

216. The Solubility of Non-electrolytes. Part II. The Influence of the Polar Group on the Free Energy of Hydration of Aliphatic Compounds.

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IN Part I (this vol., p. 280) measurements were given of the free energies of hydration (evaluated as $RT \cdot \log p/N$, where p = partial pressure of the solute over a very dilute aqueous solution of molar fraction N) of a number of aliphatic alcohols. In order to examine the influence of the nature of the polar group on this quantity the measurements have now been extended to a number of other aliphatic compounds including amines, acids, nitriles, and esters.

Materials.—Methyl and ethyl acetates were purified by Young's method (*Proc. Roy. Soc., Dublin*, 1910, **12**, 344), dried with phosphoric oxide, and fractionated. Ethylene glycol was purified by Gattermann's method ("Laboratory Methods of Organic Chemistry," p. 102) and fractionated. A.R. Glycerol (B.D.H.) containing 99.97% glycerol was used, $D_4^{25} = 1.2552$, $n_D^{20} = 1.4703$. *n*-Propionitrile was purified by Thorpe's method (*J.*, 1880, **37**, 205) and fractionated. Ethylamine was used in the form of an aqueous solution, prepared by absorbing in water the gas formed by the action of concentrated sodium hydroxide on the hydrochloride. The other substances were purified by fractional distillation. The ranges over which the fractions used were collected, and their b. p.'s (corrected to 760 mm.) are given in the following table.

	Range.	B. p.
Methyl acetate	56.54—56.64°/745 mm.	57.15°
Ethyl acetate	77.10—77.14/759	77.15
Ethylene glycol	197.4—197.6/764	197.3
<i>n</i> -Propionitrile	96.52—96.62/747	97.2
<i>n</i> -Butyronitrile	116.36—116.66/743	117.3
<i>n</i> -Propylamine	49.01—49.31/764	49.25
<i>n</i> -Butylamine	77.01—77.32/751	77.81
<i>n</i> -Propionic acid	140.25—140.35/744	141.25
<i>n</i> -Butyric acid.....	162.46—162.66/764	162.4
Phenol	181.3—181.6/762	181.2
Aniline	184.05—184.06/752	184.4

Method.—Dilute aqueous solutions ($N = 10^{-2}$ — 10^{-3}) of these substances were prepared, and the partial vapour pressures of the solutes determined, as previously described, by bubbling dry

air at 25° through the solutions, condensing the vapour carried over, and determining the concentration of the solute in the condensate by comparison with standard solutions in the Zeiss interferometer.

Results.—In the following table, N is the molar fraction of the solute in the dilute aqueous solution, x the weight % of solute in the condensate (the mean of at least two reasonably concordant determinations), p the partial pressure of the solute over the solution at 25° in mm. of mercury. The value of $RT \cdot \log p/N$ is in cal. The value for acetic acid is that obtained by Fredenhagen and Liebster (*Z. physikal. Chem.*, 1932, *A*, **162**, 449), who made a correction for the association in the vapour phase. This correction is quite small, and the results for propionic and butyric acids have not been similarly corrected. The value for acetone has been obtained by extrapolation to zero concentration from the measurements of Beare, McVicar, and Ferguson (*J. Physical Chem.*, 1930, **34**, 1310).

Partial vapour pressures in dilute aqueous solution at 25°.

	$N \times 10^3$.	x .	p .	p/N .	$RT \cdot \log p/N$.
Ethylamine	0.484	2.10	0.204	421	3580
<i>n</i> -Propylamine	0.445	3.15	0.236	530	3720
<i>n</i> -Butylamine	0.588	6.03	0.376	639	3830
Acetic acid	—	—	—	12.6	1500
<i>n</i> -Propionic acid	5.021	1.59	0.093	18.5	1730
<i>n</i> -Butyric acid	2.089	0.96	0.047	22.5	1850
<i>n</i> -Propionitrile	1.111	18.42	1.75	1579	4360
<i>n</i> -Butyronitrile	0.984	25.82	2.15	2189	4560
Methyl acetate	0.500	24.91	1.92	3832	4890
Ethyl acetate	0.976	52.86	5.44	5580	5110
Acetone	—	—	—	1390	4800
Glycol	10.37	0.39	0.026	2.55	550
Glycerol	10.93	0.17	0.008	0.71	—200

The values of p/N for a number of substances of limited miscibility, which are given below, were obtained from the recorded values of the solubility (N_s) and the vapour pressure p^0 at 25°. The values for the hydrocarbon gases were obtained from the absorption coefficients (I.C.T., **3**, 260).

Values of $RT \cdot \log p/N$ derived from solubilities and vapour pressures.

	N_s .	p^0 .	$RT \cdot \log p/N$.		N_s .	p^0 .	$RT \cdot \log p/N$.
Diethyl ether	0.0154	537	6240	Methane	0.0423	736	9080
Ethyl propyl ether	0.0037	178	6390	Ethane	0.0432	736	9000
Dipropyl ether	0.00044	65	7050	<i>n</i> -Butane	0.0415	736	9460
Propyl acetate	0.0039	33	5350				

DISCUSSION.

The values of the free energies of hydration of the various groups of compounds are tabulated below. It is clear that although in a homologous series of compounds this quantity increases by approximately constant increments, yet the value depends to a great extent on the nature of the polar group. The increment for an additional methylene group is of the same order as that previously observed in the alcohols.

Standard free energies of compounds in aqueous solution referred to the gaseous state.

Radical (R).	RH.	R-OH.	R-NH ₂ .	R-CO ₂ H.	RCN.	CH ₂ -CO ₂ R.
CH ₃	9080	3090	—	1500	—	4890
C ₂ H ₅	9000	3190	3580	1730	4360	5110
C ₃ H ₇	—	3380	3720	1850	4560	5350
C ₄ H ₉	9460	3490	3830	—	—	—

The free energy of hydration can thus be regarded, at least approximately, as an additive function of the various groups in the molecule. Additive constants for these groups could be derived in various ways, but we shall utilise the formulation given by Butler, Maclennan, and Thomson (J., 1933, 674). The work done in bringing a molecule of the solute from the vapour into water may be written as

$$\phi = \Sigma\gamma_{W-W} - \Sigma\gamma_{A-W} \dots \dots \dots (1)$$

where $\Sigma\gamma_{W-W}$ is the work done in making a cavity in the water large enough to hold the solute molecule, and $\Sigma\gamma_{A-W}$ is the work of interaction of the various groups of the solute

molecule with the surrounding water molecules. Neglecting forces of greater range than those operative between adjacent molecules, we may write this as

$$\phi = n/2 \cdot \gamma_{w-w} - \Sigma a\gamma_{A-w} \quad \dots \quad (2)$$

where γ_{w-w} is the work done in separating a single pair of water molecules, and n the total number of water molecules at the surface of the cavity, for we may suppose that, in making the cavity, $n/2$ water-water contacts are broken. γ_{A-w} is the work of interaction of the group A of the solute molecule with an adjacent water molecule, and a the number of water molecules adjacent to the group.

To estimate the values of these terms from the information at present available, it is necessary to assume a rather simple arrangement of molecules in the solution. We shall suppose that water has on the whole the pseudo-crystalline tetrahedral arrangement suggested by Bernal and Fowler (*J. Chem. Physics*, 1933, 1, 515). Thus when the molecule of ethane is introduced into water, we may suppose that each methyl group is adjacent to three water molecules. The number of water molecules at the surface of the cavity is then six, and we have

$$\phi_{C_2H_6} = 3\gamma_{w-w} - 6\gamma_{O-w} \quad \dots \quad (3)$$

Similarly, when a molecule of ethyl alcohol is introduced into water, we shall suppose that there are eight water molecules at the surface of the cavity, of which five are in contact with the ethyl group and three with the hydroxyl group, so that

$$\phi_{C_2H_5.OH} = 4\gamma_{w-w} - 5\gamma_{O-w} - 3\gamma_{OH-w} \quad \dots \quad (4)$$

Similarly the following expressions are obtained for *n*-butyl alcohol and the isomeric diethyl ether :

$$\phi_{C_4H_9.OH} = 6\gamma_{w-w} - 9\gamma_{O-w} - 3\gamma_{OH-w} \quad \dots \quad (5)$$

$$\phi_{(C_2H_5)_2O} = 6\gamma_{w-w} - 10\gamma_{O-w} - 2\gamma_{OH-w} \quad \dots \quad (6)$$

The various interaction constants could be derived from the differences between these expressions when γ_{w-w} is known. We shall use for this purpose the *total energy term* corresponding to γ_{w-w} , which can be estimated. This may be justified by the fact that there is usually a parallelism between the free energy and total energy changes of reactions of similar compounds. Moreover, according to Trouton's rule, which is widely valid among normal liquids, the entropy of vaporisation under certain conditions is a constant. Extending this rule to solutions, we may reasonably expect to find that the entropy of solution of not too dissimilar compounds in a given solvent will be constant, and therefore the total and free energies of solvation will differ by a constant amount.

According to Bernal and Fowler (*loc. cit.*), the energy of interaction of a pair of water molecules in the tetrahedral structure is about 6000 cal. We shall therefore take as our starting point $\gamma_{w-w} = 6000$. Now, when a hydrocarbon chain is increased by an additional carbon atom, the change of the free energy of hydration is about 200 cal. A tetrahedral arrangement being assumed, the number of water molecules at the surface of the cavity is thereby increased by two, so that the change of free energy may be expressed by $\phi_{\Delta O} = \gamma_{w-w} - 2\gamma_{O-w}$, from which it follows that $\gamma_{O-w} = 2900$ cal. The difference of ϕ between a hydrocarbon and the corresponding alcohol is 6000 cal., whence, using (3) and (4), we find that $\gamma_{OH-w} = 5000$ cal. Similarly from (5) and (6) we find that for the oxygen atom of an ether $\gamma_{O-w} = 4700$ cal. The other values given in the following table were similarly derived.

Interaction constants of various groups with water.

γ_{w-w}	6000 cal.	γ_{OH-w}	5000 cal.	γ_{O-w} (ether)	4700 cal.
γ_{C-w}	2900	γ_{NH_2-w}	4900	γ_{O-w} (ketone)	4500

The experimental value of the free energy of hydration contains terms which depend on the units of measurement of p/N , and therefore differs from the value of ϕ as calculated from these constants by a constant which has the average value of + 8600 cal. The equation $RT \cdot \log p/N = \phi + 8600$ reproduces the observed figures within about 200 cal.

The numerical values of the interaction constants depend on the initial value assumed for γ_{w-w} , but even if this value is incorrect, they should be in the correct relation to each other. It is significant that the constant of the interaction between the hydroxyl group and the water molecule approaches the value of that between two water molecules and the constants of etheric and ketonic oxygen are only slightly less.

On this formulation no large differences are to be expected between aliphatic isomerides having the same polar group, *e.g.*, a molecule of *n*-amyl alcohol makes the same number of contacts with water on these assumptions as *tert.*-amyl alcohol. The differences of the free energy of hydration of such isomerides have been found (Part I) to be within about 200 cal., and must be regarded as secondary effects due possibly to small variations of the individual interaction energies.

The free energy difference between an ester and an isomeric acid is approximately the same as that between an ether and an isomeric alcohol, *i.e.*, in both cases the esterification of the hydroxyl group gives rise to the same change of the hydration energy. But the interaction energy of the carboxyl group is not that obtained by summing the interaction terms for the hydroxyl and the ketonic group as given above. If the interaction of the hydroxyl group and the water is supposed to have the same value as in an alcohol, the total interaction between the ketonic oxygen and water is 10,600 cal. If the oxygen is supposed to be in contact with three water molecules, the value for each interaction is 3500 cal., which is considerably smaller than the value derived from a ketone. Thus, although the evidence adduced gives strong support for an approximately additive nature of the interactions between simple organic molecules and water, yet this view must not be taken to extremes, and it is not claimed that in no circumstances do the different groups of a molecule influence each other's behaviour. Some evidence on this point is also afforded by the values for glycol and glycerol. The difference between ethyl alcohol and glycol is 2600 cal. while that between propyl alcohol and glycerol is 3600 cal.; so that the effects of additional hydroxyl groups are not additive. On the same assumptions as above, the average value of each interaction between the hydroxyl groups of glycol and an adjacent molecule is 4400 cal., while for glycerol the value is about 4000 cal.

SUMMARY.

1. The free energy of hydration of some aliphatic amines, acids, nitriles, and esters has been determined, and it is shown that, in simple compounds, this quantity is an approximately additive function of the groups present.
2. The nature of the interaction between the solutes and water is discussed, and values are derived of the additive interaction constants of various groups with water.

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