Anal. Calcd. for $C_{12}H_8O_8N_2S$: S, 9.42. Found: S, 9.22.

B. **From the Phenolic Sulfide, XII.**—The hydrogen peroxide oxidation in acetic acid of the sulfide XII was carried out by refluxing over a twelve-hour period. The lustrous light yellow needles which separated on cooling were removed, washed and dried after which they weighed 0.51 g. (39%) and melted at 233–237°. The melting point was not depressed by admixing with material obtained by procedure A. The mother liquor on dilution yielded 0.11 g. melting at 230–232°.

Bis-(2-hydroxy-4-aminophenyl) Sulfone (XI).—One gram of the benzyloxysulfone IX and 5 g. of 5% Pd–C catalyst were dispersed in about 200 ml. of hot acetic acid and shaken under 30 lb. of hydrogen pressure for one hour. The filtrate was distilled under 20 mm. pressure of nitrogen. The residue, which was rather dark and caramel-like, slowly crystallized. Two recrystallizations from water afforded about 100 mg. of well-shaped light tan-colored crystals, melting at 180–184°.

Anal. Calcd. for $C_{12}H_{12}O_4N_2S$: S, 11.43. Found: S, 11.25.

The tetraacetyl derivative, **bis-(2-acetoxy-4-acetoamidophenyl) sulfone**, was obtained in about 30% yield by the catalytic (Pd–C) reduction of 0.34 g. of X in acetic acid solution and immediate acetylation of the reduction product. The light salmon-colored powder was insoluble in cold dilute alkali and melted at 289–290.5°.

Anal. Calcd. for $C_{20}H_{20}O_8N_2S$: N, 6.24; S, 7.15. Found: N, 6.15; S, 7.03.

Bis-(2-benzyloxy-4-aminophenyl) Sulfone (XIII).—To a stirred solution of 3.52 g. (0.0156 mole) of stannous chloride dihydrate in 25 ml. of acetic acid clarified with hydrogen chloride was added 1.0 g. (0.00195 mole) of the dinitro sulfone, IX. By means of mild external heating the temperature was increased to 75° at which point the reaction mixture solidified. After cooling to room temperature the solid was removed and worked up in the usual way. Recrystallization from acetic acid afforded about 0.4 g. of almost colorless leaflets melting at 237–238.5°.

Anal. Calcd. for $C_{26}H_{24}O_4N_2S$: S, 6.96. Found: S, 6.72, 6.91.

It is suspected that the yield in this preparation was diminished by a partial splitting off of the benzyl groups since the odor of benzyl chloride was detected during the working up of the amine salt. In a larger run of the same type the reaction mixture was permitted to heat up to about 102° after the precipitate had formed. The solid then dissolved and failed to reappear, even upon concentrating the solution. In this run, which produced no pure product (and which was therefore discarded), the odor of benzyl chloride was pronounced and unmistakable.

Summary

A method has been devised for the synthesis, in good yield, of 2,8-diaminophenoxathiin-5-dioxide, which is the *o,o′*-oxygen bridged derivative of the potent antitubercular agent 4,4′-diaminodiphenyl sulfone. Also prepared for antitubercular testing was 2,2′-dihydroxy-4,4′-diaminodiphenyl sulfone, a compound having interesting structural similarities to both *p*-aminosalicylic acid and 4,4′-diaminodiphenyl sulfone.

The Action of Elementary Fluorine upon Organic Compounds. XIII. The Vapor Phase Fluorination of Trichloroethylene[1]

BY MURRAY HAUPTSCHEIN[2] AND LUCIUS A. BIGELOW

This paper is one of several[3] which deal with the direct fluorination of deactivated organic molecules, that is, molecules whose central structures either aliphatic or aromatic are electron deficient, due to the inductive effect of negative substituents such as fluorine and chlorine. Trichloroethylene has been chosen for the present study for two reasons, first because it is a simple deactivated molecule, most of whose halogen derivatives are already known, and second in order to compare the vapor phase fluorination of this molecule with the liquid phase fluorination of the same substance, which has been described in detail by Miller.[4]

The olefin was fluorinated over a close metal packing at molar reaction ratios (F_2:CHCl=CCl_2:N_2) of 2:1:8, 1:1:6, 1:1:15 and 1:1:15, and corresponding reaction zone temperatures of 71,

(1) This paper has been constructed from portions of the Doctorate Thesis presented by Murray Hauptschein to Duke University in June, 1949.

(2) Allied Chemical and Dye Corporation Fellow, 1948–1949. Grateful acknowledgment is also made to the Duke University Research Council for financial support. Present address: The Research Institute, Temple University, Philadelphia, Pa.

(3) Preceding paper in this group, THIS JOURNAL, **68**, 2187 (1946).

(4) Miller, *ibid.*, **62**, 341 (1940).

45 and 120°. The complex crude products after the removal of most of the hydrogen fluoride were washed, dried and carefully rectified. Altogether, seven distinct products were isolated, together with some polymeric material and fragments due to cleavage. The formation of these substances and their progressive conversion into one another may be illustrated conveniently by the scheme as shown.
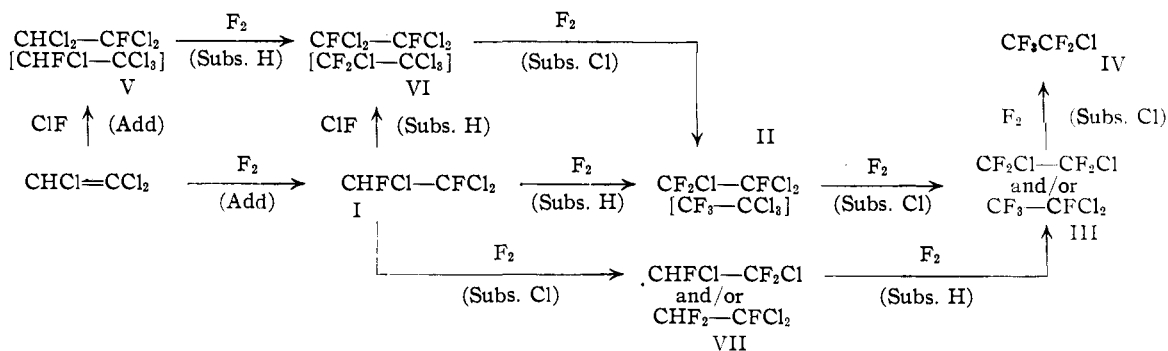
Although this diagram indicates that the transition from the original compound to the final products presumably followed several alternative routes involving both addition and substitution, the experimental evidence shows that certain of these are highly favored. Actually under the less vigorous conditions (fluorination ratio 1:1), all the above compounds were isolated in considerable proportions except III and IV; while under the stronger conditions (ratio 2:1) I, V and VII were not isolated, but II, III and VI were formed in much larger amounts instead. Thus far it is indicated that I, V and VII should be considered as the immediate precursors of II or VI, VI and III, respectively, although not exclusively so. However, since I and V were formed in approxi-

mately equal amounts under the mild conditions, while II and VI were produced in nearly the same proportions under the stronger conditions, VI must have been formed chiefly at the expense of V, and II at the expense of I. Had both II and VI been produced chiefly at the expense of I, it seems almost certain that I should have been produced in much greater amount than V under the mild conditions, which was not the case.

The pairs of isomers shown in the chart where the preferred orientation is not enclosed in brackets, are difficult to separate or to distinguish by ordinary means. However, on the basis of refractive indices and melting points, as shown in the experimental section, V and VI must be principally $CHCl_2$–$CFCl_2$ and $CFCl_2$–$CFCl_2$, respectively; while II whose precursor is I could hardly be other than CF_2Cl–$CFCl_2$.
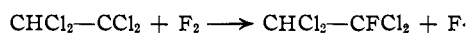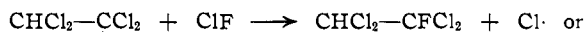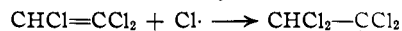
From the above considerations and since the products were essentially saturated, it follows that two important initial stages in the reaction consisted of the addition of fluorine and of chlorine fluoride to the original molecule, the latter reagent having been formed concurrently through the displacement of chlorine by fluorine. Nevertheless the products obtained under the mild operating conditions and at various boiling ranges did contain small amounts of olefinic material, such as $CHCl=CFCl$ or $CHF=CCl_2$, which indicated that the replacement of chlorine by fluorine in the original molecule did take place prior to the addition reaction, at least to some extent.

In the runs operated at a fluorination ratio of 1:1, the formation of the stable CF_2Cl–$CFCl_2$ was apparently favored by less dilution and higher temperatures, while the persistence of the ClF adduct $CHCl_2$–$CFCl_2$, was favored by high dilution and low temperatures. Also the formation of low polymers, mostly fluorochloropropanes, was favored by high temperatures, while that of the higher polymers was favored by low temperatures, as might have been expected. It should be noted here that the run at the ratio of 1:1:15 and 45°, although a vapor phase reaction (dilution ratio 1:15), nevertheless approached most nearly in operating conditions to the corresponding liquid phase fluorinations described by Miller,[4] who obtained large proportions of polymeric material from the fluorination of the same compound.

Turning now to theoretical matters, the directed addition of chlorine fluoride to the trichloroethylene to yield principally the adduct $CHCl_2$–$CFCl_2$ V, forms an important part of the fluorination under study, and requires an explanation. Kharasch, Norton and Mayo[5] have demonstrated that the peroxide catalyzed abnormal addition of hydrogen bromide to trichloroethylene yields only $CHClBr$–$CHCl_2$, and it has been shown convincingly[6] that this reaction takes place by the chain mechanism

$$CHCl=CCl_2 + Br\cdot \longrightarrow CHClBr—\dot{C}Cl_2$$

$$CHClBr—\dot{C}Cl_2 + HBr \longrightarrow CHClBr—CHCl_2 + Br\cdot$$
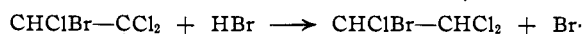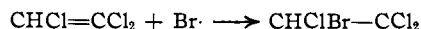
and so on, in which the primary attack of the halogen atom is on the CHCl group. From this good analogy we believe that the following mechanism for the addition of chlorine fluoride to trichloroethylene which also involves the primary attack of a halogen atom upon a CHCl group, can be defended successfully, especially since chlorine and bromine atoms are very similar.

$$CHCl=CCl_2 + Cl\cdot \longrightarrow CHCl_2—\dot{C}Cl_2$$

$$CHCl_2—\dot{C}Cl_2 + ClF \longrightarrow CHCl_2—CFCl_2 + Cl\cdot \text{ or}$$

$$CHCl_2—\dot{C}Cl_2 + F_2 \longrightarrow CHCl_2—CFCl_2 + F\cdot$$

This interpretation not only leads to the isomer which is actually produced, but the second and third steps are definitely exothermic, by some 21 and 44 kcal. per mole, respectively,[7] and so should be distinctly favored as components of a rapid chain reaction. It appears that alternative mechanisms involving the primary attack of fluorine atoms necessitate definitely endothermic intermediate steps, and so can be ruled out as highly improbable. Although free chlorine was not present in the reaction mixtures in appreciable concentrations, the necessary chlorine atoms and chlorine fluoride may readily be accounted for by the reaction of fluorine atoms with RCl or of fluorine molecules with chlorine atoms. Recent work by Henne and Ruh[8] dealing with the peroxide catalyzed dimerization of trichloroethylene fits
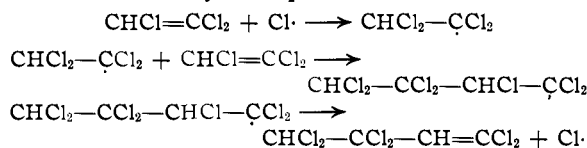
(5) Kharasch, Norton and Mayo, J. Org. Chem., 3, 48 (1938).

(6) Mayo and Walling, Chem. Revs., 27, 351 (1940).

(7) Heats calculated roughly from Pauling's bond energy values. See Pauling, "The Nature of the Chemical Bond," Cornell University Press, Ithaca, N. Y., 1940.

(8) Henne and Ruh, THIS JOURNAL, 69, 279 (1947).

in very nicely with our findings. They have shown convincingly that this dimerization always takes place by a head to tail or tail to head mechanism, but never otherwise, so that the structure of the dimer must be either $CHCl_2$—CCl_2—CH= CCl_2 or CCl_3—$CHCl$—CCl=$CHCl$ or perhaps an allylic type equilibrium between them through the intermediate $CHCl_2$—CCl=CH—CCl_3. By means of the proposed mechanism it is possible to decide definitely that the first of these formulas best represents the original structure of the dimer, as is illustrated by the equations.

$$CHCl=CCl_2 + Cl\cdot \longrightarrow CHCl_2\text{—}\overset{.}{C}Cl_2$$
$$CHCl_2\text{—}\overset{.}{C}Cl_2 + CHCl=CCl_2 \longrightarrow$$
$$CHCl_2\text{—}CCl_2\text{—}CHCl\text{—}\overset{.}{C}Cl_2$$
$$CHCl_2\text{—}CCl_2\text{—}CHCl\text{—}\overset{.}{C}Cl_2 \longrightarrow$$
$$CHCl_2\text{—}CCl_2\text{—}CH=CCl_2 + Cl\cdot$$

Finally, a comparison of the present work conducted in the vapor phase with that of Miller,[4] who fluorinated the same compound in the liquid phase at 0°, reveals the very pronounced effect of physical state on the direct fluorination process. Miller obtained no CF_2Cl-$CFCl_2$ and no $CFCl_2$-$CFCl_2$, which were two of our principal products, but instead found much more polymeric material from which he isolated some $C_4H_2Cl_8$, as well as $C_4H_2Cl_6$ in considerable yield, which according to our interpretation was probably the dimer $CHCl_2$-CCl_2-CH=CCl_2. Apparently, under these conditions, very little substitution of hydrogen by fluorine occurred which would be very much favored energetically, while the formation of a relatively large proportion of the dimer may readily be accounted for by postulating that a considerable number of the free radicals formed, instead of reacting further with fluorine, stabilized themselves by attack upon the surrounding solvent molecules (trichloroethylene itself). Miller has pointed out that on account of the low solubility of elementary fluorine in halogenated solvents, the reactions took place mostly in the vapor phase and at the liquid surface. This is undoubtedly correct insofar as the original attack of the fluorine is concerned, but it seems equally certain that the resulting free radicals would be readily soluble and so would be expected to continue reacting in the liquid phase to a large extent. Even in the presence of extremely reactive fluorine, the behavior of these free radicals of short life in solution, where collisions with solvent molecules are favored, differs fundamentally from their behavior in the vapor phase. At comparable temperatures, reactions in the vapor phase may be expected to be more directed, and affected to a greater extent by activation energies, while in the liquid phase they should be influenced to a higher degree by statistical and proximity factors, so that a more random type of reaction would be expected.

Experimental

Apparatus and Materials.—The trichloroethylene used was a commercial sample which was carefully rectified,

collecting a central cut, b. p. 87.0–87.3°. The reactor unit employed was one designed very recently in this Laboratory by Gilbert,[9] as modified by Holub,[10] and described in detail in the publications noted. The sample was carried on a current of nitrogen from a carefully calibrated saturator into the reactor, where it met and reacted with fluorine diluted with nitrogen within the meshes of the metal packing. The gaseous products were passed over sodium fluoride pellets at 100° to remove hydrogen fluoride, and then condensed in a series of traps, at first by Dry Ice and finally by liquid air. The material boiling above room temperature, including that collected in the sump at the base of the reactor, was washed with saturated sodium bicarbonate solution and dried over magnesium sulfate, while the low boiling products were passed through a solution containing 8% sodium hydroxide and 6% sodium bisulfite and dried over Drierite. The former were rectified in a Podbielniak Hyper-Cal column, and the latter in a Booth–Podbielniak low temperature fractionating unit, each equipped with semi-automatic controls and potentiometer recorder. The total crude yield of washed and dried product was in all cases essentially equal to or substantially greater than the total weight of sample fed into the reactor.

The first run was operated at a molar reaction ratio $(F_2:CHCl=CCl_2:N_2)$ of 2:1:8, and a reaction zone temperature of 71° over a period of twenty-two hours. The total crude product which was collected at the approximate rate of 8 g. per hour, and which originally contained a small amount of free chlorine, amounted to 175 g. after washing and drying. It was then carefully rectified in the low and high temperature fractionating units with the results shown in Table I.

Table I

The Rectification of Fluorinated Trichloroethylene (Molar Reaction Ratio 2:1:8; Temp. 71°)

Compound	B. p., °C.	Wt.,g.	% yield[a]	Remarks
....	< −78	3	2	Prob. CF_4 + CF_3Cl cleavage prod.
CF_3CF_2Cl	−38	2.5	1	
CF_2Cl_2	−28 to −30	2	1	Cleavage prod.
$C_2F_4Cl_2$	+3–4	20	11	CF_2Cl-CF_2Cl and/ or CF_3-$CFCl_2$
$CF_2ClCFCl_2$	45–48	42.5	24	
$CFCl_2CFCl_2$	90–94	41.1	23	Possibly contam. with CF_2Cl-CCl_3
Low polymers	128–208	14.6	8	
Residue	> 208	8.3	5	
Total transitions	....	21,4	12	

[a] Weight per cent. of total crude product.

CF_3CF_2Cl **Fraction.**—Mol. wt. calcd. 154; found 153; known b. p. −38°.

CF_2Cl_2 **Fraction.**—Mol. wt. calcd. 121; found 122; known b. p. −28°.

$C_2F_4Cl_2$ **Fraction.**—Mol. wt. calcd. 171; found 171; known b. p. CF_2ClCF_2Cl, 3.8°, CF_3CFCl_2, 3.6°.[11]

CF_2Cl-$CFCl_2$ **Fraction.**—Nearly all of this material boiled at 46.5 to 47.5°, known 47.7°. Central cut: mol. wt. calcd. 187; found 186, 187; $n^{25}D$ known 1.35572[12]; found 1.3558.

$CFCl_2$-$CFCl_2$ **Fraction.**—Nearly all of this material boiled at 91.5 to 92.5°. A central cut melted at 23–24°, $n^{25}D$ 1.4130. The known values are $CFCl_2$–$CFCl_2$, m. p. 24.65°, 28.1°,[12] b. p. 92.8°, 91.5°,[13] $n^{25}D$ 1.4130; CF_2Cl-CCl_3, m. p. 40.6°, b. p. 91°. Consequently this fraction must have consisted of $CFCl_2CFCl_2$ which could

(9) Gilbert and Bigelow, This Journal, **72**, 2411 (1950).
(10) Holub and Bigeleow, ibid., in press.
(11) Henne and Ruh, ibid., **70**, 1025 (1948).
(12) The physical constants of the known compounds prepared in the course of this work are listed in "Organic Reactions," Vol. II, John Wiley and Sons, Inc., New York, N. Y., 1944, p. 76.
(13) Hovorka and Geiger, This Journal, **55**, 4759 (1933).

Table II

The Rectification of Fluorinated Trichloroethylene at Various Molar Reaction Ratios and Temperatures

Compound	B. p., °C.	% Yield[a] at molar reacn. ratio and reacn. zone temp. of 1:1:6 (71°)	% Yield[a] 1:1:15 (45°)	% Yield[a] 1:1:15 (120°)	
....	< -78	1			Prob. $CF_4 + CF_3Cl$
$CF_3CF_2Cl + CF_2Cl_2$	-78 to $+3$	1	} 1	} 2	
$C_2F_4Cl_2$	3–4	2			
$C_2HF_3Cl_2$	27–30	4	4	3	$CHFCl-CF_2Cl$ and/or CHF_2-CFCl_2
$CF_2ClCFCl_2$	45–48	10	6	8	
$CHFCl-CFCl_2$	70–74	6	8	7	
$CHCl=CCl_2$	84–88	30	26	30	Recov.
$CFCl_2CFCl_2$	90–94	5	5	6	Possibly contam. with $CF_2Cl-CCl_3$
$CHCl_2-CFCl_2$	112–116	6	9	6	Possibly contam. with $CHFCl-CCl_3$
Low polymers	128–208	9	8	11	
Residue	>208	7	10	5	
Total transitions	....	12	12	9	

[a] Weight per cent. of total crude product.

nevertheless have been contaminated with some of the higher melting isomer.

Low Polymer Fraction.—This material consisted largely of a complex mixture of fluorochloropropanes formed, at least to some extent, by the attack of halogenated one-carbon free radicals on haloethenes. A 3-g. portion, b. p. 128–131°, yielded a central cut b. p. 130°, $n^{25}D$ 1.4170, which appeared to be impure $C_3HF_3Cl_4$, calcd. Cl, 60.1; found Cl 61.5. Actually $CFCl_2-CHCl-CF_2Cl$ boils at 128.7°, $n^{20}D$ 1.41569, and $CHCl_2-CFCl-CF_2Cl$ at 129.8°, $n^{20}D$ 1.41967.

Residue.—This intractable mixture probably consisted of fluorochlorobutanes and -enes together with other more highly polymerized products. The next three runs were operated under milder conditions than the preceding one, but were handled in essentially the same manner. The molar reaction ratios were 1:1:6, 1:1:15 and 1:1:15, corresponding to reaction zone temperatures of 71°, 45 and 120°, and to operating times of sixteen, fourteen and one-half and seventeen hours, respectively. The yields of crude product, which contained no free chlorine, amounted to 193, 138 and 169 g. after washing and drying in the three cases, and the results of the several rectifications have been collected in Table II.

General Comment.—The remarks made concerning the several fractions in Table I are in general equally valid for the corresponding fractions in Table II.

$C_2HF_3Cl_2$ Fraction.—Mol. wt. 154, $n^{20}D$ 1.3378. This portion was probably a mixture of $CHFCl-CF_2Cl$, b. p. 28°, mol. wt. 153, $n^{20}D$ 1.327, and CHF_2-CFCl_2 which is unreported. The transition material preceding this fraction, b. p. 15–27°, gave a positive test for unsaturation with bromine indicating that traces of either $CFCl=CFCl$, b. p. 22°, or $CF_2=CCl_2$, b. p. 19°, may have been present in it; while the transition following, b. p. 30–45°, was distinctly unsaturated, and on bromination in sunlight the three runs yielded 1 g., 2 g. and 0.5 g., respectively of a liquid dibromide, b. p. 160–164°, $n^{20}D$ 1.5088, 1.5095 and 1.5078. Actually $CHClBr-CFClBr$ boils at 163.5°, $n^{23}D$ 1.5160, and $CHFBr-CCl_2Br$ also at 163.5°, which indicates that either $CHCl=CFCl$, b. p. 35.1°, or $CHF=CCl_2$, b. p. 37.3°, or both of these were present in the origi-

nal product, and to the greatest extent when the fluorination was carried out at the lowest temperature:

$CHFCl-CFCl_2$ Fraction.—Nearly all of this fraction boiled at 71–72°. It also showed signs of unsaturation, and in one case (reaction ratio 1:1:6) it yielded 0.2 g. of an impure solid dibromide, m. p. about 100°, while $CFClBr-CCl_2Br$ melts at 122.5°. This indicates the possible presence of $CFCl=CCl_2$, b. p. 71°, as a contaminant. After the removal of this olefin by bromination the product also boiled at 71–72°, $n^{20}D$ 1.3941; known b. p. 72.5°, $n^{20}D$ 1.3942.

$CHCl_2-CFCl_2$ Fraction.—Nearly all of this fraction boiled at 114 to 115.5°; central cut b. p. 115°, $n^{20}D$ 1.4484. Actually $CHCl_2-CFCl_2$ boils at 116.6°, $n^{20}D$ 1.4487, and $CHFCl-CCl_3$ at 116.7°, $n^{20}D$ 1.4525, which indicates that this fraction consisted mostly of the former compound.

Summary

A study of the direct fluorination of trichloroethylene in the vapor phase over a close metal packing has been made under a number of mild operating conditions.

This fluorination has been shown to take a somewhat directed, rather than a completely random course. The reaction proceeded in considerable part by certain preferred routes which were established by determining the principal precursors of a number of the products.

The results of this vapor phase fluorination have been compared with those reported by Miller, who fluorinated the same compound in the liquid phase, and have been found to be distinctly different.

Certain theories which account well for these facts have been presented.