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Thermodynamics of some nucleic acid bases and nucleosides in water, and their transfer to aqueous glucose and sucrose solutions at 298.15 K

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The partial molar heat capacities and volumes of some of the constituents of nucleic acids have been determined in water and 1 molal aqueous glucose and sucrose solutions in order to elucidate the nature of interactions occurring between various nucleic acid bases, nucleosides and the sugar (glucose and sucrose) molecules. The results have been explained in terms of the contributions from hydrophobic interactions, hydrophilic interactions and the hydrogen bonding between the solute and solvent molecules. The results have also been compared with those of amino acids and peptides in aqueous glucose and sucrose solutions.

1. Introduction

Nucleic acids are the fundamental molecules of life. Deoxyribonucleic acid (DNA) is primarily a storehouse of genetic information and this is expressed in living systems in the form of proteins which carry out the various functions of life. It is well known that hydrogen bonding and stacking interactions between the nucleic acid bases play important roles in stabilization of the nucleic acids. However, it is not yet clearly known whether the stacking interactions of nucleic acid bases and nucleosides are hydrophobic or electrostatic in nature or both. Calorimetric studies on DNA [1] and poly(rA-rU) [2,3] have yielded ΔH values of between 7 and 9 kcal/mol per base-pair. Hydrogen bonding between bases has been believed to contribute 3–4 kcal/mol per base-pair to the melting enthalpy of DNA. The remaining enthalpy of 5 kcal/mol per base-pair has been attributed to stacking interactions and other unidentified interactions [4]. The involvement of hydrophobic interactions in the structural stability of nucleic acids has been a matter of controversy. For instance, it has been indicated by some workers [5,6] that hydrophobic interactions of the free bases are of little importance in their solution behaviour, whereas others [7–9] have argued that hydrophobic interactions are of great importance in stabilizing the native structure of nucleic acids in aqueous solutions. The effect of solvents on the thermodynamic behaviour of the nucleic acids can provide useful information regarding the contribution of hydrophobic and electrostatic interactions to the conformational stability of nucleic acids. The introduction of polyhydric alcohols and sugars into the solvent medium has been found to stabilize biological macromolecules in solution [10–17]. It has been observed that these additives increase the denaturation temperature of macromolecules [18,19].

The object of this study is to clarify the nature of the interactions of various nucleic acid bases and nucleosides with water and aqueous glucose

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and sucrose solutions. We have measured the partial molar heat capacities and volumes of some nucleic acid bases and nucleosides in water, and in 1 molal aqueous glucose and sucrose solutions at 298.15 K.

2. Experimental

Adenine, cytosine, uracil and thymine were procured from Fluka and nucleosides were obtained from Sigma. Guanine and guanosine could not be investigated due to their extremely low solubility in water and aqueous solutions of glucose and sucrose. All the compounds studied were of the best available purity grade. After drying in a vacuum desiccator for nearly 72 h prior to use in measurements, these nucleic acid bases and nucleosides were used as such. No moisture content was detected using a Karl Fischer Aquatest-IV trace water analyser. Analytical reagent grade glucose and sucrose from Glaxo Laboratories and BDH, respectively, were used as supplied.

The specific heat capacities and densities were measured with a Picker flow microcalorimeter and an Anton Paar vibrating-tube digital densitometer, respectively. The precision of the microcalorimeter is 0.5% with a limit of detectability of 7×10^{-5} J K^{-1} g^{-1}. Current/voltage measurements and recordings were performed using a Systronics digital multimeter and a Bryans-28000 potentiometric strip chart recorder. Details of the experimental set-up of the microcalorimeter and the operational procedure have been described elsewhere [20]. The specific heat capacity and density for the reference 'water' were taken as 4.1796 J K^{-1} g^{-1} [20] and 0.997047 g cm^{-3} [21], respectively. The calorimeter was calibrated by measuring the heat capacities of the aqueous NaCl solutions at 298.15 K and a correction of 4% in the power output was applied after comparing our data with those of Picker et al. [20].

An Anton Paar DMA 60/602 vibrating-tube digital densitometer was employed to measure solution densities. Its experimental set-up and operational procedure have been described elsewhere [22]. A Tronac PTC-40 proportional temperature controller and an MK-70 ultracryostat were used to control the temperature of the thermostatic bath for the densitometer. Temperature-controlled water was then circulated through the jacket around the densitometer cell at a flow rate of 3 dm^3 min^{-1} and the stability of the temperature was $\pm 1 \times 10^{-3}$ K. The precision of the densitometer is $\pm 1.5 \times 10^{-6}$ g cm^{-3}. The densitometer was calibrated by measuring the densities of aqueous NaCl solutions at 298.15 K and the volumetric results were in excellent agreement with the literature [22]. The distilled water used for the heat capacity and density measurements was first deionized by passage through a Barnstead mixed-bed ion-exchange resin column, and then distilled over alkaline $KMnO_4$ to remove organic impurities, followed by degassing. All solutions were made by weight.

3. Results

The apparent molar heat capacity (ϕ_c) and apparent molar volume (ϕ_v) were calculated as follows:

$$\phi_c = MC_p - \frac{1000(C_p^0 - C_p)}{m}$$

$$\phi_v = M/d - \frac{1000(d - d_0)}{mdd_0}$$

where M is the molar mass of solute, C_p and C_p^0 the specific heat capacity of the solution and solvent, respectively, d and d_0 the density of the solution and solvent, respectively, and m the molality of the solution. For heat capacity measurements in water, C_p^0 and d_0 represent the heat capacity and density of water, respectively, and for measurements in 1 molal aqueous glucose and sucrose solutions, these refer to 1 molal aqueous glucose and sucrose solutions. C_p and d in the former case denote the heat capacity and density for the nucleic acid base or nucleoside in water, respectively, in the latter, corresponding to the water-sugar mixture. In most cases, a negligible concentration dependence was observed for ϕ_c and ϕ_v, hence ϕ_c^0 and ϕ_v^0 were evaluated by taking the average of all data points and standard deviations were evaluated from the mean. In some cases

Table 1

Apparent molar heat capacities (ϕ_c) and volumes (ϕ_v) of some nucleic acid bases and nucleosides in water at 298.15 K

m (mol kg^{-1})	d (g cm^{-3})	ϕ_c (J K^{-1} mol^{-1})	ϕ_v (cm^3 mol^{-1})	m (mol kg^{-1})	d (g cm^{-3})	ϕ_c (J K^{-1} mol^{-1})	ϕ_v (cm^3 mol^{-1})
Cytosine				Cytidine			
0.018578	0.997747	173	73.47	0.017424	0.998596	–	154.25
0.023744	0.997939	–	73.57	0.019063	0.998740	–	154.32
0.026351	0.998035	–	73.64	0.019697	0.998803	401	–
0.029420	0.998150	–	73.63	0.036383	1.000267	–	154.39
0.030861	0.998210	168	73.43	0.037334	1.000353	408	154.33
0.037309	0.998436	176	73.87	0.040344	1.000615	–	154.40
0.046979	0.998811	171	73.52	0.042455	1.000802	412	154.36
0.047875	0.998841	168	73.60	0.043955	1.000928	410	154.50
0.050231	0.998938	–	73.43	0.050190	1.001492	416	–
0.050742	0.998943	170	73.70	0.050674	1.001534	415	–
0.052217	0.998989	–	73.87	0.067226	1.002975	420	–
0.055268	0.999113	–	73.67	0.067342	1.002970	417	154.53
0.057072	0.999181	177	73.66	0.102593	1.006005	423	154.70
0.059354	0.999258	171	73.39				
0.059829	0.999292	–	73.52	Uridine			
0.075322	0.999860	172	73.65	0.025325	0.999355	400	–
0.078757	0.999994	–	73.57	0.031047	0.999887	394	152.47
				0.037012	1.000442	401	152.13
Uracil				0.041044	1.000801	392	152.34
0.007383	0.997343	–	72.08	0.055461	1.002110	402	152.32
0.012421	0.997541	150	72.39	0.073845	1.003767	401	152.35
0.012849	0.997557	154	72.47				
0.013823	0.997591	149	–	Thymidine			
0.016305	0.997697	–	72.28	0.025784	0.998966	468	167.72
0.016498	0.997707	–	72.14	0.026020	0.998973	463	168.13
0.014662	0.997633	152	72.18	0.030056	0.999270	468	168.14
0.018167	0.997773	152	72.39	0.031488	0.999380	–	167.99
0.018276	0.997781	–	71.98	0.035569	0.999678	–	168.07
0.019589	0.997826	158	72.57	0.037596	0.999828	466	168.04
0.020762	0.997881	–	71.96	0.053253	1.000964	469	168.27
0.021262	0.997896	–	72.41	0.060052	1.001478	470	167.94
0.024177	0.998004	149	72.54	0.070169	1.002214	468	167.97
0.026165	0.998087	152	73.37				
				Adenosine			
Thymine				0.012665	0.998260	–	171.47
0.011489	0.997478	239	88.72	0.017469	0.998716	509	171.59
0.018000	0.997783	243	88.71	0.019559	0.998921	–	171.29
0.019112	0.997761	242	88.85	0.020005	0.998963	–	171.32
0.019628	0.997783	238	88.71	0.020449	0.999004	504	171.39
0.020788	0.997829	–	88.58	0.020625	0.999015	506	171.66
0.021275	0.997843	244	88.78	0.021111	0.999059	509	171.77
0.021437	0.997847	247	88.88	0.023414	0.999290	–	171.24
0.022464	0.997891	241	88.63	0.024564	0.999398	504	171.31
0.024876	0.997979	237	88.72	0.026591	0.999592	–	171.28
0.025796	0.998009	–	88.89				

Table 2

Apparent molar heat capacities (ϕ_c) and volumes (ϕ_v) of some nucleic acid bases and nucleosides in 1 molal aqueous glucose solutions at 298.15 K

m (mol kg^{-1})	d (g cm^{-3})	ϕ_c (J K^{-1} mol^{-1})	ϕ_v (cm^3 mol^{-1})
Cytosine			
0.027750	1.058420	–	73.80
0.035260	1.058667	–	74.16
0.038378	1.056361	191	74.11
0.040305	1.056454	193	–
0.040658	1.058861	–	73.97
0.053931	1.056874	194	74.37
0.062433	1.059617	–	73.90
0.065217	1.057262	196	74.26
0.068757	1.059799	–	74.37
0.069528	1.057314	196	74.37
Uracil			
0.013597	1.069017	155	–
0.018807	1.069236	156	71.21
0.018981	1.069226	151	71.99
0.021347	1.069296	155	71.89
0.026596	1.069505	153	71.48
0.028508	1.069592	151	–
0.030478	1.069630	152	72.13
Thymine			
0.015567	1.057669	222	–
0.016846	1.057836	223	86.15
0.016931	1.057838	222	86.21
0.017979	1.057868	224	86.65
0.018472	1.057890	224	86.45
0.021935	1.057935	223	–
0.023470	1.058063	228	86.37
0.023650	1.057995	222	–
Adenine			
0.008378	1.057847	–	86.88
0.009923	1.058364	244	–
0.010203	1.057939	–	86.12
0.011039	1.058406	250	85.92
0.011843	1.058433	245	86.72
Cytidine			
0.025416	1.059440	–	155.40
0.026353	1.059524	–	155.19
0.035478	1.060299	443	–
0.037835	1.060463	442	155.45
0.040319	1.060673	438	155.33
0.042410	1.060837	446	155.50
0.049259	1.061402	447	155.45
0.055551	1.061928	440	155.29
Uridine			
0.029473	1.060187	422	153.36
0.036945	1.060182	415	–
0.039740	1.061068	423	153.34
0.049914	1.061620	414	–
0.052993	1.062187	–	153.57
0.061374	1.062231	424	153.23
0.088787	1.065225	417	153.45
Thymidine			
0.024034	1.058933	–	169.04
0.032746	1.059432	473	–
0.039213	1.059955	471	168.70
0.048429	1.060569	475	168.67
0.049428	1.060630	465	168.76
0.049502	1.060649	473	168.51
Adenosine			
0.016619	1.058994	512	170.94
0.018852	1.058973	512	–
0.019176	1.058995	516	–
0.019289	1.058953	514	–
0.020493	1.059079	–	171.32
0.020989	1.059393	–	170.82
0.023497	1.059318	513	–
0.025420	1.059528	512	171.15
0.028720	1.059826	–	171.17

(for nucleosides in water and few bases in aqueous sugar solutions) where an appreciable concentration dependence was observed, the ϕ_c^0 and ϕ_v^0 values were calculated by least-squares regression analysis of the following equations:

$$\phi_c = \phi_c^0 + S_c m$$

$$\phi_v = \phi_v^0 + S_v m$$

where S_c and S_v represent the respective slopes of the ϕ_c and ϕ_v vs. m plots Since at infinite dilution, the apparent molar terms ϕ_c^0 and ϕ_v^0 have the same meaning as the partial molar terms $\bar{C}_{p2}^0$ and $\bar{V}_2^0$, the latter terms will henceforth be used.

Tables 1–3 include the ϕ_c and ϕ_v data in water and in 1 molal aqueous glucose and sucrose solutions, respectively. $\bar{C}_{p2}^0$ and $\bar{V}_2^0$ data for all the nucleic acid bases and nucleosides have been listed in table 4 along with their standard deviations. The corresponding values for the partial molar heat capacity of transfer ($\bar{C}_{p2,tr}^0$) and partial molar

Table 3

Apparent molar heat capacities (ϕ_c) and volumes (ϕ_v) of some nucleic acid bases and nucleosides in 1 molal aqueous sucrose solutions at 298.15 K

m (mol kg^{-1})	d (g cm^{-3})	ϕ_c (J K^{-1} mol^{-1})	ϕ_v (cm^3 mol^{-1})
Cytosine			
0.020329	1.103300	–	72.19
0.023026	1.103365	185	–
0.023792	1.104375	–	72.01
0.024705	1.103499	184	72.27
0.040358	1.103959	190	72.87
0.044319	1.104083	–	73.05
0.045059	1.104108	–	73.04
0.046673	1.105144	196	72.46
0.058224	1.105446	196	–
0.058360	1.105543	194	72.74
0.070565	1.105944	191	72.86
Uracil			
0.015895	1.103843	158	71.33
0.019363	1.103960	155	71.77
0.020168	1.103922	153	–
0.022796	1.104085	153	71.75
0.024322	1.104148	–	71.49
0.024955	1.104104	157	–
Thymine			
0.008068	1.103110	–	87.01
0.013109	1.103612	240	–
0.013866	1.103641	239	87.19
0.014337	1.103556	242	–
0.018369	1.103738	240	86.99
0.018658	1.103727	–	87.11
Cytidine			
0.027953	1.105545	457	–
0.030625	1.105687	461	156.03
0.045796	1.106883	460	155.64
0.075225	1.109145	457	155.76
0.078480	1.109403	461	155.69
0.154327	1.115203	467	155.39
Uridine			
0.036298	1.106172	435	153.26
0.046474	1.106984	442	153.61
0.067142	1.108645	447	153.74
0.089106	1.110380	444	153.97
0.148331	1.115033	449	154.06
Thymidine			
0.034164	1.105634	492	168.89
0.037394	1.105519	–	169.51
0.038874	1.105913	493	169.40
0.045224	1.106004	–	169.23
0.045950	1.106292	498	169.19
0.072402	1.108003	498	–
0.092594	1.109107	494	168.91
Adenosine			
0.017429	1.104750	–	171.62
0.017457	1.109535	538	–
0.019064	1.109648	537	171.39
0.019612	1.109693	–	171.45
0.021439	1.109904	553	–
0.021921	1.105136	–	171.51
0.022165	1.110015	531	–
0.033445	1.111050	535	–

volume of transfer ($\overline{V}^0_{2,tr}$) from water to 1 molal aqueous glucose and sucrose solutions have also been listed in table 4. These parameters were evaluated as follows:

$$\overline{C}^0_{p2,tr} \text{ or } \overline{V}^0_{2,tr} \text{ (water} \rightarrow \text{1 molal glucose or sucrose)} = \overline{C}^0_{p2} \text{ or } \overline{V}^0_2 \text{ (in 1 molal aqueous glucose or sucrose)} - \overline{C}^0_{p2} \text{ or } \overline{V}^0_2 \text{ (in water)}$$

A comparison with the literature data is listed in table 5.

In general, the accord with the literature data is not very satisfactory. In many cases the agreement is fair within the combined uncertainty. However, in some cases the discrepancy is very large. We believe our results to be more accurate as the apparent molar heat capacities have been directly determined using the Picker flow microcalorimeter, whereas the values reported in the literature have been obtained from the temperature dependence of enthalpies of solution which have large uncertainties, in particular, due to low solubility and slow dissolution of the nucleic acid bases and of adenosine in water.

4. Discussion

4.1. Heat capacity and volume in water

The partial molar heat capacities ($\overline{C}^0_{p2}$) and volumes ($\overline{V}^0_2$) of the nucleic acid bases studied were in the following order: thymine ~ adenine > cytosine > uracil. The $\overline{C}^0_{p2}$ values of all four bases

Table 4

Infinite dilution partial molar heat capacities and volumes of some nucleic acid bases and nucleosides in water, aqueous glucose and sucrose solutions at 298.15 K [a]

Compound	$\bar{C}^0_{p2}$ ($J\,K^{-1}\,mol^{-1}$) (water)	$\bar{V}^0_2$ ($cm^3\,mol^{-1}$) (water)	$\bar{C}^0_{p2}$ ($J\,K^{-1}\,mol^{-1}$)		$\bar{V}^0_2$ ($cm^3\,mol^{-1}$)		$\bar{C}^0_{p2,tr}$ ($J\,K^{-1}\,mol^{-1}$)		$\bar{V}^0_{2,tr}$ ($cm^3\,mol^{-1}$)	
			1 molal glucose	1 molal sucrose	1 molal glucose	1 molal sucrose	water → 1 molal glucose	water → 1 molal sucrose	water → 1 molal glucose	water → 1 molal sucrose
Cytosine	172	73.60	187	181	74.14	72.61	15	9	0.54	−0.99
	(4)	(0.14)	(4)	(4)	(0.22)	(0.39)	(6)	(6)	(0.26)	(0.41)
Uracil	152	72.29	153	155	71.74	71.58	1	3	−0.55	−0.71
	(4)	(0.20)	(4)	(4)	(0.38)	(0.21)	(6)	(6)	(0.43)	(0.29)
Thymine	241	88.75	224	240	86.37	87.07	−17	1	−2.38	−1.68
	(4)	(0.10)	(4)	(4)	(0.20)	(0.09)	(6)	(6)	(0.22)	(0.13)
Adenine	242 [b]	90.39 [b]	246	–	86.41	–	4	–	−3.98	–
	(4)	(0.26)	(4)	–	(0.46)	–	(6)	–	(0.53)	–
Cytidine	399	154.19	443	460	155.37	155.70	44	61	1.18	1.51
	(4)	(0.04)	(4)	(4)	(0.11)	(0.23)	(6)	(6)	(0.12)	(0.23)
Uridine	398	152.32	419	436	153.39	153.25	21	38	1.07	0.93
	(4)	(0.12)	(4)	(4)	(0.13)	(0.18)	(6)	(6)	(0.18)	(0.22)
Thymidine	467	168.03	471	495	168.74	169.19	4	28	0.71	1.16
	(4)	(0.15)	(4)	(4)	(0.19)	(0.25)	(6)	(6)	(0.24)	(0.29)
Adenosine	506	171.43	513	535	171.08	171.49	7	29	−0.35	0.06
	(4)	(0.18)	(4)	(4)	(0.20)	(0.10)	(6)	(6)	(0.27)	(0.21)

[a] Entries in the parentheses are the standard deviations.
[b] From ref. 32.

studied in water were found to be considerably high (ranging from 152 to 242 $J\,K^{-1}\,mol^{-1}$) but less than that of the corresponding six-membered ring benzene ($\bar{C}^0_{p2} = 361–374\,J\,K^{-1}\,mol^{-1}$) [23,24]. These results show that the bases enhance the structure of the water surrounding them, however, their hydrophobic character is weakened due to the presence of various polar groups attached to them. Thymine and adenine exhibit maximum $\bar{C}^0_{p2}$ and $\bar{V}^0_2$ values because of the presence of an additional methyl group in thymine and the second fused ring in adenine. The difference in heat capacities of cytosine and uracil can be ascribed to the difference in polarity of the $\geqslant C–NH_2$ and $> C=O$ groups which shows that the replacement of a $> C=O$ by a $\geqslant C–NH_2$ group increases $\bar{C}^0_{p2}$ by about 20 $J\,K^{-1}\,mol^{-1}$ and $\bar{V}^0_2$ by 1.31 $cm^3\,mol^{-1}$. The difference in $\bar{C}^0_{p2}$ values of uracil and thymine gives the value of the contribution by the $–CH_2–$ group to $\bar{C}^0_{p2}$ as 89 $J\,K^{-1}\,mol^{-1}$. This figure is close to the values reported by various workers [25–30] for homologous series of compounds containing different functional groups. Similarly, we determined the contribution of the $–CH_2–$ group to $\bar{V}^0_2$ as 16.5 $cm^3\,mol^{-1}$ which is close to the value reported by Hepler and coworkers [26] of 16.8 $cm^3\,mol^{-1}$ on methyl-substituted pyridine, but a little higher than those of other compounds determined by DiPaola and Belleau [29] as 15.8 $cm^3\,mol^{-1}$ and by Mishra and Ahluwalia [31] as 15.9 $cm^3\,mol^{-1}$. It appears that the contribution of the $–CH_2–$ group to $\bar{V}^0_2$ in six-membered ring compounds differs from that in acyclic compounds.

In adenosine, cytidine and uridine, the respective bases adenine, cytosine and uracil, are attached to the ribose group whereas thymidine has thymine base attached to deoxyribose. The $\bar{C}^0_{p2}$ and $\bar{V}^0_2$ values of the nucleosides in water are greater than those of the corresponding nucleic acid bases, this being due to the additional ribose group which itself shows a high molar heat capacity and volume in water [32–35]. The order of $\bar{C}^0_{p2}$ and $\bar{V}^0_2$ for the nucleosides in water is: adenosine

Table 5

Comparison with the literature

Compound	$\bar{C}_{p2}^0$ (J K^{-1} mol^{-1}) (water)	$\bar{V}_2^0$ (cm^3 mol^{-1}) (water)
Cytosine	172 ± 4 [a]	73.60 [a]
	208 ± 21 [b]	73.59 [c]
	166 ± 3 [c]	
Uracil	152 ± 4 [a]	72.29 [a]
	233 [d]	72.21 [c]
	153 ± 6 [c]	
Thymine	241 ± 4 [a]	88.75 [a]
	256 ± 26 [e]	89.15 [c]
	320 [d]	
	339 [f]	
	248 ± 7 [c]	
Cytidine	399 ± 4 [a]	154.19 [a]
	389 [g]	153.30 [c]
	382 ± 3 [c]	153.50 [i]
Uridine	398 ± 4 [a]	152.32 [a]
	402 [g]	151.67 [c]
	375 ± 2 [c]	151.45 [i]
Adenosine	506 ± 4 [a]	171.43 [a]
	397 [h]	171.27 [c]
	515 ± 4 [c]	
Thymidine	467 ± 4 [a]	168.03 [a]
		167.55 [i]

[a] Present work, [b] ref. 47, [c] ref. 32, [d] ref. 27, [e] ref. 49, [f] ref. 6, [g] ref. 50, [h] ref. 51, [i] ref. 52.

> thymidine > cytidine > uridine. Since thymidine contains deoxyribose, the absence of one oxygen accounts for its lower $\bar{C}_{p2}^0$ and $\bar{V}_2^0$ values in water as compared to those of adenosine, the rest of the trend remaining the same as in the case of nucleic acid bases.

4.2. $\bar{C}_{p2,tr}^0$ and $\bar{V}_{2,tr}^0$ for transfer from water to 1 molal aqueous glucose and sucrose solutions

The $\bar{C}_{p2,tr}^0$ values for transfer of the nucleic acid bases from water to 1 molal aqueous glucose solutions are in the following order: cytosine > uracil > adenine > thymine. Only cytosine shows an appreciably positive $\bar{C}_{p2,tr}^0$ value whereas for uracil and adenine this change is not significant, and thymine displays a decrease. The different types of interactions which can occur between glucose molecules and the nucleic acid bases are as follows:

(i) Hydrophilic-hydrophilic group interactions between the –OH groups of glucose with the polar/hydrophilic parts of the base (e.g., $-NH_2$, > C=O, > NH, etc.);

(ii) Hydrophilic-hydrophobic group interactions between the –OH groups of glucose and the non-polar parts of the nucleic acid base.

The results have been explained by the cosphere overlap model, as developed by Gurney [36] and Frank and Evans [37]. The properties of water molecules in the hydration cosphere depend on the nature of the solute species [38]. For cytosine, which is the most hydrophilic base, the former interactions appear to play a dominant role. The –OH groups of the glucose molecules which can interact with hydrophilic groups of the base through hydrogen bonding would give a positive contribution to the heat capacity, since overlapping of the hydrophilic cospheres would lead to an increase in magnitude of the hydrogen-bonding interactions. The structure of water formed around the –OH groups of glucose and the hydrophobic groups of the nucleic acid base is reduced due to their overlap, resulting in a negative contribution to the $\bar{C}_{p2,tr}^0$ values. Our results show that more hydrogen bonds are formed between the cytosine and glucose than in the case of water and overall the interactions of hydrophilic-hydrophilic groups dominate over those of hydrophilic-hydrophobic groups.

A comparison of the results for transfer of thymine and uracil from water to 1 molal aqueous glucose solutions indicates that the values of $\bar{C}_{p2,tr}^0$ and $\bar{V}_{2,tr}^0$ for thymine are lower (by 18 J K^{-1} mol^{-1} and 1.83 cm^3 mol^{-1}, respectively) as compared to those of uracil. This difference can be attributed to the additional $-CH_2-$ group in thymine. On the basis of solubility studies, Spencer and Judge [39] have suggested that the difference in the thermodynamic state of uracil and thymine in water is due to hydrophobic hydration at the methyl group. The differences in enthalpies and heat capacities of transfer from water to dimethyl sulphoxide (DMSO) support the above hydrophobic effect [27]. The different behaviour of thymine and uracil has also been reported by

Tanford [40] who observed the free energy of transfer of one $-CH_2-$ group to be -2.93 kJ mol^{-1} for transfer from water to ethanol and attributed this to hydrophobic hydration. Our results further indicate that the hydrophobic hydration shell of the methyl group of thymine, which would interact with the hydrophilic hydration sphere of the –OH groups of glucose and has been found to make a negative contribution to the heat capacity of transfer, dominates over the effect of interaction of polar groups in thymine with the –OH groups of glucose. Lakshmi and Nandi [41] have also shown that the interaction between non-polar molecules or groups increases in sugar solutions. Ahluwalia et al. [42] have observed a smaller decrease in $\overline{C}^0_{p2,tr}$ (approx. 7 and 10 J K^{-1} mol^{-1}) and $\overline{V}^0_{2,tr}$ (approx. 0.23 and 0.21 cm^3 mol^{-1}) per $-CH_2-$ group of amino acids and peptides for transfer from water to glucose and sucrose solutions. This could arise from the differing environments of the $-CH_2-$ group in the nucleic acid base, amino acid and peptide.

The heat capacity values of thymine and adenine are about the same in water, but in sugar solutions, the decrease in heat capacity for thymine is large compared to that of adenine. Both the nucleic acid bases are more hydrophobic than the rest of the bases studied but adenine has a greater number of hydrogen-bonding sites [43]. It is the greater number of hydrogen bonds formed between adenine and –OH groups of glucose which accounts for the higher heat capacity of adenine as compared to thymine in 1 molal aqueous glucose solutions. The polar interactions may take place around the periphery of the molecule and the unfavourable hydrophobic interactions operate at the planar surface of the molecule [44]. The enthalpies of solution of purine and adenine [45] in water and DMSO show that the $-NH_2$ group of adenine interacts with DMSO through the formation of hydrogen bonds.

The $\overline{C}^0_{p2,tr}$ values for the nucleosides are in the following order: cytidine > uridine > adenosine > thymidine.

All the nucleosides studied show positive heat capacities of transfer but of lower magnitude for adenosine and thymidine. The possible interactions of the nucleic acid bases with glucose molecules have already been explained and the results for the nucleosides can be analysed on the basis that, on going from nucleic acid base to nucleoside, there is an addition of a sugar (ribose) moiety which is sufficiently hydrophilic due to –OH groups. The increase in hydrophilicity results in stronger hydrophilic-hydrophilic group interactions between nucleoside and glucose leading to the increase in $\overline{C}^0_{p2,tr}$ value. This argument is further supported by our experimental observation that the heat capacity of ribose increased on transfer from water to 1 molal aqueous glucose solutions.

The trend in $\overline{C}^0_{p2,tr}$ values for transfer from water to 1 molal aqueous sucrose solutions of nucleic acid bases is nearly the same as that observed in the case of 1 molal aqueous glucose solutions. However, the plot of ϕ_c in 1 molal aqueous glucose and sucrose solutions for cytosine as a function of the concentration of cytosine shows a clear concentration dependence, indicating that glucose and sucrose affect the interaction between the cytosine and solvent molecules to a greater extent. This may be attributed to cytosine being the most hydrophilic base. No clear concentration dependence in the plots of ϕ_c values as a function of the remaining bases was observed.

On comparing the relative effect of sucrose with glucose, we observed no significant difference in the values of $\overline{C}^0_{p2,tr}$ and $\overline{V}^0_{2,tr}$ for cytosine and uracil in glucose and sucrose solutions. However, the higher values of $\overline{C}^0_{p2,tr}$ and $\overline{V}^0_{2,tr}$ of thymine and nucleosides in 1 molal aqueous sucrose solution as compared to that in aqueous glucose solution may be attributable to the greater number of hydrophilic-hydrophilic group interactions, since sucrose has effectively twice as many –OH groups as glucose at the same concentration. On the basis of solubility studies, Lakshmi and Nandi [41] have observed the free energy of transfer for thymine in 1 molal glucose and sucrose solutions to be 30 and 0 cal mol^{-1}, respectively, which also shows more favourable interactions of thymine with sucrose than with glucose. We were unable to measure accurately the $\overline{C}^0_{p2,tr}$ value of adenine in 1 molal aqueous sucrose solution because in addition to its low solubility, the solution was too viscous. The behaviour of $\overline{C}^0_{p2,tr}$ values for the nucleosides re-

mains the same in 1 molal aqueous glucose and sucrose solutions, however the magnitude is larger in the latter. This is again due to more hydrophilic-hydrophilic group interactions, due to the higher number of hydroxyl groups of sucrose interacting with those of the ribose, than in the case of glucose.

More negative partial molar volumes of transfer of thymine and adenine from water to aqueous glucose and sucrose solutions can be attributed to their greater hydrophobic character in comparison to that of cytosine and uracil. The trend in partial molar volumes of transfer in the nucleic acid bases and nucleosides also follows nearly the same order as for the heat capacity of transfer. The results on $\overline{V}^0_{2,tr}$ support the conclusion drawn from those on $\overline{C}^0_{p2,tr}$.

5. Conclusions

The infinite dilution partial molar heat capacities and volumes of transfer from water to aqueous glucose and sucrose solutions for the nucleic acid bases and nucleosides (constituents of nucleic acids) are similar to those reported [42] for amino acids and peptides (constituents of proteins). We can conclude that the interactions of the aqueous sugar solutions with the amino acids, peptides, nucleic acid bases and nucleosides are similar in nature. Since sugars are known to stabilize proteins [46], it may be inferred that the sugar molecules would also stabilize the nucleic acid helix.

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