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# Ionic interactions in aqueous mixtures of hydrophilic and -phobic ions*

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*Abstract*: Ions of both hydrophilic and -phobic nature play a pivotal role in biological systems and during synthesis of many organic molecules. However, the interaction of a hydrophilic ion with a hydrophobic one is not a simple physical process and is useful in understanding the rate enhancement in organic transformations and thermal stability of DNA and RNA. During the talk, an attempt was made to present some of the experimental work on aqueous mixtures of these ions carried out at National Chemical Laboratory, Pune, and give a theoretical interpretation of the binary, ternary, and quaternary interactions operating in these systems. The contribution of these interaction terms to the excess free energy of mixing, $\Delta_m G^E$, will be analyzed.

*Keynotes*: aqueous solutions; ionic solutions; excess free energy; mixing effects; hydrophobic ions.

## INTRODUCTION

The modeling of thermodynamic properties of mixed electrolyte solutions requires accurate knowledge of the excess Gibbs free energy of mixing, $\Delta_m G^E$. The mixed electrolyte systems have numerous potential applications, including many in chemical engineering, sea brines, geochemical, atmospheric aerosol chemistry, and biological systems such as proteins, amino acids, and nucleic acids [1–3].

The theory to describe thermodynamic properties of very dilute solutions was put forward by Debye and Hückel [4]. A large body of experimental data and the development of different empirical models to estimate thermodynamic properties of aqueous single- and mixed-electrolyte solutions up to high concentrations have followed since then [5].

Major developments in understanding the ionic interactions in electrolyte mixtures have been made in terms of Mayer's ionic solution theory [6] and Friedman's cluster integral expansion theory [7]. These theories were later used to develop Pitzer's specific ion interaction theory [8]. The Pitzer theory is based on a combination of long-range interaction forces determined by the Debye–Hückel equation and short-range interaction forces evaluated by virial coefficients. On mixing of two electrolytes with or without a common ion, interactions between the cations and anions of two different electrolytes also emerge along with those present between a cation and an anion of the same electrolyte. For instance, in a mixture of two electrolytes, MX and NY (M and N are cations, X and Y are anions), the M–N and X–Y interactions assume importance in addition to those present between the pairs of M–X and N–Y. Similarly, the interactions due to MNX, MNY, MXY, and NXY species can also be significant at higher ionic concentrations. In the Pitzer theory, electrolyte mixtures are analyzed by incorporating the Pitzer

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coefficients of pure electrolytes and then fitting the residuals in terms of binary mixing, $\theta^{ik}$ and ternary $\psi^{ijk}$ interaction parameters for their thermodynamic properties. No provision, however, was made by Pitzer to account for quaternary and higher-order multiplet interactions that are important in the mixtures containing hydrophobic ionic species. Electrolytes and their constituent ions can be classified as hydrophilic and -phobic species on the basis of their abilities to "like" or "dislike" water molecules surrounding them in their aqueous solutions. The interactions of hydrophilic ions with water are relatively straightforward and better understood than those of hydrophobic ones. Tetraalkyl ammonium and guanidinium ($Gn^+$) cations are hydrophobic in nature [3,9–11]. Moreover, tetraalkyl ammonium halides are known to form clathrates [9]. The evidence obtained from the ultrasonic absorption spectra of the clathrate-forming quaternary ammonium salts and GnCl indicates the formation of large clusters owing to the association of ions [10,11]. An important criterion for probing the quaternary interactions in such mixtures is to apply Harned's rule [12] to correlate activity coefficients of one electrolyte with the composition of another electrolyte characterized by the clathrate formation. The rule is completely violated in such electrolytes. Higher-order terms, however, are required for the analysis of mixtures, containing at least one clathrate-forming or hydrophobic species.

In general, the Pitzer theory assumes that the main contribution to total $\Delta_m G^E$ of a mixture of strong electrolytes is due to binary and ternary interactions. The contribution of ternary interactions is much less as compared to the binary ones. It can, therefore, be stated that though three or four Pitzer coefficients are sufficient to correlate the property-concentration data, the parameters are not the true indicators of the types of interactions in the mixtures containing clathrate-forming or hydrophobic species. Secondly, the Pitzer equation completely neglects interactions between the same ions. For example, the interactions between M–M, N–N, X–X, and Y–Y are assumed negligible. In the mixtures of simple electrolytes such as NaCl, $MgCl_2$, $CaCl_2$, etc., these interactions (e.g., $Na^+$–$Na^+$, $Mg^{2+}$–$Mg^{2+}$, $Ca^{2+}$–$Ca^{2+}$) are thus assumed to be negligible within the framework of the Pitzer theory.

Another important theory in this connection was put forward by Scatchard, Rush, and Johnson [13]. The Scatchard–Rush–Johnson (SRJ) equations, with a combination of the Debye–Hückel function and other adjustable parameters, have been employed to analyze the $\Delta_m G^E$ of electrolyte solutions [14,15]. The SRJ equations employ several adjustable parameters and offer greater advantage in terms of the examination of contributions from different mixing terms to total $\Delta_m G^E$. The SRJ equations incorporate the contributions of the binary, ternary, quaternary, and higher-order interactions to total $\Delta_m G^E$. A simple and rigorous procedure was developed by Leifer and coworkers [16] to determine and separate contributions of binary, ternary, quaternary, and higher-order interactions to $\Delta_m G^E$.

## DISCUSSION

The work carried out in our laboratory [17–20] on different aqueous electrolyte mixtures is based upon the osmotic coefficient, $\varphi$ data obtained from isopiestic measurements. The density and speed of sound were also carried out. The analysis of $\varphi$ data by the SRJ equations, summarized in Table 1 for immediate reference, leads to the calculations of activity coefficients of an electrolyte, $\gamma_\pm$ in the mixed electrolyte systems. For example, we plot the ln $\gamma_{\pm NaCl}$ as a function of $y_2$ and ln $\gamma_{\pm GnCl}$ values as a function of $y_1$ in Figs. 1a and 1b, respectively. Herein, the ionic strength fraction of component 1 is given by $y_1 = m_1/(m_1 + m_2)$ with $y_2 = 1 - y_1$. Ionic strength, $I$, is given by $0.5 \sum m_i z_i^2$; $z_i$ being the ionic charge. Except at $I = 0.5$ mol kg$^{-1}$, the ln $\gamma_{\pm NaCl}$ values vary nonlinearly with respect to $y_2$. On the other hand, we note large deviations from linearity in the ln $\gamma_{\pm GnCl}$ and $y_1$ plots (Fig. 1b). The ln $\gamma_{\pm GnCl}$ is greatly influenced in NaCl-rich mixture at $I = 3$ and 4 mol kg$^{-1}$. The activity coefficients of NaCl first decrease and then increase with an increase in concentration. On the other hand, a hydrophobic cation like $Gn^+$ is characterized by a decrease in the activity coefficients of its chloride salt in a monotonous manner with concentration. The plots of $\gamma_\pm$ against $m$ for aqueous solutions of both salts show exactly opposite trends upon addition of GnCl with the ln $\gamma_{\pm NaCl}$ in the mixture, indicating a fall in the hydrophilic character of $Na^+$. The hydrophobic nature of $Gn^+$ is reduced at higher NaCl concentration as is evident from the enhanced $\ln \gamma_{\pm \mathrm{GnCl}}$ in a NaCl-rich mixture (Fig. 1b).

**Table 1** The SRJ equations.

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(1) The SRJ equations for correlating $\varphi$ with molality of aqueous single electrolytes:

$$\begin{aligned}\varphi - 1 &= (1/\nu\, \mathrm{m})\\ &\{(2S/a^3 I)\,[1 + \mathrm{a}\, I^{1/2} - 1/(1 + a\, I^{1/2}) - 2 \ln (1 + a\, I^{1/2})] + a^{(1)} I + a^{(2)} I + a^{(2)} I^2 + a^{(3)} I^3 + \ldots\}\end{aligned} \tag{1}$$

$\nu$ = the number of moles of ions per mole of electrolyte, $\nu = \nu_c + \nu_a$ with $\nu_c$ and $\nu_a$ being the number of cation and anion, respectively; parameter $a$ = the distance-of-closest approach parameter; $a^{(1)}, a^{(2)}, a^{(3)}$ ... = SRJ parameters; $S$ = Debye–Hückel limiting slope with a value of $-1.17582\ (\mathrm{mol\ kg})^{-1/2}$ at 298.15 K.

(2) The SRJ equations for the mixed electrolytes:

$$\begin{aligned}\varphi - 1 &= [I/(\nu_A\, \mathrm{m}_A + \nu_B\, \mathrm{m}_B)]\\ &\{y_A\, \alpha_A + y_B\, \alpha_B + y_A\, y_B\, [\beta^{(0)}{}_{AB} + \beta^{(1)}{}_{AB}\, (y_A - y_B) + \beta^{(2)}{}_{AB}\, (y_A - y_B)^2 + \ldots]\}\end{aligned} \tag{2}$$

$\beta^{(0)}{}_{AB}$, $\beta^{(1)}{}_{AB}$, and $\beta^{(2)}{}_{AB}$, etc. = the SRJ mixing parameters.

(3) Activity coefficient of the electrolyte, A, in the mixture:

$$\begin{aligned}\ln \gamma_{\pm A} &= (I_A/\nu_A\, \mathrm{m}_A)\,[(\mathrm{A}_A + \alpha_A) + (\alpha_B - \alpha_A)\, y_B + y_B\, [\mathrm{B}^{(0)}{}_{AB} +\\ &\mathrm{B}^{(1)}{}_{AB}\, ((y_A - y_B) + y_A) + \mathrm{B}^{(2)}{}_{AB}\, ((y_A - y_B)^2 + 2\, y_A\, (y_A - y_B)) + \ldots +\\ &\mathrm{B}^{(n)}{}_{AB}\, (y_A - y_B)^n + n\, y_A\, (y_A - y_B))^{n-1})] + y_A\, y_B\, [(\beta^{(0)}{}_{AB} - \mathrm{B}^{(0)}{}_{AB}) +\\ &(\beta^{(1)}{}_{AB} - 2\, \mathrm{B}^{(1)}{}_{AB})\, (y_A - y_B) + \ldots +(\, \beta^{(n)}{}_{AB} - (n + 1)\, \mathrm{B}^{(n)}{}_{AB})\, (y_A - y_B)^n]]\end{aligned} \tag{3}$$

where

$$\begin{aligned}\alpha_A &= (2\, \mathrm{S}/a_A\, I)\,[1 + a_A\, I^{1/2} - 1\,/(1 + a_A\, I^{1/2}) - 2 \ln (1 + a_A\, I^{1/2}\,)] +\\ &a^{(1)}{}_A\, I + a^{(2)}{}_A\, I^2 + a^{(3)}{}_A\, I^3 + \ldots\end{aligned} \tag{4a}$$

$$(\mathrm{A}_A + \alpha_A) = [2\, \mathrm{S}\, I^{1/2}/(1 + a_A\, I^{1/2})] + 2\, a^{(1)}{}_A\, I + 3\, a^{(2)}{}_A\, I^2/2 + 4\, a^{(3)}{}_A\, I^3/3 + \ldots \tag{4b}$$

The above terms can also be written for B by substituting A by B.

Definitions of $\beta^{(n)}{}_{AB}$ and $\mathrm{B}^{(n)}{}_{AB}$:

$$\beta^{(n)}{}_{AB} = \sum_{k=n+1}^{k'} I^k b^{(n,k)}{}_{AB} \tag{5a}$$

$$\mathrm{B}^{(n)}{}_{AB} = \sum_{k=n+1}^{k'} \left(I^k/k\right)\, b^{(n,k)}{}_{AB} \tag{5b}$$

In eqs. 5 and 6, $k = 1$ for pairs, $k = 2$ for triplets, $k = 3$ for quadruplets and so on.

(4) The expression for $\Delta_m G^E$ in terms of the SRJ parameters given by

$$\Delta_m G^E = \mathrm{RT}\, I\, y_A\, y_B\, [\mathrm{B}^{(0)}{}_{AB} + \mathrm{B}^{(1)}{}_{AB}\, (y_A - y_B) + \ldots + \mathrm{B}^n{}_{AB}\, (y_A - y_B)^n] \tag{6}$$

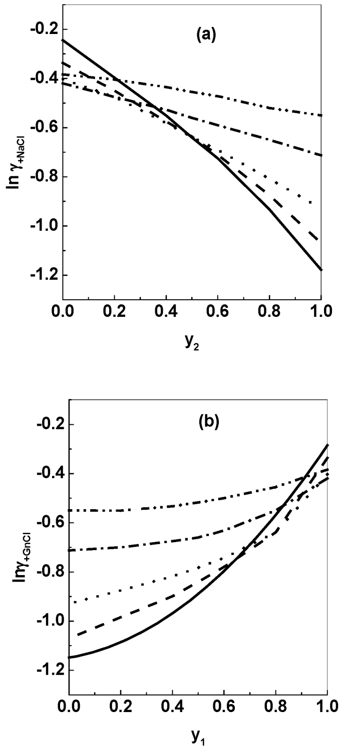

**Fig. 1** (a) Variation of ln $\gamma_{\pm NaCl}$ with $y_2$ in the NaCl–GnCl mixtures at constant ionic strengths; (b) variation of ln $\gamma_{\pm GnCl}$ with $y_1$ in the NaCl–GnCl mixtures at constant ionic strengths; (–··–··) $I = 0.5$, (–·–·–·) $I = 1$, (- - - - ) $I = 2$, (— — — ) $I = 3$, (———— ) $I = 4$ mol kg$^{-1}$.

As mentioned above, there is no provision in the Pitzer theory to account for the quaternary interactions, while in SRJ theory these interactions are given by $b^{(0,3)}$, $b^{(1,3)}$, and $b^{(2,3)}$ parameters. First, we fitted the $\varphi$ data of these mixtures by setting $b^{(0,3)} = b^{(1,3)} = 0$, the correlated $\varphi$ values showed large deviations from the experimental ones. Then, we treated $b^{(0,3)}$ and $b^{(1,3)}$ as adjustable parameters and evaluated the importance of the $b^{(2,3)}{}_{AB}$ parameter in correlating osmotic coefficients of the mixtures containing guanidinium salts without and with $b^{(2,3)}$. In the case of NaCl–GnAc, the deviations, $\Delta\varphi$ ($\Delta\varphi$ = experimental $\varphi$ – calculated $\Delta\varphi$ with and without $b^{(2,3)}{}_{AB}$, are significant in the NaCl-rich region at lower ionic strength. These deviations, however, become high at higher ionic strength in the $GnNO_3$-rich mixtures of NaCl–$GnNO_3$. The $\Delta\varphi$ values are also important in the NaCl-rich mixture with $GnClO_4$ at lower ionic strengths. At moderate ionic strength, say 1.5 mol kg$^{-1}$, the systematic deviations are noted in the case of NaCl–$Gn_2SO_4$ independent of the mixture composition. These observations as demonstrated in Fig. 2 point out the importance of quaternary interactions parameter, $b^{(2,3)}{}_{AB}$, in representing the $\varphi$ data within experimental accuracy. No further parameters were required to fit the data, indicating the absence of higher-order mixing terms in these systems.

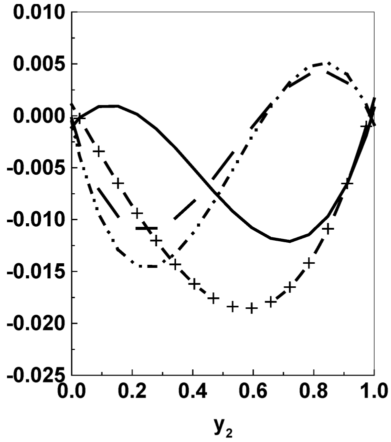

**Fig. 2** The differences, $\Delta\varphi$ [$\Delta\varphi$ = experimental $\varphi$ – calculated $\Delta\varphi$ without $b^{(2,3)}{}_{\mathrm{AB}}$] as a function of $y_2$ for the mixtures of NaCl with (— — —) $CH_3COOGn$ at $I$ = 1 mol kg$^{-1}$, (——) $GnNO_3$ at $I$ = 1.4 mol kg$^{-1}$, (— · · —) $GnClO_4$ at $I$ = 0.5 mol kg$^{-1}$, (— + —) $Gn_2SO_4$ at $I$ = 1.5 mol kg$^{-1}$.

The mutual effect of these ions can be examined in terms of the $\Delta_m G^E$ values. The values computed using the equations collected in Table 2 are plotted in Fig. 3. We note negative $\Delta_m G^E$ below $y_2 \approx 0.5$ at all the ionic strengths. The $\Delta_m G^E$ values decrease with ionic strength in the region $y_2 < 0.5$, indicating that the water molecules are ordered in this region. The lowest $\Delta_m G^E$ values are observed at $y_2 \approx 0.2$. Beyond $y_2 \approx 0.2$, the increasing concentration of GnCl causes the water molecules to be disturbed, thus increasing the $\Delta_m G^E$ values. In the region $y_2 > 0.5$, the positive magnitude of $\Delta_m G^E$ in the GnCl-rich mixtures reaches maxima at $y_2 \approx 0.75$, pointing to a maximum water-disordering in the system. We note $\Delta_m G^E$ to be ≈0 at $y_2 \approx 0.5$. This situation indicates a neutralization of the opposing water-ordering and -disordering effects [21]. NaCl and GnCl are known to be the structure-maker and -breaker salts, respectively. In the GnCl-rich mixtures, the positive $\Delta_m G^E$ above $y_2 \approx 0.5$ indicates the repulsion between $Na^+$ and $Gn^+$ ions with opposite tendency for orienting water molecules around them. The negative $\Delta_m G^E$ indicates the presence of pairwise interactions reaching a maximum at $y_2 \approx 0.2$. The triple interactions are likely in the GnCl-rich region as evidenced by the positive $\Delta_m G^E$.

**Table 2** Estimation of contribution of binary, ternary, quaternary, and higher-order interaction terms to total $\Delta_m G^E$ in terms of the Scatchard parameters.

$$\Delta_m G_p{}^E = RT\, I^2\, y_A\, y_B\, b^{(0,1)}{}_{AB} \tag{7}$$

$$\Delta_m G_t{}^E = 0.5\ RT\, I^3\, y_A\, y_B\, b^{(0,2)}{}_{AB} + b^{(1,2)}{}_{AB}\,(y_A - y_B)] \tag{8}$$

$$\Delta_m G_q{}^E = 0.3334\ RT\, I^4\, y_A\, y_B\, [b^{(0,3)}{}_{AB} + b^{(1,3)}{}_{AB}\,(y_A - y_B) + b^{(2,3)}{}_{AB}\,(y_A - y_B)^2] \tag{9}$$

$$\Delta_m G_{hoi}{}^E = (I^{n+2}/n + 1)\ RT\, y_A\, y_B\, [b^{[0,(n+1)]}{}_{AB} + b^{[1,(n+1)]}{}_{AB}\,(y_A - y_B) + \ldots + b^{[n,(n+1)]}{}_{AB}\,(y_A - y_B)^n] \tag{10}$$

Total $\Delta_m G^E$ given by

$$\Delta_m G^E = \Delta_m G_p{}^E + \Delta_m G_t{}^E + \Delta_m G_q{}^E + \ldots + \Delta_m G_{hoi}{}^E \tag{11}$$

The subscripts p, t, q, and hoi refer to the binary, ternary, quaternary, and higher-order interactions, respectively. In the above, $b^{(0,1)}$ = binary interactions, $b^{(0,2)}$, $b^{(1,2)}$ = binary and ternary interactions, $b^{(0,3)}$, $b^{(1,3)}$, $b^{(2,3)}$ = the quaternary interactions.

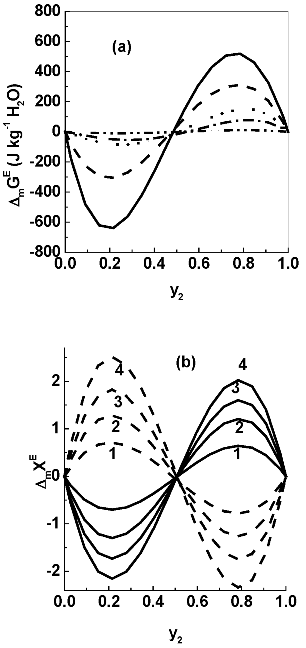

**Fig. 3** (a) NaCl–GnCl system: $\Delta_mG^E$ as a function of $y_2$ at different ionic strengths $I$ expressed by 1, 2, 3, and 4 mol kg$^{-1}$. (b) $\Delta_mX^E$, i.e., $\Delta_mV^E$ (———) and $\Delta_mK^E$ (- - - - -) as a function of $y_2$ at different ionic strengths, multiplication factors for $\Delta_mV^E$ and $\Delta_mK^E$ are $10^{-6}$ (m$^3$ kg$^{-1}$ H$_2$O) and $10^{-15}$ (m$^3$ Pa$^{-1}$ kg$^{-1}$ H$_2$O).

Interesting trends are also observed in some other systems. Refer to Fig. 4 for illustrations. The $\Delta_mG^E$ values are negative throughout the ionic strengths studied for the mixtures of both KCl and ($n$Bu$_4$)NCl with GnCl. The negative ΔmGE values in both these systems are the result of mixing of K$^+$ with Gn$^+$ and ($n$-Bu$_4$)N$^+$ with Gn$^+$. Negative $\Delta_mG^E$ suggests that the water molecules are ordered in these systems. The minima in $\Delta_mG^E$ for KCl and tetrabutylammonium chloride [($n$-Bu$_4$)NCl] systems are recorded at $y_2 \approx 0.6$. Asymmetry of the $\Delta_mG^E - y_2$ plots indicates the presence of ternary interactions (K$^+$, Gn$^+$, Cl$^-$, and ($n$-Bu$_4$)N$^+$, Gn$^+$, Cl$^-$) in the GnCl-rich region. The degree of asymmetry of the plots tends to diminish toward lower ionic strengths, i.e., higher-order interactions tend to reduce at these ionic concentrations, suggesting that ternary interactions become weaker in dilute mixtures. As ($n$-Bu$_4$)N$^+$ is strongly hydrophobic in nature, its mixture with Gn$^+$ gives rise to lower $\Delta_mG^E$ as compared to the mixture of K$^+$ with Gn$^+$. K$^+$ is a structure-breaker ionic species. The mixing of Mg$^{2+}$ and Ca$^{2+}$ with Gn$^+$ gives very interesting trends in $\Delta_mG^E$ at constant ionic strengths. In the case of Ca2$^+$–Gn$^+$ mixing, first a minimum of $\Delta_mG^E$ (≈–630 J kg$^{-1}$ H$_2$O) occurs at about $y_2 \approx 0.25$. This suggests a maximum in ordering of the water molecules in $y_2 \approx 0.25$ of GnCl mixture. Further addition of Gn$^+$ in CaCl$_2$ solution causes an increase in the disordering of water molecules, which is manifested as an increase in $\Delta_mG^E$ increases with $y_2$. At $y_2 \approx 0.64$, one observes that $\Delta_mG^E$ is 0. At this mixture composition, a neutralization of hydrophilic and -phobic tendencies of both Ca$^{2+}$ and Gn$^+$ takes place. Higher GnCl fraction ($y_2 \approx 0.6$) is required for the neutralization of hydrophobic–hydrophilic interactions in the CaCl$_2$–GnCl mixture as compared to NaCl–GnCl ($y_2 \approx 0.5$), as Ca$^{2+}$ is more hydrophilic than Na$^+$. In the mixtures containing more than $y_2 = 0.64$ of GnCl, there is an increase in $\Delta_mG^E$, reaching a maximum (≈330 J kg$^{-1}$ H$_2$O) at $y_2 \approx 0.8$. This region suggests disordering of the water molecules and the presence of ternary interactions. The minimum in $\Delta_mG^E \approx -630$ J kg$^{-1}$ H$_2$O is opposite but not equal to ≈330 J kg$^{-1}$ H$_2$O, confirming the asymmetry and hence presence of strong ternary interactions. Considering the stronger structure-making ability of Mg$^{2+}$ over Ca$^{2+}$, the $\Delta_mG^E$ is throughout higher

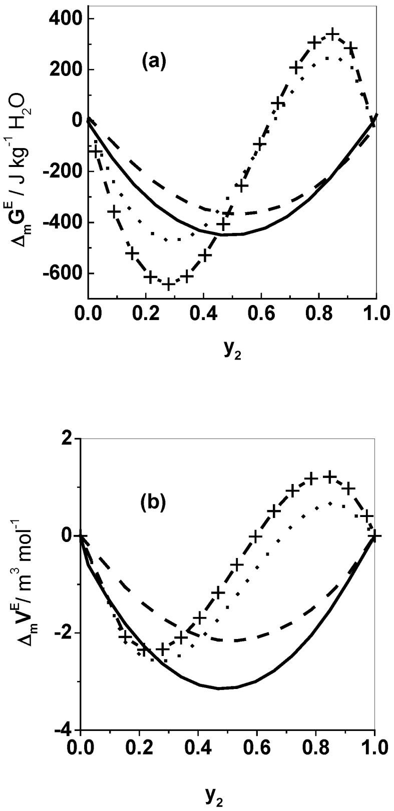

**Fig. 4** (a) Plots of $\Delta_m G^E - y_2$ for KCl–GnCl (——), ($n$-Bu$_4$)NCl–GnCl (____); MgCl$_2$–GnCl (.....); CaCl$_2$–GnCl (-+-+-+) mixtures at $I = 2$ mol kg$^{-1}$; (b) plots of $\Delta_m V^E - y_2$ for KCl–GnCl, ($n$-Bu$_4$)NCl–GnCl, MgCl$_2$–GnCl, CaCl$_2$–GnCl mixtures at $I = 2$ mol kg$^{-1}$. Multiplication factor for $\Delta_m V^E$ is $10^{-6}$. Symbols are defined in Fig. 4a.

than that noted in the case of Ca$^{2+}$. Results can be interpreted in a similar fashion. However, zero $\Delta_m G^E$ in the Mg$^{2+}$–Gn$^+$ mixing is noted at $y_2 \approx 0.68$ and can be compared with those obtained for Ca$^{2+}$ and Na$^+$ species as discussed above. Higher concentration of Gn$^+$ is needed to neutralize the effect of Mg$^{2+}$ than that for Ca$^{2+}$, Na$^+$ due to the differences in their water-structure-altering abilities. The $\Delta_m V^E$ obtained from independent experimental density measurements argue well in favor of information on different ionic interactions obtained from free energy data as shown above.

In order to understand the comparative role of various type of interactions, we plot the contributions of the binary, ternary, and higher-order mixing terms to the total $\Delta_m G^E$ for ($n$-Bu$_4$)NCl–GnCl (hydrophobic–hydrophobic cation mixing) in Fig. 5a and for MgCl$_2$–GnCl (hydrophilic–hydrophobic cation mixing) in Fig. 5b, both at $I = 2$ mol kg$^{-1}$. In the case of ($n$-Bu$_4$)NCl–GnCl, binary interactions are predominant throughout the mixture composition. The ternary interactions are enhanced in the region up to $y_2 \approx 0.6$ and are disfavored in the high concentrations of GnCl ($y_2 > 0.6$). Higher-order interactions are not favored at any mixture composition of ($n$-Bu$_4$)NCl–GnCl system. The $\Delta_m G^E$ of the ($n$-Bu$_4$)NCl–GnCl is largely contributed by the interactions between ($n$-Bu$_4$)N$^+$–Gn species, where the negative $\Delta_m G^E$ is attributed to the interactions between two hydrophobic ions. Interesting plots are seen in the case of MgCl$_2$–GnCl. At about $y_2 \approx 0.6$, the binary interactions are dominant as shown by $\Delta_m G^E$ calculated for the binary interactions. In the GnCl-rich region, the binary interactions are weak. Strong ternary interactions involving Mg$^{2+}$–Gn$^+$–Cl$^-$ are prevalent, contributing to total $\Delta_m G^E$ in the Mg$^{2+}$-rich mixtures. Ternary interactions can be located at $y_2 \approx 0.25$. Addition of GnCl above $y_2 \approx 0.25$ re-

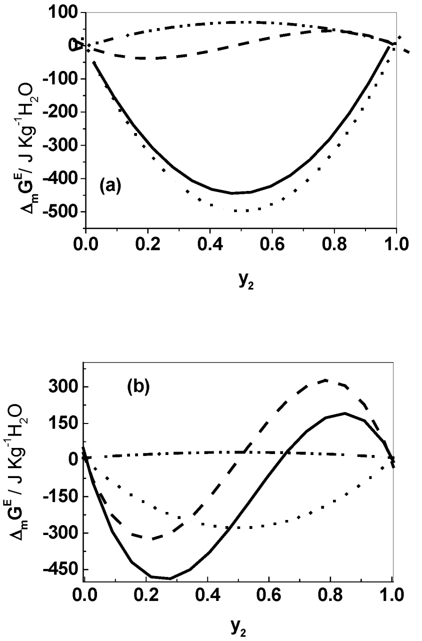

**Fig. 5** Contribution of binary, ternary, and higher-order interactions to total $\Delta_m G^E$ at $I$ = 2 mol kg$^{-1}$; (a) ($n$-Bu$_4$)NCl–GnCl; (b) $MgCl_2$–GnCl; binary (….), ternary (——), higher-order (-..-..-).

duces occurrence of ternary interactions. Higher-order interactions are not favored and hence do not contribute to total $\Delta_m G^E$. The $\Delta_m G^E$ values plotted in Figs. 5a and 5b clearly demonstrate how the ionic interactions vary with mixture composition when a hydrophobic or -philic cation is mixed with another hydrophobic cation.

In the NaCl–$CH_3COOGn$ system (Fig. 6a), the binary interactions are negligible at low ionic strengths, say at $I$ = 0.5 mol kg$^{-1}$. The binary interactions, however, gradually become important with increasing ionic strength and are maximized in ~50 % mixtures of NaCl in $CH_3COOGn$ at the highest $I$ = 2.5 mol kg$^{-1}$. The ternary interactions become significant with increasing ionic strength. Interestingly, the ternary interactions are significant in the NaCl-rich region with a maximum enhancement in ~80 % of NaCl. With the decreasing NaCl concentration at constant ionic strength, the ternary interactions decrease and are minimized at ~35 % of NaCl. The ternary interactions are not favored in the mixtures rich in $CH_3COOGn$. This effect is also seen at low ionic strength, say 0.5 mol kg$^{-1}$. In the $CH_3COOGn$-poor mixtures, the ternary interactions are enhanced sharply with increasing ionic strength. This enhancement is poor in the NaCl-rich mixtures at constant ionic strength. On the other hand, the quaternary interactions are found to be significant at lower ionic strength, particularly in the $CH_3COOGn$-poor mixtures, and are absent in the mixture of $I > 1$ mol kg$^{-1}$. In the NaCl with $CH_3COOGn$ mixtures ($I < 1$ mol kg$^{-1}$) rich in NaCl, the quaternary interactions are maximized in ~80 % of NaCl.

The quaternary interactions decrease significantly with the increasing concentration of $CH_3COOGn$. In a nutshell, at $y_B$ = 0.5 and $I$ = 0.5 mol kg$^{-1}$ 53 % of pairs, 16 % of triplets and 31 % of quaternary interactions contribute to $\Delta_m G^E$ in the NaCl–$CH_3COOGn$ mixture. On the other hand, at $I$ = 2.5 mol kg$^{-1}$, $y_B$ = 0.5, the contributions of binary, ternary, and quaternary interactions to $\Delta_m G^E$ is estimated to be 35, 15, and 50 %, respectively. In terms of total $\Delta_m G^E$, the minimum occurs in about 20 % of $CH_3COOGn$ in the NaCl–$CH_3COOGn$ mixtures, indicating that the water molecules are ordered in this region. However, since $CH_3COOGn$ is a structure-breaker, higher concentration of

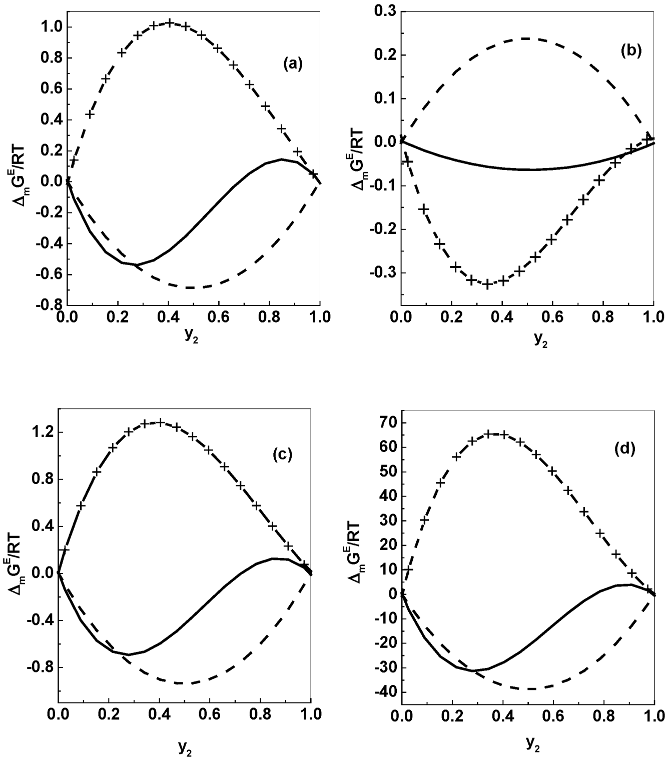

**Fig. 6** The contribution of (— — —) binary $\Delta_m G_p^E$/RT, (———) ternary $\Delta_m G_t^E$/RT, and (— + —) quaternary $\Delta_m G_q^E$/RT interaction terms to total $\Delta_m G^E$/RT for the mixtures of NaCl with (a) $CH_3COOGn$ $I = 2.5$ mol kg$^{-1}$; (b) $GnNO_3$ $I = 1.4$ mol kg$^{-1}$; (c) $GnClO_4$ $I = 2.6$ mol kg$^{-1}$; and (d) $Gn_2SO_4$ $I = 6$ mol kg$^{-1}$.

$CH_3COOGn$ at constant ionic strength decreases the orderliness of water molecules. The ternary and quaternary ionic interactions emerge into the picture with increasing concentration of $CH_3COOGn$ at the expense of binary interactions.

The $\Delta_m G^E$ values (Fig. 6b) are minimized at ~25 % of $GnNO_3$ and become zero at ~70 % of $GnNO_3$ in its mixtures, with NaCl showing neutralization of hydrophilic forces ($Na^+$) and hydrophobic forces ($Gn^+$). In the NaCl-poor mixtures, the effect of $GnNO_3$ on $\Delta_m G^E$ is less than that of $CH_3COOGn$. The pairwise interactions do not contribute to $\Delta_m G^E$ in the case of NaCl and $GnNO_3$ at all compositions and ionic strengths. The ternary interactions in this system are present and are weaker in strength as compared to the quaternary interactions. One notes the asymmetry in the $\Delta_m G^E - y_2$ curve in the low $NaCl^-$ mixture, indicating maximum quaternary interactions. The ternary interactions decrease with increasing ionic strength in the $GnNO_3$-poor mixtures. This reduction in the ternary interactions is compensated by the quaternary interactions that are progressively present with the increase in ionic strength. This situation becomes opposite in the $GnNO_3$-rich mixtures with NaCl.

When $GnClO_4$ is mixed with NaCl (Fig. 6c), the binary interactions become important, both at low and high ionic strengths. These binary interactions are maximized in about 1:1 mixture at all studied ionic strengths. Lower ionic strengths of the mixtures are not characterized by the ternary interactions. The ternary interactions are enhanced with ionic strength of the mixture. At $I = 2.4$ mol kg$^{-1}$, the ternary interactions are dominant in the NaCl-rich region and are decreased upon addition of $GnClO_4$. The ternary interactions are not favored in these mixtures containing more than 70 % of $GnClO_4$. The quaternary interactions are not favored in this system at higher ionic strengths. However, at $I = 0.5$ and 1 mol kg$^{-1}$, the $GnClO_4$-poor mixture is enriched with quadruplets. When higher concentrations of

$GnClO_4$ are added to NaCl at constant $I = 0.5$ or 1 mol kg$^{-1}$, the quaternary interactions are not favored. For example, in 20 % mixture of $GnClO_4$ at $I = 0.5$ mol kg$^{-1}$, the binary interactions increase with increasing ionic strength, while the quaternary interactions follow the inverse rule.

On mixing with $Gn_2SO_4$ in NaCl (Fig. 6d) at high ionic strength, the binary interactions are favored and are enhanced with ionic strength at all the mixture compositions. In lower ionic strength, the binary interactions are not favored. The ternary interactions occur at all the ionic strengths and are maximized in about ~20 % mixture of $Gn_2SO_4$ in NaCl. The ternary interactions are reduced with increasing concentration of $Gn_2SO_4$ in higher ionic strengths. On the other hand, these mixtures with $y_B \leq 0.5$ and up to $I = 1.5$ mol kg$^{-1}$ are enriched with quadruplets that are absent at $I = 3$ and 6 mol kg$^{-1}$. The quaternary interactions are significant in the middle compositions of NaCl–$Gn_2SO_4$ mixtures in low ionic strengths. In the $Gn_2SO_4$-rich mixtures at the highest $I = 6$ mol kg$^{-1}$, the enhanced contribution of the binary interactions is compensated by the reduced ternary and quaternary interactions.

The Young's rule, an important tool to understand thermodynamics of multicomponent electrolytes, assumes that the properties of the mixture can be approximated by some suitable weighting of the properties of the component single electrolyte solutions [22]. The Young's cross square rule (YCSR) suggests that the sum of the $\Delta_m G^E$ values for the four 2-electrolyte mixtures with common ion prepared from M, N, X, and Y (M, N = cations; X and Y = anions). For a mixture having no common ion, for example, MX–NY mixture, four mixtures of two electrolytes each with common ion are possible. These are: MY–NY, MY–MX, MX–NX, NX–NY. Two more pairs, namely, MX–NY and MY–NX, are possible which have no common ions. The YCSR suggests that the sum of the $\Delta_m G^E$ values for the four 2-electrolyte mixtures with common ion prepared from M, N, X, and Y equals to the sum of $\Delta_m G^E$ of those two pairs having no common ions. Thus, at a constant ionic strength and a fixed composition, YCSR can be written as

$$\begin{aligned}&\Delta_m G^E\,(\mathrm{MX–MY}) + \Delta_m G^E\,(\mathrm{MY–NY}) + \Delta_m G^E\,(\mathrm{NX–NY}) + \Delta_m G^E\,(\mathrm{MX–NX}) = \\ &\Delta_m G^E\,(\mathrm{MX–NY}) + \Delta_m G^E\,(\mathrm{MY–NX})\end{aligned} \tag{5}$$

In the current situation, we therefore have:

(a) NaCl–$CH_3COOGn$, pairs with common ion: NaCl–$CH_3COONa$, NaCl–GnCl, $CH_3COONa$–$CH_3COOGn$, GnCl–$CH_3COOGn$; pairs with uncommon ion: NaCl–$CH_3COOGn$, GnCl–$CH_3COONa$
(b) NaCl–$GnNO_3$, pairs with common ion: NaCl–$NaNO_3$, NaCl–GnCl, $NaNO_3$–$GnNO_3$, GnCl–$GnNO_3$; pairs with uncommon ion: NaCl–$GnNO_3$, GnCl–$NaNO_3$
(c) NaCl–$GnClO_4$, pairs with common ion: NaCl–$NaClO_4$, NaCl–GnCl, $NaClO_4$–$GnClO_4$, GnCl–$GnClO_4$; pairs with uncommon ion: NaCl–$GnClO_4$, GnCl–$NaClO_4$
(d) NaCl–$Gn_2SO_4$, pairs with common ion: NaCl–$Na_2SO_4$, NaCl–GnCl, $Na_2SO_4$–$Gn_2SO_4$, GnCl–$Gn_2SO_4$; pairs with uncommon ion: NaCl–$Gn_2SO_4$, GnCl–$Na_2SO_4$

Application of the YCSR to our systems is demonstrated in Table 3, where we list the $\Delta_m G^E$ values for different pairs. Let us first take the case of NaCl–$Gn_2SO_4$. The sum of the $\Delta_m G^E$ values for the NaCl–$Na_2SO_4$, NaCl–GnCl, $Na_2SO_4$–$Gn_2SO_4$, and GnCl–$Gn_2SO_4$ pairs at $I = 3$ mol kg$^{-1}$ is –1155 J kg$^{-1}$ $H_2O$, which is very near (3 %) to the sum of the $\Delta_m G^E$ values of NaCl–$Gn_2SO_4$ and GnCl–$Na_2SO_4$, i.e. –1186 J kg$^{-1}$ $H_2O$. The calculations show that the YCSR is obeyed by the above system containing $SO_4^{2-}$ ions in the environment of $Na^+$ and $Gn^+$ ionic species with opposite tendency to alter the arrangement of water molecules around them. This is probably due to the moderating effect of $SO_4^{2-}$ (structure-maker) on $Gn^+$ (structure-breaker). There are, however, violation of YCSR in the mixtures of NaCl with $CH_3COOGn$, $GnNO_3$, and $GnClO_4$ as shown in Table 3. As seen above, the $CH_3COOGn$ mixtures with NaCl do not show the presence of binary interactions, and these mixtures are populated with ternary and quaternary interactions. The $GnNO_3$ and $GnClO_4$ systems with NaCl also fail to obey YCSR owing to the presence of strong ternary and quadruples. The deviations between the $\Delta_m G^E$ values obtained as a sum of pairs with common ion and those with uncommon ions are about 80, 48, and 32 % for the $CH_3COOGn$, $GnNO_3$, and $GnClO_4$ systems, respectively. Unlike $SO_4^{2-}$, $CH_3COO^-$, $NO_3^-$, and $ClO_4^-$ are the structure-breaker ions and further add to the structure-breaking character of $Gn^+$ ion.

**Table 3** Testing the YCMR for $\Delta_m G^E$ of the mixtures of NaCl with the guanidinium salts; $y_2 = 0.5$.

| Mixtures with common ion | $\Delta_m G^E$ J kg$^{-1}$ $H_2O$ | Mixtures with uncommon ions | $\Delta_m G^E$ J kg$^{-1}$ $H_2O$ |
|---|---|---|---|
| $I = 1$ mol kg$^{-1}$ | | | |
| NaCl–$CH_3COONa$ | 3 | NaCl–$CH_3COOGn$ | 7 |
| NaCl–GnCl | 4 | GnCl–$CH_3COONa$ | 20 |
| $CH_3COONa$–$CH_3COOGn$ | 3 | | |
| GnCl–$CH_3COOGn$ | 5 | | |
| Total | 15 | | 27 |
| $I = 1$ mol kg$^{-1}$ | | | |
| NaCl–$NaNO_3$ | –185 | NaCl–$GnNO_3$ | –267 |
| NaCl–GnCl | 4 | GnCl–$NaNO_3$ | –200 |
| $NaNO_3$–$GnNO_3$ | 6 | | |
| GnCl–$GnNO_3$ | –141 | | |
| Total | –316 | | –467 |
| $I = 1$ mol kg$^{-1}$ | | | |
| NaCl–$NaClO_4$ | –222 | NaCl–$GnClO_4$ | –247 |
| NaCl–GnCl | 4 | GnCl–$NaClO_4$ | –273 |
| $NaClO_4$–$GnClO_4$ | 9 | | |
| GnCl–$GnClO_4$ | –185 | | |
| Total | –394 | | –520 |
| $I = 3$ mol kg$^{-1}$ | | | |
| NaCl–$Na_2SO_4$ | –590 | NaCl–$Gn_2SO_4$ | –576 |
| NaCl–GnCl | 17 | GnCl–$Na_2SO_4$ | –610 |
| $Na_2SO_4$–$Gn_2SO_4$ | 23 | | |
| GnCl–$Gn_2SO_4$ | –605 | | |
| Total | –1150 | | –1186 |

The above results show that the YCSR cannot be employed to reasonably estimate the excess free energy of mixing of the electrolyte mixtures, where ternary and quaternary interactions are dominant over the binary interactions. Thus, YCSR is unable to provide empirical guidance to create a mechanistic model to describe the excess free energy of mixing of guanidinium containing non-sulfate mixtures.

## CONCLUSIONS

In summary, we can state that it is possible to account for more complete description of ionic interactions in aqueous ionic solutions with hydrophobic species by using the SRJ equation. As such, there is no provision in Pitzer's specific ion interaction theory to consider explicitly the effects due to quaternary and higher-order interactions. The interactions higher than ternary in the systems discussed above should be evaluated within the framework of the method of Wigent and Leifer. Further, the interactions between two guanidinium cations are significant and should not be ignored. Another important conclusion of this work is that though the Pitzer equations can be used with confidence to analyze the thermodynamic properties of strong electrolytes in general, the use of the above methodology is recommended when the systems contain hydrophobic and/or clathrate-forming ionic solutes.

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## REFERENCES

1. Y. Hagihara, S. Aimoto, A. L. Fink, Y. Goto. *J. Mol. Biol.* **231**, 180 (1993).
2. (a) L. M. Mayr, F. Schmid. *Biochemistry* **32**, 7994 (1993); (b) P. H. Von Hippel, T. Schleich. *Acc. Chem. Res.* **2**, 257 (1969).
3. For a review, see: (a) R. Breslow. *Acc. Chem. Res.* **24**, 159 (1991); (b) A. Kumar. *J. Org. Chem.* **59**, 230 (1994); (c) A. Kumar. *Pure Appl. Chem.* **70**, 625 (1998); (d) S. S. Pawar, U. Phalgune, A. Kumar. *J. Org. Chem.* **64**, 7055 (1999).
4. (a) P. Debye, E. Hückel. *Physik. Z.* **24**, 185 (1923); (b) P. Debye, E. Hückel. *Physik. Z.* **24**, 334 (1923); (c) P. Debye, E. Hückel. *Physik. Z.* **25**, 97 (1924).
5. For a compilation of different equations with original citations, see: J. F. Zemaitis Jr., D. M. Clark, M. Rafal, N. C. Scrvner. *Handbook of Aqueous Electrolyte Thermodynamics*, American Institute of Chemical Engineers, New York (1986).
6. J. E. Mayer. *J. Chem. Phys.* **18**, 1426 (1950).
7. (a) H. L. Friedman. *J. Phys. Chem.* **32**, 1134 (1960); (b) H. L. Friedman. *J. Phys. Chem.* **32**, 1351 (1960); (c) for a complete account, see: H. L. Friedman. *Ionic Solution Theory*, Interscience, New York (1962).
8. (a) K. S. Pitzer. *J. Phys. Chem.* **77**, 268 (1973); (b) K. S. Pitzer, J. J. Kim. *J. Am. Chem. Soc.* **96**, 5701 (1974); (c) K. S. Pitzer. "Ion interaction approach: Theory and data correlation", in *Activity Coefficients in Electrolyte Solutions*, 2nd ed., K. S. Pitzer (Ed.), Chap. 3, CRC Press, Boca Raton (1991).
9. For a summary with original citations, see: Y. Wen. In *Water and Aqueous Solutions*, R. A. Horne (Ed.), Chap. 15, p. 613, John Wiley, New York (1972).
10. V. Kuhnel, U. Kaatze. *J. Phys. Chem.* **100**, 19747 (1996).
11. S. Lileev, A. K. Lyshchenko, P. Yastremskii. *Russ. J. Phys. Chem. (Eng.)* **59**, 978 (1985).
12. H. S. Harned, B. B. Owen. *The Physical Chemistry of Electrolyte Solutions*, Reinhold, New York (1950).
13. G. Scatchard, R. M. Rush, J. S. Johnson. *J. Phys. Chem.* **74**, 3786 (1970).
14. Y. C. Wu, R. M. Rush, G. Scatchard. *J. Phys. Chem.* **72**, 4048 (1968).
15. Y. C. Wu, R. M. Rush, G. Scatchard. *J. Phys. Chem.* **73**, 2047 (1969).
16. (a) L. Leifer, R. W. Wigent. *J. Phys. Chem.* **89**, 244 (1985); for application, see: (b) R. J. Wigent, L. Leifer. *J. Phys. Chem.* **88**, 4420 (1984); (c) D. M. Fox, L. Leifer. *J. Phys. Chem. B* **104**, 1058 (2000); (d) D. M. Fox, L. Leifer. *Fluid Phase Equilib.* **213**, 1 (2003).
17. A. Kumar. *J. Phys. Chem. B* **104**, 9505 (2000).
18. A. Kumar. *J. Phys. Chem. B* **105**, 9828 (2001).
19. A. Kumar. *J. Phys. Chem. B* **107**, 2808 (2003).
20. A. Kumar. *J. Phys. Chem. B* **109**, 11743 (2005).
21. Y. Marcus. *Ion Solvation*, John Wiley, New York (1986).

22. (a) T. F. Young, N. B. Smith. *J. Phys. Chem.* **58**, 716 (1954); (b) T. F. Young, Y. C. Wu, A. A. Krawetz. *Discuss. Faraday Soc*. **24**, 37 (1957).