(*S*)-**1** (R = R′ = Me) is stereospecific within error of the measurements.

Control Experiments. The phosphinate and phosphinothiolate ester products, **2** (R = Me) and **3** (R′ = Me), from the hydrolysis of (*S*)-**1** (R = R′ = Me) were shown to be configurationally stable under the reaction conditions for hydrolysis by submitting a sample of each to the exact conditions. Recovery of unreacted **2** (R′ = Me) after 30 sec and unreacted **3** (R = Me) after 2 min yielded a product of unchanged stereochemistry.

Differential Hydrolysis Rates of the Two Products from Hydrolysis of 1. The phosphinate ester products, **2**, have previously been shown to be chemically stable to the hydrolysis reaction conditions of 0.01 *M* NaOH in 50% aqueous dioxane for a reaction time of less than 1 min. To test the possibility of hydrolysis of the phosphinothiolate esters (**3**), mixtures of each of esters **3** and **2** (R = *i*-Pr) were submitted to the reaction conditions for 2 min. The ratio of **3** to **2** (R = *i*-Pr) was unchanged for **2** (R′ = Et) and **2** (R′ = *i*-Pr), indicating the absence of any hydrolysis. For **2** (R′ = Me) a starting ratio of **2**/**3** of 0.8 was decreased to 0.6 indicating *ca.* 25% reaction of **2**. This corresponds to a pseudo-first-order rate constant of *ca.* 2×10^{-3} sec^{-1}. Thus, under the reaction time of 15 sec, less than 5% of **2** (R′ = Me) could have reacted.

Hydrolysis of *tert*-Butylmethoxy(methylthio)phenylphosphonium Hexachloroantimonate (7). By a procedure identical with that above for the hydrolysis of **1** except that a longer reaction time (*ca.* 40 sec) was necessary, the hydrolysis of **7**[16] (pmr ($CDCl_3$): $PCCH_3$, d, δ 1.41, J_{PCCH} = 20 Hz; $POCH_3$, d, δ 4.35, J_{POCH} = 12.5 Hz; $PSCH_3$, d, δ 2.56, J_{PSCH} = 13.0 Hz) afforded two products. These products were identified by pmr ($CDCl_3$) to be methyl *tert*-butylphenylphosphinate ($PCCH_3$, d, δ 1.13, J_{PCCH} = 15.9; $POCH_3$, d, δ 3.70, J_{POCH} = 10.9 Hz) and methyl *tert*-butylphenylphosphinothiolate ($PCCH_3$, d, δ 1.20, J_{PCCH} = 17.0 Hz; $PSCH_3$, d, δ 2.13, J_{PSCH} = 10.8 Hz) in the ratio of 78:22, respectively.

Acknowledgment. We are indebted to the donors of the Petroleum Research Fund, administered by the American Chemical Society, and BSSG grant from Colorado State University for support of this research.

Alkaline Hydrolysis of 1-X-1-Alkoxy-2,2,3,4,4-pentamethylphosphetanium Salts. An Unusual Order of Ligand Kinetic Axiophilicities

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Abstract: The stereochemistry of the products from the alkaline hydrolysis of *cis*- and *trans*-1-X-1-alkoxy-2,2,3,4,4-pentamethylphosphetanium hexachloroantimonates where X is methoxy, ethoxy, isopropoxy, dimethylamino, methylthio, or chloro has been investigated. Assuming a mechanism involving axial attack of the hydroxide ion and axial loss of the leaving group, an unusual order of ligand axiophilicities is implicated from the product analysis. Thus, the ability of a phosphorane to undergo an intramolecular isomerization involving the positional exchange of a ligand from an equatorial position to an axial position in a trigonal bipyramid depends on the nature of the ligand with increasing ability in the order: NMe_2 < OMe, OEt, O-*i*-Pr < SMe $\simeq$ Cl. An interpretation of the origin of this order is advanced involving the electronegativity of the ligand and the ability of the lone pairs of electrons in the heteroatom of the ligand to overlap with phosphorus.

The importance of pentacoordinate phosphorus species (phosphoranes) as intermediates in displacement reactions at tetrahedral phosphorus has become recognized in the last decade. Westheimer and coworkers,[1] in their elegant studies of the mechanism of the hydrolysis of cyclic phosphorus esters, have invoked phosphorane intermediates and emphasized the importance of isomerization pathways available to these intermediates in determining the product composition. We have observed a similar product control by intermediates and their isomerization pathways in displacements at acyclic phosphonium salts[2a-c] and phosphorus esters.[2d] Although gross empiricisms have resulted from these studies, it is of importance to further establish the factors controlling the geometry of the intermediates initially formed in a reaction and the relative energetics of possible isomerization and decomposition pathways available to these intermediates.

We have undertaken the present study to elucidate one aspect of the problem; namely, the effect various ligands have on the energies for intramolecular isomerizations. Specifically, our study has probed the relative kinetic ability of ligands such as alkoxy, dimethylamino, methylthio, and halo, which are common to many reactions of phosphorus, to undergo positional exchange from an equatorial position in a trigonal bipyramid to an axial position (axiophilicity). Other workers have been able to obtain similar information on saturated and unsaturated carbon ligands as well as phenoxy and dimethylamino,[3] which with our study, provide a wide range of ligands whose relative kinetic axiophilicities have now been established.

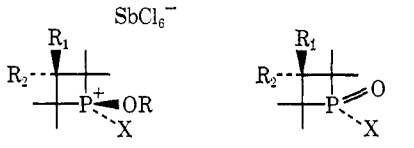
The system utilized in this study was the alkaline hydrolysis of 1-X-1-alkoxy-2,2,3,4,4-pentamethylphosphetanium hexachloroantimonates (**1** and **2**). Because of the small ring, the number of isomerization pathways of the pentacoordinate intermediates is limited. In addition, if one assumes axial approach of the nucleo-

(1) (a) For a general review, see F. H. Westheimer, *Accounts Chem. Res.*, **1**, 70 (1968); (b) R. Kluger, F. Covitz, E. Dennis, L. D. Willlams, and F. H. Westheimer, *J. Amer. Chem. Soc.*, **91**, 6066 (1969); (c) R. Kluger and F. H. Westheimer, *ibid.*, **91**, 4143 (1969).

(2) (a) K. E. DeBruin and J. R. Petersen, *J. Org. Chem.*, **37**, 2272 (1972); (b) K. E. DeBruin and K. Mislow, *J. Amer. Chem. Soc.*, **91**, 7393 (1969); (c) K. E. DeBruin and D. M. Johnson, *ibid.*, **95**, 4675 (1973); (d) K. E. DeBruin and D. M. Johnson, unpublished results.

(3) R. K. Oram and S. Trippett, *J. Chem. Soc., Chem. Commun.*, 554 (1972).

phile, the ring forces the two potential leaving groups, alkoxy or X, to occupy equatorial positions of similar chemical environment enabling a comparative analysis of the two modes of reaction to yield either or both of the two possible products. Since the 1-X-2,2,3,4,4-pentamethylphosphetane oxide products (**3** and **4**) are the precursors of the phosphetanium salts **1** and **2**, the stereochemical analysis is simplified.



1, R_1 = Me; R_2 = H
2, R_1 = H; R_2 = Me
a, X = OMe
b, X = OEt
c, X = O-*i*-Pr
3, R_1 = Me; R_2 = H
4, R_1 = H; R_2 = Me
d, X = NMe_2
e, X = SMe
f, X = Cl

Results

Hydrolyses of Phosphetanium Salts. The hydrolyses of the phosphetanium salts listed in Tables I (R = Me) and II (R = Et) were carried out in 0.05 *M* NaOH in 50% aqueous dioxane at room temperature with a reaction time of *ca.* 30 sec. The products and their ratios listed in the tables were determined by ^{1}H nmr and are the average of five independent hydrolyses (standard deviation ±2%). For **1d** and **2d**, the hydrolyses were stereospecific involving exclusive cleavage of the alkoxy group with retention of configuration at phosphorus. All other hydrolyses proceeded with partial or complete loss of stereospecificity. In the hydrolyses of **1e** and **2e** as well as **1f** and **2f**, cleavage of the methylthio or chloro group, respectively, was the predominant pathway. That **1a** (R = Me, Table I) and **1b** (R = Et, Table II), where both leaving groups are identical, gave unequal amounts of the corresponding products **3a** *vs.* **4a** and **3b** *vs.* **4b**, respectively, reflects the energy difference between diastereomeric transition states to form the diastereomeric products, the larger difference occurring for the hydrolysis of **1b** (R = Et).

Table I. Products from the Alkaline Hydrolyses of 1-Methoxy-1-X-2,2,3,4,4-pentamethylphosphetanium Salts

Phosphetanium salt			Products (%)[a]			
No.	X	Config	**3a**	**4a**	**3b–f**	**4b–f**
1a	OMe		55	45		
1b	OEt	Trans	11	7	49	33
2b	OEt	Cis	16	9	39	36
1c	O-*i*-Pr	Trans	10	4	44	42
2c	O-*i*-Pr	Cis	15	2	40	43
1d	NMe_2	Cis	0	0	100	0
2d	NMe_2	Trans	0	0	0	100
1e	SMe	Trans	36	61	3	0
2e	SMe	Cis	63	37	0	0
1f	Cl	Trans	37	63	0	0
2f	Cl	Cis	64	36	0	0

[a] Per cent total nonacidic products.

Table II. Products from the Alkaline Hydrolyses of 1-Ethoxy-1-X-2,2,3,4,4-pentamethylphosphetanium Salts

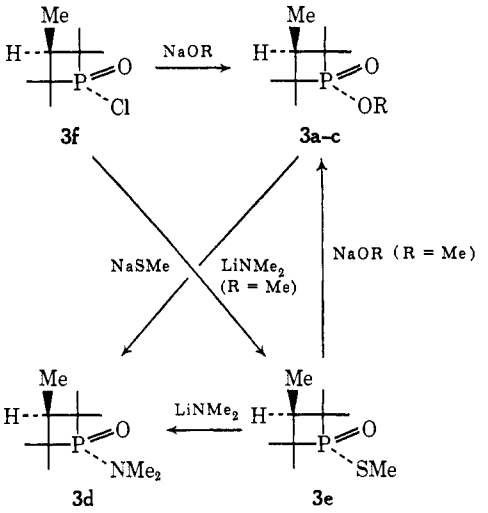
Phosphetanium salt			Products (%)[a]			
No.	X	Config	**3b**	**4b**	**3a,c–f**	**4a,c–f**
1a	OMe	Cis	39	36	16	9
2a	OMe	Trans	49	33	11	7
1b	OEt		63	37		
1c	O-*i*-Pr	Trans	17	9	45	29
2c	O-*i*-Pr	Cis	19	9	47	25
1d	NMe_2	Cis	0	0	100	0
2d	NMe_2	Trans	0	0	0	100
1e	SMe	Trans	34	57	9	0
2e	SMe	Cis	60	40	0	0
1f	Cl	Trans	30	70	0	0
2f	Cl	Cis	70	30	0	0

[a] Per cent total ester products.

Stereochemical Considerations. The syntheses of the phosphetanium salts **1** and **2** were carried out by O-methylation or O-ethylation of the corresponding phosphetane oxides **3** and **4**. Pure samples of **1a–f** (R = Me or Et) were obtained from configurationally pure **3a–f**. As it is difficult to obtain configurationally pure **4a–f**, mixtures (*ca.* 1:1) of **3**/**4** were alkylated to form mixtures of **1**/**2**. When these mixtures of phosphetanium salts of known composition were hydrolyzed, the products were corrected for the amount of **1** which had been hydrolyzed separately in the pure state.

The absolute configurations of the phosphetane oxides **3a–e** were correlated by synthesis from **3f**[4] of known configuration[5] as shown in Scheme I.[6] All reactions were stereospecific and assumed to proceed with retention of configuration.[6,7] Parellel reactions

Scheme I



were run starting with a mixture of **3f**/**4f**,[8] establishing the stereospecificity of each reaction.

In support of the assumption that the displacements in Scheme I proceed with retention, ^{1}H-nmr analyses of the ring methyl region showed a distinct difference between the diastereomers **3** and **4**. The difference in chemical shifts ($\Delta\delta$) between the diastereotopic methyl groups in the phosphetane oxide (**4**) with the 3-methyl cis to the phosphoryl oxygen was, in general, greater than the difference in **3** with the trans arrangement.

(4) J. J. McBride, E. Jungermann, J. V. Killhefer, and R. J. Clutter, *J. Org. Chem.*, 27, 1833 (1962).
(5) (a) Mazhar-ul-Haque, *J. Chem. Soc. B*, 934 (1970); (b) S. E. Cremer, *Chem. Commun.*, 616 (1970).
(6) This scheme is virtually identical with that of J. R. Corfield, R. K. Oram, D. J. H. Smith, and S. Trippett, *J. Chem. Soc., Perkin Trans. 2*, 713 (1972).
(7) S. E. Cremer and B. C. Trivedi, *J. Amer. Chem. Soc.*, **91**, 7200 (1969).
(8) J. R. Corfield and S. Trippett, *Chem. Commun.*, 721 (1971).

The pertinent chemical shifts are indicated in Table III. This observation is consistent with that of Cor-

Table III. Dependence of Diastereotopic Methyl Group Nonequivalence on the Configuration of the Phosphetane Oxides (3 and 4)

Compd No.	Compd X	Chemical shifts,[a] δ, ppm	Δδ, ppm
3a	OMe	1.00 (18); 1.12 (19)	0.12
3b	OEt	1.02 (18); 1.13 (19)	0.11
3c	O-*i*-Pr	1.02 (18); 1.07 (19)	0.05
3d	NMe_2	1.04 (18); 1.17 (18)	0.13
3e	SMe	1.05 (21); 1.16 (19)	0.11
3f	Cl	1.03 (23); 1.14 (21)	0.11
4a	OMe	0.94 (18); 1.22 (19)	0.28
4b	OEt	0.95 (18); 1.22 (19)	0.27
4c	O-*i*-Pr	0.95 (18); 1.15 (19)	0.20
4d	NMe_2	0.97 (17); 1.21 (18)	0.24
4e	SMe	0.97 (22); 1.22 (19)	0.25
4f	Cl	0.97 (23); 1.24 (21)	0.27

[a] Solvent benzene, J_{PCCH} in parentheses.

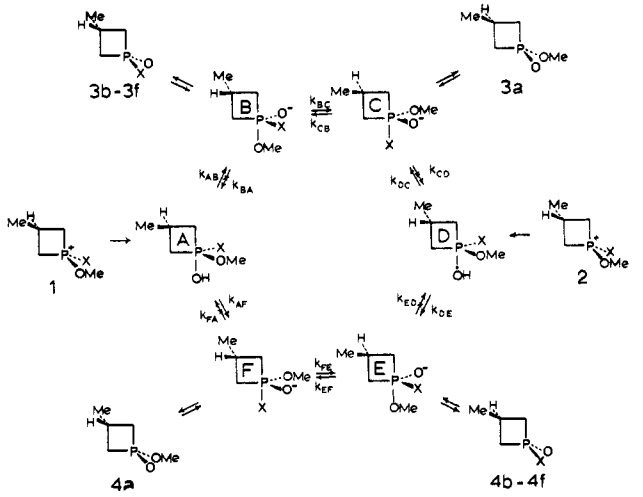


Figure 1. Relationship between tetracoordinate and pentacoordinate structures in displacement reactions of the phosphetane system.

field and Trippett[8] who obtained further evidence for absolute configurational assignments on similar compounds using chemical shift reagents.

Discussion

Pathways for Hydrolysis. The general scheme for nucleophilic displacements on phosphorus in a phosphetane ring system has been developed in a previous paper.[9] Incorporated in the scheme are the stereochemical relationships between the tetracoordinate phosphetane system and the pentacoordinate intermediates available in a displacement reaction. The pentacoordinate intermediates containing the four-membered ring in diequatorial positions are considered energetically unobtainable and ignored. The essential portion of the scheme is shown in Figure 1, for the hydrolysis of **1a–f** and **2a–f**, where R = Me.

From our above results on displacements connecting **3a–f** as depicted in Scheme I as well as from several other reports in the literature,[6–10] nucleophilic displacements on ester derivatives of the phosphetane oxide system occur, in general, with retention of configuration at phosphorus. The mechanism which has been advanced[9] for this displacement stereochemistry involves axial attack of the nucleophile, forming an intermediate phosphorane with the ring spanning axial–equatorial positions and the leaving group in an equatorial position. Loss of the leaving group, after an isomerization which places the leaving group in an axial position, results in the observed stereochemistry. In Figure 1, this mechanism is indicated by example in the steps **3e** → B → C → **3a**.

An important consequence of the observed stereospecificity in these displacements on the phosphetane oxide system is that isomerizations B → A, F → A, C → D, and E → D do not occur. Otherwise, these isomerizations would provide access to formation of products with inverted configuration at phosphorus (*e.g.*, **3e** → B → A → F → **4a**). Apparently, the basicity of the medium in the various reactions which involved protic solvents is sufficiently high that isomerizations resulting in the leaving group occupying the axial position (*e.g.*, B → C) are of much lower energy than isomerizations resulting in the oxy ligand (O^- or OH)[1b,1c,2a] assuming the axial position (*e.g.*, B → A).

In the hydrolysis of the phosphetanium salts,[11] axial attack of hydroxide would initially form phosphorane A from **1** and D from **2**. These intermediate phosphoranes in turn have two isomerization pathways available to each. Isomerizations of A to B or F result in either the alkoxy group or the group X, respectively, occupying an axial position of the new phosphorane. Similarly, isomerizations of D to E or C result in an analogous ligand exchange. Since the basicity of the hydrolysis medium (0.05 *M* NaOH in 50% aqueous dioxane) is approximately that employed in the alkoxide displacement reactions on the phosphetane oxides such as **3e** or **3f** (0.3 *M* NaOMe in MeOH), it follows that the above isomerizations of A or D are again irreversible. To eventually account for all four products being formed in some cases from both **1** and **2**, isomerizations between B and C and E and F with decomposition by loss of the axial ligand from each would then occur.

A further observation of importance can be made from Figure 1. The products from axial loss of a ligand from B or C are only of the configuration of **3**, while those from E or F have the configuration of **4**. Thus, the product ratio **3**/**4** from **1** reflects the kinetic competition between the isomerizations A → B and A → F, while the ratio **4**/**3** from **2** reflects the relative energies for isomerization D → E and D → C. The results in Tables I and II indicate that only **1d** and **2d** have a strong preference in the above competition, forming only **3d** from **1d** and **4d** from **2d**. We will return to this point later.

Isomerization *vs.* Decomposition Energies. From the data in Tables I and II it is apparent that **1e** and **2e** as well as **1f** and **2f** (R = Me or Et) undergo predominant displacement of the methylthio or chloro groups, respectively. Thus, to explain the formation of **3a** from either **1e** or **1f** in terms of Figure 1, the isomerization

(9) K. E. DeBruin, K. Naumann, G. Zon, and K. Mislow, *J. Amer. Chem. Soc.*, **91**, 7031 (1969).

(10) For a summary of the important references, see G. A. Gray and S. E. Cremer, *J. Org. Chem.*, 37, 3458 (1972), ref 21 and 22 therein.

(11) K. E. DeBruin and M. J. Jacobs, *Chem. Commun.*, 59, (1971).

B → C must be of lower energy than direct loss of the axial alkoxy group from B. A similar analysis applies to the formation of **4a** from **2e** or **2f**.

In the hydrolyses of **1a–c** and **2a–c** (R = Me or Et), a near equilibrium between B and C and between E and F has been obtained prior to product formation since the ratios of **3a**/**3b–f** and **4a**/**4b–f** are approximately constant when starting from either **1** or **2** (see Tables I and II). Thus, both **1** and **2** form equilibrium mixtures of B and C as well as E and F, and the products formed are determined by the respective equilibrium constants and relative rate constants for loss of the axial leaving groups. Only in the cases where methoxide ion is one of the leaving groups, *e.g.*, **1b** (R = Me), is there a slight deviation from equilibrium. Competitive loss of methoxide ion from B and isomerization to C would give a greater ratio of **3b–f**/**3a** when starting from **1** than from **2** as is observed [compare 49/11 from **1b** (R = Me) to 39/16 from **2b** (R = Me)]. These results indicate that isomerizations of the type B to C are of nearly the same or slightly less energy than loss of a methoxide ion from B.

The above observation is directly applicable to the study by Cremer and Trivedi[7] on the methoxide ion exchange of **3a**. They observed that **3a** undergoes displacement with $^{-}OCD_3$ with retention of configuration at phosphorus presumably *via* the pathway **3a** → C → B → **3** (X = OCD_3). Our results would indicate that the rate-limiting step in this exchange is formation or decomposition of the intermediate and not isomerization.[11]

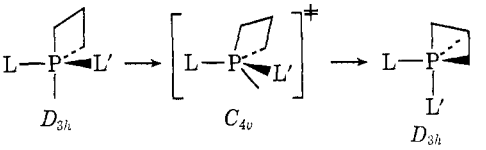
Axiophilicities of Ligands. If one accepts the above assumptions that attack of hydroxide ion on **1** forms phosphorane A and that isomerizations of A to B or F are irreversible under the reaction conditions, it follows that the product ratio **4**/**3** obtained from the hydrolysis of **1** is equal to the ratio of the rate constants k_{AF}/k_{AB} for isomerizations A → F and A → B, respectively. Since the isomerization A → B results in the alkoxy ligand assuming an axial position in the phosphorane B while the isomerization A → F places the ligand X in the axial position of F, the ratio of rate constants, k_{AF}/k_{AB}, reflects the relative kinetic axiophilicity[12] of the ligand X compared to the alkoxy ligand. A similar determination of the relative kinetic axiophilicity of ligand X can be obtained from a comparison of the product ratio **3**/**4** from **2**. Table IV lists these product ratios **4**/**3** and **3**/**4** from **1** and **2**, respectively, as a function of the ligand X. The diastereomeric relationship between the transition states for k_{AB} and k_{DE} as well as for k_{AF} and k_{DC} accounts for the slight difference in the product ratio **4**/**3** from **1** compared to **3**/**4** from **2**. The magnitude of this difference can be best assessed by analysis of the product ratio from **1a** (R = Me) or **1b** (R = Et) since in these two cases **1** ≡ **2**. Thus, in the alkoxy systems, there is an inherent preference for isomerization of A → B (or D → E) over A → F (or D → C) of 55/45 for R = Me and 63/37 for R = Et. Presumably, this difference is of a steric nature.

Table IV. Product Ratios Obtained from the Hydrolysis of the Phosphetanium Salts

Phosphetanium salt X	Product ratios: 4/3 from 1 (R = Me)	4/3 from 1 (R = Et)	3/4 from 2 (R = Me)	3/4 from 2 (R = Et)
OMe	0.80	0.78	1.2	1.5
OEt	0.67	0.59	1.2	1.7
O-*i*-Pr	0.85	0.60	1.2	1.6
NMe_2	0	0	0	0
SMe	1.6	1.3	1.7	1.5
Cl	1.7	2.3	1.8	2.3

The important qualitative observation from Table IV is that isomerizations involving positional exchange of a methylthio ligand or a chloro ligand from an equatorial position to an axial position are slightly more facile than that for an alkoxy ligand which in turn is much easier than that for a dimethylamino ligand. Thus, the relative kinetic axiophilicities of the various ligands are in the order: $NMe_2 \ll OMe \simeq OEt \simeq$ O-*i*-Pr < SMe ≃ Cl.

It has been recognized for some time both from empirical[13] and theoretical[14–18] considerations that the electronegativity of a ligand on pentacoordinate phosphorus strongly influences its positional preference in the trigonal bipyramid (D_{3h}) ground state. In addition, theoretical calculations[18] on the stability of idealized C_{4v} structures reveal that the more electronegative ligands prefer the basal sites. Thus, if one assumes that an intramolecular ligand exchange proceeds by the Berry mechanism[19] ($D_{3h} \rightarrow C_{4v} \rightarrow D_{3h}$), not only will an isomerization involving positional exchange of an equatorial ligand to an axial position be thermodynamically preferred for a more electronegative ligand, but also kinetically preferred. It follows that in competitive isomerizations resulting in the positional exchange of either of two groups (L or L′, eq 1) from an equatorial position to an axial position, the transition state containing the more electronegative ligand



(1)

in the basal position will be of lower energy (*i.e.*, L′ is more electronegative and will have the greater relative kinetic axiophilicity[20]).

(12) In an isomerization involving the positional exchange of a ligand from an equatorial to an axial position in a trigonal bipyramid, the term *thermodynamic axiophilicity* refers to the $\Delta G°$ for this process while *kinetic axiophilicity* refers to the energy of activation, $\Delta G^{\ddagger}$. The higher the axiophilicity, the lower the energy. Other workers[3] have used the term apicophilicity for the same process; however, we feel this term should be reserved for isomerizations between apical and basal positions of, *e.g.*, tetragonal pyramid structures.

(13) (a) E. L. Muetterties, W. Mahler, and R. Schmutzler, *Inorg. Chem.*, **2**, 613 (1963); (b) E. L. Muetterties, W. Mahler, K. J. Packer, and R. Schmutzler, *ibid.*, **3**, 1298 (1964); (c) E. L. Muetterties and R. A. Schunn, *Quart. Rev., Chem. Soc.*, **20**, 245 (1966).

(14) P. C. Van Der Voorn and R. S. Drago, *J. Amer. Chem. Soc.*, **88**, 3255 (1966).

(15) (a) R. J. Gillespie, *Inorg. Chem.*, **5**, 1634 (1966); (b) R. J. Gillespie, *J. Chem. Educ.*, **40**, 295 (1963); R. J. Gillespie and R. S. Nyholm, *Quart. Rev., Chem. Soc.*, **11**, 339 (1957).

(16) (a) R. E. Rundle, *Surv. Progr. Chem.*, **1**, 81 (1963); (b) R. E. Rundle, *Rec. Chem. Progr.*, **23**, 195 (1962).

(17) (a) L. S. Bartell, *Inorg. Chem.*, **5**, 1635 (1966); (b) L. S. Bartell and K. W. Hansen, *ibid.*, **4**, 1775 (1965).

(18) (a) A. Rauk, L. C. Allen, and K. Mislow, *J. Amer. Chem. Soc.*, **94**, 3035 (1972), and references therein; (b) J. B. Florey and L. C. Cusachs, *ibid.*, **94**, 3040 (1972).

(19) R. S. Berry, *J. Chem. Phys.*, **32**, 933 (1960).

(20) According to our definitions in ref 12, in this case, where the comparison is between two transition states of C_{4v} idealized symmetry, the thermodynamic apicophilicities of the ligands in the C_{4v} structure will reflect the kinetic axiophilicities of the D_{3h} structure. Thus, the

Although the numerous measures of electronegativity create ambiguity in their usage, it is apparent that the observed kinetic axiophilicities of the ligands in this study are *not* in the order of their electronegativity. The unanimous aspect of all the electronegativity scales is that an oxygen or alkoxy ligand is more electronegative than any of the other ligands investigated above (see Table V); however, the axiophilicity of an alkoxy ligand was found to be slightly *lower* than that for the less electronegative methylthio or chloro ligands.

Table V. Atomic or Group Electronegativities of the Various Ligands

Ligand	Electronegativities		
	X^a	X^b	X^c
OR	3.5	3.50	2.68 (R = Me)
NMe_2	3.0	3.07	2.48
Cl	3.0	2.83	
SMe	2.5	2.44	2.45

[a] Pauling atomic electronegativities: L. Pauling, "Nature of the Chemical Bond," 3rd ed, Cornell University Press, Ithaca, N. Y., 1960, p 60. [b] Allred–Rochow atomic electronegativities: A. L. Allred, *J. Inorg. Nucl. Chem.*, **17**, 215 (1961). [c] Huheey group electronegativities: J. E. Huheey, *J. Phys. Chem.*, **69**, 3284 (1965).

In a recent paper by Hoffmann, Howell, and Muetterties,[21] an extended Hückel approach to the molecular orbital picture of pentacoordinate phosphorus revealed that the ability of a ligand to donate or accept π electrons will also influence its positional preference in the idealized D_{3h} and C_{4v} structures. A π-donor ligand would prefer the equatorial position in the trigonal bipyramid structure and the apical position in the tetragonal pyramid structure. Thus, everything else being equal, the relative kinetic axiophilicity of a ligand will be greater for the poorer π donor. In eq 1, the isomerization will be of lower energy when L is the better π donor or L′ the poorer π donor.[22]

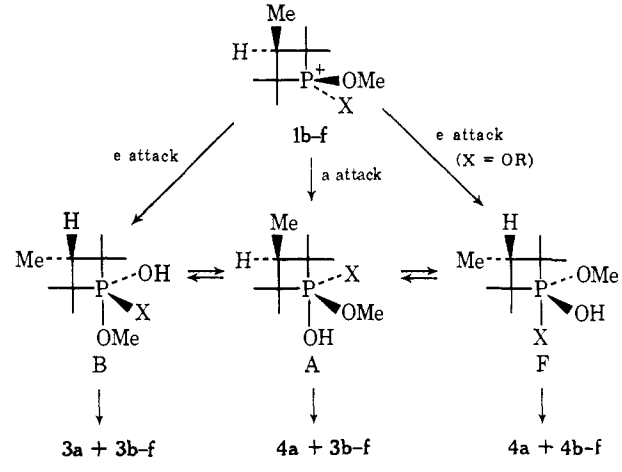
With these ideas in mind, the best explanation of our observed order of relative kinetic axiophilicities requires an alkoxy ligand to be a better π donor than methylthio or a chloro ligand, which compensates for its greater electronegativity. The latter ligands would involve 3p orbitals while the alkoxy ligands would utilize 2p orbitals. In support of the importance of π-orbital overlap in controlling the relative kinetic axiophilicities is the observation by Oram and Trippett[3] that a phenyl ligand has a lower axiophilicity or a higher barrier for isomerization from an equatorial position to an axial position than a methyl ligand. Thus again, the greater electronegativity of the phenyl group is over compensated by its π-donor ability in determining the kinetic axiophilicity. It should be emphasized that the above analysis or hypothesis requires an isomerization proceeding by the Berry mechanism and whose transition state is subject to the same symmetry considerations as developed for the idealized PH_5 geometries.[21] Neither of these requirements may hold.

A third factor, steric hindrance against isomerization of a ligand from an equatorial position to the more hindered axial position in a trigonal bipyramid, may also affect the order of relative axiophilicities of the ligands.[26–28] However, we observed virtually no effect in the series OMe, OEt, and O-*i*-Pr. For the alkylthio and chloro ligands, this steric factor should decrease, if anything, their axiophilicities which in the absence of steric constraints would require a greater difference in the relative kinetic axiophilicities than was observed. Thus, steric considerations would not be expected to affect the order of axiophilicities suggested above.

In summary, our results, in conjunction with those of Oram and Trippett[3] and others,[13] would suggest the following order of relative kinetic axiophilicities: aryl, vinyl < alkyl ≤ dimethylamino < alkoxy, aryloxy ≤ methylthio ≃ chloro.

Alternative Considerations. In the above discussion, a attack and a loss were the assumed modes for phosphorane formation and decomposition. Although this assumption has been successful in explaining a wide variety of results in displacement reactions of phosphorus and has been tested in the hydrolysis of acyclic phosphonium salts,[2c] an interesting situation arises if this assumption is not made; but instead, one assumes the stability of the initially formed phosphorane determines the mode of reaction. Thus, a attack of hydroxide ion on **1** to form A would be of similar energy to e attack to form B since A and B should be of similar energy. When X = OR, F will also be formed. However, when X = SMe, Cl, or NMe_2, the initially formed phosphoranes are limited to A and B since F would contain a relatively electropositive group in the axial position. Direct decomposition of these initially formed intermediates by loss of the appropriate ligands, without postulating a positional preference for leaving, would yield the products of stereochemistry indicated in Scheme II.

Scheme II



In the hydrolysis of **1a–c**, all three phosphoranes could be initially formed eventually resulting in for-

ligand L in the C_{4v} structure will have the greater relative thermodynamic apicophilicity. Note that L′ has the greater relative kinetic axiophilicity.

(21) R. Hoffmann, J. M. Howell, and E. L. Muetterties, *J. Amer. Chem. Soc.*, **94**, 3047 (1972).

(22) Evidence that such π-electron donation occurs has been found.[23–25]

(23) (a) S. C. Peake and R. Schmutzler, *Chem. Commun.*, 1662 (1968); (b) *J. Chem. Soc. A*, 1049 (1970).

(24) J. S. Harman and D. W. A. Sharp, *Inorg. Chem.*, **10**, 1538 (1971).

(25) E. L. Muetterties, P. Meakin, and R. Hoffmann, *J. Amer. Chem. Soc.*, **94**, 5674 (1972).

(26) J. E. Huheey, *J. Phys. Chem.*, **69**, 3284 (1965).

(27) S. E. Cremer, R. J. Chorvat, and B. C. Trivedi, *Chem. Commun.*, 769 (1969).

(28) J. R. Corfield, J. R. Shutt, and S. Trippett, *ibid.*, 789 (1969).

Table VI. Data on the Phosphetanium Salts (1 and 2)

Phosphetanium, salts (1 and 2) X	OR	Chemical shifts,[a] ppm ^{1}H nmr Region	δ(1)	δ(2)	Elemental analysis Calcd C	Calcd H	Found C	Found H
OMe	OMe	$POCH_3$	4.25 (11)	4.29 (11)	22.25	4.11	22.32	4.09
OEt	OMe		4.23 (11)	4.26 (11)	23.86	4.37	24.19	4.65
O-*i*-Pr	OMe		4.16 (11)	4.20 (11)	25.39	4.62	25.60	4.91
NMe_2	OMe		3.97 (12)	4.02 (12)	23.90	4.56	23.98	4.50
SMe	OMe		4.17 (13)	4.20 (13)	21.61	3.99	22.01	4.00
Cl	OMe		4.35 (13)	4.40 (13)	19.86	3.52	20.02	3.47
OMe	OEt	$POCH_2CH_3$	4.56 (7)	4.60 (7)	23.86	4.37	24.25	4.58
OEt	OEt		4.56 (7)	4.60 (7)	25.36	4.62	25.57	4.71
O-*i*-Pr	OEt		4.55 (7)	4.58 (7)	26.84	4.85	26.86	4.85
NMe_2	OEt	$PNCH_3$	3.02 (10)	2.97 (10)	25.43	4.80	25.87	4.91
SMe	OEt	$PSCH_3$	2.62 (11)	2.59 (11)	23.19	4.25	23.11	4.23
Cl	OEt	$POCH_2CH_3$	4.75 (7)	4.78 (7)	21.52	3.79	21.40	3.88

[a] J_{PH} in parentheses.

mation of both diastereomers **3a** and **4a** from **1a** (X = OR = OMe) and all four possible products from **1b** and **1c**. For the hydrolysis of **1d–f**, a constant ratio of A to B, independent of the nature of the X ligand, would be formed. Decomposition of these two phosphoranes, when X = NMe_2 from **1d**, would yield only **3d** *via* loss of the alkoxy ligand. In contrast, decomposition of A and B from **1e** and **1f** would result in the loss of the better leaving group (alkylthio or chloro) and form **3a** from B and **4a** from A. Since the ratio of **3a**/**4a** is dependent only on the ratio B/A, which is insensitive to X, both **1e** and **1f** result in the same product ratio as was observed. The fact that **1e** and **1f** resulted in *ca.* 60/40 ratio of **4a**/**3a** would require a very slight preference for a attack to form A.

Although the above analysis accounts for the results obtained without assuming a strong preference for a attack, it is precisely this lack of preference which decreases its credibility. From a steric viewpoint alone, if e attack is visualized as approach of the neucleophile in the plane of the phosphorus and the two ligands which will ultimately become axial, the presence of the ring methyl groups should make e attack even less competitive in this system compared to acyclic or unhindered cyclic systems where a attack is necessary to explain the observed results.[29] Thus, unless the phosphetane system exerts an unusual control on the mode for phosphorane formation, we would prefer the initial analysis of the factors controlling the product ratios and stereochemistry.

Experimental Section

Reactions of Phosphetane Oxides, 3a–f. Conversion of 3f to 3a–c.[6] A solution of diastereomerically pure 1-chloro-2,2,3,4,4-pentamethylphosphetane oxide[4] (**3f**) (5.0 g, 0.025 mol) in methanol (20 ml) was added dropwise to a solution of sodium methoxide (0.3 *M*, 0.03 mol) in methanol (100 ml), and the mixture was stirred at room temperature for 24 hr. After evaporation of the solvent, the residue was dissolved in dichloromethane, extracted with water, dried, and reconcentrated to give a clear oil. Kugelrohr distillation (70° (0.1 mm)) afforded pure 1-methoxy-2,2,3,4,4-pentamethylphosphetane oxide[7] (**3a**) (4.5 g, 92% yield). Similar procedures utilizing sodium ethoxide in ethanol and potassium isopropoxide in 2-propanol afforded 1-ethoxy-2,2,3,4,4-pentamethylphosphetane oxides[7,8,30] (**3b**) and 1-isopropoxy-2,2,3,4,4-pentamethylphosphetane oxide (**3c**), respectively. Tables III and VII contain some pertinent ^{1}H-nmr data on these products.

Table VII. ^{1}H Nmr Analysis Regions for Determination of Product Ratios and Stereochemistry

Compd No.	X	Analysis region	Chemical shift[a,b] δ, ppm	Δδ, ppm
3a	OMe	$POCH_3$	3.52 (10)	0.07
4a	OMe	$POCH_3$	3.45 (10)	
3b	OEt	$POCH_2CH_3$	4.03 (8)	0.05
4b	OEt	$POCH_2CH_3$	3.98 (8)	
3c	O-*i*-Pr	$POCH(CH_3)_2$	4.62 (7)	0.02
4c	O-*i*-Pr	$POCH(CH_3)_2$	4.60 (7)	
3d	NMe_2	$PN(CH_3)_2$	2.47 (10)	0.15
4d	NMe_2	$PN(CH_3)_2$	2.32 (10)	
3e	SMe	$PSCH_3$	2.17[c] (9)	0.03[c]
4e	SMe	$PSCH_3$	2.14[c] (9)	
3f	Cl	Ring	*d*	*d*
4f	Cl	Methyls		

[a] Solvent benzene. [b] J_{PH} coupling constants in parentheses. [c] Solvent CH_2Cl_2. [d] See Table III.

A similar procedure to that above was used in the conversion of **3e** to **3a** beginning with 1-methylthio-2,2,3,4,4-pentamethylphosphetane oxide (**3e**).

Conversion of 3f to 3d. A solution of **3f** (1.0 g, 0.005 mol) in THF (10 ml) was added dropwise to a solution of lithium dimethylamide (0.005 mol) in THF (28 ml), prepared by the addition of butyllithium (5.0 ml, 1.0 *M* solution) to a solution of dimethylamine (2 ml) in THF (20 ml) at −78°. After stirring for 30 min at −78° and 24 hr at 25°, the reaction mixture was added directly to ice and extracted with dichloromethane. The extracts were dried with magnesium sulfate and concentrated to yield a white solid, mp 93–94° (0.9 g, 90% yield).[31]

A similar procedure was utilized in the conversion of 3a to 3d (90% yield) and the conversion of 3e to 3d (84% yield). ^{1}H-nmr data on the above products is given in Tables III and VII.

Conversion of 3f to 3e. This reaction was carried out by the same procedure utilized above in the conversion of **3f** to **3d** except methyl mercaptan was substituted for dimethylamine. The product consisted of a colorless liquid after purification by Kugelrohr distillation (80° (0.1 mm)), which was identified as 1-methylthio-2,2,3,4,4-pentamethylphosphetane oxide (**3e**) (80% yield). See Tables III and VII for pertinent ^{1}H-nmr data of **3e**.

Synthesis of Phosphetanium Salts 1a–f and 2a–f. Identical procedures were used in the synthesis of all the phosphetanium hexachloroantimonate salts in this study. Equivalent amounts (0.005 mol) of the trialkyloxonium hexachloroantimonate and the phosphetane oxide were added to dichloromethane (50 ml), and the resulting mixture was stirred at room temperature for 1 hr. After concentrating to 10 ml, the solution was added to anhydrous ether (75 ml), producing a white powdery solid. ^{1}H-nmr spectra on the products were consistent with O-alkylated products. Table VI contains some of the important data on the products.

Hydrolysis of Phosphetanium Salts. The following procedure was used in the hydrolysis of each phosphetanium salt **1a–f** (R =

(29) For example, if e attack is permitted, it is difficult to explain the exclusive ring opening observed in the alkaline hydrolysis of the cyclic phosphonate ester, 1-methoxy-2-oxaphospholane oxide.[2]

(30) K. Bergesen, *Acta Chem. Scand.*, **21**, 1587 (1967).

(31) P. Haake and T. Koizumi, *Tetrahedron Lett.*, 4849 (1970).

Me or Et). A solution of 0.05 *M* NaOH in 50% (v/v) aqueous dioxane (300 ml) was added at once to a solution of the phosphetanium salt (0.5 mmol) in dioxane (2 ml) at 25°. After stirring for 30 sec, the mixture was immediately extracted with dichloromethane (300 ml). Drying the extracts with magnesium sulfate and concentrating afforded a crude mixture of the possible phosphetane oxide products. The crude sample was analyzed directly by ^{1}H nmr without purification. Table VII indicates the regions utilized in determining the product ratios.

The products resulting from the hydrolyses of **2a–f** were obtained by reacting a known mixture of **1** and **2** determined by ^{1}H nmr (see Table VI) and then correcting for the products which would have arisen from **1** as determined above.

All hydrolyses were repeated five times, and the product percentages indicated in Tables I and II are the average of these determinations (standard deviation *ca.* ±2%). In all cases, the products accounted for greater than 90% of theoretical, indicating very little if any further hydrolysis to the phosphinic acid.

Acknowledgment. We would like to thank Research Corporation for the generous support of this research.

Peracid Oxidation of Imines. Kinetics of Oxazirane Formation from Benzylidene-*tert*-butylamines and Perbenzoic Acid

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Received October 7, 1972

Abstract: The reaction of perbenzoic acid (PBA) with benzylidene-*tert*-butylamines to afford oxaziranes has been studied kinetically in order to decide whether the mechanism is either one step (epoxidation type) or two step (the Baeyer–Villiger type). Although the rates are summarized as $v = k_{obsd}[C{=}N][PBA]$, the reaction exhibits complex kinetics because of two adverse effects, acceleration by carboxylic acids and protic solvents and retardation by basic solvents including ethers and alcohols. Thus, various alcohols can catalyze the oxidation with similar effectiveness as carboxylic acids, while the reaction is retarded on addition of excess of some alcohols. The substituent effect on the imines changes with reaction conditions; the effect becomes very small in the presence of ethanol. These data for the oxazirane formation show behaviors different from the PBA oxidation of amines and olefins, which has a one-step mechanism. It may be concluded that the oxazirane formation has a two-step mechanism similar to the Baeyer–Villiger reaction, where the addition to C=N is rate determining under most conditions. Significant amounts of nitrones were also formed with imines bearing electron-donating substituents.

The following two mechanisms have been developed for the formation of oxaziranes by the peracid oxidation of imines.[1–5]

One-step mechanism

$$>C{=}N- + RCO_3H \longrightarrow >C(O)-N- + RCO_2H \quad (1)$$

Two-step mechanism

$$>C{=}N- + RCO_3H \longrightarrow -C(OOCOR)-NH- \longrightarrow >C(O)-N- + RCO_2H \quad (2)$$

Originally, Emmons[1] regarded the one-step mechanism more probable than the two-step one without any convincing evidence, while Schmitz, *et al.*,[3] preferred the latter (eq 2). Recently, Madan and Clapp[4] chose the former (eq 1) in view of the kinetic data especially from negative ρ values for substituted imines and significant acid catalysis.

We felt, however, that the two-step mechanism (eq 2) cannot be ruled out in view of the facts that imines are susceptible to nucleophilic attacks,[6,7] that the peracid oxidation of *N*-benzoylimines affords the Baeyer–Villiger-type rearranged products, *i.e.*, phenols,[8] and that a reaction of an aliphatic imine with hydrogen peroxide gave an adduct, which is converted to an oxazirane on gentle heating.[9] Moreover, Madan and Clapp's kinetic results for the imine oxidation[4] are fairly similar to those for the Baeyer–Villiger reaction of aromatic carbonyl compounds with perbenzoic acid (PBA).[10]

On the other hand, if the one-step mechanism is operative, it is of interest to study which electrons of C=N attack the peroxidic oxygen, C=N π-bonding electrons (oxazirane formation), or N lone-pair electrons (nitrone formation). This problem is also concerned with asym-

(1) W. D. Emmons, *J. Amer. Chem. Soc.*, **79**, 5739 (1957).
(2) W. D. Emmons, *Chem. Heterocycl. Compounds*, **19** 630 (1964).
(3) E. Schmitz, R. Ohme, and D. Murawski, *Chem. Ber.*, **98**, 2516 (1965).
(4) V. Madan and L. B. Clapp, *J. Amer. Chem. Soc.*, **91**, 6078 (1969); **92**, 4902 (1970).
(5) The peracid oxidation of imines is an important way for synthesis of oxaziranes: L. A. Paquette, "Principles of Modern Heterocyclic Chemistry," W. A. Benjamin, New York, N. Y., 1968, p 63; ref 1; W. Krim, *Chem. Ber.*, **91**, 1057 (1958); R. G. Pews, *J. Org. Chem.*, **32**, 1628 (1967).
(6) R. W. Layer, *Chem. Rev.*, **63**, 489 (1963).
(7) W. P. Jencks, *Progr. Phys. Org. Chem.*, **2**, 63 (1964).
(8) A. Padwa, *J. Amer. Chem. Soc.*, **87**, 4365 (1965).
(9) E. Höft and A. Rieche, *Angew. Chem.*, **77**, 548 (1965).
(10) Y. Ogata and Y. Sawaki, *J. Amer. Chem. Soc.*, **94**, 4189 (1972); *J. Org. Chem.*, **37**, 2953 (1972).