76. *Chemical Constitution and the Dissociation Constants of Monocarboxylic Acids. Part IV. A Discussion of the Electrolytic Dissociation of Substituted Benzoic and Phenylacetic Acids in Relation to Other Side-chain Processes.*

By J. F. J. DIPPY, H. B. WATSON, and F. R. WILLIAMS.

THE earlier parts of this series (Dippy and Williams, J., 1934, 161, 1888, and preceding paper) contain an account of the determination, by an accurate and rapid method, of the dissociation constants of a number of substituted benzoic and phenylacetic acids in water at 25°. In the present communication these results are considered in the light of modern electronic conceptions, and in their relationship with other relevant data.

The extensive work of Ostwald (results summarised in *Z. physikal. Chem.*, 1889, **3**, 418) made it clear that substituents may either increase or decrease the strength of a carboxylic acid, and Derick (*J. Amer. Chem. Soc.*, 1911, **33**, 1152) expressed the " negativity " or " positivity " of a group as a logarithmic function of the dissociation constant of the appropriate substituted acid. It was pointed out by Lewis (" Valence and the Structure of Atoms and Molecules," 1923, pp. 85, 139) that the observed effect is due to the electron-attractive or electron-repelling character of the group, but the derivation of a quantitative relationship between acid strengths and the polarities of substituents was not possible before the accumulation of knowledge of dipole moments. It has recently been observed by Nathan and Watson (J., 1933, 893; cf., however, Waters, *Phil. Mag.*, 1929, **8**, 436) that the logarithms of the dissociation constants (Ostwald's values) of a number of substituted acetic acids $CH_2X{\cdot}CO_2H$ are given by the expression $\log K = \log K_0 - 2{\cdot}4(\mu + 0{\cdot}032\mu^2)$, where K and K_0 refer to the substituted and unsubstituted acids respectively, and μ (in Debye units) is the dipole moment of the corresponding substituted methane CH_3X. The value of the dissociation constant of diphenylacetic acid (Part I, *loc. cit.*) is in agreement with Nathan and Watson's expression ($10^5K^*_{\text{class.}}$: obs., 11·7; calc., assuming $\mu = -2 \times 0{\cdot}39$, 11·46). The saturated aliphatic monocarboxylic acids thus appear to present an unusually simple case, where the dipole (inductive) effect accounts quantitatively for the changes in acid strength.

A vast number of observations have indicated, however, that the influence of a substituent attached directly to the benzene nucleus is frequently of a complex character. In the realm of aromatic substitution, for example, all neutral, non-ion-forming groups with unshared electrons adjacent to the nucleus (*e.g.*, –OR, –NHAc) are *op*-directive, irrespective of the direction of the dipole (Ingold, *Rec. trav. chim.*, 1929, **48**, 802), and phenomena of this kind, which were formerly related to characters such as the " state of saturation " (Vorländer) or the " affinity demand " (Flürscheim) of the group, are now ascribed to electromeric displacements *away* from the substituent ($+T$). Conversely, groups having oxygen doubly linked to the atom attached to the nucleus (*e.g.*, $-NO_2$, –COR) can give rise to electromeric displacements *towards* the group ($-T$). In other words, quantum-mechanical resonance is possible between alternative configurations (here benzenoid and quinonoid) of similar energy, and the stable condition of the molecule is actually intermediate between these " unperturbed states " (" mesomerism," Ingold, J., 1933, 1120; *Chem. Reviews*, 1934, **15**, 232). Examples of the operation of this effect are found in the methoxy- and nitro-substituted aromatic acids.

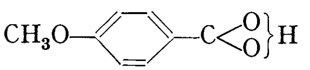
Influence of Methoxyl.—Methylglycollic (33·5) and *m*-methoxybenzoic (8·8) acids are stronger than acetic (1·80) and benzoic (6·0) acids respectively [the values in parentheses are those of $10^5K_{\text{class.}}$, the first, third, and fourth being due to Ostwald, and the other to Pip (Diss., Heidelberg, 1898, quoted from International Critical Tables)], indicating electron-attraction by methoxyl. Ostwald found $10^5K_{\text{class.}}$ for *p*-anisic acid, however, to be 3·2, and the values $10^5K_{\text{therm.}} = 3{\cdot}38$ and 6·27 for *p*-anisic and benzoic acids respectively (Part II), obtained by the aid of modern technique and of the Debye–Hückel–Onsager equation, can leave no doubt as to the relatively low dissociation constant in the former case. The order of acid strengths is $m\text{-}OCH_3 > H > p\text{-}OCH_3$, and this is further confirmed by the recent results of Branch and Yabroff (*J. Amer. Chem. Soc.*, 1934, **56**, 2568; $10^5K_{\text{therm.}}$ for benzoic acids in 25% alcohol at 25°; *m*-OCH_3, 2·87; unsubstituted, 2·29; *p*-OCH_3, 1·16). The same order is found in the acetoxybenzoic (*m*-$O{\cdot}CO{\cdot}CH_3 = 9{\cdot}9$, *p*-$O{\cdot}CO{\cdot}CH_3 = 4{\cdot}2$; Ostwald), in the ethoxybenzoic (*m*-$OC_2H_5 = 9{\cdot}0$, *p*-$OC_2H_5 = 5{\cdot}0$; Pip), and in the phenetylboric acids ($10^{10}K_{\text{therm.}}$ in 25% alcohol at 25°; *m*-phenetylboric, 3·05; phenylboric, 1·97; *p*-phenetylboric, 0·608; Branch, Yabroff, and Bettmann, *J. Amer. Chem. Soc.*, 1934, **56**,

---

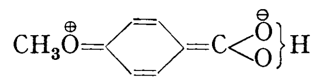
* $K_{\text{class.}}$ is here quoted, since comparison is made with Ostwald's values, upon which the expression was based. As pointed out by Nathan and Watson, the relative inaccuracy of the older values is here unimportant in view of their wide range.

All dissociation constants referred to in this communication, unless otherwise defined, are for aqueous solutions at 25°.

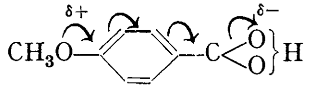
937). Similarly, Ostwald found values of 8·5 and 5·2 for *m*- and *p*-acetamidobenzoic acids respectively. In all these cases, resonance between alternative configurations * such as (I) and (II), usually expressed as (III), will reduce the strength of the *p*-substituted acid (compare Ingold, J., 1933, **1124**; Branch, Yabroff, and Bettmann, *loc. cit.*). Since the *m*-quinonoid form is not possible, these groups in the *m*-position exert only the dipole effect, which increases acidity. Similar differences in the influence of *m*- and *p*-methoxyl have been observed in various side-chain reactions such as the hydrolysis and the reduction of benzyl bromides (Lapworth and Shoesmith, J., 1922, **121**, 1394; Shoesmith and Slater, J., 1926, 217), and the alkaline hydrolysis of benzoic esters (Kindler, *Annalen*, 1926, **450**, 3; 1927, **452**, 90).



(I.)



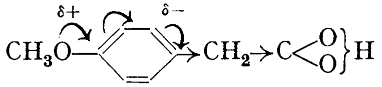
(II.)

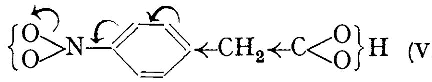


(III.)

A depression of acid strength, though of smaller magnitude, is also observed in *p*-methoxyphenylacetic acid [$10^5K_{\text{therm.}} = 4{\cdot}36$ (Part II), as compared with 4·88 for phenylacetic acid (Part I)]. This would not, perhaps, have been anticipated, since the transmission of the electromeric effect, as such, is rendered impossible by the intervening methylene group. It is simplest to suppose that electromeric displacements, initiated by methoxyl, proceed to the *p*-carbon atom, and that the effect of the resulting fractional negative charge is propagated inductively (or through the medium) to the carboxyl group. The methoxyl group thus exerts " what is virtually a relayed general or inductive effect " (Robinson, J., 1933, 1115). This may be represented as in (IV). Methoxyl in the *m*-position appears again to behave in accordance with its dipole effect, 3 : 4-dimethoxyphenylacetic acid ($10^5K_{\text{therm.}} = 4{\cdot}64$, Part II) being somewhat stronger than the *p*-methoxy-acid.

(IV.)





(V.)

An interpretation akin to that outlined above is applicable to the activating influence of phenyl in the nitration of guaiacol benzyl ether (Allan and Robinson, J., 1926, 376; compare Allan, Oxford, Robinson, and Smith, *ibid.*, p. 407), where the initiation of electromeric displacements by ethereal oxygen is facilitated, and to the effect of *p*-methoxyl upon the reactions of aryl β-chloroethyl sulphides (Baddeley and Bennett, J., 1933, 261), where ionisation of chlorine is facilitated and reaction with iodide ion is retarded.

Influence of Nitroxyl.—In accordance with expectation, the nitro-group, when present in any position, increases very considerably the strength of an aromatic acid ($10^5K_{\text{class.}}$ for *m*- and *p*-nitrobenzoic acids = 34·5 and 39·6 respectively, Ostwald; $10^5K_{\text{therm.}}$ for *m*- and *p*-nitrophenylacetic acids = 10·8 and 14·1, Parts I and II; $10^9K_{\text{therm.}}$ for *m*- and *p*-nitrophenylboric acids in 25% alcohol at 25° = 6·9 and 9·8 respectively, Bettmann, Branch, and Yabroff, *J. Amer. Chem. Soc.*, 1934, **56**, 1865). It has been pointed out by the last-named authors, however, that the dipole effect, if operative alone, would be expected to lead to the order of strengths $m > p$, while the reverse is actually the case. This applies to all the pairs of acids referred to above, and, indeed, an inspection of available data shows that the influence of nitroxyl upon side-chain processes is usually greater in the *p*- than in the *m*-position. Bettmann, Branch, and Yabroff ascribe the phenomenon to resonance (— *T*), and it may be pointed out that Opolski and Zwislocki (*Ber.*, 1916, **49**, 1606) assigned the formula $CO_2Et{\cdot}CH{:}C_6H_4{:}NO{\cdot}OM$ to certain highly coloured salts which they prepared from ethyl *p*-nitrophenylacetate. It is not suggested, of course, that a

---

* $-\mathrm{C}\Big\langle{\mathrm{O} \atop \mathrm{O}}\Big\}\mathrm{H}$ and $-\mathrm{N}\Big\langle{\mathrm{O} \atop \mathrm{O}}\Big\}$ are written for carboxyl and nitroxyl respectively, in view of the resonance between the structures $-\mathrm{C}\begin{smallmatrix}/\!\!/\mathrm{O}\\ \backslash\mathrm{OH}\end{smallmatrix}$, $-\mathrm{C}\begin{smallmatrix}/\mathrm{O}\\ \backslash\!\!\backslash\mathrm{OH}\end{smallmatrix}$ and $-\mathrm{N}\begin{smallmatrix}/\!\!/\mathrm{O}\\ \searrow\mathrm{O}\end{smallmatrix}$, $-\mathrm{N}\begin{smallmatrix}\nearrow\mathrm{O}\\ \backslash\!\!\backslash\mathrm{O}\end{smallmatrix}$ (Ingold, J., 1933, 1126; Pauling and Sherman, *J. Chem. Physics*, 1933, **1**, 606)

hydrogen atom of the methylene group of *p*-nitrophenylacetic acid is actually free in aqueous solution, but a position such as that represented in (V) would account for the enhanced strength.

The present conception of the *T* effect renders unnecessary the postulate that it cannot operate *against* the attack of a reagent (compare Baddeley and Bennett, *loc. cit.*, p. 265; Shoppee, J., 1932, 698), and, indeed, numerous examples are available of the operation of resonance as a retarding influence, such as the depression by *p*-methoxyl of the alkaline hydrolysis of benzoic, phenylacetic, hydrocinnamic, and cinnamic esters (Kindler, *Annalen*, 1927, **452**, 95) and of benzamides (Reid, *Amer. Chem. J.*, 1900, **24**, 397), and of the reaction of aryl β-chloroethyl sulphides with iodide ion (Baddeley and Bennett, *loc. cit.*). Indeed, one cannot ignore the possibility that the powerful deactivation of the *o*- and *p*-positions by nitroxyl and carbonyl, leading to *m*-substitution, may be due, in some way, to resonance; this would render unnecessary the assumption of a *p*-linkage (Ingold, *Ann. Reports*, 1926, **23**, 133).

Influence of Halogens.—The dissociation constants of the halogen-substituted benzoic and phenylacetic acids fall, as a group, into the anticipated position, the acids being stronger than the unsubstituted, and weaker than the nitro-substituted, acids, $NO_2 > Hal > H$. The order of the halogens among themselves, however, is not that of their inductive effects. The relative strengths of the halogenoacetic acids ($10^3K_{\text{class.}}$: F, 2·17; Cl, 1·55; Br, 1·38; I, 0·71; Scudder, "Conductivity and Ionisation of Organic Compounds," 1914) and the percentages of *m*-derivative formed in the nitration of the benzyl halides (F, 17·5; Cl, 11·6; Br, 6·6; Flürscheim and Holmes, J., 1928, 1611; Ingold and Ingold, *ibid.*, p. 2253) lead inevitably to the order $F > Cl > Br > I$ for inductive effects. The dissociation constants ($10^5K_{\text{therm.}}$) of the *p*-halogenoaromatic acids, however, are as follows (Parts I and III):

Benzoic: *p*-F, 7·22; *p*-Cl, 10·55; *p*-Br, 10·7.
Phenylacetic: *p*-F, 5·68 *; *p*-Cl, 6·45; *p*-Br, 6·49; *p*-I, 6·64.

The values for the chloro- and bromo-acids are, of course, scarcely distinguishable, but the general sequence is clear, and it is the reverse of that to which the inductive effects would lead. A similar inversion has been found in the strengths of the halogenophenylboric acids ($10^{10}K_{\text{therm.}}$: *p*-F, 3·66; *p*-Cl, 6·30; *p*-Br, 7·26; Bettmann, Branch, and Yabroff, *loc. cit.*), and in a number of side-chain reactions (see lists given by Baddeley and Bennett, *loc. cit.*, and by Nathan and Watson, J., 1933, 1248; an additional example has recently been observed by Davies and Lewis, J., 1934, 1599). Allied problems are presented by the values of the dipole moments of the halogenobenzenes and by the *op*-directive influence of the halogens. It is clearly necessary to postulate a displacement of electrons opposite in direction to the inductive effect; this must be permanent, to some degree at least, since it is evident in the measured moments of the halogenobenzenes. We are in agreement with Baddeley and Bennett's conclusion (*loc. cit.*; compare Bennett, J., 1933, 1112) that the phenomenon of inversion requires for its interpretation an effect which diminishes in magnitude in the order $F > Cl > Br > I$ (compare Bettmann, Branch, and Yabroff, *loc. cit.*, who, however, suggest that this is the "resonance order"). It seems inevitable, however, that, of the four halogens, fluorine must control its electrons most powerfully, and iodine, with the largest atom, least powerfully, and for this and other reasons (also pointed out by Baddeley and Bennett) it is difficult to accept the view that the halogens can initiate electromeric displacements by a mechanism similar to that which has proved adequate to interpret the influence of groups such as alkoxyl and dialkylamino. In support of this conclusion, it may be pointed out that, whereas *p*-halogen substituents *decrease* the speed of acid-catalysed prototropy of acetophenone strictly in accordance with the order of inductive effects (Nathan and Watson, J., 1933, 890), Mr. V. G. Morgan, working in these laboratories, has shown that the substitution of methoxyl in the *p*-position results in a very considerable *increase* of speed.

It has been pointed out by Burton and Ingold (*Proc. Leeds Phil. Soc.*, 1929, **1**, 424) that "the aryl group contains an available mechanism for the extensive distribution of

---

* See preceding paper, p. 344, regarding this value.

an ionic charge of either sign," and Baddeley and Bennett (*loc. cit.*) consider that, since this is the case, a halogen atom attached to the nucleus becomes a partial negative pole, the positive equivalent being largely distributed throughout the nucleus. They thus arrive at the conception of a " reversed field," resulting in the initiation of electromeric displacements which are transmitted to the *o*- and *p*-positions, their magnitude decreasing in the required order, *viz.*, that of inductive effects. The application of this view provides an explanation of the inverted order of the dissociation constants of the *p*-halogeno-benzoic and -phenylacetic acids, as compared with those of the corresponding acetic acids.

In the latter case, there is no mechanism for the distribution of the positive charge residing upon the carbon end of the C–Hal dipole, and the relationship between acid strength and dipole moment is thus a simple and quantitative one, as observed by Nathan and Watson. The inverted order when halogen is attached to the benzene nucleus arises from the distribution of the positive charge, for the resulting " reversed field " mechanism leads to a decrease in acidity. The main influence is still the inductive effect of the halogen, since all the dissociation constants are considerably higher than those of the unsubstituted acids, but on this is superimposed, as a " fine adjustment," the opposing effect of the reversed field, which decreases in the order $F > Cl > Br > I$ and is of sufficient magnitude to invert the order of the halogens among themselves.

It must be emphasised that the view here adopted does not forecast inversion in *every* case where halogens are attached to aryl groups. Although the electromeric displacements set up by the reversed field are to some extent permanent, they are nevertheless dependent upon the *polarisability* of the nucleus, and their magnitude is governed by the extent to which they are permitted or favoured by external conditions, attacking reagents, and groups inside the molecule. Thus, in the acid hydrolysis of *p*-fluorobenzyl bromide (Shoesmith and Slater, *loc. cit.*), they are sufficiently powerful even to outweigh the inductive effect of the halogen, while in the acid-catalysed prototropy of substituted acetophenones their influence is so unimportant that the strict order of inductive effects is followed. It is not surprising, indeed, that the halogens sometimes show a normal and an inverted sequence in different reactions of the same compounds (Baddeley and Bennett, *loc. cit.*). Cases of a partial inversion, too, are not unexpected, and reference may be made to the order of the dipole moments of the halogenobenzenes, *viz.*, $Cl > Br > F > I$; all the values indicate a permanent displacement of charges which affects the electrical centres of positive and negative electricity in such a way as to reduce the resultant moment (Sutton, *Proc. Roy. Soc.*, 1931, **133**, 686), but only in fluorobenzene is this effect sufficiently great to change the *order* of the values. Other cases of partial inversion are quoted by Shoppee (J., 1933, **1119**). It is not possible to forecast the order of reactivities of halogen-substituted benzene derivatives in any particular case, since no means exists for determining the effect of a given set of conditions, internal and external, upon the polarisability of the nucleus.

Although the conception of the " reversed field " is not free from difficulties, we feel that the application of Baddeley and Bennett's ideas leads to an interpretation which fits the facts more closely than does the more conventional assumption of covalency increase between halogen and nuclear carbon. It is, of course, possible, that a completely satisfactory solution of this and many other problems will emerge only after the further development of the wave-mechanical conception of molecular orbitals.

We express our indebtedness to Messrs. Imperial Chemical Industries, Ltd., for substantial grants.

THE TECHNICAL COLLEGE, CARDIFF.

[*Received, January* 16*th*, 1935.]