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Mixing Schemes in Binary Aqueous Solutions of Non-electrolytes

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Our thermodynamic studies on Mixing Schemes operating in aqueous solutions of non-electrolytes are reviewed. We use the data of higher order of G than hitherto utilized. Generally there are three distinctively different Mixing Schemes present over the entire composition range. Some details of each Mixing Schemes are described as much as known at this time. The findings by other techniques are also discussed where applicable.

1. Introduction
－Partial Molar Quantities and Interactions

Studies of aqueous solutions up to early 1980's have been reviewed comprehensively.[1-3] Since late 1980's, we have introduced a novel methodology in solution thermodynamics and applied it to studies of aqueous solutions. The earlier results using this methodology were summarized in the mid 1990's.[4,5] The present article is to review our more recent works on binary aqueous non-electrolytes. Where applicable, we include findings by other techniques; spectroscopy, scattering etc. The applications of the same methodology to ternary aqueous solutions were summarized recently.[6]

Our methodology is to measure thermodynamic quantities that are higher order derivatives of Gibbs energy than hitherto exercised. Furthermore, we take one more derivative of these measured data graphically without resorting to any fitting functions. Thus we have still higher order derivative quantities that are model-free and accessible purely experimentally. **Table 1** lists thermodynamic quantities in the Gibbs ensemble, the (p, T, n_i) variable system. n_i is the amount of the i-th component. Those listed within { } are the variables of differentiation.[4,5] The excess partial molar entropy of i, for example, is defined as,

$$S_i^{\mathrm{E}}\ ;\ \{T,\ n_i\} \equiv -(\partial^2 G^{\mathrm{E}}/\partial T\ \partial n_i) \tag{1}$$

Each partial differentiation is taken by keeping other variables constant. Superscript E stands for the excess quantity. We measured the excess partial molar quantities, the second derivatives of G, directly. The details of measurement were described elsewhere; H_i^{E} [7,8], μ_i^{E} [9-11] (and hence S_i^{E}), and V_i^{E}.[12-15] These partial molar quantities signify the actual contribution of the i-th component in the mixture towards the thermodynamic quantity of the entire system. Thus, they show the actual thermodynamic situation of the i-th component in the system. Since we make the point of obtaining these data in small increments, we can take one more derivative with respect to the amount of j-th component. The method of ensuring the goodness of graphical differentiation was discussed earlier.[16]

For enthalpy, for example, we define the enthalpic interaction, H_{i-j}^{E}, as

$$H_{i-j}^{\mathrm{E}}\ ;\{T,\ n_i,\ n_j\} \equiv N\,(\partial H_i^{\mathrm{E}}/\partial n_j), \tag{2}$$

$$=(1-x_j)(\partial H_i^{\mathrm{E}}/\partial x_j) \text{ for a binary system} \tag{3}$$

where $N=\Sigma n_i$ is the total amount. Analogous expressions for entropy, volume and chemical potential are available by changing H to S, μ, and V. They all signify the effect of the j-th component on the partial molar quantity of i, or the degree of the $i-j$ interaction. For the former three, the thermodynamic stability criteria can be applied and we could understand such interaction is favorable (attractive) or unfavorable (repulsive) by the sign of H_{i-j}^{E} (and its S, or μ analog).

Table 1 Excess thermodynamic quantities in the Gibbs ensemble, the (p, T, n_i) variable system. The variables in { } are the variables of differentiation, keeping others constant.

Order	0th	1st	2nd	3rd
Number.	1	4	7	11
Function	G^E	H^E ; {T}	H_i^E ; {T, n_i}	H_{i-j}^E ; {T, n_i, n_j} (See text)
		S^E ; {T}	S_i^E ; {T, n_i}	S_{i-j}^E ; {T, n_i, n_j} (See text)
		V^E ; {p}	V_i^E ; {p, n_i}	V_{i-j}^E ; {p, n_i, n_j} (See text)
		μ_i^E ;{n_i}	μ_{i-j}^E ; {n_i, nj}	?* ; {n_i, n_j, n_k}
			C_p ; {T, T}	${}^S\delta_i$ or ${}^S\Delta_i$; {T, T, n_i} (See text)
			κ_T ; {p, p}	${}^V\delta_i$ or ${}^V\Delta_i$; {p, p, n_i} (See text)
			α_p ; {p, T}	${}^{SV}\delta_i$ or ${}^{SV}\Delta_i$; {p, T, n_i} (See text)
				? ; {T, T, T}
				? ; {T, T, p}
				? ; {T, p, p}
				? ; {p, p, p}

*Third derivative quantities with "?" have not been defined nor exploited.

2. Fluctuation Functions

The response functions, isobaric heat capacity, C_p, isothermal compressibility, κ_T, and isobaric expansivity, α_p, are other second derivatives of G, and are related respectively to the entropy, volume and entropy-volume cross fluctuations.[17] In defining fluctuation, however, a local thermodynamic value is to be determined in a coarse grain, the size of which must be large enough for a thermodynamic quantity to be evaluated but small enough for fluctuation to be detected. The problem is that we have no *a priori* knowledge about its proper size. Furthermore, when comparing the degree of fluctuation among different systems or situations, we would like to distinguish between amplitude and wavelength of fluctuation, the latter of which must be related to an unknown coarse grain size. To cope with these problems we devised two fluctuation functions; the mean-square fluctuation densities, ${}^q\delta$,[18,19] and the (mean-square) normalized fluctuations, ${}^q\Delta$,[18-23], where $q = S$, V, or SV, meaning fluctuation in entropy, volume or entropy-volume cross fluctuation respectively. Namely,

$$ {}^V\delta \equiv <(V-<V>)^2>/(k<V>) = T\kappa_T, \tag{4a}$$

$$ {}^S\delta \equiv <(S-<S>)^2>/(k<V>) = <C_p>/<V> = C_{p\,m}/V_m, \tag{4b}$$

$$ {}^{SV}\delta \equiv <(V-<V>)(S-<S>)>/(k<V>) = T\alpha_p, \tag{4c}$$

where V and S are evaluated in a coarse grain containing a fixed but unknown number of molecules. < > signifies its ensemble average. C_{pm} and V_m are the molar heat capacity and volume respectively.

We also defined[20-23] the mean square normalized fluctuations as,

$$ <\{(V-<V>)/<V>\}^2> = k\,T\kappa_T/<V>, \tag{5a}$$

$$ <\{(S-<S>)/<V>\}^2> = k<C_p>/<V>^2, \tag{5b}$$

$$ <\{(V-<V>)(S-<S>)/<V>^2\}> = k\,T\alpha_p/<V> \tag{5c}$$

We then re-define ${}^q\Delta$'s as,

$$ {}^V\Delta \equiv R\,T\kappa_T/V_m, \tag{6a}$$

$$ {}^S\Delta \equiv R\,C_{pm}/V_m^2, \tag{6b}$$

$$ {}^{SV}\Delta \equiv R\,T\alpha_p/V_m \tag{6c}$$

From eq.(5) to (6), we convert k to R and $<V>$ to V_m. By forcing $<V>$, which should reflect the appropriate size of fluctuation wavelength for each system, to a constant value, V_m, ${}^q\Delta$'s contain qualitative information about the relative size of fluctuation wavelength. Namely, if ${}^q\delta$ happens to be the same between two systems and if ${}^q\Delta$ for one is larger than the other, then it suggests that the wavelength of fluctuation is larger for that system, though qualitatively.[18,19]

Furthermore, we define the partial molar fluctuation of the i-th component - the effect of the i-th component on the respective fluctuation function as,

Table 2 H_i^{E}, μ_i^{E}, and V_i^{E} *etc.* for binary aqueous solutions of non-electrolytes.

Solute	Abbr.	Type	temp ℃	Values at $x_i=0$ H_i^{E}/kJ mol^{-1}	(Ref)	μ_i^{E}/kJ mol^{-1}	(Ref)	V_i^{E} initial decrease ? Yes/No	(Ref)
				±0.1		±0.1			
Methanol	ME	a	25	−7.4	(24)	1.3	(37)	Yes	(38)
Ethanol	ET	a	25	−10.2	(24)	3.3	(37)	Yes	(38)
1-Propanol	1P	a	25	−10.4	(24)	6.6	(37)	Yes	(38)
2-Propanol	2P	a	25	−13.1	(24)	5.0	(37)	Yes	(39)
1-Butanol	1B	a	25	−9.3	(25)	10.0	(25)	Yes	(25)
tert-Butanol	TBA	a	26.9	−17.0	(26)	6.6	(9, 11)	Yes	(40)
		a	45.17	−12.9	(26)				
		a	59.49	−10.0	(26)				
2-*n*-Butoxyethanol	BE	a	25	−17.0	(27)	9.2	(10)	Yes	(14, 15)
		a	29.90	−15.8	(28)				
		a	40.00	−12.9	(28)				
		a	50.09	−10.5	(28)				
		a	60.13	−7.8	(28)				
2-*iso*-Butoxyethanol	iBE	a	20	−10.7	(29)	6.0	(29)	Yes	(29)
Acetonitrile	ACN	a	6.0	−3.3	(35)				
		a	20.0	−1.9	(35)	5.8	(35)	Yes	(35)
		a	30.0	−1.0	(35)				
		a	37.0	−0.4	(35)				
		a	45.0	0.4	(35)				
iso-Butyric acid	IBA	b	25	−1.6	(31)				
		b	27	−1.5	(31)				
2-Butanone	BUT	b	25	−10.5	(36)	−4.0	(36)		
Dimethylsulfoxide	DMSO	c	25	−17.5	(34)	−6.9	(34)	Yes	(36)
1,2-Propanediol	12P	c	25	−10.5	(32)	−0.3	(32)	Yes	(32, 41)
1,3-Propanediol	13P	d	25	−8.7	(32)	−0.4	(32)	Yes	(32, 41)
Glycerol	Gly	d	25	−5.6	(33)	−2.1	(33)	NO	(33)
Acetone	AC	d	25	−15.2	(30)	5.0	(30)	Yes	(30)
Tetramethyl urea	TMU	d	25	−23.5	(30)	1.5	(30)	Yes	(42)

$$ {}^{q}\delta_i \equiv N\,(\partial\,{}^{q}\delta/\partial n_i)=(1-x_i)(\partial\,{}^{q}\delta/\partial x_i), \qquad (7)$$

$$ {}^{q}\Delta_i \equiv N\,(\partial\,{}^{q}\Delta/\partial n_i)=(1-x_i)(\partial\,{}^{q}\Delta/\partial x_i) \qquad (8)$$

The last equality for both eq.(7) and (8) is true for a binary system.

We have used partial molar quantities, eq.(1) and its analogues for enthalpy, chemical potential and volume, the interaction functions, eq.(2) and its analogues and fluctuation functions, eq.(4) and (6), and partial molar fluctuations, eq.(7) and (8), among second and third derivative quantities listed in **Table 1**. We have thus learned the mixing schemes in aqueous solutions in more detail than before. We summarize our findings briefly below, without going through the details of discussion leading to conclusions, which were described in respective original papers.

3. Mixing Schemes in Aqueous Solutions of Non-electrolytes

Table 2 shows all the solutes whose binary aqueous solutions we have studied so far. The abbreviations for solute shown in the table are used throughout of this article. The solute type in the table refers to the manner of the x_i-dependence of H_{i-i}^{E}, eq.(2), which is discussed

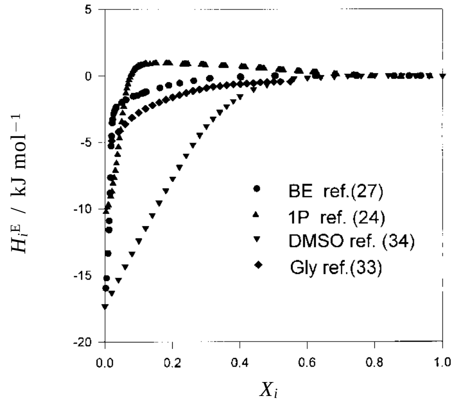

Fig.1 Excess partial molar enthalpies of some selected solute i, H_i^E, at 25℃. i = BE, 1P, DMSO and Gly. See Table 2 for abbreviation of solute.

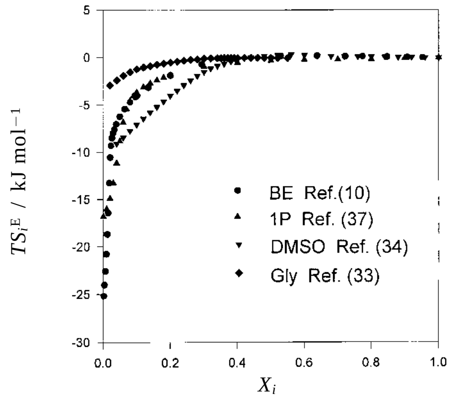

Fig.2 Excess partial molar entropies of some selected solute i, TS_i^E, at 25℃. i = BE, 1P, DMSO and Gly. See Table 2 for abbreviation of solute.

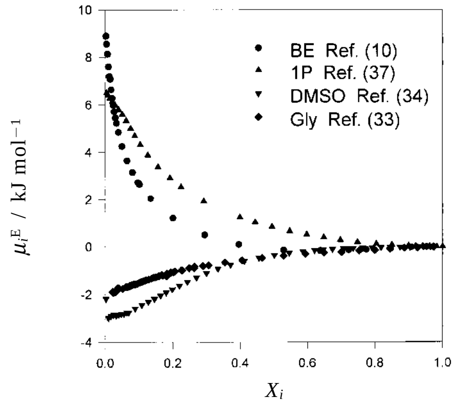

Fig.3 Excess chemical potentials of some selected solute i, μ_i^E, at 25℃. i = BE, 1P, DMSO and Gly. See Table 2 for abbreviation of solute.

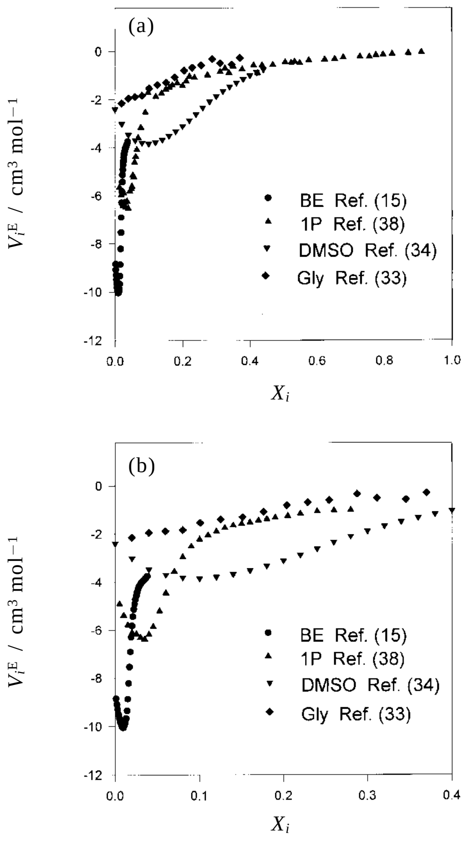

Fig.4 Excess partial molar volumes of some selected solute i, V_i^E, at 25℃. i = BE, 1P, DMSO and Gly. See Table 2 for abbreviation of solute.

in detail below. **Figs.1** to **4** show the excess partial molar quantities for some typical solutes, and the values at $x_i = 0$ and other information are given in **Table 2**. The table also contains information whether V_i^E shows the initial decrease on increasing x_i as shown for BE and 1P in **Fig.4**. This initial decrease is a signature of the "iceberg" formation with a concomitant reduction of hydrogen bond probability in the bulk H_2O away from solute.[4,5,15]

Figs.1 to **4** indicate that the sharp x_i-dependence of the excess partial molar quantity of i-th component in the water-rich region dies down rapidly and for $x_i > 0.6$ they become almost zero and constant. Hence, in all the solute cases, the mixing scheme, the way in which the solute and the solvent H_2O mix together, is not just a single kind over the entire composition range. At least in the water-rich region and in the solute-rich region

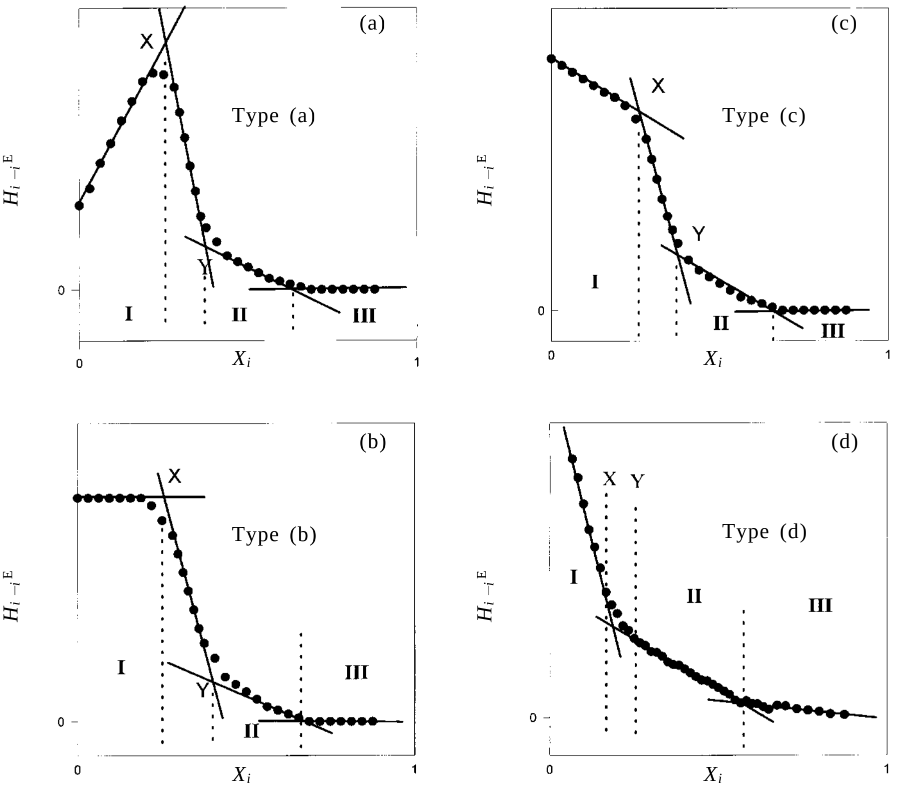

Fig.5 Four types of the x_i-dependences of the enthalpic interaction, H_{i-i}^{E}. I, II and III are regions in which Mixing Schemes I, II and III are operative. Points X and Y mark the transition region from I to II. See text.

it is qualitatively different from each other. On evaluating the third derivative quantities, H_{i-i}^{E}, for example, it becomes apparent that there are three regions in each of which the solute and H_2O interact with each other in a different manner. **Fig.5** shows the x_i-dependence of H_{i-i}^{E}, and their values and other pertinent information are listed in **Table 3**. Due to entropy-enthalpy compensation prevalent in aqueous solutions,43) the entropy analog, TS_{i-i}^{E}, shows almost the same x_i-dependence of H_{i-i}^{E}.4,5) We have encountered four types of x_i-dependences as shown in **Fig.5(a)** to **5(d)**. Following the discussions in the original papers, some of which will be summarized below, we recognize three x_i-regions where Mixing Scheme I, II and III are operative, with the transition region from I to II marked as point X and Y in the figure. Basically Mixing Scheme I is that the integrity of liquid H_2O is retained while that of solute is kept in III. In the intermediate region, two kinds of clusters, one rich in H_2O and the other in solute, mix together and for some cases they grow to a macroscopic size and phase separation occurs. We call this mode of mixing (or rather unmixing at the molecular level), Mixing Scheme II. The loci of these boundaries are listed in **Table 3**. D'Angelo *et al.*44) and Sato *et al.*45-47) also recognized the existence of multi-mixing schemes in aqueous solutions of small alcohols by analysis of carefully determined compressibility data and IR spectra47) and dielectric relaxation data46,47) respectively, although the loci of the boundaries are slightly different from each other and from those in **Table 3**.

3.1 Mixing Scheme III－Solute-rich situation

As is evident in **Fig.1** to **4**, the values of the excess partial molar quantities of solute are almost zero and constant up to $x_i = 1$ in the solute-rich region. Furthermore, **Fig 5** shows that H_{i-i}^{E} in this range is almost zero, also. This indicates that the solute molecules see their environment to be almost the same as in their pure

Table 3 μ_{i-i}^{E} and H_{i-i}^{E}.

Solute	Temp.	μ_{i-i}^{E} (Ref)	type	H_{i-i}^{E} at $x_i=0$	H_{i-i}^{E} at point X	Loci of X	Y	II−III	(Ref)
ME	25	−ve (37)	a	26±3	32±3	0.07	0.25	0.45	(24)
ET	25	−ve (37)	a	35±5	73±5	0.06	0.19	0.35	(24)
1P	25	−ve (37)	a	40±7	210±10	0.05	0.09	0.27	(24)
2P	25	−ve (37)	a	50±7	180±10	0.05	0.11	0.16	(24)
1B	25	−ve (25)	a			phase separation at 0.018			(25)
TBA	26.90	−ve (9, 11)	a	90±20	350±20	0.045	0.065	0.38	(26)
	45.17		a	90±20	290±20	0.03	0.055		(26)
	59.49		a	90±20	220±20	0.025	0.045		(26)
BE	25	−ve (10)	a	350±30	1100±50	0.017	0.021	0.42	(27)
	29.90		a	350±30	1050±50	0.0155			(27)
	40		a	350±30	910±50	0.0145			(27)
	50.09		a	350±30	750±50	0.013			(27)
	60.13		a	350±30	680±50	0.011			(27)
iBE	20	−ve (29)	a	240±30	550±50	0.012	0.026	0.37	(29)
ACN	6		a	40±5	133±7	0.0125	0.085		(35)
	20	−ve (35)	a	40±5	122±7	0.0106			(35)
	30		a	40±5	110±7	0.0088			(35)
	37		a	40±5	100±7	0.0080	0.060	0.45	(35)
	45		a	40±5	95±7	0.0065			(35)
IBA	25		b	170±10	170±10	0.022	0.043		(31)
	27		b	170±10	170±10	0.022	0.044		(31)
BUT	25	−ve then +ve (36)	b	139±8	139±8	0.04			(36)
DMSO	25	+ve (34)	c	51±5	34±5	0.21	0.35	0.56	(34)
12P	25	0 (32)	c	78±7	47±7	0.10	0.19	0.37	(32)
13P	25	0 (32)	d	59±5	25±3	0.10	0.20	0.30	(32)
Gly	25	+ve (33)	d	42±5	13±3	0.10	0.15	0.34	(33)
AC	25	−ve (30)	d	120±10	40±5	0.10	0.25	0.50	(30)
TMU	25	−ve (30)	d	220±15	100±8	0.07	0.25	0.40	(30)

state, in this composition region. Namely, the solute molecules stay as clusters of their own kind. The "solvent" H_2O's behaviour in this region will be apparent from partial molar quantity of H_2O. For BE[27] and DMSO,[34] the values of the excess partial molar enthalpy of H_2O, $H_{\mathrm{W}}^{\mathrm{E}}$, are constant and hence the H_2O-H_2O interaction, $H_{\mathrm{W-W}}^{\mathrm{E}}$, is zero. Thus, H_2O molecules interact with BE and DMSO clusters independently as a single molecule. For TBA,[48] $H_{\mathrm{W}}^{\mathrm{E}}$ and $S_{\mathrm{W}}^{\mathrm{E}}$ show a modest but definite x_i-dependence hinting a gradual clustering of H_2O as the amount of H_2O increases. For other solutes, $H_{\mathrm{W}}^{\mathrm{E}}$ is yet to be determined. A recent neutron scattering study by Dixit et al. on ME-H_2O at 0.7 mole fraction of ME, which is in Mixing Scheme III region (see Table 3), suggests the existence of small H_2O clusters in basically liquid ME.[49] Our recent X-ray diffraction study on DMSO-H_2O indicates that the radial distribution function of solutions in Mixing Scheme III is identical to that of pure DMSO right down to the II-III mixing scheme boundary,[50] indicating the main structural feature of DMSO-H_2O in this composition range is identical to that of pure liquid DMSO.

3.2 Mixing Scheme I − H_2O-rich situation

H_2O is a unique liquid and its uniqueness is due to the spatially almost but not quite symmetric hydrogen bond capability of H_2O. Due to this slight non-symmetry, the degree of fluctuation in H_2O is larger than normal liquid in terms of amplitude as well as wavelength.[18,19,21] Among many possible interpretations, we use here the site-correlated percolation model by Stanley *et al.*[51] for liquid H_2O. Its convenience[21] is that some global hydrogen bond probability is all that is required to parameterize the bond percolation nature of the hydrogen bond network and the putative existence probability of ice-like patches. Thus, the x_i -dependence of thermodynamic quantities, **Figs.1-5**, reflects the process of modification of these unique properties of H_2O by a solute non-electrolyte.

3.2.1 Type (a)－Mono-ols and Acetonitrile

By far the most common x_i -dependence of H_{i-i}^E that we have encountered is type (a). All the mono-ols and acetonitrile belong to this type. For these solutes, Mixing Scheme I was discussed extensively, using the data of H_i^E, S_i^E, V_i^E, H_{i-i}^E, and S_{i-i}^E,[4,5,24,35] and also fluctuation functions.[18,19] Main points of discussion were described in the previous reviews.[4,5] We shall not repeat the discussion here, but summarize our findings below, with additional reference to our pertinent original papers.

(1) A solute molecule enhances the hydrogen bond network of H_2O in its immediate vicinity (the so-called "iceberg" formation) with a concomitant reduction of the hydrogen bond probability of bulk H_2O away from solute.[52,53]

(2) Up to point X in **Fig.5**, however, the hydrogen bond probability of bulk H_2O is still high enough, so that the hydrogen bond network is connected throughout the entire bulk－*i.e.* the bond percolation is intact.[11,15,28,54]

(3) The "iceberg" portion of H_2O is rigid and does not participate in fluctuation characteristic to liquid H_2O.[18,19]

(4) The interaction between "iceberg" clad solutes occurs via the fluctuating hydrogen bond network of bulk H_2O, *i.e.* H_2O-mediated interaction.[18,19,23]

(5) The "iceberg" clad solutes are the likely components for formation of an addition compound (most likely a clathrate) on freezing.[55-57]

(6) As x_i increases, the bulk hydrogen bond probability is reduced progressively and at point X in **Fig.5**, the hydrogen bond of the strongest end of its strength distribution reaches the bond percolation threshold and hence the network connectivity is partially lost. At point Y those at the weakest end of distribution and hence all the hydrogen bonds have no bond percolation any longer. Hence one of the unique features of liquid H_2O is lost and Mixing Scheme II sets in.[4,5]

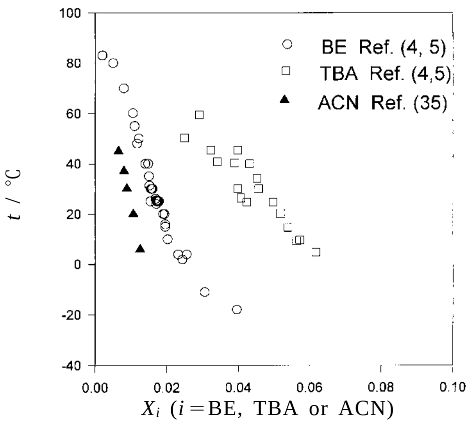

Fig.6 The loci of point X for BE-, TBA- and ACN-H_2O systems in the x_i -T field. Sometimes called "Koga line". See Table 2 for abbreviation of solute.

(7) H_{i-i}^E and TS_{i-i}^E up to point X in **Fig.5(a)** becomes progressively more positive as x_i increases－more unfavourable in terms of enthalpy but more favourable entropy-wise. For all type (a) solutes we studied, the values of the latter is larger resulting in the net attraction in terms of chemical potential - μ_{i-i}^E is negative as shown in **Table 3**. Thus the net $i-i$ attraction is entropy-driven.[9,10]

(8) As the size of hydrophobic alkyl group increases in mono-ol series, the loci of point X becomes lower and the values of H_{i-i}^E at point X becomes larger, as shown in **Table 3**. Thus, the thermodynamic behaviour we observe here is primarily due to "hydophobicity" of solute alcohol. Furthermore from the trend in the x_i and H_{i-i}^E values at point X, we suggest ranking of ME < ET < 2P < 1P < TBA < BE for the hydrophobicity in mono-ol series at 25 ℃.[58]

(9) The loci of point X of H_{i-i}^E and anomalous points of other third derivative quantities form a line, some times called Koga line.[59-61] See **Fig.6** for BE, TBA and ACN. The loci of these lines in **Fig.6** seems to extrapolate to about 80 ℃ at x_i = 0, as was pointed

out earlier for BE and TBA.[4,5] We note that the hydrogen bond probability of liquid H_2O estimated by Stanley et al. reaches 0.39,[51] the bond percolation threshold for the diamond bond connectivity at about 80 ℃. Thus, Koga line seems to mark the end of the percolation nature of the hydrogen bond network of H_2O – *i.e.* the loss of one of the important characteristics of H_2O.[4,5]

The anomaly in H_{i-i}^{E} shown in **Fig.5(a)** resembles the heat capacity anomaly associated with phase transition. Indeed, Desnoyers et al. named "pseudo-phase transition" for the anomaly in the partial molar heat capacity (a third derivative of G) in BE-H_2O.[62] "Phase" is a macroscopic entity and its transition is associated with anomalies in heat capacity, a second derivative of G. We are dealing with the phenomenon here within a single phase domain, and a transition is more subtle which is associated with anomalies in third derivatives of G. We thus prefer to use "transition of mixing scheme" rather than (pseudo- or micro-) "phase" transition.

As shown in **Table 3** the region of Mixing Scheme I is narrow, at most to $x_i = 0.07$ for ME. Generally studies of aqueous solutions by other techniques tend to miss this low composition region. For BE-H_2O, however, Verrall et al. showed that the hydrodynamic radius of a diffusing species is about 50 times larger for $x_i < 0.016$ than that in $x_i > 0.048$.[63] Pecora et al. observed by dynamic light scattering about 100-fold jump in the mutual diffusion coefficient form $x_i = 0.0139$ to 0.0207 for BE-H_2O at 25 ℃.[64] (The locus of point X for BE-H_2O is at 0.017, see Table 3.) These are consistent with the "iceberg" concept. Holz *et al.*[65] showed by an NMR study the existence of boundary at about $x_i = 0.03$ at 25 ℃, below which a single TBA molecule is hydrated, whereas the higher concentration region is characterized by microstructures where TBA molecules are associated. Furthermore, this boundary was found to shift to a smaller x_i value as temperature increases.[65] While the value of x_i of this boundary is a little smaller than that of our point X ($x_i = 0.045$, see **Table 3**), the general picture is consistent with each other. Nishi *et al.*[66,67] and more recently Wakisaka *et al.*[68] used mass spectroscopy to study clusters in aqueous solutions of small alcohols, and suggest alcohol-alcohol clustering even in very dilute region, dilute enough to be in Mixing Scheme I. This point is discussed below in connection with DMSO – H_2O.

3.2.2 Type (b) – *iso*-Butyric Acid (IBA) and 2-Butanone (BUT)

Both systems have liquid-liquid phase separations. The fact that both consist of a $>C=\mathrm{O}$ group may have some bearing to this type of x_i-dependence of H_{i-i}^{E}, which indicates that the $i-i$ interaction in terms of enthalpy stays constant up to point X. Elucidation of the details of Mixing Scheme I for type (b) solutes needs further investigation. As will be discussed collectively for Mixing Scheme II below, the signs of H_{i-i}^{E} for both solutes past the step anomaly shown in **Fig.5(b)** are consistent with the way the phase boundaries slant. Namely, for BUT-H_2O, in which the phase boundary slants in the way $dT/dx_i < 0$ in the x_i -T field, H_{i-i}^{E} and TS_{i-i}^{E} have proper positive signs.[4,5,36] For IBA, on the other hand, the sign of H_{i-i}^{E} past the step anomaly is properly negative for a system having a phase separation with UCST(upper critical solution temperature).[31] We thus suggest, though further elucidation as to its details is required, that there is Mixing Scheme I operative as indicated in **Fig.5(b)**, in which the integrity of liquid H_2O is retained.

3.2.3 Type (c) – Dimethylsulfoxide (DMSO) and 1,2-Propanediol (12P)

As shown in **Fig.5(c)**, the unfavourable $i-i$ interaction in terms of enthalpy, H_{i-i}^{E}, decreases gradually as x_i increases in contrast to types (a) and (b) and at point X it nosedives to the typical behaviour for Mixing Scheme II. Thus, the detail of Mixing Scheme I for this type of solutes could be different from that for type (a) which we know reasonably well. However, the excess partial molar volume, V_i^{E}, show the initial decrease as shown in **Table 2** and **Fig.4**, just as type (a) solutes, hinting the "iceberg" formation with a concomitant reduction of hydrogen bond probability of bulk H_2O away from solute. Indeed, Safford *et al.*[69] used neutron and *x*-ray diffraction for DMSO-H_2O at $x_i = 0.05$, 0.07, 0.13 and 0.22 and concluded that for $x_i < 0.2$, DMSO induces a cooperative orientation of H_2O around DMSO.

Another point to note is that the locus of point X occurs at $x_i = 0.21$ for DMSO and 0.1 for 12P (**Table 3**), the ratio of 4 H_2O molecules for 1 DMSO, or 9 H_2O for every 12P molecule. If Mixing Scheme I is preparing for formation of an addition compound of DMSO$(H_2O)_3$ or DMSO$(H_2O)_{2.5}$ that are known to exist,[70] it is not a typical clathrate similar to BE$(H_2O)_{26}$.[55] This ratio for BE to H_2O is a reasonable number that could surround a BE molecule. Thus, the ratio for H_2O to DMSO seems unduly small. Our *x*-ray diffraction study[50] reveals that the $S-S$ distance is in fact shorter in this composition region $x_i<0.28$ (Mixing Scheme I) than that of pure state as well as in Mixing Scheme III. This hints that DMSO molecules cluster together specifically via $S=O$ dipoles resulting in tighter clusters than pure DMSO exposing methyl groups outward with hydrophilic $S=O$ groups in, to which H_2O molecules interact as a type (a) solute. If the size of such cluster is m, then the addition compound could be of $(DMSO)_m\ (H_2O)_{3m}$ type and 3*m* could be a reasonable number of H_2O molecules to surround a tight *m*-mer DMSO cluster.

For smaller alcohols, ME, ET or 1P, the loci of point X occur at 0.07 for ME, 0.06 for ET, 0.05 for 1P and 0.045 for TBA. They are much higher than 0.017 for BE. Thus, following the same argument above for DMSO, it is quite probable that these small alcohols may cluster together in this composition region as pointed out by Nishi *et al.*[66,67] and Wakisaka *et al.*[68] While they suggest alcohol clustering in this composition region to occur via alkyl group-alkyl group clustering, we point out the initial decrease in V_i^E in these aqueous alcohols, the signature of "hydrophobicity", **Table 2** and **Fig.4**. We hint that, if any solute clustering in Mixing Scheme I of aqueous solutions of small alcohols, it could occur via-OH groups with alkyl groups pointing outward as suggested for DMSO. We note recent careful determination of the liquid-solid phase diagrams of H_2O-small alcohols by Takaizumi.[56,57] They indicate the existence of the addition compounds, $AL(H_2O)_m$, with $m=1.7$, 5.6 (4.2), 7.7(5,7), 5.7 (5.6), and about 7.7 for ME, ET, 1P, 2P, and TBA respectively.[56,57] All of them are peritectic just as for BE-H_2O[55], but the values of m are much smaller than 26 for BE. If these peritectic addition compounds were to be of clathrate, then there should be some degree of alcohol clustering. A structural determination of these addition compounds is awaited.

3.2.4 Type (d)－Acetone, 1,3-propanediol, glycerol and tetramethyl urea.

As x_i increases, H_{i-i}^E decreases sharply and then turns into the region with a less sharp slope, which we identify as Mixing Scheme II as shown in **Fig.5(d)**, by similarity of the value and the slope of H_{i-i}^E to other solutes (a) to (c). However, Gly is unique in that there is no initial decrease in V_i^E, **Table 2**. There are a few examples of this non-hydrphobic behaviour of V_i^E; urea,[71] formamide,[71] and d-fructose,[72] to name but a few. Gly has indeed no hydrophobic alkyl group together with urea *etc.* The remaining solutes in this group do have a hydrophobic group, which manifests itself in the initial decrease of V_i^E. From our similar studies of ternary systems of 1P-X-H_2O type with various third components X,[6] urea[73] and Gly[16,74] seem to participate in the hydrogen bond network of H_2O via their own proton donor and accepter and hence keep hydrogen bond connectivity intact but rigidify the network[75] and the high degree of fluctuation characteristic to liquid H_2O is reduced.[73] Furthermore, in comparing the entropy-volume cross fluctuation data, $^{SV}\Delta$, between Gly-H_2O and BE-H_2O systems,[33] we concluded Mixing Scheme I for Gly-H_2O is indeed to retain the integrity of H_2O, although the way in which the solute modifies liquid H_2O is different; in a hydrophilic *vs.* hydrophobic manner. A recent O^{17} NMR studies on binary diol-H_2O systems including 12P- and 13P-H_2O indicated that at the infinite dilution 10-15 H_2O molecules surround methylcarbinol group.[76] While the details of Mixing Scheme I for this type solute must be studied further, it may be reasonable to suggest that the x_i-dependence of H_{i-i}^E, **Fig.5(d)** reflects the process of modifying the characteristics of liquid H_2O in a hydrophilic manner.

3.3 Mixing Scheme II

Our conjecture for Mixing Scheme II is that the mixture consists of two kinds of clusters, one rich in H_2O and the other in solute. There are ample evidences for this at least in some of the solutes we have studied. For BE-, ACN-, IBA-, and BUT-H_2O, there are phase separation within the composition regions of Mixing Scheme II. As we discussed at some length,[4,5,36] the signs of H_{i-i}^E and S_{i-i}^E were found proper for each type of phase separation. For BE-H_2O for example, which has an LCST (lower critical solution temperature) at 49.4℃ at $x_i=0.07$,[77] both H_{i-i}^E and S_{i-i}^E are positive for $0.02<x_i<0.42$ in the range of Mixing Scheme II. This is consistent with the thermodynamic situation of the system having an LCST. Thus, we suggested[4,5] that the mixture consists of two kinds of clusters which will grow to the macroscopic size when temperature is raised higher than 49.4℃. Namely, at room temperature the system is preparing for phase separation and thus the mixture should consist of two kinds of clusters, one rich in H_2O and the other with BE. Indeed the light scattering studies indicate that large scattering centers are present in this concentration region.77,78) For other smaller mono-ols, light scattering79,80) and small angle *x*-ray scattering81-86) studies also indicate large forward scattering in the composition region of respective Mixing Scheme II. For ACN-H_2O, the sign of H_{i-i}^E is negative as it should for the system with a UCST (upper critical solution temperature), and small angle *x*-ray scattering work by Nishikawa et al. indeed shows a large forward scattering in this region and that its intensity increases on lowering temperature.87) For TBA-H_2O, an H/D substitution neutron scattering study88) at $x_i = 0.06$, 0.11 and 0.16, which are all in Mixing Scheme II (see **Table 3**), indicates nonpolar to nonpolar contacts of TBA molecules,88) consistent with our conjecture mentioned above. For IBA- and BUT-, both belonging to type (b) solute, H_{i-i}^E have correct signs. For IBA-H_2O, with a UCST, the sign of H_{i-i}^E is negative, while for BUT whose phase boundary slants with $dT/dx_i < 0$ (similar to the system with an LCST but freezing setting in before the LCST) the sign of H_{i-i}^E is properly positive. Thus, for type (b) solutes also, Mixing Scheme II is such that the mixture is precursory to phase separation, and hence it consists of two kinds of clusters, one rich in H_2O and the other in solute. Soper and Luzar89) did a neutron diffraction study with H/D substitution for DMSO-H_2O at $x_i = 0.21$ and 0.35 (exactly at point X and Y, see **Table 3**) and concluded that the percentage of H_2O molecules that are hydrogen bonded to each other is reduced, while an increasing fraction of H_2O are bonded to the lone pair electrons of DMSO.89) These suggestions are again not inconsistent with ours. For other type (c) than DMSO and type (d) solutes, further investigation is required for elucidation of Mixing Scheme II. However, since Mixing Scheme I is the retention of integrity of liquid H_2O and Mixing Scheme III is that of solute, equal to type (a) and (b) solutes, it is likely that the solution similarly consists of two kinds of clusters, each reminiscent of Mixing Scheme I and III.

4. Concluding Remarks

As Sato and Chiba pointed out,90) H_2O and an alcohol do not mix indeed. We may reasonably extend this statement to include non-electrolytes as well. Soper *et al.*49) also concluded the same by neutron scattering in the concentration region of Mixing Scheme III for ME-H_2O. However, their suggestion that the classical picture of the "iceberg formation" must therefore be erroneous49) is premature. We pointed out here that in the water-rich region only, the "iceberg" concept is applicable for type (a) solutes, with additional finding that the hydrogen bond probability of bulk H_2O away from solutes is progressively reduced.

Thus, thermodynamic studies are as useful as spectroscopy, diffraction, scattering *etc.* in elucidating the details of Mixing Schemes in aqueous solutions, as long as accurate data of higher order derivatives of *G* are available. It is therefore our future challenge to measure third derivative quantities directly.

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要　旨

非電解質水溶液の混ざり方の詳細を新しい溶液熱力学的手法で研究した。ギブスエネルギー*G*の従来より高次な微分量のデーターを使った。三つの濃度領域で，混ざり方の詳細が質的にちがうことは一般的らしい。各々の領域でどのような混ざり方をしているか，現時点でわかったかぎりをまとめる。また，他の研究手段をつかっての研究成果もできるかぎり解説する。

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趣味：テニスはJake（73），司馬遼太郎は「街道を行く」，バッハは全曲