JOURNAL
OF THE AMERICAN CHEMICAL SOCIETY

Registered in U. S. Patent Office.

VOLUME 90, NUMBER 22 OCTOBER 23, 1968

Physical and Inorganic Chemistry

Thermodynamics of Proton Ionization in Dilute Aqueous Solution. X. ΔG° (pK), ΔH°, and ΔS° Values for Proton Ionization from Several Monosubstituted Carboxylic Acids at 10, 25, and 40°[1a]

James J. Christensen,[1b] John L. Oscarson, and Reed M. Izatt[1c]

Contribution from the Departments of Chemical Engineering and Chemistry, Brigham Young University, Provo, Utah 84601. *Received April 13, 1968*

Abstract: A calorimetric study has been made of proton ionization in aqueous solution from aliphatic monocarboxylic acids at 10, 25, and 40° (15 acids) and at 25° (8 acids). The resulting ΔH° values were combined with ΔG° values obtained from the literature or determined from potentiometric measurements to calculate corresponding ΔS° values. Values of ΔC_p are reported in those cases where the ΔH° values were determined at three temperatures. It has been found that the trends in ΔG°, ΔH°, and ΔS° are best described by an electrostatic model. Deviations from this model were taken as a measure of nonelectrostatic substituent effects for carboxylic acids.

This study was undertaken as part[2] of a program to determine the thermodynamic quantities associated with proton ionization from a variety of donor atom types. The present study deals with proton ionization from the carboxyl group of straight-chain aliphatic carboxylic acids containing one substituent group (*i.e.*, chloro, bromo, iodo, methoxy, methyl, ethyl, hydroxyl, and protonated amino groups). Thermodynamic pK, ΔH°, and ΔS° values are given at 10, 25, and 40° for 15 of the acids studied, and at 25° for eight other acids. ΔC_p values calculated from the change in enthalpy with temperature are given at 25° for 15 acids.

The amino acids consisting of five acids with the amino group on the second carbon atom and six acids with the amino group on the terminal carbon atom were the most complete series of carboxylic acids investigated in this study. The amino acids provide a good model for studying electrostatic effects on proton ionization from the -COOH group since the protonated amino group has a formal charge of +1.

The other acids investigated are the beginning of a study of the effects of noncharged substituents on the thermodynamic quantities involved in proton ionization from carboxylic acids. Although this study is a continuing one, a preliminary discussion of the effect of the substitution on ΔG°, ΔH°, and ΔS° is included in this paper.

Precise pK values for a large number of carboxylic acids are available[3,4] and ΔH° and ΔS° values in many cases have been determined using temperature coefficient methods, but relatively few ΔH° values have been determined calorimetrically. Despite the availability of a considerable number of ΔH° data, most discussion of the relative strengths of carboxylic acids is based on

---

[1] (a) Supported by National Institutes of Health Research Grant RG-9430-06. Presented in part at the Northwest Regional Meeting of the American Chemical Society, Richland, Wash., June 15-16, 1967. (b) Supported (in part) by Public Health Service Research Career Development Award No. 1-K3-GM-24, 361-01. (c) Supported (in part) by Public Health Service Research Career Development Award No. 1-K3-GM-35, 250-01.

[2] (a) Part VII: J. J. Christensen, R. M. Izatt, and L. D. Hansen, *J. Amer. Chem. Soc.*, **89**, 213 (1967). (b) Part VIII: J. J. Christensen, J. H. Rytting, and R. M. Izatt, *J. Phys. Chem.*, 71, 2700 (1967). (c) Part IX: J. J. Christensen, D. P. Wrathall, R. M. Izatt, and D. O. Tolman, *ibid.*, 71, 3001 (1967).

[3] G. Kortum, W. Vogel, and K. Andrussow, "Dissociation Constants of Organic Acids in Aqueous Solution," Butterworth and Co., Ltd., London, 1961.

[4] L. G. Sillen and A. E. Martell, "Stability Constants of Metal Ion Complexes," 2nd ed, Special Publication No. 17, The Chemical Society, London, 1964.

Table I. Thermodynamic Quantities for Proton Ionization in Aqueous Solution from Carboxylic Acids at $\mu = 0^a$

Name	Formula[b]	Temp, °C	pK	$\Delta G°$, kcal/mol	$\Delta H°$, kcal/mol	$\Delta S°$, cal/deg mol	ΔC_p, cal/deg mol
1. α-Alanine	$CH_3CHNH_3^+$	10	2.392^c	3.099^c	1.25 ± 0.06 $(1.28)^c$	−6.5	
		25	2.348^c	3.203^c	0.75 ± 0.05^d $(0.80)^c$	−8.2	−34
		40	2.328^c	3.334^c	0.23 ± 0.14 $(0.23)^c$	−9.9	
2. β-Alanine	$NH_3^+(CH_2)_2$	10	3.606^e	4.673^e	1.60 ± 0.06	−10.9	
		25	3.551^e	4.845^e	1.04 ± 0.03 $(1.08)^d$	−12.8	−33
		40	3.517^e	5.040^e	0.62 ± 0.05	−14.1	
3. α-Aminobutyric	$CH_3CH_2CHNH_3^+$	10	2.315^c	3.000^c	0.77 ± 0.03 $(0.80)^c$	−7.7	
		25	2.286^c	3.119^c	0.38 ± 0.05 $(0.31)^c$	−9.2	−24
		40	2.289^c	3.280^c	0.04 ± 0.02 $(-0.31)^c$	−10.4	
4. γ-Aminobutyric	$NH_3^+(CH_2)_3$	10	4.057^f	5.257^f	0.75 ± 0.03	−15.9	
		25	4.031^f	5.500^f	0.39 ± 0.04 $(0.405)^f$	−17.2	−25
		40	4.027^f	5.771^f	0.01 ± 0.02	−18.5	
5. α-Aminohexanoic	$CH_3(CH_2)_3CHNH_3^+$	10	2.363^c	3.062^c	0.92 ± 0.21 $(0.98)^c$	−7.6	
		25	2.335^c	3.186^c	0.43 ± 0.05 $(0.56)^c$	−9.2	−33
		40	2.324^c	3.330^c	-0.07 ± 0.02 $(-0.50)^c$	−10.7	
6. ε-Aminocaproic	$NH_3^+(CH_2)_5$	10	4.392^g	5.716^g	0.10 ± 0.05 $(0.53)^g$	−19.8	
		25	4.373^g	5.967^g	-0.32 ± 0.04 $(-0.01)^g$	−21.1	−30
		40	4.388^g	6.288^g	-0.79 ± 0.08 $(0.83)^g$	−22.6	
7. Glycine	$NH_3^+CH_2$	10	2.397^h	3.015^h	1.41 ± 0.06 $(1.67)^i$	−5.8	
		25	2.350^h	3.206^h	0.98 ± 0.05^d $(0.953)^h$ $(1.18)^i$ $(1.16)^j$	−7.5	−29 $(-34.5)^h$
		40	2.327^h	3.334^h	0.47 ± 0.03 $(0.630)^i$	−9.2	
8. ω-Aminoheptanoic	$NH_3^+(CH_2)_6$	25	4.502	6.142	-0.47 ± 0.03	−22.2	
9. α-Aminovaleric	$CH_3(CH_2)_2CHNH_3^+$	10	2.347^c	3.094^c	0.83 ± 0.07 $(1.18)^c$	−8.0	
		25	2.318^c	3.163^c	0.39 ± 0.04 $(0.55)^c$	−9.3	−30
		40	2.309^c	3.309^c	-0.06 ± 0.04 $(0.06)^c$	−10.7	
10. δ-Aminovaleric	$NH_3^+(CH_2)_4$	10	4.26	5.51	0.28 ± 0.02	−18.5	
		25	4.20^k	5.72^k	-0.22 ± 0.02	−19.9	−30
		40	4.25	6.08	-0.61 ± 0.05	−21.4	
11. Acetic	CH_3	10	4.762^l	6.170^l	0.47 ± 0.05 $(0.389)^l$	−20.2	
		25	4.756^l	6.487^l	-0.02 ± 0.05^d $(-0.112)^l$ $(0.09)^m$	−21.9	−34
		40	4.769^l	6.834^l	-0.50 ± 0.03 $(-0.628)^l$	−23.4	
12. Bromoacetic	$BrCH_2$	25	2.902^n	3.960^n	-1.10 ± 0.04 $(-1.239)^n$	−17.0	−22
		40	2.93	4.199	-1.43 ± 0.02	−19.9	
13. β-Bromopropionic	$Br(CH_2)_2$	25	3.992^o	5.447^o	-0.17 ± 0.06 $(-0.32)^d$	−18.9	
14. *n*-Butyric	$CH_3(CH_2)_2$	25	4.817^p	6.576^p	-0.64 ± 0.04 $(-0.691)^p$	−24.2	−32
		40	4.854^p	6.958^p	-1.12 ± 0.05 $(-1.437)^p$	−25.8	
15. Chloroacetic	$ClCH_2$	10	2.827^q	3.771^q	-0.46 ± 0.01 $(-0.593)^q$	−15.0	
		25	2.858^q	3.901^q	-0.99 ± 0.04 $(-1.170)^q$	−16.4	−36
		40	2.910^q	4.171^q	-1.53 ± 0.05 $(-1.639)^q$	−18.2	
16. β-Chloropropionic	$Cl(CH_2)_2$	25	3.992^r	5.447^r	-0.51 ± 0.03 $(-0.32)^r$	−20.0	
17. α-Ethylbutyric	$(CH_3CH_2)_2CH$	25	4.74^s	6.465^s	-1.86 ± 0.26 $(-2.030)^s$	−27.6	

Table I (*Continued*)

	Name	Formula[b]	Temp, °C	pR	$\Delta G°$, kcal/mol	$\Delta H°$, kcal/mol	$\Delta S°$, cal/deg mol	ΔC_p, cal/deg mol
18.	Glycolic	$HOCH_2$	10	3.848[t]	4.986[t]	0.53 ± 0.10 (0.73)[t]	−15.8	
			25	3.831[t]	5.245[t]	0.15 ± 0.05 (0.11)[d] (0.210)[t]	−17.1	−31
			40	3.835[t]	5.496[t]	−0.39 ± 0.24 (0.43)[t]	−18.8	
19.	Iodoacetic	ICH_2	10	3.124	4.048	−0.75 ± 0.08	−16.9	
			25	3.175[n]	4.324[n]	−1.21 ± 0.07 (−1.416)[u]	−18.6	−29
			40	3.211	4.601	−1.51 ± 0.12	−19.5	
20.	Isobutyric	$(CH_3)_2CH$	25	4.853[r]	6.610[r]	−0.76 ± 0.05 (−0.775)[r]	−24.7	
21.	Isocaproic	$(CH_3)_2CH(CH_2)_2$	25	4.845[i]	6.617[i]	−0.61 ± 0.01 (−0.716)[i]	−24.2	
22.	Isovaleric	$(CH_3)_2CHCH_2$	25	4.770[r]	6.505[r]	−1.15 ± 0.01 (−1.168)[r]	−25.9	
23.	Methoxyacetic	CH_3OCH	10	3.544[u]	4.592[u]	−0.35 ± 0.06	−17.4	
			25	3.570[u]	4.856[u]	−0.94 ± 0.01 (−0.960)[u]	−19.4	−38
			40	3.613[u]	5.177[u]	−1.148 ± 0.07	−22.3	

[a] The uncertainties are given as twice the standard deviation. Values for ΔH and ΔC_p, determined by previous investigators for the acids studied here, are given in parentheses. [b] The formula given is R corresponding to R–COOH. [c] P. K. Smith, A. C. Taylor, and E. R. B. Smith, *J. Biol. Chem.*, **122**, 109 (1937). [d] J. J. Christensen, R. M. Izatt, and L. D. Hansen, *J. Amer. Chem. Soc.*, **89**, 213 (1967). [e] M. May and W. A. Felsing, *ibid.*, **73**, 406 (1951). [f] E. J. King, *ibid.*, **76**, 1006 (1954). [g] E. R. B. Smith and P. K. Smith, *J. Biol. Chem.*, **146**, 187 (1942). [h] E. J. King, *J. Amer. Chem. Soc.*, **73**, 155 (1951). [i] H. S. Harned and N. D. Embree, *ibid.*, **56**, 1050 (1934). [j] G. Aksnes, *Acta Scand. Chem.*, **16**, 1967 (1962). [k] C. L. A. Schmidt, W. K. Appelman, and P. L. Kirk, *J. Biol. Chem.*, **81**, 723 (1929). [l] H. S. Harned and R. W. Ehlers, *J. Amer. Chem. Soc.*, **55**, 652 (1933). [m] I. Wadso, *Acta Chem. Scand.*, **16**, 479 (1962). [n] D. J. G. Ives and J. H. Pryor, *J. Chem. Soc.*, 2104 (1955). [o] A. W. Walde, *J. Phys. Chem.*, **43**, 431 (1939). [p] H. S. Harned and R. O. Sutherland, *J. Amer. Chem. Soc.*, **56**, 2039 (1934). [q] D. D. Wright, *ibid.*, **56**, 314 (1934). [r] T. L. Cottrell, G. W. Drake. D. L. Levi, K. J. Tully, and J. H. Wolfendon, *J. Chem. Soc.*, 1016 (1948). [s] D. H. Everett, D. A. Landsman, and B. R. W. Pinsent, *Proc. Roy. Soc.* (London), **A215**, 403 (1952). [t] L. F. Nims, *J. Amer. Chem. Soc.*, **58**, 987 (1936). [u] E. J. King, *ibid.*, **82**, 3575 (1960).

pK data. Since the magnitude of the pK values is determined by the relative magnitudes of the corresponding $\Delta H°$ and $T\Delta S°$ values, a knowledge of these values is important for an understanding of the pK trends in any series. Correlations by other workers of $\Delta H°$ and $\Delta S°$ values with acid strength have been summarized.[2a]

Experimental Section

Materials. The following compounds were obtained in the best grade available: α-alanine, β-alanine, α-aminobutyric acid, γ-aminobutyric acid, α-aminocaproic acid, α-aminovaleric acid, bromoacetic acid, β-bromopropionic acid, chloroacetic acid, β-chloropropionic acid, α-ethylbutyric acid, iodoacetic acid, methoxyacetic acid (Eastman White Label), ε-aminocaproic acid, ω-aminoheptanoic acid (City Chemical Corp.), sodium acetate, sodium glycolate, isovaleric acid (Baker Analyzed), butyric acid (Fisher, Highest Purity), isobutyric acid (Fisher, Certified Reagent), glycine (Calbiochem, A Grade), and δ-aminovaleric acid (Sigma).

All the amino acids were recrystallized twice from alcohol–water solutions and dried under vacuum at 50° for several hours. The other solid acids were recrystallized twice from an appropriate solvent (alcohol–water mixture, ether, or benzene) and dried in a similar manner. The liquid acids were fractionally distilled under reduced pressure. They were then treated with slightly less than a stoichiometric amount of sodium hydroxide (Baker, Analyzed Reagent, carbonate free, 50% solution). The resultant solutions of the salts were washed with benzene and ether, and the water was slowly evaporated and alcohol was added until the solutions became slightly turbid. The salts crystallized from the cooled solutions. The salts were then recrystallized from an alcohol–water solution and dried under vacuum. Perchloric acid (Baker and Adamson) was used in all titrations.

Procedure. 1. Calorimetric Determinations. The thermometric titration calorimeter used in this study has been described.[5,6] The calorimeter used allows measurement of heats of 1–10 cal with an accuracy of 0.1%. Solutions of the amino acids and of the sodium salts of the other acids were titrated with perchloric acid solutions at 10, 25, and 40°. At least four thermometric titrations were made for each acid with $\mu \leq 0.02$. Previous studies have shown that at this low ionic strength ΔH values do not vary significantly with μ;[2a] therefore, the ΔH values were assumed to be equal to $\Delta H°$ values, within experimental error, where $\Delta H°$ refers to the standard state defined to be an ideal 1 M solution behaving as an infinitely dilute solution. Heat of dilution data for $HClO_4$ at 25° were taken from the literature.[7] Unpublished heat of dilution values[8] for $HClO_4$ determined in this laboratory at 10 and 40° were used. The heat of ionization of water at 25° was taken from the literature[9,10] while the values of the heat of ionization of water at 10 and 40° were determined in this laboratory.[11]

2. pK Determinations. The method for determining pK values potentiometrically has been described.[12]

Calculations. The method used to calculate $\Delta H°$ values from the thermometric titration data has been described.[6,13] The calculations were aided by an IBM 7040 computer. The computer programs (Fortran IV), input data, and average output data for each run are available.[14]

Results

In Table I are presented the pK, $\Delta G°$, $\Delta H°$, $\Delta S°$, and ΔC_p values determined in this study together with

---

(5) J. J. Christensen, R. N. Izatt, and L. D. Hansen, *Rev. Sci. Instr.*, **36**, 779 (1965).

(6) L. D. Hansen, Ph.D. Dissertation, Brigham Young University, Provo, Utah, 1965; *cf. Dissertation Abstr.*, **26**, 5000 (1966).

(7) J. A. Swanson, Ph.D. Dissertation, University of Nebraska, 1962; *cf. Dissertation Abstr.*, **23**, 92 (1962).

(8) H. D. Johnston, Ph.D. Dissertation, Brigham Young University, Provo, Utah, 1968.

(9) J. D. Hale, R. M. Izatt, and J. J. Christensen, *J. Phys. Chem.*, **67**, 2605 (1963).

(10) C. E. Vanderzee and J. A. Swanson, *ibid.*, **67**, 2608 (1963).

(11) R. M. Izatt, J. J. Christensen, H. D. Johnston, and G. L. Kimball, to be submitted for publication.

(12) L. D. Hansen, J. A. Partridge, R. M. Izatt, and J. J. Christensen, *Inorg. Chem.*, **5**, 569 (1966).

(13) J. J. Christensen, R. M. Izatt, L. D. Hansen, and J. A. Partridge, *J. Phys. Chem.*, **70**, 2003 (1966).

(14) J. L. Oscarson, Undergraduate Thesis, Department of Chemical Engineering, Brigham Young University, Provo, Utah, 1968.

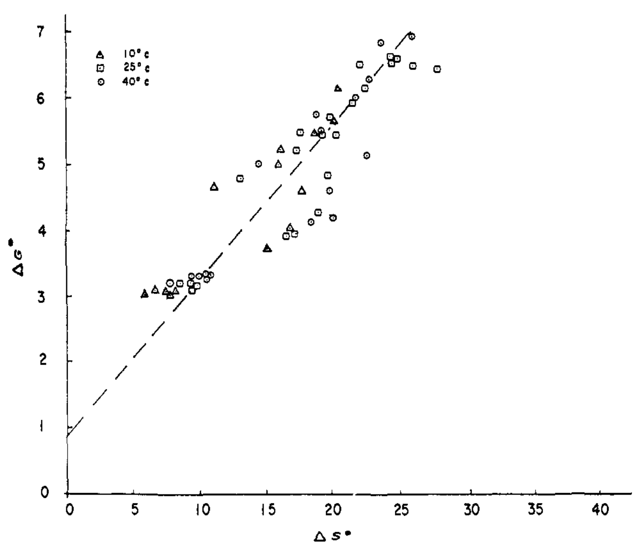


Figure 1. Plot of ΔG° *vs.* ΔS° for proton ionization from carboxylic acid.

previously determined data (in parentheses). All the data in Table I are valid at $\mu = 0$. The precision of the pK values determined in this study is ±0.01 pK unit. The accuracy of the ΔH° values is estimated to be ±50 cal and was obtained from a consideration of the accuracy of the values previously obtained for the heat of ionization of water using the same equipment. The precision reported for the ΔH values listed in Table I is twice the standard deviation of the ΔH values for each set of runs for a given acid. Stated precision values larger than ±50 cal are probably due to errors in the pK values used to calculate the amount of reaction. The combined uncertainties in the pK and ΔH° values will result in an estimated precision of ±0.3 cal/deg mol in the ΔS° values. The combined uncertainties in the ΔH° values at each temperature will result in an estimated precision of 6 cal/deg mol in the ΔC_p values.

Discussion

Generally good agreement is observed between the ΔH° and ΔC_p values determined in this study and those reported by previous workers.

It has been shown[2a] that, as predicted by electrostatics, a plot of ΔG° *vs.* ΔS° for proton ionization from the –COOH group of carboxylic acids is linear. Figure 1 shows that the acids investigated in this study at 10, 25, and 40° also exhibit this linear relationship. The slope of the best line through these points is −243 (Born theory predicts −218) and is the same as that found previously for 103 mono-, di-, and tricarboxylic acids at 25°.[2a] In the present study the acids showing the greatest deviations from the linear correlation are, with the exception of β-alanine, all α-substituted (halogen, ethyl, and protonated amino) acids.

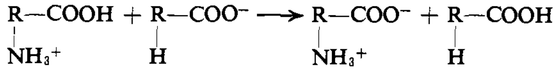
In considering the mechanisms of proton ionization and related energy changes from molecules having charged or polar substituents, it is convenient to think of the thermodynamic properties as consisting of a nonelectrostatic part which includes bond dissociation energies, changes in translational, rotational, and vibrational degrees of freedom, and specific solvent effects, an electrostatic part, and a statistical part.[2a,15] Thermodynamic properties for reaction 1 can therefore be thought of as representing total properties including

$$\mathrm{HA_1 + H_2O \longrightarrow A_1 + H_3O^+} \qquad (1)$$

$$\mathrm{HA_1 + A_2 \longrightarrow A_1 + HA_2} \qquad (2)$$

all three of the above-mentioned quantities whereas thermodynamic properties represented by reaction 2 represent only electrostatic and statistical changes for the ionization of HA_1. The nonelectrostatic changes are essentially eliminated in reaction 2 by choosing an acid HA_2 with as nearly as possible the same nonelectrostatic changes in its thermodynamic properties as acid HA_1. By thus matching the acids, it is possible to cancel the nonelectrostatic change. In the subsequent discussion of substituted acids, whenever reactions of the form of reaction 2 are used, the reference acid (HA_2) will correspond to the primary acid (HA_1) with the substituted group replaced with a hydrogen atom. Thus for ionization of the hydrogen from the carboxyl group in reaction 2, the changes in thermodynamic properties correspond to removing the proton from the electrostatic field of the substituted group.

The amino acids were extensively studied in this work and provide a basis for investigating the effect of a positively charged substituent (protonated amino group) on proton ionization from the carboxyl group. For amine-substituted carboxylic acids reaction 2 takes the form


(3)

$$\underset{\mathrm{NH_3^+}}{\mathrm{R}}\mathrm{{-}COOH} + \underset{\mathrm{H}}{\mathrm{R}}\mathrm{{-}COO^-} \longrightarrow \underset{\mathrm{NH_3^+}}{\mathrm{R}}\mathrm{{-}COO^-} + \underset{\mathrm{H}}{\mathrm{R}}\mathrm{{-}COOH} \qquad (3)$$

The electrostatic theories of Born, Bjerrum, and Kirkwood–Westheimer[16] all lead to the same equation for ΔH for reaction 3

$$\Delta H^{\mathrm{elect}} = \frac{-Ne^2Z}{R\epsilon}\left[1 + T\left(\frac{\partial \ln \epsilon}{\partial T}\right)_{\mathrm{p}}\right] \qquad (4)$$

where $\Delta H^{\mathrm{elect}}$ is the enthalpy change for the proton being removed from the electrostatic field of the positively charged amino group. In eq 4 N = Avagadro's number, e = proton charge, Z = charge number of substituent group, R = proton-charge distance, ϵ = dielectric constant, and T = absolute temperature. It should be noted that the negative sign in eq 4 arises because the substituent is positively charged. The Born and Bjerrum models define ϵ as the effective dielectric constant of the medium, $\epsilon_{\mathrm{water}}$, whereas the Kirkwood–Westheimer model defines ϵ as the effective dielectric constant, ϵ_{eff}, calculated from the estimated dielectric constants of the acid and the medium. Since $T\partial \ln \epsilon_{\mathrm{water}}/\partial T < -1$ for water at 10, 25, and 40°,[17] the quantity in parentheses in eq 4 will be negative and $\Delta H^{\mathrm{elect}}$ will be positive. Some values of $\Delta H^{\mathrm{elect}}$ calculated from the data in Table I for α-amino acids as a function of the number of carbon atoms in the chain at 25° are given in Table II. The values of $\Delta H^{\mathrm{elect}}$ are positive and constant as predicted by the electrostatic theories.

If the value of R, the proton-charge distance, in eq 4 is approximated by nr where n = number of carbon

---

(15) E. J. King, "Acid-Base Equilibria," The Macmillan Co., New York, N. Y., 1965, p 156.

(16) E. J. King, "Acid-Base Equilibria," The Macmillan Co., New York, N. Y., 1965, Chapters 7 and 8.

(17) H. S. Harned and B. B. Owen, "The Physical Chemistry of Electrolytic Chemistry," 3rd ed, Reinhold Publishing Corp., New York, N. Y., 1958, p 161.

Table II. $\Delta H^{\mathrm{elect}}$ (Reaction 3) for a Series of α-Amino Acids at 25°

Acid[a]	Reference acid[b]	$\Delta H^{\mathrm{elect}}$
Glycine	Acetic	1.00
α-Alanine	Propionic	0.89
α-Aminobutyric	*n*-Butyric	1.92
α-Aminovaleric	Valeric	1.11
α-Aminohexanoic	Hexanoic	1.13

[a] Table I. [b] Ref 2a.

atoms between the protonated amino group and the proton on the carboxyl group (*i.e.*, $n = 2$ for glycine, $n = 3$ for β-alanine, etc.) and r = the average distance between carbon atoms in the chain, then the electrostatic models[16] predict linear relationships between $1/n$ and $\Delta G^{\mathrm{elect}}$, $\Delta H^{\mathrm{elect}}$, and $\Delta S^{\mathrm{elect}}$, respectively. These relationships given in eq 5, 6, and 7 predict that a plot of

$$\Delta G^{\mathrm{elect}} = -\frac{Ne^2Z}{\epsilon_r}\left(\frac{1}{n}\right) \tag{5}$$

$$\Delta H^{\mathrm{elect}} = -\frac{Ne^2Z}{\epsilon r}\left[1 + T\left(\frac{\partial \ln \epsilon}{\partial T}\right)_{\mathrm{p}}\right]\left(\frac{1}{n}\right) \tag{6}$$

$$\Delta S^{\mathrm{elect}} = -\frac{Ne^2Z}{\epsilon r}\left(\frac{\partial \ln \epsilon}{\partial T}\right)_{\mathrm{p}}\left(\frac{1}{n}\right) \tag{7}$$

$1/n$ *vs.* $\Delta G^{\mathrm{elect}}$ will have a negative slope while plots of $1/n$ *vs.* $\Delta H^{\mathrm{elect}}$ or $\Delta S^{\mathrm{elect}}$ will have positive slopes. Plots for proton ionization at 25° were constructed and were found to have the predicted slopes and, except for the α-amino acids, to be linear. MacInnes[18] has obtained similar results from plots of pK *vs.* $1/n$. Similar plots at 10 and 40° could not be constructed because of the lack of data for the appropriate reference acids at these temperatures.

The Born theory predicts[19] that for reactions similar to reaction 1, plots of $\Delta G°$, $\Delta H°$, and $\Delta S°$ *vs.* $1/n$ should also be linear and the slopes should have the same signs as those predicted by eq 5, 6, and 7. Plots were constructed which showed, except for the α substituted amino acids, good agreement with the Born theory and showed the following empirical relationships: $\Delta G° = (-6.7/n) + 7.1$, $\Delta H° = (8.3/n) - 1.7$, and $\Delta S° = (50/n) - 29$. The electrostatic models also predict a proportionality between the electrical parts of the entropy changes and the heat capacity changes as shown in eq 8. Evidence of this proportionality is

$$\Delta S^{\mathrm{elect}} = \frac{\Delta C_{\mathrm{p}}^{\mathrm{elect}}}{\left(\frac{\partial \ln \epsilon}{\partial T}\right)_{\mathrm{p}} T} \tag{8}$$

inconclusive from the results of this study in that for any given series not more than two sets of values of ΔS and ΔC_{p} are available. The data do indicate that ΔC_{p} remains almost constant while ΔS undergoes changes of from 4 to 22 eu.

Not enough acids having noncharged substituents are represented in this study to make correlations of $\Delta G°$, $\Delta S°$, or $\Delta H°$ *vs.* $1/n$ meaningful for any given series. However, since the acids studied show the same linear relationship between $\Delta G°$ and $\Delta S°$ as the amino acids (Figure 1), it would be expected that the electrostatic model would also predict the trends in the $\Delta G°$, $\Delta H°$, and $\Delta S°$ values for proton ionization from these acids. Work is now in progress to determine more fully the roles noncharged substituents play in determining the thermodynamic quantities associated with proton ionization from carboxylic acids.

From the above discussion, it is seen that the electrostatic model predicts the effects of substituent groups on $\Delta G°$, $\Delta H°$, and $\Delta S°$ for proton ionization from carboxylic acids except for the cases where the substituent is in the α position. Therefore, there is no need to invoke other explanations such as inductive effects to account for the change in the thermodynamic quantities with the possible exception of the α-substituted acids. The $\Delta H°$ values for the α-amino acids are more negative than electrostatics alone predicts, but the data in Table II show that the electrostatic effects still dominate, as the over-all $\Delta H^{\mathrm{elect}}$ (eq 4) is positive. The specific nonelectrostatic effect that is being observed in the case of the α-amino acids is difficult to assess but is probably due to the inductive effect resulting from the protonated amino group shifting the electron density toward itself and away from the carboxyl group. This would make the ionized carboxyl group more stable, lower the energy of the ionized molecule, and make $\Delta H^{\mathrm{elect}}$ more negative.[20]

---

(18) D. A. MacInnes, *J. Amer. Chem. Soc.*, **50**, 2587 (1928).

(19) Reference 15, p 205.

(20) R. T. Morrison and R. N. Boyd, "Organic Chemistry," Allyn and Bacon, Inc., Boston, Mass., 1959, pp 451, 454.