Osmotic and Activity Coefficients of Alkylureas in Water at 25°C

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The osmotic coefficients of the following alkylureas are determined: methylurea, ethylurea, propylurea, symmetric and asymmetric dimethylurea, symmetric and asymmetric diethylurea, and hexahydropyrimidinone. Treatment of the experimental data for the evaluation of the activities and activity coefficients is examined critically. Models proposed for the explanation of the thermodynamic properties are considered.

The study of physicochemical properties of aqueous solutions of nonelectrolytes has become increasingly interesting in recent years (8). From this research it is possible to obtain information about the structure of water and aqueous mixtures. The nonelectrolytes, moreover, are suitable as model molecules of biological and synthetic macromolecules and/or can act as conformational perturbants of the same species. As a consequence, the study of aqueous solutions of nonelectrolytes can contribute to the clarification of the type and entity of forces that stabilize the macromolecule conformations.

The thermodynamic properties of aqueous solutions of urea are well known (5, 15), whereas the properties of aqueous solutions of alkylureas are only partially known (3, 4, 12, 16). In view of an extensive study on the properties of these substances, we have been systematically collecting experimental data in recent years. In this paper the osmotic and activity coefficients of some alkylureas in water are determined and are compared with data reported in the literature.

Experimental

The following substances were examined: monosubstituted methylurea (MMU), ethylurea (MEU), propylurea (MPU), and disubstituted dimethylurea and diethylurea, symmetric and asymmetric ureas (1,3-DMU, 1,1-DMU, 1,3-DEU, 1,1-DEU, respectively). All ureas (recrystallized several times from ethanol) were Carlo Erba, Fluka, or K & K products; a cyclic compound, hexahydropyrimidinone-2, $\overline{NHCONHCH_2CH_2CH_2}$ (HHP-2), was supplied by Professor Montaudo of the University of Catania. After purification the substances had the following melting points: MMU, 102°; MEU, 92°; MPU, 110°; 1,3-DMU, 102°; 1,1-DMU, 182°; 1,3-DEU, 111°; and 1,1-DEU, 72°, in agreement with data reported in the literature. For HHP-2 the melting point was 207°. The trisubstituted ureas were not available as commercial products, and the tetrasubstituted ureas were liquid (tetramethylurea) or fairly insoluble (tetraethylurea) at 25°C. All solutions were prepared by weight with deionized and bidistilled water.

All determinations of osmotic coefficients ϕ were made by the isopiestic gravimetric method, by use of platinum weighing bottles placed on an aluminum block, contained in a stainless-steel vessel equipped with a plexiglas window. The vessel was evacuated and adapted to a rotating apparatus in a large thermostatic bath (300-l. capacity; temperature: 25.00° ± 0.03°C). The equilibration was accomplished in one week (about two weeks for the diluted solutions). As reference we

chose KCl aqueous solutions and used Robinson and Stokes osmotic coefficients (13). Special care was taken to avoid contact of the solutions with air humidity and CO_2 at the opening of the vessel. Measurement of the conductance of the solutions is the most sensitive test for dissolution of CO_2 and for decomposition of the alkylureas. Changes in the conductance at the end of measurements gave only a negligible decomposition. All calculations were performed with an IBM 360/44 computer and a Hewlett-Packard HP10 calculator.

Results and Discussion

The range of molal concentrations examined was 0.4–3m for all substances, except for HHP-2 and the two diethylureas, whose solubilities are less than 3m. The experimental values of osmotic coefficients, defined as $\phi = -55.51/m \ln a_1$ (where a_1 is the water activity) are reported in Table I. The osmotic coefficient values diminish generally with increasing concentration, number, and length of the chains of alkyl substituents. The order of ϕ is: MMU > 1,1-DMU > MEU $\simeq$ 1,3-DMU > HHP-2 > MPU > 1,1-DEU > 1,3-DEU. It is remarkable that the symmetric alkylureas depart from ideality more than the asymmetric compounds. All values are lower than

Table I. Experimental Osmotic Coefficients at 25° C

MMU		MEU		MPU	
m	ϕ	m	ϕ	m	ϕ
0.535	0.973	0.525	0.951	0.547	0.913
0.675	0.966	0.701	0.931	0.730	0.894
0.930	0.955	1.034	0.906	1.075	0.872
1.343	0.940[a]	1.335	0.889	1.385	0.857
1.987	0.917[a]	1.536	0.887	1.620	0.841
2.263	0.908	2.108	0.857	2.194	0.823
		2.638	0.835	2.717	0.811

1,1-DMU		1,3-DMU		HHP-2	
m	ϕ	m	ϕ	m	ϕ
0.522	0.957	0.550	0.947	0.397	0.947
0.690	0.946	0.698	0.935	0.636	0.931
1.011	0.927	0.971	0.915	0.715	0.912
1.288	0.921	1.754	0.866	0.873	0.910
1.486	0.917	2.462	0.835	0.996	0.892
2.016	0.896				
2.508	0.878				

1,1-DEU		1,3-DEU	
m	ϕ	m	ϕ
0.423	0.889	0.432	0.866
0.592	0.880	0.586	0.852
0.693	0.854	0.871	0.818
0.960	0.827	0.987	0.805
1.047	0.811	1.124	0.790
1.307	0.798	1.214	0.785
1.734	0.772	1.443	0.768
1.976	0.752	1.774	0.742
2.023	0.751	2.093	0.716

[a] Data from ref. 4 at 24.72° C. These data are directly comparable to the data at 25.00° C because the correction we may introduce for the temperature difference ($\Delta \phi \simeq -5 \cdot 10^{-5}$) is negligible in this range of concentration.

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those related to urea. Furthermore, they are smaller than the ideal values: the expression of ϕ in function of the molality m (for nonelectrolyte aqueous solutions) is:

$$\phi = 1 - 0.009m + 0.000108m^2 - \ldots + \ldots \quad (1)$$

Some authors, as outlined by Stokes (15), erroneously assumed a unit value for the practical osmotic coefficient in the whole range of concentration. That is true for the "rational osmotic coefficient" defined as $g = \ln a_1/\ln x_1$, where a_1 and x_1 are the activity and the molar fraction of the solvent. On the other hand, there is a trivial error in the paper of Stokes: the exact formulation is that reported above.

The relation between the practical osmotic coefficient and the activity coefficient of the solute (on the scale of the molality), γ_2, in the case of nonelectrolytes is (11):

$$\ln \gamma_2 = (\phi - 1) + \int_0^m \frac{(\phi - 1)}{m} \, dm \quad (2)$$

The experimental data were fitted by the least-squares method with polynomials to solve the expression (2). Polynomials of the third order [with the condition $\phi(0) = 1$] supply a good fit in the concentration range examined, in relation to the small number of experimental data: higher order polynomials would give a misleading improvement. For MMU two data points from ref. 4 were also used. The polynomial coefficients and standard deviations are reported in Table II. The coefficients were used with four meaningful digits, which introduces an approximation less than $3 \cdot 10^{-4}$ on ϕ.

For some thermodynamic properties, the data show a marked curvature in the dilute range of concentration and a fairly linear pattern at higher concentrations. For these a polynomial of the third order does not provide a good representation of the data when taken over a wide range of concentration (0–12 m, as in our case). In the case of aqueous solutions of urea, Stokes used a particular equation describing the trend of osmotic coefficients and other properties up to 20 m (15).

Polynomials of the fourth order appear to supply a good fit of the data for MMU and 1,3-DMU up to 12 m. The coefficients are reported in Table III. In Tables IV and V, values for these two substances, obtained by interpolation of experimental data grouped in different ways, are compared. For MMU the data of ref. 4 were adjusted to 25°C, whereas for 1,3-DMU the data of ref. 3 were recalculated with the osmotic coefficients of the reference solutions reported by Robinson and Stokes (13).

From Tables IV and V, two main features are apparent. First, our experimental results are in good agreement with the data reported in the literature as shown by comparison of the interpolated values in the range 0–3 m. The second feature is the consistency of the different methods of interpolation. Nevertheless, the values calculated with the data of refs. 3 and 4 differ little from the values calculated with the data relative to the range 0–3 m or relative to the entire range. Actually, this behavior arises essentially from the curvatures of ϕ vs. m functions at low concentrations. When data at relatively low concentrations are available, the curvature seems more marked than that obtainable by extrapolating data at higher concentrations. The reverse occurs in the region of intermediate concentrations, since the curvature drawn from data at low concentration is too great.

The experimental data are reproduced from the equations reported in Table III with an average deviation of $0.9 \cdot 10^{-3}$ on ϕ; a maximum deviation of $2-3 \cdot 10^{-3}$ for 5 points with respect to 23 points was observed. Only the values of the activity coefficients for 1,3-DMU, calculated here, disagree remarkably from the values reported by Bonner and Brezeale (3). We are unable to provide any explanation for this discrepancy. On the other hand, these authors do not define γ, nor do

they discuss their method of integration or interpolation of the experimental data. In Table VI interpolated values of ϕ and γ_2 are tabulated for the other six substances studied by us.

Table II. Coefficients of Polynomials in Range 0–3 m

$\phi = 1 + A_1 m + A_2 m^2 + A_3 m^3$
$\ln \gamma_2 = 2 A_1 m + \frac{3}{2} A_2 m^2 + \frac{4}{3} A_3 m^3$
N = number of experimental data

Substance	$A_1 \cdot 10^2$	$A_2 \cdot 10^2$	$A_3 \cdot 10^3$	$SD \cdot 10^3$	N
MMU	−5.448	+0.8120	−0.8652	0.3882	6[a]
MEU	−10.93	+2.334	−1.957	3.930	7
MPU	−20.42	+9.377	−16.49	4.016	7
1,1-DMU	−10.37	+4.306	−8.373	2.123	7
1,3-DMU	−10.87	+2.360	−2.755	5.007	5
HHP-2	−18.14	+15.31	−78.96	4.892	5
1,1-DEU	−31.87	+18.58	−44.58	6.019	9
1,3-DEU	−40.05	+27.23	−70.88	6.863	9

[a] Two data from ref. 4: see Table I.

Table III. Coefficients of Polynomials in Range 0–12 m

$\phi = 1 + A_1^* m + A_2^* m^2 + A_3^* m^3 + A_4^* m^4$
$\ln \gamma_2 = 2 A_1^* m + \frac{3}{2} A_2^* m^2 + \frac{4}{3} A_3^* m^3 + \frac{5}{4} A_4^* m^4$

Substance	$A_1^* \cdot 10^2$	$A_2^* \cdot 10^2$	$A_3^* \cdot 10^3$	$A_4^* \cdot 10^5$	$SD \cdot 10^3$	N
MMU	−5.390	+0.6995	−0.4582	+1.175	1.250	11[a]
1,3-DMU	−10.65	+1.999	−1.725	+5.532	1.250	12[b]

[a] Seven data from ref. 4 at 24.72°C, corrected for temperature: corrections were $\Delta\phi \cong -2 \cdot 10^{-4}$ in the range 3.5–7.5 m and $\Delta\phi \cong -1 \cdot 10^{-4}$ in the range 7.5–12 m. [b] Seven data from ref. 3 recalculated by use of data of ref. 10 for reference solutions.

Table IV. Osmotic and Activity Coefficients of MMU at 25°C

m	ϕ^a	γ_2	ϕ^b	γ_2	ϕ^c	γ_2
0.2	0.989	0.979	0.990	0.979	0.989₅	0.979
0.4	0.979	0.959	0.980	0.960	0.979₅	0.959
0.6	0.970	0.941	0.970₅	0.942	0.970	0.941
0.8	0.961	0.923	0.962	0.924	0.961	0.923
1.0	0.953	0.907	0.953	0.908	0.953	0.907
1.2	0.945	0.891	0.945	0.892	0.945	0.891
1.4	0.937	0.876	0.938	0.878	0.937	0.876
1.6	0.930	0.862₅	0.930	0.864	0.930	0.862
1.8	0.923	0.849	0.924	0.851	0.923	0.849
2.0	0.917	0.837	0.917	0.838	0.917	0.837
2.2	0.910	0.824	0.911	0.826	0.911	0.825
2.4	0.904	0.813	0.905	0.815	0.905	0.814
2.6	0.898	0.801₅	0.900	0.804	0.900	0.803
2.8	0.892	0.791	0.895	0.794	0.894₅	0.793
3.0	0.886	0.780	0.890	0.784₅	0.890	0.783
3.4			0.881	0.767	0.881	0.765
3.8			0.873₅	0.750	0.873₅	0.749
4.0			0.870	0.743	0.870	0.742
4.2			0.867	0.735₅	0.867	0.735
4.6			0.860₅	0.722	0.861	0.721
5.0			0.855	0.710	0.855	0.709
6.0			0.844₅	0.683	0.846	0.682₅
7.0			0.836	0.661	0.836	0.660₅
8.0			0.830	0.643	0.830	0.642
9.0			0.825	0.626	0.824₅	0.625
10.0			0.819₅	0.611₅	0.820	0.611
11.0			0.814	0.598	0.815₅	0.598
12.0			0.808	0.584	0.812	0.586

[a] From equation: $\phi = 1 + A_1 m + A_2 m^2 + A_3 m^3$ (coefficients of Table II). [b] From equation: $\phi = 1 - 5.292 \cdot 10^{-2} m + 6.500 \cdot 10^{-3} m^2 + -3.812 \cdot 10^{-4} m^3 + 7.998 \cdot 10^{-6} m^4$ obtained from data of ref. 4 corrected for temperature (see Table III). [c] From equation: $\phi = 1 + A_1^* m + A_2^* m^2 + A_3^* m^3 + A_4^* m^4$ (coefficients of Table III).

Table V. Osmotic and Activity Coefficients of 1,3-DMU at 25°C

m	ϕ^a	γ_2	ϕ^b	γ_2	ϕ^c	γ_2
0.2	0.979	0.959	0.980	0.961	0.979$_5$	0.959
0.4	0.960	0.922	0.962	0.925	0.960$_5$	0.923
0.6	0.943	0.888	0.945	0.893	0.943	0.889
0.8	0.927	0.858	0.929	0.863	0.927	0.858
1.0	0.912	0.831	0.914	0.836	0.912	0.831
1.2	0.899	0.806	0.901	0.811	0.898	0.805$_5$
1.4	0.886$_5$	0.783	0.888	0.788	0.885$_5$	0.782
1.6	0.875	0.762	0.876$_5$	0.766	0.874	0.761
1.8	0.865	0.742	0.866	0.747	0.863$_5$	0.741$_5$
2.0	0.855	0.724	0.856	0.729	0.854	0.724
2.2	0.846	0.707$_5$	0.847	0.712	0.845	0.707
2.4	0.837	0.692	0.839	0.697	0.837	0.692
2.6	0.828$_5$	0.677	0.832	0.683	0.830	0.678
2.8	0.820	0.662$_5$	0.825	0.670	0.824	0.665
3.0	0.812	0.649	0.819	0.657	0.818	0.653
3.4			0.808$_5$	0.636	0.808$_5$	0.632
3.8			0.800	0.617	0.801	0.613$_5$
4.0			0.797	0.608	0.797$_5$	0.605
4.2			0.793$_5$	0.600	0.795	0.598
4.6			0.788	0.586	0.790	0.584
5.0			0.784	0.573	0.786	0.571
6.0			0.778	0.547$_5$	0.779$_5$	0.545
7.0			0.775	0.527	0.775	0.525
8.0			0.773	0.510	0.770$_5$	0.507
9.0			0.770	0.496	0.766	0.491
10.0			0.767	0.482	0.762	0.477
11.0			0.765	0.470	0.761	0.466
12.0			0.764	0.460	0.767	0.459

^{a} From equation: $\phi = 1 + A_1m + A_2m^2 + A_3m^3$ (coefficients of Table II). ^{b} From equation $\phi = 1 - 0.1021m + 1.765 \cdot 10^{-2}m^2 + -1.369 \cdot 10^{-3}m^3 + 3.914 \cdot 10^{-5}m^4$ obtained from data of ref. 3 recalculating the osmotic coefficients of reference solutions on the basis of ref. 10. ^{c} From equation: $\phi = 1 + A_1^*m + A_2^*m^2 + A_3^*m^3 + A_4^*m^4$ (coefficients of Table III).

Table VI. Osmotic and Activity Coefficients at 25°C

m	MEU ϕ	γ_2	MPU ϕ	γ_2	1,1-DMU ϕ	γ_2
0.2	0.979	0.958$_5$	0.963	0.927	0.981	0.962
0.4	0.960	0.921	0.932	0.867	0.965	0.929
0.6	0.942	0.888	0.908	0.820	0.951$_5$	0.902
0.8	0.926$_5$	0.857	0.888	0.780	0.940	0.878
1.0	0.912	0.830	0.873	0.748	0.931	0.857
1.2	0.899	0.805	0.861	0.722	0.923	0.839
1.4	0.887	0.783	0.853	0.700	0.916	0.823
1.6	0.877	0.763	0.846	0.681$_5$	0.910	0.809
1.8	0.867$_5$	0.744	0.840	0.665	0.904	0.795
2.0	0.859	0.728	0.835	0.650	0.898	0.782
2.2	0.852	0.712	0.829	0.636	0.891	0.769
2.4	0.845	0.698	0.822	0.622$_5$	0.883	0.756
2.6	0.839	0.685$_5$	0.813	0.608	0.874	0.742
2.8	0.834	0.674	0.801	0.592	0.863$_5$	0.727
3.0	0.829	0.663	0.786	0.575	0.850	0.710

m	HHP-2 ϕ	γ_2	1,1-DEU ϕ	γ_2	1,3-DEU ϕ	γ_2
0.2	0.969	0.938	0.943	0.890	0.930	0.865
0.4	0.947	0.891	0.899	0.807	0.879	0.770
0.6	0.929	0.854	0.866	0.745	0.842	0.702
0.8	0.912	0.821	0.841	0.696	0.818	0.652
1.0	0.893^a	0.788^a	0.822$_5$	0.658	0.801	0.614
1.2			0.808	0.627	0.789	0.585
1.4			0.796	0.601	0.778$_5$	0.560
1.6			0.783	0.577	0.766	0.536
1.8			0.768	0.554	0.748	0.512
2.0			0.749	0.530	0.721	0.485
2.2			0.724	0.504	0.682	0.453

^{a} Extrapolated values: at 25°C the solubility is lower than 1.0m.

In the case of urea, there are two models for the physicochemical properties of aqueous solutions. One is a thermodynamic model of "quasi-ideality" (14, 15) that ascribes the deviation from ideality entirely to a dimerization process of the solute via hydrogen bonding: however, Klotz and Franzen (9) determined that there is no spectral evidence for hydrogen bonding. An improvement of the model is the hypothesis of Kresheck (10) who suggests that the association of urea (and of the alkylamides) molecules can be regarded as due to a dipole–dipole interaction. According to these models, the activity of the solute diminishes with the concentration because of the increasing formation of dimers.

On the contrary, Frank and Franks (7, 8) showed that the decrease of the activity of the solute can be explained on the basis of the structure-breaking effect of urea on water. A spectroscopic evidence (indication of the nonexistence of urea dimers) has also been supplied (6). Moreover, the Frank and Franks model is more general and provides an explanation for the solubility of hydrocarbons in these solutions and for other phenomena. We have shown that the action of alkylureas on H_2O–D_2O mixtures is opposite the action of urea (2): alkylureas can be regarded as structuring agents, in that they increase the —OH . . . O fraction. According to the first model, the trends of osmotic coefficients of alkylureas can be explained on the basis of formal association constants, whose values increase with the number and chain length of alkyl substituents.

Actually, we showed that the correspondence between the observation $\phi_{real} < \phi_{ideal}$ and the hypothesis of association of the solute is not necessary. In fact, developing the statistical model of Frank and Franks for solutes promoting the water structure (according to the above definition) but not strongly

interacting with the solvent, it is possible to foresee the decrease of ϕ and of γ_2 and an increase of the activity of water with respect to the ideal values (1). Solutes of this type show the so-called hydrophobic or aperipheral hydration. For hydrophilic solutes, such as the saccharides, hexamethylentetramine (4) (which forms even clathrates), the direct hydration of the polar groups is the prevailing effect. This would lead to a decrease of free water and of the activity of the solvent and, as a consequence, to an increase of the osmotic and activity coefficient of the solute. Further work is in progress in our laboratory to develop a statistical model mostly on the basis of thermochemical data.

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