was prepared[29] but failed to yield a radical cation. Glycolaldehyde dimer from Aldrich Chemical Co. did not yield a spectrum in sulfuric acid solution. Lactaldehyde dimer was prepared[30] and also failed to yield a signal. Norcamphorquinone gave a weak and uninformative spectrum. No signal could be detected from camphorquinone, glucose, or fructose.

---

[29] K. Rühlmann, H. Seefluth, and H. Becker, *Chem. Ber.*, **100**, 3824 (1927).

[30] R. Burthes, *J. Chem. Soc.*, **127** 585 (1925); R. Dworzak and P. Pfiifferling, *Monatsh. Chem.*, **50**, 467 (1928).

Trifluoroacetyl Hypohalites as Aromatic Halogenating Agents

Jerry R. Barnett, L. J. Andrews,* and R. M. Keefer

Contribution from the Department of Chemistry, University of California, Davis, California 95616. Received December 16, 1971

Abstract: Equilibrium constants for formation of trifluoroacetyl hypohalite and trifluoroacetoxymercuric halide from the reactions of iodine and bromine with mercuric trifluoroacetate in trifluoroacetic acid have been determined spectrophotometrically. The kinetics of halogenation of trifluoromethylbenzene and *p*-nitrotoluene in solutions of iodine and mercuric trifluoroacetate have been investigated, and rate constants have been evaluated on the assumption that the actual halogenating agent is trifluoroacetyl hypoiodite. A similar interpretation has been placed on the results of a study of the reaction of nitrobenzene in trifluoroacetic acid solutions of bromine and the mercury salt. From the results of this and earlier studies it has been established that the reactivities of various electrophilic aromatic halogenating agents increase in the order $\mathrm{Br_2 \simeq ICl \simeq CH_3COOI \ll CF_3COOI < CH_3COOBr \ll CF_3COOBr}$. Solutions of acetyl hypoiodite have been prepared from the reaction of iodine and silver acetate in acetic acid and the kinetics of iodination of pentamethylbenzene by the hypoiodite so generated have been investigated. The rate constant for the second-order reaction compares favorably with that evaluated previously for the halogenation of pentamethylbenzene in acetic acid solutions of iodine and mercuric acetate.

The reactions of both bromine and iodine with aromatic compounds in the presence of silver trifluoroacetate are known to yield products which are characteristic of electrophilic substitution processes.[1,2] The effective halogenating agent is presumed to be trifluoroacetyl hypobromite or hypoiodite. Because of the inductive effect of the trifluoromethyl group it can be anticipated that these particular hypohalites should be unusually reactive as sources of positive halogen in attacking the aromatic nucleus. The current investigation has been undertaken primarily to compare semiquantitatively the reactivities of these hypohalites with those of structurally related electrophilic aromatic halogenating agents.

It has been demonstrated previously that in acetic acid solutions of mercuric acetate and bromine or iodine equilibria are established as represented in eq 1.[3,4] In

$$\mathrm{Hg(OCOCH_3)_2 + X_2 \rightleftarrows Hg(OCOCH_3)X + CH_3COOX} \tag{1}$$

such solutions benzene and its methyl substitution products undergo ring halogenation. The kinetics of these reactions have been explained[3,4] on the assumption that in the slow step acetyl hypohalite attacks the aromatic substrate (eq 2 and 3).

$$\mathrm{CH_3COOX + ArH \longrightarrow ArX + CH_3COOH} \tag{2}$$

where

$$-\mathrm{d[X_2]_T}/\mathrm{d}t = k\mathrm{[ArH][CH_3COOX]} \tag{3}$$

$$\mathrm{[X_2]_T = [X_2] + [CH_3COOX]}$$

In connection with the comparative study in question the equilibria for the formation of trifluoroacetyl hypoiodite and hypobromite from mercuric trifluoroacetate and the appropriate halogen in trifluoroacetic (*cf.* eq 1) acid have been investigated. In addition rate constants for reaction of the trifluoroacetyl hypohalites (as generated from the mercuric salts) with various benzene derivatives (eq 3) have been determined.

In a subsidiary study the kinetics of reaction of pentamethylbenzene with acetyl hypoiodite generated through the reaction of silver acetate and iodine in acetic acid have been investigated. The results support the conclusion that eq 3 is the correct rate law for mercuric acetate induced reactions of halogen and aromatic substrates in acetic acid.

Experimental Section

Materials. Commercial samples of bromine, toluene, silver oxide (Mallinckrodt Analyzed Reagent), and pentamethylbenzene (Eastman Organic Chemicals) were used without further purification. Reagent grade iodine (CP Baker) was sublimed before use. Baker and Adamson reagent grade silver acetate was dried at 40° *in vacuo* for 24 hr.

Mallinckrodt glacial acetic acid was refluxed with 2% by volume acetic anhydride for 24 hr and then distilled using a Widmer column. A constant boiling middle fraction (118°) was collected for use in kinetic studies.

Mallinckrodt trifluoroacetic acid was distilled using a Widmer column. A constant boiling middle fraction (72°) was collected and stored in a desiccator before use as a solvent. The water content of this material was less than 0.1% as established by titration with Karl-Fischer reagent.

Nitrobenzene (Eastman Organic Chemicals) was steam distilled from 3 *N* sulfuric acid, washed with distilled water, and dissolved in ether. The dried ether solution was distilled. A constant boiling middle fraction of nitrobenzene was collected at 1.5 mm pressure for use in kinetic studies.

p-Nitrotoluene (Eastman Organic Chemicals) was dissolved in acetone, and the solution was treated with decolorizing carbon.

---

[1] A. L. Henne and W. F. Zimmer, *J. Amer. Chem. Soc.*, **73**, 1362 (1951).

[2] R. N. Haszeldine and A. G. Sharpe, *J. Chem. Soc.*, 993 (1952).

[3] Y. Hatanaka, R. M. Keefer, and L. J. Andrews, *J. Amer. Chem. Soc.*, **87**, 4280 (1965).

[4] E. M. Chen, R. M. Keefer, and L. J. Andrews, *ibid.*, **89**, 428 (1967).

After filtration of the solid and removal of the acetone the *p*-nitrotoluene was dissolved in ether. The solution was washed with dilute hydrochloric acid and dried. An equal volume of petroleum ether was added and the total volume of the solution was reduced by half. This last operation was repeated twice. The solution was then chilled and the precipitated *p*-nitrotoluene (used in rate work) was collected and dried *in vacuo*.

Trifluoromethylbenzene (Matheson Coleman and Bell) was distilled twice. A constant boiling middle cut (99°) was collected for use in rate work.

Mercuric trifluoroacetate was prepared by the procedure of Brown and Wirkkala[5] and dried *in vacuo*. The mercury content of various batches which were prepared (as determined by volumetric analysis using a standard solution of potassium thiocyanate) was within 0.5% of the theoretical value for $Hg(OCOCF_3)_2$.

Silver trifluoroacetate was prepared by the method of Janssen and Wilson[6] and dried *in vacuo* for 2 days.

Determination of the Equilibrium Constant for Formation of Trifluoroacetyl Hypoiodite. Data required to calculate the equilibrium constant for the reaction of mercuric trifluoroacetate and iodine in trifluoroacetic acid were obtained spectrophotometrically. Solutions were prepared for measurement by adding trifluoroacetic acid (at a temperature of 25°) to the mark of a volumetric flask containing weighed amounts of the two reactants or by mixing aliquots of solutions of known concentration of iodine and mercuric trifluoroacetate. Samples of the solutions were transferred to 1-cm silica absorption cells, and these were stored in a temperature-controlled housing (25.0°) of a Beckman DU spectrophotometer. After temperature equilibration of the cell and the housing, the free iodine content of each reaction mixture was established through measurement of its absorbance at 514 mμ using pure trifluoroacetic acid as a blank

The molar absorptivity of iodine in trifluoroacetic acid at 514 mμ was ascertained through measurement of the absorbances of solutions, the halogen content of which was determined by iodometric titration. The average molar absorptivity obtained, as based on a series of determinations, was 787 ± 5. This same value was obtained from the absorbance of a solution, the iodine concentration of which was calculated from its volume and the weight of solid iodine used in its preparation. The value reported previously[7] for this constant (815) is considerably higher.

Mercuric trifluoroacetate does not absorb significantly in trifluoroacetic acid at 514 mμ, nor does the other salt $[Hg(OCOCF_3)I]$ in the equilibrium mixtures. A solution of the latter salt was prepared for optical measurement by dissolving mercuric iodide in a solution of mercuric trifluoroacetate in trifluoroacetic acid. Since the solubility of mercuric iodide in the presence of mercuric trifluoroacetate is much greater than its solubility in pure trifluoroacetic acid, it was assumed that the increased solubility is associated with the formation of $Hg(OCOCF_3)I$ (eq 4). The absorption of trifluoroacetyl hypoiodite at 514 mμ is negligible (trifluoroacetic acid solutions of iodine with excess silver trifluoroacetate show little or no absorption at this wavelength).

$$HgI_2 + Hg(OCOCF_3)_2 \longrightarrow 2Hg(OCOCF_3)I \qquad (4)$$

The equilibrium constants (K_{CF_3COOI}) were calculated from the results of the optical measurements as described in the Results section. Relatively high concentrations of mercuric trifluoroacetate were avoided in preparing the equilibrium mixtures ($>20 \times 10^{-3}$ *M*) inasmuch as the salt appeared to catalyze decomposition of trifluoroacetyl hypoiodite. It was observed through iodometric analysis using standard sodium thiosulfate solution that a trifluoroacetic acid solution which was initially 42.10×10^{-3} *M* in $Hg(OCOCF_3)_2$ and 2.27×10^{-3} *M* in iodine lost approximately 30% of its oxidizing power in 24 hr. By contrast a solution initially 9.54×10^{-3} *M* in $Hg(OCOCF_3)_2$ and 1.43×10^{-3} *M* in halogen retained its oxidizing power over that same period.

In a number of cases the equilibrium constants were evaluated from data recorded during the course of rate runs (later described) rather than by the direct method outlined above. The reaction rates were investigated by noting changes in the absorbance (514 mμ) with time of trifluoroacetic acid solutions of iodine, $Hg(OCOCF_3)_2$, and an aromatic compound. The equilibrium free iodine concentration at the start of each run was deduced through extrapolation of a plot of absorbance *vs.* time to the time of initiation of reaction. In using this value to calculate the equilibrium constant it was assumed that the result would not be influenced by the presence of aromatic substance in the medium. An average value of 0.114 obtained for the equilibrium constant from rate runs is in good agreement with the value of 0.111 obtained from the equilibrium measurements. The constant did not appear to be sensitive to traces of water in the medium inasmuch as inclusion of small amounts of trifluoroacetic anhydride in reaction mixtures did not noticeably affect the results.

Formation of Trifluoroacetyl Hypobromite from Mercuric Trifluoroacetate and Bromine. Stock solutions of bromine were prepared at 25° by dissolving weighed quantities of the halogen in known volumes of trifluoroacetic acid. It was established that the molar absorptivity of bromine in this solvent is 160 at 411 mμ, a value which is in agreement with that reported previously.[7] Weighed samples of mercuric trifluoroacetate contained in volumetric flasks were dissolved to the mark in the halogen solution. To establish the free bromine concentrations of the resultant mixtures their optical densities were measured at 411 mμ (at a temperature of 25°) *vs.* a trifluoroacetic acid blank. Equilibrium constants (K_{CF_3COOBr}) were calculated from the results as later described.

Several experimental problems encountered in these measurements were reflected markedly in the accuracy of the results. The bromine solutions in trifluoroacetic acid were readily subject to loss of halogen through volatilization, which complicates transfer operations. The reaction mixtures were found to be photosensitive and subject to steady decreases in optical density when exposed to room light. Finally, and most serious of all, the equilibrium constant (K_{CF_3COOBr}) is low in value. and changes in optical density attending the formation of the hypobromite were very small (0.015–0.035 unit in the measurements in question).

Iodination Rate Studies. Rate runs were initiated by adding 5 ml of a solution of known concentration of the aromatic substrate to 5 ml of a solution containing known amounts of iodine and mercuric trifluoroacetate. The solvent was trifluoroacetic acid and the temperature of the solutions was 25.0°. A sample of the reaction mixture was transferred to a glass stoppered silica absorption cell. The stopper was sealed with paraffin, and the cell was transferred to the temperature controlled cell housing of the Beckman spectrophotometer. The absorbance of the cell contents at 514 mμ was determined at appropriate intervals using trifluoroacetic acid in the blank cells. The corresponding free halogen concentrations were calculated using the known molar absorptivity of iodine at this wavelength. The acetyl hypohalite concentrations of the rate samples were calculated at various reaction times using the appropriate free halogen concentrations and the equilibrium constant for the reaction of the halogen and mercuric acetate (K_{CF_3COOX}).

Bromination Rate Studies. The procedure used in investigating the rate of bromination of nitrobenzene in trifluoroacetic acid was patterned closely after that used in the iodination studies (see above). The optical density measurements of rate samples to determine free bromine concentration were made at 411 mμ.

Reaction of Silver Acetate and Iodine in Acetic Acid. Silver iodide precipitates when solutions of iodine and of silver acetate in acetic acid are mixed. If silver acetate is in excess, the solid is finely divided and the solutions remain cloudy for a long period of time. If iodine is in excess, the precipitate forms in clumps and can be filtered. The residual iodine concentration of the filtrate (as established spectrophotometrically) is within 1% of that expected for quantitative reaction of silver acetate. The spectrum of the solution shows strong ultraviolet absorption (peak below 290 mμ) not characteristic either of iodine or silver acetate solutions. The solutions of acetyl hypoiodite thus prepared undergo a slow loss in oxidizing power (13% in 25 hr in the case of a solution in which iodine was in slight excess, $[AgOAc]_i = 0.02$ *M* and $[I_2]_i = 0.021$ *M*).

Reaction of Silver Trifluoroacetate and Iodine in Trifluoroacetic Acid. When solutions of these two reactants in trifluoroacetic acid are mixed, the iodine color decreases in intensity and silver iodide precipitates. The disappearance of iodine is not however as great as expected for reaction according to eq 5.

$$I_2 + CF_3COOAg \longrightarrow CF_3COOI + AgI \qquad (5)$$

For example, a solution the initial reactant concentrations of which were $[CF_3COOAg]_i = 2.05 \times 10^{-3}$ *M* and $[I_2]_i = 2.36 \times 10^{-3}$ *M* (after mixing) was shown spectrophotometrically to contain iodine at a concentration of 0.65×10^{-3} *M* after removal of precipitated silver iodide. The spectrum of the product solution

---

[5] H. C. Brown and R. A. Wirkkala, *J. Amer. Chem. Soc.*, **88**, 1447 (1966).

[6] D. E. Janssen and C. V. Wilson, "Organic Syntheses," Collect. Vol. IV, Wiley, New York, N. Y., 1963, p 547.

[7] R. E. Buckles and J. F. Mills, *J. Amer. Chem. Soc.*, **76**, 6021 (1954).

contains an absorption maximum at 280 mμ which is not present in the spectrum of either reactant. The solutions are subject to a decrease in oxidizing power with time but less so than in the case of acetyl hypoiodite solutions produced from silver acetate and iodine. A solution generated through reaction of 2.0×10^{-3} *M* silver salt and 2.1×10^{-3} *M* iodine showed a 14% decrease in oxidizing power over a 6-day period. Correspondingly the optical density (1-cm cell) of the solution at 514 mμ increased from 0.162 to 0.283 and that at 280 mμ decreased from 1.21 to 0.96.

Rate Studies of the Reaction of Pentamethylbenzene with Acetyl Hypoiodite (Generated from Silver Acetate). Solutions of acetyl hypoiodite were prepared by treating silver acetate with a slight excess of iodine in acetic acid. Known volumes of the supernatant solution were mixed with known volumes of stock solutions of pentamethylbenzene in acetic acid at the temperature at which the reactions were investigated. Samples of the reaction mixtures were removed at various times and were added to solutions containing excess potassium iodide. These solutions were analyzed by titration with sodium thiosulfate for total oxidizing power [Ox] where $[\mathrm{Ox}] = [\mathrm{CH_3CO_2I}] + [\mathrm{I_2}]_{\mathrm{free}}$. The values of $[\mathrm{I_2}]_{\mathrm{free}}$ were obtained by analysis of samples taken at termination of reaction. Rate constants were calculated from the slopes of plots of $\ln ([\mathrm{CH_3CO_2I}]_i[\mathrm{ArH}]_t)/([\mathrm{ArH}]_i[\mathrm{CH_3CO_2I}]_t)$ *vs.* time. The plots were linear for about 75% of the reaction. Curvature beyond that point is probably associated with hypohalite decomposition.

Products of Aromatic Halogenation by Trifluoroacetyl Hypohalites. A. In the Reaction of Benzene in a Solution of Iodine and Mercuric Trifluoroacetate. Analysis of the products of this reaction was conducted by a vapor-phase chromatographic method since the solubility of iodine in trifluoroacetic acid is low enough to preclude direct recovery of iodobenzene. To a solution of 25 ml of 2.5×10^{-3} *M* iodine and 2×10^{-2} *M* mercuric trifluoroacetate in trifluoroacetic acid was added excess (0.01 mol) benzene. The iodine color was discharged immediately. To the resultant solution 100 ml of water was added, and the mixture was extracted three times with 50 ml of petroleum ether. The combined extracts were washed with dilute base and dried. The volume of the petroleum ether solution of product was then reduced to 11.7 ml by distillation using a Vigreux column. A 10 μl sample of the residue was injected onto a 15-ft Carbowax 20M column (impregnated on Chromosorb W). The column temperature was 171° and the flow rate of helium carrier gas was 25 ml per min. A lone nonsolvent peak was detected at 22 min, the reaction time of an authentic sample of iodobenzene. By use of appropriate standard solutions it was established that the recovery of iodine as iodobenzene was 88%. It was further established using solutions of known concentration of iodobenzene in trifluoroacetic acid that the recovery in the extraction procedure was 88%. That is, the conversion of iodine to iodobenzene in the reaction with mercuric trifluoroacetate is essentially quantitative.

B. In the Reaction of Toluene in a Solution of Iodine and Mercuric Trifluoroacetate. Excess toluene (8×10^{-2} mol) was added to 25 ml of a solution of 2.7×10^{-3} *M* iodine and 1×10^{-2} *M* mercuric trifluoroacetate in trifluoroacetic acid. The iodine color was discharged with immediate precipitation of a yellow solid (identified by its melting point (240–250°) as mercuric iodide). The product solution was subjected to petroleum ether extraction and the extract was concentrated to 9.75 ml (*cf.* the corresponding conditions for work-up of the product of iodination of benzene). The gas chromatogram of a sample of this residue (same conditions as in the preceding paragraph) showed a single nonsolvent peak at 30.5 min which is the time at which *p*-iodotoluene emerges. It was established by use of appropriate standards that the recovery of ring iodinated toluene, as based on initial iodine, was 80%. No effort was made to establish whether the iodotoluene produced was entirely the para isomer. By separate experiment it was shown that benzyl iodide does not survive on a chromatograph column under the conditions employed.

C. In the Reaction of Toluene in a Solution of Bromine and Mercuric Trifluoroacetate. Excess toluene (0.01 mol) was added to a solution of 25 ml of 6.4×10^{-2} *M* bromine and 2.8×10^{-1} *M* mercuric trifluoroacetate in trifluoroacetic acid. The bromine color was discharged with immediate precipitation of mercuric bromide (mp 230–236°). The procedure for analyzing the product solution by gas chromatography was essentially as described above. The chromatogram showed two peaks at 31.5 and 33.5 min, corresponding respectively to the absorption times of authentic samples of *o*- and *p*-bromotoluene. By use of appropriate standards it was established that the combined yield of the two bromotoluenes was 88% as based on initial bromine and that the ratio of ortho to para isomer was 42/58. Inasmuch as it was established that recovery of bromotoluene in a test of the extraction procedure was also 88% it was concluded that the bromination reaction is essentially quantitative.

D. *m*-Bromotrifluoromethylbenzene, *m*-Bromonitrobenzene, and 2-Bromo-4-nitrotoluene. To a mixture of 14.5 g (0.067 mol) of mercuric oxide in 50 ml of trifluoroacetic acid were added 8.4 g (0.033 mol) of trifluoroacetic anhydride and 12.45 g (0.085 mol) of trifluoromethylbenzene and then dropwise 8.35 g (0.053 mol) of bromine. Precipitated mercuric bromide (mp 230–236°) was filtered and the volume of the product solution reduced by evaporation. A mixture of ether and water were added. The ether phase was washed with base, dried, and concentrated under reduced pressure. The residue was taken up in pentane and the solution chilled in a bath of acetone and solid $\mathrm{CO_2}$. The crystals of *m*-bromotrifluoromethylbenzene thus produced melted at 37.5–39° (lit.[8] mp 34–36°).

In similar experiments *m*-bromonitrobenzene, mp 41–43° (lit.[9] mp 42–44°), and 2-bromo-4-nitrotoluene, mp 76–78° (lit.[10] mp 42–44°), were prepared from nitrobenzene and *p*-nitrotoluene, respectively.

E. Iodopentamethylbenzene from Pentamethylbenzene, Silver Acetate, and Iodine. To a stirred solution of 7.37 g (0.041 mol) of silver acetate in 100 ml of acetic acid were added 3.83 g (0.026 mol) of pentamethylbenzene and 9.87 g (0.039 mol) of iodine in 100 ml of acetic acid. The precipitated silver iodide was filtered and the volume of the filtrate reduced by evaporation. The residue was taken up in ether. The ether solution was washed with dilute base, dried, and concentrated *in vacuo*. The recovered 6-iodo-1,2,3,4,5-pentamethylbenzene was recrystallized from ethanol, melting point and mixture melting point identical with an authentic sample, 135–136°.

Results

Trifluoroacetyl Hypohalite Formation. As in the corresponding reaction of halogens with mercuric acetate in acetic acid, the addition of excess mercuric trifluoroacetate to iodine or bromine in trifluoroacetic acid results in a decrease in the intensity of halogen color of the solution without concomitant precipitation of insoluble mercuric halide. The change in color intensity is ascribed to the formation of trifluoroacetyl hypohalite. As described in the Experimental Section, the free halogen concentrations of solutions of varying initial concentrations of halogen and mercuric salt have been determined spectrophotometrically. On the assumption that hypohalite is formed in these solutions according to eq 6, equilibrium constants (eq 7) as reported in Tables I and II have been calculated.

$$\mathrm{Hg(OCOCF_3)_2 + X_2 \rightleftarrows Hg(OCOCF_3)X + CF_3COOX} \quad (6)$$

$$K_{\mathrm{CF_3COOX}} = [\mathrm{Hg(OCOCF_3)X}][\mathrm{CF_3COOX}]/[\mathrm{Hg(OCOCF_3)_2}][\mathrm{X_2}] \quad (7)$$

Table I. Equilibrium Constant for the Formation of Trifluoroacetyl Hypoiodite in Trifluoroacetic Acid at 25°

$10^3[\mathrm{Hg(OCOCF_3)_2}]_i$ *M*	$10^3[\mathrm{I_2}]_i$ *M*	$10^3[\mathrm{I_2}]_{\mathrm{eq}}$ *M*	$K_{\mathrm{CF_3COOI}}$
18.98	1.435	0.440	0.125
11.89	1.363	0.513	0.127[a]
7.99	0.575	0.174	0.122
3.04	2.48	1.82	0.101
2.31	0.254	0.099	0.113
1.54	1.315	0.976	0.098
0.77	0.762	0.578	0.100
Average of 38 determinations 0.111 ± 0.010			

[a] Trifluoroacetic anhydride present in the medium (4% by volume).

---

(8) K. Inukai and T. Ueda, *Kogyo Kagaku Kasshi*, **64**, 2156 (1961).

(9) B. T. Newbold and R. P. LeBlanc, *J. Org. Chem.*, **27**, 312 (1962).

(10) G. R. Jackson, Jr., and M. S. Frant, *J. Amer. Chem. Soc.*, **77**, 5625 (1955).

Table II. Equilibrium Constant for Formation of Trifluoroacetyl Hypobromite in Trifluoroacetic Acid at 25.0°

10^3[Hg-$(OCOCF_3)_2]_i$ M	$10^3[Br_2]_i$ M	A_i[a]	A_{eq}[b]	$10^4K_{CF_3COOBr}$
3.98	5.34	0.855	0.829	1.3
3.25	2.47	0.395	0.380	1.0
2.48	5.13	0.820	0.786	4.0
2.00	5.25	0.840	0.816	2.2
1.27	4.99	0.798	0.778	2.8

[a] Absorbance of the solution at 411 mμ before introducing mercuric trifluoroacetate. [b] Absorbance of the equilibrium mixture at 411 mμ.

For reasons discussed in the Experimental Section the determination of K_{CF_3COOBr} is subject to serious error, and in fact the constants reported in Table II vary over a wide range. Their average value rounded off to one significant figure is 2×10^{-4} (25.0°). The corresponding equilibrium constant for reaction of bromine and mercuric acetate[3] is larger by a factor of 10^3 ($K_{AcOBr} = 0.198$ at 25.0°), while K_{AcOI} at 25.0°[4] (2.43) is only of the order of 20 times as large as K_{CF_3COOI} (0.11 at 25.0°). The very low value for K_{CF_3COOBr} is most likely associated with the inductive effect of the CF_3 group, which must subject the halogen atom of a trifluoroacetyl hypohalite to strongly positive polarization. A bromine atom is unquestionably far more resistant to such polarization than an iodine atom, a fact which appears to be reflected dramatically in the relative stabilities of CF_3COOI and CF_3COOBr.

Kinetics of Aromatic Halogenation by CF_3COOI and CF_3COOBr. In the study of the kinetics of aromatic iodination in trifluoroacetic acid solutions of iodine and mercuric trifluoroacetate, *p*-nitrotoluene and trifluoromethylbenzene were chosen as substrates since they both react at a rate convenient for experimental work at room temperature. In the case of the corresponding bromination reaction nitrobenzene proved to be an appropriate aromatic substrate. In all rate runs the initial halogen concentration was less than that of the mercury salt and substantially less than that of the aromatic substrate. The results are summarized in Tables III and IV. The rate constants k listed in Table III are calculated on the assumption that reaction proceeds according to the rate law,

$$d[ArX]/dt = -d[X_2]_T/dt = k[\text{substrate}][CF_3COOX] \quad (8)$$

where $[X_2]_T$ represents the sum of the concentrations of free halogen and trifluoroacetyl hypohalite in the reaction mixture. The procedure for calculating $[CF_3COOI]$ from K_{CF_3COOI} and the free iodine concentrations determined spectrophotometrically during the course of the runs was exactly analogous to that used in the earlier study[4] of the reaction of pentamethylbenzene in acetic acid solutions of iodine and mercuric acetate. The rate of the reaction was evaluated at various times by determining the slope of plots of $[X_2]_T$ *vs.* time. These rates were then divided by the product of the concentrations of the substrate and hypoiodite to obtain the rate constant. The rate constants reported in Table III are the average values obtained for each run. In general the rate constants calculated at different times during a run deviated by less than 10% from the average value up to 75% reaction. In several runs with trifluoromethylbenzene the rate constant was evaluated from the initial rate only.

Table III. Rate Constants for Iodination of *p*-Nitrotoluene and Trifluoromethylbenzene in Trifluoroacetic Acid Solutions of Iodine and Mercuric Trifluoroacetate at 25.0°

[Aromatic] M	10^3[Hg-$(OCOCF_3)_2]_i$ M	$10^3[I^2]_i$ M	10^4k M^{-1} sec^{-1}
	Aromatic = *p*-$NO_2C_6H_4CH_3$		
0.258	22.95	2.08	2.7
0.258	11.43	2.08	2.9
0.258	6.30	2.14	2.8
0.257	6.21	1.08	3.3
0.257	6.26	0.514	4.3
0.257	3.12	0.566	3.6
0.257	1.66	0.523	3.2
0.140	10.77	1.05	2.7
0.082	11.83	1.09	2.3
0.041	5.92	1.09	2.2
			Av 3.0 ± 0.5
	Aromatic = $C_6H_5CF_3$		
0.784	4.57	0.516	7.3
0.392	9.14	1.032	8.1
0.228	10.04	0.849	7.5[a]
0.111	10.12	0.849	7.3[a]
			Av 7.6 ± 0.3

[a] Calculated from the initial rate only.

Table IV. Rate Constants for Bromination of Nitrobenzene in Trifluoroacetic Acid Solutions of Bromine and Mercuric Trifluoroacetate at 25.0°

$[C_6H_5NO_2]$ M	10^3[Hg-$(OCOCF_3)_2]_i$ M	$10^3[Br_2]_i$ M	10^4kK
0.248	11.7	3.64	1.20
0.242	23.4	5.45	1.23
0.242	23.4	2.73	0.92
0.176	17.5	4.40	1.40
0.089	18.4	5.00	1.32
0.045	9.2	5.00	1.36
			Av 1.2 ± 0.1

The rate data for the bromination of nitrotoluene were analyzed by a slightly different method than that used for the iodination reactions. Since K_{CF_3COOBr} is extremely small, $[CF_3COOBr]$ will be small and $[Br_2]$ is approximately equal to the total bromine concentration $[Br_2]_T$. One can then rewrite eq 8 as

$$-\frac{d[Br_2]}{dt} = k[\text{substrate}]K_{CF_3COOBr}\frac{[Hg(OCOCF_3)_2][Br_2]}{[[Br_2]_i - [Br_2]]} \quad (9)$$

This rate law may be integrated to give

$$-[Br_2]_i \ln [Br_2] + [Br_2] = kK_{CF_3COOBr}[\text{substrate}][Hg(OCOCF_3)_2]t + C \quad (10)$$

if $[Hg(OCOCF_3)_2]$ and [substrate] are large compared to $[Br_2]_i$. For individual runs plots of values of the left term of eq 10 *vs.* time were linear to better than 80% reaction. The values of kK_{CF_3COOBr} reported in Table IV were obtained by dividing the slopes of the straight lines by the corresponding value of [substrate][Hg$(OCOCF_3)_2$]. If we divide the average value of kK (1.2×10^{-4}) obtained in Table IV by the value of

Table V. Relative Reactivities of Several Aromatic Halogenating Agents

Aromatic[a] substrate	Halogenating[b] agent	Solvent[b]	$k(25.0°)$, l./mol sec	Rel reactivities of aromatics	Rel reactivities of halogenating agents	Ref
B	AcOBr	AcOH	3.2×10^{-3}			*m*
PMB	AcOI	AcOH	7.8×10^{-2}			*n*
PMB/B				2×10^{7} [c]		*d*
	AcOBr/AcOI	AcOH			8×10^{5}	
NB	TBOBr	TFOH	0.6			*e*
PNT	TFOI	TFOH	3.0×10^{-4}			*e*
PNT/NB				4.8×10^{2} [f]		
	TFOBr/TFOI	TFOH			1×10^{6}	
NB	TFOBr	TFOH	0.6			*e*
B	AcOBr	AcOH	3.2×10^{-3}			*m*
B/NB				1.2×10^{5} [g]		*h*
	TFOBr/AcOBr				2.2×10^{4} [i]	
PNT	TFOI	TFOH	3.0×10^{-4}			*e*
PMB	AcOI	AcOH	7.8×10^{-2}			*n*
PMB/PNT				2.6×10^{9} [j]		
	TFOI/AcOI				1.0×10^{4} [i]	
NB	TFOBr	TFOH	0.6			*e*
B	Br_2	TFOH	7.6×10^{-7}			*o*
B/NB				6.3×10^{4} [g]		
	TFOBr/Br_2	TFOH			5×10^{10}	
PNT	TFOI	TFOH	3.5×10^{-4}			*e*
T	ICl	TFOH	1.4×10^{-2}			*k*
T/PNT				6.3×10^{4} [l]		
	TFOI/ICl	TFOH			2×10^{3}	
T	ICl	TFOH	1.4×10^{-2}			*k*
T	Br_2	TFOH	1.97×10^{-3}			*o*
	Br_2/ICl	TFOH			0.14	

[a] The letters B, PMB, NB, PNT, and T are used respectively to represent benzene, pentamethylbenzene, nitrobenzene, *p*-nitrotoluene, and toluene. [b] Trifluoroacetic acid and trifluoroacetyl hypobromite and hypoiodite are represented respectively by TFOH, TFOBr, and TFOI. [c] The ratio of deuteration rates in trifluoroacetic acid; by way of comparison, the ratio of rates of zinc chloride catalyzed bromination of the two aromatic hydrocarbons in acetic acid is *ca.* 10^6 (L. J. Andrews and R. M. Keefer, *J. Amer. Chem. Soc.*, **78**, 4549 (1956). [d] W. Lauer and G. Stedman, *ibid.*, **80**, 6439 (1958). [e] This investigation. [f] The ratio of rates of reaction of toluene and benzene with AcOBr in HOAc (ref 3); it is assumed that this is also the reactivity ratio for *p*-nitrotoluene and nitrobenzene. [g] The ratio of bromination rates in concentrated H_2SO_4. [h] P. B. D. de la Mare and I. C. Hilton, *J. Chem. Soc.*, 997 (1962). [i] Corrected for the difference in solvents (see text). [j] Calculated from values of PMB/B, NB/B, and NB/PNT given in the table. [k] L. J. Andrews and R. M. Keefer, *J. Amer. Chem. Soc.*, **79**, 1412 (1957). [l] Assumed to be the same as the reactivity ratio B/NB. [m] Reference 3. [n] Reference 4. [o] Reference 5.

K_{CF_3COOBr} from Table II (2×10^{-4}), we obtain 0.6 for the rate constant k of eq 3.

Relative Strengths of Acetyl and Trifluoroacetyl Hypohalites as Electrophilic Aromatic Halogenating Agents. As is the case for aromatic halogenation by an acetyl hypohalite in acetic acid,[3,4] the products of reaction of a number of aromatic substances with trifluoroacetyl hypoiodite or hypobromite in trifluoroacetic acid have been identified (Experimental Section) as those to be expected of polar substitution processes. Therefore, in comparing the relative reactivities of the various acetyl and trifluoroacetyl hypohalites, one is in effect comparing their strengths as electrophilic halogenating agents. Such a comparison is made in Table V in which among other items a summary of second-order rate constants for the reaction of the hypohalites with various aromatic substances is presented.

To illustrate the construction of Table V, the method of estimating the relative reactivities of acetyl hypobromite and hypoiodite (AcOBr/AcOI), as presented in the top section, is considered in detail. As established previously[3,4] the rate constants for reaction of the hypobromite with benzene and of the hypoiodite with pentamethylbenzene at 25.0° are 3.2×10^{-3} and 7.8×10^{-2} M sec, respectively. The relative reactivities of the two aromatic substrates in electrophilic substitution processes (benzene (B) and pentamethylbenzene (PMB)) are subject to variation with the solvent, the identity of the electrophile, the temperature, etc. For present purposes the relative substrate reactivities which are used are based on reactions similar in type to the halogenations under consideration. The ratio PMB/B = 2×10^7 applies to deuteration in trifluoroacetic acid. Using this figure the ratio AcOBr/AcOI is calculated as $(3.2 \times 10^{-3})(2 \times 10^{7})/(7.8 \times 10^{-2}) = 8 \times 10^{5}$. This is admittedly a relatively crude estimate because of uncertainty concerning the appropriate figure to use for PMB/B (in this connection see footnote *c* of Table V). Other reported reactivity ratios for the various halogenating agents were calculated in similar fashion. In obtaining the ratios TFOBr/AcOBr and TFOI/AcOI a correction was made to account for the fact that different solvents were used in determining rate constants for the acetyl and trifluoroacetyl hypohalites. The correction factor applied (10^3) represents the approximate increase in rate observed for an electrophilic aromatic substitution process when the solvent is changed from acetic to trifluoroacetic acid.[5,11]

By using these reactivity ratios (second column from the right, Table V) the relative strengths of the several halogenating agents can be assigned in the order $Br_2 < ICl \simeq CH_3COOI \ll CF_3COOI < CH_3COOBr \ll$

---

(11) R. M. Keefer and L. J. Andrews, *ibid.*, **81**, 1360 (1959).

CF_3COOBr. With the exception of the value for CF_3COOBr itself, this reactivity series has been arrived at without reference to data presented in Table V concerning reactions of trifluoroacetyl hypobromite. Although the series has been established by making certain assumptions which are *approximate at best* (see footnotes *c*, *f*, *j*, and *l* of Table V), it is obvious that there is a wide variation in reactivity along the series. If one uses the figures of Table V to make numerical comparisons, it can be reasoned that CF_3COOI, CH_3COOBr, and CF_3COOBr are respectively 10^4, 10^6, and 10^{10} as reactive as Br_2. Certainly these figures are reliable to no more than a power of 10. Clearly the trifluoroacetyl hypohalites, notably the hypobromite, are powerful electrophiles.

Kinetics of Reaction of Pentamethylbenzene with Acetyl Hypoiodite. The results of the rate studies of the reaction of pentamethylbenzene with acetyl hypoiodite, as generated from iodine and silver acetate in acetic acid, are presented in Table VI. The changes in concentration of the hypoiodite during the course of the runs were determined through iodometric analysis of rate samples, and the reported rate constants were calculated on the assumption that the reaction is first order in aromatic hydrocarbon and in hypoiodite. The average value for the rate constant at 25° (0.10 M^{-1} sec^{-1}) is in reasonably good agreement with that reported[4] (0.08 M^{-1} sec^{-1}) for the iodination of pentamethylbenzene in acetic acid solutions of iodine and mercuric acetate and calculated on the assumption that reaction (to form 6-iodo-1,2,3,4,5-pentamethylbenzene) proceeds according to eq 2. The activation energy (12 kcal mol^{-1}) is also the same within the limits of error as that observed for pentamethylbenzene iodination in the presence of mercuric acetate. It appears virtually certain, as has been assumed[3,4] in analyzing the results of rate studies, that the effective halogenating agent in the reaction of aromatic substances with halogen in the presence of mercuric acetate is acetyl hypohalite.

Table VI. Rate Constants for the Reaction of Pentamethylbenzene with Acetyl Hypoiodite (Generated from Silver Acetate and Iodine) in Acetic Acid at 25.0°

$10^3[C_6H(CH_3)_5]_i$ M	$10^3[CH_3COOI]_i$ M	$10^3[I_2]_{free}$ M	k M^{-1} sec^{-1}
40.91	8.66	1.38	0.09
21.32	10.87	9.56	0.14
20.87	8.69	1.51	0.10
21.12	2.57	0.75	0.09
8.83	8.00	2.00	0.12
21.17	4.89	0.30	0.08[a]
21.17	4.32	0.45	0.28[a,b]
		Av (25.0°)	0.10 ± 0.02

[a] The same stock solution of acetyl hypoiodite was used in the last two runs of the table. [b] Run temperature was 45.2°; the activation energy based on the rate constants for the last two runs of the table is 12 kcal mol^{-1}.

An attempt was made to prepare solutions of trifluoroacetyl hypoiodite by reaction of iodine with silver trifluoractate in trifluoroacetic acid. In contrast to what was observed for the corresponding reaction of iodine (in excess) and silver acetate, the concentration of free halogen remaining in solution after precipitation of silver iodide was found to be larger than expected if silver trifluoroacetate reacted quantitatively to form the hypoiodite. Similar observations made by Haszeldine and Sharpe[2] concerning the incompleteness of reaction of iodine and silver trifluoroacetate in nitrobenzene have been explained on the assumption that trifluoroacetyl hypohalite forms a complex with silver trifluoroacetate ($CF_3COOI \cdot AgOCOCF_3$).[12] No convincing evidence has, however, been obtained that such a complex is actually formed when the reaction takes place in trifluoroacetic acid. Because of the uncertainty concerning the stoichiometry of that reaction, the original plan to do a rate study of aromatic halogenation in the product solution has been abandoned.

Acknowledgment. Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this research.

---

(12) For related observations concerning complexes of this kind see (a) C. V. Wilson, *Org. React.*, **9**, 332 (1957); (b) G. H. Crawford and J. H. Simons, *J. Amer. Chem. Soc.*, **77**, 2605 (1955).