The Schmidt Reaction of Dialkyl Acylphosphonates[1]

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Abstract: The scope of the Schmidt rearrangement of ketones has been extended to dialkyl acylphosphonates (**11a–11l**). Surprisingly, it was found that **11a–11d** and **11g**, in which the acyl moiety was benzoyl alone or benzoyl bearing an electron-attracting or mildly electron-releasing substituent, yielded an overwhelming portion of products resulting from C-to-N migration of the aryl group (*N*-arylcarbamoylphosphonates, **12**, and *N*-arylformamides, **15**). Contrariwise, the arenecarbonylphosphonates, which carry a powerful electron-releasing *p*-alkoxy group, yielded products resulting from phosphonate group migration from C to N or elimination (dialkyl *N*-arenecarbonylphosphoramidates, **13**, and arenecarbonitriles, **17**, respectively). These counterintuitive results are rationalized by application of the concept of "degree of electron demand" to this area of intramolecular rearrangements. The possible existence of an additional pathway for the Schmidt rearrangement, involving protonation of the iminodiazonium ion, is proposed.

Introduction

Despite the large amount of work which has been reported on both the synthetic and the mechanistic aspects of the Schmidt rearrangement of ketones,[2] the balance of factors effecting the outcome in any particular case is still poorly understood. In many cases product composition is unpredictable even in a qualitative sense, and *a posteriori* and *ad hoc* rationalizations abound in the literature.[3] Scheme 1 depicts possible pathways for this reaction. Most authors have favored the iminodiazonium (ID) pathway, 'a' (*via* **3** or **3'**), vigorously expounded by Smith,[2f,g] including the provision based on indirect evidence that C → N migration is concomitant with N_2 release.[2,3] It must therefore involve the group *anti*periplanar to the diazonium function, in analogy with the well-established stereochemical requirement of the Beckmann rearrangement of ketoximes.[2,3] While calculations confirm that *E* → *Z* isomerization (**3** ⇄ **3'**) by lateral shift of the diazonium group would be too slow to occur under the usual reaction conditions,[4] such equilibration could certainly be achieved by rapid hydration to an azidohydrin and redehydration[2g,3k4,5] (**3** ⇄ **2** ⇄ **3'**) or an equivalent process involving another nucleophile). The isolation, in the case of highly sterically congested reactants, of the products of N insertion into C–H bonds shows that in certain circumstances the release of N_2 from the ID ion and the formation of a divalent nitrogen (nitrenium ion) species, **5**, precede C → N migration.[6] The proposal of the ID intermediate was supported by the isolation, in many cases, of tetrazole byproducts (**7**, Scheme 2), which were assumed to be formed by the reaction of a second mole of hydrazoic acid with the rearranged iminium ion (**4** or **4'**).[2] Moreover, the Schmidt reaction with ketones had been found to proceed with hydrazoic acid but not with alkyl azides.[7] This was consistent with the necessary intermediacy of an ID ion (**3** or **3'**). Other researchers focused on the fact that the "migratory aptitudes" which they found in the Schmidt reaction of ketones did not reflect the findings in the Beckmann rearrangement. They therefore opted for the protonated azidohydrin (AH), **1**, as the species undergoing decomposition–rearrangement (Scheme 1, path 'b'),[3b,j] though this proposal, too, proved far from satisfactory in rationalizing product composition data. Yet others found that the ratio of the two products stemming from the migration of different groups (**6** or **6'**) was affected by the identity and concentration of the acid catalyst used.[3d,k,j] This led to the obviously simplest, but at present not very edifying, postulate that both pathways are operative competitively.[3f,g,i,k] In other words, they generally have rather similar energy barriers, the relative rates along them being determined in any specific case by experimental conditions and the interplay of the particular electronic and steric factors.

Recently Aubé discovered the conditions necessary for the Schmidt rearrangement of ketones using alkyl azides rather than hydrazoic acid,[8] thus dispelling the long-standing myth that only the latter is effective and supporting the competency of an AH structure (**8**, Scheme 3) as an intermediate which may suffer C → N migration upon N_2 release. Amyes and Richard have lately reported for the first time a direct demonstration of the formation

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(1) The experiments reported here were performed in the laboratories of the Department of Chemistry, Tel Aviv University, Ramat Aviv, Tel Aviv, Israel.

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(4) Bach, R. D.; Wolber, G. J. *J. Org. Chem.* **1982**, *47*, 239–245. The barrier is, of course, subject to modification by substituent.

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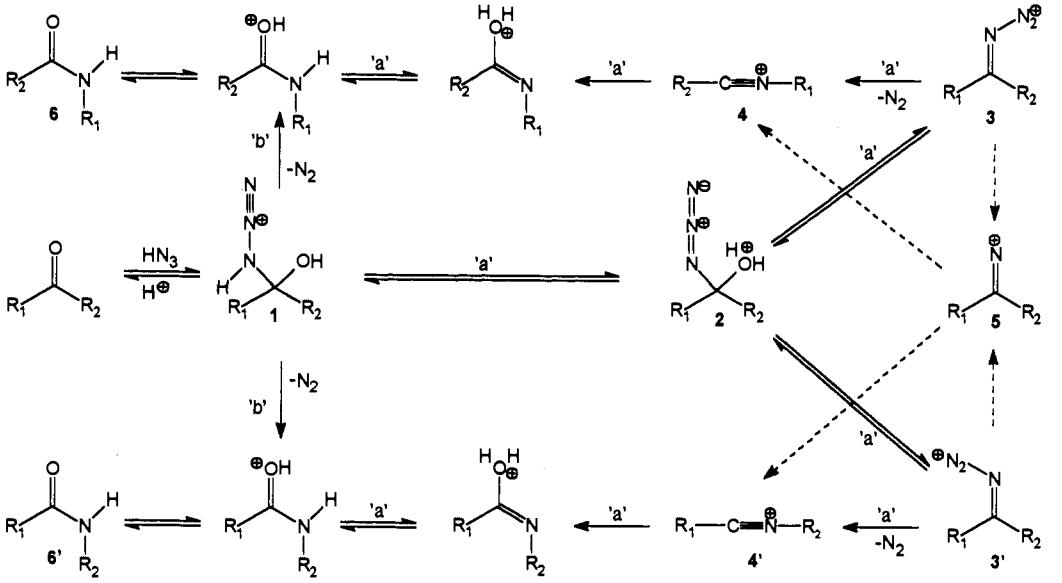
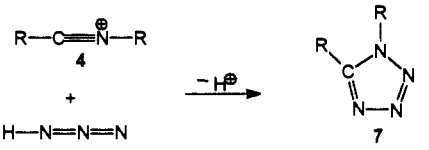
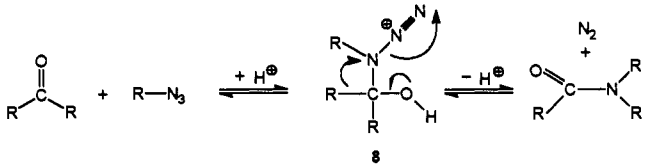
Scheme 1



Scheme 2



Scheme 3



and the reactivity of ID ions (*i.e.*, α-azido carbocations, **3** and **3'**) and have set limitations on the competency of such species as intermediates in the Schmidt reaction.[5] They calculated rate constants of approximately 10^7 and 10^5 s^{-1} for the addition of solvent to benzylidene and p-methoxybenzylidene iminodiazonium ions, respectively, in neutral aqueous solution at 25 °C, the reaction with azide ion to give a *gem*-diazide (**9**) being diffusion limited. The equilibrium concentrations of ID ions were extremely small, and no N_2 release or decomposition products were found. As *gem*-diazides have now been shown to be respectable, though perhaps capricious, compounds[9] which may also be produced in solution from ID ions,[5] or possibly even directly from AHs under Schmidt conditions, it is no longer necessary to conclude that tetrazoles must originate from the addition of hydrazoic acid to the iminium ion **4**. They may possibly be formed *via* the acid-catalyzed monodecomposition of a *gem*-diazide (**9**) to an *N*-diazonioamidine ion (**10**) which cyclizes (Scheme 4). The new experimental findings and their implications have undermined much of the ratiocination upon which the identification of the ID ion (**3** or **3'**) as the one undergoing decomposition–rearrangement was based. Regarding theoretical work, early calculations concluded that the release of N_2 from an ID ion unaccompanied by C → N migration would be highly endothermic, and that an ID intermediate could be reasonably entertained only if the energy gain due to concomitant rearrangement was very considerable.[4] In contrast, a recent report based on a higher level of theory (though lacking the extensive configuration interaction calculations which are generally considered necessary for really high quality results for such decompositions) finds that the decomposition of $H_2C{=}N_3^+$ to $H_2C{=}N^+$ and N_2 has a calculated energy barrier in the gas phase of only 4.6 kcal/mol.[10] Solvation effects should lower it, while conjugating electron-donating substituents should raise it. In any case, this report, if qualitatively relevant to the usual solution conditions, would support the viability of the ID pathway 'a' (with the possibility of **5** as a distinct high-energy intermediate). These new contributions to the area prompt us to report the details of work on the Schmidt rearrangement of dialkyl acylphosphonates[11] which, while undertaken at the time as part of our research to elucidate characteristics of the dialkyl phosphonate function,[12] extends the scope of said rearrangement and bears on its mechanism.

(9) (a) Nishiyama, K.; Oba, M.; Watanabe, A. *Tetrahedron* **1987**, *43*, 693–700. (b) Nishiyama, K.; Watanabe, A. *Chem. Lett.* **1984**, 455–458.

Results and Discussion

The dialkyl acylphosphonates used in this study were readily prepared by reaction of the corresponding acyl chlorides with trialkyl phosphites (eq 1) according to the procedure of Berlin

$$RCOCl + (R'O)_3P \rightarrow RCOPO(OR')_2 + R'Cl \quad (1)$$

et al.[13] and were thoroughly characterized (Experimental Section). Though the reactions of dialkyl acylphosphonates with most nucleophilic reagents parallel those of ketones,[12a,c,14] the hydrolytic behavior of dialkyl acylphosponates is reminiscent of that of acyl halides or esters.[14,15] Since the Schmidt reaction must be carried out in strongly acidic and potentially hydrolytic media, it was satisfying to find conditions for the reaction of the substrates in question which did not lead to significant hydrolysis. In the event, the chloroform solutions of the acylphosphonates were treated at 0 °C for 10–30 min with a 5 mol % excess of hydrazoic acid in the presence of concentrated sulfuric acid. The resulting product mixtures were divided by extraction into neutral, acidic, and basic fractions, and these were further separated and the individual compounds purified by column chromatography and appropriately characterized (Experimental Section) and identified.

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(12) (a) Sprecher, M.; Nativ, E. *Tetrahedron Lett.* **1968**, 4405–4408. (b) Sprecher, M.; Kost, D. *Tetrahedron Lett.* **1969**, 703–706. (c) Kost, D.; Sprecher, M. *Tetrahedron Lett.* **1975**, 4483–4486.
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Scheme 4

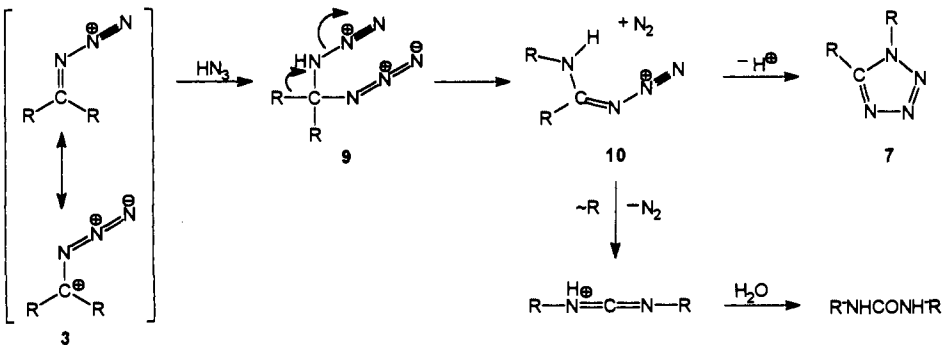


Table 1. Schmidt Reaction of α-Ketophosphonates [RCOPO(OR′)$_2$, **11**][a] and Product Distribution[b]

			product								
compd	R	R′	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	X[c]
11a	Ph	Et	9	3.1	1	53	14		0.2		
11b	*p*-ClPh	Et	19	1.8		65	4		4	1.8	
11c	*m*-ClPh	Me		1	1.5	39	6.5				
11d	*p*-tolyl	Et	11.4	3.3	1.3	70	6.5	7	0.4		
11e	*p*-CH_3OPh	Me		46				47			
11e[d]	*p*-CH_3OPh	Me		45				51			
11f	*p*-CH_3OPh	Et		30				62			
11f[e]	*p*-CH_3OPh	Et		31				54			
11g	*m*-CH_3OPh	Et		2	0.8	59	8.5	6			3[f]
11h	3,4-methylenedioxyphenyl	Et		28				51			
11i	2,6-dimethoxyphenyl	Et						62			17[g]
11j[h]	mesityl	Et					43				
11k	2,6-dimethyl-4-methoxyphenyl	Et					50				47[g]
11l	$(CH_3)_2CH$	Me				57				0.5	0.7[i]

[a] Unless otherwise indicated the reactions were carried out for 10–30 min at 0 °C using concentrated H_2SO_4 and 1.05 equiv of HN_3. [b] In mol % based on α-ketophosphonate. [c] Other compounds isolated. [d] In the presence of 1 equiv of diethyl phosphite. [e] In the presence of 1 equiv of dimethyl phosphite. [f] *m*-$CH_3OC_6H_4COOEt$. [g] Unreacted starting material. [h] Reaction for 20 h at room temperature. Under the usual reaction conditions, 76% of unreacted starting material and 16% of **16j** were isolated. [i] $(CH_3)_2CHCONHCH(CH_3)_2$.

Scheme 5

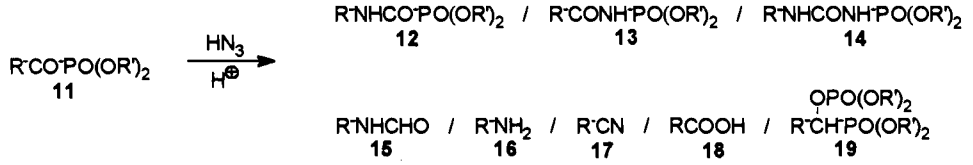


Table 1 lists the dialkyl acylphosphonates (**11a–11l**) used in this study and the variety and yields of products isolated in each case. In all, eight types of products (**12–19**, Scheme 5) were found. The diethyl *N*-arylcarbamoylphosphonates (**12**) and the diethyl (or dimethyl) *N*-arenecarbonylphosphoramidates (**13**) are the primary products of Schmidt rearrangements involving C → N migrations of the aryl or dialkyl phosphonate groups, respectively. For confirmation of identity, an authentic sample of **12a** was prepared by reaction of phenyl isocyanate with diethyl phosphite (eq 2). Compounds of type **12** appear in the neutral

$$C_6H_5N{=}C{=}O + HPO(OEt)_2 \rightarrow C_6H_5NHCOPO(OEt)_2 \quad (2)$$

fraction. They are further distinguished from those of type **13** by their IR spectra (N–H stretching ~3200 cm^{-1}, C=O stretching ~1660 cm^{-1}, doubling of P—O stretching absorption band at ~1220, ~1255 cm^{-1};[16] *cf.* Table 2) and their N—H ^{1}H NMR spectra. In compounds **13**, the NH grouping flanked by carbonyl and phosphonate functions shows the expected imide-type acidity due to stabilization of the conjugate anion, as well as the consequent spectral shifts. The -PO(OR′)$_2$ substituent on the N reduces the nitrogen–electron pair delocalization into the carbonyl group, strengthening the double bonding in the latter.

(16) 16. Corlinidge, D. E. C. *Topics Phosphorous Chem.* **1969**, *6*, 235–365.

The assignment of structures **13** was confirmed by preparation of authentic samples from the corresponding benzamides by reaction with phosphorus pentachloride followed by ethoxide/ethanol treatment (eq 3).[17]

$$RCONH_2 + PCl_5 \rightarrow [RCON{=}PCl_3] + EtOH/EtONa \rightarrow RCONHPO(OEt)_2 \quad (3)$$

In four cases, minor quantities of products of type **14**, *N*-aryl-*N*′-dialkyloxyphosphinoylurea (a dialkyl arylcarbamoylphosphoramidate), were found in the sodium hydroxide extracts of the reaction mixtures. Structure assignment rests both on elemental analysis, IR, and ^{1}H NMR spectra which show, *inter alia*, the presence of two NH groups and CO and PO functions, and on the characteristic mass spectral fragmentations appropriate for **14**. Furthermore, the unsubstituted **14a** had been reported in the literature[18] and comparison was possible. Formally, **14** is derived from the starting α-ketophosphonate by the insertion of two NH groups, one on each side of the carbonyl, and might be thought to be the product of a second Schmidt rearrangement of either **12** or **13**. However, amides are not known to undergo such a reaction, and, in fact, only unchanged **12a** and **13a** were recovered from control experiments under the reaction conditions;

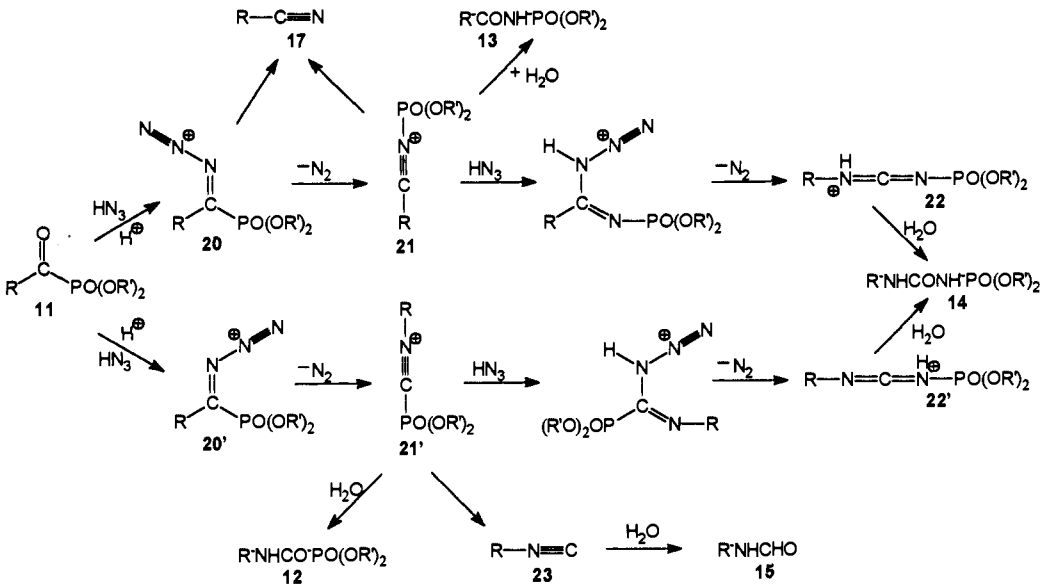
(17) Almasi, L.; Paskucz, L. *Chem. Ber.* **1967**, *100*, 2625–2632.
(18) Kirsanov, A. V.; Levchenko, E. S. *Zhur. Obshchei. Khim.* **1956**, *26*, 2285–2289; *Chem. Abstr.* **1957**, *51*, 1875f.

Table 2. Selected Spectral Properties of Dialkyl *N*-Arylcarbamoylphosphonates [RNHCOPO(OR′)$_2$, **12**], Dialkyl *N*-Arenecarbonylphosphoramidates [RCONHPO(OR′)$_2$, **13**], and *N*-Aryl-*N*′-dialkoxyphosphinoylureas [RNHCONHPO(OR′)$_2$, **14**]

			IR (KBr), cm^{-1}			
compd	R	R′	NH	CO	PO	^{1}H NMR ($CDCl_3$) δ_{NH} (mult, *J* in Hz)
12a	Ph	Et	3160–3215	1665	1220, 1255	9.25 (br s)
12b	*p*-ClPh	Et	3150–3210	1660	1220, 1250	9.28 (br s)
12d	*p*-tolyl	Et	3205	1655	1225, 1255	9.10 (br s)
13a	Ph	Et	3125	1677	1222	9.22 (d, 8)
13b	*p*-ClPh	Et	3100, 3140	1680	1230	9.81 (d, 9)
13bb[a]	*p*-ClPh	Me	3105	1685, 1670[b]	1225	9.79 (d, 9)
13c	*m*-ClPh	Me	3120	1680	1230	9.84 (br s)
13cc[a]	*m*-ClPh	Et	3150	1680	1230	9.68 (d, 9)
13d	*p*-tolyl	Et	3085–3130	1680	1237	9.22 (d, 8)
13dd[a]	*p*-tolyl	Me	3100–3160	1680	1235	9.56 (br s)
13e	*p*-CH_3OPh	Me	3120–3140	1680	1230	9.23 (d, 9)
13f	*p*-CH_3OPh	Et	3140	1665	1235	9.40 (d, 9)
13g	*m*-CH_3OPh	Et	3160	1680	1240	9.61 (d, 8)
13gg[a]	*m*-CH_3OPh	Me	3170	1680	1255	9.55 (br s)
13h	3,4-(methylenedioxy)phenyl	Et	3120	1665	1230	9.40 (br s)
14a	Ph	Et	3125, 3180–3265	1675	1230	7.72 (br s), 8.92 (s)
14c	*m*-ClPh	Me	3170, 3225	1700	1230	7.80 (br s), 8.85 (s)
14d	*p*-tolyl	Et	3165, 3240–3270	1670	1230	8.15 (br s), 8.79 (s)
14g	*m*-CH_3OPh	Et	3180, 3220	1690	1220	7.90 (br s), 8.90 (s)

[a] Synthesized; not isolated from Schmidt reaction. [b] 1685 cm^{-1} in $CHCl_3$ solvent.

Scheme 6



neither **14** nor any other product could be identified. The second molecule of hydrazoic acid must therefore have reacted with a precursor of either **12** or **13**. Two pathways come to mind, one *via* an ID ion (**20** or **20′**) and a rearranged cation (**21** or **21′**, Scheme 6) and the other *via* two successive acid-catalyzed decomposition–rearrangements of a *gem*-diazide (Scheme 4). A carbodiimide structure, presumably protonated (**22** or **22′**), lies along both pathways, and its hydration yields the urea derivatives **14**.[19]

For a number of reactants, N-arylformamides (formanilides) **15** were the major products. Control experiments on compounds **12** showed that they were not precursors of **15**. Thus **12a** and **12b**, but not **15** or any other product, were recovered after treatment with hydrazoic or sulfuric acid or a combination of the two under the conditions employed for the rearrangements. A simple electron count shows that the dialkyl phosphonate function must have been eliminated as a cation or its equivalent. Furthermore, consideration of possible reasonable alternatives leads to the conclusion that this elimination occurred after C → N aryl migration on the ID pathway; otherwise, other stable products such as nitriles, benzamides, or **12** would have been formed. The rearranged intermediate, **21′**, yields an aryl isocyanide, **23**, upon loss of $(RO)_2PO^+$ either as such or as the result of nucleophilic attack on phosphorous. An analogy to this mechanism of isocyanide formation may be found in the Beckmann rearrangement of some ketones bearing one carbonyl ligand capable of being split off as a stabilized cation.[20a] Acid-catalyzed hydration of the isocyanides produces the *N*-arylformamides.[20b] The formation of *N*-arylformamides **15** accompanying formation of nitriles **17** (see below) is, of course, reminiscent of the Schmidt reaction of aromatic aldehydes.[21a] No mechanistic conclusions may, however, be drawn from this superficial similarity. In the case of aldehydes, the formamides could be the direct product of the rearrangement of AHs, whereas in our work such rearrange-

(19) We thank a referee for bringing the work of Vaughan, J.; Smith, P. A. S. *J. Org. Chem.* **1958**, *23*, 1909–1912 and Smith, P. A. S.; Leon, E. *J. Am. Chem. Soc.* **1958**, *80*, 4647–4654 (and references cited) on the synthesis and thermal breakdown of tetrazoles, to our attention. They reported the formation of unsymmetrically N,N′-disubstituted ureas by the hydration of presumed protonated carbodiimide species whose precursors were analogous to those proposed in Schemes 4 and 6.

(20) (a) Reference 2f, p 502. (b) Smith, P. A. S., *The Chemistry of Open Chain Organic Nitrogen Compounds*; W. A. Benjamin: New York, 1965; Vol. 1, pp 223–231.

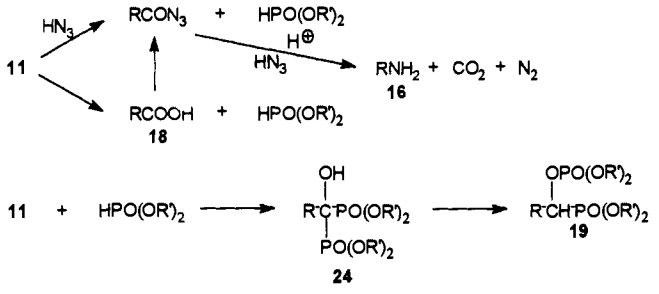
(21) (a) McEwen, W. E.; Conrad, W. E.; Vanderwerf, C. A. *J. Am. Chem. Soc.* **1952**, *74*, 1168–1171. (b) Hassner, A.; Levy, A. B. *J. Am. Chem. Soc.* **1971**, *93*, 5469–5474. These authors have reported a formally similar loss of an $RCBr_2^+$ fragment from an ID ion to yield a nitrile.

ment leads, as indicated above, to structure **12**. In fact, the ketophosphonates which yielded *N*-arylforamides were not the ones which led to large yields of nitriles.

As may be seen in Table 1, many of the reactions produced considerable quantities of nitriles **17**. Control experiments showed that the latter could not have arisen from **13** since members of series **13** were recovered unchanged after subjection to the reaction conditions. Considerations similar to those mentioned in the previous paragraph indicate that they were produced from an intermediate cation on the ID pathway by elimination of $(RO)_2PO^+$ either as such or as the result of nucleophilic attack on phosphorus.[21b] This intermediate might be **20** and might involve either simultaneous or successive loss of N_2 and $(RO)_2$-PO; or, it might be **21** following loss of N_2 and C → N migration of $(RO)_2PO$ (Scheme 6). In all except one case, the formation of a nitrile was accompanied by formation of the dialkyloxyphosphinoyl migration product **13**. Thus either **20** or **21** partitions between **13** and **17**.

The small amounts of benzoic acids **18** found in three cases may have been produced by hydrolysis either of the starting α-ketophosphonates **11** under the acidic reaction conditions or of residual **11** during the base extraction step of the workup. In either event, diethyl phosphite would also be produced. The reaction of the latter with additional **11** can give **24**, whose rearrangement would yield **19** (Scheme 7).[22] Such a product, diethyl 1-(4-chlorophenyl)-1-((diethoxyphosphinoyl)oxy)-methylphosphonate (**19b**, 1.8%), was found in the reaction of **11b**, which was also the only reaction from which a significant amount of the carboxylic acid (**18b**, 4%) was isolated (Table 1).

Scheme 7



The provenance of the anilines **16** is probably the acid-catalyzed rearrangement of benzoyl azide formed from **11** directly or by way of hydrolysis to a carboxylic acid (**18**, Scheme 7). However, conceivable limited hydrolysis of the formanilides **15** was not rigorously excluded.

The possibility was considered that in the reactions under discussion the azide may be adding to the phosphonate function, forming a P(V) intermediate which releases N_2 and suffers P → N migration of the arenecarbonyl group to give a structure of type **13**. It appears to be excluded by the finding that both diethyl phenylphosphonate and diethyl benzylphosphonate were resistant to the reaction conditions.

Irrespective of the details of mechanism of the molecular rearrangements reported herewith, some of them clearly involve a 1,2-migration of a *dialkyl phosphonate* group to an electron-deficient terminus. The intramolecularity of the rearrangement was demonstrated by carrying out the reaction of dimethyl *p*-anisoylphosphonate (**11e**) in the presence of diethyl phosphite and that of diethyl *p*-anisoylphosphonate (**11f**) in the presence of dimethyl phosphite. In both cases, no exchange of the dialkoxyphosphinoyl group was detected in the products **13e** and **13f**, respectively. Similar phenomena of dialkyl phosphonate migration have been observed by others and by us in C → C carbenium,[12b,c,14,23] carbene,[24] and 1,3-diradical[25] rearrangements and the C → O Bayer-Villiger rearrangement[12a]; at the time of the preliminary report,[11] these were the first such results for C → N migration. In the interim we have found additional examples in the reaction of dimethyl α-(*N*-alkyl-*N*-chloroamino)alkylphosphonates with silver ion in benzene solution;[26] the thermal and acid-catalyzed Beckmann rearrangements of dimethyl (*E*)-α-hydroxyiminobenzylphosphonate to dimethyl *N*-benzoylphosphoramidate has been noted by Breuer[27] and by others.[28]

In numerous known intramolecular 1,2-migrations to electron-deficient termini, the groups of relatively high "migration aptitude" have been found to be those capable of electron release.[29] In contrast, the phosphonate group is better known for its electronegative character and stabilization of α-anions.[30] The facility with which it migrated to neighboring carbenium ions was regarded with some surprise when originally discovered.[12,23,31] In fact, Warren has rationalized such 1,2-migrations of diphenylphosphinoyl groups in preference to alkyl groups by pointing out that the alternative migration of an alkyl group would produce a carbenium ion α to what he argued would be a highly destabilizing phosphinoyl function.[32] The same argument would apply *a fortiori* to the more electronegative dialkoxyphosphinoyl group. The seeming reasonableness of Warren's contention notwithstanding, Creary, in a study of the solvolysis of α-mesyloxydiethoxyphosphinoylalkanes, has shown that in fact the group in question may at most only marginally destabilize an α-carbenium ion, not at all what would be expected from its σ_p (0.52) and σ^+ (0.505) values.[33] Creary attributes this either to p_π-d_π-p_π conjugation permitting transfer of electron density from O *via* P to trigonal C or to the polarizability of the phosphorus. We propose to rationalize the comparatively low energy of activation of 1,2-migration of a $(RO)_2P(O)$- group by the following consideration. While this group is electron attracting with respect to what is ligated to it, it itself should be relatively stable as a cation, delocalizing the electron deficiency and positive charge from the phosphorus to the three oxygen atoms. Wadsworth has presented evidence for the formation of such a species, [(RO)-(R'O)P(O)$^+$], in solution as an intermediate in the stereoisomerization at phosphorus.[34] This cation is isoelectronic with dialkyl carbonate and is presumably planar at the phosphorus. It may of course also be viewed as a di-O-alkylated metaphosphate. Having presented this more explicit formulation for expecting the C–P bond in phosphonates to be highly polarizable upon strong electron demand from the carbon side, we postulate that the 1,2-migration of a $(RO)_2PO$ group proceeds *via* a "loose" transition state in which considerable positive charge has developed on this group. Such a transition state may most simply be described as involving the interaction of a dialkoxyphosphinoyl cationic species with a newly forming π-bond between the migration origin and terminus. The stability of this π-bond and

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its electron density are therefore determinative for the energy of the transition state.

Reverting to the product composition of the Schmidt reactions under study, we note in Table 1 that in the cases of compounds **11a-d** and **11g** (group A), in which the phenyl group is unsubstituted or substituted with electron-attracting or mildly electron-releasing substituents, and the case of the aliphatic ketophosphonate **11l**, large quantities of products **12** and/or **15**, in which the aryl (alkyl) group had migrated, were formed, but only very small amounts of **13** (and **14**, **17**) the product (possible products) of (initial) phosphonate group migration formed. Contrariwise, compounds **11e,f,h**, (group B), bearing good electron-donating *p*-alkoxy substituents, yielded no isolable product of aryl migration but only **13** and **17**, which result from phosphonate group migration and elimination (possibly subsequent to migration), respectively. These results lead one, by the following reasoning, to the conclusion that an AH cannot be the intermediate whose decomposition–rearrangement is responsible for the products (specifically **12** or **13**) of *both* group A and group B. The acid-catalyzed decomposition–rearrangement behavior of an AH should be qualitatively similar to that of a tertiary azide. For the latter it has been found that *p*-methoxyphenyl migrates in preference to phenyl, electronic transition-state stabilization dominating.[35] Therefore, if group A forms **12** directly from the AH, then group B must be yielding **13** from the ID ion, the dehydration certainly being facilitated by the *p*-methoxy substituent. However, it has already been argued above that **15** must have been produced *via* the ID ion. Application of Occam's razor leads to the plausible, though admittedly not necessary, conclusion that group A compounds also react exclusively *via* the ID pathway. For α-ketophosphonates at least, Smith's long-standing contention[28] that this is the preferred, if not the exclusive, pathway seems valid, recent results mentioned in the Introduction section notwithstanding.

Clearly, steric bulk effects along the ID path cannot be responsible for the differing behavior of groups A and B, as para substituents do not affect the relevant bulk of the aryl groups. Furthermore, the results of Callot and Benezra indicate that a phenyl and a dimethoxyphosphinoyl group have comparable effective steric bulks.[36] The explanation must lie in differential electronic effects on the ground and on the transition states. It has been demonstrated in a number of systems[33,37] and found in a theoretical study[38] that the ability of a group to stabilize an electron-deficient center may be dependent on the extent of the electron demand of that center. Thus, for example, in solvolyses which produce substituted benzyl carbocations, good electron-donating substituents, including specifically *p*-OCH_3, appear to monopolize the function of stabilizing the electron-deficient center, ($\rho^+ \leq -10$), precluding the participation of other available electron-supplying processes. However, in the transition to the region of electron-attracting substituents, sharp breaks in the Hammett plots are noted. The much less negative values of ρ^+ in this region demonstrate a greatly reduced sensitivity of the ionization process to the electronic effect of the substituent as other cation-stabilizing phenomena (*e.g.*, anchimeric assistance, solvent nucleophilicity) intrude to satisfy the increased electron demand left unsatisfied by the substituent. The Hammett plot breaks referred to appear in or about the region of the unsubstituted or the alkyl-substituted phenyl group. It is to be expected that the position of the break along the σ^+ axis will depend on the degree of electron deficiency and on the efficacy of the additional processes available for its relief.

The ID ion is an α-azido carbocation (*cf.* canonical structures, Scheme 4), and its trigonal carbon is highly electron deficient. It is a relatively high-energy structure whose equilibrium concentration is very low,[5] though in the strongly acidic medium of the Schmidt reaction conditions—which limit the activity of nucleophiles including solvent—its concentration is not as vanishingly small as in the neutral medium studied by Amyes and Richard.[5] Its competence as a Schmidt reaction intermediate is attributable, in the wake of the results of Hoz and Wolk,[10] to the remarkably low energy of activation for N_2 release. The ID ions derived from group B compounds enjoy substantial stabilization of their ground state by conjugative electron donation from the *p*-OCH_3 group to the carbocationic center (Scheme 8). Polarization of the C–P bond (*vide ante*) is therefore not invoked. Said conjugative stabilization, which requires coplanarity of the aromatic ring and the C(P)N triad, is preserved—even enhanced—in the transition state(s) for N_2 release and dialkoxyphosphinoyl migration whether these are concerted or not. The bonding of the phosphonate function to the carbon has not been strengthened by polarization in the ground state, and it shifts to the nitrogen in the manner suggested above. The alternative 1,2-shift of the aryl ring in a mode permitting its stabilization of the transition state (as found in the Beckmann, pinacol, and related rearrangements[29]) would require its rotation into a plane perpendicular to the C(P)N triad (Scheme 8). The experimental results show that this alternative transition-state stabilization is insufficient to compensate for the loss of both ground-state and additional transition-state stabilization from a coplanar *p*-alkoxyphenyl group. In an extension of the above reasoning, one may argue that a stabilizing contribution of the canonical structure such as **x** (Scheme 8) strengthens the bonding between N^1 and N^2, as well as the basicity of N^1 of the ID ion, inhibiting the release of dinitrogen ($N^2 \equiv N^3$). The latter may therefore conceivably be acid catalyzed, occurring from a protonated species **y**. In such a structure, it is of course only the phosphonate group and not the *p*-methoxyphenyl group which is available for migration. To test the above explanations, we synthesized the arenecarbonylphosphonates **11j** and **11k**. Our reasoning was that in the ID ions derived from them coplanarity of the ring with the C(P)N triad was sterically hindered by the two ortho substituents, and therefore the conjugative ground- and transition-state stabilization afforded by the *p*-alkoxy substituent to group B ID ions would not be available in **11k**, and group A behavior should be observed. The di-*o*-methyl groups should not interdict the perpendicular orientation of the ring which enables transition-state stabilization for aryl group migration. The analogous compound **11j**, carrying a *p*-methyl in place of the *p*-methoxyl, was also investigated to provide a standard for comparison. It is known that 2,6-dimethyl substituted aromatic ketones do not react readily in the Schmidt reaction, and in fact **11j**, when subjected to our usual conditions followed by an additional 15 min at room temperature, yielded only 16% of the 2,4,6-trimethylaniline (**16j**), and 76% **11j** was recovered unchanged. After 20 h at room temperature, only 43% of **16j** and 5% of a mixture of unidentified neutral compounds were isolated. Equally disappointing was the result of the reaction of **11k**. After 1 h at 0 °C, a 50% yield of the amine **16k** was obtained, and 47% of the starting material was recovered. We presume that **16j** and **16k** are products of the Schmidt reaction of the respective arenecarbonyl azides which were formed from the reaction of the acylium ions with azide ion. Acylium ions are well-established intermediates in the reactions in concentrated sulfuric acid of mesitoic acid derivatives in which nucleophilic addition to the carbonyl is hindered and in the present instances would have been formed by acid-catalyzed release of diethyl phosphite. From the reaction of diethyl 2,6-dimethoxybenzoylphosphonate (**11i**) under the standard conditions 17% of starting material, 62% of

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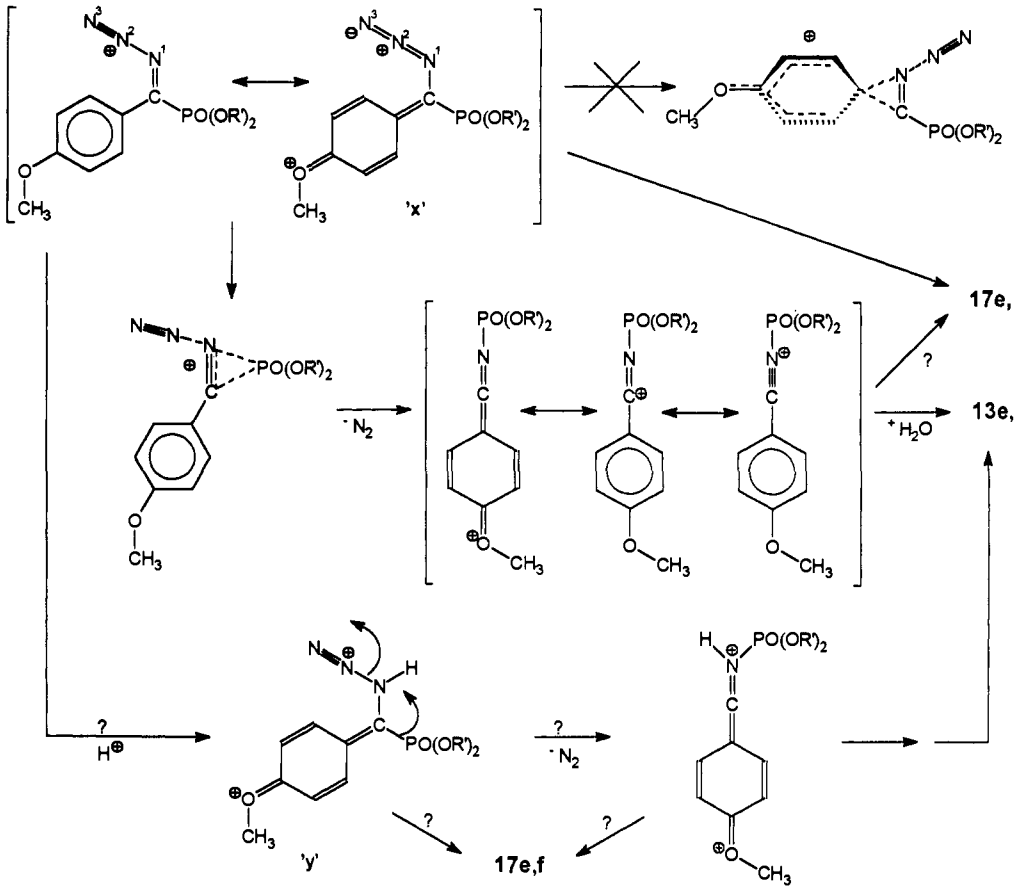
Scheme 8



nitrile (**17i**) and 1% of a mixture of acidic compounds apparently containing some **13i** were isolated. The large portion (20%) of unaccounted-for material precludes a definite conclusion, though the result is compatible with expected group B behavior. In the case of a group A compound, the carbocationic center of the derived ID ion does not receive sufficient electronic charge from the aromatic ring, substituted as it is by only a weakly electron-donating or electron-withdrawing group. Polarization and strengthening of the C–P bond occurs, and the shift of the aryl group, with its much smaller loss of ground-state though limited gain of transition-state stabilization, is what transpires.

The unexpected results reported herewith have thus prompted the extension of a mechanistic concept (electron demand) to the area of molecular rearrangements, as well as the consideration of a possible additional pathway for the Schmidt rearrangement in certain cases. Confirmation of the proposals await further appropriate investigations.

Experimental Section

Melting points were determined in capillaries using a Thomas-Hoover instrument and are uncorrected. Infrared (IR) spectra were recorded on a Perkin-Elmer 337 spectrometer, as liquid films, in pressed KBr pellets, or as chloroform solutions in NaCl cells, as indicated, and are reported in cm^{-1}. ^1H NMR spectra of $CDCl_3$ solutions were recorded on a Varian HA-100 spectrometer operating at 100 MHz for protons. Chemical shifts (δ) are reported in ppm downfield from internal tetramethylsilane, and coupling constants (J) are in hertz. As is common in many diethyl phosphonates, $J_{P-CH2} = J_{CH2-CH3}$, resulting in an apparent quintet for the CH_2 protons. This pattern is abbreviated here as qt. UV–visible spectra were measured on a Perkin-Elmer 137 spectrophotometer. Mass spectra were measured on a single-focusing Hitachi–Perkin-Elmer RMU-6 instrument using direct inlet. Column chromatography was done on Merck 7734 silica gel, with 0.05–0.2 mm particle size, and eluted, unless otherwise noted, with a petroleum ether-acetone mixture varying between 10 and 30% acetone. Thin-layer chromatographic analysis (TLC) was carried out on locally prepared plates coated with Merck silica gel containing 5% gypsum and eluted with the same solutions used for column chromatography. Elemental analyses were performed by M. Manser Laboratory in Switzerland.

Dialkyl Acyl- and Arenecarbonylphosphonates 11a-l. These compounds were synthesized by Berlin's method:[13] to 0.1 mol of acyl or arenecarbonyl chloride stirred under nitrogen was added dropwise over 30 min 0.1 mol of triethyl (or trimethyl) phosphite. The reaction was kept at room temperature by means of a water bath for 3–4 h. The products were distilled under reduced pressure and characterized as follows.

11a: bp 106–109 °C at 0.01 Torr (lit.[39] bp 136–137 °C at 1.4–1.5 Torr); 61% yield; ^1H NMR δ 1.35 (t, 6H, J = 7, CH_3), 4.25 (qt, 4H, J = 7, CH_2), 7.50 (m, 3H, arom), 8.25 (m, 2H, arom); IR (film) ν 2960, 2910, 2885, 1650, 1590, 1575, 1475, 1250, 1220, 1160, 1045, 1020.

11b: bp 112–113 °C at 0.01 Torr (lit.[39] bp 192–197 °C at 0.4–0.6 Torr); 74% yield; ^1H NMR δ 1.33 (t, 6H, J = 7, CH_3), 4.22 (qt, 4H, J = 7, CH_2), 7.42 (d, 2H, J = 9, arom), 8.18 (d, 2H, J = 9, arom); IR (film) ν 2955, 2910, 2880, 1650, 1580, 1565, 1475, 1250, 1220, 1160, 1050, 1020.

11c: bp 114–118 °C at 0.05 Torr; 45% yield; ^1H NMR δ 3.89 (d, 6H, J_{PH} = 11, CH_3O), 7.50 (m, 2H, arom), 8.14 (m, 2H, arom). Anal. Calcd for $C_9H_{10}ClO_4P$: C, 43.48; H, 4.06; P, 12.46. Found: C, 43.30; H, 4.15; P, 12.37. 2,4-Dinitrophenylhydrazone: mp 172.5–173.5 °C (from chloroform–methanol). Anal. Calcd for $C_{15}H_{14}ClN_4O_7P$: C, 42.02; H, 3.29; Cl, 8.27; N, 13.07; P, 7.22. Found: C, 41.73; H, 3.28; Cl, 8.32; N, 13.15; P, 7.29.

11d: bp 116–117 °C at 0.03 Torr; 65% yield; ^1H NMR δ 1.37 (t, 6H, J = 7, CH_3CH_2), 4.26 (qt, 4H, J = 7, CH_2), 2.40 (s, 3H, CH_3Ar), 7.29 (d, 2H, J = 8, arom), 8.18 (d, 2H, J = 8, arom). 2,4-Dinitrophenylhydrazone: mp 180–181 °C (from methanol). Anal. Calcd for $C_{18}H_{21}N_4O_7P$: C, 49.54; H, 4.85; N, 12.84; P, 7.10. Found: C, 49.27; H, 4.79; N, 12.68; P, 6.30.

11e: bp 145–147 °C at 0.1 Torr (lit.[13a] bp 170 °C at 2.5 Torr); solidifies on standing, mp 21 °C; 83% yield.

11f: bp 165 °C at 0.05 Torr (lit.[13a] bp 158 °C at 0.4 Torr); 71% yield.

11g: bp 121–124 °C at 0.07 Torr; 73% yield; ^1H NMR δ 1.39 (t, 6H, J = 7, CH_3CH_2), 4.27 (qt, 4H, J = 7, CH_2), 3.84 (s, 3H, CH_3O), 7.70 (br s, 1H, arom H_2), 7.16 (dd, 1H, $J_{4,5}$ = 8, $J_{4,6}$ = 2, arom H_4), 7.41 (t, 1H, $J_{4,5} = J_{5,6}$ = 8, arom H_5), 7.96 (dd, 1H, $J_{4,6}$ = 2, $J_{5,6}$ = 8, arom H_6);

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IR (film) ν 3050, 2960, 2820, 1655, 1595, 1575, 1485, 1260, 1160, 1030. Anal. Calcd for $C_{12}H_{17}O_5P$: C, 52.94; H, 6.29; P, 11.38. Found: C, 52.98; H, 6.30; P, 11.24. 2,4-Dinitrophenylhydrazone: mp 157–158 °C (from chloroform–ethanol). Anal. Calcd for $C_{18}H_{21}N_4O_8P$: C, 47.79; H, 4.68; N, 12.39; P, 6.85. Found: C, 47.72; H, 4.66; N, 12.50; P, 6.61.

11h: bp 149–150 °C at 0.1 Torr; 74% yield; ^{1}H NMR δ 1.38 (t, 6H, J = 7, CH_3CH_2), 4.23 (qt, 4H, J = 7, CH_2), 6.04 (s, 2H, OCH_2O), 7.60 (br s, 1H, arom H_2), 6.87 (d, 1H, $J_{5,6}$ = 8, arom H_5), 8.10 (dd, 1H, $J_{5,6}$ = 8, $J_{2,6}$ = 2, arom H_6); IR (film) ν 2960, 2880, 1630, 1595, 1500, 1485, 1440, 1260, 1160, 1035. Anal. Calcd for $C_{12}H_{15}O_6P$: C, 50.36; H, 5.28; P, 10.82. Found: C, 50.30; H, 5.31; P, 10.64. 2,4-Dinitrophenylhydrazone mp 197–198 °C (from chloroform–ethanol). Anal. Calcd for $C_{18}H_{19}N_4O_9P$: C, 46.36; H, 4.11; N, 12.01; P, 6.64. Found: C, 46.43; H, 4.08; N, 12.17; P, 6.49.

11i: bp 152–153 °C at 0.05 Torr (lit.[39] bp 186–189 °C at 0.6–0.8 Torr); mp 32 °C; 90% yield; ^{1}H NMR δ 1.30 (t, 6H, J = 7, CH_3CH_2), 4.16 (qt, 4H, J = 7, CH_2), 3.79 (s, 6H, CH_3O), 6.57 (d, 2H, $J_{3,4}$ = 8.5, arom H_3, H_5), 7.35 (t, 1H, $J_{3,4}$ = 8.5, arom H_4); IR (film) ν 2955, 2815, 1670, 1590, 1470, 1250, 1155, 1105, 1045, 1015; λ_{max} ($CHCl_3$) 289 nm (ϵ = 3350). 2,4-Dinitrophenylhydrazone: mp 168–169 °C (from ethanol). Anal. Calcd for $C_{19}H_{23}N_4O_9P$: C, 47.31; H, 4.81; N, 11.62; P, 6.42. Found: C, 47.16; H, 4.81; N, 11.57; P, 6.33.

11j: bp 131–132 °C at 0.3 Torr; 59% yield based on mesitoic acid; ^{1}H NMR δ 1.29 (t, 6H, J = 7, CH_3CH_2), 4.17 (split qt, 4H, J = 7, CH_2), 2.23 (s, 6H, 2,6-diMe), 2.26 (s, 3H, 4-Me), 6.84 (s, 2H, arom); IR (film) ν 2955, 2890, 2840, 1665, 1600, 1250, 1155, 1050, 1020. Anal. Calcd for $C_{14}H_{21}O_4P$: C, 59.15; H, 7.45; P, 10.90. Found: C, 59.02; H, 7.41; P, 10.75.

11k. This arenecarbonylphosphonate was prepared in several steps as follows.

3,5-Dimethyl-4-bromophenol was prepared in 33% yield by bromination of 3,5-dimethylphenol according to a literature procedure and had mp 100–110 °C after one crystallization from benzene–petroleum ether.[41,42] It was used without further purification.

3,5-Dimethyl-4-bromoanisole. To a 100-g (0.5 mol) solution of 3,5-dimethyl-4-bromophenol in 0.5 L of 10% aqueous sodium hydroxide was added dropwise dimethyl sulfate (63 g, 0.5 mol, 100 mol % excess). The product separated as an oily layer, which was extracted twice with chloroform. The extracts were combined and dried over $MgSO_4$, and the solvent was removed under reduced pressure. Two fractions were collected by distillation; the first boiled at 134–143 °C at 23 Torr, 9 g, and was found by NMR to contain 75% of the desired product and 25% of the isomeric 3,5-dimethyl-2-bromoanisole. The second fraction, 50 g of pure 3,5-dimethyl-4-bromoanisole (47% yield), was collected at 143–148 °C at 23 Torr (lit.[42] 131–134 °C at 14–15 Torr): ^{1}H NMR δ 2.39 (s, 6H, CH_3C), 3.76 (s, 3H, CH_3O), 6.67 (s, 2H, arom); IR (film) ν 2930, 2815, 1585, 1465, 1320, 1190, 1160, 1075, 1015, 850, 830.

2,6-Dimethyl-4-methoxybenzoic Acid. The Grignard reagent from 46 g (0.214 mol) of 3,5-dimethyl-4-bromoanisole was prepared according to a known procedure[41] and reacted with dry ice to yield, after workup, 30 g (78%) of the acid: mp 144–146 °C (from benzene–petroleum ether) (lit.[41,42] mp 144.5–145 °C); ^{1}H NMR δ 2.46 (s, 6H, CH_3–C), 3.80 (s, 3H, CH_3–O), 6.60 (s, 2H, arom), 8.96 (very br s, 1H, O*H*; disappears with D_2O); IR (KBr) ν 3200–2300, 1675, 1595, 1570.

11k. 2,6-Dimethyl-4-methoxybenzoic acid (17 g) was treated with a large excess of thionyl chloride and refluxed for 30 min, after which the mixture was left at ambient temperature for 24 h. The excess of thionyl chloride was removed under reduced pressure, and the resulting product was used without purification for the preparation of **11k** in the usual manner. The yield from acid was 85% (24.1 g) of a product boiling at 141 °C (0.02 Torr): ^{1}H NMR δ 1.27 (t, 6H, J = 7, CH_3CH_2), 2.24 (s, 6H, CH_3-arom), 3.74 (s, 3H, CH_3–O), 4.15 (qt, 4H, J = 7, CH_2), 6.53 (s, 2H, arom); IR (film) ν 2960, 2890, 2825, 1670, 1600, 1570, 1250, 1190, 1145, 1040–1015; λ_{max} (cyclohexane) 283 nm (ϵ = 1880), 299 nm (1910). Anal. Calcd for $C_{14}H_{21}O_5P$: C, 56.00; H, 7.05; P, 10.31. Found: C, 55.83; H, 7.09; P, 10.02.

11l: bp 112–116 °C at 22 Torr (lit.[40] bp 100–103 °C at 9 Torr); 65% yield; ^{1}H NMR δ 1.18 (d, 6H, J = 7, $CH(CH_3)_2$), 3.13 (sp, 1H, J = 7, $CH(CH_3)_2$), 3.86 (d, 6H, J_{PH} = 11, OCH_3); IR (film) ν 2950, 2855, 2835, 1680, 1260, 1180, 1032. 2,4-Dinitrophenylhydrazone: , mp 117.5–118.0 °C (from ethanol). Anal. Calcd for $C_{12}H_{17}N_4O_4P$: C, 40.01; H, 4.76; N, 15.55; P, 8.60. Found: C, 39.47; H, 4.55; N, 15.49; P, 8.36.

General Procedure for the Schmidt Reaction. All operations with hydrazoic acid were carried out behind a safety shield. Hydrazoic acid solutions in chloroform were prepared as described previously.[2h] The HN_3 concentration was determined prior to each experiment by titration with 0.1 N NaOH solution. The concentrations varied between 1.2 and 1.73 mol L^{-1} and were found to depend on the temperature at which the solutions were made (between 0 and −10 °C): the lower the temperature, the higher the concentration. The concentration decreased after storage for 1 month at −10°C only from 1.595 to 1.550 mol L^{-1}.

A mixture of 37.5 mL of sulfuric acid and 112.5 mL of chloroform was mechanically stirred in a three-necked 500-mL round-bottom flask, protected from moisture by means of a $CaCl_2$ tube. The mixture was cooled in an ice bath, and a 110 mL of a chloroform solution containing 0.048 mol of **11a** and 32.5 mL of a 1.55 N HN_3 solution (0.0504 mol, 5 mol % excess) was added over 5 min through a dropping funnel. The mixture was allowed to react for another 5 min, after which the contents were poured over *ca.* 100 g of ice. The layers which formed were separated, and the organic layer was washed once with water and the wash combined with the aqueous layer. The organic layer was extracted twice with 10% NaOH solution and dried over anhydrous $MgSO_4$, and the solvent was removed under reduced pressure. This fraction, which should contain only neutral products, will be termed A.

The combined NaOH extracts were acidified to pH 1 using dilute HCl and were extracted thrice with chloroform. The extracts were combined and dried over $MgSO_4$, and the solvent was removed. This residue will be termed B.

The first aqueous H_2SO_4 layer was cooled in an ice bath and made alkaline using a 20% NaOH solution. Chloroform extraction, drying of the organic extract, and removal of solvent yielded a residue which is named fraction C.

This general procedure was used for the Schmidt reaction of all of the acyl- and arenecarbonylphosphonates **11**. Product isolation and characterization steps for each of the three fractions are given below for each reaction. Where chromatographic separation is mentioned, the corresponding mixture was run through a 90-g silica gel column using light petroleum ether containing 10–30% acetone as eluent. Where necessary, an aliquot was taken from each fraction (A-C) so that the actual material applied to the column amounted to *ca.* 1 g. The product composition was then normalized and is reported here in terms of overall yields of the reaction.

Schmidt Reaction of 11a. Elution of one fifth (0.98 g) of fraction A (a total of 4.93 g) yielded first 0.210 g (9%) of **12a**, identified by spectral and chromatographic comparison with an authentic sample (for the synthesis see below). This was followed by 0.590 g of formanilide (**15a**), identified by comparison with authentic material. An additional 92 mg of **15a** was isolated from fraction B after chromatography, bringing the total yield from A and B up to 53%. Further elution of B gave 15 mg (0.2% yield) of benzoic acid, **18a**. The next fraction eluted was **14a**, 1%, mp 127–128 °C (from methanol; lit.[44] mp 125–127 °C): ^{1}H NMR δ 1.35 (t, 6H, J = 7, CH_3), 4.21 (qt, 4H, J = 7, CH_2), 7.72 (br s, 1H, N*H*), 8.92 (s, 1H, N*H*), 7.23 (m, 5H, arom); IR (KBr) ν 3280–3250, 3180, 3125, 3075, 2965, 2880, 1675, 1600, 1550, 1480, 1230, 1160, 1030; MS (*m/e*) 272 (16, M^{+}), 180 (4, $[CONHPO(OEt)_2]^{+}$), 154 (15), 152 (30), 127 (20), 126 (16), 124 (41), 105 (39), 93 (100). Anal. Calcd for $C_{11}H_{17}N_2O_4P$: C, 48.53; H, 6.29; N, 10.29; P, 11.34. Found: C, 48.54; H, 6.25; N, 10.30; P, 11.14.

Immediately after **14a**, **13a** was eluted in 3.1% yield. It was identified by comparison with an authentic sample (preparation below).

Fraction C consisted of aniline, **16a**, 0.615 g, 14% yield, identified by spectral comparison.

Diethyl Phenylcarbamoylphosphonate (12a). (Prepared according to a literature procedure for the preparation of the homologous dimethyl phenylcarbamoylphosphonate.)[43] To a mixture of 12 g (0.1 mol) of phenyl isocyanate and 13.8 g (0.1 mol) of diethyl phosphite was added 1 mL of triethylamine. Spontaneous heating up to 80 °C was observed, following which the reaction was kept for another hour at 100 °C. After cooling, the mixture was dissolved in 100 mL of chloroform, the solution was washed twice with water and dried over anhydrous $MgSO_4$, and the solvent was removed. The residue was distilled, and 24.2 g (94% yield) was collected at 149 °C (0.05 Torr): ^{1}H NMR δ 1.38 (t, 6H, J = 7, CH_3), 4.28 (qt, 4H, J = 7, CH_2), 7.4 (m, 5H, arom), 9.25 (br s, 1H, N*H*); IR (film) ν 3215–3160, 3100, 3030, 2960, 1665, 1600, 1540, 1255, 1220,

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1155, 1045, 1025. Anal. Calcd for $C_{11}H_{16}NO_4P$: C, 51.36; H, 6.27; N, 5.44; P, 12.04. Found: C, 51.36; H, 6.31; N, 5.33; P, 11.92.

Diethyl Benzoylphosphoramidate (13a).[45,46] Phosphorus pentachloride (22.9 g, 0.11 mol) was added in small portions under nitrogen to a well-stirred, ice-cold solution of 12.1 g (0.1 mol) of benzamide in 20 mL of CCl_4. A vigorous reaction commenced, accompanied by evolution of HCl gas. After the initial reaction had subsided, the mixture was kept at 50 °C for 15 min until all the solid went into solution. The solvent was removed under reduced pressure at 30–40 °C, and the residue was dissolved in 100 mL of dry benzene. This solution was added dropwise over 60 min to an ice-cold sodium ethoxide solution prepared by dissolving 9.2 g (0.4 mol) of sodium in 220 mL of absolute ethanol. The reaction was left overnight, after which most of the solvent was removed in vacuum. One liter of water was added, and the solution was washed once with chloroform. The aqueous solution (containing the sodium salt of **13a**) was acidified and extracted twice with chloroform. After being dried over $MgSO_4$, the solvent was removed to yield 7.0 g of **13a** (27%), mp 75–77 °C (lit.[47] mp 78 °C). After one crystallization from methanol–water, the mp rose to 78 °C: ^{1}H NMR δ 1.37 (t, 6H, J = 7, CH_3), 4.28 (qt, 4H, J = 7, CH_2), 7.47 (m, 3H, arom), 8.07 (dd, 2H, J_1 = 2, J_2 = 4, arom ortho H), 9.22 (d, 1H, J_{PH} = 8, N*H*); IR (KBr) δ 3125, 2970, 2890, 1677, 1595, 1575, 1497, 1260, 1222, 1160, 1020.

Schmidt Reaction of 11b. Fractions A, B, and C were obtained by the usual reaction and workup procedure. Solid *p*-chloroformanilide (**15b**, 3.5 g) was separated from fraction A by trituration with cold benzene followed by filtration (mp 92–98 °C, raised to 99–101 °C after one crystallization from benzene). It was identified by spectral comparison and mixture mp with an authentic sample. Removal of solvent from the filtrate under reduced pressure yielded a residue of which one quarter (1.25 g) was chromatographed to yield first 660 mg (19% overall yield) of **12b**, mp 79–80 °C (from methanol): ^{1}H NMR δ 1.41 (t, 6H, J = 7, CH_3), 4.18 (qt, 4H, J = 7, CH_2), 7.30, 7.63 (ABq, 4H, J_{AB} = 9, arom), 9.28 (br s, 1H, N*H*); IR (KBr) ν 3210, 3150, 3080, 3015, 2960, 1660, 1590, 1530, 1490, 1250, 1220, 1170, 1155, 1040–1020; MS (*m/e*) 293, *291* (1, *3*, $M^{\cdot+}$), 179, *177* (4, *12*), 153, *151* (35, *100*, $[ClC_6H_4NCO]^{\cdot+}$), 138 (26, $[HPO(OEt)_2]^{\cdot+}$), 129 (12), 127 (50), 125 (42), 111 (73), 90 (36), 83 (64). Anal. Calcd for $C_{11}H_{15}ClNO_4P$: C, 45.30; H, 5.18; Cl, 12.16; N, 4.80; P, 10.62. Found: C, 45.03; H, 5.20; Cl, 11.98; N, 4.93; P, 10.43.

Continued elution yielded a further 310 mg of **15b**, followed by 88 mg (1.8%) of **19b**, identified by comparison with authentic material (synthesis below).

From fraction B, crystals of *p*-chlorobenzoic acid (**18b**, 300 mg, 4%) were separated by trituration with cold chloroform and filtration. The filtrate, which after removal of solvent weighed 1.2 g, was chromatographed and yielded the following products: *p*-chloroaniline (**16b**, 26 mg), mp 69–71 °C; 230 mg of **15b**, in addition to the quantity separated from fraction A, bringing the total yield up to 65%; and 256 mg of **13b**, identified by comparison with an authentic sample (preparation below). **13b** had mp 108–110 °C after one crystallization from methanol–water. Fraction C consisted of 220 mg of pure **16b**, with a total yield of 4% after being combined with the portion isolated from B.

Preparation of 19b. (a) Diethyl α-Hydroxy-*p*-chlorobenzylphosphonate. Triethylamine (5 mL) was added to a stirred solution of 28.1 g (0.2 mol) of *p*-chlorobenzaldehyde and 27.6 g (0.2 mol) of diethyl phosphite. The temperature rose spontaneously, and the solution became viscous. After additional heating for 1 h at 100 °C, the mixture was cooled, dissolved in chloroform, washed twice with water, dried over $MgSO_4$, and stripped of solvent on a rotary evaporator. The residue was a yellow solid, 47.3 g (85% yield), mp 72–73 °C after two recrystallizations from benzene–petroleum ether (lit.[48] mp 55–56 °C): ^{1}H NMR δ 1.22, 1.25 (two t, 6H, $J_1 = J_2$ = 7, CH_3), 4.03 (qt, 4H, J = 7, CH_2), 4.97 (m, 2H, O*H* + PC*H*) [after addition of D_2O, 4.97 (d, 1H, J_{PH} = 11, PC*H*)], 7.33 (m, 4H, arom); IR (KBr) ν 3215, 2935, 2860, 1490, 1405, 1230, 1200, 1060, 1025. Anal. Calcd for $C_{11}H_{16}ClO_4P$: C, 47.41; H, 5.79; Cl, 12.72; P, 11.11. Found: C, 47.36; H, 5.72; Cl, 12.65; P, 10.96.

(b) Diethyl phosphorochloridate ($(EtO)_2P(O)Cl$; 7.6 g, 0.044 mol) was added dropwise to an ice-cold solution of 11.2 g (0.04 mol) of diethyl α-hydroxy-*p*-chlorobenzylphosphonate in 50 mL of pyridine. Stirring was maintained for 48 h at ambient temperature, after which dilute HCl was added and the mixture was extracted 4 times with ether. The combined extracts were washed twice with dilute HCl and then with a sodium bicarbonate solution and finally with a saturated sodium chloride solution, followed by $MgSO_4$ drying and removal of solvent. The liquid residue (7 g) was distilled under reduced pressure and 3.526 g (22%) of **19b** was collected at 170 °C at 0.1 Torr: ^{1}H NMR δ 1.30 (m, 12H, CH_3), 4.10 (m, 8H, CH_2), 5.51 (dd, 1H, J_{P1-H} = 14, J_{P2-H} = 10, POC*H*P); IR (film) ν 2955, 2880, 1585, 1255, 1160, 1050–1025. Anal. Calcd for $C_{15}H_{25}ClO_7P_2$: C, 43.44; H, 6.07; Cl, 8.55; P, 14.93. Found: C, 43.33; H, 6.05; Cl, 8.33; P, 14.78.

Diethyl *p*-Chlorobenzoylphosphoramidate (13b) and Dimethyl *p*-Chlorobenzoylphosphoramidate. The compounds were prepared as described above for **13a** from 29.5 g (0.19 mol) of *p*-chlorobenzamide and 41.7 g (0.198 mol) of phosphorus pentachloride. After evaporation of CCl_4 and dissolution of the residue in 200 mL of benzene, the solution was separated into two halves: one was reacted with 200 mL of an ethanol solution of 0.4 mol of sodium, the other with 200 mL of a methanol solution of 0.4 mol of sodium. After workup (as described for **13a**), the first portion yielded 18.0 g (33%) of **13b**, melting at 102–109 °C. After one recrystallization from methanol–water, the mp rose to 112–113.5 °C: ^{1}H NMR δ 1.37 (t, 6H, J = 7, CH_3), 4.26 (split qt, 4H, J = 7, CH_2), 7.40, 8.09 (ABq, 4H, J_{AB} = 8.5, arom), 9.81 (d, 1H, J_{PH} = 9, N*H*); IR (KBr) ν 3140, 3100, 2965, 2890, 1680, 1585, 1430, 1280, 1262, 1230, 1155, 1030. Anal. Calcd for $C_{11}H_{15}ClNO_4P$: C, 45.30; H, 5.18; Cl, 12.15; N, 4.80; P, 10.62. Found: C, 45.17; H, 5.19; Cl, 12.11; N, 4.85; P, 10.44.

The second portion, which was reacted with sodium methoxide solution, yielded after similar workup 28.2 g (56% yield) of dimethyl *p*-chlorobenzoylphosphoramidate, mp 127.5–128.5 °C (from methanol–water) (lit.[46] mp 125–126 °C): ^{1}H NMR δ 3.89 (d, 6H, J_{PH} = 11, CH_3), 7.42, 8.08 (ABq, 4H, J_{AB} = 8.5, arom), 9.79 (d, 1H, J_{PH} = 9, N*H*); IR (KBr) ν 3105, 2940, 2835, 1685, 1670, 1590, 1255, 1225, 1065, 1040, 1030.

Schmidt Reaction of 11c. The reaction was run in the usual manner with 6 g (0.0242 mol) of **11c** and 0.0255 mol of hydrazoic acid in 55 mL of chloroform solution. Fraction A consisted, according to its ^{1}H NMR spectrum, of *m*-chloroformanilide (**15c**) and *ca.* 20% of phosphonate-containing material (δ 3.78, d, J = 11). However, only **15c** and no phosphorus-containing products could be isolated from this fraction by chromatography. Chromatographic separation of fraction B afforded more **15c** (total yield 39%), followed by a mixture of **13c** and **14c**. The yields of each of these products were determined from the integration ratio in the NMR spectra of the mixed fractions (**13c**, 1%, and **14c**, 1.5% yield). **14c** was isolated by crystallization from methanol and had mp 132–133.5 °C: ^{1}H NMR δ 3.88 (d, 6H, J_{PH} = 11, CH_3), 7.16 (m, 3H, arom), 7.61 (s, 1H, arom), 7.80 (br s, 1H, N*H*), 8.85 (s, 1H, N*H*); IR (KBr) ν 3225, 3170, 2930, 2825, 1700, 1605, 1590, 1545, 1450, 1230, 1050; MS (*m/e*) 280, *278* (2, 7, $M^{\cdot+}$), 151 (14, $[OCNPO(OMe)_2]^{\cdot+}$), 129, *127* (32, *100*, $[ClC_6H_4NH_2]^{\cdot+}$), 121 (80), 120 (24), 109 (8, $[PO(OMe)_2]^+$). Anal. Calcd for $C_9H_{12}ClN_2O_4P$: C, 38.80; H, 4.34; N, 10.05. Found: C, 38.50; H, 4.36; N, 9.98.

13c was identified by comparison with an authentic sample (preparation below). Fraction C consisted of 200 mg (6.5% yield) of *m*-chloroaniline (**16c**).

Dimethyl *m*-Chlorobenzoylphosphoramidate (13c) and Diethyl *m*-Chlorobenzoylphosphoramidate. The procedure described for **13b** was used on 8.4 g (0.054 mol) of *m*-chlorobenzamide and 11.9 g (0.057 mol) of phosphorus pentachloride, yielding 1.2 g (9% yield) of **13c** and 1.2 g (8%) of the diethyl phosphoramidate. **13c** had mp 110–111 °C (from methanol–water): ^{1}H NMR δ 3.91 (d, 6H, J_{PH} = 11, CH_3), 7.42 (m, 2H, arom), 8.10 (m, 2H, arom), 9.84 (br s, 1H, N*H*); IR (KBr) ν 3120, 2930, 2825, 1680, 1590, 1570, 1265, 1230, 1180, 1055. Anal. Calcd for $C_9H_{11}ClNO_4P$: C, 41.01; H, 4.21; Cl, 13.45; N, 5.31; P, 11.75. Found: C, 40.93; H, 4.19; Cl, 13.37; N, 5.39; P, 11.84.

The diethyl compound melted at 68.5–69 °C (methanol): ^{1}H NMR δ 1.37 (t, 6H, J = 7, CH_3), 4.28 (qt, 4H, J = 7, CH_2), 7.40 (m, 2H, arom), 8.10 (m, 2H, arom), 9.68 (d, 1H, J_{PH} = 9, N*H*); IR (KBr) ν 3150, 2960, 1680, 1570, 1262, 1230, 1055, 1050. Anal. Calcd for $C_{11}H_{15}ClNO_4P$: C, 45.30; H, 5.18; Cl, 12.16; N, 4.80; P, 10.62. Found: C, 45.31; H, 5.19; Cl, 12.24; N, 4.86; P, 10.82.

The total yield of the reaction from *m*-chlorobenzamide was 17%.

Schmidt Reaction of 11d. **11d** (15.36 g, 0.06 mol) was reacted with 0.063 mol of hydrazoic acid in the usual manner. Fraction A, of 1.02 g (out of a total of 9.14 g), was chromatographed to yield *p*-tolunitrile (**17d**, 55 mg, 7%), identified by the IR and NMR spectra: ^{1}H NMR δ 2.40 (s, 3H, CH_3), 7.24, 7.52 (ABq, 4H, J_{AB} = 8, arom); IR (film) ν 2900, 2210, 1600, 1500.

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The next fraction was 206 mg (11.4%) of a colorless oil identified as **12d**: ^{1}H NMR δ 1.37 (t, 6H, J = 7, CH_3CH_2), 2.30 (s, 3H, $CH_3C_6H_4$), 4.27 (qt, 4H, J = 7, CH_2), 7.32 (m, 4H, arom), 9.10 (br s, 1H, N*H*); IR (film) ν 3205, 3080, 3010, 2960, 2890, 2840, 1655, 1595, 1510, 1255, 1225, 1160, 1040, 1020; MS (*m/e*) 276 (4, impurity), 271 (32, $M^{\cdot+}$), 187 (5), 169 (5), 160 (4), 149 (3), 141 (10), 139 (34), 138 (100, $[HPO(OEt)_2]^+$), 133 (23, $[CH_3C_6H_4NCO]^{\cdot+}$), 132 (34), 131 (34), 111 (80), 110 (24), 109 (24), 107 (6), 106 (20), 105 (27), 104 (29), 103 (8), 91 (49, $[C_7H_7]^+$). Anal. Calcd for $C_{12}H_{18}NO_4P$: C, 53.14; H, 6.69; N, 5.16; P, 11.24. Found: C, 52.96; H, 6.59; N, 5.15; P, 11.13.

Next was eluted 630 mg (70%) of **15d**, identified by mp and spectral comparison with authentic material.

From fraction B (0.905 g) was first separated by chromatography 30 mg (0.4%) of *p*-toluic acid (**18d**), followed by **14d** (222 mg, 1.3%). The latter had mp 143–145 °C (from methanol): ^{1}H NMR δ 1.36 (t, 6H, J = 7, CH_3CH_2), 2.28 (s, 3H, $CH_3C_6H_4$), 4.21 (qt, 4H, J = 7, CH_2), 7.07, 7.33 (ABq, 4H, J_{AB} = 8, arom), 8.15 (br s, 1H, N*H*), 8.79 (s, 1H, N*H*);IR (KBr) ν 3270–3240, 3165, 3080–3040, 2950, 2865, 1670, 1600, 1535, 1475, 1230, 1160, 1030;MS (*m/e*) 286 (2, $M^{\cdot+}$), 152 (41, $[NHPO(OEt)_2]^+$), 150 (5), 136 (10), 124 (60), 107 (87, $[CH_3C_6H_4NH_2]^{\cdot+}$), 106 (100, $[CH_3C_6H_4NH]^+$). Anal. Calcd for $C_{12}H_{19}N_2O_4P$: C, 50.35; H, 6.69; N, 9.79; P, 10.82. Found: C, 50.27; H, 6.63; N, 9.61; P, 10.65.

Immediately following **14d** there eluted 546 mg of **13d**, identified by comparison with an authentic sample (preparation below). Fraction C consisted of nearly pure *p*-toluidine (**16d**), 420 mg (6.5%).

Diethyl *p*-Tolylphosphoramidate (13d) and Dimethyl *p*-Tolylphosphoramidate. The preparation was similar to that of **13a-13c**, using 8 g (0.059 mol) of *p*-toluamide and 13.8 g (0.066 mol) of phosphorus pentachloride, dividing the intermediate into two portions and reacting one with sodium ethoxide solution and the other with sodium methoxide solution (each prepared from 4 g of sodium in 100 mL of the corresponding alcohol). **13d** (3.5 g, 22% yield) was obtained from the first portion, mp 101–102 °C (from methanol): ^{1}H NMR δ 1.37 (t, 6H, J = 7, CH_3CH_2), 2.40 (s, 3H, $CH_3C_6H_4$), 4.26 (qt, 4H, J = 7, CH_2), 7.29, 8.18 (ABq, 4H, J_{AB} = 8, arom), 9.22 (d, 1H, J_{PH} = 8, N*H*); IR (KBr) ν 3130–3085, 2965, 2855, 1680, 1605, 1515, 1260, 1237, 1160, 1045, 1020. Anal. Calcd for $C_{12}H_{18}NO_4P$: C, 53.14; H, 6.69; N, 5.16; P, 11.42. Found: C, 53.00; H, 6.70; N, 5.07; P, 11.28.

From the second portion, the dimethyl ester was isolated in 45% yield (6.4 g), mp 128.5–130 °C (from methanol): ^{1}H NMR δ 2.40 (s, 3H, $CH_3C_6H_4$), 3.87 (d, 6H, J_{PH} = 12, CH_3O), 7.25, 8.02 (ABq, 4H, J_{AB} = 8, arom), 9.56 (br s, 1H, N*H*); IR (KBr) ν 3160–3100, 2930, 2830, 1680, 1605, 1570, 1510, 1270, 1235, 1187, 1050. Anal. Calcd for $C_{10}H_{14}NO_4P$: C, 49.39; H, 5.80; N, 5.76; P, 12.74. Found: C, 49.36; H, 5.79; N, 5.64; P, 12.63.

The total yield of the reaction for both products was 67%.

Schmidt Reaction of 11e. The reaction was carried out in the usual manner with 9.75 g (0.04 mol) of **11e** and 0.042 mol of hydrazoic acid. Fraction A solidified after removal of the solvent and was identified as *p*-methoxybenzonitrile (**17e**), obtained in 47% yield (2.5 g), mp 58.5–59.5 °C (from methanol): ^{1}H NMR δ 3.84 (s, 3H, CH_3), 6.92, 7.55 (ABq, 4H, J_{AB} = 8, arom);IR (KBr) ν 2205.

Fraction B consisted of 4.8 g of white crystalline material, identified as **13e** (46% yield). Its IR and NMR spectra were identical with those of an authentic sample (preparation below). Its mp after crystallization from methanol was 97.5–99 °C.

Fraction C consisted of 100 mg of an unidentified mixture.

Schmidt Reaction of 11f. **11f** (8.16 g, 0.03 mol) was reacted with 0.032 mol of hydrazoic acid in the usual manner. Fraction A crystallized as white needles of *p*-methoxybenzonitrile, **17e**, 2.99 g (62%). From fraction B was isolated, after methanol trituration, 2.59 g (30% yield) of crystalline **13f**, identical with an authentic sample. No other products could be isolated or identified from the trituration solution or from fraction C. The latter weighed 130 mg.

Dimethyl Anisoylphosphoramidate (13e) and Diethyl Anisoylphosphoramidate (13f). These were prepared from 28 g (0.185 mol) of anisamide and 41.3 g (0.203 mol) of PCl_5, followed by partition and reaction of one half with sodium methoxide solution and the other with sodium ethoxide (each prepared from 12 g of Na dissolved in 200 mL of the appropriate alcohol). The first half yielded 30.1 g (63%) of crystalline **13e**, mp 98–99 °C (from methanol): ^{1}H NMR δ 3.87 (d, 6H, J_{PH} = 11, CH_3OP), 3.85 (s, 3H, CH_3OC), 6.93, 8.06 (ABq, 4H, J_{AB} = 9, arom), 9.23 (d, 1H, J_{PH} = 9, N*H*); IR (KBr) ν 3140–3120, 2925, 2830, 1680, 1600, 1570, 1505, 1435, 1273, 1255, 1230, 1177, 1050, 1020; MS (*m/e*) 259 (47, $M^{\cdot+}$), 230 (5), 152 (19, $[CONHPO(OMe)_2]^+$), 135 (100, $[MeOC_6H_4CO]^+$), 126 (33), 109 (17, $[PO(OMe)_2]^+$), 92 (19). Anal. Calcd for $C_{10}H_{14}NO_5P$: C, 46.34; H, 5.44; N, 5.40; P, 11.95. Found: C, 46.24; H, 5.45; N, 5.46; P, 12.16.

13f was obtained from the second portion, 5.4 g (10% yield), mp 118.5–119 °C (from methanol): ^{1}H NMR δ 1.34 (t, 6H, J = 7, CH_3CH_2), 3.82 (s, 3H, CH_3O), 4.23 (split qt, 4H, J = 7, CH_2), 6.91, 8.09 (ABq, 4H, J_{AB} = 9, arom), 9.40 (d, 1H, J_{PH} = 9, N*H*); IR (KBr) ν 3140, 3050, 2960, 2920, 1665, 1600, 1573, 1515, 1255, 1235, 1180, 1100, 1050, 1025; MS (*m/e*) 287 (22, $M^{\cdot+}$), 259 (2.5 $[M - C_2H_4]^{\cdot+}$), 180 (2, $[CONHPO(OEt)_2]^+$), 154 (31), 152 (4), 151 (6, $[MeOC_6H_4CONH_2]^{\cdot+}$), 135 (100, $[MeOC_6H_4CO]^+$), 134 (18), 133 (11), 127 (25), 126 (9), 124 (11). Anal. Calcd for $C_{12}H_{18}NO_5P$: C, 50.18; H, 6.32; N, 4.88; P, 10.78. Found: C, 50.11; H, 6.28; N, 4.86; P, 10.95.

Schmidt Reaction of 11e in the Presence of Diethyl Phosphite. The same method and quantities were used as in the reaction of **11e**, except that an equimolar amount (0.04 mol) of redistilled diethyl phosphite was added to the reagent mixture prior to its addition to sulfuric acid. The usual workup afforded 2.7 g (51%) of **17e**, as well as 4.7 g (45%) of **13e**. Fractions A and B were subjected to TLC, and no sign of the crossover product **13f** could be detected (in comparison with an authentic sample).

Schmidt Reaction of 11f in the Presence of Dimethyl Phosphite. The reaction was run as described for **11f**, with the addition of 0.04 mol of dimethyl phosphite to the reagent mixture prior to addition to the acid. **17e** (2.9 g, 54%) and **13f** (3.5 g, 31%) were isolated. No trace of **13e** was found in the TLC of fraction B.

Schmidt Reaction of 11g. **11g** (6.53 g 0.024 mol) and 19.4 mL of a 1.35 N hydrazoic acid solution (0.0252 mol) were made up to a total volume of 55 mL using chloroform. The solution was added over 5 min to a mixture of 18.8 mL of H_2SO_4 and 56 mL of chloroform. A total of 4.133 g of fraction A was obtained, one quarter of which was separated by chromatography. First was eluted 30 mg of ethyl *m*-methoxybenzoate (3%), identified by its IR and ^{1}H NMR spectra: ^{1}H NMR δ 1.38 (t, 6H, J=7, CH_3CH_2), 3.82 (s, 3H, CH_3O), 4.15 (q, 4H, J = 7, CH_2), 7.30 (m, 4H, arom); IR (film) ν 1715. This was followed by 47 mg (6%) of **17g**: ^{1}H NMR δ 3.80 (s, 3H, CH_3O), 7.25 (m, 4H, arom); IR (film) ν 2215. Third was eluted 0.52 g of *m*-methoxyformanilide (**15g**), identified by spectral comparison with an authentic sample.

Fraction B (381 mg) upon chromatography yielded first an additional 50 mg of **15g** (total yield 59%). The following fraction was a mixture of **13g** and **14g**, a total of 191 mg, containing (by NMR integration) 70% of the former and 30% of the latter (yields 2 and 0.8%, respectively). **13g** and **14g** were isolated from this mixture by fractional crystallization from methanol: first crystallized **14g**, and **13g** crystallized from the mother liquor after being cooled in an acetone–dry ice bath and seeded with the authentic material (preparation below). **14g** had mp 116–117.5 °C: ^{1}H NMR δ 1.38 (t, 6H, J = 7, CH_3CH_2), 3.76 (s, 3H, CH_3O), 4.22 (qt, 4H, J = 7, CH_2), 7.90 (br s, 1H, N*H*), 8.90 (s, 1H, N*H*); IR (KBr) ν 3320, 3180, 2960, 2880, 1690, 1597, 1550, 1220, 1155, 1045; MS (*m/e*) 302 (6, $M^{\cdot+}$), 287 (17), 180 (6, $[CONHPO(OEt)_2]^+$), 155 (12), 154 (14), 152 (90, $[NHPO(OEt)_2]^+$), 150 (12, $[MeOC_6H_4NHCO]^+$),149 (10, $[MeOC_6H_4NCO]^{\cdot+}$), 135 (28, $[MeOC_6H_4CO]^+$), 134(13), 124(100), 123(90, $[MeOC_6H_4NH_2]^{\cdot+}$), 107(36, $[MeOC_6H_4]^+$), 106 (34), 94 (28), 93 (22). Anal. Calcd for $C_{12}H_{19}N_2O_5P$: C, 47.68; H, 6.34; N, 9.27; P, 10.25. Found: C, 47.40; H, 6.25; N, 9.10; P, 10.39.

Fraction C consisted of 270 mg (8.5% yield) of **16g**, identified by its NMR and IR spectra: ^{1}H NMR δ 3.53 (s, 2H, NH_2), 3.76 (s, 3H, CH_3O), 6.32 (m, 3H, arom), 7.06 (t, 1H, J = 8, arom H_5); IR (film) ν 3410, 3340, 2940–2910, 2815, 1625, 1600, 1490.

Diethyl *m*-Methoxybenzoylphosphoramidate (13g) and Dimethyl *m*-Methoxybenzoylphosphoramidate. These were prepared as described above from 3.1 g (0.0205 mol) of *m*-methoxybenzamide and 4.6 g (0.022 mol) of PCl_5. One half of the intermediate mixture was reacted with a solution prepared from 1.2 g of sodium and 30 mL ethanol and the other with a solution prepared from 1.2 g of sodium and 30 mL of methanol. From the first portion, 2.3 g (39% yield) of **13g** was isolated, mp 79–81 °C (from methanol–water): ^{1}H NMR δ 1.37 (t, 6H, J = 7, CH_3CH_2), 3.86 (s, 3H, CH_3O), 4.24 (qt, 4H, J = 7, CH_2), 7.40 (m, 4H, arom), 9.64 (d, 1H, J_{PH} = 8, N*H*); IR (KBr) ν 3160, 2965, 2840, 2815, 1680, 1595, 1585, 1270, 1240, 1180, 1155, 1035. Anal. Calcd for $C_{12}H_{18}NO_5P$: C, 50.18; H, 6.32; N, 4.88, P, 10.78. Found: C, 50.10; H, 6.23; N, 4.85; P, 10.70.

From the second portion, 3.2 g (60%) of the dimethyl homologue was obtained, mp 88.5–90 °C (from methanol–water): ^{1}H NMR δ 3.86 (s, 3H, CH_3OC), 3.87 (d, 6H, J_{PH} = 12, CH_3OP), 7.40 (m, 4H, arom), 9.55 (br s, 1H, N*H*); IR (KBr) ν 3170, 2940, 2830, 2810, 1680, 1600, 1590, 1255, 1180, 1065, 1040. Anal. Calcd for $C_{10}H_{14}NO_5P$: C, 46.34; H, 5.44; N, 5.40; P, 11.95. Found: C, 46.16; H, 5.38; N, 5.45; P, 12.04.

Schmidt Reaction of 11h. Hydrazoic acid (0.0252 mol) was reacted with 6.864 g (0.024 mol) of **11h** in the usual manner. Fraction A consisted of 1.81 g (51% yield) of **17h**, mp 90–92 °C (from methanol), identified by its NMR and IR spectra: ^{1}H NMR δ 6.03 (s, 2H, CH_2), aromatic H, 6.99 (d, 1H, J_{H2-H6} = 2, H_2), 6.83 (d, 1H, J_{H5-H6} = 8, H_5), 7.17 (dd, 1H, J_{H5-H6} = 8, J_{H2-H6} = 2, H_6); IR (KBr) ν 2205, 1610, 1590.

Fraction B consisted of pure (according to NMR spectrum) diethyl 3,4-(methylenedioxy)benzoylphosphoramidate (**13h**), 2.00 g (28% yield), mp 161–162 °C (needles, from ethanol): ^{1}H NMR δ 1.35 (t, 6H, J = 7, CH_3), 4.25 (split qt, 4H, J = 7, CH_3CH_2), 6.01 (s, 2H, CH_2O_2), aromatic H, 6.82 (d, 1H, J_{H5-H6} = 8, H_5), 7.60 (d, 1H, J_{H2-H6} = 2, H_2), 7.71 (dd, 1H, J_{H5-H6} = 8, J_{H2-H6}=2, H_6), 9.40 (br s, 1H, NH); IR (KBr) ν 3120, 2960, 2880, 1665, 1610, 1500, 1230, 1250, 1150, 1035; MS (*m/e*) 301 (55, M^{+}), 180 (9), 165 (17, $[CH_2O_2C_6H_3NH_2]^{+}$), 154 (35), 152 (14), 149 (100, $[CH_2O_2C_6H_3CO]^{+}$), 148 (21), 147 (17), 146 (10), 127 (47), 126 (14), 124 (26), 121 (25). Anal. Calcd for $C_{12}H_{16}NO_6P$: C, 47.85; H, 5.35; N, 4.65; P, 10.28. Found: C, 47.74; H, 5.34; N, 4.59; P, 9.20.

In fraction C, 63 mg of an unidentified mixture remained.

Schmidt Reaction of 11i. The usual reaction conditions were applied to 9.06 g (0.03 mol) of **11i**. From fraction A, 5.55 g of **17i** was first crystallized (2.60 g) using methanol. It had mp 114–116 °C (lit.[49] mp 118 °C from ethanol): ^{1}H NMR δ 3.88 (s, 6H, CH_3), 6.54 (d, 2H, J_{H3-H4} = 8, arom H_3, H_5), 7.43 (t, 1H, J = 8, arom H_4); IR (KBr) ν 3088, 2963, 2825, 2200, 1595, 1580. The remaining mother liquor, after removal of solvent, weighed 2.92 g, of which one third was chromatographed. First was eluted an additional 143 mg of **17i**, bringing the total yield of **17i** up to 62%. This was followed by 503 mg (17%) of unreacted starting material.

Fraction B contained 110 mg of unidentified materials, whereas essentially nothing remained in fraction C.

Schmidt Reaction of 11j. The reaction was carried out using 1.7 g (0.006 mol) of **11j**, 0.007 mol of hydrazoic acid, and 4.6 mL of sulfuric acid. After the usual workup, 1.287 g (76%) of unreacted **11j** was obtained in A (IR and ^{1}H NMR). No residue was found in B, and C consisted of 130 mg of an oil identified as 2,4,6-trimethylaniline (**16j**), pure by NMR standards (16% yield): ^{1}H NMR δ 2.20 (s, 6H, 2,6-diCH_3), 2.27 (s, 3H, 4-CH_3), 3.30 (s, 2H, NH_2), 6.82 (s, 2H, arom); IR (film) ν 3420, 3340, 2970, 2940, 2885, 2830, 1618, 1595, 1490.

The reaction was repeated with 1.2 g (0.0042 mol) of **11j** and 0.0052 mol of hydrazoic acid for 20 h at ambient temperature. In fraction A there were 63 mg of a complex (unidentified) mixture, as determined from the NMR spectrum. No significant residue was found in B, and C consisted again of pure **16j**, 241 mg (43%).

Schmidt Reaction of 11k. The reaction of 9 g (0.03 mol) of **11k**, 0.0315 mol of hydrazoic acid, and 23.2 mL of sulfuric acid was carried out in the usual manner, with the exception that it was allowed to proceed for 1 h in an ice bath. Fraction A was identified as unreacted **11k** (4.2 g, 47%). No residue was found in B, and C was identified as 2,6-dimethyl-4-methoxyaniline (**16k**), 2.271 g (50% yield), pure by NMR: ^{1}H NMR δ 2.18 (s, 6H, CH_3C), 3.13 (br s, 2H, NH_2), 3.73 (s, 3H, CH_3O), 6.58 (s, 2H, arom); IR (film) ν 3410, 3340, 2900, 2810, 1628, 1600, 1490.

Schmidt Reaction of 11l. A chloroform solution (70 mL) containing 8.64 g (0.048 mol) of **11l** and 0.0504 mol of hydrazoic acid was allowed to react with 37.5 mL of H_2SO_4 in 112.5 mL of chloroform in the usual manner. Fraction A weighed 955 mg and was separated by chromatography. First a white solid was separated, 40 mg (0.7%), identified as *N*-isopropylisobutyramide, mp 103–104 °C (lit.[50] mp 102 °C): ^{1}H NMR δ 1.09 (d, 6H, J = 7, CH_3C), 2.16 (septet, 1H, CHCO), 4.01 (m, 1H, CHNH), 5.56 (br s, 1H, NH); IR (KBr) ν 3265, 2945, 2900, 2845, 1633, 1535, 1455, 1355, 1235. Second was eluted 280 mg of *N*-isopropylformamide (**15l**), identified by spectral comparison with an authentic sample prepared from formic acid and isopropylamine. Finally there eluted 65 mg (0.5%) of **19l**: ^{1}H NMR δ 1.05, 1.08 (two d, 6H, J = 7, CH_3CH), 2.27 (m, 1H, CH_3CH), 3.745, 3.76 (two d, 6H, J_{PH} = 11.5, C–PO-$(OCH_3)_2$), 3.77 (d, 6H, J_{PH} = 11.0, OPO$(OCH_3)_2$), 4.52 (ddd, 1H, J_{HH} = 4.3, J_{POCH} = 8.5, J_{PCH} = 11.2, PCH); MS (*m/e*) 290 (0.3, M^{+}), 275 (5, [M – Me]$^{+}$), 259 (2), 248 (5), 235 (2), 219 (11), 218 (18), 188 (8), 187 (8), 181 (100, [M - PO$(OMe)_2]^{+}$), 173 (5), 164 (32, [M - HOPO-$(OMe)_2]^{+}$), 149 (8), 127 (84), 110 (16, $[HPO(OMe)_2]^{+}$), 109 (37, [PO-$(OMe)_2]^{+}$), 93 (29), 79 (28).

Fraction B contained 280 mg of unidentified material. Fraction C was identified as **15l**, 2.1 g. The total yield of **15l** in this reaction was 57%.

(49) De Bruyn, L. *Recl. Trav. Chim.* **1883**, *2*, 205–235.
(50) LaPlanche, L. A.; Rogers, M. T. *J. Am. Chem. Soc.* **1964**, *86*, 337–341.

Control Experiments. Schmidt Reaction of Diethyl Benzylphosphonate. Diethyl benzylphosphonate was prepared by the Arbuzov reaction between benzyl chloride and triethyl phosphite and was collected at 190 °C (20 Torr). The Schmidt reaction was run in the manner used for the arenecarbonylphosphonates, by dropwise addition of a solution prepared from 5.47 g (0.024 mol) of diethyl benzylphosphonate and 0.0252 mol of hydrazoic acid in chloroform (volume made up to 55 mL by the addition of solvent) into a cold solution of 18.75 mL of H_2SO_4 and 56 mL of chloroform. After the usual workup, 5.3 g of the starting material was isolated in fraction A, while no significant residue was found in B or C.

Schmidt Reaction of Diethyl Phenylphosphonate. Diethyl phenylphosphonate (5.134 g, 0.024 mol) was subjected to the same reaction conditions and quantities as described in the previous experiment. The unchanged starting material was quantitatively (5.20 g) isolated from fraction A, as identified by its IR and NMR spectra.

Stability of 11b to Sulfuric Acid. 11b (2.2 g) was allowed to react under the regular Schmidt reaction conditions without the hydrazoic acid. After 30 min of being stirred at ambient temperature under nitrogen, the reaction mixture was poured over ice, the organic layer was separated, washed with $NaHCO_3$ solution, and dried, and the solvent was removed. The remaining liquid (2.3 g) had identical IR and NMR spectra to those of the starting material. The sodium bicarbonate washings were combined and acidified, but no significant product was found.

Stability of 11b to Hydrazoic Acid. A solution of 2.0 g (0.007 mol) of **11b** and 0.0084 mol of hydrazoic acid in 19 mL of chloroform was stirred at ambient temperature for 1 h, following which the solvent was removed under reduced pressure. The IR and NMR spectra of the residue were identical to those of the starting material.

Stability of 13e to Sulfuric Acid. Two hundred milligrams of **13e** was reacted under the normal Schmidt reaction conditions in the absence of hydrazoic acid. Unreacted starting material (189 mg) was isolated from fraction B, whereas practically no residue was found in fractions A and C.

Stability of 13f and 13b to Sulfuric Acid. The same test was applied to **13f** and **13b**. **13f** was isolated in near quantitative yield from fraction B. During workup of the reaction with **13b**, its sodium salt separated and interfered with the extractions. The reaction was repeated using larger volumes of solvents for extraction to avoid crystallization. Unreacted **13b** was isolated from fraction B.

Stability of 12b to Sulfuric Acid. A solution composed of 85 mg of **12b**, 0.25 mL of sulfuric acid, and 2 mL of chloroform was stirred in an ice bath for 1 h. After regular workup, 37 mg of unchanged **12b** was isolated from fraction A. Nothing could be isolated from the other fractions. Despite the loss of material, this experiment proves that **12b** is not an intermediate in the formation of *p*-chloroformanilide (**15b**), as the latter was not detected in either fraction A or B.

Stability of 12a to Sulfuric Acid. The stability of 200 mg of **12a** toward sulfuric acid was tested in the manner described in the previous experiment. Unchanged starting material (125 mg) was isolated from fraction A, while only negligible residues were found in fractions B and C. In none of the fractions could a trace of formanilide be detected.

Feasibility of Formation of 14a by a Second Schmidt Reaction of 12a. The usual Schmidt reaction was done on 2.76 g (0.01 mol) of **12a**. After workup, 1.175 g of **12a** was isolated from A, identified by its IR and NMR spectra. An additional 10 mg of **12a** was isolated from C. Three milligrams of an unidentified material was found in fraction B. However, its IR spectrum was incompatible with that of **14a**.

Feasibility of Formation of 14a by a Second Schmidt Reaction of 13a. **13a** (312 mg, 0.001 25 mol) was subjected to the usual Schmidt reaction conditions. After workup, 265 mg of the starting material **13a** was isolated from fraction B. No traces of possible **14a** could be detected in the NMR spectrum of the isolated material.

Solubility of Formanilide (15a) in 10% Sodium Hydroxide Solution. The appearance of several formanilides in fraction B, in addition to their abundance in the neutral fraction A, raised the question of whether formanilides are soluble in alkaline solution or whether they could be formed during workup by hydrolysis of other products present in B. One gram of formanilide was dissolved in 10 mL of chloroform and shaken in a separatory funnel with 10 mL of a 10% NaOH solution. After separation of the layers, 890 mg of **15a** was isolated from the organic layer, and 76 mg was separated from the aqueous layer after acidification followed by two chloroform extractions, drying over $MgSO_4$, and removal of the solvent.