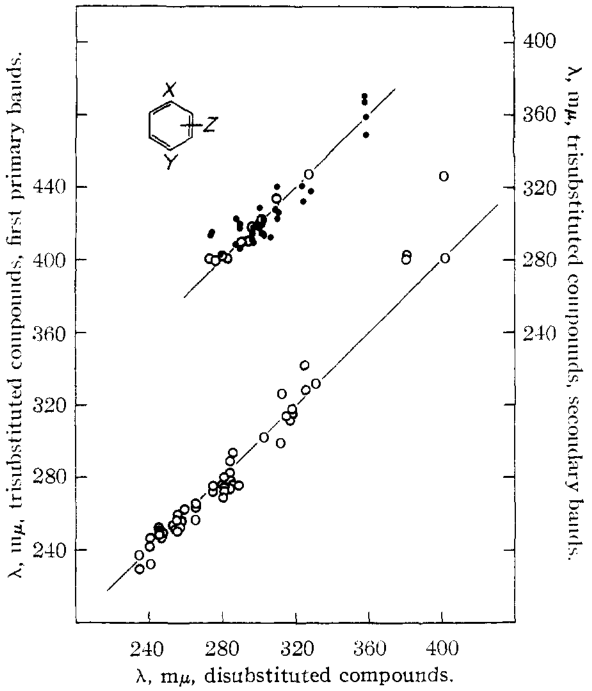

Fig. 4.—Wave lengths of trisubstituted compounds of Table I (only X or Y is *meta* directing) plotted *vs.* the most displaced bands of corresponding constituent disubstituted compounds: bottom, first primary bands; top, secondary bands. The ordinate axis for the secondary bands is at the right of the figure. In the upper group, solid points represent data identified by footnote *c* in Table I.

and vibrational symmetries which are exclusive of those required for the other resonance forms.

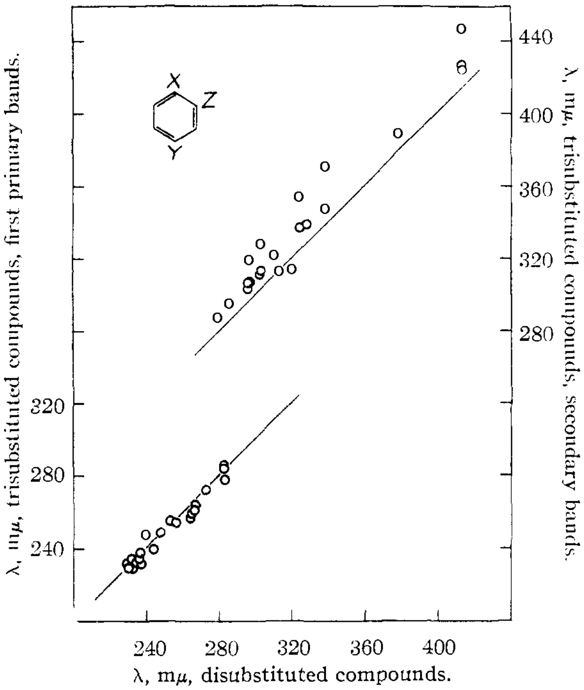

Fig. 5.—Wave lengths of trisubstituted compounds of Table II (only Z is *meta* directing) plotted *vs.* the most displaced bands of corresponding constituent disubstituted compounds: bottom, first primary bands; top, secondary bands. The ordinate axis for the secondary bands is at the right of the figure.

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[Contribution No. 1977 from the Gates and Crellin Laboratories of Chemistry, California Institute of Technology]

Exchange Reactions of Deuterated Benzene Derivatives with Potassium Amide in Liquid Ammonia[1a]

By George E. Hall,[1b] Richard Piccolini and John D. Roberts

Received March 7, 1955

The rates of deuterium-protium exchange have been determined for *o*-, *m*- and *p*-deuterated fluorobenzene, benzotrifluoride and anisole in liquid ammonia solution in the presence of potassium amide. The exchange rates were found to be greatest for the *ortho* compounds and smallest for the *para* compounds. Deuterobenzene and *o*-deuterotoluene reacted too slowly for convenient measurement. The results are interpreted on the basis of the operation of combined inductive and field effects of the substituents, mesomeric effects appearing to be of minor importance.

An understanding of the effect of substituents on the acidity of hydrogens located on benzene rings is important to the interpretation of the unusual rearrangements encountered in amination of aromatic halides.[2-4] For this reason, we have determined the rates of replacement of deuterium by protium for appropriate deuterated benzene derivatives in the presence of a strong base (NH_2^-) and a proton-donating solvent (NH_3).[5] Although, in principle, the rate constants k for removal of particular hydrogens need not necessarily be related to the equilibrium ionization constants K_A of the same hydrogens, in practice, the relation $\log k = x \log K_A + C$ (Brönsted catalysis law)[6] is generally observed for acids of similar structures. We will assume that this sort of parallelism between k and K_A holds for the compounds under discussion and,

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[1a] Supported in part by The Upjohn Company.

[1b] Faculty Fellow of The Fund for the Advancement of Education, 1953–1954.

(2) *Cf.* J. D. Roberts, H. E. Simmons, Jr., L. A. Carlsmith and C. W. Vaughan, This Journal, **75**, 3290 (1953).

(3) J. D. Roberts, D. A. Semenow, H. E. Simmons, Jr., and L. A. Carlsmith, *ibid.*, papers submitted for publication.

(4) J. D. Roberts, C. W. Vaughan, L. A. Carlsmith, H. E. Simmons, Jr., and D. A. Semenow, *ibid.*, papers submitted for publication.

(5) The feasibility of these experiments was first demonstrated qualitatively by H. E. Simmons, Jr., Ph.D. Thesis, Massachusetts Institute of Technology, 1954.

(6) L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., New York, N. Y., 1940, pp. 222–227.

furthermore, that the proportionality constant x is positive, so that a high rate constant implies a high relative acidity.

The exchange reactions were carried out by adding a solution of potassium amide in liquid ammonia to a solution of the deuterated benzene derivative in liquid ammonia. After an appropriate time, the amide was neutralized by addition of ammonium chloride. Whenever practical, a run was made with each compound for at least one half-life. The deuterobenzene derivatives were 0.25–0.6 M (partly depending on solubility) and the potassium amide was 0.6 M throughout. The reasonable assumption was made that the reactions were first order with respect to the deuterium compound. The mole per cent. of unreacted deuterium derivative in the reaction product was determined by comparison of the intensities of the infrared absorption bands due to deuterium with the intensities of the same bands in the starting material.[7] Pseudo first-order rate constants were calculated from the usual equations.

Results and Discussion

The exchange rate constants are given in Table I. The experiments giving nearly 50% exchange are considered to be the most reliable. With fluorobenzene-2-*d*, the shortest practical reaction time, 10 sec., still gave complete exchange to within the limits of accuracy of the analytical method. The rate constants for anisole-3-*d* and -4-*d* and benzene-*d* are only approximate because of the small extent of reaction.

An attempt was made to alkylate the anion from fluorobenzene with methyl iodide in liquid ammonia solution containing equal molar amounts of fluorobenzene and potassium amide. No fluorotoluene could be isolated from the reaction mixture and it is possible that the anion was not present in significant concentration.

A salient feature of the experimental results is that the rate constant for replacement of a deuterium atom in a *meta*-position is intermediate between those for the *ortho*- and *para*-positions for all of the compounds studied. This is in marked contrast to the usual belief, based on evidence from electrophilic and "activated" nucleophilic aromatic substitution, that the positions *ortho* and *para* to activating substituents are electrically similar and more powerfully activated than *meta*-positions. However, it should be clear that, in these exchange reactions, there is neither electrophilic nor nucleophilic attack on the benzene nucleus but attack of a base on the hydrogen attached to the nucleus. This type of attack has been suggested[8] for the metalation of benzotrifluoride by *n*-butyllithium and recently designated[9] as a "protophilic" process. Hydrogen isotope effects have been demonstrated[10] for the metalation of benzene and toluene by ethylpotassium and these corroborate the suggestion that the carbon–hydrogen bonds are directly involved in the rate-determining step.

TABLE I

PSEUDO FIRST-ORDER RATE CONSTANTS FOR DEUTERIUM-PROTIUM EXCHANGE OF SUBSTITUTED DEUTEROBENZENES (C_6H_4DX) WITH 0.6 M POTASSIUM AMIDE IN LIQUID AMMONIA (AT BOILING POINT)

X	Reaction time sec.	λ,[a] μ	Mole % C_6H_4DX	k,[b] sec.$^{-1}$
2-F	80	7.82	<1.4	
		9.60	<1.0	
	10	10.54	<2.4	>4 × 10^{-1}
		11.83	<3.9	
3-F	7.2 × 10^3	7.83	5.9	4 × 10^{-4}
	1.8 × 10^3	6.96	49.4	4 × 10^{-4}
		7.83	48.9	
4-F	7.2 × 10^3	7.05	87.0	
		9.13	88.8	2 × 10^{-5}
		13.98	87.6	
	3.6 × 10^4	7.05	40.6	2 × 10^{-5}
		13.98	43.2	
2-CF_3	11	10.41	50.2	6 × 10^{-2}
		11.50	49.4	
3-CF_3	6.1 × 10^2	6.71	42.2	1 × 10^{-3}
		12.29	42.0	
	4.9 × 10^2	6.71	53.5	
		12.29	52.5	1 × 10^{-3}
4-CF_3	1.3 × 10^2	13.41	86.4	1 × 10^{-3}
	6.4 × 10^2	13.41	52.8	1 × 10^{-3}
2-OCH_3	3.6 × 10^3	11.81	11.1	6 × 10^{-4}
	1.2 × 10^3	11.81	22.9	1 × 10^{-3}
	5.7 × 10^2	11.81	50.7	1 × 10^{-3}
3-OCH_3	5.7 × 10^5	4.44	92.3	~1 × 10^{-7}
		9.08	92.6	
4-OCH_3	1.5 × 10^6	11.47	99.3	~10^{-8}
		13.85	95.6	
2-CH_3	4.1 × 10^4	4.44	100.0	
		11.94	100+	....
		12.90	100+	
None	5.7 × 10^5	10.78	96.7	~10^{-7}
		11.63	95.5	

[a] Wave length of absorption band used for analysis. [b] Average figure where more than one determination at different wave lengths was made for a given reaction time.

Direct attack on benzenoid hydrogens by bases should not involve the π-electron system of the benzene ring in an important way. In such reactions, the combined inductive and field effects[11] of substituents appear to be of major importance and the electromeric effects of negligible or minor importance.[8,9,12] The rates of the potassium amide induced exchanges here reported are in agreement with this concept. Electronegative substituents, –F, –CF_3 and –OCH_3, increase the rates by decreasing the electron density at the carbon where deuterium is attached, thereby increasing the ease with which a deuteron may be removed by a base. The only evidence for any importance of the electron-donating resonance or electromeric effects, usually postulated for the methoxy group, is that anisole-4-*d* seems to exchange its deuterium somewhat more slowly than benzene-*d*. However, both substances reacted so sluggishly at the boiling point of liquid ammonia that an accurate comparison was not possible. The ratio k_{meta}/k_{para} was found in all

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[7] The analytical procedure was developed by Dr. D. A. Semenow in connection with related experiments.

[8] J. D. Roberts and D. Y. Curtin, THIS JOURNAL, **68**, 1658 (1946).

[9] D. Bryce-Smith, *J. Chem. Soc.*, 1079 (1954).

[10] D. Bryce-Smith, V. Gold and D. P. N. Satchell, *ibid.*, 2743 (1954).

[11] J. D. Roberts and W. T. Moreland, Jr., THIS JOURNAL, **75**, 2167 (1953); J. D. Roberts and R. Carboni, *ibid.*, paper in press.

[12] G. Wittig, U. Pockels and H. Dröge, *Ber.*, **71**, 1903 (1938); and G. Wittig, *Naturwiss.*, **30**, 698 (1942).

TABLE II

PHYSICAL CONSTANTS AND CHARACTERISTIC INFRARED ABSORPTION BANDS OF SUBSTITUTED DEUTEROBENZENES (C_6H_4DX)

X	B.p.		$n^{25}D$	Absorption peaks[a], μ
	°C.	Mm.		
2-F	83.0–85.0	745	1.4622	7.82(29), 8.97(31), 9.60(19), 10.54(8.0), 11.83(16), 13.57(36)
3-F	82.5–83.5	744	1.4616	6.96(23), 7.83(25), 12.83(44), 14.84(31)
4-F	82.3–84.0	752	1.4612	7.05(7.8), 9.13(21), 11.72(83), 13.98(28)
2-CF_3	99.8–100.5	742	1.4113	7.78(73), 10.41(16), 11.50(8.7)
3-CF_3	100.0–101.2	738	1.4120	6.71(11), 11.52(7.8), 12.29(77), 14.01(20), 14.81(6.3)
4-CF_3	100.1–100.5	740	1.4118	7.07(44), 11.55(63), 13.41(12)
2-OCH_3	149.0–150.5	742	1.5137	8.60(22), 8.90(36), 10.17(9.7), 10.56(6.7,) 11.53(6.5), 11.81(9.7)
3-OCH_3	149.0–150.0	743	1.5138	4.44(7.3), 7.53(34), 9.08(9.7), 11.15(17), 12.65(52), 14.73(51)
4-OCH_3	149.0–150.0	742	1.5133	9.02(32), 10.15(13), 11.47(11), 11.81(57), 13.85(18)
2-CH_3	108.9–109.0	740	1.4938	4.44(5.2), 6.76(38), 8.87(4.5), 9.54(15), 10.89(5.6), 11.38(3.8), 11.52 (5.3), 11.94(15), 12.49(29), 12.90(29)
H	79.0–79.0	741	1.4954	4.43(5.8), 6.89(27), 9.28(8.8), 10.78(8.0), 11.63(12), 12.82(51), 14.31 (44)

[a] Principal infrared absorption peaks which are not also present in the corresponding undeuterated C_6H_5X. The extinction coefficients are given in parentheses for each absorption peak in l. mole^{-1} cm.$^{-1}$.

cases to be less than k_{ortho}/k_{meta} and this fact we attribute to fall-off of the combined inductive and field effects with increasing distance from the electron-attracting substituent group. The rate of fall-off of log *k* with the substituent position seems to be a function of the number of intervening carbon atoms between the deuterium and the electronegative group and not of the nature of the substituent group (compare benzotrifluoride with fluorobenzene and anisole as in Fig. 1).[13]

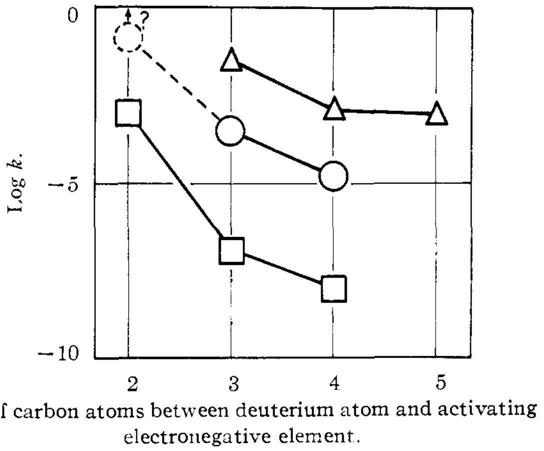

Fig. 1.—Relation between log *k* and position of deuterium undergoing exchange: ○, -F; □, -OCH_3; △, -CF_3.

The rates of exchange of benzene-*d* and toluene-2-*d* were too slow for accurate measurement in the media used in this work. However, Bryce-Smith[9] has found that isopropyl and *t*-butyl groups deactivate all positions in the benzene nucleus toward metalation by ethylpotassium. This deactivating influence was greater for the tertiary group than for the secondary group. The order of increasing deactivation for both substituents was *para* < *meta* < *ortho*. These observations were interpreted[9] as being in accord with a predominate inductive effect.

The potassium amide–liquid ammonia exchanges show much greater rate differences for the various positions than were found by Bryce-Smith for metalations with ethylpotassium. This is reasonably attributable to the fact that amide ions are much weaker bases than ethide ions, and therefore discriminate more highly between the various benzenoid hydrogens. The lower temperature of the liquid ammonia exchanges is also expected to contribute to the magnitude of the rate differences.

Experimental Part

Deuterated benzene derivatives were prepared by conversion of suitable bromo compounds to the corresponding Grignard reagents and decomposition of the latter substances with deuteroacetic acid. The deuteroacetic acid was obtained from the reaction of acetic anhydride with deuterium oxide and was preferred over deuterium oxide for decomposition of the Grignard reagents because it is more economical of deuterium and its ether solubility permits better control of the reaction than is possible with deuterium oxide. The physical constants and principal infrared absorption bands of the deuterobenzene derivatives are listed in Table II. *o*-Bromofluorobenzene,[14] *m*-bromofluorobenzene,[14] *o*-bromobenzotrifluoride,[15] *p*-bromobenzotrifluoride,[16] and *m*-bromoanisole[17] were prepared by previously reported procedures. The physical constants of the products were in substantial agreement with those reported in the literature. The other bromo compounds were obtained from commercial sources.

Fluorobenzene-2-*d*.—Contrary to the experience of other investigators,[16] *o*-bromofluorobenzene and magnesium were found to react smoothly in diethyl ether. However, as reported,[18] the reaction product was not the expected Grignard reagent. A gelatinous precipitate was formed which gave a positive test for fluoride ion and was presumably magnesium fluoride. The *o*-bromofluorobenzene was successfully converted to the Grignard reagent with dimethyl ether as solvent. *o*-Bromofluorobenzene (61.3 g., 0.350 mole) was dissolved in 60 ml. of dry diethyl ether. A piece of magnesium was added to 1 ml. of this solution and,

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[13] A. A. Morton, THIS JOURNAL, **69**, 969 (1947), has contended that predominant *ortho*-metalation with substituents carrying shared electron pairs is *solely* due to preliminary electrophilic coördination of the metal of the metalating agent with the substituent. It is noteworthy that there appears to be a very close relationship between orientation in metalation and the deuterium exchange rates with potassium amide in liquid ammonia in which solvent any electrophilic tendencies of the metal ion should be minimized by tight solvation with ammonia molecules.

[14] A. Roe, "Organic Reactions," Vol. V, John Wiley and Sons, Inc., New York, N. Y., 1949, p. 193.

[15] R. A. Benkeser and R. G. Severson, THIS JOURNAL, **73**, 1353 (1951).

[16] R. G. Jones, *ibid.*, **69**, 2346 (1947).

[17] H. J. Lucas and D. Pressman, "Principles and Practice in Organic Chemistry," John Wiley and Sons, Inc., New York, N. Y., 1949, p. 380.

[18] M. S. Kharasch, H. Pines and J. H. Levine, *J. Org. Chem.*, **3** 347 (1938).

when the reaction was well started, the mixture was added to 8.50 g. (0.350 g. atom) of magnesium in a 500-ml. three-necked flask equipped with stirrer, Dry Ice condenser protected with a drying tube, dropping funnel and gas inlet. Gaseous dimethyl ether dried by passage through a Drierite-filled tower was run in until 50 ml. of liquid had condensed. The remainder of the ethereal bromide solution was added dropwise during 100 minutes. After an additional 60 minutes, a solution of 26.2 g. (0.430 mole) of deuteroacetic acid in diethyl ether was added dropwise to the vigorously stirred Grignard mixture. After the addition was complete, the dimethyl ether was allowed to evaporate and the residue taken up in diethyl ether. The solution gave a negative test for Grignard reagent. The organic products were then separated, washed and dried in the usual manner. On distillation, 9.7 g. of starting material, b.p. 154–158° (745 mm.), $n^{25}\text{D}$ 1.5291, was recovered. The fluorobenzene-2-*d* amounted to 18.8 g. (55% conversion, 66% yield) and had b.p. 83.0–85.0° (745 mm.).

Exchange Reactions.—The deuterium–protium exchange reactions were carried out at the boiling point of liquid ammonia using an apparatus similar to that described by Schlatter[19] for sodium amide reactions except that 100-ml. flasks were employed. A solution of potassium amide in liquid ammonia was prepared in one flask by adding 1.8 g. (0.046 g. atom) of potassium metal to 25 ml. of stirred liquid ammonia containing a small crystal of ferric nitrate nonahydrate. The amide solution was then forced by air pressure into the second flask which contained 3.00 g. of the substituted deuterobenzene dissolved in 50 ml. of the liquid ammonia. The reaction mixture was stirred under reflux for the desired interval and then 4.8 g. of ammonium chloride was added. The reaction mixture was diluted with 25 ml. of ether and the ammonia allowed to evaporate. The ethereal solution was boiled under reflux for 10 minutes to drive off any residual ammonia, then shaken twice with dilute hydrochloric acid, washed with water and dried. The reaction products were distilled twice through a semimicro fractionating column.[20] The volume of liquid ammonia in the deuterofluorobenzene experiments was 25 ml. with the potassium and ammonium chloride reduced to 1.2 and 3.2 g., respectively.

In the short-time reactions (under 10 minutes), rapid quenching was essential. This was achieved by forcing a solution containing one equivalent of ammonium chloride in liquid ammonia into the reaction mixture by air pressure.

Determination of Extent of Deuterium–Protium Exchange.—The infrared spectra of the deuterobenzene derivatives, the non-deuterated compounds and the exchange reaction products were determined with a Perkin-Elmer Model 21 Spectrometer, using a 0.028 mm. sample cell *vs.* a salt block. The major absorption peaks appearing in the spectra of the deuterated compounds which were not found in the spectra of the non-deuterated substances, together with their molecular extinction coefficients, are given in Table II.

For each deuterium derivative, absorption peaks of moderate intensity in a region relatively free of absorption by the corresponding non-deuterated derivative were chosen. In addition to the absorption of the pure deuterium compound measurements were made on solutions containing 25, 50 and 75 mole % of non-deuterated substance. The absorption intensity for each of the analytical peaks was determined by the method of Heigl, Bell and White.[21] A linear least-square fit was made to the absorption intensity and concentration data. The resulting calibration plot was used to calculate the composition of the reaction products from the intensity of the characteristic infrared absorption peaks. The results are given in Table I.

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[19] M. J. Schlatter, *Org. Syntheses*, **23**, 20 (1943).

[20] C. W. Gould, Jr., G. Holzman and C. Niemann, *Anal. Chem.*, **20**, 361 (1948).

[21] J. J. Heigl, M. F. Bell and J. U. White, *ibid.*, **19**, 293 (1947).

PASADENA 4, CALIFORNIA

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, UNIVERSITY OF SOUTHERN CALIFORNIA, LOS ANGELES]

Application of the Hammett Equation to the Substituted Tetrazane–Hydrazyl Free Radical System. I. Equilibrium Constants[1]

BY W. K. WILMARTH AND NEWTON SCHWARTZ

RECEIVED MARCH 18, 1955

The equilibrium constants for the dissociation of the substituted 1,1,4,4-tetraphenyl-2,3-dibenzoyltetrazanes (where the phenyl substituents are *para* CH_3, H and Br) to form the 1,1-diphenyl-2-benzoylhydrazyl free radicals have been determined in acetone. The equilibrium constants can be correlated with the Hammett ρ–σ equation with a ρ of -1.52. A linear relation exists between entropies and enthalpies, and this is discussed in reference to the Hammett equation with the conclusion that differences in enthalpies reflect relative potential energies. The effect of substituents is interpreted in terms of the radical resonance energies, which are determined by the formation of a three-electron bond. It was found that the nitro substituted radicals form complexes with the nitro substituted 1,1-diphenyl-2-benzoylhydrazines.

Introduction

The Hammett ρ–σ equation,[2a] which correlates the effects of *meta* and *para* substituents on rate and equilibrium constants for aromatic systems, was originally established and has had its most frequent applications in the field of heteropolar reactions. In recent years,[3] the equation has been applied with a fair degree of success to the kinetic data of a variety of reactions involving the formation or reactions of free radicals. The applications of the equation to the unimolecular dissociation of a homopolar bond to form two free radicals are interesting because of the implication of the nature of the forces which affect the strength of that particular bond.[4] However, the prototype of such a reaction, the dissociation equilibria of substituted hexaphenylethanes, is generally recognized as not being correlatable with the Hammett equation, since substituents with either positive or negative σ-values increase the dissociation.[5]

Since all the applications of the Hammett equation to free radical systems involve the calculation of rate constants or reactivity ratios, and in view

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[1] A portion of this work was presented at the 126th Meeting of the American Chemical Society, New York, September, 1954 Based on the Dissertation presented by Newton Schwartz to the Graduate School of the University of Southern California in partial fulfillment for the Ph.D. degree.

[2] L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1940, (a) p. 184, (b) p. 76.

[3] H. H. Jaffé, *Chem. Revs.*, **53**, 191 (1953), has a complete compilation of applications of the Hammett equation.

[4] (a) C. G. Swain, W. H. Stockmayer and J. T. Clarke, THIS JOURNAL, **72**, 5426 (1950); (b) A. T. Blomquist and A. J. Buselli, *ibid.*, **73**, 3883 (1951); (c) A. T. Blomquist and I. A. Bernstein, *ibid.*, **73**, 5546 (1951).

[5] C. S. Marvel, C. M. Himel and J. F. Kaplan, *ibid.*, **63**, 1892 (1941); C. S. Marvel, F. C. Dietz and C. M. Himel, *J. Org. Chem.*, **7**, 392 (1942); C. S. Marvel, J. Whitson and H. W. Johnston, THIS JOURNAL, **66**, 415 (1944).