

# ASPECTS OF PYRAMIDAL INVERSION AND PSEUDOROTATION

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## ABSTRACT

Stereochemically non-rigid molecules may undergo a variety of conformational changes, processes which do not involve bond-making or breaking. This paper deals with features of pyramidal inversion and pseudorotation which have been studied in our laboratory, with special emphasis on compounds of the second row elements.

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BROADLY defined<sup>1</sup>, conformers are isomers resulting from atomic motions which break no bonds within a molecular framework. This definition, less restrictive than the usual one which identifies conformers with rotamers, enlarges the scope of conformational analysis and justifies discussion under this heading of a diversity of intramolecular motions other than rotation about single bonds. In this paper, I plan to deal with some aspects of pyramidal inversion and pseudorotation, conformational changes (according to the above definition) which have attracted considerable attention in recent years.

Pyramidal inversion is commonly encountered in compounds of the type  $\text{MX}_3$ , in which M also bears one unshared pair of electrons and generally belongs to Groups IV to VI of the Periodic Table. Pseudorotation is most frequently associated with hypervalent<sup>2</sup> compounds of formula type  $\text{MX}_5$ , in which M again belongs to Groups IV to VI. Work in our laboratory has dealt largely with compounds in which the coordinating element M belongs to the second row (*Figure 1*). The energy profiles for single step inversional and pseudorotational motions are illustrated for the case of phosphorus in *Figure 2*. Pyramidal phosphines of formula type  $\text{Pabc}$  are converted into their enantiomers by way of a planar transition state. Trigonal-bipyramidal phosphoranes of formula type  $\text{Pabcde}$  are converted into diastereomers by way of tetragonal-pyramidal transition states<sup>3</sup>. We shall have more to say about the energetics of this motion in connection with work to be discussed below.

Our interest in this area was stimulated by studies in the stereochemistry of nucleophilic displacements at phosphorus. We had found that the deoxygenation of optically active acyclic phosphine oxides with hexachlorodisilane proceeds with overall inversion of configuration<sup>4</sup> (Scheme I), that the base-catalysed hydrolysis of ethoxyphosphonium salts derived from optically

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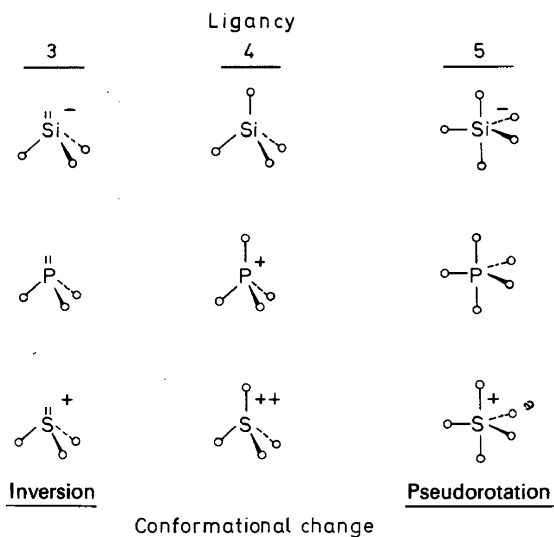


Figure 1

active acyclic phosphine oxides likewise proceeds with overall inversion of configuration<sup>5</sup> (Scheme II), but that the same nucleophilic displacement reactions proceed with overall retention of configuration when the phosphorus atom is constrained in a four-membered ring (phosphetane) system<sup>6</sup> (Figure

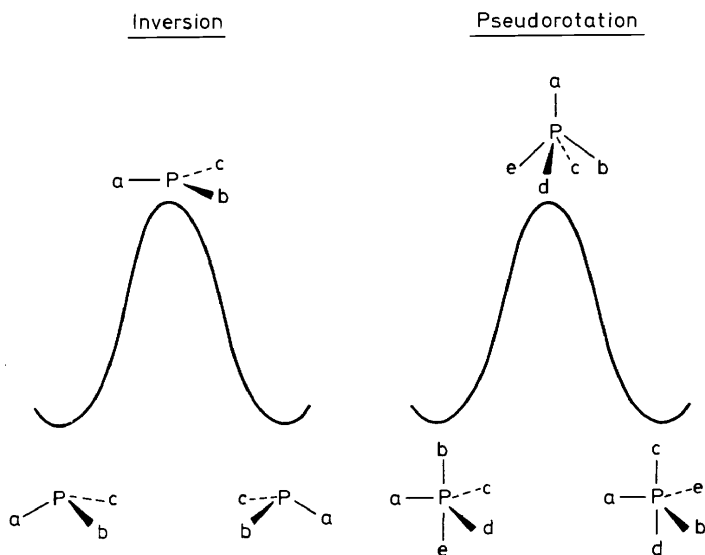
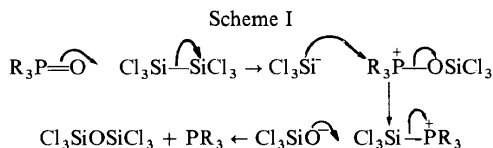
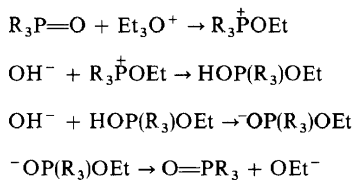


Figure 2

3). In order to assess the factors responsible for these contrasting results, we undertook a detailed analysis of the stereochemistry at the intermediate stage.



Scheme II



It is well known<sup>7</sup> that phosphoranes are intermediates in nucleophilic displacement reactions analogous to those discussed. As illustrated in *Figure 4*, a given enantiomer of an optically active phosphonium ion can undergo attack at any one of four different faces or six different edges: face-attack

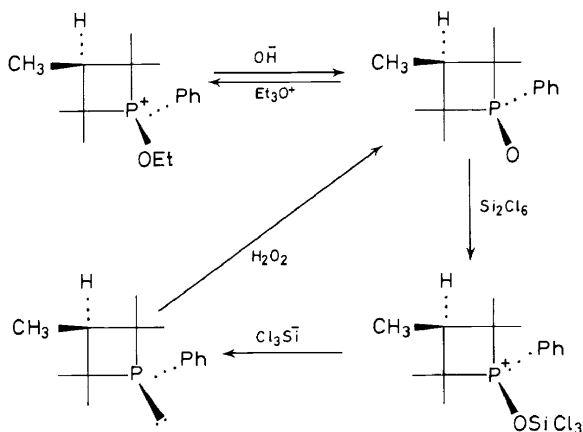


Figure 3

and edge-attack place the entering substituent in the apical and equatorial positions, respectively. In the general case, and in the absence of special constraints, there are thus produced ten diastereomeric phosphoranes from a given enantiomer of the starting phosphonium ion, or a total of twenty chiral phosphoranes from both enantiomers of the starting substrate. These phosphoranes are, in principle, capable of interconversion by pseudorotation. Several pathways for this intramolecular motion have been

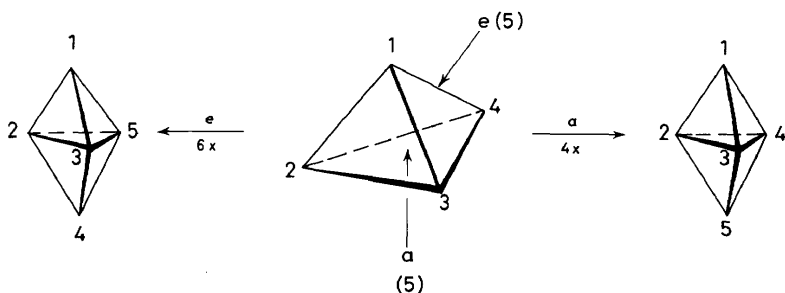


Figure 4

recognized<sup>8</sup>, but the original mechanism proposed by Berry<sup>9</sup>, which involves interchange of ligands in the two apical sites with two of the ligands in the equatorial sites through a tetragonal-pyramidal transition state, appears to be a favoured route<sup>3, 8</sup>. Since each pseudorotation by the Berry mechanism exchanges a pair of equatorial and apical ligands, and since there are three possible combinations of pairs of equatorial ligands, three access routes lead, by a single step, from any given stereoisomer to three others. It follows that the maximum number of interconnecting pseudorotations equals thirty. The somewhat complicated network of twenty isomers and thirty interconversions can be conveniently represented by a centric graph, such as that depicted by Balaban *et al.*<sup>10</sup> or by Lauterbur and Ramirez<sup>11</sup>. Our own geometric realization<sup>12</sup> of the 20-vertex graph is shown in Figure 5. The idealized image

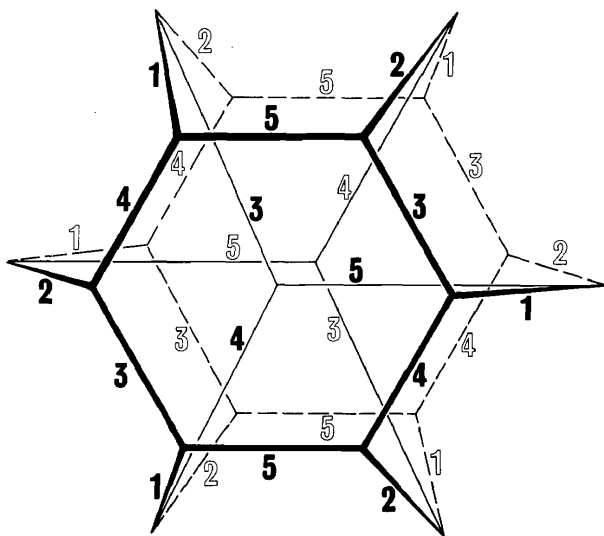
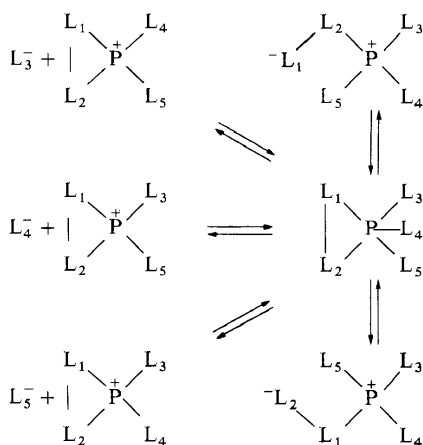


Figure 5

has  $D_{3d}$  symmetry. Pseudorotations are designated by the numerical indices over the edges which are related through the centre of symmetry, each such number denoting the index of the pivot ligand. Consequently, the identity of each isomer, represented by a vertex, is automatically defined, except for chirality. The pattern of the indices is straightforward and easily memorized: two numerals alternate around the top and bottom edges of the points of the star, and the six edges corresponding to each of the other three numerals are all parallel. This simple scheme permits identification of all edges and vertices by designation of only five of the edges.

In considering application of this representation to the chemical systems under discussion, it must be noted that, just as attack by an external nucleophile on phosphorus in a small ring system may lead to retention of configuration, attack by an internal nucleophile on phosphorus in an acyclic system may also lead to retention of configuration whenever the intermediate phosphorane contains a phosphorus atom incorporated in a small ring system. Accordingly, displacement reactions by internal or external attack have in common the same set of phosphorane intermediates, as indicated in Scheme III.

Scheme III



If the phosphorus-containing ring system in the intermediate phosphoranes is small, and thus incapable of spanning the two apical positions, a constraint is imposed which removes two enantiomeric phosphoranes from the set of twenty. Using the convention (consistent with Scheme III) of indexing the ring termini 1 and 2, the two vertices in the graph removed are those in the centre of *Figure 5*. As a result *Figure 6* now resembles the carbon skeleton of hexa-asterane, a member of the asterane series of hydrocarbons<sup>1,3</sup>. The twelve vertices on the top and bottom hexagons represent isomers in which the ring spans apical and equatorial positions. The six vertices at the points of the star represent isomers in which the ring spans two equatorial positions, and therefore structures which may be relatively high in energy. A unique feature of the hexa-asterane representation is the presence of three planes and

two other surfaces which group the eighteen phosphoranones represented by the vertices of the graph into subsets of nine whose members are generically related to phosphonium ions of given configuration. The three planes are indicated in *Figure 6*. The subset of phosphoranones in the sectors formed by

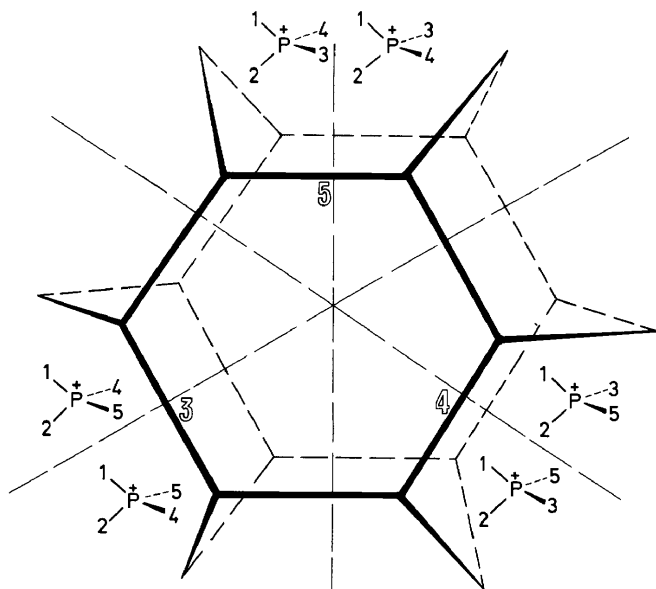


Figure 6

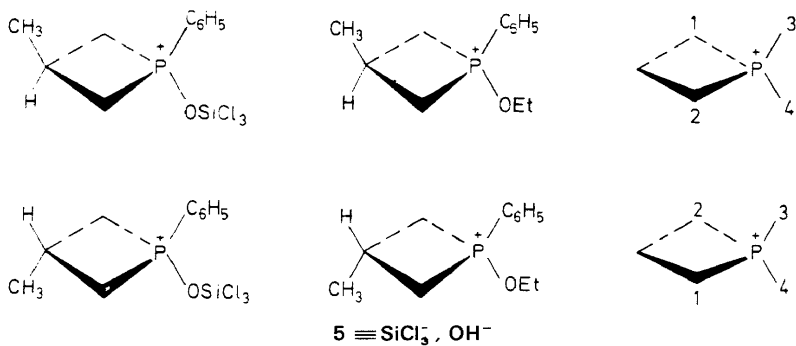


Figure 7

each plane contains the nine diastereomers which are, in principle, the initial products of attack by an external nucleophile and ligand-to-be on a given enantiomer of a phosphonium ion (bearing in mind the above constraint).

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The diagram in *Figure 6* provides, at a glance, a map of the stereochemical consequences of displacement reactions on phosphorus in cyclic phosphonium ions which are initiated by external nucleophilic attack. As an application, let us return to the phosphetanium systems previously discussed. We begin by labelling the ligands, as shown in *Figure 7*. Assuming that apical attack is the preferred mode of addition, and discounting formation of phosphoranes in which the four-membered ring spans the equatorial positions, the initially formed phosphoranes derived from *cis*- and *trans*-phosphetanium ions are shown in *Figure 8*. We note a remarkable feature

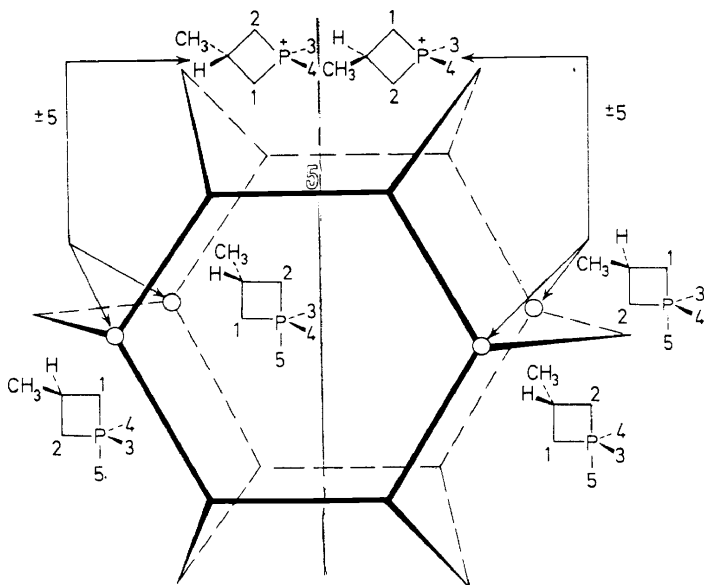
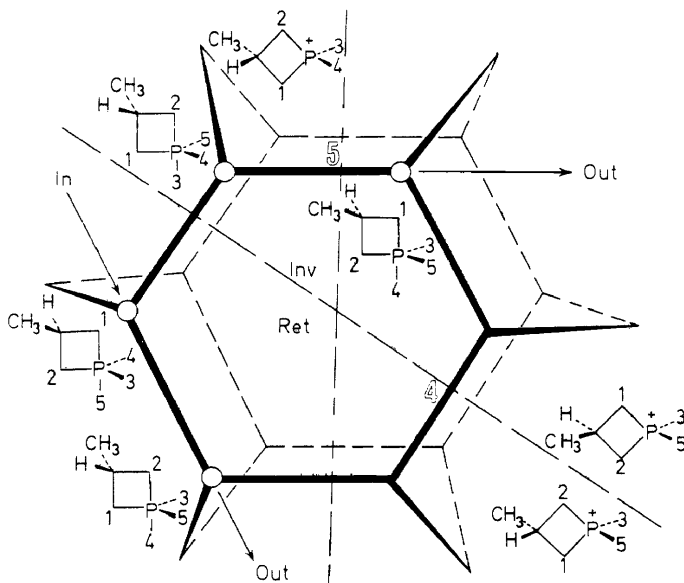


Figure 8

of the systems under discussion: the horizontal mirror plane ( $\sigma_h$ ) of the idealized hexa-asterane graph is related to the symmetry properties of the molecules represented by the vertices, even though the centric nature of the basic graph remains with respect to the chirality of the phosphorus atom:  $\sigma_h$  contains the star-point vertices, which represent achiral molecules, and enantiomers on the top and bottom hexagons are reflected into each other by  $\sigma_h$ . To simplify our discussion, we shall ignore distinctions between enantiomeric phosphoranes, since they will suffer the same chemical fate under achiral conditions, and we shall arbitrarily restrict our analysis to reactions of the *cis*-phosphetanium ion, since analysis of the reactions of the *trans* isomer follows similar lines. In *Figure 9* is shown one enantiomer of the phosphorane which is initially formed from the *cis*-phosphetanium ion (see *Figure 8*). Retention or inversion depends on the sector in which the ultimate phosphorane is located. Since the effect of the displacement reaction is to substitute  $L_5$  for  $L_4$ , it is immediately recognized that retention of configuration will result if the ultimate phosphorane is located in the southwest sector, whereas inversion obtains if the ultimate phosphorane is located in the northeast sector. Granting apical attack of  $L_5$ , departure of  $L_4$  must

also occur from the apical position, according to an extended principle of microscopic reversibility<sup>14</sup>, and consideration of the ultimate phosphoranes is thus restricted to the two isomers indicated in *Figure 9*. Consequently, if the rate of loss of  $L_4$  is faster than the rate of pseudorotation, a clockwise mech-



*Figure 9*

anism leads from the initial phosphorane to the ultimate phosphorane in two pseudorotational steps, resulting in inversion of configuration (i.e. formation of the *trans* product), while a counterclockwise mechanism leads, in one pseudorotation, to the ultimate phosphorane which affords *cis* product, i.e. retention of configuration. The remaining task is to decide which of the two pathways is the preferred one.

As seen by inspection of *Figure 9*, the clockwise pathway involves the intermediacy of a phosphorane in which the electronegative groups,  $L_4$  and  $L_5$ , occupy equatorial positions, while the electropositive group,  $L_3$ , occupies an apical position. There exists a body of evidence which supports the view that such an arrangement corresponds to a structure of high energy<sup>14,15</sup>, and a theoretical study of pseudorotation<sup>16</sup> bears out this view. Non-empirical LCAO-MO-SCF (Hartree-Fock) calculations, using a moderately large Gaussian basis set, were performed on the hypothetical molecule  $PH_5$  in two conformations,  $D_{3h}$  and  $C_{4v}$ . A small change in the nuclear charge of any of the hydrogen atoms has the effect of changing the effective electronegativity of that hydrogen, and the modified atom ( $H'$ ) thus simulates an atom of electronegativity greater than that of hydrogen. In the present calculations, the nuclear charge used for  $H'$  was 1.1.  $PH_5$  and  $PH_5'$  were calculated to be more stable in the  $D_{3h}$  than in the  $C_{4v}$  conformation by 3.9



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and 3.3 kcal/mole, respectively. For  $\text{PH}_3\text{H}'_2$ , there are three different trigonal-bipyramidal conformations. These are interconverted according to the structures shown at the bottom of *Figure 10*, where groups 1 and 2 represent  $\text{H}'$ , and groups 3, 4 and 5 represent  $\text{H}$ . Of the calculated potential curves shown in *Figure 10*, the one for  $\text{PH}_3\text{H}'_2$  is particularly relevant, for not only does it show that the trigonal-bipyramidal structure with the simulated electronegative groups (1 and 2) in the apical positions is the most stable

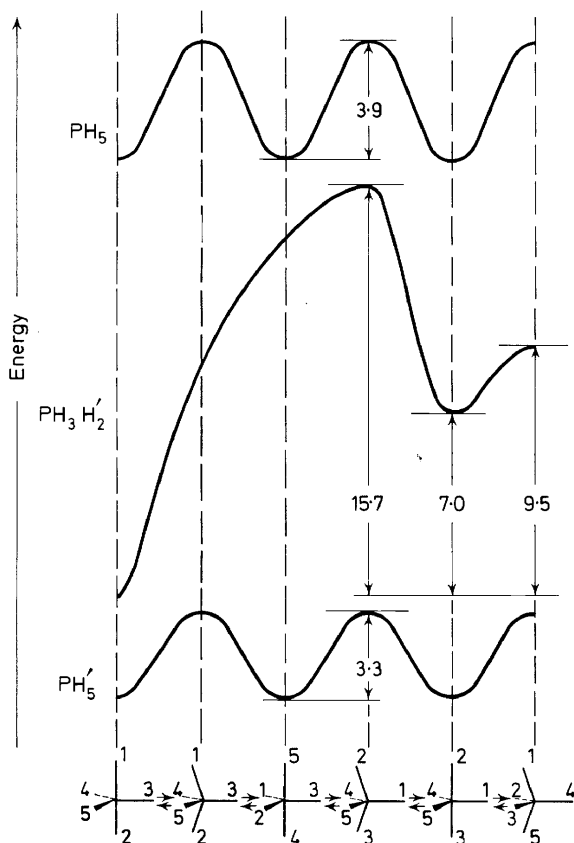


Figure 10

isomer<sup>14, 15</sup>, but it also indicates that passage of a trigonal-bipyramidal structure in which the electronegative groups occupy apical and equatorial positions (corresponding to the initial western phosphorane in *Figure 9*) to one in which both electronegative groups occupy equatorial positions (corresponding to the intermediate northwestern phosphorane) requires an energy barrier *ca.* 6 kcal/mole higher than passage to a structure stereo-electronically equivalent to the starting one (corresponding to the ultimate southwestern phosphorane).

Consequently, it is safe to conclude that the counterclockwise pathway is preferred, and that retention of configuration is the expected result. Our observations are thus accounted for.

Two other surfaces divide the hexa-asterane graph into subsets of nine phosphoranes, represented by the vertices on one or the other of the two hexagons and alternate star-point vertices. Since the latter represent high energy structures, they may be ignored, and it suffices to consider division of the graph by a horizontal plane which is perpendicular to the three shown in *Figure 6*. This representation is relevant to intramolecular nucleophilic attack (Scheme III). For example, consider the cyclic displacement

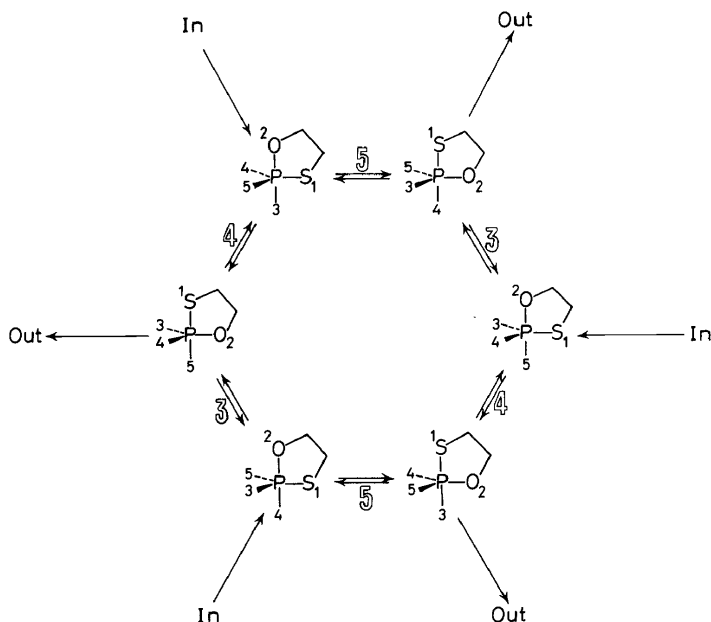


Figure 11

summarized in Scheme IV, in which an oxide terminus displaces a sulphide terminus on phosphorus. Denoting the ligands in the intermediate phosphorane by the indices shown in Scheme IV, it is seen from inspection of *Figure 11* that the displacement reaction results in retention of configuration, regardless of which are the initial and ultimate phosphoranes, for the six diastereomers are all constrained to one side of the horizontal plane, i.e. they all belong to the same configurational subset. Indeed, retention of configuration was experimentally demonstrated<sup>12</sup> by the observation that the phosphine oxide produced in the oxidation of the phosphine (Scheme IV) has the same sign and magnitude of rotation whether the reagent is hydrogen peroxide or bis(2-hydroxyethyl) disulphide.

In contrast to the base-catalysed hydrolysis of ethoxyphosphetanium salts, which results in retention of configuration, the base-catalysed hydrolysis

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of ethoxythietanium salts proceeds with inversion of configuration (*Figure 12*)<sup>17</sup>. Using the analytical scheme described for the phosphorus analogues, this observation leads to the conclusion that pseudorotation in the family of

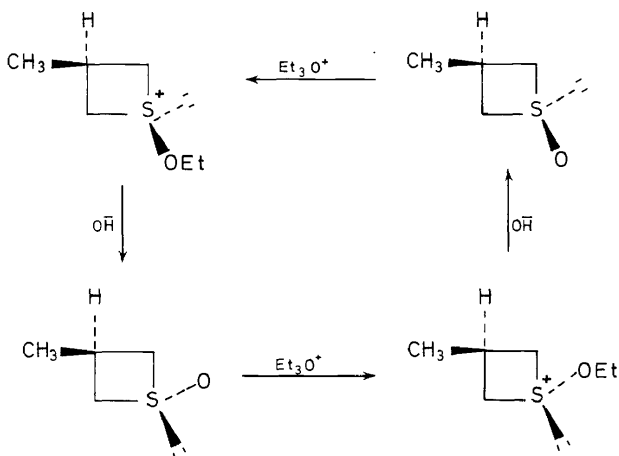
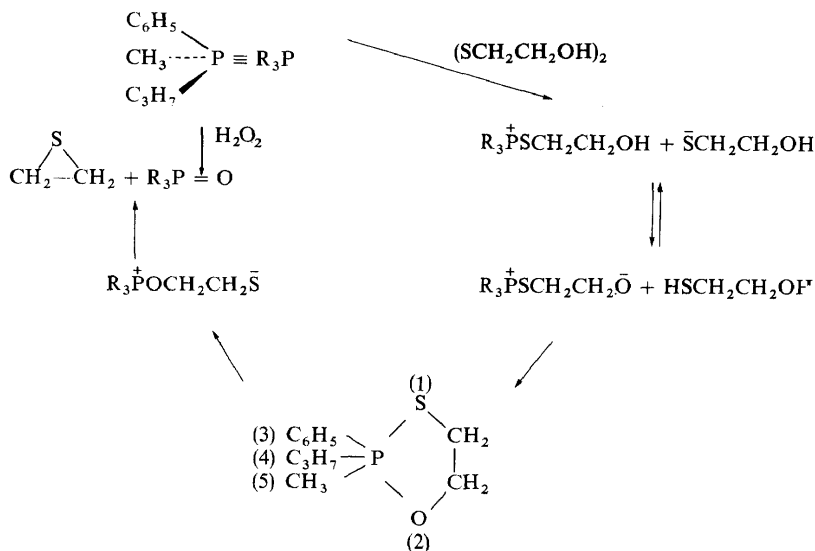


Figure 12

'pentacoordinate' sulphur compounds of the formula type  $:SR_4$ , if it occurs at all, is less facile than in the phosphoranes, or, alternatively, that the reaction does not proceed through an intermediate ( $:SR_4$ ) of significant

Scheme IV



lifetime and is better described as a direct  $S_N2$  displacement. The same conclusion applies to nucleophilic displacement at phosphorus in chlorophosphetanes, which also proceeds with inversion of configuration<sup>18</sup>. It thus appears that the stereochemistry of pentacoordinate compounds cannot be safely extrapolated to those cases in which a lone pair of electrons acts as a phantom ligand in the coordination sphere.

A hint that the presence of a lone pair may have a special effect in these systems comes from quite an independent set of observations. It was found<sup>19</sup> that in the thermal racemization (130°, hydrocarbon solvents) of  $\alpha$ -deuterated allylmethylphenylphosphine, no detectable exchange of label between the  $\alpha$ - and  $\gamma$ -positions of the allyl group takes place. The half-life for exchange at 175° in benzene was found to be about 300 times the half-life for racemization at the same temperature. Consequently, allylic rearrangements play no significant role in the racemization process, and mechanisms such as the inversion pathway shown in *Figure 13* (the asterisk marks the label) are ruled out†. It is of some interest however that even at

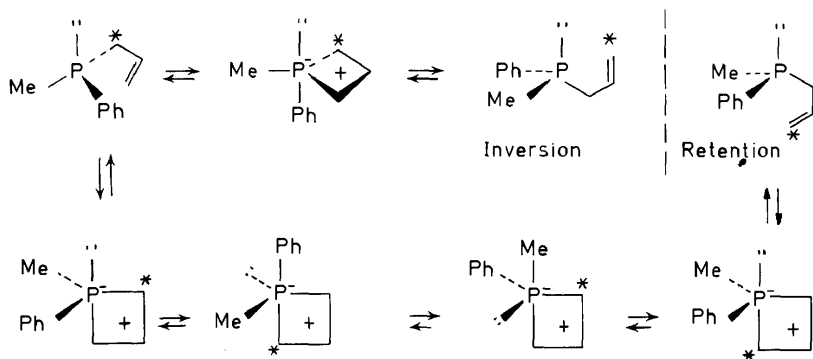


Figure 13

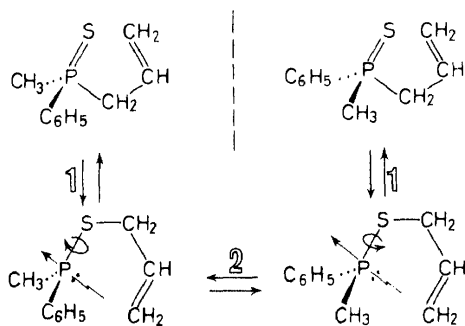
elevated temperatures, scrambling does not take place (to any significant extent) by retention pathways such as the one shown in *Figure 13*. While charge separation in the intermediate phosphoranes or placing of electro-positive groups in the apical positions may be largely responsible for this result, it is possible that the presence of the lone pair is a decisive factor, as conjectured above. In any event, the conclusion is inescapable that allylmethylphenylphosphine racemizes simply by pyramidal inversion.

Pyramidal inversion is also implicated in the thermal racemization of allylmethylphenylphosphine sulphide, which racemizes in xylene at temperatures near 200°<sup>20</sup>. Racemization, as shown in *Figure 14*, proceeds in two discrete steps: (1) a rearrangement step, in which bonds are made and broken in a concerted [2, 3] sigmatropic process; (2) the racemization step proper, a conformational change in which bonds are neither made nor broken. In that respect, the racemization of allylmethylphenylphosphine sulphide is mech-

† Other mechanisms are similarly excluded, such as attack by the lone pair of electrons on phosphorus at the  $\gamma$ -position of the allyl group, followed by cleavage of the P-C bond.

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Stereomutation by intramolecular  
ligand exchange



- 1: Concerted bond making and breaking  
([2,3]-sigmatropic process)
- 2: Conformational change: torsion and inversion

Figure 14

anistically analogous to the racemization of allyl sulphoxides<sup>21</sup>, the chief difference residing in the nature of the conformational interconversion which takes place in step 2 of the intermediate stage: whereas both torsion *and* pyramidal inversion are required to interconvert enantiomeric thiophosphinites (Figure 14), torsion alone (about single bonds) suffices to interconvert enantiomeric conformers of sulphenates.

Our earlier investigation of (*p-p*)  $\pi$ -conjugative effects on pyramidal inversion at sulphur in aryl *p*-tolyl sulphoxides<sup>22</sup> is currently being extended to phosphorus and nitrogen in arylmethylphenylphosphines and 1-aryl-2,2-dimethylaziridines, respectively, to determine the extent and nature of such intercorrelations. Additional studies in progress include testing for (*p-d*)  $\pi$ -conjugative effects on inversion barriers at phosphorus in phosphines of formula type  $R_3M-Pab$  ( $M = Si, Ge$  and  $Sn$ ), as well as probing for conformational effects of cyclic (*3p-2p*)  $\pi$ -delocalization ('aromaticity') in phospholes and annelated derivatives. Although work in these areas is just beginning, preliminary results indicate that the study of pyramidal inversion at phosphorus, and possibly higher-row Group V elements, will provide deeper insight into the nature of the inversion process, especially with regard to barrier lowering phenomena that cannot be studied using analogous nitrogen systems.

The preceding examples may have served to illustrate some of the uses of conformational analysis in systems other than those to which the term is conventionally applied. I should like to close by thanking my students, whose skill and devotion made this work possible.

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