

The other solvents and reagents were purified in the manner described previously.<sup>14</sup>

**Procedures.** The kinetic procedures and the technique used to determine the isomer distributions were identical with those previously described for toluene.<sup>14</sup> A 150-ft capillary column packed

with tricresyl phosphate was used for the analysis of the isomeric bromoalkylbenzenes: 125° for the bromoethyl-, 135° for the bromoisopropyl-, and 145° for the bromo-*t*-butylbenzenes. In all cases the isomers were eluted in the order *ortho*, *meta*, *para*.

## Rates and Isomer Distributions for the Mercuration of the Monohalobenzenes in Trifluoroacetic Acid. Partial Rate Factors for the Mercuration Reaction<sup>1-3</sup>

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*Contribution from the Richard B. Wetherill Laboratory of Purdue University, Lafayette, Indiana. Received November 27, 1965*

**Abstract:** The rate constants and isomer distributions for the mercuration of fluorobenzene, chlorobenzene, and bromobenzene in trifluoroacetic acid at 25° were determined. Simple, second-order kinetic data were realized in all cases. The product distribution in fluorobenzene is 11.4% *ortho*, 0.8% *meta*, and 87.8% *para*. Utilizing the relative rate value, 0.287, the partial rate factors become  $o_i^F$  0.0983,  $m_i^F$  0.00687, and  $p_i^F$  1.51. The chlorobenzene/benzene reactivity ratio is 0.0470. The isomer distribution for the mercuration of chlorobenzene under these conditions is 11.9% *ortho*, 5.8% *meta*, and 82.3% *para*. These data provide the partial rate factors  $o_i^{Cl}$  0.0168,  $m_i^{Cl}$  0.00820, and  $p_i^{Cl}$  0.232. Finally, in the case of bromobenzene, the relative rate, 0.0397, and the isomer distributions, 10.6% *ortho*, 8.0% *meta*, and 81.4% *para*, lead to the partial rate factors,  $o_i^{Br}$  0.0126,  $m_i^{Br}$  0.00954, and  $p_i^{Br}$  0.194. The results reveal that the order of reactivity of the *ortho* and *para* positions is F > Cl > Br. In the *meta* position, the inductive order is obtained, F < Cl < Br. The available data for the mercuration of mono-substituted benzenes in trifluoroacetic acid are assembled and examined. An excellent linear free energy correlation is realized for the substitution data vs. the electrophilic substituent constants,  $\sigma^+$ , based on the solvolysis of the *t*-cumyl chlorides. The reaction constant  $\rho$  was established as -5.68.

The reaction of mercuric acetate in acetic acid with the monohalobenzenes was examined previously.<sup>6</sup> Unfortunately, a major difficulty was encountered. The reactions are quite slow and reaction of the mercuric acetate with the solvent competes seriously with the reaction with the aromatic constituent. For example, in the case of fluorobenzene, this side reaction represents 40% of the total mercuric acetate consumed, while for chlorobenzene it represents 80% of the total reaction. Consequently, it was necessary to utilize the less accurate competitive procedure for determining the relative rates of reaction of chlorobenzene and bromobenzene.

Application of this procedure to less active aromatics would mean that the reaction with the aromatic would involve a smaller and smaller fraction of the total reaction, greatly magnifying the experimental difficulties and uncertainties. To circumvent this problem, we examined the reaction of mercuric trifluoroacetate in trifluoroacetic acid with benzene and toluene<sup>7</sup> and with the higher monoalkylbenzenes.<sup>8</sup>

The reaction proved to involve simple kinetics, being clearly second order, and far faster by a factor of 10<sup>5</sup>

than the related reaction in acetic acid. The enhanced speed is obviously a great advantage in studying the rates of reaction of aromatics containing deactivating substituents. Even more important, no evidence was encountered for any side reaction of the mercurating agent with the solvent. It appeared desirable, therefore, to apply this reaction to the monohalobenzenes. Accordingly, a study of the reaction rates and isomer distributions for the halobenzenes at 25° was undertaken.

### Results

The rates of mercuration of the halobenzenes with mercuric trifluoroacetate were determined by following the decrease in mercuric ion concentration titrimetrically with standard thiocyanate solution employing ferric alum as indicator.<sup>7</sup> Second-order plots were made and the rate constants were obtained from a least-squares analysis of the slopes. Excellent second-order plots were obtained in experiments carried to 70–80% completion. The results are summarized in Table I.

The isomer distributions were determined for reaction conditions similar in all respects to those utilized for the kinetic measurements. The reaction mixtures were quenched at appropriate time intervals in aqueous sodium bromide. The precipitated arylmercuric bromides were converted into the isomeric bromohaloaromatics by treatment with bromine in carbon disulfide. The isomeric compositions were established by means of gas chromatography.

The observed rates and the isomer distributions were employed to calculate the partial rate factors. The

- (1) Directive Effects in Aromatic Substitution. LVIII.
- (2) Based upon a thesis submitted by Robert A. Wirkkala in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
- (3) This research was supported in part by the Petroleum Research Fund administered by the American Chemical Society.
- (4) National Science Foundation Summer Fellow at Purdue University, 1959.
- (5) Ethyl Corporation Fellow at Purdue University, 1960–1961.
- (6) H. C. Brown and G. Goldman, *J. Am. Chem. Soc.*, **84**, 1650 (1962).
- (7) H. C. Brown and R. A. Wirkkala, *ibid.*, **88**, 1447 (1966).
- (8) H. C. Brown and R. A. Wirkkala, *ibid.*, **88**, 1453 (1966).

**Table I.** Rate Constants, Isomer Distributions, and Partial Rate Factors for the Reaction of the Monohalobenzenes with Mercuric Trifluoroacetate in Trifluoroacetic Acid at 25°

Compound	Rate constant, $k_2 \times 10^3$ l. mole <sup>-1</sup> sec <sup>-1</sup>	Relative rate	Isomer distribution, %			Partial rate factors		
			<i>ortho</i>	<i>meta</i>	<i>para</i>	$\rho_t$	$m_t$	$p_t$
Benzene	2.85	1.00						
Fluorobenzene	0.818	0.287	11.4	0.8	87.8	0.0983	0.00687	1.51
Chlorobenzene	0.134	0.0470	11.9	5.8	82.3	0.0168	0.00820	0.232
Bromobenzene	0.113	0.0397	10.6	8.0	81.4	0.0126	0.00954	0.194

data and derived partial rate factors are summarized in Table I.

### Discussion

The observation that this procedure permitted the direct observation of the reaction rates for the halobenzenes is gratifying. It suggests that this mercuriation reaction will prove exceedingly helpful in extending the study of the Selectivity Relationship<sup>9</sup> to strongly deactivating substituents.

The *ortho* and *para* rate factors follow the order,  $F > Cl > Br$ , indicative of the importance of resonance contributions by the halogens in stabilizing the electron-deficient center in the  $\sigma$  intermediate. It is commonly observed that electron supply by the conjugative mechanism is largest for fluorine, among the halogens, and decreases with increasing atomic weight.<sup>10</sup> For the chloro and bromo substituents in the *para* position, the inductive effect is somewhat larger than the resonance effect. Therefore, there is a net electron withdrawal and the partial rate factors are less than unity. However, for fluorine the resonance effect is sufficiently large as to overcome the unfavorable inductive influence of the halogen, resulting in a net increase in the value of the partial rate factor over hydrogen.

The much smaller partial rate factors observed for *ortho* substitution are believed to arise from the much larger inductive influence of the neighboring halogen, as well as to the apparent large steric effect of the mercurating species.<sup>8</sup>

In the *meta* position, the inductive contributions of the halogens are larger than in the more remote *para* position, and the conjugative contributions are much

smaller.<sup>10</sup> Consequently, there is observed the order,  $F < Cl < Br$ , corresponding to the pure inductive order anticipated for the halogens.

With the completion of the present study, there now are available 14 partial rate factors for *meta* and *para* substituents. The data (Table II) are correlated with highly satisfactory precision by the  $\sigma^+$  substituent constants based on the solvolysis of *t*-cumyl chloride (Figure 1).

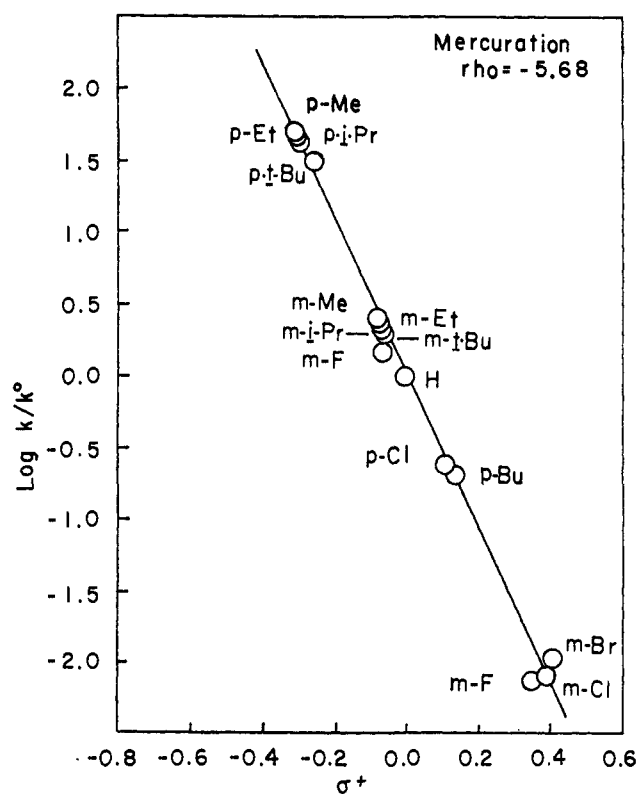


Figure 1. The relationship between the partial rate factors for the mercuriation of monosubstituted benzenes in trifluoroacetic acid at 25.0° with the  $\sigma^+$  constants.

**Table II.** Substituent Constants and Partial Rate Factors for the Reaction of Mercuric Trifluoroacetate with Monosubstituted Benzenes in Trifluoroacetic Acid at 25.0°

Substituent	Partial rate factors			Substituent constants	
	$\rho_t$	$m_t$	$p_t$	$\sigma_m^+$	$\sigma_p^+$
Methyl	3.62	2.55	46.9	-0.066	-0.311
Ethyl	1.96	2.37	42.8	-0.064	-0.295
Isopropyl	0.533	2.18	39.0	-0.060	-0.280
<i>t</i> -Butyl	0	1.97	32.3	-0.059	-0.256
Fluoro	0.0983	0.00687	1.51	0.352	-0.073
Chloro	0.0168	0.00820	0.232	0.399	0.114
Bromo	0.0126	0.00954	0.194	0.405	0.150

(9) For a review of the Selectivity Relationship, with literature references, see L. M. Stock and H. C. Brown in "Advances in Physical Organic Chemistry," Vol. I, V. Gold, Ed., Academic Press Inc., New York, N. Y., 1963, pp 35-154.

(10) H. C. Brown, Y. Okamoto, and G. Ham, *J. Am. Chem. Soc.*, **79**, 1906 (1957).

The data define a reaction constant  $\rho$  of  $-5.68$ . The reaction constant for mercuriation in glacial acetic acid is  $-4.00$ .<sup>6</sup> Thus mercuriation in trifluoroacetic acid, in spite of its enhanced rates of reaction, is a more selective reaction than mercuriation in glacial acetic acid.

### Experimental Section

**Materials.** The halobenzenes and bromohalobenzenes were available from the earlier study of mercuriation in glacial acetic acid.<sup>6</sup> Their physical properties are there reported.

The purification of trifluoroacetic acid and the preparation

of mercuric trifluoroacetate were carried out as reported previously.<sup>6</sup>

**Procedures.** The procedures for the kinetic runs and the isomer distribution determinations were carried out as previously described for the toluene<sup>7</sup> and the monoalkylbenzenes.<sup>8</sup> The gas

chromatographic analysis of the isomeric mixtures of the bromohalobenzenes was carried out, utilizing a 2-m tricresyl phosphate on a Celite column, at 100° for the bromofluorobenzenes, 125° for the bromochlorobenzenes, and 130° for the dibromobenzenes. Excellent resolution of the three isomers was realized.

## Selective Reductions. IX. Reaction of Lithium Aluminum Hydride with Selected Organic Compounds Containing Representative Functional Groups<sup>1</sup>

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*Contribution from the Richard B. Wetherill Laboratory of Purdue University, Lafayette, Indiana. Received November 3, 1965*

**Abstract:** The stoichiometry of the reaction of excess lithium aluminum hydride with 56 selected organic compounds containing representative functional groups under standardized conditions (tetrahydrofuran solution, 0°) was examined in order to compare the behavior of the parent compound with its derivatives, lithium trimethoxy- and tri-*t*-butoxyaluminumhydride, previously explored. In general the data confirm the results already available in the literature, but provide data in a single solvent with controlled concentration and temperature. Although the behavior of lithium trimethoxyaluminumhydride resembles that of lithium aluminum hydride closely, there are significant differences. The latter reagent reduces epoxides, cyclohexanone oxime, azobenzene, and cyclohexyl tosylate, whereas the reduction of these compounds by lithium trimethoxyaluminumhydride is either much slower or does not occur under these conditions. Consequently, a number of selective reductions appear practical with the latter reagent which would offer difficulties with lithium aluminum hydride. Lithium trimethoxyaluminumhydride also appears more selective in opening up unsymmetrical epoxides and it was previously shown to be more stereoselective in reducing cyclic and bicyclic ketones. Finally, considerable hydrogen evolution is observed in reducing aliphatic nitriles with lithium aluminum hydride, whereas this undesirable side reaction appears to be absent in the corresponding reduction with lithium trimethoxyaluminumhydride. It was previously reported that lithium tri-*t*-butoxyaluminumhydride is a far more selective reducing agent than the other two under discussion. Consequently, the availability of detailed surveys of the reducing characteristics of these three reagents should prove helpful in selecting the most favorable reagent for a specific reduction.

The reducing action of lithium aluminum hydride has been extensively studied.<sup>3</sup> However, most of the data available are for reactions carried out in ether for preparative purposes, with the concentrations of the reactants, the temperature of the reaction, and the time not specified.

We had recently carried through a systematic study of the approximate rates and the stoichiometry of the reaction of lithium tri-*t*-butoxyaluminumhydride<sup>4</sup> and of lithium trimethoxyaluminumhydride<sup>5</sup> in tetrahydrofuran solution at 0° with a standard list of compounds representative of the more common functional groups. In attempting to compare the behavior of these new reagents with the characteristics of lithium aluminum hydride, we were frustrated by the wide variation in the experimental conditions used as well as by the frequent failure to report the experimental conditions. As a consequence we decided to undertake a systematic

examination of the reaction of lithium aluminum hydride with the standard list under the standard conditions.

### Results and Discussion

The general procedure involved preparing a reaction mixture of lithium aluminum hydride (0.25 *M*, 1.00 *M* in hydride<sup>6</sup>) and compound (0.25 *M*) in tetrahydrofuran at 0°. The hydrogen evolved on adding the compound to the reagent was noted. After the desired reaction time, the solution was hydrolyzed and the hydrogen evolved was noted. A blank reaction was performed under identical conditions, but without addition of the compound. From the difference in yields of hydrogen in the two cases, the hydride utilized by the compound for reduction was calculated. In this way it was possible to arrive at a value for the number of moles of hydride utilized by the compound to evolve hydrogen and the number of moles of hydride utilized for reduction.

In some cases the hydride/compound ratio of 4:1 was inadequate to achieve complete reduction. In such cases the hydride concentration was maintained constant, but the concentration of compound was re-

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(2) Graduate research assistant on a research grant (DA-ARO(D)-31-124-117) supported by the U. S. Army Research Office (Durham).

(3) For comprehensive reviews, see (a) N. G. Gaylord, "Reduction with Complex Metal Hydrides," Interscience Publishers, Inc., New York, N. Y., 1956; (b) W. G. Brown, *Org. Reactions*, 469 (1951); (c) V. M. Mićović and M. L. Mihailović, "Lithium Aluminum Hydride in Organic Chemistry," Naučna Knjiga, Belgrade, Yugoslavia, 1955.

(4) H. C. Brown and P. M. Weissman, *Israel J. Chem.*, 1, 430 (1963).

(5) H. C. Brown and P. M. Weissman, *J. Am. Chem. Soc.*, 87, 5614 (1965).

(6) It is convenient to discuss the utilization of the reagent in terms of moles of hydride taken up per mole of compound. Thus a ketone utilizes 1 mole of hydride and an ester 2 moles in being reduced to the alcohol stage.