Anal. Calcd for $C_8H_{15}NO_2$: C, 61.15; H, 9.55; N, 8.92. Found: C, 61.02; H, 9.46; N, 9.35.

β-(n-Propoxy)caprolactam (XII).—Sodium (25.3 g) was treated with 1.2 l. of anhydrous *n*-propyl alcohol. At 60°, 192 g of α-bromocaprolactam in 600 ml and *n*-propyl alcohol was added in a dropwise fashion. The reaction mixture was refluxed for 3 hr. After cooling, the NaBr was filtered off and *n*-propyl alcohol was distilled. The oil was dissolved in chloroform, extracted with 10% aqueous HCl solution until neutral, then with a saturated $NaHCO_3$ solution and water. The chloroform solution was dried with anhydrous Na_2SO_4, the chloroform was removed, and the oil distilled: bp 68° (0.13 mm). The yield was 85.5 g (50.0%).

Anal. Calcd for $C_9H_{17}NO_2$: C, 63.20; H, 9.95; N, 8.20. Found: C, 63.09; H, 10.02; N, 8.35.

Registry No.—ε-Caprolactam, 105-60-2; I, 10139-43-2; IVa, 2228-79-7; IVa-Ac, 18753-61-2; IVb, 18761-61-0; IVb-Ac, 18753-62-3; V, 18753-63-4; VI (dipotassium salt), 18753-64-5; VII, 18753-65-6; VIII, 18753-66-7; IX, 10139-44-3; X, 18753-68-9; XI, 18753-69-0; XII, 18753-70-3.

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Direct Liquid Phase Fluorination of Methyl Trichloroacetate and Acetic Anhydride

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Direct liquid phase fluorination of methyl trichloroacetate gave fluoromethyl trichloroacetate and difluoromethyl trichloroacetate. Under similar conditions, followed by hydrolysis of the fluorination mixture, acetic anhydride yielded fluoroacetic acid and difluoroacetic acid.

Selective, noncatalytic direct liquid phase fluorination of saturated aliphatic hydrocarbons has been the subject of only sporadic research efforts. In fact, less than a handful of publications dealing with this subject have appeared since Moissan's time.

Early attempts to fluorinate organic compounds with elementary fluorine resulted in explosions, firings, and complete destruction of substrate molecules to hydrogen fluoride and carbon tetrafluoride. The possibility of obtaining substitution products in this manner appeared very remote.[1]

In 1919, Hemiston[2] discovered that reactions between organic compounds and fluorine could be moderated considerably using fluorine diluted with inert gases such as carbon dioxide or nitrogen. However, even under these milder fluorination conditions, Hemiston was unable to obtain substitution products in the fluorination of acetone or chloroform. Hemiston's finding that carbon tetrachloride was relatively inert toward fluorine, and could be used as fluorination medium, contributed considerably to the subsequent development of the liquid phase fluorination technique.

Employing the fluorination conditions introduced by Hemiston, Bockemuller,[3] in 1933, investigated the fluorination of *n*-butyric acid, its anhydride, and chloride, obtaining mixtures of the corresponding β- and γ-fluoro derivatives. In the same work he reported fluorination of isobutyric acid to its β-fluoro derivative, and fluorination of cyclohexane and *n*-hexadecane to the corresponding monofluorocarbons. Bockemuller also attempted to fluorinate acetic, succinic, and glutaric anhydrides, and acetic acid in carbon tetrachloride solution, but found that these substrates were unreactive.

During the past several years, direct liquid phase fluorination technique has been successfully applied in the synthesis of N-fluoro derivatives. Fluorination of aqueous urea,[4] substituted urea,[8] alkyl carbamates,[5,6] simple amides,[5] and amines[7] yielded N-fluoro and N,N-difluoro derivatives. In all of the above cases the fluorination occurred selectively on nitrogen. "Burning" and explosions often reported in connection with direct fluorination reactions in earlier literature have not been encountered in these studies.

Recently, the direct liquid phase fluorination technique has been applied in the synthesis of fluorocarbons. Fluorodinitromethyl derivatives have been obtained in excellent yields in the fluorination of aqueous nitronate salts,[8,9] and aromatic electrophilic substitution leading to aromatic fluorocarbons has been reported.[10] This communication deals with direct liquid phase fluorination of methyl trichloroacetate and acetic anhydride.

Alkyl esters were considered in the search for inert solvents suitable as heat transfer media in direct liquid phase fluorination reactions. It was found, however, that simple alkyl acetates and formates reacted readily with fluorine and, therefore, could not be em-

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[1] H. Moissan, "Das Fluor und Seine Verbindurgen," Verlag M. Krayn, Berlin, 1900, pp 242 ff.

[2] B. Hemiston, *J. Phys. Chem.*, **23**, 573 (1919).

[3] W. Bockemuller, *Ann.*, **506**, 20 (1933).

[4] V. Grakauskas, Abstracts, 140th National Meeting of the American Chemical Society, Chicago, Ill., Sept 1961, p 23M; V. Grakauskas and K. Baum, *J. Amer. Chem. Soc.*, **91**, 1679 (1969).

[5] R. E. Banks, R. N. Haszeldine, and J. P. Lalu, *J. Chem. Soc., C*, 1514 (1966).

[6] V. Grakauskas, Third International Fluorine Symposium, Munich, Sept 1965.

[7] C. M. Sharts, *J. Org. Chem.*, **33**, 1008 (1968).

[8] V. Grakauskas and E. E. Hamel, British Patent 1,077,065 (July 1967).

[9] R. A. Wiesboeck and J. K. Ruff, *J. Org. Chem.*, **33**, 1257 (1968).

[10] V. Grakauskas, Fourth International Fluorine Symposium, Estes Park, Colo., July 1967.

ployed for the intended purpose. This finding led to the investigation of direct liquid phase fluorination of several acetates.

Methyl trichloroacetate and acetic anhydride were chosen as the substrates in this investigation. The former, containing the "blocked" acid portion of the molecule, could undergo fluorination only in the alcohol moiety. Acetic anhydride, on the other hand, could be fluorinated only in the acid methyl group. A practical reason motivating the selection of these substrates was to minimize the number of fluorination products and thus simplify the identification problems.

The material obtained in the fluorination of methyl trichloroacetate in 1,1,2-trichloro-1,2,2-trifluoroethane solution at a 1:1 molar ratio of fluorine to substrate consisted of a mixture containing approximately equal amounts of starting material and its monofluoro derivative, contaminated with a small amount of difluoro derivative.

$$CCl_3CO_2CH_3 + F_2 \longrightarrow CCl_3CO_2CH_2F + HF$$

Pure fluoromethyl trichloroacetate was isolated from the mixture by gas chromatography, and the compound was identified by its elemental analysis and its infrared and nmr spectra. The proton nmr spectrum consisted of a doublet at δ 5.89, and its fluorine nmr spectrum showed a triplet at ϕ 159.6 ppm with coupling constants of 50 cps. Although other halomethyl carboxylic esters are known, fluoromethyl esters have not been reported and fluoromethyl trichloroacetate represents the first member of this new class of compounds.

The preparation of fluoromethyl trichloroacetate suggested that difluoromethyl and possibly trifluoromethyl esters could be obtained in the above fluorination reaction. For this reason a portion of the crude fluorination mixture obtained above was subjected to further fluorination at a slower rate and at a higher temperature. The reaction product contained a mixture of fluoromethyl and difluoromethyl trichloroacetates, and a small amount of methyl trichloroacetate. An analytical sample of difluoromethyl trichloroacetate was isolated from the mixture by gas chromatography, and the compound was identified on the basis of its elemental analysis, its infrared spectrum, and its nmr spectrum.

$$CCl_3CO_2CH_2F + F_2 \longrightarrow CCl_3CO_2CHF_2 + HF$$

The compound's proton nmr spectrum consisted of a triplet centered at δ 7.19 (J_{HF} = 71 cps) and its fluorine nmr spectrum showed a doublet at ϕ 91.8 ppm (J_{HF} = 69.5 cps). It should be noted that the α,α-dihaloalkyl esters had not been previously reported.

Trifluoromethyl trichloroacetate, another possible fluorination product of methyl trichloroacetate, was not obtained in this investigation. It should be noted, however, that no concerted efforts were made to synthesize the compound by employing yet more strenuous fluorination conditions.

Chemical reactions of fluoromethyl and difluoromethyl trichloroacetates have not been investigated. Both compounds were stored at room temperature for several months without any noticeable changes. Test-tube experiments indicated that both esters are significantly more susceptible to alkaline hydrolysis than methyl trichloroacetate. The esters were insoluble in water but dissolved readily in cold dilute aqueous sodium hydroxide, and a distinct formaldehyde odor was detectable after a few minutes in the case of fluoromethyl trichloroacetate.

$$CCl_3CO_2CH_2F + OH^- \longrightarrow CCl_3CO_2^- + [FCH_2OH]$$

$$[FCH_2OH] + OH^- \longrightarrow HCHO + H_2O + F^-$$

The fluorination of acetic anhydride in 1,1,2-trichloro-1,2,2-trifluoroethane solution (partially in suspension) was carried out to a 3:1 molar ratio of fluorine to substrate, but a considerable amount of unreacted fluorine escaped from the reactor. No attempts were made to isolate fluoroacetic anhydrides. Instead, the fluorination mixture was hydrolyzed and the resulting aqueous solution was analyzed by nmr. The proton nmr spectrum of the hydrolysate consisted of two signals—a doublet at δ 5.00 (J_{HF} = 47 cps), and a symmetrical triplet at δ 6.12 (J_{HF} = 53 cps) assigned[11] to fluoroacetic acid and difluoroacetic acid, respectively.

$$(CH_3CO)_2O + F_2 \longrightarrow \text{fluorinated acetic anhydrides} + HF \xrightarrow{H_2O} FCH_2CO_2H + F_2CHCO_2H$$

Trifluoroacetic acid was not present among the fluorination products. It is likely, however, that the compound could be obtained under more forcing fluorination conditions.

Direct fluorination of simple carboxylic acid anhydrides might provide an economical route toward the synthesis of the corresponding fluoroanhydrides and fluorocarboxylic acids.

Similarities in the rate of fluorination of methyl trichloroacetate and acetic anhydride suggested that esters, in general, should undergo substitution in alkyl and acyl portions of the molecule. Consequently, the fluorination of ethyl chloroacetate was examined next.

Ethyl chloroacetate underwent fluorination in 1,1,2-trichloro-1,2,2-trifluoroethane solution and gave a mixture of fluoro derivatives. The material balance, visual observations, and physical properties of the product indicated that the fluorination proceeded without fragmentation of ethyl chloroacetate. The elemental analysis showed that the fluorination product contained on the average 1.5 fluorine atoms per molecule. Its nmr analysis indicated that the material was a multicomponent mixture of monofluoro- and polyfluoro derivatives of ethyl chloroacetate containing fluorine in both acid and alcohol portions of the molecule. Thus the presence of $CHFClCO_2$ derivatives in the mixture was implied by two doublet signals at δ 6.0–6.8 ($J_{HF} \cong$ 50 cps) in the proton spectrum, and by two doublet signals at ϕ 146.5 and 148.0 ($J_{HF} \cong$ 50 cps) in the fluorine nmr spectra. Proton nmr signals at δ 7.1–5.8, doublets of quartets ($J_{HF} \cong$ 50 cps) and

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(11) The proton nmr spectrum of fluoroacetonitrile, reported by G. P. Van der Kelen and Z. Eeckhaut [*J. Mol. Spectrosc.*, **10**, 141 (1963)], comprises a doublet at δ 5.05, J_{HF} = 45.2 cps, and that of difluoroacetonitrile, a triplet at δ 6.25, J_{HF} = 52.2 cps. Fluorine nmr spectra of fluoroacetic acid and ethyl difluoroacetate, reported by the same authors, consisted of a triplet, J_{HF} = 47.6 cps, and a doublet, J_{HF} = 52.8 cps, respectively.

fluorine signals at ϕ 123.1 and 126.9, and doublets of quartets ($J_{HF} \cong 50$ cps) were assigned to fluoroethyl groups, -CO_2CHFCH_3. Similarly, the presence of -$CO_2CH_2CH_2F$ moiety was implied by fluorine nmr signal at ϕ 225 (triplet of triplets, $J_{HF} = 50$ cps).

Although analytical data, particularly the nmr spectra, indicated strongly that the fluorination of ethyl chloroacetate proceeded by substitution in both alkyl and acyl groups of the molecule, individual compounds could not be isolated by fractionation of the mixture. The reason for this is that there is generally a unique proximity of boiling points for fluoro derivatives of a hydrocarbon. Several attempts to isolate pure compounds by gas chromatography also proved unsuccessful because of very similar retention times of isomeric fluorocarbons.

Experimental Section

General.—Fluorinations were carried out in glass standard taper three-necked flasks equipped with a mechanical stirrer, a glass inlet tube extending below the liquid level, and a standard taper thermometer well with an opening for gas exit. Standard fluorine handling hardware[12] was used, and fluorine was diluted with nitrogen (1:3 to 1:5 ratio).

Fluoromethyl Trichloroacetate.—A solution of 35.5 g (0.2 mol) of methyl trichloroacetate in 350 ml of 1,1,2-trichloro 1,2,2-trifluoroethane was fluorinated at −10° until 0.25 mol of fluorine was passed into the reaction mixture (1.5 hr). The reaction mixture was concentrated and the residual liquid was fractionated to give 31 g of a colorless liquid, bp 25–30° (0.1 mm). Nmr spectra indicated that the product was approximately an equimolar mixture of starting material and fluoromethyl trichloroacetate. A pure sample of the fluoromethyl ester was obtained by gas chromatography utilizing a 10 ft long × 0.25 in. diameter column of 10% six-ring polyphenyl ether on Chromosorb W at 110°, and 50 cm^3/min helium flow rate.

Anal. Calcd for $C_3H_2Cl_3FO_2$: C, 18.4; H, 1.0; F, 9.7. Found: C, 18.3; H, 0.9; F, 9.3.

The proton nmr spectrum in carbon tetrachloride using tetramethylsilane (TMS) as internal reference consisted of a sharp doublet ($J_{HF} = 50$ cps) at δ 5.89. The ^{19}F spectrum consisted of a sharp triplet ($J_{HF} = 49$ cps) at ϕ 159.6 ppm. The infrared spectrum consisted of peaks at 3.35 (w), 5.61 (s,) 7.35 (m), 8.25 (s), 8.60 (w), 9.40 (s), 9.90 (s), 11.85 (s), 12.10 (s), 13.25 (w), and 14.15 μ (s).

Difluoromethyl Trichloroacetate.—A solution of 23 g of the above crude distillate in 300 ml of 1,1,2-trichloro-1,2,2-trifluoroethane was fluorinated at 10° until approximately 0.2 mol of fluorine was passed into the reaction mixture. The solution was distilled to give 3.5 g of a colorless liquid, bp 57–60° (30 mm), and 16.5 g of a colorless liquid, bp 60° (30 mm). The nmr analysis indicated that difluoromethyl trichloroacetate was the predominant component in the first fraction, while the second fraction contained mainly fluoromethyl trichloroacetate. An analytically pure sample of difluoromethyl trichloroacetate was obtained from the first fraction by gas chromatography utilizing the same column and conditions as in the separation of fluoromethyl trichloroacetate.

Anal. Calcd for $C_3HCl_3F_2O_2$: C, 16.9; H, 0.5; F, 17.8. Found: C, 16.9; H, 0.5; F, 17.9.

The proton nmr spectrum of a carbon tetrachloride solution of the compound consisted of a triplet ($J_{HF} = 71$ cps) at δ 7.19. The ^{19}F spectrum consisted of a doublet ($J_{HF} = 69.5$ cps) at ϕ 91.8 ppm. The infrared spectrum consisted of peaks at 3.3 (w), 5.58 (s), 7.33 (m), 8.19 (s), 8.70 (s), 8.92 (s), 9.60 (s), 11.25 (s), and 12.12 μ (s). Differential thermal analysis of difluoromethyl trichloroacetate showed endotherm at 125°, indicating that this was the boiling point of the compound.

Fluorination of Acetic Anhydride.—A solution (partially in suspension) of 5.1 g (0.05 mol) of acetic anhydride in 300 ml of 1,1,2-trichloro-1,2,2-trifluoroethane was fluorinated at −20 to 10° until approximately 0.15 mol of fluorine was passed into the reaction mixture (2 hr). Water (15 ml) was added; the resulting mixture was allowed to warm to 25–30° and was stirred vigorously at this temperature for 45 min. The phases were separated and the aqueous phase was examined by nmr.

The proton nmr spectrum of the aqueous solution of the mixture consisted of a symmetrical triplet ($J_{HF} = 53$ cps) at δ 6.12, area 12, representing CHF_2 protons; a doublet ($J_{HF} = 47$ cps) at 5.00, area 58, representing CH_2F protons; and a sharp singlet at δ 2.11, area 113, representing CH_3 of acetic acid. Sodium 2,2-dimethyl-2-silapentane-5-sulfonate (SDSS) was used as internal reference. Proton nmr spectra of authetic samples of aqueous fluoro- and difluoroacetic acid exhibited identical patterns.

Fluorination of Ethyl Chloroacetate.–A solution of 31 g (0.25 mol) of ethyl chloroacetate in 350 ml of 1,1,2-trichloro-1,2,2-trifluoroethane was fluorinated at −25 ± 5° until 0.5 mol of fluorine was passed into the reaction mixture (2.5 hr). The reaction mixture was allowed to warm to 25° and the clear and colorless solution was stirred with 75 g of sodium bicarbonate for 90 min, filtered, and the filtrate separated into three fractions on distillation: (1) 12.3 g, bp 55–65° (28 mm); (2) 8.8 g, bp 65–75° (25 mm); and (3) 10.2 g, bp 40–45° (0.1 mm). Elemental analyses of materials of all three fractions were practically identical.

Anal. Calcd for $C_4H_{5.5}ClF_{1.5}O_2$: C, 32.1; C, 32.1; H, 3.7; F, 19.1. Found: C, 31.4; H, 3.3; F, 18.5.

The proton and fluorine nmr spectra were obtained in carbon tetrachloride solution with TMS and chlorotrifluoromethane as internal references. The spectra of all three fractions exhibited the same signals, but in varying intensities.

Registry No.—Methyl trichloroacetate, 598-99-2; acetic anhydride, 108-24-7; fluoromethyl trichloroacetate, 18753-52-1; difluoromethyl trichloroacetate, 18753-53-2.

Acknowledgment.—The author wishes to thank Mr. K. Inouye for elemental analysis, and Mr. L. A. Maucieri for the nmr spectra.

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[12] Allied Chemical Corp., Data Sheet PD-TA-8513A.