Phosphoric Carboxylic Imides. 1. Preparation and Fragmentation Behavior of Dialkylphosphoryl (and Phosphinyl) Acetyl (and Benzoyl) Imides and Related Systems

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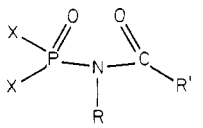
Six phosphoric carboxylic imides $X_2P(O)$–NR–C(O)R′ (I, X = MeO, EtO, Et; R = H, Me; R′ = Me, Ph) were synthesized and characterized. Mass spectra of compounds I were recorded, and the observed fragmentation behavior is compared with that of phosphoric amides $X_2P(O)NHR$ and carboxylic amides R′(O)NHR reported in the literature and obtained in this work. The main pathways of fragmentation of the imides I indicate that the molecular ions involve mainly the radical cationic center at the carbonyl oxygen. All imides give products resulting from the fragmentation following the initial isomerization of substrates to the corresponding *O*-phosphoryl (or phosphinyl) imidates $X_2P(O)$–O–C(NR)R′. Under recording conditions, tertiary substrates (I, R = Me) undergo (70 eV, 200 °C) reaction, yielding the corresponding tetraalkyl pyrophosphates $(RO)_2P(O)OP(O)(OR)_2$, which give rise to new peaks in the mass spectra. For the *O*-ethyl derivatives (I, X = OEt), structural features favoring the loss of ethylene (McLafferty rearrangement) or the loss of the vinyl radical (double hydrogen rearrangement) are discussed.

Our interest in the chemistry of phosphoric and carboxylic amides[1] led us to investigate the structure and reactivity of the imide system incorporating both nitrogen–phosphoryl and nitrogen–carbonyl bonds in the same molecule. Besides the solvolytic[2] and nucleophilic[3] behavior of this system, its fragmentation pattern under conditions of electron impact seemed to be a useful probe for investigation of the bonding characteristics and the dynamics of the >P(O)–N–C(O)– functional group. We decided therefore to synthesize some secondary (R = H) and tertiary (R = alkyl) derivatives (I), record and interpret their mass spectra, and compare their behavior with that of related systems. In this work we report our results obtained for the following *N*-acylphosphoramidates and -phosphinamidates: $(MeO)_2P(O)$–NH–COPh (Ia); $(MeO)_2P(O)$–NMe–COMe (Ic); $(EtO)_2P(O)$–NMe–COPh (Ie); $(EtO)_2P(O)$–NH–COPh (Ib); $(EtO)_2P(O)$–NMe–COMe (Id); $Et_2P(O)$–NMe–COMe (If).



I

Results and Discussion

Secondary substrates can be easily prepared by the established procedure,[4] but the available information on the preparation of the tertiary derivatives is scarce. The preparation of Ic from the sodium salt of *N*-methyldimethylphosphoramidate and acetyl chloride was reported in the patent literature.[5] We were not able to repeat this synthesis; prolonged reaction yielded the unchanged phosphoramidate and ketene, presumably via α-hydrogen abstraction from acetyl chloride by the amide anion. Compounds Ic–f can, however, be synthesized by the reaction of the phosphoro (or phosphino) chloridates with the sodium salt of the carboxylic amide in toluene. Products of reaction 1 were isolated and purified by column chromatography and their structures confirmed by elemental analysis and IR and ^1H NMR spectroscopy. In all cases the amide salts behaved as *N*-nucleophiles, and we did not observe any formation of the isomeric O-phosphorylated benz- or acetimidates, R–C(NMe)OP-(O)X_2.

$$X_2P(O)Cl + RCO\text{–}NNaMe \rightarrow \underset{\text{Ic–f}}{X_2P(O)\text{–}NMe\text{–}COR} \qquad (1)$$

X = MeO, EtO, Et; R = Me, Ph

The degree of interaction of the nitrogen atom in I with the neighboring phosphoryl and carbonyl centers can be inferred from the spectroscopic data. The phosphorus–hydrogen coupling constant for the ^1H NMR signal of the *N*-Me group in Ic–f is low; the J_{PNCH} values in the N-substituted system $(MeO)_2P(O)NXMe$ increase in the order X = COMe (7.5 Hz) < X = Ph (8.0 Hz)[6] < X = Me (10.0 Hz).[7] This order indicates strong resonance interactions within the N(Me)CO group increasing the sp^2 character of the nitrogen atom.[8] The effect of nitrogen substitution on the IR stretching frequencies of the phosphoryl and carbonyl groups in the series of N-substituted *N*-methylphosphoramidates and -acetamides is presented in Table I. The bond order of both the phosphoryl and carbonyl groups (as measured by the value of $\nu_{Y=O}$, Y = P, C) is sensitive to the nature of group X at

(1) T. A. Modro, in "Phosphorus Chemistry", L. D. Quin and J. Verkade, Eds, American Chemical Society, Washington, ACS Symp. Ser., No. 171, p. 128.
(2) V. Mizrahi and T. A. Modro, to be submitted for publication.
(3) V. Mizrahi, T. Hendrickse, and T. A. Modro, Submitted for publication.
(4) A. V. Kirsanov and R. G. Makitra, *Zh. Obshch. Khim.*, 28, 35 (1958).
(5) W. Perkow, DAS. 1067433 (1957), Nordd. Affinerie u. C.F. Spiess and Sohn; Chem. Zent. 16232 (1960).
(6) T. A. Modro and B. P. Rijkmans, *J. Org. Chem.*, in press.
(7) T. A. Modro and D. G. Graham, *J. Org. Chem.*, 46, 1923 (1981).
(8) Analogous variations in the magnitude of the spin–spin coupling transmitted through the nitrogen atom have been observed for other phospohorus compounds.[9]
(9) (a) J. F. Nixon, *J. Chem. Soc. A*, 1087 (1969); (b) D. C. H. Bigg, R. Spratt, and B. J. Walker, *Tetrahedron Lett.*, 107 (1970); (c) I. Irvine and R. Keat, *J. Chem. Soc., Dalton Trans.*, 17 (1972).
(10) R. A. Nyquist and W. J. Potts, in "Analytical Chemistry of Phospohorus Compounds", M. Halmann, Ed., Wiley-Interscience, New York, 1972, 209.
(11) G. A. Foulds, B. P. Rijkmans, and T. A. Modro, *S. Afr. J. Chem.*, *34*, 72 (1981).
(12) H. Lenormant, *Bull Soc. Chim. Fr.*, 33 (1948).
(13) R. N. Jones and C. Sandorfy, in "Chemical Applications of Spectroscopy", W. West, Ed., Interscience, New York, 1956, Chapter IV, 525.
(14) C. M. Lee and W. D. Kumler, *J. Am. Chem. Soc.*, 84, 575 (1962).

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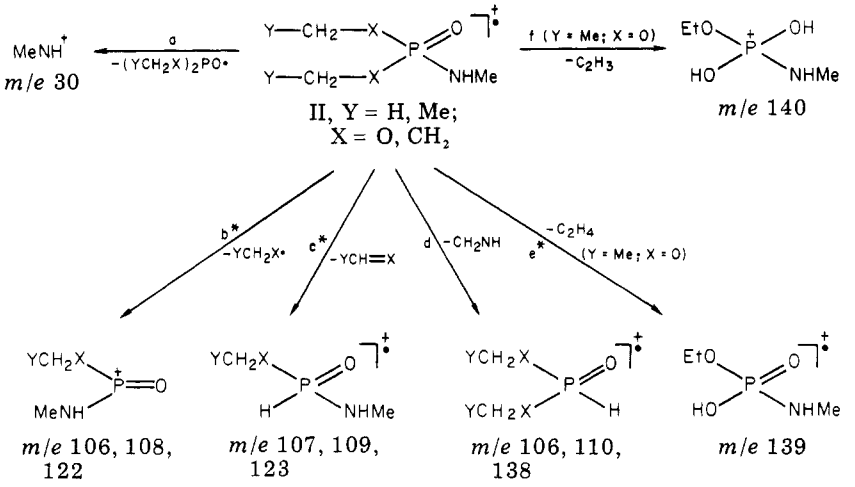
Table I. Stretching Frequencies (cm^{-1}) for the P=O and C=O Groups in $(MeO)_2P(O)N(X)Me$ (A) and $MeC(O)N(X)Me$ (B)

	X				
system	Me	$P(O)Et_2$	Ph	$P(O)(OMe)_2$	C(O)Me
A, P=O	1260[a]		1275[b]		1294[c]
B, C=O	1660[d]	1668[e]	1692[f]	1697[c]	1706[g]

[a] Reference 10. [b] Reference 11. [c] This work, compound Ic. [d] Reference 12. [e] This work, compound If. [f] Reference 13. [g] Reference 14.

Scheme I



the amide nitrogen. For both groups a significant hypsochromic shift is observed when the nitrogen substituent X is changed from methyl to a group acting as a resonance acceptor with respect to the nitrogen nonbonding electrons. From the values obtained for system B it is clear that the acetyl group is a stronger electron acceptor than the substituted phosphoryl groups.[15] The detailed electron distribution in I should of course modify the ionization potential of the oxygen and nitrogen atoms of the (O)PNC(O) linkage and thus determine the predominant structures of the parent radical ions derived from I upon electron impact.

Since compounds I are structurally derived from both carboxylic and phosphoric amides, the interpretation of their mass spectra has to be necessarily related to the behavior of the parent systems. We were interested in determining the degree of retention of the fragmentation patterns characteristic of simple amides, as well as finding new pathways, resulting from the presence of an unsymmetrical (phosphoric and carboxylic) imide skeleton. The main fragmentation schemes for secondary and tertiary carboxy amides are well established; the available information on the mass spectroscopy of phosphoric amides is, however, much more scarce. In order to obtain the relevant material for comparison, we have recorded and analyzed the mass spectra of the following secondary organophosphorus *N*-methylamides: $(MeO)_2P(O)$–NHMe (IIa); $(EtO)_2P(O)$–NHMe (IIb); $Et_2P(O)$–NHMe (IIc). The spectra of amidates IIa and IIb were compared with those of the corresponding primary amides reported before;[17] phosphinic derivative IIc could be compared with diethylphosphinic acid or its esters.[18]

Some of the fragmentation pathways are observed for all three derivatives (IIa–c), and some are specific only to the diethyl ester IIb. The primary products formed in the fragmentation of substrates II are listed in Table II. Primary products then give rise to subsequent fragments; for the sake of clarity these ions have not been included in Table II. The fragmentation patterns, characteristic of amides II are presented in Scheme I; the pathways supported by metastable peaks are indicated by an asterisk.[19]

Table II. Selected Ions in the Mass Spectra of Dialkyl *N*-Methylphosphoramidates and -phosphinamidates

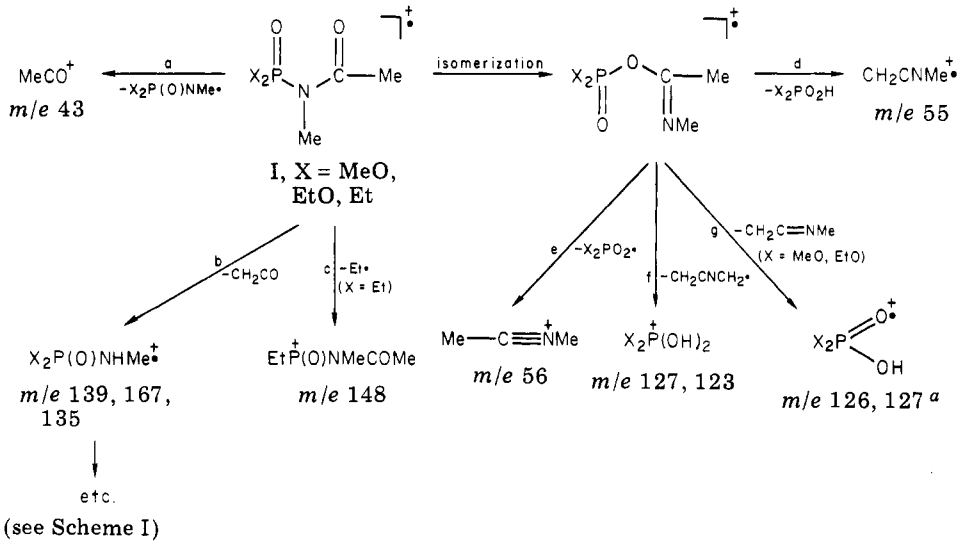
		substrate[b]		
pathway[a]	m/e	IIa	IIb	IIc
a	30	98	96	34
b	106			100
	108	66		
	122		16	
c	107			28
	109	100		
	123		16	
d	106			100
	110	96		
	138		24	
e	139		31	
f	140		14	

[a] Scheme I. [b] Relative intensities (%).

The molecular ions derived from substrates II are capable of undergoing P–N bond cleavage by liberating a disubstituted phosphoryl radical and $MeNH^+$ ion (pathway a). In this respect, N-substituted phosphoric amides parallel the behavior of *N*-methylcarboxamides, the mass spectra of which contain the same peak at *m/e* 30.[20] The second homolytic cleavage common to all substrates II is that of the P–X bond (pathway b), resulting in the formation of a phosphorylium ion stabilized by the adjacent nitrogen atom (*m/e* 106, 108, 122). Another route commonly available to system II is via an elimination reaction

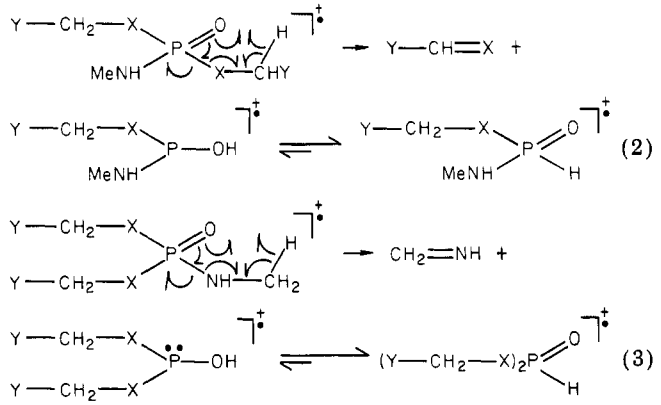
(15) This is in agreement with our earlier observation on substituent effects upon the ^{13}C NMR shielding in aromatic derivatives.[16]
(16) T. A. Modro, *Phospohorus Sulfur*, 5, 331 (1979).
(17) P. Jakobsen, S. Treppendahl, and J. Wieczorkowski, *Org. Mass. Spectrosc.*, 6, 1303 (1972).
(18) P. Haake and P. S. Ossip, *Tetrahedron*, 24, 565 (1968).
(19) Although for some of the primary fragmentations the corresponding metastable peaks were not observed, they were observed for the subsequent analogous fragmentations of the primary products.
(20) J. A. Gilpin, *Anal. Chem.*, 31, 935 (1959).

Scheme II



[a] See footnote b, Table III.

involving the loss of aldehyde or ethylene (pathway c, eq 2), as well as methyleneimine (pathway d, eq 3). In IIb



the presence of the β-carbon atom in the ester function makes the mass spectrum of this compound more complex. The P(O)OEt function in the parent ion is responsible for some additional fragmentations, well established for ethyl derivatives of phosphoric acid.[17,21-23] Loss of ethylene (pathway e) occurs via the typical McLafferty rearrangement;[24] loss of vinyl radical[23] (pathway f) involves a double hydrogen rearrangement. In conclusion, the mass spectra of amides II demonstrate that the radical ion produced from the molecular system $X_2P(O)$–NHR has a complex decomposition pattern involving both the group X and the amide function and often accompanied by hydrogen and skeletal rearrangements.

N-Acylphosphoramidates (I) can be considered as derivatives of benzamide and acetamide molecules, modified structurally at the amide nitrogen. The characteristic features of the mass spectra of aromatic amides are the presence of an M − 1 peak (loss of H· from the aromatic ring) and a benzoylium ion peak, resulting from acyl–nitrogen bond cleavage.[25] The typical mass spectral behavior of acetamides, most relevant to our discussion, is the loss of ketene from the parent ion[26] (eq 4). If reaction

Table III. Selected Ions in the Mass Spectra of Dialkyl *N*-Methyl-*N*-acetylphosphoramidates and -phosphinamidates

		substrate[b]		
pathway[a]	*m/e*	Ic	Id	If
a	43	44	30	28
b	139	86		
	167		9	
	135			7
c	148			29
d	55	95	46	76
e	56	25	20	100
f	127	18		
	123			7
g	126	14		
	127[c]		67	

[a] Scheme II. [b] Relative intensities (%). [c] The radical ion of diethyl phosphate (*m/e* 154), formed from isomerized (Id) according to pathway g, Scheme II, is not stable and immediately loses a C_2H_3· radical, yielding the ion *m/e* 127:

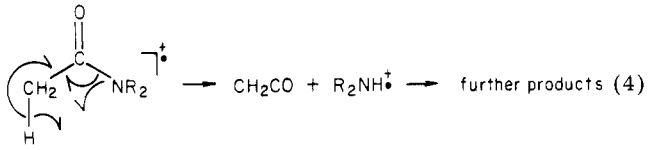
isomer Id+· $\xrightarrow{-CH_2CNMe}$ $(EtO)_2PO_2H^{+}\cdot$ (m/e 154) $\xrightarrow{-C_2H_3\cdot}$ $EtOP(OH)_3^{+}$ (m/e 127)

Table IV. Selected Ions in the Mass Spectra of the Dialkyl *N*-Benzoylphosphoramidates

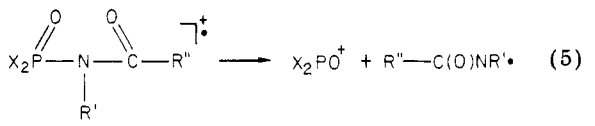
		substrate[b]		
pathway[a]	*m/e*	Ia	Ib	Ie
a	105	100	100	100
b	228	16		
c	201	9		
	243			4
d	152	59		
	180		14	
e	117			50
f	104	14	27	
	118			63
g	126	94		
	154		49	

[a] Scheme III. [b] Relative intensities (%).

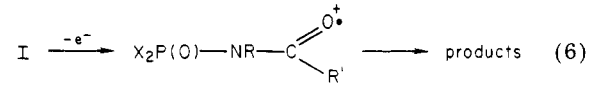
(21) W. J. McMurray, S. R. Lipsky, C. Zioudrou, and G. L. Schmir, *Org. Mass Spectrosc.*, **3**, 1031 (1970).
(22) D. A. Bafus, E. J. Gallegos, and R. W. Kiser, *J. Phys. Chem.*, **70**, 2614 (1966).
(23) J. G. Prichard, *Org. Mass Spectrosc.*, **3**, 163 (1970).
(24) M. C. Hamming and N. G. Foster, "Interpretation of Mass Spectra of Organic Compounds", Academic Press, New York, 1972, p 312.



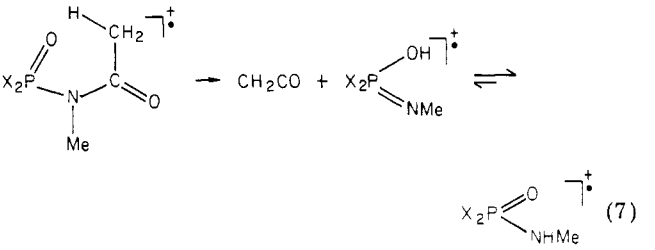
4 was also operating for structures Ic–f, the initially formed products would be identical with the parent ions of II a–c, and the subsequent fragmentations would follow the pathways presented in Scheme I. The primary fragmentation products observed for the *N*-acetyl (Ic, d, f) and *N*-benzoyl (Ia,b,e) derivatives (I) are listed in Tables III and IV, respectively. Fragmentation patterns responsible for the formation of these products are presented in Schemes II and III. The fragmentation behavior of the mixed phosphoric carboxylic imides (I) resembles in certain respects the behavior of the corresponding amides (carboxylic and phosphoric), but at the same time some new features are also observed. For the three *N*-benzoyl derivatives studied, only Ia shows the loss of H· from the parent ion (pathway b, Scheme III), but all three undergo carbonyl–nitrogen bond cleavage producing the benzoylium ion (pathway a, Scheme III).[25] Similar acyl (carboxylic)–nitrogen bond fission yielding acetylium ion is found for all *N*-acetyl compounds (pathway a, Scheme II). The analogous cleavage of the P–N bond in the parent ion should produce the corresponding phosphorylium ion and the carboxylic amide radical (eq 5). We never in fact



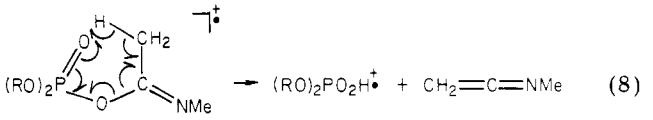
observed the formation of diethylphosphorylium ion ($(EtO)_2PO^+$) in the mass spectrum of Ib–d or diethylphosphinylium ion Et_2PO^+ in the mass spectrum of If. However, the dimethylphosphorylium ion observed for substrate Ia results from a secondary fragmentation.[27] Such a difference in the N-P(O) vs. N–C(O) bond fission can stem from two diffrent reasons. Firstly, acylium ions $R–CO^+$ are apparently much more stable species than the phosphorylium ions X_2PO^+.[28] Secondly, the observed fragmentation preference can indicate that in the parent ions derived from I the radical ion character is localized at the N–C(O) rather than at the N–P(O) function. In our opinion both factors contribute to the preferential cleavage of the carbonyl–nitrogen bond in the systems studied. All benzoyl derivatives yield upon fragmentation the benzoylium ion (*m/e* 105) as a base peak, an obvious indication of the high stability of the ion. The major fragmentations of compounds I can be best explained in terms of the lowest energy molecular ion formed by the ionization of one of the carbonyl oxygen nonbonding electrons (eq 6). Decomposition of the molecular ion (Schemes II and III)



via formation of an acylium ion or via loss of H· and Ph· involves fragmentation of the R′–C(O)–NR moiety of substrates I. *N*-Acetyl derivatives also show a property characteristic of acetamides,[26] namely, loss of a molecule of ketene (pathway b, Scheme II) to give radical ions identical with the molecular ions derived from phosphoramidates II. Loss of ketene can be even easier in these systems than in simple acetamides (eq 4) due to the possible participation of the phosphoryl group in hydrogen migration (eq 7). It is worthwhile to point out that the

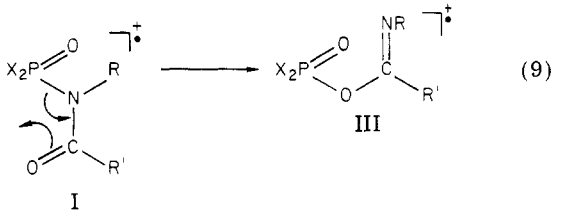


corresponding fragmentation, involving loss of a nitrogen analogue of ketene ($CH_2=C=NMe$) is also observed for the isomerized products of both Ic and Id (Scheme II and eq 8). Another feature of the mass spectra of I that



requires discussion is the loss of CO. This type of fragmentation was observed before [31] for substituted imides RCONMeCOR with the substituent R at the carbonyl group migrating either to the oxygen (R = alkyl) or to the nitrogen (R = aryl) atom. We found this behavior only partly retained in phosphoric carboxylic imides; although the loss of CO and phenyl → nitrogen migration takes place for Ia and Ie (Scheme III, pathway c), no corresponding methyl migration to the phosphoryl oxygen was observed for *N*-acetyl derivatives.

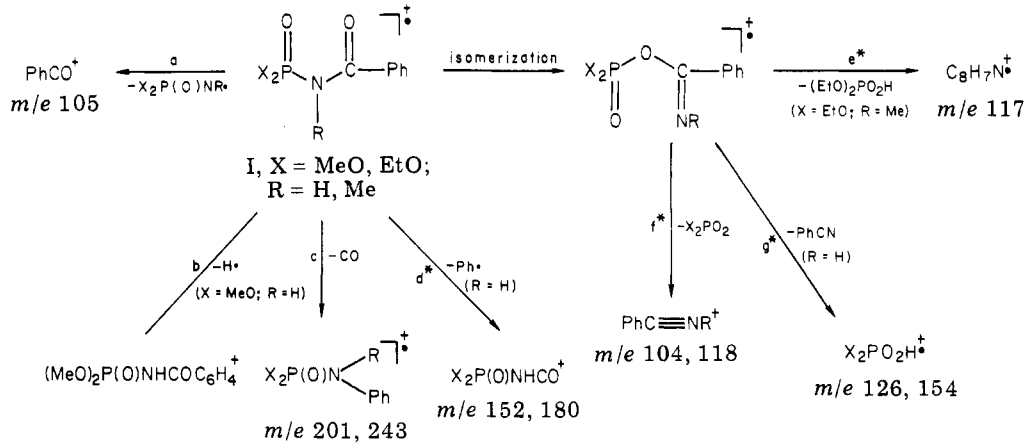
The common property of all the *N*-acylphosphoramidates (I) is that they rearrange to the corresponding O-phosphorylated benz- or acetimidates (III) (eq 9). The



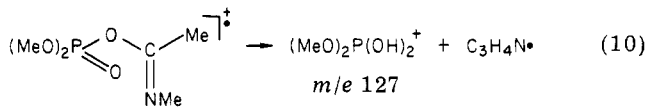
rearranged products (III) give rise to new fragmentation patterns, also included in Schemes II and III. They all readily lose the X_2PO_2· radical and yield *N*-protonated or *N*-methylated nitrilium ions $R'–C\equiv N^+–R$ (R = H, Me; R′ = Me, Ph). Hydrogen transfer to the phosphoryl group accompanied by C–O bond fission also takes place (pathways g) and the dialkyl phosphate radical ion is formed, which then fragments according to the known pathways of X_2PO_2H derivatives.[32] An interesting fragmentation

(25) A. M. Duffield, G. de Martino, and C. Djerassi, *Org. Mass. Spectrosc.*, 9, 137 (1974).
(26) Z. Pelah, M. A. Kielczewski, J. M. Wilson, M. Ohashi, H. Budzikiewicz, and C. Djerassi, *J. Am. Chem. Soc.*, 85, 2470 (1963); K. G. Das, P. T. Funke, A. K. Bose, *ibid.*, 86, 3729 (1964).
(27) Dimethylphosphorylium ion is observed in the mass spectrum of Ia as a result of the loss of isocyanic acid from the ion of *m/e* 152 (fragmentation supported by the corresponding metastable peak), derived from the parent ion via the loss of phenyl radical (pathway d, Scheme III).
(28) Acylium ions can easily be generated in solution from a variety of precursors,[29] whereas there is no evidence for the participation of phosphorylium ions in reactions of phosphoryl compounds.[30]
(29) M. Liler, "Reaction Mechanisms in Sulfuric Acid", Academic Press, London, 1971, Chapter 4.3.1.3.
(30) P. Haake and P. S. Ossip, *J. Am. Chem. Soc.*, 93, 6919 (1971).
(31) C. Nolde, S. O. Lawesson, J. H. Bowie, and R. G. Cooks, *Tetrahedron*, 24, 1051 (1968).
(32) P. Haake, M. J. Frearson, and C. E. Diebert, *J. Org. Chem.* 34, 788 (1969).

Scheme III

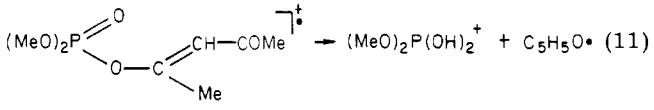


of acetimidate derivatives (III, R′ = Me) occurs via C–O bond cleavage and a double hydrogen rearrangement to give the protonated phosphate, as illustrated in Scheme II by the formation of an m/e 127 peak (pathway f and eq 10). The released radical is resonance stabilized



(10)

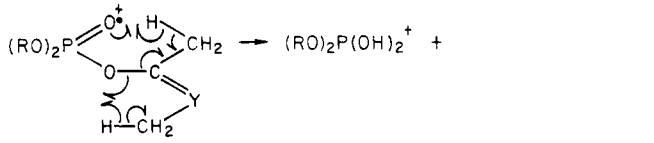
(CH_2=Ċ-N=CH_2 ↔ CH_2=C=N-ĊH_2), and reaction 10 is an extension of the double hydrogen shift releasing vinyl radical C_2H_3· observed for ethyl esters of phosphoric acid.[23] Literature reports another example of this type of rearrangement. Protonated dimethyl phosphate (m/e 127) was observed in the mass spectrum of the insecticide Phosdrin (IV),[33] a compound structurally closely related to isomerization products III (see eq 11). Since both III and IV



(11)

IV

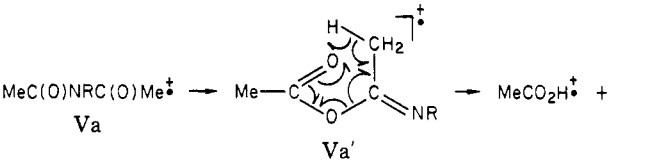
have no hydrogens at the α-carbon atom, the mechanism of the double hydrogen rearrangement proposed for ethyl esters (abstraction of one α and one β hydrogens from OC_2H_5 group)[23] has to be considered as a specific case of the more general behavior. For systems like III or IV one hydrogen atom can still be transferred from the β position via a six-membered cyclic transition state, whereas the other has to be donated by the more remote N-methyl (III) or C-methyl (IV) groups (eq 12).



III, Y = N
IV, Y = CHCO

CH_2=C=Y-CH_2• (12)

We believe that the electron impact induced acyl migration from nitrogen to oxygen (eq 9) is not limited to mixed carboxylic phosphoric imides but is a general property of N,N-diacyl systems. In their work on the mass spectra of substituted imides,[31] Nolde et al. pointed to the loss of CO and ketene as the major routes of fragmentation of compounds of the type RCONR′COMe (V). However, careful examination of the reported[31] spectra reveals for some of the diacetyl derivatives (Va, R = Me), the presence of acetic acid radical ion (m/e 60). This ion can only be formed if the imide → O-acetylimidate rearrangement takes place prior to fragmentation (eq 13). We have



CH_2=C=NR (13)

recorded the mass spectra of N-acetyl-N-methylacetamide (Va, R = R′ = Me) (reported previously by Nolde et al.[31]) and N-acetyl-N-methylbenzamide (Vb, R = Ph; R′ = Me), paying particular attention to the presence of peaks that might be derived from rearranged products. In both cases we observed peaks corresponding to acetic (m/e 60) and benzoic (m/e 122) acids; one acetyl methyl group evidently serves as a hydrogen donor in the fragmentation step.

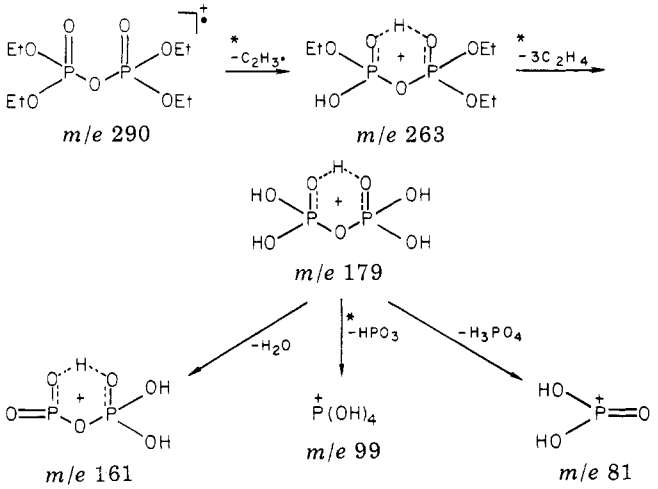
Fragmentation of the rearranged products Va′ can also involve loss of a neutral molecule of RCO_2H, since in both cases we observed the presence of the ion CH_2=C=NMe+· (m/e 55), also present in spectra reported by Nolde.[31] This dual fragmentation of Va′ indicates the highly delocalized nature of this radical ion.

The mass spectra of the three tertiary dialkylphosphoryl imides Ic–e show an additional common feature—the presence of peaks of m/e values greater than those of the corresponding molecular ions, accompanied by peaks obviously derived from those high-mass ions (for clarity purposes, these peaks are not listed in the tables). The heaviest fragment in the mass spectrum of Ic has an m/e value of 234; Id and Ie produce the same m/e 290 peak. These peaks were identified as corresponding to tetramethyl (VIa) and tetraethyl (VIb) pyrophosphate derived from Ic and Id, e, respectively. In order to unambigously identify the additional components of the mass spectra of substrates I, we recorded and analyzed the mass spectrum of synthetically prepared VIb. Although the mass spectrum of VIb has been mentioned in the literature,[34] no fragmentation patterns for this and other tetraalkyl pyrophosphates were reported. We expected therefore that the mass spectrum of VIb would not only serve the iden-

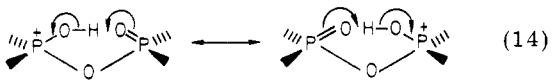
(33) M. Halman, Ed., "Analytical Chemistry of Phosphorus Compounds", Wiley-Interscience, New York, Part II, p 328.

(34) (a) A. Tatematsu, H. Yoshiuzumi, and T. Goto, *Bunseki Kagaku*, **17**, 774 (1968); *Chem. Abstr.*, **69**, 66421u (1968). (b) W. J. Stec, B, Zielinska, and J. R. Van Wazer, *Org. Mass Spectrosc.* **10**, 485 (1975).

Scheme IV



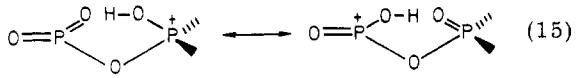
tification purposes but might also provide additional information about the fragmentation behavior of systems consisting of two acyl groups linked via a heteroatom (nitrogen or oxygen) bridge. The main fragmentation pathways characteristic for substrate VIb are summarized in Scheme IV. The most characteristic feature[35] of the fragmentation of VIb is the formation of quasi-phosphonium ions VII stabilized not only because of the oxygen–phosphorus p_π–d_π back donation but also by the charge delocalization involving another phosphoryl group (see eq 14). The molecular ion of VIb can produce such a sta-



(14)

VII

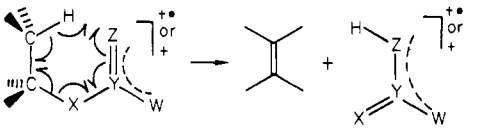
bilized ion (m/e 263) via a double hydrogen migration (loss of $C_2H_3^{\cdot}$); the sequence of fragmentation m/e 263 → m/e 235 → m/e 207 → m/e 179 involves loss of remaining ethyl groups via the McLafferty rearrangement. The whole sequence is characterized by the formation of intense peaks (rel intensity 99, 62, 48, and 79, respectively), indicating high stability of the ions formed. Ions VII can also dehydrate yielding another phosphoryl-stabilized ion: the protonated phosphoric–metaphosphoric anhydride VIII. (Scheme IV, fragmentation m/e 179 → m/e 161)[36] (see also eq 15). Although the loss of ethylene is the main frag-



(15)

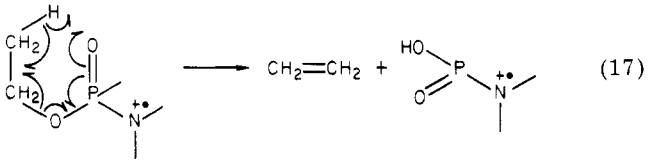
VIII

mentation of ions VII derived from VIb, we do not observe this reaction for the molecular ion itself (no M – 28 peak). McLafferty rearrangement operates for ions (or radical ions) capable of electronic shift involving a six-membered cyclic transition state in the molecular skeleton[24] given in eq 16. As far as the radical ion precursors are concerned, it seems that reaction 16 depends strongly on the specific localization of the charge/radical center, i.e., the nature



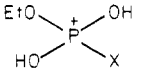
(16)

of atoms X, Y, W, and Z in the precursor molecule. In this work we observe that the eliminating of ethylene takes place from the following radical ions: $(EtO)_2P(O)NHMe^{+\cdot}$, $(EtO)(HO)P(O)NHMe^{+\cdot}$, $(EtO)(H)P(O)NHMe^{+\cdot}$, and $(EtO)_2P(O)NHCOPh^{+\cdot}$; in all cases but the last, the fragmentation is supported by the corresponding metastable peak. Similarly, reaction 16 was observed for $(EtO)_2P(O)NH_2$[17] and $(EtO)_2P(O)NHPh$,[21] and for both fragmentations the presence of metastable peaks was reported. On the other hand, we found that the McLafferty rearrangement was absent in the fragmentation of $(EtO)_2P(O)OP(O)(OEt)_2^{+\cdot}$; it was also not observed for such precursors as $(EtO)_2P(O)Cl^{+\cdot}$,[23] $(EtO)_2P(O)H^{+\cdot}$,[23] and diethyl alkylphosphonates $RP(O)(OEt)_2^{+\cdot}$.[38] The behavior of triethyl phosphate (IX) itself is more ambigous; although McLafferty reports[39] the low-intensity (2.8%) M – 28 peak in the mass spectrum of IX, this peak is absent in the spectrum of IX reported by Bafus et al.,[22] where all peaks of intensity greater than 2.5% have been listed. Consequently, the literature data and our results indicate that reaction 16 is facilitated in the phosphoramidate system (W = N), where the charge/radical center is probably located at the nitrogen atom, labilizing the ester CO bond (eq 17). For precursors with W = H, Cl, and (probably)

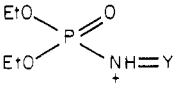


(17)

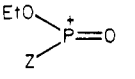
O, the charge/radical is most likely localized at the phosphoryl oxygen, facilitating double hydrogen migration (loss of $C_2H_3^{\cdot}$) rather than a single hydrogen shift in a McLafferty rearrangement. McLafferty rearrangement has also been confirmed in this work and in other reports to operate for a variety of ions (not radical ions) containing the EtO function in the vicinity of a positive charge. All these ions susceptible to the loss of ethylene can be grouped into three structurally different classes: (i) quasi-phosphonium ions (X); (ii) phosphoryl derivatives containing a positively charged atom bonded to phosphorus (XI); (iii) phosphorylium ions (XII). Examples of structures X–XII observed in this work are given below. In



X, X = H, OH, $OP(O)X_2$



XI, Y = CH_2, CO



XII, Z = OH, NHMe, OEt[23]

all cases strong electron deficiency developed at or near the phosphorus atom facilitates the elimination reaction.

The formation of tetraalkyl pyrophosphate from *N*-methyl-*N*-acylphosphoramidates (I) represents a problem in itself. Since the formation of a symmetrical anhydride from a mixed precursor necessarily requies a bimolecular reaction, we believe that the pyrophosphate esters are formed thermally at the ion source, prior to electron impact induced fragmentation. Ramirez et al.,[40] in their study on

(35) The molecular ion of VIb also loses ethoxy radical and acetaldehyde molecule. Since these fragmentations are the consequence of the ethyl ester, not the anhydride function, they are not included in Scheme IV.

(36) The widespread occurence of metaphosphate-type species in mass spectra organophosphorus compounds has been demonstrated before by Ramirez and his co-workers.[37]

(37) S. Meyerson, E. S. Kuhn, F. Ramirez, J. F. Marecek, and H. Okazaki, *J. Am. Chem. Soc.*, **100**, 4062 (1978), and references cited therein.

(38) J. L. Occolowitz and G. L. White, *Anal. Chem.*, **35**, 1179 (1963).

(39) E. W. McLafferty, *Anal. Chem.*, **28**, 306 (1956).

(40) S. Meyerson, E. S. Kuhn, F. Ramirez., J. F. Marecek, and H. Okazaki, *J. Am. Chem. Soc.*, **102**, 2398 (1980).

the mass spectra of phosphate esters, observed numerous components stemming from thermal reactions occurring in the instrument. For example, phosphoacetoin (C_4 substrate) yields C_{12} as well as C_{16} species, presumably via condensation/dehydration proceses.[40]. The most obvious process leading to the anhydride system is the thermal dehydration of the dialkyl phosphate XIII (eq 18). For-

$$2(RO)_2P(O)OH \rightarrow (RO)_2P(O)OP(O)(OR)_2 \quad (18)$$
XIII

mation of acids XIII can be envisaged as a result of the collapse of the rearranged substrate III involving internal hydrogen transfer from the R'CNR fragment of III to the phosphoryl oxygen. Since the presence of tetraalkyl pyrophosphates was observed only for tertiary substrates (I, R = Me), it is probably the *N*-methyl substituent that acts as a hydrogen donor, and the transfer is accompanied by some skeletal rearrangement of the R'CNMe–H fragment.

The thermal formation of tetraalkyl pyrophosphates is supported by some preliminary evidence. First, the mass spectra of the dialkyl phosphinic acids, R_2PO_2H, revealed the presence of the corresponding anhydrides, $(R_2PO)_2O$.[32] Second, we recorded the mass spectrum of Id at constant ionizing potential (70 eV) but at variable souce temperature. At 200 °C (the standard temperature for all spectra reported in this work) the molecular ion of the tetraethyl pyrophospohate appears as a peak (*m/e* 290) of 4.2% intensity. At 100 °C the intensity of this peak decreased to 1.4%, and at 60 °C the *m/e* 290 peak, as well as all peaks resulting from the fragmentation of VIb, are absent in the mass spectrum of Id.

Experimental Section

^{1}H NMR spectra were recorded in $CDCl_3$ on a 100-MHz Varian XL00 spectrometer with Me_4Si as internal standard. Infrared spectra were recorded on a Model 180 Perkin-Elmer IR spectrometer. Mass spectra were recorded on a VG Micromass 16F spectrometer operating at 70 eV and an ion source temperature of 200 °C. Silica gel 60 (Merck Art. 9385, 230–400 mesh) was used for column chromatography.

Substrates. Phosphoramidates IIa and IIb were prepared from methylamine and the corresponding dialkyl phosphorochloridate IIa: bp 66–68 °C (0.1 mmHg) (lit.[41] bp 81 °C (1 mmHg). IIb: bp 92 °C (0.3 mmHg) (lit.[42] bp 130 °C (15 mmHg). IIc was prepared from methylamine and diethylphosphinyl chloride[43] (prepared from tetraethyldiphosphine disulfide[44]): yield 42%; bp 129–131 °C (0.5 mmHg); ^{1}H NMR ($CDCl_3$) δ 1.13 (d of t, 6 H, J_{HP} 18 Hz, $J_{H,H}$ = 8 Hz, β-CH_3), 1.55–1.90 (m, 4 H, α-CH_2), 2.63 (d, 3 H J_{HP} = 11 Hz, NCH_3), 3.3 (s, 1 H, NH). Anal. Calcd for $C_5H_{14}NOP$: C, 44.43; H, 10.44; N, 10.37. Found: C, 42.90; H, 9.85; N, 8.60%. *N*-Benzoylphosphoramidates Ia and Ib were prepd. from *N*-benzoyltrichloromonophosphazenes and sodium alcohols:[4] Ia; mp 117–118 °C (lit.[4] mp 116–118 °C); Ib, mp 71–73 °C. Anal. Calcd for $C_{11}H_{16}NO_4P$: C, 51, 36; H, 6.27; N, 5.45. Found: C, 51.20; H, 6.30; N, 5.45.

Dialkyl *N*-Methyl-*N*-acylphosphoramidates and Phosphinamidates Ic–f. General Procedure.[45] To a stirred mixture of finely divided sodium (0.168 mol) and 150 cm^3 of dry toluene is added a solution of amide R'C(O)NHMe (0.168 mol) in 20 cm^3 of dry toluene, dropwise over 30 min. The mixture is refluxed under anhydrous conditions until all the sodium has disappeared, giving a suspension of the salt. To the cooled suspension is added dropwise with stirring a solution of $X_2P(O)Cl$ in dry toluene at 5–10 °C. The mixture is slowly warmed to room temperature and stirred overnight. The mixture is filetered and the filtrate evaporated under reduced pressure, leaving a dark oil. The crude product is chromatographed, eluting with 20% EtOAc in $CHCl_3$ to remove unreacted substrates and byproducts. Ic and Id were further purified by distillation.

Ic (38% yield): bp 68–72 °C (0.15 mmHg); ^{1}H NMR ($CDCl_3$) δ 2.39 ((s, 3 H, $C(O)CH_3$), 3.05 (d, 3 H, P–N–CH_3, $J_{H,P}$ = 7.5 Hz), 3.83 (d, 6 H, P–O–CH_3, $J_{H,P}$ = 11 Hz); IR (0.1% CCl_4) 1294 ($\nu_{P=O}$), 1697 cm^{-1} ($\nu_{C=O}$). Anal. Calcd for $C_5H_{12}NO_4P$: C, 33.15; H, 6.67; N, 7.73. Found: C, 33.10; H, 6.72; N, 7.44.

Id (34% yield): bp 76–79 °C (0.02 mmHg); ^{1}H NMR ($CDCl_3$) δ 1.38 (t, 6 H, CH_3, $J_{H,H}$ = 7 Hz), 2.39 (s, 3 H, $C(O)CH_3$), 3.04 (d, 3 H, P–N–CH_3, $J_{H,P}$ = 7.5 Hz), 4.17 (m, 4 H, CH_2); IR (0.1% CCl_4) 1295 ($\nu_{P=O}$); 1697 cm^{-1} ($\nu_{C=O}$). Anal. Calcd for $C_7H_{16}NO_4P$: C, 40.19; H, 7.71; N, 6.70. Found: C, 39.75; H, 7.70; N, 6.55.

Ie (30% yield): ^{1}H NMR ($CDCl_3$) δ 1.22 (t, 6 H, CH_3, $J_{H,H}$ = 7 Hz), 3.15 (d, 3 H, P–N–CH_3, $J_{H,P}$ = 8 Hz), 4.03 (m, 4 H, CH_2), 7.3–7.6 (m, 5 H, aryl H); IR (5%; CCl_4) 1268 (m), 1302 (s) ($\nu_{P=O}$), 1676 cm^{-1} ($\nu_{C=O}$). Anal. Calcd for $C_{12}H_{18}NO_4P$: C, 53.13; H, 6.69; N, 5.16. Found: C, 53.06; H, 6.62; N, 5.02. If (75% yield): ^{1}H NMR ($CDCl_3$) δ 1.11 (pair of triplets, 6 H, CH_3, $J_{H,H}$ 8 Hz, $J_{H,P}$ = 18 Hz), 1.9–2.2 (m, 4 H, CH_2), 2.25 (s, 3 H, $C(O)CH_3$), 3.16 (d, 3H, P–N–CH_3, $J_{H,P}$ = 6.5 Hz); IR (0.1% CCl_4) 1319 cm^{-1} ($\nu_{P=O}$), 1668 cm^{-1} ($\nu_{C=O}$). Anal. Calcd for $C_7H_{16}NO_2P$: C, 47.45; H, 9.10; N, 7.91. Found: C, 47.30; H, 9.05; N, 7.75.

Tetraethyl pyrophosphate (VIb) was prepared from diethyl phosphorochloridate according to Toy;[46] bp 109–111 °C (0.1 mmHg) (lit.[46] bp 138 °C (1 mmHg)).

N-Acetyl-*N*-methylacetamide (Va) and *N*-acetyl-*N*-methylbenzamide (Vb) were prepared from the corresponding *N*-methylcarboxamide and isopropenyl acetate according to the literature procedure.[47] Va: bp 88–89 °C (12 mmHg) (lit.[47b] bp 71 °C (7 mmHg). Anal. Calcd for $C_5H_9NO_2$: C, 52.16; H, 7.90; N, 12.16. Found: C, 52.01; H, 7.90; N, 11.55. Vb: bp 90–93 °C (0.02 mmHg). Anal. Calcd for $C_{10}H_{11}NO_2$: C, 67.78; H, 6.26; N, 7.91. Found: C, 67.75; H, 6.30; N, 7.85.

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Registry No. Ia, 24856-23-3; Ib, 16102-45-7; Ic, 82134-80-3; Id, 13294-10-5; Ie, 82134-81-4; If, 82134-82-5; IIa, 52420-88-9; IIb, 6326-73-4; IIc, 82134-83-6; Va, 1113-68-4; Vb, 7449-76-5; VIb, 107-49-3; $(MeO)_2P(O)Cl$, 813-77-4; $(EtO)_2P(O)Cl$, 814-49-3; $(Et)_2P(O)Cl$, 1112-37-4; MeCONNaMe, 51206-97-4; PhCONNaMe, 82134-84-7.

(41) M. I. Kabachnik and V. A. Gilyarov, *Izv. Akad. Nauk SSSR*, 816 (1961).
(42) B. C. Saunders, G. J. Stacey, , F. Wild, and J. G. E. Wilding, *J. Chem. Soc.*, 699 (1948).
(43) K. Sasse, "Organische Phosphorverbindungen, Methoden der Organischen Chemie", G. Thieme, Stuttgart, 1963, Vol. XII/1, p 245.
(44) K. Issleib and A. Tzschach, *Chem. Ber.*, **92**, 704 (1959).
(45) The yields of products Ic–e are low because of large quantities of tetraalkyl pyrophosphates accompanying the main products. Phosphinic derivative If was found free from the corresponding anhydride, hence the higher yield of this compound.
(46) A. D. F. Toy, *J. Am. Chem. Soc.*, **70**, 3882 (1948).
(47) (a) H. J. Hagemeyer, Jr., U.S. Patent 2656360, 1953; *Chem. Abstr. 49*, 5522g (1955). (b) H. K. Hall, M. K. Brandt, and R. M. Mason,, *J. Am. Chem. Soc.*, **80**, 6424 (1958).