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Ultraviolet Irradiation of Fenitrothion and the Synthesis of the Photolytic Oxidation Products

Roy Greenhalgh* and William D. Marshall

The ultraviolet irradiation of fenitrothion in oxygenated solutions produced isomerization, oxidation, and solvolysis. In hexane, both the P=S and the aryl methyl group were oxidized to give fenitrooxon and formylfenitrothion. Small amounts of denitrofenitrothion were also formed. Irradiation in methanol gave carbomethoxyfenitrothion formed from oxidation followed by solvolysis. Isomerization of fenitrothion to its *S*-methyl isomer took place on a small scale in all solvents; however, no *S*-aryl isomer was detected. Irradiation of hydroxymethylfenitrothion in hexane readily gave formyl- and carboxyfenitrothion. This supports the suggestion that hydroxymethylfenitrothion is a reactive intermediate formed in the photolysis of fenitrothion. Several potential oxidation products, hydroxymethyl, formyl, carboxy, and carbomethoxy analogues of fenitrothion and fenitrooxon were prepared together with the *S*-aryl isomer. The mass spectral (MS) and nuclear magnetic resonance (NMR) data, gas chromatographic (GC), and thin-layer chromatographic (TLC) properties of these compounds and other fenitrothion derivatives are given.

Fenitrothion [*O,O*-dimethyl *O*-(4-nitro-*m*-tolyl) phosphorothioate] (I) is an important insecticide used in many countries for orchard and field crops. In Canada, its main use is to control defoliators in forests.

It is structurally similar to parathion, the ultraviolet (uv) photolysis of which has been extensively studied (Cook and Pugh, 1957; Frawley et al., 1958; Koivistoinen and Merilainen, 1963; El-Rafai and Hopkins, 1966; and Joiner and Baetcke, 1974). In contrast, little work has been carried out on the photolysis of fenitrothion. Brewer et al. (1974) reported the formation of two products on irradiation of fenitrothion with light >300 nm, one of which was identified as 4-nitro-*m*-cresol (II). A more exhaustive investigation was carried out by Ohkawa et al. (1974) who studied the photodecomposition in various solvents and as films by both uv and sunlight. Five products were isolated, resulting from photoinduced isomerization, oxidation, hydrolysis, and solvolysis. The predominant reaction in benzene, acetone, methanol, and aqueous methanol was oxidation of the aryl methyl group to give carboxyfenitrothion and its oxygen analogue, which were characterized by nuclear magnetic resonance (NMR) and infrared (ir) spectroscopy.

Chemistry and Biology Research Institute, Agriculture Canada, Ottawa, Ontario, K1A 0C6 Canada.

It would be expected that oxidation of the aryl methyl group of fenitrothion would also form hydroxymethyl- and formylfenitrothion as precursors to carboxyfenitrothion. Efforts to detect these partially oxidized products of fenitrothion in the past have been hampered by a lack of synthetic standards. To this end, several potential oxidation products and isomers of fenitrothion have been synthesized and details of their chromatographic behavior recorded.

EXPERIMENTAL SECTION

Chemicals. Fenitrothion (99.6%) was obtained by purifying technical grade Sumithion (Sumitomo Chemical Co., ~97%) after the manner of Kovacicova et al. (1971). *S*-Methylfenitrothion [*O,S*-dimethyl *O*-(4-nitro-*m*-tolyl) phosphorothioate] (III) (Kovacicova et al., 1973) and fenitrooxon [*O,O*-dimethyl *O*-(4-nitro-*m*-tolyl) phosphate] (IV) (Marshall et al., 1974) were synthesized according to the procedures referenced. The starting materials 4-nitro-*m*-cresol, 5-hydroxy-2-nitrobenzaldehyde, and *m*-cresol were purchased from Aldrich Chemical Co. (Milwaukee, Wis.).

S-Arylfenitrothion [*O,O*-dimethyl *S*-(4-nitro-*m*-tolyl) phosphorothioate] (V) was synthesized in moderate yield (~35%) by the reaction of trimethyl phosphite (0.85 ml, 8.1 mM) with 4-nitro-*m*-thiocresol (VI) (5.4 g, 32 mM) in the presence of bromotrichloromethane (1.64 ml, 16.2 mM)

using the general procedure of Murdock and Hopkins (1968). The neat reactants were heated to 90 °C for 1 h, and the crude reaction products dissolved in chloroform and washed several times with dilute sodium carbonate. The organic layer was dried (sodium sulfate) and filtered and the solvent removed to give a pale yellow oil which was purified by preparative liquid chromatography. Major contaminants in the crude product were identified as methyl (4-nitro-*m*-tolyl) thioether and unreacted 4-nitro-*m*-thiocresol. The purified product was a viscous orange oil: NMR ($CDCl_3$) τ 6.10 (CH_3OP, d, 6 H, J_{CH_3OP} = 12 Hz), 7.38 (CH_3–Ar, s, 3 H), 2.25 (aromatic protons, m, 3 H); ir NO_2–Ar, 1510, 1350; P=O, 1260; P–O–alkyl, 1020 cm^{-1}.

Formylfenitrothion [*O,O*-dimethyl *O*-(4-nitro-*m*-formylphenyl) phosphorothioate] (VII) was prepared by the dropwise addition of dimethyl chlorothiophosphate in dry acetone to an ice cold equimolar solution of 5-hydroxy-2-nitrobenzaldehyde in benzene containing 1.1 equiv of sodium hydride. The reaction mixture, maintained in an atmosphere of nitrogen, was allowed to come to room temperature when the addition was complete and then was refluxed for 8 h. The solvent was removed; the residues were cautiously suspended in water and then extracted three times with chloroform. The combined organic washes were dried (sodium sulfate) and filtered, and the solvent removed to yield a pale yellow oil. The product, a yellow oil when purified by preparative liquid chromatography, showed the following spectral characteristics: NMR τ 6.04 (CH_3OP, d, 6 H, J_{CH_3OP} = 14 Hz), –0.39 (C(O)H, s, 1 H), 2.04 (aromatic protons, m, 3 H); ir NO_2–Ar, 1505, 1330; P=S, 845; P–O–alkyl, 1020; P–O–aryl, 1230; C=O, 1700 cm^{-1}.

Formylfenitrooxon [*O,O*-dimethyl *O*-(4-nitro-*m*-formylphenyl) phosphate] (VIII) was prepared by reaction of dimethyl chlorophosphate with 4-nitro-*m*-cresol following the above procedure: NMR τ 6.04 (CH_3OP, d, 6 H, J_{CH_3OP} = 11 Hz), –0.41 (C(O)H, s, 1 H), 2.05 (aromatic protons, m, 3 H), ir NO_2–Ar, 1530, 1350; CHO, 1700; P=O, 1260; P–O–alkyl, 1040 cm^{-1}.

Hydroxymethylfenitrothion [*O,O*-dimethyl *O*-(4-nitro-*m*-hydroxymethylphenyl) phosphorothioate] (IX) and hydroxymethylfenitrooxon [*O,O*-dimethyl *O*-(4-hydroxymethyl-*m*-nitrophenyl) phosphate] (X) were prepared from the corresponding aldehydes VII and VIII, respectively, by reduction with sodium borohydride in ethanol at 0 °C for 90 min. After purification by preparative liquid chromatography, the products showed the following spectral characteristics: NMR IX: τ 6.07 (CH_3OP, d, 6 H, J_{CH_3OP} = 14 Hz), 4.97 (CH_2OH, s, 2 H), 2.22 (aromatic protons, m, 3 H); ir IX: OH, 3420; Ar–NO_2, 1530, 1350; P–O–alkyl, 1040; P=S, 840 cm^{-1}; NMR X: τ 6.09 (CH_3OP, d, 6 H, J_{CH_3OP} = 11 Hz), 5.00 (CH_2OH, s, 2 H), 2.25 (aromatic protons, m, 3 H); ir X: OH, 3405; Ar–NO_2, 1530, 1350; P=O, 1280; P–O–alkyl, 1050 cm^{-1}. 5-Hydroxy-2-nitrobenzyl alcohol (XI) was prepared as above by reduction of 5-hydroxy-2-nitrobenzaldehyde.

Carboxyfenitrothion [*O,O*-dimethyl *O*-(4-nitro-*m*-carboxyphenyl) phosphorothioate] (XII) was obtained by oxidation of VII with 1.2 equiv of chromium trioxide/sulfuric acid in acetone (Bowden et al., 1946): NMR τ 6.08 (CH_3OP, d, 6 H, J_{CH_3OP} = 14 Hz), 2.22 (aromatic protons, m, 3 H); ir Ar–COOH (broad abs), 3400–2700; C=O, 1710; Ar–NO_2, 1530, 1350; P–O–alkyl, 1025; P=S, 875 cm^{-1}.

Carboxyfenitrooxon [*O,O*-dimethyl *O*-(4-nitro-*m*-carboxyphenyl) phosphate] (XIII) was prepared by oxidation of VII in acetone with an excess of potassium permanganate/magnesium sulfate at room temperature. The reaction was essentially complete after 15 min. Filtration of the crude reaction mixture and removal of the solvent yielded a white crystalline material, which was recrystallized from ether: mp 114–115 °C; NMR τ 6.08 (CH_3OP, d, 6 H, J_{CH_3OP} = 11 Hz), 2.25 (aromatic protons, m, 3 H); ir Ar–COOH (broad abs), 3400–2700; C=O, 1715; Ar–NO_2, 1535, 1350; P=O, 1270; P–O–alkyl, 1030 cm^{-1}.

Denitrofenitrothion [*O,O*-dimethyl *O*-(*m*-tolyl) phosphorothiate] (XIV) was prepared by the reaction of dimethyl chlorothiophosphate with *m*-cresol in the presence of 1.1 equiv of sodium hydride following the procedure described above. The crude reaction product was dissolved in chloroform and washed with sodium carbonate and then dried and the solvent was removed. The crude product was distilled under high vacuum: bp 83–84 °C (0.05 mm); NMR τ 6.37 (CH_3OP, d, 6 H, J_{CH_3OP} = 14 Hz), 7.66 (Ar–CH_3, s, 3 H), 3.62 (aromatic protons, m, 4 H); ir P–O–alkyl, 1020; P=S, 875 cm^{-1}.

All the synthetic standards were purified by preparative liquid chromatography using a 52 cm × 0.95 cm i.d. column packed with Porasil A (37–75 μm) and a Waters M-6000 pumping system. Mixtures of ethyl acetate and hexane at 6 ml/min were used as the eluent.

Thin-Layer Chromatography. Compounds were spotted on silica gel plates (0.25 mm, Polygram-Macherey Nagel & Co.) containing a fluorescent indicator and developed in either (a) 3:2 ethyl acetate/hexane, (b) 1:3 ethyl acetate/cyclohexane, or (c) 5:7:1 toluene/ethyl acetate/acetic acid. The spots were visualized by spraying with 2,6-dichloro-*N*-bromo-*p*-benzoquinone imine, the enzyme spray as modified by Mendoza (1972) or by exposure to iodine vapor. The chromatographic behavior of the synthetic standards in each solvent system is given in Table I.

Gas Chromatograph. A Pye gas chromatograph, Model 104, fitted with an alkali flame ionization detector and a rubidium chloride annulus was used throughout. Separations were effected using a 1.52 m × 6.35 mm o.d. glass column packed with either 4% SE 30/6% QF 1 or 3% SE 30 on 100/120 Mesh Gas-Chrom Q. The column flow was set at 40 ml/min nitrogen; on-column injection was used and the injector port was not heated. The retention times of the synthetic standards relative to fenitrothion are also reported in Table I.

Equipment. Ir spectra were recorded as films or as nujol mulls using a Beckman IR-20A infrared spectrophotometer. Proton NMR spectra were determined in deuterated acetone (unless otherwise specified) with Me_4Si as internal standard using a Varian T-60 NMR spectrometer. Mass spectra were obtained on a Finnigan 3100 GC–MS coupled to a D6000 data acquisition system.

Photolysis. Purified fenitrothion, dissolved in solvent (concentration 0.02 mg/ml), was irradiated at constant temperature (25 °C) with a low-pressure ultraviolet Pen Ray lamp (Model 11, SC-IL, 5.5 W, Ultraviolet Products Inc., San Gabriel, Calif.; 253.7 mμ line comprises 92% of total irradiation), while oxygen (20 ml/min) was bubbled through the solution. For the kinetic study, samples were taken at 10-min intervals and analyzed by GC. The amount of fenitrothion was determined by comparison of the peak area with those of standards. Concentration of the photolytic products was determined using standards.

RESULTS AND DISCUSSION

The disappearance of fenitrothion on uv irradiation in oxygenated solvents was found to follow first-order kinetics, similar to the photolysis of phosphorodithioates (Klisenko and Pis'mennaya, 1973). With the experimental conditions employed, the half-life ($t_{1/2}$) of fenitrothion in

Table I. GC and TLC Characteristics of Fenitrothion, Its Potential Photolytic Products, and Other Derivatives

Compd	No.	Rel retention times		R_f		
		3% SE 30[a]	4% SE 30/6% QF-1[b]	EtOAc/ hexane (3:2)	EtOAc/ cyclohexane (1:3)	EtOAc/ HAc/ toluene (7:1:5)
Fenitrothion	I	1.0	1.0	0.47	0.57	0.51
Hydroxymethylfenitrothion	IX	2.48	2.06	0.45	0.23	0.55
Formylfenitrothion	VII	1.41	1.56	0.47	0.26	0.58
Carboxyfenitrothion	XII				0.15	0.55
Carbomethoxyfenitrothion	XV	2.19	2.16	0.44	0.38	0.50
Denitrofenitrothion	XIV	0.28	0.22	0.48	0.41	0.57
S-Methylfenitrothion	III	1.58	1.67	0.30	0.1	0.38
S-Arylfenitrothion	V	1.40	1.64	0.26	0.09	0.43
Fenitrooxon	IV	0.84	1.12	0.22	0.06	0.32
Hydroxymethylfenitrooxon	X		2.19	0.14	0.01	0.26
Formylfenitrooxon	VIII	1.22	1.82	0.21	0.34	0.36
Carboxyfenitrooxon	XIII			0.16	0.01	0.31
Carbomethoxyfenitrooxon	XVI	1.82	2.16		0.03	
4-Nitro-*m*-thiocresol	VI	0.25	0.23	0.47	0.26	0.58
4-Nitro-*m*-cresol	II	0.31	0.29	0.42	0.20	0.52

[a] Column temperature, 190 °C; retention time of fenitrothion, 3.7 min. [b] Column temperature, 225 °C; retention time of fenitrothion, 3.5 min.

hexane was 85 min (coefficient of correlation (r) = 0.980 for the best fit straight line for plots of log concentration vs. time), which compares with $t_{1/2}$ = 120 min (r = 0.996) and $t_{1/2}$ = 7 min (r = 0.980) in methanol and water, respectively.

The main product of the reaction in hexane when half the fenitrothion had disappeared was fenitrooxon IV (14%), which was characterized by its GC–mass spectrum. Two minor products were also formed with retention times of 0.22 (5%) and 1.56 (7%) relative to fenitrothion. The first compound had a parent ion, m/e 232, and a base peak, m/e 109. Its NMR spectrum showed a doublet at τ 6.13 (6 H, J = 14 Hz), a singlet at τ 7.66 (3 H), and a multiplet at τ 3.62 (4 H). The compound was assigned the structure denitrofenitrothion (XIV), based on the parent ion in the MS, the coupling constant of the doublet in the NMR, and the absence of any absorption corresponding to a nitro group in the infrared. The structure was later confirmed by comparison of the spectral data with that of the synthetic standard.

The second minor product (relative retention time = 1.56) had a parent ion at m/e 291, with a base ion at m/e 125. In the NMR spectrum, the aromatic protons appeared as a multiplet at τ 2.04 equivalent to three protons and there was a singlet at τ −0.4, equivalent to one proton. The ir spectrum revealed strong absorption at 1700 cm^{-1}, which was attributed to the carbonyl stretching vibration of an aryl aldehyde group. The structure assigned to this compound was that of formylfenitrothion (VII) which was also confirmed by synthesis. A third minor product (relative retention time = 0.7), which had a molecular ion at m/e 231 and prominent ions at m/e 125 and 109, remains unidentified. Small amounts of *S*-methylfenitrothion (III) (≃0.7%) and 4-nitro-*m*-cresol (II) were also detected and characterized by GC–MS.

When fenitrothion was irradiated in methanol, the major product (16%) detected by GC after the disappearance of the insecticide had a relative retention time of 2.16. The MS of this product showed a parent ion at m/e 321, and a base ion at m/e 125. The absence of an M − 17 ion indicated changes had occurred at the aryl methyl position. The NMR showed a doublet at τ 6.09 (J = 14 Hz equivalent to six protons), a singlet at τ 6.02 equivalent to three protons, and a multiplet at τ 2.25 for three aromatic protons. On the basis of its NMR spectrum and the presence of a carbonyl band at 1725 cm^{-1} in the infrared, this product was assigned the structure of carbomethoxyfenitrothion (XV). Esterification of XII with etheral diazomethane resulted in a product with identical spectral and chromatographic characteristics. The carbomethoxyfenitrothion detected on irradiation resulted from the solvolysis of the intermediate carboxyfenitrothion (XII) formed on oxidation of the aryl methyl group of fenitrothion. Other products produced in lesser amounts were 4-nitro-*m*-cresol (≃3%) and *S*-methylfenitrothion (0.9%); only traces of fenitrooxon were detected in the initial stages of the reaction.

When acetone was used as the reaction medium, the only decomposition product detected by GC was 4-nitro-*m*-cresol; however, when the crude reaction mixture was treated with diazomethane, carbomethoxyfenitrothion (XV) and carbomethoxyfenitrooxon (XVI) were detected and characterized.

Ohkawa et al. (1974) showed that the principal mode of decomposition on photolysis involved oxidation of the aryl methyl group to give carboxyfenitrothion. The rate of photodecomposition of fenitrothion varies with the solvent but not the ratio of the products. With the experimental conditions employed in this work, solvent polarity affected both the rate and the products formed. Irradiation of fenitrothion in nonpolar hexane appeared to favor oxidation of the P=S, whereas in polar solvents oxidation occurred at the aryl methyl group.

Although formylfenitrothion (VII) was a photolytic product, no evidence for its precursor, hydroxymethylfenitrothion (IX), was found among the reaction products obtained on the irradiation of fenitrothion in hexane, acetone, or methanol. GC of the crude photolyzed mixtures revealed no peak when monitored by MS in the specific ion mode for the ions m/e 293, 125, 109, and 47. It appears that hydroxymethylfenitrothion is photolytically unstable and rapidly oxidized to formylfenitrothion (VII) and carboxyfenitrothion (XII). This instability contrasts strongly with that of the hydroxymethyldiazinon [*O,O*-diethyl *O*-(2-(2′-hydroxypropyl)-6-methylpyrimidin-4-yl) phosphorothioate] which was isolated on irradiation of diazinon and as a metabolite in plants (Pardue et al., 1970), and in animal tissues (Machin et al., 1971). The only oxidation product of fenitrothion involving the aryl methyl group that has been reported is carboxyfenitrothion (XIII), which was found in plants (Ohkawa et al., 1974) and in in vitro animal studies (Douch et al., 1968). The fact that

Table II. Mass Spectra of Fenitrothion, Its Photolytic Products, and Other Derivatives[a,b]

Fenitrothion	I	109, 125 (87), 79 (66), 93 (36), 277 (20) p, 260 (18), 62 (17), 51 (15), 77 (14), 89 (13)
Hydroxymethyl-fenitrothion	IX	125, 109 (48), 79 (45), 64 (24), 93 (23), 110 (12), 134 (12), 62 (12), 51 (10)
Formylfenitrothion	VIII	125, 79 (44), 63 (30), 109 (28), 217 (27), 93 (19), 62 (14), 142 (11)
Carbomethoxyfenitrothion	XV	125, 109 (92), 79 (59), 63 (51), 47 (44), 93 (26), 62 (23), 321 (21) p, 151 (13), 75 (12), 181 (11)
Carboxyfenitrothion[c]	XII	125, 63 (91), 79 (88), 109 (79), 171 (96) 307 (90)
S-Methylfenitrothion	III	125, 79 (51), 51 (27), 52 (25), 260 (24), 77 (22), 63 (21), 78 (19), 39 (17), 62 (15), 89 (15), 136 (11)
S-Arylfenitrothion	V	109, 79 (36), 125 (24), 63 (20), 121 (17), 93 (15) 39 (17), 45 (17), 77 (17), 47 (14), 51 (14), 260 (13), 69 (12), 78 (11)
Denitrofenitrothion	XIV	109, 232 (68) p, 105 (64), 79 (48), 125 (45), 93 (44), 91 (41), 63 (41), 63 (40), 65 (31), 77 (30), 104 (30), 51 (18)
Fenitrooxon	IV	109, 79 (28), 63 (20), 244 (20), 90 (17), 77 (15), 51 (14), 89 (14), 52 (13)
Formylfenitrooxon	X	109, 245 (47), 79 (43), 63 (40), 161 (29), 127 (25), 75 (12), 275 (12) p, 93 (11)
Carbomethoxyfenitrooxon	XVI	109, 104 (48) 79 (36), 274 (25), 63 (27), 199 (19), 77 (10), 125 (14), 51 (13), 244 (13), 193 (12), 93 (10), 127 (10), 305 (10) p
Carboxyfenitrooxon[c]	XIII	109, 79 (87), 63 (85), 274 (38), 200 (34), 199 (31), 135 (25), 286 (24), 62 (18), 64 (16), 107 (16)

[a] Ions < 50 amu or with an intensity < 10% base peak are not reported. [b] Figures in parentheses represent percent of base peak. [c] Probe sample.

hydroxymethyldiazinon is a tertiary alcohol whereas hydroxymethylfenitrothion is a primary alcohol could account for the difference in stability.

A synthetic sample of hydroxymethylfenitrothion was irradiated in oxygenated hexane; when all the starting material had disappeared, the crude photodecomposition mixture was separated into neutral and acid fractions. The presence of formylfenitrothion in the neutral fraction was confirmed by GC–MS. Esterification of the acid fraction with ethereal diazomethane gave carbomethoxyfenitrothion (XV) as the main product. This supports the postulate that hydroxymethylfenitrothion is a reactive intermediate in the photolysis of fenitrothion. A second product was found in the esterified acid fraction in small amounts (<3%). Its GC–MS showed the same parent ion as for carbomethoxyfenitrooxon, *m/e* 305, but with a completely different fragmentation pattern. It had a base peak *m/e* 259, together with prominent ions *m/e* 125, 109, 93, 79, and 63 typical of dimethyl phosphorothioate esters. This product was tentatively identified as carbomethoxynitrosofenitrothion [*O,O*-dimethyl *O*-(4-nitroso-*m*-carbomethoxyphenyl) phosphorothioate] (XVII). It could have been formed by a photoinduced rearrangement of fenitrothion aldehyde (VII) to yield carboxynitrosofenitrothion, which was subsequently esterified by treatment with diazomethane. The photolytic transformation of *o*-nitrobenzaldehyde to the corresponding *o*-nitrosobenzoic acids has been reported in solution (Sachs and Hilpert, 1904, 1906) and in the solid state (Schmidt, 1967).

To study this rearrangement of *o*-nitroarylaldehydes, formylfenitrothion (VII) was irradiated in hexane under nitrogen, in order to suppress the oxidation reaction. When the starting material had disappeared, the photodecomposition products were subjected to GC–MS analysis. Among the products, one was observed which was isomeric with but different from the starting aldehyde VII. The MS of this compound with parent ion *m/e* 291 and a base ion *m/e* 259 suggested the structure of carboxynitrosofenitrothion [*O,O*-dimethyl *O*-(4-nitroso-3-carboxyphenyl) phosphorothiate] (XVIII).

Another side reaction observed on the photolysis of fenitrothion was the loss of a nitro group to give denitrofenitrothion; this reaction took place rapidly in hexane but to a lesser extent in methanol. Parathion also loses a nitro group on uv irradiation. Joiner and Baetcke (1974) detected both denitroparathion [*O,O*-diethyl *O*-phenyl phosphorothioate] and its corresponding oxon analogue.

By further analogy with the irradiation of parathion, where both the *S*-alkyl and *S*-aryl isomers have been reported (Joiner and Baetcke, 1973, 1974), isomerization should also occur in the case of fenitrothion. Ohkawa et al. (1974) detected traces of *S*-methylfenitrothion only when fenitrothion was irradiated in methanol under nitrogen. In this study, it was detected in all reactions involving oxygenated solvents. However, no *S*-aryl isomer was detected even by specific ion monitoring of the crude photolytic products, even though *S*-arylfenitrothion is relatively stable to uv irradiation. This could be explained by the relative ease of isomerization of methyl esters of phosphorothioic acid compared to the ethyl and aryl esters (Eto et al., 1968).

The general scheme proposed by Ohkawa et al. (1974) for the photolysis of fenitrothion can be expanded to include the new products, together with those from formyl- and hydroxymethylfenitrothion (Figure 1).

The syntheses of hydroxymethyl-, formyl-, and carboxyfenitrothion, their oxon analogues, and *S*-arylfenitrothion were readily achieved by standard methods. Prominent ions in the mass spectra of these fenitrothion derivatives are presented in Table II. Apart from denitrofenitrothion, none of the compounds show a strong parent ion. In general, dimethyl aryl phosphorothioates (P=S) show a base peak *m/e* 125 [$(CH_3O)_2PS^+$] plus a strong ion *m/e* 93 [$(CH_3O)_2P^+$], due to direct fragmentation of the P–O–aryl bond. Fragmentation can also occur following isomerization in the source to give ions *m/e* 109 [$(CH_3O)_2PO^+$] and *m/e* 79 [CH_3OPOH^+] (Jorg et al., 1966). Fenitrothion itself has a base peak *m/e* 109, together with a strong ion *m/e* 125, indicative of fragmentation occurring by both mechanisms. The two phosphorothioates (P–S–C), *S*-methylfenitrothion and *S*-arylfenitrothion, show different base ions, *m/e* 125 [$CH_3S{\cdot}CH_3OP(O)^+$] and *m/e* 109, respectively, due to cleavage of the P–O–aryl and P–S–aryl bonds. Finally,

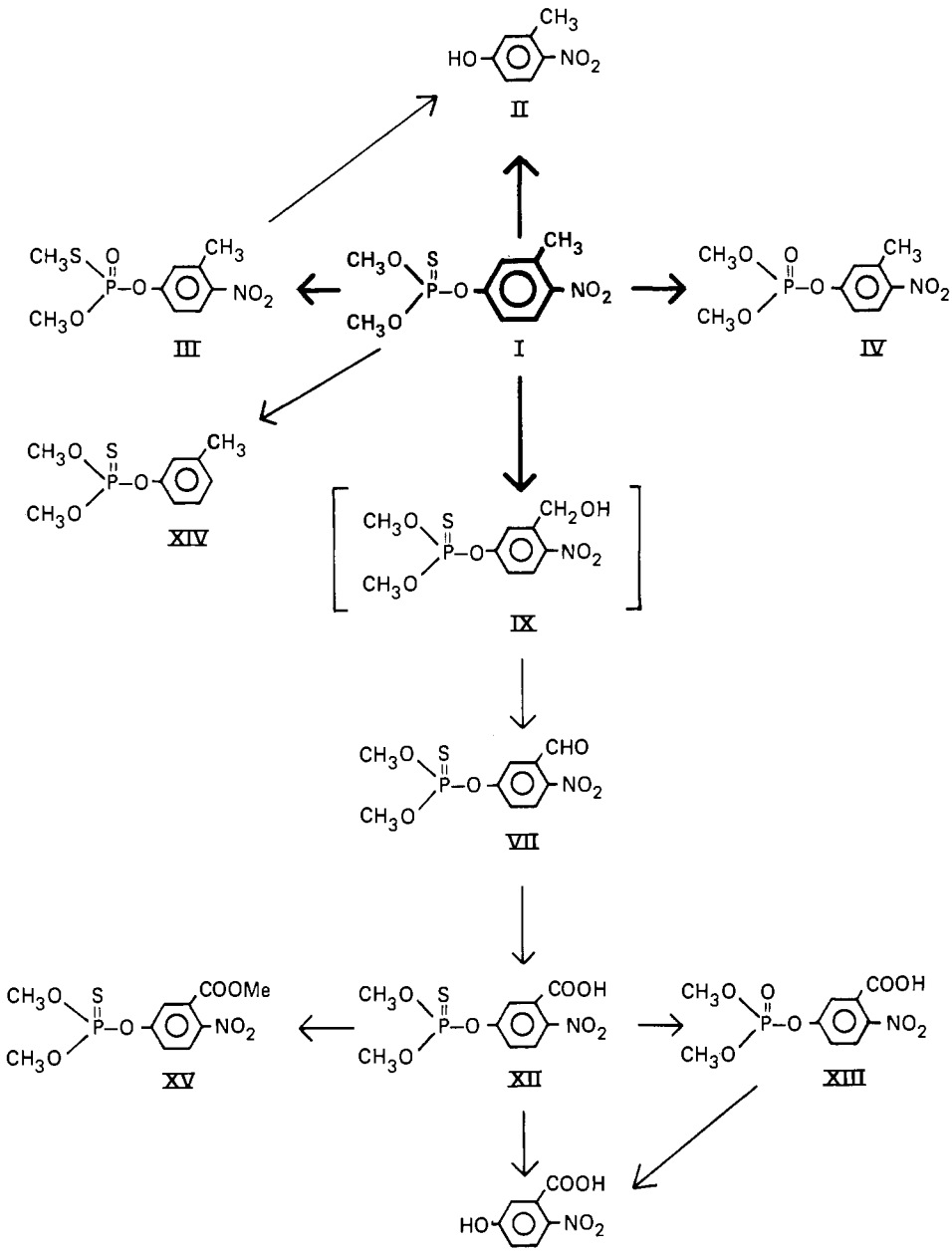

Figure 1. Photolytic degradation of fenitrothion in organic solvents.

dimethyl aryl phosphates generally show the ion m/e 109 [$(CH_3O)_2PO^+$] as the base ion, together with a strong ion m/e 79 [CH_3OPOH^+].

All compounds possessing the methyl group adjacent to the nitro group show an M – 17 ion. It is thought to be due to the loss of OH by a McLafferty rearrangement involving proton abstraction by an oxygen of the nitro group. It was used diagnostically to indicate an intact methyl group adjacent to the nitro group on the aromatic ring.

In summary, oxidation is confirmed as the major photolytic decomposition route for fenitrothion in solution. In hexane this preferentially involved the P=S, whereas in polar solvents oxidation of the aryl methyl group is the main reaction. The loss of the nitro group together with isomerizations, such as the formation of the *S*-methyl isomer and the conversion of *o*-nitroarylaldehyde to *o*-nitrosoarylcarboxylic acids, have been shown to take place; however, they represent minor degradative pathways. Fenitrothion differs from parathion in that it did not form any *S*-aryl isomer on irradiation.

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Crystal and Molecular Structure of Organophosphorus Insecticides. 3. Azinphos-methyl

Wayne J. Rohrbaugh, Elaine K. Meyers, and Robert A. Jacobson*

The crystal and molecular structure of azinphos-methyl (*O,O*-dimethyl *S*-(4-oxo-1,2,3-benzotriazin-3-yl)methyl phosphorodithioate), $C_{10}H_{12}N_3O_3PS_2$, has been determined by three-dimensional x-ray analysis. The compound crystallizes in the monoclinic space group $P2_1/c$ with $a = 12.084 \pm 0.007$, $b = 15.190 \pm 0.008$, $c = 7.856 \pm 0.003$ Å, and $\beta = 98.39 \pm 0.03°$ with $Z = 4$. Graphite-monochromated Mo Kα radiation ($\lambda = 0.70954$ Å) was used for measurement of diffraction data at 10 °C. The structure was solved via direct methods and refined by a full-matrix least-squares procedure to a final discrepancy index of $R = \Sigma||F_o| - |F_c||/\Sigma|F_o| = 0.080$. The phosphorus–(carbonyl carbon) distance corresponding to the anionic–esteratic site separation of acetylcholinesterase is 4.83 (2) Å for azinphos-methyl in the solid state. No appreciable intramolecular interactions which might limit the accommodation of a large range of anionic–esteratic separations were observed.

As discussed by Baughman and Jacobson (1975), accurate three-dimensional structural analyses of organophosphorus insecticides can provide useful information toward the elucidation of bioactive mechanisms. In the first of this series of structural investigations of organophosphorus insecticides, ronnel (*O,O*-dimethyl *O*-2,4,5-trichlorophenyl phosphorothioate) was studied and characterized. From that structural analysis it was found that the distance from the phosphorus to the meta hydrogen on the phenyl ring was 5.51 Å. When the autotoxicosis through inhibition of acetylcholinesterase (AChE) by organophosphorus insecticides is considered, it is interesting to note that the nitrogen to carbonyl carbon atom distance in acetylcholine is estimated at 4.7 Å (Chothia and Pauling, 1969), when the molecule is in a proper conformation to react with bovine erythrocyte AChE. From a series of experiments carried out by Hollingworth et al. (1967), however, it was concluded that the distance between the anionic and esteratic centers of fly head AChE may be as much as 1 Å greater than in the mammalian enzyme. Consequently, the distance between the phosphorus and an electron-deficient site in an effective organophosphorus insecticide would appear to be between approximately 4.7 and 5.7 Å.

The ubiquitous or specific effectiveness of a particular organophosphorus insecticide may depend, then, on its ability to accommodate a range of esteratic–anionic site distances in various AChE enzymes. In some organophosphorus insecticides, the range of phosphorus to positive center distances attainable by the molecule is limited by a single rotational degree of freedom for phosphorus about the aryl ring system. For example, in ronnel, the phosphorus–meta hydrogen distance is limited by rotation of phosphorus about the C(1)–O(1) bond (Baughman and Jacobson, 1975). This limitation is reflected in a comparison of ronnel's LD_{50} for a particular AChE enzyme with the LD_{50}'s of other organophosphorus insecticides, assuming that the in vivo transport properties are similar and that the inhibition of AChE is the primary toxic mode.

For ronnel, the LD_{50} in female rats is 1740 mg/kg, whereas for azinphos-methyl it is 16 (Pesticides and Toxic Substances Effects Laboratory, 1973). This implies that azinphos-methyl, or more likely its P=O metabolite, is approximately 100 times more efficient than ronnel or its corresponding metabolite in the inhibition of rat AChE. It therefore becomes interesting to investigate the charge separation distance and steric hindrances in azinphos-methyl and to compare them to ronnel. Consequently, a single-crystal x-ray diffraction investigation of azinphos-methyl (*O,O*-dimethyl *S*-(4-oxo-1,2,3-benzotriazin-3-yl)methyl phosphorodithioate) was carried out.

EXPERIMENTAL SECTION

Crystal Data. A sample of the title compound was kindly supplied by P. A. Dahm. A crystal of dimensions 0.2 × 0.2 × 0.3 mm was mounted on a glass fiber with Duco cement and subsequently attached to a standard goniometer head. From six preliminary ω-oscillation photographs taken on an automated four-circle x-ray diffractometer at various χ and ϕ settings, 14 independent reflections were selected and their coordinates were input to the automatic indexing program ALICE (Jacobson, 1974).

The resulting reduced cell and reduced cell scalars indicated $2/m$ (monoclinic) symmetry. A monoclinic crystal system was confirmed by inspection of axial ω-

The Ames Laboratory–ERDA and the Department of Chemistry, Iowa State University, Ames, Iowa 50011.