Photochemical Deoxygenation of Aromatic Nitro Compounds in Triethyl Phosphite. Substituent Effects and Evidence for the Involvement of Aryl Nitrenes[1a]

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Abstract: Nitrobenzene and substituted nitrobenzenes are deoxygenated at 30 ± 5° when irradiated in triethyl phosphite solution. Triethyl phosphite is oxidized to triethyl phosphate and the deoxygenated nitro compound is converted to the corresponding triethyl N-arylphosphorimidate and to the aniline derivative. When the nitrobenzene is substituted with an *o*-alkyl group, rearranged products containing the pyridine ring are also found. Deoxygenation in the presence of diethylamine generates 2-diethylamino-3H-azepines. The mechanism of these transformations are discussed and evidence that aryl nitrenes are intermediates is put forward.

The photochemistry of aromatic nitro compounds has been of substantial recent interest. Among the general reaction types which have been recognized are hydrogen abstraction and other reduction processes,[2] aromatic substitutions,[3] as well as cyclizations and cycloadditions.[4] Reviews of the earlier work on nitroaromatic photochemistry are available.[5] In this paper we describe a study of the irradiation of substituted nitrobenzenes in triethyl phosphite. At room temperature photoinitiated oxygen-transfer reactions take place generating triethyl phosphate and deoxygenated intermediates derived from the nitrobenzenes. We have found this reaction to be quite general, and we focus attention here primarily on the fate of the reactive deoxygenated intermediate. Photochemical deoxygenations of aromatic nitro compounds have been reported from at least two other laboratories. Taylor and Garcia[6] briefly examined photochemical deoxygenation as an alternative to a thermal deoxygenation for the synthesis of 1,3-dimethyl-6-(*p*-methoxyphenyl)-5H-2,4-(1H,3H)-pyrrolo[3,2-*d*]pyrimidinedione from 1,3-dimethyl-5-nitro-6-(*p*-methoxy)styryluracil. Obrycki and Griffin[7] observed photochemical deoxygenation of nitrobenzenes during their investigation of photochemical arylation of triethyl phosphite, but the systems which they studied failed to yield characterizable products from the deoxygenated nitro compound.

Results

Our standard procedure for deoxygenation involved subjecting a solution of 0.10 mol of the aromatic nitro compound in approximately 1 mol of triethyl phosphite to irradiation from a 200-W Hanovia mercury lamp (filtered through Pyrex) for a 12-hr period. The solution was maintained at 30 ± 5° by cooling water which passed through an immersion well containing the lamp. Three different procedures for isolation of products have been employed. Method A involved fractional distillation and analysis of the various fractions by nmr. Table I records the amount of nitro compound recovered and yields of products. In all cases in which the yield of triethyl phosphate was quantitatively estimated it was within ±10% of the amount anticipated for formation of 2 mol of triethyl phosphate/mol of nitro compound deoxygenated. The higher boiling fractions in general consisted of mixtures of triethyl N-arylphosphorimidates and, from *o*-methylnitrobenzenes, substituted acetimidylpyridines. These components could not be separated by fractional distillation but the nmr spectra of the mixtures normally permitted quantitative estimation of the ratio of the two products (see Scheme I).

N-(*o*-Tolyl)-2-acetimidylpyridine (**3b**) has been characterized earlier in this laboratory[8] as a product of the chemical deoxygenation of *o*-nitrosotoluene at 0° and during that work it was synthesized from 2-acetylpyridine and *o*-toluidine. Its presence in the high-boiling product from the photochemical deoxygenations of *o*-nitrotoluene was established in several ways. Both the infrared and nmr spectra of the mixture showed peaks characteristic of **3b**, as well as of the phosphorimidate **2b**. Examination of the high-boiling product mixture by glpc shows two principal peaks corresponding in retention time with authentic **2b** and **3b**. Reduction of the product mixture with sodium borohydride followed by isolation and purification of the basic product gave 2-[1-(2-methylanilino)ethyl]-

(1) (a) This work was supported by National Institutes of Health Grant GM-14344. Preliminary communication: R. J. Sundberg, W. G. Adams, R. H. Smith, and D. E. Blackburn, *Tetrahedron Letters*, 777 (1968). (b) National Defense Education Act Fellow, 1966–present.

(2) R. Hurley and A. C. Testa, *J. Am. Chem. Soc.*, **89**, 6917 (1967); G. A. Russell and E. J. Geels, *Tetrahedron Letters*, 1333 (1963); E. T. Strom and J. Weinstein, *J. Org. Chem.*, **32**, 3705 (1967); V. I. Stenberg and D. J. Holter, *ibid.*, **29**, 3420 (1964); J. T. Pinhey and E. Rizzardo, *Chem. Commun.*, 362 (1965); R. L. Ward, *J. Chem. Phys.*, **38**, 2588 (1963); R. E. McMahon, *Tetrahedron Letters*, 2307 (1966); A. J. Tench and P. Coppens, *J. Phys. Chem.*, **67**, 1378 (1963).

(3) O. L. Chapman, D. C. Heckert, J. W. Reasoner, and S. P. Thackaberry, *J. Am. Chem. Soc.*, **88**, 5550 (1966); C. S. Foote, P. Engel, and T. W. Del Pesco, *Tetrahedron Letters*, 2669 (1965); A. van Vliet, M. E. Kronenberg, and E. Havinga, *ibid.*, 5957 (1966); R. L. Letsinger and G. G. Wubbels, *J. Am. Chem. Soc.*, **88**, 5041 (1966); R. L. Letsinger, and J. H. McCain, *ibid.*, **88**, 2884 (1966); R. L. Letsinger and O. B. Ramsay, *ibid.*, **86**, 1447 (1964).

(4) M. L. Scheinbaum, *J. Org. Chem.*, **29**, 2200 (1964); E. C. Taylor, B. Furth, and M. Pfau, *J. Am. Chem. Soc.*, **87**, 1400 (1965); D. J. Neadle and R. J. Pollitt, *J. Chem. Soc.*, 1764 (1967).

(5) P. de Mayo and S. T. Reid, *Quart. Rev.* (London), **15**, 393 (1961); O. L. Chapman, *Advan. Photochem.*, **1**, 323 (1963).

(6) E. C. Taylor and E. E. Garcia, *J. Org. Chem.*, **30**, 655 (1965).

(7) R. Obrycki and C. E. Griffin, *ibid.*, **33**, 632 (1968).

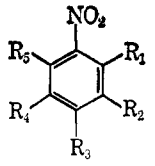
(8) R. J. Sundberg, *J. Am. Chem. Soc.*, **88**, 3781 (1966).

Table I. Products of Photochemical Deoxygenation

Nitro compd	% deoxygenated[a,b]	Yields,[c] % 2 (method A)	3 (method A)	5 (method B or C)	6 (method B)	7 (method B or C)
1a	73	~1	0	<1 (B)	0	
1b	52	23	24	5 (B)	7	13 (B)
1c	65	<3	0	3 (B)	0	12 (B)
1d	72	13	38	3 (B)	22	15 (B)
1e	76	53	16[d]	27 (B)	5	7 (B)
1f	67	40	6[d]	18 (B)	4	8 (B)
1g	52[e]	<3[e]	0[e]			
1h	67	>9[f]	6[d,e]	14 (B)[e]	8	8 (B)
1i	60				9[e]	11 (B)[e]
1j	59			26 (B), 26 (C)		13 (B)
1k	72	40	0	19 (C)		13 (C)
1l	43			40 (C)		9 (C)
1m	33[e]			4 (C)[e]		Trace (C)
1n	42[e]			31 (C)[e]		
1o	48[e]			22 (C)[e]		
1p	54[e]			28 (C)[e]		11 (C)

[a] For a 12-hr irradiation period. [b] Average of two or more comparable runs. [c] Based on amount of nitro compound deoxygenated. [d] Nmr integration was impractical as an analytical tool because of the small amount of **3** present. Yield recorded is the yield calculated from the amount of 2-acetylpyridine found after hydrolysis of the distilled product. [e] Single run. [f] A third product in addition to **2h** and **3h** in the distillate presents more precise determination of the yield.

Scheme I

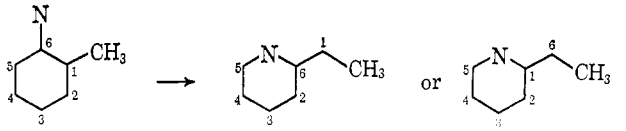


Compd	R_1	R_2	R_3	R_4	R_5
1a	H	H	H	H	H
1b	CH_3	H	H	H	H
1c	H	H	CH_3	H	H
1d	CH_3	CH_3	H	H	H
1e	CH_3	H	CH_3	H	H
1f	CH_3	H	H	CH_3	H
1g	H	CH_3	CH_3	H	H
1h	CH_3	H	CH_3	H	CH_3
1i	CH_3	Cl	H	H	H
1j	OCH_3	H	H	H	H
1k	H	H	OCH_3	H	H
1l	CO_2CH_3	H	H	H	H
1m	H	CO_2CH_3	H	H	H
1n	H	H	CO_2CH_3	H	H
1o	CN	H	H	H	H
1p	H	H	CN	H	H
1q	$CH_2CH_2CH_3$	H	H	H	H

pyridine (**4b**) which was identified by direct comparison with a sample of **4b** which had been prepared in previous work.[8] A similar reduction of the deoxygenation product from **1e** gave the analogous product 2-[1-(2,4-dimethylanilino)ethyl]-4-methylpyridine (**4e**). Finally, when the crude reaction product was treated with 10% hydrochloric acid, it was possible to isolate diethyl N-(*o*-tolyl)phosphoramidate (**5b**), 2-acetylpyridine (**6b**), and *o*-toluidine (**7b**), each of which was identified by spectral comparison with an authentic sample. Treatment of triethyl N-arylphosphorimidates with acids is known[8,9] to give rise to the corresponding phosphoramidate and **6b** and **7b** are expected to arise from hydrolysis of **3b**.

The direct acid-catalyzed hydrolysis of the crude deoxygenation mixture after removal of triethyl phosphate and unreacted nitro aromatic by distillation proved to be a valuable alternative method for processing the reaction mixture (method B). The yields of substituted 2-acetylpyridines, anilines, and phosphoramidates obtained by this method are recorded in Table I. The yields of phosphoramidates are lower than the yields of phosphorimidates isolated by direct distillation. This probably reflects losses both by hydrolysis and during subsequent purification.[10]

The 2-acylpyridines **6b**, **6d–f**, **6h,i**, and **6q** and the substituted anilines **7b**, **7d–f**, **7h,i**, and **7q** isolated from the acidic hydrolysis solution were separated by preparative gas chromatography. In order to establish the structural relationship between the deoxygenated nitrobenzene and the rearranged 2-acetylpyridines, it was necessary to establish the position of the substituents on the pyridine ring. The nmr spectrum of 2-acetylpyridine (**6b**) has been fully assigned.[11] By comparing the nmr spectrum of the various 2-acetylpyridines with that of **6b** it was possible to arrive at tentative structural assignments for **6d–f**, **6h,i**, and **6q**. These assignments were confirmed in the case of **6d–f** by synthesizing authentic samples of the 2-acetylpyridines by the method of Case and Kasper.[12] The structures of **6d–f** and **6h,i** established that the net course of the skeletal rearrangement must be as shown schematically below, and that it must involve, as a minimum, two 1,2 shifts.[13]



A third work-up procedure (method C) involved removal of the triethyl phosphite and triethyl phosphate

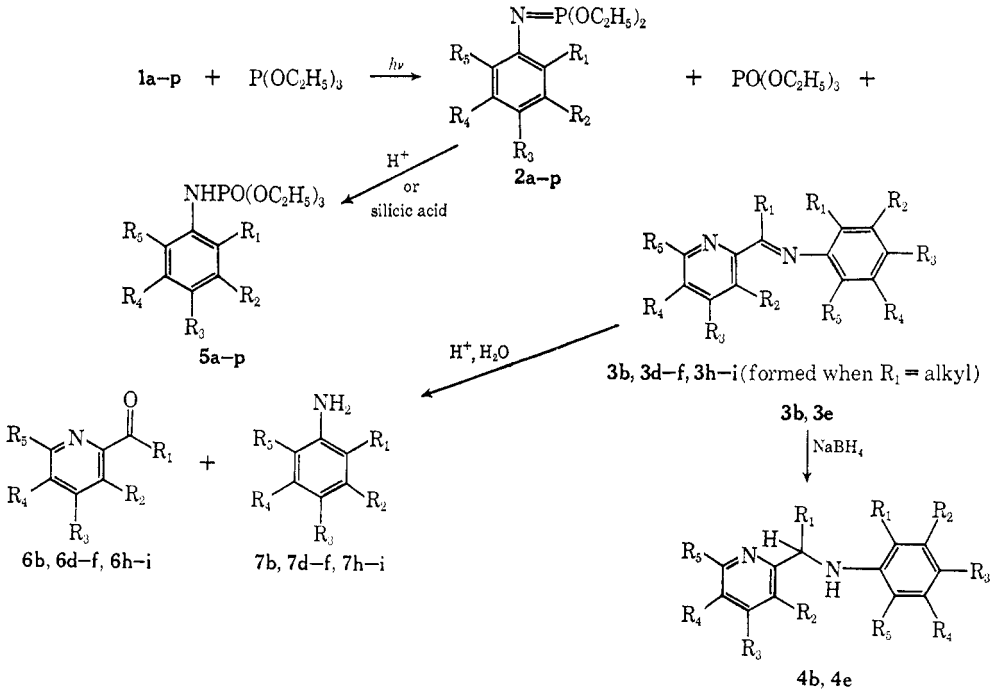
(9) M. I. Kabachnik and V. A. Gilyarov, *Izv. Akad. Nauk SSSR, Otd. Khim. Nauk*, 790 (1956); *Chem. Abstr.*, **51**, 1823 (1957).

(10) A. W. Garrison and C. E. Boozer, *J. Am. Chem. Soc.*, **90**, 3486 (1968).

(11) W. Brugel, *Z. Elektrochem.*, **66**, 159 (1962); V. J. Kowalewski and D. G. de Kowalewski, *J. Chem. Phys.*, **37**, 2603 (1962).

(12) F. H. Case and T. J. Kasper, *J. Am. Chem. Soc.*, **78**, 5842 (1956).

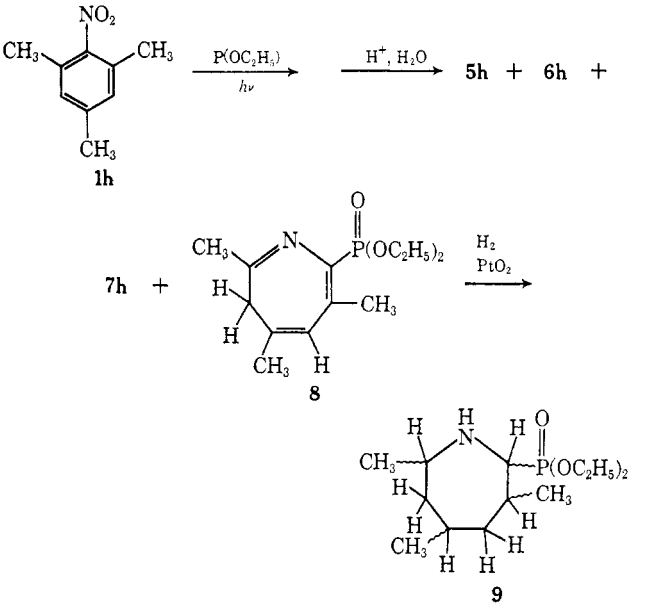
(13) Our previous speculation[8] concerning the mechanism of formation of **3b** from *o*-nitrosotoluene is, therefore, incorrect since it predicts a different structural change.



by vacuum distillation followed by chromatography on silicic acid. Silicic acid effects the conversion of triethyl N-arylphosphorimidates to diethyl N-arylphosphoramidates[8,14] and the phosphoramidate can then be eluted from the column, usually in a rather pure state. The yields of diethyl N-arylphosphoramidates obtained in this manner are also recorded in Table I. Phosphoramidates **5l–n** were identified by spectral comparison with authentic samples.

2-Nitromesitylene (**1h**) gave in addition to **2h** and **3h** a basic, high-boiling liquid which was isolated along with **6h** and **7h** from the acidic hydrolysis of the crude reaction mixture. The infrared and nmr spectra of this compound (**8**) indicated the presence of a diethoxyphosphoryl group and elemental analysis and mass spectrometry established the molecular formulas as $C_{13}H_{22}NO_3P$. A single proton appears as a doublet (J = 5 Hz) at 5.97 ppm. The multiplicity and chemical shift are inconsistent with this being a proton attached to a 1,2,3,5-tetrasubstituted aromatic ring and, thus, indicates that **8** contains a rearranged fragment of **1h**. The spectral and analytical data are consistent with assigning **8** the structure diethyl 2-(3,5,7-trimethyl-6H-azepinyl)phosphonate.[15] Catalytic reduction of **8** over platinum oxide gives **9**, $C_{13}H_{28}NO_3P$ (see Scheme II). The infrared spectrum of **9** shows a sharp peak at 3300 cm^{-1} indicative of an NH group. The methyl peaks in the nmr spectrum are split and there are no signals downfield of the ethoxy quintet at 4.06 ppm. At 3.06 ppm there is a signal integrating for one proton having a doublet of doublets structure (J = 6, 25 Hz). We assign this signal to the proton at C-2 of diethyl 2-(3,5,7-trimethylhexahydroazepinyl)phosphonate. We assign the couplings of 6 and 25 Hz to coupling with the proton at C-3 and to phosphorus, respectively. This signal provides evidence that the diethoxyphosphoryl group is attached to C-2. If it were on C-4 or C-6 the signal for the proton would be expected to show a doublet of triplets pattern. The stereochemistry of

Scheme II



(14) R. J. Sundberg, *J. Org. Chem.*, **30**, 3604 (1965).

(15) The 5-Hz splitting of the vinyl proton must arise from coupling with phosphorus. The magnitude of the coupling seems most consistent with formulating **8** as the 6H tautomer in preference to the 4H tautomer. In the absence of closely related models, however, we cannot completely rule out the 4H tautomer.

9 is potentially very complex. Our sample was readily crystallized and shows normal melting point behavior suggesting that the reduction has led preferentially to a single stereoisomer.

We have previously described the conversion of certain nitrobenzenes to N-arylphosphorimidates by thermal deoxygenation in triethyl phosphite.[8,14] It was of interest to compare the behavior of certain of the nitro compounds toward photochemical and thermal deoxygenation. Table II records the yields of triethyl

Table II. Yields of Triethyl N-Arylphosporimidates by Thermal Deoxygenation

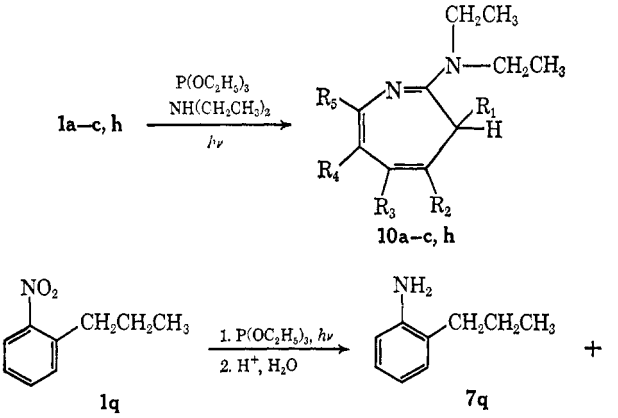
Nitro compd	Triethyl N-arylphosphor-imidate, %	Nitro compd	Triethyl N-arylphosphor-imidate, %
1a	<5[a]	**1e**	77
1b	64[a]	**1f**	68
1c	42	**1g**	60
1d	79	**1h**	67[b]
		1k	46[c]

[a] Reference 8. [b] A 19% yield of **8** is also isolated. The nmr spectrum of the crude product suggests that some diethyl N-(2,4,6-trimethylphenyl)-N-ethylphosphoramidate is present in the distilled product. [c] The nmr spectrum suggests that some diethyl N-(4-methoxyphenyl)phosphoroamidate is present.

N-arylphosphorimidates isolated by distillation of thermal deoxygenation mixtures.

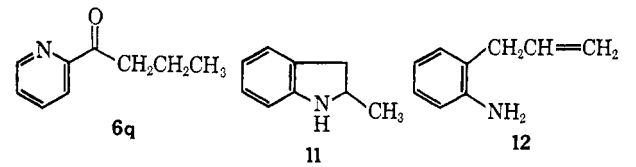
No evidence was found for the formation of the rearranged products **3b** and **3d** in the thermal deoxygenation of **1b** and **1d**, respectively. The crude product from **1b** was subjected to acidic hydrolysis but no 2-acetylpyridine was present in the hydrolysis product. The nmr spectrum of the **2d** obtained by thermal deoxygenation of **1d** showed none of the peaks characteristic of **3d**. The azepinylphosphonate **8** was formed in 19% yield from the thermal deoxygenation of **1h**.

The isolation of 3H-azepines has been observed when phenyl nitrene is generation in the presence of amines by pyrolysis[16] or photolysis[17] of phenylazide, by deoxygenation of nitrosobenzene[18] or nitrobenzene,[19] or by photolysis of 3,3-disubstituted-2-phenyloxaziridines.[20] In order to use azepine formation as a probe for the formation of aryl nitrenes during photochemical deoxygenation, we have irradiated solutions of **1a**, **1b**, **1c**, and **1h** in triethyl phosphite containing diethylamine. In each case a 2-diethylamino-3H-azepine (**10a**, **10b**, **10c**, and **10h**) has been detected. 2-Diethylamino-3H-azepine (**10a**) has been characterized previously[16-18] and it was isolated in 10% yield (nmr analysis prior to complete purification of **10a** indicated a 22% yield) from a deoxygenation carried out in a solution containing about 20% by volume diethylamine. The identity of the product was established by comparison with published spectral data. The structure of the



azepine formed from *o*-nitrotoluene (**1b**) was of particular interest since either 2-diethylamino-3-methyl-3H-azepine or 2-diethylamino-7-methyl-3H-azepine or both could conceivably have been formed. The nmr spectrum of the isolated product showed that the 3-methyl derivative **10b** was formed. The most significant features of the spectrum are the appearance of the methyl signal as a doublet at 0.65 ppm and of a single-proton doublet at 6.9 ppm. The latter signal shows the same chemical shift and multiplicity as the proton at C-7 of **10a**. The ultraviolet spectrum of **10b** was very similar to that of **10a** indicating the presence of identical chromophores in the two compounds. The yield of **10b** by nmr analysis was 8%. The nmr spectrum (see the Experimental Section) of the azepine derived from **1c** confirms that it is the expected 2-diethylamino-5-methyl-3H-azepine (**10c**). The yield of **10c** was 34% by nmr analysis and an 18% yield was isolated. 2-Diethylamino-3,5,7-trimethyl-3H-azepine (**10d**) was formed in about 3% yield from the deoxygenation of 2-nitromesitylene in the presence of diethylamine. Compound **10d** was isolated and purified by preparative gas chromatography. Its structure follows from elemental analysis and spectral data recorded in the Experimental Section.

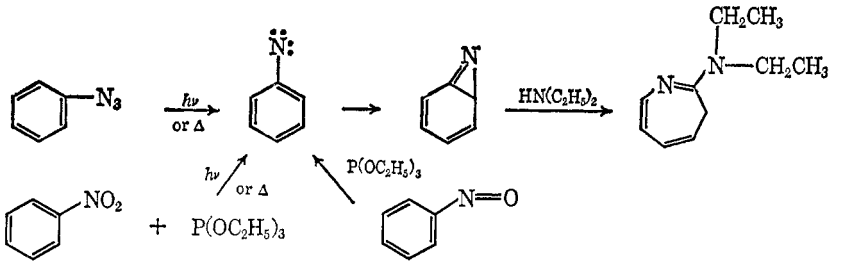
o-Nitropropylbenzene was deoxygenated under the standard conditions and subjected to hydrolytic work-up. The basic fraction from the hydrolysis gave a mixture containing *o*-propylaniline (**7q**, 14% yield) and 2-butyrylpyridine (**6q**, 9% yield). No traces of the potential C–H insertion product 2-methylindoline (**11**) or the intermolecular hydrogen abstraction product *o*-allylaniline (**12**) were detected under glpc conditions permitting the resolution of **11** and **12** from **7q** and **6q**.



(not formed)

Certain "crossover" type experiments were performed. Deoxygenation of *o*-nitrotoluene (**1b**) was carried out in the presence of added triethyl N-(2,4-dimethylphenyl)phosphorimidate (**2e**). The product of the reaction was reduced with sodium borohydride. The amine **4b** was isolated in 15% yield but no 2-[1-(2,4-dimethylanilino)ethyl]pyridine (**13**) was detected. The amine **13** would have been formed if the phos-

(16) R. Huisgen and M. Appl. *Chem. Ber.*, **91**, 12 (1958).
(17) W. von E. Doering and R. A. Odum, *Tetrahedron*, **22**, 81 (1966).
(18) R. A. Odum and M. Brenner, *J. Am. Chem. Soc.*, **88**, 2074 (1966).
(19) J. I. G. Cadogan and M. J. Todd, *Chem. Commun.*, 178 (1967).
(20) (a) E. Meyer and G. W. Griffin, *Angew. Chem. Intern. Ed. Engl.*, **6**, 634 (1967); (b) J. S. Splitter and M. Calvin, *Tetrahedron Letters*, 1445 (1968).



phorimidate **2e** had served as a source of the anilino fragment in the acetimidylpyridine product. The synthesis of **13** is described in the Experimental Section. It was shown to be detectable by glpc analysis in the presence of **4b**.

Equimolar amounts of nitrobenzene (**1a**) and 2,4-dimethylnitrobenzene (**1e**) were deoxygenated together. The crude product was reduced by sodium borohydride and investigated by glpc and column chromotography. The amine **4e** was found but 2-(2,4-dimethylanilinomethyl)pyridine (**15**) was not formed in significant amounts. Amine **15** was prepared independently and shown to be detectable by glpc. When mixtures of *o*-nitrotoluene (**1b**) and 2,4-dimethylnitrobenzene (**1e**) were deoxygenated and the crude product reduced by sodium borohydride, the amines **4b** and **4e** were detected by glpc as was the "crossover" product 2-[1-(2,4-dimethylanilino)ethyl]pyridine (**13**). The other "crossover" product, 2-(1-*o*-toluidinoethyl)-4-methylpyridine, was presumably also formed but an authentic sample of this compound was not available for comparison.

When *o*-tolyl azide was photolyzed in triethyl phosphate and the crude product was subjected to hydrolytic work-up only *o*-toluidine was found in the basic product. No trace of 2-acetylpyridine was found. Photolysis of *o*-tolyl azide in diethylamine gives the azepine **10b** in 31% yield.

Discussion

Two lines of evidence have been cited to support the hypothesis that aryl nitrenes are intermediates in the thermal deoxygenation of aromatic nitro and nitroso compounds. The first of these is the formation of substantial amounts of 2-diethylamino-3H-azepine when nitrobenzene[19] and nitrosobenzene[18] are deoxygenated in the presence of diethylamine. Thermal or photochemical decomposition of phenyl azide in the presence of amines also results in the formation of azepines.[16,17] Thermal or photochemical azide decomposition is assumed to generate phenyl nitrene which is transformed to a new intermediate generally formulated as 7-azabicyclohepta[2.4.6]triene which serves as the precursor of the azepines.[16-19,20b,21,22] The fact that azepines **10a**, **10b**, **10c**, and **10h** are formed when **1a**, **1b**, **1c**, and **1h** are photochemically deoxygenated can then be taken as evidence for the involvement of aryl nitrenes as intermediates.

Thermal deoxygenation at about 150° of aromatic nitro compounds with appropriate *ortho* substituents leads to C–H insertion products.[8,24] The same C–H insertion products are obtained in higher yield by thermal decomposition of the corresponding azides.[8,24] Thermal decomposition of *o*-nitrosopropylbenzene or *o*-nitrosobutylbenzene at 0° does not lead to detectable amounts of insertion products although small amounts are apparently formed at 150°.[8] Photochemical deoxygenation of *o*-nitropropylbenzene at 30° led to no detectable amount of C–H insertion products. This result does not add any support to the hypothesis that aryl nitrenes are intermediates in the photochemical deoxygenation, but it is not unexpected in view of the lack of C–H insertion in nitroso deoxygenations at 0°. The fact that no significant amounts of insertion products are formed in the deoxygenations at lower temperatures suggests that the activation energies for C–H insertion and other irreversible transformations of *o*-propylphenyl nitrene are such that the C–H insertion reaction is competitive at 150° but not at 30° and below.

It should be noted that the photochemical deoxygenation of *o*-nitrotoluene at 30° rather closely parallels the thermal deoxygenation of nitrosotoluene at 0°. The formation of triethyl N-(*o*-tolyl)phosphorimidate (**2b**) and the imine **3b** in roughly equal amounts is observed in both cases.[8] A similar correspondence between the products of photochemical deoxygenation of **1e** and thermal deoxygenation of the corresponding nitroso compound has been noted. In each case the phosphorimidate **2e** is the predominant product, accompanied by lesser amounts of **3e**.[25] If the view that deoxygenation of aromatic nitroso compounds generates aryl nitrenes is accepted, the similarity of the course of the photochemical deoxygenations and nitroso aromatic deoxygenations supports the intermediacy of aryl nitrenes in the photochemical process. The product-determining step in photochemical deoxygenation of nitro aromatics may involve thermal deoxygenation of aromatic nitroso compounds generated in the reaction mixture by removal of one oxygen atom from the nitro group (Scheme III). There is no reason to expect that both oxygen atoms would be transferred simultaneously in a termolecular

(21) R. A. Abramovitch and B. A. Davis, *Chem. Rev.*, **64**, 149 (1964), and references therein.

(22) The existence of the 7-azabicycloheptatriene intermediate is unsupported by any physical evidence to date, although it has been widely invoked to explain the formation of azepines. The formation of such an intermediate has analogy in the formation of azirines from vinyl azides.[23] We also invoke this intermediate recognizing that other formulations of the rearranged species, for example, as 2-azacycloheptatrienylidene, are conceivable.

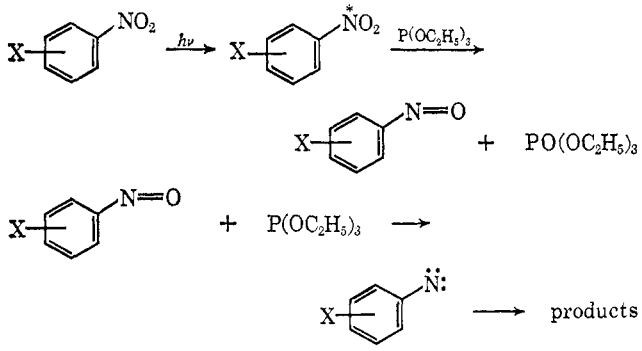
(23) A. Hassner and F. W. Fowler, *J. Am. Chem. Soc.*, **90**, 2869 (1968); G. Smolinsky, *J. Org. Chem.*, **27**, 3557 (1962).

(24) G. Smolinsky and B. I. Feuer, *ibid.*, **31**, 3882 (1966); G. Smolinsky and B. I. Feuer, *ibid.*, **29**, 3097 (1964); *J. Am. Chem. Soc.*, **86**, 3085 (1964).

(25) R. H. Smith, Jr., unpublished work.

event and thermal deoxygenation of aromatic nitroso compounds proceeds very rapidly even at 0° in pure triethyl phosphite. We propose the scheme below as the most probable gross description of the process under study.

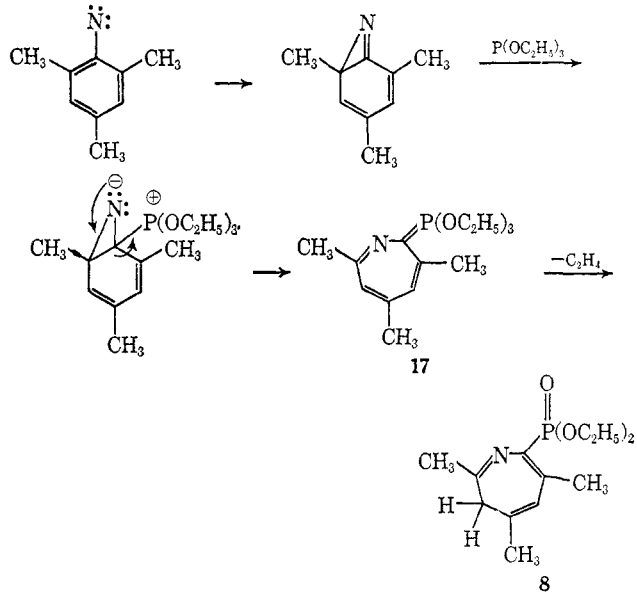
Scheme III



Phenyl nitrene, irrespective of its mode of generation, appears to have a strong tendency to be transformed to the azabicycloheptatriene intermediate which is the precursor of azepines in the presence of secondary amines. The intermediate can apparently be effectively trapped by diethylamine, as Cadogan and Todd have isolated 2-diethylamino-3H-azepine in 83% yield under one set of conditions.[19] Carbon monoxide may be an effective trap for phenyl nitrene at high temperature and pressure[26] but under most conditions it leads to variable amounts of azobenzene, aniline, and much tar.[21] In particular, C–H reactions do not proceed in high yield[27] and triethyl phosphite is apparently incapable of trapping unrearranged phenyl nitrene at 156° or lower temperatures.[8,28,29] Ring substitution appears to significantly effect the efficiency of coupling of aryl nitrenes with triethyl phosphite. Phosphorimidates **2e**, **2f**, and **2k** can be isolated in 53, 40, and 40% yields, respectively. Bunyan and Cadogan also obtained a good yield of the appropriate phosphorimidate when *p*-dimethylaminonitrosobenzene was deoxygenated in triethyl phosphite.[29] Comparable reactions involving nitrobenzene or nitrosobenzene give negligible amounts of the phosphorimidate.[8,28–30] If the extent of phosphorimidate formation depends upon the relative rate of coupling of the aryl nitrene with triethyl phosphite *vs.* irreversible rearrangement to a new reactive intermediate, electron-releasing substituents may favor coupling by diminishing the electron deficiency of the nitrogen atom and thereby slowing the rate of transformation of the nitrene to the azabicycloheptatriene intermediate.

The tendency of aryl nitrenes substituted by electron-releasing substituents to be trapped more effectively than phenyl nitrene by triethyl phosphite is also indicated by the data in Table II which reports yields of phosphorimidates by thermal deoxygenation in refluxing triethyl phosphite. Whereas very little phosphorimidate can be isolated from deoxygenations of nitrobenzene, the methyl-substituted nitro aromatics **1b–1h** and *p*-nitroanisole give isolated 40–79% yields of phosphorimidates. It can be concluded from comparison of the data on the photochemical process that aryl nitrenes are trapped more effectively by triethyl phosphite at 156° than at 30°.

2-Nitromesitylene gives about 15–20% of the phosphorimidate **2h** from photochemical deoxygenation whereas the yield for **1e** is 53%. These results initially seem anomalous since a 2,4-6-trimethylphenyl group would be expected to effectively stabilize the nitrene. The coupling reaction between triethyl phosphite and the nitrene carrying two *ortho* substituents may suffer significant steric hindrance. This would tend to disfavor coupling in competition with intramolecular bonding to give an azabicycloheptatriene intermediate. The photochemical deoxygenation of **1h** followed by hydrolytic work-up gives rise to a product in addition to the expected transformation products of the phosphorimidate **2h** and the imine **3h**. Evidence that the product is diethyl 2-(3,5,7-trimethyl)-6H-azepinylphosphonate (**8**) is summarized in the Results section. A mechanism for formation of the phosphorane **17** can be written which is similar to the reaction of the azabicycloheptatriene with diethylamine in that it is initiated by nucleophilic attack on the intermediate at the carbon which was C-1 in the original aromatic system.

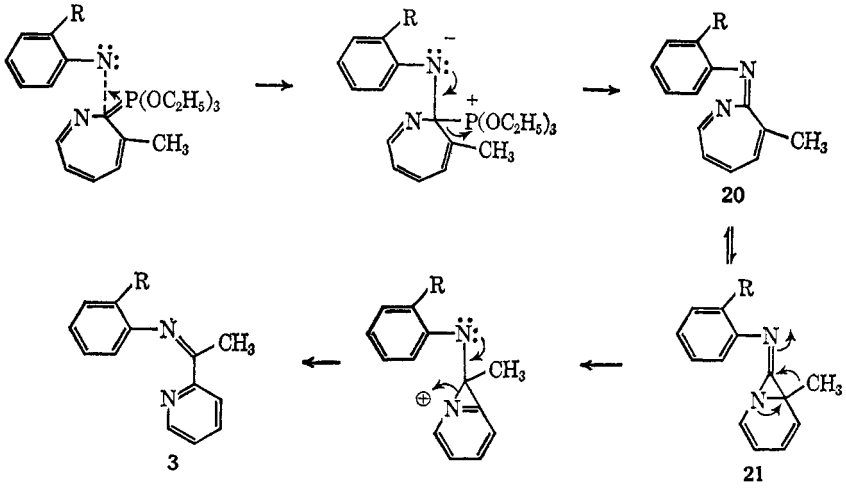


The azepinylphosphonate **8** is also formed in 19% yield during thermal deoxygenation of **1h**. This indicates that transformation of 2,4,6-trimethylphenyl nitrene to a rearranged intermediate must compete with coupling with triethyl phosphite even at 156°. Cadogan and coworkers have recently reported that azepinylphosphonates are formed from **1a**, **1b**, and *o*-ethylnitrobenzene during deoxygenation by triethyl phosphite.[30]

From the data in Table I we must conclude that aryl nitrenes substituted by electron-withdrawing groups

(26) B. P. Bennett and W. B. Hardy, *J. Am. Chem. Soc.*, **90**, 3295 (1968).
(27) J. H. Hall, J. W. Hill, and H. Tsai, *Tetrahedron Letters*, 2211 (1965); J. H. Hall, J. W. Hill, and J. M. Fargher, *J. Am. Chem. Soc.*, **90**, 5313 (1968).
(28) (a) J. I. G. Cadogan, M. Cameron-Wood, R. K. Mackie, and R. J. G. Searle, *J. Chem. Soc.*, 4831 (1965).
(29) P. J. Bunyan and J. I. G. Cadogan, *ibid.*, **42**, (1963).
(30) J. I. G. Cadogan, R. K. Mackie, and M. J. Todd, *Chem. Commun.*, 736 (1968).

Scheme IV

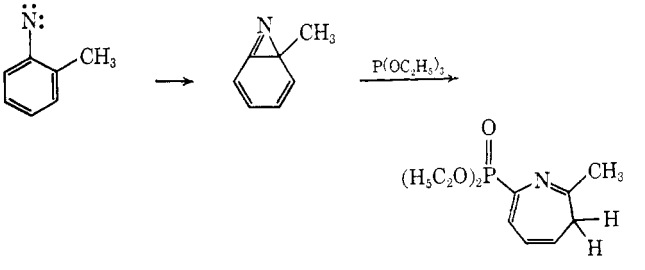


are also trapped more effectively by triethyl phosphite than phenyl nitrene. Thus the *o*- and *p*-carbomethoxy- and *o*- and *p*-cyano-substituted compounds **1l**, **1n**, **1o**, and **1p** give rise to phosphoramidates **5l**, **5n**, **5o**, and **5p**, respectively, in 20–30% yield. If phosphorimidate formation is interpreted as successful competition of coupling between triethyl phosphite and aryl nitrene *vs.* transformation of the nitrene to other species, it must be concluded that electron-withdrawing substituents favor the former process. An electron-withdrawing substituent presumably will increase the electrophilicity of a nitrene and favor coupling with the nucleophilic phosphite. The availability of π-electron density for intramolecular conversion to an azabicycloheptatriene intermediate will also be diminished by electron-withdrawing substituents and this mode of destruction of the nitrene may be slowed by such substituents, although the increased electrophilicity of the nitrogen would presumably work in the opposite direction.

It is conceivable that the substituent effects on the coupling reaction involve differing chemical reactivities of the triplet and singlet species and that substituents determine which species is present. It has been concluded that transformation to the azabicycloheptatriene intermediate is a reaction of the singlet state[20b] but we have no evidence which would permit us to establish the multiplicity of the species which couples with triethyl phosphite.

We assume that the intriguing skeletal rearrangement which leads to the isolation of pyridine derivatives is related to the rearrangement involved in the formation of azepines. One of the bonding changes which is involved in converting *o*-tolyl nitrene to a 2-ethylpyridine skeleton has taken place in the cyclization of *o*-tolyl nitrene to 5-methyl-7-azabicyclo[4.1.0]heptatriene. *o*-Tolyl azide behaves "normally" on photolysis in the presence of diethylamine giving 2-diethylamino-3H-azepine. The "crossover" experiments described in the Results section make it unlikely that the phosphorimidates present in the reaction mixture are the source of the unrearranged portion of the imine **3**. Triethyl phosphite seems to be a necessary component of the system for conversion of *o*-tolyl nitrene to the imine **3b** since no **3b** is formed when *o*-tolyl azide is photolyzed in triethyl phosphate. To date, pyridine formation has been observed in each *o*-alkylnitrobenzene studied and in no case has a pyridine been formed from nitro compound lacking an *ortho* alkyl substituent. Except for the ambiguity concerning C-1 and C-6, the skeletal change involved in the rearrangement has been defined. With these results in hand we suggest the transformations in Scheme IV which implicate azepinylidenephosphoranes as intermediates as a rationalization of the formation of acetimidylpyridines. The skeletal change **20** to **3** is formally reminiscent of various base-catalyzed ring contractions of tropones[31] and can be formulated as a pinacol-type rearrangement *via* the valence tautomer **21**. This mechanism leads to the prediction that a methyl migration as well as ring expansion and contraction are involved in pyridine formation. Cadogan[32] has very recently put forward an interesting alternative suggestion.

An interesting point that has arisen in the course of this work is the high degree of specificity with which *o*-tolyl nitrene is apparently converted to 2-diethylamino-3-methyl-3H-azepine (**10b**). No trace of the 7-methyl isomer was detected in our sample of **10b** from photochemical deoxygenation or azide photolysis. It is most intriguing that the reported[30] isolation of 2-methyl-3H-azepin-7-ylphosphonate from thermal deoxygenation suggest that triethyl phosphite reacts in the opposite sense with rearranged *o*-tolyl nitrene in that it would formally be derived from 1-methyl-7-azabicyclo[4.1.0]hepta-2,4,6-triene.



(31) P. L. Pauson, *Chem. Rev.*, **55**, 9 (1955).
(32) J. I. G. Cadogan, *Quart. Rev.* (London), **22**, 222 (1968).

Experimental Section

General. Infrared spectra were recorded on a Perkin-Elmer Model 337 spectrometer. Nmr spectra were recorded on either a Varian A-60 instrument or a Varian HA-100 instrument. Unless otherwise specified the spectra were run on 15–25% solutions in carbon tetrachloride. Thin layer chromatography was done using Merck silica gel H plates which were equilibrated with the atmosphere prior to use. Unless otherwise stated ether–benzene solutions were used as the developing solvent. Silicic acid powder (Mallinckrodt or Baker and Adamson) was used for column chromatography. Successful separations required that most of the triethyl phosphate be removed from mixtures prior to chromatography. Benzene, benzene–ether mixtures, and ether were usually used as the eluting solvents. Unreacted nitro compounds were eluted with benzene, anilines with benzene-rich ether–benzene mixtures, and the diethyl N-arylphosphoramides were eluted by ether-rich ether–benzene mixtures.

Standard Deoxygenation Procedures. The deoxygenations were carried out in a cylindrical flask of 200-ml capacity which was fitted with a capillary gas inlet, a gas outlet, and a water-cooled quartz immersion well containing a Pyrex filter sleeve and a 200-W Hanovia Type S lamp. The nitro compound was dissolved in sufficient triethyl phosphite to give a total volume of 195–200 ml. Normally 0.100 mol of nitro compound was used. In cases where this concentration exceeded the solubility of the nitro compound in triethyl phosphite, 0.050 mol of nitro compound was used. The resulting solution was purged with N_2 for 0.5 hr or more prior to irradiation. The solution was then irradiated for 12 hr, the N_2 purge being continued during the irradiation period. The water flow in the immersion well maintained the solution at 30 ± 5° during the irradiation. The solution was then transferred to a vacuum distillation apparatus and unreacted triethyl phosphite was recovered by distillation through a Vigreux column, bp 20–35° (0.1–0.3 mm). The residue was processed by one of the three methods described below.

Method A. Distillation. The residue was transferred to a small vacuum distillation apparatus and vacuum distilled to give two fractions. The lower boiling fraction (bp 50–80° (0.1 mm)) was normally a mixture of triethyl phosphate and unreacted nitro compound, and occasionally traces of the aniline derived from the nitro aromatic were present. The composition of the mixture was estimated by integration of the nmr spectrum. The higher boiling fractions (bp 90–150° (0.1 mm)) were generally mixtures of triethyl N-arylphosphorimidates and, in the case of *o*-methylnitro aromatics, N-arylacetimidylpyridines. The composition of the mixture was estimated by integration of the nmr spectrum. When the acetimidylpyridine was present in too low an amount for reliable integration, the high-boiling fraction was hydrolyzed and the yield of acetimidylpyridine calculated from the amount of 2-acetylpyridine obtained after hydrolysis.

Method B. Hydrolysis. The residue obtained by removal of triethyl phosphite from the photolysis mixture was transferred to a small distillation apparatus and the nitro aromatic and triethyl phosphate were collected by distillation and analyzed by nmr as in method A. The distillation was terminated after collection of the triethyl phosphate–nitro aromatic mixture and the residue was stirred into 100 ml of 10% hydrochloric acid in a continuous extractor. The acidic solution was then continuously extracted for 16 hr or more with ether. The ether was dried and concentrated. The diethyl N-arylphosphoramidates were isolated by crystallization or chromatography. Yields are recorded in Table I. The acidic aqueous layer was rendered alkaline with concentreated sodium hydroxide and extracted with ether. The ether was dried and concentrated. Short-path distillation gave mixtures of anilines and acetylpyridines which were analyzed by nmr or glpc. Yield data are recorded in Table I. Samples for characterization were obtained by preparative glpc using either a 5-ft 10% Carbowax 20M on Chromosorb G (treated with hexamethyldisilazane) or a 10-ft 10% Apiezon on Chromosorb G column.

Method C. Chromatography. Triethyl phosphite and triethyl phosphate were collected by distillation as in methods A and B. The residue consisting of unreacted nitro aromatic and reaction products was dissolved in benzene and placed on a column of 60–100 g of silicic acid packed in benzene, and the column was kept at room temperature for 24 hr or more. It was then eluted with benzene and ether–benzene mixtures and the various fractions were combined on the basis of tlc. The yields of diethyl N-arylphosphoramidates obtained in this manner are recorded in Table I.

Photochemical Deoxygenation of 2-Nitromesitylene (1h). Hydrolytic Work-up. A solution of **1h** (16.5 g, 0.100 mol) in triethyl phosphite (185 ml) was irradiated for 12 hr in the usual apparatus. Unreacted triethyl phosphite was collected by vacuum distillation followed by a fraction, bp 45–80° (0.05 mm), which contained triethyl phosphate and recovered 2-nitromesitylene (5.5 g, 33% recovery). The residue was stirred into 10% hydrochloric acid and continuously extracted with ether for 12 hr. The ether extract was dried over magnesium sulfate and chromatographed on silicic acid. Benzene eluted a reddish oil which crystallized from cold hexane (0.20 g, 0.75 mmol, 2%) as deep orange needles, mp 73–75° (lit.[33] for azomesitylene mp 75°). The infrared and nmr spectra support the identification of this substance as azomesitylene. Ether–benzene eluted the phosphoramidate **5h** (2.5 g, 0.0092 mol, 14%).

The acidic aqueous solution was made alkaline with aqueous sodium hydroxide and extracted with ether. Two fractions were collected in a simple distillation apparatus. The low-boiling fraction (1.30 g, bp 55–65° (0.5 mm)) consisted of 2-acetyl-4,6-dimethylpyridine (0.80 g, 0.0054 mol, 7%) and 2,4,6-trimethylaniline (0.50 g, 0.0036 mol, 5%) as analyzed by nmr. The higher boiling fraction (**8**, 2.05 g, 0.00753 mol, 11%) was further purified by chromatography on silicic acid, from which it was eluted by ether–benzene and ether–ethanol mixtures, and redistillation; ν 1620 (C=C or C=N), 1250 (P=O), and 970 and 1035 (POC) cm^{-1}; nmr peaks at δ 1.28 (6 H, t), 2.0 (3 H, s), 2.1 (3 H, d, J = 2 Hz), 2.3 (3 H, d, J = 4 Hz), 2.4 (2 H, m), 4.13 (4 H, quintet), 5.95 (1 H, doublet of doublets, J = 5, 2 Hz); λ_{max} mμ (log ϵ) in 95% ethanol 266 (3.87) and 248 (3.88).

Anal. Calcd for $C_{13}H_{22}NO_3P$: C, 57.55, H, 8.17; N, 5.16; P, 11.42. Found: C, 57.45; H, 8.18; N, 5.20; P, 11.51.

Hydrogenation of 8 to 9. A solution of **8** (0.25 g, 0.0093 mol) in ethanol (20 ml) containing concentrated hydrochloric acid (0.4 ml) was hydrogenated over platinum oxide for 12 hr. The ethanol was evaporated, and the basic product was isolated by a standard extraction sequence and recrystallized from hexane to give **9** (0.12 g, 0.0043 mol, 46%). An additional recrystallization from hexane gave the analytical sample, mp 81–83°; ν 3300 (NH), 1240 (P=O), and 960 and 1050 cm^{-1} (POC); nmr peaks at δ 0.88 (3 H, d, J = 7 Hz), 0.95 (3 H, d, J = 7 Hz), 1.06 (3 H, d, J = 7 Hz), 1.28 (8 H, triplet overlapping other signals, J = 7 Hz), 1.4–2.0 (~4 H, multiplets), 3.05 (1 H, doublet of doublets, J = 5, 24 Hz), 4.03 (4 H, overlapping quintets).

Anal. Calcd for $C_{13}H_{28}NO_3P$: C, 56.31; H, 10.06; N, 4.86. Found: C, 56.29; H, 10.18; N, 5.05.

Photochemical Deoxygenation of *o*-Nitropropylbenzene (1q). A solution of **1q** (8.05 g, 0.0500 mol) in triethyl phosphite (190 ml) was deoxygenated for 12 hr at 25°. Triethyl phosphite, triethyl phosphate, and unreacted **1q** (1.4 g, 18% recovery) were collected by vacuum distillation. The residue was subjected to hydrolytic conditions as in method B and gave a basic product (1.35 g) containing 0.65 g of **5q** (0.0043 mol, 9%) and 0.70 g of **6q** (0.0052 mol, 13%). Examination of the mixture on a 10-ft Carbowax 20M column under conditions which permit clean resolution of 2-methylindoline and *o*-allylaniline from **6q** and **7q** showed neither compound to be present in detectable amounts. An analytical sample of **6q** was obtained by preparative glpc followed by vacuum distillation; ν 1705 (C=O) cm^{-1}; nmr peaks at δ 1.04 (3 H, t), 1.80 (2 H, sextet), 3.20 (2 H, t), 7.4–8.4 (3 H, m), 8.9 (1 H, d).

Anal. Calcd for $C_9H_{11}NO$: C, 72.4; H, 7.4; N, 9.4. Found: C, 73.3; H, 7.7; N, 9.2.

Thermal Deoxygenation Reactions. A solution of 0.10 mol of the aromatic nitro compound in 1.00 mol of triethyl phosphite was refluxed under a nitrogen atmosphere for 5 hr. Triethyl phosphite was recovered by distillation at 19–20 mm and then the residue was vacuum distilled. Triethyl phosphate was collected in nearly quantitative yield at 50–60° (<0.05 mm) and the phosphorimidate was then collected. The yields are recorded in Table III. Analytical samples were prepared by redistillation. Compounds **2e** and **2h** were also prepared by the method of Kabachnik and Gilyarov[9] from the appropriate aryl azide. Comparison of the infrared and nmr spectra of the samples of **2e** from thermal and photochemical deoxygenation with **2e** from 2,4-dimethylazidobenzene were identical except for weak phosphoryl absorption at 1250 cm^{-1} in the thermal deoxygenation sample. Although the infrared spectrum of **2h** from thermal deoxygenation was very similar to that prepared from the azide, the nmr spectrum indicated the presence of **8** and also probably diethyl N-ethyl-N-(2,4,6-trimethyl)-phosphoramidate. When the sample of **2h** prepared by thermal

(33) G. Schultz, *Ber.*, **17**, 463 (1884).

Table III. Triethyl N-Arylphosphorimidates

Compd	Bp, °C (mm)	Calcd, % C	Calcd, % H	Calcd, % N	Found, % C	Found, % H	Found, % N
2c	98–101 (0.2)	57.6	8.2	5.2	57.3	8.2	5.3
2d	125–127 (0.07)	59.0	8.5	4.9	59.1	8.6	5.2
2e	110–112 (0.05)	59.0	8.5	4.9	58.8	8.6	4.7
2f	101–105 (0.02)	59.0	8.5	4.9	59.2	8.5	5.1
2g	113–115 (0.2)	59.0	8.5	4.9	59.0	8.4	5.1
2h	112–114 (0.05)	60.2	8.8	4.7	59.9	8.6	4.8
2k	123–125 (0.2)	54.4	7.7	4.9	54.2	7.6	4.9

deoxygenation was processed by the hydrolytic method (method B), a 19% yield of **8** was obtained.

Authentic Diethyl N-Arylphosphoramidates. Authentic samples of **5b, 5d, 5e,** and **5f** were prepared by the method of Atherton, Openshaw, and Todd[34] (method D) from the appropriate aniline, triethylamine, diethyl phosphite, and carbon tetrachloride. Authentic sample of **5l, 5m,** and **5n** were prepared by method of McCombie, Saunders, and Stacey[35] from the aniline and triethyl phosphite (method E). Melting point and analytical data for the new phosphoramidates prepared are recorded in Table IV. In all

Table IV. Diethyl N-Arylphosphoramidates

Compd	Method[a]	Mp, °C	Calcd, % C	Calcd, % H	Calcd, % N	Found, % C	Found, % H	Found, % N
5d	B, D	72–74	56.0	7.8	5.4	56.8	8.0	5.5
5e	B, D	88–89	56.0	7.8	5.5	56.4	8.0	5.8
5f	B, D	67–79	56.0	7.8	5.5	56.0	7.9	5.5
5g	*b*	88[c]	56.0	7.8		56.2	7.9	
5h	B	69–70	57.6	8.1		57.5	8.1	
5j	B	36–37	50.9	6.9	5.4	51.1	6.9	5.2
5k	C	64–65	50.9	6.9	5.4	51.0	7.0	5.4
5l	C, E	46–47	50.2	6.3	4.9	50.2	6.4	4.8
5m	C, E	82–83	50.2	6.3	4.9	50.4	6.5	5.1
5n	C, E	83	50.2	6.3	4.9	49.9	6.2	4.8
5o	C	101–102	52.0	5.9	11.0	52.1	6.4	11.5
5p	C	135–137	52.0	5.9	11.0	52.0	6.1	11.0

[a] Methods B and C refer to the respective methods for photochemical deoxygenation. [b] Isolated from the high-boiling distillate from thermal deoxygenation of **5g**. [c] Resolidifies and remelts at 97–98°.

cases where samples were prepared by two methods identity was established by nmr and infrared spectral comparison. The spectra recorded for all compounds in Table IV were consistent with the assigned structures.

Authentic 2-Acetylpyridines. Authentic samples of 3-, 4-, 5-, and 6-methyl-2-acetylpyridine were prepared from the appropriate methyl-2-aminopyridine *via* the nitrile following the conditions reported by Case and Kasper[12] (method F). The oximes were prepared by treating about 4 mmol of the acetylpyridine with a solution of hydroxylamine hydrochloride (1.4 g) and sodium hydroxide (0.8 g) in water (10 ml) and allowing the resulting solution to stir overnight. The oximes were isolated by filtration and recrystallized from benzene–hexane (see Table V).

Deoxygenations in the Presence of Diethylamine. A. Nitrobenzene. Nitrobenzene (0.10 mol) was irradiated for 12 hr in a solution of diethylamine (29.2 g, 0.40 mol) and triethyl phosphite (155 ml). After the irradiation period the diethylamine was removed using a rotary evaporator and unreacted triethyl phosphite was removed by distillation through a Vigreux column at 0.1 mm. Distillation of the residue gave 18.3 g of material, bp 50–70° (0.1 mm). Analysis by nmr indicated 11.0 g of triethyl phosphate, 5.1 g (41% recovery) of nitrobenzene, and 2.2 g (0.013 mol 23%) of 2-diethylamino-3H-azepine (**10a**). A portion of the sample resolved by preparative gas chromatography (5-ft Carbowax 20M column, HMDS-treated Chromosorb G, 200°) gave a sample of **10a** having an nmr spectra identical with the published spectrum.[17] In a separate run the late portion of the 50–70° (0.1 mm) fraction was collected separately, dissolved in ether, and extracted with dilute hydrochloric acid. The acidic extract was made alkaline and extracted with ether. After drying and distillation, 0.91 g (0.0056 mol, 10% yield) of 2-diethylamino-3H-azepine containing ~10% triethyl phosphate as a contaminant (nmr analysis) was obtained.

B. *p*-Nitrotoluene. The deoxygenation of *p*-nitrotoluene was carried out as described above. By nmr analysis the yield of 2-diethylamino-5-methyl-3H-azepine (**10c**) was 34%. Distillation and extraction as described above gave an 18% yield of pure **10c,** bp 68–70° (0.2 mm); nmr peaks at δ 1.10 (6 H, t), 1.83 (3 H, s), 2.45 (2 H, d), 3.30 (4 H, q), 4.70 (1 H, t), 5.45 (1 H, d), and 6.82 (1 H, d).

Anal. Calcd for $C_{11}H_{18}N_2$: C, 74.11; H, 10.18; N, 15.71. Found: C, 74.13; H, 10.29; N, 15.77.

C. *o*-Nitrotoluene. *o*-Nitrotoluene (0.10 mol) was deoxygenated in triethyl phosphite (155 ml) containing diethylamine. After removal of unreacted diethylamine and triethyl phosphite the reaction mixture was vacuum distilled. A fraction, bp 50–60° (0.1 mm), contained unreacted nitro compound and triethyl phosphate. The amount of unreacted *o*-nitrotoluene was estimated by nmr analysis. The portion of the distillate boiling at 61–80° (0.1 mm) contained triethyl phosphate, *o*-nitrotoluene, *o*-toluidine, and 2-dimethylamino-3-methyl-3H-azepine (**10b**). Four such runs gave values of 10, 8, 8, and 7% for the yield of **10b**. A pure sample was prepared by glpc (10 ft 5% Apiezon–5% KOH on Chromosorb G, 220°) followed by extraction from ether into dilute hydrochloric acid and reisolation by basifying the extract and extracting with ether. Bulb-to-bulb distillation gave the analytical sample; nmr peaks at δ 0.72 (3 H, d), 1.15 (6 H, t), 3.41 (4 H, q), 4.18 (1 H, quintet), 5.19 (1 H, t), 5.62 (1 H, t), 6.30 (1 H, multiplet), and 7.08 (1 H, d); λ_{max} 304 mμ (log ε 3.90).

Anal. Calcd for $C_{11}H_{18}N_2$: C, 74.11; H, 10.18; N, 15.71. Found: C, 74.22; 74.59; H, 10.48, 10.54; N, 15.13, 15.25.

D. 2-Nitromesitylene. 2-Nitromesitylene (16.5 g, 0.100 mol) was deoxygenated in a solution of diethylamine (29.2 g, 0.400 mol) and triethyl phosphite (155 ml). After irradiation for 15 hr, the unreacted diethylamine was removed on a rotary evaporator. The residue was separated by vacuum distillation into fractions of bp 25–40 (0.1–0.5 mm) (recovered triethyl phosphite), 50–58 (mainly triethyl phosphate), 58–110, and 110–160°. The fraction, bp 58–110°, was separated into neutral and basic fractions by an extraction sequence. Analysis of the 50–58° fraction and the neutral portion of the 58–110° fraction indicated the recovery of 4.35 g (16%) of 2-nitromesitylene. The basic portion of the 58–110° fraction (3.45 g) was analyzed by glpc and estimated to contain 1.7 g of 2,4,6-trimethylaniline (0.012 mol, 15%) and 0.48 g (0.0023 mol, 3%) of 2-diethylamino-3,5,7-trimethyl-3H-azepine (**10h**). This fraction also gave 0.63 g of a compound, $C_{13}H_{20}N_2O$, which appears on the basis of spectral data to be 2-diethylamino-3,5,7-trimethyl-4-oxo-4H-azepine or 2-diethylamino-3,5,7-trimethyl-6-oxo-6H-azepine. The three components were isolated by preparative gas chromatography on a 10 ft × 0.25 in. column packed with 10% Apiezon M–5% KOH at an oven temperature of 215°. 2,4,6-Trimethylaniline was identified by spectral comparison with an authentic sample.

The azepine **10h** was distilled in a short-path still after collection to give a yellow liquid; nmr peaks at δ 0.67 (1 H, d), 1.13 (6.6 H, t), 1.81 (5 H, s), 1.95 (3 H, s), 3.33 (4.1 H, q), 3.77 (1 H, m), 4.73 (0.9 H, d), and 5.29 (0.8 H, s).

Anal. Calcd for $C_{13}H_{22}N_2$: C, 75.67; H, 10.75; N, 13.58. Found: C, 75.58; H, 10.76; N, 13.53.

The third principal component was a liquid; ν 1680 (C=O) cm^{-1}; nmr peaks at δ 0.97 (6 H, t), 2.10 (3 H, s), 2.33 (6 H, closely spaced singlets), 3.21 (4 H, q), and 6.43 (1 H, s).

Anal. Calcd for $C_{13}H_{20}N_2O$: C, 70.90; H, 9.13; N, 12.70. Found: C, 70.87; H, 9.15; N, 12.71.

Deoxygenation of *o*-Nitrotoluene (1b) Followed by Sodium Borohydride Reduction. 2-[1-(2-Methylanilino)ethyl]pyridine (4b). A solution of **1b** (13.5 g, 0.100 mol) in triethyl phosphite (180 ml) was irradiated for 14 hr and recovered **1b** (6.2 g, 0.046 mol) and triethyl phosphate (18.7 g, 0.103 mol) were obtained by distillation as described in method B. The residue was dissolved in absolute ethanol (100 ml) and treated slowly with solid sodium borohydride (2.5 g) at 0°. After 0.5 hr the reaction solution was allowed to warm to room temperature and stirred for 0.5 hr after which the ethanol was removed on a rotary evaporator. Water (50 ml) was added to the residue followed by careful addition of 50 ml of 20% hydrochloric acid. The resulting solution was continuously extracted with ether for 20 hr. The acidic layer was made alkaline

(34) F. R. Atherton, H. T. Openshaw, and A. R. Todd, *J. Chem. Soc.*, 660 (1945).

(35) H. McCombie, B. C. Saunders, and G. J. Stacey, *ibid.*, 921 (1945).

Table V. 2-Acetylpyridines

Substn	Method[a]	Calcd, % C	Calcd, % H	Calcd, % N	Found, % C	Found, % H	Found, % N	Mp, °C	Oximes: Calcd, % C	Oximes: Calcd, % H	Oximes: Calcd, % N	Oximes: Found, % C	Oximes: Found, % H	Oximes: Found, % N
3-Methyl	B, F	71.1	6.7	10.4	71.0	6.5	10.4							
4-Methyl	B, F	71.1	6.7		71.0	6.9		100–102	64.0	6.7	18.7	64.4	6.9	18.8
5-Methyl	B, F							128–130	64.0	6.7	18.7	64.2	6.9	18.8
4,6-Dimethyl	B	72.5	7.4	9.4	72.4	7.5	9.6							
3-Chloro	B	54.0	3.9	9.0	54.3	3.9	8.9							

[a] Method B refers to method B for photochemical deoxygenation.

with concentrated sodium hydroxide and extracted with ether. Distillation of the concentrated extract gave crude **4b** (2.4 g). Redistillation gave **4b** (1.4 g, 0.0066 mol, 24% based on unrecovered **1b**). The infrared spectrum was identical with that of authentic **4b**.[8]

Deoxygenation of *o*-Nitrotoluene (1b) in the Presence of Triethyl N-(2,4-Dimethylphenyl)phosphorimidate (2e). A solution of **1b** (13.5 g, 0.100 mol) and freshly distilled **2e** (6.0 g, 0.021 mol) in triethyl phosphite (175 ml) was irradiated for 15 hr with light from a 450-W Hanovia lamp (Pyrex filter). Distillation at 25–40° (0.1 mm) removed unreacted triethyl phosphite and then a fraction, bp 40–70° (0.1 mm), was collected. The nmr spectrum showed this to be triethyl phosphate indicating that the nitro compound had been completely consumed. The residue was dissolved in absolute ethanol (120 ml) and cooled to 0°. Solid sodium borohydride (2.5 g) was added slowly and the solution was stirred in an ice bath for 0.5 hr. The solution was allowed to come to room temperature and after stirring for 0.5 hr the ethanol was removed on a rotary evaporator and water (50 ml) was added. Concentrated hydrochloric acid (30 ml) was carefully added and the resulting solution was continuously extracted with ether. The basic product was isolated by making the solution alkaline and extracting with ether. Short-path distillation gave 2.3 g of a mixture of triethyl phosphate and *o*-toluidine. The high-boiling fraction (2.4 g, bp 105–125° (0.02 mm)) was examined by glpc (4-ft column of 5% Carbowax 20M–5% KOH on Chromosorb G at 220°). No 2-[1-(2,4-dimethylanilino)ethyl]pyridine (**13**) was found under conditions which permitted detection of authentic **13**. The main portion of the high-boiling basic fraction was purified by chromatography giving 2-[1-(2-methylanilino)ethyl]pyridine (**4b**, 1.60 g, 0.0075 mol, 15%) having an infrared spectrum identical with an authentic sample.[8]

N-(2,4-Dimethylphenyl)-2-acetimidylpyridine (14). 2-Acetylpyridine (5.0 g, 0.041 mol) and 2,4-dimethylaniline (5.0 g, 0.041 mol) were heated together at 170° in the presence of zinc chloride (0.1 g). The reaction mixture was cooled and extracted with hexane. The oil obtained by evaporation of the hexane was distilled in a short-path apparatus giving **14** (2.6 g, 0.0161 mol, 39%).

Anal. Calcd for $C_{15}H_{16}N_2$: C, 80.3; H, 7.2; N, 12.5. Found: C, 80.0; H, 7.2; N, 12.8.

2-[1-(2,4-Dimethylanilino)ethyl]pyridine (13). Reduction of N-(2,4-dimethylphenyl)-2-acetimidylpyridine (**14**) with sodium borohydride gave **13** which was purified by two short-path distillations; nmr peaks at δ 1.37 (3 H, d), 2.13 (6 H, s), 3.93 (broad singlet), 4.53 (1 H, q), 6.21 (1 H, d), 6.57–7.27 (4 H, m), 7.47 (1 H, t), and 8.47 (1 H, d).

Anal. Calcd for $C_{15}H_{18}N_2$: C, 79.6; H, 8.0; N, 12.4. Found: C, 79.4; H, 8.0; N, 12.5.

Deoxygenation of 2,4-Dimethylnitrobenzene (1e) Followed by Sodium Borohydride Reduction. 2-[1-(2,4-Dimethylanilino)ethyl]-4-methylpyridine (4e). A solution of **1e** (18.1 g, 0.120 mol) was deoxygenated in the normal manner, and 4.7 g of **1e** (0.031 mol, 26%) was recovered. The residual liquid was obtained by removing triethyl phosphate, and **1e** was dissolved in absolute ethanol, reduced, and processed as described above for **1b**. Distillation of the basic product gave 1.45 g of an oil, bp 135–155° (0.15–0.2 mm). Purification by chromatography followed by redistillation gave pure **4e**; nmr peaks at δ 1.52 (3 H, d), 2.13 (3 H, s), 2.17 (3 H, s), 2.21 (3 H, s), 4.09 (1 H, broad singlet), 4.55 (1 H, quartet), 6.33 (1 H, d), 6.69–7.15 (4 H, multiplet), and 8.39 (1 H, d).

Anal. Calcd for $C_{16}H_{20}N_2$: C, 80.00; H, 8.33; N, 11.66. Found: C, 79.82; H, 8.52; N, 11.57.

Deoxygenation of an Equimolar Mixture of Nitrobenzene (1a) and 2,4-Dimethylnitrobenzene (1e). A solution of **1a** (6.15 g, 0.050 mol) and **1e** (7.55 g, 0.050 mol) in triethyl phosphite (185 ml) was irradiated for 12 hr and unreacted triethyl phosphite was removed by vacuum distillation. Triethyl phosphate and a mixture of the unreacted nitro compounds (22.5 g) were removed at 40–54° (0.15–0.2 mm), the residue was dissolved in absolute ethanol (150 ml), and sodium borohydride (3 g) was added in small portions with stirring. After 1 hr the solvent was removed at reduced pressure and the residue stirred with water (50 ml) for 45 min. Concentrated hydrochloric acid (30 ml) was carefully added and the resulting solution was continuously extracted with ether for 16 hr. The acidic aqueous solution was made alkaline with sodium hydroxide solution and extracted with ether. After drying and evaporation the basic product was distilled and the fraction, bp 120–190° (0.2–0.5 mm), was analyzed by glpc [10% Carbowax 20M on Chromosorb G (HMDS treated, 220°)]. Glpc indicated at most a trace (less the 5% of the amount of **4e**) of 2-(2,4-dimethylanilinomethyl)pyridine (**15**) but substantial amounts of 2-[1-(2,4-dimethylanilino)ethyl]-4-methylpyridine (**4e**) were detected by glpc and tlc. Attempts to isolate traces of **15** by column chromatography gave none. In a control experiment in which authentic N-(2,4-dimethylphenyl)formimidylpyridine (**16**) (1.0 g) was added to a deoxygenation of **1e** prior to photolysis and reductive work-up as above it was possible to detect approximately equal amounts of **15** and **4e** by glpc analysis under conditions similar to those above.

N-(2,4-Dimethylphenyl)formimidylpyridine (16). A mixture of pyridine-2-carboxaldehyde (6.0 g, 0.056 mol) and 2,4-dimethylaniline (6.8 g, 0.056 mol) was heated to 120° for 45 min and at 140–145° for 15 min. The reaction mixture was cooled, diluted with ether, and dried over potassium carbonate. The solid residue obtained by evaporation of the ether was crystallized from hexane giving **16** (10.2 g, 0.049 mol, 87%), mp 61.5–62°; nmr peaks at δ 2.28 (3 H, s), 2.34 (3 H, s), 6.69–7.09 (3 H, m), 7.23 (1 H, m), 7.69 (1 H, t), 8.21 (1 H, d), 8.49 (1 H, s), and 8.65 (1 H, d).

Anal. Calcd for $C_{14}H_{14}N_2$: C, 80.0; H, 6.7; N, 13.3. Found: C, 80.1; H, 6.6; N, 13.2.

2-(2,4-Dimethylanilinomethyl)pyridine (15). To a solution of the imine **16** (2.0 g, 0.0095 mol) in absolute ethanol at 0° there was added in small portions 1.5 g of solid sodium borohydride. After 45 min the solution was allowed to come to room temperature, and after 30 min at room temperature the ethanol was removed on a rotary evaporator. The residue was treated with water, made strongly alkaline with sodium hydroxide, and extracted with ether. Concentration of the dried ether gave a solid which was crystallized from hexane to give **15**, mp 52.5–53.5°; nmr peaks at δ 2.09 (6 H, s), 4.37 (3 H, sharp singlet overlapping broad NH singlet), 6.43 (1 H, d), 6.77–7.57 (5 H, multiplet), and 8.53 (1 H, d).

Anal. Calcd for $C_{14}H_{16}N_2$: C, 79.2; H, 7.5; N, 13.2. Found: C, 79.4; H, 7.6; N, 13.2.

Deoxygenation of an Equimolar Mixture of *o*-Nitrotoluene (1b) and 2,4-Dimethylnitrobenzene (1e). A solution of **1b** (0.050 mol) and **1e** (0.050 mol) in triethyl phosphite was irradiated and distilled in the usual manner to remove triethyl phosphite, triethyl phosphate, and the unreacted nitro compounds. The residue was reduced by sodium borohydride in ethanol and the basic products were isolated by extraction. The basic product mixture was analyzed by glpc on a Carbowax 20M column at 220°. Peaks corresponding in retention time to **4b**, **4e**, and **13** were found.

Attempt to Isolate 2-Acetylpyridine from Thermal Deoxygenation of *o*-Nitrotoluene (1b). A solution of **1b** (13.7 g) in triethyl phosphite (166 g) was refluxed for 4 hr in a nitrogen atmosphere. Triethyl phosphite and triethyl phosphate were collected by vacuum distillation. The residue was dissolved in 10% hydrochloric acid (100 ml) and continuously extracted for 24 hr. Diethyl N-(*o*-tolyl)phosphoramidate was isolated from the ether extract. The

acidic solution was made strongly alkaline with sodium hydroxide solution and extracted with ether. The extract was dried and evaporated. The residue was distilled in a short-path apparatus giving a mixture shown by ir and glpc to contain *o*-toluidine and triethyl phosphate but no 2-acetylpyridine.

***o*-Azidotoluene.** *o*-Azidotoluene was prepared from toluidine (76% yield) by Smolinsky's modification[36] of the general procedure of Smith and Brown.[37]

Photolysis of *o*-Azidotoluene in Triethyl Phosphate. A solution of *o*-azidotoluene (6.65 g, 0.05 mol) in triethyl phosphate (200 ml) was photolyzed for 24 hr with a 450-W Hanovia lamp (Pyrex filter). After this irradiation period, glpc indicated 49% of the azide had been decomposed. The triethyl phosphate and unreacted azide were removed by distillation and the residue was processsed by the hydrolytic work-up procedure (method B). The basic product was identified as toluidine (37 mg). No 2-acetylpyridine was detected.

Photolysis of *o*-Azidotoluene in Diethylamine. A solution of the azide (5.5 g, 0.041 mol) in diethylamine (180 ml) was photolyzed under nitrogen for 40 hr using a 200-W Hanovia lamp (Pyrex filter). The excess diethylamine was removed on a rotary evaporator, and the residue was distilled giving recovered *o*-azidotoluene (0.5 g) and 2-diethylamino-3-methyl-3H-azepine (**10b**) (2.25 g, 0.0126 mol, 31%). The nmr and infrared spectra were identical with the sample prepared by photochemical deoxygenation of *o*-nitrotoluene.

Anal. Calcd for $C_{11}H_{18}N_2$: C, 74.11; H, 10.18; N, 15.71. Found: C, 73.99; H, 10.03 N, 15.82.

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(36) G. Smolinsky, *J. Org. Chem.*, **26**, 4108 (1961).
(37) P. A. S. Smith and B. B. Brown, *J. Am. Chem. Soc.*, **73**, 2438 (1951).

The Oxidation of 2-Propanol by Bromine and by Hypobromous Acid in Aqueous Solution

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Abstract: The rate of oxidation of 2-propanol by bromine water at pH 6.7 is confirmed[2] to be higher than in acid solution. However, the dependence of the rate on the concentration of added bromide shows that the pH effect cannot be due to hypobromous acid being a faster oxidizing agent than molecular bromine. The *converse* assumption, *viz.*, $k_{HOBr} \ll k_{Br_2}$, is shown to be consistent with these results. This is further confirmed by the slowness of the reaction in bromine-free hypobromous acid solution. Tribromide ion is found to be kinetically inactive. On this basis, k_{Br_2} is calculated and found to increase with pH even more strongly than does the observed rate constant. As in previous cases, it is suggested that this increase of k_{Br_2} with increasing pH might be due to the anion RO^- being oxidized at a very much higher rate than the molecule ROH. The correlation between the pK of the substrate and the form of the curve representing the dependence of the rate constant on pH is discussed.

A number of hydroxylic substances are quantitatively oxidized by bromine water,[3-7] no substitution taking place provided the pH is not too high. The rate of the reaction increases with increasing pH in a manner which in some cases parallels the increase in the relative concentration of hypobromous acid with increasing pH, according to

$$Br_2 + H_2O \rightleftharpoons H^+ + Br^- + HOBr \qquad (I)$$

The hypothesis that hypobromous acid should be a more rapid oxidizing agent than molecular bromine might therefore seem attractive.[8] However, for formic acid,[4] ethanol[3,6] acetaldehyde hydrate,[3,6] methanol,[9] and D-glucose,[5] where this hypothesis was subjected to closer scrunity, it proved to be untenable. Firstly, the oxidation by bromine-free hypobromous acid was extremely slow.[3-6] Secondly, the increase of the rate with increasing pH was most pronounced when the formation of hypobromous acid was largely *repressed* by the addition of bromide.[6]

Nevertheless, the influence of pH on the rate of oxidation of 2-propanol by bromine has recently been interpreted[2] on the basis of the hypobromous acid hypothesis. Our findings on the pH dependence of the rate of oxidation of ethanol[6] were adduced as a corroboration of this hypothesis, whereas our interpretation of the effect was rejected.[2]

It therefore seemed desirable to take up once more the question of the kinetically active species in bromine

(1) (a) Hebrew University, Jerusalem, Israel. (b) Tel Aviv University, Tel Aviv, Israel.
(2) N. C. Deno and N. H. Potter, *J. Am. Chem. Soc.*, **89**, 3555 (1967).
(3) L. Farkas, B. Perlmutter, and O. Schächter, *ibid.*, **71**, 2829 (1949).
(4) L. Binoun and B. Perlmutter-Hayman, *Bull. Res. Council Israel*, **5A**, 52 (1955), where literature is quoted.
(5) B. Perlmutter-Hayman and A. Persky, *J. Am. Chem. Soc.*, **82**, 276, 3809 (1960).
(6) B. Perlmutter-Hayman and Y. Weissmann, *ibid.*, **84**, 2323 (1962).
(7) P. T. McTigue and J. M. Sime, *J. Chem. Soc.*, 1303 (1963); P. T. McTigue, *Australian J. Chem.*, **17**, 1210 (1964); J. Konecny, *Helv. Chim. Acta*, **48**, 1817 (1965); see also R. Stewart, "Oxidation Mechanisms," W. A. Benjamin, Inc., New York, N. Y., 1964, p 131.
(8) K. C. Grover and R. C. Mehrota, *Z. Physik. Chem.* (Frankfurt), **14**, 345 (1958).
(9) B. Perlmutter, unpublished results, 1950.