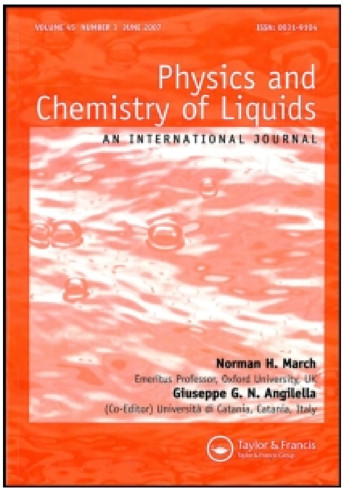

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Thermochemical Investigations of Tautomeric Equilibrium. Variation of the Calculated Equilibrium Constant with Binary Solvent Composition

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THERMOCHEMICAL INVESTIGATIONS OF TAUTOMERIC EQUILIBRIUM. VARIATION OF THE CALCULATED EQUILIBRIUM CONSTANT WITH BINARY SOLVENT COMPOSITION

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A conventional nonelectrolyte solution model which has led to successful predictive equations for solute solubility and infinite dilution chromatographic partition coefficients is extended to systems containing a tautomeric solute dissolved in a binary solvent mixture. The derived expression predicts that the tautomeric solute concentration in a binary solvent is a geometric average of the pure solvent ratios and permits calculation of solute-solvent association constants from variation of the stoichiometric tautomeric solute concentration ratios as a function of binary solvent composition. Experimental data for phenylazonaphthol dissolved in aqueous-ethanol and aqueous-acetone solvent mixtures is discussed in relation to the theoretical model.

KEY WORDS: Tautomeric equilibria, thermodynamic model, binary solvent, solute-solvent complexation, molecular complexation, equilibrium constants.

LIST OF SYMBOLS

A_{ij}	binary interaction parameter for components i and j used in Gibbs free energy model
ΔG^{mix}	Gibbs free energy of mixing
$\Delta \bar{G}_{BC}^{\text{fh}}$	excess molar Gibbs free energy of mixing of the binary solvent mixture based on the Flory-Huggins model for solution ideality
K_{AB}^{ϕ}	volume fraction based equilibrium constant for the formation of the AB complex
K_{AC}^{ϕ}	volume fraction based equilibrium constant for the formation of the AC complex
K_{tau}^{ϕ}	equilibrium concentration ratio of the tautomeric solute, based on the uncomplexed solute species
$K_{\text{tau}}^{\text{app}}$	equilibrium concentration ratio of the tautomeric solute, based on the stoichiometric concentrations of both tautomeric forms
n_i	stoichiometric number of moles of component i in the solution
$\hat{n}_i$	true number of moles of component i in the associated solution

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$\bar{V}_i$	molar volume of component i
X_B^0 and X_C^0	mole fraction composition of the binary solvent mixture, calculated as if the solute were not present
ϕ_i	ideal volume fraction of component i
ϕ_B^0 and ϕ_C^0	ideal volume fraction composition of the binary solvent mixture, calculated as if the solute were not present
$\hat{\phi}_i$	ideal volume fraction of component i, calculated assuming an associated solution

INTRODUCTION

Molecular complexation and chemical equilibrium occur in many systems having biological and engineering significance. Calculation of meaningful association constants is an important first step in understanding molecular interactions and solution nonideality. Spectroscopic and solubility methods have been developed to facilitate equilibrium constant determination. Spectroscopic methods require differences between the uv/vis absorbances of the molecular complex and the monomeric solute, and are generally limited in application to those systems where the complexing solvent concentration is considerably greater than solute molarity. Equilibrium constants are obtained through a least squares analysis of absorbance versus concentration.[1,2]

Solubility methods attribute the increase in solute solubility at constant fugacity in a complex-inert solvent mixture, relative to the solubility in pure inert solvent, to the formation of molecular complexes. This primary assumption is common to several experimental methods, such as the partitioning of solutes between two immiscible liquid phases, measurement of infinite dilution gas–liquid chromatographic partition coefficients and the increased solubility of solid solutes. Extraction of a meaningful equilibrium constant from solubility data requires a thermodynamic solution model for assessing what portion of the observed enhancement is due to specific solute-solvent complexation. The model used should provide a smooth transition between complexing and noncomplexing systems without pre-assuming the strength of the molecular complex believed to be present. A major difficulty encountered in using solubility methods has been the lack of thermodynamic models for systems containing very weak association complexes or tautomeric solutes.

Our earlier studies[3–8] were primarily devoted to the development of mixing models for describing the thermochemical properties of a solute near infinite dilution in binary solvent mixtures. Expressions were derived for the calculation of solute-solvent association constants from measured solute solubility based on the Extended Nearly Ideal Binary Solvent (NIBS) model[3–6]

$$A_1 + C_1 \rightleftharpoons AC \qquad K_{AC}^{\phi} = \hat{\phi}_{AC}/(\hat{\phi}_{A_1}\hat{\phi}_{C_1})$$

$$\ln \phi_A^{\text{sat}} = \phi_B^0 \ln(\phi_A^{\text{sat}})_B + \phi_C^0 \ln(\phi_A^{\text{sat}})_C + \ln[1 + \bar{V}_A K_{AC}^{\phi} \phi_C^0/(\bar{V}_A + \bar{V}_C)] - \phi_C^0 \ln[1 + \bar{V}_A K_{AC}^{\phi}/(\bar{V}_A + \bar{V}_C)] + \frac{\bar{V}_A \Delta\bar{G}_{BC}^{\text{fh}}}{RT(X_B^0 \bar{V}_B + X_C^0 \bar{V}_C)} \tag{1}$$

and the Competitive Associated NIBS model[7]

$$A_1 + B_1 \rightleftharpoons AB \qquad K^{\phi}_{AB} = \hat{\phi}_{AB}/(\hat{\phi}_{A_1}\hat{\phi}_{B_1})$$

$$A_1 + C_1 \rightleftharpoons AC \qquad K^{\phi}_{AC} = \hat{\phi}_{AC}/(\hat{\phi}_{A_1}\hat{\phi}_{C_1})$$

$$\begin{aligned}\ln \phi_A^{\text{sat}} = {} & \phi_B^0 \ln(\phi_A^{\text{sat}})_B + \phi_C^0 \ln(\phi_A^{\text{sat}})_C - \phi_B^0 \ln[1 + \bar{V}_A K^{\phi}_{AB}/(\bar{V}_A + \bar{V}_B)] \\ & + \ln[1 + \bar{V}_A K^{\phi}_{AB} \phi_B^0/(\bar{V}_A + \bar{V}_B) + \bar{V}_A K^{\phi}_{AC} \phi_C^0/(\bar{V}_A + \bar{V}_C)] \\ & - \phi_C^0 \ln[1 + \bar{V}_A K^{\phi}_{AC}/(\bar{V}_A + \bar{V}_C)] + \frac{\bar{V}_A \Delta \bar{G}^{\text{fh}}_{BC}}{RT(X_B^0 \bar{V}_B + X_C^0 \bar{V}_C)} \qquad (2)\end{aligned}$$

In the absence of solute-solvent complexation, Eq. (1) (with $K^{\phi}_{AC} = 0$) and Eq. (2) (with $K^{\phi}_{AB} = K^{\phi}_{AC} = 0$) reduce to the basic NIBS model which has been shown to provide very reasonable predictions for enthalpies of solution,[9] gas-liquid chromatographic partition coefficients[10,11] and solid solute solubilities[12–18] in systems containing only nonspecific interactions. Various symbols used in Eqs (1) and (2) are defined in the List of Symbols found at the beginning of the paper.

McCargar and Acree[5,6,8,19] compared values of the carbazole-dibutyl ether association constant calculated from experimental carbazole solubilities in ten binary dibutyl ether + alkane solvent mixtures. A simple stoichiometric complexation model based entirely on specific solute-solvent interactions required two equilibrium constants to mathematically describe the observed solubility data. Calculated constants in isooctane cosolvent were significantly different from values for cyclooctane. In comparison, the Extended NIBS model described the experimental solubilities to within an average absolute deviation of about ±2% using a single carbazole-dibutyl ether association constant. Variation of the calculated constant with inert cosolvent was slight, numerical values ranging from $K^{\phi}_{AC} = 22$ for *n*-heptane to $K^{\phi}_{AC} = 30$ for isooctane cosolvent. In followup studies[7,20] the Competitive Associated NIBS model was derived to explain the solubility behavior of carbazole in four binary chloroalkane + dibutyl ether solvent mixtures. Assuming the prescence of a very weak chloroalkane-carbazole complex, the authors illustrated the surprisingly large effect that a weak secondary AB complex can have on the calculated K^{ϕ}_{AC} constant. Neglect of a *presumed* weak carbazole-chlorohexane complex with $K^{\phi}_{AB} = 2$ resulted in over a two-fold decrease in the calculated carbazole-dibutyl ether equilibrium constant.

The success of Eqs (1) and (2) in describing the thermochemical properties of a ternary associated solution suggests that the basic mixing model might be applicable to other types of chemical equilibria. To pursue this idea further, we present the development of expressions for a tautomeric solute dissolved in a binary solvent mixture. The derived expressions indicate that in systems containing only nonspecific interactions the calculated equilibrium constant should be a geometric volume fraction average of measured constants in the two pure solvents. Compositional dependence does become more complex if a solvent component hydrogen bonds or associates with one (or both) form of the tautomeric solute, in which case an additional solute-solvent association constant would be needed for each molecular complex formed. Tautomeric equilibrium constants for 4-phenylazo-1-naphthol in

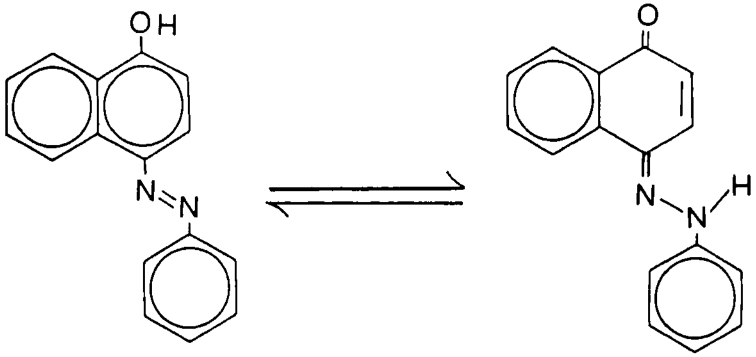

Figure 1 Tautomeric equilibrium between the azo (left side) and hydrazone (right side) forms of phenylazonaphthol. Equilibrium shifts towards the hydrazone form in polar solvents.

binary ethanol + water and acetone + water solvent mixtures, determined by Nishimura *et al.*,[21] are discussed using the newly-derived thermodynamic expressions and simulated computations. Phenylazohaphthol exists in tautomeric equilibrium between its azo and hydrazone forms (see Figure 1) in solution, with the hydrazone form being favored in the more polar solvents.[21–26]

SOLUTE TAUTOMERISM MODEL FOR SYSTEMS CONTAINING ONLY NONSPECIFIC INTERACTIONS

The specific form of the basic NIBS model which has been most successful for describing the excess chemical potential of solutes is based on a simple mixing model of a multicomponent system:

$$\Delta G^{\mathrm{mix}} = RT \sum_{i=1}^{N} n_i \ln \phi_i + \left(\sum_{i=1}^{N} n_i \bar{V}_i \right) \left(\sum_{i=1}^{N} \sum_{j>i} \phi_i \phi_j A_{ij} \right) \tag{3}$$

in which n_i is the number of moles of component i, ϕ_i is the volume fraction and A_{ij} is a binary interaction parameter that is independent of solvent composition. The application of Eq. (3) to a quarternary system having a tautomeric solute (components A and H) dissolved in a binary solvent mixture (components B and C) takes the form

$$A \rightleftharpoons H \qquad K_{\mathrm{tau}}^{\phi} = \phi_H / \phi_A$$

$$\begin{aligned} \Delta G^{\mathrm{mix}} = {} & RT[n_A \ln \phi_A + n_B \ln \phi_B + n_C \ln \phi_c + n_H \ln \phi_H] \\ & + (n_A \bar{V}_A + n_B \bar{V}_B + n_C \bar{V}_C + n_H \bar{V}_H)[\phi_A \phi_B A_{AB} + \phi_A \phi_C A_{AC} + \phi_A \phi_H A_{AH} \\ & + \phi_B \phi_C A_{BC} + \phi_B \phi_H A_{BH} + \phi_C \phi_H A_{CH}] \end{aligned} \tag{4}$$

The chemical potentials of the two solute forms relative to the pure liquids ($\mu_A^{\bullet}$ and $\mu_H^{\bullet}$) are

$$\begin{aligned}\mu_A - \mu_A^{\bullet} = {} & RT[\ln \phi_A + 1 - \bar{V}_A/\bar{V}_{\mathrm{soln}}] \\ & + \bar{V}_A[\phi_B(1-\phi_A)A_{AB} + \phi_C(1-\phi_A)A_{AC} + \phi_H(1-\phi_A)A_{AH} - \\ & \phi_B\phi_C A_{BC} - \phi_B\phi_H A_{BH} - \phi_C\phi_H A_{CH}]\end{aligned} \tag{5}$$

$$\begin{aligned}\mu_H - \mu_H^{\bullet} = {} & RT[\ln \phi_H + 1 - \bar{V}_H/\bar{V}_{\mathrm{soln}}] \\ & + \bar{V}_H[\phi_A(1-\phi_H)A_{AH} + \phi_B(1-\phi_H)A_{BH} + \phi_C(1-\phi_H)A_{CH} \\ & - \phi_A\phi_B A_{AB} - \phi_A\phi_C A_{AC} - \phi_B\phi_C A_{BC}]\end{aligned} \tag{6}$$

obtained through the appropriate differentiation.

Mathematical manipulation of Eqs (5) and (6), combined with the requirement that $\mu_A = \mu_H$ at equilibrium, permits the equilibium ratio of solute concentration ($K_{\mathrm{tau}}^{\phi} = \phi_H/\phi_A$) at infinite dilution to be expressed in terms of the initial binary solvent composition (ϕ_B^0 and ϕ_C^0) and 5 binary interaction parameters

$$\begin{aligned}(\mu_H - \mu_H^{\bullet}) - (\mu_A - \mu_A^{\bullet}) = {} & RT[\ln(\phi_H/\phi_A) - (\bar{V}_H - \bar{V}_A)/(X_B^0\bar{V}_B + X_C^0\bar{V}_C)] \\ & + \phi_B^0(\bar{V}_H A_{BH} - \bar{V}_A A_{AB}) + \phi_C^0(\bar{V}_H A_{CH} - \bar{V}_A A_{AC}) \\ & - (\bar{V}_H - \bar{V}_A)\phi_B^0\phi_C^0 A_{BC}\end{aligned} \tag{7}$$

$$\begin{aligned}RT \ln K_{\mathrm{tau}}^{\phi} = RT \ln(\phi_H/\phi_A) = {} & (\mu_A^{\bullet} - \mu_H^{\bullet}) + RT(\bar{V}_H - \bar{V}_A)/(X_B^0\bar{V}_B + X_C^0\bar{V}_C) \\ & + \phi_B^0(\bar{V}_A A_{AB} - \bar{V}_H A_{BH}) + \phi_C^0(\bar{V}_A A_{AC} - \bar{V}_H A_{CH}) + (\bar{V}_H - \bar{V}_A)\phi_B^0\phi_C^0 A_{BC}\end{aligned} \tag{8}$$

provided that the solute concentration is sufficiently small. Inspection of Eq. (8) reveals that for model systems obeying this solution model the five binary A_{ij} parameters can be eliminated from the basic model *via*

$$RT \ln(K_{\mathrm{tau}}^{\phi})_B = (\mu_A^{\bullet} - \mu_H^{\bullet}) + RT(\bar{V}_H - \bar{V}_A)/\bar{V}_B + \bar{V}_A A_{AB} - \bar{V}_H A_{BH} \tag{9}$$

$$RT \ln(K_{\mathrm{tau}}^{\phi})_C = (\mu_A^{\bullet} - \mu_H^{\bullet}) + RT(\bar{V}_H - \bar{V}_A)/\bar{V}_C + \bar{V}_A A_{AC} - \bar{V}_H A_{CH} \tag{10}$$

the measured solute concentration ratios in the two pure solvents, $(K_{\mathrm{tau}}^{\phi})_B$ and $(K_{\mathrm{tau}}^{\phi})_C$, and

$$\Delta\bar{G}_{BC}^{\mathrm{fh}} = \phi_B^0\phi_C^0(X_B^0\bar{V}_B + X_C^0\bar{V}_C)A_{BC} \tag{11}$$

the excess Gibbs free energy of the binary solvent calculated relative to the Flory-Huggins model. Performing these substitutions, the expression for the equilibrium solute concentration ratio in a binary solvent mixture becomes

$$\ln K_{\mathrm{tau}}^{\phi} = \phi_B^0 \ln(K_{\mathrm{tau}}^{k})_B + \phi_C^0 \ln(K_{\mathrm{tau}}^{\phi})_C + \frac{(\bar{V}_H - \bar{V}_A)\Delta\bar{G}_{BC}^{\mathrm{fh}}}{RT(X_B^0\bar{V}_B + X_C^0\bar{V}_C)} \tag{12}$$

which often simplifies to

$$K_{\text{tau}}^{\phi} = (K_{\text{tau}}^{\phi})_B^{\phi_B^0}(K_{\text{tau}}^{\phi})_C^{\phi_C^0} \tag{13}$$

a geometric volume fraction average of the measured values in the two pure solvents. In most cases the molar volumes of the tautomeric solute forms are approximately equal, $\bar{V}_A \approx \bar{V}_H$, and the solvent "unmixing" contribution in Eq. (12) will be negligible.

SOLUTE TAUTOMERISM MODEL FOR SYSTEMS CONTAINING AN AC SOLUTE-SOLVENT COMPLEX

Thermodynamic modelling of the chemical equilibria for a tautomeric solute dissolved in a complexing binary solvent mixture is more complicated. Solute-solvent association complexes increase the number of species which exist in solution. The simplest case involves a single solute–solvent complex. Application of Eq. (3) to a pentanary system (A, B, C, H and AC) takes the form:

$$A_1 \rightleftharpoons H \qquad K_{\text{tau}}^{\phi} = \hat{\phi}_H/\hat{\phi}_{A_1}$$

$$A_1 + C_1 \rightleftharpoons AC \qquad K_{\text{tau}}^{\phi} = \hat{\phi}_{AC}/(\hat{\phi}_{A_1}\hat{\phi}_{C_1})$$

$$\begin{aligned}\Delta G^{\text{mix}} = {} & RT[\hat{n}_{A_1}\ln\hat{\phi}_{A_1} + \hat{n}_B\ln\hat{\phi}_B + \hat{n}_{C_1}\ln\hat{\phi}_{C_1} + \hat{n}_{AC}\ln\hat{\phi}_{AC} + \hat{n}_H\ln\hat{\phi}_H] \\ & + (\hat{n}_{A_1}\bar{V}_A + \hat{n}_B\bar{V}_B + \hat{n}_{C_1}\bar{V}_C + \hat{n}_H\bar{V}_H + \hat{n}_{AC}\bar{V}_{AC})[\hat{\phi}_{A_1}\hat{\phi}_B A_{A_1B} + \hat{\phi}_{A_1}\hat{\phi}_{C_1}A_{A_1C_1} \\ & + \hat{\phi}_{A_1}\hat{\phi}_H A_{A_1H} + \hat{\phi}_{A_1}\hat{\phi}_{AC}A_{A_1AC} + \hat{\phi}_B\hat{\phi}_{C_1}A_{BC_1} + \hat{\phi}_B\hat{\phi}_H A_{BH} + \hat{\phi}_B\hat{\phi}_{AC}A_{BAC} \\ & + \hat{\phi}_{C_1}\hat{\phi}_H A_{C_1H} + \hat{\phi}_{C_1}\hat{\phi}_{AC}A_{C_1AC} + \hat{\phi}_H\hat{\phi}_{AC}A_{HAC}]\end{aligned} \tag{14}$$

with the chemical potentials of the two *uncomplexed* solutes, A_1 and H, obtained

$$\begin{aligned}\mu_{A_1} - \mu_A^{\bullet} = {} & RT[\ln\hat{\phi}_{A_1} + 1 - \bar{V}_A/\hat{V}_{\text{soln}}] + \bar{V}_A[\hat{\phi}_B(1 - \hat{\phi}_{A_1})A_{A_1B} \\ & + \hat{\phi}_{C_1}(1 - \hat{\phi}_{A_1})A_{A_1C_1} + \hat{\phi}_H(1 - \hat{\phi}_{A_1})A_{A_1H} + \hat{\phi}_{AC}(1 - \hat{\phi}_{A_1})A_{A_1AC} \\ & - \hat{\phi}_B\hat{\phi}_{C_1}A_{BC_1} - \hat{\phi}_B\hat{\phi}_H A_{BH} - \hat{\phi}_B\hat{\phi}_{AC}A_{BAC} - \hat{\phi}_{C_1}\hat{\phi}_H A_{C_1H} - \hat{\phi}_{C_1}\hat{\phi}_{AC}A_{C_1AC} \\ & - \hat{\phi}_H\hat{\phi}_{AC}A_{HAC}]\end{aligned} \tag{15}$$

$$\begin{aligned}\mu_H - \mu_H^{\bullet} = {} & RT[\ln\hat{\phi}_H + 1 - \bar{V}_H/\hat{V}_{\text{soln}}] + \bar{V}_H[\hat{\phi}_{A_1}(1 - \hat{\phi}_H)A_{A_1H} \\ & + \hat{\phi}_B(1 - \hat{\phi}_H)A_{BH} + \hat{\phi}_{C_1}(1 - \hat{\phi}_H)A_{C_1H} + \hat{\phi}_{AC}(1 - \hat{\phi}_H)A_{HAC} \\ & - \hat{\phi}_{A_1}\hat{\phi}_B A_{A_1B} - \hat{\phi}_{A_1}\hat{\phi}_{C_1}A_{A_1C_1} - \hat{\phi}_{A_1}\hat{\phi}_{AC}A_{A_1AC} - \hat{\phi}_B\hat{\phi}_{C_1}A_{BC_1} \\ & - \hat{\phi}_B\hat{\phi}_{AC}A_{BAC} - \hat{\phi}_{C_1}\hat{\phi}_{AC}A_{C_1AC}]\end{aligned} \tag{16}$$

through the appropriate differentiation of the Gibbs free energy of mixing. The carets (ˆ) denote the compositions of the the *true* species in the solution, rather than the stoichiometric concentrations. For simplicity, the molar volume of the AC complex is assumed to be equal to the sum of the *uncomplexed* solute and complexing solvent molar volumes, *i.e.*, $\bar{V}_{AC} = \bar{V}_A + \bar{V}_C$.

Equations (15) and (16) obviously contain far too many parameters for useful applications, but reasonable assumptions enable the number to be greatly reduced. Treatment of the A_{A_1AC}, A_{C_1AC}, A_{BAC} and A_{HAC} interaction parameters in a manner similar to that employed by Acree and McCargar[7] for *presumed* carbazole-dibutyl ether and carbazole-chloroalkane complexes leads to:

$$A_{A_1AC} = \bar{V}_C^2(\bar{V}_A + \bar{V}_C)^{-2}A_{A_1C_1}$$

$$A_{C_1AC} = \bar{V}_A^2(\bar{V}_A + \bar{V}_C)^{-2}A_{A_1C_1}$$

$$A_{BAC} = \frac{\bar{V}_A A_{A_1B}}{\bar{V}_A + \bar{V}_C} + \frac{\bar{V}_C A_{BC_1}}{\bar{V}_A + \bar{V}_C} - \frac{\bar{V}_A \bar{V}_C A_{A_1C_1}}{(\bar{V}_A + \bar{V}_C)^2}$$

$$A_{HAC} = \frac{\bar{V}_A A_{A_1H}}{\bar{V}_A + \bar{V}_C} + \frac{\bar{V}_C A_{C_1H}}{\bar{V}_A + \bar{V}_C} - \frac{\bar{V}_A \bar{V}_C A_{A_1C_1}}{(\bar{V}_A + \bar{V}_C)^2}$$

Substitution of these approximations into Eqs (15) and (16), after suitable mathematical manipulations, yields the following expressions for the chemical potentials of the uncomplexed solutes A_1 and H_1

$$\begin{aligned}\mu_{A_1} - \mu_A^{\bullet} = {} & RT[\ln \hat{\phi}_{A_1} + 1 - \bar{V}_A/\hat{V}_{\text{soln}}] + \bar{V}_A[\phi_B(1 - \phi_A)A_{A_1B} \\ & + \phi_C(1 - \phi_A)A_{A_1C_1} + \phi_H(1 - \phi_A)A_{A_1H} - \phi_B\phi_C A_{BC_1} \\ & - \phi_B\phi_H A_{BH} - \phi_C\phi_H A_{C_1H}]\end{aligned} \tag{17}$$

$$\begin{aligned}\mu_H - \mu_H^{\bullet} = {} & RT[\ln \phi_H + 1 - \bar{V}_H/\hat{V}_{\text{soln}}] + \bar{V}_H[\phi_A(1 - \phi_H)A_{A_1H} \\ & + \phi_B(1 - \phi_H)A_{BH} + \phi_C(1 - \phi_H)A_{C_1H} - \phi_A\phi_B A_{A_1B} \\ & - \phi_A\phi_C A_{A_1C_1} - \phi_B\phi_C A_{BC_1}]\end{aligned} \tag{18}$$

and the infinite dilution equilibrium solute concentration ratio

$$\begin{aligned}RT \ln K_{\text{tau}}^{\phi} = {} & RT(\phi_H/\hat{\phi}_{A_1}) = (\mu_A^{\bullet} - \mu_H^{\bullet}) + RT(\bar{V}_H - \bar{V}_A)/(X_B^0\bar{V}_B + X_C^0\bar{V}_C) \\ & + \phi_B^0(\bar{V}_A A_{A_1B} - \bar{V}_H A_{BH}) + \phi_C^0(\bar{V}_A A_{A_1C_1} - \bar{V}_H A_{C_1H}) \\ & + (\bar{V}_H - \bar{V}_A)\phi_B^0\phi_C^0 A_{BC_1}\end{aligned} \tag{19}$$

where $\phi_A = \hat{\phi}_{A_1} + \hat{\phi}_{AC}\bar{V}_A/(\bar{V}_A + \bar{V}_C)$ and $\phi_C = \hat{\phi}_{C_1} + \hat{\phi}_{AC}\bar{V}_C/(\bar{V}_A + \bar{V}_C)$.

Careful examination of Eq. (19) reveals that when the five interaction parameters are eliminated from the basic mixing model using measured binary solvent $\Delta\bar{G}_{BC}^{\text{fh}}$ values and pure solvent K_{tau}^{ϕ} values, the resulting expression is

$$\ln K_{\text{tau}}^{\phi} = \phi_B^0 \ln(K_{\text{tau}}^{\phi})_B + \phi_C^0 \ln(K_{\text{tau}}^{\phi})_C + \frac{(\bar{V}_H - \bar{V}_A)\Delta\bar{G}_{BC}^{\text{fh}}}{RT(X_B^0\bar{V}_B + X_C^0\bar{V}_C)}$$

identical to Eq. (12) derived previously for noncomplexing systems. As long as the tautomeric equilibrium is defined in terms of the concentrations of the *uncomplexed* solutes, it is impossible to ascertain information regarding the K_{AC}^{ϕ} solute-solvent association constant by measuring the variation of K_{tau}^{ϕ} with binary solvent composition. Only in the very special circumstance described by

$$RT(\bar{V}_H - \bar{V}_A)/\bar{V}_B + \bar{V}_A A_{A_1B} - \bar{V}_H A_{BH} = RT(\bar{V}_H - \bar{V}_A)/\bar{V}_C + \bar{V}_A A_{A_1C_1} - \bar{V}_H A_{C_1H} \tag{20}$$

will the calculated equilibrium concentration ratio appear to be independent of binary solvent composition.

RESULTS AND DISCUSSION

The chemical literature contains a large number of qualitative studies for tautomeric solutes dissolved in both polar and nonpolar solvents. Most studies are primarily concerned with spectral changes and few report actual solute concentration ratios or equilibrium constants. Numerical data for solutes dissolved in binary solvent mixtures is relatively scarce. A search of the published literature did reveal K_{tau}^{ϕ} values for 4-phenylazo-1-naphthol in aqueous ethanol and aqueous acetone mixtures. Limited phenylazonaphthol solubility in water did limit the measurements of Nishimura *et al.*[21] to mixtures containing high mole fractions of the organic solvent. Concentration ratios for phenylazonaphthol in the mixed solvents are depicted graphically in Figures 2 and 3 as ln K_{tau}^{ϕ} versus organic solvent volume fraction. Examination of the two figures reveals that the linear ln K_{tau}^{ϕ} versus ϕ_B^0 behavior suggested by Eq. (12) for both noncomplexing and complexing systems is not obeyed.

In experimentally determined K_{tau}^{ϕ} values it must be remembered that the concentrations of both tautomeric solute forms may not be measured. Often, one will measure the concentration of only form (*i.e.*, only ϕ_H) and calculate the concentration of the remaining form from a mass balance on the total amount of dissolved solute. In this later case, both the uncomplexed and complexed solute concentrations are incorporated into the equilibrium concentration ratio, $K_{\text{tau}}^{\text{app}} = \phi_H/\phi_A$. A simple solute mass balance is

$$\phi_A = \hat{\phi}_{A_1}[1 + \bar{V}_A K_{AC}^{\phi} \phi_C^0/(\bar{V}_A + \bar{V}_C)] \tag{21}$$

$$K_{\text{tau}}^{\text{app}} = K_{\text{tau}}^{\phi}/[1 + \bar{V}_A K_{AC}^{\phi} \phi_C^0/(\bar{V}_A + \bar{V}_C)] \tag{22}$$

used to relate the two different equilibrium concentration ratios. Expressed in terms of the *apparent* $K_{\text{tau}}^{\text{app}}$ value, Eq. (12) predicts

$$\begin{aligned}\ln K_{\text{tau}}^{\text{app}} = {} & \phi_B^0 \ln(K_{\text{tau}}^{\phi})_B + \phi_C^0 \ln(K_{\text{tau}}^{\text{app}})_C - \ln[1 + \bar{V}_A K_{AC}^{\phi} \phi_C^0/(\bar{V}_A + \bar{V}_C)] \\ & + \phi_C^0 \ln[1 + \bar{V}_A K_{AC}^{\phi}/(\bar{V}_A + \bar{V}_C)] + \frac{(\bar{V}_H - \bar{V}_A)\Delta\bar{G}_{BC}^{\text{fh}}}{RT(X_B^0 \bar{V}_B + X_C^0 \bar{V}_C)}\end{aligned} \tag{23}$$

a more complex mathematical relationship between measured solute concentration ratios and binary solvent compositions. Similar expressions can be derived for systems containing AC_2, AB, HB and/or HC association complexes. The various weighting factor approximations for these derivations are given in earlier papers.[7,26,27]

Mathematical behavior of Eq. (23) is illustrated in Fig. 4 assuming different numerical values for the K_{AC}^{ϕ} association constant. Properties used in the computations include equilibrium concentration ratios of $(K_{\text{tau}}^{\phi})_B = 1$ and $(K_{\text{tau}}^{\text{app}})_C = 0.1$, and molar volumes of Solute A and complexing cosolvent C of $\bar{V}_A = 200\,\text{cm}^3/\text{mol}$ and $\bar{V}_C = 100\,\text{cm}^3/\text{mole}$, respectively. For simplicity, the binary solvent "unmixing" term, $(\bar{V}_H - \bar{V}_A)\Delta\bar{G}_{BC}^{\text{fh}}/RT(X_B^0 \bar{V}_B + X_C^0 \bar{V}_C)$, is assumed negligible. Tautomeric solute molar volumes should be nearly identical, $\bar{V}_H \approx \bar{V}_A$. Inspection of Figure 4 reveals that in the absence of solute-solvent complexation ($K_{AC}^{\phi} = 0$) ln $K_{\text{tau}}^{\text{app}}$ is linearly related to the volume composition of the binary solvent mixture. Nonlinearity becomes pronounced as the solute-solvent association constant increases. Variation of the concentration

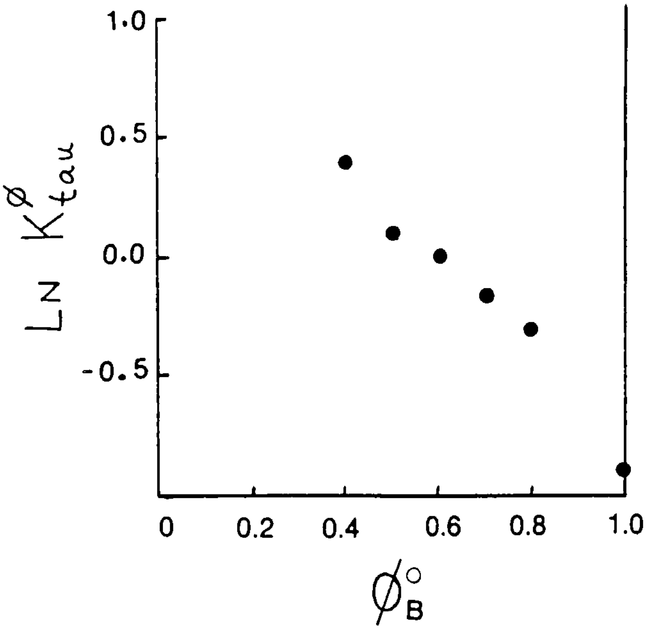

Figure 2 Tautomeric equilibrium concentration ratios (K^{ϕ}_{tau}) for phenylazonaphthol dissolved in ethanol (B) + water (C) mixtures as a function of solvent composition.

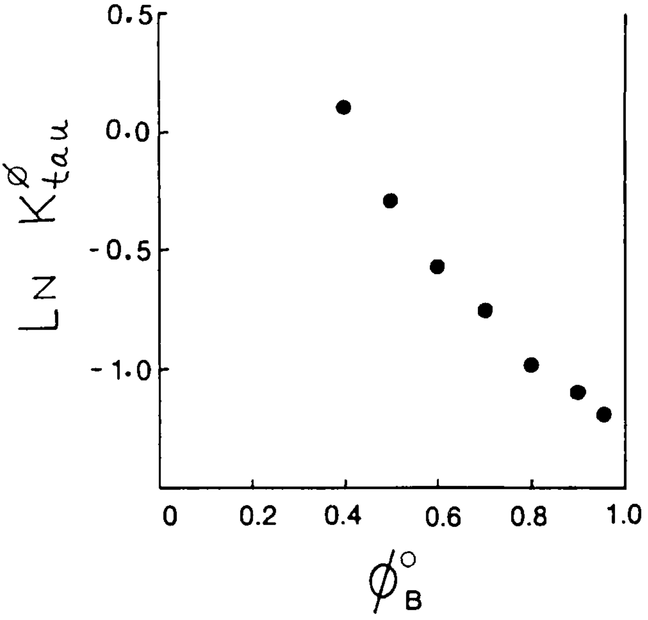

Figure 3 Tautomeric equilibrium concentration ratios (K^{ϕ}_{tau}) for phenylazonaphthol dissolved in acetone (B) + water (C) mixtures as a function of solvent composition.

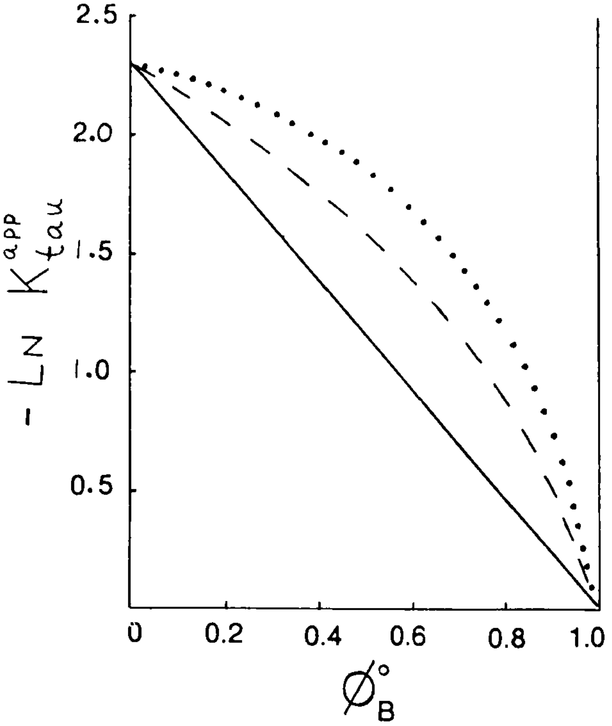

Figure 4 Calculated equilibrium concentration ratios of a hypothetical solute based on Eq. (23) and assumed K^{ϕ}_{AC} values. Various curves correspond to numerical solute-solvent association constants of $K^{\phi}_{AC} = 0$ (——), $K^{\phi}_{AC} = 10$ (- - -) and $K^{\phi}_{AC} = 20$ (·······). Notice that the nonlinear behavior becomes more pronounced with increasing K^{ϕ}_{AC}.

ratios for phenylazonaphthol with binary aqueous-organic solvent composition can be qualitatively rationalized using Eq. (23), provided that there are only one or two possible association complexes to consider. Unfortunately, these two systems are much too complex as a number of molecular complexes can be hypothesized simply from molecular structure considerations. Water and ethanol are known to self-associate and both can form hydrogen bonds with electron donor and acceptor molecules. Studies are currently underway to determine equilibrium concentration ratios and solubilities of tautomeric solutes in simpler binary solvent systems to better test the limitations and applications of the proposed thermodynamic model.

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