Electron Distribution in Molecules. I. F19 Nuclear Magnetic Shielding and Substituent Effects in Some Benzene Derivatives[1]

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The influence of substituents on the electron distribution in benzene produces changes in the nuclear magnetic shielding of fluorine atoms in the molecule. A comparison of the F19 nuclear magnetic shielding in fluorobenzene with that in a substituted fluorobenzene is used in defining a δ-parameter. Experimental δ-values are reported for a considerable number of mono- and polysubstituted fluorobenzenes. An empirical correlation of δ-values for meta and para substituents with the corresponding Hammett substituent σ-constants reveals systematic differences which are attributed to the dependence of the δ-values on the nature of the electronic interactions of the substituent. Thereby, a detailed analysis of the δ- and σ-values for particular substituents permits evaluation of the nature of their electronic effects. Consideration of ortho substituents suggests that besides the usual inductive and electromeric effects at the meta and para positions, an additional interaction contributes to the δ_o-values in some cases. The potential uses and limitations of δ_o-values in evaluating ortho-effects and entropies of reaction are discussed. It is concluded from δ-values for polysubstituted fluorobenzenes that the electronic effects of substituents are usually remarkably additive but with significant non-additivity demonstrating interactions between substituents in about a third of the compounds investigated. A δ'-parameter, analogous to δ, is defined in terms of the change produced by a substituent in the ring on the F19 nuclear magnetic shielding in benzotrifluorides. The δ'-values are about a tenth of the δ-values for the same substituent, indicating the extent of attenuation in the side chain of the substituent effects. Less conclusive discussions and comparisons are given of various other aspects of the data and experimental method.

Introduction

Several features of the microwave and radiofrequency spectra of molecules are associated with their electronic structure. Nuclear electric quadrupole splittings of microwave rotational spectra[2a] and the radiofrequency pure quadrupole spectra[2b,c] are determined by the variation in electrostatic field at the nucleus. Electric field gradients have been calculated for assumed electronic structures and compared with experimental values to give considerable information about bond hybridization.[2a] This report is concerned primarily with another similar effect, the magnetic shielding of fluorine nuclei[3] and its dependence upon substituents in fluorobenzenes.

Nuclei with magnetic moments exhibit radiofrequency spectra in the one to forty megacycle range when placed in magnetic fields of 5,000 to 10,000 gauss.[4] Resonance absorption, corresponding to the reorientation of the nuclear magnetic moment with respect to the applied magnetic field direction,[5] occurs at a frequency given by the Larmor equation, $\nu = g\beta H_o/h$. g is the nuclear gyromagnetic ratio, β is the nuclear magneton and H_o is the magnetic field at the nucleus. However, the magnetic field at a nucleus differs to a small but measurable extent from the magnetic field in the macroscopic sample.[6] The applied magnetic field interacts with the motions of the electrons in the system, which thereby contribute a component to the net magnetic field at the nucleus. This electronic component is proportional to the

applied field and is usually in the opposite direction. The effect may be considered an internal diamagnetism or a magnetic shielding of the nucleus.

The magnitude of this nuclear magnetic shielding depends upon the nucleus and the electronic structure of the sample ·in which it is observed.[7] A general theory has been proposed[8] for nuclear magnetic shielding in molecules, but the complexity of the calculations has restricted application thus far to the hydrogen molecule. However, in an experimental survey of the binary covalent fluorides, the F19 magnetic shielding was found[3] to decrease approximately linearly with increasing electronegativity of the atom to which the fluorine is bonded. A reasonably accurate physical picture is that the more tightly electrons are held by the atom bound to the fluorine, the less effective they are in shielding the fluorine. These empirical results suggested that F19 magnetic shielding values might serve to evaluate electronegativities, or electron densities. At least, the fluorine magnetic shielding in a molecule is related directly to the electron distribution of the group bound to the fluorine.

Some preliminary measurements have been reported[9] for an F19 shielding parameter, δ, defined in terms of the change in shielding caused by a substituent in fluorobenzene. Substituents in benzene of course influence a considerable variety of other properties.[10–12] In most instances it is generally

(1) Supported in part by ONR.

(2) (a) C. H. Townes and B. P. Dailey, *J. Chem. Phys.*, **17**, 782 (1949); (b) H. G. Dehmelt and H. Krüger, *Naturwissenschaften*, **37**, 111 (1950); (c) R. Livingston, *Phys. Rev.*, **82**, 289 (1951).

(3) H. S. Gutowsky and C. J. Hoffman, *J. Chem. Phys.*, **19**, 1259 (1951), and references cited therein.

(4) (a) E. M. Purcell, H. C. Torrey and R. V. Pound, *Phys. Rev.*, **69**, 37 (1946); (b) F. Bloch, W. W. Hansen and M. Packard, *ibid.*, **69**, 127 (1946).

(5) (a) E. M. Purcell, *Science*, **107**, 433 (1948), gives an excellent introductory description of nuclear magnetism; (b) G. E. Pake, *Am. J. Phys.*, **18**, 438, 473 (1950), has published a more detailed discussion and a bibliography.

(6) (a) W. E. Lamb, Jr., *Phys. Rev.*, **60**, 817 (1941); (b) W. C. Dickinson, *ibid.*, **80**, 563 (1950).

(7) (a) W. D. Knight, *ibid.*, **76**, 1259 (1949); (b) W. G. Proctor and F. C. Yu, *ibid.*, **77**, 717 (1950); (c) W. C. Dickinson, *ibid.*, **77**, 736 (1950).

(8) N. F. Ramsey, *ibid.*, **78**, 699 (1950).

(9) (a) H. S. Gutowsky, D. W. McCall, B. R. McGarvey and L. H. Meyer, *J. Chem. Phys.*, **19**, 1328 (1951); (b) an earlier suggestion was given by H. S. Gutowsky and C. J. Hoffman, *Phys. Rev.*, **80**, 110 (1950).

(10) (a) G. E. K. Branch and M. Calvin, "The Theory of Organic Chemistry," Prentice-Hall, Inc., New York, N. Y., 1941, p. 183; (b) M. J. S. Dewar, "The Electronic Theory of Organic Chemistry," Oxford at the Clarendon Press, London, 1949, pp. 50, 160; (c) L. P. Hammett, "Physical Organic Chemistry," 1st Ed., McGraw-Hill Book Co., Inc., New York, N. Y., 1940.

(11) C. K. Ingold, *Chem. Revs.*, **15**, 225 (1934).

(12) (a) L. E. Sutton, *Proc. Roy. Soc. (London)*, **133A**, 668 (1931); (b) L. E. Sutton, *Trans. Faraday Soc.*, **30**, 789 (1934).

agreed that the effects result primarily from the perturbing influence of the substituent on the molecular electronic distribution. Among the properties affected are reactivities and orientation in substitution reactions,[11] dipole moments,[12] the dissociation constants[13] or relative rates of reaction[10c] of substituted compared to unsubstituted compounds, spectroscopic moments[14] and vibrational frequencies.[15] A comparison of the Hammett substituent constants,[10c] σ, with the corresponding preliminary δ-values revealed[9a] a fairly linear correlation. In this article are presented the experimental details, δ values for a wide variety of monosubstituted and polysubstituted fluorobenzenes, and similar data for several benzotrifluorides. A detailed comparison of σ and some of the other substituent effects with the considerable number of δ-values now available confirms their general similarity, and develops several interesting exceptions.

Experimental

Apparatus and Procedure.—Figure 1 is a block diagram of the experimental arrangement. The spectroscope used a radiofrequency bridge[16] and was identical with that described in detail elsewhere,[3] except for the manner of field modulation and sample comparison. The signal generator was set at a fixed frequency of about 25.5 megacycles/second, the F^{19} magnetic resonance frequency in the 6365 gauss field of the permanent magnet. The saw-tooth voltage generated in a Dumont 304-H oscilloscope was applied at a frequency of 2 cycles/second to the horizontal axis and also to a cathode follower. The current of the latter was fed through a field modulation coil[17] about one magnet pole. By connecting the d.c. output of the detector in the communications receiver to the vertical axis of the oscilloscope the absorption line was displaced on the oscilloscope as a function of the magnetic field applied to the sample. In addition, the position on the oscilloscope of the absorption lines was adjustable by passing a direct current through another coil about the other pole of the magnet.
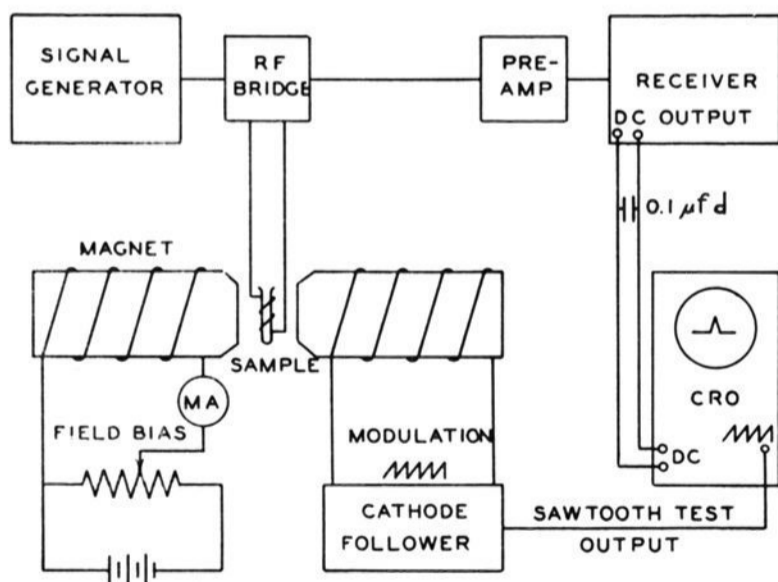

Fig. 1.—Block diagram of the radiofrequency spectroscope with slow sweep modulation for measuring molecular differences in nuclear magnetic shielding.

Under otherwise fixed conditions, the position of an F^{19} absorption line on the oscilloscope depends upon the F^{19} mag-

netic shielding in the sample. Relative absorption intensities are proportional to the number of nuclei. Figure 2 is an oscilloscope photograph of the F^{19} absorption line in 2,3,5-trifluorobenzotrifluoride. The strong line is from the CF_3 group; the three weaker lines, with equal intensities, are from the three structurally distinguishable F^{19} nuclei attached directly to the benzene ring. It is apparent that the F^{19} magnetic shielding differences are readily observable. The differences were measured quantitatively by determining the change necessary in the field biasing current to center on the oscilloscope first one resonance line and then the other. Calibration of the field biasing current in terms of magnetic field has been described.[3] δ, the F^{19} magnetic shielding parameter is defined[9a] as $10^5 \times (H_r - H_c)/H_r$ where H_c is the applied magnetic field for the F^{19} resonance in the given substituted fluorobenzene and H_r is that for the reference, fluorobenzene itself.
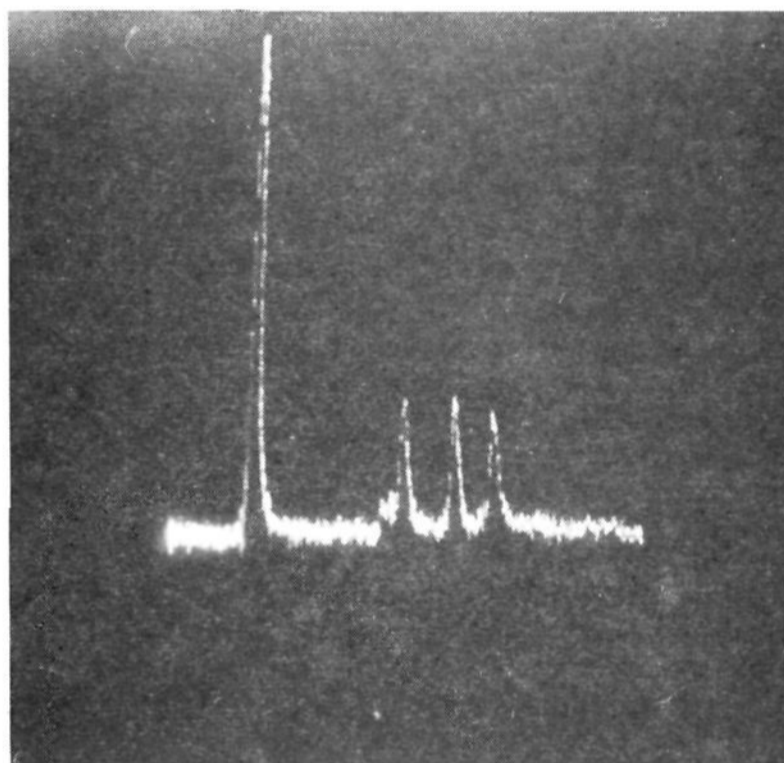

Fig. 2.—Oscilloscope photograph of the F^{19} magnetic resonance absorption lines in 2,3,5-trifluorobenzotrifluoride. The strong line is assigned to the F^{19} nuclei in the CF_3 group; the three weak lines, from left to right, to the 5-, 3- and 2-fluorines. The horizontal sweep is about 0.9 gauss, increasing from left to right; total applied magnetic field, 6365 gauss.

Samples were placed in short lengths of 5-mm. o.d. Pyrex tubing, sealed at one end. These tubes fitted snugly in the r.f. coil of the bridge element in the magnetic field. Most of the samples observed were liquid at room temperature. In this event one drop was added to a drop of a reference compound and the F^{19} magnetic resonance observed on the oscilloscope. The addition of more reference compound increased the intensity of its absorption line, identifying the different lines. Fluorobenzene was used as a reference for substituted fluorobenzenes unless the separation of the absorption lines was less than about 0.007 gauss, the limiting resolution. In such cases, p-fluoroanisole was used as a secondary reference, and the measurements reduced to the fluorobenzene scale. For the substituted benzotrifluorides, p-iodofluorobenzene was used as a reference, and the values then converted to a benzotrifluoride scale, denoted as δ'. Data on the binary covalent fluorides[3] have been referred to fluorine gas as an arbitrary zero.[18] These data were reported as relative shielding values defined as $(H_c - H_{F2})/H_{F2}$. δ- and δ'-values can be converted to this scale by using the fluorobenzene and benzotrifluoride values of 54.32×10^{-5} and 49.33×10^{-5}, respectively, on the F_2 scale. One should note that the signs of δ and δ' are reversed from that of the F_2 scale.

(13) J. F. J. Dippy, *Chem. Revs.*, **25**, 151 (1939).

(14) J. R. Platt, *J. Chem. Phys.*, **19**, 263 (1951).

(15) (a) M. St. C. Flett, *Trans. Faraday Soc.*, **44**, 767 (1948); (b) A. H. Soloway and S. L. Friess, THIS JOURNAL, **73**, 5000 (1951).

(16) N. Bloembergen, E. M. Purcell and R. V. Pound, *Phys. Rev.*, **73**, 679 (1948).

(17) This arrangement is similar to that used earlier by J. T. Arnold, S. S. Dharmatti and M. E. Packard, *J. Chem. Phys.*, **19**, 507 (1951).

(18) Trifluoroacetic acid is an excellent reference compound which we have used for most measurements on non-aromatic compounds; its shielding value on the F_2 scale is 50.76×10^{-5}.

In a few cases, the samples were solid and solutions were required to obtain the narrow lines essential for accurate measurements.[3] Aromatic solvents, principally nitrobenzene, were used when possible because small solvent effects were found with dissimilar substances. The fluorobenzoic acids and fluoroacetanilides required ethanol to obtain a solution concentrated enough for measurement. The solutions were handled in the same manner as the liquids.

All measurements were made at room temperature.[19] Sources and magnitudes of errors have been discussed[3] for the somewhat different sample interchange and field modulation methods used earlier.[3,3a] The new slow sweep modulation and combined unknown-reference samples improved the consistency of these measurements. Low positive biasing currents, less than 0.5 gauss, were maintained to reduce hysteresis effects. Also, a double-pole bias switch made it possible to center the two resonances with separate rheostats. This permitted a rapid change from one resonance to another, virtually eliminating error introduced by drift in the signal generator frequency. At least one series of five to ten measurements was made on each compound, and two or three on most. The probable errors of the reported δ- and δ'-values are less than ± 0.03.

Materials.—The compounds used were obtained from several sources. The purity was not critical as long as there was no question regarding the identity of the major constituent. In fact, observation of the F^{19} absorption lines was found quite useful on several occasions in determining the nature and extent of some fluorine-containing impurities. The o-fluorochlorobenzene, p-fluoroanisole, p-fluorobenzonitrile, p-fluorobenzenesulfonyl chloride, and 4-fluorobiphenyl were the purest grade available from Eastman Kodak Co. The o-fluoroanisole, and o-, m- and p-fluorophenetoles were from Custom Chemical Co. The p-fluorodimethylaniline and N-phenyl-p-fluoroaniline were furnished by Dr. Nelson J. Leonard, of this department. The o-, m- and p-trifluoromethyl benzotrifluorides were furnished by Dr. O. R. Pierce of Purdue University. The m-fluorobromobenzene, m-fluoroiodobenzene and m-fluorobenzonitrile were synthesized. The remainder of the samples were supplied by Dr. Glenn C. Finger, head of the Fluorspar Division of the Illinois State Geological Survey.

Results and Discussion

Monosubstituted Benzene Derivatives

A Comparison of σ- and δ-Values.—Table I lists δ-values determined for a variety of o-, m- or p-monosubstituted fluorobenzenes. In Fig. 3, δ-values from Table I are plotted against Hammett's substituent constant[10c] σ where the latter are available. It is seen that there is a general correlation between the two parameters, although scatter of individual points from a straight line is often greater than experimental error. In particular, the meta substituents follow a trend differing from that of the para substituents. A linear least squares solution for all the meta and para points gives $\sigma = 0.600\delta + 0.243$, with a residual sum of 2.38. Separate solutions for the meta and para points give $\sigma_m = 1.69\delta_m$ and $\sigma_p = 0.560\delta_p + 0.271$ with residual sums of 0.26 and 0.71, respectively.

The improvement in fitting the data by separate solutions demonstrates a fundamental difference in the particular effects operative at the meta and para positions. Of course, the general correlations between σ- and δ-values confirm the accepted view that the effects of substituents on reactivity are basically electronic in nature. In addition, the previously established dependence of the F^{19} magnetic shielding on the electronegativity of the attached atom suggests that the substituent effects may be interpreted as changes in electronegativity

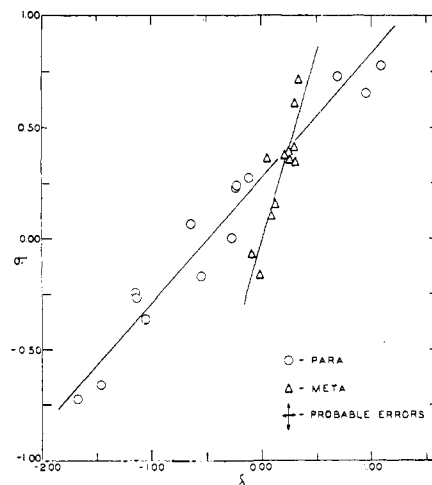(19) The F^{19} shielding values appear to be temperature independent in fluorocarbons; see, e.g., reference 9b and 8.

Fig. 3.—A plot of Hammett's σ versus values of δ from Table I, for meta and para substituents in benzene.

TABLE I

F^{19} NUCLEAR MAGNETIC SHIELDING δ-VALUES FOR MONO-SUBSTITUTED BENZENE DERIVATIVES[a]

Substituent	Ortho δ	Meta δ	Meta σ	Para δ	Para σ
NO$_2$	−0.56	+0.33	+0.710	+1.08	+0.778
CN	+ .52	+ .30	+ .608[d]	+0.96	+ .656[d]
CO$_2$H	+ .35	+ .05	+ .355	+ .69	+ .728
I	+1.93	+ .26	+ .352	− .12	+ .276
Br	+0.55	+ .24	+ .391	− .23	+ .232
Cl	− .27	+ .21	+ .373	− .24	+ .227
F	−2.59	+ .31	+ .337	− .64	+ .062
CH$_3$	−0.50	− .09	− .069	− .55	− .170
CH$_3$CONH[b]	−1.28	+ .10	......	− .57	......
OH	−2.50	+ .09	+ .10[e]	−1.06	− .36[e]
CH$_3$O	−2.24	....	......	−1.14	− .268
C$_2$H$_5$O	−2.17	+ .13	+ .15	−1.15	− .25
NH$_2$	−2.31	− .02	−.161	−1.46	− .660

Substituent	δ	σ	Substituent	δ	σ
p-SO$_2$Cl[b]	+1.26		p-N(CH$_3$)$_2$	−1.68	−0.720[f]
p-CCl$_3$	+0.26		o-CH=CHCO$_2$H[c]	−0.27	
p-Phenyl[b]	− .27	+0.009	m-CF$_3$	+ .28	+ .41[g]
p-O—C$_6$H$_4$—F[b]	− .67		m-CH(OH)CH$_3$	.00	
p-NH—C$_6$H$_5$[b]	− .94		m-O—C$_6$H$_4$—F	− .05	

[a] σ values are from reference 10c unless otherwise indicated. [b] In ethanol solution. [c] In H—C(=O)—N(CH$_3$)$_2$ solution. [d] J. D. Roberts and E. A. McElhill, THIS JOURNAL, 72, 628 (1950). [e] Computed from the ionization constants for m- and p-hydroxybenzoic acids from reference 13. [f] C. C. Price and D. C. Lincoln, THIS JOURNAL, 73, 5838 (1951). [g] J. D. Roberts, R. L. Webb and E. A. McElhill, ibid., 72, 408 (1950).

or electron density at the point of reaction. A total increase in electronegativity of 2.5 units was found[3] to correspond[20] to an increase in F^{19} magnetic shielding of 60×10^{-5}. The observed range of δ in the monosubstituted benzene derivatives is 4.5, or a range in electronegativity of about 0.2, if the same relation holds. This is at best a rough estimate, particularly in view of the differences between the meta and para positions. Jaffé has computed[21] theoretical electron densities by molecular orbital methods for several monosub-

(20) The dependence of the F^{19} magnetic shielding on electronegativity varies somewhat for different groups in the periodic table. For all reported binary covalent fluorides $dE_n/d\delta$ is about 4.1×10^{-2}, while for Group IV fluorides it is about 6.5×10^{-2}.

(21) H. H. Jaffé, J. Chem. Phys., 20, 778 (1952). We are indebted to Dr. Jaffé for sending us a copy of his article prior to publication.

stituted benzenes and obtained results also agreeing with the σ-values.[22]

The differences between the σ- and δ-values raise some interesting questions. The line for meta substituents has a slope three times larger than that for para. Moreover, while the meta line includes the origin, the para scale is displaced systematically by $+0.27$. And, finally, deviations of several of the points from the appropriate meta or para curve exceed experimental error by significant amounts. Both σ and δ have operational definitions so these effects must arise from factors implicit in the nature of the experiments. A possible major factor is that δ is determined with the molecule in its normal state, while σ is evaluated from rate or equilibrium data and depends therefore on the character of the transition state.[23]

Hammett's basic definition of σ is

$$\sigma = \log K_i - \log K_i^0 \tag{1}$$

where K_i and K_i^0 are the ionization constants for the substituted and unsubstituted benzoic acids. However, a more general development is required to determine the relation of σ to the transition state. Accordingly, the following transition state expressions are proposed for the rate constants of the forward and reverse ionization of the substituted benzoic acid

$$k_f = \kappa \frac{kT}{h} e^{\Delta S_f^{\ddagger}/R} e^{-(\Delta H_f^{\ddagger} - \rho\sigma')/RT} \tag{2}$$

and

$$k_r = \kappa \frac{kT}{h} e^{\Delta S_r^{\ddagger}/R} e^{-(\Delta H_r^{\ddagger} + \rho\sigma')/RT} \tag{3}$$

with similar expressions, without the $\rho\sigma'$, for the unsubstituted benzoic acid. In the equations, κ is the transmission coefficient; k, Boltzmann's constant; h, Planck's constant; $\Delta H^{\ddagger}$, the enthalpy of activation exclusive of substituent effects; $\Delta S^{\ddagger}$, the entropy of activation. σ' is related to the substituent effect on electron distribution and ρ is a reaction constant such that $-\rho\sigma'$ gives the effect of the substituent on the enthalpy of activation. Substituting the rate constant expressions in the definition of σ, and assuming the transmission coefficients to be unity,[23] or at least to cancel

$$\sigma = \frac{\Delta S_i - \Delta S_i^0}{2.3R} + \frac{2\rho\sigma'}{2.3RT} \tag{4}$$

where ΔS_i and ΔS_i^0 are entropies of ionization, i.e., $\Delta S_f^{\ddagger}$, $- \Delta S_r^{\ddagger}$. By defining $\rho = 1$ for the substituted benzoic acid ionization reaction, and making the usual assumption that entropies of ionization are the same for substituted acids as for the unsubstituted, $\sigma = 2\sigma'/2.3RT$. Analogous equations are obtained if σ is determined from the influence of the substituent on the rate of a reaction, the entropy term in eq. 4 then becoming $\Delta S_s^{\ddagger} - \Delta S_u^{\ddagger}$ the difference in the entropies of activation

of substituted and unsubstituted reactants; also, the last term in eq. 4 becomes $\rho\sigma'/2.3RT$ since the rate constant in only one direction enters the derivation.

It was suggested earlier[9a] that the differences between σ and δ might be caused by the effects of substituents on the entropies of activation. In eq. 4, δ should be related directly only to σ'. Any entropy differences would combine with the σ' term to give the observed σ, but would not contribute to δ. However, the relatively few reported experimental entropy differences[24] are generally too small and not systematic enough to explain the recent observations. Still, some of the deviations may be attributed in part to entropy effects.

Another way in which the normal molecule differs from the transition state is the polarization of the molecule by the attacking group. Transmission of polarizability effects to the meta position is by the relatively poor inductive mechanism, while the much stronger resonance, or electromeric, mechanism operates at the ortho and para positions. At first glance, this might appear to account for the different meta and para curves. Unfortunately for the present purpose, the polarizability and static electromeric effects are in the same direction.[10b] So the σ_p/δ_p ratio should be larger than the σ_m/δ_m ratio, since σ_p incorporates both effects while σ_m and both δ-values depend primarily on the static effect. Actually, the reverse is true.

Thus, it does not appear that the main σ, δ differences can be ascribed to transition versus normal state differences; so normal state effects would appear responsible. A great deal of indirect evidence[10] indicates that substituents influence the meta position chiefly by the inductive mechanism, the para by the electromeric, and the ortho by a combination of inductive, electromeric and steric mechanisms. There is no basis in Ramsey's theory of nuclear magnetic shielding,[8] or otherwise, for supposing that the fundamentally different inductive and electromeric effects would produce changes in δ in a ratio identical to the changes in σ. In fact, it may be concluded that the separate meta and para curves are a direct demonstration of the different character of the main electronic effects at the meta and the para positions. The smaller slope of the para curve then means that the electromeric effects change δ relatively more than σ, as compared to the inductive effects. Fortunately, this is consistent with the para intercept. All substituents other than hydrogen have π or unshared p-electrons and therefore produce electromeric effects at the ortho and para positions. The σ_p zero value corresponds to a balance of opposing inductive $(+I)$ and electromeric $(-E)$ effects.[25] However, for δ_p the electromeric effect is larger than the inductive, with a resultant negative δ_p, as observed. The inductive effect must be positive for $\sigma_p = 0$ because the substituents for which σ_p is about zero have positive σ_m values.

(22) Another terminology can be based on the relation between partial ionic character of a bond and the electronegativity difference of the bonded atoms. δ-Values and thereby σ-values can be interpreted as expressing the influence of substituents on the partial ionic character of the corresponding bonds in the molecule.

(23) S. Glasstone, K. J. Laidler and H. Eyring, "The Theory of Rate Processes," McGraw-Hill Book Co., Inc., New York, N. Y., 1941.

(24) See reference 10c, pages 84 and 121 for typical values.

(25) Following Dewar, reference 10h, the signs of the E and I effects are defined to correspond to the charges produced on the benzene ring by the substituent. These agree also with the signs of σ and δ. The usage of "electromeric" to include static as well as dynamic effects is also that of Dewar.
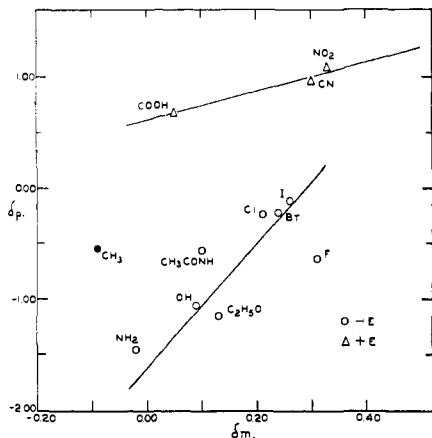
Fig. 4.—A plot of δ_p- versus δ_m-values for substituted benzenes.

Fig. 5.—A plot of δ_p- versus δ_o-values for substituted benzenes.

Interdependence of the δ-Values.—In Fig. 4, the δ_p-values are plotted against the δ_m-values for the same substituent. It is seen that the data fall into two distinct classes, in each of which δ_p is roughly proportional to δ_m. The CH₃·group stands somewhat alone. In Fig. 5 the δ_p-values are plotted against the δ_o. The same substituents are demonstrated clearly to be divided into the same two classes. Also, it is evident that the CH₃ group falls in the class with the halogens and other substituents without multiple bonds. The six δ_p-values in Table I for which the corresponding δ_m-values have not been observed follow the same rules as those in Fig. 4, insofar as the δ_m-values can be estimated from the observed σ_m.

Several conclusions can be drawn from the results graphically presented in the two figures. The electromeric effects are generally proportional to the inductive. This follows from the approximate linearity of both δ_p–δ_m curves and their positive slopes, in conjunction with the previous conclusion that δ_p-values are determined mainly by electromeric effects and δ_m, by inductive. The separate curves prove the existence of two different types of electromeric interaction. The class with negative δ_p-values includes only substituents with unshared p-electrons; these substituents have been considered generally[10b] to be $-E$ electromeric in nature. The class with positive δ_p-values includes all substituents with π-electrons, NO₂, CN and COOH, the $+E$ substituents.

The δ_p–δ_o curve in Fig. 5 for $-E$ substituents supports the view that both the E and the I interactions are more important at the ortho than each is, respectively, at the para and meta positions. For example, NH₂ has the weakest I effect, with a δ_m of -0.02, so the δ_o-value of -2.31 is mainly the $-E$ effect. This is to be compared with the δ_p-value for NH₂ of -1.46. As the $+I$ character of the $-E$ substituents increases, the δ_o-values become proportionately more positive compared to the δ_p. The methyl group is anomalous again; it is $-I$, yet the δ_o-value is even more positive than many of the substituents which are $+I$. The fluorine substituent with its relatively large $+I$ effect presents another anomaly in its large negative δ_o-value compared to its value for δ_p.

The δ_p–δ_o curve in Fig. 5 for $+E$ substituents is
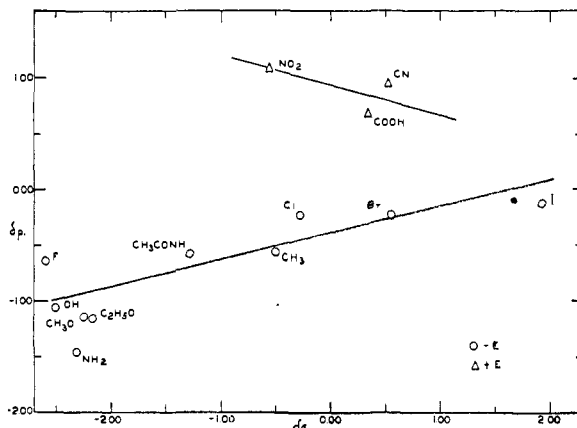
also exceptional. The $+E$ substituents exhibit $+I$ interactions, as is seen from the positive δ_m- values in Fig. 4. However, δ_o-NO₂ is *negative* and the δ_o-values for COOH and CN are *less than* the δ_p-values. The implication is that these substituents have some variety of negative effect on δ which falls off much more rapidly than do the $+I$ and $+E$ upon going from the ortho to the meta and para positions. The methyl group is a $-I$, $-E$ substituent and exhibits a similar but positive effect at the ortho position. This question will be discussed in more detail in the section on the halogen derivatives.

The interdependence of the δ-values is related also to the differences in the behavior of the σ- and δ-values discussed above. If one plots σ_p *versus* σ_m, a fairly good single line is obtained. The contrasting fact that $+E$ substituents have a separate δ_p–δ_m curve, with larger, positive, values than the $-E$, supports the conclusion of the previous section that E interactions change δ proportionately more than do I interactions. The scatter of points from the δ_p–δ_m curves indicates varying proportions of I and E interactions, which in turn show up in deviations from the σ–δ curves.

δ-Values for the Halogens.—The δ-values of the halogens suggest differences from the other $-E$ substituents. In Fig. 6, there is shown the dependence of the δ-values on the electronegativity of the halogen; the σ_m and σ_p data are included for comparison. The main point of interest is the δ_o curve, in which δ_o becomes more positive in the sequence F, Cl, Br and I with δ_o-values of -2.59 and $+1.93$ for fluorine and iodine, respectively. The $+I$ effects depend on the electron affinity of the halogen and decrease in the order F $>$ Cl $>$ Br $>$ I. The $-E$ effects depend ordinarily on the ionization energy and on this basis would decrease in magnitude in the order I $>$ Br $>$ Cl $>$ F.

According to this argument, iodine has the weakest $+I$ and the strongest $-E$ effects, and therefore the strongest net negative substituent effect of the halogens. Actually the δ-values, as well as the σ, show that the $-E$ effects are reversed for the halogens,[26] decreasing in the same order as

(26) See, e.g., A. E. Remick, "Electronic Interpretations of Organic Chemistry," John Wiley and Sons, Inc., New York, N. Y., 1943, and articles cited therein.
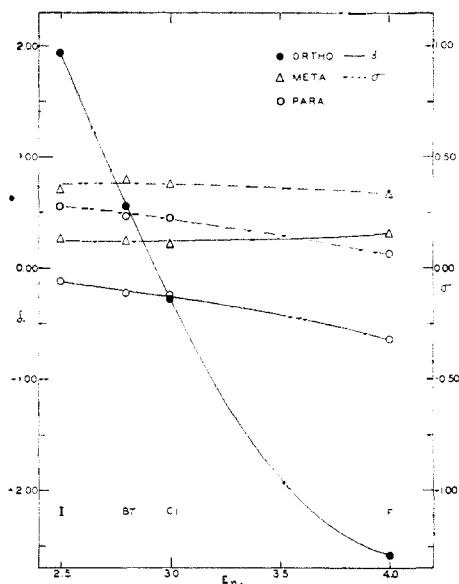
Fig. 6.—δ- and σ-values compared with the electronegativity of the halogens.

the $+I$ effects, F > Cl > Br > I. With the two effects in opposing directions but in the same order, then by varying their relative magnitudes, almost any desired sequence of resultant effect can be obtained.[27] The justification given for reversing the order of the $-E$ effects is that the larger atoms, particularly those past the first row, do not readily increase their covalencies,[28] as required for the $-E$ effect.

The δ_m- and δ_p-values are in partial accord with this argument. It has been remarked in the discussion of the δ_p versus δ_m plot in Fig. 4 that fluorine appeared somewhat anomalous, being separated from the other halogens. It has the largest δ_m-value $(+I)$ and yet the largest negative δ_p-value $(-E)$, as predicted. However, the positive δ_m-values for the other halogens are I > Br > Cl, the reverse of the predicted $+I$ order. And then, there is the previously noted exceptionally large δ_o-value for iodine. These observations are incompatible with the small range, from -0.24 to -0.12 in δ_p on going from chlorine to iodine. The indicated small corresponding range in $-E$ effects cannot account for the change in δ_o from -0.27 to $+1.93$; and the predicted direction of the $+I$ sequence, Cl > Br > I, is the reverse of that required to explain the trend in δ_o.

Thus, there seems to be an additional positive δ_o-interaction for the halogens in order I > Br > Cl > F, similar perhaps to that noted above for the $+E$ substituents and for CH_3. This δ_o-interaction may be electromeric in nature since, when present, its sign is opposite to that of the usual electromeric effect, while there is no such correlation with the inductive effect. There are several mechanisms possible, but there is not sufficient evidence for a critical choice. However, at least in the case of the halogens, the usual sorts of interaction would

(27) J. F. J. Dippy and R. H. Lewis, J. Chem. Soc., 644 (1936).
(28) Recently, K. S. Pitzer, This Journal, 70, 2140 (1948), has given an interesting discussion of this effect in terms of inner electron shell repulsions.

appear to give a negative rather than a positive effect, or else be in the wrong sequence. One way in which the halogens might withdraw electrons selectively from the ortho position is by a small overlap of the vacant low-lying d-orbitals of the halogen with the π-orbitals in benzene. This would give the sequence I > Br > Cl since the d-orbitals are lowest lying for iodine, and absent of course in the valence shell of fluorine.

δ_o-Values and Entropy Effects.—The hope was voiced earlier[11a] that δ_o-values in combination with rate or equilibrium constants would permit evaluation of the entropy terms. Thus, if δ_o could be related directly to σ' in eq. 4, and the reaction constant ρ applied to ortho as well as meta and para substituents, then experimental rate or equilibrium constants could be used to compute entropies of activation or of ionization. It is now clear, however, that the varying influence on δ of the several electronic interactions severely limits such an approach. Nonetheless, it may be of some interest to give a comparison of δ_o with several "σ_o"-values, where the "σ_o"-values are obtained in the same way as σ_m and σ_p, from the influence of an ortho substituent on a rate or equilibrium constant.

Values of "σ_o" were obtained from the equation "σ_o" $= (1/\rho) \log (K/K_u)$ using Dippy's tabulation[13] of dissociation constants, which includes a limited number of ortho-substituted benzoic and phenylacetic acids and the o-halophenols. Reaction constant ρ's of $+1.00$, $+0.47$ and $+2.01$, respectively,[10c] were used for the three series of compounds. The resulting values of "σ_o" are plotted in Fig. 7 against the δ_o-values. It is seen that the data for the halogens fall upon separate smooth curves for the three series of compounds. The parallelism and large separation of the curves suggests an interaction between the ortho substituents and the reacting group,[10a] the interaction being characteristic of the reacting group and relatively insensitive to the particular halogen.
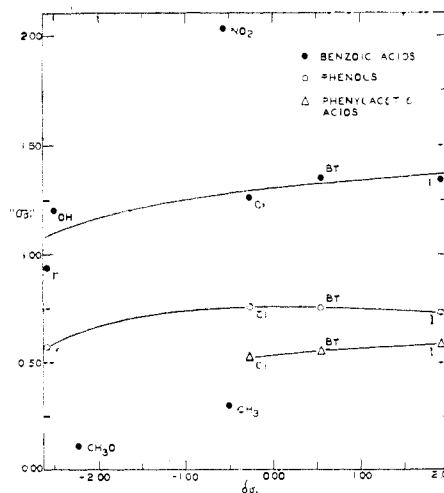

Fig. 7.—A comparison of δ_o-values with "σ_o"-values calculated from the effect of ortho substituents on dissociation constants.

Data for other substituents are limited mainly to the benzoic acids. The point for OH in Fig. 7

lies fairly well on the same curve as the halogens, probably accidentally; however, the CH_3O, CH_3 and NO_2 points are scattered widely. The relative magnitudes of entropy and electronic effects in these deviations from a smooth "σ_o"–δ_o curve are not separable at present, but it does seem reasonable that if two substituents are very similar in their electronic effects, then any deviations in their "σ_o"-values arise mainly from entropy effects. For instance, the δ-values for OH, CH_3O and C_2H_5O are nearly identical for each of the three positions, yet "σ_o" for OH is $+1.20$ and for CH_3O, $+0.30$. Ascribing the "σ_o" difference to the entropy term in eq. 4, ΔS_i for the o-hydroxybenzoic acid is about 4 e.u. larger than for the o-methoxybenzoic acid. This is in the wrong direction to be a steric effect of the larger CH_3O group and, instead, chelation of the OH group with the CO_2^- anion is indicated, as proposed by Branch[10a] and reviewed by Dippy.[13] A detailed general analysis of the δ_o-values requires more experimental dissociation or rate constants and entropies than are presently available.

Other Substituent Parameters Compared to δ.— Most of the other numerical substituent parameters are correlated to some degree with the σ-values and therefore with the δ-values. Price[29] has used $\Delta\sigma = \sigma_p - \sigma_m$ as a measure of electromeric effects, the negative σ_m term correcting for the small amount of inductive effect at the para position. A plot of $\Delta\sigma$ versus $\Delta\delta$ shows separate lines for the $+E$ and $-E$ substituents, related to those in Fig. 4. $\Delta\delta$ is defined as $\delta_p - \delta_m$, by analogy to $\Delta\sigma$; however, since δ_p is primarily electromeric, it alone gives nearly as good correlations as $\Delta\delta$. Very similar results are obtained upon comparing δ_p or $\Delta\delta$ with the $\Delta\lambda_{calcd}$ of Doub and Vandenbelt.[30] In Fig. 8, the substituent spectroscopic moments of Platt[14] are plotted against $\Delta\delta$. In this case, the data for $+E$ as well as $-E$ substituents appear to be along a single straight line.

Another parameter of considerable potential interest is the influence of a substituent on the chlorine quadrupole coupling constants in substituted chlorobenzenes. Preliminary results of this sort at Harvard,[31] and similar work started independently here at a later time, suggest a single linear relation between the coupling constants and the meta and para σ's.

Polysubstituted Benzene Derivatives

Polysubstituted fluorobenzenes were investigated primarily to determine the extent to which the substituent effects are additive. No previous attempt seems to have resulted in a systematic quantitative analysis of the problem.[32] Remick[26] reviews the question in some detail and cites results suggesting in several cases that interactions between substituents alter their relative directive powers.

The δ-values observed in a number of polysubstituted fluorobenzenes are listed in the first numerical column of Table II. The next column

(29) C. C. Price, *Chem. Revs.*, **29**, 37 (1941).

(30) L. Doub and J. M. Vandenbelt, THIS JOURNAL, **69**, 2714 (1947); *ibid.*, **71**, 2414 (1949).

(31) Private communication, E. B. Wilson, Jr.

(32) See, for example, reference 10b, p. 165, and papers cited therein.
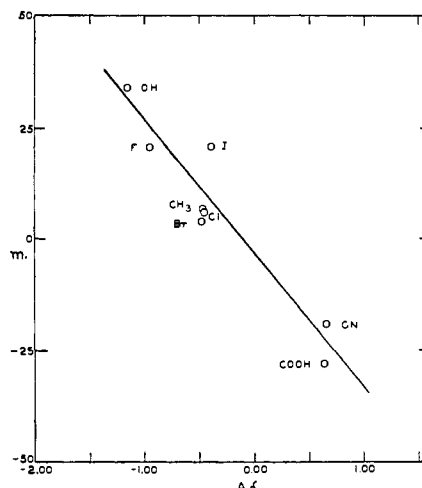
Fig. 8.—A comparison of $\Delta\delta = \delta_p - \delta_m$ with the substituent spectroscopic moment of Platt.

lists predicted δ's, the sums of the δ-values from Table I for the individual substituents. The thirty-eight complete entries in Table II represent twenty-four polysubstituted fluorobenzenes; the designations of substituents follows the convention that the observed fluorine is at the 1-position. Entries for different fluorines in the same compound are enclosed by brackets. It was possible to assign the observed δ-values to the different fluorines by comparison with the predicted values. The last column in Table II is ($\delta_{obsd} - \delta_{pred}$), a quantitative measure of non-additivity of the substituent effects.

It is seen that deviations from additivity do occur frequently but that they are generally fairly small. The sum of the absolute values of the deviation is 5.06, and of δ_{pred}, 42.27. The probable errors of each experimental δ is conservatively ± 0.03. Applying the theory of error propagation, the average fractional deviation from additivity, exclusive of experimental error, is somewhere between 6 to 12%. The 5.06 deviation sum represents ninety individual δ-values so the average non-additivity per *substituent* is only from 0.03 to 0.06 δ-unit. The root mean square deviation per *compound*, including experimental error, is ± 0.17.

The arithmetic sum of the deviations is $+3.56$ or an average value per compound of $+0.10$, demonstrating that the observed δ is generally larger than that predicted. Only seven of the deviations are negative. The sum of the δ_{pred} is -27.55, with only eleven of the values positive, suggesting a general correlation between the net negative direction of the substituent effects and the positive deviations from additivity. The several large deviations demonstrate significant interactions among the substituents, but a systematic analysis of more compounds appears necessary to disclose the conditions required for interaction. It should be pointed out that the existence of substituent interactions may have some bearing on the σ–δ relations discussed above. δ is evaluated by comparing fluorobenzene with a substituted fluorobenzene, and any interaction between the substituent and the fluorine would not need to be the same as that between fluorine and the hydrogen in the unsubstituted fluorobenzene.

TABLE II

δ-VALUES FOR POLYSUBSTITUTED BENZENE DERIVATIVES

Substituents[a]	δ observed	δ predicted	Deviation (δobsd − δpred)
3-NO₂,4-NH₂[b]	−1.43	−1.13	−0.30
2-NO₂,4-NH₂[b]	−2.16	−2.02	−.14
3,5-DiF	+0.55	+0.62	−.07
3-F,5-I	+.45	+.57	−.12
2,4-DiNO₂	+.54	+.52	+.02
2-NH₂,4-F	−2.87	−2.95	+.08
3-NH₂,4-F	−0.58	−0.66	+.08
2-NH₂,5-F	−1.83	−2.00	+.17
3-F,4-NH₂	−1.15	−1.15	.00
2-NO₂,4-F	−1.03	−1.20	+.17
3-NO₂,4-F	−0.20	−0.31	+.11
2-NO₂,5-F	+.11	−0.25	+.36
3-F,4-NO₂	+1.49	+1.39	+.10
2,4-DiF	−3.04	−3.23	+.19
3,4-DiF	−0.24	−0.33	+.09
2,5-DiF	−2.09	−2.28	+.19
2-Cl,4-F	−0.86	−0.91	+.05
3-Cl,4-F	−.39	−.43	+.04
2-Cl,5-F	+.20	+.04	+.16
3-F,4-Cl	+.20	+.07	+.13
2-Br,4-F	−.08	−.09	+.01
3-Br,4-F	−.40	−.40	.00
2-I,4-F	+1.23	+1.29	−.06
3-I,4-F	−0.45	−0.38	−.07
2-I,5-F	+2.36	+2.24	+.12
3-F,4-I	+0.30	+0.19	+.11
2-CF₃,4-F	−.74	....	....
3-CF₃,4-F	−.40	−0.36	−.04
2,4,6-TriCH₃	−1.50	−1.55	+.05
2,5-DiCl,4-F	−0.55	−0.70	+.15
2,5-DiBr,4-F	+.22	+.15	+.07
2,4,5-TriF	−2.67	−2.92	+.25
2-Br,4,5-DiF	+0.43	+0.22	+.21
2,4-DiF,5-Br	−2.75	−2.99	+.24
2,5-DiF,4-Br	−2.06	−2.51	+.45
2,5-DiF,3-CF₃	−1.77	−2.00	+.23
2,4-DiF,6-CF₃	−3.20	....	....
3,4-DiF,5-CF₃	+0.07	−0.05	+.12
2,4,6-TriCH₃,3-F	−.96	−1.24	+.28
2,4,6-TriCH₃,3,5-DiF	−.90	−0.93	+.03

[a] The designation of substituents follows the convention that the observed fluorine is at the 1-position. [b] In nitrobenzene solution.
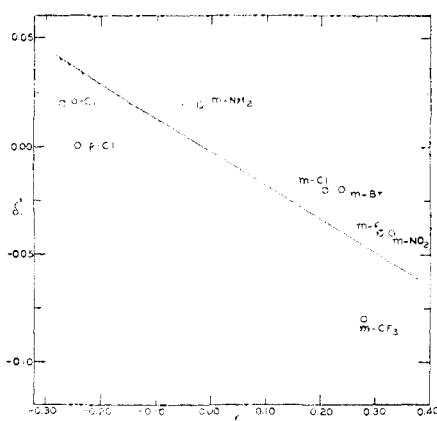

Fig. 9.—A comparison of substituent effects in substituted benzotrifluorides, δ', with those in fluorobenzene, δ.

The δ-values for the polysubstituted benzenes might be used to investigate the transmission mechanism of the substituent effects. The inductive effect, particularly, could operate directly through space as well as via the benzene nucleus. If this be so, an ortho substituent could block at least partially the direct inductive effect of an adjacent meta substituent. However, as yet not enough compounds of this type have been measured for any conclusions to be drawn.

Monosubstituted Benzotrifluorides

Several δ'-values, for monosubstituted benzotrifluorides, are listed in Table III. These give the influence on the fluorines in the CF₃ group of substituents in the benzene ring. A comparison of the δ'- with the δ-values for the same substituents reveals two interesting results. The δ'-values are only about a tenth of the δ; moreover, the sign of δ' is the reverse of δ. This may be seen by the negative slope in Fig. 9, in which the data are plotted.

TABLE III

δ'-VALUES FOR MONOSUBSTITUTED BENZOTRIFLUORIDES

Substituent	δ'	δ	Substituent	δ'	δ
o-Cl	+0.02	−0.27	p-CF₃	−0.08	....
m-Cl	−.02	+.21	o-NH₂	+.02	−2.31
p-Cl	.00	−.24	m-NH₂	+.02	−0.02
o-CF₃	+.33	....	m-F	−.04	+.31
m-CF₃	−.08	+.28	m-Br	−.02	+.24
			m-NO₂	−.04	+.33

Most of the tabulated δ'-values are not much larger than experimental error. However, the fact that all of the δ'-values are of sign opposite to the corresponding δ is strong evidence that the sign reversal is real. The tenfold attenuation and the sign reversal may depend to some extent on differing behavior of δ' and δ to electron distribution in the two types of compounds. Still, the indicated extension of the δ-parameter to classes of compounds other than substituted fluorobenzenes has widespread potentialities.

One δ'-value of particular immediate interest is that for o-CF₃-benzotrifluoride. It is +0.33 compared to −0.08 for the m- and p-isomers and from −0.04 to +0.02 for the other eight compounds in Table III. The CF₃ groups ortho to each other are close enough to cause direct interaction between the fluorines. The closest distance of approach of the fluorines in the adjacent groups is about 1.50 Å., and the greatest separation, 1.65 Å., which are to be compared with the accepted fluorine van der Waals radius of 1.35 Å. The high δ'-value appears to be further evidence of the large fluorine–fluorine repulsions postulated to account for molecular distortion in various cyclofluorocarbons.[33]

General Comments

The utility of nuclear magnetic shielding data is discussed above. In addition, it should be pointed out that relatively few nuclei are well suited for this type of experiment. The requirements are: a nuclear spin of 1/2 to avoid quadru-

(33) See W. L. Roth in "Annual Review of Physical Chemistry," Annual Reviews, Inc., Stanford, California, 1951, p. 222.

polar broadening; a large enough magnetic moment and isotopic abundance to give observable absorption; at least a moderate atomic number so there are measurable changes in magnetic shielding with compound; and, finally, chemical properties such that enough compounds are available for a more or less empirical analysis. Nuclei meeting these requirements are F^{19}, P^{31} and H^1, in decreasing order on a rough, over-all basis. On the other hand, of the nuclei unsuitable for magnetic shielding measurements because they have spins greater than 1/2, several have electric quadrupole moments of a convenient size for determining quadrupole coupling constants.[2] These include the other halogens and nitrogen, with the latter of particular interest in connection with electron distribution in double

bonds. So either the nuclear magnetic or quadrupole radiofrequency spectrum can be observed for a considerable number of nuclei, and thereby a wide variety of problems in molecular electronic distribution can be investigated.

Solubilities and Structures in Aqueous Aliphatic Hydrocarbon Solutions

BY W. F. CLAUSSEN[1] AND M. F. POLGLASE

A microcombustion method was developed for detecting hydrocarbons in water. This method was utilized for determining solubilities of methane, ethane, propane and n-butane. Calculated heats of solution are interpreted in terms of the hypothesis of iceberg formation around the solute hydrocarbon molecule. The pentagonal dodecahedron and pentagonal–hexagonal 14- and 16-hedra are considered as models for the solution icebergs of methane, ethane and propane, respectively.

The solubilities of methane and ethane in water had been first reported by Bunsen[2] and by Schickendantz[3] and later with greater precision by Winkler.[4] The method of solubility determination was a physical one, in which a volume of gas was measured, a sample of water was saturated with this gas and finally the amount of gas which did not dissolve was measured. Single solubility determinations of propane and n-butane at $17°$ are reported.[5,6] In this investigation a chemical method of solubility determination is described, which consists in removing the dissolved hydrocarbon with oxygen, burning and weighing the resultant carbon dioxide.

The purpose of this investigation was first to develop this microcombustion method of solubility determination, then to check some of the values in the literature and to determine some unreported solubilities, and finally to interpret these data in regard to solution structure. It seemed especially important to check some of the earlier solubility data, using another method than originally employed, because these data occupied such a pivotal position in the theoretical deductions concerning water solutions.[7] The reported temperature coefficients of solubility indicated that methane and ethane dissolve in water with a liberation of heat; further, the entropies of solution in water calculated from these heats of solution are much more negative than in corresponding non-aqueous solutions.

Frank and Evans have postulated an ice formation which surrounds the dissolved hydrocarbon molecules in order to explain the existing thermal data. Some of these same gases which exhibit such anomalous effects in solution also form a new and once-puzzling type of hydrate, puzzling because little attractive force is known to exist between these gas molecules and water.[8,9] After the solubility work of this paper was completed, the structures of these inert gas hydrates were proposed by Claussen.[10] The character of these structures has proven[11] to be as suspected, that the water molecules in these hydrates are in an arrangement energetically almost equivalent to that found in ordinary ice, while, in addition, the arrangement in the hydrate contains some void spaces, much larger than those in ordinary ice, in which spaces are entrapped the inert molecules. The suggestion that these water structures surrounding the voids in the hydrates are the same water structures which constitute the icebergs in the inert gas solutions is made in this paper.

Experimental Details.[12]—The procedure of hydrocarbon solubility determination involved a modified microcombustion technique. The main components of the micro train and technique, as described by Niederl and Niederl,[13] were

(1) Corning Glass Works, Corning, New York.

(2) R. Bunsen, *Ann.*, **93**, 1 (1855).

(3) F. Schickendantz, *ibid.*, **109**, 116 (1859).

(4) L. W. Winkler, *Ber.*, **34**, 1408 (1901).

(5) M. P. Lebeau, *Bull. soc. chim. France*, [3] **33**, 1139 (1905).

(6) M. P. Lebeau, *Chem. Zentr.*, **79**, II, 292 (1908).

(7) H. S. Frank and M. W. Evans, *J. Chem. Phys.*, **13**, 519 (1945).

(8) W. Schroeder, *Sammlung Chem. Chemisch.-techn. Vortrage*, **29**, 1 (1927), F. Enke, Stuttgart.

(9) W. M. Deaton and E. M. Frost, Jr., "Gas Hydrates and Their Relation to the Operation of Natural-Gas Pipe-Lines," U. S. Bur. Mines Monograph 8 (1949).

(10) W. F. Claussen, *J. Chem. Phys.*, **19**, 259, 662, 1425 (1951).

(11) M. v. Stackelberg and H. R. Müller, *Naturwissenschaften*, **38**, 456 (1951); **39**, 20 (1952).

(12) This work is part of a thesis submitted by M. F. Polglase as part of a requirement for the M.S. degree from the University of Illinois.

(13) J. B. Niederl and V. Niederl, "Micromethods of Quantitative Organic Analysis," John Wiley and Sons, Inc., New York, N. Y., 1942, pp. 101-137.