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The Mechanism of Trifluoroacetic Acid-catalyzed Aromatic Chlorination by Iodobenzene Dichloride in Carbon Tetrachloride

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In acetic acid, iodobenzene dichloride serves as a halogenating agent for aromatic hydrocarbons by prior dissociation to give the free halogen, which is the effective chlorinating agent. Kinetic evidence now has been obtained that in carbon tetrachloride in the presence of trifluoroacetic acid as a catalyst durene (at moderate concentration) may undergo a direct attack by iodobenzene dichloride. A second highly reactive chlorinating species, probably $C_6H_5I(Cl)(OCOCF_3)$, also is present in effective quantity in the reaction mixture when the hydrogen chloride content of the medium is small.

Iodobenzene dichloride can serve as a halogen source in addition reactions with unsaturated substances as well as in aromatic substitution reactions. It has been established unequivocally that in acetic acid the dichloride functions as a chlorinating agent for polyalkylbenzenes by first dissociating to provide molecular chlorine rather than by making a direct attack on the hydrocarbons.[1,2] In a non-polar medium such as carbon tetrachloride iodobenzene dichloride does not dissociate to iodobenzene and chlorine at an appreciable rate unless a polar catalyst is present.[3] It does, however, react with a variety of cyclic unsaturated substances in solvents of low polarity,[4–7] to give vicinal dichlorides of geometric configurations opposite to those of the adducts obtained using free chlorine. The suggestion[5] that iodobenzene dichloride can, in certain circumstances, react directly with an unsaturated system (rather than through prior breakdown to the halogen) therefore seems reasonable.

Experimental conditions now have been found under which nuclear chlorination of an aromatic substance, durene, with iodobenzene dichloride occurs without the formation of chlorine as an intermediate. This reaction takes place in carbon tetrachloride solution when trifluoroacetic acid is present to serve as a catalyst. Trifluoroacetic acid also promotes the dissociation of iodobenzene dichloride to iodobenzene and chlorine in carbon tetrachloride, but this reaction is slow compared to that which occurs when durene is present in the reaction mixture at moderate concentration. Through a detailed study of the kinetics of this reaction with durene it has been ascertained that both $C_6H_5ICl_2$ and a reactive intermediate, which has been postulated as $C_6H_5I(Cl)(OCOCF_3)$ or $C_6H_5ICl^+$ in the form of an ion pair with the anion of the catalyst, may serve as the effective chlorinating species.

Experimental

Materials.—Iodobenzene dichloride was freshly prepared as needed for rate work by a procedure described previously.[8] Stock solutions of the dichloride in carbon tetrachloride which were prepared for rate work were analyzed iodometrically. In the absence of catalyst the dichloride in these solutions remained completely undissociated over the period required for completion of even the slowest of the rate runs later described. Eastman Organic Chemicals trifluoroacetic acid and spectro grade carbon tetrachloride were used. The former was freshly distilled for rate work. The durene, which was recrystallized from ethanol, and the iodobenzene, which was redistilled before use, also were obtained from Eastman Organic Chemicals. Solutions of hydrogen chloride in carbon tetrachloride were prepared using a commercial sample of the anhydrous hydrogen halide. These solutions were standardized by shaking measured volumes with water and then gravimetric analysis of the water phase for chloride ion.

It was assumed in preparing rate samples containing both carbon tetrachloride and trifluoroacetic acid that the volumes of these two components are additive.[9]

The Kinetic Measurements.—The equilibration of iodobenzene dichloride with iodobenzene and chlorine in carbon tetrachloride at various concentrations of trifluoroacetic acid catalyst was followed spectrophotometrically in much the same fashion as has been described previously.[1,3,8] The spectrophotometric measurements were conducted at a wave length of 380 mμ. Equilibrium constants, K, and dissociation rate constants, k_1, as defined in eq. 1 and 2 were calculated from optical densities recorded during the runs by the methods of earlier investigations.[8] The extinction coefficients of the reactant and products required for these calculations were found to vary slightly with changes in the catalyst concentration of the medium. Typical values of the extinction coefficients (1.08M trifluoroacetic acid solutions in carbon tetrachloride at 380 mμ) are 101 and 22.1 for iodobenzene dichloride and chlorine, respectively; the absorption of iodobenzene is negligibly small at this wave length. The dichloride extinction coefficients were calculated from extrapolated initial optical densities (zero time) of solutions prepared for rate studies.

The rate samples for reactions with durene present were prepared by mixing aliquots of stock solutions of durene, the dichloride and the catalyst directly in the absorption cells. Again the reactions were followed at 380 mμ using the general procedures described above. In a few runs at lower dichloride concentrations a lower wave length setting (360 mμ) was used. In general the measured optical densities were subject to a small correction based on very low optical densities recorded after the dichloride was completely consumed. In analyzing these runs it was assumed that the only substance which contributed to these corrected absorptions, d_c, was iodobenzene dichloride.

The Products of Reaction of Iodobenzene Dichloride and Durene.—Under conditions approximating those used in the rate experiments the durene was subject primarily to nuclear rather than to side-chain halogenation. This was proved by investigation of the products formed when a solution of 0.551 g. (2.00×10^{-3} mole) of freshly prepared iodobenzene dichloride and 0.268 g. (2.00×10^{-3} mole) of durene in 150 ml. of carbon tetrachloride was treated with 9.00 g. (0.079 mole) of trifluoroacetic acid. The solution was stored in the dark overnight. It then was washed with water and dilute sodium hydroxide and dried over calcium chloride. The solvent was removed by evaporation, first at atmospheric

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[1] R. M. Keefer and L. J. Andrews, THIS JOURNAL, **79**, 4348 (1957); **81**, 2374 (1959).

[2] L. J. Andrews and R. M. Keefer, *ibid.*, **81**, 4218 (1959).

[3] L. J. Andrews and R. M. Keefer, *ibid.*, **80**, 1723 (1958).

[4] C. J. Berg and E. S. Wallis, *J. Biol. Chem.*, **162**, 683 (1946).

[5] D. H. R. Barton and R. Miller, THIS JOURNAL, **72**, 370 (1950).

[6] S. J. Cristol, F. R. Stermitz and P. S. Ramey, *ibid.*, **78**, 4939 (1956).

[7] R. K. Summerbell and H. E. Lunk, *ibid.*, **79**, 4802 (1957).

[8] R. M. Keefer and L. J. Andrews, *ibid.*, **80**, 277 (1958).

[9] L. J. Andrews and R. M. Keefer, *ibid.*, **82**, 3059 (1960).

pressure and then under vacuum. The semi-solid residue which remained was heated with alcoholic silver nitrate to test for benzylic halide. The silver chloride which thus was precipitated weighed 0.0092 g. (6.4×10^{-5} mole). That is, about 3.2% of the dichloride must have been consumed in side-chain halogenation. The ethanol filtrate from the silver chloride precipitation was diluted with a large volume of water. White crystals which melted from 140–175° and which gave a positive sodium fusion test for halogen were obtained. These probably were a mixture of unreacted durene and 3,6-dichloro-1,2,4,5-tetramethylbenzene. The latter is reported[10] to melt from 189–190°. A second crop (25 mg.) of crystals obtained by chilling the filtrate had a m.p. of 45–46° (reported[11] for 3-chloro-1,2,4,5-tetramethylbenzene, m.p. 47°). Only an oil, which could not be induced to crystallize, was obtained by adding more water to the mother liquor remaining from these crystallizations.

It can be estimated using rate constants presented in Tables I and II that more than 50% of the iodobenzene dichloride, in the preceding experiment, reacted by attacking durene directly or in the form of $C_6H_5I(Cl)(OCOCH_3)$. At the low durene concentration of the experiment some halogenation must have occurred by the attack of free chlorine, formed by prior dissociation of the dichloride, on the hydrocarbon. Since almost no benzylic halide product was formed, it can be concluded that all three of the active chlorinating agents in the reaction mixture attack the aromatic nucleus rather than the side chain.

Results

Rate constants, k_1, for the trifluoroacetic acid induced dissociation of iodobenzene dichloride in carbon tetrachloride, as defined in eq. 1, are given in Table I. The corresponding equilibrium constants (eq. 2), which were calculated from the equilibrium concentrations of the reactants and products, are also listed.

$$-d(C_6H_5ICl_2)/dt = k_1(C_6H_5ICl_2) - k_2(C_6H_5I)(Cl_2) \quad (1)$$

$$K = k_1/k_2 = (C_6H_5I)(Cl_2)/(C_6H_5ICl_2) \quad (2)$$

The order of the dissociation reaction with respect to the catalyst was estimated from the slope of the line obtained by plotting values of log k_1 *versus* the logarithms of the corresponding trifluoroacetic acid concentrations. The apparent order, which has a minimum value of 2.2, increases somewhat as the catalyst concentration increases. The rate of dissociation of the dichloride of *p*-methyl iodobenzoate in carbon tetrachloride shows a very similar dependence on the trifluoroacetic acid content of the medium.[9] Presumably, as has been suggested previously,[9,12] a minimum of two catalyst dimer molecules are required to solvate the substantially polar activated complexes (which probably are structurally related to the ion pairs $ArICl^+Cl^-$) which separate the dichlorides from their dissociation products. The equilibrium constants for dichloride dissociation increase somewhat as the catalyst concentration of the medium is diminished. This is in keeping with the earlier observation that the degree of dichloride dissociation is enhanced as the solvent becomes less polar.[13]

TABLE I

RATE CONSTANTS FOR THE TRIFLUOROACETIC ACID-CATALYZED DISSOCIATION OF $C_6H_5ICl_2$ (CCl_4, 25.0°)

$10^3(C_6H_5ICl_2)_i$, moles/l.	$(\text{Catalyst})_i$, moles/l.	$10^4 k_1$, sec.$^{-1}$	$10^3 K$, moles/l.
8.75	4.31	27.4	7.7
4.38	4.31	26.8	7.9
2.19	4.31	25.8	7.7
4.38	2.16	4.31	12.8
4.38	1.08	0.73	13.7
4.26	0.539	0.15	17.4

In the rate runs with durene present, the aromatic hydrocarbon was in large excess of the iodobenzene dichloride. Individual runs were interpreted in terms of the rate law

$$-d \ln(C_6H_5ICl_2)/dt = k_0 \quad (3)$$

It was observed quite generally that at a particular catalyst concentration, k_0 values were substantially larger than k_1 values for the dissociation of iodobenzene dichloride. At 1.08 M trifluoroacetic acid (25.0°), k_1 is about 7×10^{-5} sec.$^{-1}$. From the slopes of plots of log $(C_6H_5ICl_2)$ *versus* time for runs (at this catalyst concentration) in which the initial dichloride concentration was 4.26×10^{-3} M and the durene concentrations were 0.062 and 0.124 M, respectively, k_0 values at 25.0° of 3.5×10^{-3} and 6×10^{-3} sec.$^{-1}$ were evaluated. Since the rate of chlorination of durene by the dichloride is strongly dependent on the hydrocarbon content of the reaction mixture, the slow step of the reaction cannot, as is the case for chlorination of reactive polymethylbenzenes in acetic acid[1,2] (even when their concentrations are relatively high), be the dissociation of the dichloride (eq. 4).

$$C_6H_5ICl_2 \xrightarrow{k_1} C_6H_5I + Cl_2 \quad (4)$$

Actually the lines obtained by plotting log $(C_6H_5ICl_2)$ *versus* time for the runs with durene showed considerable curvature. That is, k_0 diminishes as reaction proceeds. The k_0 values recorded in the preceding paragraph apply to the reaction at 30% of completion. On the assumption that the reaction is subject to inhibition by one of the products, runs were conducted with iodobenzene and also with hydrogen chloride initially present. Although the added iodobenzene had no significant effect on the rate of consumption of the dichloride, hydrogen chloride slowed the reactions appreciably. These facts are illustrated in Fig. 1 in which log d_c values for several pertinent runs are plotted against reaction times (where d_c, the optical density of the reaction mixture, is directly proportional to the iodobenzene dichloride concentration). The initially added hydrogen chloride not only lowered the reaction rate but also substantially reduced the variation in k_0 during the course of the reaction.

As is illustrated in Fig. 2, k_0 varies inversely with hydrogen chloride concentration of the medium. The k_0 values upon which the points in this figure are based were taken from the slopes of the lines obtained when the experimental data were plotted as illustrated in Fig. 1. Except in cases where hydrogen chloride was added initially, its concentration was taken as the difference between the dichloride concentration at the start of the reaction and at the time corresponding to the measured k_0 value. It should be noted that the straight lines of Fig. 2 do not pass through the origin. That is, when the hydrogen chloride concentration is raised to very high levels, the reaction is relatively slow but is not stopped completely. The points of lines 2 and 3 were corrected to take into account slight

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[10] A. Töhl and O. Eberhardt, *Ber.*, **26**, 2944 (1893).

[11] G. Illuminati and G. Marino, THIS JOURNAL, **78**, 4975 (1956).

[12] R. M. Keefer and L. J. Andrews, *ibid.*, **82**, 4547 (1960).

[13] R. M. Keefer and L. J. Andrews, *ibid.*, **80**, 5350 (1958).

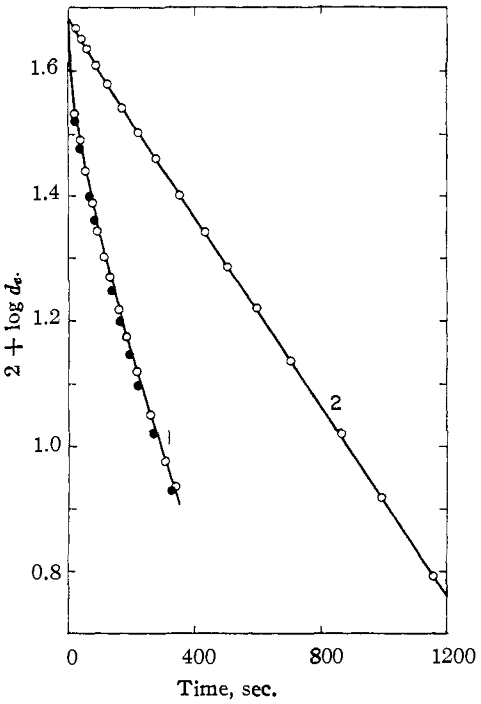
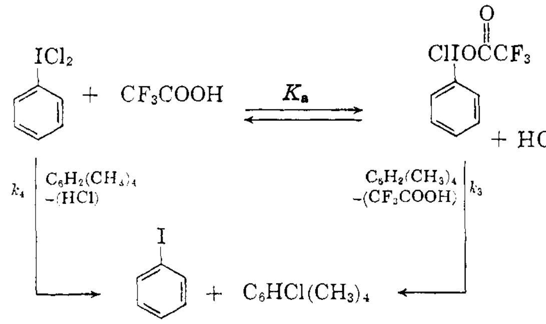


Fig. 1.—The effects of hydrogen chloride and iodobenzene on the trifluoroacetic acid-catalyzed reaction of durene with iodobenzene dichloride in carbon tetrachloride solution at 25.0°. In all runs (CF_3COOH) = 1.08 *M*, ($C_6H_5ICl_2$)$_i$ = 4.37 × 10^{-3} *M* and (durene)$_i$ = 0.124 *M*. On curve 1 the open circles apply to a run in which no additional substances were present initially; the filled circles apply to a run in which (C_6H_5I)$_i$ = 0.170 *M*. Curve 2 describes a run at (HCl)$_i$ = 0.042 *M*.

changes in the concentration of durene during the course of the runs.

The effect of hydrogen chloride on the reaction rate can best be explained if it is assumed that chlorodurene can be formed by either of two pathways, as outlined below.



(5)

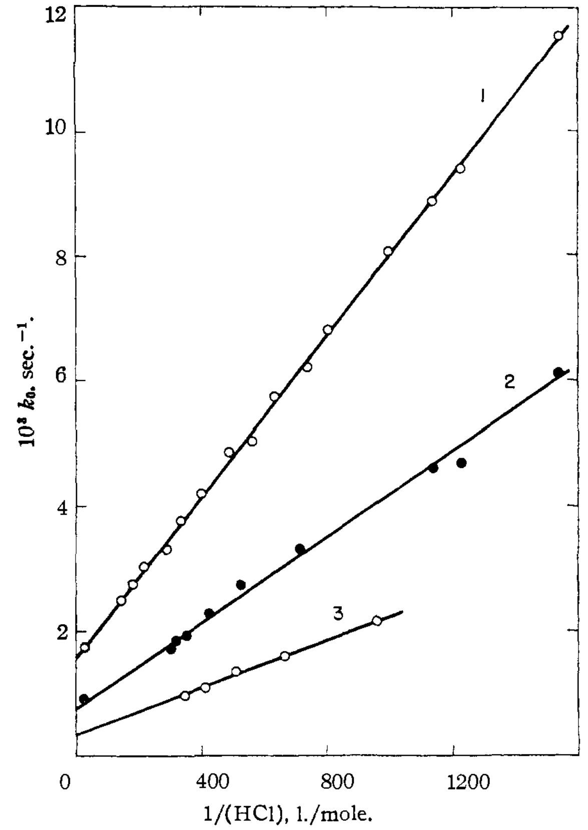
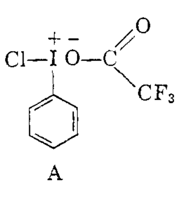


Fig. 2.—The effects of hydrogen chloride and durene on k_0. The trifluoroacetic acid concentration in all runs was 1.08 *M*. Line 1 is based on data taken in nine rate runs in which the initial durene concentration was 0.124 *M* and in which ($C_6H_5ICl_2$)$_i$ varied from 1.11 × 10^{-3}–8.88 × 10^{-3} *M*. Line 2 is based on the results of three runs at 0.062 *M* initial durene concentration with ($C_6H_5ICl_2$)$_i$ varying from 1.11 × 10^{-3}–4.37 × 10^{-3}*M*. Line 3 is based on a single run with initial durene concentrations of 0.031 *M* and 4.26 × 10^{-3}*M* iodobenzene dichloride, respectively. The points at the extreme left of lines 1 and 2 are based on runs in which hydrogen chloride (0.042 *M*) was introduced at the start of the reaction.

In this scheme durene is subject to competitive attack by the dichloride and the monochloride trifluoroacetate of iodobenzene. This last substance, which might alternately be formulated as an ion pair (A) in the above reaction sequence, is presumed to be a much better electrophilic reagent than the dichloride itself. It is further presumed that the dichloride and monochloride are in equilibrium with each other at all times during the chlorination reaction. Even in the absence of added hydrogen chloride (or hydrogen chloride formed as a product of durene chlorination) this equilibrium must lie far to the left. This can be concluded since the extinction coefficients of iodobenzene dichloride in the near-ultraviolet region in carbon tetrachloride are not much altered by the presence of trifluoroacetic acid in the medium, as would be expected if a substantial amount of dichloride were converted to the monochloride.[14]



A

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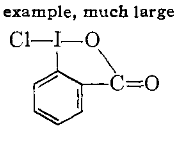
[14] The near-ultraviolet extinction coefficients in acetic acid[3] of (i) are, for example, much larger than those of (ii).



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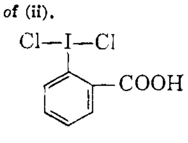


i

If durene chlorination takes place as postulated, the rate of consumption of the dichloride in the presence of a large excess of the aromatic hydrocarbon, (ArH), should proceed according to the rate law

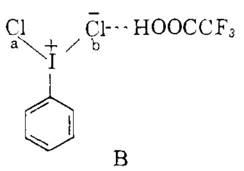
$$-\mathrm{d}(C_6H_5ICl_2)/\mathrm{d}t = k_3(\mathrm{ArH})(C_6H_5I(Cl)(OCOCH_3)) + k_4(\mathrm{ArH})(C_6H_5ICl_2) = (C_6H_5ICl_2)[k_4(\mathrm{ArH}) + k_3K_a(\mathrm{ArH})(CF_3COOH)/(HCl)] \quad (6)$$

It follows from eqs. 3 and 6 that k_0 is related to the concentrations of the reactants, the catalyst and hydrogen chloride by eq. 7.

$$k_0 = k_4(\mathrm{ArH}) + k_3K_a(\mathrm{ArH})(CF_3COOH)/(HCl) \quad (7)$$

In other words, as the hydrogen chloride concentration of the medium becomes large the concentration of $C_6H_5I(Cl)(OCOCH_3)$ is reduced sufficiently so that this substance cannot compete effectively with iodobenzene dichloride as a direct halogenating agent. As required by eq. 7 the intercepts of linear plots, of the type shown in Fig. 2, of k_0 *versus* the reciprocal of the concentration of hydrogen chloride for reactions at a fixed catalyst concentration are directly dependent on the durene concentration. This is specifically illustrated in Table II in terms of the first three values for k_4(ArH) which are listed. The three corresponding values of $k_3k_a(CF_3COOH)$ (ArH), which were taken from the slopes of the lines of Fig. 2, are also directly dependent on the durene concentration of the medium (see Table II), as also is required by eq. 7.

The rate constant, k_4, for the reaction between durene and the dichloride is between second and third order with respect to the trifluoroacetic acid concentration, and this order increases with increasing catalyst content of the medium (see the last three entries in the right hand column of Table II). Probably trifluoroacetic acid enhances the capacity of the dichloride to serve as a source of electrophilic halogen (chlorine a) in attacking durene through hydrogen bonding with the dichloride (at chlorine b) in the activation process, as crudely depicted



B

Polarization of this type must also occur in the activation process for dissociation of the dichloride to iodobenzene and chlorine. Undoubtedly more than the one catalyst molecule shown above is involved. A detailed discussion of the function of the catalyst in facilitating polarization of the I–Cl bond of the dichloride has appeared previously.[9,12]

TABLE II

VALUES OF k_3K_a(ArH)(CF_3COOH) AND k_4(ArH) FOR REACTION IN CCl_4, 25.0°[a]

(CF_3COOH), moles l.$^{-1}$	(Durene), moles l.$^{-1}$	10^6k_3K (ArH) (CF_3COOH), sec.$^{-1}$ mole l.$^{-1}$	10^3k_4(ArH), sec.$^{-1}$
1.08	0.031	1.9	0.35
1.08	.062	3.4	0.76
1.08	.124	6.4	1.55
0.54	.124	0.31	0.15
0.27	.124	0.033	0.034

[a] Based on runs in which $(C_6H_5ICl_2)_i$ varied from 1.11–8.88 × $10^{-3}M$.

The values of $k_3K_a(CF_3COOH)$ show an apparent high order dependence on the catalyst concentration. This order ranges approximately from third to fifth as the trifluoroacetic acid varies from 0.27–1.08 *M*. Presumably K_a is sensitive to changes in the trifluoroacetic acid content of the medium. Also k_3, like k_4, probably is second or higher order dependent on trifluoroacetic acid. The monochloride trifluoroacetate as well as the dichloride must undergo a catalyst-assisted polarization when it functions as an electrophilic reagent.

From a comparison of the rate constants of Tables I and II it may be concluded that in reaction mixtures such as were used in the rate runs described in Fig. 2 and Table II little, if any, durene chlorination occurred by a process in which the dichloride first dissociated to give free chlorine. At durene concentrations below those used in these runs the magnitude of k_1 may become appreciable compared to that of k_0 (see eq. 7). It also should be noted that values of $k_3K_a(\mathrm{ArH})(CF_3COOH)/(HCl)$ fall off much more sharply as the catalyst concentration decreases than do those of k_4(ArH) and k_1. Thus at low catalyst concentration $C_6H_5I(Cl)(OCOCF_3)$ may not be important as a chlorinating species. It follows that under certain conditions a substantial portion of the trifluoroacetic acid-catalyzed reaction of iodobenzene dichloride and durene in carbon tetrachloride may proceed *via* eq. 4 as the rate-determining step.

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