

Short communication

Enthalpies of transfer of urea and methyl-substituted ureas from water to methanol at 298.15 K

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Abstract

The enthalpies of solution of urea and its *N*-methyl-substituted analogues (methylurea, 1,1-dimethylurea, 1,3-dimethylurea, and 1,1,3,3-tetramethylurea) in water and methanol were measured at 298.15 K. Enthalpies of transfer from water to methanol were calculated. The enthalpies of transfer of methyl-substituted ureas are endothermic, the enthalpy of transfer of urea is negative. It has been concluded that the structure-making effects do not play the key role in methanol. The earlier assumption of an independent solvation of either side (alkylated or unsubstituted amino group) of the molecules is supported.

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1. Introduction

Interest in solutions of urea and its analogues is due to both biochemical importance and peculiarities of hydration of such systems [1–3]. In the case of *N*-methyl-substituted ureas in aqueous solutions, hydration is defined by the superposition of hydrophilic (near the NH- and C=O-groups) and hydrophobic (near the CH₃-groups) hydration [4–6].

The experimentally observed pattern of solvation changes significantly between aqueous and other amphiprotic media. The structural features of the solvent play an important role in these changes. Methanol (MeOH) is simultaneously similar to both water (in H-bond formation) and condensed methane (in molecular packing) [7]. Unlike other aliphatic alcohols, MeOH molecules contain no methylene units. This provides an explanation for atypical behavior of MeOH, which manifests itself in the “negative partial expansibility” effect observed for urea (U) dissolved in methanol [8–10].

We report here a calorimetric study of dilute solutions of U, monomethylurea (MeU), 1,1-dimethylurea (1,1-Me₂U), 1,3-dimethylurea (1,3-Me₂U), and 1,1,3,3-tetramethylurea (Me₄U) in MeOH and water at 298.15 K. Enthalpies of solution of methyl-substituted ureas in pure nonaqueous solvents have been published for the systems containing *N,N*-dimethylformamide (DMF) and CHCl₃ only [5,6].

2. Experimental

U (Aldrich, Analytical grade), MeU (Aldrich, Analytical grade), and 1,3-Me₂U (Aldrich, Analytical grade) were recrystallized from absolute ethanol (EtOH). 1,1-Me₂U (Aldrich, Purum) was twice recrystallized from a mixture of EtOH and chloroform [5]. Before measurements, all solid preparations were dried in a vacuum chamber at *ca.* 60 °C for 48 h and stored in an vacuum-dessicator over P₂O₅. Me₄U (Fluka, Purum) was distilled at reduced pressure. MeOH of Reagent grade was purified additionally by distillation with Mg₂(OCH₃)₂. In all experiments only the middle fractions of Me₄U and MeOH were used. The water content of these liquids, determined with a Karl Fisher titration, was below 0.02 mass%. All ureas were dissolved in deionized and twice-distilled water.

The experimental enthalpies of solution of the ureas $\Delta_{\text{sol}}H^m$ were measured at (298.15 ± 0.005) K using an isoperibol

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Table 1
Enthalpies of solution ($\Delta_{\text{sol}}H^\circ$) of the ureas and enthalpies of their transfer ($\Delta_{\text{tr}}H^\circ$) from water to methanol at 298.15 K

Solute	$\Delta_{\text{sol}}H^\circ$ (kJ mol ⁻¹)		MeOH	$\Delta_{\text{tr}}H^\circ$ (kJ mol ⁻¹) H ₂ O → MeOH
	H ₂ O			
	This work	Other data		
Urea	15.25 ± 0.05	15.27 ± 0.04 [6] 15.42 ± 0.14 [14] 15.29 ± 0.03 [15] 15.28 ± 0.03 [16]	10.82 ± 0.02	-4.43 ± 0.06
Methylurea	10.64 ± 0.03	11.19 ± 0.01 [5]	14.21 ± 0.04	3.57 ± 0.05
1,1-Dimethylurea	12.60 ± 0.06	12.01 ± 0.05 [5]	19.54 ± 0.10	6.94 ± 0.12
1,3-Dimethylurea	0.96 ± 0.02	1.05 ± 0.04 [5] 0.57 ± 0.02 [14]	10.29 ± 0.06	9.33 ± 0.07
1,1,3-Trimethylurea	–	-3.18 ± 0.02 [6]	–	–
1,1,3,3-Tetramethylurea	-22.19 ± 0.05	-24.53 ± 0.01 [5] -23.96 ± 0.09 [14] -22.07 ± 0.05 [17]	-4.58 ± 0.01	17.61 ± 0.05

ampoule-type calorimeter equipped with a 60 cm³ reaction vessel and electrical calibration. The error of measuring single heat effects was below 0.2%. Calibration of the calorimeter by the heat of solution of KCl in water at 298.15 K gave 17.23 ± 0.07 kJ mol⁻¹ (17.22 ± 0.04 kJ mol⁻¹ [11]). The calorimeter setup and experimental procedure were described previously [12,13].

3. Results

At concentrations from 0.005 to 0.014 *m*, $\Delta_{\text{sol}}H^m$ was independent of the molality *m* within the experimental error. Therefore, the mean values obtained from five to six determinations were taken to be equal to the enthalpy of solution $\Delta_{\text{sol}}H^\circ$. The results are listed in Table 1 together with data from other sources.

The obtained values of the enthalpies of solution are in good agreement with literature data. Scatter in the data for Me₄U can be explained by the difference in the quality of the preparation of the samples. Note, however, that the consistency of our data with published data is less important than determining $\Delta_{\text{tr}}H^\circ$ (H₂O → MeOH) values.

4. Discussion

Dissolution of the ureas in methanol and water is endothermic except for Me₄U. Me₄U has a substantially more positive value of $\Delta_{\text{tr}}H^\circ$ than the other methyl-substituted ureas. The enthalpy of transfer is negative only in the case of unsubstituted U (similar in sign, although more significant enthalpic change is characteristic of the transfer of U from water to DMF [5,6]).

The transfer function $\Delta_{\text{tr}}H^\circ$ (H₂O → MeOH) shows the same variations as enthalpies of solution, but does not contain contributions from interactions in the pure solute. Hence $\Delta_{\text{tr}}H^\circ \equiv \delta\Delta_{\text{sol}}H^\circ$ reflects the enthalpic difference in solvation of the solute by molecules of water and methanol. For this reason, the degree of solvation of the methyl-substituted ureas

in methanol is substantially lower than that in water. Such a weakening of the solvation process increases in the series: MeU < 1,1-Me₂U < 1,3-Me₂U < Me₄U (see Table 1), showing the structure-making effects do not play the key role in methanol.

In the case of U, on the contrary, the tendency to strengthening of the solute solvation is observed, that is, $\delta\Delta_{\text{sol}}H^\circ$ (H₂O → MeOH) < 0. We assume that it can be explained mainly by H-bonding between the solvent and U when H₂O is replaced with MeOH. The conclusion is supported by the fact that the limiting partial volume (\bar{V}^∞) of U decreases by more than 8 cm³ mol⁻¹ in going from aqueous solution to methanol [9].

These conclusions are confirmed by the data schematically presented in Fig. 1.

Fig. 1 shows that an additivity scheme is not applicable to the $\Delta_{\text{tr}}H^\circ$ (H₂O → MeOH). Introduction of one methyl group (on the 1-*cis* position), to form MeU, causes a shift in $\Delta_{\text{tr}}H^\circ$ of 8.00 kJ mol⁻¹. This is substantially higher than the effect of a second methyl group on the same N atom (on the 1-*trans* position), to form 1,1-Me₂U, which is 3.37 kJ mol⁻¹. However, introduction of a second methyl group on the other N atom (on the 3-*cis* position), to form 1,3-Me₂U, results in a shift (5.76 kJ mol⁻¹) which is about half the average of the above-mentioned values.

These facts confirm [3,5,18] that the NH₂, NHCH₃, or N(CH₃)₂ groups on either side of the molecule are solvated independently. This also suggests that the experimental enthalpy

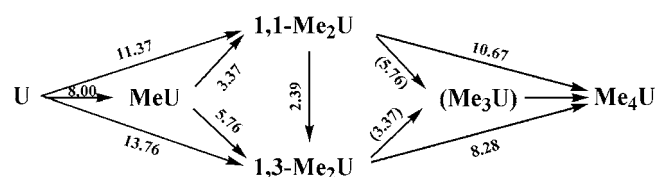


Fig. 1. Changes in the enthalpies of transfer from H₂O to MeOH for ureas caused by methyl substitution. Values placed in parentheses are estimated on the basis of supposition of an energy equivalence of the methyl substitution at the N atom on the 1,3-*cis* and 1,3-*trans* positions, correspondingly (energies are in kJ mol⁻¹).

of transfer of Me₄U will be larger (or smaller) than that predicted by the scheme in Fig. 1: $8.00 + 5.76 + 3.37 + 3.37 = 20.50 \text{ kJ mol}^{-1}$. Experimentally the difference in $\Delta_{\text{tr}}H^\circ$ (H₂O → MeOH) for U and Me₄U is found to be $22.04 \text{ kJ mol}^{-1}$. It is interesting that the value $(22.04 - 20.50) + 3.37 = 4.91 \text{ kJ mol}^{-1}$, which corresponds hypothetically to the change in $\Delta_{\text{tr}}H^\circ$ caused by a *virtual* introduction of a methyl group into 1,1,3-trimethylurea (Me₃U) (on the 3-*trans* position). This is roughly equal to half of the sum of the enthalpic shifts evaluated for 1,1-Me₂U(1,3-Me₂U) → Me₃U transitions: $(5.76 + 3.37)/2 = 4.57 \text{ kJ mol}^{-1}$ (see Fig. 1).

It follows that there is a correlation between the $\Delta_{\text{tr}}H^\circ$ values and the changes in the solvation of U and its methyl-substituted analogues at their transfer from water to MeOH. According to inferences made in [6,19], the $\Delta_{\text{tr}}H^\circ$ (H₂O → MeOH) values for the molecules in question are influenced by the following: (1) a contribution from methyl group itself (hydrophobic and steric), (2) hindrance of the hydrogen-bonding ability of the substituted amino group, and finally (3) a decrease in the hydrogen-bonding ability of the carbonyl group. In particular, by comparing the $\Delta_{\text{tr}}H^\circ$ values of a pair of isomers, 1,1-Me₂U and 1,3-Me₂U, the second reason mentioned above may be most important. The 1,1-isomer has one unsubstituted amino group, and so it has more hydrogen-bonding ability than the corresponding 1,3-isomer, that is, the former exhibits a greater $\Delta_{\text{tr}}H^\circ$ enthalpy decrease due to hydrogen bonding. At the same time, although the magnitudes of the changes depicted in Fig. 1 are determined by different effects, *e.g.* changes in solute–solvent hydrogen-bonding, we believe them to be due largely to hydrophobic hydration of methyl groups.

5. Conclusion

To summarize, analysis of the enthalpy changes caused by a sequential *N*-methyl-substitution into the urea molecules at their transfer from water to MeOH directly supports the previously made assumption of an independent solvation of the either structural fragment of the compounds under consideration. In addition, the data obtained in this work show that the

structure-making effects (hydrophobic hydration type) intrinsic in aqueous solutions of the methyl-substituted ureas do not play the key role in methanol.

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