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The Substituent Effect. VI. Inductive and π-Electronic Effects in the Phenol Hydroxyl Chemical Shifts in DMSO

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Substituent effects on the NMR chemical shifts of the hydroxyl proton of *m*- and *p*-substituted phenols in DMSO have been studied by means of the LSFE equation. The effect of substituents was found to be considerably modified in the DMSO solution as compared with that in aqueous solution through strong substituent-solvent interactions. The LSFE equation was applied to the apparent substituent effects of such solvent-modified systems, and the practical set of parameters for the inductive and the π-electronic effects of the DMSO-modified substituents were estimated. The treatment was successful for $+R$ substituents but not for $-R$ substituents. This may be attributed to the much stronger solvent-substituent interactions. Characteristic features of LSFE treatment were discussed in comparison with Taft and Swain-Lupton treatments. It is suggested that the dual resonance reaction constants for $+R$ and $-R$ *para* substituents are required for Taft-type correlations.

Substituent effects on chemical and physical properties in a number of benzene derivatives have been treated by the following *Linear Aromatic Substituent Reactivity* (LArSR) *Relationship*:[2]

$$\log (k/k_0) \text{ or } P-P_0 = \rho\bar{\sigma} = \rho(\sigma^0+r^+\Delta\bar{\sigma}_R{}^+ + r^-\Delta\bar{\sigma}_R{}^-) \qquad (1)$$

where $\Delta\bar{\sigma}_R{}^+$ and $\Delta\bar{\sigma}_R{}^-$ are the resonance substituent constants describing the capability of π-electron delocalization of conjugatively electron releasing $(-R)$ and electron attracting $(+R)$ *para* substituents, respectively. r^+ or r^- is the resonance reaction constant characteristic of given reaction giving a measure of the resonance exaltation. This equation gives a purely empirical description of the substituent effect on reactivities of substituted benzene derivatives in terms of the unexalted polar effect of substituted phenyl groups and aryl resonance exaltation effect. From the success of the treatment and particularly from the generality of the resonance parameters $\Delta\bar{\sigma}_R{}^+$ and $\Delta\bar{\sigma}_R{}^-$ for various types of reactions, we have extended Eq. (1) to an alternative theoretically simple expression, the *Linear Substituent Free Energy* (LSFE) *Relationship*:

$$\log (k/k_0)_p = \rho\bar{\sigma}_p = \rho(\sigma_i+q_r{}^+\sigma_\pi{}^+ + q_r{}^-\sigma_\pi{}^-) \qquad (2)$$

$$\log (k/k_0)_m = \rho\bar{\sigma}_m = \rho(1.17\sigma_i+0.50\sigma_\pi{}^\pm) \qquad (2')$$

where the substituent effect is given as a first approximation by the combination of inductive and resonance effects of given substituents.[3] σ_i is the inductive substituent constant, which remains constant for a given substituent independent of its variable resonance contribution. $\sigma_\pi{}^+$ and $\sigma_\pi{}^-$ are the parameters for the capabilities of $-R$ and $+R$ classes of substituents respectively to donate or withdraw electron through π-electronic delocalization, being constants characteristic only of substituents and not dependent upon the nature of reactivities, systems, and perhaps, detection variables. $q_r{}^+$ and $q_r{}^-$ are the characteristic variables of a given reaction or system, indicating the degree of π-electronic interaction of $+R$ and $-R$ groups with detection center. Both $q_r{}^+$ and $q_r{}^-$ are standardized by definition to be unity in the $\sigma_p{}^0$ scale; *i.e.*, $\sigma_p{}^0=1.00\,\sigma_i+1.00\,\sigma_\pi{}^\pm$. $\sigma_\pi{}^+$ corresponds numerically to $0.42\,\Delta\bar{\sigma}_R{}^+$ and $\sigma_\pi{}^-$ to $0.73\,\Delta\bar{\sigma}_R{}^-$.[4] The σ_i values are proportional to the relative inductive strength of substituents in the saturated system, and correspond to $0.74\,\sigma'$.

The applicability of Eqs. (1) and (2) to conjugatively electron attracting $(+R)$ substituents in the nucleophilic exalted-resonance reactions has not yet been examined sufficiently, due to the lack of data on $+R$ substituents. In this series of studies, we have thus dealt with the effect of conjugatively electron attracting substituents, especially in various types of nucleophilic reactions, in order to ascertain the applicability and limitation of our treatment of the substituent effects in the benzene system.[4,5]

We reported a complete set of NMR chemical shift data of the hydrogen-bonding hydroxyl proton of *m*- and *p*-substituted phenols in DMSO,[5] and demonstrated a satisfactory fit of the substituent chemical shifts to Eq. (1), giving a ρ value of 1.53 and r^- 0.67. The apparent substituent constant for particular substituents differs significantly from the standard one. However, the effects remained essentially the same in the related series of the hydroxyl chemical shifts of 4-substituted 2- and 3-cresols and 2,6-xylenols in DMSO, as evidenced by excellent linear $\Delta\delta$—$\Delta\delta$ plots.

We have treated these series of chemical shift data in terms of Eq. (2), and attempted to estimate a practically useful set of the π-electronic and inductive substituent parameters, $(\sigma_\pi)_{\text{DMSO}}$ and $(\sigma_i)_{\text{DMSO}}$, for the DMSO-modified substituent groups. The present paper includes a comparison of the results with those of similar treatments based on Taft[6] and Swain-Lupton Equations.[7]

Results and Discussion

Table 1 gives the apparent substituent constants derived from the NMR chemical shifts of the hydroxyl proton of phenols in DMSO.[5] The constants obtained from 4-substituted phenols were identical with those derived from the corresponding 2- and 3-cresols[8] and 2,6-xylenols using appropriate ρ values.

According to Eq. (1), enhancement of the apparent $\bar{\sigma}_p$ values from corresponding σ^0 values are proportional to the resonance parameters, $\Delta\bar{\sigma}_R{}^-$ or $\Delta\bar{\sigma}_R{}^+$. Figure 1 gives a plot of apparent enhancement $\bar{\sigma}_p-\sigma_p{}^0$ for conjugatively electron attracting $(+R)$ substituents in *p*-substituted phenols against standard $\Delta\bar{\sigma}_R{}^-$. Most substi-

Table 1. Apparent substituent constants in DMSO

No.	Subst.	$\bar{\sigma}_p$	$\bar{\sigma}_m$
1	NO_2	1.121	0.722
2	CN	0.844	0.583
3	CHO	0.840	0.411
4	SO_2CH_3	0.825	0.596
5	$SOCH_3$	0.498	0.422
6	SO_2NH_2	0.613	
7	SCN	0.583	
8	$SMe_2^+I^-$	0.926	0.721
9	$NMe_3^+I^-$	0.547	0.601
10	COC_6H_5	0.735	0.356
11	$COCH_3$	0.655	0.297
12	$COOCH_3$	0.658	0.337
13	COOEt	0.647	0.318
14	$CONH_2$	0.410	0.184
15	CF_3	0.635	0.508
16	$CH=CHNO_2$	0.713	0.305
17	CH=CHCOOEt	0.449	0.201
18	$CH=NC_6H_5$	0.536	
19	$N=CHC_6H_5$	0.122	
20	$N=NC_6H_5$	0.652	
21	C_6H_5	0.151	
22	H	0.002	
23	I	0.238	0.288
24	Br	0.244	0.369
25	Cl	0.229	0.367
26	F	0.025	0.359
27	SCH_3	0.079	0.115
28	OC_6H_5	0.011	0.181
29	NHAc	−0.112	0.008
30	NHC_6H_5	−0.198	−0.085
31	*t*-Bu	−0.138	−0.088
32	Et	−0.149	
33	CH_3	−0.162	−0.071
34	OCH_3	−0.276	0.030
35	OH	−0.467	−0.113
36	NMe_2	−0.467	−0.210
37	NH_2	−0.643	−0.323
38	$(CH_3)_2$		−0.151
39	Cl_2		0.725

tuents fall near the correlation line, but certain carbonyl and sulfonyl derivatives deviate from it. The deviation is large for the $CONH_2$ and SO_2NH_2 groups; that of the latter in particular suggests an unlikely electron releasing resonance contribution of this group. The scattered pattern is similar to that observed in DMF solution.[4] These deviations may arise from solvent-modification of the electronic nature of substituents in the DMSO solution. Since the standard σ_p^0 is the parameter referable to the substituents modified with water, the quantities $\bar{\sigma}_p-\sigma_p^0$ should include certain extraneous effects due to the change of solvents from H_2O to DMSO. The deviations in the above correlation are not merely due to the solvent-modification of π-electronic interaction of substituents but include changes in the inductive nature of substituents caused by solvation. It appears necessary to deal with the solvent-modified substituent effects in terms of both inductive and π-electronic effects.

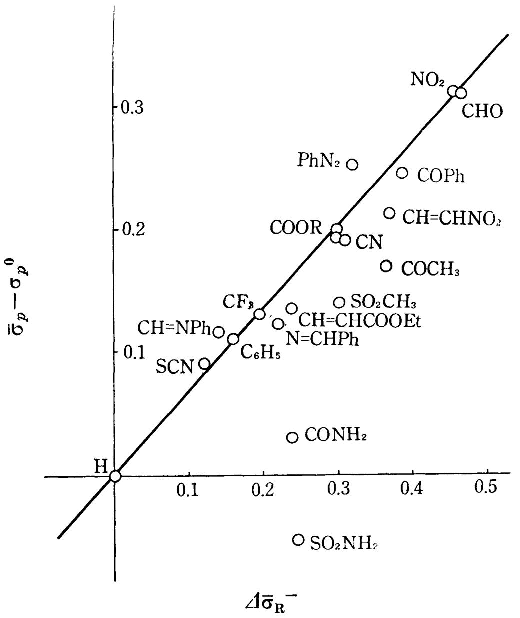

Fig. 1. Plot of the apparent resonance enhancements $\bar{\sigma}_p-\sigma_p^0$ against standard $\varDelta\bar{\sigma}_R^-$ values for $+R$ substituents.

From Eqs. (2) and (2′), we can eliminate the inductive contribution by using the unique *para*/*meta* inductive contribution ratio of 0.85 ($=1/1.17$) and obtain the following equation as the simplest linear resonance free energy relationship.

$$\log (k/k_0)_p-0.85\log (k/k_0)_m = \rho(\bar{\sigma}_p-0.85\bar{\sigma}_m) = \rho(q_r^{\pm}-0.425)\sigma_\pi^{\pm} \quad (3)$$

This relationship should also be valid for the solvent-modified substituent. q_r^+ is not generally identical with q_r^- in nucleophilic or electrophilic resonance-exalted reactions. Accordingly, both $+R$ and $-R$ substituents can not be treated with a single q_r parameter. This paper deals with the effect of conjugatively electron attracting ($+R$ class) substituents, for which the results are successfully correlated.

The π-electronic effect of DMSO-modified +R substituents of interest can thus be given for the present system by the following equation since $\sigma_\pi^-=0.73\varDelta\bar{\sigma}_R^-$ by definition.

$$(\varDelta\delta_p-0.85\varDelta\delta_m)/1.529 = C_{DMSO}^-(\sigma_\pi^-)_{DMSO} = 0.73C_{DMSO}^-(\varDelta\bar{\sigma}_R^-)_{DMSO} \quad (4)$$

where C_{DMSO}^- is a coefficient giving the degree of effective resonance contributions from $+R$ substituents in the given system in DMSO and corresponds to $q_r^- -0.425$ for the system. $(\bar{\sigma}_\pi^-)_{DMSO}$ or $(\varDelta\bar{\sigma}_R^-)_{DMSO}$ denotes the π-electronic (resonance) substituent parameters for the DMSO-modified $+R$ substituent. The correlation of the same type can be derived for $-R$ substituents, while the coefficient C_{DMSO}^+ is not necessarily the same as the C_{DMSO}^- even in the same system.

The C_{DMSO}^- can be determined experimentally from the slope of the plots of $(\bar{\sigma}_p-0.85\bar{\sigma}_m)_{DMSO}$ against $(\varDelta\bar{\sigma}_R^-)_{DMSO}$ or $(\bar{\sigma}_\pi^-)_{DMSO}$. We may utilize standard $\varDelta\bar{\sigma}_R^-$ values for $(\varDelta\bar{\sigma}_R^-)_{DMSO}$ since the effect of solvent modification is relatively small for most substituents. This process in turn can be used to determine a set of $(\varDelta\bar{\sigma}_R^-)_{DMSO}$ and $(\sigma_\pi^-)_{DMSO}$. Figure 2 shows the plot for $+R$ substituents of the present phenol system against standard $\varDelta\bar{\sigma}_R^-$,

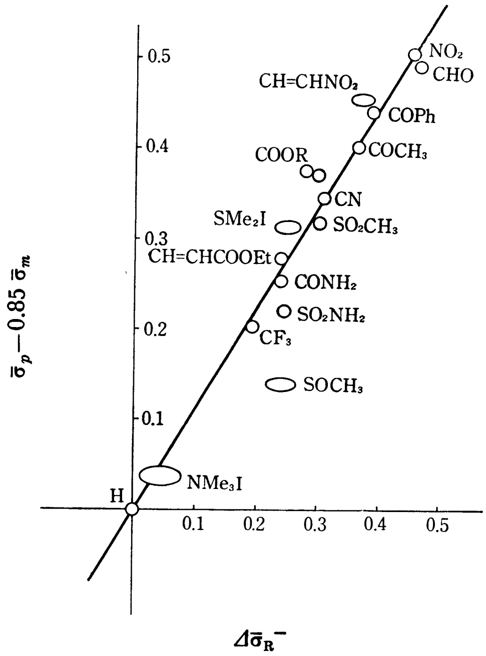

Fig. 2. Plot of the quantities $\bar{\sigma}_p-0.85\ \bar{\sigma}_m$ against standard $\Delta\bar{\sigma}_R^-$ values, for $+R$ substituents.

giving the slope of 1.12 with satisfactory linearity; correlation coefficient 0.987 and standard deviation±0.028. A similar correlation has been obtained for the corresponding resonance quantities of the same series in DMF solution.[4] The modification of substituents with DMSO and DMF solvents is related more closely to each other than to those in aqueous solution, because of similarity in their aprotic and basic character. $(\Delta\bar{\sigma}_R^-)_{\text{DMF}}$ in fact give a much better correlation ($s=\pm0.010$ and $R=0.998$) than standard $\Delta\bar{\sigma}_R^-$. From the slope 1.12, $(\Delta\bar{\sigma}_R^-)_{\text{DMSO}}$ is obtained, and converted into $(\sigma_\pi^-)_{\text{DMSO}}$; *i.e.*, $(\sigma_\pi^-)_{\text{DMSO}}=0.818\ (\bar{\sigma}_p-0.85\bar{\sigma}_m)$. The inductive substituent constants are given by

$$(\sigma_i)_{\text{DMSO}} = \bar{\sigma}_p - 1.43(\Delta\bar{\sigma}_R^-)_{\text{DMSO}}.$$

$(\sigma_p^0)_{\text{DMSO}}$ can also be derived by combining $(\sigma_\pi^-)_{\text{DMSO}}$ and $(\sigma_i)_{\text{DMSO}}$. These sets of substituent constants are compared with corresponding standard parameters (Table 2).

Comparison of the DMSO-modified substituent parameters with standard σ^0 and σ^- parameters suggests that NO_2, CHO, CN, CF_3, COC_6H_5, and COOMe can be classified as well-behaving substituents even in the aprotic solvent since for these groups the effect of solvent-modification is negligible. Discrepancies are significant in $COCH_3$, $SOCH_3$, $CONH_2$, SO_2NH_2, Me_3N^+, and Me_2S^+ groups. In the first two loss of the hydrogen-bonding at the oxygen with aqueous solvents appears to be an important factor to lower the electron attracting power of these groups in aprotic DMSO.[4,5] For the amides the negative charge arising from the donating hydrogen-bonding to DMSO makes these groups less electron-attracting. The charged substituents are known to be highly sensitive to changes of solvents and reaction conditions, so that even the standard parameter values have not been definitely evaluated.[9] However, it is of interest to note that the Me_3N^+ group in the present system is effectively more electron attracting from *meta* than *para* position (Table 1). The trend $\bar{\sigma}_p<\bar{\sigma}_m$ is generally observed for this group as in the pK_a of benzoic acids and of phenols in various solvents.[10] According to Taft's assumption $\sigma_I^m=\sigma_I^p$, this group should be conjugatively electron releasing since $\bar{\sigma}_p-\bar{\sigma}_m<0$. In our treatment this group appears to be a weak $+R$ class or almost exclusively inductive class,[11] as indicated by the small positive value of $\bar{\sigma}_p-0.85\ \bar{\sigma}_m$. On the other hand, Me_2S^+ group is suggested from either treatment to be considerably strong $+R$ class substituent, not depending on solvent.

We see that the resonance parameters $(\Delta\bar{\sigma}_R^-)_{\text{DMSO}}$ as well as $(\sigma_\pi^-)_{\text{DMSO}}$ are generally in agreement with the standard values within uncertainty of average ±0.01 or so in σ unit except for $SOCH_3$ group (Table 2). The $(\sigma_i)_{\text{DMSO}}$ values are consistently less positive than the standard values for all substituents. The difference between the two values is significant for about a half of the entries, and particularly remarkable for SO_2NH_2 and $CONH_2$ and charged substituents Me_3N^+ and Me_2S^+. The substantial changes can be explained at least quali-

Table 2. DMSO-Modified substituent parameters for $+R$ groups

Subst.	$\Delta\bar{\sigma}_R^-$	$(\Delta\bar{\sigma}_R^-)_{\text{DMSO}}$	σ_π^-	$(\sigma_\pi^-)_{\text{DMSO}}$	σ_i	$(\sigma_i)_{\text{DMSO}}$	σ_p^0	$(\sigma_p^0)_{\text{DMSO}}$	σ_p^-	$(\sigma_p^-)_{\text{DMSO}}$
NO_2	0.455	0.454	0.332	0.331	0.46	0.473	0.800	0.804	1.255	1.26
CHO	0.47	0.440	0.34	0.321	0.22	0.212	*ca.*0.53	0.533	1.030	0.97
CN	0.309	0.311	0.226	0.227	0.42	0.400	0.653	0.627	0.96	0.94
CF_3	0.196	0.182	0.143	0.133	0.34	0.375	0.50	0.508	0.686	0.69
$COCH_3$	0.365	0.361	0.266	0.264	0.214	0.140	0.491	0.404	0.850	0.77
COC_6H_5	0.387	0.387	0.28	0.283	0.20	0.183	0.49	0.466	0.877	0.85
$COOCH_3$	0.30	0.333	0.22	0.243	0.23	0.183	0.46	0.426	0.76	0.76
COOEt	0.28	0.337	0.20	0.246	0.24	0.166	0.45	0.412	0.73	0.75
SO_2CH_3	0.302	0.285	0.22	0.208	0.46	0.418	0.69	0.626	0.99	0.91
$CH{=}CHNO_2$	*ca.*0.37	0.406	0.27	0.296	*ca.*0.23	0.134	*ca.*0.50	0.430	0.88	0.84
CH=CHCOOEt		0.249		0.182		0.144		0.326		0.58
$CONH_2$	0.24	0.227	0.175	0.166	*ca.*0.20	0.086	*ca.*0.38	0.252	0.62	0.48
SO_2NH_2	0.25	0.197	0.18	0.144	*ca.*0.46	0.332	*ca.*0.65	0.476	0.90	0.67
$SOCH_3$	0.24	0.124	0.175	0.091	0.31	0.321	0.49	0.412	0.73	0.54
$SMe_2^+I^-$	*ca.*0.25	0.280	0.18	0.204	*ca.*0.82	0.526	1.0	0.730	*ca.*1.25	1.01
$NMe_3^+I^-$	*ca.*0.05	0.032		0.023	0.7	0.501	0.8	0.524	0.80	0.56

tatively in terms of the specific substituent-solvent interactions with DMSO, as discussed before.4,5) The discrepancies of these DMSO values from ordinary $\sigma_p{}^0$ and $\sigma_p{}^-$ appear to be caused largely by the modification of the inductive nature of substituents in DMSO, as far as $+R$ class substituents are concerned. Only the $SOCH_3$ group, with an exceptional behavior, shows a remarkable decrease in the π-electronic contribution without noticeable decrease in the inductive contribution in DMSO solution. This suggests that in hydroxylic solvents the contribution of the cannonical structure, O^-–$\dot{S}^+$–CH_3, is particularly enhanced through hydrogen bonding, but in aprotic DMSO the decreased polarization due to loss of hydrogen-bonding makes the (p—d)π interaction far less effective giving no noticeable change in the inductive polarity.

It is possible that the specific magnetic term which does not correlate with any ordinary substituent parameters might fortuitously be cancelled out by process (4) to result in a set of parameters proportional to the resonance substituent constants. Such a non-electronic effect may be accommodated in the residual parameters, so that the resulting $(\sigma_i)_{\rm DMSO}$ parameters are no longer proportional to the ordinary σ_i values. However, this does not seem reasonable from the fact that the deviation of $(\sigma_i)_{\rm DMSO}$ from the standard σ_i value is remarkable in only carbamido and sulfonamide groups while negligible in other carbonyl and sulfonyl groups. Accordingly, any specific magnetic effect, if operative at all, is not so important that it does not overcome the solvent-modification of substituent inductive effects. This conclusion is further supported by the fact that the $(\sigma_i)_{\rm DMSO}$ values essentially parallel the changes of ^{19}F NMR chemical shift of *m*-substituted fluorobenzenes in the same solvent.6b)

When we consider the process of the derivation, $(\sigma_i)_{\rm DMSO}$ and even $(\sigma^0)_{\rm DMSO}$ and $(\sigma^-)_{\rm DMSO}$ might be less reliable than $(\Delta\bar{\sigma}_R{}^-)_{\rm DMSO}$ or $(\sigma_\pi{}^-)_{\rm DMSO}$ parameters. However, the parameters, especially the resonance parameters, should serve as a useful measure to estimate the substituent effects in the aprotic DMSO. For the substituents whose standard parameter values are not yet known precisely, the present set of parameters should have practical value for estimation of the conjugative powers of the substituents. As an example, $CH{=}CHNO_2$ and $CH{=}CHCOOC_2H_5$ would have relatively strong electron-attracting resonance-ability. The set of DMSO-parameters can be applied to reactions in most anhydrous aprotic solvents, and to even those in aqueous organic solvent, more satisfactorily than the standard set of parameters.

For conjugatively electron releasing ($-R$) substituents, quantities $(\bar{\sigma}_p - 0.85\ \bar{\sigma}_m)$ give poor linear correlation with standard $\Delta\bar{\sigma}_R{}^+$ values. This is perhaps due to the deviation from the basic requirement that the solvent-modification of the nature of substituents should be of minor significance as compared with the electronic change of the detection site by substituents. The deviations of OH and NH_2 substituents are the most remarkable. The nature of the substituents is modified by DMSO to the same extent as the changes of the detection function OH or NH_2, caused by the hydrogen-bonding with DMSO. The interaction of such a substituent with DMSO should considerably differ at *meta* and *para* positions, to the same extent as the detection site being affected by a substituent from both positions. Thus the solvent-modification of a substituent could not be assumed to be the same for *meta* and *para* positions, which is especially important for a substituent capable of strong substituent-DMSO interaction. In view of the fit of the $+R$ substituents in the above treatment (4), however, it is reasonable that the quantities $(\bar{\sigma}_p - 0.85\ \bar{\sigma}_m)$ for most $-R$ groups in DMSO solution would be also, as a first approximation, proportional to the plausible $(\Delta\bar{\sigma}_R{}^+)_{\rm DMSO}$ values. If the present set of apparent $\bar{\sigma}_p$ for $-R$ groups are assumed to be of the $\sigma_p{}^0$ class,4) the $C^+_{\rm DMSO}$ value of 0.575 can be given for the $-R$ substituents, from the *meta*/*para* π-contribution ratio of 0.50 which is characteristic of the σ^0 scale. The resonance contribution scale of these substituents can be roughly approximated on this basis:

$$(\bar{\sigma}_p - 0.85\bar{\sigma}_m) = 0.242(\Delta\bar{\sigma}_R{}^+)_{\rm DMSO} \tag{5}$$

This leads also to a crude estimation of $(\sigma_i)_{\rm DMSO}$ values for $-R$ substituents. The results are very close to those obtained in the treatment of the chemical shift in DMF solution. The uncertainty in the contribution scale of resonance for $-R$ substituents does not permit further discussion of these parameter values especially of $(\sigma_i)_{\rm DMSO}$ values. It might be said that their general application can not yet be warranted for this class of substituents. However, we might conclude that the contribution scale of the $-R$ resonance in this system does not differ much from the scale in standard σ^0 constant; at most, less than that of the σ_p scale.12)

Comparison with Related Treatment. From the above results, the hydroxyl chemical shifts of *para*-substituted derivatives in DMSO can be given by

$$\Delta\delta_p = 1.529[(\sigma_i)_{\rm DMSO} + (\sigma_\pi{}^+)_{\rm DMSO} + 1.96(\sigma_\pi{}^-)_{\rm DMSO}] \tag{6}$$

The second term applies to the $-R$ class and the third to $+R$ class substituents.13) The use of the standard substituent constants in place of the DMSO values does not appear to affect the characteristics of the correlation at least for the $+R$ groups even though the precision of fit would be a little lowered. The higher $q_r{}^-$ value evidently indicates the important contribution from only $+R$ class *para* substituents in this system, while the $q_r{}^- = 1.96$ is less than the $q_r{}^-$ value $= 2.37$ for the pK_a of phenols in water, suggesting that the resonance contribution of *para* $+R$ substituents to the hydroxyl hydrogen-bonding is less important than that to the dissociation of the hydroxyl proton.

Fischer *et al.*14) have applied the Taft equation

$$\log (k/k_0) = \rho_I\sigma_I + \rho_R\sigma_R{}^0 \tag{7}$$

for sixteen *para* substituents in Traynham's data15) to give the correlation

$$\Delta\delta_p = 1.53(\sigma_I + 1.54\sigma_R{}^0).$$

Although no detail of the treatment was given, it appears that the exaltation of resonance for $+R$ groups suggested by the $\rho_R/\rho_I = 1.54$ is significantly less than that expected from $q_r{}^- = 1.96$, since $\sigma_R{}^0$ values for the $+R$ groups are numerically of the order of 1/2 or less of the corresponding $\sigma_\pi{}^-$ values.16) It should be noted that this treatment appears similar to but stands on a considerably different basis from ours. As the wide applicability of Eq. (1) indicates,[2] the general σ^+ class electrophilic reactivity is such that only the resonance effect of $-R$ but not of $+R$ class substituents is significantly exalted, and the reverse is held in the general σ^- class nucleophilic resonance reactivities. Such characteristics of exalted resonance for both classes are still retained in Eq. (2) with the introduction of dual parameters q_r^- and q_r^+ each for $+R$ and $-R$ class substituents. With this flexibility of π-electronic contributions, a full range of various types of reactivities from an extreme σ^+ class to the other extreme σ^- class can generally be treated by a single equation (2).[4,6a]

Apart from the question of fit, treatment with a single resonance reaction constant inevitably gives an indiscriminate change (parallel increase or decrease) in the resonance contributions from both $+R$ and $-R$ class *para* substituents in a given reaction. In the Taft treatment using a single ρ_R coefficient for both $-R$ and $+R$ groups, no combinations of σ_I and $\sigma_R{}^0$ can reproduce even Brown's σ^+ constants or σ^- constants where either the $-R$ or the $+R$ class substituents exerts the exalted resonance contribution. The results of Fischer *et al.*[14] do not offer any indication whether the system is of the σ^- or σ^+ type. The same criticism applies also to the Swain and Lupton equation,[7] log k/k_0=fF+rR, which in principle does not differ from Eq. (7). From a slightly different view, Wiley and Miller[17] have questioned the significance of the Swain and Lupton f, r or % R values.

Although many correlations using Eq. (7) as well as the related equations with the single resonance coefficient have been reported for σ^+ or σ^- type reactivities, in most cases, the numbers of $-R$ and $+R$ substituents examined were not well balanced, so that the correlations obtained should be judged as those weighted more or less heavily on the effect of either $+R$ or $-R$ substituents. The correlations can be generally improved by excluding either $+R$ or $-R$ class substituents from the data set. Swain and Lupton gave[7] a satisfactory correlation for $\sigma_p{}^-$ values with reasonable precision in terms of the F–R combination or the equation, log k/k_0= $a\sigma_m+b\sigma_p$, while a few effective $-R$ groups were included in their calculation. For the same set of data, an excellent correlation can be obtained when the treatment is made only for $+R$ substituent groups; the latter treatment of the $\sigma_p{}^-$ values for only $+R$ substituents gives a correlation, $\sigma_p{}^-=-0.13\sigma_m+3.44\sigma_p-0.011$, with remarkably improved precision of a correlation coefficient 0.996 and a standard deviation ±0.027.[18] The same is true for the correlation of $\sigma_p{}^+$ values for only the $-R$ substituents.[19] The results cast doubts upon the applicability of the single resonance coefficient treatments. It appears that the different ρ_R coefficients which are characteristic of reactions should be required for the effects of each $+R$ and $-R$ class substituents in exalted resonance type reactions as long as the resonance parameters $\sigma_R{}^0$ derived from the σ^0-reactivity are used. For such restrictions, Taft has noted[6c] that Eq. (7) with a single ρ_R (in terms of σ_I and $\sigma_R{}^0$) should be applied as a useful approximation to a limited class of substituted phenyl reactivities effectively insulated from the resonance interaction with the reaction site, and that apparent resonance parameters $\bar{\sigma}_R$ given by the difference between apparent $\bar{\sigma}_p$ and corresponding σ_I is applicable for most of substituents in only closely related types of reactions.[6] It is necessary for this treatment to utilize a most suitable set of apparent $\bar{\sigma}_R$ values for a given reaction, since any set of $\bar{\sigma}_R$ values does not cover evenly over a series of $+R$ and $-R$ substituents.[3,6,18] Consequently, the increase in the number of required sets of σ_R parameters is inevitable when a single ρ_R is employed.[20] Taft has demonstrated[6a] that at least four distinctive sets of $\bar{\sigma}_R$ parameters are required in practice for his treatment, depending on the σ^0, σ, σ^+, and $\bar{\sigma}^-$ type of reactivity. This is clearly not in line with Taft's original aim to accomplish an unified treatment of the aromatic substituent effect, retaining the simplicity of the linear free energy relationship. This very important deficiency is believed to arise primarily from an improper definition of the effective scale of the substituent inductive effect in the substituted benzene system. As relationship (2) shows, only with the assumption of the inductive scale for the *p*-substituted benzene system being 0.74 σ_I instead of 1.00 σ_I, a universal set of π-electronic effect parameters can be obtained by $\bar{\sigma}-0.74\sigma_I$ from any class of reactivity.[3,4] Disagreement between both treatments appears to depend simply upon whether or not one might accept the continuum of the π-electronic contribution of respective substituents over a wide spectra of the reactivity changes from an extreme σ^+ to the other extreme σ^- classes, as well as the existence of a set of π-electronic parameters of substituents independent of reactivity classes.

Nevertheless, a separate determination of both q_r^+ and q_r^- parameters is not convenient, and the single q_r treatment has a practical advantage over the dual q_r treatment, especially when the number of substituents in a given data set is limited. From a practical point of view, the employment of a Taft-type equation only with a proper set of resonance parameters might be acceptable as a useful approximation. According to Eq. (2), any particular scale of the π-electronic effects over a range from extremely electron-releasing to -attracting substituents can reasonably be given for any class of $\bar{\sigma}_p$'s, by setting a proper ratio of q_r^- to q_r^+ values. Thus, the LSFE equation with dual q_r values can be easily reduced to the equation with a single q_r coefficient,[21] although the range of validity of such treatment with a fixed q_r^+/q_r^- ratio may be limited to a similar extent as that of the Taft equation.

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