Table V. Oxidative Bioactivation or Detoxification as Acetylcholinesterase Inhibitors of the Enantiomers of Profenofos by Mouse Liver Microsomal Oxidases and Soluble Fraction

protein, mg		AChE inhibition, %	
microsome	soluble	−NADPH	+NADPH
	(−)-Profenofos (20 μM)		
0	0	89 ± 2	90 ± 3
1	0	11 ± 6	96 ± 1
1	0.5	46 ± 2	97 ± 1
1	1	49 ± 5	98 ± 2
0	1	59 ± 5	81 ± 3
	(+)-Profenofos (10 μM)		
0	0	78 ± 2	84 ± 2
1	0	45 ± 5	59 ± 4
1	0.5	42 ± 5	47 ± 4
1	1	57 ± 4	49 ± 8
0	1	65 ± 4	52 ± 7

the toxicity of the profenofos enantiomers is due to a combination of factors: intrinsic potency as AChE inhibitors; bioactivation, presumably by S-oxidation; detoxification of the parent compound and the activated intermediate; aging differences for AChE inhibited by the (+)- and (−)-isomers depending on the leaving group on direct reaction or after oxidase activation. Sulprofos has the additional feature of requiring three sequential oxidative activation steps to form the oxon sulfone. These studies illustrate the value of optically resolved phosphorus compounds in studies on insecticide mode of action (Ohkawa, 1982).

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We thank our laboratory colleagues Greg Gorder for advice on the enzyme studies and Luis Ruzo for determination of the mass spectra.

Registry No. 1, 92642-31-4; 1a, 92642-32-5; 1b, 92642-33-6; 2, 92642-34-7; 3, 92642-35-8; 4, 92642-36-9; 4a, 92642-37-0; 4b, 92642-38-1; 5, 92642-39-2; 6, 92642-40-5; 6a, 92642-41-6; 6b, 92642-42-7; 7, 92760-41-3; 7a, 81116-98-5; 7b, 81123-19-5; 8, 92760-44-6; 8a, 92642-43-8; 8b, 92642-44-9; 9, 92760-45-7; 9a, 92642-45-0; 9b, 92642-46-1; 10, 92642-47-2; 11 (isomer I), 92642-48-3; 11 (isomer II), 92642-49-4; 12 (isomer I), 92642-50-7; 12 (isomer II), 92642-51-8; 13a, 92760-42-4; 13b, 92760-43-5; 14a, 92642-52-9; 14b, 92642-53-0; acetylcholinesterase, 9000-81-1; 4-(methylthio)phenol, 1073-72-9; *S*-propyl phosphorodichloridodithioate, 5390-61-4; L-proline ethyl ester, 5817-26-5; 4-bromo-2-chlorophenol, 3964-56-5; pentachlorophenol, 87-86-5.

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Photochemistry of Polychlorinated Phenoxyphenols. 2. Phototransformations of *m*-(Pentachlorophenoxy)-2,4,5,6-tetrachlorophenol

Peter K. Freeman* and Violet Jonas

The direct irradiation of *m*-(pentachlorophenoxy)-2,4,5,6-tetrachlorophenol (**1b**) in cyclohexane at 300 nm generates products resulting from reductive dechlorination (60%), ether cleavage (10%), and cyclization (1%). In contrast, photolysis in acetone at 300 nm provides 66% cyclization, 10% reductive dechlorination, and less than 2% ether cleavage. Irradiation of perchloro-*m*-phenoxyphenol (**1b**) in cyclohexane (300 nm) in the presence of *m*-methoxyacetophenone results in cyclization (7%), dechlorination (28%), and less than 1% ether cleavage. Photolysis of *m*-phenoxyphenol in acetone in the presence of the electron donor triethylamine at 300 nm leads to 54% dechlorination, 18% ring closure, and less than 1% ether cleavage. The mechanistic implications of these results are described.

Our interest in the phototransformations of the isomeric perchlorophenoxyphenols (**1a–c**) is based upon their presence as major impurities in pentachlorophenol (up to 15% present in the technical product) (Rappe and Nilsson, 1972; Jensen and Renberg, 1972; Nilsson and Renberg, 1974; Deinzer et al., 1978, 1979, 1981a), their absorption in the sunlight range (near 300 nm), and their potential for photocyclization to polychlorodibenzodioxins and

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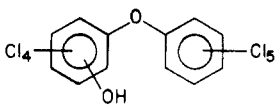


1a, ortho OH
1b, meta OH
1c, para OH

hydroxypolychlorodibenzofurans. In our earilier study of ortho isomer **1a** (Freeman and Srinivasa, 1983), we observed that direct irradiation of predioxin (**1a**) results in ether cleavage and reductive dechlorination, while sensitized irradiations generate polychlorodibenzodioxins and hydroxyheptachlorodibenzofuran. If an analogous photochemical cyclization process occurs with meta substrate **1b** and is followed by photodechlorination in the presence of hydrogen donor, there is the potential for formation of polychlorodibenzofurans that mimic the highly toxic nature of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) (Greig, 1979) in the dibenzofuran series [e.g., 2,3,7,8-tetrachlorodibenzofuran is only slightly less toxic than TCDD (Moore et al., 1979)].

EXPERIMENTAL SECTION

Materials Used for the Photolyses. Spectograde cyclohexane (Mallinckrodt), spectrograde acetone (Baker), and *m*-methoxyacetophenone (Aldrich, 99%) were used as obtained.

Synthesis of Perchloro-*m*-Phenoxyphenol. The synthesis of perchloro-*m*-phenoxyphenol (**1b**) was carried out according to the procedures of Deinzer et al. (1981b) and Ballester (1960).

Product Analyses. The photoproducts were identified by gas–liquid chromatographic–mass spectrometric (GLC–MS) analysis. For the products for which authentic samples were available [chlorinated benzenes, pentachlorophenol, chlorocyclohexane, bicyclohexyl, and perchloro-*m*-phenoxyphenol (**1b**)], the structures were determined by comparison of GLC retention times and mass spectra. The structures of other product components were determined (in some cases partially) by analysis of the electron impact (EI) mass spectra, negative ion chemical ionization (CI) mass spectra, and in some cases positive ion CI mass spectra. Mass spectra were obtained at 70 eV by using a Finnigan 4023 mass spectrometer equipped with a Finnigan 9610 gas chromatograph. In most cases a 6 ft × 2 mm i.d. Pyrex column packed with 7% OV-101 on 100/120 HP Chromasorb W was used, and the column temperature was programmed from 50 to 310 °C at 10 °C/min. For the acetone photolysis mixture a GLC–negative ion CI MS analysis was also carried out using a 15 m × 0.25 mm i.d. SE-54 capillary column; in this case the column temperature was programmed from 200 to 310 °C at 2 °C/min. Also, GC–mass spectral analysis was carried out on methylated photolysis mixtures. In each case a known portion of the photolysis mixture was methylated with a solution of diazomethane in ether.

Gas chromatographic analyses were also carried out using a Varian 3700 gas chromatograph equipped with a flame ionization detector and a Hewlett-Packard 3373B integrator. A 6-ft glass column (o.d. = $^1/_4$ in., i.d. = 2 mm) packed by Supelco with 3% SP-2100 on Supelcoport was used; the temperature was programmed from 60 (2-min hold) to 270 °C at 10 °C/min, and the helium flow rate was 46 mL/min. Earlier analyses were done using either a 5 ft × $^1/_8$ in. copper column packed with 0.56% SE-30 on Anakrom-AS (110–120 mesh) or a 4 ft × $^1/_8$ in. aluminum column packed with 0.55% SE-30 on Anakrom-AS (70–80 mesh). The response factors for known compounds (chlorinated benzenes, pentachlorophenol, chlorocyclohexane, bicyclohexyl, and perchloro-*m*-phenoxyphenol (**1b**) were determined by using dodecane as the internal standard. For the other products, the response factors were carefully estimated in the following manner. Since the response factors for PCP and perchloro-*m*-phenoxyphenol (**1b**) were found to be approximately equal for similar concentrations of these two compounds, **1b** was used for determining the response factors for the products containing six chlorines or more, and PCP was used for determining the response factors for products **18–20**. The unmethylated photolysis mixtures were used for the quantitative analyses.

The HPLC analyses and separations were carried out using a Waters Associates ALC 202 HPLC equipped with a Model 6000A pump system and a differential UV detector (254-nm wavelength was used). A 4.6 mm i.d. × 25 cm stainless steel column packed with LiChrosorb Si 60 (particle size = 5 μm) was used, and a mixture of 75% or more 2,2,4-trimethylpentane, 15% or less dichloromethane, and 10% or less methanol was used as the eluting solvent. Quantitative analyses of 3-hydroxyheptachlorodibenzofuran (**2**), 3-hyroxyhexachlorodibenzofuran (**4**), and perchloro-*m*-phenoxyphenol (**1b**) were carried out for all of the photolysis reaction mixtures using pentachlorophenol (PCP) as the internal standard. In each case, a known amount of PCP was added to a known fraction of the photolysis mixture after the photolysis had been carried out. A standard containing **1b** and PCP and a standard containing the dibenzofuran **2** and PCP were used for determining the HPLC response factors of **1b** and **2** vs. PCP. In order to prepare the standard containing **2**, 1 mg of **2** was isolated by HPLC from one of the acetone photolysis mixtures. Not enough **4** was isolated by HPLC; thus, its concentration was approximated by assuming its HPLC response factor to be equal to that of **2**.

General Photolysis Procedure. The samples to be photolyzed were placed in quartz tubes (170 mm × 15 mm) with Pyrex glass sliding stoppers and were degassed by using about four freeze–pump–thaw cycles and then sealed in vacuo. The photolysis samples were placed inside a Rayonet merry-go-round photochemical reactor (The Southern New England Co.) equipped with eight 3000-Å Rull lamps. During the photolysis, air was blown through the Rayonet reactor; the photolysis temperature was about 45–55 °C. Quantum yields of the photoproducts were determined by using the photoconversion of cyclopentanone to 4-pentenal as the actinometer (Dunion and Trumbore, 1965).

Identification of the Products. The formation of all of the products, except 3- and 1-hydroxyhexachlorodibenzofuran (**4, 5**), was detected by GLC–MS analysis. The formation of **4** in the photolysis in acetone in the presence of 11.6-fold excess triethylamine and the formation of **4** and **5** in the photolysis in acetone were detected in each case by mass spectral analysis of fractions obtained in an HPLC separation. Also, for the photolysis in acetone, the formation of the following compounds was detected by the HPLC–mass spectral analyis: 3- and 1-hydroxyheptachlorodibenzofuran (**2, 3**) and the acetonyl ethers of perchloro-*m*-phenoxyphenol (**1b**), (**44**) and octachloro-3-phenoxyphenol (**42, 43**). For the photolysis in cyclohexane the following compounds were detected by the mass spectral analysis of their HPLC fractions: 3-hydroxyheptachlorodibenzofuran (**2**), octachloro-3-phenoxyphenol (**25, 26, 27**), and the cyclohexyl ether of perchloro-*m*-phenoxyphenol (**1b**), (**36**).

The formation of 3-hydroxyheptachlorodibenzofuran (**2**) and 1-hydroxyheptachlorodibenzofuran (**3**) in the acetone

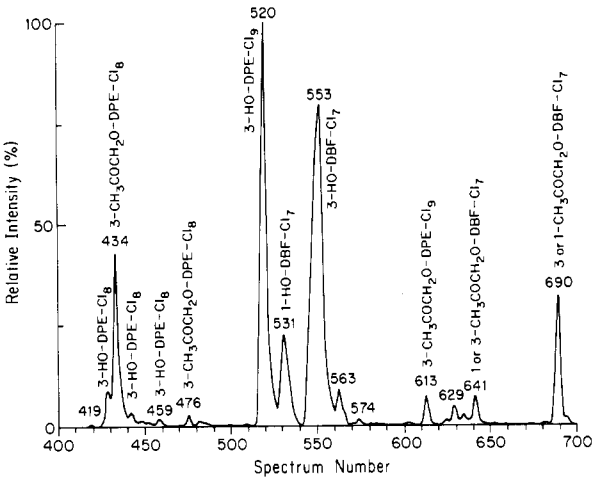


Figure 1. Ion chromatogram of the acetone photolysis product mixture under electron capture negative ion chemical ionization mass spectrometry using a 15 m × 0.25 mm i.d. SE-54 capillary column; column temperature was programmed from 200 to 310 °C at 2 °C/min.

photolysis was first detected by HPLC–mass spectral analysis as described above, and subsequently by GLC–mass spectral analysis of the photolysis mixture. The GLC retention time of **2** was greater than that of **3**, and the relative molar ratio of **2**/**3** = 12 (see Figure 1). In the EI mass spectrum of **2** the molecular ion peak cluster is based at 422, has a relative intensity of 100 at *m/e* 424, and shows the following isotope abundance pattern: 422 (44.7), 424 (100), 426 (98.8), 428 (54.4), 430 (19.1), and 432 (2.4). A small M – Cl fragment ion peak cluster is based at 387 and has a relative intensity of 4.60 at *m/e* 389. The EI mass spectrum of **3** shows the same fragmentation pattern as that of **2** and the following isotope abundance pattern for the molecular ion: 422 (41.2), 424 (100), 426 (91.1), 428 (53.4), 430 (9.59), and 432 (2.37). The negative ion CI mass spectrum of **2** shows an intense fragment ion peak cluster based on 386 due to loss of H^+ to form the phenoxide ion accompanied by loss of Cl (M – 36); it has a relative intensity of 100 at *m/e* 388 and the following isotope abundance pattern: 386 (34.3), 388 (100.0), 390 (82.6), and 392 (45.1). There is also a very weak M – 1 peak cluster with a relative intensity of 1.15 at *m/e* 423. The negative ion CI mass spectrum of **3** shows the same fragmentation patterns and the M – 36 ion cluster shows a clear 6-Cl isotope abundance pattern: 386 (48.0), 388 (100.0), 390 (84.3), 392 (39.8), 394 (9.72), and 396 (1.55).

The formation of 3-hydroxyheptachlorodibenzofuran (**2**) was confirmed by a GLC–mass spectral (negative ion CI) analysis of the heptyl ether of **2**, which was prepared by using **2** that had been isolated from the acetone photolysis mixture by HPLC (Deinzer et al., 1982). The formation of 3- and 1-hydroxyheptachlorodibenzofuran (**2**, **3**) in the photolysis in acetone and the formation of **2** in all of the photolyses were confirmed by GLC–mass spectral analysis of the methylated photolysis mixtures. In each case the EI mass spectrum of the methoxyheptachlorodibenzofuran shows an intense molecular ion peak cluster based at 436, an intense fragment ion peak cluster based at 421 (M – CH_3), and an intense peak cluster based at 393 (M – CH_3 – CO). In most cases the molecular ion peak cluster shows a relatively clear 7-chlorine pattern; e.g., for the photolysis in acetone the parent peak cluster of methylated **2** has a relative intensity of 100 at *m/e* 438 and the following isotope abundance pattern: 436 (44.2), 438 (100), 440 (96.9), 442 (53.7), and 444 (15.0). The M – CH_3 ion cluster has a relative intensity of 65.2 at *m/e* 423, and the M – CH_3 – CO ion cluster has a relative intensity of 51.4 at *m/e* 395.

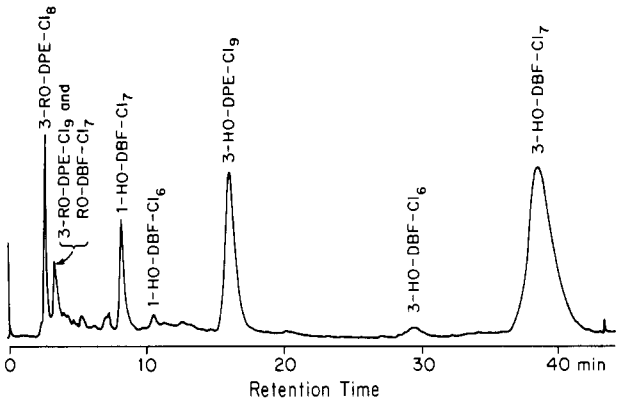


Figure 2. HPLC trace of the reaction mixture obtained in acetone. Eluting solvent: 88.9/4.4/6.7 TMP/CH_2Cl_2/MeOH.

The formation of two hydroxyheptachlorodibenzofurans is possible in the photocyclization of perchloro-*m*-phenoxyphenol (**1b**) (the 1- and 3-hydroxy species **3** and **2**), and these are both formed in the acetone photolysis in yields of 4.5 and 55.1%. The GLC retention time of the minor dibenzofuran product is shorter than that of the major dibenzofuran product but longer than that of the starting material, perchloro-*m*-phenoxyphenol (Figure 1). The HPLC retention time of the minor dibenzofuran product is very much shorter than that of the major product; in fact, the HPLC retention time of the minor product is even shorter than that of the starting material, perchloro-*m*-phenoxyphenol, whereas the HPLC retention time of the major product is significantly longer than that of perchloro-*m*-phenoxyphenol (Figure 2). These results suggest that the minor product component is the 1-hydroxy isomer, since the O–H group is positioned on the dibenzofuran ring system much more favorably for intramolecular hydrogen bonding with chlorine than in the 3-hydroxy isomer. The hydrogen of the C-1 hydroxy group may position itself significantly closer to the chlorine at C-9 than the 3-hydroxyl hydrogen can to either ortho chlorine, and in doing so, the 1-hydroxyl can come closer to achieving the ideal colinear geometry for O–H···Cl (Smith, 1973; Pimentel and McClellan, 1960) than is possible for the ortho chlorine–3-hydroxyl interaction. Thus, the stronger intramolecular hydrogen bonding of the 1-hydroxy isomer reduces its intermolecular interactions with the chromatographic stationary phase and provides a shorter retention time.

The formation of 3- and 1-hydroxyhexachlorodibenzofuran (**4**, **5**) was detected by mass spectral analysis of fractions obtained in an HPLC separation rather than by GLC–mass spectral analysis. In the EI mass spectrum of **4** isolated from the acetone photolysis mixture, the molecular ion peak cluster is based at 388 and shows the following isotope abundance pattern: 388 (55.6), 390 (100), 392 (81.5), 394 (33.3) 396 (8.08), and 398 (1.01). The EI mass spectrum of **4** isolated from the acetone photolysis in the presence of 11.6-fold excess triethylamine shows the same molecular ion and fragment ion peak clusters. This isolated **4** was methylated and subjected to GLC–mass spectral analysis. The EI mass spectrum shows a very intense molecular ion peak cluster based at 402 (relative intensity = 87.7 at *m/e* 404), a very intense fragment ion peak cluster based at 387 (M – CH_3) (relative intensity = 100.0 at *m/e* 389), and a medium ion peak cluster based at 359 (M – CH_3 – CO) (relative intensity = 38.6 at *m/e* 361), confirming **4** to be a hydroxyhexachlorodibenzofuran. The parent peak cluster has the following isotope abundance pattern: 402 (50.1), 404 (100.0), 406 (84.7), 408

(31.8), 410 (7.43), and 412 (0.95).

The formation of hepta- and octachloro-3-phenoxyphenols was detected by GLC–mass spectral analysis of both the methylated and unmethylated photolysis mixtures. The EI mass spectra of the unmethylated products **25**, **26**, and **27** each showed a medium (or sometimes weak) molecular ion peak cluster based at 458 (8-Cl pattern) and a strong M – 70 fragment ion peak cluster based at 388 (6-Cl pattern; loss of Cl_2), indicating that these three products consist of octachlorophenoxyphenols. In the case of the unmethylated products **23** and **24** the EI mass spectra each showed a medium molecular ion peak cluster based at 424 and an intense M – 70 fragment ion cluster based at 354, indicating that these two products consist of heptachlorophenoxyphenols.

The negative ion CI mass spectra of the unmethylated heptachloro-3-phenoxyphenols **23** and **24** show a medium to intense P-37 fragment ion peak cluster based at 387, indicating the loss of the phenolic hydrogen accompanied by the loss of HCl upon cyclization. The negative ion CI mass spectrum of the heptachloro-3-phenoxyphenol **23** obtained in the cyclohexane photolysis shows an intense ion cluster based at 229 and a medium ion cluster based at 194, but none at 263, whereas the negative ion CI mass spectrum of **24** shows a medium ion cluster based at 263, but none at 229, indicating that in **23** there are three chlorines on the phenolic ring and four chlorines on the nonphenolic ring, whereas in **24** there are five chlorines on the nonphenolic ring and two on the phenolic ring. The negative ion CI mass spectra of the octachloro-3-phenoxyphenols **25**, **26**, and **27** show a medium M – 37 ion cluster based at 421 (loss of phenolic H accompanied by loss of HCl upon cyclization) and a strong M – 71 ion cluster based at 387 (loss of phenolic H accompanied by loss of Cl_2 upon cyclization).

The EI mass spectra of the methylated photolysis mixtures are in agreement with the conclusion that products **23** and **24** consist of heptachlorophenoxyphenols and products **25**, **26**, and **27** consist of octachlorophenoxyphenols. The mass spectra of methylated **23** and **24** show a medium molecular ion peak cluster based at 438 and a strong M – 70 fragment ion peak cluster based at 368, and the mass spectra of methylated **25**, **26**, and **27** show a medium to intense molecular ion cluster based at 472 and a strong M – 70 ion cluster based at 402.

The masses of the molecular ion peak clusters obtained in the mass spectra of products **28–36** and **42–46** indicate the incorporation of a solvent moiety (cyclohexyl, CH_2COCH_3) into the product. GLC and GLC–mass spectral analysis of the methylated photolysis mixture indicates that in most of the dechlorination products (except **30** and **35**) the solvent moiety is attached to the oxygen atom rather than to one of the benzene carbon atoms, thus forming an ether, since there is no change in either the GLC retention time or in the mass spectra upon treatment with diazomethane.

GLC and GLC–mass spectral analysis of the methylated photolysis mixture (cyclohexane) indicates that product **35** is phenolic and thus that the cyclohexyl group is attached to one of the benzene carbon atoms. Methylation caused the GLC peak corresponding to product **35** to shift to a retention time that was 83 s shorter. The EI mass spectrum of the new GLC peak shows a medium molecular ion peak cluster with a clear 8-Cl pattern based at 554 instead at 540, indicating methylation of a free hydroxy group. Analogous results were obtained for product **30**. In the EI mass spectrum of methylated **30** the molecular ion cluster is based at 520 instead of 506, indicating methylation of the hydroxy group.

Table I. Photolysis[a] of Nonachloro-3-phenoxyphenol in Cyclohexane

compound[b]	yield,[c] mol %	quantum yield × 10^3
6, chlorocyclohexane	41.5	12.4
7, 1,3-dichlorobenzene[d]	1.9	0.6
8, 1,4-dichlorobenzene[d]		
9, 1,2-dichlorobenzene	2.4	0.7
10, 1,3,5-trichlorobenzene	1.0	0.3
11, 1,2,4-trichlorobenzene	1.3	0.4
12, 1,2,3-trichlorobenzene	0.5	0.1
13, bicyclohexyl	6.9	2.1
14, 1,2,3,5-tetrachlorobenzene[d]	0.4	0.1
15, 1,2,4,5-tetrachlorobenzene[d]		
16, 1,2,3,4-tetrachlorobenzene	0.8	0.2
17, pentachlorobenzene	1.1	0.3
18, tetrachlorophenol	0.3	0.1
19, pentachlorophenol	0.6	0.2
20a–e, cyclohexyl derivatives of ether cleavage products[e]	0.7	0.2
21, **22**, hexachloro-*m*-phenoxyphenols	0.6	0.2
23, heptachloro-*m*-phenoxyphenol	4.0	1.2
24, heptachloro-*m*-phenoxyphenol	5.0	1.5
25, **26**, **27**, octachloro-*m*-phenoxyphenols	30.0	9.0
1b, unreacted perchloro-*m*-phenoxyphenol	19.7	
2, 3-hydroxyheptachlorodibenzofuran	1.3	0.4
28, 3-cyclohexoxyhexachlorodiphenyl ether	0.3	0.1
29, 3-cyclohexoxyheptachlorodiphenyl ether	1.4	0.4
30, cyclohexylheptachloro-*m*-phenoxyphenol	2.1	0.6
31, **32**, **33**, **34**, 3-cyclohexoxyoctachlorodiphenyl ethers	9.7	2.9
35, cyclohexyloctachloro-*m*-phenoxyphenol	4.6	1.4
36, 3-cyclohexoxynonachlorodiphenyl ether	3.9	1.2
38, 3-cyclohexoxycyclohexylheptachlorodiphenyl ether	1.7	0.5
39, 3-cyclohexoxycyclohexyloctachlorodiphenyl ether	0.5	0.1

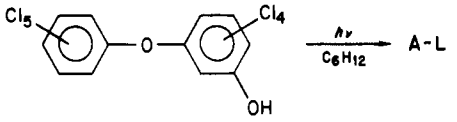
[a] Two hours at 300 nm; concentration of **1b** = 0.00494 M. [b] All of the product components are listed in order of increasing GLC retention time. [c] The yields are based on the moles of product formed per mole of nonachloro-3-phenoxyphenol photolyzed. [d] The GLC peaks for 1,3- and 1,4-dichlorobenzene as well as those for 1,2,3,5- and 1,2,4,5-tetrachlorobenzene could not be resolved on the SE-30, the OV-101, or the SP-2100 column, all of which were used for the analyses. [e] See Scheme I for more detail.

RESULTS AND DISCUSSION

Since perchloro-*m*-phenoxyphenol (**1b**) exhibits a λ_{max} at 300 nm, all photolyses were carried out at this wavelength. Irradiation of **1b** in cyclohexane for 2 h yielded the products shown in Scheme I and in Table I. The major reaction pathways are (a) reductive dechlorination leading to the chlorinated phenoxyphenols **21–27**, (b) ether cleavage producing pentachlorobenzene (**17**) and dechlorination products of **17** (**7–12**, **14–16**), as well as some tetra- and pentachlorophenol (**18** and **19**), and (c) ring closure yielding 3-hydroxyheptachlorodibenzofuran (**2**). Each of the pathways is accompanied by cyclohexyl derivative formation, the cyclohexane ring being attached either to the hydroxy oxygen atom or to one of the aromatic carbon atoms. Two products are formed (**38** and **39**), each containing two cyclohexane rings, one of the rings being attached to the oxygen atom and the other ring to an aromatic carbon atom. Also, the cyclohexyl ether of the starting material is produced (**36**). The results in Table I indicate that 59.9% of the starting material undergoes reductive dechlorination, 10.2% undergoes ether cleavage, and 1.3% undergoes ring closure.

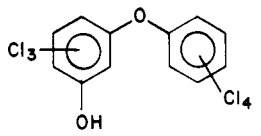
Photolysis of perchloro-*m*-phenoxyphenol (**1b**) in acetone results in the same three photoconversion pathways that were observed for the photolysis using cyclohexane

Scheme I



1b

A, dichlorobenzenes (7, 8, 9)
B, trichlorobenzens (10, 11, 12)
C, tetrachlorobenzenes (14, 15, 16)
D, pentachlorobenzene (17) and cyclohexylpentachlorobenzene (20a)
E, tetrachlorophenol (18), cyclohexoxytetrachlorobenzene (20b), and cyclohexyltetrachlorophenol (20c)
F, pentachlorophenol (19) and cyclohexoxypentachlorobenzene (20d)
G, 3-cyclohexoxytetrachlorophenol (20e)
H, hexachloro-*m*-phenoxyphenols (21, 22) and a cyclohexyl derivative (28)
I, heptachloro-*m*-phenoxyphenols (23, 24) and their cyclohexyl derivatives (29, 30, 38)
J, octachloro-3-phenoxyphenols (25-27) and their cyclohexyl derivatives (31-35 and 39)
K, 3-hydroxyheptachlorodibenzofuran (2)
L, 3-cyclohexoxynonachlorodiphenyl ether (36)



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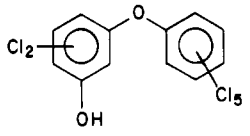


24

Table II. Photolysis[a] of Nonachloro-3-phenoxyphenol in Acetone

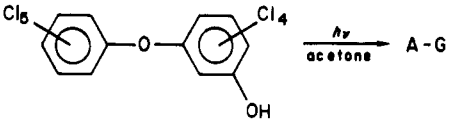
compound[b]	yield,[c] mol %	quantum yield × 10^3
17, pentachlorobenzene	0.6	0.2
19, pentachlorophenol	0.9	0.3
40, 3-acetonoxyheptachlorodiphenyl ether	0.4	0.1
41, 3-acetonoxyheptachlorodiphenyl ether[d]	0.2	0.06
24, heptachloro-*m*-phenoxyphenol[d]		
25, 26, 27, octachloro-*m*-phenoxyphenols	5.3	1.8
42, 43, 3-acetonoxyoctachlorodiphenyl ethers	4.1	1.4
1b, unreacted perchloro-*m*-phenoxyphenol	25.2	
3, 1-hydroxyheptachlorodibenzofuran	4.5	1.5
2, 3-hydroxyheptachlorodibenzofuran	55.1	18.3
44, 3-acetonoxynonachlorodiphenyl ether	1.6	0.5
45, 1- or 3-acetonoxyheptachlorodibenzofuran	1.4	0.5
46, 3- or 1-acetonoxyheptachlorodibenzofuran	3.2	1.1
4, 3-hydroxyhexachlorodibenzofuran	1.1	0.4
5, 1-hydroxyhexachlorodibenzofuran	1.1	0.4

[a] Two hours at 300 nm; concentration of **1b** = 0.00524 M. [b] All of the compounds are listed in order of increasing GLC retention time, except **4**, **5**, and **42**. [c] See footnote *c* of Table I. [d] The GLC peaks for **41** and **24** overlap.

as the solvent. However, in the case of acetone, cyclization to dibenzofurans is the major photoconversion pathway, reminiscent of the enhanced cyclization found in our earlier study (Freeman and Srinivasa, 1983) and that of Choudhry et al. (1977). Irradiation of **1b** at 300 nm for 2 h yielded the products shown in Scheme II and Table II.

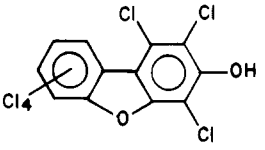
The results in Table II indicate that 66.4% of the starting material undergoes cyclization, whereas only 10.0% undergoes reductive dechlorination and 1.5% ether cleavage. The much higher yield of cyclization products in the case of acetone (66.4 mol %) relative to that of the cyclohexane experiment (1.3 mol %) suggests that acetone is acting as a photosensitizer. In order to test this view, the irradiation of perchloro-*m*-phenoxyphenol (**1b**) was carried out in cyclohexane at 300 nm in the presence of

Scheme II



1b

A, pentachlorobenzene (17)
B, pentachlorophenol (19)
C, heptachloro-3-phenoxyphenol (24) and acetonyl derivatives of heptachloro-3-phenoxyphenols (40, 41)
D, octachloro-*m*-phenoxyphenols (25-27) and acetonyl derivatives of octachloro-*m*-phenoxyphenoxyphenol (42, 43)
E, 3- and 1-hydroxyheptachlorodibenzofurans (2, 3) and their acetonyl ethers (45, 46)
F, 3- and 1-hydroxyhexachlorodibenzofurans (4, 5)
G, acetonyl ether of perchloro-*m*-phenoxyphenol (**1b**) (44)



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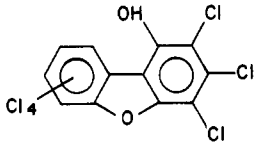

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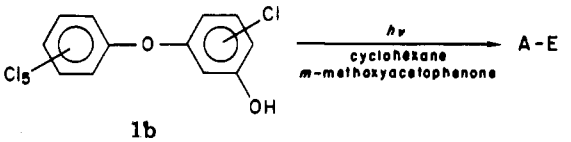
Scheme III



1b

A, pentachlorobenzene (17)
B, heptachloro-*m*-phenoxyphenols (23, 24) and cyclohexylheptachloro-3-phenoxyphenol (30)
C, octachloro-*m*-phenoxyphenols (25-27) and their cyclohexyl derivatives (32-35)
D, 3-hydroxyheptachlorodibenzofuran (2)
E, 3-cyclohexoxynonachlorodiphenyl ether (36)

Table III. Photolysis[a] of Nonachloro-3-phenoxyphenol in Cyclohexane in the Presence of 19.5-fold Excess *m*-Methoxyacetophenone

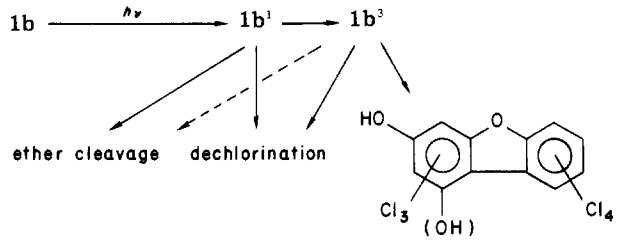
compound[b]	yield,[c] mol %	quantum yield × 10^3
17, pentachlorobenzene	0.1	0.03
23, heptachloro-3-phenoxyphenol	0.6	0.2
24, heptachloro-3-phenoxyphenol	0.3	0.1
25, 26, 27, octachloro-3-phenoxyphenol	18.1	5.8
1b, unreacted perchloro-*m*-phenoxyphenol	39.1	
2, 3-hydroxyheptachlorodibenzofuran	6.9	2.2
30, cyclohexylheptachloro-*m*-phenoxyphenol	1.0	0.3
32, 33, 34, 3-cyclohexoxyoctachlorodiphenyl ethers	4.7	1.5
35, cyclohexyloctachloro-*m*-phenoxyphenol	2.9	0.9
36, 3-cyclohexoxynonachlorodiphenyl ether	9.5	3.0

[a] Two hours at 300 nm; concentration of **1b** = 0.00500 M. [b] All of the compounds are listed in order of increasing GLC retention time. [c] See footnote *c* of Table I.

sensitizer *m*-methoxyacetophenone. The results, presented in Scheme III and Table III, show that cyclization takes place to an extent of 6.9%, 27.6% reductive dechlorination occurs, and less than 1% ether cleavage is observed.

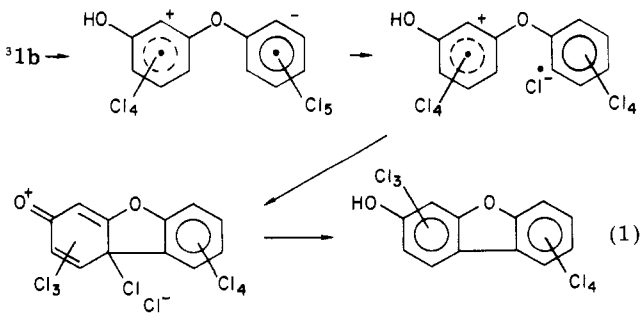
Thus, the presence of a sensitizer increases cyclization and decreases dechlorination and ether cleavage. The quantum yield for cyclization in acetone and in cyclohexane with *m*-methoxyacetophenone, relative to direct irradiation in cyclohexane, increases 56- and 6-fold, respectively. The quantum yields for dechlorination and ether cleavage (acetone and cyclohexane/methoxyaceto-

Scheme IV



phenone) decrease by factors of 0.19, 0.49, 0.16, and 0.01, respectively. A reasonable mechanistic overview can be represented as in Scheme IV with singlet leading to ether cleavage and dechlorination and triplet responsible for cyclization and dechlorination. The ether cleavage reaction and cyclization to dibenzofuran seem to be characteristic of singlet and triplet states, respectively, while dechlorination proceeds from either. The small amount of cyclization that we observe in the direct irradiation is most likely due to intersystem crossing.

This picture is very similar to the one we uncovered for ortho isomer **1a** (predioxin) (Freeman and Srinivasa, 1983). Using the group equivalents method of Benson (1976) and data of Egger and Cocks (1973), the dissociation energies of the C–O and C–Cl bonds should be 78 and 94.5 kcal/mol. Steric relief should reduce both of these values, the C–Cl bond by two ortho Cl–Cl interactions (4.4 kcal/mol), which might well bring the energy requirements within range for the singlet species (the O–O band appears to correspond to an excitation level of 95 kcal/mol or slightly less). The energy of the triplet state is 72 kcal/mol or less [E_T of *m*-methoxyacetophenone is 72 kcal/mol (Murov, 1973)]. The observation of C–Cl bond fission from the triplet state with very little accompanying C–O bond fission suggests that C–Cl bond fission benefits from an electron transfer process (Ohashi et al., 1973; Bunce et al., 1975, 1976, 1978; Ruzo et al., 1975; Chitten et al., 1978; Davidson and Goodin, 1981; Grimshaw and deSilva, 1981; Soumillion and deWolf, 1981), while C–O bond fission does not. If a cyclization process analogous to that considered for the cyclization of predioxin (**1a**) (Freeman and Srivinasa, 1983) is operative, an electron transfer, perhaps intramolecular (Okajima et al., 1977; Soumillion and deWolf, 1981; Todesco et al., 1981), followed by C–Cl bond fission would provide the key intermediates on the pathway to cyclic product (eq 1). To test the susceptibility of substrate **1b** to electron transfer, an irradiation was carried out in the presence of sensitizer and an electron donor.

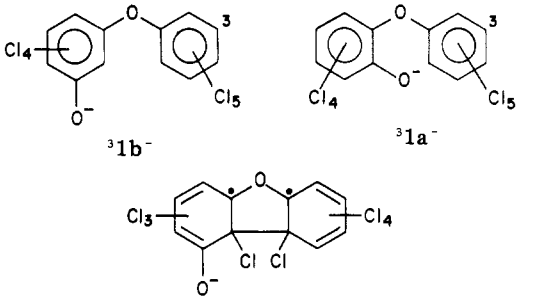


The irradiation of perchloro-*m*-phenoxyphenol **1b** in acetone in the presence of a 12-fold excess of the electron donor triethylamine for 2 h at 300 nm produces 53.9% dechlorination, 17.7% ring closure, and 0.5% ether cleavage (Table IV). We fail to observe the dramatic increase in cyclization that we observed with predioxin (**1a**) in a similar experimental comparison (Freeman and Srinivasa, 1983); instead, the quantum yield for cyclization is reduced by a factor of 0.23, the quantum yield for dechlorination increases 4.6-fold, and the quantum yield for ether cleavage remains at a low level. If intramolecular or intermolecular electron transfer via ^{3}**1b**$^-$ is operative, the ratio of cyclization to dechlorination might change, but the sum of the quantum yields for cyclization and dechlorination should increase. This does not occur and may well be due to the fact that the cyclizations for ^{3}**1b**$^-$ and ^{3}**1a**$^-$ (to dioxin) may be quite different processes. Cyclization of **1b**$^-$ (and **1b**) may occur by an electrocyclic ring

Table IV. Photolysis[a] of Nonachloro-3-phenoxyphenol in Acetone in the Presence of 11.6-fold Excess Triethylamine

compound[b]	yield,[c] mol %	quantum yield × 10^3
17, pentachlorobenzene	0.5	0.2
23, heptachloro-3-phenoxyphenol	6.2	1.8
24, heptachloro-3-phenoxyphenol	11.8	3.4
47, heptachloro-3-phenoxyphenol	1.6	0.5
48, 3-acetonoxyheptachlorodiphenyl ether	1.5	0.4
25, **26**, **27**, octachloro-3-phenoxyphenol	32.8	9.4
1b, unreacted perchloro-*m*-phenoxyphenol	24.5	
2, heptachloro-3-hydroxydibenzofuran	8.8	2.5
4, hexachloro-3-hydroxydibenzofuran	8.9	2.6

[a] Two hours at 300 nm; concentration = 0.00483 M. [b] See footnote *b* of Table I. [c] See footnote *c* of Table I.



49

closure process similar to that proposed by Grellman et al. (1981) for the photochemical cyclization of *N*-methyldiphenylamine. Such a process would produce diradical anion **49**, decay to singlet, and extrude molecular chlorine. This route to cycliic products would be competitive with an electron transfer process of ^{3}**1b**$^-$. Thus, a reduced quantum yield for cyclization and an enhanced one for dechlorination would be a reasonalbe outcome, as would a reduced sum for the quantum yields of cyclization and dechlorination, since electrocyclic ring closure from ^{3}**1b**$^-$ may not be as efficient as from ^{3}**1b**.

As a final comment, we believe it is interesting to note that we observe cyclization processes analogous to those discussed above for **1b** and **1b**$^-$ in the negative ion CI mass spectra of perchloro-*m*-phenoxyphenol **1b** (M – 1 – 70) and the cyclohexyl ethers of polychlorodiphenyl ethers (**29**, **31**, **34**, and **36**; M – 70 – 83). With parent phenol, ring closure of **1b**$^-$ is occurring, while in the case of the cyclohexyl ethers the ring closure may proceed either from a radical anion formed upon attachment of an electron or from **1b**$^-$ formed upon initial M – 83 fragmentation.

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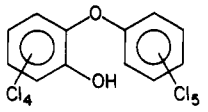
Photochemistry of Polychlorinated Phenoxyphenols. 3. Solvent Effects on the Photochemical Transformations of 3,4,5,6-Tetrachloro-2-(pentachlorophenoxy)phenol

Peter K. Freeman* and Ramanujan Srinivasa

The photochemical transformations of 3,4,5,6-tetrachloro-2-(pentachlorophenoxy)phenol (predioxin, 1) were studied at 300 nm in solvents dibutyl ether, THF, isobutyl alcohol, isopropyl alcohol, methanol, and acetonitrile. The quantum yield for cyclization increases with dielectric constant. The dependence of quantum yield for cyclization upon concentration fits better for an intramolecular electron transfer than an intermolecular one.

Our interest in the photochemical transformations of the perchlorinated phenoxyphenols (predioxin, 1, and meta



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and para isomers) is due to their presence as major contaminants in pentachlorophenol and their ready photoconversions at 300 nm to ether cleavage products, dechlorinated species, and highly toxic polychlorinated dibenzofurans and dibenzodioxins (Freeman and Srinivasa, 1983; Freeman and Jonas, 1984). This report describes some mechanistic features of the cyclization process as revealed by quantum yield dependence upon solvent polarity and substrate concentration.

EXPERIMENTAL SECTION

Materials and Methods. The solvents that were used in the photolysis were purified by distillation except for acetone and methanol, which were of spectrograde and were used as obtained. *m*-Methoxyacetophenone was used as obtained (Aldrich, 99%). Cyclopentanone was freshly distilled prior to its use.

Photolyses. The photolysis of predioxin (1) was carried out in a Rayonet merry-go-round reactor (The Southern New England Co.) equipped with eight 3000-Å Rull lamps. A continuous stream of air was passed into the reactor chamber, and the measured temperature of the chamber during the photolysis was 40 °C. The photolysis samples were placed in quartz tubes (170 mm × 15 mm) attached with Pyrex glass sliding stoppers and degassed through three or four freeze–thaw cycles and sealed in vacuum prior to irradiation. The primary quantum yields of the photoproducts were determined with a cyclopentanone–4-pentenal actinometer. *m*-Methoxyacetophenone was used as the sensitizer.

Product Analysis. The photoproducts were identified by GLC retention times by comparison with those of the known compounds (chlorophenols, chlorobenzenes, 14, 15, and 17) and by mass spectrometry. The free hydroxy compounds formed in the photolysis were converted to their corresponding methyl ethers with diazomethane before the GLC analysis owing to the thermal instability of the former on the column at elevated temperatures. The

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