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THERMODYNAMICS OF HYDROPHOBIC POLYACIDS

Paul J. MARTIN and Ulrich P. STRAUSS
Department of Chemistry, Rutgers, The State University of New Jersey, New Brunswick, New Jersey 08903

The thermodynamics of deprotonating hydrolyzed 1-1 copolymers of maleic anhydride with pentyl, hexyl and octyl vinyl ether was investigated by calorimetric and potentiometric methods. These polyacids undergo a transition from a compact to a random coil conformation upon ionization in aqueous media. The results were compared with those obtained previously for similar copolymers with smaller alkyl side-chains. The contributions of the enthalpy and entropy to the free energy were analyzed. The major effects appeared to be related to the charging of the compact form of the polyacids, the electrostriction of water by the completely ionized dicarboxylate groups and the reorganization of water around newly exposed alkyl side-chains arising from the conformational transition.

1. Introduction

The hydrophobic effect plays an important role in controlling the conformational properties of proteins and other biological systems. Much of our knowledge concerning this effect comes from studies of the transfer of selected organic "model" compounds from hydrocarbon solvents into water [1]. An alternative approach involves the examination of conformational transitions of appropriate hydrophobic polyelectrolytes which may be viewed as macromolecular model compounds. The 1-1 copolymers of maleic acid and alkyl vinyl ethers have been found especially suitable for serving in this role. The polyacids of this family with small alkyl groups are random coils under all conditions. The polyacids with intermediate size alkyl groups undergo, upon ionization, a conformational transition from a compact state, stabilized by hydrophobic forces, to a random coil [2–4].

Recent studies have shown that the enthalpy, entropy and heat capacity changes accompanying the deprotonation of these copolymers appear to be especially sensitive to the resulting rearrangements of the water structure. Such findings promise to elucidate the various types of solvent rearrangements, including those intimately associated with the hydrophobic effect. We want to review here briefly the previous work which was concerned with the methyl through n-butyl copolymers [5], and to report new results obtained with the n-pentyl, n-hexyl and n-octyl copolymers in both 0.2 M tetramethylammonium chloride (TMACl) and 0.2 M LiCl supporting media.

2. Experimental section

The methyl copolymer was GAF sample Gantrez-An #139, purified by successive precipitations using tetrahydrofuran as the solvent and ethyl ether as the non-solvent. The ethyl (sample A-VII), propyl (sample Pr-I, butyl (sample B-VI), pentyl (sample P), hexyl (sample C) and octyl (sample D) copolymers were synthesized and purified by a previously described method [2,4]. All acids, bases and electrolytes were reagent grade. Water was distilled, deionized, boiled to remove CO_2 and tested for purity by conductivity. For both the potentiometric titrations and the titration calorimetry, the titrant was standardized 2.055 M HCl and the titrand was made up to be 1.5×10^{-2} in polyacid, to be 0.2 M in chloride salt, and to have a pH of ca. 8.

Deprotonation free energy functions were determined potentiometrically. Deprotonation enthalpy functions were measured with a titration calorimeter constructed in this laboratory [5]. The determination of these functions from the raw data, as well as the subsequent calculation of the corresponding entropy functions, were carried out as described earlier [5].

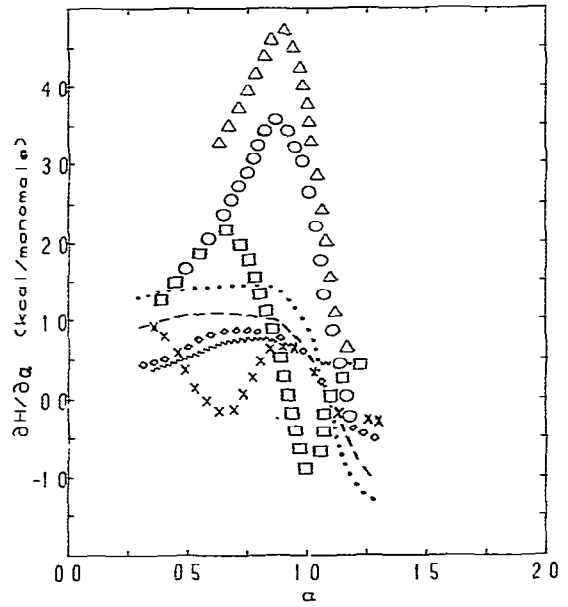

Fig. 1. Differential enthalpy of deprotonation in 0.2 M TMAC1 as a function of degree of deprotonation at 25°C: ···, methyl; – – –, ethyl; ◇◇◇, propyl; ×, butyl; □, pentyl; ~~, pentyl baseline; ○, hexyl; △, octyl.

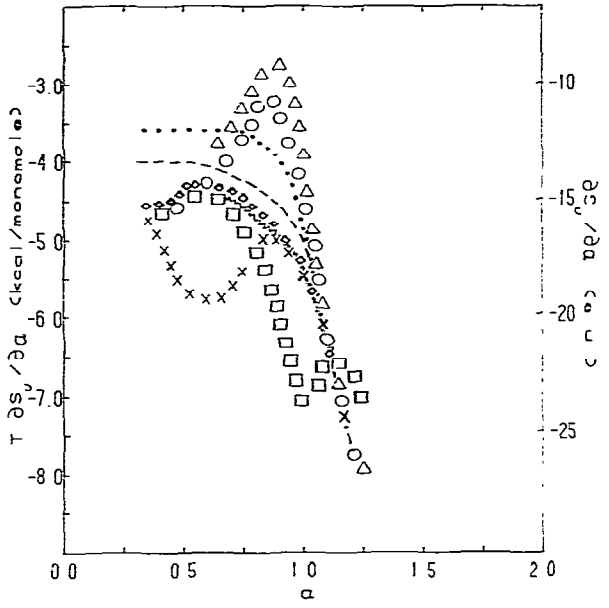

Fig. 2. Differential unitary free energy of deprotonation in 0.2 M TMAC1 as a function of degree of deprotonation at 25°C. The symbols are the same as in fig. 1.

3. Results and discussion

Figs. 1, 2 and 3 show the differential deprotonation enthalpy, $\partial H/\partial\alpha$, unitary entropy, $\partial S_u/\partial\alpha$, and unitary free energy, $\partial G_u/\partial\alpha$, respectively, plotted as a function of α for the copolymers in 0.2 M TMACl at 25°C. The ordinates of the three figures are presented on the same scale so that the relative contributions of the enthalpy and entropy to the free energy are directly apparent. For this reason the scale on the left of fig. 2 gives $T\partial S_u/\partial\alpha$, where T is the temperature in K. The degree of deprotonation, α, defined as described previously [2], ranges from 0 to 2 with deprotonation complete at $\alpha = 2$. The unitary functions have been defined so that the cratic contributions [6] which arise from the possible number of distributions of bound protons along the polymer chain at a particular value of α are removed [2,4,5,7].

The relatively simple behavior of the copolymers with short side-chains, apparent in figs. 1–3, has been explained before [5] and serves as a starting point for understanding the more complicated behavior of the

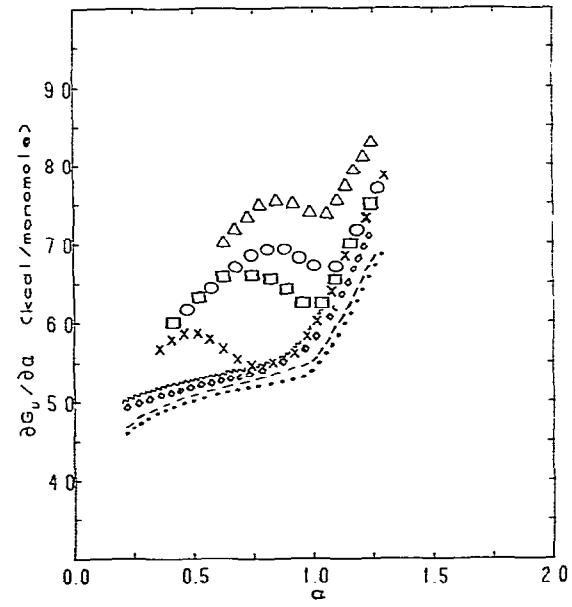

Fig. 3. Differential unitary free energy of deprotonation in 0.2 M TMACl as a function of degree of deprotonation at 25°C. The symbols are the same as in fig. 1.

other copolymers. Below $\alpha = 1$, the free energy functions of the methyl, ethyl and propyl copolymers have slightly positive slopes which are characteristic of normal polyacids and are commonly ascribed to the increase of the electrostatic potential with increasing ionization [8]. Unfortunately, the experimental uncertainty of the calorimetric method makes it impossible to assess the contributions of the enthalpy and entropy to the rise in free energy. At $\alpha = 1$, the free energy curves of these copolymers show a sharp break and initiate a steep rise in the second ionization region. This rise in free energy is associated with a sharp drop in the entropy which is partially compensated by a decrease in the enthalpy. Viewed in the light of dilatometric results [8], these thermodynamic effects must be partly or wholly attributed to the pronounced electrostriction of water by the doubly deprotonated dicarboxylate groups. Experimental limitations imposed by the large enthalpy of forming water from hydrogen and hydroxyl ions prevented the determination of the much smaller enthalpy of polyacid deprotonation above pH 8, which corresponds to approximately $\alpha = 1.3$ in the TMACl system.

As the side-chain length of these copolymers increases, a different behavior is observed. At low values of α the butyl copolymer is known to be in a compact conformation stabilized by hydrophobic forces. With increasing charge, electrostatic repulsions among the carboxylate groups overcome these hydrophobic forces and the macromolecule undergoes a transition to a random coil. The decrease in unitary free energy noticeable between $\alpha = 0.4$ and $\alpha = 0.8$ is commonly ascribed to the decreasing electrostatic attraction for hydrogen ion by the polymer as it expands during the transition [2–4]. The enthalpy and entropy curves show remarkably large dips in this region [9] which we believe to be due predominatly to the reorganization of water around newly exposed alkyl side-chains. Such large, mutually cancelling changes in the enthalpy and entropy frequently accompany the hydrophobic effect.

The pentyl copolymer shows a distinctly more hydrophobic character than does the butyl copolymer. The intial rise in the $\partial G_u/\partial\alpha$ curve which originates from the charging of a compact structure extends over a larger region of α. A similar rise extending over the same range of α is seen in the $\partial H/\partial\alpha$ curve of the pentyl copolymer. Since initially the $\partial S_u/\partial\alpha$ curve for this

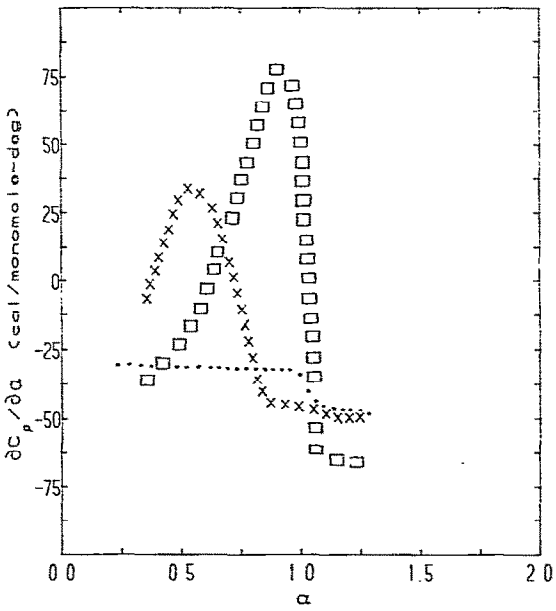

Fig. 4. Differential heat capacity of deprotonization in 0.2M TMACl as a function of degree of deprotonation. The symbols are the same as in fig. 1.

copolymer is virtually flat, the free energy rise appears to be controlled by the enthalpy. The conformational transition of the pentyl copolymer is characterized, as was that of the butyl copolymer, by minima in the $\partial H/\partial\alpha$ and $\partial S_u/\partial\alpha$ functions. However, these minima are more pronounced and occur in a higher range of α for the pentyl copolymer.

Pronounced initial slopes of the enthalpy functions are also apparent for the hexyl and octyl copolymers. These copolymers also show substantial initial positive slopes in the $\partial S_u/\partial\alpha$ functions. However, the enthalpy functions outweigh the entropy functions with their contributions to the free energy rise. The shapes of the hexyl and octyl curves appear to be similar to those of the corresponding pentyl copolymer curves. The heights of the maxima increase with increasing side-chain length. While the positions of the maxima are shifted to higher values of α for the hexyl copolymer, reflecting a further displacement of the conformational transition, the corresponding peaks for the octyl copolymer show no significant additional shift.

It is noteworthy that the entropy curves for all the

Table 1
Thermodynamic functions for the transition in 0.2M TMACl of uncharged pentyl copolymer from compact to hypothetical random coil conformation at 25°C

°C	ΔH_t^0 (cal/monomole)	ΔS_t^0 (e.u.)	ΔG_t^0 (cal/monomole)	ΔC_{pt}^0 (cal/monomole-°K)
25	329±100 (351) a)	−1.23±0.72	718±190	
30	–	–	–	27±16
35	599±120	−0.34 b)	704 b)	

a) Calculated from values of ΔG_t^0 and ΔS_t^0.
b) Calculated assuming $\Delta C_{pt}^0 = 27$ and based on 25°C data.

copolymers appear to converge in the region beyond $\alpha = 1$. The deep plunge in the entropy which characterizes this region seems to be unaffected by side-chain length. While the entropy clearly determines the direction of the free energy in this region of α, the slight differences in the free energy curves can be seen to arise from differences in the enthalpy and may be due to some minor conformational variations of the polyacids with different side-chain lengths

By measuring $\partial H/\partial\alpha$ at more than one temperature it was possible to obtain the differential heat capacity functions, $\partial C_p/\partial\alpha$. The $\partial C_p/\partial\alpha$ curve for the pentyl copolymer in 0.2M TMACl derived from the enthalpy measurements at 25°C and 35°C is compared in fig. 4 to similar results obtained previously for the methyl and butyl copolymers [5]. Below $\alpha = 1$, the heat capacity of the methyl copolymer has a value typical of the ionization of the carboxylic acids [11]. The strikingly large positive deviation of the heat capacity curve for the butyl copolymer in its transition region has been ascribed to the hydrophobic rearrangement of water around newly exposed hydrocarbon sidechains [5]. The even larger positive deviation of the pentyl copolymer which occurs in its known region of transition serves to confirm this interpretation. These large heat capacity effects reflect the lability of the water structure at the hydrocarbon interface [11–14]. The interface modifies the normal water structure in that it produces a large number of microscopic states with the same free energy but widely differing enthalpy and entropy content. A rise in temperature shifts the equilibrium to the states with higher enthalpy, thereby leading to a large positive heat capacity [12].

The free energy, ΔG_t^0 [2–4,15–17], the enthalpy, ΔH_t^0 [9,18–20], and the entropy, ΔS_t^0, for the hypothetical conformational transition of uncharged pentyl copolymer in 0.2M TMACl can be calculated using the method previously described [5]. The required baselines, which are the predicted behavior of the pentyl copolymer if it were to remain extended over the whole range of ionization, are extrapolated from the behavior of the methyl, ethyl and propyl copolymers and are illustrated in figs. 1–3. The heat capacity, ΔC_{pt}^0, was calculated from the values of ΔH_t^0 at 25°C and 35°C. Results are given in table 1. The corresponding results for the butyl copolymer were given elsewhere [5].

The transition of the pentyl copolymer has a nega-

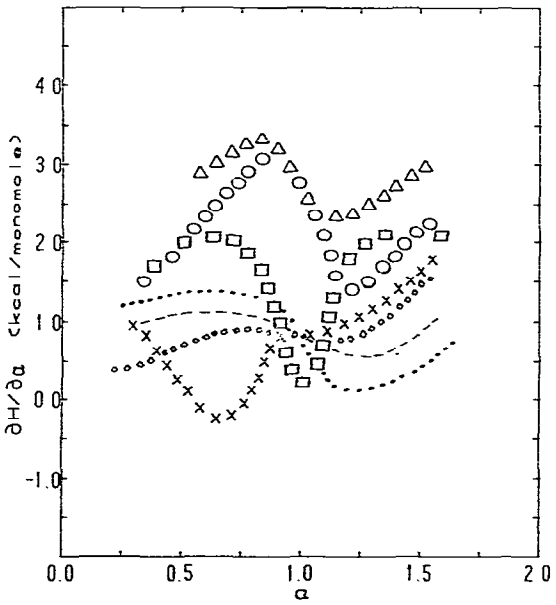

Fig. 5. Differential enthalpy of deprotonation in 0.2M LiCl as a function of degree of deprotonation at 25°C. The symbols are the same as in fig. 1.

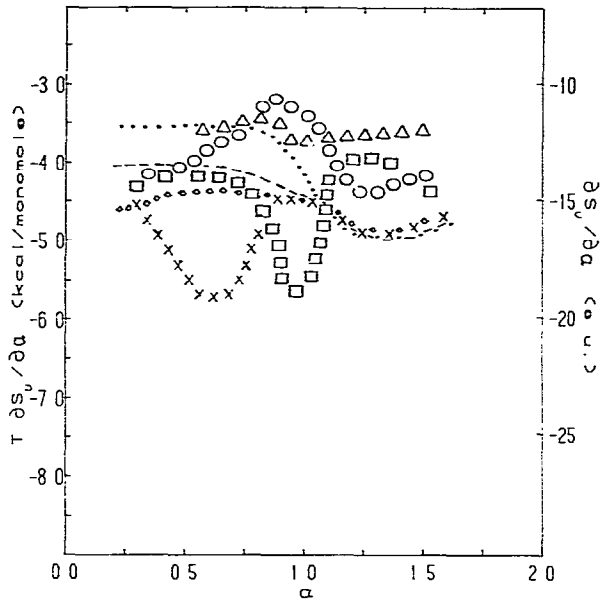

Fig. 6. Differential unitary entropy of deprotonation in 0.2 M LiCl as a function of degree of deprotonation at 25°C. The symbols are the same as in fig. 1.

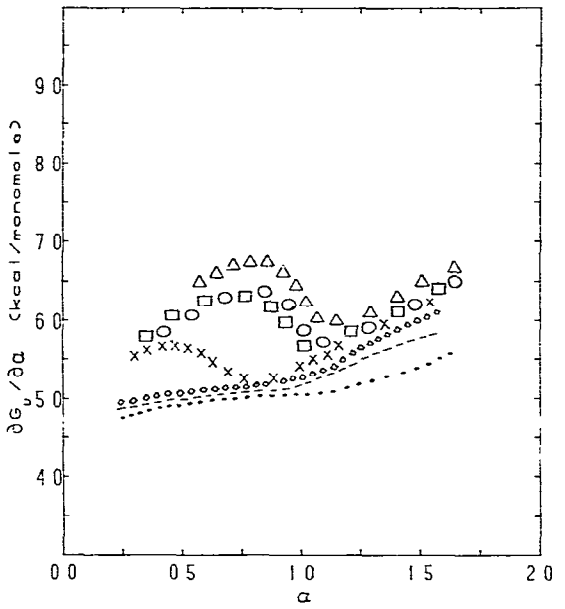

Fig. 7. Differential unitary free energy of deprotonation in 0.2 M LiCl as a function of degree of deprotonation at 25°C. The symbols are the same as in fig. 1.

tive ΔS_t^0 and a positive ΔG_t^0 near room temperature, similar to that of the butyl copolymer [5]. Unlike the butyl copolymer [4,5,9], the pentyl copolymer shows positive values of ΔH_t^0 at 25°C and 35°C. Positive enthalpies of transition have been reported for polymethacrylic acid [18,19] and for an alternating copolymer of maleic acid and styrene [21]. The present results support previous conclusions that the hydrophobic rearrangement of water may be accompanied by either positive or negative enthalpy or entropy, but is generally characterized by a positive heat capacity [5].

The thermodynamic functions for the copolymers in 0.2M LiCl are given in figs. 5–7. Detailed comparison of these results with those of the copolymers in 0.2 M TMACl allows us to summarize the counterion effects as follows. For $\alpha \leqslant 1$, the methyl, ethyl, propyl and butyl copolymers are independent of the nature of the counterion. Above $\alpha = 1$ for these copolymers, the Li^+ counterions bind to the doubly charged dicarboxylic acid groups, and thereby attenuate the steep drop of the enthalpy and entropy function observed with TMA^+ by disrupting the electrostriction of water. Furthermore, while the binding of Li^+ to these first

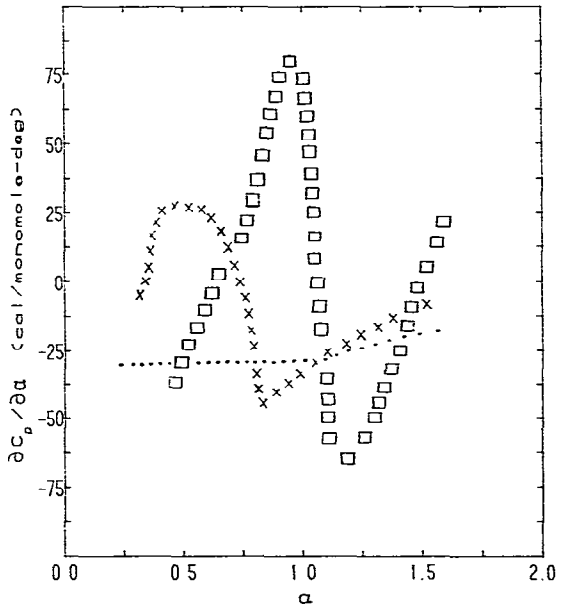

Fig. 8. Differential heat capacity of deprotonation in 0.2 M LiCl as a function of degree of deprotonation. The symbols are the same as in fig. 1.

four polyacids is independent of side-chain length and occurs only for $\alpha > 1$, the binding of Li^+ to the pentyl, hexyl and octyl copolymers depends on the side-chain length and begins well below $\alpha = 1$. These specific counterion effects at low charge are presumably due to the higher charge density of a compact polyacid molecule.

In fig. 8, the differential heat capacity, $\partial C_p/\partial\alpha$, is plotted against α for the methyl, butyl and pentyl copolymers in 0.2M LiCl. The only real difference between these results and those of the copolymers in 0.2M TMACl is the positive slope above $\alpha = 1$ induced by Li^+. This rise could possibly be due to a labile water structure around charged dicarboxylate groups with relatively weakly bound Li^+ ions.

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