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Effect of the Twisted Nitro Group on Gas Phase Acidities of Phenol, Toluene, Aniline, and Benzoic Acid. Steric Inhibition of Intrinsic Resonance Effect

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Gas phase acidities have been determined for 3,5-dimethyl-4-substituted phenols, toluenes, anilines, and benzoic acids. The reduced effect of the 4-nitro group on acidity was observed for all series compared with that in the unhindered system, being attributed to steric inhibition of resonance effect. From this result a dihedral angle between the benzene ring and the nitro group was estimated to be 38±2° for these acids.

Steric inhibition of resonance effect is a well-studied phenomenon and can be manifested by remarkable changes in UV spectrum, molecular refraction, basic or acidic strength, and rate of reaction.[1-3] These data were served as evidence for verifying the separation of resonance effect and inductive effect contributions involved in the substituent effect on their physical properties.[4, 5] Recently, it has been suggested that resonance effect of π-acceptor in the electron-rich system, σ^- type reaction, is reduced significantly in gas-phase compared with that in solution, in contrast to resonance effect of π-donor in the electron-deficient system, σ^+ type reaction.[6, 7] Since the exalted resonance effect of π-acceptor in solution must be attributed to solvent effects in principle, Taft et al. termed it the specific substituent solvation assisted resonance effect, SSSAR effect.[8, 9] These facts force us to re-examine steric inhibition of resonance effect of π-acceptor because the observed decrease in reactivity in solution must include not only the steric effect on the intrinsic resonance effect and but also that on the SSSAR effect. For this purpose, it will be useful to elucidate the effect of sterically twisted substituent on the gas phase acidity which is absolutely free from the SSSAR effect. Our attention has been focused on the resonance effect of the nitro group as a typical π-acceptor substituent because the nitro group is well-known to be twisted by the introduction of two methyl groups in position ortho to the nitro group,[10] resulting in steric inhibition of resonance effect, and because the nitro group is one of substituents having the largest SSSAR effect.[7] In this study gas phase acidities have been determined for 3,5-dimethyl-4-substituted phenols, anilines, and toluenes. Similar acidities have been also determined for the corresponding benzoic acids as a reference system of which the substituent effect is classified as an unexalted σ^0 system.[11, 12]

The gas phase acidities were obtained by measuring equilibrium constants for the proton transfer reactions (4) using the homemade pulsed ion cyclotron resonance spectrometer.[13] Methyl nitrite was used as a reagent

$$CH_3ONO + e^- \longrightarrow CH_3O^- + NO \quad (1)$$

$$CH_3O^- + AH \longrightarrow A^- + CH_3OH \quad (2)$$

$$CH_3O^- + BH \longrightarrow B^- + CH_3OH \quad (3)$$

$$A^- + BH \rightleftharpoons B^- + AH \quad (4)$$

Table 1. Relative Gas Phase Acidities of 3,5-Dimethyl-4-substituted Phenols, Anilines, Toluenes, and Benzoic Acids

	Relative gas phase acidities / kcal mol^{-1} [a]							
	Phenol		Benzoic acid		Aniline		Toluene	
Subst.	3,5-Me_2[b]	H_2[c]	3,5-Me_2[b]	H_2[c]	3,5-Me_2[b]	H_2[c]	3,5-Me_2[b]	H_2[c]
NO_2	16.5	20.9	9.9	11.7[d]	17.0	21.2	18.5	24.7
CN	15.8	16.6	9.1	9.8[e]	16.6	16.0	16.0	16.7
Cl	6.1	5.8	4.3	4.4[f]				
H[g]	(27.4)	(27.7)	(36.0)	(36.7)	(11.8)	(12.5)	(-0.6)	(0.0)

a) Positive values denote greater acidities, 1 cal = 4.184 J. b) 3,5-Dimethyl-4-substituted derivatives. c) 4-Substi-tuted derivatives, taken from Ref. 12 unless otherwise noted. d) Ref. 14. e) Revised in this work. f) Ref. 11. g) Values in parentheses denote acidities relative to that of toluene. Absolute acidity of toluene is 372.3 kcal mol^{-1}, Ref. 9.

gas for the generation of methoxy anion which abstracts proton from aromatic acids. Experimental conditions used for the present ICR study are the same as those described by McIver et al.[8, 15] The gas phase acidities of these acids relative to those of respective parent acids (ring substituent = H) are listed in Table 1. The effect of the 4-nitro group on the acidity of 3,5-Me_2 phenol is found to be reduced significantly compared with that of the untwisted phenol. On the other hand, the effects of the 4-cyano and 4-chloro groups are essentially the same in both systems, indicating that the response of the acidity to aryl substituent polarity is not influenced by the introduction of the di-o-methyl group. The weakened acidity of 3,5-dimethyl-4-nitrophenol can therefore be attributed to steric inhibition of resonance effect caused by twisting out of the coplanarity with the benzene ring. A similar decrease in effect of the nitro group was observed for the 3,5-dimethylaniline series. The toluene series showed the largest decrease of 6.2 kcal mol^{-1}, while that in the benzoic acid is only 1.8 kcal mol^{-1}. Such change of the effect of the twisted nitro group with the system appears to be indicative of varying resonance contribution involved in substituent effects of respective systems. Indeed, the smallest effect observed for the benzoic acid system is consistent with the fact that the gas phase acidities of benzoic acids can be correlated with unexalted σ^0 substituent constants.[11, 12]

The correlation analysis of the substituent effects of the unhindered systems based on our LSFE Eq. 5 [16, 17] or Taft DSP Eq. 6[12] makes it possible to separate an overall effect of a substituent to the resonance and

$$\delta\Delta G^\circ = \rho_i \sigma_i + \rho_\pi^\pm \sigma_\pi^\pm \qquad (5)$$

$$\delta\Delta G^\circ = \rho_I \sigma_I + \rho_R \sigma_R \qquad (6)$$

inductive contributions. The resonance contribution can be given by $\rho_\pi^\pm\sigma_\pi^\pm$ or $\rho_R\sigma_R$. Correlation parameters and the calculated resonance contribution of the nitro group are listed in Table 2. The extent of steric inhibition of resonance effect is generally related to the degree of twisting out of the coplanarity of the nitro group with the benzene π-ring by a following equation,[18]

$$R/R_{max} = \cos^2\theta \qquad (7)$$

Table 2. Correlation Results of LSFE Eq. and DSP Eq. for Gas Phase Acidities and Resonance Effect Contribution of the Nitro Group to Acidities

Acidity system	ΔR a)	ρ_i b)	$\rho_{\bar{\pi}}$ b)	R_{max} c)	θ d)	ρ_I e)	ρ_R e)	R_{max} f)	θ d)
Phenol	4.4	18.9	34.7	11.5	38°	19.1	47.8	8.6	45°
Aniline	4.2	16.5	38.9	12.9	35°	17.8	52.8	9.5	42°
Toluene	6.2	17.3	44.4	14.7	40°	17.7	69.1	12.4	45°
Benzoic acid	1.9	15.0	15.0	5.0	38°	15.0 g)	14.6 g)	0.0 g)	—

a) $\Delta R = \delta\Delta G^o(\text{unhind.}) - \delta\Delta G^o(\text{hind.})$ for the nitro group, in kcal mol^{-1}. b) Calculated in this study using data available in the literature, Refs. 11, 12, and 14. c) Resonance contribution calculated by $\rho_{\bar{\pi}}\sigma_{\bar{\pi}}$ where $\sigma_{\bar{\pi}}$ for NO_2 is 0.332. d) Dihedral angle calculated according to Eq. 7. e) Taken from Ref. 12. f) Resonance contribution calculated by $\rho_R\sigma_R$ where σ_R for NO_2 is 0.18. g) σ_R^+ is used for the correlation, Ref. 12.

where R_{max} and R are the resonance contributions of the coplanar nitro group and the twisted nitro group, respectively, and θ is a dihedral angle between the benzene ring and the nitro group. Since it is reasonable to assume that the inductive effect contribution is not influenced by the di-o-methyl group as seen in the effects of the cyano and chloro groups, R is given by $R_{max} - \Delta R$, where ΔR is the difference between $\delta\Delta G^o$ values of the coplanar nitro group and the twisted one. Substitution of R=3.1 kcal mol^{-1} and R_{max}=5.0 kcal mol^{-1} for benzoic acid into Eq. 7 provides a dihedral angle θ of 38°. Similarly the dihedral angles for phenol, aniline, and toluene systems can be calculated. Table 2 indicates that the dihedral angle θ is nearly constant within a narrow range of 35° to 40° for all series, suggesting that the degree of twisting out is independent of electron-richness of the aromatic ring. The θ values derived from the Taft DSP correlations seem to be somewhat larger than the corresponding values obtained from the LSFE analysis. It should be noted that the DSP correlation reveals no resonance contribution to the acidity of p-π-acceptor substituted benzoic acids because the σ_R^+ values used for the correlation are assumed to be zero for all π-acceptors.12) Nevertheless, the effect of the twisted nitro group is observed to be smaller by 1.9 kcal mol^{-1} than that of the coplanar one, indicating that the nitro group has significant resonance effect to strengthen the acidity of benzoic acid. A similar result has been observed for the gas phase basicity of 3,5-dimethyl-4-nitrobenzaldehyde.19) Thus, the assumption that σ_R^+ value is zero for all π-acceptors appears to be oversimplified for describing the substituent effect of gas phase acidities of benzoic acids.

It is instructive to compare the present result in the gas phase with the corresponding results in aqueous solution although available data are limited only for phenol and benzoic acid systems. The substituent effect on acidity of benzoic acid is assumed to involve no SSSAR effect because a relatively good linear relationship is observed for relative acidities of π-acceptors between in gas phase and in solution.11, 14) The effect of twisting of the nitro group on the acidity of benzoic acid in aqueous solution would therefore be attributed simply to the steric inhibition of resonance effect of the nitro group in the same manner as that in gas phase acidity. The apparent $\bar{\sigma}$ value for the twisted nitro group can be estimated to be 0.66 using pKa values of 3,5-dimethyl-4-substituted benzoic acids obtained in aqueous 50% ethanol.4, 20) The apparent resonance substituent constant, $\bar{\sigma}_\pi$, of 0.20 is therefore given for the twisted nitro group by $\bar{\sigma}_\pi = \bar{\sigma} - \sigma_i$. Since the ratio of $\bar{\sigma}_\pi/\sigma_\pi$ (=0.60) corresponds to R/R_{max} in Eq. 2, a dihedral angle θ of 39° is obtained. The dihedral angle in solution is in good agreement with that obtained in gas phase, indicating no solvation effect on the twisting out of the nitro group. We now consider the substituent effect of phenol acidities in solution to which the SSSAR effect contributes significantly.$^{8)}$ The observed effect of twisting of the nitro group on acidity of phenol (ΔR) is 1.23 kcal mol^{-1} in water.$^{5)}$ Since the resonance contribution to the acidity of p-nitrophenol in water is estimated to be 2.37 kcal mol^{-1} (=R_{max}) by $\rho_{\bar{\pi}}\sigma_{\bar{\pi}}$ of the LSFE analysis, where $\rho_{\bar{\pi}} = 7.15$ and $\sigma_{\bar{\pi}} = 0.332$, the resonance contribution of the twisted nitro group can be estimated to be 1.14 kcal mol^{-1} from $R_{max} - \Delta R$. If the intrinsic resonance and SSSAR effects are affected equally by twisting out of the nitro group, the ratio ($R/R_{max} = 0.48$) of resonance effect of the twisted nitro group to the corresponding coplanar one leads to a dihedral angle θ of 46° according to Eq. 7. The angle of 46° is clearly larger than that obtained from gas-phase acidities where there is no SSSAR effect contribution, suggesting that the SSSAR effect is diminished by twisting out of the nitro group more seriously than the intrinsic resonance effect because a dihedral angle θ in water is inferred to be identical to that in gas-phase from the observation for benzoic acid noted above. This may be caused by the substituent-solvent interaction weakened by steric hindrance. Thus, it is necessary to evaluate the SSSAR effect involved in substituent effects in solution when the extent of the twisting out of the substituent from the benzene ring plane is discussed on the basis of data in solution.

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References

1) B. M. Wepster, *Prog. Stereochem.*, **2**, 99 (1958).
2) M. J. S. Dewar and Y. Takeuchi, *J. Am. Chem. Soc.*, **89**, 390 (1967).
3) W. Kitching, I. de Jong, W. Adcock, and A. N. Abeywickrema, *Org. Magn. Reson.*, **14**, 502 (1980).
4) J. P. Schaefer and T. J. Miraglia, *J. Am. Chem. Soc.*, **86**, 64 (1964).
5) G. W. Wheland, R. M. Brownell, and E. C. Mayo, *J. Am. Chem. Soc.*, **70**, 2492 (1948).
6) R. W. Taft, J. L. M. Abboud, F. Anvia, M. Berthelot, M. Fujio, J.-F. Gal, A. D. Headley, W. G. Henderson, I. Koppel, J. H. Qian, M. Mishima, M. Taagepera, and S. Ueji, *J. Am. Chem. Soc.*, **110**, 1797 (1988).
7) M. Mishima, R. T. McIver Jr., R. W. Taft, F. G. Bordwell, and W. N. Olmstead, *J. Am. Chem. Soc.*, **106**, 2717 (1984).
8) M. Fujio, R. T. McIver Jr., and R. W. Taft, *J. Am. Chem. Soc.*, **103**, 4017 (1981).
9) R. W. Taft, *Prog. Phys. Org. Chem.*, **14**, 247 (1983).
10) J. Trotter, *Can. J. Chem.*, **37**, 1487 (1959).
11) T. B. McMahon and P. Kebarle, *J. Am. Chem. Soc.*, **99**, 2222 (1977).
12) R. W. Taft and R. D. Topsom, *Prog. Phys. Org. Chem.*, **16**, 1 (1987).
13) M. Mishima, M. Fujio, and Y. Tsuno, *Mem. Fac. Sci., Kyushu Univ., Ser. C*, **15(1)**, 365 (1984).
14) I. A. Koppel, M. Mishima, L. M. Stock, R. W. Taft, and R. D. Topsom, *J. Phys. Org. Chem.*, in press.
15) J. E. Bartmess, J. A. Scott, and R. T. McIver Jr., *J. Am. Chem. Soc.*, **101**, 6046 (1979).
16) Y. Yukawa and Y. Tsuno, *Memoirs ISIR, Osaka Univ.*, **23**, 71 (1966).
17) Y. Tsuno, M. Fujio, and Y. Yukawa, *Bull. Chem. Soc. Jpn.*, **48**, 3324 (1975).
18) P. B. D. de la Mare, E. A. Johnson, and J. S. Lomas, *J. Chem. Soc.*, **1964**, 5317.
19) Gas phase basicity of 3,5-dimethyl-4-nitrobenzaldehyde relative to that of 3,5-dimethylbenzaldehyde is 7.5 kcal mol^{-1} while the corresponding relative basicity is 8.7 kcal mol^{-1} for p-nitrobenzaldehyde; M. Mishima, M. Fujio, and Y. Tsuno, unpublished result.
20) The apparent $\bar{\sigma}$ of 0.66 was obtained using a ρ of -1.50 determined from ΔpKa values of p-NH_2, p-OH, p-Cl, p-Br, and p-CN in Ref. 4.

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