Characterization of Binary Solvent Mixtures of DMSO with Water and Other Cosolvents

J. Catalán,*,† C. Díaz,† and F. García-Blanco‡

Departamento de Química Física Aplicada, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain, and Departamento de Físico-Química, Facultad de Farmacia, Universidad Complutense de Madrid, 28040 Madrid, Spain

javier.catalan@uam.es

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Binary mixtures of DMSO with nine different cosolvents were characterized in light of the pure solvent scales, using suitable probe/homomorph couples. Various physical (vapor pressure, surface tension, viscosity, and enthalpy of mixing) and spectroscopic (IR and NMR) properties of the DMSO/water mixtures are described in terms of their polarity, acidity, and basicity, and the descriptions are examined with a view to establishing their potential physical significance.

Introduction

Dimethyl sulfoxide (DMSO) and its mixtures with other cosolvents (particularly water) have aroused much interest among scientists in the last few decades, so much so that Martin and Hauthal[1] claim that "only rarely can a single compound (i.e. DMSO) have found such manifold applications in so many fields (e.g. general and analytical chemistry, physical chemistry, biology,[2−4] medicine, etc.)". In fact, this compound has rapidly grown in use and found a variety of applications as an important reactant and pharmaceutical agent of very low toxicity and also as an effective solvent.

Some physicochemical properties of DMSO[5,6] suggest that the neat liquid solvent is highly associated and forms polymer chains by interactions between its sulfur and oxygen atoms;[7] these self-associated forms of DMSO can dissociate because of the effects of temperature or the presence of proton-donor solvents. Like DMSO, water self-associates (via hydrogen bonds), the association being liable to rupture by the action of proton-acceptor solvents. DMSO is highly polar (in fact, it is at the top of the solvent polarity/polarizability (SPP) scale, with SPP = 1[8]), very weakly acidic (it lies on the low end of the solvent acidity (SA) scale, with SA = 0.072[9]), and fairly basic (it falls at the medium-to-high end of the solvent basicity (SB) scale, with SB = 0.647[10]). Water is also highly polar (SPP = 0.962[8]); unlike DMSO, however, it is highly acidic (SA = 1.062[11]) and negligibly basic (SB = 0.025[10]).

As a result, the two solvents interact in a strong manner upon mixing. The interactions are hydrogen bonds between the basic portion of DMSO (viz., its oxygen atom) and the acid portion of water (viz., its protons).[1,4,12,13] The molecular clusters formed from the interaction between DMSO and water are believed to possess a well-defined geometry and to be responsible for the strongly nonideal mixing behavior reflected in maxima or minima in the variation of some physicochemical properties with the mole fraction of DMSO or water.[14−21] The greatest deviations from ideal mixing occur around a DMSO mole fraction of 33% (see Figure 1), which suggests the presence of stoichiometrically well-defined complexes of one DMSO and two water molecules (hereafter referred to as 1DMSO/2water).[1,19] Kinart et al.[19] reported a comprehensive discussion of the stoichiometry and interactions in DMSO/water complexes potentially present at a given mole fraction. These molecular clusters are also believed to be relevant to the behavior of mixtures at the liquid−vapor interface.[22,23]

Properly characterizing DMSO/water mixtures requires a knowledge of not only physical properties, such as vapor pressure (P_v), surface tension (γ), viscosity (η), and enthalpy of mixing (H_m^E), but also complementary information, such as spectroscopic (IR and NMR) data for the two mixing components. In fact, the variation of the spectroscopic signals for the mixture components [viz., the chemical shift for water protons, $\delta(H)_w$, and that

† Universidad Autónoma de Madrid.
‡ Universidad Complutense de Madrid.

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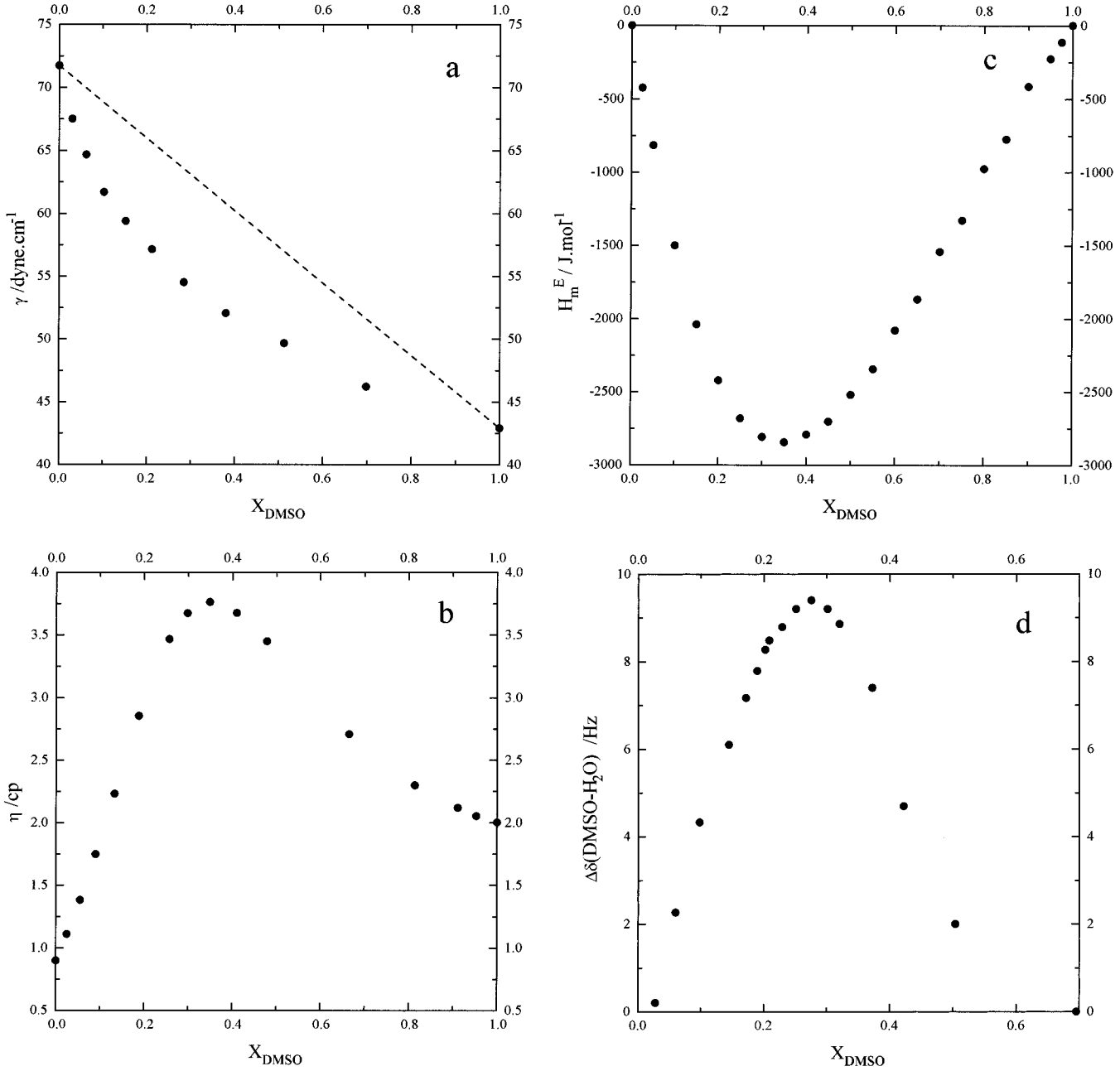

Figure 1. Plots of (a) surface tension, γ, (b) viscosity, η, (c) excess enthalpy of mixing, H_m^E, and (d) deviations from ideality for the chemical shifts of protons with respect to DMSO, $\Delta\delta$(DMSO − H_2O), vs the mole fraction, X, for the DMSO/water mixture.

for the methyl carbons in DMSO, $\delta(C)_{DMSO}$; the difference between the chemical shifts for water protons with respect to DMSO protons, δ(DMSO − H_2O); and the symmetric and antisymmetric $\tilde{\nu}$(CH) vibrational frequencies for the methyl groups in DMSO] over the composition range must reflect potential changes in clustering in the bulk mixture as its composition is altered. Recently, Mizuno et al.[24] reported such spectroscopic data for the DMSO/water mixture, with the exception of δ(DMSO−H_2O), which was determined by Kinart et al.[19]

The behavior of solvent mixtures is frequently studied by molecular dynamic simulation[13,25−28] or neutron diffraction experiments.[23] For example, these techniques have allowed the structure and mechanism of the formation of the 1DMSO/2water and 2DMSO/1water complexes to be elucidated.

In this work, we developed a different approach to the characterization of DMSO/water mixtures based on their acidity (SA), basicity (SB), and polarity/polarizability (SPP). This procedure has previously provided excellent results in the interpretation of the properties of binary solvent mixtures, the solvolysis kinetics of *tert*-butyl chloride,[29] and the decarboxylation of 3-carboxybenzisoxazoles,[30] as well as in the study of the preferential solvation model.[31]

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The acidity, basicity, and polarity/polarizability of these mixtures must be the result of the molecular interactions in their bulk; consequently, they could be of assistance in interpreting changes in their physical properties with mole fraction. In this work, the DMSO/water mixture was characterized in this respect in light of the pure solvent scales recently developed by the authors' group.[8−13,32]

The pure solvent scales were established from suitable probe/homomorph couples. Thus, the dipolarity/polarizability of a pure solvent can be characterized in terms of the solvatochromism of the probe 2-dimethylamino-7-nitrofluorene and its homomorph 2-fluoro-7-nitrofluorene; SPP values range from 0 in the absence of solvent (i.e., in the gas phase) to 1 for DMSO.[8] The SB scale is based on the solvatochromism of the probe 5-nitroindoline and its homomorph *N*-methyl-5-nitroindoline; SB values range from 0 for the gas phase to 1 for tetramethylguanidine.[10] Finally, SA is evaluated from the solvatochromism of the probe *o*-*tert*-butylstilbazolium betaine dye and its homomorph *o*,*o*′-di-*tert*-butylstilbazolium betaine dye and encompasses values from 0 for the gas phase to 0.4 for ethanol.[9] The acidity of solvents more acidic than methanol (SA = 0.605) is evaluated by applying the solvent comparison method[33] to solvatochromic measurements of the probe 3,6-diethyl-1,2,4,5-tetrazine.[11] In principle, any molecular property of a mixture can be analyzed by using an equation of the type

$$P = s(\mathrm{SPP}) + a(\mathrm{SA}) + b(\mathrm{SB}) + P_0 \qquad (1)$$

where SPP, SB, and SA are typical of the mixture, and coefficients *s*, *a*, and *b* pertain to the property in question, *P*, and describe its sensitivity to the polarity/polarizability, basicity, and acidity of the mixture, respectively. The use of eq 1 in applying the pure solvent scales is discussed elsewhere;[32] the three scales have proved to be linearly independent.

In this work, we analyzed mixtures of DMSO, not only with water but also with such disparate solvents as methanol, acetonitrile, nitromethane, benzene, pyridine, dichloromethane, chloroform, and diglyme.

Experimental Section

All solvents used were of the highest available purity and were purchased from Merck in Uvasol or similar grade. Solvent mixtures were prepared from freshly opened bottles, using Brand II 25.00 mL burets to transfer the liquids.

Polarity (SPP), basicity (SB), and acidity (SA) values were obtained from the wavenumbers of the absorption maxima for the following probe/homomorph couples: 2-(dimethylamino)-7-nitrofluorene/2-fluoro-7-nitrofluorene,[8,34] 5-nitroindoline/1-methyl-5-nitroindoline,[10] and *o*-*tert*-butylstilbazolium betaine dye/*o*,*o*′-di-*tert*-butylstilbazolium betaine dye.[9] The last couple was replaced with the probe 3,6-diethyl-1,2,4,5-tetrazine[11] for DMSO/methanol. In the case of the DMSO/water mixture, we used the 3,6-diethyl-1,2,4,5-tetrazine in the $0.0 \le X_{\mathrm{DMSO}} \le 0.3$ range and pyridazine in the $0.4 \le X_{\mathrm{DMSO}} \le 1.0$ range.[35]

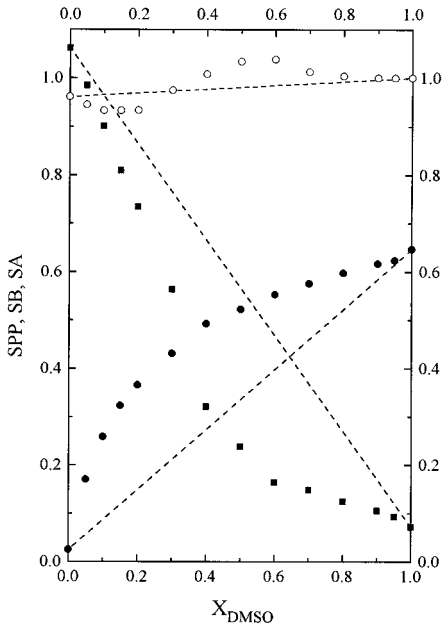

Figure 2. Plot of the SPP (○), SB (●), and SA (■) parameters against the mole fraction X_{DMSO} for the DMSO/water mixture.

UV−vis measurements were made on a Shimadzu 2100 spectrophotometer with a monochromator which was calibrated by using the 486.0 and 656.1 nm lines from a deuterium lamp. The instrument was routinely checked for wavelength accuracy by using holmium oxide and didymium filters. All spectral measurements were made at 25 °C, using a matched pair of quartz cells with a 1 cm light path.

To obtain the fits as a function of SA, SB, and SPP of the different mixtures, we used multiparametric analysis software. It provides an equation that has SA, SB, and SPP as variables. The program used is the MINITAB program.

Results and Discussion

(1) DMSO/Water Mixture. Figure 2 shows the variation of the polarity, acidity, and basicity of the DMSO/water mixture throughout the mole fraction range. As can be seen, the three parameters exhibit nonideal behavior; SB exhibits a positive deviation from linearity, and SA a negative one throughout the mole fraction range.

The polarity/polarizability of the mixture (SPP) behaves anomalously for two solvents of almost the same polarity (1 and 0.962). Thus, as DMSO is added to water, SPP initially falls below the ideal value and then rises above it at a DMSO mole fraction of 0.3; it peaks at $X_{\mathrm{DMSO}} \simeq 0.5-0.6$ and then gradually decreases to the ideal value as the composition of pure DMSO is approached. Note that changes in SPP were all quite small and that all the mixtures studied were highly polar.

The basicity of the mixture (SB) is always higher than the ideal value. The departure is maximal in the DMSO mole fraction region 0.2−0.4, beyond which it drops to the virtually negligible level of water (SB = 0.025). The basicity rises gradually from the value for pure water to that for pure DMSO, except in the above-mentioned region corresponding to highly water-rich mixtures.

The acidity of the mixture always falls below the ideal level, from the virtually negligible value for DMSO (SA = 0.070) to the high value for pure water (SA = 1.062); however, the increase in SA from DMSO to water is slow

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(35) According to the following equation: $\mathrm{SA} = 0.2407[\nu_{\mathrm{pyridazine}} - (2.153(\mathrm{SPP}) + 28.694)] + 0.086$.

up to $X_{DMSO} = 0.4$ (SA = 0.33), above which it changes more rapidly.

From Figure 2, it therefore follows that mixtures with a high DMSO content (above 60%) are basic and scarcely acidic, whereas those with a higher water content (above 60%) are acidic and scarcely basic. This allows one to relate the basicity of the mixture to DMSO and its acidity to water. A structural analysis of the behavior of these mixtures would reveal that those with $X_w \leq 0.4$ must be governed by the presence of the 1DMSO/1water complex and, hence, that the magnitude of the three solvent parameters studied is dictated by DMSO. On the other hand, the behavior of mixtures with $0.4 \leq X_w \leq 0.6$ must be governed by the presence of the 1DMSO/1water and 1DMSO/2water complexes, and those with $X_w \geq 0.6$ by the prevalence of the 1DMSO/2water complex and pure water, which endows the mixture with a high acidity and a low basicity.

This analysis is in agreement with that obtained by Skaf et al.[27] using molecular dynamic (MD) simulation for the structures and H-bond distributions involved in the DMSO/water mixture. This indicates the existence of 1DMSO/2water aggregates for $X_w > 0.5$ and 2DMSO/1water aggregates for lower X_w values.

Thereafter, Skaf[28] found a good agreement between the experimental results obtained for the static and dynamic dielectric behavior and his MD simulation results.

The thorough analysis of the species shows evidence of 1DMSO/2water complexes for $X_w > 0.65$ with a maximum at $X_w = 0.65$ and 2DMSO/1water complexes for $X_w < 0.19$.

Once the SPP, SA, and SB values for the DMSO/water mixture have been examined, let us analyze other properties in light of the multiparameter eq 1 with a view to finding the potential physical significance of its fitting coefficients.

Physical Properties. In 1960, Kenttämaa and Lindberg[36] measured the vapor pressure (P_v) of the DMSO/water mixture at 70 °C and, on the basis of an application of the Boissonnas method,[37] concluded that virtually the whole vapor consisted of water: only in the DMSO-rich region ($X_w = 0.1$) did the vapor phase reach a 1/1 DMSO/water ratio. Equation 2

$$P_v = (223 \pm 10)\mathrm{SA} + (6.80 \pm 5) \quad (2)$$

accurately reproduces the vapor pressure of the mixture ($n = 11$, $r = 0.992$, SD = 10.9 mmHg, $F = 522$) in terms of its acidity (i.e., its aqueous character).

In a mixture such as this, where the two components possess a virtually identical polarity/polarizability, one can expect changes in surface tension, γ, to be governed by specific interactions between the mixture's components. This is, in fact, the case, as shown by eq 3

$$\gamma^{25°C} = -(37.9 \pm 3.3)\mathrm{SB} + (4.3 \pm 1.7)\mathrm{SA} + (67.8 \pm 2.3) \quad (3)$$

which reproduces the behavior of the data measured by Tommila and Pajunen,[16] with $n = 11$, $r = 0.998$, SD = 0.56 dyn/cm, and $F = 1296$. On the basis of this equation, the surface tension of the mixture decreases mainly with increasing basicity (i.e., with its DMSO character).

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The dielectric behavior is one of the key ways of characterizing polar liquid environments as reaction media. Experimental measurements have been available for some time for the compositional dependence of the dielectric constant of DMSO/water mixtures.[15,21] Because of the small number of mixture compositions measured at 25 °C, we will consider jointly in this analysis those data of Tommila and Pajunen[15] with those measurements of Kaatze et al.[21] The dielectric constant is represented adequately in the whole range of molar fractions, with the aid of eq 4

$$\epsilon = (306.3 \pm 53.0)\mathrm{SPP} + (108.7 \pm 19.1)\mathrm{SB} + (108.2 \pm 13.9)\mathrm{SA} - (334.1 \pm 65.5) \quad (4)$$

$$(n = 21, r = 0.978, \mathrm{SD} = 2.4, F = 127.5)$$

On the basis of eq 4, the dielectric constant of the mixture increases mostly with polarity and, in minor contribution, with acidity and basicity. A careful analysis of the results indicates that the dielectric constant exhibits two ranges of composition, depending on whether the mixture is rich or poor in DMSO. Thus, by considering the rich DMSO mixtures ($X_{DMSO} > 0.5$), it is observed that

$$\epsilon = -(140.2 \pm 7.4)\mathrm{SB} + (137.6 \pm 4.3) \quad (5)$$

$$(n = 7, r = 0.993, \mathrm{SD} = 0.9, F = 361)$$

while for poor DMSO mixtures ($X_{DMSO} < 0.5$)

$$\epsilon = -(12.2 \pm 2.9)\mathrm{SPP} + (13.5 \pm 0.3)\mathrm{SA} + (75.8 \pm 3.0) \quad (6)$$

$$(n = 14, r = 0.998, \mathrm{SD} = 0.2, F = 1866)$$

Equations 5 and 6 allow us to conclude that the dielectric constant in rich DMSO mixtures diminishes with increasing the basicity of the mixture (i.e., with its DMSO character). Therefore, an increase of ϵ parallels the disruption of the DMSO pure structure, with the formation of 2DMSO/1water complexes. In contrast, for poor DMSO mixtures, an increase of the dielectric constant is principally due to an increase of the mixture's acidity (i.e., its aqueous character).

In theory, the viscosity of a mixture should increase with increasing interactions between its components. Equation 7

$$\eta = (60.24 \pm 10.0)\mathrm{SPP} + (25.50 \pm 3.50)\mathrm{SB} + (16.46 \pm 2.40)\mathrm{SA} - (75.55 \pm 12) \quad (7)$$

reproduces the viscosity values for the DMSO/water mixture at 25 °C measured by Cowie and Toporowski,[14] with $n = 16$, $r = 0.921$, SD = 0.410 cP, and $F = 22.5$.

One of the thermodynamic properties of the DMSO/water mixture most markedly deviating from ideality is the excess enthalpy of mixing, H_m^E (see Figure 1c). The mixing process is energetically similar to dissolution, so it encompasses a non-negligible energy term arising from the cohesive energy of the liquid mixture involved in the formation of a cavity. The variation of this property cannot be accurately described if such a contribution is ignored. Because the cohesive energy for each studied mixture was unknown, we approximated it to the boiling point (bp). The values for this parameter were taken from

Figure 2c in a review by Ranky and Nelson.[38] On the basis of eq 8

$$H_m^E = -(2270 \pm 1400)\mathrm{SPP} - (9269 \pm 440)\mathrm{SB} + (63.60 \pm 2.00)\mathrm{bp} - (3766 \pm 1350) \quad (8)$$

which reproduces the experimental results with $n = 23$, $r = 0.989$, SD = 163 J·mol^{-1}, and $F = 280$, the enthalpy of mixing for the DMSO/water mixture comprises an endothermic contribution corresponding to the formation of a cavity and an exothermic one encompassing general and specific interactions between the mixture components.

Spectroscopic Properties. Recently, Mizuno et al.[24] found δ^1H_w for water to increase and $\delta^{13}C$ for the methyl groups in DMSO to decrease with an increase in X_w for the DMSO/water mixture. Equation 9

$$\delta^1H_w = (14.1 \pm 2.5)\mathrm{SPP} + (5.60 \pm 1)\mathrm{SB} + (5.2 \pm 0.7)\mathrm{SA} - (14.30 \pm 3.10) \quad (9)$$

reproduces the behavior of δ^1H_w with $n = 16$, $r = 0.980$, SD = 0.11 ppm, and $F = 96$; eq 10

$$\delta^{13}C = -(4.04 \pm 1.09)\mathrm{SPP} - (2.31 \pm 0.09)\mathrm{SA} + (45.9 \pm 1.0) \quad (10)$$

reproduces that of $\delta^{13}C$ with $n = 13$, $r = 0.997$, SD = 0.06 ppm, and $F = 964$. On the basis of these equations, the decrease in δC^{13} is caused solely by an increase in acidity, as is the increase in δ^1H_w; the change in this latter case is partly offset by the opposing effect of basicity on this signal.

The increase in the frequencies of the symmetric ($\tilde{\nu}_s$) and antisymmetric ($\tilde{\nu}_a$) stretching vibrations of C−H bonds in DMSO is also a result of the increase in the acidity of the mixture as it is enriched with water, as shown by eqs 11 (with $n = 20$, $r = 0.996$, SD = 0.70 cm^{-1}, and $F = 784$) and 12 (with $n = 19$, $r = 0.988$, SD = 0.82 cm^{-1}, and $F = 215$).

$$\tilde{\nu}_a(\mathrm{CH}) = (94.80 \pm 16.4)\mathrm{SPP} + (36.95 \pm 6.20)\mathrm{SB} + (47.12 \pm 4.30)\mathrm{SA} + (2875 \pm 20) \quad (11)$$

$$\tilde{\nu}_s(\mathrm{CH}) = (70.40 \pm 18.30)\mathrm{SPP} + (30.55 \pm 7.15)\mathrm{SB} + (34.20 \pm 5.0)\mathrm{SA} + (2821 \pm 23) \quad (12)$$

Both vibrations are subject to similar effects from their environment.

In summary, the NMR and IR signals studied by Mizuno et al.[24] for both components of the mixture vary largely in response to changes in its acidity (see Figure 2).

Kinart et al.[19] found the chemical shifts of water protons with respect to DMSO protons to exhibit apparent maximum deviations from ideality at ∼27−29 mol % DMSO. Equation 13

$$\delta(\mathrm{DMSO} - \mathrm{H_2O}) = -(136.15 \pm 36.80)\mathrm{SPP} + (40.0 \pm 5.2)\mathrm{SA} + (246.9 \pm 38.5) \quad (13)$$

fits the data obtained by these authors over the range 2.74−50.36 mol % DMSO to the corresponding pure solvent parameters with $n = 16$, $r = 0.989$, SD = 2.05 ppm, and $F = 299$. This equation is consistent with that derived for the spectroscopic data of Mizuno et al.[24]

Worth special note here are the IR signals for the DMSO vibrations involving the sulfur atom, namely, $\tilde{\nu}_a$(C−S) and $\tilde{\nu}_s$(C−S), in addition to $\tilde{\nu}_s$(S═O), as determined for the DMSO/water mixture by Carius et al.[39] While the frequencies of these vibrations decrease as the mixture is enriched with water, thus reflecting the increased acidity and, hence, a specific attack on the lone electron pairs of the oxygen atom in DMSO, eqs 14−16 reveal the influence of polarity and, also, in some cases, of the basicity of the medium:

$$\tilde{\nu}_a(\mathrm{C{-}S}) = (47.23 \pm 18.8)\mathrm{SPP} + (26.55 \pm 9.8)\mathrm{SB} + (30.18 \pm 6.0)\mathrm{SA} + (637 \pm 25) \quad (14)$$

($n = 12$, $r = 0.991$, SD = 0.76 cm^{-1}, $F = 153$)

$$\tilde{\nu}_s(\mathrm{C{-}S}) = (22.18 \pm 10.0)\mathrm{SPP} + (9.60 \pm 1.10)\mathrm{SA} + (649 \pm 10) \quad (15)$$

($n = 12$, $r = 0.976$, SD = 0.68 cm^{-1}, $F = 91$)

$$\tilde{\nu}_s(\mathrm{S{=}O}) = -(278.3 \pm 75.5) - (119.5 \pm 39.7)\mathrm{SA} - (109.7 \pm 24.7)\mathrm{SA} - (44.34 \pm 30.04) \quad (16)$$

($n = 12$, $r = 0.971$, SD = 3.05 cm^{-1}, $F = 44$)

Two well-known molecular environment probes, namely, Kosower's Z[40] and Dimroth and Reichardt's $E_T(30)$,[41] have been used to study the DMSO/water mixture.[42] Equations 17 and 18

$$Z = (94.68 \pm 23.80)\mathrm{SPP} + (29.12 \pm 10.30)\mathrm{SB} + (42.79 \pm 7.0)\mathrm{SA} - (44.34 \pm 30.0) \quad (17)$$

($n = 11$, $r = 0.994$, SD = 0.98 kK, and $F = 181$)

$$E_T(30) = (48.38 \pm 6.20)\mathrm{SPP} + (19.98 \pm 0.60)\mathrm{SA} - (4.67 \pm 6.40) \quad (18)$$

($n = 11$, $r = 0.998$, SD = 0.40 kK, and $F = 984$)

fit the solvatochromism of these probes to the pure solvent parameters. Consistent with the known solvatochromic behavior of these two molecular probes,[32] while Z is sensitive to the three solvent properties (SPP, SA, and SB), the solvatochromism of $E_T(30)$ only appears to be dependent on the polarity and acidity of the molecular environment.

(2) Mixtures of DMSO with Nonaqueous Solvents. Table 1 shows the variation of SPP, SB, and SA with the mole fraction for the binary mixtures of DMSO with the following cosolvents: methanol (MeOH), acetonitrile (ACN), nitromethane (NM), benzene, pyridine, dichloromethane, chloroform, and 2-methoxyethyl ether (diglyme). Note that none of these mixtures resemble that of DMSO with water (compare with Figure 2). Let us

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Table 1. SPP, SB, and SA Values for the DMSO (SPP = 1.000, SB = 0.647, SA = 0.072)/Cosolvent Mixtures Studied

	X_{DMSO}									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
					Water					
SPP	0.962	0.933	0.934	0.975	1.008	1.034	1.039	1.013	1.004	1.000
SB	0.025	0.259	0.366	0.431	0.493	0.523	0.553	0.576	0.598	0.617
SA	1.062	0.901	0.735	0.564	0.321[a]	0.239[a]	0.164[a]	0.149[a]	0.125[a]	0.106[a]
					Methanol					
SPP	0.857	0.883	0.905	0.925	0.955	0.950	0.953	0.970	0.975	0.980
SB	0.545	0.540	0.545	0.570	0.600	0.610	0.617	0.620	0.618	0.630
SA	0.400	0.510	0.455	0.435	0.420	0.395	0.370	0.343	0.300	0.218
					Acetonitrile					
SPP	0.895	0.918	0.927	0.935	0.938	0.942	0.950	0.958	0.970	0.980
SB	0.286	0.455	0.545	0.578	0.600	0.615	0.625	0.630	0.638	0.645
SA	0.044	0.055	0.060	0.063	0.068	0.070	0.075	0.077	0.072	0.072
					Nitromethane					
SPP	0.907	0.916	0.926	0.946	0.913	0.915	0.921	0.938	0.956	0.976
SB	0.236	0.434	0.531	0.579	0.600	0.617	0.626	0.634	0.638	0.632
SA	0.078	0.073	0.070	0.072	0.071	0.072	0.071	0.069	0.071	0.072
					Benzene					
SPP	0.667	0.798	0.870	0.897	0.913	0.925	0.940	0.950	0.960	0.975
SB	0.124	0.625	0.632	0.635	0.640	0.643	0.648	0.648	0.645	0.645
SA	0.000	0.007	0.023	0.032	0.040	0.047	0.054	0.056	0.060	0.065
					Pyridine					
SPP	0.922	0.924	0.937	0.946	0.945	0.948	0.954	0.961	0.963	0.975
SB	0.581	0.600	0.619	0.624	0.632	0.636	0.637	0.638	0.640	0.645
SA	0.033	0.035	0.041	0.047	0.049	0.054	0.058	0.062	0.064	0.068
					Dichloromethane					
SPP	0.876	0.890	0.905	0.910	0.922	0.933	0.940	0.947	0.965	0.982
SB	0.057	0.450	0.595	0.650	0.668	0.670	0.672	0.669	0.660	0.650
SA	0.040	0.029	0.045	0.054	0.065	0.072	0.080	0.083	0.089	0.077
					Chloroform					
SPP	0.786	0.857	0.882	0.895	0.905	0.910	0.920	0.930	0.940	0.948
SB	0.071	0.375	0.573	0.638	0.662	0.672	0.667	0.660	0.650	0.645
SA	0.047	0.034	0.056	0.076	0.091	0.100	0.106	0.102	0.095	0.086
					Diglime					
SPP	0.855	0.860	0.872	0.898	0.910	0.915	0.927	0.935	0.950	0.970
SB	0.623	0.618	0.615	0.620	0.636	0.634	0.646	0.643	0.640	0.642
SA	0.000	0.000	0.008	0.022	0.030	0.033	0.042	0.042	0.048	0.059

[a] Calculated from equation from ref 35.

analyze the behavior of the above-mentioned parameters for these mixtures.

As can be seen from Table 1, SPP for the DMSO/MeOH mixtures exhibits an ideal variation with the mole fraction. As MeOH is added to DMSO, SB initially decreases to slightly below the level for pure DMSO; then, in the $0.4 \leq X_{DMSO} \leq 0.6$ range, SB varies in the ideal manner and finally tends to the value for pure MeOH (0.545). The DMSO/MeOH mixtures depart from DMSO/water mixtures in the behavior of SA. In fact, this parameter is always greater than the value expected for the ideal behavior; thus, the addition of MeOH to pure DMSO rapidly increases the acidity (from 0.072 to 0.4 over the $X_{methanol}$ range 0−0.2), which then evolves to the ideal behavior in the DMSO-rich zone.

SPP for the DMSO/ACN mixtures exhibits a virtually ideal behavior toward the mole fraction. Adding ACN to DMSO decreases SB slightly (to the value for pure ACN); however, the basicity is always higher than its ideal value (0.286). As expected, these mixtures exhibit negligible acidity throughout the mole fraction range.

The DMSO/NM mixtures possess SPP values slightly below the ideal level over the X_{NM} range 0−0.7, above which (in the NM-rich zone) they tend to reach it. Adding NM to DMSO results in a clear, positive deviation from the ideal behavior; in the X_{NM} region from 0 to 0.5, the mixtures exhibit virtually the same basicity as pure DMSO, but the basicity decreases rapidly at $X_{NM} \leq 0.2$. The acidity of these mixtures remains virtually constant at 0.07 throughout the mole fraction range.

SPP for the DMSO/benzene mixtures exhibits positive deviations from the ideal behavior that are in clear contrast with the values for the other mixtures. Enriching the mixture with benzene slightly decreases the SPP; above $X_{benzene} = 0.7$, the SPP decreases more rapidly (to the value of pure benzene, 0.667). SB for this mixture also varies in a special manner: it remains at values virtually identical with those for pure DMSO up to $X_{benzene} = 1$. Because the two mixture components differ markedly in basicity (by almost 0.5 units), SB drops almost vertically to the value for benzene. As regards SA, these mixtures exhibit a very low acidity that gradually decreases in a virtually ideal manner from the value for DMSO (0.072) to that for benzene (0).

The DMSO/pyridine mixtures bear no resemblance to the previous ones. In fact, they exhibit very small (negative) deviations from ideality in SPP at low pyridine mole fractions and slight (positive) deviations in SB throughout the composition range. On the other hand, SA behaves in the ideal manner.

The DMSO/dichloromethane mixtures have SPP values that vary almost ideally with the mole fraction. The variation of SB as dichloromethane is added to DMSO is also special: it increases slightly above the value for pure

DMSO as far as the dichloromethane-rich zone, where it drops abruptly to the value for dichloromethane (0.178). On the other hand, SA exhibits a near-ideal behavior.

SPP for the DMSO/chloroform mixtures exhibits negative deviations from ideality in the DMSO-rich zone, beyond which deviations are positive. The behavior of SB for this mixture is identical with that of the DMSO/dichloromethane mixtures. On the other hand, SA initially exhibits positive deviations from the ideal behavior (the acidity increases slightly as chloroform is added to DMSO) but subsequently tends to the value for pure chloroform (0.047).

Finally, the DMSO/diglyme mixtures exhibit an ideal behavior in SPP, SB, and SA throughout the composition range.

Spectroscopic Properties. Greenberg and Popov[43] studied the variation of the chemical shifts (δ) in the resonance of ^{23}Na as a function of the solvent composition in binary mixtures of DMSO with NM and ACN. The NMR properties of these mixtures have been used to exemplify the preferential solvation phenomenon,[44] as the mixtures clearly behave in a nonideal manner in relation to the mole fraction (see ref 31). The behavior of both properties is accurately described by their basicity,[10] expressed as

$$\delta^{23}\mathrm{Na} = -(25.16 \pm 1.90)\mathrm{SB} + (15.95 \pm 1.00) \quad (19)$$

with $n = 16$, $r = 0.961$, SD = 0.88 ppm, and $F = 170$.

Dimroth and Reichardt's $E_T(30)$ has been determined for binary mixtures of DMSO with chloroform,[45] benzene,[45] methanol,[45] nitromethane,[46] acetonitrile,[47] dichloromethane,[48] and water.[42] Equation 20

$$E_T(30) = (2.93 \pm 2.60)\mathrm{SPP} + (19.13 \pm 0.70)\mathrm{SA} - (22.61 \pm 2.40) \quad (20)$$

fits the solvatochromism of these mixtures to their polarity/polarizability and acidity with $n = 73$, $r = 0.963$, SD = 1.24 kcal/mol, and $F = 448$. As with pure solvents, only polarity and acidity are required for an accurate description here.

Conclusions

As shown in this work, the solvent scales are useful tools with a view to characterizing binary mixtures of solvents. This current work emphasizes the failure of the pure solvent parameters SA, SB, and SPP to characterize the behavior of physical−chemical properties of solutes in binary solvent mixtures. Because of the absence of methods that could allow one to measure the SA, SB, and SPP values of a solvent mixture from those values of the corresponding pure solvents, the experimental measurement of the solvent parameters for a given mixture is mandatory. Also, they provide interesting information about those molecular interactions that depend on their properties. The favorable results obtained for these mixtures encouraged us to address alcohol/water mixtures, which have so far provided highly interesting but as yet uninterpreted results in relation to protein folding.[49−55]

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