$$k_{obsd} = \frac{k_{H^+}^3 \left(\dfrac{K_R^2}{K_R^2 + K_R^1} \right)[H^+] + k_0^3 \left(\dfrac{K_R^2}{K_R^2 + K_R^1} \right)}{1 + \dfrac{[H^+]}{K_R^2 \left(\dfrac{K_R^2}{K_R^2 + K_R^1} \right)}}$$

(14)

Equation 14 refers to low pH and is based on the assumption that the third stage is the slow stage in product formation, and both the first stage and the second stage are reversible equilibria preceding it. These two equations reduce to the equations previously discussed, $k_{obsd} = k_{H^+}^1[H^+]$ and eq 4, when $k_0^2 \gg k_0^{-1}$.[17] In their present

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(17) For reduction of eq 14 to eq 9 the condition actually is $K_R^2 \gg K_R^1$ or $k_0^2/k^{-2}_{H^+} \gg k_0^{-1}/k^1_{H^+}$. Unless there is something highly unusual in $k_{H^+}^{-2}$ or $k_{H^+}^1$, this condition is met whenever $k_0^2 \gg k_0^{-1}$.

form, however, eq 5 and 6 also satisfy the observed kinetic data, the only requirement for their derivation being that $k_{H^+}^1 > k_{H^+}^3$ (and $k_{H^+}^{-2} > k_{H^+}^3$).

Registry No. 1, 76109-82-5; 2, 76109-83-6; 3, 72320-30-0; 4, 76109-84-7; 5, 76109-85-8; 6, 70637-00-2; 7, 76109-86-9; 8 tetrafluoroborate, 76109-88-1; *cis*-9, 76109-89-2; *trans*-9, 76109-90-5; 10, 66475-66-9; 11, 62977-15-5; trimethyl orthobenzoate, 707-07-3; 1,3-propanediol, 504-63-2; 2,2-dimethyl-1,3-propanediol, 126-30-7; 2,4-dimethyl-2,4-pentanediol, 24892-49-7; benzaldehyde, 100-52-7; 1,1,1-tris(hydroxymethyl)ethane, 77-85-0; *N,N*-dimethylbenzamide dimethyl acetal, 35452-04-1.

Supplementary Material Available: Table S1 of rate constants (4 pages). Ordering information is given on any current masthead page.

Analysis of the Acidities of 3- and 4-Substituted Pyridinium and Anilinium Ions[1]

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An analysis has been carried out of the gas- and aqueous-phase acidities of meta- and para-substituted pyridinium and anilinium ions by using substituent parameter treatments and ab initio molecular orbital theory calculations at the STO-3G level of approximation. The following conclusions are indicated. (1) Field/inductive effects (*F*) of strongly electron-attracting dipolar substituents are the major factor in the strongly enhanced acidities. Thus, for example, resonance stabilization of *p*-nitroaniline is only a relatively minor contributor to the greatly increased gas-phase acidity of *p*-nitroanilinium compared to anilinium ion. (2) Resonance effects of +R substituents in general are small or negligible for pyridinium ion acidities in aqueous solution and are small and perhaps reversed in the gas phase. (3) Strong π-donor (−R) substituents do contribute large acid-weakening resonance effects particularly to pyridinium ion acidities. (4) In the gas phase, there is a leveling in the π-donor effects of the strongest −R substituents, e.g., N(CH₃)₂. (5) The ratio of R effects at the meta relative to the corresponding para position (i.e., $\alpha = R^m/R^p$) are substantially greater in the gas phase than in aqueous solution. (6) *F* effects correlate well with the σ_I substituent parameters. (7) Hydrogen bond acceptor substituents, e.g., N(CH₃)₂ or CH₃CO, are found to have more positive σ_I values in aqueous solution than in the gas phase. (8) The acidities of para-substituted anilinium ions are found to be unsuitable for the definition of inherent σ_p^- or σ_R^- parameters. (9) Polarizability effects of meta and para substituents containing electronegative atoms and no large alkyl or aryl groups are found to be small or negligible in the gas-phase acidities.

There is currently substantial interest and controversy in the interpretation of the effects of 3- and 4-substituents on the acidities of pyridinium ions.[5] We report in this

paper an analysis based upon theoretical and experimental data for the effects of 3- and 4-substituents on the acidities of both pyridinium ions and another common NH⁺ system, anilinium ions. Ab initio molecular orbital theory calculations at the STO-3G level of approximation and gas-phase ion cyclotron resonance spectroscopic data are utilized. Through critical analysis of suitable comparisons of theoretical results with experimental results in both the gas phase and in aqueous solution, new evidence and insights are provided.

Both the anilinium ion and pyridinium acidities in aqueous solution have been previously considered in terms of the Hammett equation.[6] For select 3-substituents, the $\sigma_m \rho$ relationship is found to hold with relatively high precision. However, for 4-substituents the two series have come to be regarded as of opposite types in their resonance effects. Para-substituted anilinium ion acidities were used

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(5) (a) J. M. Essery and K. Schofield, *J. Chem. Soc.*, 2225 (1963); (b) A. Fischer, W. J. Galloway, and J. Vaughan, *ibid.*, 3591, 3596 (1964); (c) G. B. Ellam and C. D. Johnson, *J. Org. Chem.*, **36**, 2284 (1971); (d) R. T. C. Brownlee and R. D. Topsom, *Tetrahedron Lett.*, 5187 (1972); (e) S. Ehrenson, R. T. C. Brownlee, and R. W. Taft, *Prog. Phys. Org. Chem.*, **10**, 1 (1973); (f) C. A. Grob and R. W. Taft, *J. Am. Chem. Soc.*, **96**, 1236 (1974); (g) C. D. Johnson, I. Roberts, and P. G. Taylor, *J. Chem. Soc., Chem. Commun.*, 897 (1977); (h) E. M. Arnett, B. Chawla, L. Bell, M. Taagepera, W. J. Hehre, and R. W. Taft, *J. Am. Chem. Soc.*, **99**, 5729 (1977); (i) M. Charton, *J. Org. Chem.*, **44**, 2097 (1979); (j) D. H. Aue and M. T. Bowers in "Gas-phase Ion Chemistry", M. T. Bowers, Ed., Academic Press, New York, 1979; (k) W. R. Davidson, J. Sunner, and P. Kebarle, *J. Am. Chem. Soc.*, **101**, 1675 (1979); (l) M. Sawada, M. Ichigara, Y. Yukawa, T. Nakachi, and Y. Tsuno, *Bull. Chem. Soc. Jpn.*, **53**, 2055 (1980).

(6) H. H. Jaffé, *Chem. Rev.*, **53**, 191 (1953).

by Hammett[7] to define σ_p^- values because of enhanced resonance effects presumably associated with π electron acceptor (+R) substituents and their stabilizing interactions in the neutral anilines (I). Indeed, this point of view
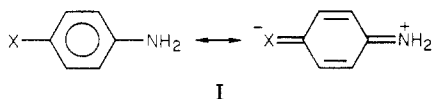
I

has been so commonly accepted[8] that the relatively high acidity of *p*-nitroanilinium ion is frequently erroneously (as we will show) attributed to this cause. On the other hand, most workers have accepted the view that the para-substituted pyridinium ion acidities are of the σ_p^+ (or σ_p) type because of enhanced resonance effects associated with π-electron donor (-R) substituents and their stabilizing interactions in these ions[5] (II). Since conjugation

II

of this kind is less important than that involved with a para electron-deficient side chain (e.g., the *tert*-cumyl cation), there has been controversy in establishing the most appropriate single-substituent parameter type. However, the use of dual-substituent parameter treatments[5e,i,l] has led to accord that there are enhanced resonance effects of -R substituents from the 4-position which reduce aqueous pyridinium ion acidities.

There has also remained the question of the importance (if any) of π-electron withdrawing effects of +R substituents on the acidities of pyridinium ions. Fischer et al.[5b] reported that in aqueous solution the resonance effects of such substituents were negligible, since the effects of all +R substituents on acidity are well correlated by σ_I values alone. Subsequent analyses[5d–f,i] have ignored these results, as Johnson has pointed out.[5g] The LSFE dual substituent parameter treatment of Yukawa and Tsuno[9] indicates specifically that reduced aqueous resonance effects are involved in +R substituents in pyridinium ion.[5l] However, the magnitudes of the resonance effects indicated by the DSP equation for +R substituents are even smaller than those obtained by the LSFE treatment (cf. subsequent discussion). There are grounds to reject (as we shall discuss) the estimated resonance effects of +R substituents in pyridinium ion acidities obtained by either method. The effects of meta and para substituents on the aqueous acidities of anilinium ions are not indicated to be appreciably better described by the DSP than the $\sigma\rho$ equation.[5e]

Both pyridinium[5h,j,10] and anilinium ion[10,11] acidities have been determined in the gas phase, the former more extensively than the latter (due to certain experimental difficulties). Although it has been proposed that significant polarizability effects are generally involved with 3- and 4-substituents in the gas-phase pyridinium acidities,[5j] our analysis indicates that only for very polarizable substituents such as alkyl groups are these effects significant. With

anilines bearing π-donor (-R) substituents in the 3-position, evidence has been presented[11] that protonation in the gas phase occurs most favorably at carbon (substituted benzenium ion formation) rather than at nitrogen (meta-substituted anilinium formation). Nevertheless, barring the latter cases, roughly linear relationships (of similar slope) have been reported between corresponding substituent effects in the gas phase and in aqueous solution for both pyridinium ion[5h,12] and anilinium ion acidities.[11] We examine these relationships more critically in this paper, as well as the evidence that substituents interact much more strongly in the cationic state than in the neutral base state for these proton-transfer equilibria.

Experimental and Theoretical Procedures

The gas-phase basicities of 3- and 4-substituted pyridines and anilines have been determined by the pulsed ion cyclotron resonance equilibrium constant method, as previously described.[13] The multiple overlapping stair-step determinations used to establish most of the $\delta\Delta G°_g$ values have been given in Figure 1 of ref 10. The results given in this figure have been slightly revised on the basis of additional results and a temperature correction which has been shown to be applicable.[13d] The latter increases the previously reported $\Delta\Delta G°_g$ values by a factor of 1.067. The overlaps used to obtain the $\delta\Delta G°_g$ values for substituted pyridines and anilines which are not shown in Figure 1 of ref 10 are recorded in Table Ia.

A full report[14] of gas-phase basicities which are greater than that of NH_3 gives the detailed multiple overlaps which have been employed to obtain the basicities of the standard bases of Table IA. The relative gas-phase basicities of 3- and 4-substituted pyridines relative to pyridine, $\delta\Delta G°_g$ (cf. Table IV), are in generally satisfactory accord (average deviation ±0.8 kcal/mol for the total range of 28.3 kcal/mol) with those reported in ref 5j. Since our $\delta\Delta G°_g$ values are based upon multiple overlaps over this entire range and have a precision of ±0.2 kcal/mol, we have utilized these values in the present analysis.

Methods of Calculation

Standard ab initio molecular orbital calculations were carried out at the STO-3G level[15a] by using the Gaussian-77 series of computer programs.[15b] Standard model geometries[15c] were used for all substrates with the exception of OCH_3 and NH_2. For OCH_3, $\angle COC = 118.0°$ was used to minimize steric interactions with the ring.[15d] For NH_2, the three angles about N were assumed equal and were optimized. A C–N bond length of 1.52 Å was utilized in substituted anilinium ions. This value was obtained through optimization of the C–N bond in the unsubstituted anilinium ion. The calculated total energies for the substituted anilines and anilinium ions are reported elsewhere.[15e]

The aromatic bonds lengths were optimized in pyridine and pyridinium ion by keeping the angles at 120° (pyri-

(7) L. P. Hammett, "Physical Organic Chemistry", McGraw-Hill, New York, 1940, Chapter VII.

(8) For example, cf. J. March, "Advanced Organic Chemistry", 2nd ed., McGraw-Hill, New York, 1977, p 241; A. Streitwieser and C. Heathcock, "Introduction to Organic Chemistry", MacMillan, New York, 1976, p 968.

(9) (a) Y. Yukawa and Y. Tsuno, *Nippon Kagaku Zasshi*, 86, 873 (1965); *Mem. Inst. Sci. Ind. Res., Osaka Univ.*, 23, 71 (1966); (b) Y. Tsuno, M. Fujio, and Y. Yakawa, *Bull. Chem. Soc. Jpn.*, 48, 3324 (1975).

(10) R. W. Taft in "Proton Transfer Reactions", E. F. Caldin and V. Gold, Eds., Chapmand and Hall, London, 1975, Chapter 2.

(11) K. D. Summerhays, S. K. Pollack, R. W. Taft, and W. J. Hehre, *J. Am. Chem. Soc.*, 99, 4585 (1977).

(12) D. H. Aue, H. M. Webb, M. T. Bowers, C. L. Liotta, C. J. Alexander, and H. D. Hopkins, Jr., *J. Am. Chem. Soc.*, 98, 854 (1976).

(13) (a) M. T. Bowers, D. H. Aue, H. M. Webb, and R. T. McIver, Jr., *J. Am. Chem. Soc.*, 93, 4313 (1971). (b) J. F. Wolf, R. G. Staley, I. Koppel, M. Taagepera, R. T. McIver, Jr., J. L. Beauchamp, and R. W. Taft, *ibid.*, 99, 5417 (1977). (c) J. E. Bartmess, J. A. Scott, and R. T. McIver, Jr., *ibid.*, 101, 6046 (1979). (d) The temperature correction established in ref 13c has also been shown by Dr. J. Bromilow to apply to the spectrometer used in the studies of ref. 13b, and the results given herein have been appropriately corrected by the factor 1.067.

(14) M. Taagepera, W. G. Henderson, J. F. Wolf, K. D. Summerhays, P. Gately, J. Echols, J.-L. M. Abboud, R. H. Staley, J. L. Beauchamp, and R. W. Taft, to be submitted for publication.

(15) (a) W. J. Hehre, R. F. Stewart, and J. A. Pople, *J. Chem. Phys.*, 51, 2657 (1967); (b) D. J. DeFrees, B. A. Levi, S. K. Pollack, R. F. Hoit, N. Blurock, W. J. Pietro, and W. J. Hehre, to be submitted for publication in the Quantum Chemistry Program Exchange; (c) J. A. Pople and M. S. Gordon, *J. Am. Chem. Soc.*, 89, 4253 (1967); (d) W. J. Hehre, L. Radom, and J. A. Pople, *ibid.*, 94, 1496 (1972); (e) A. Pross and L. Radom, *Prog. Phys. Org. Chem.*, 13, 1 (1980).

Table I

A. Overlaps Used To Obtain $\delta_\Delta G^\circ_g$ Values Given in Table IV

	standard base	$\delta_\Delta G^\circ$, kcal/mol[a]
	Substituted Pyridine	
4-N(CH$_3$)$_2$	[CH$_2$N(CH$_3$)$_2$]$_2$	+ 0.3
4-N(CH$_3$)$_2$	i-Pr$_2$(C$_2$H$_5$)N	+ 1.3
3-N(CH$_3$)$_2$	i-Pr$_2$NH	+ 0.8[b]
3-N(CH$_3$)$_2$	n-Pr$_2$NH	+ 2.6[b]
3-OCH$_3$	4-CH$_3$C$_5$H$_4$N	− 1.0
4-CO$_2$CH$_3$	neo-C$_5$H$_{11}$NH$_2$	− 0.5
3-CO$_2$CH$_3$	neo-C$_5$H$_{11}$NH$_2$	− 1.0
4-CH$_3$CO	n-C$_4$H$_9$NH$_2$	− 0.8
4-CH$_3$CO	CF$_3$CH$_2$N(CH$_3$)$_2$	+ 2.1
3-CH$_3$CO	4-FC$_5$H$_4$N	+ 0.2
3-F	2-ClC$_5$H$_4$N	− 0.3
	Substituted Aniline	
p-OCH$_3$	CF$_3$(CH$_2$)$_3$NH$_2$	0.0
p-OCH$_3$	p-CH$_3$C$_6$H$_4$NH$_2$	− 0.7
p-CH$_3$	3-CF$_3$C$_5$H$_4$N	+ 1.0
p-CH$_3$	4-CF$_3$C$_5$H$_4$N	+ 0.6
m-Cl	p-FC$_6$H$_4$NH$_2$	− 0.5
m-Cl	m-FC$_6$H$_4$NH$_2$	+ 0.4
m-F	F$_2$CHCH$_2$NH$_2$	− 0.5

B. Calculated Total Energies (STO-3G, hartrees) for Substituted Pyridines, Pyridinium Ions, Anilines, and Anilinium Ions

X	pyridine (XC$_5$H$_4$N)	pyridinium ion (XC$_5$H$_4$NH$^+$)	aniline (XC$_6$H$_4$NH$_2$)	anilinium ion (XC$_6$H$_4$NH$_3^+$)
H	−243.633 65	−244.076 37	−282.208 92	−282.634 03
3-CH$_3$	−282.217 06	−282.663 83	−320.792 98	−321.220 20
4-CH$_3$	−282.218 39	−282.669 13	−320.791 96	−321.221 05
3-NH$_2$	−297.948 35	−298.396 57	−336.529 10	−336.956 07
4-NH$_2$	−297.949 74	−298.418 12	−336.525 19	−336.960 05
3-OCH$_3$	−365.047 88[c]	−356.490 20[c]	−394.624 22	−395.050 23
4-OCH$_3$	−356.048 44	−356.506 39	−394.620 80	−395.052 67
3-F	−341.091 38	−341.524 13	−379.669 16	−380.088 24
4-F	−341.091 87	−341.534 30	−379.666 96	−380.090 24
3-CF$_3$	−574.596 31	−575.028 14	−613.173 60	−613.590 76
4-CF$_3$	−574.596 54	−575.028 48	−613.174 66	−613.590 50
3-CHO	−354.857 43[d]	−355.294 36[e]	−393.434 28	−393.855 46
4-CHO	−354.857 52	−355.295 73	−393.435 82	−393.854 20
3-CN	−334.184 01	−334.606 90	−372.762 29	−373.173 09
4-CN	−334.183 05	−334.607 61	−372.764 47	−373.172 94
3-NO$_2$	−444.323 22	−444.738 17	−482.902 13	−483.308 15
4-NO$_2$	−444.321 97	−444.734 17	−482.905 56	−483.307 22

[a] A positive sign denotes greater basicity than for the indicated standard base and a negative sign smaller basicity. [b] We are indebted to Dr. J. L. M. Abboud for these measurements. [c] N···COC *cis*. [d] N···CCO *trans*. [e] N···CCO *cis*.

dine, NC$_2$ = 1.357 Å, C$_2$C$_3$ = 1.390 Å, C$_3$C$_4$ = 1.357 Å; pyridinium ion, all 1.376 Å), and these geometries were used throughout. The calculated total energies obtained for the substituted pyridines and pyridinium ions are given in Table IB.

Results and Discussion

Acidities of Meta- and Para-Substituted Anilinium and Pyridinium Ions in Aqueous Solution. Table II lists substituent effects on the standard free energies of energies of ionization in water at 25 °C based upon critical examination of the literature.[16] Only substituents for which data are available in both series are considered. In Figure 1, these data are plotted, i.e., relative pyridinium

ion acidities vs. relative anilinium ion acidities. Select meta substituents which are known to follow the Hammett relationship with relatively high precision and a very high degree of generality[17] do define an excellent, linear, free-energy relationship ($\delta\Delta G^\circ_{pyrH^+} = 2.14\delta\Delta G^\circ_{ArNH_3^+} + 0.08$; $r = 0.998$; $n = 11$; average deviation = ±0.11 for a 6.66-kcal/mol range in acidities of pyridinium ions). This LFER is also followed by the para substituents Cl, Br, CH$_3$, and OCH$_3$, although for the latter substituent this is probably rather coincidental (cf. subsequent discussion). However, the strong π electron donor (−R) NH$_2$ substituent falls well above (by 1.5 kcal/mol) the correlation line in Figure 1 as a para substituent and probably significantly above (by 0.81 kcal/mol) as a meta substituent. Large deviations in the same direction are also to be noted for the +R para substituents. It is significant that the latter substituents do not form a separate LFE relationship. Thus, for these pyridinium ions acidity increases in the sequence: CH$_3$CO $\simeq$ CO$_2$R < CF$_3$ < CN < NO$_2$. This is the familiar inductive order, and, indeed, correlation with the σ_I values given by Ehrenson, Brownlee, and Taft[5e] is

(16) Data for pyridinium ion acidities in water at 25 °C are taken from ref 5k, except for 3- and 4-N(CH$_3$)$_2$-substituted pyridines, which are unpublished results of Professor H. D. Hopkins, Jr., quoted in ref 5i. The data for anilinium ion acidities are selected values taken from the following sources: A. V. Willi, *Z. Physik. Chem. (Wiesbaden)*, 233 (1961); A. I. Biggs and R. A. Robinson, *J. Chem. Soc.*, 388 (1961); R. A. Robinson and A. I. Biggs, *Aust. J. Chem.*, 10, 128 (1957); W. A. Sheppard, *J. Am. Chem. Soc.*, 84, 3072 (1962); F. G. Bordwell and G. D. Cooper, *ibid.*, 74, 1058 (1952); A. Bryson, *ibid.*, 82, 4858 (1960); J. Vandenbelt, C. Henrick, and S. Vandenberg, *Anal. Chem.*, 25, 726 (1954); P. D. Bolton and F. M. Hall, *J. Chem. Soc. B*, 259 (1969); Y. Tsuno, private communication.

(17) (a) R. W. Taft and I. C. Lewis, *J. Am. Chem. Soc.*, 81, 5343 (1959); (b) A. J. Hoefnagel and B. M. Wepster, *ibid.*, 95, 5357 (1973).

Table II. Effects of Meta and Para Substituents on the Acidities of Pyridinium and Anilinium Ions
in Water at 25 °C (in kcal/mol)

X	pyridinium ions					anilinium ions				
	$\delta\Delta G°_p$	$\delta\Delta G°_m$	$F^p_{aq}{}^a$	$\sigma_I{}^b$	$R^p_{aq}{}^c$	$\delta\Delta G°_p$	$\delta\Delta G°_m$	$F^p_{aq}{}^d$	$\sigma_I{}^e$	$R^p_{aq}{}^c$
N(CH$_3$)$_2$	6.25	1.71	-1.64	0.19	7.9					
NH$_2$	5.33	1.13	-1.90	0.23	7.2	1.72	0.11	-0.73	0.18	2.5
OCH$_3$	1.87	-0.59	-2.13	0.26	4.0	1.03	-0.53	-1.33	0.33	2.3
SCH$_3$	1.01	-1.06	-2.25	0.27	3.3	-0.27	-0.75	-0.98	0.24	0.7
CH$_3$	1.12	0.63	0.19	-0.02	0.9	0.65	0.18	-0.06	0.02	0.7
H	0.00	0.00	0.00	0.00	0.0	0.00	0.00	0.00	0.00	0.0
F		-3.00				0.07	-1.43	-2.20	0.54	2.2
Cl	-1.88	-3.27	-3.60	0.43	1.7	-0.85	-1.47	-1.80	0.44	1.0
Br	-1.99	-3.22	-3.37	0.40	1.4	-1.00	-1.50	-1.76	0.43	0.8
I		-2.62				-1.12	-1.35	-1.47	0.36	0.4
CF$_3$	-3.40	-3.75	-3.31	0.40	-0.1	-2.46	-1.85	-1.78	0.42	-0.8
CO$_2$CH$_3$	-2.35	-2.89	-2.73	0.33	0.4	-2.88	-1.36	-1.19	0.29	-1.6
CH$_3$CO	-2.32	-2.71	-2.49	0.30	0.2	-3.29	-1.40	-1.58	0.28	-1.7
CN	-4.57	-5.27	-4.79	0.57	0.2	-3.94	-2.51	-2.34	0.57	-1.6
NO$_2$	-5.43	-6.03	-5.36	0.64	-0.1	-4.88	-2.91	-2.69	0.66	-2.2
C$_6$H$_5$CO	-2.54	-2.77	-2.77	0.29	-0.1					

^{a} $F^p = (\delta\Delta G°_m - \alpha\delta\Delta G°_p)/(K - \alpha)$; $\alpha = 0.45$ and $K = 1.12$ for all substituents. ^{b} $\sigma_I = F^p/-8.30$; from eq 7. ^{c} $R^p = \delta\Delta G°_p - F^p$. ^{d} $F^p \simeq F^m = (\delta\Delta G°_m - \alpha\delta\Delta G°_p)/(1 - \alpha)$; $\alpha = 0.34$ for $-R$ and a 10 for $+R$ substituents. ^{e} $\sigma_I = F^p/-4.09$.
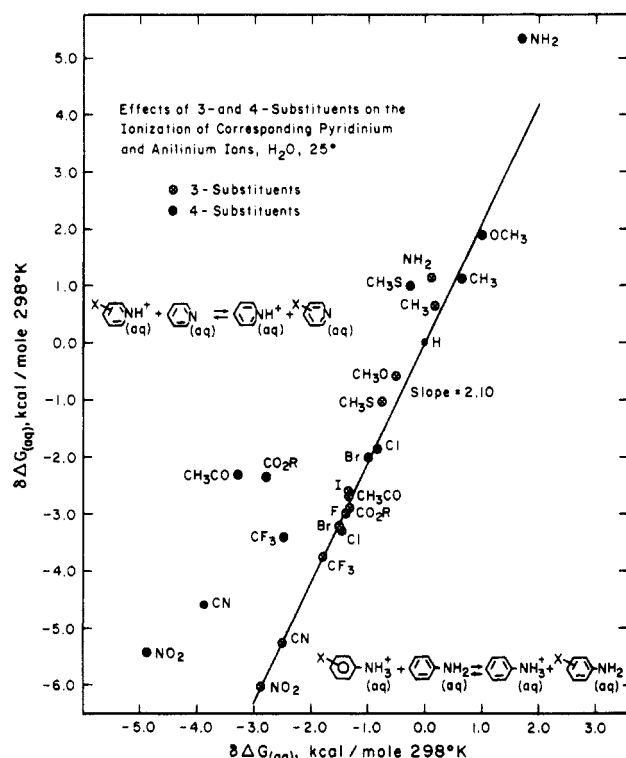
Figure 1. Effects of 3- and 4-substituents on the acidities of pyridinium ions vs. corresponding effects of meta and para substituents on the acidities of anilinium ions: H$_2$O, 25 °C.

excellent:[5b] $\delta\Delta G°_p = 8.30\sigma_I$; average deviation = ±0.12 for a range of 5.43 kcal/mol. On the other hand, for para-substituted anilinium ions acidity increases in the sequence CF$_3$ < CO$_2$R < CH$_3$CO < CN < NO$_2$ which is the familiar σ_p^- order:[7] $\delta\Delta G°_p = -3.90\sigma_p^-$; average deviation = ±0.04 for a range of 4.91 kcal/mol.

While it would be desirable to have additional +R para-substituent data which are common to both series, the presently available data, particularly in combination with the gas-phase and theoretical results to be discussed below, do appear to be adequate for confirming that the +R substituents have little or no resonance effects for pyridinium ion acidities.

The data may also be analyzed by the method of Taft and Lewis.[18] The substituent effects are taken as the sum

of field/inductive effects, F, and of resonance (i.e., π-electron delocalization effects), R (eq 1 for meta and eq 2 for para). The ratio of the R effects at the meta relative

$$\delta\Delta G°_m = F^m + R^m \qquad (1)$$

$$\delta\Delta G°_p = F^p + R^p \qquad (2)$$

to the para position is taken to be an approximate constant, α (generally a fraction ranging from ~0.2 to 0.6), for a given reaction series or a given substituent class (+R or -R) for the given reaction, i.e., $R^m \simeq \alpha R^p$. Further, the ratio of the F effects at the meta relative to the para position is taken to be a constant, K (generally, very near to unity), for a given reaction, i.e., $F^m = KF^p$. From the latter conditions, one obtains the expressions of eq 3–7 for separation of F and R effects.

$$\delta\Delta G°_p = F^m/K + R^m/\alpha \quad \text{or} \qquad (3)$$

$$\alpha\delta\Delta G°_p = \alpha F^m/K + R^m \quad \text{from which} \qquad (4)$$

$$\delta\Delta G°_m - \alpha\delta\Delta G°_p = F^m(1 - \alpha/K) \qquad (5)$$

$$F^p = F^m/K = \frac{\delta\Delta G°_m - \alpha\delta\Delta G°_p}{K - \alpha} \qquad (6)$$

$$R^p = \delta\Delta G°_p - F^p = \frac{K\delta\Delta G°_p - \delta\Delta G°_m}{K - \alpha} \qquad (7)$$

Table II lists values of F^p obtained (by trial and error methods) for pyridinium ion acidities with the use of $K = 1.12$ and $\alpha = 0.45$ for all substituents and for anilinium acidities with $K = 1.00$ and $\alpha = 0.34$ for $-R$ and 0.10 for $+R$ substituents. In Figure 2 the F^p values from Table II are plotted for anilinium vs. pyridinium ions. Considering the approximations involved and the accumulation of errors which occurs, one sees that the linear relationship obtained is quite satisfactory. Both sets of F^p values follow the σ_I parameters, as shown by the general agreement between literature values of these parameters[5e] and ones calculated (given in parentheses in Table II) from the F^p values by using the indicated ρ_I values, i.e., $\sigma_{I(calcd)} = F^p/\rho_I$.

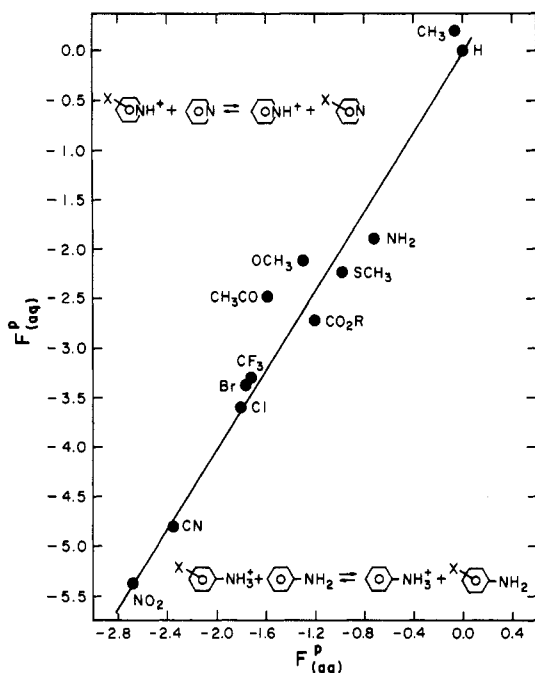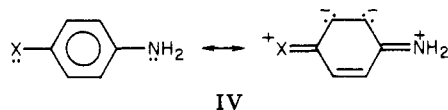The R^p values obtained from eq 7 are also given in Table II. It is immediately apparent that there is no linear re-

(18) R. W. Taft and I. C. Lewis, *J. Am. Chem. Soc.*, 80, 2436 (1958); 81, 5343 (1959).

Figure 2. Field/inductive effects of para substituents on the acidities of pyridinium ions vs. corresponding anilinium ions: H_2O; 25 °C; ordinate, F^p_{aq}, kcal/mol; abscissa, F^p_{aq}, kcal/mol.

Table III. Evaluation of Aqueous F^p and R^p Values for Pyridinium Ion Acidities Based upon Use of 4-Substituted Quinuclidinium Ion Acidities (Values in kcal/mol)

X	$1.08\delta\Delta G^\circ_Q{}^{21a}$	F^p_{eq6}	R^p_{eq8}	R^p_{eq7}
$N(CH_3)_2$	−1.43	−1.64	7.7	7.9
NH_2	−1.45	−1.90	6.8	7.2
OCH_3	−2.66	−2.13	4.5	4.0
SCH_3	−2.44	−2.25	3.4	3.3
CH_3	−0.16	0.19	1.3	0.9
H	0.00	0.00	0.0	0.0
Cl	−3.70	−3.60	1.8	1.7
Br	−3.90	−3.37	1.9	1.4
CO_2CH_3	−2.51	−2.73	0.2	0.4
CH_3CO	−2.50	−2.49	0.2	0.2
CN	−4.47	−4.79	−0.1	0.2
NO_2	−5.13	−5.36	−0.3	−0.1

lationship for these values between the pyridinium and anilinium ion series. The results are consistent with and offer an explanation of both the linear and nonlinear behavior displayed in Figure 1. Meta substituent behavior is dominated by the underlying linear field/inductive effect relationship between the two series. Thus only relatively large resonance effects with accompanying small field/inductive effects (as for m-NH_2) will tend to upset the LFE relationship. However, at the para position, resonance effects are generally sufficiently large and nonlinear between the two series so that appreciable deviations occur.

For anilinium ions, R^p values are nearly equal for the strong $-R$ (F, OMe, and NH_2) substituents, while, in contrast, the corresponding R^p values increase markedly for pyridinium ions. These results are expected as a consequence of dominant resonance interactions for $-R$ substituents in aqueous pyridinium ions (cf. II) whereas no comparable kind of induced resonance interactions in aqueous anilinium ions (III) are possible. However, R^p

III
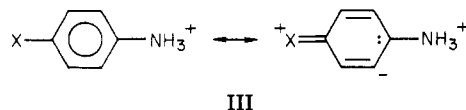
values for $-R$ para-substituted anilinium ions are consistent with both field-induced resonance effect contributions[31] as well as repulsive π-electron saturation interactions[19,20] in the aniline free bases (IV).

IV

The R^p values for +R-substituted pyridinium ions are near zero in accord with the observation of no effect of

twisting the NO_2 substituent on the acidity of 3,5-dimethyl-4-nitropyridine[5a] and the correlation of both $\delta\Delta G^\circ_m$ and $\delta\Delta G^\circ_p$ values for these ions with σ_I values.[5b] This result is consistent with the expected repulsive π-electron saturation interactions in both pyridinium ions and pyridines. There are moderately negative R^p values for the +R para-substituted anilinium ions which are also expected as the consequence of stabilizing resonance interactions in the aniline free bases (cf. I). However, it is to be noted that in general the $-R^p$ values are either comparable in magnitude or less than the corresponding $-F^p$ values. This result is in quantitative agreement with that obtained from the effects of complete steric inhibition of resonance of the p-nitro substituent on the acidity of anilinium ions in water.[21] For example, Wepster[21a] gives $R^p \simeq 2.0$ and $F^p \simeq 3.3$ kcal/mol. Thus, the frequent assertion[8] that p-nitroanilinium ion is a stronger acid than anilinium ion because of resonance stabilization in p-nitroaniline is clearly incorrect even in aqueous solution (it is even less correct in the gas phase as will be shown subsequently).

An independent confirmation of the F^p values of Table III for pyridinium ion acidities comes from the use of 4-substituted quinuclidinium ion acidities ($\delta\Delta G^\circ_Q$ values) as models for the field/inductive effects.[22] Table III shows that the agreement between corresponding F^p and 1.08 $\delta\Delta G^\circ_Q$ is generally quite good. The use of the factor 1.08 indeed seems reasonable since there is evidence that the charge–dipole distance ratio for 4-substituted quinuclidinium ions relative to 4-substituted pyridinium is of this magnitude.[23]

Values of R^p for 4-substituted pyridinium ions can also be obtained, of course, from the relationship given in eq 8. These results are given in Table III and confirm in

$$R^p = \delta\Delta G^\circ_p - 1.08\delta\Delta G^\circ_Q \qquad (8)$$

particular the conclusion that there are relatively small if any resonance effects on pyridinium ion acidities for +R substituents.

The separation of $\delta\Delta G^\circ_p$ to F^p and R^p values for +R substituents obtained through the use of DSP[5e] or LSFE[9] treatments is not quantitatively satisfactory. Thus, for the +R substituents CF_3, CO_2CH_3, CH_3CO, CN, and NO_2, these treatments give the following R^p values, respectively: −0.3, −0.4; −0.5, −0.7; −0.6, −0.8; −0.5, −0.7; −0.6, −1.0. The very high correlation coefficients obtained with the use of

(19) A. J. Hoefnagel, M. A. Hoefnagel, and B. M. Wepster, *J. Am. Chem. Soc.*, 98, 6194 (1976).

(20) J. Bromilow, R. T. C. Brownlee, D. J. Craik, M. Sadek, and R. W. Taft, *J. Org. Chem.*, 45, 2429 (1980).

(21) (a) B. M. Wepster, *Recl. Trav. Chim. Pays-Bas*, 76, 335, 357 (1957). Also cf. *Prog. Stereochem.*, 2, 152 (1958); (b) R. W. Taft and H. D. Evans, *J. Chem. Phys.*, 27, 1427 (1957).

(22) (a) C. A. Grob and M. G. Schlageter, *Helv. Chim. Acta*, 59, 264 (1976); (b) C. A. Grob and R. W. Taft, *J. Am. Chem. Soc.*, 96, 1236 (1974).

(23) M. Charton, *Prog. Phys. Org. Chem.*, 13, 0000 (1980).

Table IV. Effects of Meta and Para Substituents on the Gas-Phase Acidities of Pyridinium and Anilinium Ions (in kcal/mol)

X	pyridinium ions					anilinium ions	
	$\delta\Delta G^{\circ}{}_p$	$\delta\Delta G^{\circ}{}_m$	$F^{p}{}_g{}^{a}$	$\sigma_I{}^{b}$	$R^{p}{}_g{}^{c}$	$\delta\Delta G^{\circ}{}_p$	$\delta\Delta G^{\circ}{}_m$
$N(CH_3)_2$	15.6	9.5	−1.4	0.07	17.0		
OCH_3	7.2	3.0	−4.1	0.21	11.3	4.0	
CH_3	4.3	2.9	0.2	−0.01	4.1	3.2	
H	0.0	0.0	0.0	0.00	0.0	0.0	0.0
F	−4.1	−7.0	−10.5	0.52	6.4	−2.3	−3.4
Cl	−3.3	−6.2	−10.0	0.50	6.7	−1.8	−2.8
CF_3	−8.3	−8.6	−7.9	0.39	−0.4		
CO_2CH_3	−2.3	−2.8	−3.2	0.16	0.9		
CH_3CO	−3.7	−3.9	−3.7	0.19	0.0		
CN	−11.2	−12.0	−11.5	0.57	0.3		
NO_2	−12.7	−13.5	−12.7	0.64	0.0		
CHO	−6.1^{d}		−6.4^{e}	0.32^{e}	0.3		

^{a} $F^p = \delta\Delta G^{\circ}{}_m - \alpha\Delta G^{\circ}{}_p/(K - \alpha)$; $\alpha = 0.65$ and $K = 1.06$ for all substituents. ^{b} $\sigma_I = F^p/-20.0$. ^{c} From eq 7. ^{d} From ref 5i. ^{e} Calculated from the σ_I value from ref 25.

these treatments do not necessarily mean that equally highly precise separations of field/inductive and resonance effects have been achieved. The difficulty lies in the fact that the substituent parameters for the F and R effects (in water; in particular cf. subsequent discussion) are not sufficiently nonparallel for the available substituent data. Thus, the dual-substituent parameter treatments may give a whole series of relatively precise fittings and there can be no assurance that the best fit is the correct one. Hopefully, this situation may be improved with the further acquisition of data for additional appropriate +R substituents (those which strongly enhance nonlinearity between field/inductive and resonance effect parameters, i.e., $C(CN)_3$ and COCN).

Gas-Phase Acidities of Pyridinium Ions. Table IV lists the gas-phase $\delta\Delta G^{\circ}$ values for acidities of a substantial variety of 3- and 4-substituted pyridinium ions. Also listed are the few available gas-phase acidities of 3- and 4-substituted anilinium ions. Meager data in the latter series at this time prevents the construction of a meaningful gas-phase plot corresponding to that for aqueous solution (Figure 1). However, in the next section such a plot is made and analyzed for theoretically calculated m- and p-substituent effects on the acidities of corresponding pyridinium and anilinium ions.

In Figure 3 are plotted the gas-phase pyridinium ion acidities $\delta\Delta G^{\circ}{}_g$ vs. the corresponding aqueous solution values, $\delta\Delta G^{\circ}{}_{aq}$. The data for 4-substituents define a roughly linear relationship having the following least-squares fit: $\delta\Delta G^{\circ}{}_g = 2.48\delta\Delta G^{\circ}{}_{aq} + 1.4$ [standard deviation (SD) = 1.3 kcal/mol; f = SD/rms = 0.150]. The strong π-donor (−R) 3-substituents [3-$N(CH_3)_2$ and 3-OCH_3] deviate very substantially from this correlation line, and other substituents show appreciable scatter. There is little to recommend treating 3-substituents separately from 4-substituents (based upon only 3-substituents, the linear regression statistics are as follows: $\delta\Delta G^{\circ}{}_g = 2.95\delta\Delta G^{\circ}{}_{aq} + 3.5$; SD = 1.7 kcal/mol; f = 0.244). Indeed, there appears to be nothing to recommend the view that, in general, gas-phase substituent effects differ from corresponding solution effects by a precisely fixed solvent attenuation factor. This may be seen by examining the ratio $\delta\Delta G^{\circ}{}_g/\delta\Delta G^{\circ}{}_{aq}$ for individual substituents. For the para position, this ratio varies from 0.99 for CO_2CH_3 to 3.85 for OCH_3; for the meta position, this ratio varies from −5.1 for OCH_3 (which decreases acidity in the gas phase but increases it in aqueous solution) to 5.56 for $N(CH_3)_2$.

On the other hand, the application of the method of Taft and Lewis gives results which reveal conditions leading to a precise linearity between gas and aqueous substituent effects. Values of $F^p{}_g$, $F^m{}_g$, $R^p{}_g$, and $R^m{}_g$ obtained through
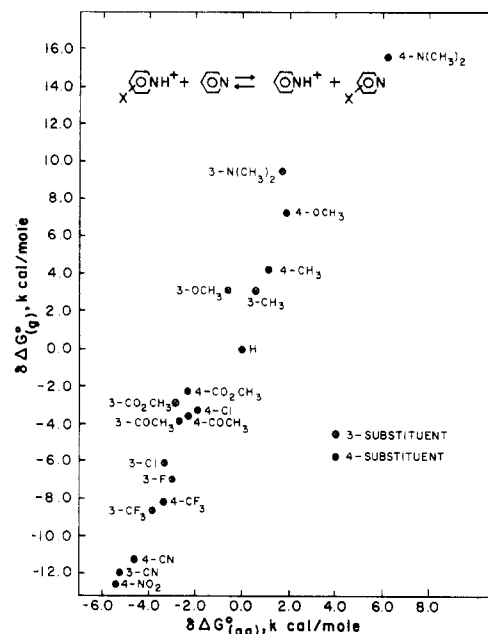

Figure 3. Effects of 3- and 4-substituents on the gas-phase acidities of pyridinium ions vs. corresponding effects on aqueous acidities.

applications of eq 6 and 7 with $K = 1.06$ and $\alpha = 0.65$ for all substituents are given in Table V. There is probably no significance in the different K values for the gas and aqueous phases; i.e., $K = 1.09 \pm 0.03$. On the other hand, a greater α value for the gas-phase than aqueous solution (0.45) appears to be quite significant; cf. the subsequent discussion.

The ratio of $F^p{}_g/F^p{}_{aq}$ is equal to a constant of 2.5 ± 0.2 (the slope of Figure 3) for all meta and para substituents which are either very weak or are non-hydrogen-bond acceptors in their interaction with water. The strong hydrogen bond acceptor substituents $N(CH_3)_2$, CO_2CH_3, and CH_3CO in both meta and para positions give F_g/F_{aq} ratios of only 0.9–1.4. This result indicates (in accord with other evidence[24]) that hydrogen bonding of water to these hydrogen bond acceptor substituents increases substantially their field/inductive effects. The increase is by factors of the same order of magnitude as the aqueous solvent attenuation factor (2.5) for non-hydrogen-bond acceptor

(24) (a) R. W. Taft, E. Price, I. R. Fox, I. C. Lewis, K. K. Andersen, and G. T. Davis, *J. Am. Chem. Soc.*, **85**, 709 (1963); (b) J. Bromilow, R. T. C. Brownlee, V. O. Lopez, and R. W. Taft, *J. Org. Chem.*, **44**, 4766 (1979).

Table V. F and R Values for Meta- and Para-Substituted Pyridinium Ion Acidities in the Gas and Aqueous Phases (in kcal/mol)

Para Position

	$F^p{}_g$	$R^p{}_g$	$F^p{}_{aq}$	$R^p{}_{aq}$	$F^p{}_g/F^p{}_{aq}$	$R^p{}_g/R^p{}_{aq}$
N(CH₃)₂	-1.4	17.0	-1.6	7.9	0.9	2.2
OCH₃	-4.1	11.3	-2.1	4.0	2.0	2.8
CH₃	0.2ᵃ	4.1ᵃ	0.2	0.9	b	4.5
Cl	-10.0	6.7	-3.6	1.7	2.8	3.9
CF₃	-7.8	-0.5	-3.3	-0.1	2.4	
CO₂CH₃	-3.2	0.9	-2.8	0.4	1.1	
CH₃CO	-3.7	0.0	-2.5	0.2	1.5	
CN	-11.5	0.3	-4.8	0.2	2.4	
NO₂	-12.9	0.2	-5.4	-0.1	2.4	

Meta Position

	$F^m{}_g$	$R^m{}_g$	$F^m{}_{aq}$	$R^m{}_{aq}$	$F^m{}_g/F^m{}_{aq}$	$R^m{}_g/R^m{}_{aq}$
N(CH₃)₂	-1.5	11.0	-1.8	3.5	0.8	3.1
OCH₃	-4.3	7.3	-2.4	1.8	1.8	4.0
CH₃	0.3ᵃ	2.6ᵃ	0.2	0.4	b	6.5
Cl	-10.6	4.2	-4.0	0.7	2.7	6.0
CF₃	-8.4	0.2	-3.7	0.0	2.3	
CO₂CH₃	-3.4	0.6	-3.1	0.2	1.1	
CH₃CO	-3.9	0.2	-2.8	0.1	1.4	
CN	-12.2	0.2	-5.4	0.1	2.3	
NO₂	-13.7		-6.0	0.0	2.3	

ᵃ Unreliable since a polarizability correction is presumably required. ᵇ Uncertain.
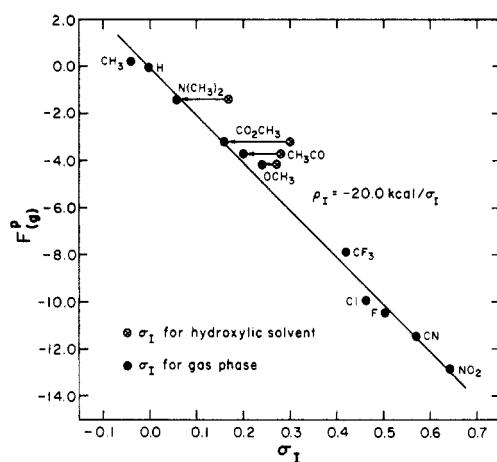
Figure 4. Field/inductive effects of para substituents on the gas-phase acidities of pyridinium ions plotted vs. σ_I substituent parameters: ordinate, $F^p{}_g$, kcal/mol; abscissa, σ_I.

substituents. The F_g/F_{aq} ratios of 1.8 and 2.0 for the m-OCH₃ and (probably) the p-OCH₃ substituents indicate that there are small hydrogen bond acceptor effects for the methoxy group in the aqueous pyridinium ion acidities.

In Figure 4 the $F^p{}_g$ values are plotted vs. σ_I values. By use of the σ_I values which are based upon acidity measurements in water or similar hydroxylic solvents, the points for N(CH₃)₂, CO₂CH₃, CH₃CO, and to a lesser extent the OCH₃ substituents do deviate substantially from the line defined by the points for very weak or non-hydrogen-bond acceptor substituents. If σ_I values based upon gas-phase phenol acidities[25] are used for the former substituents in Figure 4, an excellent linear relationship is obtained for all substituents. This relationship indicates that the assumed relationship $R^m = 0.65R^p$ must hold quite

(25) M. Fujio, R. T. McIver, Jr., and R. W. Taft, unpublished results.
(26) R. W. Taft in "Steric Effects in Organic Chemistry", M. S. Newman, Ed., Wiley, New York, 1956, pp 570, 580.
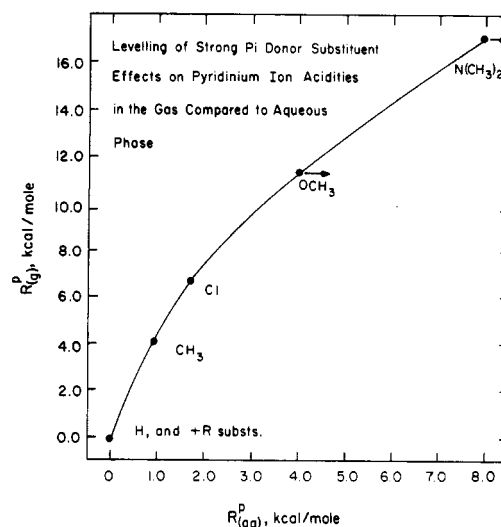
Figure 5. Leveling of strong π-donor-substituent effects on pyridinium ion acidities in the gas compared to aqueous phase.

well in view of the very large R^m and R^p values for $-R$ substituents (Table V). The excellent quality of the $F^p{}_g$ vs. σ_I correlation also indicates that there are little or no important effects on the gas-phase pyridinium ion acidities from variable meta or para substituent polarizabilities, except probably for very polarizable substituents having a high hydrocarbon content.

The R^p and R^m values for all +R substituents are near zero; i.e., the $\delta\Delta G^m{}_p$ and $\delta\Delta G^p{}_g$ values for gas-phase pyridinium acidities correlated well with σ_I values (only). In the absence of hydrogen bonding enhanced σ_I values for the CH₃CO and CO₂CH₃ substituents, the gas-phase acidities are more discriminating in this matter than are the aqueous acidities: $\delta\Delta G^p{}_g = -19.2\sigma_I$, average deviation = ±0.3 for a range of 12.7 kcal/mol; $\delta\Delta G^m{}_g = -20.7\sigma_I$, average deviation = ±0.3 for a range of 12.0 kcal/mol. In the final section, we have presented additional critical analysis regarding the dependence of $\delta\Delta G^p{}_g$ and $\delta\Delta G^m{}_g$ values upon σ_I and $\sigma_R{}^+$ parameters.

The ratio R_g/R_{aq} is not a constant for $-R$ substituents but varies from about 2.2 to 4.0 at the para position and from about 3.1 to 6.0 at the meta position. Since the effect, if any, of hydrogen bonding by water to the strong $-R$ substituents, N(CH₃)₂ or CCH₃, would be to lower R_{aq} and hence raise the ratio of R_g/R_{aq}, the lower values of this ratio observed for these than for the other $-R$ substituents (cf. Table V) must be due to another cause. Apparently the very large R_g values, particularly for the N(CH₃)₂ substituent, do not increase linearly with the stronger electron demand made by the unsolvated pyridinium ion center but are leveled (cf. Figure 5, which plots $R^p{}_g$ vs. the corresponding $R^p{}_{aq}$ values). This explanation appears to be supported by the fact that the ratio $(R^m/R^p)_{aq} = R^m{}_g/R^m{}_{aq}/R^p{}_g/R^p{}_{aq} = \alpha_g/\alpha_{aq} = 0.65/0.45 = 1.4$ is an excellent constant for all of the $-R$ substituents. This result is one of general interest and importance since it shows that the significantly smaller resonance effects generally observed in aqueous solution acidities at the meta relative to the para position are in part an artifact of solvent effects. That is, the gas-phase R values indicate that the resonance effects of $-R$ substituents are less at the meta compared to the para position by a factor of only 1/1.54 in comparison with the factor of 1/2.22 in aqueous solution. There are two explanations of this result which seem plausible. First, the greater electron demand made by the unsolvated pyridinium ion center on $-R$ substituents may inherently increase π electron donation by a greater factor for the

Table VI. Calculated Effects (STO-3G) of Meta and Para Substituent Effects on the Acidities of Pyridinium and Anilinium Ions (in kcal/mol)[g]

	pyridinium ion acidities		anilinium ion acidities	
	$\delta \Delta E^{\circ}_4$	$\delta \Delta E^{\circ}_3$	$\delta \Delta E^{\circ}_{\mathrm{p}}$	$\delta \Delta E^{\circ}_{\mathrm{m}}$
NH_2	16.1^a $(15.6)^b$	3.5^a $(9.5)^b$	6.1^e	1.2^e
OCH_3	9.3 (7.2)	−0.3 (3.0)	4.2 (4.0)	0.6^f
CH_3	5.0 (4.3)	2.5 (2.9)	2.4 (3.2)	1.3^f
H	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
F	−0.2 (−4.1)	−6.3 (−7.0)	−1.1 (−2.3)	−3.8 (−3.4)
CF_3	−6.8 (−8.3)	−6.8 (−8.6)	−5.9	−5.0
CHO	$-2.9 (-3.7)^c$	$-3.6 (-3.9)^c$	−4.2	−3.6
CN	−11.4 (−11.2)	−12.4 (−12.0)	−10.4	−9.0
NO_2	−16.7 (−12.7)	$-17.4 (-13.6)^d$	−14.8	−12.0

[a] Calculations are for coplanar NH_2. [b] Experimental values are for $N(CH_3)_2$. [c] Experimental values are for CH_3CO. [d] Value estimated as $1.07\delta \Delta E^{\circ}_{\mathrm{p}}$, as followed by the other meta +R substituents. [e] Calculations for trigonal NH_2. [f] Calculated for N protonation. Experimental results indicate that this aniline protonates preferentially at carbon.[11] [g] Experimental values are given for comparison in parentheses.

weaker meta interaction than for the corresponding para interaction. Alternatively, and perhaps somewhat more likely, the π-electron donation from the meta position may be indirect[25] rather than direct as suggested by valence bond resonance forms, e.g.:
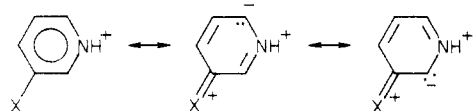
These indirect (or field-induced resonance, FIRE) meta resonance effects are more subject to reduction by the dielectric effects of solvation[5k] (higher effective dielectric constant in solution) than are the direct para resonance effects.

Ab Initio Calculations of Meta and Para Substituent Effects on Pyridinium and Anilinium Ion Acidities. The results of ab initio calculations at the STO-3G level of approximation are given in Table VI as $\delta \Delta E^{\circ}$ values. Given for comparison in Table VI in parentheses are all of the available corresponding experimental gas-phase $\delta \Delta G^{\circ}$ values. There is fair agreement between observed and calculated values, although, as previously noted,[10] agreement between calculated and experimental values seems to be substantially better for anilinium than for pyridinium ions. Poorest agreement is obtained for *m*- and *p*-NO$_2$ and *p*-F in the pyridinium ion series. The tendency for NO$_2$ effects to be overestimated has been previously noted.[27]

Figure 6 plots the theoretically calculated substituent effects, $\delta \Delta E^{\circ}_{\mathrm{calcd}}$, for pyridinium ion acidity vs. the corresponding quantity for the anilinium ion acidity. Figure 6 reflects remarkably well most of the features displayed in the LFE plot, i.e., $\delta \Delta G^{\circ}_{\mathrm{aq}}$ for pyridinium ion acidity plotted vs. the corresponding $\delta \Delta G^{\circ}_{\mathrm{aq}}$ for anilinium acidity (Figure 1). This result is obtained in spite of the fact that the magnitudes of the calculated effects are generally 2–4 times greater than corresponding $\delta \Delta G^{\circ}_{\mathrm{aq}}$ values. Evidence is therefore provided that a crude constancy of the aqueous solvent attenuation factor tends to prevail. Further, the theoretical calculations are indicated to be capable of showing the interrelationships between families of acids and bases more accurately than the agreement between gas-phase results and theoretically calculated substituent effects might suggest. Such a result is reasonable since some of the errors introduced in the theoretical approximations will tend to cancel when the "theoretical
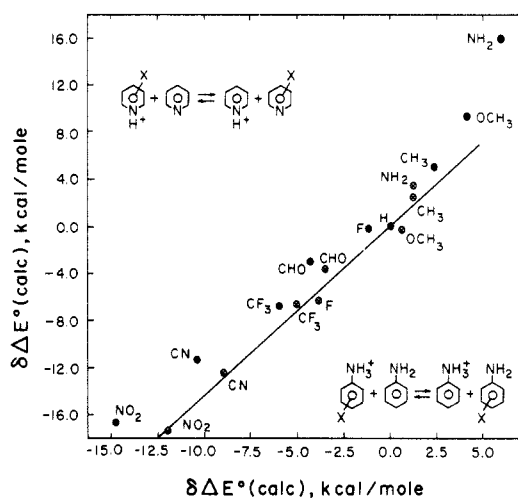
Figure 6. Theoretical (STO-3G) calculations of the effects of 3- and 4-substituents on the acidities of pyridinium ions vs. corresponding effects of meta and para substituents on the acidities of anilinium ions.

substituent" is compared with the corresponding "theoretical substituent" in the two different series.

Specifically, Figure 6 shows that an approximately linear relationship prevails for the select meta substituents, *m*-CH$_3$, *m*-F, *m*-CF$_3$, *m*-CN, and *m*-NO$_2$, as in Figure 1. The slope difference between Figures 1 and 6 indicates a somewhat greater aqueous solvent attenuation factor for the anilinium ion than that for the pyridinium ion series. This is expected in terms of the 13-kcal/mol greater heat of solvation of anilinium than pyridinium ion and the analysis previously given for this figure.[28] Consistent with Figure 1, the para π-electron donor (−R) substituents (*p*-NH$_2$, *p*-OMe, *p*-CH$_3$, and *p*-F) tend to lie above the correlation line in Figure 6 as do also the para π-electron acceptor (+R) substituents (*p*-CHO, *p*-CF$_3$, *p*-CN, and *p*-NO$_2$). The very strong π-donor NH$_2$ substituent also lies in this direction in the meta position as well.

This excellent agreement between the patterns of behavior in Figures 1 and 6 suggests that the theoretical calculations can provide new insights into the analysis of the experimental substituent effects. The method of Taft and Lewis has been successfully applied to theoretical calculations of substituent effects on acidity.[29] Application

(27) W. F. Reynolds, P. G. Mezey, W. J. Hehre, R. D. Topsom, R. W. Taft, *J. Am. Chem. Soc.*, **99**, 5821 (1977).

(28) R. W. Taft, J. F. Wolf, J. L. Beauchamp, G. Scorrano, and E. M. Arnett, *J. Am. Chem. Soc.*, **100**, 1240 (1978).

(29) (a) A. Pross, L. Radom, and R. W. Taft, *J. Org. Chem.*, **45**, 818 (1980); (b) G. Kemister, A. Pross, L. Radom, and R. W. Taft, *ibid.*, **45**, 1056 (1980).

Table VII. F^p and R^p Values from Theoretically Calculated Acidities of Meta- and Para-Substituted Pyridinium and Anilinium Ions (in kcal/mol)

	pyridinium ions					anilinium ions				
	$\delta \Delta E°_p$	$\delta \Delta E°_m$	$F^p_{theor}{}^a$	$\sigma_I{}^b$	$R^p{}^c$	$\delta \Delta E°_p$	$\delta \Delta E°_m$	$F^p_{theor}{}^d$	$\sigma_{I(theor)}{}^e$	$R^p{}^c$
CH$_3$	5.0	2.5	1.1	−0.06	3.9	2.5	1.3	0.5	−0.04	2.0
H	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.00	0.0
NH$_2$	16.1	3.5	−3.0	0.18	19.1	6.1	1.2	−2.0	0.17	8.1
OCH$_3$	9.3	−0.3	−5.1	0.30	14.1	4.2	0.5	−2.0	0.17	6.2
CHO	−2.9	−3.6	−3.7	0.22	0.8	−4.2	−3.6	−3.5	0.29	−0.7
CF$_3$	−6.8	−6.8	−6.2	0.37	−0.6	−5.9	−5.0	−4.8	0.40	−1.1
F	−0.2	−6.3	−8.7	0.51	8.5	−1.3	−3.8	−5.5	0.46	4.2
CN	−11.4	−12.4	−11.8	0.70	0.4	−10.4	−9.0	−8.6	0.72	−1.8
NO$_2$	−16.7	−17.4	−16.3	0.96	−0.4	−14.8	−12.0	−11.3	0.94	−3.5

^{a} Obtained from eq 6 by using $\alpha = 0.35$ and $K = 1.06$ for all substituents. ^{b} $\rho_I = -17.0$ kcal/σ; i.e., $\sigma_{I(theor)} = F^p/-17.0$. ^{c} Obtained from eq 7. ^{d} Obtained from eq 6 by using $K = 1.00$ and $\alpha = 0.2$ for $+R$ and $\alpha = 0.4$ for $-R$ substituents. ^{e} $\rho_I = -12.0$ kcal/σ_I; i.e., $\sigma_{I(theor)} = F^p/-12.0$.

of this method to the present calculations for pyridinium and anilinium ion acidities provides further evidence that the calculations appropriately applied can provide trustworthy new insights. In Table VII are given "theoretical" F^p values calculated from eq 6 by using the calculated meta and para substituent effects for the pyridinium ions ($\alpha = 0.35$ and $K = 1.06$) and for the anilinium ions ($K = 1.00$ and $\alpha = 0.20$ for $+R$ substituents and 0.40 for $-R$ substituents). The theoretical F^p values give a very satisfactory linear field/inductive effect relationship (analogous to Figure 2). This is shown in Table VII by the general agreement between corresponding calculated σ_I values and supports the idea expressed above concerning the use of "theoretical" substituents. The slope of the linear F^p vs. F^p relationship is 1.42 = $\rho_I(\text{pyrH}^+)/\rho_I(\text{ArNH}_3^+)$. This is the same slope as obtained from the $\delta\Delta E°$ vs. $\delta\Delta E°$ relationship (Figure 6), a result which shows the dominance of the field/inductive effects in giving rise to inherent LFE-type relationships.

The "theoretical" R^p values (obtained from eq 7) are also given in Table VII. Agreement with the gas-phase R^p values for pyridinium ion acidities (Table V) is generally satisfactory. For $-R$ substituents the "theoretical" R values tend to be somewhat greater than the experimental values but follow closely the same trends. For $+R$ substituents, both the theoretical and experimental R^p values deviate randomly from zero ($\sim 0.0 \pm 0.5$ kcal/mol), tending to confirm the absence of appreciable resonance effects for π-electron acceptor substituents in pyridinium ion acidities. In the absence of experimental values, the theoretical R^p values obtained for anilinium ion acidities are of particular interest. For $-R$ substituents, large unfavorable resonance effects are indicated, ranging from $R^p = 2.0$ kcal/mol (for CH$_3$) to 8.1 kcal/mol (for NH$_2$). These values follow qualitatively a σ_R substituent effect sequence. For $+R$ substituents, there are, as expected, finite resonance effects ranging from $R^p = -0.7$ kcal/mol (for CHO) to -3.5 kcal/mol (for NO$_2$) in generally a σ_R^- order. However, the unexpected result (in terms of previous discussions of anilinium ion acidities[19]) is that the *magnitudes* of these resonance effects for the $+R$ substituents are generally substantially *less* than those for the $-R$ substituents.

The theoretical calculations provide a means of bisecting the substituent effects on acidity into the interaction energies involved in the ions (the acid forms) and in the neutral molecules (base forms). This analysis is of general interest in connection with the origins of intrinsic substituent effects on acidity and is of specific interest with respect to the "unexpected" theoretically calculated R^p values obtained above for anilinium ion acidities.

Theoretical Calculations of Substituent Interaction Energies in Pyridines, Pyridinium Ions, Anilines, and Anilinium Ions. For meta- and para-substituted pyridines, the substituent interaction energies,[29] $\Delta\epsilon$, are obtained as the change in ground-state electronic energy for the following general (hypothetical) reaction:
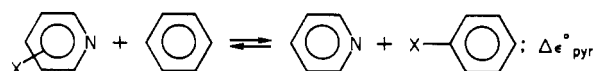
Similarly, for pyridinium ions, the substituent interaction energies are the energy changes for the (hypothetical) reaction
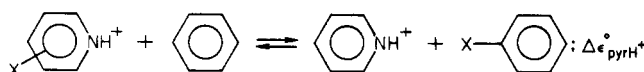
The sign convention employed for all of the substituent interaction energies is that positive values denoted preferential stabilization of the disubstituted system compared to the two monosubstituted ones, and conversely.

The calculated substituent effect on acidity, $\delta\Delta E°_{\text{pyrH}^+}$, corresponding to the reaction
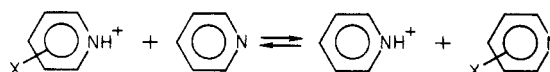
is equal to the difference in substituent interaction energies between the pyridinium ion and the corresponding pyridine, i.e.

$$\delta\Delta E°_{\text{pyrH}^+} = \Delta\epsilon°_{\text{pyrH}^+} - \Delta\epsilon°_{\text{pyr}}$$

Analogous hypothetical reactions for meta- and para-substituted anilines and anilinium ions give the substituent interaction energies $\Delta\epsilon°_{\text{ArNH}_2}$ and $\Delta\epsilon°_{\text{ArNH}_3^+}$, respectively. The calculated substituent effect on the acidity of the anilinium ion, $\Delta E°_{\text{ArNH}_3^+}$, is similarly given by the following equation:

$$\delta\Delta E°_{\text{ArNH}_3^+} = \Delta\epsilon°_{\text{ArNH}_3^+} - \Delta\epsilon°_{\text{ArNH}_2}$$

Table VIII gives values of the substituent interaction energies that have been obtained for all four systems. Also given in Table VIII are the differences in the interaction energies, Δ, for a given substituent between the para and the meta positions, which serve as an approximate measure of resonance effects.

The largest interaction energies obtained are for destabilization of the cations by substituents with large positive σ_I values (large unfavorably oriented substituent

(30) W. J. Hehre, R. Ditchfield, L. Radom, and J. A. Pople, *J. Am. Chem. Soc.*, **92**, 4796 (1970); L. Radom, W. J. Hehre, and J. A. Pople, *ibid.*, **93**, 289 (1971).

Table VIII. Substituent Interaction Energies in Pyridines, Pyridinium Ions, Anilines, and Anilinium Ions (in kcal/mol)

X	$\Delta \epsilon^{\circ}_{pyr}$	$\Delta \epsilon^{\circ}_{pyrH^+}$	$\Delta \epsilon^{\circ}_{ArNH_2}$	$\Delta \epsilon^{\circ}_{ArNH_3^+}$
p-NH₂	1.8	18.0	-1.6	4.5
m-NH₂	1.0	4.4	0.8	2.0
Δ	0.8	13.6	-2.4	2.5
p-OCH₃	0.6	9.9	-1.5	2.8
m-OCH₃	0.0	-0.3	0.7	1.2
Δ	0.6	10.2	-2.2	1.6
p-CH₃	0.6	5.7	-0.5	2.0
m-CH₃	-0.2	2.3	0.2	1.5
Δ	0.8	3.4	-0.7	0.5
p-F	-0.7	-0.9	-0.8	-2.0
m-F	-1.0	-7.3	0.6	-3.2
Δ	0.3	6.4	-1.4	1.2
p-CF₃	-1.0	-7.8	0.8	-5.1
m-CF₃	-1.2	-8.0	0.1	-4.9
Δ	0.2	0.2	0.7	-0.2
p-CN	-2.4	-13.8	1.4	-9.0
m-CN	-1.8	-14.3	0.1	-8.9
Δ	-0.6	0.5	1.3	-0.1
p-NO₂	-3.0	-19.7	2.2	-12.6
m-NO₂	-2.3	-19.7	0.0	-12.0
Δ	-0.7	0.0	2.2	-0.6
p-CHO	-0.9	-3.8	1.0	-3.2
m-CHO	-1.2	-4.8	0.0	-3.6
Δ	0.3	1.0	1.0	0.4

Table IX. Calculated Substituent Effects for Double Proton Transfer from Anilinium Ion to Anilide Ion (Reaction 9)[d]

	$\delta \Delta E^{\circ}_p$[9]	$\delta \Delta E^{\circ}_m$[9]	F^p_{theor}[a]	R^p_{theor}[c]
NH₂	10.9	1.3	-5.2 (0.18)[b]	16.1
OCH₃	7.1 (4.9)	-1.7	-7.5 (0.26)	14.1
CH₃	3.6 (4.4)	1.6	0.3 (-0.01)	3.2
F	-2.6 (-3.9)	-8.8 (-7.4)	-13.0 (0.46)	10.4
H	0.0	0.0	0.0 (0.00)	0.0
CF₃	-16.6	-12.6	-11.6 (0.41)	-5.0
CN	-30.6	-22.4	-22.9 (0.80)	-7.7
NO₂	-42.5	-28.9	-25.5 (0.90)	-17.0
CHO	-17.5	-9.3	-7.3 (0.26)	-10.2

[a] Obtained from eq 6 by using $K = 1.00$ and $\alpha = 0.2$ for +R and 0.4 for -R substituents. [b] $\sigma_{I(theor)} = F^p/-28.5$. [c] Obtained from eq 7. [d] Values in kilocalories/mole. Experimental values are given in parentheses.

dipoles) and for stabilization of these ions by strong π-electron donor substituents (with large negative σ_R values). The interaction energies for the neutral molecules, while significant in some cases, are entirely second order by comparison with the corresponding quantities for the cations. The destabilization energies produced by the field/inductive interactions of a given diplar substituent (as judged by the meta-substituent interaction energies) decrease in the order pyrH⁺ > ArNH₃⁺ ≫ pyr > ArNH₂ (aniline shows no apparent σ_I-type effect).[29b] Likewise, the stabilization energies produced by a given strong π-electron donor substituent (as judged by the para-substituent interaction energies) decrease in this same order: pyrH⁺ > ArNH₃⁺ > pyr > ArNH₂. Now, in fact, the interaction energies change from small stabilizations in the pyridine to π-repulsive destabilizations in the aniline.

Resonance effects may be approximately judged by the interaction energy difference for a given substituent between the para and the meta positions. These are the Δ values listed in Table VIII. The Δ values follow the relationships noted above but in addition appear to show the following results. There appear to be little or no resonance effects of +R substituents in either pyrH⁺, pyr, or ArNH₃⁺. Given this conclusion, the Δ values for +R substituents in these systems seem to be consistent with the assumed K values used with eq 6; i.e., $K = 1.06$ for pyridinium and $K = 1.00$ for anilinium ions. Admittedly, the generally small Δ values, however, cannot be taken to provide strong confirmatory evidence for these conclusions. Anilines are increasingly stabilized by increasingly strong π-electron acceptor substituents and are increasingly destablized by π-donor substituents of increasing strength. The large positive $\delta\Delta E^{\circ}$ values obtained for -R para substituents in the calculated acidities of anilinium ions are shown to result predominantly from field-induced resonance (FIRE) stabilization[31] of the anilinium ion (positive $\Delta_{ArNH_3^+}$ values) with second-order contributions from π repulsive saturation effects in the aniline (negative Δ_{ArNH_2} values). While hydration of the anilinium ion is expected to reduce the FIRE interactions,[28,32] there can be no assurance in view

of the present results that these are negligible or even the minor consideration in the aqueous solution acidities.

The interaction energies of +R para substituents in aniline ($\Delta\epsilon^{\circ}_{ArNH_2}$ values of Table VIII) are in remarkably good agreement with the experimental R^p values obtained (cf. Table II) for aqueous anilinium ion acidities and seem to identify this as the origin of the latter effects.

However, the relative magnitudes of the substituent interaction energies (the clear dominance of F over R effects in Tables VII and VIII) indicate that it must be a coincidence of the consequences of aqueous medium effects on anilinium ion solvation that the acidities of anilinium ions in aqueous solution are of the σ^- type, i.e., give a linear free-energy relationship with the acidities of phenols in water. No such LFER is anticipated in the gas phase in terms of the present analysis. A plot of the theoretically calculated phenol acidities[29a] vs. the corresponding calculated anilinium ion acidities (Table VII) is so highly scattered as to clearly make this prediction. Inherent σ^--type parameters must be based upon gas-phase phenol acidity or very similar acidities.[25,29b]

Double-Proton-Transfer Equilibria. The theoretical calculations for substituent effects on anilinium ion acidities may be combined with those for aniline acidities[29] to give the substituent effects for the hypothetical double-proton-transfer reaction (9). The results obtained for

$$XC_6H_4NH_3^+ + C_6H_5NH^- \rightleftharpoons XC_6H_4NH^- + C_6H_5NH_3^+ \tag{9}$$
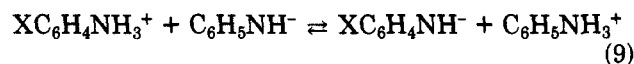
reaction 9 are recored in Table IX and are compared with the available experimental values. Agreement is generally good. Also given in Table IX are the F^p and R^p values calculated by using eq 6 and 7, with $K = 1.00$ and $\alpha = 0.2$ for +R and 0.4 for -R substituents. The F^p values divided by -28.5 ($=\rho_I$) give the calculated σ_I values which are in excellent accord with those obtained in theoretical calculations for other acidity series. This is a significant result since it has been shown that polarizability effects are largely eliminated in double-proton-transfer reactions,[33] e.g., reaction 9. The agreement of the results from reaction 9 with those for corresponding anilinium ion acidities (cf. Table VII) therefore offers further evidence for the absence of significant polarizatility effects for most of the substituents involved in the latter reaction.

The R^p values for reaction 9 are of the expected signs and large magnitudes. In accord with the analysis of the

(31) T. J. Broxton, G. Bull, R. Liu, L. H. Teo, R. D. Topsom, and A. R. Katritzky, J. Chem. Soc., Perkin Trans. 2, 463 (1974).

(32) Cf. also M. Taagepera, D. DeFrees, W. J. Hehre, and R. W. Taft, J. Am. Chem. Soc., 102, 424 (1980).

(33) R. W. Taft, M. Taagepera, J. L. M. Abboud, J. F. Wolf, D. J. DeFrees, W. J. Hehre, J. E. Bartmess, and R. T. McIver, Jr., J. Am. Chem. Soc., 100, 7765 (1978).

Table X

	deviation, $\delta \Delta G^P_{aq}$(calcd) – $\delta \Delta G^P_{aq}$(obsd), kcal/mol		
	A^a	B^a	C^a
CO_2CH_3	-0.09	-0.13	-0.11
CH_3CO	0.04	-0.01	-0.01
CF_3	-0.26	-0.23	-0.19
CN	0.02	0.04	0.03
NO_2	0.14	0.17	0.15
C_6H_5CO	0.10	0.06	0.07
av dev	±0.11	±0.11	±0.09
SD	±0.15	±0.16	±0.15

^{a} Correlation equations: A, $\delta \Delta G^P_{aq} = -8.13\sigma_I$, $n - 1 = 5$; B, $\delta \Delta G^P_{aq} = -7.95\sigma_I - 0.67$, $n - 2 = 4$; C, $\delta \Delta G^P_{aq} = -8.01\sigma_I - 1.16\sigma_R{}^+ + 0.10$, $n - 3 = 4$ (the H point as 0.00 is included).

Table XI

	deviation, $\delta \Delta G^P_g$(calcd) – $\delta \Delta G^P_g$(obsd), kcal/mol			
	A'^a	B'^a	C'^a	D'^a
CO_2CH_3	-1.0	-0.6	-0.5	-1.2
CH_3CO	-0.5	-0.1	-0.1	-0.9
CF_3	0.2	0.0	0.1	0.1
CN	0.1	-0.1	-0.1	-0.1
NO_2	0.2	0.0	0.0	0.0
CHO	0.0	0.4	0.4	0.5
av dev	±0.3	±0.2	±0.2	±0.7
SD	±0.5	±0.4	±0.4	

^{a} Correlation equations: A', $\delta \Delta G^P_g = -19.2\sigma_I$, $n - 1 = 5$; B', $\delta \Delta G^P_g = -20.5\sigma_I + 4.3\sigma_R{}^+$, $n - 2 = 4$; C', $\delta \Delta G^P_g = -20.6\sigma_I + 3.4\sigma_R{}^+ + 0.2$, $n - 3 = 4$ (the H point as 0.0 is included); D', $\delta \Delta G^P_g = -19.0\sigma_I - 2.2\sigma_R{}^+$.

experimental results presented in a previous section of this paper, it is to be noted that for the π-electron acceptor substituents, CF_3, CN, and NO_2, the $-F^p$ values are of greater magnitude than the corresponding $-R^p$ values.

Isolated Molecule Calculations. Ab initio molecular orbital theory calculations may be applied toward investigation of the nature of F-effect contributions to substituent interaction energies. In particular, it is of interest to learn from theory the relative contributions from field charge–dipole interaction,[34] charge-induced polarization of the aromatic π-electrons (π-inductive effect[35]), and internal σ bond inductive effects. This question may be investigated through the use of "isolated molecule" calculations[36] in which the substituent interaction energies in anilinium ions are compared with those obtained for the following "isolated" molecule reaction:
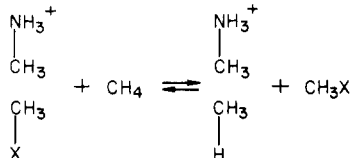
In the above hypothetical reaction, the orientations and distances of the substituents, X, and the $NH_3{}^+$ reaction center are made identical with those for the corresponding substituted anilinium ions. The change in ground-state electronic energy calculated for this "isolated molecule" reaction is represented as $\Delta\epsilon°_{IM}$. Comparing the $\Delta\epsilon°_{IM}$ calculated values with the corresponding $\Delta\epsilon°_{ArNH_3{}^+}$ values for para CF_3, CHO, CN, and NO_2 substituents, one finds the latter to be greater by a factor of 1.6 ± 0.1 ($\Delta\epsilon°_{IM}$ and $\Delta\epsilon°_{ArNH_3{}^+}$ values are in kilocalories/mole, respectively: 3.3, 5.1; 2.1, 3.5; 5.3, 9.0; 7.8, 12.6). This result is contrary to that obtained with saturated molecular cavities for which the isolated molecule calculations are found to be equal to those for the molecular system.[37] We may conclude, consequently, that either or both of the following considerations lead to the substantially larger interaction energies in the anilinium system: (a) greater s hybridization of the

ring carbon atoms; (b) substituent-induced polarization of the ring π electrons (π inductive effects[35]).

Further Analysis of Field/Inductive Effects for Pyridinium Ion Acidities and the +R Substituent Classification. In the presence of relatively large field/inductive effects it is a nontrivial matter to correctly identify the magnitudes of secondary resonance effects or even their sign. We illustrate this point with several alternate fits of the data for +R para-substituted pyridinium acidities. First, consider the aqueous solution phase data (Table X), for which the average experimental error is approximately ±0.10 kcal/mol.

In correlation eq A–C of Table X, EBT parameters have been employed.[5e] The average deviations and root-mean-square standard deviations for all three correlations are close to experimental error. However, we believe that the correlation of relatively precisely measured substituent effects with a single generalized substituent parameter, involving no adjustable degree of freedom in the intercept (correlation A), is to be given some preference over correlation equations with two and three adjustable parameters (B and C, respectively), unless there is truly a significant different in the precision of fit *relative to the experimental errors*. However, the fact that both correlations B and C indicate small R^p_{aq} values (of the same signs) means that one cannot exclude with high confidence the contributions of small electron-withdrawing R^p_{aq} effects. Correlation C places R^p_{aq} values between –0.09 kcal/mol for the CF_3 substituent and –0.19 kcal/mol for CH_3CO, a level of contribution which is not very important nor very clearly outside of the experimental error.

The larger gas-phase substituent effects tend to be somewhat more discriminating. The experimental errors of these data are estimated to be ±0.2 kcal/mol. Equations A'–D' (see Table XI) are based upon these data with the use of $\sigma_{I(g)}$ values from ref 25 and $\sigma_R{}^+$ values from ref 5e (0.22 has been used for the $\sigma_R{}^+$ value for CHO[24b]). The correlation eq B' and C', which both have dependences on $\sigma_R{}^+$ (which are in sign π-electron-donating effects), give somewhat better fits, and these are similar to the experimental errors. Further, t tests indicate that for correlation eq C' the dependence on $\sigma_R{}^+$ is significant at an ~92% confidence level[38] but that there is no significance to the intercept of 0.2. However, since σ_I values tend to be appreciably larger than $\sigma_R{}^+$ values and both sets of parameters have uncertainties, there must be reserve in preferring either eq B' or C' over eq A' which involves only a σ_I dependence. For example, with $-\rho_I \simeq 20$ kcal/mol/σ_I unit (cf. Figure 4), an uncertainty of 0.03 in the σ_I value cor-

(34) Cf. C. S. Yoder and C. H. Yoder, *J. Am. Chem. Soc.*, **102**, 1245 (1980).

(35) (a) G. L. Anderson, R. C. Parish, and L. M. Stock, *J. Am. Chem. Soc.*, **93**, 6984 (1971); (b) W. F. Reynolds, I. R. Peat, M. H. Freedman, and J. R. Lyerla, *Can. J. Chem.*, **51**, 1857 (1973); (c) S. K. Dayal and R. W. Taft, *J. Am. Chem. Soc.*, **95**, 5595 (1973); (d) W. F. Reynolds and G. K. Hamer, *ibid.*, **98**, 7296 (1976); (e) R. T. C. Brownlee, G. Butt, M. P. Chan, and R. D. Topsom, *J. Chem. Soc., Perkin Trans. 2*, 1486 (1976); (f) D. F. Ewing, S. Sotheeswaran, and K. J. Toyne, *Tetrahedron Lett.*, 2041 (1977); (g) W. Adcock and T. C. Khor, *J. Am. Chem. Soc.*, **100**, 7799 (1978).

(36) R. G. Mezey and W. F. Reynolds, *Can. J. Chem.*, **55**, 1567 (1977).

(37) R. D. Topsom, *Tetrahedron Lett.*, 403 (1980).

(38) S. Ehrenson, *J. Org. Chem.*, **44**, 1793 (1979).

responds to an uncertainty in F^p_g values of 0.6 kcal/mol. The R^p_g values indicated by correlations B' and C' range from 0.3 for CF_3 to 0.9 kcal/mol for CHO. These values are not, therefore, clearly outside this level of uncertainty. However, it must be pointed out also that if the strongly demanding unsolvated pyridinium ion center does reverse the usual direction of π-electron effects, i.e., making normally +R substituents instead π donors (as suggested by eq B' and C'), then more appropriate σ_R^+ values are doubtlessly required. These more appropriate σ_R^+ values could reasonably lead to a more significant improvement in the fit. There is a significant point shown further by the results from D', an equation which is not a least-squares best fit but is one which retains acid-strengthening negative R^p_g values for the +R substituents with $\rho_R/\rho_I = \lambda_g \simeq 0.1$, the same as indicated by eq B and C for the aqueous acidities. The average deviation for eq D' (± 7 kcal/mol) is greater than 3 times the experimental error and greater than 2 times the average deviations for eq A'–C'. The much poorer fit by eq D' offers evidence that there is a reversal in sign of the (relatively small) resonance effects of normally +R substituents between the hydrated and the unhydrated pyridinium ions. Finally, the fact that the gas-phase data show no tendency toward a significant postive intercept argues that any acid-weakening polarizability effects are small.

Our theoretical calculations do offer confirmation of the possibility that there are small resonance effects on gas-phase acidities, resulting from π-electron donation from the p-CF_3, p-CN, p-CHO, and p-NO_2 substituents to the strongly acceptor-unsolvated pyridinium ion center. The total π electronic charge, Δq_π, *transferred to* the ring from these substituents in the ion is found to be -4×10^{-3}, -27×10^{-3}, -21×10^{-3}, and -15×10^{-3} electrons, respectively, while in the neutral base these substituents act as π acceptors by 9×10^{-3}, 16×10^{-3}, 24×10^{-3}, and 22×10^{-3} electrons, respectively. The calculations indicate further that one hydrogen bond donor water molecule attached to the pyridinium ion center reduces the π donor effects of CF_3 and CN to -1×10^{-3} and -16×10^{-3} electrons, respectively.[39] Evidence has been accumulating that under high electron demand, substituents which are more normally π-electron acceptors become π-electron donors.[40] In this sense it appears that there are few, if any, substituents that act uniquely as π-electron acceptors but by nature are all amphielectronic.

Conclusions

An analysis has been carried out of the gas- and aqueous-phase acidities of meta- and para-substituted pyridinium and anilinium ions by using methods of substituent parameter treatments and ab initio molecular orbital theory calculations at the STO-3G level of approximation. The following conclusions are indicated. (1) Field/inductive effects (F) of strongly electron-attracting dipolar substituents are the major factor in the strongly enhanced acidities. π-Electron delocalization effects (R) tend to be second order by comparison, especially in the gas phase. Thus, for example, resonance stabilization of p-nitroaniline is only a relatively minor contributor to the greatly increased acidity of p-nitroanilinium ion (compared to that for anilinium ion), the major contributor being the

field/inductive destabilization of the anilinium ion by the nitro substituent. Even though aqueous medium effects tend to strongly attenuate this F effect, the R effect remains the smaller contributor to the greater acidity of p-nitroanilinium ion compared to that of anilinium, even in water. (2) Resonance effects of +R substituents in general are small or negligible for aqueous pyridinium acidities and are probably small and reversed for gas-phase acidities. The small π-donor (not acceptor) interactions of the normally +R substituents result from the high electron demand of the unsolvated pyridinium ion center. (3) Strong π-donor (–R) substituents do contribute large acid-weakening R effects both to anilinium ion and particularly to pyridinium ion acidities. The R effects for these substituents in the gas-phase acidities of the pyridinium ions indicate that the high electron demand of the unsolvated pyridinium center is unable to invoke a fixed enhancement factor from all –R substituents, but, instead, there is a leveling in the π-donor effects of the strongest –R substituents, e.g., $N(CH_3)_2$. Further, the R effects at the meta relative to the para position (i.e., $\alpha = R^m/R^p$) are substantially greater in the gas phase than in aqueous solution. (4) Field/inductive effects correlate well with the σ_I substituent parameters. Hydrogen bond acceptor substituents, e.g., $N(CH_3)_2$ or CH_3CO, are found to have more positive σ_I values in aqueous solution than in the gas phase as a result of hydrogen bonding by water to these substituents. (5) The acidities of para-substituted anilinium ions are found to be unsuitable for the definition of inherent σ_p^- or σ_R^- parameters. Aqueous medium effects are indicated to be such as to tend to produce a *coincidental* LFER relationship in aqueous solvents between anilinium ion and corresponding phenol acidities. (6) Polarizability effects of meta and para substituents containing electronegative atoms and no large alkyl or aryl groups are found to be small or negligible in the gas-phase acidities.

(39) W. J. Hehre, M. Taagepera, R. W. Taft, and R. D. Topsom, *J. Am. Chem. Soc.*, in press.

(40) (a) R. W. Taft, R. H. Martin, and F. W. Lampe, *J. Am. Chem. Soc.*, **87**, 2490 (1965), footnote 10; (b) P. G. Gassman and J. J. Talley, *ibid.*, **102**, 1214 (1980); (c) W. F. Reynolds, P. Dais, R. W. Taft, and R. D. Topsom, submitted for publication in *Tetrahedron Lett.*

Kinetic Study of the Reversible Formation of Cyclic Hemiacetals from 2-(Hydroxymethyl)benzaldehyde and 2-(β-Hydroxyethyl)benzaldehyde

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The title aldehydes 1 and 3 exist in equilibrium with cyclic hemiacetal forms 2 and 4, respectively, with equilibrium constants in water of 6.7 (1 ⇌ 2) and 20 (3 ⇌ 4). These equilibria are displaced toward the hemiacetals in strongly basic solutions because of their ionization. Acidity constants have been determined to be 12.29 (2) and 12.38 (4). The kinetics of the equilibration have been studied in the pH range 1–8 in carboxylic acid and alkylphosphonic acid buffers. The base forms (RCOO$^-$ and RPO$_3$$^{2-}$) produce a common Brønsted line, while the acid forms produce two distinct Brønsted relations, with that for RHPO$_3$$^-$ being displaced about one logarithmic unit above that for RCOOH. It is concluded that the former are not acting as bifunctional catalysts but owe their enhanced reactivity to an electrostatic effect. It is, moreover, suggested that the acid-catalyzed equilibrations are proceeding by way of two competing mechanisms, one involving as an intermediate the protonated hemiacetal and the other the protonated benzaldehyde. Several acetals related to 2 and 4 have also been prepared, and the kinetics and mechanism of their hydrolyses are discussed.

The reversible addition of water and alcohol molecules to aldehydes has been a subject of considerable interest.[1] The reaction represents the simplest example of the important class of reactions in which a nucleophile undergoes reversible addition to a carbonyl group. It requires the making or breaking of only one bond between heavy atoms and the net transfer of one proton. Catalysis by both acids and bases is invariably observed, although the exact nature of the catalysis has been the topic of much speculation, particularly with regards to the timing of the various processes.[1,2] Detailed investigations have in general been limited to aliphatic systems, since it is only with these that the addition reaction occurs to a significant extent. Acetaldehyde, for example, is approximately 50% hydrated in water, and, consequently, detailed kinetic study presents little problem.[3] Benzaldehydes on the other hand are much less hydrated, unless they contain strongly electron-withdrawing substituents.[4-8] The parent benzaldehyde, for example, is estimated to be only about 1% hydrated in aqueous solution.[5,8] Hydroxide ion[5,7,9] and methoxide ion[10] do readily undergo addition to benzaldehyde, but studies of this are limited to strongly basic solutions. Kinetic data have recently been reported for the breakdown of benzaldehyde hemiacetals formed as intermediates in the hydrolysis of precursor acylals[11] or acetals.[12,13] These studies are somewhat limited in that the breakdown of the hemiacetal can only be studied when this reaction proceeds more slowly than the hemiacetal is formed. Moreover, information relating to the reverse addition reaction requires certain assumptions to be made. A detailed kinetic study of the hydration of phthalaldehyde has also been recently reported.[14] However, the overall reaction here is not a simple hydration, since the ultimate produce is a cyclic species.

We report here a study of the reactions described in eq 1, involving the intramolecular addition of an alcohol group

1, n = 1   2, n = 1
3, n = 2   4, n = 2
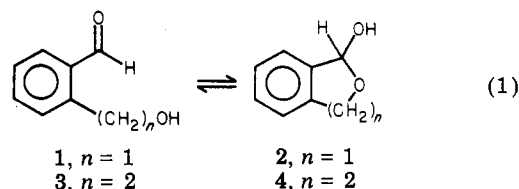
to a benzaldehyde to form a cyclic hemiacetal.[15] In ad-

(1) (a) Bell, R. P.; Higginson, W. C. E. *Proc. R. Soc. London, Ser. A* **1949**, *197*, 141. (b) Gruen, L. C.; McTique, P. T. *J. Chem. Soc.* **1963**, 5224. (c) Jencks, W. P. *Prog. Phys. Org. Chem.* **1964**, *2*, 63. (d) Bell, R. P. *Adv. Phys. Org. Chem.* **1966**, *4*, 1. (e) Eigen, M. *Discuss. Faraday Soc.* **1965**, *39*, 7. (f) Jencks, W. P. *Acc. Chem. Res.* **1976**, *9*, 425.

(2) Funderburk, L. H.; Aldwin, L.; Jencks, W. P. *J. Am. Chem. Soc.* **1978**, *100*, 5444.

(3) Bell, R. P.; Rand, M. H.; Wynne-Jones, K. M. A. *Trans. Faraday Soc.* **1956**, *52*, 1093.

(4) Sander, E. G.; Jencks, W. P. *J. Am. Chem. Soc.* **1968**, *90*, 6154.

(5) Greenzaid, P. *J. Org. Chem.* **1973**, *38*, 3164.

(6) Sayer, J. M. *J. Org. Chem.* **1975**, *40*, 2545.

(7) Bell, R. P.; Sorenson, P. E. *J. Chem. Soc., Perkin Trans. 2* **1976**, 1594.

(8) Guthrie, J. P. *Can. J. Chem.* **1978**, *56*, 962.

(9) Bover, W. J.; Zuman, P. *J. Chem. Soc., Perkin Trans. 2* **1973**, 786.

(10) Arora, M.; Cox, B. G.; Sorenson, P. E. *J. Chem. Soc., Perkin Trans. 2* **1979**, 103.

(11) Capon, B.; Nimmo, K.; Reid, G. L. *J. Chem. Soc., Chem. Commun.* **1976**, 871.

(12) Jensen, J. L.; Lenz, P. A. *J. Am. Chem. Soc.* **1978**, *100*, 1291.

(13) Finley, R. L.; Kubler, R. G.; McClelland, R. A. *J. Org. Chem.* **1980**, *45*, 644.

(14) McDonald, R. S.; Martin, E. V. *Can. J. Chem.* **1979**, *57*, 506.