [δ(P) 24.8]
Me	**33** [δ(P) 24.3]
H	**34** [δ(P) 22.7]
Me	**35** [δ(P) 22.7]

In contrast to the above, reaction of the allenylphosphonate 19 with imidazole or pyrazole yielded allylphosphonates **39** or 40, respectively, in 60-70% yield (Scheme 9). In an earlier work, an equilibrium between enamine structures analogous to **30-38** and **39-40** [H. Altenbach and R. Korff, *Tetrahedron Lett.*, 1981, 22, 5175] was proposed, but a compound of the latter type was never isolated. The structure of 40 was confirmed by X-ray crystallography.

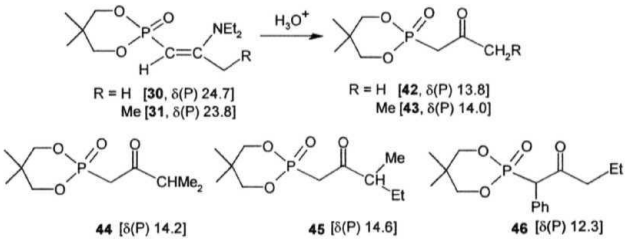
Scheme 9



19

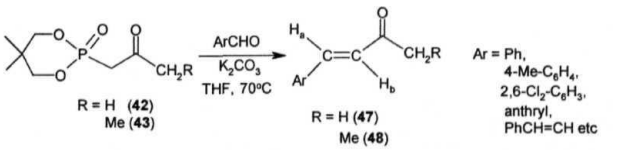
Although the *β*-enaminophosphonates 30-31 could be isolated, they are readily hydrolyzed by 2N HC1 to form the /?-ketophosphonates 42 and 43 (Scheme 10). In fact, we were able to isolate the *β*-ketophosphonates 44-46 also although the corresponding enaminephosphonates could not be isolated from the reaction of 21-23 with diethylamine.

Scheme 10



Compounds 42-46 are interesting as reagents for HWE reaction and may be useful for complexing with metals; we have restricted ourselves to the former in this study. Our initial attempts of the HWE reaction using NaH/ THF gave either none or only very low yields of olefinic products. However, when K_2CO_3 was used in place NaH in refluxing THF, the reaction proceeded smoothly to afford the (*E*)-*α*,*β*-unsaturated ketones 47 (9 examples) and 48 (8 examples) in moderate to high yields (Scheme 11).

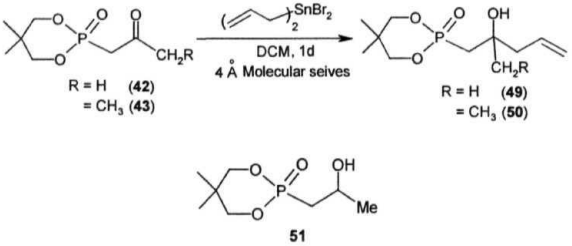
Scheme 11



The *β*-ketophosphonates 42 and 43 were allylated by diallyltin dibromide to produce the corresponding *β*-hydroxyphosphonates 49 and 50. We found that 42-43

reacted with diallyltin dibromide at room temperature in dichloromethane *in the absence of a Lewis acid* to give β-hydroxyphosphonates (Scheme 12) in yields of 40-60%. The β-hydroxyphosphonate (51) is also synthesized by the reduction of *p*-ketophosphonates 42 with $NaBH_4$

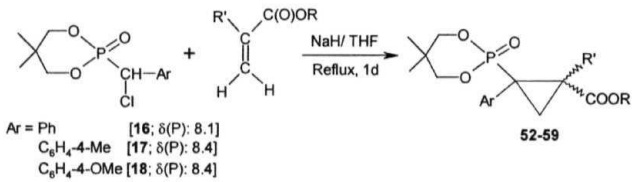
Scheme 12



(c) *Cyclopropyl **phosphonates** via Michael addition*

The cyclopropyl phosphonates **52-59** have been prepared by treating the *a*-chlorophosphonates **16-18** with electron-deficient alkenes using THF as the solvent under reflux conditions (Scheme 13). The cyclopropanation takes place *via* Michael addition followed by the cyclization. The compounds are interesting substrates for ring-opening reactions leading formally to substituted phosphonic acids.

Scheme 13

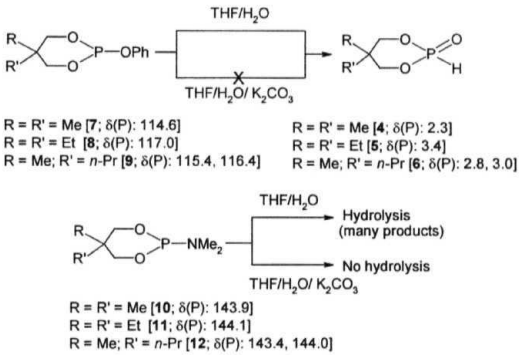


(ii) Hydrolysis of Cyclic Phosphites/ Phosphoramidites and Its Inhibition-Reversible Cyclization of Acyclic Phosphonate Salts to Cyclic Phosphites

Trivalent P(III) compounds of the type $(RO)_3P$ or $(RO)_2PNR'R''$ are frequently used as precursors to organophosphonates and as antioxidants and heat stabilizers for synthetic polymers/ plastics. Hydrolysis in particular is a commonly encountered hurdle during synthesis, storage and use. In an effort to improve the hydrolytic

stablility of the phosphites by addition of basic components (stabilizer), we employed $(OCH_2CRR'CH_2O)PCl$ [R, R' - Me (1), Et (2), R = Me, R' = *n*-Pr (3)], its derivatives $(OCH_2CRR'CH_2O)POPh$ [R, R` = Me (7), Et **(8),** R = Me, R' = *n*-Pr (9)] and $(OCH_2CRR'CH_2O)PNMe_2$ [R, R' = Me (10), Et **(11),** R = Me, R' = n-Pr (12)] for the present study. Normal hydrolysis of 7-9 to lead to cyclic H-phosphonates $(OCH_2CRR'CH_2O)P(O)H$ [(R, R' = Me (4), R, R' = Et (5), R = Me, R' = *n*-Pr (6)] occurs upon addition of stoichiometric amounts of water under neat conditions (Scheme 14). When compounds 7-9 are stirred with an excess of water (3 mole equivalents) in tetrahydrofuran for 12 h, 4-6 as well as further hydrolysis products are observed [^{1}P NMR]. *An analogous reaction with water, when conducted in the presence of K_2CO_3, left 7-9 completely unaffected.*

Scheme 14

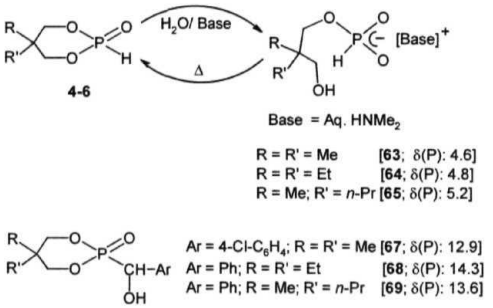


This inhibition of hydrolysis was also realized when either KF, $MgSO_4$, triethylamine, or molecular sieves was used in place of K_2CO_3, but K_2CO_3 gave the best results. Both KF and K_2CO_3 are no doubt hygroscopic, but the effectiveness of the latter in inhibiting hydrolysis is very impressive.

We also conducted competitive reactions of $(OCH_2CMe_2CH_2O)PX$ [X = Cl (1), NMe_2 **(10)]** with a mixture of water and a phenol to ascertain whether any mechanistic contribution is there or not in the inhibition of hydrolysis by K_2CO_3. Under these conditions, the phenol reacts preferentially to give the phenoxy derivatives 7-9. We believe that these observations can be put to practical use while handling P(III) compounds in laboratory and as well as in industrial conditions.

Reversible hydrolysis of 4-6, examples of which are very rare, in the presence of an amine base were also performed. The first stage hydrolysis products 4-6 undergo facile hydrolysis in the presence of aqueous amines to the acyclic phosphonates 63-66 (90-95% yield) [Scheme 15]. An X-ray structure of 66 [base = N, N-dimethylaminopyridine (DMAP)], that exists as a hydrogen-bonded dimer, confirms the identity of these products. What is perhaps a lot more interesting is that the *salts* 63-65 *can be thermally converted back to the cyclic phosphites* 4-6; this is readily confirmed by ^{31}P NMR as well as derivatization of 4-6 to the Pudovik products 67-69 *(cf.* Scheme 15).

Scheme 15



Chapter 6 gives details of the experimental procedures.

PART A

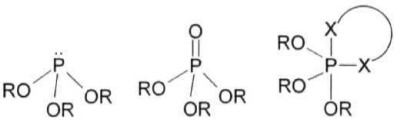
CYCLO ADDITION AND OXIDATIVE ADDITION REACTIONS OF PHOSPHORUS(III) COMPOUNDS

CHAPTER 1

INTRODUCTION

Phosphorus, in the form of various compounds, is present in all forms of life where it constitutes roughly 1 % of the total weight. It is also widely distributed in the form of phosphates in soils, rocks, oceans, food etc.[1] In living beings, phosphorus compounds are involved in various metabolic activities such as energy transfer, nerve function, heredity (via DNA) and in the production of bones and teeth.[2] Unlike the predecessor nitrogen, phosphorus exhibits two stable valencies, three and five, but only the latter is found in compounds found in nature.

Synthetically, P(III)* compounds 1.1** can be oxidized to P(V) compounds by various routes including air-oxidation.[3] In this process, new bonds to phosphorus are formed leading to either heterocyclic or acyclic P(V) derivatives (e.g. **1.2**-**1.3**).

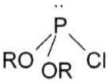


1.1 **1.2** **1.3**

* *Note:* In this thesis, P(III) refers to phosphorus in trivalent state and P(V) refers to phosphorus in pentavalent state.

***A note on the numbering of compounds:* In the introductory chapters 1 and 4, compounds are numbered as 1.1, 1.2, 4.5 etc. In other chapters bold Hindu-Arabic numerals (1, 2, 5, etc.) are used for compounds prepared in the present study; literature compounds as well as intermediates/ transition state species are denoted by Roman numerals (I, II, etc.) in the order in which they appear in the text.

Chlorophosphites 1.4, like the phosphite esters 1.1, also possess trivalent tricoordinate phosphorus.[3b] By reacting with primary/ secondary amines, they pave way for various phosphoramidites [$(RO)_2P$-NR'R"]. Such chloro and amino derivatives are valuable intermediates in the synthesis of other tri-, tetra- and pentacoordinate phosphorus compounds.[3b,3c]

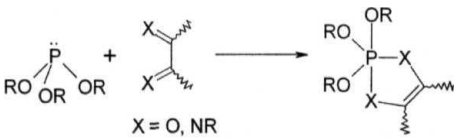


1.4

Apart from the presence of a lone pair of electrons on the phosphorus atom, it is the presence of reactive substituents on phosphorus that confer upon P(III) compounds a high degree of reactivity. In the present work, we restrict ourselves to cycloaddition/ oxidative-addition reactions. Two common ways in which phosphites undergo cycloaddition reactions are the following:

(i) Both the lone pair of electrons as well as other reactive substituents like -CN2, -N3, or -NCO present on the phosphorus atom participate in dipolar cycloaddition reactions by reacting with various dipolarophiles.[4] The phosphorus heterocycles initially formed in these reactions need not necessarily be the final products, but can react further or undergo insertion/ elimination reactions leading to new types of compounds.[5]

(ii) Just the lone pair of electrons present on the phosphorus atom is involved in (4+1) cycloaddition with reactants like 1,2-diketones, ketoimines and other α,β-unsaturated compounds.[6] The final products formed are the pentacoordinate phosphoranes 1.5.[6,7] Hence these reactions are called as oxidative addition reactions, wherein the reactants oxidatively add on to the phosphorus atom. Four atoms from the diketone/ ketoimine, and the phosphorus atom of the phosphite take part in this [4+1] cycloaddition.



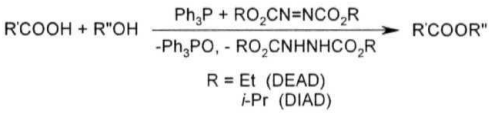
1.5

Features in the addition reactions of phosphorus(III) compounds with dialkyl azodicarboxylates (in the context of Mitsunobu reaction) are a point of interest in this work; in Section 1.1 a survey of relevant literature is presented. This is followed by literature pertinent to dipolar cycloaddition reactions in Section 1.2. A brief description of structural features of pentacoordinate phosphorus compounds is given in Section **1.3.**

1.1 Reactions of phosphorus (III) compounds with dialkyl azodicarboxylates (in the context of Mitsunobu reaction)

The triphenylphosphine (TPP)/ diethyl azodicarboxylate (DEAD) or diisopropyl azodicarboxylate (D1AD) mediated esterification of an acid with clean inversion of configuration for asymmetric alcohols, known as the Mitsunobu reaction, has proven useful in a wide variety of synthetic applications. This reaction has been subjected to considerable mechanistic scrutiny in recent years (Scheme 1.1).[8]

Scheme 1.1



Mechanistic discernment of the Mitsunobu reaction with respect to the initial redox chemistry has received substantial documentation.[9] Several other key features of this important reaction have been investigated by various groups.[10-12] The reaction is believed to proceed through the following steps (Scheme 1.2).[8a]

(a) Addition of phosphorus(III) compounds to DEAD/ D1AD to lead to the Morrison-Brunn-Huisgen intermediate I,

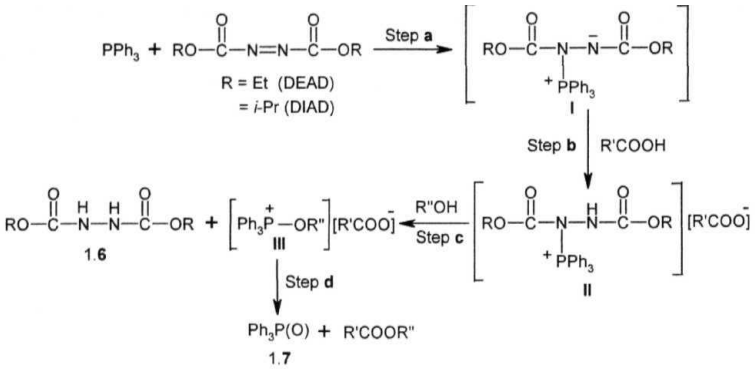
(b) Protonation of I,

(c) Formation of the alkoxy phosphonium salt **III** and

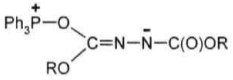
(d) S_N2 Displacement of R'COOR" from **III.**

Details of these steps are discussed below.

Scheme 1.2



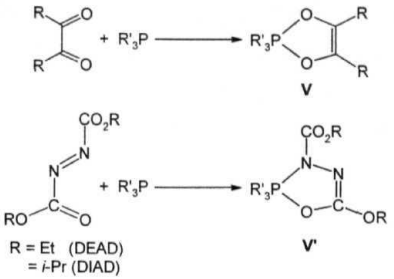
(a) *Addition of* ***phosphorus(III)*** *compounds to DEAD/ DIAD:* In earlier literature, Morrison reported that Michael type nucleophilic addition reaction of PPh_3 and DEAD/ DIAD leads to the formation of betaine I,[13] although Ginsburg *et al.* proposed the alternate O-phosphonium salt IV.[14] Later, Brunn and Huisgen have conclusively shown the formation of betaine I and hence the latter is called the Morrison-Brunn-Huisgen [MBH] betaine I.[15] This step is of primary interest in the present work.



IV

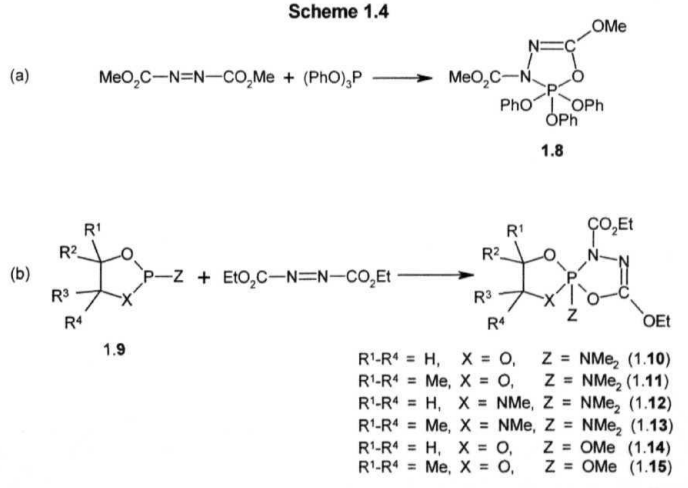
However, looking at the same reactants from a different perspective, we note that (i) P(III) compounds undergo facile cycloaddition reactions with a variety of 1,2-diketones (or ketoimines) to afford pentacoordinate phosphoranes of the type V (Scheme 1.3),[16] and (ii) dialkyl azodicarboxylates are analogous to 1,2-diketones (or the related 1,2-ketoimines). Thus it is possible that in the reaction of P(III) compounds with dialkyl azodicarboxylates, N,O-cycloaddition could take place to give pentacoordinate phosphorus intermediates V that are analogous to V.[17] Isolation/ identification of such species could support the possible intermediacy of the P-0 bonded tetracoordinate intermediate of the type **IV**.[15]

Scheme 1.3

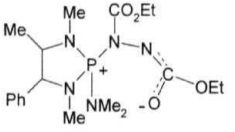


Earlier literature reveals that there does exist a different mode of addition of DEAD/ DIAD to tricoordinate phosphorus compounds forming products other than the traditional MBH betaine **I**.[1] Arbuzov *et al* reported that triphenyl phosphite reacts with dimethyl azodicarboxylate via N-O cycloaddition to give the pentacoordinate phosphorus compound 1.8 (Scheme 1.4a).[17a] Later, Gonclaves *et al* prepared a series of pentacoordinate phosphoranes 1.10-1.15 derived from the reaction of DEAD with various phosphites (Scheme 1.4b). However, none of these phosphoranes has been structurally characterized by X-ray crystallography.[17b]

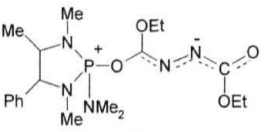
Scheme 1.4



Tetracoordinate species 1.16 and 1.17 have also been proposed in the reaction using phosphoramidites, but no X-ray structure is available. Formation of tetracoordinate (betaine I, 1.16-1.17) and pentacoordinate phosphoranes (1.11-1.15) in the first step of Mitsunobu reaction suggests that the nature of the intermediates could vary depending upon the electronic environment around the P(III) precursor.



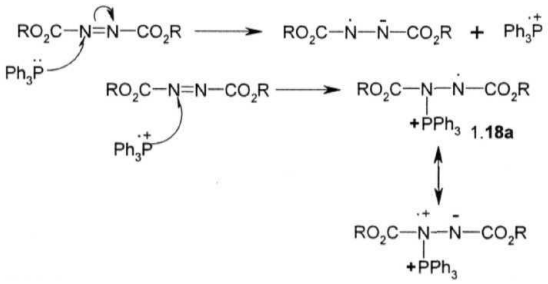
1.16



1.17

Various groups have monitored the progress of Mitsunobu esterification by P NMR, and have strongly supported formation of the betaine I.[8,19] EPR spectroscopy suggests formation of the betaine I can also occur through radical cations of type RO_2C-N-(Ph_3P^+)-N$^{\bullet}$-CO_2R (1.18a) (Scheme 1.5).[21] Additionally, it is noted that treatment of DIAD with tributylphosphine gives a much weaker EPR signal relative to that with triphenylphosphine, while a much more intense signal could be detected in the reaction of DIAD with tris(dimethylamino)phosphine. As regards the esterification using PPh_3/ DIAD, it is reported that when the acid is added last, or when a large excess of azodicarboxylate and triphenylphosphine are used, radicals are certainly generated prior to the formation of the betaine 1.[23]

Scheme 1.5



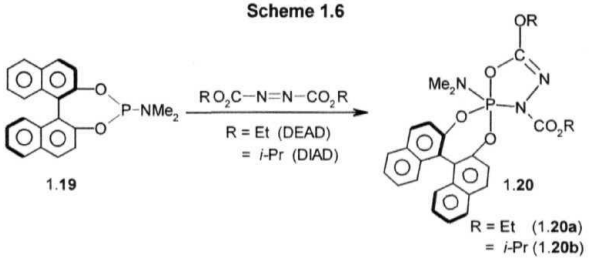
1 18b

The use of tri-*n*-butyl phosphine in place of the triphenyl phosphine offers different results in the coupling reaction of N-hydroxyphthalimide and 2,3,4,6-tetra-*O*-acetylglucofuranose with DEAD.[24] It is also observed that in the formation of 2-

oxazolidones from CO_2 and ethanolamines using a Mitsunobu protocol, the use of triphenylphosphine and tributylphosphine affords different isomers[24] thus posing an intriguing question on the nature of the intermediate involved. Isolation of such intermediates will be an interesting aspect to study further.

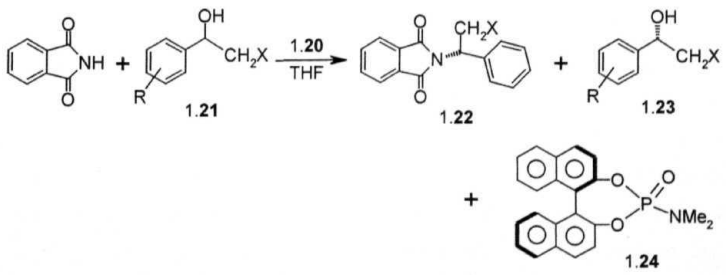
Recently it is also shown that the dimethylamino derivative 1.19 reacts with DEAD/ DIAD to yield the pentacoordinate phosphoranes **1.20**, and not the betaine I (Scheme 1.6). This species also has not been characterized by X-ray crystallography. Compound 1.20 *does participate in the Mitsunobu coupling* between alcohol and acid.[18]

Scheme 1.6



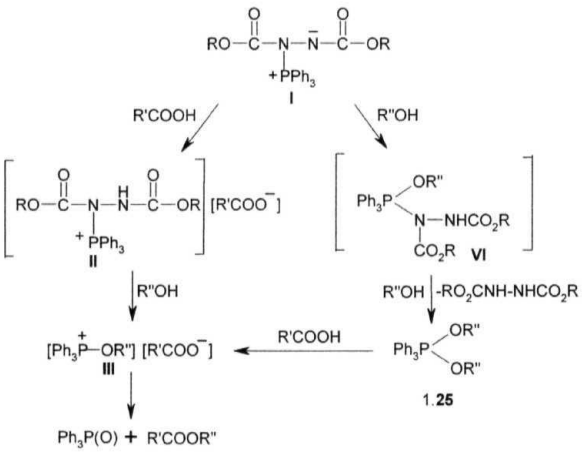
Using a similar protocol, enantioselective reaction of racemic secondary alcohols with phthalimide in the presence of **1.20** is effected resulting in unreacted, enantiomerically enriched alcohols (Scheme 1.7).[25] These results also suggest that even when the initial products of the P(III) compound with DEAD/ DIAD are different from a betaine of type I, Mitsunobu reaction takes place smoothly, thus leaving room to explore other P(III) compounds for specific reactions.

Scheme 1.7



(b) ***Profanation*** *of* ***betaine I.*** The betaine I formed in the first step can react with either alcohols/ or carboxylic acids giving phosphoranes or oxophosphonium ions respectively. The order of addition of the acid and the alcohol to betaine I in the Mitsunobu esterification has a profound effect on the reaction pathway, implying potential duality of the mechanism.[9,19] Thus, different types of phosphorus intermediates could be involved depending upon the order of addition. The intermediate formed by the reaction of acid R'COOH and the betaine I is a species of type $[RO_2CN\text{-}(P^+Ph_3)\text{-}NHCO_2R][R'COO^-]$ (II, Scheme 1.8);[10] the stability of this species may be enhanced by hydrogen bonding. Oxaphosphorane intermediates $Ph_3P(OR")_2$ (**1.25**) are formed by the reaction of I with alcohols R"OH (Scheme 1.8).[9]

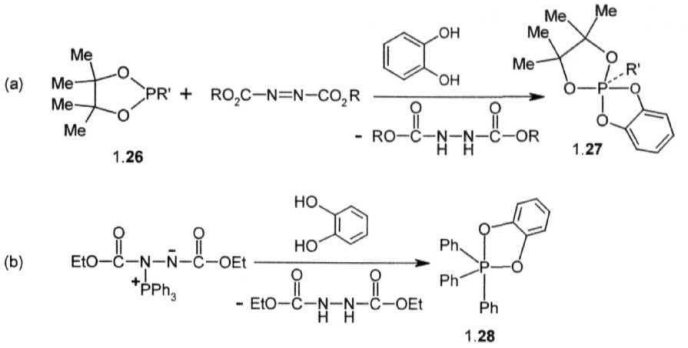
Scheme 1.8



Initial addition *of* ***alcohols/diols****:* Dialkoxytriphenylphosphoranes (1.25), dialkoxytributylphosphoranes and diaryloxytriphenylphosphoranes can be readily prepared from the reaction of betaine I with alcohols or phenols.[9a-d,10d,20,26-34] Walker has stated that a dialkoxytriphenylphosphorane is the only intermediate in the Mitsunobu reaction in the special case where the acid is added last.[26] An elegant use of this feature was reported by Trippett and coworkers for the synthesis of various cycic phosphoranes **1.27-1.28** (Scheme 1.9).[32] Later, this reaction was also utilized for probing the mechanism of the Mitsunobu reaction.[9] In fact, Mitsunobu protocol offers

a simple procedure for the preparation of five (with 1,2-diols),[32,35] six (with 1,3-diols) and seven membered (with 1,4-diols) dioxytriphenylphosphoranes.[36]

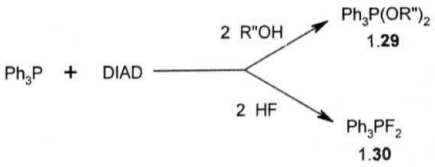
Scheme 1.9



It will be interesting to study these reactions (addition of diols to betaine I) when phosphorus bears a functionality (NCS, NCO, N3) to see whether the functional groups remain intact or involve themselves in the reaction.

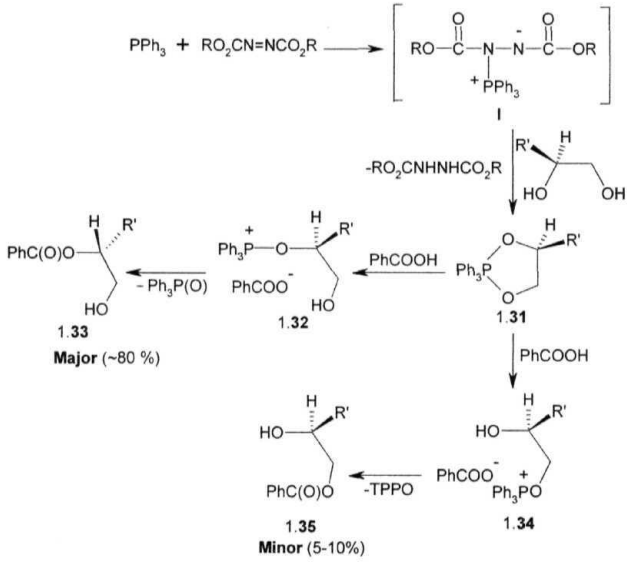
Besides the synthesis of oxyphosphoranes as described above, Mitsunobu reaction is also useful to prepare difluorophosphorane of type R3PF2 from a range of trivalent phosphorus compounds under mild conditions (Scheme 1.10).[37] Previous methods for the preparation of R3PF2 involved the use of reagents such as dimethylaminosulfur trifluoride,[38a] hexafluoroacetone,[38b] dinitrogen tetraflouride,[38c] sulfur tetraflouride,[38d] phenyl carbamoyl fluoride,[3911] and difluorodiaziridine.[39b] The method for the synthesis of R3PF2 under Mitsunobu conditions is cheap and the reagents can be handled very easily.

Scheme 1.10



Chemoselectivity: When unsymmetrical 1,2-diols (e.g. 1,2-propanediol and 1-phenyl-1,2-ethanediol) are used in the Mitsunobu reaction, monoesterification occurs affording thermodynamically least stable secondary ester as the major product (Scheme 1.11).[40,41] 1,3,2 λ^5-Dioxaphospholane **1.31** is initially formed by the addition of diol to the betaine I, and is assumed to be the key intermediate. Hydrogen bonding interactions and ultimately proton transfer from the acidic component to the least hindered oxygen of phospholane **1.31** initiates chemoselective ring opening to form the C-2 secondary phosphonium salt. Finally, attack of benzoate anion on the carbon center, followed by elimination of triphenylphosphine oxide (TPPO) affords predominantly the C-2 benzoate with inversion of configuration.[42]

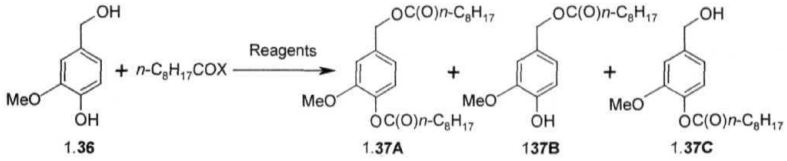
Scheme 1.11



When a substrate containing both aliphatic and aromatic hydroxyls is involved, the Mitsunobu reaction serves as an extremely elegant tool to distinguish them in the esterification reactions.[43] Table 1.1 vividly demonstrates poor discrimination between the hydroxyls bound to aliphatic and aromatic carbons by other reagents when compared to the Mitsunobu protocol; only ytterbium triflate promoted esterification gives excellent chemoselectivity (however with only modest

yield). Mitsunobu conditions appear to be the best in the synthesis of vanillyl nonanoate.[43]

Table 1.1 Synthesis of vanillyl nonanoate under various reaction conditions.

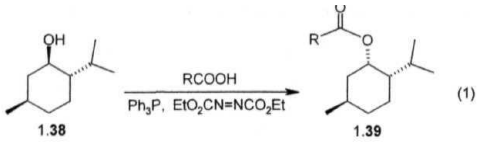


1.36 1.37A 137B 1.37C

X	Reagents	1.37A (%)	**1.37B (%)**	**1.37C(%)**
Cl	pyridine	22	29	7
OCOR	pyridine	17	25	9
OPiv	TEA*, DMAP*	36	10	
OH	DCC*, DMAP*	4	**11**	20
OH	$Yb(OTf)_2$, THF	-	19	
OH	**DIAD, PPh_3, THF**	-	**67**	

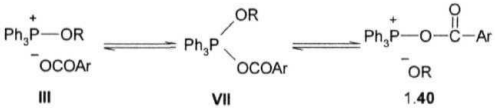
TEA Triethylamine
DCC N,N'-Dicyclohexylcarbodiimide
DMAP 4-N,N-Dimethylaminopyridine

***Initial addition** of acid **and** effect of strength of **the** acid:* Protonation of the MBH betaine I can also be achieved by the addition of variety of carboxylic acids as mentioned previously.[44] Mitsunobu inversion of secondary alcohols are dramatically influenced by the strength of the acidic component (protonating agent). Stronger acids generally provides higher yields of the inverted product 1.39.[45] A similar effect is also demonstrated by other groups while comparing chloroacetic acid, benzoic acid and acetic acid (using menthol as alcohol; eq. 1). Better yields of the esters are obtained by starting with chloroacetic acid.[45-48]



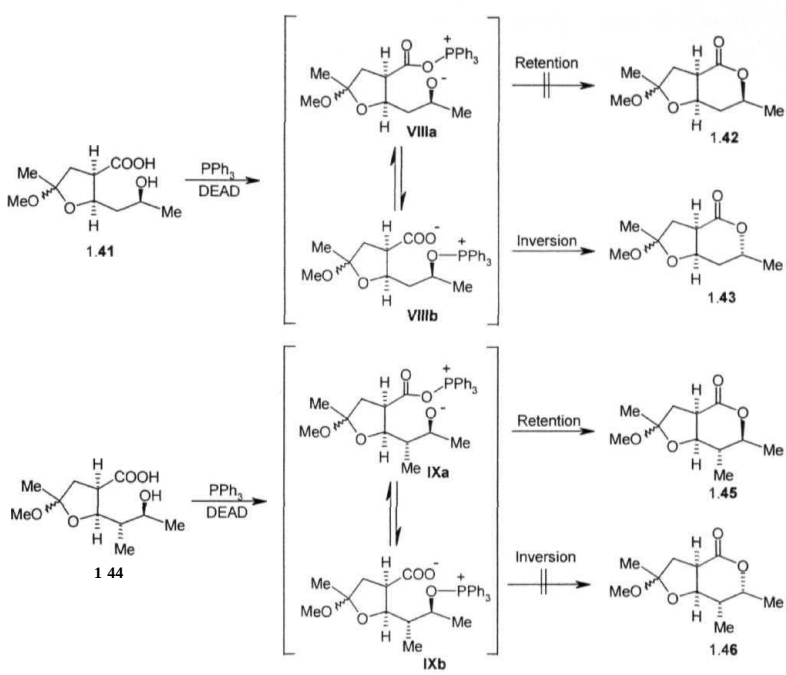
(c) *Formation of the alkoxy* ***phosphonium*** *salt III:* The MBH betaine I or phosphorane **1.25** *(cf.* Scheme 1.8) reacts with an acid or an alcohol to produce the alkoxy phosphonuim salt **III** *(cf.* Scheme 1.8). When a sterically hindered alcohol and an acid of high pK_a (weak acid) are used in the Mitsunobu reaction, more of acid anhydride and less of the desired ester are formed.[49] It is suggested that one of the reasons for the lower yields is the competitive formation of acid anhydride[49] via acyloxyphosphonium salts **1.40** (Scheme 1.14). It is proposed that there is an equilibrium between alkoxyphosphonium intermediate **III** and acyloxyphosphonium salt **1.40** through a phosphorane intermediate **VII.** Equilibrium shifts towards **III** or **1.40** depending on the pK_a of the acid (Scheme 1.14). Strong acids give an increased preference for the formation of **III.**[49]

Scheme 1.14



Retention of configuration: In general, Mitsunobu reaction occurs typically with inversion of configuration in the esterification reaction using secondary alcohols, but in some cases where a very sterically hindered alcohol and a moderately strong acid are used, retention in configuration is observed.[50,53] A possible rationale for this observation by invoking the equilibrium between **Villa** and **VIIIb (IXa** and **IXb)** has been provided by Deshong *et al* (Scheme 1.15).[54]

Scheme 1.15



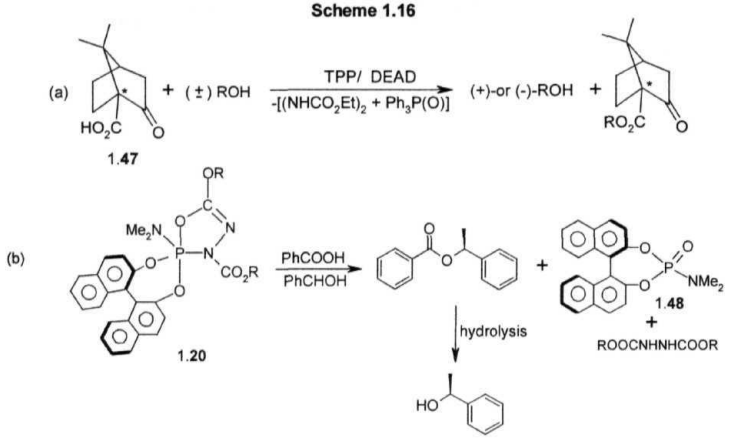
(d) ***SN2*** *Displacement of R'COOR" from III:* S_N2 Displacement of R'COOR" from III or analogous species results in the inverted product (Scheme 1.15).

1.11 Synthetic applications of Mitsunobu reaction

A few applications of the Mitsunobu reaction have already been discussed above. The Mitsunobu reaction has found widespread use in many fields because of its high reliability and extensive applicability.[855,57] Till recently, the chiral recognition and enantioselectivity were the least explored aspects of the Mitsunobu reaction. The design of chiral version of the Mitsunobu reaction is an interesting exercise. Among many available possibilities, the chiral auxiliary can be any one of the phosphine/ phosphite used, azodicarboxylate itself or the acidic component used. Scheme 1.16 demonstrates the kinetic resolution of the secondary alcohols with **1.47** (a chiral acidic component) and 1.20 (phosphorane derived from a chiral phosphite) in the

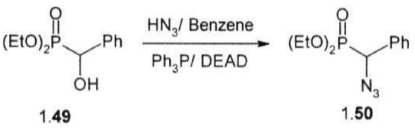
Mitsunobu reaction.[58-59,18b] Use of the acidic component, as a chiral auxiliary is the simplest of the all the possible choices.[58]

Scheme 1.16



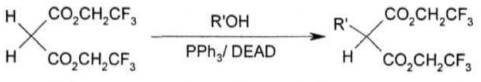
Diethyl 1-azido benzylphosphonate 1.50 is obtained in high yield in the presence of Ph_3P/ DEAD (Mitsunobu conditions) by the reaction of diethyl-1-hydroxy benzylphosphonate **1.49** with hydrazoic acid (Scheme 1.17).[60-64]

Scheme 1.17



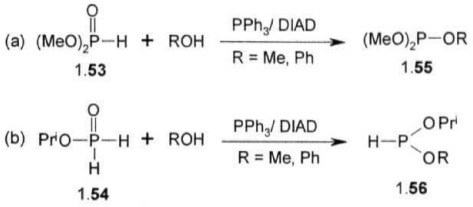
Alkylation of compounds containing active methylene group, like bis(2,2,2-trifluoroethyl)malonate (**1.51**) under Mitsunobu conditions provides the product 1.52 in excellent yields (Scheme 1.18).[65-67]

Scheme 1.18



Mitsunobu reaction can also be used to convert (pentavalent) dimethyl phosphonate **1.53** and isopropyl phosphinate **1.54** to (trivalent) phosphite **1.55** and dialkyl phosphinite 1.56 respectively. This route provides an alternative to the phosphorylation of alcohols by the use of dibenzyl and di-*tert*-butyl phosphoramidites (Scheme 1.19).[68-69]

Scheme 1.19

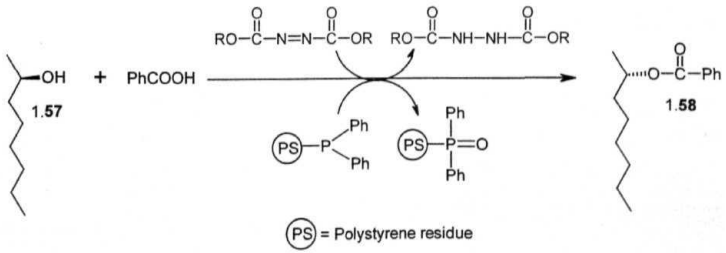


The versatility of the Mitsunobu reaction is also shown by replacing the traditionally used acidic component with a variety of nucleophiles such as metal halides (LiBr),[55a] silanols,[55b] amides/ imides,[55c] nitronates,[55d] fluorinated alcohols[55e] and mercury (II) or zinc halides,[55f-g] thus rendering the reaction widely applicable in organic synthesis.

1.12 Modified Mitsunobu reaction

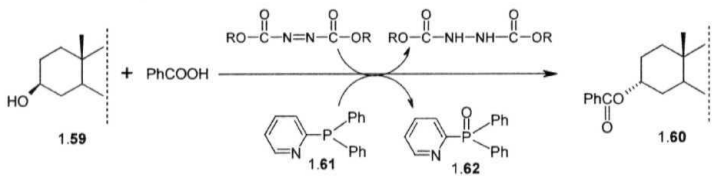
Separation of phosphine oxide as a by-product often haunts the isolation of the desired products in the traditional Mitsunobu reaction. When polystyryl diphenylphosphine is used in the Mitsunobu reaction in place of Ph_3P, the resulting phosphine oxide is anchored to the polystyrene resin and can be easily removed by means of filtration. Thus, the chiral 2-octanol (1.57) reacts with benzoic acid with complete inversion to give the corresponding ester **1.58** that can be separated from the resin (Scheme 1.20).[70-72]

Scheme 1.20



An alternative to remove the phosphine oxide formed is by introducing the basic functional group in the phosphine. Using diphenyl(2-pyridyl)phosphine **1.61** in place Ph_3P in the Mitsunobu reaction of cholestane 3α-ester **1.59** with benzoic acid produced the ester **1.60** in good yields. The byproduct phosphine oxide 1.62 is easily removed by washing with 2M HC1 (Scheme 1.21).[73]

Scheme 1.21

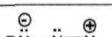
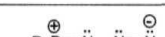
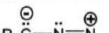
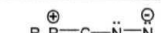
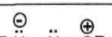
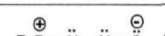


1.2 Dipolar cycloaddition reactions of phosphorus(III) compounds

The two most important classical cycloaddition reactions, Diels-Alder and 1,3-dipolar cycloaddition, occur usually through a concerted mechanism. 1,3-Dipolar cycloaddition reactions constitute a large class of synthetically useful processes and offer a remarkably wide range of utility in the construction of five membered heterocycles.[74] Organic isocyanates, azides, nitriles etc are valuable substrates in such cycloadditions and behave typically as 1,3-dipoles toward dipolarophiles.

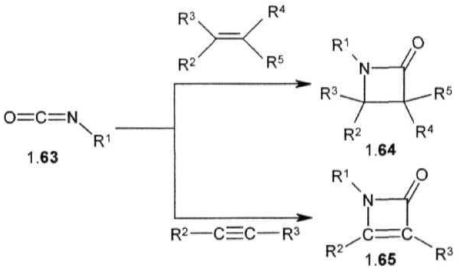
The classical reactivity of organic functionalities can be dramatically altered by the presence of electron withdrawing groups such as acyl,[75a] sulfonyl[75b] and phosphoryl groups.[76] The lone pair of electrons on the phosphorus atom can participate in the cycloaddition reactions wherein λ^3-phosphorus compounds are converted into λ^5-phosphorus compounds. Thus, the phosphorus substituent is of particular importance as a reactive peripheral functional group in cycloaddition reactions. In some cases, due to the presence of phosphorus, the organic 1,3-dipole transforms into 1,4-dipole (Table 1.2).[76]

Table. 1.2. Dipolar nature of various functional groups

Classical organic functional group	1,3-Dipolar nature	Phosphorus substituted functional group	1,4-Dipolar nature
	1,3-(N,N) dipole		1,4-(P,N) dipole
	1,3-(C,N) dipole		1,4-(P,N) dipole
	1,3-(N,C) dipole		1,4-(P,C) dipole

The organic isocyanate **1.63** undergoes [2+2] cycloaddition with activated olefins or acetylenes to lead to unstable azetidinone **1.64** or azetones **1.65** (Scheme 1.22) as the primary products.[77]

Scheme 1.22

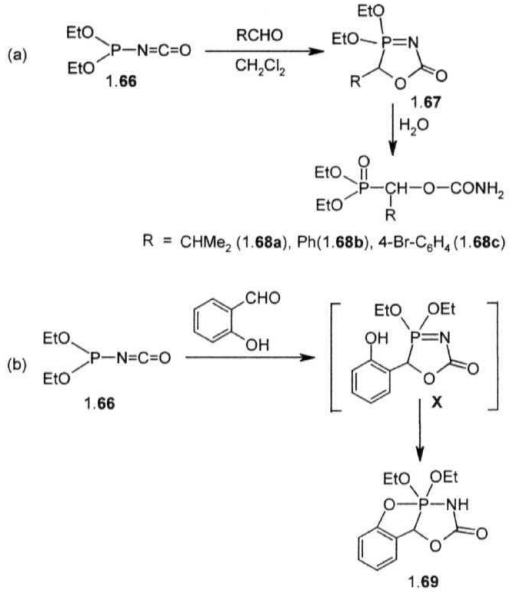


By contrast, dialkyl isocyanatophosphites [(RO)2P-N=C=O] and their isothiocyanato analogues [$(RO)_2$P-N=C=S] act as typical 1,3-(P,C) dipoles in reactions with dipolarophiles.[78-83] In most of the cases this is best explained in terms of nucleophilic attack of the phosphino residue at the electrophilic carbon of the dipolarophiles leading to phosphorus based heterocycles. The diverse reactivity of trivalent phosphorus compounds containing N=C groups makes it possible to synthesize a wide variety of both cyclic and acyclic tetra and pentacoordinate phosphorus compounds.[78] Some of these are outlined below.

Diethoxy isocyanatophosphine 1.**66** reacts with a variety of aldehydes at low temperatures (-10°C) to form azophospholines 1.67 via 1,3-(P,C) dipolar

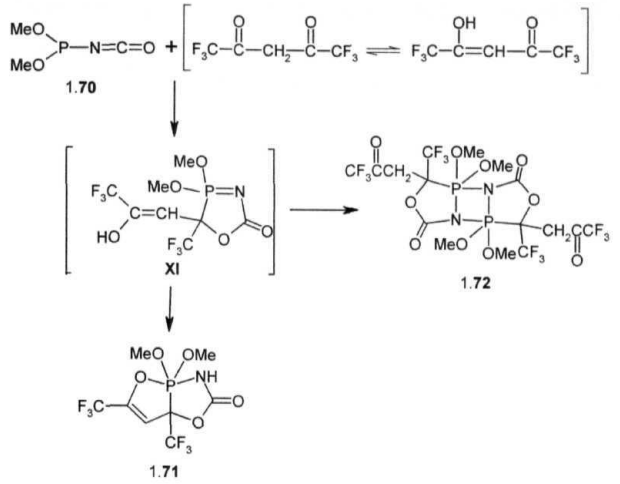
cycloaddition. Compounds 1.67 thus formed are not stable and are easily hydrolyzed to give acyclic C-phosphorylated carbamates 1.68 (Scheme 1.23a).[79] However, the reaction of diethoxyisocyanatophosphine 1.66 with salicylaldehyde afforded stable phosphoranes 1.69 (Scheme 1.23b).[79]

Scheme 1.23



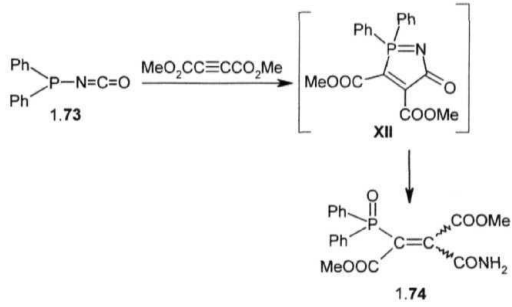
The reaction of dimethoxyisocyanatophosphine 1.70 with hexafluoroacetylacetone (β-diketone) proceeds in a fashion similar to that with aldehydes resulting in the formation of azaphospholine XI that dimerises to crystalline bi- and tricyclic pentacoordinate phosphorus compounds 1.71 and 1.72 (Scheme 1.24).[80]

Scheme 1.24



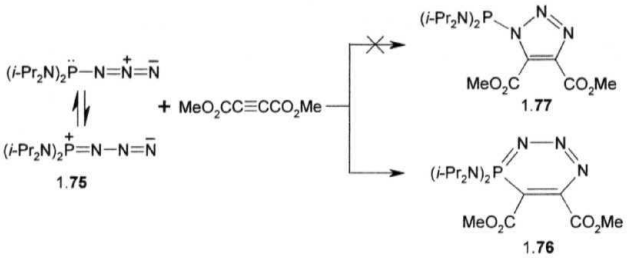
Diphenylisocyanatophosphine 1.73 react with DMAD to form the unstable azaphosphole XII, which hydrolyzes to give the tetracoordinate (P=O) compound 1.74 (Scheme 1.25).[81]

Scheme 1.25



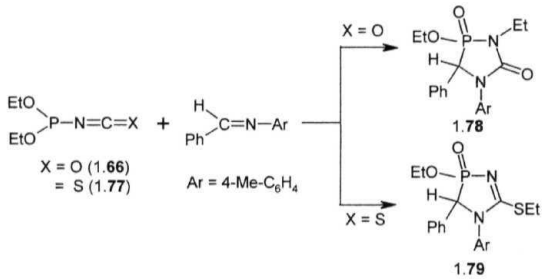
Isoelectronic P(III) azide [$(i\text{-PrN})_2$P-N=N=N] (1.75) reacts with dipolarophile such as DMAD to lead a novel heterocylcle 1.76 featuring a six membered heterocycle formed by the 1,4-(P,N) dipolar addition of acetylene (Scheme 1.26).[84]

Scheme 1.26



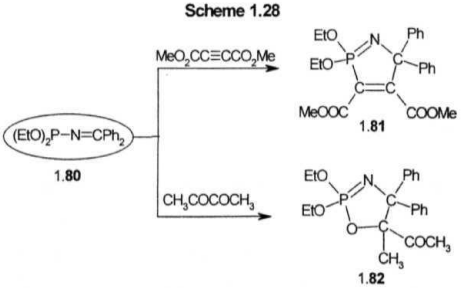
Diethoxyisocyanatophosphine reacts with imines under forced conditions (80-90°C) to form diazaphospholidines **1.78**; instead, diethoxyisothiocyanatophosphine reacts with imines to give diazaphopholine **1.79** (Scheme 1.27).[83]

Scheme 1.27



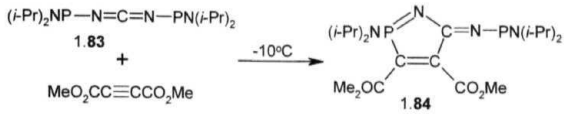
In most of the cases, (diphenylmethyleneamino)diethylphosphite 1.80 behaves as a 1,3-(P,C) dipole and react with dipolarophiles leading to phosphorus-based heterocycles. Two examples are shown in Scheme 1.28.[79,82,85]

Scheme 1.28

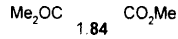


Similarly, Bis[bis(diisopropylamino)phosphino] carbodiimide 1.83 reacts with DMAD to afford the cycloadduct **1.84** in high yields, proving the 1,3-(P,C) dipolar nature of **1.83** (Scheme 1.29).[86,87]

Scheme 1.29



MeO2CC≡CCO2Me



1.84

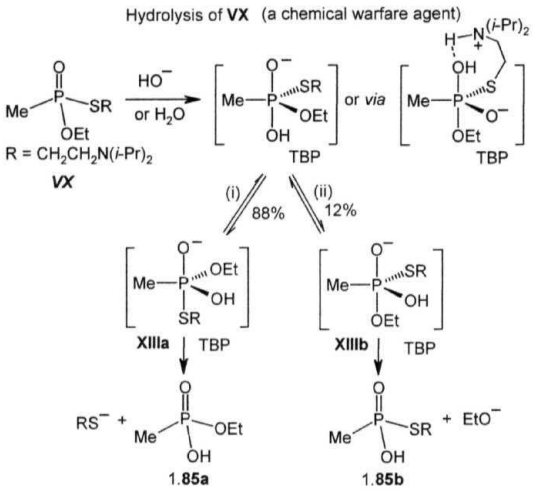
It is clear from the above details that the dipolar cycloaddition a reaction of phosphorus(III) compounds with dipolarophiles is still a fertile ground to explore further.

1.3 Reactions of P(III) compounds with *o*-chloranil and other diketones/ ketoimines - Pentacoordinate phosphorus compounds

P(III) compounds undergo facile cycloaddition reactions with a variety of 1,2-diketones (or ketoimines) to afford pentacoordinate phosphoranes as mentioned above (*cf.* Scheme 1.2, Section 1.1).[6] Another useful method involves the addition of a diol to phosphites in the presence of N-chloro diisopropylamine.[7,88] These methods have been discussed sufficiently in earlier literature.[6,7,88] The pentacoordinate phosphorus compounds thus obtained have a unique place in phosphorus chemistry and biochemistry because in numerous nucleophilic substitution reactions at tetrahedral P(V) center an unstable intermediate (or a transition state species) involving pentacoordinate phosphorus is often assumed.[88-91] Stereochemistry of the products formed would depend on the disposition of the substituents in the transition state species just before its break-up, and hence several investigations have been directed at finding the relative tendency of a group to occupy the apical site (apicophilicity) in the commonly assumed trigonal bipyramidal geometry;[89(b),92] even in neutral molecules the question of apical/ equatorial preferences is a topic of interest.[8900] For example, in the hydrolysis of exceedingly toxic nerve gas agent *VX* [*O*-ethyl *S*-(2-diisopropylamino)ethyl methylphosphonothiolate] with an alkali, a trigonal bipyramidal transition state is envisaged leading to the products **1.85a** or **1.85b** (Scheme 1.30).[93] The difference between pathways (i) and (ii) in Scheme 1.30 lies in

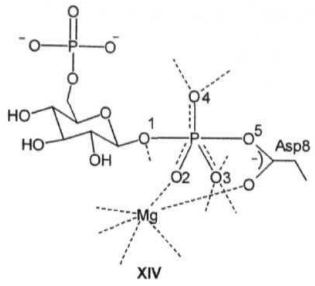
the disposition of substituents in species **XIIIa** and **XIIIb**. Whereas an –SR group is apical in **XIIIa**, an –OEt group is apical in **XIIIb**.

Scheme 1.30



Enzymatic and non-enzymatic hydrolysis of RNA, cleavage and isomerisations of the phosphodiester bonds of the RNA catalysed by Bronsted acid/base also take place via cyclic pentacoordinate trigonal bipyramidal transition state species.[94]

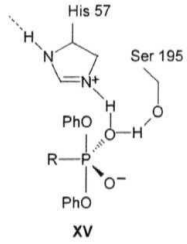
It is assumed that the phosphoryl transfer reactions such as energy transfer and DNA formation via ATP also go through the pentacoordinate phosphorus intermediate, which is formed by the nucleopilic attack at the tetracoordinate phosphorus center. The mechanism of these reactions as regards to whether the enzyme-catalyzed transfer of phosphate is a dissociative or associative process is a long disputed problem.[90a] Recently Lahiri *et al* have identified the pentacoordinate phosphorus intermediate **XIV** in a phosphoryl transfer reaction (Fig.1.1).[95]



XIV

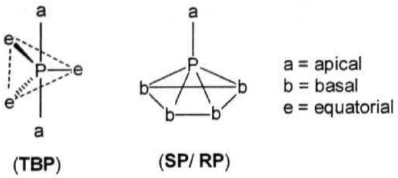
Fig. 1.1 A simplified drawing of the P-glucose-l,6-(bis) phosphate intermediate XIV structure in the active site of β-phosphoglucomutase. The extra hatched-line bonds from 0(1), O(3) and O(4) at the pentacoordinated phosphorus are hydrogen bonds.

In a study on the inhibition of human a-thrombin by Deadman and coworkers on (α-aminoalkyl) phosphonate tripeptide have reported the existence of pentacoordinate phosphorus intermediate XV (X-ray).[96] The histidine and serine residues are parts of the enzyme, a-thrombin.



XV

As regards geometry at pentacoordinate phosphorus, between trigonal bipyramidai (TBP) and square/ rectangular pyramidal (SP/ RP) [leaving out the unobserved planar geometry], the former is found in most of the compounds.[97] Due to this, the mechanism of substitution reactions at a tetrahedral P(V) center is most often explained based on the trigonal bipyramidai geometry at the phosphorus center in the transition state; inter-conversion among various TBP forms is assumed to take place *via* a SP/ RP species.



Due to the difficulty in synthesizing ionic species such as **XIII** (Scheme 1.30), **XIV** and XV in the laboratory, an alternative approach is to use the cyclic pentacoordinate phosphoranes as models for transition state species in the nucleophilic substitutions at the tetracoordinate phosphorus center.[99-102] This approach is used by several researchers (and is followed in the present study).

Available literature reveals that two aspects, apicophilicity (a thermodynamic aspect) and intramolecular exchange processes (pseudorotation, a kinetic aspect) are important for pentacoordinated phosphorus compounds.[89-104] A few points on these are outlined below.

1.31 Apicophilicity and ring strain

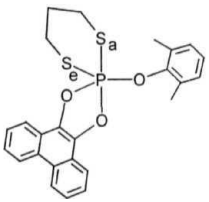
The relative preference of the substituents for the apical positions as opposed to the equatorial positions in the trigonal bipyramidal phosphorus is termed as "apicophilicity".[89b,103] This aspect may be useful in ascertaining the stereochemistry of the products in the nucleophilic substitution reactions at a tetrahedral P(V) center wherein it is necessary to be able to assess the relative stability of various TBP's that can be formed. Both experimental results[101,105] and theoretical calculations[106] have indicated that many factors influence the apicophilicity.

The apicophilicity of a group is assumed to depend on the electronegativity, π-interactions (with phosphorus), and steric factors with high apicophilicity being favored by high electronegativity and small size.[107] Corbridge[89b] and Trippett[107] have established the experimental apicophilicity scales independently, based on the free energy of activation for pseudorotation of pentacoordinate phosphorus compounds using dynamic NMR techniques, which is of kinetic nature. Recently Akiba *et al.* deduced the scale based on the activation enthalpy.[108] The three scales of apicophilicity [due to Corbridge, Trippett, Akiba] are given in Table 1.3.

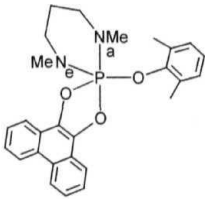
Table 1.3 Different scales of apicophilicity

	Based on activation energy		Based on activation enthalpy
	Corbridge[89b]	Trippett[107]	Akiba[108]
Increasing Apicophilicity ⇑	F	SPh	OMe ≈ H
	OPh	OR	COMe ≈ SMe
	Cl	NR_2	NMe_2
	SMe	Ph	Me
	OMe	Me	*n*-Bu
	NMe_2		
	Me		
	Ph		

However, it is most often observed that in spirocyclic phosphoranes with a TBP phosphorus, ring constraints dominate over the electronegativity effects in apical site occupancy even for highly electronegative substituents.[10 09] In compounds **1.86** and 1.87, it can be readily seen that the more electronegative oxygen of the phenoxy group is forced to occupy the equatorial site and the less electronegative sulfur and nitrogen moieties are occupying the apical positions.



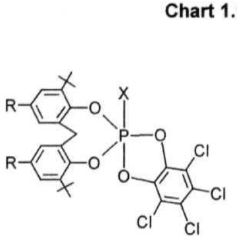
1 86

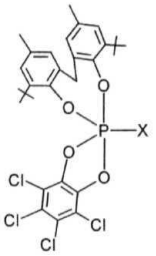


1 87

Pentacoordinate phosphorus compounds in which both the apical–equatorial and diequatorial dispositions for the ring are feasible depending on the other substituents is the sterically hindered eight-membered ring. A large number of structural studies on analogous systems **1.88-1.91** (Chart 1.1) have been carried out by our group as well as Holmes and coworkers.

Chart 1.1





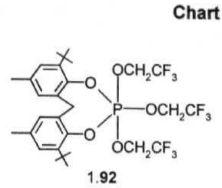
1.88 [R = *t*-Bu, X = Ph]
1.89 [R = *t*-Bu, X = Et]
1.90a [R = Me, X = N_3]
1.90b [R = Me, X = Ph]
1.90c [R = Me, X = NMe_2]
1.90d [R = Me, X = SC_6H_4Cl]
1.90e [R = Me, X = $NCHMe(CH_2)_2CHMe$]
1.90f [R = Me, X = NMePh]
1.90g [R = Me, X = $N(i\text{-}Pr)_2$]
1.90h [R = Me, X = N_3]

1.91a [X = Me]
1.91b [X = NH_2]
1.91c [X = NHMe]
1.91d [X = NHPh]
1.91e [X = N = PPh_3]

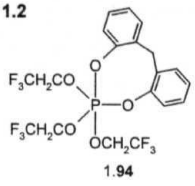
Compounds **1.88, 1.90a-h** (except **1.90e)** and **1.91a-e** have been characterized by X-ray crystallography. This study shows that a secondary amino group (-NMe_2), which is certainly bulkier than primary amino (NHMe) group is more apicophilic showing reverse apicophilicity.[110] In addition to the above it is also evident that the phenyl group in **1.90b** is definitely more apicophilic than the methyl group in **1.91a.** Although this is consistent with Trippett's observation,[107] it contradicts that of Corbridge.[89b]

Steric effects seem to play role in occupancy of the eight-membered ring at the TBP phosphorus center. This is evident in compounds **1.92-1.95**.[111] The eight membered ring spans the diequatorial sites of a TBP in **1.92-1.93;** by way of contrast, when alkyl substituents on the aryl components of the rings are removed as in **1.94**[109] and **1.95**,[111] the TBP structures have the rings occupying apical-equatorial sites (Chart 1.2).

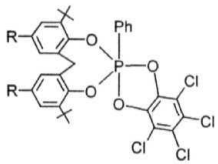
Chart 1.2



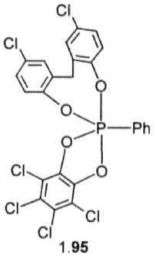
1.92



1.94

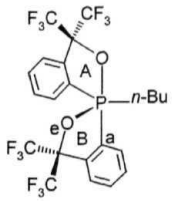


R = Me (1.93a), *t*-Bu (1.93b)

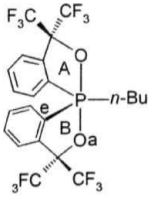


1.95

An interesting case of reverse apicophilicity involving a five-membered ring system has been reported recently.[109c-d] Two stereoisomers **1.96a** and **1.96b** for the spirophosphorane $[\{o\text{-}OC(CF_3)_2C_6H_4\}_2P(n\text{-}Bu)]$ have been isolated. The less electronegative carbon of ring B in 1.96a occupies an apical position instead of oxygen. From the relative stability of these spirophosphoranes, it is concluded that steric effect is the major cause for stabilization against pseudo-rotation in the isomers that exhibit reversed apicophilicity.



1.96a



1.96b

1.32 Intramolecular exchange processes (Berry-pseudorotation)

Pseudorotational process constitutes a special feature of trigonal bypyramidal compounds. It involves the interchange of substituent groups without bond breaking

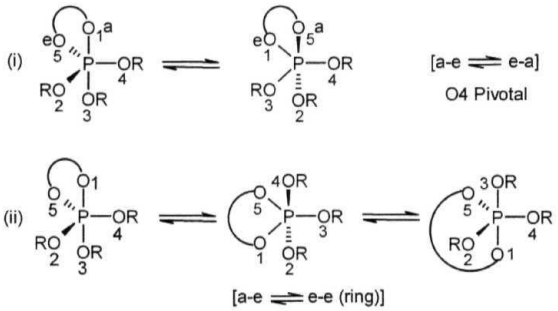
and enables the interconversion of isomers to take place. A commonly accepted exchange behavior is the Berry-pseudorotation.[104]

In the case of monocyclic pentacoordinated phosphorus compounds with TBP geometry, two types of Berry-pseudorotational processes are envisaged (Scheme 1.31, the square pyramidal transition state is not shown):"[2]

(i) The ring is maintained in the a-e position and exchange of ligands in the apical and equatorial positions with the other pivotal ligand in the equatorial position.

(ii) The ring is relocated in the diequatorial fashion from the a-e position. This process would require more energy especially when the ring is four or five membered.

Scheme 1.31



Psuedorotational processes can be inhibited by lowering the temperature. Thus, one way of investigating these exchange processes is by variable temperature NMR spectroscopy. An example from our laboratory is discussed below.

The variable temperature ^{31}P NMR behavior of compound $[CH_2\{6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O\}_2]P(NMePh)(1,2\text{-}O_2C_6Cl_4)$[110b] (1.90f) is shown in Fig. 1.2. At 232 K two peaks are observed at 5 -47.0 and -51.7. Upon increasing the temperature (323 K), only one peak at 8 -48.1, which is closer to the down-field peak δ -47.0 is seen. This unsymmetrical coalescence is not reported earlier for pentacoordinate phosphorus compounds.[110]

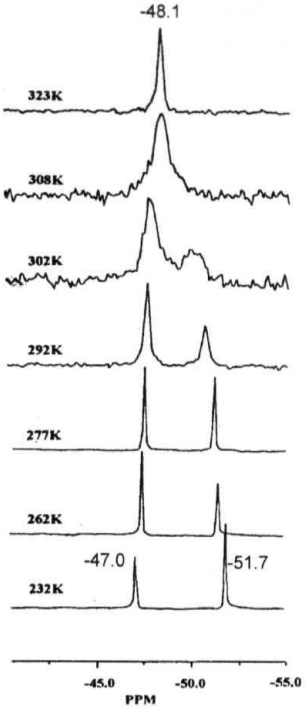


Fig. 1.2 Variable-temperature ^{31}P NMR spectra for **1.90f**

Pentacoordinate phosphorus compounds showing three or more signals in ^{31}P NMR (at low or room temperature) are rare and the intramolecular exchange aspects of such compounds would be an interesting topic to study.

OBJECTIVES OF THE PRESENT WORK

1. To study the reaction of dialkyl azodicarboxylates with different phosphorus(III) substrates in an effort to isolate and characterize compounds analogous to the proposed intermediates in the Mitsunobu reaction.

2. To investigate dipolar cycloaddition reactions of phosphorus(III) isocyanates with dipolarophiles like dimethyl acetylenedicarboxylate (DMAD)/ diethyl acetylenedicarboxylate and then study the reactivity of the products thus obtained.

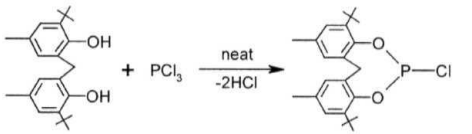
3. To synthesize pentacoordinate phosphorus compounds from the oxidative addition (4 + 1 cycloaddition) reaction of the corresponding cyclic phosphites with *o*-chloranil, in order to study the *apical* vs *equatorial* preferences for different substituents in trigonal bipyramidal phosphorus by means of solid-state structure as well as solution state NMR.

CHAPTER 2

RESULTS AND DISCUSSION

2.1 Synthesis of phosphorus(III) compounds

This part of the present work is essentially based on the key precursor $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2PCl$ (1) that has an eight-membered 1,3,2-dioxaphosphocin ring. In the present study, 1 is prepared by treating 2,2'-methylenebis(6-*t*-butyl-4-methylphenol) with phosphorus trichloride under neat conditions followed by sublimation (eq. 1).



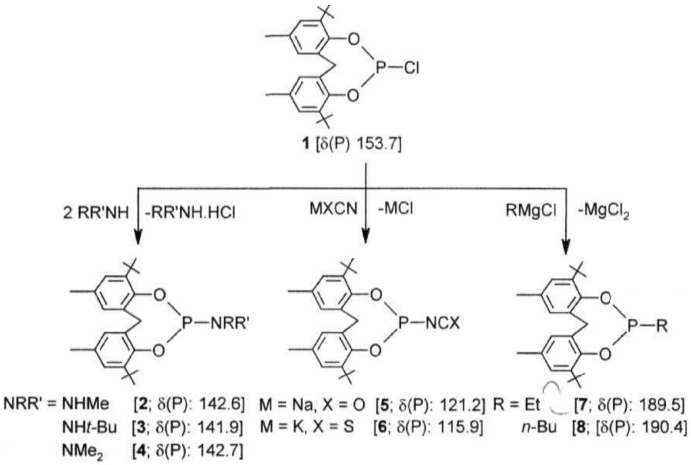
(1)

1 [Mp:150-152°C, δ(P): 153.7]
Yield: 80-85%

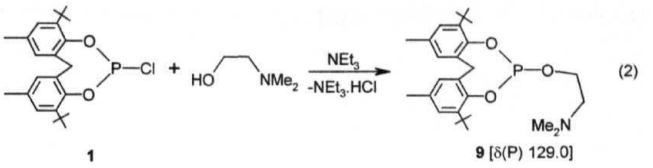
The literature method involves the use of a solvent (Et_2O) in the presence of a base (NEt_3) and subsequent crystallization."[3] Thus our simple modification besides being cost effective (eliminating the use of the solvent and base), offers the advantage that 1 can be easily purified by sublimation in vacuum (150°C/ 0.2 mm Hg). The eight-membered phosphocin ring generally remains intact in further reactions under normal conditions. Compound 1 is relatively less moisture-sensitive when compared to other cyclic phosphochloridites like *o*-phenylene phosphochloridite"[4] and 1,1'-binapthyl-2,2'-dioxaphosphochloridite."[5] Compound 1 can be stored under dry nitrogen atmosphere for several months without significant hydrolysis. More importantly, 1 possesses a sterically encumbered phosphorus, a feature that could facilitate isolation and structural characterization of the products formed from 1 and study their reactivity.

Treatment of 1 with appropriate amines gave the corresponding aminophosphites (phosphoramidites) 2-4. The isocyanato and isothiocyanato phosphites 5 and 6 have been prepared by treating 1 with an excess of sodium isocyanate or potassium isothiocyanate in acetonitrile. Alkylphosphites 7 and 8 were obtained by reacting 1 with EtMgCl or *n*-BuMgCl respectively. These reactions are shown in Scheme 1. All these compounds could be purified by crystallization. In the case of 5, a sharp peak at 5 120.7 (~5 %) observed in addition to the broad peak at 5 121.2 in the ^{31}P NMR. In the ^{1}H NMR, the ArCH_AH_B shows a doublet [V(HH) ~ 13-16 Hz] and doublet of doublet [^{2}J(HH) ~ 13-16, V(PH) ~ 3-6 Hz], which are quite well separated. The IR spectrum of the methylamino or the *t*-butylaminophosphite shows the characteristic N*H* stretch around 3390 cm^{-1}; the isocyanato compound 5 shows a very strong band at 2250 cm^{-1}.

Scheme 1

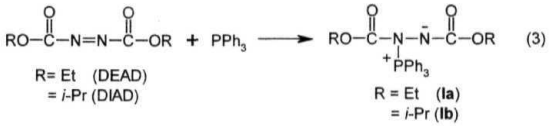


The dimethylaminoethylphosphite 9 was prepared by reacting 1 with N,N-dimethylaminoethanol in toluene in the presence of triethylamine (eq. 2). The choice of this precursor was dictated by the possibility of obtaining hypervalent compounds *via* additional N→P coordination.



2.2 Reactions of phosphorus(III) compounds with dialkyl azodicarboxylates (in the context of Mitsunobu reaction)

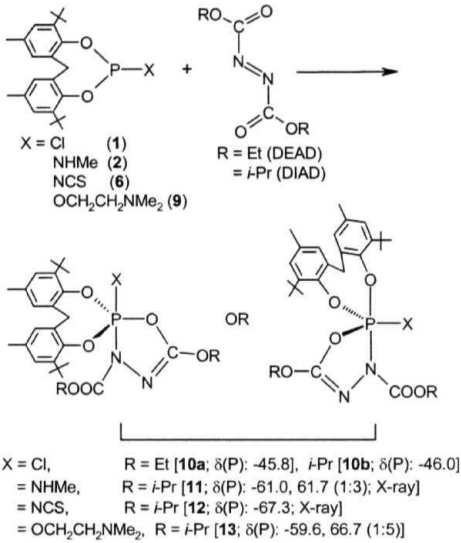
In the original Mitsunobu reaction, triphenylphosphine that contains three carbons attached to phosphorus is utilized and the Morrison-Brunn-Huisgen (MBH) betaine I* is proposed as the intermediate in the first step (eq. 3).[1]



We have been interested in structurally characterizing compounds of type I. In this connection, we reacted phosphorus(III) compounds 1, 2, 6 and 9 bonded to oxygen and/or nitrogen atoms with diethyl azodicarboxylate (DEAD)/ diisopropyl azodicarboxylate (DIAD). Rather than the intermediate of type I, we obtained the pentacoordinate phosphoranes **10-13** respectively (^{31}P NMR) (Scheme 2).[89a,116] Although formation of pentacoordinate compounds in analogous reactions has been reported before,[17,18] complete structural characterization was not done. In the present study, compounds 11 and 12 are characterized by X-ray crystallography."[9] Both 11 and 12 show trigonal bipyramidal geometry at phosphorus. In 11, the NHMe occupies at equatorial position with both the eight and the five-membered ring spanning apical-equatorial positions. In 12, the eight-membered ring spans at diequatorial position and the five-membered ring spans at apical-equatorial allowing the NCS group to occupy the apical position. These are also shown in Scheme 2.

A note on the numbering of compounds:* In this chapter literature compounds and also intermediates/ transition state species are denoted by Roman numerals (I, **II, etc.) and bold Hindu-Arabic numerals (1, 2, 3, etc.) are used for compounds prepared in the present study.

Scheme 2



The molecular structures of 11 and 12 are shown in Figures 1 and 2; the geometrical parameters are given in Tables 1 and 2 respectively.

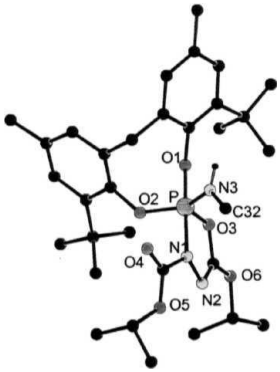


Fig. 1 Molecular structure of 11 showing all non-hydrogen atoms (N(3)-H); only selected atoms are labeled.

Table 1. Selected bond lengths [A] and bond angles [°] for 11 with esd's in parentheses

P-O(1)	1.665(2)	P-N(3)	1.621(2)
P-O(2)	1.607(2)	N(l)-N(2)	1.417(2)
P-O(3)	1.645(2)	N(3)-C(32)	1.465(3)
P-N(l)	1.813(2)		

O(1)-P-O(2)	93.34(7)	O(2)-P-N(1)	86.89(8)
O(1)-P-O(3)	86.52(7)	O(3)-P-N(1)	85.52(7)
O(1)-P-N(1)	171.53(8)	O(3)-P-N(3)	118.38(9)
O(1)-P-N(3)	93.59(8)	N(l)-P-N(3)	92.73(9)
O(2)-P-N(3)	129.97(9)	C(32)-N(3)-P	133.01(16)
O(2)-P-O(3)	111.46(8)	N(2)-N(l)-P	113.25(13)

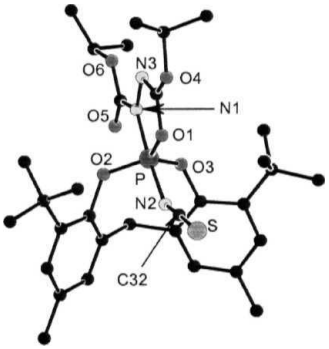


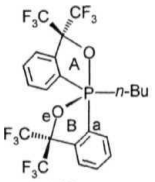
Fig. 2 Molecular structure of 12 showing all non-hydrogen atoms; only selected atoms are labeled.

Table 2. Selected bond lengths [A] and bond angles [°] for 12 with esd's in parentheses

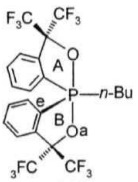
P-O(1)	1.640(2)	P-N(2)	1.770(2)
P-O(2)	1.577(2)	N(2)-C(32)	1.180(3)
P-O(3)	1.581 (2)	S-C(32)	1.569(3)
P-N(l)	1.755(2)	N(l)-N(3)	1.403(3)

O(1)-P-O(2)	121.58(10)	O(2)-P-O(3)	119.44(10)
O(1)-P-O(3)	118.95(10)	O(3)-P-N(1)	91.70(10)
O(1)-P-N(1)	85.41(10)	O(3)-P-N(2)	93.19(10)
O(1)-P-N(2)	85.39(10)	N(l)-P-N(2)	170.78(11)
O(2)-P-N(1)	91.22(10)	N(2)-C(32)-S	177.5(3)
O(2)-P-N(2)	93.18(10)	P-N(2)-C(32)	139.6(2)

From the X-ray structure of 11, it can be readily noted that nitrogen of the five-membered ring, rather than the oxygen, is at the apical position of the trigonal bipyramidal phosphorus although it is less electronegative than oxygen and carries a sterically bulky group. This feature *contradicts* the well-known preference rule for substituents that "high apicophilicity is favored by high electronegativity and small size" (*cf.* Section **1.31**).[89b,109] It can be argued that the -C(O)O-*i*-Pr group increases the (group) electronegativity at nitrogen. However, overriding the more electronegative oxygen (which is also certainly sterically less crowded in our system) of the five-membered ring, the nitrogen has occupied the apical position; this was not expected.[107] It can be noted that in Akiba's compounds (compounds **1.96a** and **1.96b** *cf.* Section **1.31**)[109e] there is a competition between aryl carbon and *O*-C(CF$_3$)$_2$ of the five-membered ring, whereas in our compound 11 there is a competition between *N*(COO-*i*-Pr) and *O*-C(O-*i*-Pr) of the five-membered ring. In our example, we have a substituent on nitrogen. Thus, both electronegativity and steric factors are supposed to be unfavorable for this nitrogen to occupy the apical position.



1.96a



1.96b

The P(l)-N(l) (apical) distance of 1.813 A in 11 is significantly longer than that in CH$_2$(6-*t*-Bu-4-Me-C$_6$H$_2$O)$_2$P(NMe$_2$)(O$_2$C$_6$Cl$_4$) **(1.90c;** *cf.* Section **1.31)** [1.682(5) A] and that calculated according to the Schomaker-Stevenson empirical expression[¥] (1.770 A).[117] This feature suggests that there is no significant π-character in this bond. The equatorial P-N(3) distance [P-N(3) 1.621(2) A] is similar to that in CH$_2$(6-*t*-Bu-4-Me-C$_6$H$_2$O)$_2$P(NHMe)(O$_2$C$_6$Cl$_4$) **(1.91c;** ***cf*** Section **1.31) [1.611(5) A].**

The P-0 bond distances are in the expected range with apical bonds longer than the equatorial ones. However, the equatorial P-O bond in the eight-membered [P-O(2) 1.607(2) A] is slightly shorter than that in the five-membered ring [P-O(3) 1.645(2) A].[118] The equatorial disposition of the -NHMe group and a-e disposition of the eight-membered ring are analogous to that found in **1.91c**.[110a] The N(3)-P-O(2) bond angle is 171.53(8)°, suggesting a distorted trigonal bypyramidal geometry at phosphorus.

In the structure of 12 (Fig. 2) also, nitrogen of the five-membered ring, rather than the oxygen, is at the apical position. Thus, again a reversal of the expected apicophilicity is exhibited. The P-N(apical) bond lengths in 12 [P-N(l) 1.755(2), P-N(2) 1.770(2) A] are close to those calculated using the Schomaker-Stevenson empirical expression[¥] for a P-N single bond [1.77 A], but are significantly longer than those in the pentacoordinate compounds $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(NMePh)(1,2\text{-}O_2C_6Cl_4)$ (1.90f; Section 1.31), [1.727(4) A] and $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P\{N(i\text{-}Pr)_2\}(1,2\text{-}O_2C_6Cl_4)$ (1.90g; section 1.31) [1.672(2) A] that have nitrogen at the apical position."[0] The P-O bond distances are normal. The apical N(l)-P-N(2) angle of 170.78(11)° shows that the geometry around phosphorus is distorted TBP. However, in 12 the eight-membered ring takes up a diequatorial position at the trigonal bipyramidal phosphorus. The N(2)-C(32)-S bond angle of 177.5(3)° shows that NCS group is almost linear.

Thus, these compounds *defy* the commonly accepted "apicophilicity" rules for substituents at pentacoordinate phosphorus and add another interesting facet to the reversed apicophilicity phenomenon.[107]

One may argue that in the above cases the thermodynamically most favored structure is simply not reached. However, a growing body of evidence suggests that at

Y The Schomaker-Stevenson empirical expression is given below.

$r_{AB} = r_A + r_B - 0.09\ (x_A - x_B)$

r_{AB} =distance between the two atoms A and B.

r_A and r_B are the covalent radii (A) and x_A and x_B are the electronegativities of the atoms A and B. Any bond shortening beyond that expected (r_{AB}) from electronegativity difference is probably attributable to π character of the bond.

least in our system the steric and electronegativity rules for pentacoordinate phosphorus are often not followed and the products isolated could be the thermodynamically favored ones."[0]

The ^{31}P NMR chemical shifts of compounds **10-13** in solution are in the expected pentacoordinate region.[89] However, compound **11** exhibits two closely spaced peaks in the ^{31}P NMR [6 -61.0, -61.7; A8 0.7; ratio 1:2] in $CDCl_3$ solution at room temperature (298 K). In toluene-d_8, two peaks at -60.1 and -60.4 (intensity ratio 3:2) [Fig. 3] are observed; in addition, a broad hump at 8 -39.5 is also seen. With raise in temperature, intensity of the downfield hump [8 -39.5] increases at the cost of the two up-field peaks (which merge eventually). At 338 K, the peak at 8 -39.5 is the most predominant one. The spectra are reversible with respect to temperature. The large value of AS (ca 20.5 ppm) between the down-field signal and the two closely spaced up-field signals suggests a significant change in the ligand arrangement at phosphorus between the isomers corresponding to these. At low temperatures (233 K; toluene-d_8), whether the NMR sample was prepared at 298 K or 233 K, the ^{31}P NMR showed only the two closely spaced signals at 8 -61.0 and -61.7.

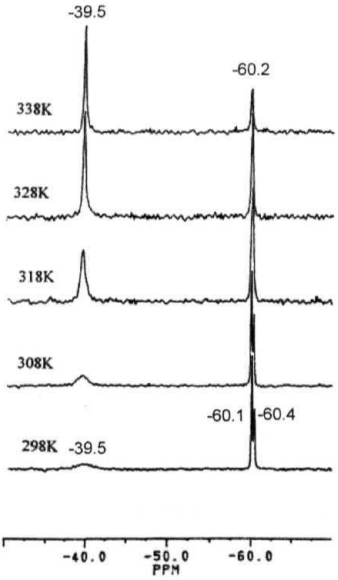
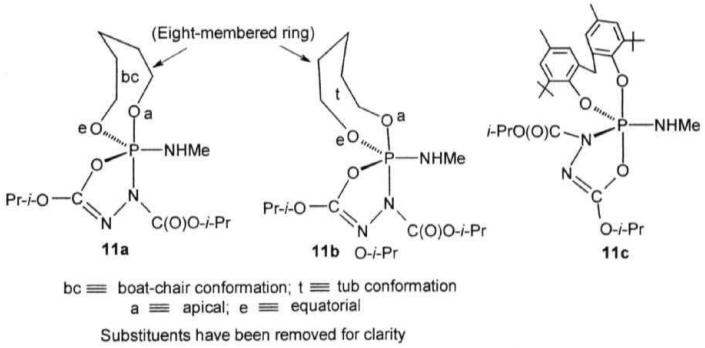


Fig. 3 Variable-temperature ^{31}P NMR spectra for **11**

The observation of closely spaced up-field signals is reminiscent of the ^{31}P NMR behavior of $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(NHR)(O_2C_6Cl_4)$[110] [R = H **(1.91b,** *cf.* Section **1.31;** 8 -50.6, -50.9); R = Me **(1.91c,** *cf.* Section **1.31;** 8 -52.2, -52.5)] (X-ray structures available); the latter feature was attributed to tub ⇔ boat-chair conformational isomerism of the a-e located eight-membered ring with the -NHMe group spanning equatorial position. Thus, the closely spaced up-field signals in **11** can be attributed to isomers **11a** and **11b**. The change in the local environment at phosphorus **11a** and **11b** is small and hence only a small difference in 8(P) value can be expected. For the downfield signal which is predominant at high temperature, we assign structure **11c** in which both the -NHMe and -NC(O)(O-*i*-Pr) groups are equatorial. It is also expected that this signal [8 -39.5] is due to a tetracoordinate species, but the chemical shift value is too up-field."[6] Peaks in the 'H NMR spectra were quite broad and hence a detailed analysis could not be made.



We have also recorded NMR (^1H and ^{31}P) spectra for compound $[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(NCS)\{N(CO_2\text{-}i\text{-Pr})NC(O\text{-}i\text{-Pr})O\}]$ (12) in toluene-d_8 at different temperatures. In the ^{31}P NMR at 298 K only one peak 8 −67.0 ppm was observed. At 263 K, three peaks appeared [8 -67.0, -76.0, -82.1; ratio 9:1:1]. Upon further decrease in temperature (222 K), four peaks at [8 -66.7, -67.2, -76.0, -82.1; ratio 2:5:2:1] (Fig. 4). The spectra are reversible with respect to temperature. These features suggest the presence of isomeric phosphoranes at low temperatures.

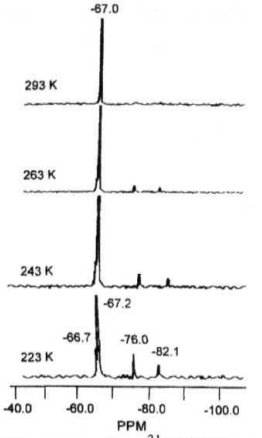
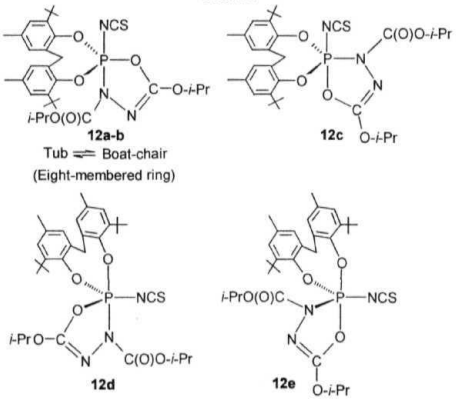


Fig. 4 Variable-temperature ^{31}P NMR spectra for **12**

Based on the previously available data, the close spaced peaks [8 -66.7, -67.2, $\Delta\delta$ 0.5; ratio 4:1] attributed to **12a-b** (Chart 1) tub $\Leftrightarrow$ boat-chair conformational isomers of the diequatorially located eight-membered ring. The two up-field signals at -76.0 and -82.1 may be assigned to two of the other three possible isomers **12c-e** (Chart 1).[110]

Chart 1

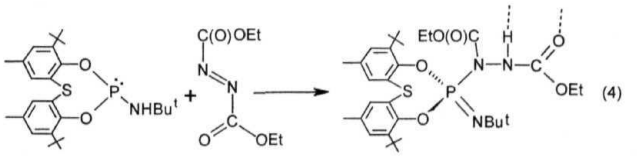


In the ^{1}H NMR spectrum at 298 K, chemical shifts of the protons corresponding to $OC(CH_3)_2$, $C(CH_3)_3$, $ArCH_3$, $(Ar)_2CH_AH_B$ are sharp and well separated. The spectra get broadened with decrease in temperature but no conclusion could be drawn.

In the precursor $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(OCH_2CH_2NMe_2)$ (9), the phosphorus has three oxygen atoms around it. In the product with DIAD, there is a possibility of additional $N\rightarrow P$ coordination (through $-NMe_2$ residue) that could stabilize hypervalent phosphorus."[6] However ^{31}P NMR spectrum of the product **13** [5(P) -59.6, −66.7 (1:5)] reveals only pentacoordination.[110] It is likely that steric factors have prevented the formation of the additional $N\rightarrow P$ coordinate bond.

The reaction of *t*-butylamino phosphoramidite $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2PNH\text{-}t\text{-Bu}$ (3) with DEAD and DIAD affords compounds with composition $[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(N\text{-}t\text{-Bu})\{N(CO_2R)NH(CO_2R)\}$; R = Et **(14a), *i*-Pr (14b)]** as shown by 'H and ^{31}P [solution and solid] NMR as well as elemental analysis.

The ^{31}P NMR of compounds **14a-b** are also in the expected pentacoordinate region. However, IR (KBr) spectra showed two ν(NH) bands [for **14a** at 3264, 3154 cm^{-1}; **14b** at 3260, 3159 cm^{-1}] *this is different from a single ν(NH) band at 3383 cm^{-1} observed for the pentacoordinate methylamino compound* $[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(NHMe)\{N(CO_2\text{-}i\text{-Pr})NC(O\text{-}i\text{-Pr})O\}]$ (**11**).[119] There is also a fairly strong band at 1209 cm^{-1} ascribable to ν(P=N). These features are analogous to that for compound $[S(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(N\text{-}t\text{-Bu})\{N(CO_2Et)NH(CO_2Et)\}]$ (II) prepared in our laboratory by the same route (eq. 4).'[20] The latter compound was characterized by X-ray crystallography, which clearly showed (i) a strong P=N(*t*-Bu) bond [P-N 1.464(4) A], and (ii) the carbamate type linkage -NH-C(O)OR as a hydrogen bonded dimer through the NH and the C=O moieties.

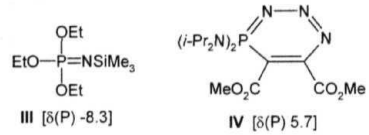


II [δ(P) -56.3; X-ray]

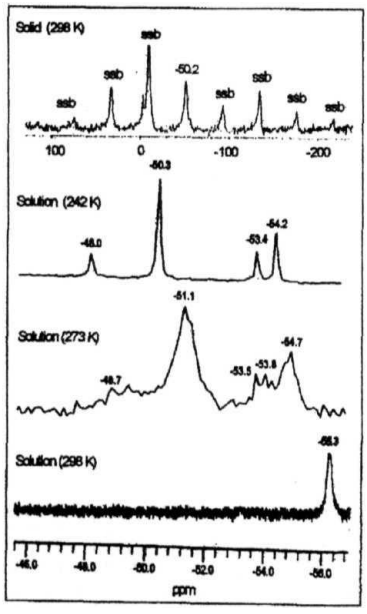
Hatched lines on NH and C=O represent Hydrogen bonding

The 5(P) value of -56.3 [$C_6D_5CD_3$, 298 K, sharpens at higher temperatures] for 14a is clearly in the *pentacoordinate* region (*cf.* compounds **10-13)** and quite up-field when compared to the *tetracoordinate* region *[cf.* compounds **III, IV**].[121, 87] The solid-state ^{31}P NMR signal [5 -50.2] is also in the pentacoordinate region. Thus, these

spectra for 14a [Fig. 5] are analogous that for II (pentacoordination) and appear to be *inconsistent* with the X-ray structure II (tetracoordination).



In addition to posing a unique structural problem as described above, a low temperature ^{31}P NMR study on 14a reveals an *unprecedented* solution state behavior wherein *at least four* isomeric phosphoranes are observed at 242 K [Fig. 5]. Upon warming to 298 K, the original spectrum was obtained. Based on previously available data,[89,110] these signals can be ascribed to pentacoordinate isomers **14a$_1$-14a$_4$** [Chart 2, the extra low intensity peak at 273 K is perhaps due to a conformational isomer involving the eight-membered ring"^{0}]. To our knowledge, this is the first ever observation of four distinct isomeric phosphoranes in solution.



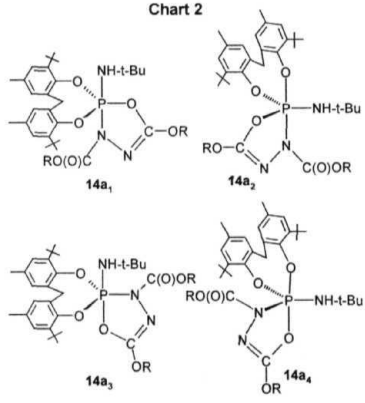
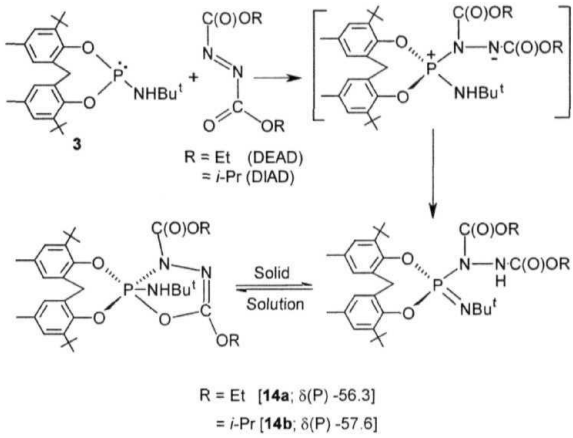


Fig. 5. Solution (VT) and solid-state (5 kHz) ^{31}P NMR spectra for compound 14a; ssb refers to spinning side bands. The spinning side bands were verified by recording the solid-state spectrum at 7 kHz also.

On the basis of above data (IR, NMR and X-ray structure of II), we propose that there is an equilibrium between the tetracoordinate and the pentacoordinate forms for 14a (and 14b) as shown in Scheme 3. The apparent inconsistency between IR and X-ray on the one hand and NMR on the other hand may be related to different time-scales in these techniques.

Scheme 3



R = Et [**14a**; δ(P) -56.3]
= *i*-Pr [**14b**; δ(P) -57.6]

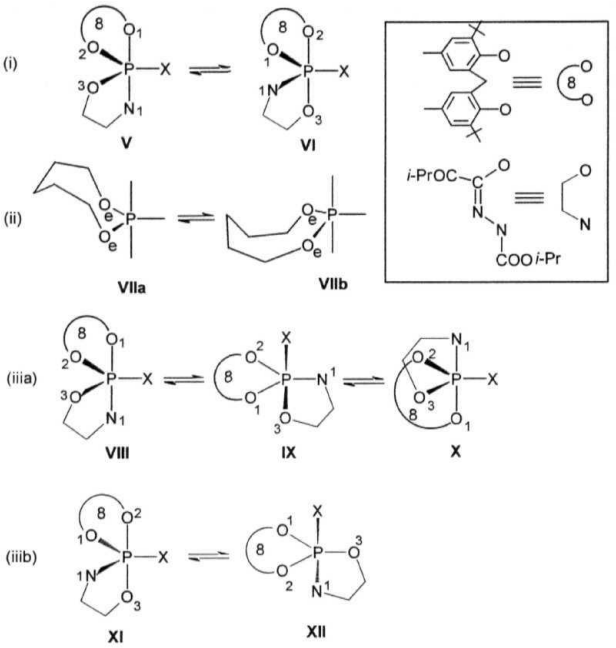
From the above observations (for compounds **11,** 12 and **14a),** and based on the previous work from our laboratory,"[0] three possible intramolecular processes may be operating in compounds 11, 12 and **14a** (Scheme 4; the transition state square pyramidal species is not shown).

(i) An a-e ↔ e-a exchange process for the two rings, possibly of low energy, with X as the pivotal ligand. A moderate change in 5(P) values for V and VI is expected.

(ii) *Boat-chair* to *tub* conformational change for the eight-membered ring located e-e (shown in Scheme 4) and *tub* to *boat-chair* for the eight-membered ring located a-e (not shown in Scheme 4). The change in the local environment at phosphorus in **VIIa** and **VIIb** is small and hence only a small difference in 8(P) value can be expected.

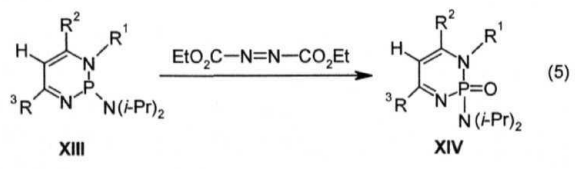
(iii) An a-e ↔ e-e (or e-e ↔ a-e) exchange process involving the eight-membered ring, with O(2) pivotal. A similar process could be considered for the five-membered ring also, except that it will be having much higher activation barrier. A significant change in 8(P) values among the isomers **(VIII, IX)** is expected.

Scheme 4



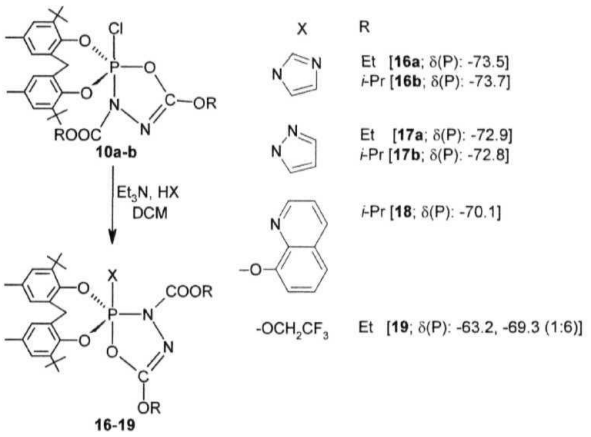
In case of compound 11, processes (i) and (ii) are involved, whereas for 12 and **14a** all the three intramolecular processes (i-iii) may be involved. At this stage, it is not clear why a particular process is involved in a particular case.

In the reaction of compound $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2PNMe_2$ (4) with DIAD, the product isolated **[15;** 5(P) 0.6] showed that it is $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(O)NMe_2$ [15; obtained by treating $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(O)Cl$ with excess $HNMe_2$]. Analogous reaction of **XIII** with DEAD is reported to give **XIV** (eq. 5), but the mechanism is not very clear.[57]



The chloro compounds [CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$PCl{N(CO_2R)NC(OR)O-}] (**10a-b**) are useful precursors to various substituted derivatives and hence we have reacted **10a-b** with imidazole, pyrazole, 8-hydroxy quinoline and 2,2,2-trifluoroethanol. These reactions led to compounds **16-19** (Scheme 5; assignment of structures for **lOa-b** is based on that available for 12). The structures of compounds **16b** and 18 were unambiguously proved by X-ray crystallography.

Scheme 5



The molecular structure and the geometrical parameters for **16b** are shown in Fig. 6 and Table 3 respectively. In contrast to 12, the expected apical placement of the oxygen and equatorial placement of the nitrogen for the five-membered ring is observed in compound **16b.** However, the nitrogen of the imidazole ring spans the apical position rather than an oxygen of the eight-membered ring, again showing the 'reversed apicophilicity' phenomenon.[891,10,,,109] This feature is however similar to that observed in [CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$PPh{N(CO_2-*i*-Pr)NC(O-*i*-Pr)O}] (XV) where the phenyl ring spans at the apical position."[9] The equatorial P-N bond length in **16b** [P-N(l) 1.685(5) A] is shorter when compared to that in XV [P-N 1.701(2) Å].[119] The apical P-N(3) distance [1.759 A] is shorter than that in 12 [1.770(2) A]. The P-0 bonds also follow a similar trend [i.e. the apical P-O(3) 1.724(4) A is shorter in **16b** than that in XV [1.754(2) A]. The O(3)-P-N(3) angle of 176.7(4)° shows that the geometry around phosphorus is essentially a TBP.

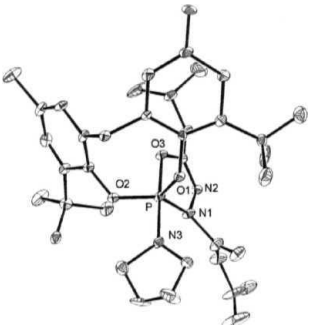
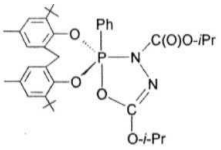


Fig. 6 Molecular structure of **16b**.$C_6H_5CH_3$ showing all non-hydrogen atoms; only selected atoms are labeled. Solvent molecule is not shown.

Table 3. Selected bond lengths [A] and bond angles [°] for **16b**.$C_6H_5CH_3$ with esd's in parentheses

P-O(l)	1.619(8)	P-N(l)	1.685(5)
P-O(2)	1.584(8)	P-N(3)	1.759(5)
P-O(3)	1.724(4)	N(1)-N(2)	1.431(7)
O(1)-P-O(2)	116.9(2)	O(2)-P-N(1)	124.1(6)
O(1)-P-O(3)	92.3(4)	O(2)-P-N(3)	88.8(4)
O(1)-P-N(1)	119.0(6)	O(3)-P-N(1)	85.4(2)
O(1)-P-N(3)	89.7(5)	O(3)-P-N(3)	176.7(3)
O(2)-P-O(3)	92.6(4)	P-N(l)-N(2)	117.3(4)



XV [δ(P): -51.7; X-ray]

As regards the molecular structure and geometrical parameters in the oxinate compound 18 [Fig. 7, Table 4], the P-O bond distances are in the expected range.[110] The P-N(l) bond of 1.682(4) A is also shorter when compared to that in XV [P-N 1.701(2) Å],[119] but is close to that in **16b.** The apical placement of the oxygen and equatorial placement of the nitrogen for the five-membered ring is expected and is

similar to that in **16b** and XV. The apical O(3)-P-O(7) angle of 173.07 (18)° shows that the geometry around phosphorus is distorted trigonal bipyramid.

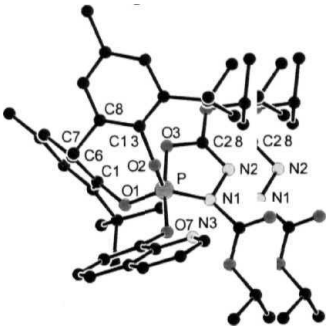


Fig. 7 Molecular structure of **18**.$C_6H_5CH_3$ showing all non-hydrogen atoms

Table 4. Selected bond lengths [A] and bond angles [°] for **18**.$C_6H_5CH_3$ with esd's in parentheses

P-O(1)	1.610(3)	O(3)-C(28)	1.337(6)
P-O(2)	1.600(3)	C(28)-N(2)	1.263(6)
P-O(7)	1.633(3)	N(l)-N(2)	1.427(5)
P-N(l)	1.682(4)		
O(1)-P-O(2)	113.93(2)	O(2)-P-N(1)	125.6(2)
O(1)-P-O(3)	91.78(2)	O(3)-P-N(1)	85.40(2)
O(1)-P-O(7)	92.38(2)	O(3)-P-O(7)	173.1(2)
O(1)-P-N(1)	120.5(2)	N(1)-P-O(7)	87.71(2)
O(2)-P-O(3)	91.77(2)	P-N(l)-N(2)	117.5(3)
O(2)-P-O(7)	91.64(2)	P-O(3)-C(28)	111.6(3)

The ^{31}P NMR spectra of **16-19** (in $CDCl_3$) at 298 K are in the expected pentacoordinate region.[90] However, compound 19 exhibits two peaks at 8 –63.5 and -69.5 [(1:5); A8 ~ 6.0] in the ^{31}P NMR in $CDCl_3$ solution at 298 K.

As regards **16b,** a single peak at δ -72.9±0.4 is observed in the ^{31}P NMR spectrum. This remained unchanged in the temperature range 233-338 K. In the ^{1}H NMR spectra ($C_6D_5CD_3$) (Fig. 8), two signals for the Ar-C(CH_3)$_3$ [δ 1.67, 1.74] and Ar-CH_3 [8 2.24, 2.32] protons are observed at 233 K; the signals at this temperature are slightly broad probably because of the low solubility (or due to the slowing down

of the intramolecular exchange). At temperatures ~283 K (T_c), only one major signal is observed; an activation barrier ($\Delta G^{\#}$ = 12.5 kcalmol^{-1}) is calculated for this process. The difference in 5 values of the two *t*-butyl signals is only 0.07 ppm ($\Delta\upsilon$ 14.0 Hz). We attribute this feature to restricted rotation around P-O-bonds and not due to isomerism [Note: a single line in the ^{31}P NMR].

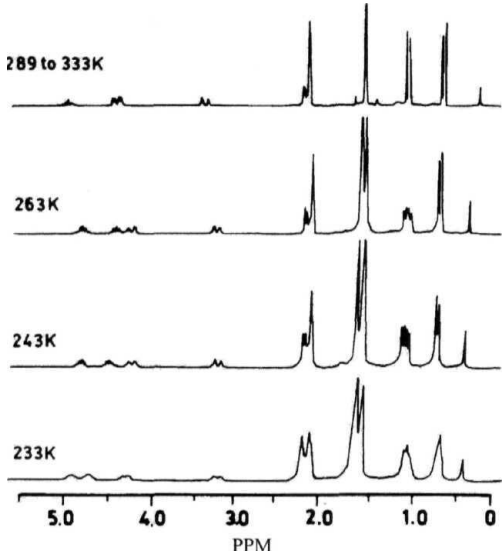


Fig. 8 Variable-temperature ^{1}H NMR spectra for **16b**

There are two different types of $CH(CH_3)_2$ environment in the molecule in any fixed geometry [P-O-C-OCH(CH_3)$_2$ and P-N-C(O)-O-CH(CH_3)$_2$]. Two signals centered at 5 0.80 and 1.20 are observed corresponding to these. The down-field signal shows a 4-line pattern [ascribable to P-O-COCH(CH_3)$_2$ because of less conformational freedom] whereas the up-field one is the expected doublet (V(HH) =6.5 Hz). The 4-line pattern may be associated with restricted rotation at the isopropyl carbons $CHCH_{3(a)}CH_{3(b)}$ At temperatures 298 K, these show up as a simple doublet.

Activation energies are calculated using the equation given below.

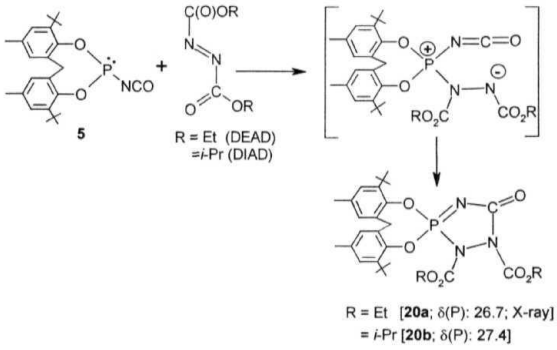
$\Delta G^{\#}$ = 4.57 x $10^{-3}T_c$ [10.32 + Log ($T_c\sqrt{2}$/ *n* At))]

T_c = Coalescence temperature in K, *Av* -- Line separation in Hz.

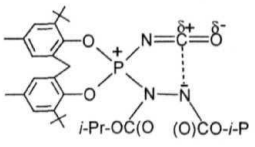
In compound 18, there is a possibility of additional N→P coordination that could stabilize hypervalent phosphorus. However, only pentacoordination is shown by X-ray structure [see above] as well as ^{31}P NMR [5(P) -70.1; *cf.* compounds 10-13]."[0119] It is likely that steric factors (like in compound 13) have prevented the formation of the additional N→P coordinate bond.

In contrast to the above, reaction of the P(III) isocyanate, $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P\text{-NCO}$ (5) with DEAD/ D1AD takes an entirely different turn with the formation of the cyclic products **20a-b,** presumably *via* betaine in a step-wise pathway (Scheme 6).[119120]

Scheme 6



Compound **20b** exhibits an IR stretch at 2259 cm^{-1} (which is same as that in the precursor 5). In the ^{13}C NMR spectrum of **20b,** the two $OCHMe_2$ signals are much closer [5 72.6, 73.2; A5 0.6] than in the isothiocyanate derivative [CH2(6-/-Bu-4-Me-$C_6H_2O)_2P(NCS)\{N(CO_2\text{-}i\text{-Pr})NC(O\text{-}i\text{-Pr})O\}$] (12) [5 69.9. 74.7; A5 4.8]; this feature suggests that the two $OCHMe_2$ groups in **20b** are nearly in the same environment.[122] The 5(P) value of 27.4 in $CDCl_3$ for **20b** is also quite down-field.[121,87] Based on the above observations, initially we suggested an additional interaction between N and C leading to a five-membered ring **20b'** as shown below.



20b'

Later, we prepared the analogous DEAD compound [CH2(6-/-Bu-4-Me-$C_6H_2O)_2P\{N(CO_2Et)N(CO_2Et)$-C(O)-N}] **(20a).** An X-ray crystallographic study (details will be discussed later) on this derivative revealed that in fact a five-membered ring with pure covalent bond *{cf.* Scheme 6) is involved. Hence, the DIAD derivative **20b** should also have the same structure.

We have recorded variable time ^{31}P NMR spectra for **20b.** After 15 min of the addition of DIAD to a solution of $CH_2(6$-*t*-Bu-4-Me-$C_6H_2O)_2$P-NCO (5) in C_6D_6, we observed a peak at 5(P) –64.9 in the pentacoordinate region[110] along with the peak at 5(P) 28.6 in the tetracoordinate region.[121] After 25 min the intensity of the down-field peak at 5(P) 28.6 increased at the cost of the up-field peak; after 35 min, the down-field peak at 5(P) 28.6 was the most predominant one (Fig. 9). This corresponds to **20b;** the slight difference in S(P) values in $CDCl_3$ [5 27.4] and C_6D_6 [8 28.6] is likely to be due to solvent effects. A possible pathway for the formation down-field compound **20b** [δ 28.6] from the up-field compound [δ -64.9] is explained in Scheme 7. Similar observation can be expected for **20a** also.

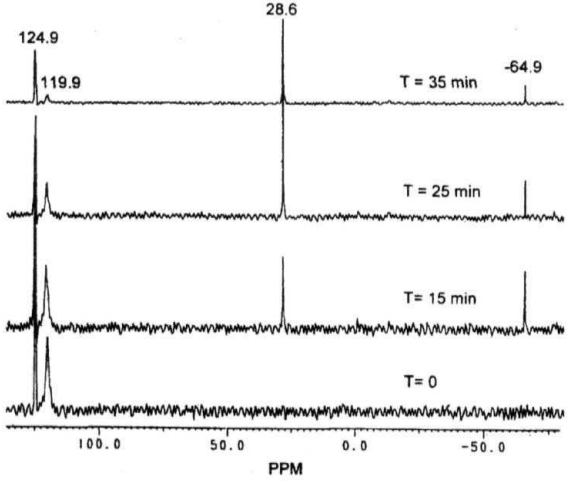
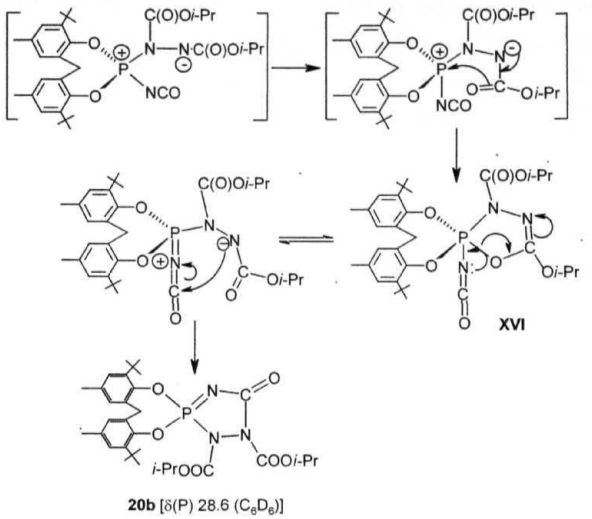


Fig. 9 Variable-time ^{31}P NMR spectra for **20b**

Scheme 7

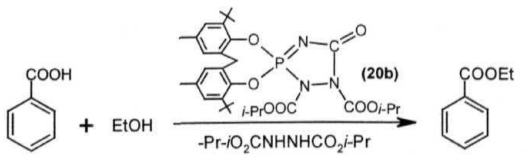


20b [δ(P) 28.6 (C_6D_6)]

Previously, pentacoordinate *isothiocyanate* compound [CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$P(NCS){N(CO_2-*i*-Pr)NC(O-*i*-Pr)O}] (12) was obtained from analogous reaction of CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$P-NCS (6) with DIAD.[119] The difference in the reactivity of this *isothiocyanate* 6 from the *isocyanate* 5 probably stems from a better charge separation at the C=O end in the latter compared to the C=S end in the former.

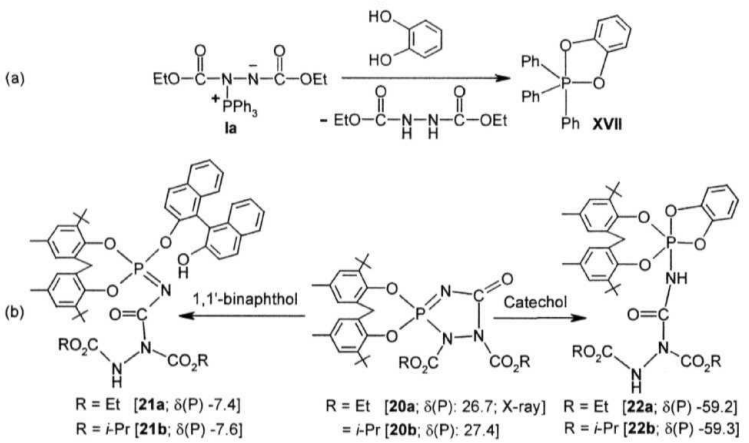
Interestingly, despite having a structure different from the betaine I, compound 20b *does participate in the Mitsunobu coupling*[1] between ethanol and benzoic acid (Scheme 8), suggesting that the five-membered heterocycle is in equilibrium with the betaine.

Scheme 8



In an earlier work, Trippett and coworkers used the betaine **Ia** as a precursor to various pentacoordinate phosphoranes *[cf.* Scheme 9a)].[32] In these reactions, DEAD becomes the hydrazine derivative $EtO_2CNHNHCO_2Et$ and the pentacoordinate compound $Ph_3P(1,2\text{-}O_2C_6H_4)$ **(XVII)** is formed. By contrast, compounds **20a-b** undergo a two-step addition depending on the diol. First, the P-N single bond is cleaved and then addition across the P=N (double) bond takes place. When **l,l'-bi-2-**naphthol is used, the reaction stops at the first stage to lead to tetra-coordinate compounds **21a-b.** When catechol is used, the addition across the P=N bond also takes place to lead to the pentacoordinate compounds 22a-b. These reactions are shown in Scheme 9(b). The structures of **21b** and **22b** have been confirmed by X-ray crystallography. The ^{31}P NMR of 21a-b and 22a-b are in the expected tetra and pentacoordinate regions.

Scheme 9



In place of the diol in the above reactions, we also used *o*-phenylenediamine and o-aminophenol. In case of *o*-phenylenediamine the reaction stops at the first stage to lead to tetracoordinate compound [8(P) -10.6] as the major product and in the case of o-aminophenol, pentacoordinate product [8(P) -56.4] is formed as the major product. Due to the formation of a complex mixture of products, a pure solid could not be isolated and hence we did not proceed further.

X-ray structures of 20a, 21b and 22b

The molecular structure and geometrical parameters for **20a** are shown in Figure 10 and Table 5 respectively. The formal P=N bond in this compound [P-N(l) 1.564(4) A] is significantly longer than that in **II** [P-N 1.464(4) Å][120] or **XVIII** [P-N 1.488(3) Å],[120] suggesting some phosphonium character *[cf.* **20a']** in it. The P-N single bond distance [P-N(2) 1.656(3) A] is significantly shorter than that in the pentacoordinate compounds **11** [P-N(l) 1.813(2) A] and 12 [P-N(l) 1.755(2) A].[119] The P-0 distances [mean ~1.55 A] are shorter than that in phosphinimine II [mean ~1.59 A] as well as those at the spiro-phosphorus atom in compounds **11** [mean P-0 ~1.63 A] and 12 [mean P-0 ~1.61 A].

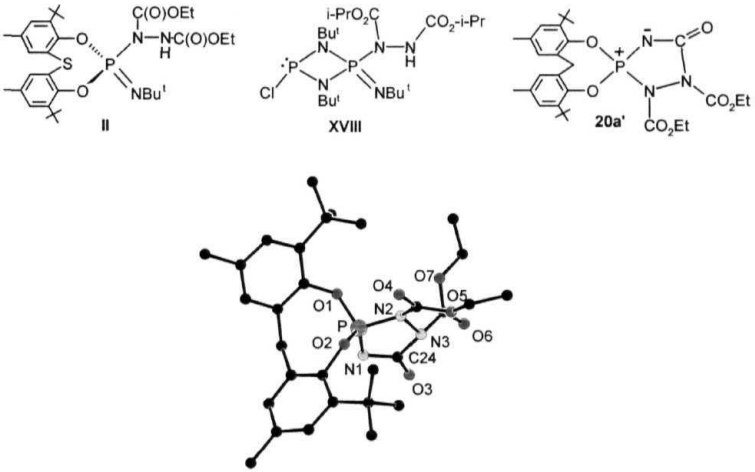


Fig. 10 Molecular structure of **20a**.CH_2Cl_2 showing all non-hydrogen atoms; only selected atoms are labeled. Solvent atoms are not shown.

Table 5. Selected bond lengths [A] and bond angles [°] for **20a**.CH_2Cl_2 with esd's in parentheses

P-O(1)	1.556(3)	N(2)-N(3)	1.429(4)
P-O(2)	1.547(3)	N(3)-C(24)	1.476(5)
P-N(l)	1.564(4)	C(24)-O(3)	1.200(5)
P-N(2)	1.656(3)	C(24)-N(l)	1.359(6)

O(1)-P-O(2)	106.50(15)	N(2)-N(3)-C(24)	108.4(3)
O(1)-P-N(1)	116.96(18)	N(l)-C(24)-N(3)	112.4(4)
O(1)-P-N(2)	108.00(16)	P-N(l)-C(24)	112.0(3)
O(2)-P-N(1)	115.92(18)		
O(2)-P-N(2)	110.18(16)		

In 21b (Fig. 11, Table 6), the P=N bond [P-N(l) 1.546(3) A] is slightly shorter than that in 20a [P-N(l)l .564(4) A], but is still significantly longer than those in II or XVIII. The compound is a hydrogen bonded dimer through N(3)-H...O(8'); the binaphthol O(9)-*H* is involved only in intramolecular H-bonding to 0(4). The P-0 distances [mean ~ 1.55 A] are similar to 20a, and are shorter when compared to II, 11 and 12.

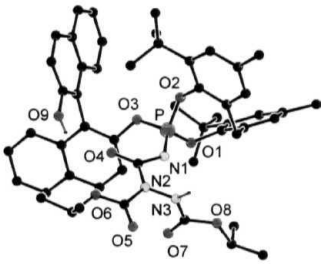


Fig. 11 Molecular structure of compound **21b**.3/2$C_6H_5CH_3$ showing all non-hydrogen atoms (except O(9)-H and N(3)-H); only selected atoms are labeled. Solvent atoms are also not shown.

Table 6. Selected bond lengths [A] and bond angles [°] for **21b.**3/2$C_6H_5CH_3$ with esd's in parentheses*

P-O(1)	1.565(2)	P-O(3)	1.553(3)
P-O(2)	1.545(2)	P-N(l)	1.546(3)

O(1)-P-O(2)	105.87(13)	O(2)-P-N(1)	117.82(16)
O(1)-P-O(3)	106.19(13)	O(2)-P-O(3)	99.14(14)
O(1)-P-N(1)	109.19(16)	O(3)-P-N(1)	117.4(14)

* D-H, H...A, D...A and D-H...A parameters: N(3)-H(3)…O(8') [dimeric] 0.87, 2.24, 3.062(4) A, 156.8°; O(9)-H(9)...O(4) [intramolecular] 0.83, 2.31, 2.778(4) A, 116.1°.

In the pentacoordinate compound 22b the newly formed -NHC(O)N(CO_2-*i*-Pr)NH(CO_2-*i*-Pr) and catecholate oxygen are at the apical positions of trigonal-bipyramidal phosphorus (Fig. 12, Table 7). The eight-membered ring spans diequatorial position. Since "nitrogen" (of the NHR residue) rather than "oxygen" (of the eight-membered ring) occupies an apical position, this compound also falls into the category of pentacoordinate phosphoranes with *reversed apicophilicity*. The P-0 and P-N bond distances are in the expected range."[0] The apical O(3)-P-N(1) angle of 173.0(3) shows that the geometry around phosphorus is slightly distorted TBP. The apical NHR residue is involved in intramolecular H-bonding to the carbonyl oxygen 0(6). However, the structure is dimeric *via* hydrogen bonding through N(3)H and 0(9).

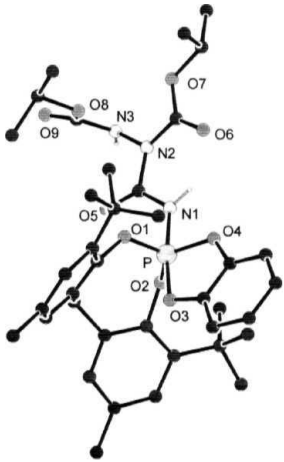


Fig. 12 Molecular structure of compound **22b**.3/2$C_6H_5CH_3$ showing all non-hydrogen atoms (except N(l)-H); only selected atoms are labeled. Solvent atoms are also not shown.

Table 7. Selected bond lengths [A] and bond angles [°] for **22b**.3/2$C_6H_5CH_3$ with esd's in parentheses*

P-O(1)	1.596(2)	P-O(4)	1.648(2)
P-O(2)	1.587(3)	P-N(l)	1.738(3)
P-O(3)	1.717(2)		

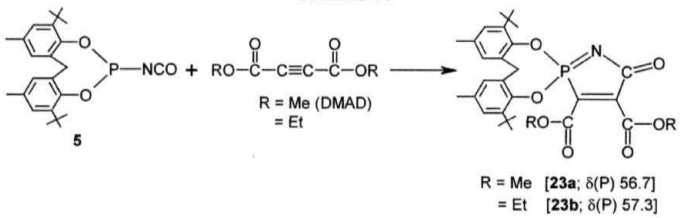
O(1)-P-O(2)	117.52(3)	O(2)-P-O(3)	91.61(2)
O(1)-P-O(3)	93.45(2)	O(2)-P-O(4)	123.86(2)
O(1)-P-O(4)	118.45(3)	O(3)-P-N(1)	173.16(2)
	91.0(2)	O(3)-P-O(4)	89.23(2)
O(2)-P-N(1)	90.40(2)	O(4)-P-N(1)	84.22(2)

*D-H, H...A, D...A and D-H...A parameters: N(1)-H(N1)…O(6) [intramolecular] 0.86(3), 1.87(3), 2.613(4) A, 144(3)°; N(3)-H(N3)…O(9') [dimeric] 0.99(4), 1.99(4), 2.955(5), 166(4)°.

2.3 Reactions of phosphorus(III) isocyanates with dipolarophiles: Reactivity of the products

The reaction of CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$P-NCO (5) with dipolarophiles like DMAD and diethyl acetylenedicarboxylate in toluene yielded products **23a-b** (Scheme 10). The structure of **23a,** for a sample prepared by my colleague,[123] was unambiguously proved by X-ray crystallography. This gives a convincing demonstration of 1,3-(P,C) dipolar nature of P(III) isocyanates. For the sake of further discussion, some details on the structure are given in Fig.13.[123]

Scheme 10



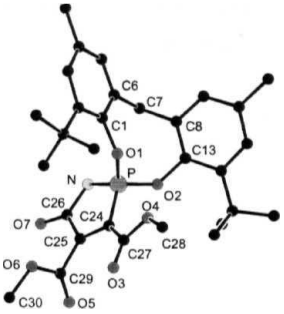
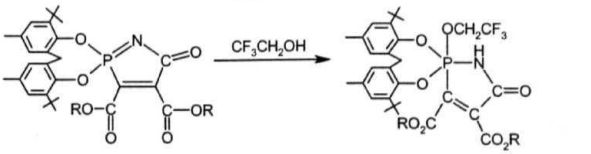


Fig. 13 Molecular structure of compound **23a** showing all non-hydrogen atoms (ref. 123); only selected atoms arc labeled. Selected bond parameters: P-0(1) 1.542(2), P-0(2) 1.549(2), P-N 1.558(2), P-C(24) 1.773(2), N-C(26) 1.359(3), C(24)-C(25) 1.321(4), C(25)-C(26) 1.521(4) A.

Reaction of the isocyanatophosphite 5 with other dipolarophiles [methyl propiolate, tetracyanoethylene, maleic anhydride, norbornene, phenyl ethylpropiolate and the imine derived from nitrobenzaldehyde and aniline did not take place at room temperature and compound 5 was recovered as such. In the case of methyl propiolate, even after heating the reactants upto 175° C, the reaction did not proceed (^{1}PNMR).

Compounds **23a-b** are useful substrates for further reactions. They have a P-N double bond across which alcohols or any acidic components can be added.[84,86] It can also be noted that there is an α,β-unsaturated ester group in these compounds. The first feature is realized in the reaction of **23a-b** with 2,2,2-trifluoroethanol to lead to the pentacoordinate phosphoranes **24a-b** (Scheme 11). The structure of **24a** is unambiguously proved by X-ray crystallography (see below for details).

Scheme 11



R = Me [**23a**; δ(P): 56.7]
= Et [**23b**; δ(P): 57.3]

R = Me [**24a**; δ(P): -65.0, -72.5; X-ray]
= Et [**24b**; δ(P): -64.7, -71.9]

The ^{31}P NMR spectra of **24a-b** at room temperature show that the pentacoordination is retained in solution. Low temperature spectra [Fig. 14] recorded for **24a** showed three peaks [8(P) -71.4, –69.9, –64.3] in toluene-d_8 solution. The spectra are reversible with respect to temperature. The two up-field peaks are more closely spaced [$\Delta\delta$ 1.5] and the downfied peak is well separated from these. Based on the discussion presented earlier, the closely spaced two up-field signals in **24a** can be attributed to **$24a_1$** and **$24a_2$**. The down-field signal has been assigned to the isomer **$24a_3$** where there is a significant change in the ligand environment, but the OCH_2CF_3 is still apical. This formulation is consistent with those given for the products **(11, 12** and **14a)** from the reaction of **P(III)** compounds with DIAD/ DEAD [Section 2.2].

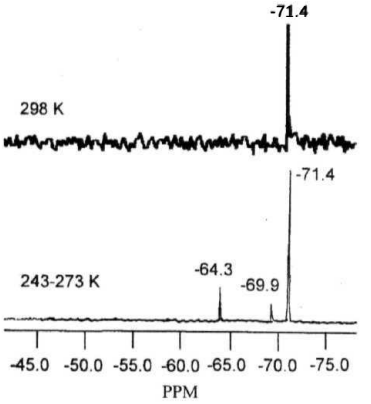
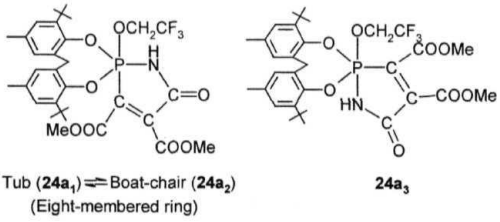


Fig. 14. Variable-temperature ^{31}P NMR spectra for **24a**



Consistent with the observation of three signals in the ^{31}P NMR, ^{1}H NMR spectra at low temperatures also showed three signals (one major, two minor) for the

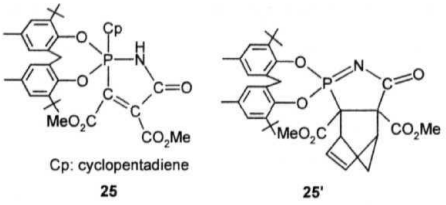
methyl protons of the /-butyl residues. However, because of the low intensities and merging of the signals in the other regions, a detailed analysis was not possible.

The above results prompted us to check the reactivity of the P=N bond in 23a with other acidic reagents. The results are summarized in Table 8. The acidic proton in the first five entries in Table 8 are expected to attack over P=N bond of 23a producing pentacoordinate compounds. From the reaction with mesitoic acid and *p*-toluene sulfonic acid, solids that showed 5(P) at [-67.8 (>85%); other peak at –0.62] and [–66.2 (>70%); remaining peak at -1.4] were obtained. Thus in these cases also, the products have structures similar to 24a. Although it would be interesting to see the X-ray structures of these acid containing pentacoordinate compounds the purity was not good enough for further characterization.

Table 8. Summary of the reaction of the heterocycle 23a with acids and other reagents.

S.No	Reactant	Reaction mixture ^{31}P NMR [δ(P)]
1	Mesitoic acid	-67.7(~>85%), -0.62
2	*P*-Toluenesulfonic acid	-66.2(~>70%),-1.4
3	2,6-Dichoro phenol	-68.2 (~20%), -1.7, 0.4, 7.0, 13.0, 18.1
3	Acetyl acetone (enolic form)	-60.6 (~20%), 19.3,21.5, 26.7,61.6,65.1
5	l,l'-Bi-2-naphthol	-72.5 and 6.7 (4:1)
6	Cyclopentadiene monomer	24.8 and 56.4 (1:1)

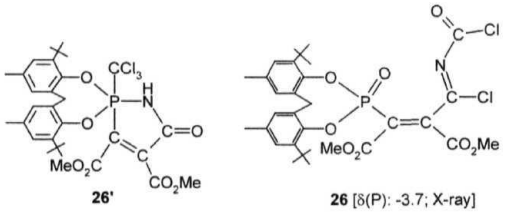
We also hoped that cyclopentadiene monomer would react with 23a to yield addition product 25 or 25'. Although an additional peak at 5 24.8 (50%) appeared in ^{31}P NMR, we could not effect the completion of the reaction. The 8(P) value is in the tertracoordinate region. A possible structure for this compound is 25'; however, we could not isolate a pure product.



Cp: cyclopentadiene

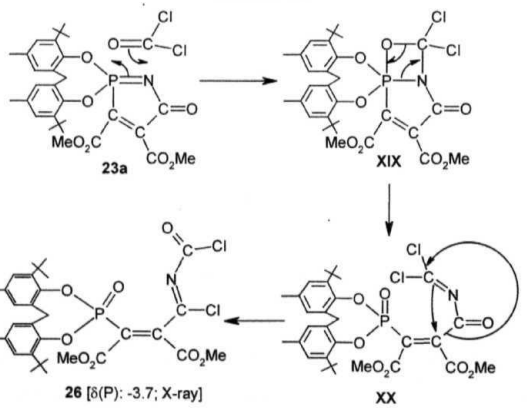
25 **25'**

Chloroform also has an acidic proton and therefore it was of interest to see whether a compound of type 26' could be obtained by heating **23a** with $CHCl_3$. However, compound 26 isolated had the structure shown below. Formation of 26 could involve addition of phosgene ($COCl_2$ formed by the air oxidation of CHCl3) to **23a.** The formation of 26 from **23a** is not clear, but may involve **XIX** and **XX** as possible intermediates (Scheme 12). It is also possible that 26 is formed via 26', but we could not formulate a logical pathway.



26' **26** [δ(P): -3.7; X-ray]

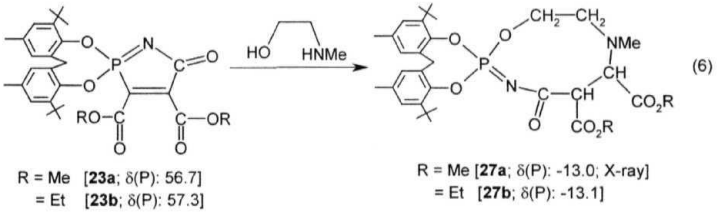
Scheme 12



In order to check the generality of the above reaction, **23a** was reacted with benzoyl chloride and a peak at 5(P) 6.8 is seen along with some other peaks. Due to the presence of a complex mixture of products [^{31}P NMR], we did not proceed further.

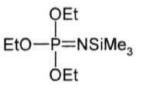
In contrast to the reaction with 2,2,2-trifluoroethanol *(cf.* **24a-b),** 2-(methylamino)ethanol adds to the compound **23a-b** in a different style utilizing the α,β-unsaturated ester moiety to give the products **27a-b** where an unprecedented ring expansion from five to nine has occurred (Scheme 13). The ^{31}P NMR chemical shift of **27a-b** in solution is close to those observed for **III** and **XXI** and the compounds **27a-b** could be recovered from the solution.[121123,, 24] These features suggest that the spirocyclic structure is retained in the solution state. A possible pathway for the formation of **27a-b** from **23a-b** is shown in Scheme 14. A Michael-type [1,4] addition in which the attack of amine at a carbon adjacent to phosphorus is the key step, cleavage of P-C bond occurs during subsequent attack by the hydroxy group on the phosphorus to yield **27a-b.**

Scheme 13

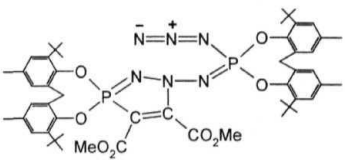


R = Me [**23a**; δ(P): 56.7]
= Et [**23b**; δ(P): 57.3]

R = Me [**27a**; δ(P): -13.0; X-ray]
= Et [**27b**; δ(P): -13.1]

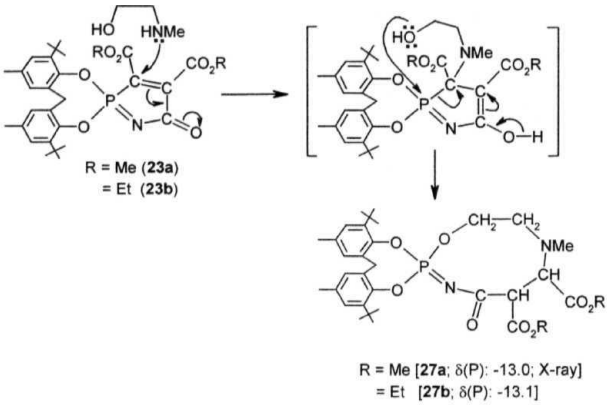


III [δ(P) -8.3]

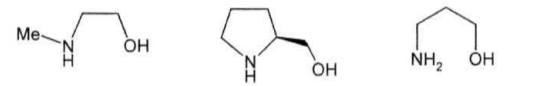


XXI [δ(P) 46.0, -3.7; X-ray]

Scheme 14



It is of interest to note that the P=N bond remains intact in this reaction. We tried to explore this reaction further by treating L-prolinol and 1-amino-propane-3-ol. Although both of these reacted, a pure product could not be isolated. The 6(P) values of the major products [with prolinol, 8(P) -14.9 (65%); with l-amino-propane-3-ol, 8(P) -8.9 (60%)] suggest that products similar to 27 are formed.



Structural aspects of 24a, 26 and 27a

The molecular structure of **24a** is shown in Fig. 15 and the geometrical parameters are given in Table 9. It can be readily noted that the 2,2,2-trifluoroethanol is at the apical position of the trigonal bipyramidal phosphorus. The apical P-O(8) bond [1.652(2) A] is slightly longer than that in 11 [1.602(2) A]. The apical C(28)-P-0(8) angle of 176.59(12) shows that the geometry around phosphorus is essentially a TBP. The sum of the bond angles at N(l) is ~ 359.6° suggesting a planar geometry at this nitrogen.

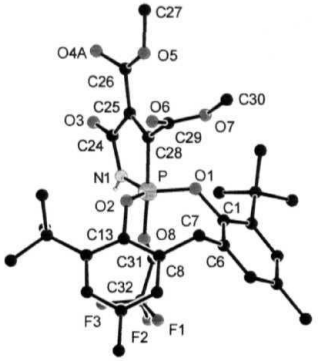


Fig. 15 Molecular structure of **24a.**CH_3CN showing all non-hydrogen atoms [except N(l)-H]. Only selected atoms are labeled. The N-H hydrogen is hydrogen bonded to the nitrogen of the solvent acetonitrile. N(l)-H...NCCH3 0.66(4), 2.47(4), 3.085(5) A, 156(5)° (not shown in the drawing).

Table 9. Selected bond lengths [A] and bond angles [°] for **24a.**CH_3CN with esd's in parentheses

P-O(1)	1.603(2)	P-C(28)	1.889(3)
P-O(2)	1.597(2)	N(l)-C(24)	1.378(4)
P-O(8)	1.652(2)	C(24)-C(25)	1.468(5)
P-N(l)	1.675(3)	C(25)-C(28)	1.328(4)
O(1)-P-O(2)	118.61(11)	O(2)-P-O(8)	90.66(10)
O(1)-P-O(8)	97.04(11)	O(2)-P-C(28)	87.63(11)
O(1)-P-N(1)	118.93(12)	N(l)-P-C(28)	85.74(13)
O(1)-P-C(28)	86.37(11)	N(1)-P-O(8)	92.66(12)
O(2)-P-N(1)	121.39(13)	O(8)-P-C(28)	176.59(11)

The molecular structure and the geometrical parameters for 26 are shown in Fig. 16 and Table 10 respectively. The P-C bond length in 26 [1.794(17) A] is in the expected single bond distance and close to the P-C bond length [1.773(2) A] in the **23a.** The P-O bond distances are normal.[89] The C(24)-C(27) double bond distance

[1.335(6) A] and N(l)-C(30) distance [1.229(6) A] are also in the expected range *[cf.* structures of 18 and **23a].**

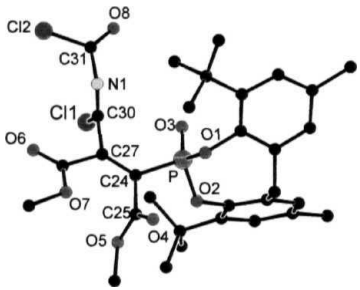


Fig. 16 Molecular structure of 26 showing all non-hydrogen atoms

Table 10. Selected bond lengths [A] and angles [°] for 26 with esd's in parentheses

P-O(1)	1.578(3)	C(24)-C(27)	1.335(6)
P-O(2)	1.582(3)	C(24)-C(25)	1.510(6)
P-O(3)	1.443(3)	C(27)-C(30)	1.497(6)
P-C(24)	1.794(4)	C(30)-N(l)	1.229(6)
C(30)-Cl(l)	1.727(5)	N(l)-C(31)	1.393(7)
C(31)-O(8)	1.165(7)	C(31)-C1(2)	1.715(6)
O(1)-P-O(2)	107.60(16)	P-C(24)-C(27)	124.3(3)
O(1)-P-O(3)	116.43(18)	P-C(24)-C(25)	114.8(3)
O(1)-P-C(24)	99.61(17)	C(25)-C(24)-C(27)	120.9(4)
O(3)-P-O(2)	116.26(17)	Cl(2)-C(31)-O(8)	122.3(5)
O(3)-P-C(24)	116.06(19)	N(l)-C(30)-Cl(l)	124.2(4)
O(2)-P-C(24)	98.24(17))		

Compound **27a** represents a rare example of phosphorus heterocycle with a 9-membered ring. The molecular structure and the geometrical parameters are shown in Figure 17 and Table 11 respectively. The P-N(l) bond distance [1.550(3) A] is comparable to the P=N distances in **20a** [1.564(4)] and **23a** [1.558(2) A]. The P-0 bond lengths [mean: 1.569 A] are slightly longer than those in **23a** [mean: 1.55 A].

Compound **27a** is the only phosphorus heterocycle with two very large membered rings known todate. The 9-membered ring has a twisted boat half chair conformation. In the literature compound **XXII,** the 9-membered ring containing phosphorus has a twist-chair-chair conformation.[125]

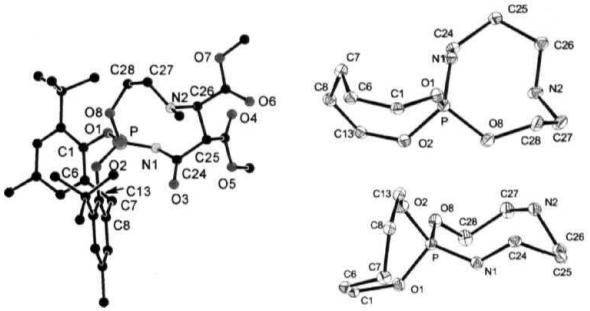
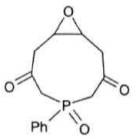


Fig. 17 Molecular structure of **27a**.$C_6H_5CH_3$. The solvent and hydrogen atoms are not shown here and only selected atoms are labeled. The conformations of the 8 and 9-membered rings are also shown.



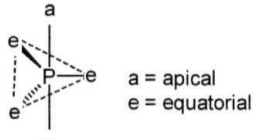
XXII

Table 11. Selected bond lengths [A] and angles [°] for of **27a**.$C_6H_5CH_3$ with esd's in parentheses

P-O(1)	1.573(2)	N(2)-C(26)	1.471(3)
P-O(2)	1.566(2)	N(2)-C(27)	1.467(3)
P-N(l)	1.550(2)	C(24)-C(25)	1.533(3)
P-O(8)	1.580(2)	C(25)-C(26)	1.539(3)
N(l)-C(24)	1.370(2)	C(27)-C(28)	1.510(3)
O(1)-P-O(2)	107.08(15)	O(2)-P-O(8)	97.22(10)
O(1)-P-O(8)	105.00(9)	N(1)-P-O(8)	115.93(9)
O(1)-P-N(1)	106.37(9)	P-O(8)-C(28)	121.51(13)
O(2)-P-N(1)	123.66(10)	P-N(l)-C(24)	129.88(12)

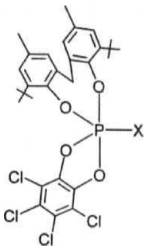
2.4 (4+1) Cycloaddition reactions of phosphites with *o*-chloranil: Pentacoordinate phosphoranes

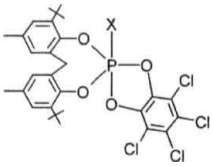
In earlier studies from our laboratory, we observed that in pentacoordinate phosphorus compounds (involving the eight-membered ring used in this present study) the bulkier **-NMe_2** group is more apicophilic than the -NH2 group.[110] This is opposite to the general trend that a sterically more demanding group [e.g. **-NMe_2** in structure CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2P(NMe_2)$(1,2-$O_2C_6Cl_4$) (**1.90c**; *cf.* Section **1.31)**] should be less apicophilic than a sterically less demanding group [e.g. **–NH_2** in CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2P(NH_2)$(1,2-$O_2C_6Cl_4$); **(1.91b;** *cf.* Section **1.31)**].[14] These results in conjunction with those of Holmes and coworkers[111 13] have shown that in compounds of type CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2P(R)$(1,2-$O_2C_6Cl_4$) the eight-membered ring can span either diequatorial (e-e) or apical-equatorial (a-e). The five membered ring always tends to occupy apical-equatorial (a-e) disposition. Hence, the fifth substituent 'R' can occupy either apical or equatorial position depending upon whether the eight-membered ring spans diequatorial (e-e) or apical-equatorial (a-e) disposition around trigonal bipyramidal phosphorus (TBP). Thus, it is possible to ascertain relative apicophilicities of several functional groups 'R'. These studies have significantly enhanced our understanding of the structural preferences of pentacoordinate phosphorus,[110,126-127] which in turn are important in the context of nucleophilic substitution reactions at a tetrahedral phosphorus (V) centre.[89-9



(TBP)

In continuation of our study, we reacted P(NI) precursors CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2PR$ [R = Et (7), *n*-Bu (8)] with tetrachloro-l,2-benzoquinone (*o*-chloranil) to obtain the pentacoordinate derivatives CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2P(R)$(1,2-$O_2C_6Cl_4$) [R = Et (28), n-Bu (29)]. Yields after crystallization are in the range of 80-90%. The ^{31}P NMR spectra of these compounds confirm that the pentacoordinate structure is preserved in solution.





X = Me [1.**91a**; 5(P): **-21.0**; X-ray]* X = Et [28; 8(P): -18.5, -25.3 (1:7) X-ray]
NH_2 [1.**91b**; 8(P):-50.1; X-ray]* *n*-Bu [**29**; 8(P): -19.6, -22.6 (1:7)]
NMe_2 [1.90c; 8(P): -46.5, **-42.3** (1.4); X-ray]*

(* Compounds 1.90c, 1.91a and 1.91b *cf.* Section 1.31)

The disposition of ethyl group in 28 is unambiguously proved by X-ray crystallography. The molecular structure is shown in Fig. 18 and the geometrical parameters are given in Table 12.

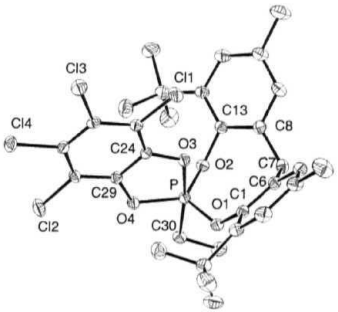


Fig. 18 Molecular structure of **28**.CH_2Cl_2 showing all non-hydrogen atoms

Table 12 Selected bond lengths [A] and bond angles [°] for **28**.CH_2Cl_2 with esd's in parentheses

P-O(1)	1.599(3)	P-O(4)	1.675(3)
P-O(2)	1.600(3)	P-C(30)	1.829(4)
P-O(3)	1.750(3)	C(30)-C(31)	1.515(6)

O(1)-P-O(2)	117.42(16)	O(2)-P-C(30)	92.00(18)
O(1)-P-O(3)	90.46(14)	O(3)-P-O(4)	87.27(13)
O(1)-P-O(4)	121.10(16)	O(3)-P-C(30)	174.81(18)
O(1)-P-C(30)	92.40(18)	O(4)-P-C(30)	87.54(17)
O(2)-P-O(3)	90.52(14)	C(31)-C(30)-P	116.3(3)
O(2)-P-O(4)	121.44(16)		

The ethyl group is at the apical position of a trigonal bipyramid; this can be contrasted with the equatorial disposition of the methyl group in 1.91a (*cf.* Section 1.31).[110a] That this result is not serendipitous is shown by the fact that the bulky *t*-Bu group in $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(t\text{-Bu})(1,2\text{-}O_2C_6Cl_4)$ (XXIII; X-ray structure done from our laboratory[126]) also occupies an apical position. The P-C bond distance in 28 [1.829(4) A] is slightly shorter than that in XXIII [P-C 1.879(2) A], but is significantly longer than that in $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(Me)(1,2\text{-}O_2C_6Cl_4)$ (1.91a) [1.792(3) A, carbon equatorial].[110a] The O(3)-P-C(30) angle [174.81(18)°] clearly shows that the phosphorus in compound 28 has a trigonal bipyramidal (TBP) geometry.

From the present and previous data, we observe that the eight-membered 1,3,2-dioxaphosphocin ring has a *tub* conformation when located apical-equatorially (Fig. 19a) and *boat-chair* conformation when located diequatorially (Fig. 19b). These features for the phosphocin ring, when located diequatorially or apical-equatorially in trigonal bipyramidal phosphorus, have also been observed in similar compounds earlier.[110]

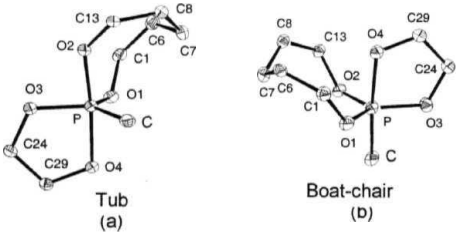


Fig. 19 Plots showing conformation of the 1,3,2-dioxaphosphocin ring in (a) 1.91a and (b) 28 (also XXIII).

Variable temperature NMR behavior

Compounds 28 and 29 exhibit two peaks in the ^{31}P NMR spectra **[28:** 8 -18.5, -24.3 (br); 29: 8 −19.6, -22.6 (br)] in $CDCl_3$ as well as in toluene-d_8 solutions at room temperature. Due to the presence of the two signals at room temperature [not expected; *cf.* X-ray structure of 28] we made an attempt to study the ^{31}P NMR spectra of these compounds in the solid (at 298 K) as well as in solution state (at different temperatures). The essential features in the variable-temperature ^{31}P NMR spectra for 28 (Fig. 20) and 29 (Fig. 21) are as follows:

(i) For the P-Et compound 28, in the ^{31}P NMR spectrum at 246 K three peaks were observed at 8 -14.1, -18.6 and -25.3 (Fig. 20). This is quite different from the room temperature spectrum. The solid-state ^{31}P NMR spectrum showed two very broad signals [8 -10.6 (major), -25.0 (minor)], which is apparently inconsistent with its solution state NMR behavior.

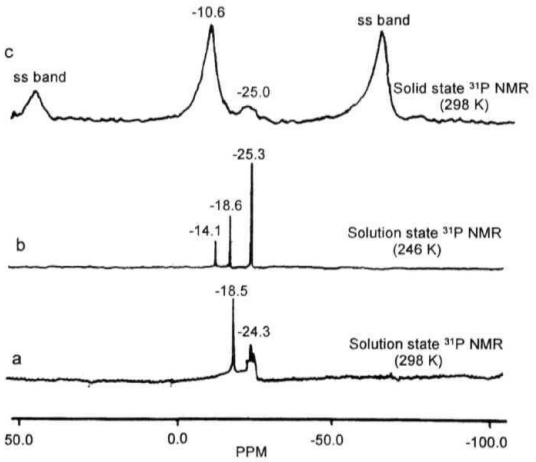


Fig. 20 ^{31}P NMR spectra of 28 (a) at 298 K in the solution-state (b) at 246 K in the solution-state and (c) at 298 K in the solid-state.

(ii) The ^{31}P NMR spectrum for the P-*n*-Bu compound 29 showed three peaks at 8 -15.3, -20.0 and -26.0 (major) at 242 K (Fig. 21). The solid-state ^{31}P NMR spectrum for 29 (Fig. 21c) shows a single peak at 8 -26.0 and is same as the major peak seen at low temperatures in solution [Fig. 21, Table 13].

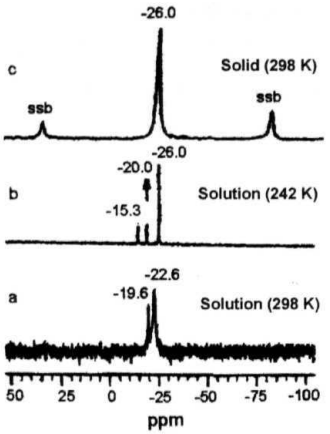


Fig. 21 ^{31}P NMR spectra of 29 (a) at 298 K in the solution-state ($C_6D_5CD_3$), (b) at 242 K in the solution-state ($C_6D_5CD_3$) and (c) at 298 K in the solid-state.

Table 13. Solution (toluene-d_8) and solid-state ^{31}P NMR data for the phosphoranes {CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$}P(R)(1,2-$O_2C_6Cl_4$)

R (compd)	Solution	Temp. (K)	Solid (298 K)
Et **(28)**	-14.1,-18.6,-25.3	246	
	-18.5 (minor), –24.3 (br)	298	-10.6 (major),-25.0
n-Bu **(29)**	-15.3,-20.1,-26.0 (major)	242	
	–19.6, –22.6 (br)	298	-26.0
Me **(1.91a)**	-15.8,-21.0,-27.2 (minor)	243, 233	
	-20.7	298	-13.7
t-Bu **(XXIII)**	-22.6	233-298	-23.5

It should be noted that in the case of the *t*-Bu compound **XXIII,** no significant change was observed in the solid or solution state ^{31}P NMR spectra. Since the major signal for 29 in solution (up-field peak at 242 K) is also the one seen in the solid state, the up-field ^{31}P NMR signals are most likely due to the isomer with apical C(alkyl) with compound 28 showing a borderline behavior. Thus for 28 we assign the peak at -25.3 (br) to the isomer wherein the ethyl group spans an apical position. Compound **1.91a** shows a fairly sharp solid-state signal [5(P) –13.7] which is close to the down-

field peak observed at low temperatures in solution [8(P) –15.8]. Thus the most down-field peak may be ascribed to the isomer with C(alkyl) group equatorial.

It is interesting to note that there are three distinct ^{31}P NMR signals in solution at low temperatures for 28 and 29 in the pentacoordinate region. To our knowledge, such a phenomenon in systems containing pentacoordinate phosphorus is rare. Another system in which four signals are observed is described earlier in this thesis. ' ' Since it is clear that the eight-membered phosphocin ring can (i) either occupy diequatorial or apical-equatorial sites in trigonal bipyramid readily and (ii) have two favored conformations (boat-chair and tub),[110] there are four possible isomers; three of these are observed in the ^{31}P NMR (solution; Figure 22). Although 'H NMR spectra of 28 and 29 have showed multiple resonances, because of the overlapping and broad signals with poor resolution in the temperature region studied, a detailed analysis was not possible.

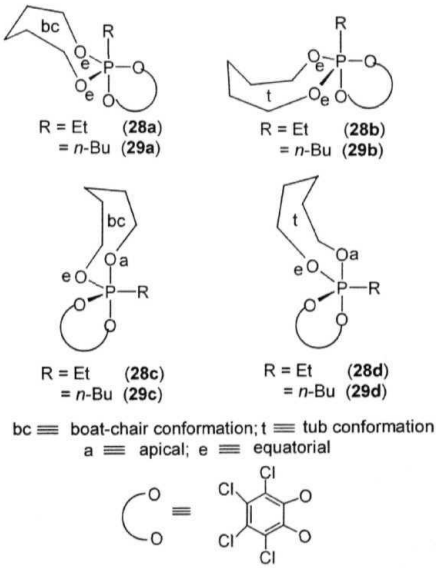


Fig. 22 Four possible isomers for the compounds **28** and **29**

2.41 Attempted synthesis of $\{CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2\}PH(1,2\text{-}O_2C_6Cl_4)$: Preparation and structure of the aluminum complex |j($H_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2\}P(O)(OC_6Cl_4O)]_3Al.LiH$

Since we had observed the 'reversed apicophilicity' phenomenon in many of our pentacoordinate phosphorus compounds as outlined above, we became interested in knowing the site preference (apical or equatorial) for the small hydrido group. In this connection we wanted to prepare the P-H phosphorane $[CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2PH(1,2\text{-}O_2C_6Cl_4)]$ (31). But treatment of $\{CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2\}PH$ (30) with tetrachloro-l,2-benzoquinone (*o*-chloranil) resulted in a black insoluble material that could not be analysed further. In another route, when the chlorophosphorane $[CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2P(Cl)(1,2\text{-}O_2C_6Cl_4)]$ **(32)**[131] was treated with $LiAlH_4$, again the expected compound 31 could not be isolated. Instead, crystals of a small quantity (ca 15% yield) of the hexacoordinate aluminum compound $[CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2P(O)(OC_6Cl_4O)]_3Al$ (33) was isolated. This could have resulted from the reaction of the intermediate hydrolysis product $[CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2]P(O)(OC_6Cl_4OH)$[131] with $LiAlH_4$. The X-ray structure *[cf.* Fig. 23, Table 14] shows that three phosphoryl oxygens and three catecholate oxygens are connected to aluminum. The Al-O(4) bond [1.845(2) A] to the catecholate oxygen is shorter than the Al-O(5) bond [1.946(2) A] to the phosphoryl oxygen; this is expected, because the former is a covalent and the latter is coordinate covalent bond. The geometry at aluminum is distorted octahedral. Since this was not the theme of the present work, we have not investigated this area further.

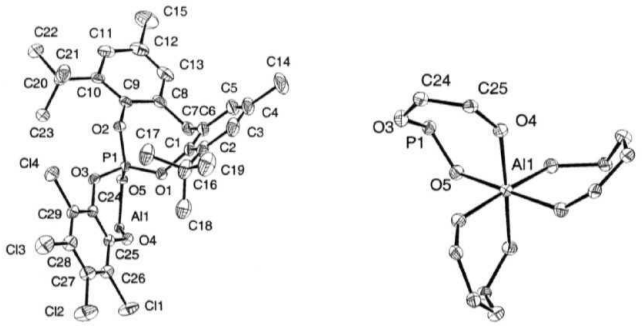


Fig. 23 Molecular structure of 33.LiH showing all non-hydrogen atoms

Table 14. Selected bond lengths [A] and bond angles [°] for 33.LiH with esd's in parentheses

Al(1)-O(4)	1.845(2)	Al(1)-O(5)	1.946(2)
P(1)-O(1)	1.559(2)	P(1)-O(2)	1.549(2)
P(1)-O(3)	1.559(2)	P(1)-O(5)	1.474(2)
O(1)-P(1)-O(2)	105.98(9)	O(4)-Al(1)-O(4)	97.11(7)
O(1)-P(1)-O(3)	105.86(9)	O(4)-Al(1)-O(5)	90.59(6)
O(1)-P(1)-O(5)	116.97(9)	O(5)-Al(1)-O(5)	83.15(7)
O(2)-P 1-0(5)	112.42(9)	P(1)-O(5)-Al(1)	124.85(9)
O(2)-P(1)-O(3)	100.98(8)	C(25)-O(4)-Al(1)	138.94(14)
O(3)-P(1)-O(5)	113.14(9)	C(9)-O(2)-P(1)	127.36(14)

2.5 SUMMARY

1. The naive-looking reaction of DEAD/ DIAD with P(III) compounds, the key to the enormous synthetic utility of the Mitsunobu reaction, leads not just to the MBH betaine I $[Ph_3P^+N(COOR)N^-COOR]$, but has the potential to open up new frontiers. When electronegative substituents are present on P(II1) precursors, one of the preferred pathways is the formation of pentacoordinate derivatives. When reactive functionalities (e.g. NCO) are present on phosphorus, other pathways including cycloaddition are possible. The results obtained herein could be useful while trying to improve on the original Mitsunobu procedure wherein removal of the byproduct triphenylphosphine oxide could pose problems in specific cases.

2. New modes of dipolar cycloaddition of electron deficient acetylenes to P(III) isocyanates have been discovered. Novel reactions of thus obtained products including an unprecedented ring expansion reaction (from 5 to 9-membered) have been presented.

3. Examples of compounds containing a PO_4C framework in a TBP geometry at phosphorus that demonstrate that the familiar steric and electronegativity rules for the apicophilicity of alkyl group are not followed, have been provided. Possible rationalization for this observation is discussed. Thus, this study is expected to significantly enhance our understanding of the structural preferences of pentacoordinate phosphorus, which in turn is important in the context of nucleophilic substitution reactions at a tetrahedral phosphorus(V) centre.

In all the above systems, wherever possible, X-ray structural proof is provided.

CHAPTER 3

EXPERIMENTAL SECTION

General: Chemicals and solvents were procured from Aldrich/ Fluka or local manufacturers. Further purification was done according to standard procedures wherever required.[128] All operations, unless otherwise specified, were carried out under dry nitrogen atmosphere using standard vacuum line techniques.[129]

Melting points: Melting points were determined using a SUPERFIT hot stage apparatus and are uncorrected.

Elemental analyses: Elemental analyses were carried out on a Perkin- Elmer 240C CHN analyzer or obtained from elsewhere [Indian Association for the Cultivation of Science (Kolkata, India)].

Mass spectra: Mass spectra were recorded on a CEC-21-110B double focusing mass spectrometer operating at 70 eV using direct inlet system.

Infrared spectroscopy: IR spectra were recorded on a JASCO FT/IR 5300 spectrophotometer.

NMR Spectroscopy: 'H, ^{13}C and ^{31}P NMR spectra were recorded using 5 mm tubes on a Bruker 200 MHz or 400 MHz NMR spectrometer in $CDCl_3$ solution (unless specified otherwise) with shifts referenced to $SiMe_4$ (^{1}H, ^{13}C: 8 = 0) or ext. 85% H_3PO_4 (^{31}P: 8 = 0) respectively; *J* values are in Hz.

3.1 Preparation of P(III) derivatives

Most of these compounds (although were pure) were moisture sensitive and hence characterization was done mainly by spectroscopy; for stable compounds elemental analyses was performed. ^{13}C and ^{31}P NMR of representative compounds are illustrated in the Appendix.

(a) $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2PCl$ (1) (*Improved procedure*)

An excess of PCl_3 (4.13 g, 30.0 mmol) was added to 2,2-methylenebis-6-*tert*-butyl-4-methyl phenol (3.40 g, 10.0 mmol) and the mixture was refluxed for 2 d. Excess PCI3 was removed by distillation to obtain a pale yellow solid which on sublimation (150 °C/ 0.2 mm Hg) yielded 1. This procedure is more convenient and the yield is better than that reported before.[130]

Yield: 3.28 g (81%).

Mp: **146-148°C [lit** 145-147°C[130]].

^1H NMR: 5 1.41 (s, 18 H, *t*-Bu-*H*), 2.03 (s, 6 H, ArCH_3), 3.55 **(d,** ^2J(HH) = 13.0 **Hz, 1 H,** CH_AH$_X$), 3.84 **(d,** V(HH) ~ 13.0 **Hz, 1 H,** CH$_A$$H_X$), 6.84-7.04 (m, **4 H,** *Ar-H).*

^{31}P NMR: **5** 153.7 **[lit** 158.0[130]].

(b) $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2PNHMe$ (2)

To a stirred solution of 1 (4.05 g, 10.0 mmol) in toluene (60 mL) at –60°C was passed an excess of methylamine gas for 3 h with continuous stirring. The reaction mixture was stirred further for 0.5 h at the same temperature and filtered after warming to room temperature. Solvent was completely removed from the filtrate and the residue crystallized from hexane to give **2**.[110a]

Yield: 3.63 g (91%).

Mp: 170-172°C.

IR (KBr): 3343, 1623, 1360, 1197, 1010, 897 cm^{-1}.

^1H NMR: 5 1.41 (s, 18 H, *t*-Bu-*H*), 2.28 (s, 6 H, ArCH_3), 2.97 (dd, V(HH) = 5.9 **Hz, V(PH)** = 8.8 Hz, 3 H, NHCH_3), 3.35 (d, V(HH) = 13.0 **Hz, 1 H,** CH_AH$_X$), 4.33 **(dd, V(PH)** ~ 4.0 Hz, ^2J(HH) = 13.0 Hz, **1** H, CH$_A$$H_X$), 6.98-7.10 (m, **4 H,** Ar-*H*).

^{31}P NMR: 5 **142.6 [lit.** 142.6[110a]].

(c) **$CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2PNHt\text{-Bu}$** (3)

To a stirred solution of 1 (0.81 g, 2.0 mmol) in toluene (20 mL) was added *tert*-butyl amine (0.40 g, 5.54 mmol) at room temperature. After stirring for 12 h, filtration followed by removal of solvent afforded 3 as a white solid.

Yield: 0.84 g (95%).

Mp: 116-118°C.

IR (KBr): 3389, 1738, 1603, 1464, 1387, 1362, 1200, 1014, 828 cm^{-1}.

^1H NMR: 8 1.52 (s, 18 H, *t*-Bu-*H*), 1.58 (s, 9 H, N*t*-Bu-*H*), 2.35 (s, 6 H, $ArCH_3$), 3.10 (d, V(PH) = 17.6 Hz, 1 H, P-N*H*-*t*-Bu), 3.50 (d, $^2J(HH)$ = 12.7 Hz, 1 H, $ArCH_AH_X$), 4.36 (d, $^2J(HH)$ = 12.7 Hz, 1 H, $ArCH_AH_X$), 7.08-7.35 (m, 4 H, Ar-*H*).

^{13}C NMR: 8 21.2 (s, $ArCH_3$), 31.2 (s, $C(CH_3)_3$), 33.2 (d, V(PC) = 4.7 Hz, $PNHC(CH_3)_3$), 35.0 (s, $ArCH_2$), 35.4 (s, CMe_3), 53.1 (d, V(PC) ~ 10.0 Hz, $PNHCMe_3$), 125.5, 126.4, 127.2, 128.4, 128.7, 129.0, 129.2, 132.7, 135.9, 141.6, 148.7, 148.8.

^{31}P NMR: 8 141.9.

Anal. Calcd for $C_{27}H_{40}NO_2P$: C, 73.42; H, 9.13; N, 3.17. Found: C, 73.25; H, 9.00; N, 3.22.

(d) **$CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2PNMe_2$** (4)

To a stirred solution of 1 (2.03 g, 5.0 mmol) in toluene (30 mL) at -60°C was passed an excess of dimethyl amine gas for 3 h with continuous stirring. The reaction mixture was stirred further for 0.5 h at the same temperature and filtered after warming to room temperature. Solvent was completely removed from the filtrate and the residue crystallized from hexane to give 4.

Yield: 1.90 g (92%).

Mp: 207-209°C.

IR (KBr): 2957, 1599, 1498, 1437, 1273, 1057, 835 cm^{-1}.

^1H NMR: 8 1.39, 1.41 (2 s, 18 H, *t*-Bu-*H*), 2.29 (s, 6 H, $ArCH_3$), 2.94 (d, V(PH) = 9.0 Hz, 6 H, $N(CH_3)_2$), 3.32 (d, $^2J(HH)$ = 12.4 Hz, 1 H, CH_AH_X), 4.32 (dd, V(PH) ~ 3.0 Hz, $^2J(HH)$ - 12.5 Hz, 1 H, CH_AH_X), 7.01-7.09 (m, 4 H, Ar-*H*).

^{31}P NMR: 8 143.6 [lit: 143.6, 142.7[110a]].

(e) **$CH_2(6\text{-}t\text{-Bu-}4\text{-Me-}C_6H_2O)_2PNCO$** (5)

Sodium cyanate (previously dried by evacuating in vaccum for 1 h; 1.95 g, 30.0 mmol) was added to a stirred solution of 1 (4.05 g, 10.0 mmol) in acetonitrile (40 mL) and the mixture was stirred for 2 d. The solvent was removed in *vacuo* and heptane (35 mL) was added to the residue. Filtration followed by complete removal of solvent gave a solid that was crystallized from acetonitrile to give 5.

Mp: 124-126°C.

Yield: 3.90 g (95%).

IR (KBr): 2259, 1719, 1439, 1213, 1130, 860 cm^{-1}.

^1H NMR: 8 1.42 (s, 18 H, *t*-Bu-*H*), 2.32 (s, 6 H, ArCH_3), 3.64 (d, ^2J(HH) = 13.0 Hz, 1 H, CH_AH$_X$), 3.84 (dd, V(HH) ~ 13-16, V(PH) - 3-6 Hz 1 H, CH$_A$$H_X$), 7.06, 7.13 (2 s, 4 H, *Ar-H*).

^{13}C NMR: 21.0 (s, Ar-CH_3), 30.7 (s, Ar-C(CH_3)$_3$), 34.6 (s, Ar-C(CH$_3$)$_3$), 34.7 (s, Ar-CH_2), 126.7 (V(P-C) = 9.0 Hz), 127.1, 128.9,, 134.3, 135.6, 141.6, 146.8 (Ar-*C*).

^{31}P NMR: δ 120.7 (~5 %), 121.2 (br, ~95%).

(f) $CH_2(6\text{-}t\text{-Bu-}4\text{-Me-}C_6H_2O)_2PNCS$ (6)

Potassium thiocyanate (previously dried at 130°C for 1 d; 2.91 g, 30.0 mmol) was added to a stirred solution of 1 (4.05 g, 10.0 mmol) in acetonitrile (45 mL) and the mixture was stirred for 2 d. The solvent was removed in *vacuo* and heptane (35 mL) was added to the residue. After filtration, the precipitate was further washed with heptane (10 mL) and the washings added to the filtrate. The combined solution was concentrated (~ 5 mL). The required compound 6 was obtained as a crystalline solid after 1 d.[110b]

Mp: 126-128°C.

Yield: 3.63 g (76%).

^1H NMR (C_6D_6): δ 1.41 (s, 18 H, *t*-Bu-*H*), 2.03 (s, 6 H, ArCH_3), 3.55 (d, ^2J = 13.0 Hz, 1 H, CH_AH$_X$), 3.84 (d, ^2J ~ 13.0 Hz, 1 H, CH$_A$$H_X$), 6.84-7.04 (m, 4 H, Ar-*H*).

^{31}P NMR (C_6D_6): δ 115.9.

(g) **CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$PEt** (7)

To Mg turnings (0.48 g, 20 mmol) in THF (10 mL) was added a peck of iodine without stirring. After the mixture decolorized, ethyl bromide (1.08 g, 0.74 mL, 10 mmol) in THF (5 mL) was added drop-wise with stirring. After 10 h, compound 1 (4.05 g, 10 mmol) in THF (10 mL) was added drop-wise (10 min) and the contents stirred overnight. The solvent was removed *in vacuo* and toluene (*ca.* 15 mL) was added to the residue. Filtration followed by concentration of the filtrate to 4 mL and addition of *n*-heptane (3 mL) afforded compound 7 as a white solid.

Yield: 3.35 g (85%).

Mp: 174-176°C.

^{1}H NMR: 5 1.47 (s, 18 H, *t*-Bu-*H*), 1.60 (m, 3 H, PCH_2CH_3), 2.21 (m, 2 H, PCH_2CH_3), 2.38 (s, 6 H, Ar-CH_3), 3.42 (d, ^2J(H-H) = 13.1 Hz, 1 H, CH_AH_X), 4.43 (dd, V(P-H) - 2.8 Hz, ^2J(H-H) = 13.1 Hz, 1 H, CH_AH_X), 7.06-7.21 (m, 4 H, Ar-*H*).

^{13}C NMR: 8 5.2 (d, ^2J(P-C) = 7.1 Hz, PCH_2CH_3), 21.1 (s, Ar-CH_3), 28.0 (d, ^1J(P-C) = 14.5 Hz, PCH_2CH_3), 30.8 (s, Ar-C(CH_3)$_3$), 34.5 (s, Ar-*C*(CH_3)$_3$), 34.8 (s, Ar-CH_2), 125.4 126.4, 126.7, 127.1, 128.3, 128.9, 129.1, 133.1, 133.5, 136.0, 136.1, 140.9, 142.1, 151.5, 151.6 (all Ar-*C*).

^{31}P NMR: δ 189.5.

(h) **CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$PBu^n** (8)

The procedure was the same as that for 7 using *n*-butyl bromide (1.37 g, 1.07 mL, 10 mmol). Filtration followed by concentration of the filtrate to (4 mL) and addition of *n*-heptane (2 mL) afforded compound 8 as a white solid.

Yield: 3.19 g (75%).

Mp: 116-118 °C.

^{1}H NMR: 5 1.15 (t, V(H-H) ~ 6 Hz, $P(CH_2)_3CH_3$), 1.45 (br s, 20 H, *t*-Bu-*H* + $P(CH_2)_2CH_2CH_3$), 1.55 (m, 2 H, $PCH_2CH_2CH_2CH_3$), 2.16 (m, 2 H, $PCH_2CH_2CH_2CH_2$), 2.38 (s, 6 H, Ar-CH_3), 3.42 (d, V(H-H) ~ 13.0 Hz, 1 H, CH_AH_X), 4.45 (dd, V(P-H) ~ 2.5 Hz, ^2J(H-H) ~ 13.0 Hz, 1 H, CH_AH_X), 6.90-7.30 (m, 4 H, Ar-*H*).

^{13}C NMR: δ 13.9 (s, $PCH_2CH_2CH_2CH_3$), 21.1 (s, Ar-CH_3), 23.2 (d, V(P-C) - 7.0 Hz, $PCH_2CH_2CH_2CH_3$), 24.5 (d, V(P-C) = 7.1 Hz, $PCH_2CH_2CH_2CH_3$), 30.8, 30.9 (2 s, Ar-C(CH_3)$_3$), 34.5 (s, Ar-*C*(CH_3)$_3$), 34.7 (s, Ar-CH_2),

35.2 (d, ^{1}J(P-C) = 15.3 Hz, $PCH_2CH_2CH_2CH_3$), 125.4 126.4, 126.7, 127.1, 128.3, 128.9, 129.1, 133.1, 133.5, 136.0, 136.1, 140.9, 142.1, 151.5, 151.6 (all Ar-*C*).

^{31}P NMR: δ 190.4.

(i) CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2POCH_2CH_2NMe_2$ (9)

To a stirred solution of 1 (0.81 g, 2.0 mmol) in toluene (20 mL) at 0°C was added triethylamine (0.20 g, 0.28 mL, 2.0 mmol) drop-wise, followed by N,N-dimethylethanolamine (0.15 g, 0.22 mL, 2.0 mmol), over a period of 0.5 h. After stirring for 12 h, filtration followed by the removal of solvent afforded 9 as a white solid.

Yield: 0.79 g (86 %).

Mp: 104-105°C.

IR (KBr): 1605, 1462, 1361, 1258, 1022, 951 cm^{-1}.

^{1}H NMR: 5 1.44 (s, 18 H, *t*-Bu-*H*), 2.31 (s, 6 H, ArCH_3), 2.41 (s, 6 H, $OCH_2CH_2N(CH_3)_2$), 2.80 (t, V(HH) = 12.0 Hz, 2 H, $OCH_2CH_2NMe_2$), 3.39 (d, ^{2}J(HH) = 16.1 Hz, 1 H, ArCH_AH_X), 4.28 (dd, V(PH) ~ 4.3 Hz, ^{2}J(HH) = 16.1 Hz, 1 H, ArCH_AH_X), 4.58 (m, 2 H, $OCH_2CH_2NMe_2$), 7.05, 7.12 (2 br s, 4 H, Ar-*H*).

^{13}C NMR: 8 21.0 (s, ArCH_3), 30.0 (s, $C(CH_3)_3$), 30.9, 31.0 (2 s, $C(CH_3)_3$), 34.5 (s, ArCH_2), 45.6 (s, $OCH_2CH_2N(CH_3)_2$), 59.5 (s, $OCH_2CH_2NMe_2$), 60.7 (d, ^{2}J(PC) = 3.8 Hz, $POCH_2CH_2NMe_2$), 126.6, 128.2, 136.1, 133.4, 136.2, 141.9, 142.0, 145.9, 146.0, 150.2.

^{31}P NMR: 8 129.0.

Anal. Calcd for $C_{27}H_{40}NO_3P$: C, 70.85; H, 8.81; N, 3.06. Found: C, 70.71; H, 8.75; N, 2.95.

3.2 Reactions of phosphorus(III) compounds with DEAD/ DIAD: Reactvity of the products

Synthesis of [CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2PCl${N(COOEt)NC(OEt)-O-}] (10a)

DEAD (1.74 g, 10.0 mmol) was added in one lot to a solution of 1 (4.05 g, 10.0 mmol) in dry toluene (30 mL) and the mixture was stirred for 72 h at room

temperature. The solution was concentrated and the crystallization was done using dichloromethane (~5 mL).

Yield: 5.15 g (89%)

Mp: 179-181°C.

IR (KBr): 1730, 1698, 1601, 1331, 1202, 1084, 1013 cm^{-1}.

^1H NMR: 8 1.30 (t, V(HH) = 7.2 Hz, 3 H, CH_2CH_3), 1.38 (s, 18 H, *t*-Bu-*H*), 1.44 (t, V(HH) = 7.2 Hz, 3 H, CH_2CH_3), 2.32, 2.34 (2 s, 6 H, $ArCH_3$), 3.43 (dd, V(HH) = 2.9 Hz, ^2J(HH) = 13.7 Hz, 1 H, $ArCH_AH_X$), 4.35, 4.45 (2 qrt, V(HH) = 7.2 Hz each, 4 H, CH_2CH_3), 5.34 (dd, V(PH) = 5.8 Hz, ^2J(HH) = 13.7 Hz, 1 H, $ArCH_AH_X$), 7.04, 7.17 (2 br s, 4 H, Ar-*H*).

^3C NMR: 8 14.2, 14.6 (2 s, CH_2CH_3), 21.2 (s, $ArCH_3$), 30.9 (s, $C(CH_3)_3$), 32.9 (s, $C(CH_3)_3$), 34.9 (s, $ArCH_2$), 62.3, 66.3 (2 s, OCH_2CH_3), 127.1, 129.6, 134.6, 134.7, 135.1, 140.1, 140.2, 148.0, 148.4, 149.9, 153.4, 153.6.

^{31}P NMR: 8-45.8.

The ^{13}C and ^{31}P NMR spectrum are illustrated in Appendix I (Fig. 1).

Synthesis of **[CH_2(6-*t*-Bu-4-Me-C_6H_2O)$_2$PCl{N(CO_2-*i*-Pr)NC(O-*i*-Pr)-O-}]** (10b)

The procedure was the same as that for 10a using 1 (4.05 g, 10.0 mmol) and DIAD (2.02 g, 10.0 mmol).

Yield: 4.85 g (80%).

Mp: 177-180°C.

IR (KBr): 1755, 1690, 1600, 1315, 1085,992 cm^{-1}.

^1H NMR: 8 1.33-1.47 (many lines, 30 H, $CH(CH_3)_2$ + *t*-Bu-*H*), 2.33, 2.34, 2.36 (3 s, 6 H, $ArCH_3$), 3.35-3.80 (m, 2 H, $ArCH_AH_X$), 5.10 - 5.30 (m, 2 H, $CHMe_2$), 7.00 - 7.26 (m, 4 H, Ar-*H*).

^{13}C NMR: 8 21.0, 21.5, 21.9 (3 s, $ArCH_3$ + $CH(CH_3)_2$), 30.7 (s, $C(CH_3)_3$), 33.0(s, CMe_3), 34.7 (s, $ArCH_2$), 69.9, 74.6 (2 s, $OCHMe_2$), 127.0, 128.8, 129.4, 134.4, 134.5, 134.9, 135.0, 139.9, 140.1, 148.0 (d, ^2J(PC) = 17.0 Hz), 149.1 (d, ^2J(PC) = 19.1 Hz), 153.0 (d, ^2J(PC) = 10.5 Hz).

^{31}P NMR: 8-46.0.

Anal. Calcd for $C_{31}H_{44}N_2O_6PCl$: C, 61.32; H, 7.30; N, 4.61. Found: C, 61.48; H, 7.36; N, 4.66.

Synthesis of [CH_2(6-*t*-Bu-4-Me-C_6H_2O)$_2$PNHMe{N(CO_2-*i*-Pr)NC(O-*i*-Pr)O-}](11)

DIAD (2.02 g, 10.0 mmol) was added in one lot to a solution of 2 (3.99 g, 10.0 mmol) in dry toluene (30 mL) and the mixture was stirred for 72 h at room temperature. The solution was concentrated to (~3 mL) and crystallizaton was done using *n*-heptane - toluene (1:1) mixture.

Yield: 5.11 g (85%).

Mp: 140-143°C.

IR(KBr): 3383, 1676 cm^{-1}.

^1H NMR: 5 1.30-1.50 (many lines, 30 H, $CH(CH_3)_2$ + *t*-Bu-*H*), 2.28, 2.30 (2 s, 6 H, $ArCH_3$), 2.63, 2.72 (2 d, V(PH) = 12.0 Hz each, $NHCH_3$), 3.44 (d, V(HH) = 16.0 Hz, 1 H, $ArCH_AH_X$), 3.50 - 3.55 (br, 1 H, -N*H*), 4.55 (d, V(HH) = 16.0 Hz, 1 H, $ArCH_AH_X$), 5.00-5.20 (m, 2 H, $CHMe_2$), 6.80 - 7.20 (many lines, 4 H, Ar-*H*).

^{13}C NMR: 6 20.8, 21.7, 21.8, 21.9, 22.2, 22.3, 29.8, 30.2, 30.5, 31.1, 34.3, 34.6, 35.1, 35.8, 68.2, 68.3, 71.5, 73.1, 126.2, 127.0, 127.4, **128.4, 129.0,** 132.5, 133.0, 133.8, 140.5, 141.0, 147.8, 150.0, 153.1, 153.8 (complexity suggests the presence of isomers).

^{31}P NMR: 8 –61.0, –61.7 (1:3). The ^{31}P NMR spectrum of **11,** by dissolving it (*ca* 20 sec. for dissolution) in toluene-d_8 in an NMR tube maintained at -40°C for 1 h and immediately inserting into the NMR spectrometer with probe maintained at -40°C also exhibited the same two signals (recording time <10 min).

^{31}P NMR ($C_6D_5CD_3$): Please see Fig. 3 (Section 2.2).

The variable temperature ^1H NMR spectra were quite broad and hence a detailed analysis could not be made.

Anal. Calcd for $C_{32}H_{48}N_3O_6P$: C, 63.87; H, 8.04; N, 6.98. Found: C, 63.79; H, 8.10; N, 7.08.

X-ray structural analysis was performed on this sample.

Synthesis of [CH_2(6-*t*-Bu-4-Me-C_6H_2O)$_2$PNCS{N(CO_2-*i*-Pr)NC(O-*i*-Pr)O-}] (12)

DIAD (2.02 g, 10.0 mmol) was added in one lot to a solution of 6 (4.27 g, 10.0 mmol) in dry toluene (20 mL) and the mixture was stirred for 72 h at room

temperature. Concentration to 2 mL, followed by the addition of heptane (8 mL) afforded crystals of 12 after *ca* 24 h.

Yield: 5.35 g (85%).

Mp: 191-193°C.

IR(KBr): 2024, 1715, 1694 cm^{-1}.

^{1}H NMR: 5 1.28 (d, V(HH) = 6.2 Hz, 6 H, $CH(CH_3)_2$), 1.35 (s, 18 H, *t*-Bu-*H*), 1.42 (d, ^{3}J(HH) = 6.2 Hz, 6 H, $CH(CH_3)_2$), 2.34, 2.35 (2 s, 6 H, $ArCH_3$), 3.39 (dd, V(PH) ~2.7 Hz, ^{2}J(HH) = 14.0 Hz, 1 H, $ArCH_AH_X$), 5.05-5.25 (m, 3 H, $ArCH_AH_X$ + $CHMe_2$), 7.06, 7.19 (2 s, 4 H, Ar-*H*).

^{13}C NMR: 5 21.2, 21.6, 22.0 (3 s, $ArCH_3$ + $CH(CH_3)_2$), 30.6 (s, $C(CH_3)_3$), 32.7 (s, $ArCH_2$), 34.7 (s, $C(CH_3)_3$), 69.9, 74.7 (2 s, $OCHMe_2$), 127.3, 129.3, 129.8, 134.3, 135.2, 136.0, 140.2, 147.2 (d, V(PC) = 16.8 Hz), 149.2 (^{2}J(PC) ~ 19.0 Hz), 153.1 (^{2}J(PC) =10.1 Hz). The NCS signal is probably merged with those due to others.

^{31}P NMR: 5-67.3.

^{31}P NMR ($C_6D_5CD_3$): Please see Fig. 4 (Section 2.2).

In the ^{1}H NMR spectrum ($C_6D_5CD_3$) at 298 K, chemical shifts of the protons corresponding to $OC(CH_3)_2$, $C(CH_3)_3$, $ArCH_3$, $(Ar)_2CH_AH_B$ are sharp and well separated. The peaks get broadened with decrease in temperature; but no conclusion could be drawn.

Anal. Calcd for $C_{32}H_{44}N_3O_6PS$: C, 61.03; H, 7.04; N, 6.67. Found: C, 61.10; H, 7.06; N, 6.72.

X-ray structural analysis was performed on this sample.

Synthesis of [CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2P(OCH_2CH_2NMe_2)${N($CO_2$-*i*-Pr)NC(O-*i*-Pr)O-}] (13)

DIAD (0.20 g, 1.0 mmol) was added in one lot to a solution of 9 (0.46 g, 1.0 mmol) in dry toluene (10 mL) and the mixture was stirred for 72 h at room temperature. Concentration to (4 mL) and addition of *n*-heptane (3 mL) afforded compound 13 as a white solid.

Yield: 0.46 g (70%).

Mp: 198-202°C.

IR(KBr): 1682, 1597, 1510, 1259, 1172, 1109, 1020 cm^{-1}.

^{1}H NMR: 6 1.35 (br, 30 H, *t*-Bu-*H* + CH(CH_3)$_2$), 2.20, 2.30 (2 s, 12 H, ArCH_3 + N(CH_3)$_2$), 2.55 (t, V(H-H) ~ 6.0 Hz, 2 H, OCH_2CH_2), 3.45 (d, V(H-H) ~ 14.0 Hz, 1 H, ArCH_AH$_X$), 4.35 (m, 3 H, OCH_2CH$_2$ + ArCH$_A$$H_X$), 5.0 (br m, 2 H, C*H*Me$_2$), 6.95-7.25 (m, 4 H, Ar-*H*).

^{13}C NMR: 6 21.0, 22.0, 31.1, 34.1, 35.0, 45.6, 70.5, 72.7, 127.8, 128.8, 132.8, 135.2, 141.1, 144.7, 153.1, 153.5, 155.0.

^{31}P NMR: 8-59.6,-66.7(1:5).

Anal. Calcd for $C_{35}H_{54}N_3O_7P$: C, 63.70; H, 8.25; N, 6.37. Found: C, 63.61; H, 7.98; N, 6.20.

Synthesis of [CH$_2$(6-*t*-Bu-4-Me-C$_6$H$_2$O)$_2$P(N-*t*-Bu){N(CO$_2$Et)NH(CO$_2$Et)}] (14a)

DEAD (0.17 g, 1.0 mmol) was added in one lot to a solution of 3 (0.44 g, 1.0 mmol) in dry toluene (10 mL) and the mixture was stirred for 72 h at room temperature. Removal of all the solvent afforded **14a** as a white solid. Crystallization was done using toluene - heptane mixture [4:3].

Yield: 0.48 g (76%).

Mp: 96-98°C.

IR (KBr): 3258, 3164, 1719, 1437, 1345, 1279, 1205, 1134, 1062, 933 cm^{-1}.

^{1}H NMR: δ 0.97, 1.32, 1.45(3 br s, 33 H, Ar*t*-Bu-*H* + N*t*-Bu-*H* + CH_2CH_3), 2.24, 2.35 (2 s, 6 H, ArCH_3), 3.75 (br m, 1 H, ArCH_AH$_X$)4.17-4.28 (m, 3 H, CH_2CH$_3$ + ArCH$_A$$H_X$), 4.45 (qrt, V(H-H) ~ 4.5 Hz, 2 H, CH_2CH$_3$), 6.50 (br s, 1 H, N(*H*)*t*-Bu), 6.93-7.10 (m, 4 H, Ar-*H*).

^{13}C NMR: (A complex spectrum; for reasons see ^{31}P NMR data) δ 13.5, 14.0, 14.7, 20.8, 20.9, 30.6, 31.3, 31.8, 33.7, 33.8, 34.4, 34.9, 35.4, 36.1, 50.3, 50.5, 61.9, 63.1, 65.3, 126.7, 127.0, 128.9, 129.2, 130.0, 132.6, 132.8, 133.4, 140.2, 140.4, 147.0, 147.2, 154.5, 154.9, 155.6.

^{31}P NMR ($C_6D_5CD_3$): -56.3 (br); please see Fig. 5 (Section 2.2)

^{31}P NMR (solid-state, taken at 5 kHz and 7 kHz to determine the center peak): δ -50.2 (>93%), -2.5 (unassigned, minor).

Anal. Calcd for $C_{33}H_{50}N_3O_6P$: C, 64.36; H, 8.18; N, 6.82. Found: C, 64.55; H, 8.13; N, 6.90.

Synthesis of $[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(N\text{-}t\text{-Bu})\{N(CO_2\text{-}i\text{-Pr})NH(CO_2\text{-}i\text{-Pr})\}]$ (14b)

The procedure was same as in the preparation of **14a,** using 1.0 mmol each of 3 and DIAD. Crystallization was done using toluene - heptane **[1:1]** mixture.

Yield: 0.56 g (87%).

Mp: 174-178°C.

IR (KBr): 3346,3159, 1713, 1694, 1601,1302, 1205, 1105, 1028,916 cm^{-1}.

^1H NMR: 5 1.32 (d, $^3J(HH)$ = 6.2 Hz, 6 H, $CH(CH_3)_2$), 1.38 (s, 18 H, Ar*t*-Bu-*H*), 1.42, 1.45, 1.49 (3 lines, 15 H, N*t*-Bu-*H* + $CH(CH_3)_2$), 2.33, 2.35 (2 s, 6 H, $ArCH_3$), 3.42 (dd, V(PH) = 2.7 Hz, V(HH) = 16.0 Hz, 1 H, $ArCH_AH_X$), 5.17 (m, 3 H, $ArCH_AH_X$ + $OCHMe_2$), 5.32 (s, 2 H, CH_2Cl_2),7.07-7.20 (m, 4 H, Ar-*H*).

^{13}C NMR: 5 20.9, 21.1, 21.6, 22.0, 22.6 (5 s, $ArCH_3$ + $CH(CH_3)_2$), 30.9 (s, $C(CH_3)_3$), 33.3, (d, $^3J(PC)$ - 20.7 Hz, $PNC(CH_3)_3$), 34.9 (s, $ArCH_2$), 35.3, 35.9 (2s, $C(CH_3)_3$), 70.0 (s, $OCHMe_2$), 53.4 (s, CH_2Cl_2), 74.8 (s, $OCHMe_2$), 126.7, 127.1, 128.8, 129.4, 129.5, 133.0, 133.3, 134.6, 134.7, 140.0, 140.2, 147.2, 148.4, 149.1, 153.3.

^{31}P NMR: 8-57.6(br).

Anal. Calcd for $C_{35}H_{54}N_3O_6P$: C, 65.93; H, 8.29; N, 6.40. Found: C, 66.02; H, 8.35; N, 6.48.

Synthesis of **$CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P\{N(COOEt)NC(OEt)\text{-}O\text{-}\}](NCH{=}NCH{=}$** CH-) (16a)

To a stirred solution of **10a** (0.61 g, 1.0 mmol) in dichloromethane (10 mL) was added triethylamine (0.10 g, 0.14 mL, 1.0 mmol) and imidazole (0.07 g, 1.0 mmol) at 0°C. The mixture was stirred at room temperature for 24 h, dichloromethane was removed in *vacua,* dry toluene (15 mL) was added and the mixture was filtered. Concentration of the filtrate to 2 mL, followed by the addition of heptane (4 mL) afforded crystals of **16a** [0.54 g (83%)] after keeping at 0°C for *ca* 24 h.

Mp: 137-138°C.

IR (KBr): 1763, 1665, 1439, 1267, 1206, 1127, 1067 cm^{-1}.

^1H NMR: 8 0.92, 1.13 (2 t, $^3J(HH)$ = 6.8 Hz each, 6 H, CH_2CH_3), 1.41 (br s, 18 H, *t*-Bu-*H*), 2.33, 2.34 (2 s, 6 H, $ArCH_3$), 3.43 (d, $^2J(HH)$ - 13.7 Hz, 1

H, ArCH_AH_X), 3.67 (qrt, ^3J(HH) = 6.8 Hz, 2 H, CH_2CH$_3$), 4.18 (dd, V(PH) = 4.6 Hz, ^2J(HH) = 13.7 Hz, 1 H, ArCH$_A$$H_X$)4.38 (qrt, V(HH) = 6.8 Hz, 2 H, CH_2CH$_3$), 6.92 (br s, 1 H, imidazolyl-//), 7.06, 7.18 (2 br s, 4 H, Ar-*H*), 7.48, 8.22 (2 br s, 2 H, imidazolyl-//).

^{13}C NMR: 8 13.5, 14.0 (2 s, CH$_2$*C*H$_3$), 21.0 (s, Ar*C*H$_3$), 30.8, 31.0 (2 s, C(*C*H$_3$)$_3$), 33.8 (s, *C*(CH$_3$)$_3$), 34.9 (s, Ar*C*H$_2$), 64.7, 64.8 (2 s, O*C*H$_2$CH$_3$), 120.9, 121.0, 121.3, 127.4, 128.2, 128.9, 129.0, 129.2, 129.3, 132.9, 133.0, 134.7, 134.8, 139.5, 147.3, 147.6, 155.7.

^{31}P NMR: δ −73.5.

X-ray structural analysis was performed for the analogous compound **16b.**

Synthesis of [CH$_2$(6-*t*-Bu-4-Me-C$_6$H$_2$O)$_2$P{N(CO$_2$-*i*-Pr)NC(O-*i*-Pr)O-} (NCH=N CH=CH-)] (16b.C$_6$H$_5$CH$_3$)

The procedure was same as in the preparation of **16a** using 1.0 mmol each of **10b** and imidazole. Crystallization was done using a mixture of toluene (1 mL) and heptane (2 mL).

Yield: 0.54 g (85%).

Mp: 190-193°C.

IR (KBr): 1755, 1663, 1262, 1101, 1013, 947 cm^{-1}.

'H NMR: 5 0.78 (d, V(HH) = 5.9 Hz, 6 H, CH(C*H*$_3$)$_2$), 1.12 (br, 6 H, CH(C*H*$_3$)$_2$), 1.41 (s, 18 H, *t*-Bu-*H*), 2.32 (s, 6 H, ArC*H*$_3$), 3.52 (dd, ^{5}*J*(PH) = 1.4 Hz, V(HH) = 13.6 Hz, 1 H, ArCH_AH$_X$), 3.83 (m, 1 H, C*H*Me$_2$), 4.17 (dd, 1 H, ^{5}*J*(HH) = 3.9 Hz, ^{2}*J*(HH) = 13.6 Hz, 1 H, ArCH$_A$$H_X$), 4.69 (m, 1 H, C*H*Me$_2$), 6.98-7.32 (m, 5 H, 4 Ar-*H* + 1 imidazolyl-//), 7.46, 8.18 (brs, 2 H, imidazolyl-//).

Variable temperature ^{1}H NMR at selected temperatures [see also Section 2.2, Fig. 8]:

298 K: δ 0.75 (d, V(HH) - 6.3 Hz, 6 H, CH(C*H*$_3$)$_2$), 1.11 (d, ^{3}*J*(HH) = 6.3 Hz, 6 H, CH(C*H*$_3$)$_2$), 1.58 (s, 18 H, *t*-Bu-*H*), 2.17 (s, 6 H, ArC*H*$_3$), 3.26 (d, V(HH) = 13.3 Hz, 1 H, ArCH_AH$_X$), 3.83 (m, 1 H, C*H*Me$_2$), 4.23 (m, 2 H, C*H*Me$_2$ = ArCH$_A$$H_X$), 4.72 (m, 1 H, C*H*Me$_2$), 7.00-7.32 (m, 5 H, 4 Ar-// + 1 imidazolyl-*H*), 7.82, 8.56 (br s, 2 H, imidazolyl-//).

263 K: 8 0.72 (d, ^{3}*J*(HH) = 6.3 Hz, 6 H, CH(C*H*$_3$)$_2$), 1.06 (4 lines, 6 H, CH(C*H*$_3$)$_2$), 1.54, 1.60 (2 s, 18 H, *t*-Bu-*H*), 2.13, 2.21 (2 s, 6 H, ArC*H*$_3$), 3.18 (d, ^{2}*J*(HH) ~ 13.0 Hz, 1 H, ArCH_AH$_X$), 4.14 (dd, 1 H,

V(HH) ~ 3.0 Hz, V(HH) ~ 13.0 Hz, 1 H, $ArCH_AH_X$), 4.35, 4.72 (2 m, 2 H, $CHMe_2$), 6.90-7.23 (m, 4 H, Ar-*H*), 7.45, 7.84, 8.61 (br s, 2 H, imidazolyl-*H*).

243 K: δ 0.84 (3 lines, 6 H, $CH(CH_3)_2$), 1.16 (4 lines, 6 H, $CH(CH_3)_2$), 1.67, 1.74 (2 s, 18 H, *t*-Bu-*H*), 2.24, 2.32 (2 s, 6 H, $ArCH_3$), 3.26 (d, V(HH) ~ 13.0 Hz, 1 H, $ArCH_AH_X$), 4.24 (dd, 1 H, ^5J(HH) ~ 3.0Hz, ^2J(HH) ~ 13.0 Hz, 1 H, $ArCH_AH_X$), 4.62, 4.81 (2 m, 2 H, $CHMe_2$), 6.98-7.36 (m, 4 H, Ar-*H*), 7.60, 8.00, 8.76 (br s, 2 H, imidazolyl-*H*).

^{13}C NMR: δ 21.0, 21.2, 21.5, 21.8, 21.9 (5 lines, $ArCH_3$ + $CH(CH_3)_2$), 30.9, 31.1 (2 s, $C(CH_3)_3$), 33.7 (s, $C(CH_3)_3$), 34.9 (s, $ArCH_2$), 72.7, 73.2 (2 s, $OCHMe_2$), 120.7, 121.1, 125.3, 127.3, 127.8, 128.6, 128.9, 129.0, 129.2, 133.1, 134.7, 135.1, 139.5, 140.5, 147.7, 155.1.

^{31}P NMR: δ −73.7.

Anal. Calcd for $C_{34}H_{47}N_4O_6P$: C, 63.93; H, 7.41; N, 8.77. Found: C, 64.34; H, 7.55; N, 8.61.

X-ray structural analysis was performed on the sample crystallized from toluene.

Synthesis of CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$P{N(COOEt)N(COEt)-O-}](NN=CHCH=CH-) **(17a)**

To a stirred solution of **10a** (0.58 g, 1.0 mmol) in dichloromethane (10 mL) was added triethylamine (0.10 g, 0.14 mL, 1.0 mmol) and pyrazole (0.07 g, 1.0 mmol) at 0°C. The mixture was stirred at room temperature for 24 h, dichloromethane removed in *vacuo*, dry toluene (15 mL) added and the mixture was filtered. Concentration of the filtrate to 2 mL, followed by the addition of heptane (4 mL) afforded crystals of **17a** [0.58 g (89%)] after keeping at 0°C for *ca* 24 h.

Mp: 146-149°C.

IR(KBr): 1771, 1671, 1439, 1263, 1209, 1130, 1071 cm^{-1}.

^{1}H NMR: δ 0.91, 1.07 (2 t, V(HH) = 6.9 Hz each, 6 H, CH_2CH_3), 1.42 (s, 18 H, *t*-Bu-*H*), 2.34 (s, 6 H, $ArCH_3$), 3.53 (d, V(HH) = 13.6 Hz, 1 H, $ArCH_AH_X$), 3.65 (qrt, ^3J(HH) = 6.9 Hz, 2 H, CH_2CH_3), 3.90 (qrt, V(HH) =6.9 Hz, 2 H, CH_2CH_3), 4.21 (dd, V(PH) = 4.8 Hz, ^2J(HH) = 13.6 Hz, 1 H, $ArCH_AH_X$), 6.32 (br s, 1 H, pyrazolyl-*H*), 7.06, 7.17 (2 br s, 4 H, Ar-*H*), 7.72 and 8.22 (2 d, V(HH) ~ 3.0 Hz each, 2 H, pyrazolyl-*H*).

^{13}C NMR: 8 13.6, 14.1 (2 s, CH_2CH_3), 21.1 (s, $ArCH_3$), 30.8 (s, $C(CH_3)_3$), 34.1 (s, CMe_3), 34.9 (s, $ArCH_2$), 64.1, 64.6 (2 s, OCH_2CH_3), 105.1, 105.2, 125.3, 127.1, 128.3, 129.1, 133.0, 133.1, 134.3, 134.4, 134.6, 140.0, 140.1, 141.1, 141.4, 147.6, 147.9, 153.7, 154.0.

^{31}P NMR: 8-72.9.

Synthesis of **[CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$P{N(CO_2-*i*-Pr)NC(O-*i*-Pr)O-}(NN=CH** CH=CH-)] **(17b)**

The procedure was same as in the preparation of 17a using 1.0 mmol each of 10b and pyrazole. Crystallization was done using a mixture of toluene (2 mL) and heptane (4 mL).

Yield: 0.49 g (78 %).

Mp: 176- 178°C.

IR (KBr): 1753, 1667, 1605, 1414, 1263, 1209, 1107, 947 cm^{-1}.

'H NMR: δ 0.77, 1.06 (2 d, V(HH) = 5.9 Hz each, 12 H, $CH(CH_3)_2$), 1.41 (s, 18 H, *t*-Bu-*H*), 2.32 (s, 6 H, $ArCH_3$), 3.50 (d, ^2J(HH) = 16.0 Hz, 1 H, $ArCH_AH_X$), 3.70-3.83 (m, 1 H, $CHMe_2$), 4.21 (dd, 1 H. ^5J(PH) = 3.0 Hz, ^2J(HH) ~ 16.0 Hz, 1 H, $ArCH_AH_X$), 4.58-4.71 (m, 1H, $CHMe_2$), 6.32 (br s, 1 H, pyrazolyl-*H*), 7.04-7.28 (m, 4 H, Ar-*H*), 7.68 and 8.20 (2 d, V(HH) ~ 2.5 Hz each, 2 H, pyrazolyl-*H*).

^{13}C NMR: δ 21.0, 21.4, 21.5, 21.8, 22.0 (5 lines, $ArCH_3$ + $CH(CH_3)_2$), 30.6, 31.1 (2 s, $C(CH_3)_3$), 34.0 (s, CMe_3), 34.9 (s, $ArCH_2$), 71.7, 72.8 (2 s, $OCHMe_2$), 105.3, 127.0, 127.8, 128.8, 133.2, 134.2, 134.4, 140.2, 141.1, 141.4, 148.5, 153.0, 153.2, 154.2, 154.4.

^{31}P NMR: 8-72.8.

Anal. Calcd for $C_{34}H_{47}N_4O_6P$: C, 63.93; H, 7.41; N, 8.77. Found: C, 63.98; H, 7.38; N, 8.80.

The ^{13}C and ^{31}PNMR spectrum are illustrated in Appendix I (Fig. 2).

Synthesis of **[CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$P{N(CO_2-*i*-Pr)NC(O-*i*-Pr)O-}(8-O-** Quinoline)] **(18.$C_6H_5CH_3$)**

The procedure was same as in the preparation of 16a using 1.0 mmol each of 10b and 8-hydroxy quinoline. Crystallization was done using a mixture of toluene and heptane (2 mL + 1 mL).

Yield: 0.57 g (80%).

Mp: 152-154°C.

IR(KBr): 1752, 1667, 1468, 1385, 1271, 1209, 1107, 932 cm^{-1}.

^1H NMR: 5 0.87 (br s, 6 H, $CH(CH_3)_2$), 1.20 (d, V(HH) ~ 5.9 Hz, 6 H, $CH(CH_3)_2$), 1.35 (s, 18 H, *t*-Bu-*H*), 2.30 (s, 6 H, $ArCH_3$), 3.39 (d, V(HH) ~16.0 Hz, 1 H, $ArCH_AH_X$), 3.92 (br m, 1 H, $CHMe_2$), 4.02 (br, 1 H, $ArCH_AH_X$), 4.15 (br m, 1 H, $CHMe_2$), 6.78-8.04 (m, 10 H, Ar-*H* + oxinato-*H*).

^{13}C NMR: 5 20.9, 21.5, 21.7, 22.0 (4 s, $ArCH_3$ + $CH(CH_3)_2$), 30.8, 31.1 (2 s, $C(CH_3)_3$), 34.2 (s, CMe_3), 34.9 (s, $ArCH_2$), 70.6, 70.7, 72.5, 72.7 (4 s, $OCHMe_2$), 120.3, 121.4, 123.3, 125.3, 126.1, 126.7, 127.1, 128.2, 128.8, 129.1, 129.5, 133.4, 135.1, 140.2, 140.4, 149.3.

^{31}P NMR: 8-70.1(br).

Anal. Calcd for $C_{40}H_{50}N_3O_7P$: C, 67.11; H, 7.04; N, 5.87. Found: C, 67.22; H, 7.10; N, 5.95.

X-ray structural analysis was performed on the sample crystallized from toluene.

Synthesis of [CH_2(6 *t*-Bu-4-Me-$C_6H_2O)_2P${N(COOEt)NC(OEt)-O-}(OCH_2CF_3)] (19)

The procedure was same as in the preparation of **16a** using 1.0 mmol each of **10a** and 2,2,2-trifluoroethanol.

Yield: 0.57 g (85%)

Mp: 137-139°C.

IR (KBr): 1748, 1665, 1605, 1346, 1294, 1209, 1169, 1113, 1015, 941 cm^{-1}.

^1H NMR: δ 0.83 (t, ^3J(HH) = 7.3 Hz, 3 H, CH_2CH_3), 1.36 (br s, 18 H, *t*-Bu-*H*), 1.37 (t, V(HH) = 7.3 Hz, 3 H, CH_2CH_3), 2.32 (s, 6 H, $ArCH_3$), 2.95 and 4.31 (2 d, ^2J(HH) ~ 4.0 Hz, 2 H, OCH_2CF_3), 3.51 (qrt, V(HH) = 7.3 Hz, 2 H, CH_2CH_3), 4.18-4.38 (m, 4 H, $ArCH_AH_X$ + CH_2CH_3), 4.59 (m, 2 H, OCH_2CF_3), 7.03-7.14 (m, 4 H, Ar-*H*).

^{13}C NMR: δ 13.7, 14.0 (2 s, CH_2CH_3), 21.0 (s, $ArCH_3$), 30.6, 31.1 (2 s, $C(CH_3)_3$), 34.0 (s, CMe_3), 34.8 (s, $ArCH_2$), 45.9 (s, OCH_2CF_3), 64.0, 64.2 (2 s, OCH_2CH_3), 126.2, 127.1, 127.9, 129.0, 129.5, 132.8, 132.9, 134.1, 135.1, 140.1, 140.3, 147.3, 147.6, 154.3, 154.7, 154.8, 155.2.

^{31}P NMR: 5-63.2,-69.3(1:6).

Analgous reaction of 10b with trifluoroethanol also afforded a product that showed two ^{31}P NMR resonances [δ -63.5, -69.6 (1:6 ratio)].

Synthesis of **[CH_2(6-*t*-Bu-4-Me-C_6H_2O)$_2$P{N(CO_2Et)N(CO_2Et)-C(O)-N-}] (20a.CH_2Cl_2)**

Diethyl azodicarboxylate (1.74 g, 10.0 mmol) was added in one lot to a solution of 5 (4.11 g, 10.0 mmol) in dry toluene (20 mL) and the mixture was stirred for 72 h at room temperature. After removing the solvent, compound 20a was obtained as a white solid. This was crystallized (as CH_2Cl_2 solvate) using dichloromethane - hexane mixture (3:4).

Yield: 4.97 g (85%).

Mp: 116-120°C.

IR (KBr): 2266, 1699, 1601, 1443, 1381, 1314, 1206, 1123, 961 cm^{-1}.

^{1}H NMR: δ 1.25-1.43 (many lines, 24 H, *t*-Bu-*H* + CH_2CH_3), 2.29 (s, 6 H, $ArCH_3$), 3.71 (d, ^2J(HH) = 16.6 Hz, 1 H, $ArCH_AH_X$)4.27-4.57 (m, 5 H, CH_2CH_3+ $ArCH_AH_X$), 5.30 (s, 2 H, CH_2Cl_2), 7.01-7.10 (m, 4 H, Ar-*H*).

^{13}C NMR: 5 14.0, 14.3 (2 s, CH_2CH_3), 20.9 (s, $ArCH_3$), 30.6 (s, $C(CH_3)_3$), 34.7 (s, CMe_3 + $ArCH_2$), 53.4 (s, CH_2Cl_2), 64.4, 64.6 (2 s, OCH_2CH_3), 128.0, 128.9, 130.0, 135.9, 139.7, 139.9, 147.2, 147.5, 152.5.

^{31}P NMR: δ 26.6.

Anal. Calcd (after drying in vacuum for 2 h) for $C_{30}H_{40}N_3O_7P$: C, 61.52; H, 6.88; N, 7.17. Found: C, 61.48; H, 6.80; N, 7.20.

X-ray structural analysis was performed on the sample crystallized from CH_2Cl_2

Synthesis of **[CH_2(6 *t*-Bu-4-Me-C_6H_2O)$_2$P{N(CO_2-*i*-Pr)N(CO_2-*i*-Pr)-C(O)-N-}]** (20b)

DIAD (2.02 g, 10.0 mmol) was added in one lot to a solution of 5 (4.11 g, 10.0 mmol) in dry toluene (30 mL) and the mixture was stirred for 72 h at room temperature. The solution was concentrated (~ 3 mL) and heptane (~ 4 mL) was added and tried to crystallize. Unfortunately, the crystals were not suitable for X-ray work.

Yield: 5.2 g (85%).

MS (FAB): *m/z* 613 [M^+].

Mp: 170-173°C.

IR (KBr): 2259, 1714, 1696 cm^{-1}.

^{1}H NMR: 8 1.33 (d, ^3J(HH) = 6.0 Hz, 6 H, $CH(CH_3)_2$), 1.35 (s, 18 H, *t*-Bu-*H*), 1.40 (d, V(HH) = 6.1 Hz, 6 H, $CH(CH_3)_2$), 2.30 (s, 6 H, $ArCH_3$), 3.70 (d, ^2J(HH) = 15.9 Hz, 1 H, $ArCH_AH_X$), 4.53 (d, ^2J(H-H) = 16.1 Hz, 1 H, $ArCH_AH_X$), 5.03-5.11 (m, 2 H, $CHMe_2$), 7.01, 7.10 (2 s, 4 H, Ar-*H*).

^{13}C NMR: δ 20.7, 21.6 (s each, $ArCH_3$ + $CH(CH_3)_2$), 30.5 (s, $CH(CH_3)_2$), 30.8 (s, $C(CH_3)_3$), 34.6 (s, $ArCH_2$ + CMe_3), 72.6, 73.2 (2 s, $OCHMe_2$), 127.2 (d, ^2J(PC) = 21.0 Hz, NCO),[122] 127.8, 128.8, 129.8, 135.7, 139.6, 139.8, 147.1, 147.3, 148.9, 149.0, 152.0 (V(PC) = 6.0 Hz, CO_2R), 152.7 (^2J(PC) - 10.0 Hz, CO_2R) [the ^{13}C NMR spectrum recorded at -20°C showed broadened resonances and hence a satisfactory assignment of the low intensity P-N*C*O doublet could not be made at this temperature].

^{31}P NMR: δ 27.4.

Anal. Calcd for $C_{32}H_{44}N_3O_7P$: C, 62.63; H, 7.23; N, 6.85. Found: C, 62.79; H, 7.25; N, 6.90.

Synthesis of **$[CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2P(2,2'\text{-}OC_{10}H_6\text{-}C_{10}H_6\text{-}OH)\{NC(O)(CO_2Et)NH(CO_2Et)\}]$** (21a)

Racemic 1,1'-bi-2-naphthol (0.29 g, 1.0 mmol) was added in one lot to a solution of 20a (0.59 g, 1.0 mmol) in dry THF (10 mL) and the mixture was stirred for 72 h at room temperature. Crystallization was done using toluene-heptane mixture (4:2, *ca* 5 mL).

Yield: 0.77g (89%).

Mp: 120-123°C.

IR (KBr): 3409, 3368, 1765, 1726, 1680, 1593, 1516, 1439, 1354, 1302, 1204, 1132, 1100, 1007 cm^{-1}.

^{1}H NMR: δ 1.13, 1.27 (2 t, V(H-H) ~6.0 Hz, 6 H, CH_2CH_3), 1.45 (s, 18 H, *t*-Bu-*H*), 2.25 (s, 6 H, $ArCH_3$), 3.48 (d, V(H-H) = 15.8 Hz, 1 H, $ArCH_AH_X$),

4.14 (br m, 4 H, OCH_2CH_3), 5.61 (br s, NH), 6.54 (br s, 1 H, $ArCH_AH_X$), 6.77-8.14 (m, 16 H, *Ax-H).*

^{13}C NMR: 8 14.0, 14.3 (2 s, CH_2CH_3), 20.9 (s, $ArCH_3$), 30.2, 30.5 (2 s, $C(CH_3)_3$), **34.4** (s, $C(CH_3)_3$), 34.7 (s, $ArCH_2$), 61.8, 62.2, 63.0 (3 s, OCH_2CH_3), 111.8, 114.2, 117.9, 119.2, 120.1, 123.1, 124.5, 125.3, 125.9, 126.1, 126.2, 126.9, 127.1, 127.2, 127.4, 127.9, 128.2, 128.3, 129.0, 129.1, 129.4, 129.9, 131.0, 131.6, 133.7, 133.9, 134.6, 135.0, 140.4, 140.6, 147.6, 152.8, 155.4.

^{31}P NMR: 8-7.4.

Anal. Calcd for $C_{50}H_{54}N_3O_9P$: C, 68.89; H, 6.20; N, 4.82. Found: C, 68.63; H, 6.10; N, 4.62.

Synthesis of [CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$P(2,2'-$OC_{10}H_6$-$C_{10}H_6$-OH){NC(O)-(CO_2-*i*-Pr)NH(CO_2-*i*-Pr)}](21b.3/2$C_6H_5CH_3$)

Racemic 1,1'-bi-2-naphthol (0.29 g, 1.0 mmol) was added in one lot to a solution of **20b** (0.61 g, 1.0 mmol) in dry THF (10 mL) and the mixture was stirred for 72 h at room temperature. Crystallization was done using toluene-heptane mixture (4:3, *ca* 5 mL).

Yield: 0.68 g (76%).

Mp: 145-148°C.

IR: 3378, 1732, 1682, 1470, 1385, 1198, 1101, 1005 cm^{-1}.

^1H NMR: 5 **1.12, 1.16** (2 d + **br** s, **21** H, *t*-Bu-*H* + $CH(CH_3)_2$), 1.46 (s, 9 H, *t*-Bu-*H),* 2.25 (s, 6 H, $ArCH_3$), 3.50 (d, ^2J(H-H) = 14.5 Hz, 1 H, $ArCH_AH_X$), 4.83-4.95 (m, 2 H, $-CHMe_2$), 6.40 (br, 1 H, $ArCH_AH_X$), 6.67-8.11 (m,

^{13}C NMR: 8 20.7, 21.3, 21.5, 21.8 (4 s, $ArCH_3$ + $CH(CH_3)_2$), 30.1, 30.4 (2 s, $C(CH_3)_3$), 34.2 (s, $C(CH_3)_3$), 34.6 (s, $ArCH_2$), 69.4, 70.7 (2 s, $OCHMe_2$), 114.9, 118.6, 120.2, 122.9, 124.4, 125.2, 125.6, 126.0, 126.8, 127.1, 127.7, 128.1, 128.9, 129.0, 129.6, 130.0, 130.5, 131.5, 133.6, 134.7, 137.7, 140.2, 146.8, 147.5, 152.4, 152.8, 154.8.

^{31}P NMR: 8-7.6.

Anal. Calcd (after drying in vacuum for 2 h) for $C_{52}H_{58}N_3O_9P$: C, 69.31; H, 6.45; N, 4.66. Found: C, 69.05; H, 6.42; N, 4.58.]

X-ray structural analysis was performed on the sample crystallized from toluene.

Synthesis of [CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$P(1,2-$O_2C_6H_4$){NHC(O)-N(COOEt)NH (COOEt)}] (22a)

The procedure was same as in the preparation of **21a** using **20a** and catechol (0.11 g, 1.0 mmol). Crystallization was done using toluene-heptane mixture (4:3, *ca* 5 mL).

Yield: 0.67 g (82%).

Mp: 70-72°C.

IR: 3295, 1755, 1490, 1120, 1054 cm^{-1}.

^{1}H NMR: 5 1.17 (s, 18 H, *t*-Bu-*H*), 1.29, 1.38 (2 t, ^3J(H-H) ~ 6.0 Hz, 6 H, CH_2CH_3), 2.38 (s, 6 H, $ArCH_3$), 3.58 (d, ^2J(H-H) = 14.0 Hz, 1 H, $ArCH_AH_X$), 4.26 (br m, 4 H, $-OCH_2CH_3$), 5.33 (br, 1H, $ArCH_AH_X$), 6.11 (br s, N*H*), 6.74-7.23 (m, 8 H, Ar-*H*).

^{13}C NMR: 6 14.2, 14.4 (2 s, CH_2CH_3), 21.1 (s, $ArCH_3$), 30.3 (s, $C(CH_3)_3$), 33.7 (s, $C(CH_3)_3$), 34.5 (s, $ArCH_2$), 62.4, 63.9 (2 s, OCH_2CH_3), 109.2 (d), 110.4 (d), 115.2, 119.7, 120.4, 123.3, 125.7, 126.4, 128.3, 129.1, 133.6, 133.8, 139.0, 139.2, 142.0, 144.4, 148.7, 149.0, 151.8, 155.9, 156.0.

^{31}P NMR: 5-59.2.

Anal. Calcd for $C_{36}H_{46}N_3O_8P$: C, 63.60; H, 6.82; N, 6.18. Found: C, 63.46; H, 6.83; N, 5.98.

Synthesis of [CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2$P(1,2-$O_2C_6H_4$){NHC(O)-N(CO_2-*i*-Pr)NH (CO_2-*i*-Pr)}] (22b.3/2$C_6H_5CH_3$)

The procedure was same as in the preparation of **21a** using catechol (0.11 g, 1.0 mmol). Removal of all the solvent afforded **22b** as a white solid. This was crystallized using toluene (*ca* 4 mL).

Yield: 0.58 g (80%).

Mp: 118-120°C.

IR (KBr): 3290, 1752, 1491, 1375, 1258, 1101, 1034 cm^{-1}.

^{1}H NMR: δ 1.10, 1.12 (2 s, 18 H, *t*-Bu-*H*), 1.27 (d, ^3J(H-H) = 6.0 Hz, 6 H, $CH(CH_3)_2$), 1.39 (d, V(H-H) ~ 6.0 Hz, 6 H, $CH(CH_3)_2$), 2.33 (s, 6 H, $ArCH_3$), 3.55 (d, V(H-H) = 13.6 Hz, 1 H, $ArCH_AH_X$), 4.95-5.18 (m, 3 H, $ArCH_AH_X$ + $CHMe_2$), 6.10 (br s, 1 H, -N*H*), 6.64-7.28 (m, 8 H, Ar-*H*), 9.98 (d, V(P-H) ~ 16.0 Hz, 1 H, P-N*H*).

^{13}C NMR: 5 20.9, 21.3, 21.7 (3 s, $ArCH_3$ + $CH(CH_3)_2$), 30.2 (s, $C(CH_3)_3$), 33.5 (s, $C(CH_3)_3$), 34.3 (s, $ArCH_2$), 69.9, 71.9 (2 s, $OCHMe_2$), 108.9, 110.1, 119.4, 123.0, 125.2, 126.2, 128.1, 128.9, 133.3, 133.7, 138.9, 148.5, 148.8, 151.4, 155.1 (d, ^2J(P-C) = 15.3 Hz).

^{31}P NMR: 5-59.3.

Anal. Calcd (after drying in vacuum for 2 h) for $C_{38}H_{50}N_3O_9P$: C, 63.05; H, 6.96; N, 5.80. Found: C, 63.15; H, 6.92; N, 5.87.

X-ray structural analysis was performed on the sample crystallized from toluene.

Mistunobu coupling of ethanol and benzoic acid

To a solution of **20b** (0.61 g, 1.0 mmol) and ethanol (0.07 g, 1.5 mmol in ether (10 mL) was added drop-wise to a solution of benzoic acid (0.12 g, 1.0 mmol) in ether (5 mL) at room temperature. A white precipitate of triphenylphosphine oxide and diisopropyl hydrazinedicarboxylate appeared. After stirring the mixture for 12 h, the precipitate was removed by filtration. Solvent from the filtrate was evaporated in *vacuo* and the liquid obtained purified by column chromatography (silica gel; hexane-ethyl acetate).

Yield: 0.15 g, 60%.

3.3 Reaction of phosphorus(III) isocyanates with dipolarophiles: Reactivity of the products

Synthesis of [CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2P${C(CO_2Me)C(CO_2Me)-C(O)-N-}] (23a)

To a solution of 6 (4.11 g, 10.0 mmol) in toluene (30 mL) was added DMAD (1.42 g, 10.0 mmol) all at once and the solution stirred for 72 h at room temperature. Concentration (~ 3 mL) followed by addition of heptane (4 mL) gave crystals of 23a.

Yield: 4.70 g (85%).

Mp: 138-144°C (frothing).

IR (KBr): 2275, 1736, 1220, 1096 cm^{-1}.

^1H NMR: 8 1.20 (s, 18 H, *t*-Bu-*H*), 2.20 (s, 6 H, $ArCH_3$), 3.62 (d, ^2J(HH) = 16.1 Hz, 1 H, $ArCH_AH_X$), 3.72 (s, 3 H, OCH_3), 3.86 (s, 3 H, OCH_3), 4.70 (d, V(H,H) = 16.1 Hz, 1 H, $ArCH_AH_X$), 6.92 and 6.98 (2 s, 4 H, Ar-*H*).

^{31}P NMR: 8 56.7.

Anal. Calcd for $C_{30}H_{36}NO_7P$:C, 65.09; H, 6.55; N, 2.53. Found: C, 64.92; H, 6.66; N, 2.61.

Synthesis of $[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P\{C(CO_2Et)C(CO_2Et)\text{-}C(O)\text{-}N\text{-}\}]$ (23b)

The procedure was same as in the preparation of **23a** using 10.0 mmol each of 5 and diethyl acetylenedicarboxylate. Removal of all the solvent afforded **23b** as a white solid. This was crystallized using a mixture of toluene (1 mL) and heptane (3 mL).

Yield: 4.80 g (85%).

Mp: 168-170°C.

IR (KBr): 2280, 1734, 1703, 1221, 1094 cm^{-1}.

^1H NMR: 5 1.23 (t, $^3J(HH)$ = 7.2 Hz, 3 H, CH_2CH_3), 1.30 (s, 18 H, *t*-Bu-*H*), 1.39 (t, V(HH) = 7.2 Hz, 3 H, CH_2CH_3), 2.28 (s, 6 H, $ArCH_3$), 3.72 (d, $^2J(HH)$ = 16.0 Hz, 1 H, $ArCH_AH_X$), 4.28, 4.36 (2 qrt, V(HH) = 7.2 Hz each, 4 H, OCH_2CH_3), 4.75 (d, $^2J(HH)$ = 16.0 Hz, 1 H, $ArCH_AH_X$), 7.03, 7.07 (2 br s, 4 H, Ar-*H*).

^{13}C NMR: δ 13.8, 14.0 (2 s, CH_2CH_3), 20.9 (s, $ArCH_3$), 30.7 (s, $C(CH_3)_3$), 34.7 (s, $ArCH_2$), 34.9 (s, CMe_3), 62.6, 62.9 (2 s, OCH_2CH_3), 127.7, 128.8, 129.2 ($^1J(PC)$ - 180.0 Hz) 129.4, 131.3, 135.6, 139.8, 139.9, 147.0, 147.2, 157.8, 159.4, 162.2, 167.0, 167.6. The P-C carbon appears along with the aromatic carbons and the assignment is tentative.

^{31}P NMR: 8 57.4.

X-ray structure for the analogous compound 23a was performed.

Synthesis of $[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(OCH_2CF_3)\ \{C(CO_2Me)C(CO_2Me)\text{-}C(O)\text{-}NH\text{-}\}]$ (24a.CH_3CN)

To a solution of **23a** (0.55 g, 1.0 mmol) in THF (10 mL) was added 2,2,2-trifluoroethanol (0.10 g, 0.07 mL, 1.0 mmol) via syringe and the reaction mixture stirred for 72 h at room temperature. After removal of the solvent, the residue was crystallized form acetonitrile.

Yield: 0.53 g (76 %).

Mp.: 190-192°C.

IR (KBr): 3439, 3324, 1732 (br) cm^{-1}.

^{1}H NMR: 8 1.33, 1.35 (2 s, 18 H, *t*-Bu-*H*), 2.00 (s, ~ 3 H, CH_3CN), 2.32 (br s, 6 H, $ArCH_3$), 2.95 and 4.55 (2 m, 2 H, OCH_2CF_3), 3.30-3.60, 4.10-4.20, 5.40 and 6.10 (br signals, 3 H, $NH + ArCH_AH_X$), 7.00-7.15 (m, 4 H, Ar-*H*).

^{31}P NMR: δ −65.1, −72.5 (1:2 ratio).

^{31}P NMR ($C_6D_5CD_3$): See Fig. 14; Section 2.3.

X-ray structural analysis was performed on this sample.

Synthesis of $[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(OCH_2CF_3)\{C(CO_2Et)C(CO_2Et)\text{-}C(O)\text{-}NH\text{-}\}]$ (24b)

The procedure was similar to that described for **24a** using 1.0 mmol each of **23b** and 2,2,2-trifluoroethanol. After removal of the solvent, the residue **(24b)** was crystallized form acetonitrile.

Yield: 0.58 g (85 %).

Mp: 178-180°C.

IR (KBr): 3439, 3324, 1759, 1732, 1262 cm^{-1}.

^{1}H NMR: 8 1.19, 1.24 (2 t, V(HH) = 7.2 Hz each, 6 H, CH_2CH_3), 1.28, 1.31 (2 s, 18 H, *t*-Bu-*H*), 2.32 (s, 6 H, $ArCH_3$), 2.95 and 4.55 (2 m, 2 H, OCH_2CF_3), 3.42 (dd, V(PH) ~ 4.0 Hz, ^2J(HH) = 13.0 Hz, 1 H, $ArCH_AH_X$), 3.53 (dd, V(PH) ~ 4.0 Hz, ^2J(HH) = 13.0 Hz, 1 H, $ArCH_AH_X$), 4.35, 4.45 (2 qrt, ^3J(HH) - 7.2 Hz each, 4 H, CH_2CH_3), 5.93 (br, 1 H, *NH*), 7.00-7.15 (m, 4 H, Ar-*H*).

^{31}P NMR: 8-64.5,-72.0(1:3).

X-ray structure is available for the analogous DMAD derivative **24a.**

Synthesis of **$[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(O)C(CO_2Me)C(CO_2Me)CClNC(O)Cl]$** (26)

Compound **23a** (0.55 g, 1.0 mmol) in excess $CHCl_3$ (10 mL) was heated at 70°C for 1 d with continuous stirring. Removal of the solvent afforded 26 as a white solid. This was crystallized using a mixture of dichloromethane (2 mL) and hexane (1 mL).

Yield: 0.46 g (70%).

Mp: 142-144°C.

IR (KBr): 1750, 1730, 1458, 1375, 1260, 1211, 1100 cm^{-1}.

^1H NMR: 8 1.42 (s, 18 H, *t*-Bu-*H*), 2.29 (s, 6 H, $ArCH_3$), 3.51 (d, $^2J(HH)$ = 13.5 Hz, 1 H, $ArCH_AH_X$), 3.96, 3.98 (2 s, 6 H, OCH_3), 4.25 (dd, V(PH) = 2.8 Hz, $^2J(HH)$ = 13.5 Hz, 1 H, $ArCH_AH_X$), 7.06 (br, 4 H, Ar-*H*).

^{31}P NMR: δ −3.8.

X-ray structural analysis was performed on this sample.

Synthesis of $[CH_2(6\ t\text{-Bu-4-Me-}C_6H_2O)_2P\{(OCH_2CH_2NMe)CH(CO_2Me)CH(CO_2Me)\text{-}C(O)\text{-}N\}]$ (27a.$C_6H_5CH_3$)

To a solution of **23a** (0.55 g, 1.0 mmol) in THF (10 mL) was added 2-(methylamino)ethanol (0.07mL, 0.07 g, 1.0mmol) via syringe and the reaction mixture stirred for 72 h at room temperature. The solution was concentrated (~3 mL) and crystallizaton was done using *n*-heptane - toluene (1:1) mixture.

Yield: 0.40 g (65 %).

Mp: 198-201°C(decomp).

IR(KBr): 1736, 1670 cm^{-1}.

^1H NMR: δ 1.36, 1.43 (2 s, 18 H, *t*-Bu-*H*), 2.27, 2.29 (2 s, total 9 H, $ArCH_3$ + NCH_3), 2.37 (s, ~ 3 H, $ArCH_3$), 2.83-3.32 (m, 2 H, NCH_AH_X), 3.57 and 5.00 (2 AX doublets, $^2J(HH)$ = 15.6 Hz, 2 H, $ArCH_AH_X$), 3.67 and 3.73 (2 s, 3+3 H, OCH_3), 3.89 and 4.37 (dd and d respectively, V(HH) = 11.2 Hz, V(PH) ~ 5.3 Hz, 2 H, $CHCO_2Me$), 4.00-4.30 and 4.80-5.10 (m each, 2 H, P-OCH_AH_X), 6.97-7.25 (m, 4+5 H, Ar-*H* + tolyl-*H*);

^{31}P NMR: 8-13.0.

Anal. Calcd for $C_{33}H_{45}N_2O_8P$ (after powdering and drying *in vacuo):* C, 63.04; H, 7.21; N, 4.45. Found: C, 63.21; H, 7.09; N, 4.35.

X-ray structural analysis was performed on this sample.

Synthesis of $[CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P\{(OCH_2CH_2NMe)CH(CO_2Et)CH(CO_2Et)\text{-}C(O)\text{-}N\}]$ (27b)

The procedure was similar to that described for **27a** using 1.0 mmol each of **23b** and 2-(methylamino)ethanol. After removing the solvent, compound **27b** was obtained as a white solid. This was crystallized using *n*-heptane–toluene (1:1) mixture.

Yield: 0.43 g (66 %).

Mp: 173-174°C.

IR (KBr): 1734, 1443, 1256 cm^{-1}.

^1H NMR: 8 1.14 (t, V(HH) = 7.0 Hz, 3 H, CH_2CH_3), 1.28 (t, V(HH) = 7.0 Hz, 3 H, CH_2CH_3), 1.34, 1.40 (2 s, 18 H, *t*-Bu-*H*), 2.25, 2.27, 2.30 (3 s, 9 H, $ArCH_3$ + NCH_3), 2.83-3.32 (m, 2 H, NCH_AH_X), 3.58 (d, ^2J(HH) = 15.5 Hz, 1 H, $ArCH_AH_X$), 3.89 (dd V(HH) = 11.2 Hz, V(PH) - 5.1 Hz, 1 H, $CHCO_2Et$), 4.13 and 4.20 (2 qrt, V(HH) = 7.0 Hz, 4 H, OCH_3), 4.37 (d, V(HH) = 11.2 Hz, 1 H, $CHCO_2Et$), 4.98 (dd, ^5J(PH) - 4.4 Hz, V(HH) ~ 13.0 Hz, 1 H, $ArCH_AH_X$), 6.97-7.25 (m, 4 H, Ar-*H*).

^{31}P NMR: 8-13.0.

X-ray structure was obtained for the analogous compound 27a.

3.4 Pentacoordinate phosphoranes: (4+1) Cycloaddition reactions of phosphites with *o*-chloranil

Compound [CH_2(6-*t*-Bu-4-Me-$C_6H_2O)_2PEt$(1,2-$O_2C_6Cl_4$)] (28.CH_2Cl_2)

A mixture of the P(III) precursor 7 (0.39 g, 0.97 mmol) and o-chloranil (0.24 g, 0.97 mmol) in toluene (5 mL) was heated at 70°C for 5 min. After 1 d the solvent was removed and the white solid obtained was crystallized from a mixture of dichloromethane (1 mL) and hexane (4 mL) to afford 28.

Yield: 0.51 g (82%).

Mp: 204-206°C.

'H NMR: 8 1.26 (s, 18 H, *t*-Bu-*H*), 1.60 (m, 3 H, PCH_2CH_3), 2.38 (s, 6 H, Ar-CH_3), 2.54 (m, 2 H, PCH_2CH_3), 3.64 (d, ^2J(H-H) ~ 13.0 Hz, 1 H, CH_AH_X), 4.43 (d, ^2J(H-H) ~ 13.0 Hz, 1 H, CH_AH_X), 7.00-7.39 (m, 4 H, Ar-*H*).

^{13}C NMR: 8 10.4 (br s, PCH_2CH_3), 21.1 (s, Ar-CH_3), 29.9 (br d, ^1J(P-C) ~ 186.0 Hz, PCH_2CH_3), 30.2 (s, $C(CH_3)_3$), 34.2 (s, CMe_3), 34.5 (s, Ar-CH_2), 125.4, 126.6, 128.3, 129.0, 129.1, 132.8, 133.5, 137.9, 139.1, 141.0, 148.8, 149.1 (all Ar-*C*).

^{31}P NMR: 8 -22.5, -18.4 (3:1). The spectrum was the same after heating the sample to 85°C, cooling and recording. Although variable temperature ^1H NMR spectra ($C_6D_5CD_3$) were recorded, not much information could be obtained because of the broadness of the peaks.

^{31}P NMR ($C_6D_5CD_3$) and ^{31}P(solid): See Fig. 20; Section 2.4.

X-ray structural analysis was performed on this sample.

Compound **[CH_2(6-*t*-Bu-4-Me-C_6H_2O)$_2$P(*n*-Bu)(1,2-$O_2C_6Cl_4$)]** (29)

The procedure was the same as that for 28 using each of 1.0 mmol of 8 and *o*-chloranil. After 1 d the solvent was removed and the white solid obtained was crystallized from a mixture of dichloromethane (1 mL) and hexane (4 mL) to afford **29.**

Yield: 0.44 g (65%).

Mp: 196-198°C.

^{1}H NMR: 5 0.98 (t, V(H-H) ~ 6 Hz, $PCH_2CH_2CH_2CH_3$), 1.18 (br s, 20 H, *t*-Bu-*H* + $PCH_2CH_2CH_2CH_3$), 1.46 (m, 2 H, $PCH_2CH_2CH_2CH_3$), 1.98 (br m, 2 H, $PCH_2CH_2CH_2CH_2$), 2.38 (s, 6 H, Ar-CH_3), 3.56 (d, ^2J(H-H) ~ 15.0 Hz, 1 H, CH_AH_X), 4.45 (d, V(H-H) ~ 15.0 Hz, 1 H, CH_AH_X), 6.90-7.30 (m, 4 H, Ar-*H*).

^{13}C NMR: 5 13.7 (br s, $PCH_2CH_2CH_2CH_3$), 21.0 (s, Ar-CH_3), 23.9 (br, $PCH_2CH_2CH_2CH_3$), 24.3 (br, PCH2CH2CH2CH3), 28.9 (br d, ^1J(PC) ~ 115.0 Hz, $PCH_2CH_2CH_2CH_3$, buried in the signals due to other carbons), 30.2 (s, $C(CH_3)_3$), 34.2 (s, CMe_3), 34.5 (s, Ar-CH_2), 125.3, 126.5, 128.2, 129.0, 132.6, 133.4, 139.1, 148.8, 149.1 (all Ar-*C*).

^{31}P NMR: 5 -22.7, -19.6 (3:1). The spectrum was the same after heating the sample to 85°C, cooling and recording.

^{31}P NMR ($C_6D_5CD_3$) and ^{31}P (solid): See Fig. 21; Section 2.4.

CH_2{6-*t*-Bu-4-Me-C_6H_2O}$_2$PH (30)

To a stirred solution of 1 (4.04 g, 10.0 mmol) in THF (30 mL) at 0°C was added lithium aluminum hydride (LAH) (0.38 g, 10.0 mmol) portion-wise in about 10 min. After warming to room temperature, the reaction mixture was stirred further for 10 h. Solvent was removed in *vacuo* and toluene (20 mL) was added to the residue and filtered. The filtrate was concentrated (to ~5 mL) and compound 30 was obtained as a crystalline solid after 1 d.

Yield: 2.78 g (75%).

Mp: 114-116°C.

^{1}H NMR: 8 1.45, 1.47 (2 s, 18 H, *t*-Bu-*H*), 2.35, 2.37 (2 s, 6 H, ArCH_3), 3.64 (d, ^2J(HH) = 12.6 Hz, 1 H, CH_AH$_X$), 4.24 (d, V(HH) = 12.6 Hz, 1 H, CH$_A$$H_X$), 6.75 (d, ^1J(PH) = 200.3 Hz, 1 H, P*H*), 7.05, 7.19 (2 br s, 4 H, Ar-*H*).

^{31}P NMR: δ 165.2.

The compound was not air-stable and hence elemental analysis was not attempted.

3.5 Attempted synthesis of **[CH$_2$(6-*t*-Bu-4-Me-C$_6$H$_2$O)$_2$P(H)(1,2-O$_2$C$_6$Cl$_4$)]** (31):

This reaction was done by treating 30 with *o*-chloranil following a procedure similar to that for 28, but only an insoluble black material was obtained.

3.6 Preparation of **[{CH$_2$(6-*t*-Bu-4-Me-C$_6$H$_2$O)$_2$}P(O)(OC$_6$Cl$_4$O)]$_3$Al (33.LiH)**

To a stirred solution of [CH$_2$(6-*t*-Bu-4-Me-C$_6$H$_2$O)$_2$P(Cl)(1,2-O$_2$C$_6$Cl$_4$)][131] (1.27 g, 1.96 mmol) in dry THF (20 mL), lithium aluminum hydride (LAH) was added slowly in small portions (~ 10 min) at 0°C, and the reaction mixture is stirred continuously for 24 h. Solvent was removed in *vacuo* and dry toluene was added. Filtered and concentration of the filtrate to 4 mL afforded crystals of 33 after keeping at 0°C for *ca* 24 h.

Yield: 0.27 g (15%).

Mp: 270°C (charring).

^{1}H NMR: δ 1.00 (s, 18 H, *t*-Bu-H), 2.28, 2.33 (2 s, 6 H, ArCH_3), 2.60 (d, V(HH) = 15.7 Hz, 1 H, CH_AH$_X$), 4.35 (d, V(HH) = 15.7 Hz, 1 H, CH$_A$$H_X$), 6.30-7.20 (m, 4 H, Ar*H*).

^{31}P NMR: 5 -14.0 (~93%), -14.4(~7%).

Anal. Calcd for C$_{87}$H$_{90}$AlCl$_{12}$O$_{15}$P$_3$: C, 54.37; H, 4.69; Found: C, 53.95; H, 4.56.

X-ray data were collected on a sample crystallized from toluene. The residual electron density was analysed as LiH that is in the form of a six-membered Li$_6$ ring with hydrogen bridges connecting the lithium atoms. Although, we could not determine the lithium content quantitatively, its presence was detected by a flame test.

3.7 X-ray crystallography

A suitable crystal of **11**, **12**, **16b**.$C_6H_5CH_3$, **18**.$C_6H_5CH_3$, **20a**.CH_2Cl_2, **21b**.3/2$C_6H_5CH_3$, **22b**.3/2$C_6H_5CH_3$, **24a**.CH_3CN, **26**, **27a**.$C_6H_5CH_3$ **28**.CH_2Cl_2, **33.LiH** was inserted into a Lindemann capillary and X-ray data collected at 293 K on an Enraf-Nonius MACH3 or on a Bruker AXS-SMART diffractometer using Mo-K_α radiation (λ = 0.71073 A). Structures were solved and refined using standard methods.[133] Crystal data are summarized in Tables 15-17.

Table 15 Crystal data for compounds **11, 12, 16b** and **18**.

Compound	**11**	**12**	**16b.$C_6H_5CH_3$**	**18.$C_6H_5CH_3$**
Emp. formula	$C_{32}H_{48}N_3O_6P$	$C_{32}H_{44}N_3O_6PS$	$C_{41}H_{55}N_4O_6P$	$C_{47}H_{58}N_3O_7P$
Formula weight	601.70	629.73	730.86	807.93
Crystal system	Monoclinic	Monoclinic	Orthorhombic	Monoclinic
Space group	$P2_1/c$	$P2_1/c$	Pna21	$P2_1/c$
a /Å	16.2599(8)	19.2601(10)	17.296(4)	16.7166(11)
b /Å	18.4942(9)	9.9781(5)	13.142(4)	15.0867(19)
c /Å	11.2391(5)	19.7255(10)	18.792(7)	19.0574(14)
α/deg	90.00	90.00	90.00	90.00
β/deg	101.54(1)	114.07(1)	90.00	106.40(1)
γ/deg	90.00	90.00	90.00	90.00
V /Å^3	3311.5(3)	3461.3(3)	4272(2)	4610.7(7)
Z	4	4	4	4

D_{calc} /g cm^{-3}]	1.207	1.208	1.136	1.164
μ /mm^{-1}	0.128	0.184	0.111	0.110
F(000)	1296	1344	1568	1728
Crystal size [mm]	0.4 x 0.32 x 0.3	0.45 x 0.2 x 0.15	0.3 x 0.3 x 0.2	0.3 x 0.3 x 0.2
2θ max.	50	50	55	50
Observed reflections (I>2σ(I))	3841	3702	1815	2931
Data/ restraints/ parameters	5832/ 0/ 389	6088/ 0/ 388	4992/ 15/ 482	8091/ 0/ 566
S	1.012	1.021	1.361	1.007
R1 [I>2σ(I)]	0.0472	0.0579	0.0886	0.0711
wR2 [all data]	0.1073	0.1112	0.2819	0.2205
Max./min. residual electron dens. [eÅ^{-3}]	0.296/ -0.324	0.275/ -0.296	0.752 / -0.585	0.352/ -0.356

Table 15 Crystal data for compounds **20a, 21b, 22b** and **24a**

Compound	**20a.CH_2Cl_2**	**21b.3/2$C_6H_5CH_3$**	**22b.3/2$C_6H_5CH_3$**	**24a.CH_3CN**
Emp. formula	$C_{31}H_{42}Cl_2N_3O_7P$	$C_{62.50}H_{71}N_3O_9P$	$C_{97}H_{124}N_6O_{18}P2$	$C_{34}H_{42}F_3N_2O_8P$
Formula weight	670.55	1038.19	1723.96	694.67
Crystal system	Orthorhombic	Triclinic	Triclinic	Triclinic
Space group	Pcab	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$
a /Å	15.1196(18)	12.4123(7)	9.6724(8)	9.455(3)
b /Å	17.9591(16)	16.2723(10)	11.9518(10)	10.861(3)
c /Å	25.632(2)	17.5862(10)	22.0645(19)	19.023(5)
α/deg	90.00	63.7960(10)	80.273(2)	93.24(2)
β/deg	90.00	70.9040(10)	86.782(2)	91.41(2)
γ/deg	90.00	79.2730(10)	73.459(4)	107.85(2)
V /Å^3	6959.9(12)	3007.9(3)	2409.9(4)	1854.6(9)
Z	8	2	2	2

D_{calc} /g cm^{-3}]	1.280	1.146	1.188	1.244
μ /mm^{-1}	0.280	0.101	0.113	0.138
F(000)	2832	1106	922	732
Crystal size [mm]	0.3 x 0.3 x 0.2	0.38 x 0.38 x 0.18	0.25 x 0.10 x 0.05	0.4 x 0.3 x 0.2
2θ max.	50	50	50	50
Observed reflections (I>2σ(I))	2728	5907	3501	4419
Data/ restraints/ parameters	6087/ 0/ 415	10548/ 19/ 684	8496/ 14/ 581	6520/ 0/ 454
S	1.102	1.098	1.019	1.100
R1 [I>2σ(I)]	0.0614	0.0759	0.0691	0.0605
wR2 [all data]	0.2077	0.2170	0.1325	0.1997
Max./min. residual electron dens. [eÅ^{-3}]	0.341/ -0.383	0.631/ -0.505	0.445/ -0.384	0.443/ -0.467

Table 17 Crystal data for compounds **26, 27a, 28** and **33**

Compound	**26**	**27a.$C_6H_5CH_3$**	**28.CH_2Cl_2**	**33**
Emp. formula	$C_{31}H_{36}Cl_2NO_8P$	$C_{40}H_{53}N_2O_8P$	$C_{32}H_{37}Cl_6O_4P$	$C_{88.50}H_{91.50}AlCl_{12}LiO_{15}P_3$
Formula weight	652.48	720.81	729.29	1947.35
Crystal system	Monoclinic	Triclinic	Monoclinic	Rhombohedral
Space group	$P2_1/n$	$P\bar{1}$	$P2_1/c$	R-3
a /Å	9.284(2)	11.792(7)	10.842(5)	22.406(1)
b /Å	17.582(8)	12.580(7)	30.340(4)	22.406(1)
c /Å	20.665(3)	15.162(9)	10.832(6)	33.854(2)
α/deg	90.00	110.66(6)	90.00	90.00
β/deg	102.658(15)	103.36(7)	92.77(2)	90.00
γ/deg	90.00	90.53(7)	90.00	120.00
V /Å^3	3291.2(17)	2037(2)	3559(3)	14718.8(12)
Z	4	2	4	6

D_{calc} /g cm^{-3}]	1.317	1.175	1.361	1.318
μ /mm^{-1}	0.295	0.118	0.562	0.455
F(000)	1368	772	1512	6045
Crystal size [mm]	0.3 x 0.3 x 0.2	0.4 x 0.3 x 0.3	0.3 x 0.3 x 0.2	0.55 x 0.5 x 0.5
2θ max.	50	48	50	50
Observed reflections (I>2σ(I))	2680	5108	3241	4591
Data/ restraints/ parameters	5773/ 0/ 398	5850/ 0/ 480	6243/ 0/ 406	5770 / 0/ 374
S	1.054	1.033	1.124	1.043
R1 [I>2σ(I)]	0.0626	0.0423	0.0539	0.0447
wR2 [all data]	0.2074	0.1292	0.1880	0.1384
Max./min. residual electron dens. [eÅ^{-3}]	0.325/ -0.481	0.296/ -0.263	0.485/ -0.625	0.441/ -0.304

REFERENCES

1 (a) N. N. Greenwood and A. Earnshaw, *Chemistry of the Elements,* Pergamon Press (Oxford), 1984, p. 577; (b) A. L. Lehninger, *Principles of Biochemistry,* Worth publishers (New York), 1982, p. 793.

2 (a) R. L. Hilderband, *The Role of Phosphonates in Living Systems,* CRC Press, Boca Raton, FL, 1982; (b) R. Engel, *Chem. Rev.*, 1977, 77, 349; (e) P. A. Frey, *Tetrahedron,* 1982, **38,** 1541.

3 (a) D. J. H. Smith, *in Comprehensive Organic Chemistry; D.* H. R. Barton, V. D. Ollis, Eds; Vol. 2, I. O. Sutherland, Vol. Ed.; Pergamon: Exeter, 1979, pp. 1189; (b) J. Emsley and D. Hall, *The Chemistry of Phosphorus,* Harper and Row, London, 1976, 379; (c) F. H. Osman and F. A. El-Samahy, *Chem. Rev.,* 2002, **102,** 629.

4 (a) R. Francke and G. V. Röschenthaler, *Z. Anorg. Allg. Chem.,* 1989, 572, 135; (b) T. Facklam, O. Wagner, H. Heydt and M. Regitz, *Angew. Chem. Int. Ed,* 1990, **29,** 314; (c) G. Bertrand, *Angew. Chem. Int. Ed,* 1998, 37, 270; (d) R. Francke, J. Heine and G. V. Röschenthaler, *Phosph.,Sulf. Silicon,* 1990, **49/50,** 377.

5 (a) M. Regitz, *Chem. Rev.,* 1990, **90,** 191; (b) G. Bertrand and R. Reed, *Coord. Chem. Rev.,* 1994, **137,** 323; (c) C. Buron, H. Gornitzka, V. Romanenko and G. Bertrand, *Science,* 2000, **288,** 834; (d) E. Niecke, A. Fuchs, F. Baumeister, M. Nieger and W. W. Schoeller, *Angew. Chem. Int. Ed,* 2000, **34,** 951.

6 R. R. Holmes, *Pentacoordinated Phosphorus - Structure and Spectroscopy* (Vol. I) and *Reaction Mechanisms* (Vol. II), ACS Monographs 175 and 176 respectively, American Chemical Society, Washington, DC; 1980.

7 (a) W. S. Sheldrick, *Top. Curr. Chem.,* 1978, **73,** 1; (b) R. R. Holmes, R. O. Day, J. M. Deiters, K. C. Kumara Swamy, J. M. Holmes, J. Hans, S. D. Burton and T. K. Prakasha, *in Phosphorus Chemistry-Development in American Science,* ACS Symposium Series 486, E. N. Walsh, E. J. Griffith, R. W. Parry and L. D. Quin, Eds, 1992, Chapter 2, and references cited therein; (c) K. C. Kumara Swamy, S. D. Burton, J. M. Holmes, R. O. Day and R. R. Holmes, *Phosphorus, Sulfur and Silicon,* 1990, **53,** 437; (d) V. G. Ratner, E. Lork, K. 1. Pashkevich and G. V. Röschenthaler, *J. Fluorine Chem.,* 2000, **102,** 73; (e) Y. V. Rassukana, K. O. Davydova, P. P. Onys'ko and A. D. Sinitsa, *J. Fluorine Chem.,* 2002, **117,** 107.

8 (a) O. Mitsunobu, *Synthesis,* 1981, 1; (b) D. L. Hughes, *Org. React.,* 1992, **42,** 335; (c) O. Mitsunobu and M. Yamada, *Bull. Chem. Soc. Jpn.,* 1967, **40,** 2380; (d) O. Mitsunobu and M. Eguchi, *Bull. Chem. Soc. Jpn.,* 1971, **41,** 3427; (e) O. Mitsunobu, M. Wada and T. Sano, *J. Am. Chem. Soc,* 1972, **94,** 679.

9 For Mechanism on Mitsunobu Reaction, see: (a) R. D. Gurthrie and I. D. Jenkins, *Aust. J. Chem.,* 1982, **35,** 767; (b) M. von Itzstein and I. D. Jenkins, *J. Chem. Soc, Perkin Trans. 1,* 1986, 437; (c) M. von Itzstein and I. D. Jenkins, *J. Chem. Soc, Perkin Trans. 1,* 1987, 2057; (d) D. Camp and I. D. Jenkins, *J. Org Chem.,* 1989, **54,** 3045, 3049; (e) D. Crich, H. Hyker and R. J. Harris, *J. Org Chem.,* 1989, **54,** 257; (f) D. Camp, P. C. Healy, I. D. Jenkins, B. W. Skelton and A. H White, *J. Chem. Soc, Perkin Trans. 1,* 1991,1323; (g) W. Adam, N. Narita and Y. Nishizawa, *J. Am. Chem. Soc,* 1984, **100,** 1843; (x) D. L. Hughes, R. A. Reamer, J. J. Bergan and E. J. J. Grabowski, *J. Am. Chem. Soc,* 1998, **110,** 6487.

10 (a) J. Michalski, A. Skowronska and R. Bodalski, *Phosphorus-31 NMR Spectroscopy in Stereochemical Analysis:* J. G. Verkade, L.D. Quin, Eds.; VCH, Deerfield Beach, Florida, 1987, Chapter 8, pp 255-296; (b) W. Adam, N. Narita and Y. Nishizawa, *J. Am. Chem. Soc,* 1984, **106,** 1843; (c) M. Varasi, K. A. M. Walker and M. L. Maddox, *J. Org. Chem.,* 1987, **52,** 4235; (d) D. L. Hughes, R. A. Reamer, J. J. Bergan and E. J. J. Grabowski, *J. Am. Chem. Soc,* 1988, **110,** 6487; (e) A. Pautard-Cooper and S. A. Evans, Jr. *J. Org. Chem.,* 1989, **54,** 2485; (f) M. Kodaka, T. Tomohiro and H. Okuno, *J. Chem. Soc, Chem. Comm.,* 1993, 81.

11 (a) S. S. Nikam, B. E. Kornberg and M. F. Rafferty, *J. Org. Chem.,* 1997, **62,** 3754; (b) D. Saylik, M. J. Horvath, P. S. Elmes, W. R. Jackson, C. G. Lovel and K. Moody, *J. Org. Chem.,*

1999, 64, 3940; (c) S. Fukumoto, S. Fukushi, S. Terao and M. Shiraishi, *J. Chem. Soc, Perkin Trans. 1,* 1996, 1021; (d) M. J. Di Grandi and J. W. Tilley, *Tetrahedron Lett.,* 1996, 37, 4327;. (e) R. Persky and A. Albeck, *J. Org. Chem.,* 2000, 65, 377; (f) B. K. Shull, T. Sakai, J. B. Nichols and M. Koreeda, *J. Org. Chem.,* 1997, 62, 8294; (g) A. G. M. Barrett, R. S. Roberts and J. Schroder, *Org. Lett.,* 2000, 2, 2999; (h) J. C. Racero, A. J. Macías-Sánchez, R. Hernández-Galán, P. B. Hitchcock, J. R. Hanson and I. G. Collado, *J. Org. Chem.,* 2000, 65, 7786; (i) A. B. Charette, M. K. Janes and A. A. Boezio, *J. Org. Chem.,* 2001, 66, 2178.

12 For macrolactonisation using Mitsunobu conditions, See: (a) D. H. Shin, H. W. Lee, S. S Park, J. H. Kim, L. S. Jeong and M. W. Chun, *Arch. Pharmac. Res.,* 2001, 23, 302; (b) I. Paterson, C. D. Savi and M. Tudge, *Org. Lett.,* 2001, **3**, 213; (c) T. Kan, A. Fujiwara, H. Kobayashi and T. Fukuyama, *Tetrahedron,* 2002, 58, 6267; (d) R. Shen, C. T. Lin, E. J. Bowman, B. J. Bowman, and J. A. Porco Jr., *Org. Lett.,* 2002, 4, 3103; (e) R. Shen, C. T. Lin, J. A. Porco Jr., *J. Am. Chem. Soc,* 2002, **124,** 5650; (f) A. B. Smith III , and G. R. Ott, *J. Am. Chem. Soc,* 1998, **120,** 3935; (g) A. K. Ghosh, Y. Wang and J. T. Kim, *J. Org. Chem.,* 2001, 66, 8973; (h) M. T. Crimmins, M. G. Stanton and S. P. Allwein, *J. Am. Chem. Soc,* 2002, **124,** 5958.

13 D. C. Morrison, *J. Org. Chem.,* 1958, 23, 1072.

14 A. Ginsburg, M. N. Vasileva, S. S. Dubov and A. Y. Yakubovich, *Zh. Obshch. Khim.,* 1960,30,2854.

15 E. Brunn and R. Huisgen, *Angew. Chem. Int. Ed.,* 1969, 8, 513.

16 (a) K. C. Kumara Swamy, J. M. Holmes, R. O. Day and R. R. Holmes, *J. Am. Chem. Soc,* 1990, **112**, 6092; (b) D. J. H. Smith, In *Comprehensive Organic Chemistry;* D. H. R. Barton, V. D. Ollis, Eds.; I. O. Sutherland, Vol. Ed.; Pergamon: Exeter, 1979; Vol. 2, pp 1233-1256; (c) K. C. Kumara Swamy, C. Muthiah, S. Kumaraswamy and M. A. Said, *Proc. Indian Acad. Sci. (Chem Set),* 1999, **111**, 489.

17 For earlier literature on the formation of pentacoordinate compounds from the reactions of P(III) species with DEAD/ DIAD, see: (a) B. A. Arbuzov, N. A. Polezhaeva and V. S. Vinogradova, *Izv. Akad. Nauk SSSR, Ser. Khim.,* 1968, 2525, (b) H. Gonclaves, J. R. Domroy, Y. Chapleur, B. Castro, H. Faudet and R. Burgada, *Phosphorus Sulfur,* 1980, 147.

18 (a) J. P. Majoral, R. Kraemer, T. NGando M'Pondo and J. Navech, *Tetrahedron Lett,* 1980, 21, 1307; (b) R. Hulst, A. van Basten, K. Fitzpatrick, R. M. Kellogg, *J. Chem. Soc., Perkin Trans. 1,* 1995, 2961; (c) J. -P. Majoral, R. Kraemer, T. NGando M'Pondo and J. Navech, *Tetrahedron Lett.,* 1980, **21,** 1307.

19 Other phosphorus intermediates other than betaine (a) O. Mitsunobu , M. Yamada and T. Mukaiyama, *Bull. Chem. Soc. Jpn.,* 1967, 40, 935; (b) B. Beijer, E. von Hinrichs and I. Ugi, *Angew. Chem. Int. Ed.,* 1982, **11,** 929; (c) H. Loibner and E. Zbiral, *Helv. Chim. Acta,* 1976, 59, 2100; (d) R. Huisgen, R. Knorr, L. Möbius and G. Szeimies, *Chem. Ber.,* 1965, 98, 4014; (e) J. T. Carlock and M. P. Mack *Tetrahedron Lett.,* 1978,18,5153.

20 E. Grochowski, B. D. Hilton, R. J. Kupper and C. J. Michejda, *J. Am. Chem. Soc,* 1982,104,6876.

21 Formation of free radicals in Mitsunobu reaction, see: D. Camp, G. R. Hanson and I. D. Jenkins, *J. Org. Chem.,* 1995, 60, 2977.

22 (a) A. Schmidpeter, J. Luber, D. Schomburg and W. S. Sheldrick, *Chem. Ber.* 1976, **109,** 3581; (b) Other example by the addition of azodicarboxylates to two-coordinate phosphorus, see: A. Schmidpeter, *Chem. Ber.,* 1981, **114,** 825.

23 D. Camp, G. R. Hanson and I. D. Jenkins, *J. Org. Chem.,* 1995, 60, 2977.

24 M. Kodaka, T. Tomohiro and H. Okuno, *J. Chem. Soc, Chem. Commun.,* 1993, 81.

25 Z. Li, Z. Zhou, L. Wang, Q. Zhou and C. Tang, *Tetrahedron Asymmetry,* 2002, 13, **145.**

26 M. Varasi, K. A. M. Walker and M. L. Maddox, *J. Org. Chem.,* 1987, 52, 4235.

27 M. von Itzstein and I. D. Jenkins, *Aust. J. Chem.,* 1984, **37**, 2447.

28 D. Camp and I. D. Jenkins, *Aust. J. Chem.,* 1992, **45, 47.**

29 W. Adam, N. Narita and Y. Nishizawa, *J. Am. Chem. Soc,* 1984, **106**, 1843.
30 A.M. Pautard and S. A. Evans, *J. Org. Chem.*, 1988, 53, 2300.
31 (a) J. W. Kelly and S. A. Evans, Jr., *J. Am. Chem. Soc,* 1986, **108,** 7681; (b) M. von Itzstein and I. D. Jenkins, *J. Chem. Soc, Perkin I.,* 1987, 2057;
32 S. A. Bone and S. Trippett, *J. Chem. Soc, Perkin I.,* 1976, 156.
33 For (acyloxy)alkoxyphosphorane in the Mitsunobu reaction see Ref. 17, 18.
34 R. D. Guthrie, I. D. Jenkins, S. Thang and R. Yamasaki, *Carbohydrate Res.,* 1983, **121,** 109 and 1988, **176,** 306.
35 J. Navech, R. Kraemer and J. Majoral, *Tetrahedron Lett.,* 1980, 1449.
36 (a) M. von Itzstein and I. D. Jenkins, *J. Chem. Soc, Perkin I.,* 1986, 437; (b) B. C. Chang, W. E. Conard, D. B. Denney, D. Z. Denney, R. Edelman, R. L. Powell and D. W. White, *J. Am. Chem. Soc,* 1971, 93, 4004.
37 P. J. Harvey and I. D. Jenkins, *Tetrahedron Lett.,* 1994, 35, 9775.
38 (a) R. R. Holmes, J. M. Holmes, R. O. Day, K. C. Kumara Swamy and V. Chandrasekhar, *Phosph. Sulf. Silicon,* 1995, **103**, 153; (b) R. Ramirez, C. Smith and S. Meyerson, *Tetrahedron Lett.,* 1966, 5, 3651; (c) W. C. Firth, S. Frank, M. Graber and V. P. Wystrach, *Inorg. Chem.,* 1965, 4, 765; (d) Y. Kobayashi and C. Akashi, *Chem. Pharm. Bull.,* 1968, **16**, 1009.
39 (a) R. Appel and A. Gilak, *Chem. Ber.,* 1974, **107,** 2169. (b) R. A. Mitsch, *J. Am. Chem. Soc,* 1967,89,6297.
40 A. M. Pautard and S. A. Evans Jr. *J. Org Chem.,* 1988, 53, 2300.
41 O. Mitsunobu, J. Kimura, K. Iiizuni and N. Yanigida, *Bull. Chem. Soc. Jpn.,* 1976. 49, 510.
42 A. Pautard-Cooper and S. A. Evans Jr. *J. Org Chem.,* 1989, 54, 2485.
43 G. Appendino, A. Minassi, N. Daddario, F. Bianchi, and G. C. Tron, *Org. Lett.,* 2002, 4, 3839.
44 D. J. Hughes and R. A. Reamer, *J. Org Chem.,* 1996, **61,** 2967.
45 J. A. Dodge, J. I. Trujillo and M. Presnell, *J. Org Chem.,* 1994, 59, 234.
46 S. F. Martin and J. A. Dodge, *Tetrahedron Lett.,* 1991, **32,** 3017.
47 M. Saiah, M. Bessodes and K. Antonakis, *Tetrahedron Lett.,* 1992, **33,** 4317.
48 (a) K. Mori and I. Ikunaka, *Tetrahedron,* 1984, 40, 3471; (b) S. Jarosz, J. Glodek and A. Zamojski, *Carbohydr. Res.,* 1987, **163,** 289; (c) H. H. Brandsteter and E. Zbiral, *Helv. Chim. Acta.,* 1978, **61,** 1832; (d) P. E. Eaton, P. G. Jobe and I. D. Reingold, *J. Am. Chem. Soc,* 1984, **106,** 6347; (e) P. J. Kocienski, S. D. A. Street, C. Yeates and S. F. Campbell, *J. Chem. Soc, Perkin Trans. 1,* 1987, 2171; (f) G. Burssani, S. V. Ley, J. L. Wright and D. J. Williams, *J. Chem. Soc, Perkin Trans. 1,* 1986, 303; (g) S. Valverde, J. C. Lopez, A. M. Gomez and S. J. Garcia-Ochoa, *J. Org Chem.,* 1992, 57, 1613; (h) D. Caine and P. L. Kotain, *J. Org Chem.,* 1992, 5, 6587.
49 P. J. Harvey, M. v. Itzstein and I. D. Jenkins, *Tetrahedron,* 1997, 53, 3933.
50 B. K. Shull, T. Sakai, J. B. Nichols and M. Koreeda, *J. Org Chem.,* 1997, 62, 8294.
51 C. F. Palmer, K. P. Parry, S. M. Roberts and V. Sik, *J. Chem. Soc, Perkin Trans1,* 1991, 2051. (b) I. Fleming and S. K. Ghosh, *J. Chem. Soc, Chem. Commun.,* 1992, 1777.
52 (a) V. Farina, *Tetrahedron Lett.,* 1989, **30,** 6645. (b) C. Simon, S. Hosztafi and S. Makleit, *J. Heterocycl. Chem.,* 1997, 34, 349. (c) J. E. Audia and N. Colocci, *Tetrahedron Lett.,* 1991, **32,** 3779. (d) A. P. Davis, S. Dresen and L. J. Lawless, *Tetrahedron Lett.,* 1997, 38, 4305. (e) J. A. Campbell and D. Hart, J. *Tetrahedron Lett.,* 1992, **33,** 6247. (f) A. Ghosh, W. Y. Wang, J. P. Freeman, J. S. Althaus, P. F. Vonvoigtlander, T. A. Scahill, S. A. Mizsak and J. Szmuszkovicz, *Tetrahedron,* 1991, 47, 8653. (g) J. Freedman, M. J. Vaal and E. W. Huber, *J. Org. Chem.,* 1991, 56, 670.
53 (a) J. Mc. Nulty, A. Capretta, V. Laritchev, J. Dyck, and A. J. Robertson, *J. Org. Chem.,* 2003, 68, 1600; (b) D. L. Hughes, R. A. Reamer, J.J. Bergan and E. Grabowski, *J. Am. Chem. Soc,* 1988, **110**, 6487; (c) D. L. Hughes and R. A. Reamer, *J. Org. Chem.,* 1996,61,2967.

54 (a) C. Ahn, R. Correria and P. DeShong, *J. Org. Chem.,* 2002, 67, 1751; (b) C. Ahn, and P. DeShong, *J. Org. Chem.,* 2002, **67**, 1754.
55 (a) S. Manna, J. R. Falck and C. Mioskowski, *Synth. Commun.,* 1985, **15**, 663; (b) D. L. J. Clive and D. Kellner, *Tetrahedron Lett.,* 1991, 32, 7159; (c) D. L. Hughes, *Org Prep. Proc. Int.,* 1996, 28, 127; (d) J. R. Falck and J. Yu, *Tetrahedron Lett.,* 1992, **33**, 6723; (e) J. R. Falck, J. Yu and H. S. Cho, *Tetrahedron Lett.,* 1994, 35, 5997; (f) W. A. Szarek, H. C. Jarrell and J. K. N. Jones, *Carbohydr. Res.,* 1977, 57, C13; (g) Pak-Tsum Ho and N. Davies, *J. Org. Chem.,* 1984, 49, 3027.
56 J. Yu, H.-S. Cho, and J. R Falck, *J. Org. Chem.,* 1993, 58, 5892.
57 M. Kodaka, T. Tomohiro and H (Y). Okuno, *J. Chem. Soc, Chem. Commun.,* 1993, 81.
58 S. Chandrasekhar, and G. Kulkarni, *Tetrahedron: Asymmetry,* 2002, 13, 615.
59 Li, Z.; Zhou, Z.; Wang, L.; Zhou, Q. and Tang, C. *Tetrahedron: Asymmetry* 2002, 13, 145.
60 C. Muthiah, K. Praveen Kumar, C. Aruna Mani, and K. C. Kumara Swamy, *J. Org. Chem.,* 2001, 65, 3733 and the references cited there in.
61 (a) W. S. Wadsworth Jr. in *Organic Reactions,* Wiely-Interscience, New York, 1977, Chapter V, pp. 73-253. (b) B. Maryanoff, A. B. Reitz, *Chem. Rev.,* 1989, 89, 863, and references cited therein.
62 S. Hanessian and Y. L. Bennani, *Tetrahedron Lett.,* 1990, 31, 6465.
63 G. H. Hakiemelahi and G. Just, *Synth. Commun.,* 1980, 10, 429.
64 T. Gajda and M. Matusaik, *Synthesis,* 1992,367.
65 S. Göksu, H. Secen and Y. Sutbeyaz, *Synthesis,* 2002, 2373.
66 J. M. Takacs, Z. Xu, X. -t. Jiang, A. P. Leonov, and G. C. Theriot, *Org. Lett.,* 2002, 4, 3843.
67 J. Yu, H.-S. Cho, and J. R Falck, *J. Org. Chem.,* 1993, 58, 5892.
68 (a) J. W. Perich and R. B. Johns, *Tetrahedron lett.,* 1987, 28, 101. (b) J. W. Perich and R. B. Johns, *Synthesis,* 1988, 142.
69 1. D. Grice, P. J. Harvey and I. D. Jenkins, *Tetrahedron lett.,* 1996, 37, 1087.
70 R. A. Amos, R. W. Emblidge and N. Havens, *J. Org Chem.,* 1983, 48, 3598.
71 T. Tsunoda and S. ItÔ, *J. Synth. Org. Chem. Jpn.,* 1994, 52, 113.
72 L. D. Arnold, H. I Assil and J. C. Vederas, *J. Am. Chem. Soc.,* 1989, **111**, 3973.
73 (a) D. Camp and 1. D. Jenkins, *Aust. J. Chem.,* 1988, 41, 1835; (b) M. v. Itzstein and M. Mocerino, *Synth. Commun.,* 1990, 20, 2049.
74 (a) A. Padwa, *1,3-Dipolar Cycloaddition Chemistry,* Volumes 1 and 2, Wiley Interscience, New York, 1984; (b) A. Padwa, in *Comprehensive Organic Synthesis, Vol. 4* (Eds: B. M. Trost, 1. Fleming, Volume Editor: M. F. Semmelhack), Pergamon, Oxford, 1991, pp. 1069-1168; (c) F. A. Carey, R. J. Sundberg, *Advanced Organic Chemistry,* Part A: Structure and Mechanisms and Part B: Reactions and Synthesis, Plenum Press, New York, 1990, pp. 635-640 and pp. 300-306 respectively; (d) R. Huisgen, *Angew. Chem. Int. Ed. Engl.,* 1963, 2, 565; (e) K. Banert and F. Köhler, *Angew. Chem. Int. Ed. Engl.,* 2001, 40, 174.
75 (a) B. A. Arbuzov and N. N. Zobova, *Synthesis,* 1974, 461; (b) A. G. M. Barrett, M. J. Berts and A. Fenwick, J. *Org Chem.,* 1985, 50, 169.
76 (a) M. Granier, A. Baceiredo, M. Nieger and G. Bertrand, *Angew. Chem. Int. Ed. Engl.,* 1990, 29, 1123; (b) T. Facklam, O. Wagner, H. Heydt and M. Regitz, *Angew. Chem. Int. Ed. Engl.,* 1990, **29**, 314.
77 (a) F. P. Cossio, G. Roa, B. Lecea and J. M. Ugalde, *J. Am. Chem. Soc,* 1995, 117, 12306; (b) M. A. Pericas, F. Serratosa and E. Valenti, *J. Chem. Soc. Perkin Trans II,* 1986,961.
78 A. N. Pudovik, I.V. Konovalova and L. A. Burnaeva, *Synthesis,* 1986, 793.
79 (a) R. I. Tarasova, N. M. Kislitsina and A. N. Pudovik, *Zh. Obshch. Khim.* 1971, 41, 1972; (b) R. 1. Tarasova, T. V. Zykova, M. V. Alparova, N. I. Sinitsina and R. A Salakhutdinov, *Zh. Obshch. Khim.,* 1980, 50, 757; (c) R. 1. Tarasova, T. A. Davoinishnikova, N. 1. Sinitsina, T. V. Zykova, R. I. Tarasova and M. V. Alparova,

Zh. Obshch. Khim., 1983, 53, 1254; (d) R. I. Tarasova, N. I. Sinitsina, T. A. Davoinishnikova and V.V. Moskva, *Zh. Obshch. Khim.,* 1983, 53, 694; (e) R. I. Tarasova, N. I. Sinitsina, T. A. Davoinishnikova, A. B. Remizov, M. V. Alparova, T. V. Zykova and V.V. Moskva, *Zh. Obshch. Khim.,* 1984, 54, 6656.

80 J. Bvierley, 1. J. Dichstein and S. Trippett, *Phosphorus and Sulfur* 1979, 7, 167.

81 (a) I. V. Konovalova, L. A. Burnaeva, R. D. Gareev, E. G. Yarkova, N. M. Kashtanova, E. Temnikova and A. N. Pudovik, *Zh. Obshch. Khim.,* 1983, 53, 1478; (b) I. V. Konovalova, L. A. Burnaeva, N. M. Kashtanova, R. D. Gareev and A. N. Pudovik, *Zh. Obshch. Khim.,* 1984, 54, 2445.

82 (a) L. S. Rodionova, V. A. Galishev, V. N. Chistokletov and A. A. Petrov, *Zh. Obshch. Khim.,* 1975, 45, 1652; (b) A. S. Panevin, Y. G. Trishin, N. A. Galishev, V. N. Chistokletov and A. A. Petrov, *Zh. Obshch. Khim.,* 1983, 53, 478; (c) I. V. Konovalova, L. A. Burnaeva, E. Temnikova and A. N. Pudovik, *Zh. Obshch. Khim.,* 1983,53,931.

83 (a) 1. V. Konovalova, R. D. Gareev, L. A. Burnaeva, T. A. Faskhutdinova, O. A. Molchanova and A. N. Pudovik, USSR Patent 1977, 635101; (b) G. Bauhadir, k. Bieger, P. Livotto, R. Reau, H. Gornitzka, F. Dahan and G. Bertrand, *J. Orgmet. Chem.,* 1997,529,79.

84 (a) J. Tejeda, R. Reau, F. Dahan and G. Bertrand, *J. Am. Chem. Soc.,* 1993, 115, 7880; (b) K. Bieger, J. Tejeda, R. Reau, F. Dahan and G. Bertrand, *J. Am. Chem. Soc,* 1994,116,8087.

85 A. Shimdpeter and W. Zeiss, *Angew. Chem. Int. Ed.,* 1971, 10, 396.

86 G. veneziani, R. Rèau, F. Dahan and G. Bertrand, *J. Org. Chem.,* 1994, 59, 5927.

87 M. Granier, A. Baceiredo, Y. Dartiguenave, M. Dartiguenave, M. J. Menu and G. Bertrand, J. *Am. Chem. Soc,* 1990, 112, 6277.

88 S. Antczak, S. A. Bone, J. Brierly and S. Trippett, *J. Chem. Soc, Perkin Trans. I,* 1977,278.

89 (a) T. Uchimaru, M. Uebayashi, T. Hirose, S. Tsuzuki, A. Yliniemela, K. Tanabe and K. Taira, *J. Org. Chem.,* 1996, 61, 1599; (b) Y-C. Yang, *Acc. Chem. Res.,* 1999, 32, 109; (c) A. C. Hengge, *Acc. Chem. Res.,* 2002, 35, 105; (d) R. Engel, *Handbook of Organophosphorus Chemistry,* Marcel Dekker, New York, 1992.

90 (a) M. Oivanen, S. Kuusela and H. Lönnberg, *Chem. Rev.,* 1998, 98, 961; (b) D. E. Metzer, *Biochemistry,* Vol. 1, 2nd edn, Harcourt/ Academic Press, Burlington (USA), 2001, Chapter 12; (c) R. R.Holmes, *Progr. Inorg. Chem.* 1984, 32, 119.

91 (a) F. H. Westheimer, *Acc. Chem. Res.,* 1968, 1, 70; (b) G. R. J. Thatcher and R. Kluger, *Adv. Phys. Org. Chem.,* 1989, 25, 99.

92 (a) S. Trippett, *Phosphorus Sulfur,* 1976, 1, 89; (b) D. J. H. Smith in *Comprehensive Organic Chemistry:* D. H. R. Barton, V. D. Ollis, eds, 1. O. Sutherland, Volume Editor, Pergamon, Exeter, U. K., 1979, Vol. 2, pp. 1233-1256; (c) M. Nakamoto, S. Kojima, S. Matsukawa, Y. Yamamoto and K. -y. Akiba, *J. Organomet. Chem.* 2002, 643-644, 441; (d) R. Breslow and M. Labelle, *J. Am. Chem. Soc,* 1986, 108, 2655; (e) K. Taira, *Bull. Chem. Soc. Jpn.,* 1986, 60, 1903; (f) E. V. Anslyn and R. Breslow, *J. Am. Chem. Soc,* 1989, 111, 4473; (g) S. Kuusela and H. Lönnberg, *J. Chem. Soc, Perkin Trans. II,* 1994, 2109; (h) T. Uchimaru, M. Uebayashi, T. Hirose, S. Tsuzuki, A. Yliniemela, K. Tanabe and K. Taira, *J. Org. Chem.,* 1996, 61, 1599.

93 (a) P. Vayron, P.-Yves Renard, A. Valleix and C. Mioskowski, *Chem. Eur. J.,* 2000, 6, 1050; (b) C. Lion, M. Hedetatykkag, C. Charvy, C. Delmas, G. Magnaud, H. Sentenac-Roumanou, *Bull. Soc. Chim. Belg.,* 1997, 106, 221; (c) Y. c. Yang, L. L. Szafraniec, W. T. Beaudry, D. K. Rohrbaugh, L. R. Procell, J. B. Samuel, *J. Org. Chem.,* 1996, 61, 8407; (d) F. M. menger and M. J. Rourk, *Langmuir,* 1999, 15, 309.

94 (a) K. C. Kumara Swamy, J. M. Holmes, R. O. Day and R. R. Holmes, *J. Am. Chem. Soc,* 1990, 112, 6092; (b) R. R. Holmes, K. C. Kumara Swamy, J. M. Holmes and R. O. Day, *Inorg. Chem.,* 1991, 30, 1052; (c) N. Thirupathi, S. S. Krishnamurthy and M. Nethaji, *Inorg. Chem.,* 1999, 38, 1093; (d) R. Sonnenburg, I. Neda, H. Thönnessen, P. G. Jones and R. Schmutzler, *Z. Anorg. Allg. Chem.,* 2000, 626, 412.

95 (a) S. D. Lahiri, G. Zhang, D. Dunaway-Mariano, and K. N. Allen, *Science,* 2003, **299,** 2067; (b) G. M. Blackburn, N. H. Williams, S. J. Gamblin and S. J. Smerdon, *Science,* 2003, **301,** 1184;. (c) K. N. Allen and D. Dunaway-Mariano, *Science,* **301,** 1184.

96 E. Skordalakes, G. G. Dodson, D. St. Clair Green, C. A. Goodwin, M. F. Scully, H. R. Hudson, V. V. Kakkar and J. J. Deadman, *J. Mol. Biol.*, 2001, **311**, 549.

97 (a) F. H. Osman and F. A. El-Samahy, *Chem. Rev.,* 2002, **102,** 629; (b) W. S. Sheldrick, *Top. Curr. Chem.*, 1978, **73,** 1; (b) R. R. Holmes, R. O. Day, J. M. Deiters, K. C. Kumara Swamy, J. M. Holmes, J. Hans, S. D. Burton and T. K. Prakasha, *in Phosphorus Chemistry-Development in American Science,* E. N. Walsh, E. J. Griffith, R. W. Parry and L. D. Quin, Eds, ACS Symposium Series 486, Americal Chemical Society: Washington, DC, 1992, Chapter 2, and references cited therein; (d) K. C. Kumara Swamy, S. D. Burton, J. M. Holmes, R. O. Day and R. R. Holmes, *Phosphorus, Sulfur and Silicon,* 1990, **53**, 437; (e) V. G. Ratner, E. Lork, K. I. Pashkevich and G. V. Röschenthaler, *J. Fluorine Chem.,* 2000, **102,** 73; (f) Y. V. Rassukana, K. O. Davydova, P. P. Onys'ko and A. D. Sinitsa, *J. Fluorine Chem.,* 2002, **117**, 107.

98 (a) J. H. Yu, A. M. Arif and W. G. Bentrude, *J. Am. Chem. Soc,* 1990, **112,** 7451; (b) J. H. Yu, A. E. Sopchik, A. M. Arif and W. G. Bentrude, *J. Org. Chem.,* 1990, 55, 3444.

99 S. Mehdi, J. A. Coderre and J. A. Gerlt, *Tetrahedron,* **1983, 39**, 3483.

100 (a) P. J. J. M. van Ool and H. M. Buck, *Eur. J. Biochem.*, 1982, **121,** 329; (b) R. R. Holmes and J. A. Dieters, *Inorg. Chem.,* **1994, 33**, 3235.

101 T. K. Prakasha, S. D. Burton, R. O. Day and R. R. Holmes, *Inorg. Chem.,* 1992, **31,** 5494.

102 (a) T. Uchimaru, W. J. Stec and K. Taria, *J. Org. Chem.,* 1997, **62,** 5793; (b) R. R. Holmes, *Inorg. Chem.,* 1994, **33,** 3235; (c) A. Dejaegeve, C. Lim and M. Karplus, *J. Am. Chem. Soc,* 1991, **113,** 4353; (d) K. Taria, T. Uchimaru, J. W. Storer, A. Yliniemela, M. Uebayashi and K. Tanabe, *J. Org. Chem.,* 1993, 58, 3009.

103 (a) R. Brugada and R. Setton, in *The Chemistry of Organophosphorus Compounds;* F. R. Hartley Ed.; Wiley-Interscience: Chichester, Great Britain, 1994, Col. 3, ppl85-272; (b) J. C. Martin, *Science,* 1983, **221,** 509; (c) E. L. Muetterties, W. Mahler, and R. Schmutzler, *Inorg. Chem.,* 1963, 2, 613; (d) K.-Y. Akiba, Chemistry of Hypervalent Compounds, Weiley-VCH: New York, 1999.

104 R. S. Berry, *J. Chem. Phys.,* **1960, 32**, 933.

105 S. Kojima, K. Kajiyama, M. Nakamoto and K.-Y. Akiba, *J. Am. Chem. Soc,* 1996, **118**, 12866.

106 (a) R. Hoffmann, J. M. Howell and E. L. Muetterties, *J. Am. Chem. Soc,* 1972, **94,** 3047; (b) R. S. McDowell and A. Streitwieser, *J. Am. Chem. Soc,* 1985, **107,** 5849.

107 S. Trippett, *Phosphorus and Sulfur,* **1976, 1**, 89.

108 M. Nakamoto, S. Kojima, S. Matsukawa. Y. Yamamoto and K.-y Akiba, *J. Organomet. Chem.,* 2002, **643-644,** 441.

109 For other interesting examples with 'reversed apicophilicity', see: (a) N. V. Timosheva, T. K. Prakasha, A. Chandrasekaran, R. O. Day and R. R. Holmes, *Inorg. Chem.,* 1995, **34,** 4525; (b) T. K. Prakasha, A. Chandrasekaran, R. O. Day and R. R. Holmes, *Inorg. Chem.,* 1995, **34,** 1243; (c) N. V. Timosheva, A. Chandrasekaran, T. K. Prakasha, R. O. Day and R. R. Holmes, *Inorg. Chem.,* 1996, 35, 6552; (d) S. Kojima, M. Sugino, S. Matsukawa, M. Nakamoto and K. -y. Akiba, *J. Am. Chem. Soc,* 2002, **124,** 7674. (e) S. Kojima, K. Kajiyama, M. Nakamoto and K.-y. Akiba, *J. Am. Chem. Soc.* **1996, 118**, 12866. (f) K. Kajiyama, M. Yoshimune, M. Nakamoto, S. Matsukawa, S. Kojima and K.-y. Akiba, *Org. Lett.,* 2001, 3, **1873**.

110 (a) S. Kumaraswamy, C. Muthiah and K. C. Kumara Swamy, *J. Am. Chem. Soc,* 2000, **122,** 964. (b) P. Kommana, S. Kumaraswamy, J. J. Vittal and K. C. Kumara Swamy, *Inorg. Chem.,* 2002, **41,** 2356.

111 (a) T. K. Prakasha, A. Chandrasekaran, R. O. Day, and R. R. Holmes, *Inorg. Chem.*, 1995, 34, 1243. (b) T. K. Prakasha, R. O. Day, and R. R. Holmes, *Inorg. Chem.*, 1992, 31, 725. (c) K. Prakasha, R. O. Day, and R. R. Holmes, *Inorg. Chem.,* 1992, 31, 1913.

112 K. C. Kumara Swamy, J. M. Holmes,R. O. Day and R. R. Holmes, *J. Am. Chem. Soc,* 1990,112,6104.

113 D. J. Sherlock, A. Chandrasekharan, R. O. Day and R. R. Holmes, *Inorg. Chem.,* 1997,36,5082.

114 A. I. Vogel. *Vogel's Textbook of Practical Organic Chemistry;* 4th edition, Longman Group Limited (London), 1978, pp. 428.

115 J. Scherer, G. Huttner, M. BUchner and J. Bakos, *J. Organomet. Chem.,* 1996, 520, 45.

116 J. C. Tebby, *In Phosphorus-31NMR Spectroscopy in Stereochemical Analysis,* J. G. Verkade and L. D. Quin, Eds., VCH; Florida, USA, 1987, pp. 1-60.

117 See ref 89b (a), p 46 for more details; we have used the Pauling electronegativity for this calculation.

118 R. R. Holmes, *Chem. Rev.,* 1996, 96, 927.

119 N. Satish Kumar, Praveen Kommana, J. J. Vittal and K. C. Kumara Swamy, *J. Org. Chem.,* 2002, 67, 6653.

120 N. Satish Kumar, K. Praveen Kumar, K. V. P. Pavan Kumar, Praveen Kommana, J. J. Vittal and K. C. Kumara Swamy, *J. Org. Chem.,* 2004, 69, 1880.

121 E. P. Flindt, H. Rose and H. C. Marsmann, Z *Anorg. Alleg. Chem.,* 1977, 430, 155.

122 In the pentacoordinate compound 12, of the two $OCHMe_2$ carbons, one is connected as $N{=}C(OCHMe_2)O$- and the other as $-NC(O)(OCHMe_2)$-.

123 S. Kumaraswamy, Praveen Kommana, N. Satish Kumar and K. C. Kumara Swamy, *J. Chem. Soc, Chem. Commun.*,2002, 40.

124 N. Krause and A. Gerold, *Angew. Chem., Int. Ed. Engl.,* 1997, 36, 186.

125 L. D. Quin, E. D. Middlemas, N. S. Rao, R. W. Miller and A. T. McPhail, *J. Am. Chem. Soc,* 1982, 104, 1893.

126 Praveen Kommana, N. Satish Kumar, J. J Vittal, E. G. Jayasree, E. D. Jemmis and K. C. Kumara Swamy, *Org. Lett.,* 2004, 6, 145.

127 (a) M. A. Said, M. Pülm, R. H- Irmer and K. C. Kumara Swamy, *J. Am. Chem. Soc,* 1996, 118, 9841; (b) M. A. Said, M. PUlm, R. H- Irmer and K. C. Kumara Swamy, *Inorg. Chem.* 1997, 36, 2044; (c) K. C. Kumara Swamy, M. A. Said, S. Kumaraswamy, R.H-Irmer and M. PUlm, *Polyhedron,* 1998, 17, 3643.

128 D. D. Perrin, W. L. F. Armarego and D. R. Perrin, *Purification of Laboratory Chemicals,* Pergamon, Oxford, 1986.

129 D. F. Shriver and M. A. Dresdzon, *The Manipulation of Air Sensitive Compounds,* 2nd Edn, Wiley Insterscience , New York, 1986.

130 D. J. Sherlock, A. Chandrasekharan, R. O. Day and R. R. Holmes, *Inorg. Chem.,* 1997,36,5082.

131 S. Kumaraswamy and K. C. Kumara Swamy, *Polyhedron,* 2002, 21, 1155.

132 (a) G. M. Sheldrick, *SHELXS-90, ActaCrystallogr., Sect. A,* 1990, 46, 467; (b) G. M. Sheldrick, *SHELXL-93,* University of Göttingen 1993; (c) G. M. Sheldrick, *SHELX-97;* University of Göttingen, 1997.

PART B

(i) PHOSPHONATES - SYNTHESIS AND UTILITY

(ii) HYDROLYSIS OF PHOSPHITES/ PHOSPHOR-AMIDITES AND ITS INHIBITION

CHAPTER 4

INTRODUCTION

4.1 General Introduction

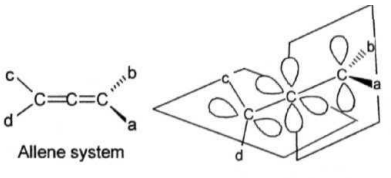
Organophosphonates and their derivatives have attracted considerable interest in recent years because they can be applied to the functionalization and manipulation of the carbon skeleton.[1,3] A number of phosphonates are also biologically active and are used as insecticides, anti-viral agents, antiacidosis agents and antibiotics.[4] Thus there has been considerable interest in developing new synthetic methodologies for various organophosphonates.

In the synthesis of various organophosphorus derivatives including organophosphonates, hydrolytically sensitive phosphorus(III) precursors are utilized[5a] and it would be advantageous to know ways of inhibiting their hydrolysis. Such a study will also be useful in polymer chemistry where phosphites are used as antioxidants.[5b] This chapter reviews literature on the above topics and that are relevant to the present work.

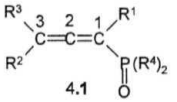
4.2 Allenylphosphonates

Allenylphosphonates (phosphorylated allenes; 4.1)* have been widely used as building blocks in organic chemistry.[6,7] Various phosphorus substituted heterocycles

The central carbon atom in allenes of type $CH_2=C=CH_2$ is sp-hybridized (it has only two bonding partners) with two sets of orthogonal *p*-orbitals, and the double bond array is linear as a result.[8-9]The ability of allenes to enter into reactions as either electrophiles[1] or nucleophiles" provides the chemist an opportunity to use them as precursors for a variety of desired end products. Heterosubstituted allenes also serve as extremely useful precursors in the synthesis of pharmaceuticals, dyes and elastomers. Suitably substituted allenes with no element of symmetry are chiral.[12]



have been synthesized by starting with allenylphosphonates.[13,14] By varying the substituents at the phosphorus atom and in the allene system, one can activate a particular reaction center selectively.[6e] In the following subsections, a brief survey of the synthesis and reactivity of allenylphosphonates will be presented.



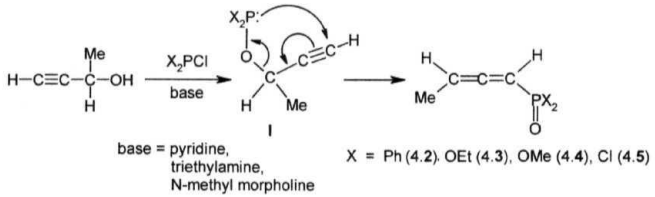
4.1

4.21 Synthesis of allenylphosphonates

Allenylphosphonates are synthesized by one of the following routes:

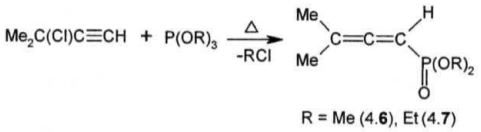
(i) Reaction of the trivalent phosphorus chlorides X_2PCl with α-acetylinic alcohols (e.g. Me(H)C(OH)C≡CH) in the presence of a base such as pyridine, triethylamine or N-methyl morpholine in a suitable solvent (e.g. ether, THF, toluene) gives an intermediate I [^{31}P NMR 5 ~120-125] which undergoes a pseudo-CIaisen type rearrangement, usually at temperatures less than 25°C, to lead to the allenylphosphonates 4.2-4.5 (Scheme 4.1).[15] The conditions used in this method are mild and the yields are moderate to high.

Scheme **4.1**



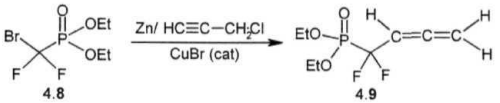
(ii) Allenylphosphonates 4.6-4.7 have also been prepared by heating 3-chloro-3-methyl-1-butyne with trialkyl phosphites (Scheme 4.2).[16]

Scheme 4.2



(iii) There do exist other non-familiar methods to synthesize specific allenylphosphonates. For example, alkylation of diethyl bromodifluorodimethylphosphonate 4.8 with zinc and propynyl chloride gives the allenylphosphonate 4.9 (Scheme 4.3).[17]

Scheme 4.3



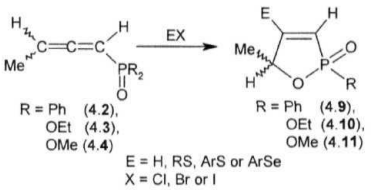
4.8 4.9

4.22 *Reactions of allenylphosphonates*

4.221 *Electrophilic addition*

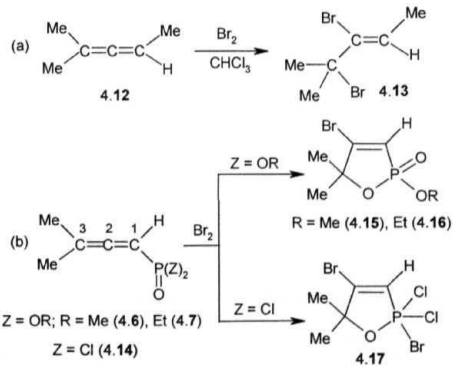
Allenylphosphonates 4.**2**-4.**4** react with electrophilic reagents to give 4.**9**-4.**11**, expanding the phosphorus based heterocyclic chemistry (Scheme 4.4).[14,18-19]

Scheme 4.4



Addition of bromine to the organic allene 4.**12** proceeds rapidly across the more substituted double bond to give 4.**13** (Scheme 4.5a).[20] By contrast, allenylphosphonates 4.**6**-4.**7** and 4.**14** cyclise on treatment with bromine giving oxophosphol-3-enes 4.**15**-4.**16** and phospholane 4.**17** (Scheme 4.5b).[14,21-23]

Scheme 4.5

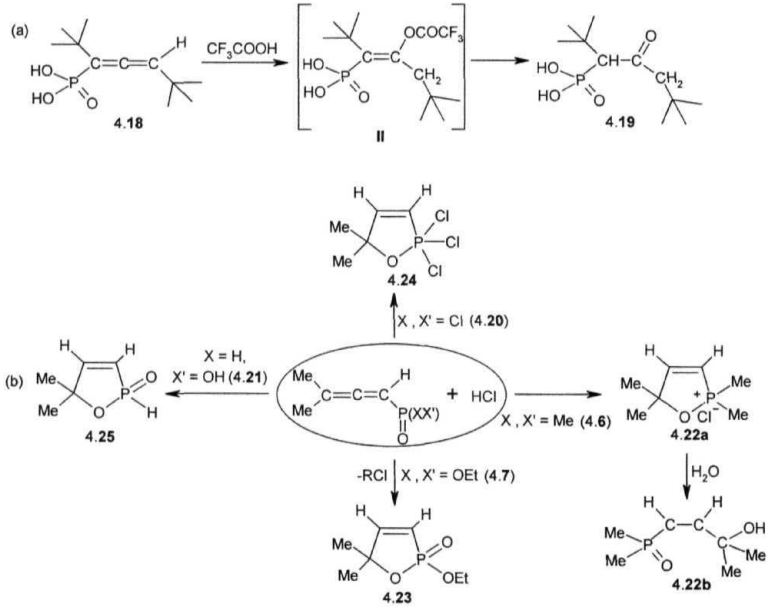


4.12 4.13 4.17

The final products in this type of reaction depend on the nature of the (i) substitutents at phosphorus, (ii) substituents at C(3) and (iii) the halogen.[11e]

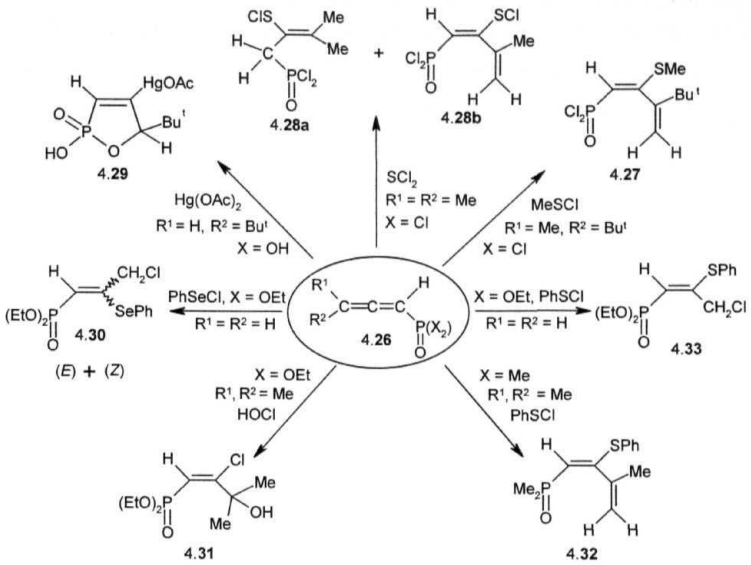
The allenyl phosphonic acid 4.18 reacts with CF_3COOH to give the β-ketophosphonate 4.19 by the electrophilic attack of proton on the terminal carbon of the phosphorylated allene system (Scheme 4.6a).[24,26] Addition of HCI (and perhaps other Br5nsted acids) to allenylphosphonates 4.6, 4.7, 4.20-4.21 also depends on the nature of the substituents around phosphorus as shown in Scheme 4.6b and the 1,2-oxaphospholene products 4.22-4.25 are obtained.[11e]

Scheme 4.6



Formation of various heterocycles and 1,2-adducts 4.27-4.33 by the reaction of electrophiles (RSC1, SCl_2, $Hg(OAc)_2$, R'SeCl, HOCl and PhSCl) with the allenylphosphonate 4.26 are shown in Scheme 4.7.[27,28] Here also the mode of interaction depends on the substituents on both the C(3) atom and phosphorus.

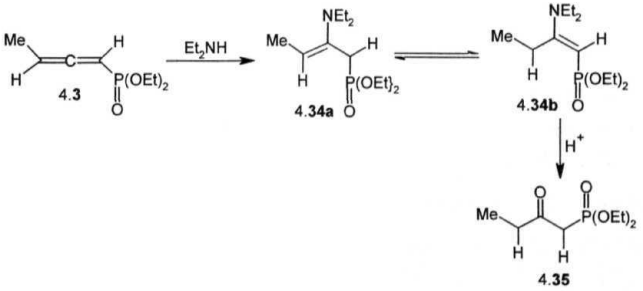
Scheme 4.7



4.222 Nucleophilic addition

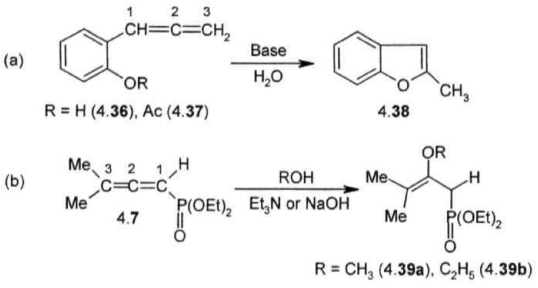
Allenes are susceptible to nucleophilic addition reaction if the allene skeleton is activated with an electron-withdrawing group (e.g. phosphonate).[29] Nucleophilic addition of diethylamine to allenylphosphonate 4.3 produces enamines 4.34a and 4.34b that are in equilibrium with each other; these enamines upon subsequent acid hydrolysis lead to the β-ketophosphonate 4.35 (Scheme 4.8).[29] Isolation of such regiospecifically substituted enamines would be an interesting area to investigate.

Scheme 4.8



o-Allenylphenol 4.36 or the corresponding acetate 4.37 cyclizes to 4.38 under base catalyzed conditions by intramolecular nucleophilic addition of the phenoxide to the central allenyl carbon C(2).[30] Similarly alcohols add exothermically to the C(2) carbon of the allenylphosphonate 4.7 in the presence of sodium hydroxide or triethylamine to produce enol ethers 4.39a-b (Scheme 4.9).[31]

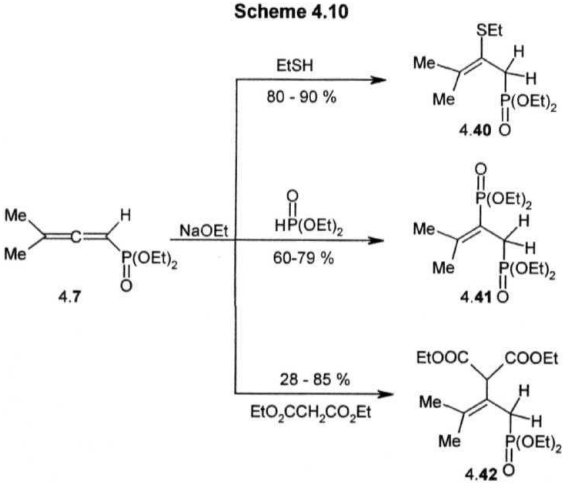
Scheme 4.9



R = CH_3 (4.39a), C_2H_5 (4.39b)

Nucleophiles such as sulfides, dialkyl hydrogen phosphites, and anions derived from active methylene compounds add readily to allenylphosphonate 4.7 to give allyl phosphonates 4.40-4.42. These reactions are summarized in Scheme 4.10.[32]

Scheme 4.10

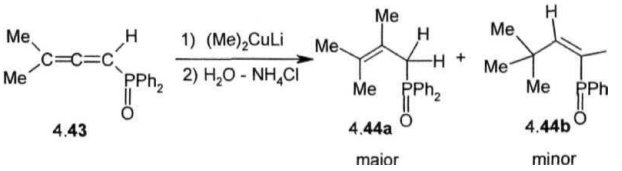


4.223 Other Reactions

(a) Reaction with organocuprates

Addition of organocuprates to phosphinylated allene **4.43** proceeds in **a** 1,2 fashion to give substituted allyl phosphonates **4.44a-b** (Scheme 4.11).[33]

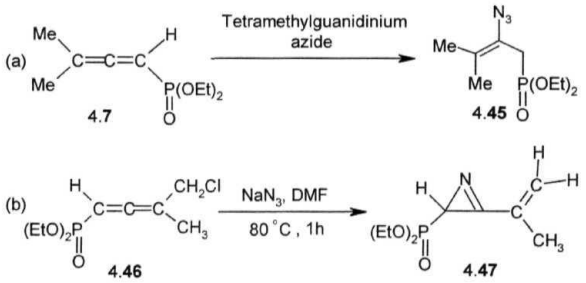
Scheme 4.11



***(b) Reaction with** azides*

Allenylphosphonate 4.7 on treatment with tetramethylguanidinium azide in dry dichloromethane produces 2-azidoallylphosphonate **4.45** (Scheme 4.12a).[34] By contrast, phosphonate **4.46** on reacting with sodium azide in dimethyl formamide leads to the azirine 4.47 (Scheme 4.12b).[35]

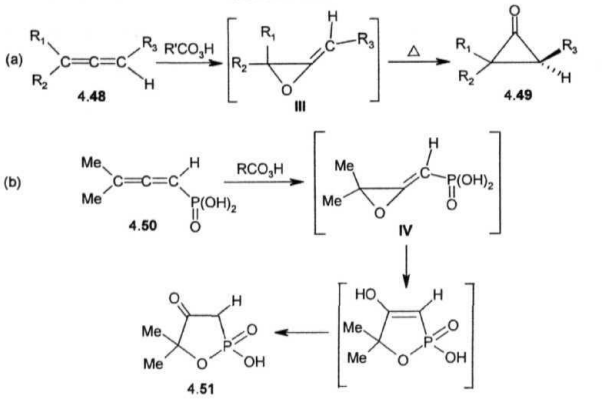
Scheme 4.12



(c) Epoxidation

The reaction of allenes 4.48 with peracids and other oxygen-transfer reagents proceeds with the formation of extremely reactive allene oxide (methyleneoxirane) intermediates of type **III,** which generally react further to produce **4.49** in most cases (Scheme 4.13).[36] Similarly, the reaction of allenic phosphinic acid 4.50 with peracids takes place via the epoxide intermediate IV to lead to the 4-keto-l,2-oxaphospholane 4.51.[37]

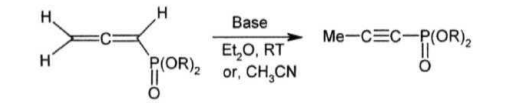
Scheme 4.13



(d) Rearrangement to alkynylphosphonates

Alkynylphosphonates 4.53a-b which are synthetically promising reagents in organic synthesis were synthesized by the rearrangement of the allenylphosphonates **4.52a-b** in the presence of a suitable base (Scheme 4.14).[38]

Scheme 4.14



R = Me (**4.52a**), Et (**4.52b**) R = Me (**4.53a**), Et (**4.53b**)

Base = NEt_3, NaH

4.3 β-Ketophosphonates

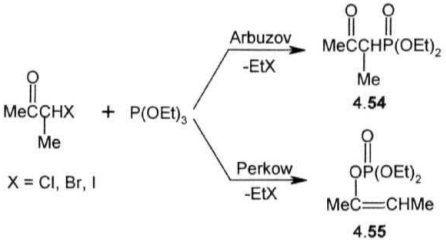
β-Ketophosphonates are valuable synthetic precursors for homologation of aldehydes and ketones to α,β-unsaturated carbonyl compounds via the Horner-Wadsworth-Emmons (HWE) reaction.[1-3,39-41] The new variations on this (HWE) reaction appear destined to further increase its usefulness in designing other structurally diverse phosphonates.[42,43]

4.31 Synthesis of β-ketophosphonates

The following routes are available for the synthesis of β-ketophosphonates:

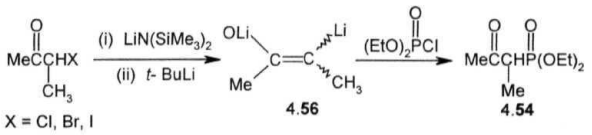
(i) β-Ketophosphonate **4.54** was prepared by the reaction of α-haloketones with triethyl phosphite (Michaelis-Arbuzov reaction).[44] This reaction works best with primary α-iodoketones and trialkyl phosphites. Primary α-bromo or α-chloro ketones often undergo a competitive Perkow process to afford enol phosphate esters **4.55** limiting the usefulness of this reaction (Scheme 4.15).[45]

Scheme 4.15



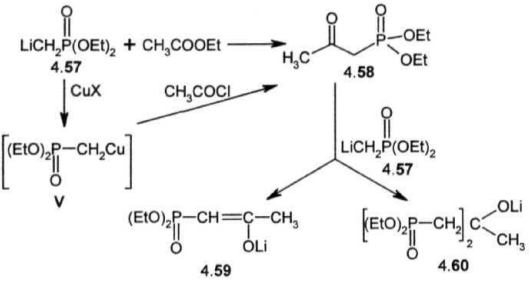
(ii) Compound **4.54** can also be prepared by the reaction of dialkyl chlorophosphate with the dilithiated derivatives 4.56 of a-haloketones (Scheme 4.16).[46] This method is useful in cases where the Arbuzov reaction of phosphites possessing secondary alkoxy substituents fails.

Scheme 4.16



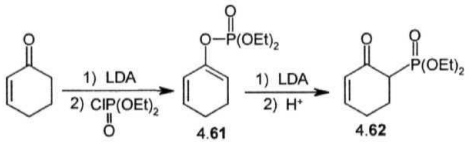
(iii) Acylation of 1-lithioalkyl phosphonate 4.57 at < 20°C produces the /?-ketophosphonate 4.58, but this method usually suffers from the limited availability of alkylphosphonates and low reactivity (Scheme 4.17). Also, thus formed **4.58** is more reactive and leads to side products 4.59 and **4.60.** This will result in lower yields of 4.58. However, the copper salt V prepared from 4.57 reacts with acid chloride giving 4.58 in good yields.[47-48] By an analogous route, *y* and 5 amino substituted β-ketophosphonates can also be synthesized.[49-5]

Scheme 4.17



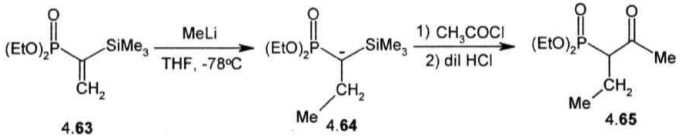
(iv) Rearrangement of phosphate esters 4.61, prepared by starting with cyclohexenone, affords the β-ketophosphonate 4.62 (Scheme 4.18); use of cyclopentenone also gives an analogous phosphonate.[53]

Scheme 4.18



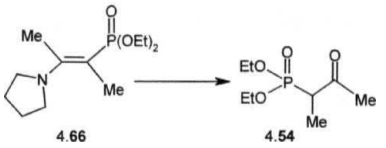
(v) β-Ketophosphonate 4.65 can be readily prepared from the 1-(trimethylsilyl) vinylphosphonate 4.63 via the carbanion 4.64 (Scheme 4.19).[54] In place of CH_3COCl; a large number of other acid chlorides can also be utilized.

Scheme 4.19



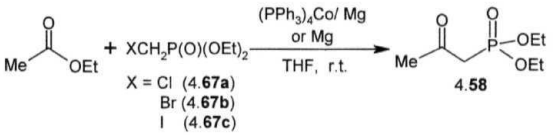
(vi) Diethyl β-dialkylaminovinylphosphonates (4.66) on mild acidic hydrolysis with either oxalic acid on SiO_2 or aq EDTA led cleanly and in high yield to *β*-ketophosphonates 4.54 (Scheme 4.20). This method gives access to a broad range of β-ketophosphonates which are difficult to obtain by Arbuzov method (i).[44] A similar route to β-ketophosphonates using allenylphosphonates is also reported.[55]

Scheme 4.20



(vii) β-Ketophosphonate **4.58** can also be prepared by the addition of α-halogenophosphonates $XCH_2P(O)(OEt)_2$ [X = Cl, Br, I] (4.67) to esters using $[(PPh_3)_4Co]$/ Mg or Mg [for X - I only] (Scheme 4.21). No side product from the attack on the carbonyl carbon of the β-ketophosphonate is formed.[51]

Scheme 4.21

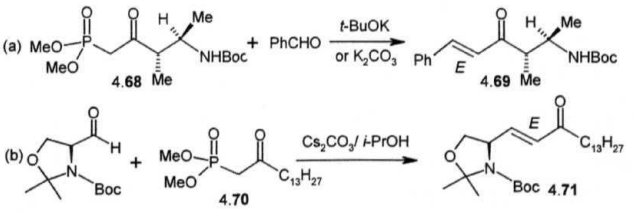


4.32 Reactions of β-ketophosphonates

The Horner-Wadsworth-Emmons reaction (HWE) is one of the most versatile methods for the synthesis of substituted alkenes.[39-41] The common protocol for this reaction calls for the deprotonation of the phosphonate with bases such as metal hydrides, alkoxides or carbonates and subsequent addition of the carbonyl compound.[41,57] HWE reaction between aldehydes and β-ketophosphonates leading to α,β-unsaturated carbonyl compounds is the most common synthetic application of β-ketophosphonates.[41]

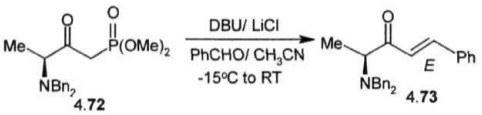
In general, HWE reaction of β-ketophosphonates with a variety of aldehydes in the presence of a base [$(K_2CO_3$/ 18-crown-6/ CH_2Cl_2/ $H_2O)$, NaH/ THF, NaOMe/ MeOH, DBU/ $PhCH_3$, $CSCO_3$/ isopropanol or Et_3N/ CH_3CN] produces E-olefins. Two examples are shown in Scheme 4.22.[41,58]

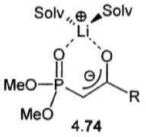
Scheme 4.22



HWE reaction of base sensitive γ-amino-β-ketophosphonates 4.72 under a variety of conditions gives either none or only very low yields of olefinic products **4.73**.[59] However, as shown by *Masamune*[60] *et al*, in the presence of lithium or magnesium halides, bases such as DBU or diisopropylethylamine can be used to achieve *E*-selective olefination of these substrates (Scheme 4.23).[60,61] It is proposed that the metal ion forms a complex of type 4.74, facilitating the ready deprotonation of phosphonate.

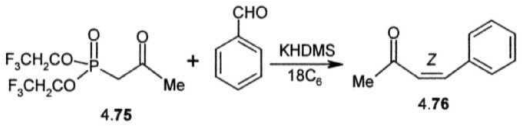
Scheme 4.23





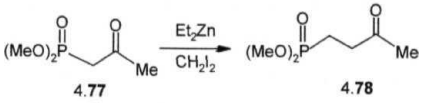
However, some reports of the formation of *Z*-olefins as main products by using five- membered cyclic phosphonates, cyclic phosphonamides and Still's reagent $(CF_3CH_2O)_2P(O)CH_2C(O)OR)]$ have appeared.[62] The modified Still's reagent 4.75 is perhaps the most effective one and has been used in HWE reaction in the presence of KHMDS/ 18-crown-6 giving (*Z*)-*α*,*β*-unsaturated ketones [e.g. 4.76; Scheme 4.24].[63]

Scheme 4.24



β-Ketophosphonates of type 4.77 have been used in the Fried landers reaction (to synthesize 2-substituted [l,8]-naphthyridines), dephosphonylation (to produce *a*,*a*-dimethyl ketones) etc.[64,65] β-Ketophosphonate 4.77 can also be converted *y*-ketophosphonate 4.78 through the reaction with ethyl (iodomethyl) zinc (Scheme 4.25).[66]

Scheme 4.25



4.77 4.78

4.4 β-Hydroxyphosphonates

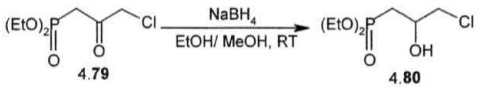
β-Hydroxyphosphonates can mimic the corresponding hydroxy carboxylic acids or amino acids.[67,68] They are intermediates in the synthesis of peptide analogues, haptens of catalytic antibodies, and phosphonic acid-based antibiotics.[69] β-Hydroxyphosphonates are also convenient substrates for the synthesis of amino alkylphosphonic acids *via* the Mitsunobu reaction.[70]

4.41 Synthesis of β-hydroxyphosphonates

β-Hydroxyphosphonates have been prepared by the following methods:

(i) A β-ketophosphonate when treated with sodium borohydride in ethanol gives the corresponding β-hydroxyphosphonate [e.g. 4.80 from 4.79; Scheme 4.26].[71]

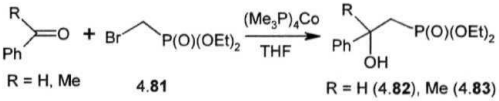
Scheme 4.26



4.79 4.80

(ii) α-Bromophosphonate 4.81 reacts with ketones or aldehydes in the presence of low oxidation-state cobalt complexes to yield β-hydroxyphosphonates 4.82-4.83 (Scheme 4.27).[72]

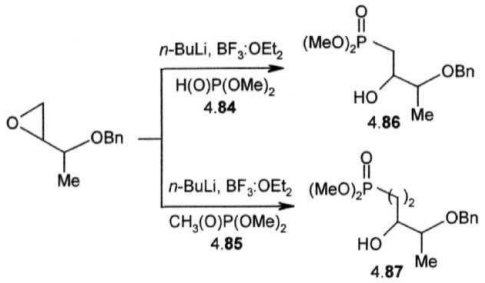
Scheme 4.27



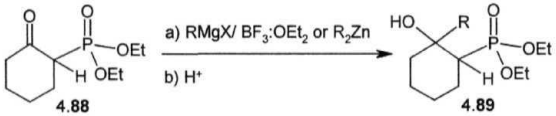
R = H, Me 4.81 R = H (4.82), Me (4.83)

(iii) Regiospecific ring opening of monosubstituted epoxides by phosphorus nucleophiles **4.84** and 4.85 in the presence of BF_3:OEt_2 furnishes the corresponding β-hydroxyphosphonates 4.86 and 4.87 respectively (Scheme 4.28).[73] Variations in the epoxide are possible.

Scheme 4.28

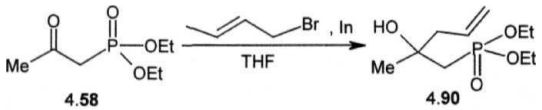


Scheme 4.29



Recently Ranu *et al* presented a very efficient addition of allyl and crotyl moieties to the carbonyl group of β-ketophosphonate 4.58 through the nucleophilic addition of the corresponding allyl and crotyl indium reagents (Scheme 4.30). Notable advantages of this method are mild conditions, fast reaction, and no requirement of the Lewis acid. The yields were also high.[75] Considering all the above factors, it will be interesting to develop a simple protocol for the allylation of β-ketophosphonates.

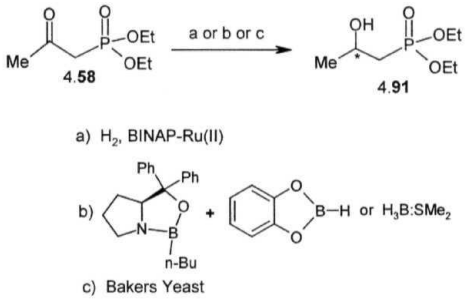
Scheme 4.30



Chiral non-racemic β-hydroxyphosphonates

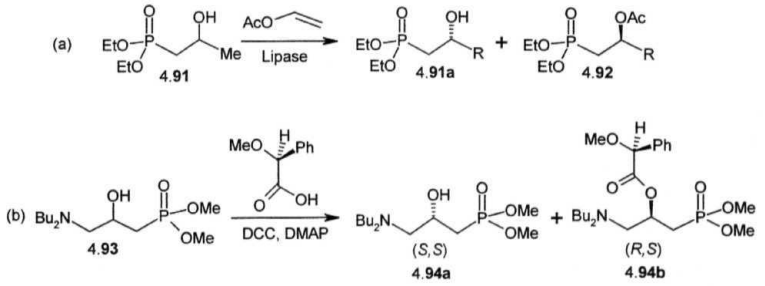
Asymmetric reduction of the β-ketophosphonate **4.58** in the presence of chiral catalysts like (S)- or (R)-BINAP-Ru(II), 1,3,2-oxazoborolidine or (-)-chlorodiisopinocamphylborane (Ipc2B-Cl) gives β-hydroxyphosphonate **4.91** in yields upto 99 % and ee upto 99 % (Scheme 4.31).[76-77] The other approach is based on the use of Baker`s yeast to give β-hydroxyphosphonate **4.91** upto 100 % ee (Scheme 4.31)[78].

Scheme 4.31



In addition, kinetic resolution (enzymatic and dynamic) of *fi*-hydroxyphosphonates **4.91,** 4.93 can also be utilized to separate the enantiomers **4.94a-b** (Scheme 4.32).[79]

Scheme 4.32

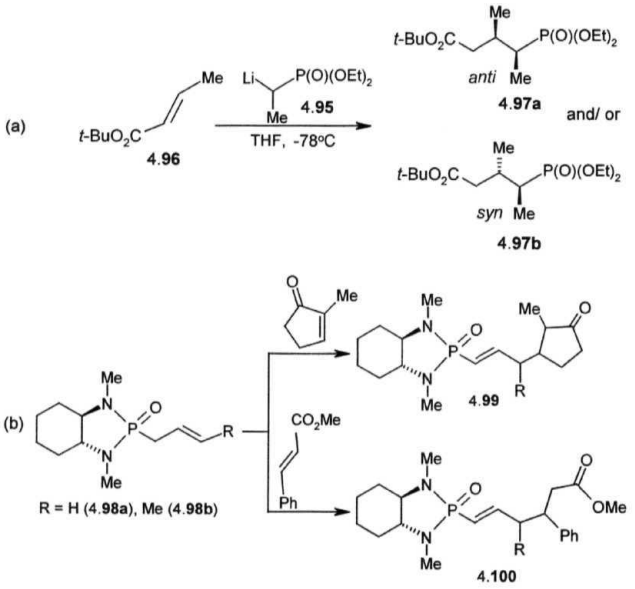


4.5 Michael addition of phosphonates to α,β-unsaturated esters

The conjugate addition of nucleophiles to acceptor-substituted double and triple bonds is one among the classical carbon-carbon bond forming reactions and is

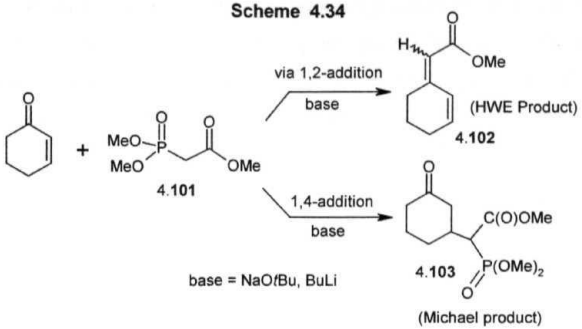
usually referred to as Michael addition.[80] Since this reaction often leads to the formation of a stereogenic center, considerable efforts have been devoted to the development of efficient stereoselective methods.[81] α-Lithiated phosphonate 4.95 adds to the α,β-unsaturated /-butyl ester 4.96 to give substituted phosphonates 4.97a-b in high yields (Scheme 4.33a).[82-83] Similarly, anions derived from chiral nonracemic allyl and crotyl bicyclic phosphonamides 4.98a-b react with cyclic enones or α,β-unsaturated esters to give 4.99 and 4.100 (Scheme 4.33b).[84-85]

Scheme 4.33



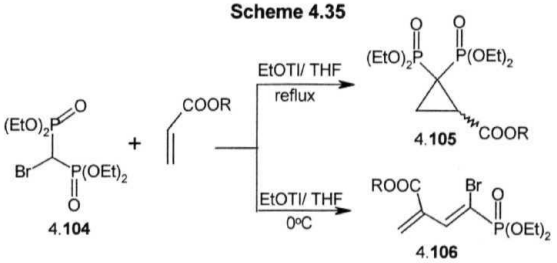
Phosphonate esters 4.101 in presence of NaO*t*Bu and BuLi react with α,β-unsaturated carbonyl compounds to give either 4.102 (HWE product) or 4.103 (Michael product) (Scheme 4.34). By contrast, a similar reaction in the presence of a heterobimetallic catalyst proceeds exclusively in 1,4 fashion.[86]

Scheme 4.34



The reaction of bromoethylenebis(phosphonate) **4.104** with alkyl acrylates in the presence of thallium(I) ethoxide under reflux conditions leads to cyclopropanediylbis(phosphonates) **4.105** *(via* Michael addition followed by cyclization), but at 0°C it gives mostly the monophosphonates **4.106** (Scheme 4.35).[87] In this connection it will be interesting to study the reaction of α,β-unsaturated esters with functional ized phosphonates, such as α-chlorophosphonates to see whether the reaction takes place in 1,4- (Michael addition followed by cyclization to cyclopropyl derivatives) or 1,2-fashion.

Scheme 4.35



4.6 Hydrolysis of phosphites/ phosphoramidites and its inhibition

Although tervalent P(III) compounds of the type $(RO)_3P$ or $(RO)_2PNR'R''$ are frequently used in the synthesis of a large number of other phosphorus compounds including organophosphonates and nucleosides/ glycosides, their high reactivity makes them susceptible to spontaneous oxidation and/ or hydrolysis.[88,89] In other significant applications of P(III) esters as antioxidants[90a-c] and heat stabilizers for

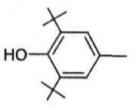
synthetic polymers/ plastics, hydrolysis in particular is a commonly encountered hurdle during synthesis, storage and use.[90d-e] Unlike the hydrolysis of phosphate esters,[91] those of phosphites/ phosphoramidites are much less investigated, although it is known that the P-N bonds in P(III) compounds can be readily cleaved under acid catalyzed conditions.[92] It is often desirable that hydrolysis of the precursor P(I1I) derivatives be prevented till reactions with the substrate is conducted.[9]

Various methods have been proposed for arriving at phosphorus(III) compounds having improved stability against hydrolysis. These include the addition of specific stabilizers which, on the one hand, reduce the tendency to hydrolyze and, on the other hand, do not result in adverse effects during the later use of the phosphites or phosphonites.[94]

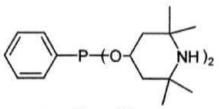
The hydrolytic behavior of commercially used phosphites was investigated by Linger *et al.*[95] and Klender *et.al.*[96] Klender proposed three methods to increase hydrolytic stability of phosphites for application as polymer stabilizers: They are

- Internal or external addition of basic components (stabilizers) to the phosphite
- Increase of steric hindrance around the phosphorus atom
- Reduction of electron density on the phosphorus atom.

It has been noticed that small amounts of basic components could hinder the hydrolysis of phosphites.[97] Many research groups have been involved in developing methods for new highly efficient stabilizers for improved hydrolytically stable phosphites.[90,94,97] Amines such as triethylamine, diethanolamine, triethanolamine and hexamethylenetetramine (5-30% by weight) can be used as stabilizers for organic phosphites. Sterically bulky phenols such as 2,6-di-*t*-butyl phenol (4.107) are also used as stabilizers.[90c-d,94] In addition, organic phosphites which contain amine groups like 2,2,6,6-tetramethylpiperidyl (4.108) are also used as stabilizers.[94,98] Use of amines, however, causes coloration of the substrate and hence it will be interesting to study and develop a method for improving the hydrolytic stability of organic phosphites and phosphoramidites.



Stabiliser
4.107



Phosphite
4.108

OBJECTIVES OF THE PRESENT WORK

The primary objectives of the present work are (i) to develop convenient routes to new organophosphonates by using the readily prepared and inexpensive precursor $(OCH_2CMe_2CH_2O)PCl$, (ii) to find utility for the phosphonates thus obtained in organic synthesis, (iii) to develop simple techniques to prevent hydrolysis of the phosphite precursors, some of which are useful for objective (i).

The following systems have been explored:

(a) Synthesis of allenylphosphonates by the pseudo-Claisen rearrangement of a propargyl phosphite- Conversion of allenyl phosphonates to other functionalized phosphonates- Use of β-ketophosphonates thus obtained in the Horner-Wadsworth-Emmons (HWE) reaction.

(b) Use of α-chlorophosphonates in the synthesis of cyclopropyl phosphonates.

(c) Hydrolysis of cyclic phosphites/ phosphoramidites and its inhibition- reversible cyclization of acyclic phosphonate salts to cyclic phosphites.

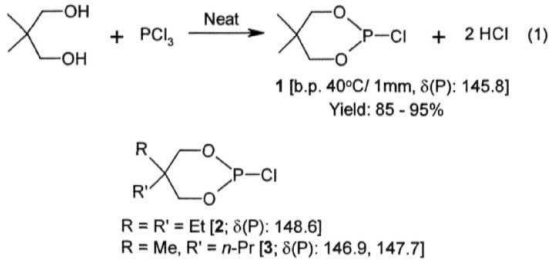
These are discussed in the same order.

CHAPTER 5

RESULTS AND DISCUSSION

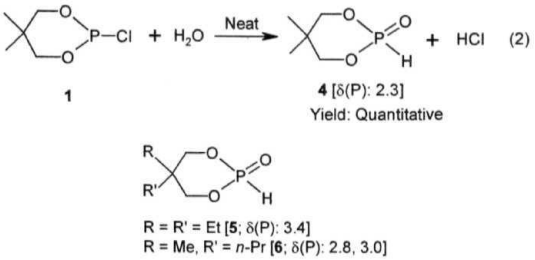
5.1 Synthesis of phosphites

This part of the present work is essentially based on the key precursor $(OCH_2CMe_2CH_2O)PCl$ (1) which has a six-membered 1,3,2-dioxaphosphorinane ring." In the present study, 1 is prepared by treating 2,2-dimethyl-l,3-propanediol with phosphorus trichloride under neat conditions (eq. 1). In an analogous manner, compounds 2 and 3 were also prepared.



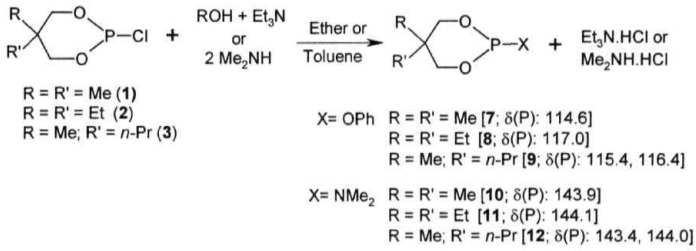
Literature methods involve the use of a solvent $[CH_2Cl_2, Et_2O$ etc] in the presence/ absence of a base. Thus, our simple modification besides being cost-effective (eliminating the use of solvent), offers the advantage that 1 can be more easily purified by a single distillation in vacuum. Coupled with this, it can be noted that (i) both the starting materials are very cheap and (ii) the six-membered phosphorinane ring generally remains intact under normal conditions in further reactions. As is the case with many P(III) compounds containing a residual P-Cl bond, 1 can be readily hydrolyzed by water to give the H-phosphonate 4 (eq. 2). Compound 4 although can be distilled in vacuum, was used as such for further reactions in the present study without any difficulty, thus making it comparable in cost to the

commercially available diethylphosphite $(EtO)_2P(O)H$. The other H-phosphonates 5 and 6 were also prepared by the same route.



Treatment of 1-3 with a phenol or dimethylamine in the presence of a base (Et_3N for alcohol or one more equivalent of the amine itself) gives the corresponding phenoxy/ dimethylamino phosphites 7-12 as shown in Scheme 1. Compounds 8, 9 and 11, 12 are new whereas 7 and 10 are known.[100] Again all these compounds are moisture-sensitive but can be preserved under nitrogen atmosphere.

Scheme 1



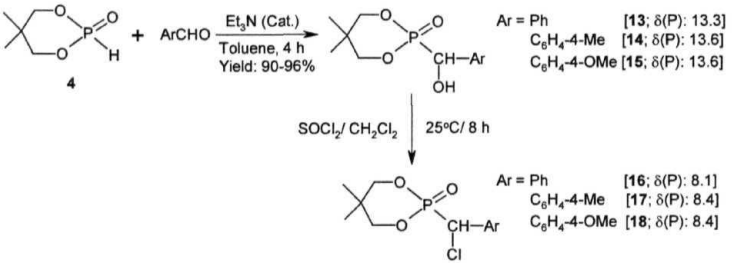
It can be noted that the ^{31}P NMR spectra of all the compounds with unsymmetrical substitution [3, 6, 9, 12] show two resonances; this feature is most likely due to the axial or equatorial occupancy of the methyl (or isopropyl) substituents in the saturated 1,3,2-dioxaphosphorinane ring assuming a chair conformation.[1 1]

5.2 Synthesis and reactivity of phosphonates

5.21 *Synthesis of α-chlorophosphonates*

The α-hydroxyphosphonates **13-15** and a-chlorophosphonates **16-18** have been synthesized by the routes developed in our laboratory previously (Scheme 2).[100b,102]

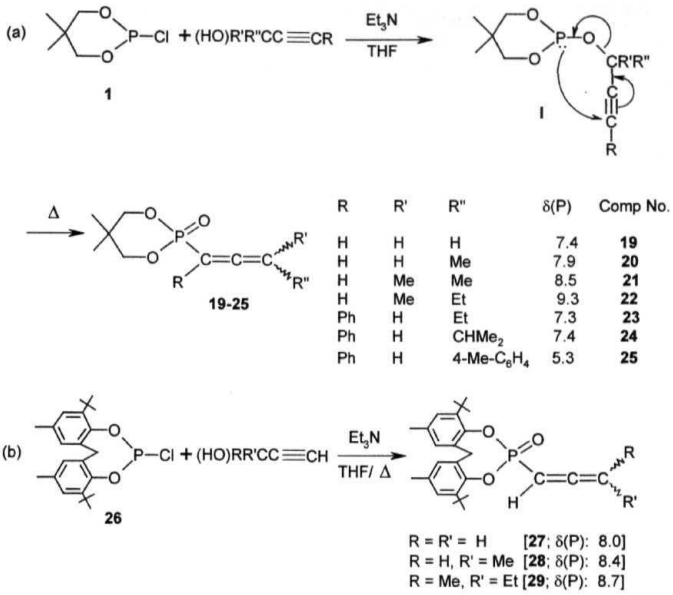
Scheme 2



5.22 *Synthesis of allenylphosphonates*

Allenylphosphonates **19-25** were prepared by the reaction of $(OCH_2CMe_2CH_2O)PCl$ (1) with a substituted propargyl alcohol in the presence of Lewis base such as triethylamine. Compounds 19 and **21** have been prepared previously by Savignac and coworkers.[103] The initially formed P(III) intermediates I [^{31}P NMR evidence; 8(P) ~120] undergoes a pseudo-Claisen-type rearrangement[15] above room temperature (< 80°C) to form the pentavalent allenylphosphonates (Scheme 3a). It is interesting to note that even with phenyl substituted propargyl alcohols the rearrangement is quite facile *(cf.* compounds **23-25).** Phosphonates **27-29** bearing an eight-membered ring were prepared by an analogous reaction of $CH_2(6\text{-}t\text{-}Bu\text{-}4\text{-}Me\text{-}C_6H_2O)_2PCl$ (26) with propargyl alcohol, 3-butyne-2-ol and 3-methyl-1-pentyne-3-ol (Scheme 3b).

Scheme 3



Allenylphosphonates **19-25** and **27-29** are stable in air in the solid state and in solution. These allenes show a characteristic strong band around 1920-1975 cm^{-1} due to asymmetric $\nu(c=c=c)$.[1a] There is also another strong band at ~840 cm^{-1} due to torsional motion of allenic terminal methylene in compounds **19** and 27. The ^{31}P NMR spectra of all these compounds show a single peak in the range of 5 5-10. In the ^{1}H NMR, the proton attached to the a-carbon (to phosphorus) in compounds 19-22 and 27-29 shows a multiplet in the region 8 5.0-5.5; this feature is due to V(HH) and/or V(HH) in addition to the normal $^{2}J(PH)$.[104] Such an assertion is also corroborated by the multiplicity in other regions of the spectra. The a-carbon appears as a doublet in the region 8 76.0-78.0 with a $^{1}J(PC)$ of ~210.0 Hz in the ^{13}C NMR; this coupling constant is significantly higher than those observed in the *a*-chlorophosphonates of type **16-18** [$^{1}J(PC)$ of ~150.0 Hz]. This feature is associated with increased *s* character at the a-carbon in the allenylphosphonates **19-25** and **27-29** [105] The β and γ carbons appear around 210 and 95 ppm respectively.

Compound **19** was characterized by X-ray crystallography (Fig. 1, Table 1). The P-0 bond distances are in the expected range. The C(6)-C(7) and C(7)-C(8) distances [mean: 1.285 A] are shorter when compared to that in $Cl_2P(O)CH{=}C{=}CH_2$ [1.318 Å].[11b] The C(6)-C(7)-C(8) bond angle of 179.3(2) shows the allene moiety is almost linear.

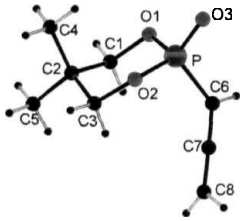


Fig. 1 Molecular structure of **19**

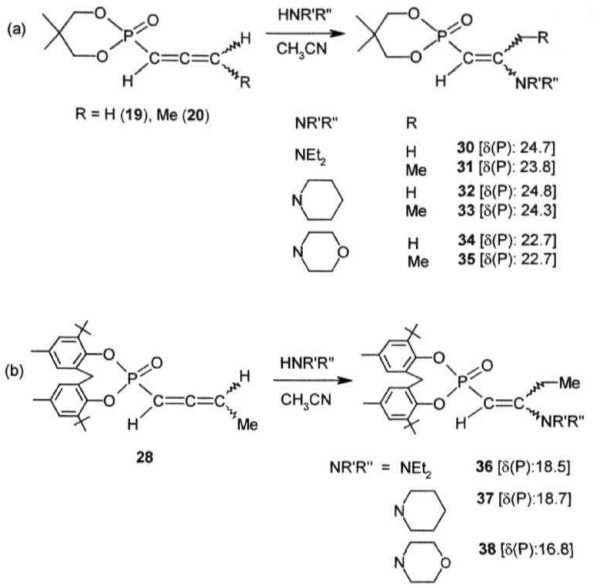
Table 1. Selected bond lengths [A] and bond angles [°] for **19** with esd's in parentheses

P-O(1)	1.568(2)	P-C(6)	1.769(2)
P-O(2)	1.574(2)	C(6)-C(7)	1.290(3)
P-O(3)	1.460(2)	C(7)-C(8)	1.280(3)
O(1)-P-O(2)	105.75(6)	O(3)-P-C(6)	112.93(10)
O(1)-P-O(3)	113.07(11)	P-C(6)-C(7)	124.3(2)
O(2)-P-O(3)	110.79(10)	C(6)-C(7)-C(8)	179.3(2)

5.23 *Synthesis of fi-enamino, p-keto and allylphosphonates*

The preparation of P-enaminophosphonatcs **30-38** was accomplished very easily and in very high yields by means of simple addition of aliphatic and cyclic amines to allenylphosphonates **19-20** and **28** in acetonitrile (Scheme 4). The reaction is complete within a couple of minutes in the case of **19** [^{31}P NMR]. To our knowledge, compounds such as **30-38** were previously isolated by starting with phosphoacetylenes only and not by starting with allenylphosphonates.

Scheme 4



Compounds **30-38** exhibit a characteristic strong band at ~1570cm^{-1} in the IR spectra ascribable to the enaminic double bond. The 'H NMR spectra of these phosphonates show *P-CH* doublet at 8 3.7-4.5 [V(PH) ~ 8.8 Hz]; these values are close to that observed in $(EtO)_2P(O)CH{=}CH(NEt_2)$ (II) and $(EtO)_2P(O)CH{=}CH(NC_5H_{10})$ **(III)** for which *E* configuration was assigned.[106] In compounds **30,** 32 and 34 the new methyl group (after rearrangement) shows up at δ ~2.3; for 31, 33 and 35-38 the CH_2CH_3 signals are also clearly seen *[cf.* Fig. 2 for **36].** These features rule out the other possible structures **IVa-b** for these compounds. The ^{13}C NMR spectrum *[cf.* Fig. 3 for 36] shows a doublet at δ 73.0-80.0 [$^1J(PC)$ ~ 230.0 Hz]. The high $^1J(PC)$ value is consistent with the sp^2 hybridization at this carbon.[105] It is interesting to note that the S(C) value is quite up-field to that of normal olefinic carbons. The C-N carbon appears around 8 162 [V(PC) ~22.0 Hz]. Selected ^{13}C NMR parameters for **30-38** are presented in Table 2. The ^{31}P NMR chemical shifts are in the range δ 22.0-25.0 for **30-35** and 16.0-19.0 for **36-38,** as expected. This type of ring

size effect in the ^{31}P NMR has been reported previously from our laboratory for tri- and pentacoordinate phosphorus compounds.[107]

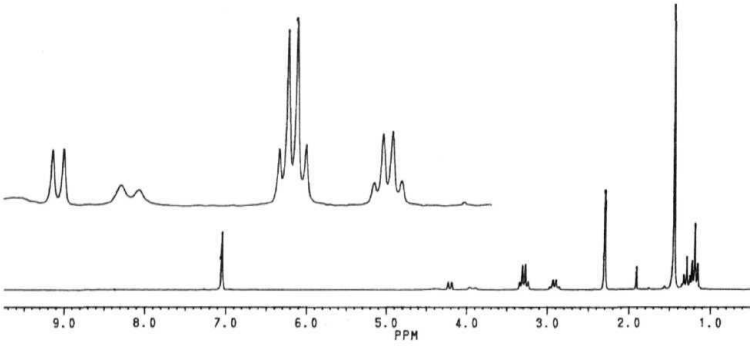


Fig. 2 ^{1}H NMR spectrum of **36**

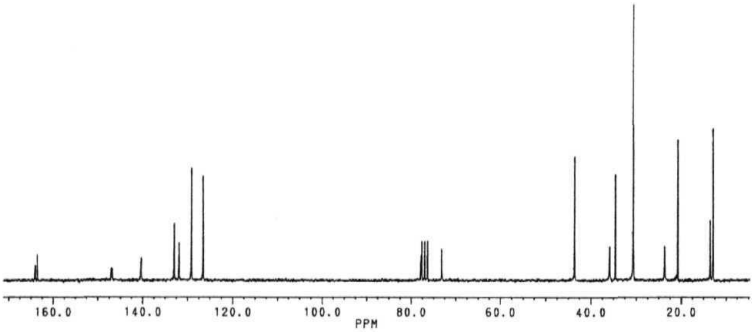
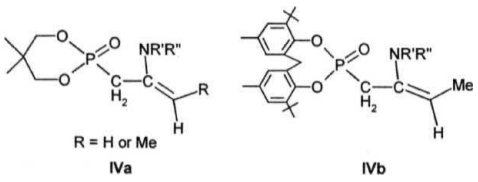


Fig. 3 ^{13}C NMR spectrum of **36**



IVa **IVb**

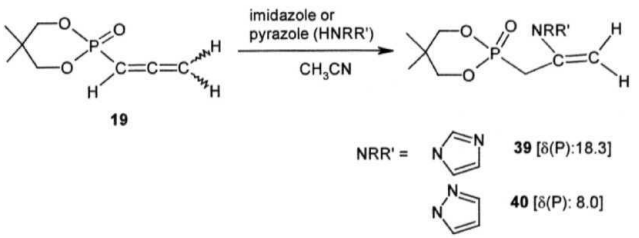
Table 2. Selected ^{13}C NMR parameters for **30-38, II** and **III**

Compd. No	Chemical shifts		Coupling constants[a]	
	5[C-P]	δ[*C*=CP)		$^{2}J_{PC}$
30	70.1	160.0	218.9	21.6
31	69.5	165.3	217.9	22.1
32	73.6	162.0	217.8	21.8
33	73.6	167.6	190.o	22.0
34	76.7	162.6	214.0	20.5
35	75.6	167.6	213.0	21.0
36	75.5	163.8	233.3	23.7
37	78.4	165.5	230.4	21.6
38	81.4	166.2	228.1	22.0
II[b]	72.4	153.48	209.2	20.1
III[b]	75.5	153.62	201.3	19.3

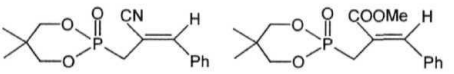
[a] $^{3}J_{PC}$ values of PC=C*C*H$_2$ or PC=C*C*H$_3$ carbons are generally < 5.5 Hz.
[b] From ref 106

In contrast to the above, reaction of the allenylphosphonate 19 with imidazole or pyrazole yielded allylphosphonates **39** or **40,** respectively, in 60-80% yields (Scheme 5). Here the double bond lies between β and γ carbon atoms. In earlier work, an equilibrium between enamine structures [*cf.* **30-38** and **39-40]** was observed,[29] but a compound of type **39-40** was never isolated.

Scheme 5



The IR spectra of 39 and 40 show a strong band at ~1650 cm^{-1} (*cf.* 1570 cm^{-1} for 30-38), ascribable to the oiefinic stretch. In the ^1H NMR *[cf.* Fig. 4 for 40], a characteristic doublet at 8 3.3-3.5 [^2J(PH) = 21.0 Hz] for the PCH_2 protons clearly distinguishes these compounds from 30-38. Two oiefinic protons also appear at δ ~5.1 and ~5.4. The carbon α to phosphorus now appears around 28.0 ppm in the ^{13}C NMR *[cf* Fig. 5 for 40]; the magnitude of ^1J(PC) [~137.5 Hz] clearly shows that this carbon has less *s* character than the corresponding one in 30-38. The resonances for β and *y* carbons in 39 and 40 appear as doublets around δ 135.0 [^2J(PC) ~10.5 Hz] and 108.0 [V(PC) - 9.0 Hz] respectively. The structure of compound 40 was unambiguously proved by X-ray crystallography (Fig. 6, Table 3) confirming our assignment of ^{31}P and ^1H NMR signals. The P-O bond distances are in the expected range. The P-C(6) bond distance of 1.797(2) A is slightly longer than that in 19 [1.769(2) A], as expected. The C(6)-C(7)-C(11) bond angle of 122.4(2)° {sp^2 carbon) is clearly different from that in 19 [C(6)-C(7)-C(8) 179.3(2)°; *sp* carbon]. The ^{31}P NMR spectra showed a peak at around 8 18, which is up-field to those for 30-35 but is close to those for the substituted allylphosphonates (V-VI) reported earlier from our laboratory.[108]



V [δ(P): 18.2] **VI** [δ(P): 18.2]

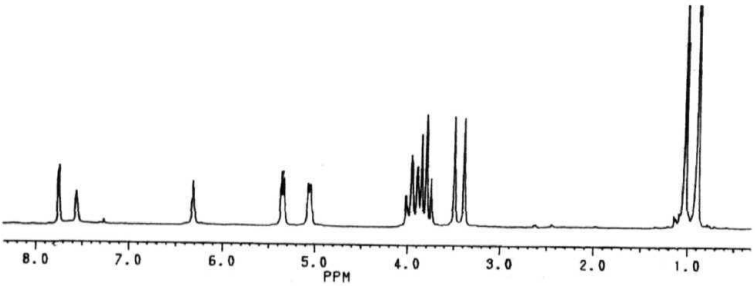


Fig. 4 ^1H NMR spectrum of **40**

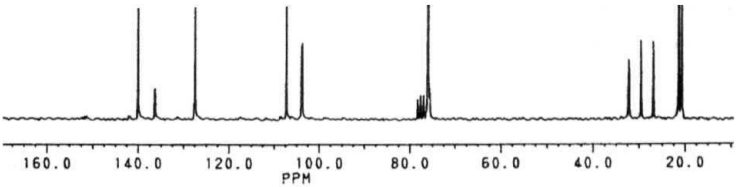


Fig. 5 ^{13}C NMR spectrum of **40**

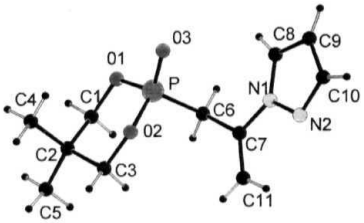


Fig. 6 Molecular structure of 40

Table 3. Selected bond lengths [A] and angles [°] for 40 with esd's in parentheses

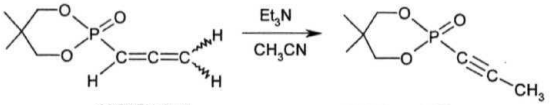
P-O(1)	1.570(2)	P-O(2)	1.569(2)
P-O(3)	1.458(2)	P-C(6)	1.797(2)
C(6)-C(7)	1.499(3)	C(7)-C(8)	1.313(3)
C(7)-N(l)	1.421(3)	N(l)-C(8)	1.344(3)
N(1)-N(2)	1.354(3)	N(2)-C(10)	1.314(3)

O(1)-P-O(2)	105.60(8)	O(3)-P-C(6)	113.58(9)
O(1)-P-O(3)	111.91(9)	C(6)-C(7)-C(11)	122.4(2)
O(2)-P-O(3)	111.77(9)	C(11)-C(7)-N(1)	121.0(2)
O(1)-P-C(6)	107.85(9)	C(6)-C(7)-N(l)	116.6(2)
O(2)-P-C(6)	105.60(8)		

It is previously shown from our laboratory that compounds **V-VI** can be used as reagents in **Horner-Wadsworth-Emmons** (HWE) reaction.[108] Hence an attempt was made to utilize 39-40 in HWE reaction with aromatic aldehydes under a variety of conditions (K_2CO_3 or NaH in THF, Et_3N in CH_3CN). Although the starting phosphonate disappeared [tlc], we were not successful in isolating the expected olefinic products.

Interestingly, when compound 19 is heated with **triethylamine** (a 3° **amine**) instead of diethylamine or **imidazole**, it undergoes a prototropic **isomerization** to give **1-propynylphosphonate** 41 (Scheme 6); this result is in line with the literature reports on analogous systems.[38] Compound 41 is an air-stable solid. Its ^{31}P NMR chemical shift is -13.0 which is very much up-field to that of the precursor 19. This feature is similar to those observed for allenic (down-field) and acetylenic (up-field) protons in the ^{1}H NMR. The ^{1}H NMR spectrum shows a characteristic doublet at 8 2.00 with a V(PH) of 4.8 Hz. It can be noted that the ^{31}P NMR chemical shift for acetylene 41 [8 -13.0] is clearly up-field to those for allenes 19-25 and 27-29 [8 5.3-10]. The **α-carbon** appears as a doublet in the region δ 67.5 with a $^{1}J(PC)$ of 291.0 Hz in the ^{13}C NMR; this coupling constant is significantly higher than those observed in the allenylphosphonates of type 19-25 [$^{1}J(PC) \sim 210.0$ Hz]. This feature is associated with increased *s* character (sp hydbridization) at the **α-carbon** in **41**.[105]

Scheme 6

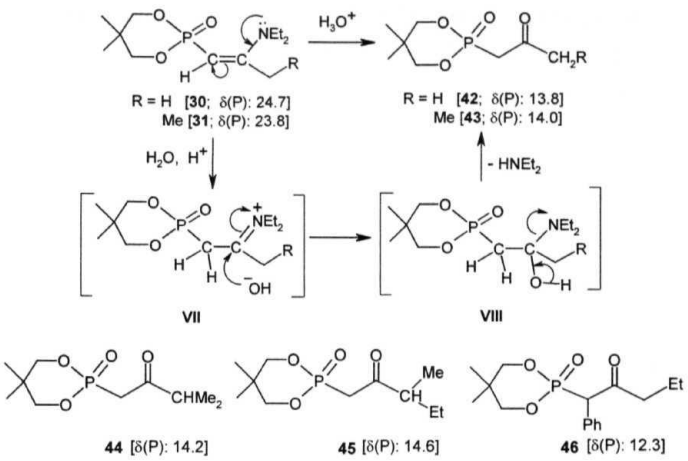


19 [δ(P): 7.4] **41** [δ(P): -13.0]

We could not effect the rearrangement of the other allenylphosphonates 20-22 under these conditions probably because of steric effects.

Although the enaminophosphonates 30-31 could be isolated, they are readily hydrolyzed by 2N HC1 to form the **β-ketophosphonates** 42 and 43 (Scheme 7). In fact, we were able to isolate the **β-ketophosphonates** 44-46 although the corresponding **enamine** phosphonates could not be isolated from the reaction of 21-23 with diethylamine. Compounds 42-46 are interesting reagents for HWE reaction[41] and may be useful for **complexing** with metals;[43] we have been successful in the former (see later) and for this study, we have not tried the **complexation.**

Scheme 7



Since this type of hydrolysis is known in the literature, it is not discussed further here.[55] However, we were curious to see if any intermediate could be identified. Addition of 2N HCl to 30 in an NMR tube experiment showed only 42 along with the starting phosphonate [^{31}P NMR] suggesting that the intermediates VII and VIII are very unstable.

Compounds 42-46 are air-stable solids. In the IR spectra, they show a band at ~1715 cm^{-1} corresponding to the carbonyl stretch. In the ^{1}H NMR, a characteristic doublet at 5 3.3-3.5 [^{2}J(PH) ~ 22.0 Hz] for the PCH_2 protons clearly shows that a rearrangement of the carbon skeleton has taken place in their formation. The ^{31}P NMR spectra of these compounds show a single peak in the range 8 10-15. The carbon α to phosphorus now appears as a doublet around 8 40.0 in the ^{13}C NMR; the magnitude of ^{1}J(PC) [~122.5 Hz] clearly shows that this carbon has less 's' character than the corresponding one in 30-38. The carbonyl group appears as a doublet around 8 203 [^{2}J(PC) ~ 6.1 Hz].

5.24 *HWE reaction using the β-ketophosphonates* 42-43: *Synthesis of α,β-unsaturated ketones*

As mentioned above, the protons connected to the α-carbon in compounds 42-43 are acidic and hence these compounds can be utilized for HWE reaction. Our

initial attempts of the HWE reaction using NaH/ THF gave either none or only very low yields of olefinic products.[57,60] However, when K2CO3 was used in place NaH in refluxing THF, the reaction proceeded to afford the α,β-unsaturated ketones **47a-i** and **48a-h** in moderate to high yields (Scheme **8,** Table 4).

Scheme 8

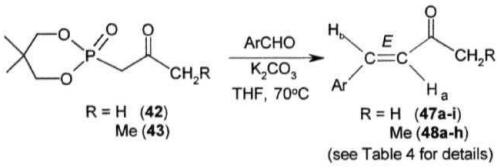


Table 4. Details on the HWE reaction of the β-ketophosphonates **42-43** with aromatic aldehydes

Entry	R	Ar	Product (*E*)	Yield (%)
1	H	Ph	**47a**	75
2	H	4-Me-C_6H_4	**47b**	72
3	H	3-Me-C_6H_4	**47c**	59
4	H	4-MeO-C_6H_4	**47d**	73
5	H	4-O_2N-C_6H_4	**47e**	51
6	H	PhCH=CH	**47f**	60
7	H	2,6-Cl_2-C_6H_3	47g	66
8	H	3,4-Cl_2-C_6H_3	**47h**	60
9	H	9-anthryl	**47i**	45
10	Me	Ph	**48a**	70
11	Me	4-Me-C_6H_4	**48b**	69
12	Me	4-MeO-C_6H_4	**48c**	66
13	Me	PhCH=CH	**48d**	50
14	Me	9-anthryl	**48c**	41
15	Me	ferrocene	**48f**	**78**
16	Me	C_6H_4	**48g**	62
17	Me	4-Cl-C_6H_4	**48h**	66

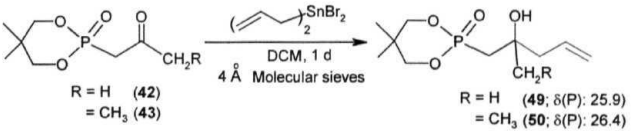
The ^1H NMR spectra of these products show two doublets around 5 6.50 and 7.20 with V(HH) ~ 15-18 Hz for the olefinic protons H_a and H_b showing that the keto

and the aryl (Ar) group are *trans* (*E*-isomer) to each other. This feature is in line with the general HWE reaction.[41] Although in the case of isobutyraldehyde (an aliphatic aldehyde) no characterizable product was isolated, this reaction worked very with aromatic aldehydes as evident from Table 4.

5.25 *Synthesis of fl-hydroxyphosphonates from fi-ketophosphonates*

In recent years, significant progress has been made in the allylation of carbonyl compounds by allylic tin reagents.[109-111] The recent report on the indium mediated allylations of β-ketophosphonates by Ranu *et al.* is also attractive[75] and analogous reactions using tin reagents are worth-attempting. In continuation of our ongoing program on the synthesis of varied substituted phosphonates,[100b,102,110a] we attempted the allylation reactions of various substituted β-ketophosphonates with diallyltin dibromide.[110] Two substituted β-ketophosphonates **42** and **43** were allylated by this procedure to produce the corresponding β-hydroxyphosphonates 49 and **50.** We found that **42-43** reacted with diallyltin dibromide at room temperature in dichloromethane *in the absence of an additional Lewis acid* to give β-hydroxyphosphonates (Scheme 9) in yields of 40-60%. The reaction was complete in 16-24 h (no starting materials; TLC). The yield was better using dichloromethane rather than THF as the solvent; addition of molecular sieves (4 A) increased the yield.[111a]

Scheme 9



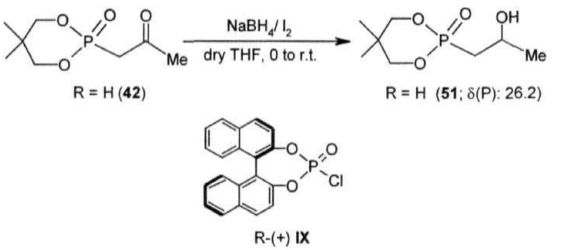
In the IR spectra, **49-50** show a band at ~3430 cm^{-1} corresponding to the hydroxyl stretch. In the ^1H NMR spectrum of 49 the PCH_2 protons appear as an AB part of an ABX [X = P] multiplet at 8 2.10 [^2J(HH) ~ 10.8 Hz; V(PH) ~ 17.3 Hz]. In **50,** PCH_2 protons show up only as a doublet at 8 2.12 [V(PH) = 17.7 Hz]. The presence of the allyl group is proven by the observation of resonances at 8 5.07 [V(HH) = 13.0 Hz] and 5.15 (multiplet). The ^{31}P NMR spectra of these compounds show a single peak around 8 26.5 in the expected phosphonate region. The carbon α

to phosphorus appears as a doublet around 8 34.0 [^1J(PC) ~ 130.0 Hz] and the olefinic carbons show up at 8 118.5 and 133.8 in the ^{13}C NMR.

We have also tried to induce the optical activity at the β-position by performing the above reaction in the presence of R-(+)–1,1'-bi-2-naphthol and triethylamine. The reaction proceeded smoothly to give the allylated products **49-50** in good yield, but no asymmetric induction was observed (no optical rotation).

We have also synthesized the β-hydroxyphosphonates **51** by the reduction of β–ketophosphonate **42** with $NaBH_4$/ I_2 (Scheme 10). An attempt to prepare chiral phosphonate (in the presence of chiral chlorophosphate IX[112]) was unsuccessful; we were not able to isolate pure **51** that is free from bi-2-naphthoxy residue. The spectral features of **51** are similar to that of 49.

Scheme 10



R = H (**42**) R = H (**51**; δ(P): 26.2)

R-(+) **IX**

5.26 *Synthesis of cyclopropyl phosphonates via Michael addition*

The cyclopropane moiety can be found in a number of natural and unnatural substances, and some of these have received particular attention due to their biological properties."[3] A novel method for the synthesis of fully functionalized cyclopropanes has been found by Hanessian based on *trans-N,N* -dimethyl-1,2-diaminocyclohexane derived phosphonamides."[4] We felt that this method could be extended to our phosphonate system also. Thus, the cyclopropyl phosphonates **52-59** have been prepared by treating the α-chlorophosphonates **16-18** with α,β-unsaturated esters using THF as the solvent under reflux conditions (Scheme 11; Table 5). The cyclopropanation takes place via Michael addition followed by the cyclization.[87] When isophorone was used instead of α,β-unsaturated esters; compounds analogous to **52-59** were not detected.

Scheme 11

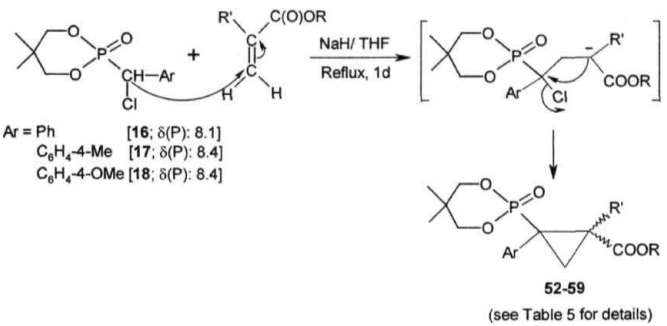
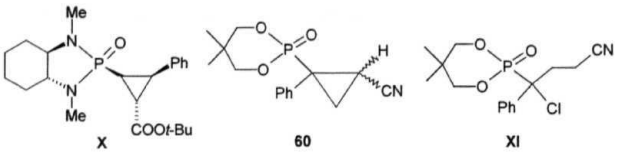


Table 5. ^{31}P NMR data and yields for **52-59**

Entry	Compd	Ar	R	R'	5(P)	Yield (%)
1	**52**	Ph	Me	H	20.3	63
2	53	Ph	Et	H	20.4,25.0(9:1))	63
3	54	Ph	Me	Me	20.6,25.9(9:1)	61
4	**55**	4-Me-C_6H_4	Me	H	20.5	66
5	56	4-Me-C_6H_4	Et	H	19.1	61
6	57	4-Me-C_6H_4	Me	Me	20.9,26.3(8:1)	60
7	58	4-MeO-C_6H_4	Me	H	19.1,20.9(20:1)	68
8	**59**	4-MeO-C_6H_4	Me	Me	20.7	61

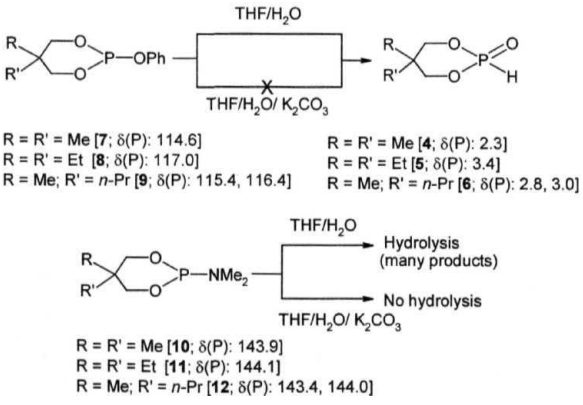
Compounds **52-59** are air-stable solids. The CH_2 protons of the cyclopropane ring in **52** show up as AX multiplets with coupling to phosphorus [V(PH) = 4.8 Hz]. The ^{31}P NMR spectra of these compounds show peaks in the range of 5 20.0-21.0 which are in line with the literature data.[93] The ^{13}C NMR spectra of these compounds show a doublet at around 5 29.0 [^2J(PC) ~ 190.0 Hz] which is close to that observed for X [187.3 Hz].[114e] The reaction mixture of 16 and acrylonitrile shows a major peak at 5 15.6 (95%) along with a minor one at 8 17.3 (5%) in the ^{31}P NMR. Although a pure compound could not be isolated, clear 8 line patterns are observed at 8 1.68 and 2.24. This pattern is consistent with the presence of cyclopropanyl CH_AH_B along with CH(CN) protons in 60 rather than the open chain structure XI (prior to HC1 elimination; literature has some examples of this kind of compounds[83"5]).



5.3 Hydrolysis of cyclic phosphites / phosphoramidites and its inhibition

In an effort to study the hydrolytic stablility of the phosphites, we employed $(OCH_2CRR'CH_2O)PCl$ [R, R' - Me (1), Et (2), R = Me, R' = *n*-Pr (3)], $(OCH_2CRR'CH_2O)POPh$ [R, R' - Me (7), Et (8), R = Me, R' = *n*-Pr (9)] and $(OCH_2CRR'CH_2O)PNMe_2$ [R, R' = Me (10), Et (11), R - Me, R' = *n-Pr* (12)] for the present study. Normal hydrolysis of 7-9 lead to cyclic H-phosphonates $(OCH_2CRR'CH_2O)P(O)H$ [(R, R' = Me (4), R, R' = Et (5), R = Me, R' = *n*-Pr (6)] occurs upon addition of stoichiometric amounts of water under neat conditions (Scheme 12). When compounds 7-9 are stirred with an excess of water (3 mole equivalents) in tetrahydrofuran for 12 h, 4-6 as well as further hydrolysis products are observed [^{31}P NMR]. An analogous reaction with water, when conducted in the presence of K_2CO_3, afforded 7-9 *completely unaffected* (Table 6). This inhibition of hydrolysis was also realized when KF, $MgSO_4$, triethylamine, or molecular sieves was used in place of K_2CO_3, but K_2CO_3 gave the best results. The salts NaF and KG were ineffective in inhibiting the hydrolysis.

Scheme 12



Even with 1:1:3 mole equivalents of 7, K_2CO_3 and H_2O in THF as the solvent no hydrolysis was observed. Both KF and K_2CO_3 are no doubt hygroscopic, but the effectiveness of the latter in inhibiting hydrolysis is very impressive. Hydrolysis of the phosphoramidites 10-12 were also inhibited by KF and K_2CO_3. In a similar way, the hydrolysis of other aminophosphites [e.g. $(OCH_2CMe_2CH_2O)P(NH\text{-}cyc\text{-}C_6H_{11})$ (XII)] could also be prevented."[6]

Table 6. Details on the hydrolysis studies of 7-12

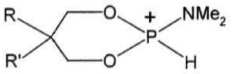
Entry	Compound	Additive	Result
1	7-12 (1 mmol) (+ 3 mmol of water)	KF	~2 % hydrolysis
2		K_2CO_3	No hydrolysis
3		Et_3N	~1 % hydrolysis
4		$MgSO_4$	~2 % hydrolysis
5		Molecular sieves	~1% hydrolysis
6		KC1	complete hydrolysis
7		NaF	complete hydrolysis

An *immediate application* of the present results is in the preservation of P(III) compounds. We could preserve $(OCH_2CMe_2CH_2O)P(OPh)$ (7; no solvent; 1.5 g, 6.6 mmol) in the presence of one mole equivalent of K_2CO_3 and two mole equivalents of water (stirred) *for 3 days without any apparent hydrolysis.*

We also checked the effect of K_2CO_3 on the hydrolysis of acyclic phosphites $P(OMe)_3$ and $P(OPh)_3$. Hydrolysis of acyclic phosphites $P(OMe)_3$ and $P(OPh)_3$ in the absence of K_2CO_3 using similar experimental conditions as above occurred to an extent of 100% and 40%, respectively. In the presence of K_2CO_3, the hydrolysis was completely inhibited. The main limitation, however, is that the reaction of phosphite bearing aromatic diol residue like $(1,2\text{-}C_6H_4O_2)P(OPh)$ [XIII; 8(P) 126.6] is still susceptible towards hydrolysis, even in the presence of K_2CO_3.

We also conducted competitive reactions of $(OCH_2CRR'CH_2O)PX$ [{X - Cl; R, R' = Me (1), Et (2), R = Me, R' = *n-Pr* (3)}, X = NMe_2; R, R' = Me (10)] with a mixture of water and a phenol to ascertain whether any mechanistic contribution is there or not in the inhibition of hydrolysis by K_2CO_3 [Table 7]. Under these conditions, the phenol reacts preferentially to give the phenoxy derivatives 7-9. The stoichiometric reaction of $(OCH_2CMe_2CH_2O)P(NMe_2)$ (10) with H_2O/ phenol led to 7

with much less hydrolysis (<10%); the inhibition of hydrolysis is most likely due to the liberated dimethylamine. Use of molecular sieves led to significant hydrolysis. These results suggest that the basic nature of K_2CO_3 does have a role in inhibiting the formation of a transition state species like (XIV)"[7] by the initial attack of the acidic proton on the phenol at the trivalent phosphorus center, hence the prevention of hydrolyzed products. The competitive reaction of $(OCH_2CMe_2CH_2O)P(NMe_2)$ (7) was also performed by sterically bulky alcohol like *t*-butanol. Water preferentially reacts with phosphoramidite over /-butanol giving the hydrolyzed product $(OCH_2CMe_2CH_2O)P(O)H$ (3) instead of *t*-butoxy phosphite. Possible reasons for this are (i) lower aciditiy of *OH* proton and / or (ii) steric affects.



(XIV)

Table 7. Competitive reaction of phosphites with phenol and water in THF

Entry	P(III) compound (1 mmol)	Additive: H_2O: phenol (mmol)[a]	Product[b]
1	1	5:1:1	7
2	2	5:1:1	8
3	3	5:1:1	9
4	10	5:3:1	7
5	10	1:3:1	7
6	10	3:1[c]	7
7	12	5:3:1	9
8	10	5:3:1 (2,6-Cl_2-C_6H_3OH)	61 (2%)[d]
9	10	5:3:1 (2,6-Me_2-C_6H_3OH)	62 (50%)[d]
10	10	3:1 (2,6-Cl_2-C_6H_3OH)	61

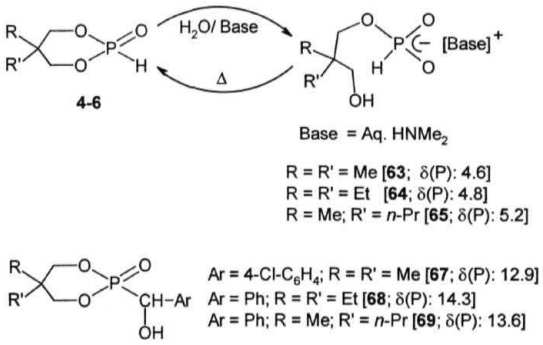
[a] In all cases except entry 10, K2CO3 was the additive; in entry 10, molecular sieves (5 times the weight of the phosphite) was used.
[b] No hydrolysis except in entries 6 and 10 where 8% and 40% hydrolysis, respectively, occurred.
[c] No additive was used.
[d] Rest was the starting phosphoramidite; $(OCH_2CMe_2CH_2O)P(OAr)$ [Ar = 2,6-$Cl_2C_6H_3O$ (61), 2,6-$Me_2C_6H_3O$ (62)].

5.31 ***Reversible cy*** *dilution* ***of acyclic phosphonate salts to H-phosphonates***

The first stage hydrolysis products $(OCH_2CRR'CH_2O)P(O)H$ [(R, R' = Me (4), R, R' = Et (5), R = Me, R' = n-Pr (6)] undergo facile hydrolysis in the presence of aqueous amines to the acyclic phosphonates **63-65** (90-95% yield) [Scheme 13]. An X-ray structure of **66** [base = N,N-dimethylaminopyridine (DMAP)] [Fig. 7; Table 8], that exists as a hydrogen bonded dimer, confirms the identity of these products.[118] What is perhaps a lot more interesting is that the *salts* **63-65** *can be thermally converted back to the cyclic phosphites* 4-6; this is readily confirmed by ^{31}P NMR as well as derivatization to the Pudovik products **67-69** *{cf.* Scheme 13).[102]

Cyclization to lead to a six-membered dioxaphosphorinane ring from an acyclic phosphate ester, to our knowledge, is observed in two cases before: (a) formation of *cyclic*-AMP from ATP in the presence of adenyl cyclase,[119] (b) formation of 3',5'-cyclic phosphates from ribonucleoside-5'-phosphates with DCC under the presence of a strong base guanidine.[120] In these cases, cleavage of a O-P or O-C bond from the acyclic precursor is required for the formation of the cyclic phosphate while in the formation of 4-6 from **63-65,** base elimination cum dehydration are involved.

Scheme 13



Molecular structure of ***66***

The molecular structure and the geometrical parameters for **66** are shown in Fig. 7 and Table 8 respectively. There are both intra and intermolecular hydrogen bonds. While the one between N(l)-H and O(2) is intramolecular, the one between O(4)-H and 0(1) is intermolecular leading to the formation of a dimer. The P-0 bond

distances are in the expected range. There is a very weak hydrogen bond between HN(1) and 0(3), which is not shown in the picture. This compound is very hygroscopic and within seconds of exposure to air becomes a liquid, probably by absorbing moisture; however, it was stable in a perfluorcarbon liquid (that was used while mounting inside the capillary).

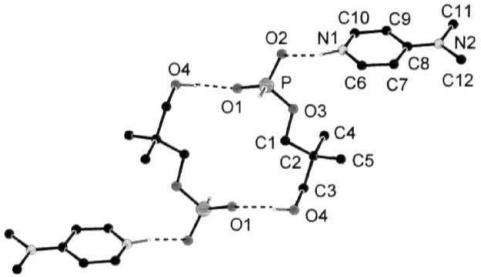


Fig. 7 A diagram showing the hydrogen bonded dimeric motif in 66; only hydrogen-bonded protons are shown and the solvent molecule is not shown.

Table 8. Selected bond lengths [A] and bond angles [°] for 66 with esd's in parentheses

P-O(1)	1.466(2)	O(4)-C(3)	1.402(5)
P-O(2)	1.477(3)		1.311(5)
P-O(3)	1.587(2)		1.326(5)
	1.432(4)		

O(1)-P-O(2)	119.02(17)	C(2)-C(3)-O(4)	115.3(3)
O(1)-P-O(3)	111.42(15)	C10-N(l)-C(6)	120.6(3)
O(2)-P-O(3)	105.28(14)	C11-N(2)-C(12)	116.4(3)
C(1)-O(3)-P	120.1(2)		

O(4)-HO(4)...O(1)0.83 (5), 1.82 (5), 2.648 (4), 177(5); N(l)-HN(l)...0(2) 0.95 (6), 1.73 (6), 2.658 (4), 168(5); N(1)-HN(1)...O(3)0.95 (6), 2.56 (6), 3.215 (4), 126(4).

5.4 SUMMARY

1) **An** easy protocol for the synthesis of allenylphosphonates by using the inexpensive precursors $(OCH_2CMe_2CH_2O)PCl$ and $CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2PCl$ has been developed.

2) β-Enaminophosphonates $[(OCH_2CMe_2CH_2O)P(O)CH{=}C(NR'R'')CH_2R]$ are formed in quantitative yields in the reaction of allenylphosphonates $[(OCH_2CMe_2CH_2O)P(O)CH{=}C{=}CH_2R]$ and saturated secondary amines. By contrast, allylphosphonates $[(OCH_2CMe_2CH_2O)P(O)CH_2C(NR'R'')=CHR]$ are obtained when imidazole and pyrazole were used. Upon hydrolysis, the β-enaminophosphonates give β-ketophosphonates.

3) HWE reaction of β-ketophosphonates with aldehydes gives an easy access to (E)-α,β-unsaturated ketones.

4) α-Chlorophosphonates undergo Michael addition, followed by cyclization, with α,β-unsaturated esters leading to cyclopropyl phosphonates.

5) A *remarkable inhibition of hydrolysis of cyclic phosphites/ phosphoramidites* $(OCH_2CRR'CH_2O)PX$ [{X - OPh; R, R' - Me (7), Et (8), R = Me, R' = *n*-Pr (9)}, {X = NMe_2; R, R' = Me (10), Et (11), R = Me, R' = n-Pr (12)}] *in the presence of added water by* salts like KF, K_2CO_3 is described. In a competitive reaction, phosphoramidites react preferentially with phenols rather than with water in the presence of K_2CO_3. These observations may be put to practical use while handling P(III) compounds in the laboratory as well as in industries.

CHAPTER 6

EXPERIMENTAL SECTION

Details of the instruments, standards etc are already given in Chapter 3.

6.1 Synthesis of P(III) compounds

General Note: Most of these precursors are in use in the laboratory and some of them are previously known. However, the procedures have been modified and hence are given here along with the spectroscopic data some of which were not reported previously.

6.11 Preparation of $(OCH_2CRR'CH_2O)PCl$ (1-3)

(i) $(OCH_2CMe_2CH_2O)PCl$ (1)

2,2-Dimethyl-l,3-propanediol (1.01 g, 10.0 mmol) was added to phosphorus trichloride (1.37 g, 0.87 mL, 10.0 mmol) portion-wise (20 min) with continuous stirring at room temperature; the mixture was stirred further for 6 h and the product distilled in *vacuo* (115°C/ 0.5 mm) to give pure 1. This procedure is more convenient and yield is comparable/ better than that reported before.[99,121]

Yield: 1.51 g (90%).

^{1}H NMR: 8 0.80, 1.26 (2 s, 6 H, $C(CH_3)_2$), 3.56 (dd→t, ^2J(HH) ~ V(PH) ~ 10.5 Hz, 2 H, OCH_AH_B), 4.25-4.34 (dd, V(PH) ~ 5.8 Hz, V(HH) ~ 10.5 Hz, 2 H, OCH_AH_B).

^{13}C NMR: δ 22.3 (s, CH_3), 32.7 (d, V(PC) = 4.3 Hz, CMe_2), 70.7 (s, OCH_2).

^{31}P NMR: 5 145.8 [lit.146.0[99]].

In an analogous manner, compounds 2 and 3 were also prepared using the same molar quantities.

(ii) $(OCH_2CEt_2CH_2O)PCl$ (2)

Bp: 115°C/ 0.5 mm.

Yield: 1.69 g (86%).

^{1}H NMR: δ 0.82, 0.90 (2 t, V(HH) = 7.5 Hz for each, 6 H, CH_2CH_3), 1.18, 1.75 (2 qrt, V(HH) = 7.5 Hz, 4 H, CH_2CH_3), 3.73 (dd → t, ^{2}J(HH) ~ V(PH) = 10.5 Hz, 2 H, OCH_AH_B), 4.32 (dd, V(PH) ~5.8 Hz, ^{2}J(HH) ~ 10.5 Hz, 2 H, OCH_AH_B).

^{13}C NMR: δ 6.2, 7.3 (2 s, CH_2CH_3), 22.6, 24.9 (2 s, CH_2CH_3), 38.0 (d, V(PC) < 4.0 Hz, CEt_2), 68.4 (s, OCH_2).

^{31}P NMR: δ 148.6 [lit.148.2[122]].

(iii) $(OCH_2C(Me)(n\text{-}Pr)CH_2O)PCl$ (3)

Bp: 130°C/ 0.5 mm.

Yield: 1.47 g (75.0%)

^{1}H NMR: δ 0.76, 1.26 (s each, total 3 H, CH_3), 0.78-1.62 (m, 7 H, $CH_2CH_2CH_3$), 3.40-3.80 (m, 2 H, OCH_2), 4.10-4.40 (m, 2 H, OCH_2).

^{13}C NMR: δ 14.6$_7$, 14.7$_4$, 15.3, 16.6, 19.4, 19.8, 36.0 (slightly broad), 36.1, 39.0, 69.4, 70.5 (2 s, OCH_2).

^{31}P NMR: δ 146.9, 147.7 (two conformers).

6.12 Preparation of $(OCH_2CRR'CH_2O)P(O)H$ (4-6)

These compounds were prepared by stirring $(OCH_2CRR'CH_2O)PCl$ (*ca* 20 mmol) with an equimolar quantity of water for 8 h followed by distillation ***in vacuo.***

(i) $(OCH_2CMe_2CH_2O)P(O)(H)$ (4)

Bp: 150 °C/ 0.5 mm.

Yield: 95%.

^{1}H NMR: δ 0.70, 1.05 (2 s, 6 H, $C(CH_3)_2$), 3.55-4.05 (m, 4 H, OCH_2), 6.69 (d, ^{1}J(PH) = 675.6 Hz, 1 H, P(O)*H*).

^{13}C NMR: δ 20.1, 21.5 (2 s, CH_3), 31.8 (d, V(PC) = 5.2 Hz, CMe_2), 75.8 (d, ^{2}J(PC) = 5.0 Hz, OCH_2).

^{31}P NMR: δ 2.3 [lit. 2.3[123]].

(ii) $(OCH_2CEt_2CH_2O)P(O)(H)$ (5)

Bp: 155°C/ 0.5 mm.

Yield: 90%.

^{1}H NMR: 5 0.69, 0.75 (2 t, V(HH) = 7.5 Hz each, 6 H, $C(CH_2CH_3)_2$), 1.12, 1.56 (2 qrt, V(HH) = 7.5 Hz each, 4 H, CH_2CH_3), 3.80-4.02 (m, 4 H, OCH_2), 6.75 (d, ^1J(PH) = 676.0 Hz, 1H, P(O)*H*).

^{13}C NMR: 6 6.9, 7.1 (2 s, CH_2CH_3), 22.3, 23.1 (2 s, CH_2CH_3), 37.1 (d, V(PC) = 5.5 Hz, CEt_2), 73.5 (d, ^2J(PC) = 5.5 Hz, OCH_2).

^{31}P NMR: 6 3.4.

(iii) $(OCH_2C(Me)(n\text{-}Pr)CH_2O)P(O)(H)$ (6)

Bp: 160°C/ 0.5 mm.

Yield: 80%.

^{1}H NMR: δ 0.66-1.13 (m, total 10 H, $CH_2CH_2CH_3$ + CH_3), 3.75-4.10 (m, 4 H, OCH_2), 6.89, 6.90 (d each, ^1J(PH) = 688.0, 675.0 respectively, 1H, P(O)*H*).

^{13}C NMR: δ 14.4, 14.6, 16.1, 16.5, 17.8, 18.0, 19.0, 34.8 (d, V(PC) = 5.0 Hz, *C*(Me)(*n*-Pr)), 35.9 (d, merged), 37.0, 74.8, 75.4 (d each, V(PC) = 4.8 Hz, OCH_2).

^{31}P NMR: 8 2.8,3.0.

***6.13 General procedure for the preparation of $(OCH_2CRR'CH_2O)P(OPh)$* (7-9)**

To freshly distilled $(OCH_2CRR'CH_2O)PCl$ [R, R' = Me (1), Et (2), R = Me, R' = n-Pr (3)] (10.0 mmol), toluene (10 mL) was added at 0°C followed by 10.0 mmol each of triethylamine and phenol in toluene (25 mL) from addition funnel slowly (~ 0.5 h). The reaction mixture was allowed to stir for 1 d, filtered and the solvent from the filtrate was removed *in vacuo*. Compounds $(OCH_2CRR'CH_2O)P(OPh)$ [R, R' = Me (7), Et (8), R = Me, R' = *n*-Pr (9)] were purified by vacuum distillation.

(i) $(OCH_2CMe_2CH_2O)P(OPh)$ (7)[100,121]

Bp: 95°C/ 0.5 mm.

Yield: 1.80 g (80%).

^{1}H NMR: 8 0.81 (s, 3 H, CH_3), 1.31 (s, 3 H, CH_3), 3.45 (~t or dd, 2 H, OCH_2), 4.35 (~ d, 2 H, OCH_2), 7.08-7.46 (m, 5 H, Ar-*H*).

^{13}C NMR: 8 22.4, 22.6 (2 s, CH_3), 32.5 (d, V(PC) < 4.0 Hz, $CMe)_2$), 69.2 (br s, OCH_2), 119.7, 119.9, 123.1, 129.6, 153.2.

^{1}P NMR: 8 114.6 [lit. 114.5[121]].

(ii) $(OCH_2CEt_2CH_2O)P(OPh)$ (8)

Bp: 125°C/ 0.5 mm.

Yield: 2.1 g(82.5%).

H NMR: 0.81, 0.93 (2 t, V(HH) = 7.6 Hz, 6 H, CH_2CH_3), 1.16, 1.84 (2 qrt, V(HH) = 7.6 Hz, 4 H, CH_2CH_3), 3.62 (t, V(HH) ~ V(PH) = 10.8 Hz, 2 H, OCH_AH_B), 4.28 - 4.34 (m, 2 H, OCH_AH_B), 7.10-7.40 (m, 5 H, Ar-*H*).

^{13}C NMR: 5 6.3, 7.5 (2 s, CH_2CH_3), 22.5, 25.1 (2 s, CH_2CH_3), 37.4 (d, V(PC) = 3.9 Hz, CEt_2), 66.7 (s, OCH_2), 119.9, 120.3, 123.3, 129.7, 153.0 (br s) (ail Ar-*C*).

^{1}P NMR: 5 117.0.

(iii) $(OCH_2C(Me)(n\text{-}Pr)CH_2O)P(OPh)$ (9)

Bp: 130 °C/ 0.5 mm.

Yield: 1.9 g (75%).

^{1}H NMR: 8 0.72, 1.30 (2 s, 6 H, CH_3), 0.82-1.80 (m, 7 H, $CH_2CH_2CH_3$), 3.40-3.65 (m, 2 H, OCH_2), 4.20-4.45 (m, 2 H, OCH_2), 7.00-7.40 (m, 5 H, Ar-*H*).

^{13}C NMR: δ 14.9, 15.5, 16.9, 19.7, 19.9, 36.0, 36.2, 39.5, 67.9, 68.9 (2 s, OCH_2), 115.6, 119.9, 120.0, 123.4, 129.6, 129.8, 153.0 (d, V(PC) ~ 6.5 Hz, P-O-*C*), 156.5.

^{31}P NMR: 8 115.4,116.4.

6.14 Preparation of $(OCH_2CRR'CH_2O)P(NMe_2)$ (10-12)

To freshly distilled $(OCH_2CRR'CH_2O)PCl$ [R, R' = Me (1), Et (2), R = Me, R' = n-Pr (3)] (10.0 mmol), toluene (20 mL) was added and the solution was bubbled with dry dimethylamine gas for about 2 h with vigorous stirring at –40°C. The reaction mixture was allowed to reach room temperature and was stirred further for 8 h, filtered and the solvent removed *in vacuo*. The required compounds $(OCH_2CRR'CH_2O)P(NMe_2)$ [R, R' = Me (10), Et (11), R = Me, R' = *n*-Pr (12)] were purified by vacuum distillation.

(i) $(OCH_2CMe_2CH_2O)P(NMe_2)$ (10)[100,124]

Bp: 60°C/ 0.5 mm.

Yield: 1.50 g (85%).

^{1}H NMR: 8 0.78, 1.24 (2 s, 6 H, $C(CH_3)_2$), 2.71 (d, V(PH) = 9.6 Hz, 6 H, $N(CH_3)_2$), 3.54-3.86 (m, 4 H, OCH_2).

^{13}C NMR: 8 21.6, 22.9 (2 s, CH_3), 32.5 (d, V(PC) ~ 5.0 Hz, CMe_2), 35.0, (d, V(PC) = 19.0 Hz, $N(CH_3)_2$), 73.7 (d, ^2J(PC) = 5.0 Hz, OCH_2).

^{31}P NMR: 8 143.9 [lit. 143.9[124]].

(ii) $(OCH_2CEt_2CH_2O)P(NMe_2)$ (11)

Bp: 87°C/ 0.5 mm.

Yield: 1.64 g (80%).

^{1}H NMR: 8 0.74, 0.84 (2 t, V(HH) = 7.5 Hz each, 6 H, $C(CH_2CH_3)_2$), 1.10, 1.66 (2 qrt, V(HH) = 7.5 Hz each, 4 H, CH_2CH_3), 2.64 (d, V(PH) = 8.8 Hz, 6 H, $N(CH_3)_2$), 3.72-3.79 (m, 4 H, OCH_2).

^{13}C NMR: 8 7.0, 7.3 (2 s, CH_2CH_3), 23.0, 24.0 (2 s, CH_2CH_3), 35.0, (d, ^2J(PC) • 21.2 Hz, $N(CH_3)_2$), 37.0, 37.3 (2 d, V(PC) = 5.0 Hz each, CEt_2), 70.7 (s, OCH_2).

^{31}P NMR: 8 144.1.

(iii) $(OCH_2C(Me)(n\text{-}Pr)CH_2O)P(NMe_2)$ (12)

Bp: 90°C/ 0.5 mm.

Yield: 1.53 g (75%).

^{1}H NMR: 8 0.67 (s, 3 H, CH_3), 0.86, 0.93 (2 t, ^3J(HH) = 7.0 and 6.6 Hz respectively, 3 H, $CH_2CH_2CH_3$), 1.13 (s, 3 H, CH_3), 1.09-1.65 (m, 4 H, $CH_2CH_2CH_3$), 2.67 (d, V(PH) = 8.9 Hz, 6 H, $N(CH_3)_2$), 3.64-3.79 (m, 4 H, OCH_2).

^{13}C NMR: 8 14.9, 16.1, 16.6, 18.5, 20.1, 34.9 (d, V(PC) = 21.1 Hz, $N(CH_3)_2$), 37.0, 38.2, 72.2, 72.3 (2 d, V(PC) = 4.1 Hz, 3.2 Hz, OCH_2).

^{31}P NMR: 8 144.0, 143.4.

6.2 Synthesis and reactivity of phosphonates

General note: In this section, elemental analyses have been obtained for representative samples. In addition, for ascertaining the purity, ^{13}C and ^{31}P NMR spectra have been illustrated for additional compounds in Appendix I at the end of this section.

6.21 Synthesis of α-hydroxy and α-chlorophosphonates

The following known α-hydroxy **(13-15),** α-chlorophosphonates **(16-18)** were prepared by a literature method in yields of 75-90%.[102,122]

SI. No	Compound	Mp(°C)	8(P) ppm
1	$(OCH_2CMe_2CH_2O)P(O)CH(OH)Ph$ (13)	151-153	13.3
2	$(OCH_2CMe_2CH_2O)P(O)CH(OH)(C_6H_4$-4-Me) (**14**)	164	13.6
3	$(OCH_2CMe_2CH_2O)P(O)CH(OH)(C_6H_4$-4-OMe) (**15**)	164	13.6
4	$(OCH_2CMe_2CH_2O)P(O)CH(Cl)Ph$ (16)	150-152	8.1
5	$(OCH_2CMe_2CH_2O)P(O)CH(Cl)(C_6H_4$-4-Me) (**17**)	184	8.4
6	$(OCH_2CMe_2CH_2O)P(O)CH(Cl)(C_6H_4$-4-OMe) (**18**)	164	8.4

6.22 *Synthesis of allenylphosphonates* 19-25 *and* 27-29

To a solution of $(OCH_2CMe_2CH_2O)PCl$ (1) (1.69 g, 1.38 mL,10.0 mmol) or $CH_2(6$-*t*-Bu-4-Me-$C_6H_2O)_2PCl$ (26) (4.05 g, 10.0 mmol) in dry THF (20 mL) was added triethylamine (1.01 g, 1.39 mL, 10.0 mmol), the mixture stirred for 5 min, and then the required substituted propargyl alcohol RC≡CCR'R"(OH) (10.0 mmol) in THF (15 mL) was added drop-wise (~ 0.5 h) at 0°C. The reaction mixture was stirred for 1 h at room temperature, and then refluxed for 8 h. Triethylamine hydrochloride formed was filtered off and solvent was removed *in vacuo* from the filtrate. Crude compounds $(OCH_2CMe_2CH_2O)P(O)C(R)=C=CR'R"$ **(19-25)** or $CH_2(6$-*t*-Bu-4-Me-$C_6H_2O)_2P(O)C(R)=C=CR'R"$ **(27-28)** so obtained were purified using column chromatography (silica gel; hexane-ethyl acetate).

(i) $(OCH_2CMe_2CH_2O)P(O)C(H)=C=CH_2$ (19)

Mp: 131-133°C.

Yield: 1.67 g (89%).

IR (KBr): 3074, 1980, 1941, 1483, 1281, 1238 cm^{-1}.

^{1}H NMR: 8 0.97, 1.17 (2 s, 6 H, C(CH_3)$_2$), 3.83-4.16 (m, 4 H, OCH_2), 5.00-5.10 (dd, V(HH) = 6.9 Hz, V(PH) = 13.6 Hz, 2 H, C=CH_2), 5.33 (t, V(PH) ~ ^{4}J(HH) ~ 8 Hz, 1 H, PC//).

^{13}C NMR: δ 21.0, 21.2 (2 s, C(*C*H$_3$)$_2$), 32.4 (d, V(PC) = 6.4 Hz, *C*Me$_2$), 76.4, 76.8 (2 d, V(PC) = 7.8 Hz each, O*C*H$_2$), 77.5 (d, ^{1}J(PC) = 200.5 Hz, PC), 89.9 (br, C=*C*H$_2$), 215.3 (s, PC(H)=C).

^{31}P NMR: 8 7.4 [lit. 8.8[103]].

Anal. Calcd for $C_8H_{13}O_3P$: C, 51.06; H, 6.96. Found: C, 50.96; H, 7.03.

An X-ray structure was obtained for a sample crystallized from CH_2Cl_2 *(cf.* Fig.1; Section 5.22).

(ii) **(OCH$_2$CMe$_2$CH$_2$O)P(O)C(H)=C=C(H)Me** (20)

Mp: 50-52°C.

Yield: 1.74 g (86%).

IR (KBr): 1956, 1476, 1373, 1281, 1061, 1011 cm^{-1}.

^{1}H NMR: 8 0.94, 1.16 (2 s, 6 H, C(CH_3)$_2$), 1.68-1.82 (m, 3 H, C=C(H)CH_3), 3.96-4.12 (m, 4 H, OCH_2), 5.24- 5.32 (m, 1 H, C*H*Me), 5.33-5.59 (m, 1 H, PC//).

^{13}C NMR: 8 12.3 (d, V(PC) = 7.0 Hz, CH*C*H$_3$), 20.4, 21.3 (2 s, C(*C*H$_3$)$_2$), 32.1 (d, V(PC) = 6.0 Hz, *C*Me$_2$), 76.4, 76.5 (2 d, ^{2}J(PC) = 6.0 Hz each, O*C*H$_2$), 77.5 (d, ^{1}J(PC) = 192.0 Hz, PC), 86.9 (d, V(PC) = 16.0 Hz, C=*C*H$_2$), 212.3 (br s, C=C=CHMe).

^{31}P NMR: 8 7.9.

(iii) **(OCH$_2$CMe$_2$CH$_2$O)P(O)CH=C=CMe$_2$** (21)

Mp: 64°C.

Yield: 1.64 g (76%).

IR (KBr): 1966, 1481, 1362, 1267, 1059, 1011 cm^{-1}.

^{1}H NMR: 8 0.82, 1.07 (2 s, 6 H, C(CH_3)$_2$), 1.65 (dd, V(PH) = 6.8 Hz, V(HH) = 2.9 Hz, 6 H, C=C(CH_3)$_2$), 3.82 (s, 2 H, OCH_2), 3.87 (m, 2 H, OCH_2), 5.02-5.13 (m, 1 H, PC//).

^{13}C NMR: 8 19.0, 19.2 (2 s, C=C(*C*H$_3$)$_2$), 20.8, 21.6 (2 s, C(*C*H$_3$)$_2$), 32.3 (d, V(PC) = 6.6 Hz, *C*Me$_2$), 76.2 (2 d, ^{1}J(PC) =193.2 Hz, PC), 76.5, 76.6

(2 s, OCH_2), 97.3 (d, V(PC) = 14.6 Hz, $C{=}CMe_2$), 210.7 (br s, $C{=}C{=}CMe_2$).

^{31}P NMR: 8 8.5 [lit. 9.9[103]].

(iv) $(OCH_2CMe_2CH_2O)P(O)CH{=}C{=}CMeEt$ (22)

Mp: 93-94°C.

Yield: 1.79 g (78%).

IR (KBr): 1958, 1474, 1372, 1277, 1061, 1009 cm^{-1}.

^1H NMR: δ 0.83, 1.04 (2 s, 6 H, $C(CH_3)_2$), 0.92 (t, V(HH) - 7.8 Hz, 3 H, $C{=}CMeCH_2CH_3$), 1.65 (dd, ^5J(PH) = 6.8 Hz, V(HH) = 2.9 Hz, 3 H, $C{=}CCH_3Et$), 1.88-1.97 (m, 2 H, $C{=}CMeCH_2CH_3$), 3.79-3.96 (m, 4 H, OCH_2),5.14-5.19 (m, 1 H, PCH).

^{13}C NMR: δ 11.7 (d, V(PC) = 2.4 Hz,$C{=}CMeCH_2CH_3$), 17.5 (d, V(PC) = 7.3 Hz, $=CMeCH_2CH_3$), 20.8, 21.5 (2 s, $C(CH_3)_2$), 26.0 (d, V(PC) = 7.3 Hz, CCH_3Et), 32.3 (d, V(PC) = 6.1 Hz, CMe_2), 77.9 (2 d, ^1J(PC) =195.3 Hz, PC), 76.2, 76.3 (2 s, OCH_2), 103.3 (d, ^3J(PC) - 17.0 Hz, $C{=}CMeEt$), 210.3 (br s, C=C=CMeEt).

^{31}P NMR: δ 9.3.

Anal. Calcd for $C_{11}H_{19}O_3P$: C, 57.39; H, 8.26. Found: C, 57.64; H, 8.13.

(v) **$(OCH_2CMe_2CH_2O)P(O)CPh{=}C{=}CHEt$** (23)

Mp: 108-109°C.

Yield: 2.45 g (84%).

IR (KBr): 3057, 3022, 1948, 1597, 1493, 1372, 1262, 1059, 1009 cm^{-1}.

^1H NMR: 8 0.83, 1.23 (2 s, 6 H, $C(CH_3)_2$), 1.09 (t, V(HH) = 7.6 Hz, 3 H, CH_2CH_3), 2.18 (qrt, V(HH) = 7.6 Hz, 2 H, CH_2CH_3), 3.77-4.01 (m, 4 H, OCH_2), 5.70-5.89 (m, 1 H, PCH), 7.17-7.28 (m, 3 H, *Ar-H* (meta and para)), 7.55 (d, V(HH) ~ 7.0 Hz, Ar-*H* (ortho)).

^{13}C NMR: 8 13.4 (s, CH_2CH_3), 20.8 (s, CH_3), 21.4 (d, V(PC) = 6.1 Hz, CH_2CH_3), 21.9 (s, CH_3), 32.5 (d, ^3J(PC) = 6.6 Hz, CMe_2), 76.8, 76.9 (2 s, OCH_2), 96.4 (d, ^1J(PC) ~ 185.0 Hz, PC), 96.8 (d, V(PC) = 14.9 Hz, $C{=}CHEt$), 127.5, 127.6, 127.7, 128.6, 132.3, 132.4, 209.5 (br s, C=C=CHEt).

^{31}P NMR: δ 7.3.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix I (Fig. 3).

(vi) **$(OCH_2CMe_2CH_2O)P(O)CPh=C=CHCHMe_2$** (24)

Mp: 114-116°C.

Yield: 2.75 g (90%).

IR (KBr): 3081, 3059, 1948, 1597, 1491, 1372, 1262, 1059, 1009 cm^{-1}.

^1H NMR: 8 0.87, 1.26 (2 s, 6 H, $C(CH_3)_2$), 1.13 (d, V(HH) = 6.8 Hz, 6 H, $CH(CH_3)_2$), 2.55 (qnt, V(HH) = 6.8 Hz, 1 H, $CHMe)_2$), 3.85-4.01 (m, 4 H, OCH_2), 5.77 (dd, ^3J(HH) - 6.8 Hz, V(PH) = 12.7 Hz, 1 H, C(Ph)=C=C*H*), 7.26-7.34 (m, 3 H, Ar-*H* (meta and para)), 7.58 (d, V(HH) = 6.8 Hz, Ar-*H* (ortho)).

^{13}C NMR: δ 20.9, 21.9 (2 s, $C(CH_3)_2$), 22.4 (s, $CH(CH_3)_2$), 28.4 (d, V(PC) = 5.8 Hz, $CHMe_2$), 32.5 (d, V(PC) = 6.9 Hz, CMe_2), 76.7, 77.4 (2 d, ^3J(PC) = 6.1 Hz each, OCH_2), 97.0 (d, ^1J(PC) = 183.3 Hz, PC), 102.4 (d, ^3J(PC) = 14.8 Hz, C=*C*HCHMe$_2$), 127.5, 127.6, 127.8, 128.6, 131.8, 132.0, 208.5 (br s, C=*C*=CHCHMe$_2$).

^{31}P NMR: δ 7.4.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix I (Fig. 4).

Anal. Calcd for $C_{17}H_{23}O_3P$: C, 66.66; H, 7.52. Found: C, 66.34; H, 7.26.

(vii) **$(OCH_2CMe_2CH_2O)P(O)CPh=C=CHC_6H_4$-4-Me** (25)

Mp: 138-141°C.

Yield: 2.73 g (77%)

IR (KBr): 1929, 1597, 1493,1372, 1263, 1063, 1013 cm^{-1}.

^1H NMR: 8 0.76, 1.27 (2 s, 6 H, $C(CH_3)_2$), 2.34 (s, 3 H, $ArCH_3$), 3.77-4.13 (m, 4 H, OCH_2), 6.77 (d, V(PH) = 12.7 Hz, 1 H, C=C*H*), 7.14-7.33 (m, 7 H, Ar-*H*), 7.68 (d, V(HH) = 7.7 Hz, 2 H, Ar-*H* (ortho)).

^{13}C NMR: 8 20.6, 21.2, 22.0 (3 s, $C(CH_3)_2$ + Ar-CH_3), 32.5 (d, V(PC) = 6.5 Hz, CMe_2), 76.8, 76.9 (2 s, OCH_2), 98.3 (d, V(PC) = 14.8 Hz, C=*C*HC$_6$H$_4$–4-Me), 99.5 (d, ^1J(PC) - 185 Hz, PC), 127.3, 127.7, 127.9, 128.2, 128.5, 128.8, 129.9, 138.4 (all Ar-*C*), 211.9 (br s, C=*C*=CHC$_6$H$_4$–4-CH_3).

^{31}P NMR: δ 5.3.

(viii) $CH_2(6$-*t*-Bu-4-Me-$C_6H_2O)_2P(O)CH=C=CH_2$ (27)

Mp: 168-170°C.

Yield: 2.76 g (65%).

IR (KBr): 1973, 1940,1603, 1456, 1364, 1275, 1204, 1127, 927 cm^{-1}.

^1H NMR: 8 1.44 (s, 18 H, *t*-Bu-*H*), 2.31 (s, 6 H, ArCH_3), 3.83 (d, V(HH) ~ 13.0 Hz, 1 H, ArCH_AH_X), 4.21 (d, V(HH) ~ 13.0 Hz, 1 H, ArCH_AH_X), 5.16-5.28 (dd, V(HH) ~ 7.0 Hz, V(PH) ~ 13.0 Hz, 2 H, C=CH_2), 5.83 (t, V(PH) ~ V(HH) ~ 8 Hz, 1 H, PC*H*), 7.08 (br s, 4 H, Ar-*H*).

^{13}C NMR: 8 21.0 (s, Ar*C*H_3), 31.0 (s, C(*C*H_3)$_3$), 34.8 (s, *C*Me_3), 34.9 (s, Ar*C*H_2), 77.6 (d, V(PC) = 17.0 Hz, C=*C*H_2), 80.5 (d, ^1J(PC) = 216.2 Hz, PC), 127.5, 129.3, 132.4, 134.6, 140.9, 145.6 (all Ar-*C*), 215.3 (br s, C=*C*=CH$_2$).

^{31}P NMR: 8 8.0.

(ix) CH_2(6-*t*-Bu-4-Me-C_6H_2O)$_2$P(O)CH=C=CHMe (28)

Mp: 154-155°C.

Yield: 3.20 g (73%).

IR (KBr): 1960, 1603, 1441, 1277, 1206, 922 cm^{-1}.

^1H NMR: 8 1.47 (s, 18 H, *t*-Bu-*H*), 1.79-1.89 (m, 3 H, C=CHCH_3), 2.32 (s, 6 H, ArCH_3), 3.83 (d, ^2J(HH) = 13.6 Hz, 1 H, ArCH_AH_X), 4.22 (d, ^2J(HH) = 13.6 Hz, 1 H, ArCH_AH_X), 5.57- 5.68 (m, 1 H, C=C//Me), 5.74-5.83 (m, 1 H, PC*H*), 7.09 (br s, 4 H, Ar-*H*).

^{13}C NMR: 8 12.5 (d, V(PC) = 7.5 Hz, C=CH*C*H_3), 21.0 (s, Ar*C*H_3), 31.0 (s, C(*C*H_3)$_3$), 34.8 (s, *C*Me_3), 34.9 (s, Ar*C*H_2), 80.5 (d, ^1J(PC) = 216.7 Hz, PC), 88.9 (d, V(PC) = 17.9 Hz, C=*C*HCH$_3$), 127.4, 129.3, 132.6, 134.5, 141.0, 141.1, 145.6, 145.8 (all Ar-C), 213.2 (br s, C=C=CHMe).

^{31}P NMR: 8 8.4.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix **I** (Fig. 5).

(X) CH_2(6-*t*-Bu-4-Me-C_6H_2O)$_2$P(O)CH=C=CMeEt (29)

Mp: 120-123°C.

Yield: 3.17 g (68%).

IR (KBr): 1964, 1603, 1464, 1366, 1273, 1209, 922 cm^{-1}.

H NMR: 6 1.15 (t, V(HH) = 7.9 Hz, 3 H, $CMeCH_2CH_3$), 1.45 (s, 18 H, *t*-Bu-*H*), 1.76-1.89 (m, 3 H, $C{=}CCH_3Et$), 2.09-2.20 (m, 2 H, $C{=}CMeCH_2CH_3$), 2.31 (s, 6 H, $ArCH_3$), 3.80 (d, $^2J(HH)$ = 13.6 Hz, 1 H, $ArCH_AH_X$), 4.22 (dd, 1 H, V(P-H) ~ 3.0 Hz, V(H-H) = 13.6 Hz, 1 H, $ArCH_AH_X$), 5.76-5.81 (m, 1 H, PC*H*), 7.07 (br s, 4 H, Ar-*H*).

^{13}C NMR: 8 11.9 (s, $CMeCH_2CH_3$), 17.6 (d, V(PC) = 7.2 Hz, $CMeCH_2CH_3$), 21.0 (s, $ArCH_3$), 26.3 (d, V(PC) = 6.7 Hz, CCH_3Et), 30.6 (s, $C(CH_3)_3$), 34.9 (s, $ArCH_2$), 80.5 (d, $^1J(PC)$ = 217.9 Hz, PCH), 105.0 (d, V(PC) - 18.2 Hz, $C{=}CHCH_3$), 127.3, 129.2, 133.6, 134.4, 141.0, 145.6, 145.8 (all Ar-*C*), 210.6 (br s, C=C=CHMe).

^{31}P NMR: δ 8.7.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix 1 (Fig. 6).

6.23 *Synthesis of fl-enaminophosphonates* 30-38

To a solution of allenylphosphonates **(19-20** and **28)** (1.0 mmol) in 15 mL acetonitrile, the amine (diethylamine, piperidine or morpholine) (1.0 mmol) was added slowly via syringe. The reaction mixture was heated under reflux for 4 h with continuous stirring. The solvent was removed in *vacuo* to get the required compound. The reaction was very clean without any side products.

(i) **$(OCH_2CMe_2CH_2O)P(O)CH{=}C(NEt_2)CH_3$** (30)

Mp: 58-60°C.

Yield: Quantitative.

IR (KBr): 1570, 1439, 1219, 1061, 1001 cm^{-1}.

^1H NMR: δ 0.92, 1.10 (2 s, 6 H, $C(CH_3)_2$), 1.09 (t, $^3J(HH)$ = 7.1 Hz, 3 H, $N(CH_2CH_3)_2$), 2.26 (d, V(PH) = 1.5 Hz, 3 H, $C(NEt_2)CH_3$), 3.20 (qrt, V(HH) = 7.1 Hz, $N(CH_2CH_3)_2$), 3.65-3.74 (m, 3 H, OCH_2 +PC*H*), 4.16-4.20 (dd→t, V(HH) = 2.3 Hz, V(PH) ~ 9.4 Hz, 2 H, OCH_2).

^{13}C NMR: δ 12.4 (s, $C(NCH_2CH_3)_2Me$), 17.2 (d, V(PC) = 4.4 Hz, $C(NEt_2)CH_3$), 21.2, 21.6 (2 s, $C(CH_3)_2$), 32.1 (d, V(PC) = 4. 8 Hz, CMe_2), 43.6 (s, $C(NCH_2CH_3)_2Me$), 70.1 (d, $^1J(PC)$ = 218.9 Hz, PC), 74.3, 74.4 (2 s, OCH_2), 160.0 (d, $^2J(PC)$ = 21.6 Hz, PCH=*C*).

^1P NMR: 8 24.7.

Anal. Calcd for $C_{12}H_{24}O_3NP$: C, 55.17; H, 9.19; N, 5.36. Found: C, 54.43; H, 8.92; N, 4.95

(ii) **$(OCH_2CMe_2CH_2O)P(O)CH=C(NEt_2)Et$ (31)**

Mp: 55-56°C.

Yield: Quantitative.

IR (KBr): 1573, 1474, 1360, 1217, 1059, 1005 cm^{-1}.

^1H NMR: 5 0.84 (s, 3 H, $C(CH_3)$), 0.99-1.06 (many lines, 12 H, $C(CH_3)$ + $N(CH_2CH_3)_2$) + $=C(CH_2CH_3)$), 1.89 (d, V(PH) = 1.5 Hz, 3 H, $C(CH_2CH_3)$), 2.56 (qrt, V(HH) = 6.6 Hz, CH_2CH_3), 3.10 (qrt, V(HH) = 6.9 Hz, $N(CH_2CH_3)_2$), 3.55-3.63 (m, 3 H, OCH_2 + PCH), 4.06 (t, V(PH) =10.5 Hz, 2 H, OCH_2).

^{13}C NMR: 5 12.3 (s, $C(NCH_2CH_3)_2Et$), 13.6 (s $C(CH_2CH_3)$), 19.6, 21.0 (2 s, $C(CH_3)_2$), 23.2 (d, V(PC) = 4.4 Hz, $C(CH_2CH_3)$), 31.9 (d, V(PC) = 5.2 Hz, CMe_2), 43.0 (s, $C(NCH_2CH_3)_2Et$), 69.5 (d, $^1J(PC)$ = 217.9 Hz, PC), 74.2, 74.3 (2 s, OCH_2), 165.3 (d, $^2J(PC)$ = 22.1 Hz, PCH=C).

^{31}P NMR: 8 23.8.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix I (Fig. 7).

(iii) **$(OCH_2CMe_2CH_2O)P(O)CH=C(NCH_2CH_2CH_2CH_2CH_2-)Me$** (32)

Mp: 78-80°C.

Yield: Quantitative.

IR(KBr): 1576, 1441, 1416, 1236, 1057, 1011 cm^{-1}.

^1H NMR: δ 0.96, 1.14 (2 s, 6 H, $C(CH_3)_2$), 1.59 (br, 6 H, $C(NCH_2CH_2CH_2CH_2CH_2-)$), 2.29 (d, V(PH) = 1.5 Hz, 3 H, $C(N(CH_2)_4-)CH_3$), 3.25 (br, 4 H, $N(CH_2CH_2CH_2CH_2CH_2-)$), 3.72 (dd, $^2J(HH)$ = 4.7 Hz, V(PH) =15.7 Hz, 2 H, OCH_AH_B), 4.00 (d, V(PH) = 8.8 Hz, PCH), 4.23 (dd, $^2J(HH)$ = 4.7 Hz, $^3J(PH)$ = 15.7 Hz, 2 H, OCH_AH_B).

^{13}C NMR: 8 18.1 (d, V(PC) = 4.5 Hz, $C(N(CH_2)_4-)CH_3$), 21.5, 22.1 (2 s, $C(CH_3)_2$), 24.2 (s, $C(NCH_2CH_2CH_2CH_2CH_2-)$), 25.3 (s, $C(NCH_2CH_2CH_2CH_2CH_2-)$), 32.1 (d, V(PC) = 4. 9 Hz, CMe_2), 47.3 (s, $C(NCH_2CH_2CH_2CH_2CH_2-)$), 73.6 (d, $^1J(PC)$ = 217.8 Hz, PC), 74.5, 74.6 (2 s, OCH_2), 162.0 (d, V(PC) = 21.8 Hz, PCH=C).

^{31}P NMR: 8 24.8.

(iv) **$(OCH_2CMe_2CH_2O)P(O)CH=C(NCH_2CH_2CH_2CH_2CH_2-)Et$** (33)

Mp: Gummy solid.

Yield: Quantitative.

IR (KBr): 1560, 1473, 1277, 1061, 1009 cm^{-1}.

^1H NMR: 8 0.87, 1.01 (2 s, 6 H, $C(CH_3)_2$), 1.02 (t, V(HH) = 7.5 Hz, 3 H, CH_2CH_3), 1.50 (br, 6 H, $C(NCH_2CH_2CH_2CH_2CH_2-)$), 2.64 (qrt, V(HH) = 7.5 Hz, 2 H, CH_2CH_3), 3.13 (br, $N(CH_2CH_2CH_2CH_2CH_2-)$), 3.62 (dd, $^2J(HH)$ - 3.7 Hz, V(PH) = 12.8 Hz, 2 H, OCH_AH_B), 3.79 (d, $^2J(PH)$ = 9.4 Hz, 1 H, PCH), 4.23 (dd→t, V(PH) = 9.4 Hz, 2 H, OCH_AH_B).

^{13}C NMR: 8 13.4, 13.5, 21.4, 21.5, 21.9, 23.1, 23.6, 23.6, 24.1, 24.2, 24.5, 32.4, 32.5 (2 d, $^3J(PC)$ = 7.5 Hz, CMe_2), 45.1, 47.4, 73.6 (d, $^1J(PC)$~ 190.0 Hz, PC), 74.6, 74.7 (2 s, OCH_2), 167.6 (d, V(PC) = 22.0 Hz, PCH=C).

^{31}P NMR: 8 24.3.

Anal. Calcd for $C_{14}H_{26}O_3NP$: C, 48.78; H, 9.06; N, 4.87. Found: C, 48.53; H, 8.79; N, 4.67.

(v) **$(OCH_2CMe_2CH_2O)P(O)CH=C(NCH_2CH_2OCH_2CH_2-)Me$** (34)

Mp: 100-102°C.

Yield: Quantitative.

IR (KBr): 1584, 1453, 1400, 1233, 1055, 997 cm^{-1}.

^1H NMR: 8 0.90, 1.04 (2 s, 6 H, $C(CH_3)_2$), 2.20 (d, V(PH) = 2.0 Hz, 3 H, $N(CH_2CH_2OCH_2CH_2-)CH_3$), 3.13 (t, V(HH) = 4.8 Hz, 4 H, $N(CH_2CH_2OCH_2CH_2-)$), 3.63 (m, 6 H, $N(CH_2CH_2OCH_2CH_2-)$ + 2 OCH_AH_B), 4.00 (d, V(PH) = 8.8 Hz, PCH), 4.23 (dd, $^2J(HH)$ ~ 2.0 Hz, $^3J(PH)$ - 10.8 Hz, 1 H, OCH_AH_B).

^{13}C NMR: 8 17.6 (d, V(PC) = 3.8 Hz, $N(CH_2CH_2OCH_2CH_2-)CH_3$), 21.4, 21.9 (2 s, $C(CH_3)_2$), 32.1 (d, V(PC) = 4.9 Hz, CMe_2), 46.2 (s, $N(CH_2CH_2OCH_2CH_2-)$), 66.2 (s, $N(CH_2CH_2OCH_2CH_2-)$), 74.5, 74.7 (2 s, OCH_2), 76.7 (d, $^1J(PC)$ = 214.0 Hz, PC), 162.6 (d, $^2J(PC)$ = 20.5 Hz, PCH=C).

^{31}P NMR: 8 22.7.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix I (Fig. 8).

(vi) **$(OCH_2CMe_2CH_2O)P(O)CH=C(NCH_2CH_2OCH_2CH_2)Et$** (35)

Mp: Gummy solid.

Yield: Quantitative.

IR (KBr): 1475, 1408,1 1269, 1055, 977 cm^{1}.

^{1}H NMR: 5 0.93, 1.08 (2 s, 6 H, $C(CH_3)_2$), 1.02 (t, V(HH) = 7.5 Hz, 3 H, CH_2CH_3), 2.73 (qrt, V(HH) = 7.5 Hz, 2 H, CH_2CH_3), 3.15 (t, V(HH) = 5.0 Hz, 4 H, $N(CH_2CH_2OCH_2CH_2$-)), 3.65-3.76 (m, 6 H, 2 OCH_AH_B + $N(CH_2CH_2OCH_2CH_2$-)), 3.98 (d, ^{2}J(PH) = 9.2 Hz, 1 H, PC//), 4.16 (dd, ^{2}J(HH) = 2.0 Hz, V(PH) = 13.4 Hz, 2 H, OCH_AH_B).

^{13}C NMR: 5 13.3, 13.4,21.0,21.3,21.5,21.7,23.4,23.5,32.3, 32.4, (2 d, V(PC) = 7.5 Hz, CMe_2), 37.5, 39.55, 40.8, 45.6, 46.3, 66.2, 66.7, 75.6 (d, $^{1}J(PC) \sim 213.0$ Hz, PC), 74.6, 76.7 (2 d, V(PC) ~ 4.5 Hz, OCH_2), 167.6 (d, V(PC) = 21.0 Hz, PCH=*C*).

^{31}P NMR: 5 22.7.

(vii) **$CH_2(6$-*t*-Bu-4-Me-$C_6H_2O)_2P(O)CH=C(NEt_2)Et$** (36)

Mp: 100-102°C.

Yield: Quantitative.

IR (KBr): 1564, 1468, 1437, 1360, 1219, 1080 cm^{-1}.

'H NMR: δ 1.19, 1.29 (2 t, V(HH) - 7.5 Hz each, 9 H, $N(CH_2CH_3)_2$ + CH_2CH_3), 1.45 (s, 18 H, *t*-Bu-*H*), 2.29 (s, 6 H, $ArCH_3$), 2.91 (qrt, V(HH) = 7.5 Hz, 3 H, $C(CH_2CH_3)$), 3.29 (qrt, V(HH) = 7.5 Hz, 3 H, $N(CH_2CH_3)_2$), 3.94 (d, ^{2}J(HH) = 14.3 Hz, 1 H, $ArCH_AH_X$), 4.20 (d, V(PH) = 5.9 Hz, 1 H, PC*H*), 4.38 (brm, 1 H, $ArCH_AH_X$), 7.04 (br, 4 H, Ar-//).

^{13}C NMR: 8 12.9 (s, $CN(CH_2CH_3)_2Et$), 13.5 (s, $C(CH_2CH_3)$, 20.8 (s, $ArCH_3$), 23.7 (s, $C(CH_2CH_3)$), 30.6 (s, $C(CH_3)_3$), 34.6 (s, $ArCH_2$), 35.9 (s, CMe_3), 43.6 (s, $CN(CH_2CH_3)_2$), 75.5 (d, ^{1}J(PC) = 233.3 Hz, PC), 126.6, 129.2, 131.9, 133.0, 140.3, 140.4, 147.0, 163.8 (d, ^{2}J(PC) = 23.7 Hz, PCH=*C*).

^{31}P NMR: 8 18.5.

The ^{1}H and ^{13}C NMR spectra illustrated in Figures 2 and 3 (Section 5.23).

(viii) **$CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(O)CH{=}C(NCH_2CH_2CH_2CH_2CH_2\text{-})Et$** (37)

Mp: 156-160°C.

Yield: Quantitative.

IR (KBr): 1564, 1460, 1254, 1215, 1013 cm^{-1}.

^1H NMR: 5 1.20 (t, $^3J(HH)$ = 3.8 Hz, 3 H, CH_2CH_3), 1.40 (s, 18 H, *t*-Bu-*H*), 1.60 (br, 6 H, $C(NCH_2CH_2CH_2CH_2CH_2\text{-})$), 2.26 (s, 6 H, $ArCH_3$), 2.90 (qrt, V(HH) = 3.8 Hz, 2 H, CH_2CH_3), 3.29 (br, 4 H, $N(CH_2CH_2CH_2CH_2CH_2\text{-})$), 4.01 (br m, 2 H, $ArCH_2$), 4.38 (d, $^2J(PH)$ = 8.2 Hz, 1 H, PC//), 7.03 (br s, 4 H, Ar-*H*).

^{13}C NMR: 5 13.0 (s, $C(CH_2CH_3)$), 20.9 (s, $ArCH_3$), 22.2 (s, $C(CH_2CH_3)$), 24.6 (s, $C(NCH_2CH_2CH_2CH_2CH_2\text{-})$), 25.4 (s, $C(NCH_2CH_2CH_2CH_2CH_2\text{-})$), 30.6 (s, $C(CH_3)_3$), 34.7 (s, $ArCH_2$), 35.6 (s, CMe_3), 48.1 (s, $C(NCH_2CH_2CH_2CH_2CH_2\text{-})$), 78.4 (d, $^1J(PC)$ = 230.4 Hz, PC), 126.9, 129.2, 132.4, 133.5, 140.8, 147.3, 165.5 (d, V(PC) = 21.6 Hz, PCH=*C*).

^{31}P NMR: 5 18.7.

(ix) **$CH_2(6\text{-}t\text{-Bu-4-Me-}C_6H_2O)_2P(O)CH{=}N(CH_2CH_2OCH_2CH_2\text{-})Et$** (38)

Mp: 200-204°C.

Yield: Quantitative.

IR (KBr): 1570, 1439, 1211, 1125, 1028, 885 cm^{-1}.

^1H NMR: 5 1.22 (t, V(HH) = 3.6 Hz, 3 H, CH_2CH_3), 1.40 (s, 18 H, *t*-Bu-*H*), 2.30 (s, 6 H, $ArCH_3$), 2.95 (qrt, V(HH) = 3.8 Hz, 2 H, CH_2CH_3), 3.23 (t, $^3J(HH)$ = 2.4 Hz, 4 H, $N(CH_2CH_2OCH_2CH_2\text{-})$), 3.69-3.73 (m, 1 H, $ArCH_AH_X$), 3.79 (t, V(HH) = 2.4 Hz, 4 H, $N(CH_2CH_2OCH_2CH_2\text{-})$), 3.98 (br, 1 H, $ArCH_AH_X$), 4.50 (d, V(PH) = 8.8 Hz, 1 H, PC//), 7.05 (br s, 4 H, Ar-*H*).

^{13}C NMR: δ 12.9 (s, CH_2CH_3), 20.9 (s, $ArCH_3$), 23.5 (d, $^3J(PC)$ = 3.0 Hz, CH_2CH_3), 30.8 (s, $C(CH_3)_3$), 34.8 (s, $ArCH_2$), 35.7 (s, CMe_3), 46.9 (s, $C(NCH_2CH_2OCH_2CH_2\text{-})$), 66.4 (s, $C(NCH_2CH_2OCH_2CH_2\text{-})$), 81.4 (d, $^1J(PC)$ = 228.1 Hz, PC), 126.9, 129.3, 132.1, 133.6, 140.6, 140.7, 146.5, 146.7, 166.2 (d, V(PC) = 22.0 Hz, PCH=*C*).

^{31}P NMR: δ 16.8.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix I (Fig. 9).

6.24 ***Synthesis of allylphosphonates*** **39-40**

To a solution of allenyl phosphonate 19 (1.88 g, 10.0 mmol) in acetonitrile (10 mL), imidazole or pyrazole (0.68 g, 10.0 mmol) was added and the reaction mixture was heated under reflux for 10 h with continuous stirring. The solvent was removed and the solid obtained was purified by column chromatography (silica gel, hexane-ethyl acetate).

(i) **$(OCH_2CMe_2CH_2O)P(O)CH_2C(NCH{=}NCH{=}CH\text{-}){=}CH_2$ (39)**

Mp: 69-71°C.

Yield: 1.58 g (62%).

IR (KBr): 1647, 1489, 1269, 1059 cm^{-1}.

^1H NMR: 8 0.95, 1.03 (2 s, 6 H, $C(CH_3)_2$), 3.15 (d, ^2J(PH) - 21.2 Hz, 2 H, PCH_2), 3.72 (dd, V(PH) = 4.8 Hz, ^2J(HH) = 12.1 Hz, 2 H, OCH_AH_B), 4.20 (dd, ^3J(PH) = 4.8 Hz, ^2J(HH) = 11.1 Hz, 2 H, OCH_AH_B), 5.12 (d, ^2J(HH) = 4.8 Hz, 1 H, $CH{=}CH_2$), 5.26-5.34 (m, 2 H, $=CH_2$), 7.07, 7.19, 7.74 (3 br s, 3 H, imidazolyl–*H*).

^{13}C NMR: δ 21.3 (s, CH_3), 31.0 (d, ^1J(PC) = 137.4 Hz, PC), 32.4 (s, CMe_2), 75.5, 75.6 (2 s, OCH_2), 108.2 (d, V(PC) = 9.6 Hz, $C{=}CH_2$), 117.5, 129.6 (2 s, imidazolyl–*C*), 133.2 (d, ^2J(PC) = 10.0 Hz, $PCH_2C{=}CH_2$), 135.6 (s, imidazolyl–*C*).

^{31}P NMR: δ 18.3.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix **I** (Fig. 10).

(ii) **$(OCH_2CMe_2CH_2O)P(O)CH_2C(NN{=}CHCH{=}CH\text{-}){=}CH_2$ (40)**

Mp: 79-81°C

Yield: 2.02 g (80 %).

IR (KBr): 1649, 1478, 1262, 1053, 1005 cm^{-1}.

^1H NMR: 8 0.91, 1.04 (2 s, 6 H, $C(CH_3)_2$), 3.45 (d, V(PH) = 21.3 Hz, 2 H, PCH_2), 3.75-4.02 (m, 4 H, OCH_2), 5.07 (d, V(HH) = 4.8 Hz, 1 H, $CH{=}CH_2$),,5.36 (d, V(HH) = 4.8 Hz, 1 H, $CH{=}CH_2$), 6.32 (d, V(HH) = 2.0 Hz, 1 H, pyrazolyl–*H*), 7.56 (s, 1 H, pyrazolyl–*H*), 7.76 (d, ^2J(HH) = 2.0 Hz, 1 H, pyrazolyl-//).

^{13}C NMR: 8 20.7, 21.4 (2 s, CH_3), 28.2 (d, ^1J(PC) = 133.1 Hz, PC), 32.1 (d, V(PC) = 5.5 Hz, CMe_2), 75.6, 75.7 (2 s, OCH_2), 103.8 (d, V(PC) = 9.7

Hz, C=CH_2), 107.3, 127.4 (2 s, pyrazolyl–*C*), 136.3 (d, ^2J(PC) = 10.5 Hz, PCH_2C), 142.0 (s, pyrazolyl–*C*).

^{31}P NMR: 8 18.0.

This compound was crystallized from CH_2Cl_2-hexane mixture and the X-ray structure was determined for the crystals thus obtained *(cf.* Fig. 6; Section 5.23) The ^{1}H and ^{13}C NMR spectra are illustrated in Figures 4 and 5 *(cf.* Section 5.23), respectively.

6.25 *Synthesis of alkynyl phosphonate* 41

To a solution of the allenyl phosphonate 19 (1.88 g, 10.0 mmol) in 10 mL of acetonitrile, triethylamine (1.01g, 1.39 mL, 10.0 mmol) was added via syringe (~2 min) and the reaction mixture was heated under reflux for 10 h with continuous stirring. The solvent was removed and the solid obtained was purified by column chromatography (silica gel, hexane-ethyl acetate) to obtain pure 41.

Mp: 91°C.

Yield: 1.41 g (75%).

IR (KBr): 2216,2174, 1279, 1057, 1001 cm^{-1}.

^{1}H NMR: 8 0.86, 1.23 (2 s, 6 H, C(CH_3)$_2$), 2.01 (d, V(PH) = 4.7 Hz, 3 H, PC≡CCH_3), 3.81-3.98 (4 lines, 2 H, OCH_2), 4.10 (d, ^2J(HH) = 10.0 Hz, V(PH) ~ 4.0 Hz, 2 H, OCH_2).

^{13}C NMR: 8 4.4 (d, ^3J(PC) = 5.0 Hz, ≡CCH_3), 20.2, 21.8 (2 s, C(CH_3)$_2$), 32.2 (d, V(PC) = 6.0 Hz, CMe_2), 67.5 (d, '/(PC) = 291.0 Hz, PC), 77.1, 77.2 (2 s, OCH_2), 100.6 (d, V(PC) = 53.0 Hz, PC≡CCH_3).

^{31}P NMR: 8-12.9.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix I (Fig. 11).

6.26 *Synthesis of fi-ketophosphonates* **(42-46)**

To the solution of allenyl phosphonates **19-23** (10.0 mmol) in dry acetonitrile (20 mL) was added diethylamine (0.73 g, 1.03 mL, 10.0 mmol) and the mixture stirred for 4 h. The reaction mixture was then treated with 2N HC1, stirred for 8 h and extracted with dichloromethane (CH_2Cl_2) (3 x 30 mL). The CH_2Cl_2 layer was dried (Na_2SO_4), the solvent was moved and the residue was purified by column chromatography (silical gel; hexane-ethyl acetate) to obtain **47a-i** or **48a-h.**

(i) $(OCH_2CMe_2CH_2O)P(O)CH_2C(O)Me$(42)

Mp: 85-86°C.

Yield: 1.94 g (94%).

IR (KBr): **1714, 1273, 1061, 1009 cm^{-1}.**

^1H NMR: 6 0.90, 0.99 (2 s, 6 H, $C(CH_3)_2$), 2.30 (s, 3 H, $C(O)CH_3$), 3.09 (d, V(PH) = 21.5 Hz, 2 H, PCH_2), 3.80-4.05 (m, 4 H, OCH_2).

^{13}C NMR: 8 21.0, 21.5 (2 s, $C(CH_3)_2$), 31.5 (d, V(PC) = 4.1 Hz, $C(O)CH_3$), 32.5 (d, V(PC) = 5.3 Hz, CMe_2), 41.7(d, ^1J(PC) = 123.9 Hz, PC), 76.1, 76.2 (2 s, OCH_2), 199.3 (d, ^2J(PC) = 6.0 Hz, $PCH_2C(O)$).

^{31}P NMR: 8 13.8.

Anal. Calcd for $C_8H_{15}O_4P$: C, 46.60; H, 7.33. Found: C, 46.84; H, 7.32.

(ii) **$(OCH_2CMe_2CH_2O)P(O)CH_2C(O)Et$** (43)

Mp: 98-100°C.

Yield: 1.87 g (85 %).

IR (KBr): 1715, 1267, 1063, 1007 cm^{-1}.

'H NMR: 8 0.93-1.09 (3 lines, 9 H, $C(CH_3)_2$ + CH_2CH_3), 2.58 (qrt, V(HH) ~ 6.0 Hz, 2 H, CH_2CH_3), 3.12 (d, ^2J(PH) = 21.0 Hz, 2 H, PCH_2), 3.83-4.12 (m, 4 H, OCH_2).

^{13}C NMR: δ 7.4 (s, CH_2CH_3), 21.1, 21.5 (2 s, $C(CH_3)_2$), 32.5 (d, V(PC) = 6.6 Hz, CMe_2), 37.5 (s, CH_2CH_3), 40.2 (d, ^1J(PC) = 122.6 Hz, PC), 76.0, 76.1 (2 s, OCH_2), 201.9 (d, ^2J(PC) - 6.1 Hz, $PCH_2C(O)$).

^{31}P NMR: δ 14.0.

Anal. Calcd for $C_9H_{17}O_4P$: C, 49.09; H, 7.78. Found: C, 48.88; H, 7.75.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix I (Fig. 12).

(iii) $(OCH_2CMe_2CH_2O)P(O)CH_2C(O)CHMe_2$ (44)

Mp: 102-104°C

Yield: 1.42 g (61%)

IR (KBr): 1713, 1474, 1267, 1059, 1009 cm^{-1}.

^1H NMR: 8 1.00, 1.10 (2 s, 6 H, $C(CH_3)_2$), 1.06 (d, V(HH) = 6.8 Hz, 6 H, $CH(CH_3)_2$), 2.77-2.87 (qnt, V(HH) - 6.8 Hz, 1 H, $CH(CH_3)_2$), 3.12

(dd, V(PH) = 19.6 Hz, V(HH) = 2.0 Hz, 2 H, PCH_2), 3.88-4.14 (m, 4 H, OCH_2).

^{13}C NMR: 5 17.9 (s, $CH(CH_3)_2$), 21.2, 21.6 (2 s, $C(CH_3)_2$, 32.5 (d, V(PC) = 6.6 Hz, CMe_2), 37.3 (s, $CH(CH_3)_2$), 40.9 (d, ^1J(PC) = 104.3 Hz, PC), 76.0, 76.1 (2 s, OCH_2), 205.5 (d, V(PC) = 6.0 Hz, $PCH_2C(O)$).

^{31}P NMR: 8 14.2.

(iv) **$(OCH_2CMe_2CH_2O)P(O)CH_2C(O)CH(Me)Et$** (45)

Mp: 92-94°C

Yield: 1.30 g (56%)

IR (KBr): 1711, 1634, 1273, 1063, 1009 cm^{-1}.

^1H NMR: 8 0.81 (t, V(HH) = 7.4 Hz, 3 H, CH_2CH_3), 1.00, 1.06 (2 s, 6 H, $C(CH_3)_2$), 1.07 (d, ^3J(HH) = 6.7 Hz, 3 H, $CHCH_3$), 1.27-1.42, 1.54-1.73 (2 m, 2 H, $CH(Me)CH_2CH_3$), 2.69 (m, 1 H, $CH(CH_3)CH_2CH_3$), 3.20 (d, ^2J(PH) = 22.3 Hz, 2 H, PCH_2), 3.89-4.14 (m, 2 H, OCH_2).

^{13}C NMR: 8 11.3 (s, $CHCH_2CH_3$), 15.2 (s, $CH(CH_3)CH_2CH_3$), 21.1, 21.6 (2 s, CMe_2), 25.4 (s, $CH(CH_3)CH_2CH_3$), 32.5 (d, V(PC) = 7.3 Hz, $C(CH_3)_2$), 38.1 (d, ^1J(PC) =126.1 Hz, PC), 48.8 (s, $CH(CH_3)CH_2CH_3$), 76.0, 76.1 (2 s, OCH_2), 205.4 (d, V(PC) = 6.0 Hz, $PCH_2C(O)$).

^{31}P NMR: 8 14.6.

(v) **$(OCH_2CMe_2CH_2O)P(O)CHPhC(O)CH_2CH_2CH_3$** (46)

Mp: 138-140°C.

Yield: 1.33 g (43%)

IR (KBr): 1717, 1263, 1059, 1005 cm^{-1}.

^1H NMR: 8 0.82, 1.01 (2 s, 6 H, $C(CH_3)_2$), 0.84 (t, V(HH) = 6.3 Hz, $CH_2CH_2CH_3$), 1.58 (m, 2 H, $CH_2CH_2CH_3$), 2.51-2.64 (m, 2 H, $CH_2CH_2CH_3$), 3.67-3.88 (m, 2 H, OCH_2), 4.03 (t, V(PH) ~ 6.0 Hz, 2 H, OCH_2), 4.53 (d, V(PH) = 21.2 Hz, 2 H, PCH_2), 7.23-7.49 (m, 5 H, Ar-H).

^{13}C NMR: 8 13.3 (s, $CH_2CH_2CH_3$), 16.9 (s, $CH_2CH_2CH_3$), 21.1, 21.7 (2 s, $C(CH_3)_2$), 32.6 (d, V(PC) = 7.4 Hz, CMe_2), 45.2 (s, $CH_2CH_2CH_3$), 58.5 (d, ^1J(PC) = 129.0 Hz, PC), 76.0, 76.1 (2 d, V(PC) = 6.7 Hz each, 2

OCH_2), 128.1, 128.8, 129.6, 129.9, 130.5, 202.9 (d, ^2J(PC) = 4.9 Hz, PCH_2C(O)).

^{31}P NMR: 5 12.3.

6.27 HWE reaction using the β-ketophosphonates 42-43: Synthesis of α,β-unsaturated ketones

To the β-ketophosphonate 42 or 43 (10.0 mmol) in dry THF (20 mL), K_2CO_3 (1.66 g, 12.0 mmol) was added and the reaction mixture was stirred for 30 min at room temperature. Then aldehyde (10.0 mmol) was added in one shot and the reaction mixture was refluxed for 24 h. After cooling to room temperature the reaction mixture was quenched with cold water (20 mL) and extracted with ether (2 x 30 mL). The ether layer was dried (Na_2SO_4), the solvent was removed and the residue was purified by column chromatography (silical gel; hexane-ethyl acetate) to obtain 47a-i or **48a**-h.

(i) **Ph(H)C=C(H)C(O)Me (47a)**

Mp: 39-41°C.

Yield: 1.20 g (82 %).

IR (KBr): 1669, 1611, 1258, 1181, 1074, 976 cm^{-1}.

^{1}H NMR: 5 2.36 (s, 3 H, CH_3), 6.70 (d, V(HH) = 16.6 Hz, 1 H, (Ph)HC=CH), 7.36-7.54 (m, 6 H, Ar-H + (Ph)HC=CH).

^{13}C NMR: δ 27.5 (s, C(O)CH_3), 127.2, 128.3, 129.0, 130.5, 134.5, 140.0, 143.4, 198.2 (s, C(O)Me).

(ii) **C_6H_4-4-Me(H)C=C(H)C(O)Me (47b)**

Mp: liquid

Yield: 1.26 g (79%).

IR (KBr): 1667, 1611, 1258, 1208, 1179, 980 cm^{-1}.

^{1}H NMR: 5 2.36 (s, 6 H, Ar-CH_3 + C(O)CH_3), 6.67 (d, V(HH) = 16.6 Hz, I H, HC=CHC(O)Me), 7.19 (d, V(HH) = 8.8 Hz, 2 H, Ar-H), 7.41-7.53 (3 lines, 3 H, Ar-H + C_6H_4-4-Me-HC=CH).

^{13}C NMR: 5 21.4 (s, ArCH_3), 27.4 (s, C(O)CH_3), 126.3, 128.3, 129.7, 131.7, 141.0,143.4, 198.3 (s, C(O)Me).

(iii) C6H4-3-Me(H)C=C(H)C(O)Me(47c)

Mp: liquid

Yield: 1.3 g (81%).

IR (KBr): 1669, 1611, 1258, 1229, 978 cm^{-1}.

^1H NMR: 8 2.37 (s, 6 H, Ar-CH_3 + C(O)CH_3), 6.69 (d, V(HH) = 15.6 Hz, 1 H, C_6H_4-3-Me(H)C=C*H*), 7.22-7.35 (m, 4 H, C_6H_4-3-Me(*H*)C=CH), 7.48 (d, V(HH) = 15.6 Hz, 1 H, C_6H_4-3-Me(*H*)C=CH).

^3C NMR: 8 21.3 (s, Ar-*C*H_3), 27.5 (s, C(O)*C*H_3), 125.5, 127.0, 128.9, 131.3, 134.4, 138.6, 143.6, 198.3 (s, C(O)Me).

(iv) C_6H_4-4-OMe(H)C=C(H)C(O)Me (47d)

Mp: 62-64°C.

Yield: 1.53 g (87%).

IR (cm^{-1}): 1771, 1744, 1229, 1103, 959 cm^{-1}.

^1H NMR: 5 2.35 (s, 3 H, C(O)CH_3), 3.83 (s, 3 H, OCH_3), 6.59 (d, V(HH) = 16.3 Hz, 1 H, C_6H_4-4-OMe(H)C=C*H*), 6.90 (d, V(HH) = 8.7 Hz, 2 H, Ar-ortho-*H*), 7.46 (d, V(HH) = 16.3 Hz, 1 H, C_6H_4-4-OMe*H*C=CH), 7.48 (d, V(HH) - 8.7 Hz, 2 H, *Ar-H).*

^{13}C NMR: 8 27.4 (s, C(O)*C*H_3), 55.4 (s, Ar-O*C*H_3), 114.5, 125.1, 127.1, 130.0, 143.2, 161.6, 198.3 (s, C(O)Me).

(v) **C_6H_4-4-NO_2-(H)C=C(H)C(O)Me** (47e)

Mp: 96-98°C.

Yield: 1.51 g (79%).

IR (KBr): 1669, 1518, 1346, 1263, 1109, 978 cm^{-1}.

^1H NMR: 8 2.42 (s, 3 H, C(O)CH_3), 6.82 (d, V(HH)= 16.6 Hz, 1 H, C_6H_4-4-NO_2-(H)C=C*H*), 7.54 (d, V(HH) = 16.6 Hz, 1 H, C_6H_4-4-NO_2-(*H*)C=CH), 7.69, 8.24 (2 d, V(HH) = 6.8 Hz each, 4 H, Ar-*H*).

^{13}C NMR: 8 28.0 (s, C(O)*C*H_3), 124.2, 128.8, 130.4, 140.0, 140.7, 148.6, 197.5 (s, *C*(O)CH_3).

(vi) **C_6H_5CH=CH-(H)C=C(H)C(O)Me** (470

Mp: liquid

Yield: 1.24g(72%).

IR (KBr): 1651, 1616, 1254, 1146, 1073,986 cm^{1}.

^{1}H NMR: 8 2.28 (s, 3 H, C(O)CH_3), 6.22 (d, V(HH) = 15.6 Hz, 1 H, C_6H_5CH=C(H)-(H)C=CH), 6.77-6.97 (m, 2 H, Ar-H), 7.20-7.46 (m, 6 H, 3 Ar-H + $C_6H_5C(H)$=C(H)-(H)C=CH).

^{13}C NMR: 8 27.3 (s, C(O)CH$_3$), 126.7, 128.9, 129.2, 130.5, 136.0, 141.2, 143.2, 143.3, 198.2 (s, C(O)Me).

(vii) C_6H_3-2,6-Cl_2(H)C=C(H)C(O)Me (47g)

Mp: 59-61°C.

Yield: 1.73 g (80 %).

IR (KBr): 1678, 1616, 1429, 1360, 1254, 1179, 1092, 978 cm^{1}.

^{1}H NMR: 8 2.43 (s, 3 H, C(O)CH_3), 6.72 (d, V(HH) = 16.6 Hz, 1 H, HC=C(H)C(O)Me), 7.05- 7.38 (m, 3 H, Ar-H), 7.57 (d, V(HH) = 16.6 Hz, 1 H, C_6H_3-2,6-Cl_2(H)C=CH).

^{13}C NMR: 8 27.6 (s, C(O)CH$_3$), 125.5, 128.8, 129.9, 132.3, 135.0, 136.7, 198.3 (s, C(O)Me).

(viii) C_6H_3-3,4-Cl_2(H)C=C(H)C(O)Me (47h)

Mp: 52-54°C.

Yield: 1.68 g (78 %).

IR (KBr): 1672, 1615, 1470, 1258, 1134, 1030,978 cm^{1}.

^{1}H NMR: 8 2.32 (s, 3 H, C(O)CH_3), 6.62 (d, V(HH) = 16.6 Hz, 1 H, C_6H_3-3,4-Cl_2(H)C=CH), 7.29- 7.54 (m, 4 H, 3 Ar-H + C_6H_3-3,4-Cl_2HC=CH).

^{13}C NMR: 8 27.8 (s, C(O)CH$_3$), 127.1, 128.4, 129.7, 130.9, 133.2, 134.2, 134.6, 140.2, 197.4 (s, C(O)Me).

(ix) **$C_{14}H_9$(H)C=C(H)C(O)Me** (47i)

Mp: 100-102°C.

Yield: 1.92 g (78 %) .

IR (KBr): 1660, 1653, 1541, 1520, 1362, 1250, 988 cm^{-1}.

'HNMR: 8 2.54 (s, 3 H, C(O)CH_3), 6.68 (d, ^{3}J(HH) = 16.6 Hz, 1 H, $C_{14}H_9$(H)C=CH), 7.46-7.50 (m, 4 H, Ar-H), 7.94-7.80 (m, 2 H, Ar-H),

8.15–8.20 (m, 2 H, *Ar-H),* 8.38 (s, 1 H, Ar-*H*), 8.42 (d, V(HH) - 16.6 Hz, 1 H, $C_{14}H_9$(*H*)C=CH).

^{13}C NMR: 8 27.9 (s, C(O)*C*H$_3$), 125.1, 125.4, 126.4, 128.5, 128.9, 129.2, 129.4, 131.3, 135.8, 140.3, 197.7 (s, C(O)Me).

The ^{13}C spectrum is illustrated in Appendix 1 (Fig. 13).

(x) Ph(H)C=C(H)C(O)Et (48a)

Mp: Gummy.

Yield: 1.41 g (88%).

IR (KBr): 1692, 1667, 1611, 1449, 1188, 1121, 993 cm^{-1}.

^{1}H NMR: δ 1.14 (t, V(HH) = 6.8 Hz, 3 H, CH$_2$C*H*$_3$), 2.65 (qrt, V(HH) = 6.8 Hz, 2 H, C*H*$_2$CH$_3$), 6.71 (d, V(HH) = 16.6 Hz, 1 H, Ph(H)C=C*H*), 7.36-7.57 (m, 6 H, *Ar-H*+ Ph(*H*)C=CH).

^{13}C NMR: 5 8.2 (s, CH$_2$*C*H$_3$), 34.0 (s, *C*H$_2$CH$_3$), 126.1, 128.2, 129.0, 130.0, 130.3, 134.6, 142.1, 200.7 (s, C(O)Et).

(xi) (4-Me-C$_6$H$_4$)(H)C=C(H)C(O)Et (48b)

Mp: Liquid.

Yield: 1.27 g (73%).

IR (KBr): 1661, 1611, 1362, 1192, 1119, 988 cm^{-1}.

^{1}H NMR: 5 1.16 (t, V(HH) = 7.4 Hz, 3 H, CH$_2$C*H*$_3$), 2.36 (s, 3 H, Ar-C*H*$_3$), 2.67 (qrt, V(HH) = 7.4 Hz, 2 H, C*H*$_2$CH$_3$), 6.69 (d, V(HH) = 16.0 Hz, 1 H, HC=C*H*C(O)Et), 7.18 (d, V(HH) = 7.8 Hz, 2 H, Ar-ortho-*H*), 7.42 (d, V(HH) = 7.8 Hz, 2 H, Ar-meta-*H*), 7.53 (d, 3 H, V(HH) = 16.0 Hz, 1 H, C$_6$H$_4$-4-Me(*H*)C=CH).

^{13}C NMR: 8 8.2 (s, CH$_2$*C*H$_3$), 21.4 (s, Ar-*C*H$_3$), 33.9 (s, *C*H$_2$CH$_3$), 125.2, 128.3, 129.7, 131.9, 140.8, 142.2, 200.9 (s, *C*(O)Et).

(xii) (C$_6$H$_4$-4-OMe)(H)C=C(H)C(O)Et (48c)

Mp: 48-50°C.

Yield: 1.68 g (89%).

IR(KBr): 1684, 1657, 1601, 1572,1512, 1254, 1177, 1119, 1026,988,831 cm^{-1}.

^{1}H NMR: 8 1.13 (t, V(HH) = 6.8 Hz, 3 H, CH_2CH_3), 2.64 (qrt, V(HH) - 6.8 Hz, 2 H, CH_2CH_3), 3.80 (s, 3 H, Ar-OCH_3), 6.59 (d, V(HH) = 16.6 Hz, 1 H, HC=C(*H*)C(O)Et), 6.87 (d, V(HH) = 8.8 Hz, 2 H, Ar-Ortho-*H*), 7.43-7.53 (m, 3 H, 2 *Ar-H* + C_6H_4-4-OMe(*H*)C=CH).

^{13}C NMR: 8 8.3 (s, CH_2CH_3), 33.9 (s, CH_2CH_3), 55.3 (s, Ar-OCH_3), 114.4, 123.9, 127.3, 129.9, 141.9, 161.5, 200.8 (s, C(O)Et).

(xiii) **C_6H_5CH=CH-(H)C=C(H)C(O)Et** (48d)

Mp: Liquid.

Yield: 1.21 g (65%).

IR (KBr): 1678, 1622, 1589, 1451, 1358, 1287, 1192, 1123, 999, 748 cm^{-1}.

^{1}H NMR: 8 1.14 (t, V(HH) = 6.7 Hz, 3 H, CH_2CH_3), 2.61 (qrt, V(HH) = 6.7 Hz, 2 H, CH_2CH_3), 6.27 (d, V(HH) = 16.0 Hz, 1 H, (H)C=C*H*C(O)Et), 6.85-6.90 (m, 2 H, C_6H_5(H)C=C(H)-(*H*)C=CH + 1 Ar-*H*), 7.31-7.48 (m, 6 H, C_6H_5(*H*)C=C(*H*)-(H)C=CH + 4 Ar-*H*).

^{13}C NMR: 8 8.3 (s, CH_2CH_3), 33.9 (s, CH_2CH_3), 126.8, 127.2, 128.8, 129.0, 129.4, 131.2, 136.2, 141.0, 142.1, 152.4, 193.3 (s, C(O)Et).

(xiv) **$C_{14}H_9$(H)C=C(H)C(O)Et** (48e)

Mp: 94-98°C.

Yield: 1.77 g (68%).

IR (KBr): 1661, 1616, 1194, 1019, 982 cm^{-1}.

^{1}H NMR: 8 1.27 (t, V(HH) - 7.6 Hz, 3 H, CH_2CH_3), 2.83 (qrt, V(HH) - 7.6 Hz, 2 H, CH_2CH_3), 6.71 (d, V(HH) = 16.4 Hz, 1 H, HC=C*H*C(O)Et), 7.44-7.50 (m, 4 H, Ar-*H*), 7.97- 8.02 (m, 2 H, Ar-*H*), 8.17-8.21 (m, 2 H, Ar-*H*), 8.43 (s, 1 H, Ar-*H*), 8.48 (d, V(HH) = 16.4 Hz, 1 H, $C_{14}H_9$(*H*)C=CH).

^{13}C NMR: 8 8.2 (s, CH_2CH_3), 34.6 (s, CH_2CH_3), 125.2, 125.4, 126.3, 128.2, 128.9, 129.5, 131.4, 134.9, 139.2, 200.8 (s, *C*(O)Et).

(xv) **$C_5H_5FeC_5H_4$(H)C=C(H)C(O)CH_2CH_3 (48f)**

Mp: 98-100°C.

Yield: 1.82 g (68%).

IR (KBr): 1686, 1657, 1605, 1360, 1125, 1034, 980 cm^{-1}.

'H NMR: 5 1.14 (t, V(HH) = 6.8 Hz, 3 H, CH_2CH_3), 2.58 (qrt, V(HH) = 6.8 Hz, 2 H, CH_2CH_3), 4.13 (s, 5 H, ferrocenyl-//), 4.41-4.42 (m, 2 H, ferrocenyl-*H*), 4.48-4.49 (m, 2 H, ferrocenyl-*H*), 6.34 (d, V(HH) = 15.6 Hz, 1 H, HC=C*H*(CO)Et), 7.44 (d, V(HH) = 15.6 Hz, 1 H, $C_5H_5FeC_5H_4$(*H*)C=CH).

^{13}C NMR: 5 8.5 (s, CH_2CH_3), 33.6 (s, CH_2CH_3), 68.7, 69.7, 70.9, 78.9 (ferrocenyl-Q, 123.6 (s, HC=*C*H(CO)Et), 143.6 (s, $C_5H_5FeC_5H_4H$ C=CH), 200.2 (s, *C*(O)Et).

The ^{13}C spectrum is illustrated in Appendix I (Fig. 14).

(xvi) EtC(O)C(H)=C(H)-C_6H_4-(H)C=C(H)C(O)Et (48g)

Mp: 112-116°C.

Yield: 1.91 g (79%).

IR (KBr): 1657, 1366, 1192, 1065, 990 cm^{-1}.

^1H NMR: 5 1.16 (t, V(HH) = 7.8 Hz, 3 H, CH_2CH_3), 2.68 (qrt, V(HH) = 7.8 Hz, 2 H, CH_2CH_3), 6.75 (d, ^3J(HH) = 16.6 Hz, 1 H, HC=C(*H*)C(O)Et), 7.48-7.56 (3 lines, 3 H, 2 Ar-*H* + (H)C=C(*H*)-C_6H_4-(*H*)C=C(H)).

^{13}C NMR: 5 8.1 (s, CH_2CH_3), 34.2 (s, CH_2CH_3), 126.5, 128.7, 136.5, 140.9, 200.5 (s, *C*(O)Et).

The C spectrum is illustrated in Appendix **I** (Fig. 15).

(xvii) C_6H_4-4-Cl(H)C=C(H)C(O)Et (48h)

Mp: 68-70°C.

Yield: 1.32 g (68%).

IR (KBr): 1688, 1659, 1491, 1406, 1190, 1092, 988 cm^{-1}.

^1H NMR: 5 1.16 (t, V(HH) = 7.0 Hz, 3 H, CH_2CH_3), 2.67 (qrt, V(HH) = 7.0 Hz, 2 H, CH_2CH_3), 6.69 (d, V(HH) = 16.1 Hz, 1 H, HC=C(*H*)C(O)Et), 7.33-7.53 (m, 5 H, 4 *Ar-H*+ C_6H_4-4-Cl(*H*)C=CH).

^{13}C NMR: 5 8.1 (s, CH_2CH_3), 34.2 (s, CH_2CH_3), 126.5, 129.2, 133.2, 136.2, 140.6, 200.4 (s, C(O)Et).

6.28 Synthesis of β-hydroxyphosphonates using β-ketophosphonates

6.281 Allylation of β-ketophosphonates 42-43 *using diallyltin dibromide*

To a solution of β-ketophosphonates 42 or **43** (1.0 mmol) in dichloromethane (20 mL) kept over molecular sieves (4A, ~0.5 g) diallyltin dibromide (0.33 g, 1.0 mmol)[110b] was added *via* syringe at room temperature and the mixture stirred for 20 h. The reaction mixture was quenched with 8 % aq. NaOH (20mL) and extracted with dichloromethane (2 x 30mL). The organic layer was dried (Na_2SO_4) and the solvent was removed to obtain the crude allylated β-hydroxyphosphonates **49-50.** These were purified by column chromatography (silical gel; hexane-ethyl acetate).

(i) $(OCH_2CMe_2CH_2O)P(O)CH_2C(OH)(CH_2CH=CH)Me$ (49)

Mp : 82-84°C.

Yield: 0.12 g (49%).

IR (KBr): 3349, 1642, 1260, 1067 cm^{-1}.

^1H NMR: 5 1.00, 1.11 (2 s, 6 H, $C(CH_3)_2$), 1.36 (s, 3 H, $C(OH)CH_3$), 2.08 (dd, $^2J(HH)$ = 10.9 Hz, $^2J(PH)$ = 17.3 Hz, 2 H, PCH_2), 2.37 (d, V(HH) = 7.3 Hz, 2 H, $CH_2CH=CH_2$), 3.79 (dd, V(HH) = 12.6 Hz, V(PH) = 11.3 Hz, 2 H, OCH_AH_B), 4.20 (t, V(PH) = 11.3 Hz, 2 H, OCH_AH_B), 5.04 (d, V(HH) = 13.0 Hz, 2 H, $CH_2CH=CH_2$), 6.82 (m, 1 H, $CH_2CH=CH_2$).

^{13}C NMR: 5 21.3, 21.7 (2 s, $C(CH_3)_2$), 28.2 (d, V(PC) = 9.4 Hz, $CH(OH)CH_3$), 32.7 (s, CMe_2), 35.5 (d, $^1J(PC)$ = 131.3 Hz, PC), 47.8 (d, V(PC) = 12.3 Hz, $CH_2CH=CH_2$), 70.2 (d, V(PC) = 4.8 Hz, CH(OH)), 74.8, 75.0 (2 s, OCH_2), 118.6 (s, $CH_2CH=CH_2$), 133.8 (s, $CH_2CH=CH_2$).

^{31}P NMR: 8 25.9.

(ii) $(OCH_2CMe_2CH_2O)P(O)CH_2C(OH)(CH_2CH=CH)Et$ (50)

Mp : 74-76°C.

Yield: 0.16 g (62%).

IR (KBr): 3434, 1647, 1240, 1060, 1015 cm^{-1}.

^1H NMR: δ 0.88 (t, V(HH) = 7.2 Hz, 3 H, CH_2CH_3), 0.97, 1.08 (2 s, 6 H, $C(CH_3)_2$), 1.62 (qrt, V(HH) = 7.2 Hz, 3 H, CH_2CH_3), 2.05 (d, V(PH) = 17.7 Hz, 2 H, PCH_2), 2.34 (d, V(HH) - 7.3 Hz, 2 H, $CH_2CH=CH_2$), 3.76 (t, $^3J(PH)$ = V(HH) = 13.7 Hz, 2 H, OCH_AH_B), 4.16 (t, V(PH) =

10.2 Hz, 2 H, OCH_AH_B), 5.07 (d, V(HH) = 13.3 Hz, 2 H, $CH_2CH=CH_2$), 6.78 (m, 1 H, $CH_2CH=CH_2$).

^{13}C NMR: 8 7.8 (s, CH_2CH_3), 21.3, 21.7 (2 s, $C(CH_3)_2$), 32.4 (d, V(PC) = 5.8 Hz, CMe_2), 32.9 (d, V(PC) = 9.1 Hz, $CH(OH)CH_2CH_3$), 33.7 (d, $^2J(PC)$ = 131.0 Hz, PCH_2), 44.2 (d, V(PC) = 9.9 Hz, $CH_2CH=CH_2$), 72.3 (d, $^2J(PC)$ = 4.8 Hz, $CH(OH)$), 74.8, 74.9 (2 s, OCH_2), 118.4 (s, $CH_2CH=CH_2$), 133.7 (s, $CH_2CH=CH_2$).

^{31}P NMR: 8 26.4.

6.282 Synthesis of β-hydroxyphosphonate 51 *using* $NaBH_4/I_2$

To $NaBH_4$ (0.04 g, 1.0 mmol) in THF (20 mL) at 0°C, I_2 (0.51 g, 2.0 mmol) in THF (15 mL) was added very slowly in about 3 h. To the generated BH_3:THF solution, β-ketophosphonate 42 (0.21 g, 1.0 mmol) was added in one shot and the reaction mixture stirred for 24 h. The reaction mixture was quenched with cold water (20 mL) and the mixture extracted with ether (2 x 30 mL). The ether layer was dried (Na_2SO_4) and the solvent removed to obtain the crude β-hydroxyphosphonate $(OCH_2CMe_2CH_2O)P(O)CH_2CH(OH)CH_3$ (51), which was purified by column chromatography (silical gel; hexane-ethyl acetate).

Mp : Gummy solid.

Yield: 0.16 g (73%).

IR (KBr): 3226, 1476, 1240, 1061, 1009 cm^{-1}.

^1H NMR: 8 0.97, 1.06 (2 s, 6 H, $C(CH_3)_2$), 1.25 (d, V(HH) - 6.2 Hz, 3 H, $CH(OH)CH_3$), 2.05 (dd, $^3J(HH)$ - 6.6 Hz, $^2J(PH)$ - 17.0 Hz, 2 H, PCH_2), 3.73-3.86 (m, 4 H, OCH_2 + $CH(OH)$), 4.16 (t, V(PH) = 10.7 Hz, 2 H, OCH_2).

^{13}C NMR: 8 21.3, 21.6 (2 s, $C(CH_3)_2$), 24.5 (d, V(PC) = 6.4 Hz, $CH(OH)CH_3$), 33.6 (d, V(PC) = 134.2 Hz, PCH_2), 32.4 (d, $^3J(PC)$ = 5.4 Hz, CMe_2), 62.5 (d, V(PC) = 4.6 Hz, $CH(OH)CH_3$), 75.0, 75.1 (2 s, OCH_2).

^{31}P NMR: 8 26.2.

6.29 Synthesis of cyclopropyl phosphonates 52-59

To a stirred suspension of NaH (0.03g, 1.2 mmol) in dry THF (20 mL) at 0°C was added the α-chlorophosphonate 16, 17 or 18 (1.0 mmol) in dry THF (10 mL) over

a period of 5 min. After 0.5 h, the methyl acrylate, ethyl acrylate or methyl methacrylate (1.5 mmol) was added drop-wise via syringe. The mixture was allowed to come to room temperature and was heated under reflux for 1 d. After cooling and quenching with cold water (20 mL), the mixture was extracted with dichloromethane (3 x 15 mL). The dichloromethane layer was dried (Na_2SO_4), the solvent removed, and the crude product obtained was purified by column chromatography (silical gel, hexane-ethyl acetate).

(i) [(OCH$_2$CMe$_2$CH$_2$O)P(O){C(Ph)CH$_2$C(H)(COOMe)-}] (52)

Mp: 147-149°C.

Yield: 0.24 g (63%).

IR (KBr): 1732, 1447, 1381, 1258, 1053, 1005 cm^{-1}.

^{1}H NMR: 5 0.48, 0.85 (2 s, 6 H, C(C*H*$_3$)$_2$), 1.88 (m, 2 H, C*H*$_A$H$_B$C(H)(COOMe) + CH$_2$C(*H*)(COOMe)), 2.72 (m, 1 H, CH$_A$*H*$_B$C(H)(COOMe)), 3.48 (s, 3 H, COOC*H*$_3$), 3.49 (m, 2 H, OC*H*$_A$H$_B$), 4.07 (m, 2 H, OCH$_A$*H*$_B$), 7.28 (br s, 5 H, Ar-*H*).

^{13}C NMR: 5 16.3 (s, *C*H$_2$C(H)(COOMe)), 20.8, 21.3 (2 s, C(*C*H$_3$)$_2$), 24.7 (s, CH$_2$*C*(H)(COOMe)), 29.3 (d, ^1J(PC) = 189.2 Hz, PC), 32.2 (d, V(PC) = 7.3 Hz, *C*Me$_2$), 51.9 (s, COO*C*H$_3$), 75.7, 76.0 (2 d, ^3J(PC) - 7.3 Hz each, O*C*H$_2$), 127.9, 128.2, 131.2, 133.6 169.5 (d, V(PC) = 4.9 Hz, *C*OOMe).

^{31}P NMR: 5 20.3.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix I (Fig. 16).

(ii) [(OCH$_2$CMe$_2$CH$_2$O)P(O){C(Ph)CH$_2$C(H)(COOEt)-}] (53)

Mp: 147-149°C.

Yield: 0.21 g (63%).

IR (KBr): 1734, 1470, 1381, 1240, 1202, 1020 cm^{-1}.

^{1}H NMR: 5 0.43, 0.79 (2 s, 6 H, C(C*H*$_3$)$_2$), 0.95 (t, V(HH) = 6.9 Hz, 3 H, COOCH$_2$C*H*$_3$), 1.78 (m, 2 H, C*H*$_A$H$_B$CH(COOEt)) + CH$_2$C(*H*) (COO Et)), 2.65 (m, 1 H, CH$_A$*H*$_B$C(H)(COOEt)), 3.46 (m, 2 H, OC*H*$_A$H$_B$), 3.85 (qrt, V(HH) = 6.9 Hz, 2 H, COOC*H*$_2$CH$_3$), 4.04 (m, 2 H, OCH$_A$*H*$_B$), 7.23 (br, 5 H, Ar-*H*).

^{13}C NMR: 6 13.8 (s, $COOCH_2CH_3$), 16.0 (s, $CH_2C(H)(COOEt)$), 20.7, 21.2 (2 s, $C(CH_3)_2$), 24.8 (s, $CH_2C(H)(COOEt)$), 29.3 (d, V(PC) = 189.2 Hz, PC), 32.2 (d, V(PC) = 7.3 Hz, CMe_2), 60.1 (s, $COOCH_2CH_3$), 75.7, 76.0 (2 d, V(PC) = 7.3 Hz each, OCH_2), 127.8, 128.0, 131.2, 133.5, 168.7 (d, V(PC) = 4.9 Hz, COOMe).

^{31}P NMR: 8 20.4,25.0(20: 1).

(iii) **[$(OCH_2CMe_2CH_2O)P(O)\{C(Ph)CH_2C(Me)(COOMe)-\}$]** (54)

Mp: 99-101°C.

Yield: 0.21 g (61%).

1R (KBr): 1734, 1462, 1354, 1262 cm^{-1}.

^{1}H NMR: δ 0.41, 0.77 (2 s, 6 H, $C(CH_3)_2$), 1.06 (s, 3 H, $C(CH_3)(COOMe)$), 1.24, 2.23 (2 dd, V(HH) ~ 8.5 Hz, V(PH) ~ 5.0 Hz, 2 H, $C(Ph)CHAH_B$), 3.32 -3.69 (m, 2 H, OCH_AH_B), 3.74 (s, 3 H, $COOCH_3$), 3.91-4.12 (m, 2 H, OCH_AH_B), 7.28 (br s, 5 H, Ar-*H*).

^{13}C NMR: 8 19.7 (s, $C(Me)CH_2$-), 20.8, 21.3 (2 s, $C(CH_3)_2$), 21.9 (d, ^2J(PC) = 18.5 Hz, CMe(COOMe)), 22.3 (s, $C(CH_3)(COOMe)$), 31.3 (d, ^1J(PC) = 189.0 Hz, PC), 32.2 (d, V(PC) ~ 7.0 Hz, CMe_2), 52.5 (s, $COOCH_3$), 75.2, 75.9 (2 d, ^3J(PC) = 6.3 Hz each, OCH_2), 127.7, 128.3, 131.2, 132.1, 134.1, 172.5 (d, ^3J(PC) ~5.0 Hz, COOMe).

^{31}P NMR: 8 20.6,25.9(9:1).

A pure product free of the component with 8(P) 25.9 could not be obtained.

(iv) **[$(OCH_2CMe_2CH_2O)P(O)\{C(4\text{-}Me\text{-}C_6H_4)CH_2C(H)(COOMe)-\}$]** (55)

Mp: 134-135°C.

Yield: 0.22 g (66%).

IR (KBr): 1732, 1518, 1441, 1381, 1258, 1053, 1003 cm^{-1}.

^{1}H NMR: 8 0.54, 0.88 (2 s, 6 H, $C(CH_3)_2$), 1.88, 2.75 (2 m, 3 H, CH_AH_B $C(H)(COOMe)$), 2.30, 2.31 (2 s, 3 H, $C(ArCH_3)$), 3.50 (m, 2 H, OCH_AH_B), 3.52 (s, 3 H, $COOCH_3$), 4.07 (m, 2 H, OCH_AH_B), 7.28 (m, 4 H, Ar-*H*).

^{13}C NMR: 8 16.4 (s, $CH_2C(H)(COOMe)$), 21.0, 21.4 (2 s, $C(CH_3)_2$), 21.2 (s, $ArCH_3$), 24.7 (s, $CH_2C(H)(COOMe)$), 29.3 (d, ^1J(PC) ~ 189.O Hz,

PC), 32.2 (d, ^3J(PC) = 7.3 Hz, CMe_2), 52.0 (s, $COOCH_3$), 75.8, 76.0 (2 d, V(PC) = 7.3 Hz each, OCH_2), 129.0, 130.3, 131.1, 137.6, 169.5 (d, ^3J(PC) ~ 5.0 Hz, COOMe).

^{1}P NMR: 5 20.5.

(v) **[(OCH$_2$CMe$_2$CH$_2$O)P(O){C(4-Me-C$_6$H$_4$)CH$_2$C(H)(COOEt)-}]** (56)

Mp: 128-129°C.

Yield: 0.21 g (61%).

IR(KBr): 1738, 1512, 1483, 1381, 1265, 1182, 1057, 1007 cm^{-1}.

^{1}H NMR: 8 0.55, 0.85 (2 s, 6 H, $C(CH_3)_2$), 1.28 (t, V(HH) - 7.1 Hz, 3 H, $COOCH_2CH_3$), 1.78, 2.18 (2 m, 3 H, $CH_AH_BC(H)(COOEt)$), 2.30 (s, $ArCH_3$), 3.49 (qrt→m, 2 H, OCH_AH_B), 4.07 (qrt, V(HH) = 6.9 Hz, 2 H, $COOCH_2CH_3$), 4.17 (m, 2 H, OCH_AH_B), 7.09 (d, V(HH) = 7.8 Hz, 2 H, Ar-ortho-*H*), 7.32 (d, V(HH) - 7.8 Hz, 2 H, Ar-meta-*H*).

^{13}C NMR: δ 14.1 (s, $COOCH_2CH_3$), 16.7 (s, $CH_2C(H)(COOEt)$), 21.0, 21.4 (2 s, $C(CH_3)_2$), 21.1 (s, $ArCH_3$), 28.4 (d, ^1J(PC) = 188.7 Hz, PC), 29.1 (s, $CH_2C(H)(COOEt)$), 32.2 (d, ^3J(PC) = 6.5 Hz, CMe_2), 61.3 (s, $COOCH_2CH_3$), 75.5, 75.6 (2 s, 2 OCH_2), 129.0, 130.8, 130.9, 135.2, 137.6, 168.8 (d, ^3J(PC) = 4.9 Hz, *C*OOEt).

^{31}P NMR: 8 19.1.

The ^{13}C and ^{31}P NMR spectra are illustrated in Appendix I (Fig. 17).

(vi) **[(OCH$_2$CMe$_2$CH$_2$O)P(O){C(4-Me-C$_6$H$_4$)CH$_2$C(Me)(COOMe)-}]** (57)

Mp: 112-116°C.

Yield: 0.21 g (60%).

IR (KBr): 1736, 1514, 1460, 1352, 1265, 1155 cm^{-1}.

^{1}H NMR: 8 0.44, 0.45, 0.80, 0.81 (s each, 6 H, $C(CH_3)_2$), 1.03, 1.04 (2 s, 3 H, $C(CH_3)(COOMe)$), 1.24, 2.21(2 m, 2 H, $C(ArCH_3)CH_AH_B$), 2.30 (s, $ArCH_3$), 3.44 (m, 2 H, OCH_AH_B), 3.72, 3.73 (2 s, 3 H, $COOCH_3$), 3.91-4.12 (m, 2 H, OCH_AH_B), 7.08, 7.11 (2 br, 4 H, Ar-*H*).

^{13}C NMR: 8 19.6 (s, $C(Me)CH_2$), 20.9, 21.1 (2 s, $C(CH_3)_2$), 21.9 (d, V(PC) - 18.5 Hz, $C(CH_3)(COOMe)$), 22.3 (s, $C(CH_3)(COOMe)$), 31.0 (d, ^1J(PC) = 188.6 Hz, PC), 32.2 (d, ^3J(PC) = 6.5 Hz, CMe_2), 52.5 (s, COOCH3),

75.3, 75.9 (2 d, ^3J(PC) = 6.3 Hz each, OCH_2), 128.9, 130.8, 131.2, 137.5, 172.5 (d, V(PC) = 7.6 Hz, COOMe), 174.2 (unassigned ?).

^{31}P NMR: 6 20.9,26.3(8:1).

(vii) **[(OCH$_2$CMe$_2$CH$_2$O)P(O){C(4-OMe-C$_6$H$_4$)CH$_2$C(H)(COOMe)-}]** (58)

Mp: 122-124°C.

Yield: 0.24 g (68%).

IR (KBr): 1740, 1611, 1514, 1437, 1377, 1254, 1213 cm^{-1}.

^{1}H NMR: δ 0.56, 0.85 (2 s, 6 H, C(CH_3)$_2$), 1.46, 2.15 (2 m, 3 H, C$H_A H_B$C(H)(COOMe)), 3.52 (m, 2 H, OCH_AH$_B$),3.75, 3.77 (2 s, 6 H, COOCH_3 + Ar-OCH_3), 4.07 (dd, ^2J(HH) = 11.0 Hz, V(PH) = 7.2 Hz, 2 H, OCH$_A H_B$), 6.81 (d, V(HH) = 8.6 Hz, 2 H, Ar-meta--H), 7.36 (dd, V(HH) = 8.6 Hz, ^4J(PH) = 3.8 Hz, 2 H, Ar-ortho-H).

^{13}C NMR: δ 16.7 (s, CH$_2$C(H)(COOMe)), 20.9, 21.4 (2 s, C(CH$_3$)$_2$), 28.3 (d, ^1J(PC) = 189.3 Hz, PC), 29.1 (s, CH$_2$$C$(H)(COOMe)), 32.2 (d, V(PC) = 7.3 Hz, CMe$_2$), 52.3 (s, COOCH$_3$), 55.3 (s, ArOCH3), 75.6, 75.7 (2 s, OCH$_2$), 113.7, 129.9, 132.0, 132.1, 158.2, 169.5 (d, V(PC) ~ 5.0 Hz, COOMe).

^{31}P NMR: δ 19.1,20.9(20:1).

Anal. Calcd for C$_{17}$H$_{23}$O$_6$P: C, 57.62; H, 6.49. Found: C, 56.65; H, 6.68.

(viii) **[(OCH$_2$CMe$_2$CH$_2$O)P(O){C(4-OMe-C$_6$H$_4$)CH$_2$C(Me)(COOMe)-}]** (59)

Mp: 117-119°C.

Yield: 0.22 g (61%).

IR (KBr): 1736, 1613, 1514, 1458, 1244, 1161, 1003 cm^{-1}.

^{1}H NMR: δ 0.49, 0.82 (2 s, 6 H, C(CH_3)$_2$), 1.06 (s, 3 H, C(CH_3)(COOMe)), 1.24, 2.23 (2 dd, V(HH) = 8.6 Hz each, V(PH) = 4.8 Hz each, 2 H, C(ArOCH$_3$)C$H_A H_B$), 3.48 (m, 2 H, OCH_AH$_B$), 3.74 (s, 3 H, COOCH_3), 3.77 (s, ArOCH$_3$), 4.05 (m, 2 H, OCH$_A H_B$), 6.89 (2 br s, 4 H, Ar-H).

^{13}C NMR: δ 19.6 (s, C(Me)CH$_2$), 21.0, 21.4 (2 s, C(CH$_3$)$_2$), 22.4 (s, C(CH$_3$)(COOMe) + CH$_2$$C$(Me)(COOMe)), 30.8 (d, ^1J(PC) = 189.6 Hz, PC), 32.4 (d, V(PC) - 4.8 Hz, CMe$_2$), 52.4 (s, COOCH$_3$), 55.3 (s,

ArOCH3), 75.2, 75.9 (2 d, V(PC) = 6.3 Hz each, OCH_2), 113.7, 126.1, 133.2 (br), 159.2, 172.4 (br, COOMe).

^{31}P NMR: 5 20.7.

Anal. Calcd for $C_{18}H_{25}O_6P$: C, 59.02; H, 6.83. Found: C, 58.38; H, 6.69.

6.3 Hydrolysis of cyclic phosphites / phosphoramidites and its inhibition

6.31 Reactions of cyclic phosphites/ ***phosphoramidites*** **7-12** ***with water in presence of metal salts or*** Et_3N

To freshly distilled $(OCH_2CRR'CH_2O)POPh$ [R, R' = Me (7), Et (8), R = Me, R' = *n*-Pr (9)] or $(OCH_2CRR'CH_2O)PNMe_2$ [R, R' = Me (10), Et (11), R = Me, R' = *n*-Pr **(12)]** (1.0 mmol), 5 mmol of KF or K_2CO_3 or $MgSO_4$ or Et_3N [or 1.5 g of molecular sieves] was added followed by dry THF (8 mL) and water (3 mmol). The reaction mixture was stirred continuously for 3 d. THF was removed by vacuum, the residue was dissolved in $CDCl_3$ (1 mL), and after *ca* 0.5 h the solution was syringed out and submitted for spectroscopic analysis (^1H, ^{13}C, ^{31}PNMR; primarily ^{31}PNMR was used for analysis). Details are given in Table 6 (*cf.* Section 5.3). The spectra in the hydrolysis of 7 and **10** were also checked in benzene-d_6/THF or THF without any deuterated solvent. The results were the same as that obtained using $CDCl_3$.

Hydrolysis of acyclic phosphites $P(OMe)_3$ and $P(OPh)_3$ in the absence of K_2CO_3 using similar experimental conditions as above occurred to an extent of 100% and 40%, respectively. In the presence of K_2CO_3, the hydrolysis was completely inhibited.

6.32 Competitive reaction of phosphites with phenol and water

To a freshly distilled $(OCH_2CRR'CH_2O)PX$ [{X = Cl; R, R' = Me (1), Et (2), R = Me, R' = *n*-Pr (3)} or X = NMe_2; R, R' - Me **(10)]** (1.0 mmol), 5.0 mmol of K_2CO_3 [or 1.5 g of molecular sieves] was added followed by dry THF (8 mL), phenol (1.0 mmol) and water (3 mmol). The reaction mixture was stirred continuously for 8 h. THF was removed by vacuum, the residue was dissolved in $CDCl_3$ (1 mL). After *ca* 0.5 h the solution was syringed out and submitted for spectroscopic analysis (^1H, ^{13}C, ^{31}P NMR; primarily ^{31}P NMR was used for analysis). In place of phenol, 2,6-dichlorophenol or 2,6-dimethylphenol was used and the reaction was not complete in these two cases. Details are given in Table 7 *{cf.* Section 5.3).

6.4 Reversible **cyclization**

6.41 Preparation of the acyclic phosphonate salts 63-65

To freshly distilled hydroxy phosphites $(OCH_2CRR'CH_2O)P(O)H$ [(R, R' = Me (4), R, R' = Et (5), R = Me, R' = n-Pr (6)] (10.0 mmol) an excess of aq. dimethylamine solution (ca 20 mL) was added and the reaction mixture stirred for 3 h. Compounds 63-65 were obtained by removing excess dimethylamine solution *in vacuo* at room temperature. These compounds are very hygroscopic and within seconds of exposure to air become a liquid. Hence they were characterized by spectroscopic methods only and not by elemental analysis.

(i) $[H_2NMe_2]^+[(HOCH_2CMe_2CH_2O)P(H)(O)(O^-)]$ (63)

Yield: 2.04 g, 96%.

^{1}H NMR: 8 0.69 (s, 6 H, CH_3), 2.43 (s, 6 H, N(CH_3)$_2$, 3.13 (s, 2 H, OCH_2), 3.40 (d, V(HH) - 9.5 Hz, 2 H, OCH_2), 6.57 (d, ^1J(PH) = 622.2 Hz, 1 H, P(O)*H*).

^{13}C NMR: 8 21.4 (s, *C*H$_3$), 34.5 (s, N(*C*H$_3$)$_2$), 36.7 (d, ^3J(PC) = 3.9 Hz, *C*Me$_2$), 67.0, 68.6 (d, ^2J(PC) = 4.0 Hz, O*C*H$_2$).

^{31}P NMR: 8 4.6.

(ii) $[H_2NMe_2]^+[(HOCH_2CEt_2CH_2O)P(H)(O)(O^-)]$ (64)

Yield: 2.28 g (95%).

^{1}H NMR: 8 0.65 (t, V(HH) = 7.4 Hz, 6 H, CH$_2$CH_3), 1.05 (m, 4 H, CH_2CH$_3$), 2.47 (s, 6 H, N(CH_3)$_2$), 3.16 (s, 2 H, OCH_2), 3.45 (d, V(PH) = 8.9 Hz, 2 H, OCH_2), 6.58 (d, ^1J(PH) - 622.2 Hz, 1 H, P(O)*H*).

^{13}C NMR: 8 6.8 (s, CH$_2$*C*H$_3$), 21.4 (s, *C*H$_2$CH$_3$), 34.5 (s, N(*C*H$_3$)$_2$), 41.5 (br s, *C*Et$_2$), 63.1, 65.0 (2 s, O*C*H$_2$).

^{31}P NMR: 8 4.8.

(iii) $[H_2NMe_2]^+[(OCH_2C(Me)(n\text{-}Pr)CH_2O)P(H)(O)(O^-)]$ (65)

Yield: 2.31 g (96%).

^{1}H NMR: 8 0.78 (s, 3 H, CH_3), 0.85 (t, ^3J(HH) = 6.9 Hz, 3 H, CH$_2$CH$_2$CH_3), 1.17-1.23 (m, 4 H, CH_2CH_2CH$_3$), 2.56 (s, 6 H, N(CH_3)$_2$), 3.29 (AB qrt, ^2J(HH) ~ 8.5 Hz, 2 H, HOCH_2), 3.58 (symmetrical m, 2 H, OCH_2), 6.73 (d, ^1J(PH) - 626.1 Hz, 1 H, P(O)*H*).

^{13}C NMR: 5 14.9 (s, CH_3), 16.2, 18.3 (2 s, $CH_2CH_2CH_3$), 34.5 (s, $N(CH_3)_2$), 36.3, 39.4 (s, $CMe(n\text{-}Pr)$), 65.8 (2 s, OCH_2), 67.3 (d, V(PC) = 3.5 Hz, OCH_2).

^{31}P NMR: 5 5.2.

(iv) $[DMAPH]^+[(HOCH_2CMe_2CH_2O)P(H)(O)(O^-)]$ (66)

To a stirred solution of $(OCH_2C(CH_3)_2CH_2O)P(O)H$ (1.50 g, 10.0 mmol) in dichloromethane (10 mL), water (0.18 g, 10.0 mmol) was added followed by DMAP (1.34 g, 11.0 mmol). The mixture was stirred for 3 h, the solution concentrated to 2 mL, toluene (8 mL) added and the solution preserved at 0°C. Crystals of **66** were obtained after 1 d.

Yield: 2.7 g (93.1%).

Mp: 88-90 C.

^1H NMR: 5 0.78 (s, 6 H, CH_3), 3.13 (s, 6 H, $N(CH_3)_2$, 3.25 (s, 2 H, OCH_2), 3.59 (d, V(PH) = 11.1 Hz, 2 H, OCH_2), 6.85 (d, $^1J(PH)$ = 621.3 Hz, 1 H, $P(O)H$), 6.70, 8.20 (2 d, V(HH) = 15.0 Hz each, 4 H, DMAP-*H*).

^{13}C NMR: δ 21.5 (s, CH_3), 37.1 (br s, CMe_2), 39.9 (s, $N(CH_3)_2$), 67.2, 68.5 (2 s, OCH_2), 106.7, 139.9, 157.1 (DMAP-*C*).

^{31}P NMR: 5 5.6.

An X-ray structure was obtained for a sample crystallized from a mixture CH_2Cl_2 and toluene (*cf.* Fig. 7; Section 5.3).

6.42 Recyclization of the salts **63-65** *to the H-phosphonates* 4-6 ***and*** *conversion of* 4-6 *to the a-hydroxyphosphonates* (67-69)

The salts **63-65** (1.2-1.3 g) were heated at 100°C for 3 h, and the resulting H-phosphonates $(OCH_2CRR'CH_2O)P(O)H$ [(R, R' - Me (4), R, R' = Et (5), R = Me, R' = *n*-Pr (6)] were distilled under vacuum. The yields of 4-6 were in the range 60-85%; however, in the conversion of these to the corresponding a-hydroxyphosphonates 67-69 by a literature procedure,[100b,102] no difficulties were encountered.

(i) $(OCH_2CMe_2CH_2O)P(O)CH(OH)4\text{-}Cl\text{-}C_6H_4$ (67)

Yield: 60 % (from cyclization route).[102]

(ii) $(OCH_2CEt_2CH_2O)P(O)CH(OH)Ph$ (68)

Mp: 130-133°C.

Yield: 85%.

^{1}H NMR: 8 0.67, 0.76 (2 t, V(HH) = 7.1 Hz for both, 6 H, CH_2CH_3), 1.05, 1.51 (2 qrt, V(HH) = 7.1 Hz, 4 H, CH_2CH_3), 3.81-4.29 (m, 4 H, OCH_2), 5.04 (d, V(PH) = 12.3 Hz, 1 H, P-C*H*-OH), 5.36 (br. s, 1 H, P-CH-O*H*), 7.14-7.52 (m, 5 H, Ph-*H*).

^{3}C NMR: 5 6.9, 7.1 (2 s, CH_2CH_3), 22.5, 22.6 (2 s, CH_2CH_3), 37.1 (d, V(PC) ~ 5.5 Hz, CEt_2), 71.9 (d, ^{1}J(PC) = 157.6 Hz, P-*C*H(OH)), 75.1, 75.8 (2 d, ^{2}J(PC)= 6.9 Hz for both, OCH_2), 126.9, 127.0, 127.8, 128.1, 137.3 (all C(Ar)).

^{31}P NMR: δ 14.3.

(iii) **$(OCH_2C(Me)(n\text{-}Pr)CH_2O)P(O)CH(OH)Ph$ (69)**

Mp: 168-170°C.

Yield: 75%.

H NMR: 5 0.71 (s, 3 H, CH_3), 0.91 (t, V(HH) = 7.0 Hz, 3 H, $CH_2CH_2CH_3$), 1.21-1.45 (m, 4 H, $CH_2CH_2CH_3$), 3.93-4.07 (m, 4 H, OCH_2), 4.35 (br s, 1 H, P-CH-O*H*), 5.12 (d, ^{2}J(PH) = 11.8 Hz, 1 H, P-C*H*-OH), 7.26-7.49 (m, 5 H, Ph-*H*).

^{13}C NMR: 5 14.4, 16.3, 17.7, 34.8 (d, V(PC) ~ 5.5 Hz, *C*Me(*n*-Pr), 36.1, 71.7 (d, ^{1}J(PC) = 160.0 Hz, P-*C*H(OH)), 75.9, 76.0, 76.4, 126.8, 126.9, 128.0, 128.2, 136.5.

^{31}P NMR: 5 13.6.

6.S X-ray crystallography

A suitable crystal was mounted on a glass fibre (for 19, 40) or inserted into a Lindemann capillary (for **66)** and X-ray data collected at 293 K on an Enraf-Nonius MACH3 or on a Bruker AXS-SMART diffractometer using Mo-K_α radiation (λ = 0.71073 A). Structures were solved and refined using standard methods.[125] Crystal data are summarized in Table 9.

Table 9 Crystal data for compounds **19**, **40** and **66**.

Compound	**19**	**40**	**66**
Emp. formula	$C_8H_{13}O_3P$	$C_{11}H_{17}N_2O_3P$	$C_{12}H_{23}N_2O_4P$
Formula weight	188.15	256.24	290.29
Crystal system	Orthorhombic	Orthorhombic	Triclinic
Space group	P2(1)2(1)2(1)	Pbca	$P\bar{1}$
a /Å	8.8325(5)	11.1757(9)	8.646(2)
b /Å	8.9436(5)	11.5516(9)	8.761(3)
c /Å	12.0211(7)	20.2850(2)	11.811(7)
α/deg	90.00	90.00	109.19(7)
β/deg	90.00	90.00	105.72(3)
γ/deg	90.00	90.00	99.38(4)
V /Å^3	949.60(9)	2618.7(4)	781.4(6)
Z	4	8	2

D_{calc} /g cm^{-3}]	1.316	1.300	1.234
μ /mm^{-1}	0.256	0.209	0.187
F(000)	400	1088	312
Crystal size [mm]	0.3 x 0.3 x 0.2	0.3 x 0.3 x 0.2	0.2 x 0.2 x 0.2
2θ max.	56	56	50
Observed reflections (I>2σ(I))	2086	2275	1810
Data/ restraints/ parameters	2269/ 0/ 118	3147/ 0/ 157	2750/ 0/ 189
S	1.089	1.013	1.184
R1 [I>2σ(I)]	0.0381	0.0504	0.0635
wR2 [all data]	0.1150	0.1403	0.1968
Max./min. residual electron dens. [eÅ^{-3}]	0.242/ -0.256	0.350/ -0.216	0.564/ -0.529

REFERENCES

1 (a) J. Boutagy and R. Thomas, *Chem. Rev.,* 1974, 74, 87; (b) M. Mizuno, K. Fuji and K. Tomioka, *Angew. Chem. Int. Ed. Engl.,* 1998, 37, 515; (c) T. J. J. Mueller, *J. Organomet. Chem.,* 1999, 1-2, 95; (d) S. R. Chemler, D. S. Coffey and W. R. Roush, *Tetrahedron Lett.,* 1999, **40,** 1269; (e) S. Sano, T. Ando, K. Yokyama and Y. Nagao, *Syn. Lett.,* 1998, 7, 777; (f) E. Diez-Barra, J. C. Garcia-Martinez and J. Rodirignez-Lopez, *Tetrahedron Lett.,* 1999, **40,** 8181; (g) T. Arai, H. Sasai, K. Yamaguchi and M. Shibasaki, *J. Am. Chem. Soc,* 1998, **120,** 441; (h) K. Kokin, K. I. Iitake, Y. Takaguchi, H. Aoyama, S. Hayashi and J. Motoyoshiya, *Phos. Sulf. Relat. Elem.,* 1998, **133,** 21; (i) J. P. Gourves, H. Couthon and G. Sturtz, *Eur. J. Org. Chem.,* 1999, 12, 3489; (j) M. C. Allen, W. Fuhrer, B. Truck, R. Wade and J. M. Wood, *J. Med. Chem.,* 1989, **32,** 1652; (k) E. K. Baylis, C. D. Campbell and J. G. Dingwall, *J. Chem. Soc, Perkin Trans. 1,* 1984, 2485; (1) F. R. Artherton, C. H. Hassal and R. W. Lamber, *J. Med. Chem.,* 1986, 29, 29.

2 W. S. Wadsworth, Jr., *Org. Reactions,* 1977, **25,** 73.

3 B. E. Maryanoff and A. B. Reitz, *Chem. Rev.,* 1989, 89, 863.

4 (a) R. Engel, *Chem. Rev.,* 1977, 77, 349; (b) R. L. Hilderbrand, *The Role of Phosphonates in Living Systems,* CRC Press, Boca Raton, FL, 1982; (c) A. S. Baskar, M. J. Ciocci, W. W. Metcalf, J. Kim, P. C. Babbit, B. L. Wanner, B. M. Martin and D. D-Mariano, *Biochemistry,* 1998, 37, 9305; (d) S. Shuto, S. Niizuma and Matsuda, *J. Org. Chem.,* 1998, 63, 4489; (e) J. E. Hanson, A. P. Kaplan and P. A. Bartlett, *Biochemistry,* 1989, 28, 6294; (0 E. P. Garvey, G. T. Lowen and M. R. Almond, *Biochemistry,* 1998, **37,** 9043.

5 (a) K. P. Kumar, C. Muthiah, S. Kumaraswamy and K. C. Kumara Swamy, *Tetrahedron Lett.,* 2001, *42,* 3219. (b) T. R. Chantara and Z. Chairul, *Polym. Degrad. Stab.,* 1999,65,481.

6 For reviews on allenylphosphonates, See: (a) A. N. Pudovik, N. G. Khusainova and I. M. Aledzheva, *J. Gen. Chem. USSR,* 1964, 34, 2484; (b) N. G. Khusainova and A. N. Pudovik, *Russ. Chem. Rev.,* 1987, 56, 564; (c) Ch. Angelov, *Phos. Sulf. Relat. Elem.,* 1983, 15, 177; (d) N. G. Khusainova and A. N. Pudovik, *Russ. Chem. Rev.,* 1978, 47, 803; (e) I. V. Alabugin and V. K. Brel, *Russ. Chem. Rev.,* 1997, 66, 205.

7 For structural features, See: (a) A. N. Cheklov, V. K. Brel, E. V. Abramkin, N. S. Zefirov, *Dokl. Akad. Nauk. SSSR,* 1991, **319,** 4117; (b) A. M. Gazaliev. O. A. Nurkenov, R. Z. Kasenov, K. M. Turdybekov and Yu. T. Struchkov, *Zh. Obshch. Khim.,* 1992, 62, 1522; (c) V. Yu. Nesterov and V. A. Naumov, *Zh. Obshch. Khim.,* 1993,63,2585.

8 (a) H. F. Schuster and G. M. Coppola, "*Allenes in Organic Synthesis",* Wiley-interscience, New York, 1984; (b) H. Fischer in S. Patai. Ed., "*The Chemistry of Alkenes",* Wiley-interscience, New York, 1964, p. 1060; (c). K. Griesbaum, *Angew. Chem. Int. Ed.* 1966, 5, 937; (d) D. R. Taylor, *Chem. Rev.,* 1967, 67, 317; (e) M. C. Caserio in B. S. Thyagarajan, Ed., Selective Organic Transformations, Vol. 1, Wiley-interscience, New York, 1970; (0 S. Patai, Ed., "*The Chemistry of Ketenes, Allenes and Related Compounds*", Wiley-interscience, New York, 1980; (g) T. H. Chan and B. S. Ong, *Tetrahedron,* 1980, 36, 2269; (h) J. A. Marshall, *Chem. Rev.,* 1996, 96, 31.

9 For recent reviews, see: (a) R. Zimmer, C. U. Dinesh, E. Nandanan, and F. Khan, *Chem. Rev.,* 2000, **100,** 3067; (b) A. S. K Hashimi,. *Angew. Chem., Int. Ed. Engl.,* 2000, **39,** 3590; (c) X. Lu, C. Zhang and Z. Xu, *Acc. Chem. Res.,* 2001, **34,** 535.

10 (a) For Electrophilic addition reactions: (a) K. Griesbaum, *J. Am. Chem. Soc,* 1964, 86, 2301; (b) K. Griesbaum, W. Naegele, and G. G. Wanless, *J. Am. Chem. Soc,* 1965, 87, 3151; (c) G. F. Hennion, and J. J. Sheehan, *J. Am. Chem. Soc,* 1964, 71, 1964; (d) R. D. Bach, J. W. Holubka and C. L. Willis, *J. Am. Chem. Soc,* 1982, **104,** 3980; (e) C. Georgoulis, W. Smadja and J. M. Valery, *Synthesis,* 1981, 572.

11 For Nucleophilic additions, see: (a) J. J. Drysdale, H. B. Stevenson and W. H. Sharkey, *J. Am. Chem. Soc,* 1959, 81, 4908; (b) E. R. H. Jones, G. Eglinton, G. H. Mansfield and M. C. Whiting, *J. Chem. Soc,* 1954, 3197.

12 For sulfer containing allenes see (a) S. Ma and Q. Wei, *J. Org. Chem.,* 1999, 64, 1026; (b) S. Ma and Q, Wei, *Eur. J. Org. Chem.,* 2000, 1939; (c) S. Ma, Q, Wei, and H. Wang, *Org. Lett.,* 2000, 2, 3893; (d) A. Padwa, M. Meske, S. S. Murohree, S. H. Watterson and Z. Ni, *J. Am. Chem. Soc,* 1995, 117, 7071; (e) N. P. Pavri and M. L. Trudell, *Tetrahedron Lett.,* 1997, 38, 7993; (f) G. Pourcelot and P. Cadiot, *Bull. Chem. Soc. Fr.,* 1966, 3016. For Oxygen and Nitrogen containing allenes, see: (g) R. Mantione, *Bull. Soc. Chim. Fr,* 1969, 4523; (h) R. W. Hoffmann and B. Kemper, *Tetrahedron Lett.,* 1981, 22, 5263; (i) A. J. Hubert and H. Reimlinger, *J. Chem. Soc. (C),* 1968, 606; (j) W. B. Dickinson and P. C. Lang, *Tetrahedron Lett.,* 1967, 8, 3035; (k) C. Bogentoft, O. Ericsson, P. Stenberg and B. Danielsson, *Tetrahedron Lett.,* 1969,10,4745.

13 (a) K. S. Mingaleva, B. I. Ionin, V. M. Ignatev, L. N. Mashlyakovskii and A. A. Petrov, *Zh. Obshch. Khim.,* 1969, 39, 1524; (b) I. I. Patsanovskii, E. N. Strelkova, E. A. Ishmaeva, A. B. Remizov, N. G. Khusainova, L. V. Naumova, A. N. Pudovik, *Zh. Obshch. Khim.,* 1982, 52, 1045; (c) G. A. Kurdy, R. S. Macomber, *J. Org. Chem.,* 1978,43,4656.

14 Phosphorus heterocycles from allenylphosphonates (a) Ch. M. Angelov, *Zh. Obshch. Khim.,* 1980, 50, 2448; (b) D. Rardon and R. S. Macomber, *J. Org. Chem.,* 1990, 55, 1493; (c) R. S. Macomber, D. E. Rardon and D. M. Ho, *J. Org. Chem.,* 1992, 57, 3874; (d) N. S. Zefirov, A. S. Kozmin, T. Kasumov and K. A. Potekhin, *J. Org. Chem.,* 1992, 57, 2433; (e) R. S. Macomber, G. A. Krudy, and M. Saki Amer, *J. Org. Chem.,* 1983, 48, 1420; (f) Ch. M. Angelov, D. D. Enchev, *Phos. Sulf.* 1988, 37, 125; (g) V. K. Brel, *Synthesis,* 1998, 710; (h) F. Palacios, D. Aparicio, J. M. de los. Santos, Tetrahedron, 1994, 50, 12727; (o) V. K. Brel, *Synthesis,* 1999, 463.

15 Synthesis of allenylphosphonates via pseudo-CIaisen type rearrangement. See: (a) D. Guillerm and M. L. Capmau, *Tetrahedron,* 1972, 28, 3559; (b) A. Sevin and W. Chodkiewicz, *Tetrahedron Lett.,* 1967, 17, 2975; (c) R. S. Macomber, *J. Org. Chem.,* 1978, 43, 1832; (d) A. P. Boisselle and N. A. Meinhardt, *J. Org. Chem.,* 1962, 27, 1828; (e) H. J. Lucas, F. W. Mitchell Jr and C. N. Scully, *J. Am. Chem. Soc,* 1950, 72, 5491; (f) C. Patois, L. Richard and P. Savignac, *J. Chem. Soc. Perkin Trans. I,* 1990, 1577; (g) M. Huche and P. Cresson, *Tetrahedron Lett.,* 1972, 22, 4933; (h) R. S. Macomber and E. R. Kennedy, *J. Org. Chem.,* 1976, 41, 3191; (i) A. J. Zapata, Y. Gu and G. B. Hammond, *J. Org. Chem.,* 2000, 65, 227.

16 A. N. Pudovik, *J. Gen. Chem.,* 1950, 29, 97.

17 D. H. Burton and. L. G. Sprague, *J. Org. Chem.,* 1989, 54, 613.

18 (a) G. A. Krudy and R. S. Macomber, *J. Org. Chem.,* 1978, 43, 4556; (b) R. S. Macomber, J. *Am. Chem. Soc,* 1983; *105,* 4386.

19 (a) C. Angelov, C. Z. Christov and D. M. Mondeshka, *Phos. Sulf. Relat. Elem.,* 1984, 21, 249; (b) C. Angelov and C. Vachkov, *Phos. Sulf. Relat. Elem.,* 1984, 21, 237.

20 A. V. Fedorova and A. A. Petrov, *J. Gen. Chem.,* 1961, 31, 3273.

21 (a) S. Braverman and D. Reisman, *Tetrahedron Lett.* 1977, 18, 1753; (b) S. Braverman and D. Reisman, *JAm. Chem. Soc,* 1977, *99,* 605.

22 C. Angelov, D. D. Enchev and M. Kirilov, *Zh. Obshch. Khim.,* 1983, 53, 1958.

23 (a) V. K. Brel, B. 1. Ionin, A. A. Petrov and I. V. Martynov, *Zh. Obshch. Khim.,* 1985, 55, 2465; (b) R. S. Macomber, *J. Am. Chem. Soc,* 1977, 99, 3072; (c) K. Shingu, S. Hagishita, M. Nakagawa, *Tetrahedron Lett.,* 1967, 17, 4371.

24 R. S. Macomber and E. R. Kennedy, *J. Org. Chem.,* 1976, 41, 3191.

25 R. S. Macomber, *J. Org. Chem.,* 1977, 42, 3297.

26 R. C. Elder, L. R. Florian, E. R. Kennedy and R. S. Macomber, *J. Org. Chem.,* 1973, 38,4177.

27 (a) R. S. Macomber, A. K. George, K. Seff, and L. E. Rendon-Diaz-Miron, *J. Org. Chem.,* 1983, 48, 1425; (b) N. G. Khusainova, L. V. Naumova, E. A. Berdnikov, G. A

Kutyrev and A. N. Pudovik, *Phos. Sulf. Relat. Elem.,* 1982, 13, 147; (c) Ch. M. Angelov, Heterocycles, 1983, 20, 791; (d) 1. V. Alabugin, V. K. Brel, A. N. chekhlov, N. S. Zefirov and P. Stang, *Tetrahedron Lett.,* 1994, 35, 8275.

28 (a) R. Gaertner, *J. Am. Chem. Soc,* 1951, 73, 4400. (b) B. S. Tyagarajan, K. K. Balasubramanian and R. B. Rao, *Tetrahedron Lett.,* 1963, 4, 1393.

29 H. Altenbach and R. Korff, *Tetrahedron Lett.,* 1981, 22, 5175.

30 R. Gaertner, *J. Am. Chem. Soc.,* 1951, **73**, 4400.

31 (a) A. N. Pudovik and N. G. Khusainova, *J. Gen. Chem.,* 1966, 36, 1251; (b) H. Altenbach and R. Korff, *Angew. Chem., Int. Ed.,* 1982, 21, 371.

32 (a) A. N Pudovik, N. G. Khusainova and I. M. Aladzheva, *J. Gen. Chem.,* 1964, 34, 248; (b) A. N. Pudovik, N. G. Khusainova and T. A. Abdulina, *J. Gen. Chem.,* 1967, 37, 809.

33 (a) J. Berlan and J-P. Battioni, *Tetrahedron Lett.,* 1976, 26, 3351; (b) K. Koosha, *Eur. J. Inorg. Chem.,* 1999, 2, 225.

34 R. A. Abramovitch, M. Konieczny, W. Pennington, S. Kanamathareddy and M. Vedachalam, *J. Chem. Soc, Chem. Commun.*, 1990, 269.

35 V. K. Brel, *Synthesis,* 2002, 1829.

36 (a) P. J. Stang, in *The Chemistry of Functional Groups, Supplement E. The Chemistry of Ethers, Crown Ethers, Hydroxyl Groups and their Sulphur Analogues;* S.Patai, Ed.; Wiley: New York, **1980;** pp 859-879; (b) T. H. Chan and B. S. Ong, *Tetrahedron,* 1980, 36, 2269; (c) R. L. Camp, and F. D. Greene, *J. Am. Chem. Soc,* 1968, **90,** 7349; (d) J. K. Crandall, W. W. Conover, J. B. Komin and W. H. Machleder, *J. Org. Chem,.* 1974, 39, 1723; (e) J. K. Crandall and W. H. Machleder, *J. Am. Chem. Soc,* 1968, **90,** 7347; (0 R. S. Macomber, *J. Org. Chem.,* 1978, 43, 1832.

37 (a) M. S. Chatta and A. M. Aguiar, *J. Org. Chem.,* 1971, 36, 2719; (b) T. M. Balthazor and R. A. Flores, *J. Org. Chem.,* 1980, 45, 529; (c) R. M. Acheson, P. J. Ansell and J. R. Muray, *J. Chem. Res. (S),* 1986, 378; *J. Chem. Res. (R),* 1986, 3001; (d)G. Sturtz, *Bull. Soc Chim. Fr.,* 1967, 1345.

38 B. Iogra, F. Eymery, D. Carmichael and P. Savignac, *Eur. J. Org. Chem.,* 2000, 3103.

39 K. Ando, *J. Org. Chem.,* 1998, 63, 8411.

40 S. E. Kelly, in *Comprehensive Organic Synthesis;* M. B. Trost and I. Flemming, Editors; S. L. Schreiber, Volume Ed.; Pergamon: Oxford, 1991, Vol. 1, p 762.

41 B. E. Maryanoff and A. B. Reitz, *Chem. Rev.,* 1989, 89, 863.

42 D. F. Weimer, *Tetrahedron,* 1997, 53, 16609.

43 (a) D. Y. Kim, M. S. Kong and T. H. Kim, *Synth. Commun.,* 1996, 26, 2487; (b) C. W. Lee, J. E. Hong and *D. Y.* Oh, *J. Org. Chem.,* 1995, 60, 7027; (c) D. Y. Kim and M. S. Kong, *J. Chem. Soc, Chem. Commun.* 1994, 3359; (d) Y. J. Koh and D. Y. Oh, *Tetrahedron Lett.,* 1993, 34, 2147.

44 B. A. Arbuzov, *Pure Appl. Chem.* 1964, 9, 307.

45 A. K. Bhattacharya and G. Thyagarajan, *Chem. Rev.,* 1981, 81, 415.

46 P. Sampson, G. B. Hammond and D. F. Weimer, *J. Org. Chem.,* 1986, 51, 4342.

47 F. Mathey and P. Savignac, *Tetrahedron,* 1978, **34**, 649.

48 (a) E. J. Corey and G. T. Kwiatkowski, *J. Am. Chem. Soc,* 1966, 88, 5653. (b) E. J. Corey and G. T. Kwiatkowski, *J. Am. Chem. Soc,* 1968, **90,** 6816. (c) M. Mikolajczyk and P. Balczewski, *Synthesis,* 1984, 691.

49 (a) M. Ordonez, R. de la Cruz, M. Fernandz-Zertuche and M-A. Munoz-Hernandez, *Tetrahedron: Asymmetry,* 2002, **13**, 559

50 R. K. Boeckman Jr, M. A. Walters and H. Koyano, *Tetrahedron Lett.,* 1989, 30, 4787.

51 F. Orsini, E. Di Teodoro and M. Ferrari, *Synthesis,* 2002, 1683.

52 H. K. Lee, E-K. Kim and C. S. Pak, *Tetrahedron Lett.,* 2002, 43, 9644.

53 (a) T. Calogeropoulou, G. B. Hammond and D. F. Weimer, *J. Org. Chem.,* 1987, 52, 4185; (b) T. J. Baker and D. F. Weimer, *J. Org. Chem.,* 1998, 63, 2613; (c) S. Hong, K. Chang, B. Ku and D. Young Oh, *Tetrahedron Lett.,* 1989, 30, 3307.

54 M. P. Cooke Jr. and R. K. Widner, *J. Am. Chem. Soc,* 1987, **109**, 931.

55 H. Altenbach and R. Korff, *Tetrahedron Lett.,* 1981, 22, 5175.
56 B. Corbel, I. L. Kervella and J.-P. Haelters, *Synth. Commun.,* 1996, 26, 2561.
57 (a) L. Homer, H. Hoffmann, H. G. Wippel and G. Klahre, *Chem. Ber.,* 1959, 92, 2499; (b) W. S. Wadsworth, Jr., and W. D. Emmons, *J. Am. Chem. Soc,* 1961, 83, 1733.
58 J. Chun, H.-S. Byun, G. Arthur and R. Bittman, *J. Org. Chem.,* 2003, 68, 355.
59 S. –K. Chung and D. -H. Kang, *Tetrahedron: Asymmetry.,* 1997, 8, 3207.
60 A. Abiko and S. Masamune, *Tetrahedron Lett.,* 1996, 37, 1077.
61 (a) E. Breuer and D. M. Bannet, *Tetrahedron Lett.,* 1977, 18, 1141; (b) C. Patois and P. Savingnac, *Tetrahedron Lett.,* 1991, 32, 1317; (c) W. C. Still and C. Gennari, *Tetrahedron Lett.,* 1983, 24, 4405.
62 (a) A. Bernardi, S. Cardani, C. Scolastico and R. Villa, *Tetrahedron,* 1988, 44, 491; (b) R. K. Boeckman Jr., C. H. Weidner, R. B. Perni and J. J. Napier, *J. Am. Chem. Soc,* 1989, 111, 8036; (c) T. Minami, T. Utsunomiya, S. Nakamura, M. Okubo, N. Kitamura, Y. Okada, J. Ichikawa, *J. Org. Chem.,* 1994, 59, 6717; (d) A. M. P. Koskinen and P. M. Pihko, *Tetrahedron Lett.,* 1994, 35, 7417.
63 W. Yu, M. Su and Z. Jin, *Tetrahedron Lett.,* 1999, 40, 6725.
64 Y. Hasiao, N. R. Rivera, N. Yasuda, D. L. Hughes and P. J. Reider, *Org. Lett.,* 2001, 3, 1101.
65 (a) J. E. Hong, W. S. Shin, W. B. Jang and D. Y. Oh, *J. Org. Chem.,* 1996, 61, 2199; (b) S. Y. Lee, C.-W. Lee and D. Y. Oh, *J. Org. Chem.,* 1996, 64, 7017.
66 C. A. Verbicky and C. K. Zercher, *J. Org. Chem.,* 2000, 65, 5615.
67 (a) L. Maier, *Phos. Sulf.,* 1983, 14, 295. (b) B. Dhawan and D. Redmore, *Phos. Sulf.,* 1987, 32, 119. (c) P. Kafarski and B. Lejczak, *Phos. Sulf. Relat. Elem.,* 1991, 63, 193. (d) V. P. Kukhar', N. Y. Svistunova, V. A. Solodenko and V. A. Soloshonok, *Russ. Chem. Rev.,* 1993,62, 261.
68 (a) H. Wynberg and A. A. Smaardijk, *Tetrahedron Lett.,* 1983, 24, 5899; (b) U. Schollkopf, 1. Hoppe and A. Thiele, *Liebigs Ann. Chem.,* 1985, 555; (c) R. Huber, A. Knierzinger, J.-P. Obrecht and A. Vasella, *Helv. Chim. Acta,* 1985, 68, 1730; (d) U. Schollkopf and R. Schiitze, *Liebigs Ann. Chem.,* 1987, 45; (e) D. Seebach, R. Charczuk, C. Gerber, P. Renaud, H. Bemer and H. Schneider, *Helv. Chim. Acta,* 1989, 72, 401;. (f) M. Sawamura, Y. Ito and T. Hayashi, *Tetrahedron Lett,.* 1989, 30, 2247; (g) S. Hanessian, Y. L. Bennani and D. Delorme, *Tetrahedron Lett.,* 1990, 45, 6461; (h) S. Laschat and H. Kunz, *Synthesis,* 1992, 90; (i) U. Groth, L. Richter and U. Schollkopf, *Tetrahedron,* 1992, 48, 117; (j) T. Yokomatsu, T. Yamagishi and S. Shibuya, *Tetrahedron: Asymmetry,* 1993,4, 1783.
69 (a) M. Hashimoto, K. Hemmi, H. Takeno and T. Kamiya, *Tetrahedron Lett.,* 1980, 21, 99; (b) J. F. Dellaria and R. G. Maki, *Tetrahedron Lett.,* 1986, 27, 2337; (c) N. S. Sampson and P. A. Bartlett, *J. Org. Chem.,* 1988, 53, 4500; (d) P. P. Giannousis and P. A. Bartlett, *J. Med. Chem.,* 1987, 30, 1603; (e) J. Heilmann, and W. F. Maier, *Angew. Chem., Int. Ed. Engl.,* 1994, 33, 471; (f) R. Hirschmann, A. B. Smith III, C. M. Taylor, P. A. Benkovic, S. D. Taylor, K. M. Yager, P. A, Sprengeler and S. J. Benkovic, *Science,* 1994, 265, 234.
70 (a) T. Gajda, M. Nowalin´ska, S. Zawadzki and A. Zwierzak, *Phosphorus, sulfur Silicon,* 1995, 105, 45; (b) R. Hirschman, K. M. Yager, C.M. Taylor, W. Moore, P. A. Sprengeler, J. Witherington, B. W. Philips and A. B. Smith III., *J. Am. Chem. Soc,* 1995,117,6370.
71 (a) M. Ordonez, A. Gonzalez-Morales, C. Ruýz, R. D. Cruz-Cordero and M. Fernandez-Zertuche, *Tetrahedron: Asymmetry,* 2003, 14, 1775; (b) M. Mikolajczyk, J. Luczak and P. Kielbasinski, *J. Org. Chem.,* 2002, 67, 7872.
72 F. Orsini, *Tetrahedron Lett.,* 1998, 39, 1425.
73 L. Zhengong, R. Saibaba D. Li, H. El-Subbagh and E. Abushanab, *J. Org. Chem.,* 1993, 58, 5779.
74 L. M. Lentsch and D. F. Wiemer, *J. Org. Chem.,* 1999, 61, 5205.
75 B. C. Ranu, S. Samanta and A. Hajra, *J. Org. Chem.,* 2001, 66, 7519.

76 (a) M. Kitumara, M. Tokunaga and R. Noyori, *J. Am. Chem. Soc,* 1995, **117, 2931;** (b) M. Kitamura, M. Tokunaga, T. Pham W. D. Lubell and R. Noyori, *Tetrahedron Lett.,* 1995, 36, 5769; (c) I. Gautier, V. Ratovelomanana-vidal, P. Savignac and J.-P Genet, *Tetrahedron Lett.,* 1996, **37,** 7721.

77 (a) C. Meier and W. H. G. Laux, *Tetrahedron: Asymmetry,* 1996, 7, 89; (b) C. Meier and W. H. G. Laux, *Tetrahedron: Asymmetry,* 1995, 6, 1089; (c) T. Gajda, *Tetrahedron: Asymmetry,* 1994, 5, 1965; (d) X. Creary, C. C. Geiger and K. Hilton, *J. Am. Chem. Soc,* 1983, **105,** 2851.

78 (a) E. Duda, P. Kafarski and B. Lejczak, *Enzyme and Microbial Technology,* 2000, 26, 265; (b) J. Zygmunt, P. Kafarski and P. Mastalerz, *Synthesis,* 1978, 609; (c) E. Duda, B. Lejczak, P. Kafarski, J. Grimaud and P. Fischer, *Tetrahedron,* 1995, **51,** 11809.

79 (a) M. Drescher, Y. Li and F. Hammerschmidt, *Tetrahedron,* 1995, **51,** 4933; (b) F. Hammerschmidt, and H. Vollenkle, *Liebigs Ann. Chem.,* 1989, 577; (c) Y. Zhang, C. Xu, J. Li and C. Yuan, *Tetrahedron: Asymmetry,* 2003, **14,** 63; (d) Y. Zhang, Z. Li and C. Yuan, *Tetrahedron Lett.,* 2003, 43, 3247; (e) R. Zurawinski, K. Nakamura, J. Drabowicz, P. Kielbasinski and M. Mikolajczyk, *Tetrahedron: Asymmetry,* 2001, 12, 3140.

80 (a) E. D.Bergmann, D. Ginsburg and R. Pappo, *Org. React.,* 1959, **10,** 179; (b) D. A. Hunt, *Org. Prep. Proced. Int.,* 1989, **21,** 705; (c) M. Ihara and K. Fukumoto, *Angew. Chem., Int. Ed. Engl.,* 1993, 32, 1010; (d) P. Perlmutter, *Conjugate Addition Reactions in Organic Synthesis;* Pergamon Press: Oxford, **1992;** (e) R. D. Little, M. R. Masjedizadeh, O. Wallquist, and J. I McLoughlin, *Org. React.,* 1995, **47,** 315; (f) N. Krause and A. Gerold, *Angew. Chem., Int. Ed. Engl.,* 1997, 36, 186; (g) N. Krause, S. Thorand, *Inorg. Chim. Acta,* 1999, **296,** 1.

81 (a) W. Oppolzer, *Tetrahedron* 1987, 43, 1969; (b) D. A. Oare, Heathcock, C. H. *Top. Stereochem.* 1989, **19,** 227; (c) B. E. Rossiter and N. M. Swingle, *Chem. Rev.,* 1992, **92,** 771; (d) J. D. Angelo, D. Desmaele, F. Dumas and A. Guingant, *Tetrahedron: Asymmetry,* 1992, 3, 459; (e) E. Juaristi, A. Beck, J. Hansen, T. Matt, T. Mukhopadhyay, M. Simson and D. Seebach, *Synthesis,* 1993, 1271; (f) N. Krause, *Angew. Chem., Int. Ed,* 1998, 37, 283; (g) J. Leonard, E. Diez-B arra and S. Merino, *Eur. J. Org. Chem.,* 1998, 2051; (h) J. Christoffers, *Eur. J. Org. Chem.* 1998, 1259.

82 (a) S. M. Ruder and V. R. Kulkarni, J. *Chem. Soc, Chem. Commun.,* 1994, 2119; (b) C. Yuan, C. Li and Y. Ding, *Synthesis,* 1991, 854; (c) S. E. Kelly in *Comprehensive Organic Synthesis;* B. M. Trost and I. Fleming, Eds.; Pergamon Press: Oxoford, 1991; Vol.1, pp.755-782; (d) M. Yamaguchi, M. Hamada, H. Nakashima and T. Minami, *Tetrahedron Lett.,* 1987,28, 1785.

83 M. Yamaguchi, Y. Tsukamoto, A. Hayashi and T. Minami, *Tetrahedron Lett.,* 1990, 31, 2423.

84 (a) J. Salaün and M. S. Baird, *Curr. Med. Chem.,* 1995, 2, 511; (b) H. N. C. Wong, M.-Y. Hon, C.-W. Tse, Y.-C. Yip, J. Tanko and T. Hudlicky, *Chem. Rev.,* 1989, 89, **165.**

85 (a) S. Hanessian, D. Andreotti and A. Gomtsyan, *J. Am. Chem. Soc,* 1995, **117,** 10393; (b) S. Hanessian, D. Andreotti and A. Gomtsyan, *J. Am. Chem. Soc,* 1996, 118,2537.

86 T. Arai, H. Sasai, K. Yamaguchi and M. Shibasaki, *J. Am. Chem. Soc,* 1998, **120,** 441.

87 C. Yuan, C. Li and Y. Ding, *Synthesis,* 1991, 854.

88 J. Stawinski and A. Kraszewski, *Acc. Chem. Res.,* 2002, **35,** 952.

89 Selected references (a) Z. Zhang and C.-H. Wong, *Glycosylation methods: Use of phosphites.* In *Carbohydrates in Chemistry and Biology.* Ernst, B., Hart, G.W., Sinay, P. (Eds.). Wiley-VCH, New York, 2000, 117; (b) N. Oka, T. Wada, and K. Saigo, *J. Am. Chem. Soc,* 2002, **124,** 4962; (c) A. Wilk, A. Grajkowski, L. R. Phillips and S. L. Beaucage, *J. Am. Chem. Soc,* 2000, **122,** 2149; (d) Y. Hayakawa, R. Kawai, A. Hirata, J. –ï. Sugimoto, M. Kataoka, A. Sakakura, M. Hirose and R. Noyori, *J. Am.*

Chem. Soc, 2001, **123,** 8165; (e) K. Burgess and D. Cook, *Chem. Rev.,* 2000, **100,** 2047.

90 (a) C. Perez-Lamela, R. Rijk and J. Simal-Gandara, *J. Agric. Food Chem.,* 1998, 46, 687; (b) H.-J. Kleiner, D. Regnat and G. Pfahler, US Patent 6,013,706, 2000. (c) U. Quotschalla and H. Linhart, US Patent 5,840,954, 1998.

91 Selected references on the hydrolysis of phosphate esters: (a) A. E. Wroblewski and J. G. Verkade, *J. Am. Chem. Soc,* 1996, **118,** 10168; (b) B. Gerratana, G. A. Sowa and W. W. Cleland, *J. Am. Chem. Soc,* 2000, **122,** 12615; (c) R. A. Torres and T. C. Bruice, *J. Am. Chem. Soc,* 2000, **122,** 781; (d) R. Kluger and L. L. Cameron, *J. Am. Chem. Soc,* 2002, **124,** 3303.

92 M. Goghova, M. Karvas and J. Durmis, *Chem. Papers,* 1989, 43, 421.

93 (a) J. Emsley and D. Hall, *"Chemistry of Phosphorus",* Harper & Row, 1976, p. 145; (b) R. S. Edmundson, in *"Comprehensive Organic Chemistry":* D. H. R. Barton and V. D., Ollis, Eds.3.; Vol. 2, I. O. Sutherland, Vol. Ed.; Pergamon: Exeter, 1979, Chapter 10.3.

94 (a) J. D. Capolupo and E. H. Jancis, US Patent 4,402,858, 1983; (b) H. Linhart, R. Salathe and J. Zingg US Patent 5,856,550, 1999.

95 G. Linger, P. Staniek and K. Stoll Paper presented at the RETEC, Houston, TX, February 1993.

96 G. J. Klender, Proceedings of the 11th Bratislava IUPAC FECS International Conference on Polymers, Stara Lesna, Slovak Republic, 24-28 June, 1996, P. 85.

97 1. Bauer, S. Körner, B. Pawelke, S. Al-Malaika and W. D. Habicher, *Polym. Degrad. Stab.,* 1998,62, 175.

98 J. Tochacek and J. Sedlar, *Polym. Degrad. Stab.,* 1995, 50, 345.

99 A. Zwierzak, *Can. J. Chem.,* 1967, **45,** 2501.

100 Compounds 7 and **10** are very well documented; see: (a) J. F. Brault and P. Savignac, *J. Organomet. Chem.,* 1974, 66, 71. (b) C. Muthiah, K. Praveen Kumar, C. Aruna Mani and K. C. Kumara Swamy, *J. Org. Chem.,* 2000, 65, 3733.

101 B. E. Maryanoff, R. O. Hutchins and C. A. Maryanoff, *Top. Stereo-chem.,* 1979, **11, 187.**

102 S. Kumaraswamy, R. S. Selvi and K. C. Kumara Swamy, *Synthesis,* 1997, 207.

103 J. -C. Guillemin, P. Savignac and J.-M. Denis, *Inorg. Chem.,* 1991, **30,** 2170.

104 J. H. Wotiz and D. E. Mancuso, *J. Org. Chem.,* 1957, **22,** 207.

105 T. A. Albright, *Org. Magn. Reson.,* 1976, **8,** 489.

106 A. E. Panarina, A. V. Dogadina, V. I. Zakharov and B. I. Ionin, *Tetrahedron Lett.,* 2001,42,4365.

107 (a) M. A. Said, M. Pülm, R. H-Irmer and K. C. Kumara Swamy, *J. Am. Chem. Soc,* 1996, **118,** 9481; (b) M. A. Said, M. PUlm, R. Herbst-Irmer and K. C. Kumara Swamy, *Inorg. Chem.,* 1997, 36, 3044; (c) C. Muthiah, M. A. Said, M. PUlm, R. Herbst-lrmer and K. C. Kumara Swamy, *Polyhedron,* 2000, **19,** 63.

108 C. Muthiah, K. Senthil Kumar and J. J. Vittal and K. C. Kumara Swamy, *SynLett.,* 2002, 1787.

109 (a) Y. Masuyama, T. P. Takahara and Y. Kurusu, *Tetrahedron Lett.,* 1989, **30,** 3437; (b) M. Sati and D. Sinou, *Tetrahedron Lett.,* 1991, **32,** 2025; (c) A. Kundu, S. Prabhakar, M. Vairamani and S. Roy, *Organometallics,* 1997, **16,** 4796.

110 (a) S. Kumaraswamy, S. Nagabrahmananda-chari and K. C. Kumara Swamy, *Synth. Commun.,* 1996, 26, 729; (b) K. Sisido and Y. Takeda, *J. Org. Chem.,* 1961, 26, 2301.

111 (a) Y. Yamamoto and B. Asao, *Chem. Rev.,* 1993, 93, 2207; (b) Y. Yamamoto, *Acc. Chem. Res.,* 1987, **20,** 243; (c) Y. Z. Huang, *Acc. Chem. Res.,* 1992, 25, 182.

112 D. Basavaih, G. J. Reddy and V. Chandrashekar, Tetrahedron: Asymmetry: 2001, 12, 685.

113 (a) J. SalaUn and M. S. Baird, *Curr. Med. Chem.,* 1995, 2, 511; (b) H. N. C. Wong, M.-Y. Hon, C.-W. Tse, Y.-C. Yip, J. Tanko and T. Hudlicky, *Chem. Rev.,* 1989, 89, 165.

114 (a) S. Hanessian, D. Andreotti and A. Gomtsyan, *J. Am. Chem. Soc,* 1995, **117,** 10393; (b) S. Hanessian, D. Andreotti and A. Gomtsyan, *J. Am. Chem. Soc,* 1996, **118,** 2537; (c) Y. L. Bennani and S. Hanessian, *Chem. Rev.,* 1997, 97, 3161; (d) S. Hanessian and L.-D. Cantin, *Tetrahedron Lett.,* 2000, 41, 787; (e) S. Hanessian, L.-D. Cantin, S. Roy, D. Andreotti and A. Gomtsyan, *Tetrahedron Lett.,* 1997, **38**, 1103.

115 For 1,4-conjugate additions of allylic chiral phosphine oxide anions, see: (a) R. K. Haynes, J. P. Stokes and T. W. J. Hambley, *Chem. Commun.*, 1991, 58. (b) R. K. Haynea, S. C. Vonwiller and T. W. Hambley, *J. Org. Chem.,* 1989, 54, 5162; (c) S. Hanessian, A. Gomtsyan, A. Payne, Y. Herve, and S. Beaudoin, *J. Org. Chem.,* 1993, 58, 5032.

116 M. A. Said, M. Vijjulatha and K. C. Kumara Swamy, presented in part at the symposium on *Modern Trends in Inorganic Chemistry-VI,* Hyderabad, August 17-19, 1995, Abstract no. P-36.

117 R. S. Edmundson, In *Comprehensive Organic Chemistry;* D. H. R. Barton, W. D. Ollis, Eds.; I. O. Sutherland, Vol. Ed.; Pergamon: Exeter, 1979; Vol. 2, Chapter 10.3, pp 1189-1231.

118 M. A. Said, K. C. Kumara Swamy, M. Veith and V. Huch, *J. Chem. Soc, Perkin Trans., 1* 1995, 2945.

119 R. Breslow, *Acc. Chem. Res.,* 1995, 28, 146.

120 H. G. Khorana, *Chemical Biology- Selected Papers of H. G. Khorana;* World Scientific: Singapore, 2000; pp 80-95.

121 W. Stec and A. Zwierzak, *Can. J. Chem.,* 1967, 45, 2513.

122 I. Morita, K. Kunimoto, T. Masami, S. Tada, K. Kise and K. Masahiro, *Chem. Pharm. Bull.*, 1987, *35*, 4144.

123 M. A. Said, K. C. Kumara Swamy, M. Veith and V. Huch, *J. Chem. Soc, Perkin Trans.1,* 1995,22,2945.

124 K. P. Kumar, C. Muthiah, S. Kumaraswamy and K. C. Kumara Swamy, *Tetrahedron Lett.*, 2001, 42, 3219.

125 (a) G. M. Sheldrick, *SHELXS-90, Acta Crystallogr., Sect. A,* 1990, 46, 467; (b) G. M. Sheldrick, *SHELXL-93,* University of Göttingen 1993; (c) G. M. Sheldrick, *SHELX-97;* University of Göttingen, 1997.

^{13}C and ^{31}P NMR spectra of representative compounds

PART A

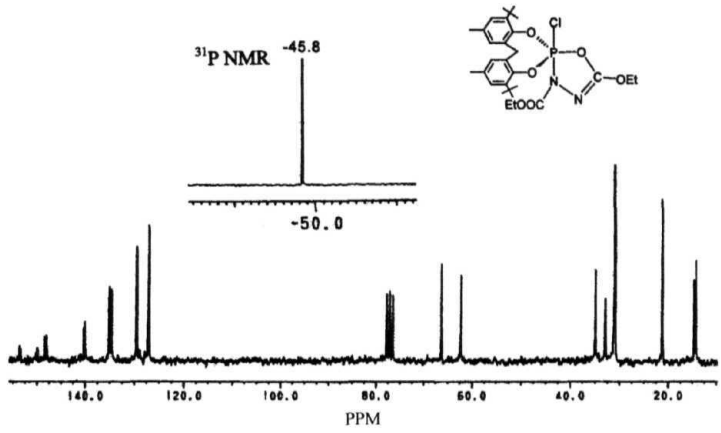


Fig. 1 The ^{13}C and ^{31}P NMR spectra for **10a**.

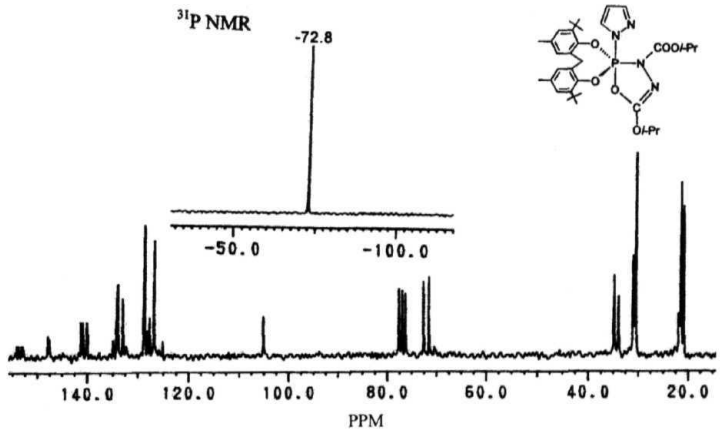


Fig. 2 The ^{13}C and ^{31}P NMR spectra for **16b**.

PART B

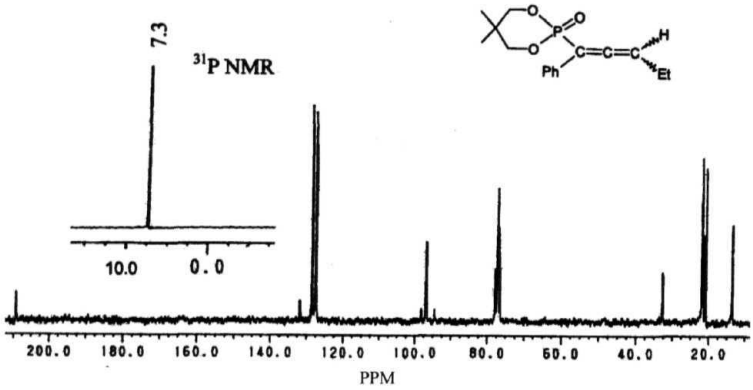


Fig. 3 The ^{13}C and ^{31}P NMR spectra for **23**.

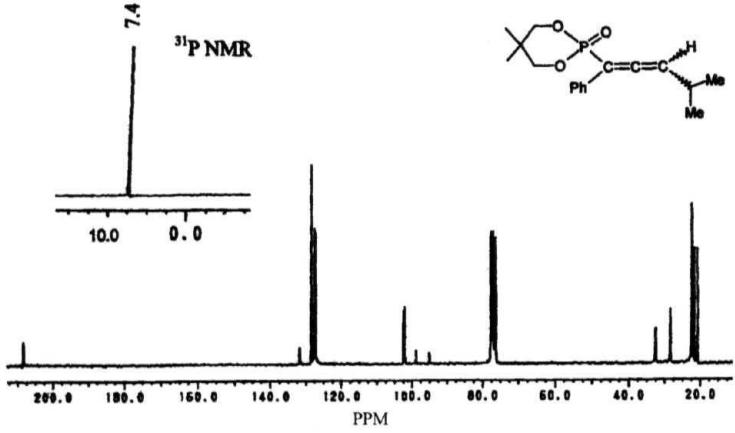


Fig. 4 The ^{13}C and ^{31}P NMR spectra for **24**.

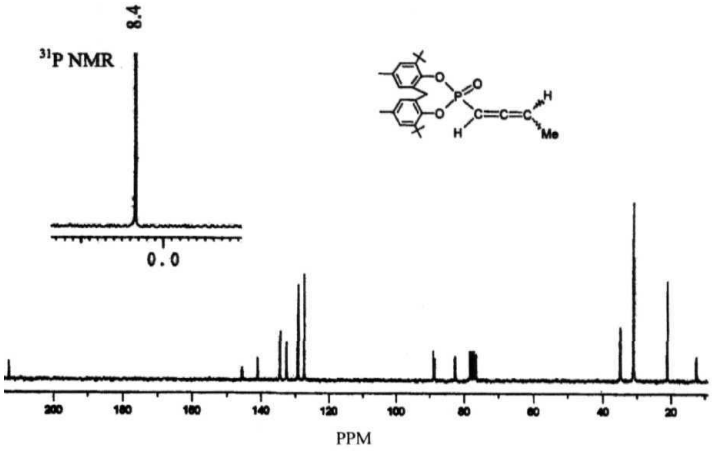


Fig. 5 The ^{13}C and ^{31}P NMR spectra for **28**.

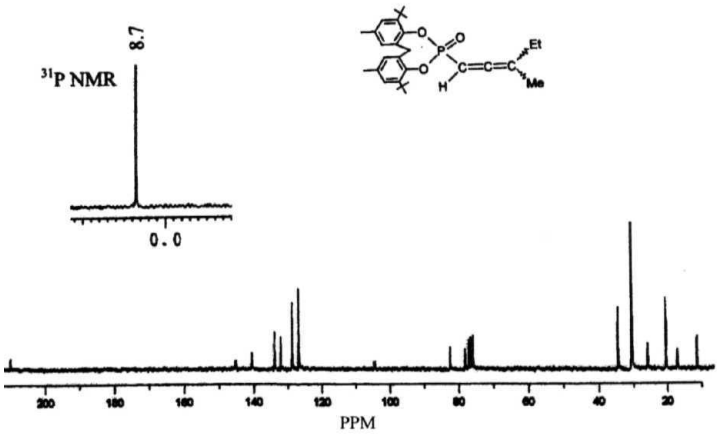


Fig. 6 The ^{13}C and ^{31}P NMR spectra for **29**.

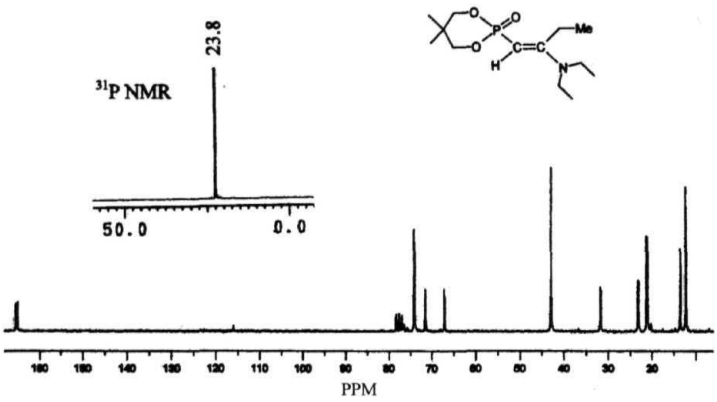


Fig. 7 The ^{13}C and ^{31}P NMR spectra for **31**.

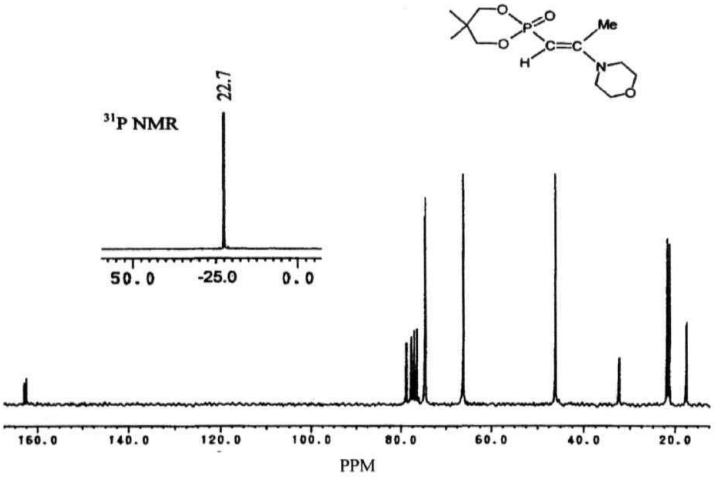


Fig. 8 The ^{13}C and ^{31}P NMR spectra for **34**.

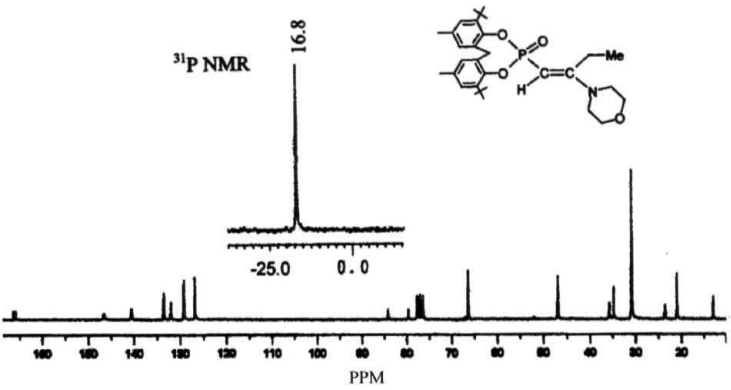


Fig. 9 The ^{13}C and ^{31}P NMR spectra for **38**.

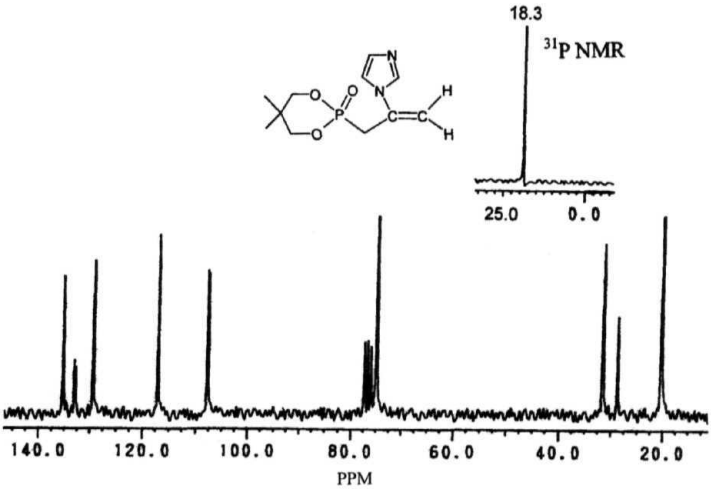


Fig. 10 The ^{13}C and ^{31}P NMR spectra for **39**.

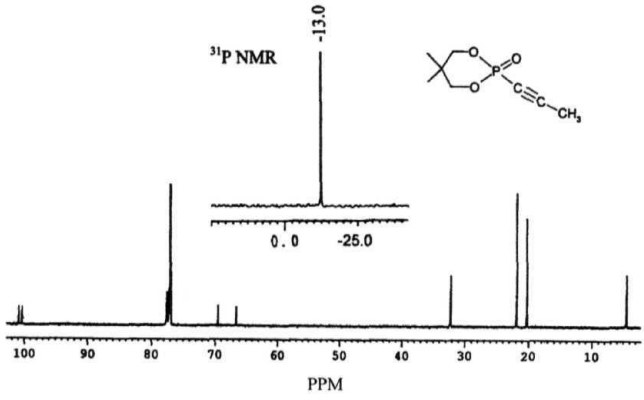


Fig. 11 The ^{13}C and ^{31}P NMR spectra for **41**.

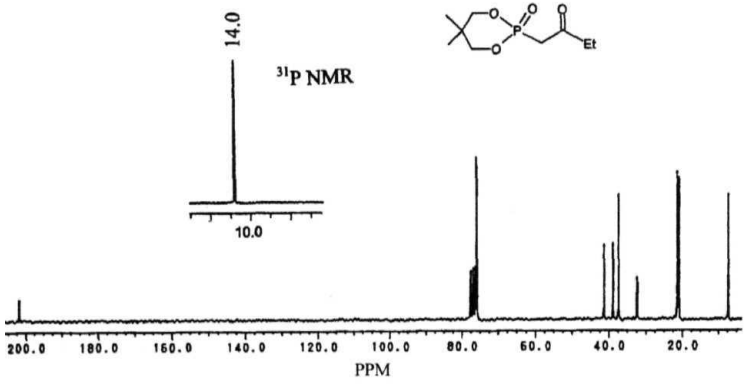


Fig. 12 The ^{13}C and ^{31}P NMR spectra for **43**.

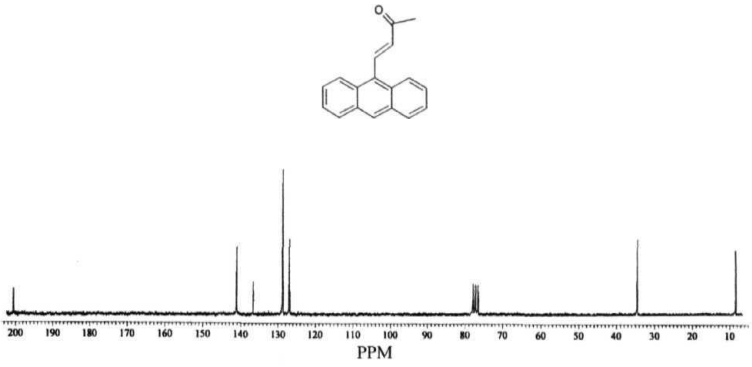


Fig. 13 The ^{13}C NMR spectrum for **47i**.

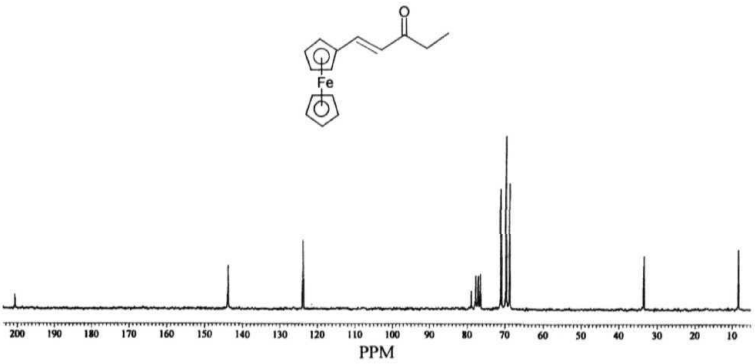


Fig. 14 The ^{13}C NMR spectrum for **48f**.

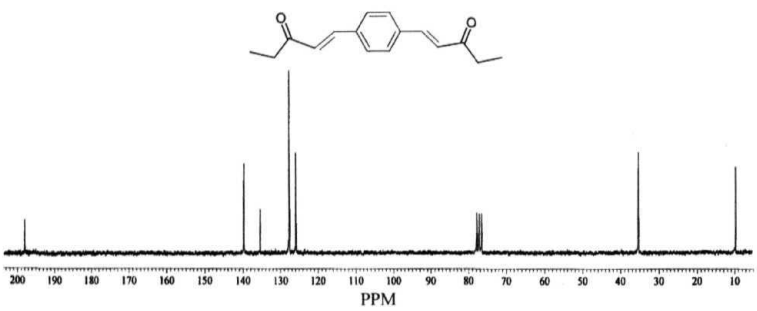


Fig. 15 The ^{13}C NMR spectrum for **48g**.

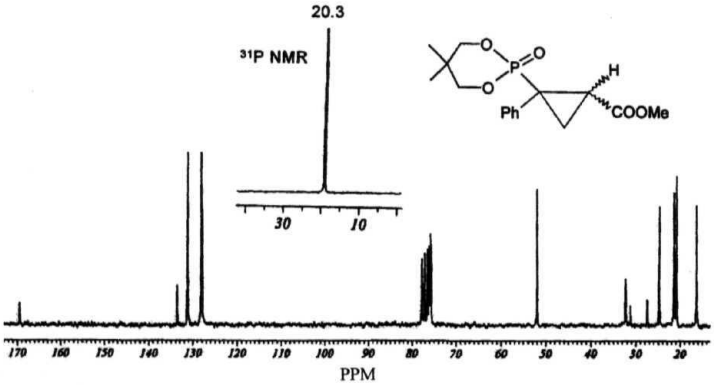


Fig. 16 The ^{13}C and ^{31}P NMR spectra for **52**.

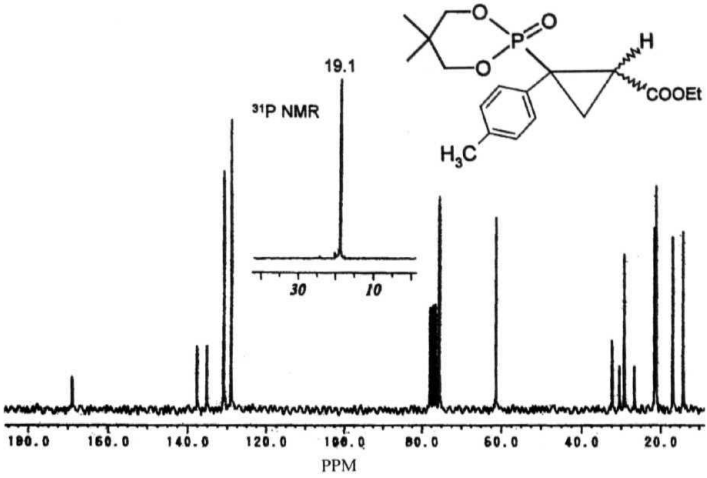


Fig. 17 The ^{13}C and ^{31}P NMR spectra for **56**.

CCDC Reference codes/ publication numbers and atomic coordinates for X-ray structures reported in this thesis

I. CCDC Reference codes or publication numbers of the published compounds

PART A

Compound	CCDC Reference code	Publication no. (Contents, pp. iv-v)
11	**EHAJAY**	**4**
12	**EHAHOK**	**4**
20a. CH_2Cl_2	-	**10**
21b. $3/2C_6H_5CH_3$	-	**10**
22b. $3/2C_6H_5CH_3$	-	**10**
24a. CH_3CN	**MEXGIF**	**2**
27a. $C_6H_5CH_3$	**MEXGEB**	**2**
28a. CH_2Cl_2	-	**9**

PARTB

Compound	CCDC Reference code	publication no. (Contents, pp. iv-v)
66		**5**

II. Selected atomic coordinates for compounds 16b.$C_6H_5CH_3$, 18. $C_6H_5CH_3$, 26 and 33 I il I from PART A and for compounds 19 and 40 from PART B

Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$ x 10^3) are given. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

PART A

Compound **16b.$C_6H_5CH_3$**

Atom	x	y		U(eq)
P	2453(1)	4304(1)	518(3)	56(1)
0(1)	1967(4)	4254(5)	-217(4)	56(2)
0(2)	1972(3)	4269(5)	1235(4)	52(2)
0(3)	2600(2)	3007(3)	523(6)	57(1)
0(4)	3534(2)	1796(3)	512(6)	77(2)
0(5)	3762(5)	5717(6)	-337(6)	114(3)
0(6)	4526(3)	5265(5)	507(7)	110(2)
N(l)	3424(3)	4391(4)	481(7)	67(2)
N(2)	3855(3)	3465(4)	532(6)	62(2)
N(3)	2359(3)	5637(4)	520(7)	61(2)
N(4)	2210(14)	7261(10)	215(8)	170(8)
C(l)	1639(5)	3398(8)	1556(7)	60(3)
C(2)	1851(6)	3040(8)	2271(6)	57(3)
C(3)	1515(8)	2230(11)	2471(7)	80(4)
C(4)	908(8)	1750(10)	2142(8)	80(4)
C(5)	665(6)	2098(8)	1482(7)	66(3)
C(6)	1001(5)	2939(8)	1208(6)	59(3)
C(7)	682(3)	3410(5)	519(7)	56(2)
C(8)	1002(5)	2969(7)	-169(5)	49(2)
C(9)	638(6)	2142(10)	-469(7)	72(3)
C(10)	881(7)	1668(10)	-1109(8)	80(4)
C(ll)	1493(6)	2181(10)	-1500(7)	81(4)
C(12)	1891(6)	3101(9)	-1166(7)	68(3)
C(13)	1611(6)	3387(8)	-529(5)	53(3)
C(14)	2482(7)	3637(12)	2704(8)	80(4)
C(15)	3301(7)	3600(12)	2294(9)	108(5)
C(16)	2257(7)	4714(11)	2793(7)	83(4)
C(17)	2584(11)	3124(15)	3432(8)	146(9)
C(18)	445(11)	775(12)	2480(11)	147(7)
C(19)	556(7)	803(10)	-1415(8)	100(5)
C(20)	2524(7)	3555(10)	-1626(6)	66(3)
C(21)	2302(11)	4746(12)	-1761(10)	130(7)
C(22)	2582(10)	3132(13)	-2375(9)	123(7)
C(23)	3268(7)	3480(13)	-1296(8)	124(7)
C(24)	3349(3)	2750(4)	508(7)	51(2)
C(25)	2924(5)	1017(5)	473(8)	81(3)
C(26)	2836(18)	521(18)	1160(9)	280(2)
C(27)	3182(17)	300(2)	-57(18)	310(2)
C(28)	3909(6)	5204(8)	182(7)	88(3)
C(29)	5092(6)	6075(9)	499(17)	165(7)

C(30)	4895(10)	6978(11)	400(2)	291(18)
C(31)	5873(6)	5608(9)	624(16)	169(8)
C(32)	1962(7)	6303(9)	1066(7)	93(4)
C(33)	2209(12)	7207(8)	853(9)	132(7)
C(34)	2571(8)	6275(7)	57(6)	93(4)
C(35)	195(17)	6100(4)	1950(3)	610(7)
C(36)	77(11)	5510(3)	2640(2)	270(3)
C(37)	106(13)	5780(2)	3360(2)	260(3)
C(38)	-38(15)	4840(3)	3700(17)	290(3)
C(39)	-180(19)	3790(3)	3570(2)	370(4)
C(40)	-206(19)	4080(3)	2858(19)	310(3)
C(41)	-140(2)	4640(3)	2240(2)	470(6)

Compound I 8.$C_6H_5($ H_3

Atom	x	y	z	U(eq)
P	7501(1)	6296(1)	2090(1)	52(1)
0(1)	8481(2)	6524(2)	2315(2)	51(1)
0(2)	6927(2)	7022(2)	1572(2)	53(1)
0(3)	7382(2)	6807(2)	2870(2)	56(1)
0(4)	6928(2)	6629(2)	3857(2)	79(1)
0(5)	6127(3)	4375(3)	1925(3)	126(2)
0(6)	7416(3)	4105(3)	1890(2)	79(1)
0(7)	7560(2)	5710(2)	1386(2)	57(1)
N(l)	7156(3)	5377(3)	2412(2)	62(1)
N(2)	6892(3)	5463(3)	3059(2)	71(1)
N(3)	6329(3)	5636(3)	102(2)	69(1)
C(l)	8930(3)	7180(3)	2800(3)	48(1)
C(2)	9549(3)	6933(3)	3430(3)	49(1)
C(3)	9966(3)	7634(4)	3860(3)	62(2)
C(4)	9819(3)	8515(4)	3679(3)	63(2)
C(5)	9243(3)	8706(4)	3019(3)	59(1)
C(6)	8796(3)	8050(3)	2565(3)	50(1)
C(7)	8209(3)	8309(3)	1831(2)	56(1)
C(8)	7327(4)	8529(3)	1843(2)	54(1)
C(9)	7121(4)	9396(4)	1941(3)	75(2)
C(10)	6321(5)	9638(5)	1923(3)	87(2)
C(ll)	5724(4)	8975(5)	1795(3)	83(2)
C(12)	5883(4)	8086(4)	1689(3)	63(2)
C(13)	6718(4)	7889(4)	1738(2)	56(1)
C(14)	9776(3)	5969(3)	3655(3)	63(2)
C(15)	10556(5)	5910(5)	4308(4)	127(3)
C(16)	9981(5)	5460(4)	3026(3)	111(3)
C(17)	9072(4)	5501(4)	3866(3)	98(2)
C(18)	10305(4)	9238(4)	4176(3)	95(2)
C(19)	6094(5)	10594(4)	2038(4)	139(3)
C(20)	5131(4)	7446(5)	1514(3)	82(2)
C(21A)	5329(12)	6632(18)	2069(12)	152(10)
C(21B)	5305(10)	6502(14)	1472(14)	119(7)
C(22A)	4540(12)	7719(19)	754(9)	150(10)
C(22B)	5079(13)	7029(15)	749(11)	124(7)
C(23A)	4643(12)	7581(12)	2089(10)	105(6)
C(23B)	4303(11)	7858(18)	1470(17)	189(12)
C(24)	6836(5)	4574(4)	2035(3)	74(2)
C(28)	7057(4)	6254(4)	3265(3)	65(2)

C(29)	6568(5)	6055(5)	4308(3)	95(2)
C(30)	6134(6)	6662(6)	4693(5)	162(4)
C(31)	7264(6)	5552(7)	4833(4)	175(4)
C(32)	7736(4)	6024(3)	759(2)	52(1)
C(33)	8508(3)	6312(4)	770(3)	60(1)
C(34)	8667(4)	6592(4)	125(3)	71(2)
C(35)	8067(4)	6579(4)	-523(3)	69(2)
C(36)	7269(4)	6249(3)	-554(2)	60(1)
C(37)	6623(4)	6192(4)	-1208(3)	80(2)
C(38)	5883(5)	5858(4)	-1201(3)	93(2)
C(39)	5759(4)	5589(4)	-530(3)	85(2)
C(40)	7084(4)	5960(3)	91(3)	57(1)
C(41)	1081(7)	6415(7)	1480(6)	140(3)
C(42)	1681(9)	6039(12)	1222(6)	197(7)
C(44)	2130(11)	7306(12)	993(9)	200(7)
C(45)	1646(9)	7887(10)	1185(8)	194(7)
C(43)	2206(9)	6266(17)	968(8)	234(9)
C(46)	1032(9)	7312(12)	1415(8)	187(5)
C(47)	543(11)	7831(10)	1658(8)	283(9)
C(25)	7073(7)	3354(5)	1373(7)	156(4)
C(26)	7360(14)	3401(8)	801(7)	356(14)
C(27)	7418(18)	2672(8)	1701(6)	560(3)

Compound 26

Atom	x	y	z	U(eq)
P	1879(1)	2659(1)	4388(1)	40(1)
0(1)	1827(3)	1762(2)	4387(1)	44(1)
0(2)	2573(3)	2925(2)	5122(1)	42(1)
0(3)	548(3)	3044(2)	4057(2)	50(1)
C(l)	569(4)	1352(2)	4464(2)	40(1)
C(2)	-239(5)	923(2)	3937(2)	49(1)
C(3)	-1492(5)	571(2)	4060(2)	53(1)
C(4)	-1902(5)	589(3)	4659(3)	53(1)
C(5)	-999(5)	967(2)	5174(2)	50(1)
C(6)	263(5)	1342(2)	5090(2)	42(1)
C(7)	1314(5)	1679(2)	5680(2)	47(1)
C(8)	1060(4)	2501(2)	5856(2)	42(1)
C(9)	216(5)	2662(3)	6310(2)	49(1)
C(10)	58(5)	3403(3)	6515(2)	52(1)
C(ll)	809(5)	3967(3)	6271(2)	51(1)
C(12)	1686(5)	3852(2)	5815(2)	46(1)
C(13)	1734(5)	3101(2)	5596(2)	41(1)
C(14)	222(6)	811(3)	3269(2)	63(1)
C(15)	1838(8)	556(5)	3393(4)	131(3)
C(16)	-688(9)	190(4)	2854(3)	119(3)
C(17)	3(12)	1528(4)	2861(3)	146(4)
C(18)	-3285(5)	198(3)	4751(3)	71(2)
C(19)	-902(7)	3572(3)	6996(3)	89(2)
C(20)	2618(6)	4494(3)	5609(2)	56(1)
C(21)	2405(7)	5247(3)	5961(3)	75(2)
C(22)	4275(6)	4271(3)	5841(3)	76(2)
C(23)	2243(7)	4633(3)	4866(2)	81(2)
C(24)	3469(4)	2802(2)	4042(2)	41(1)
C(25)	4905(5)	2524(3)	4469(2)	51(1)

0(4)	5153(4)	1876(2)	4602(3)	103(2)
0(5)	5760(3)	3092(2)	4714(2)	63(1)
C(26)	7196(6)	2892(4)	5109(3)	95(2)
C(27)	3429(5)	3118(2)	3451(2)	45(1)
C(28)	4739(6)	3208(3)	3135(3)	60(1)
0(6)	4708(6)	3580(3)	2668(3)	114(2)
0(7)	5833(4)	2774(3)	3409(2)	106(2)
C(29)	7167(6)	2839(6)	3148(4)	141(4)
C(30)	2082(5)	3435(3)	2997(2)	53(1)
C1(l)	1774(2)	4385(1)	3134(1)	96(1)
N(l)	1405(5)	3070(3)	2519(2)	66(1)
C(31)	213(7)	3352(4)	2050(3)	89(2)
Cl(2)	740(2)	3575(2)	1328(1)	137(1)
0(8)	-1007(5)	3401(4)	2103(3)	150(3)

Compound 33.J .iH

Atom	x	y	z	U(eq)
Al(1)	6667	3333	208(1)	27(1)
Cl(l)	5828(1)	1985(1)	-810(1)	74(1)
Cl(2)	4753(1)	1932(1)	-1405(1)	100(1)
Cl(3)	3877(1)	2622(1)	-1192(1)	82(1)
Cl(4)	4068(1)	3305(1)	-358(1)	60(1)
P(D	5296(1)	3086(1)	532(1)	33(1)
0(1)	4880(1)	2286(1)	571(1)	45(1)
0(2)	4967(1)	3363(1)	829(1)	41(1)
0(3)	5072(1)	3256(1)	131(1)	39(1)
0(4)	5900(1)	2691(1)	-65(1)	35(1)
0(5)	6050(1)	3423(1)	577(1)	33(1)
C(l)	4436(1)	1895(1)	886(1)	52(1)
C(2)	3773(1)	1346(1)	789(1)	67(1)
C(3)	3405(2)	944(2)	1110(1)	84(1)
C(4)	3639(2)	1055(2)	1492(1)	88(1)
C(5)	4277(2)	1615(2)	1570(1)	77(1)
C(6)	4692(2)	2043(2)	1266(1)	57(1)
C(7)	5389(2)	2644(2)	1371(1)	59(1)
C(8)	5392(1)	3298(2)	1472(1)	53(1)
C(9)	5228(1)	3666(1)	1203(1)	43(1)
C(10)	5251(1)	4288(1)	1280(1)	49(1)
C(ll)	5436(2)	4529(2)	1666(1)	69(1)
C(12)	5583(2)	4181(2)	1951(1)	75(1)
C(13)	5570(2)	3578(2)	1852(1)	70(1)
C(14)	3209(2)	578(2)	1823(2)	129(2)
C(15)	5777(3)	4478(3)	2371(1)	125(2)
C(16)	3461(2)	1222(2)	372(1)	74(1)
C(17)	3374(2)	1830(2)	258(1)	89(1)
C(18)	3898(2)	1110(2)	69(1)	81(1)
C(19)	2736(2)	580(2)	362(2)	111(2)
C(20)	5085(1)	4684(1)	973(1)	52(1)
C(21)	4335(2)	4265(2)	842(1)	77(1)
C(22)	5187(2)	5358(2)	1139(1)	87(1)
C(23)	5568(2)	4862(2)	617(1)	65(1)
C(24)	5021(1)	2939(1)	-233(1)	36(1)
C(25)	5450(1)	2673(1)	-319(1)	34(1)

C(26)	5339(1)	2353(1)	-688(1)	45(1)
C(27)	4860(1)	2332(2)	-956(1)	55(1)
C(28)	4465(1)	2629(1)	-860(1)	52(1)
C(29)	4547(1)	2930(1)	-493(1)	43(1)
Li	-70(2)	510(13)	-2(8)	250(2)

PART B

Compound 19

Atom	x	Y	z	U(eq)
P	2473(1)	10074(1)	5184(1)	54(1)
0(1)	1527(1)	8640(1)	4904(1)	54(1)
0(2)	1422(2)	11439(1)	4888(1)	59(1)
0(3)	2949(2)	10139(3)	6346(1)	94(1)
C(l)	519(2)	8611(2)	3942(2)	50(1)
C(2)	-502(2)	9969(2)	3906(1)	48(1)
C(3)	505(2)	11344(2)	3887(2)	53(1)
C(4)	-1384(2)	9915(3)	2807(2)	75(1)
C(5)	-1578(2)	10004(2)	4905(2)	62(1)
C(6)	4011(2)	10133(3)	4243(2)	64(1)
C(7)	4342(2)	9078(3)	3553(2)	59(1)
C{8)	4653(3)	8025(3)	2869(2)	71(1)

Compound 40

Atom	x	y		U(eq)
P(1)	75541(4)	67493(5)	73974(2)	45(1)
0(1)	71521(13)	54480(12)	74282(6)	53(1)
0(2)	73192(12)	71457(12)	66687(6)	51(1)
0(3)	88057(12)	68930(16)	75834(7)	69(1)
C(7)	65132(17)	72159(18)	86055(10)	52(1)
N(l)	74472(14)	76456(15)	90129(8)	53(1)
N(2)	7559(2)	7230(2)	96341(10)	84(1)
C(l)	60927(18)	50688(17)	70628(10)	56(1)
C(2)	61335(19)	54481(18)	63460(10)	54(1)
C(3)	62458(18)	67514(17)	63240(10)	52(1)
C(4)	4931(2)	5126(2)	60314(13)	86(1)
C(5)	7181(2)	4876(2)	59845(12)	76(1)
C(6)	65374(15)	75778(17)	78961(9)	48(1)
C(7)	65132(17)	72159(18)	86055(10)	52(1)
C(8)	8281(2)	8454(2)	88855(11)	66(1)
C(9)	8968(3)	8561(2)	94349(12)	77(1)
C(10)	8476(3)	7802(3)	98756(13)	89(1)
C(ll)	5686(2)	6527(2)	88441(13)	78(1)