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Thermodynamics of complex formation in mixed solvents *K* and Δ*H* for the formation reaction of [Gly18C6] at 298.15 K

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Abstract The influence of H_2O–EtOH and H_2O–Acetone mixed solvents at various compositions on the thermodynamics of complex formation reaction between crown ether 18-crown-6 (18C6) and glycine (Gly) was studied. The standard thermodynamic parameters of the complex [Gly18C6] ($\log K^\circ$, $\Delta_r H^\circ$, $\Delta_r S^\circ$) were calculated from thermochemical data at 298.15 K obtained by titration calorimetry. The complex stability and its formation enthalpy increase with increasing the non aqueous component concentration in both mixed solvents. The thermodynamic data were discussed on the basis of the solvation thermodynamic approach and the solvation contributions of the reagents and of the complex to the complex stability were analyzed.

Keywords 18-crown-6 · Complex formation · Glycine · Mixed solvents · Thermodynamics · Titration calorimetry

Introduction

Solvation of reagents and products of a chemical reaction may heavily affect thermodynamics of reaction. The study and the knowledge of the influence of solvents on reactions may afford the possibility of taming yields and heat effects to needs [1]. Thus, the determination of thermodynamic reaction parameters and thermodynamic solvation parameters of reagents and products (ΔG°, ΔH°, $T\Delta S^\circ$), the setting up of the predictive models for complex formation, the estimation of the influence of mixed solvent composition on the reactions allow to use solvents to drive the processes of complex formation in solutions.

The rules that govern the influence of aqueous-organic solvents on the thermodynamic characteristics of complex formation reactions between transition metal ions and amine or carboxylate ligands were established previously [1, 2]. As a prosecution of the studies on solvation conducted in our institutions [3–5], here we report the thermodynamics of complex formation reaction between model biological compounds such as 18-crown-6 crown ether (18C6) and glycine (Gly) in wide ranges of H_2O–EtOH and H_2O–Acetone (Ac) mixed solvents.

It is well know that the selective complexation ability of crown ethers is one of their most attractive properties [6]. Crown ethers are of considerable interest in biologically modeling of ion transport processes, molecular recognition, enzyme catalysis and antibody–antigen associations. The results of previous investigations [2, 3, 7] allow to conclude that the complexing properties of crown-ligands could be more effective in mixed and non-aqueous solvents rather than in water.

Experimental

Calorimetry

The thermodynamic parameters (Log K°, $\Delta_r H^\circ$, $\Delta_r S^\circ$) of the complex formation reaction

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$$\text{Gly} + 18\text{C}6 = [\text{Gly}18\text{C}6] \quad (1)$$

were obtained from calorimetric measurements at 298.15 K in the range of mixed solvent composition from 0.0 to 0.91 mol fractions for H_2O + EtOH mixtures and in the range from 0.0 to 0.21 mol fractions for H_2O + Ac solvents. Titration of one reagent by the other and dilution of the reagents were carried out using the TAM calorimeter MOD 2277 by Thermometric. For each solvent composition, two or three series of titration experiments were carried out. The heat effect observed by mixing solutions of 18C6 and Gly was corrected by the heat effect measured in the dilution of the reagent solutions in the same mixed solvents. The experimental error on the measurements of heat of mixing the reagents was less than 0.5%, whereas uncertainty in the measured heats of dilution was as high as 5–10% for the smallest effects. However, due to the low concentration of reagents used, the correction for dilution was on average about 2% and always lower than 5%. The calorimetric data were treated using a least-square method to obtain K and ΔH. The stoichiometric model of 1:1 complex described satisfactorily the experimental data and in agreement with the literature data [8, 9].

The concentration of Gly and 18C6 in initial solutions was in the range 0.001–0.1 mol/L. The variations of the reagent concentrations did not influence the results of calculations and the obtained thermodynamic functions were assumed as standard. The range of used concentrations of reagents and the mixed solvent compositions were limited by a low solubility of glycine in mixed solvents with high concentration of EtOH [8] or Ac and by the high volatility of Ac.

Materials

The solvents, of the best quality available, were from Fluka and were used without further purification. Glycine was purchased from Fluka and crystallized from ethanol + water mixtures and dried under vacuum at 50 °C for 48 h before use. 18C6 was from Aldrich; it was purified by drying in a desiccator under P_2O_5. All solvent mixtures and solutions were prepared by weight using doubly distilled water. The concentration of each reagent in the initial and final mixtures and water content in the solvent was checked by densimetric method.

Results and discussion

An example of experimental calorimetric titration data at $x_{\text{EtOH}} = 0.12$ is presented in Table 1. The calculated thermodynamic parameter for the complex formation reaction (1) in mixed solvents and the available literature values are given in the Table 2.

A similar influence of H_2O–EtOH and of H_2O–Ac solvents on the thermodynamic parameters of the reaction is found. The complex stability and exothermicity of complex formation reaction increase with increasing the fraction of the non-aqueous components in both mixed solutions. In the water–ethanol mixtures this increase is more evident at $x_{\text{EtOH}} = 0.91$ and $x_{\text{EtOH}} = 1.0$.

The entropy values are negative in both mixed solvents and do not favor the stabilization of the complex in the whole range of solvent compositions. Therefore, it can be concluded that the complex stability in H_2O–EtOH and H_2O–Ac mixtures is determined by the enthalpy changes.

All data obtained have been treated on the basis of the solvation-thermodynamic approach [10]. It consists in the analysis of the influence of mixed solvent composition on the complex formation equilibrium through the thermodynamic transfer functions from water into mixed solvents for the complex formation reaction, for the solvation of reagents and complex. The thermodynamic parameters for the transfer of the complex formation reaction ($\Delta_{\text{tr}}Y^{\circ}{}_{\text{r}}$) were calculated as the difference between thermodynamic parameters in mixed solvent ($\Delta_{\text{r}}Y^{\circ}{}_{(\text{sol})}$) and those in water $\Delta_{\text{r}}Y^{\circ}{}_{(\text{H}_2\text{O})}$:

$$\Delta_{\text{tr}}Y^{\circ}{}_{\text{r}} = \Delta_{\text{r}}Y^{\circ}{}_{(\text{sol})} - \Delta_{\text{r}}Y^{\circ}{}_{(\text{H}_2\text{O})}, \quad (2)$$

where $\Delta_{\text{r}}Y^{\circ}$ are $\Delta_{\text{r}}G^{\circ}$, $\Delta_{\text{r}}H^{\circ}$, $T\Delta_{\text{r}}S^{\circ}$ obtained from the calorimetric measurements of this work.

The transfer thermodynamic function $\Delta_{\text{tr}}G^{\circ}{}_{\text{r}}$, $\Delta_{\text{tr}}H^{\circ}{}_{\text{r}}$ and $T\Delta_{\text{tr}}S^{\circ}{}_{\text{r}}$ are plotted against the concentration of non aqueous components in the mixed solvent in Fig. 1a, b. The figure shows that the Gibbs energy transfer of the complex formation reaction is determined by the enthalpytransfer contributions in the whole composition range of the solvents studied. A similar influence of H_2O–EtOH composition on thermodynamic parameters was observed previously for $[\text{Ag}18\text{C}6]^{+}$ complex formation [3].

It has been observed that the thermodynamic parameters of complex formation in solution are strongly connected with the solvation of participants of processes [10]. The solvation state of the glycine and 18C6 in H_2O–EtOH can be examined by calculating the solvation enthalpy transfer by using our previous results for $\Delta_{\text{s}}H^{\circ}(18\text{C}6)$ [3] and literature data for $\Delta_{\text{s}}H^{\circ}(\text{Gly})$ [11] as follows:

$$\Delta_{\text{tr}}H^{\circ}(18\text{C}6) = \Delta_{\text{s}}H^{\circ}(18\text{C}6)_{(\text{sol})} - \Delta_{\text{s}}H^{\circ}(18\text{C}6)_{(\text{H}_2\text{O})} \quad (3)$$

$$\Delta_{\text{tr}}H^{\circ}(\text{Gly}) = \Delta_{\text{s}}H^{\circ}(\text{Gly})_{(\text{sol})} - \Delta_{\text{s}}H^{\circ}(\text{Gly})_{(\text{H}_2\text{O})} \quad (4)$$

where $\Delta_{\text{s}}H^{\circ}$ denotes the enthalpy of solution of reagents (Gly, 18C6) in mixed solvent (sol) and in water (H_2O).

The solvation enthalpy transfer of complex [Gly18C6] was calculated from a thermodynamic cycle according to the following scheme:

$$\begin{tikzcd}
\mathrm{Gly}_{(\mathrm{H2O})} \arrow[d, "\Delta_{\mathrm{tr}}Y^{\circ}(\mathrm{Gly})"] & + & 18\mathrm{C6}_{(\mathrm{H2O})} \arrow[d, "\Delta_{\mathrm{tr}}Y^{\circ}(18\mathrm{C6})"] \arrow[rr, "\Delta_{\mathrm{r}}Y^{\circ}_{(\mathrm{H2O})}"] & {} \arrow[d, "\Delta_{\mathrm{tr}}Y^{\circ}_{\mathrm{r}}"] & {[\mathrm{Gly18C6}]_{(\mathrm{H2O})}} \arrow[d, "\Delta_{\mathrm{tr}}Y^{\circ}({[\mathrm{Gly18C6}]})"] \\
\mathrm{Gly}_{(\mathrm{sol})} & + & 18\mathrm{C6}_{(\mathrm{sol})} \arrow[rr, "\Delta_{\mathrm{r}}Y^{\circ}_{(\mathrm{sol})}"] & {} & {[\mathrm{Gly18C6}]_{(\mathrm{sol})}}
\end{tikzcd}$$

where $\Delta_{\mathrm{tr}}Y^{\circ}$ represents the functions ($Y^{\circ} = G^{\circ}, H^{\circ}, TS^{\circ}$) of transfer from H_2O to mixed solvents for solvation of reagents, complex and reaction ($\Delta_{\mathrm{tr}}Y^{\circ}_{\mathrm{r}}$).

As a consequence, the change of reaction enthalpy for the transfer of reaction from water to solvent can be written as:

$$\Delta_{\mathrm{tr}}H^{\circ}{}_{\mathrm{r}} = \Delta_{\mathrm{tr}}H^{\circ}([\mathrm{Gly18C6}]) - \Delta_{\mathrm{tr}}H^{\circ}(18\mathrm{C6}) - \Delta_{\mathrm{tr}}H^{\circ}(\mathrm{Gly}). \quad (5)$$

The transfer enthalpies of the reagents were calculated from Eqs. 3 and 4. The transfer enthalpies of reaction were calculated on the basis of the Eq. 2:

$$\Delta_{\mathrm{tr}}H^{\circ}{}_{\mathrm{r}} = \Delta_{\mathrm{r}}H^{\circ}{}_{(\mathrm{sol})} - \Delta_{\mathrm{r}}H^{\circ}{}_{(\mathrm{H_2O})}, \quad (6)$$

where $\Delta_{\mathrm{r}}H^{\circ}{}_{(\mathrm{sol})}$ and $\Delta_{\mathrm{r}}H^{\circ}{}_{(\mathrm{H_2O})}$ are the enthalpies of the reaction (1) in mixed solution and in water, respectively.

Consequently, from Eq. 5 it is possible to calculate $\Delta_{\mathrm{tr}}H^{\circ}([\mathrm{Gly18C6}])$ and estimate the role of solvation effects of each reagent into the transfer enthalpy of the investigated reaction.

The results of the present procedure can be compared with the analogous analysis previously carried out for the reaction enthalpy of the formation of the complexes $[\mathrm{Ag18C6}]^+$ in H_2O–EtOH [3] solutions, and $[\mathrm{Ag18C6}]^+$,

Table 1 Analytical concentrations c of reagents and heat effect of their mixing (Q_{mix}) for two series of calorimetric titration in $x_{\mathrm{EtOH}} = 0.12$ at 298.15 K

Gly is placed in the cell[a]				18C6 is placed in the cell[b]			
Injection N	c(18C6)/mol L^{-1}	c(Gly)/mol L^{-1}	Q_{mix}[c]/mJ	Injection N	c(18C6)/mol L^{-1}	c(Gly)/mol/L	Q_{mix}[c]/mJ
1	0.008162	0.089441	722.4	1	0.057036	0.006220	443.6
2	0.015330	0.083999	653.7	2	0.053553	0.011680	391.6
3	0.021677	0.079181	585.9	3	0.050471	0.016512	340.8
4	0.027334	0.074886	532.3	4	0.047724	0.020818	298.2
5	0.032410	0.071033	479.2	5	0.045261	0.024680	258.3
6	0.036989	0.067557	432.6	6	0.043040	0.028162	230.5
7	0.041140	0.064405	390.4	7	0.041026	0.031319	200.7
8	0.044922	0.061535	350.8	8	0.039193	0.034193	179.9
9	0.048381	0.058909	318.6	9	0.037516	0.036822	158.5
10	0.051556	0.056498	288.0	10	0.035977	0.039235	142.1
11	0.054482	0.054277	260.9	11	0.034559	0.041458	128.4
12	0.057187	0.052224	237.8	12	0.033249	0.043512	116.7
13	0.059695	0.050320	217.7	13	0.032034	0.045416	102.2
14	0.062026	0.048551	197.9	14	0.030905	0.047186	94.2
15	0.064198	0.046901	181.7	15	0.029853	0.048835	85.4
16	0.066228	0.045360	166.8	16	0.028870	0.050376	78.5
17	0.068129	0.043917	152.0	17	0.027950	0.051818	70.1
18	0.069913	0.042563	140.5	18	0.027087	0.053172	66.4
19	0.071590	0.041290	132.6	19	0.026275	0.054444	59.4
20	0.073169	0.040091	121.8	20	0.025511	0.055642	56.2

[a] The cell contained 7.694 cm^3 of Gly ($c = 0.095637$ mol/L, density = 0.960736 g/cm^3); titrant 18C6 ($c = 0.125981$ mol/L, density = 0.963989 g/cm^3) was added in aliquots of 0.533 cm^3

[b] The cell contained 7.662 cm^3 of 18C6 ($c = 0.0061003$ mol/L, density = 0.960960 g/cm^3); titrant Gly ($c = 0.095637$ mol/L, density = 0.960736 g/cm^3) was added in aliquots of 0.533 cm^3

[c] Q_{mix} is the heat measured (assumed positive for exothermic effects), containing dilution and reaction

Table 2 Stability constant (log K°), Gibbs energy (Δ_rG°), enthalpy (Δ_rH°), and temperature times entropy ($T\Delta_rS^\circ$) for the [Gly18C6] complex formation reaction in H_2O–EtOH and in H_2O–Ac mixed solvents at 298.15 K

x_2	Log K°	$-\Delta_rH^\circ$/kJ mol^{-1}	$-\Delta_rG^\circ$/kJ mol^{-1}	$-T\Delta_rS^\circ$/kJ mol^{-1}
$H_2O(1)$–EtOH(2)				
0.00	0.63 ± 0.02 [9]	10.83 ± 0.08 [9]	4.5	3.2
0.00	0.73 ± 0.03	7.3 ± 0.2	4.2	3.1
0.12	1.20 ± 0.05	19.7 ± 0.3	6.8	12.9
0.25	1.64 ± 0.05	21.5 ± 0.3	9.3	12.2
0.50	2.29 ± 0.07	25.1 ± 0.4	13.0	12.1
0.74	3.01 ± 0.08	29.1 ± 0.5	17.2	11.9
0.91	3.5 ± 0.1	41.0 ± 0.6	19.9	21.1
1.0	3.81 ± 0.12 [8]	64.95 ± 0.98 [8]	21.71	43.24
$H_2O(1)$–Ac(2)				
0.08	1.02 ± 0.05	16.0 ± 0.4	5.81	10.19
0.14	1.29 ± 0.05	21.0 ± 0.5	7.35	13.65
0.21	1.51 ± 0.05	23.5 ± 0.5	8.60	14.90

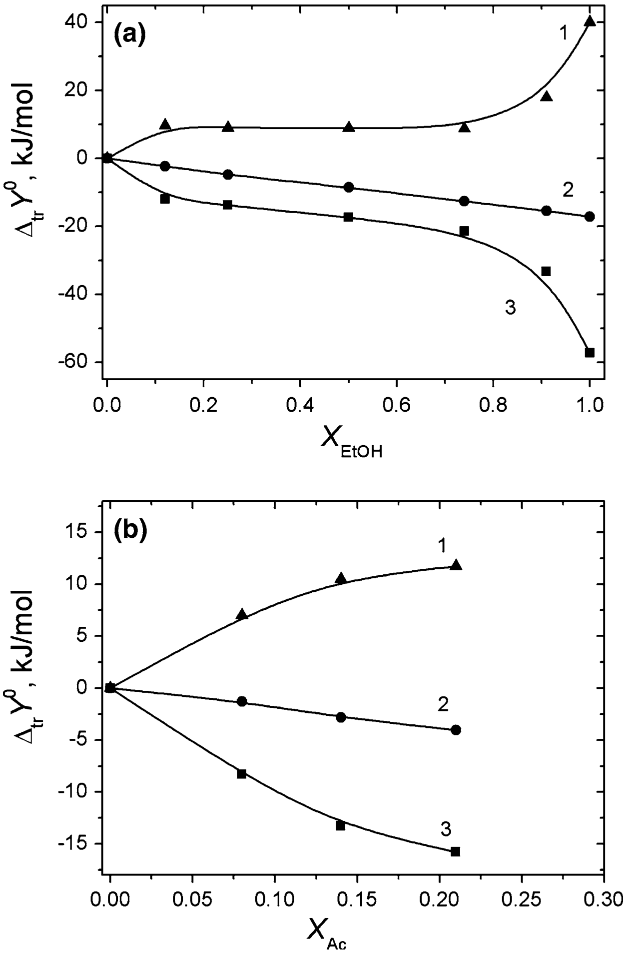

Fig. 1 The thermodynamic characteristics of complex formation reaction (1) in H_2O–EtOH (**a**) and in H_2O–Ac (**b**) mixtures at 295.15 K. $\Delta_{tr}Y^\circ = -T\Delta_{tr}S^\circ{}_r$ (1), $\Delta_{tr}G^\circ{}_r$ (2), $\Delta_{tr}H^\circ{}_r$ (3)

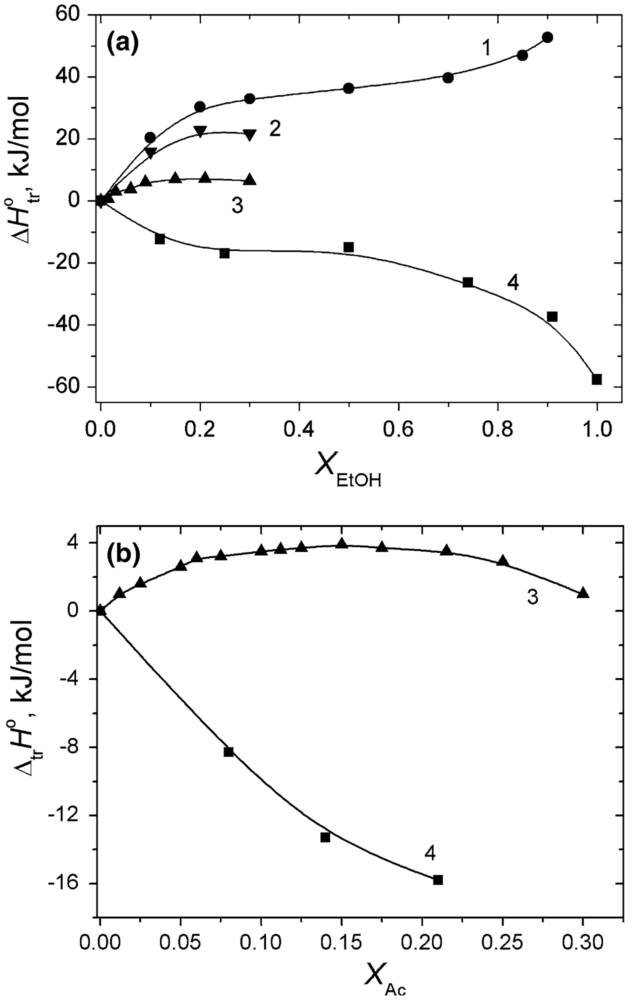

Fig. 2 The transfer enthalpy of: 18C6 (1), [Gly18C6] (2), Gly (3), and reaction of complex formation (4) from water to mixed solvents (**a**, EtOH; **b**, Ac)

$[Na18C6]^+$ and $[K18C6]^+$ in H_2O–MeOH [12–14]. Figure 3, where these comparisons have been illustrated, shows that the enthalpy transfer function of Gly in the reaction (1) behaves similarly in the available *x*-range with that of the cation. As a difference in behaviour between the reactions involving ionic complexes and that with glycine, it can be noted that for the former the transfer enthalpies of reaction, $\Delta_{tr}H°_r$, are close to those for the transfer of metal ions, whereas the transfer enthalpies of glycine are not close to those of reaction (Figs. 2a, 3a, b, c).

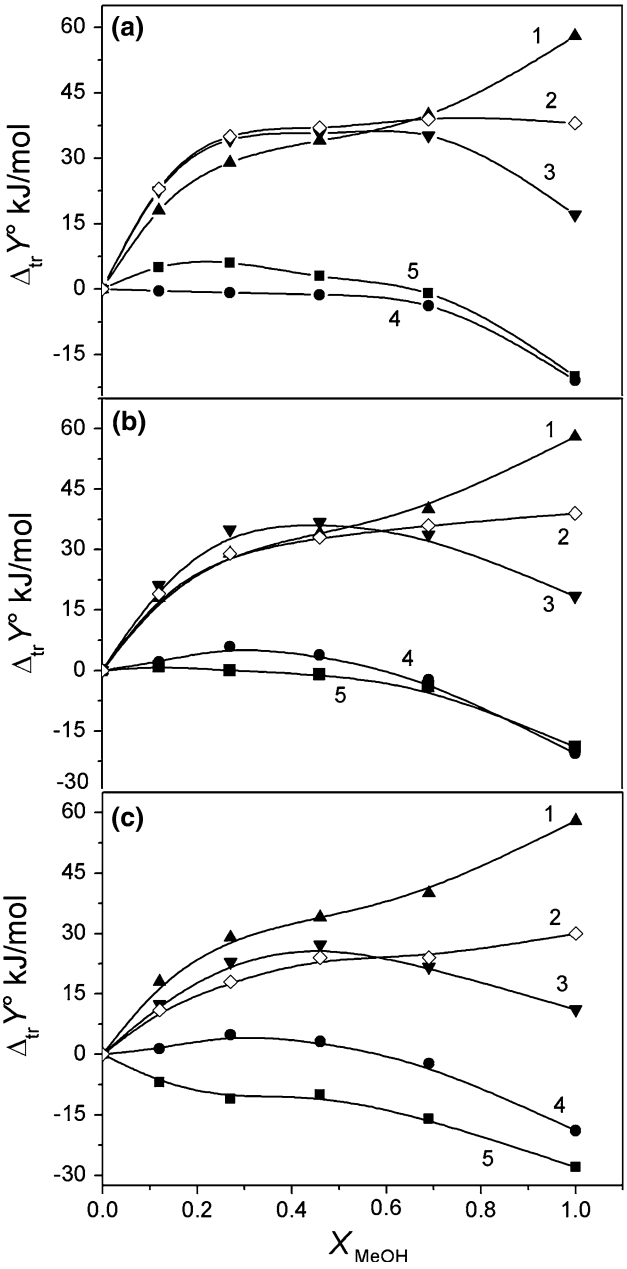

Fig. 3 The influence of H_2O–MeOH mixed solvent composition on the enthalpy characteristics for formation reaction of: $[Ag18C6]^+$ (**a**), $[Na18C6]^+$ (**b**), and $[K18C6]^+$ (**c**) [11–13]. $\Delta_{tr}Y° = \Delta_{tr}H°(18C6)$ (1), $(\Delta_{tr}H°([M18C6]^+) - \Delta_{tr}H°(M^+))$ (2), $\Delta_{tr}H°([M18C6]^+)$ (3), $\Delta_{tr}H°(M^+)$ (4), $\Delta_{tr}H°_r$ (5). $M^+ = Ag^+, Na^+, K^+$

In H_2O–Ac mixtures, the analysis of solvation contributions can be done only as to the enthalpy transfer for the reaction and for Gly [15] (Fig. 2b), the experimental values of enthalpy of solvation of 18C6 in these mixtures not being yet available.

However, analogies in the figures suggest that the increase of Ac concentration brings about an increase of the endothermicity of 18C6 solvation as in the cases of mixed solvents studied previously [3, 16], and that the enthalpy of solvation of 18C6 contributes favorably to the enthalpy of reaction and stability of [Gly18C6].

The influence of H_2O–EtOH and H_2O–Ac mixed solvents on the thermodynamics of the complex formation reaction between Gly and 18C6 is found generally similar to that for the complex formation reaction of *d*-metal ions with amines, carboxylated ligands and crown ethers [1–3]. The analysis of the mixed solvent influence has revealed that the difference between solvation change of the complex and the metal ion does not exceed the absolute values of solvation of a ligand, and this difference is proportional to the ligand solvation change [2]. This allows predicting the heat effect of the complex formation reaction on the basis of the knowledge of the ligand transfer enthalpy. A similar analysis for [Gly18C6] in H_2O–EtOH shows that $\Delta_{tr}H°([Gly18C6]) - \Delta_{tr}H°(Gly) \leq \Delta_{tr}H°(18C6)$, in agreement with the previous conclusions [2, 3]. On the contrary, the difference $\Delta_{tr}H°([M18C6]^+) - \Delta_{tr}H°(M^+)$ exceeds $\Delta_{tr}H°(18C6)$ values at $x_{MeOH} = 0$–0.6 (Fig. 3a, b) or is very close to it (Fig. 3c).

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References

1. Shormanov VA, Sharnin VA. Reagent solvation and its influence on complex formation equilibrium in aqueousorganic solvents. In: Kutepov AM, editor. Advances and problem of the theory of solvation: structural and thermodynamic aspects. Nauka, Moscow; 1998. p. 172–205 (in Russian).
2. Sharnin VA. Regularities in the influence of water-organic solvents on the thermodynamics of complex formation: II.1 Changes in enthalpy and entropy of formation of ammonia and carboxylate complexes. Russ J Gen Chem. 2001;71:1373–9.
3. Usacheva T, Ledenkov S, Sharnin VA. Complex formation of Ag^+ with polyether 18-crown-6: calorimetric and potentiometric methods. J Therm Anal Calorim. 2002;70:379–85.
4. Duce C, Tine' MR, Lepori L, Matteoli E. Thermodynamic study of (perfluoroalkane + alkane) mixtures: excess and solvation enthalpies. J Chem Thermodyn. 2007;39:1346–53.
5. Bernazzani L, Carosi MR, Ceccanti N, Conti G, Gianni P, Mollica V, et al. Thermodynamic study of organic compounds in di-

n-butyl ether. Enthalpy and Gibbs energy of solvation. PCCP. 2002;2:4829–36.

6. Lehn J-M. Supramolecular chemistry, concepts and perspectives. NY: VCH, Weinhcim; 1995.
7. Usacheva T, Ledenkov S, Sharnin VA. Studies of the complex formation of silver (I) ion with 18-crown-6 in H_2O-DMSO mixtures by calorimetric technique. J Therm Anal Calorim. 2002;70:209–16.
8. Danil de Namor AF, Ritt MC, Schwing-Weill MJ, Arnaud-Neu F, Lewis DFV. Solution thermodynamics of amino acid-18-crown-6 and amino acid-cryptand 222 complexes in methanol and ethanol. Linear enthalpy-entropy compensation effect. Chem Soc Faraday Trans. 1991;87:3231–9.
9. Kulikov OV, Lapchev PV, Terechova IV. Thermodynamic characteristics and mechanism of complexation of some macrocyclic ligands with amino acids in water. Russ J Phys Chem. 1998;72:725–9.
10. Krestov GA-M, editor. Complex formation in non-aqueous solution. Nauka, Moscow; 1989. 256 pp.
11. Smirnov VI, Badelin VG. Enthalpies of solution of glycine in the mixtures of n-propanol-water and iso-propanol-water at 298.15K. Russ J Phys Chem. 2003;77:803–6.
12. Pereselko VF, Lipovetskaia EE, Kabakova EN, Bondarev NV. Thermodynamics of Na^+ ion complexation with 18-crown-6 in methanol-water mixtures. Russ J Gen Chem. 1995;65:366–8.
13. Kabakova EN, Shevchenko IA, Jolnovach AM, Bondarev NV. Thermodynamics of complexation of metal ions with crown-esters. The system K^+-18-crown-6-H_2O-methanol. Russ J Gen Chem. 1996;66:208–11.
14. Eltsov SV, Larina OV, Petrunkina TA, Didi Y, Bondarev NV. Seventh international conference “the problems of solvation and complex formation in solutions”. Abstracts. Ivanovo, Russia; 1998. p. 364.
15. Smirnov VI, Badelin VG, Megevoi IN. Thermochemistry of dissolution of glycine in the mixtures of water-acetone and water-1,4dioxane at 298.15 K. VUZov Izv. Chim Chim Technol. 2003;46:90–3.
16. Jóźwiak M. The effect of properties of water-organic solvent mixtures on the solvation enthalpy of 12-crown-4, 15-crown-5, 18-crown-6 and benzo-15-crown-5 ethers at 298.15 K. Thermochim Acta. 2004;417:31–41.