Studies on the Enthalpic Interactions of Formamide and *N*,*N*-Dimethylformamide with *myo*-Inositol in Aqueous Sodium Chloride Solutions at 298.15 K

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The mixing enthalpies of formamide and *N*,*N*-dimethylformamide with *myo*-inositol and their respective enthalpies of dilution in aqueous sodium chloride solution have been determined by using flow-mix isothermal microcalorimetry at 298.15 K. These experimental results have been used to determine the heterotactic enthalpic interaction coefficients (h_{xy}, h_{xxy}, and h_{xyy}) according to the McMillan−Mayer theory. It has been found that the heterotactic enthalpic pairwise interaction coefficients (h_{xy}) between formamide and *myo*-inositol in aqueous sodium chloride solution are negative and become less negative with an increase in the concentration of sodium chloride. In contrast, the values of h_{xy} between *N*,*N*-dimethylformamide and *myo*-inositol are positive and become more positive with increasing concentration of sodium chloride solutions. The results are discussed in terms of solute−solute interaction and solute−solvent interaction.

Introduction

Proteins play a vital role in nearly all biological processes. However, it is quite difficult to study the interactions between proteins directly because the conformational and configurational factors that affect the structures of proteins in different solvents are very complicated. Therefore, one useful approach is to study their model compounds, such as amino acids, small peptides, and acylamide.[1−7] Formamide and *N*,*N*-dimethylformamide (DMF) are both typical acylamides. The former is the simplest possible molecule containing the CONH unit characteristic of the peptide bond, and the latter is formed if the two NH protons of the former are replaced by methyl groups.

In the biological environment, the majority of proteins exist in aqueous mixed solvents containing many organic and inorganic substances. Polyhydric alcohol and sugars can increase the thermal stability of globular proteins or reduce the extent of denaturation by other reagents.[8,9] Inositol is a water-soluble cyclic hexahydric alcohol, having high reactivity that controls many cellular processes in living organisms.[10] In the nine isomers of inositol, *myo*-inositol is the only optical one that displays biological activity. In addition, *myo*-inositol is a key factor maintaining normal brain function.[11] On the other hand, sodium chloride is a kind of electrolyte that bears an extraordinary important function in biological systems. Studies on the interactions of formamide and DMF with *myo*-inositol in aqueous sodium chloride solutions will be helpful to understand the stabilizing mechanism of proteins in the biological systems. However, to our knowledge, there are no reports where the interaction of acylamide with *myo*-inositol in aqueous sodium chloride solutions has been studied in detail.

Isothermal microcalorimetry has become a very effective technique that can measure weak interaction of biochemical species in solution.[12−14] Thus, the present work is aimed at measuring the mixing enthalpies of formamide and DMF with *myo*-inositol along with their respective dilution enthalpies in aqueous sodium chloride solutions. By analyzing the results, the heterotactic enthalpic interaction coefficients of formamide and DMF with *myo*-inositol in aqueous sodium chloride solutions with different concentrations are obtained.

Experimental Section

Materials. Both formamide and *myo*-inositol were purchased from Aldrich, and the purity is better than 99 %. They were dried under reduced pressure at 323 K before being used. Analytical reagent grade DMF (purity > 99 %, purchased from the Shanghai Chemical Co.) was used without further purification. Sodium chloride (analytical reagent, mass fraction > 99 %, from the Shanghai Chemical Co.) was recrystallized from distilled water and dried under reduced pressure at 393 K. All the reagents were stored over P_2O_5 in a vacuum desiccator for 72 h at room temperature prior to use.

Twice-distilled water was deionized by passing through a quartz sub-boiling purifier before use in the preparation of solutions. All the solutions were prepared by mass using a Mettler AG 135 balance with precision to ± 0.00001 g. The molality range of aqueous sodium chloride solutions was (0 to 0.60) mol·kg^{-1}. The molality ranges of aqueous formamide, DMF, and *myo*-inositol were all (0.10 to 0.40) mol·kg^{-1}. All the solutions were degassed with ultrasonic waves and used within 12 h of preparation.

Apparatus and Procedure. Enthalpies of dilution and mixing were determined with a 2277-204 measuring cylinder supported by a Thermometric 2277 thermal activity monitor (Thermometric, Sweden) at 298.15 K. Details of this apparatus, associated equipment, and the experimental procedure have been reported elsewhere.[15−18] The solutions were pumped through the mixing-flow vessel of the calorimeter using a VS2-10R MIDI dual-channel pumps. The variation of flow rates was less than 0.1 %. The flow rates were determined from the mass of the samples delivered in 6 min.

According to the McMillian−Mayer theory,[19−21] an excess thermodynamic property can be expressed as a virial expansion

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Table 1. Enthalpies of Mixing of Formamide and *myo*-Inositol along with Those of Their Dilution in Water and Aqueous Sodium Chloride Solutions at 298.15 K

$m_{x,\mathrm{i}}$ / mol·kg^{-1}	$m_{y,\mathrm{i}}$ / mol·kg^{-1}	m_x / mol·kg^{-1}	m_y / mol·kg^{-1}	$\Delta H_{\mathrm{dil}(x)}$ / J·kg^{-1}	$\Delta H_{\mathrm{dil}(y)}$ / J·kg^{-1}	ΔH_mix / J·kg^{-1}	ΔH^* / J·kg^{-1}	$m_{x,\mathrm{i}}$ / mol·kg^{-1}	$m_{y,\mathrm{i}}$ / mol·kg^{-1}	m_x / mol·kg^{-1}	m_y / mol·kg^{-1}	$\Delta H_{\mathrm{dil}(x)}$ / J·kg^{-1}	$\Delta H_{\mathrm{dil}(y)}$ / J·kg^{-1}	ΔH_mix / J·kg^{-1}	ΔH^* / J·kg^{-1}
m(NaCl) = 0.0000 mol·kg^{-1}															
0.1000	0.1000	0.0571	0.0501	3.81	1.87	6.64	0.96	0.2800	0.2800	0.1593	0.1391	6.05	13.32	17.27	−2.10
0.1500	0.1500	0.0859	0.0752	4.23	4.20	8.63	0.20	0.3000	0.3000	0.1722	0.1490	6.46	15.22	19.20	−2.48
0.1800	0.1800	0.1028	0.0902	4.56	5.90	10.18	−0.27	0.3200	0.3200	0.1827	0.1580	6.83	17.00	20.96	−2.87
0.2000	0.2000	0.1141	0.0999	4.80	7.13	11.34	−0.59	0.3500	0.3500	0.1976	0.1729	7.35	20.04	23.88	−3.50
0.2200	0.2200	0.1245	0.1099	5.07	8.51	12.60	−0.98	0.3800	0.3800	0.2161	0.1874	8.19	23.30	27.37	−4.12
0.2500	0.2500	0.1419	0.1237	5.52	10.76	14.74	−1.55	0.4000	0.4000	0.2270	0.1978	8.70	25.58	29.79	−4.48
m(NaCl) = 0.1000 mol·kg^{-1}															
0.1000	0.1000	0.0566	0.0499	3.83	3.44	7.19	−0.08	0.2800	0.2800	0.1580	0.1381	6.07	16.48	18.63	−3.92
0.1500	0.1500	0.0852	0.0744	4.25	6.03	9.51	−0.76	0.3000	0.3000	0.1709	0.1480	6.43	18.72	20.51	−4.64
0.1800	0.1800	0.1020	0.0890	4.57	7.88	11.11	−1.35	0.3200	0.3200	0.1811	0.1570	6.84	21.40	23.01	−5.23
0.2000	0.2000	0.1132	0.0990	4.82	9.52	12.56	−1.78	0.3500	0.3500	0.1959	0.1710	7.49	24.74	25.66	−6.57
0.2200	0.2200	0.1235	0.1087	5.13	11.43	14.26	−2.30	0.3800	0.3800	0.2142	0.1856	8.19	28.14	28.87	−7.46
0.2500	0.2500	0.1407	0.1235	5.56	13.76	16.29	−3.03	0.4000	0.4000	0.2252	0.1945	8.66	30.77	31.00	−8.42
m(NaCl) = 0.2000 mol·kg^{-1}															
0.1000	0.1000	0.0556	0.0498	3.85	1.63	7.50	2.03	0.2800	0.2800	0.1549	0.1377	5.97	11.51	16.05	−1.43
0.1500	0.1500	0.0833	0.0742	4.23	3.63	9.46	1.60	0.3000	0.3000	0.1665	0.1477	6.34	12.98	17.28	−2.03
0.1800	0.1800	0.0999	0.0888	4.54	5.15	10.63	0.94	0.3200	0.3200	0.1773	0.1567	6.70	14.63	18.71	−2.63
0.2000	0.2000	0.1110	0.0987	4.78	6.24	11.52	0.50	0.3500	0.3500	0.1939	0.1706	7.30	17.30	20.99	−3.61
0.2200	0.2200	0.1224	0.1085	5.04	7.38	12.59	0.17	0.3800	0.3800	0.2104	0.1851	7.97	20.21	23.44	−4.74
0.2500	0.2500	0.1390	0.1225	5.47	9.39	14.23	−0.63	0.4000	0.4000	0.2213	0.1940	8.43	22.02	25.01	−5.45
m(NaCl) = 0.3000 mol·kg^{-1}															
0.1000	0.1000	0.0540	0.0493	3.92	2.13	8.00	1.95	0.2800	0.2800	0.1483	0.1392	5.87	12.01	16.85	−1.03
0.1500	0.1500	0.0804	0.0741	4.28	3.79	9.38	1.32	0.3000	0.3000	0.1619	0.1474	6.22	14.23	18.88	−1.57
0.1800	0.1800	0.0961	0.0889	4.56	5.26	10.68	0.86	0.3200	0.3200	0.1716	0.1566	6.55	16.45	20.91	−2.08
0.2000	0.2000	0.1072	0.0981	4.77	6.62	11.96	0.56	0.3500	0.3500	0.1868	0.1707	7.09	19.19	23.45	−2.83
0.2200	0.2200	0.1175	0.1085	5.01	8.04	13.25	0.20	0.3800	0.3800	0.2043	0.1855	7.74	22.12	25.90	−3.96
0.2500	0.2500	0.1332	0.1224	5.40	10.09	15.10	−0.39	0.4000	0.4000	0.2124	0.1940	8.10	24.66	28.29	−4.47
m(NaCl) = 0.4000 mol·kg^{-1}															
0.1000	0.1000	0.0541	0.0521	4.15	2.37	8.64	2.12	0.2800	0.2800	0.1510	0.1443	7.80	11.65	19.07	−0.38
0.1500	0.1500	0.0814	0.0776	4.96	4.08	10.75	1.71	0.3000	0.3000	0.1634	0.1542	8.21	13.43	20.74	−0.90
0.1800	0.1800	0.0972	0.0929	5.58	5.43	12.32	1.30	0.3200	0.3200	0.1728	0.1647	8.84	15.15	22.65	−1.34
0.2000	0.2000	0.1079	0.1033	6.00	6.64	13.66	1.01	0.3500	0.3500	0.1858	0.1795	9.91	17.55	25.45	−2.01
0.2200	0.2200	0.1189	0.1134	6.39	7.99	15.08	0.70	0.3800	0.3800	0.2017	0.1947	10.88	19.93	28.05	−2.76
0.2500	0.2500	0.1350	0.1285	7.05	9.74	16.96	0.17	0.4000	0.4000	0.2152	0.2051	11.38	21.98	29.88	−3.47
m(NaCl) = 0.5000 mol·kg^{-1}															
0.1000	0.1000	0.0543	0.0517	4.10	1.63	9.28	3.56	0.2800	0.2800	0.1521	0.1427	6.35	10.07	18.27	1.85
0.1500	0.1500	0.0818	0.0773	4.55	3.46	11.25	3.24	0.3000	0.3000	0.1621	0.1530	6.78	11.27	19.65	1.60
0.1800	0.1800	0.0976	0.0917	4.92	4.76	12.63	2.95	0.3200	0.3200	0.1735	0.1634	7.10	12.59	20.95	1.25
0.2000	0.2000	0.1084	0.1025	5.20	5.63	13.64	2.81	0.3500	0.3500	0.1889	0.1781	7.75	14.70	23.22	0.77
0.2200	0.2200	0.1193	0.1121	5.46	6.58	14.64	2.60	0.3800	0.3800	0.2047	0.1924	8.40	16.86	25.52	0.26
0.2500	0.2500	0.1353	0.1277	5.85	8.27	16.37	2.24	0.4000	0.4000	0.2156	0.2029	8.79	18.31	26.96	−0.14
m(NaCl) = 0.6000 mol·kg^{-1}															
0.1000	0.1000	0.0559	0.0516	3.62	2.55	9.75	3.59	0.2800	0.2800	0.1553	0.1423	5.38	11.23	18.80	2.19
0.1500	0.1500	0.0833	0.0771	4.02	4.24	11.60	3.33	0.3000	0.3000	0.1664	0.1526	5.67	12.76	20.38	1.96
0.1800	0.1800	0.0999	0.0915	4.24	5.55	12.87	3.08	0.3200	0.3200	0.1772	0.1630	6.02	14.19	21.92	1.71
0.2000	0.2000	0.1114	0.1023	4.33	6.64	13.90	2.92	0.3500	0.3500	0.1937	0.1777	6.57	16.23	24.15	1.35
0.2200	0.2200	0.1222	0.1118	4.64	7.79	15.23	2.79	0.3800	0.3800	0.2108	0.1919	7.04	18.60	26.51	0.88
0.2500	0.2500	0.1391	0.1274	4.97	9.46	16.93	2.50	0.4000	0.4000	0.2211	0.2024	7.49	20.44	28.46	0.53

of pair and triplet interaction coefficients, which account for all variations of the solute−solute and solute−solvent interactions. The thermodynamic procedures used have been described previously,[22,23] and only a summary will be given here.

The excess enthalpy of a solution is defined as

$$H^\mathrm{E}(m_x,m_y)/w_1 = H(m_x,m_y)/w_1 - H^* - H^\infty_{x,m} - H^\infty_{y,m} = h_{xx}m_x^{\,2} + 2h_{xy}m_xm_y + h_{yy}m_y^{\,2} + h_{xxx}m_x^{\,3} + 3h_{xxy}m_x^{\,2}m_y + 3h_{xyy}m_xm_y^{\,2} + h_{yyy}m_y^{\,3} + \ldots \quad (1)$$

where $H^\mathrm{E}(m_x, m_y)/w_1$ and $H(m_x, m_y)/w_1$ represent the excess and the absolute enthalpy, respectively, of a solution containing 1 kg of solvent; m_x is mole of x; m_y is mole of y; H^* is the standard enthalpy of 1 kg of pure solvent; and $H^\infty_{x,m}$ and $H^\infty_{y,m}$ are the limiting partial molar enthalpies of species x and y, respectively. The h_{ij} and h_{ijk} terms are the enthalpic virial coefficients characterizing the pairwise and triplet interactions between the subscripted species. m_x and m_y are the molalities of the solutes x and y, respectively. In order to facilitate the calculation, an auxiliary function ΔH^* is introduced:

$$\Delta H^* = \Delta H_\mathrm{mix} - \Delta H_{\mathrm{dil}(x)} - \Delta H_{\mathrm{dil}(y)} = H^\mathrm{E}(m_x,m_y) - H^\mathrm{E}(m_x) - H^\mathrm{E}(m_y) \quad (2)$$

Thus, eq 1 can be rewritten as

$$\Delta H^*/w_1 = 2h_{xy}m_xm_y + 3h_{xxy}m_x^{\,2}m_y + 3h_{xyy}m_xm_y^{\,2} + \ldots \quad (3)$$

The dilution enthalpies ΔH_dil/J·kg^{-1} are determined by measuring the thermal power P/μW and the flow rates of the solution and the solvent (f_A and f_B/mg·s^{-1}):

$$\Delta H_\mathrm{dil} = P/(f_\mathrm{A} + f_\mathrm{B} - m_{x,\mathrm{i}}M_x f_\mathrm{A}) \quad (4)$$

Table 2. Enthalpies of Mixing of *N*,*N*-Dimethylformamide and *myo*-Inositol along with Those of Their Dilution in Water and Aqueous Sodium Chloride Solutions at 298.15 K

$m_{x,\mathrm{i}}$ / mol·kg^{-1}	$m_{y,\mathrm{i}}$ / mol·kg^{-1}	m_x / mol·kg^{-1}	m_y / mol·kg^{-1}	$\Delta H_{\mathrm{dil}(x)}$ / J·kg^{-1}	$\Delta H_{\mathrm{dil}(y)}$ / J·kg^{-1}	ΔH_{mix} / J·kg^{-1}	ΔH^* / J·kg^{-1}	$m_{x,\mathrm{i}}$ / mol·kg^{-1}	$m_{y,\mathrm{i}}$ / mol·kg^{-1}	m_x / mol·kg^{-1}	m_y / mol·kg^{-1}	$\Delta H_{\mathrm{dil}(x)}$ / J·kg^{-1}	$\Delta H_{\mathrm{dil}(y)}$ / J·kg^{-1}	ΔH_{mix} / J·kg^{-1}	ΔH^* / J·kg^{-1}
m(NaCl) = 0.0000 mol·kg^{-1}															
0.1000	0.1000	0.0502	0.0501	−1.52	1.87	9.95	9.60	0.2800	0.2800	0.1392	0.1391	−13.32	13.32	39.20	39.20
0.1500	0.1500	0.0756	0.0752	−3.60	4.20	15.46	14.85	0.3000	0.3000	0.1493	0.1490	−15.46	15.22	44.20	44.54
0.1800	0.1800	0.0893	0.0902	−5.42	5.90	19.58	19.11	0.3200	0.3200	0.1598	0.1580	−17.53	17.00	49.41	49.94
0.2000	0.2000	0.0994	0.0999	−6.79	7.13	22.82	22.49	0.3500	0.3500	0.1742	0.1729	−20.97	20.04	57.85	58.79
0.2200	0.2200	0.1098	0.1099	−8.18	8.51	26.53	26.20	0.3800	0.3800	0.1888	0.1874	−24.96	23.30	67.04	68.71
0.2500	0.2500	0.1247	0.1237	−10.54	10.76	32.37	32.15	0.4000	0.4000	0.1993	0.1978	−27.64	25.58	74.02	76.08
m(NaCl) = 0.1000 mol·kg^{-1}															
0.1000	0.1000	0.0494	0.0499	−1.92	3.44	10.02	8.50	0.2800	0.2800	0.1390	0.1381	−14.38	16.48	39.35	37.26
0.1500	0.1500	0.0748	0.0744	−4.14	6.03	15.82	13.93	0.3000	0.3000	0.1501	0.1480	−16.23	18.72	44.96	42.48
0.1800	0.1800	0.0895	0.0890	−5.93	7.88	19.94	17.99	0.3200	0.3200	0.1578	0.1570	−18.71	21.40	49.58	46.89
0.2000	0.2000	0.0996	0.0990	−7.42	9.52	23.42	21.32	0.3500	0.3500	0.1736	0.1710	−21.98	24.74	58.06	55.31
0.2200	0.2200	0.1085	0.1087	−9.08	11.43	27.10	24.75	0.3800	0.3800	0.1879	0.1856	−24.82	28.14	67.53	64.21
0.2500	0.2500	0.1219	0.1235	−11.55	13.76	32.55	30.34	0.4000	0.4000	0.1972	0.1945	−27.69	30.77	73.31	70.24
m(NaCl) = 0.2000 mol·kg^{-1}															
0.1000	0.1000	0.0498	0.0498	−1.33	1.63	7.74	7.45	0.2800	0.2800	0.1391	0.1377	−12.81	11.51	35.82	37.11
0.1500	0.1500	0.0744	0.0742	−3.35	3.63	13.16	12.88	0.3000	0.3000	0.1481	0.1477	−14.81	12.98	40.04	41.87
0.1800	0.1800	0.0894	0.0888	−4.99	5.15	17.74	17.58	0.3200	0.3200	0.1579	0.1567	−16.95	14.63	44.67	46.98
0.2000	0.2000	0.0999	0.0987	−6.26	6.24	20.61	20.63	0.3500	0.3500	0.1720	0.1706	−20.43	17.30	51.98	55.11
0.2200	0.2200	0.1096	0.1085	−7.68	7.38	23.92	24.22	0.3800	0.3800	0.1877	0.1851	−24.23	20.21	60.69	64.70
0.2500	0.2500	0.1242	0.1225	−10.08	9.39	29.44	30.14	0.4000	0.4000	0.1973	0.1940	−26.94	22.02	66.06	70.99
m(NaCl) = 0.3000 mol·kg^{-1}															
0.1000	0.1000	0.0497	0.0493	−1.45	2.13	7.28	6.60	0.2800	0.2800	0.1386	0.1392	−13.55	12.01	34.83	36.37
0.1500	0.1500	0.0745	0.0741	−3.72	3.79	12.52	12.45	0.3000	0.3000	0.1485	0.1474	−15.57	14.23	39.55	40.88
0.1800	0.1800	0.0892	0.0889	−5.28	5.26	16.56	16.58	0.3200	0.3200	0.1581	0.1566	−17.69	16.45	44.54	45.78
0.2000	0.2000	0.0990	0.0981	−6.72	6.62	19.67	19.76	0.3500	0.3500	0.1728	0.1707	−21.18	19.19	51.77	53.75
0.2200	0.2200	0.1089	0.1085	−8.35	8.04	23.16	23.46	0.3800	0.3800	0.1871	0.1855	−24.96	22.12	59.44	62.28
0.2500	0.2500	0.1237	0.1224	−10.71	10.09	28.69	29.30	0.4000	0.4000	0.1973	0.1940	−27.79	24.66	65.55	68.68
m(NaCl) = 0.4000 mol·kg^{-1}															
0.1000	0.1000	0.0495	0.0521	−1.66	2.37	8.64	5.18	0.2800	0.2800	0.1381	0.1443	−13.97	11.65	19.07	34.88
0.1500	0.1500	0.0742	0.0776	−3.79	4.08	10.75	11.42	0.3000	0.3000	0.1480	0.1542	−15.83	13.43	20.74	39.72
0.1800	0.1800	0.0889	0.0929	−5.47	5.43	12.32	15.99	0.3200	0.3200	0.1576	0.1647	−18.23	15.15	22.65	43.29
0.2000	0.2000	0.0986	0.1033	−6.94	6.64	13.66	19.02	0.3500	0.3500	0.1722	0.1795	−21.65	17.55	25.45	50.60
0.2200	0.2200	0.1085	0.1134	−8.55	7.99	15.08	23.01	0.3800	0.3800	0.1864	0.1947	−25.35	19.93	28.05	59.42
0.2500	0.2500	0.1232	0.1285	−10.87	9.74	16.96	28.52	0.4000	0.4000	0.1966	0.2051	−27.84	21.98	29.88	64.28
m(NaCl) = 0.5000 mol·kg^{-1}															
0.1000	0.1000	0.0501	0.0517	−1.56	1.63	4.74	4.68	0.2800	0.2800	0.1390	0.1427	−13.26	10.07	31.74	34.93
0.1500	0.1500	0.0745	0.0773	−3.49	3.46	9.56	9.59	0.3000	0.3000	0.1484	0.1530	−15.32	11.27	35.75	39.80
0.1800	0.1800	0.0896	0.0917	−5.24	4.76	14.10	14.58	0.3200	0.3200	0.1590	0.1634	−17.52	12.59	38.63	43.56
0.2000	0.2000	0.0993	0.1025	−6.59	5.63	18.02	18.99	0.3500	0.3500	0.1728	0.1781	−20.93	14.70	44.74	50.96
0.2200	0.2200	0.1092	0.1121	−8.08	6.58	20.72	22.22	0.3800	0.3800	0.1876	0.1924	−24.79	16.86	51.46	59.38
0.2500	0.2500	0.1242	0.1277	−10.53	8.27	25.84	28.10	0.4000	0.4000	0.1978	0.2029	−27.27	18.31	56.60	65.56
m(NaCl) = 0.6000 mol·kg^{-1}															
0.1000	0.1000	0.0496	0.0516	−1.49	2.55	4.86	3.80	0.2800	0.2800	0.1379	0.1423	−12.95	11.23	32.47	34.19
0.1500	0.1500	0.0736	0.0771	−3.18	4.24	11.04	9.98	0.3000	0.3000	0.1474	0.1526	−15.01	12.76	36.69	38.94
0.1800	0.1800	0.0886	0.0915	−4.93	5.55	15.05	14.43	0.3200	0.3200	0.1572	0.1630	−17.21	14.19	40.83	43.85
0.2000	0.2000	0.0987	0.1023	−6.28	6.64	18.46	18.10	0.3500	0.3500	0.1719	0.1777	−20.62	16.23	46.62	51.00
0.2200	0.2200	0.1084	0.1118	−7.77	7.79	21.64	21.62	0.3800	0.3800	0.1865	0.1919	−24.47	18.60	52.12	57.99
0.2500	0.2500	0.1235	0.1274	−10.22	9.46	27.03	27.79	0.4000	0.4000	0.1962	0.2024	−26.96	20.44	57.06	63.58

where $m_{x,\mathrm{i}}$ is the initial molality of the solution before dilution, and M_x is the molar mass of the solute. The final molality $m_{x,\mathrm{f}}$ may be calculated from the equation

$$m_{x,\mathrm{f}} = m_{x,\mathrm{i}}\, f_\mathrm{A}/[f_\mathrm{B}(m_{x,\mathrm{i}}M_x + 1) + f_\mathrm{A}] \qquad (5)$$

The mixing enthalpy of aqueous x solution and aqueous y solution is calculated from

$$\Delta H_\mathrm{mix} = P_\mathrm{mix}/(f_x + f_y - m_{x,\mathrm{i}}M_x f_x - m_{y,\mathrm{i}}M_y f_y) \qquad (6)$$

in which P_mix is the mixing thermal power; f_x and f_y are the flow rates of solutions x and y, respectively; and $m_{x,\mathrm{i}}$ and $m_{y,\mathrm{i}}$ are the initial molalities of solutions x and y before mixing.

Results and Discussion

The experimental values of ΔH_mix and ΔH_dil for formamide and DMF with *myo*-inositol in water and aqueous sodium chloride solutions are given in Tables 1 and 2, respectively, together with those of ΔH^*. The data were fitted by eq 3 using a least-squares procedure to obtain the heterotactic enthalpic interaction coefficients (Tables 3 and 4 for formamide−inositol and DMF−inositol systems, respectively).

The enthalpic pairwise interaction coefficients are regarded as a measure of the heat effects when two solute species approach each other. This process is accompanied by overlapping of the solvation cospheres of the solute molecules, resulting in a partial reorganization of the solvation cospheres and a change of the solute−solvent interactions. Therefore, the enthalpic pairwise interaction coefficients h_{xy} are the results of solvation effects and direct solute−solute interaction effects.[24]

Since it is difficult to interpret the higher order h coefficients, only the enthalpic pairwise coefficients h_{xy} are discussed here. Figures 1 and 2 show the h_{xy} of formamide and DMF with *myo*-

Table 3. Enthalpic Interaction Coefficients of Formamide with *myo*-Inositol in Water and Aqueous Sodium Chloride Solutions at 298.15 K[a]

m(NaCl) / mol·kg^{-1}	h_{xy} / J·kg·mol^{-2}	h_{xxy} / J·kg^2·mol^{-3}	h_{xyy} / J·kg^3·mol^{-4}	R^2	SD
0.0000	−117.38 (3.30)	406.66 (202.86)	−296.21 (322.55)	0.9996	0.0399
0.1000	−105.06 (7.28)	272.18 (591.47)	−301.91 (678.92)	0.9994	0.0825
0.2000	−93.50 (8.62)	300.03 (624.34)	−344.50 (732.36)	0.9995	0.0645
0.3000	−82.98 (6.75)	434.21 (265.51)	−187.87 (299.61)	0.9994	0.0699
0.4000	−66.69 (2.24)	−67.28 (75.83)	66.92 (78.30)	0.9998	0.0265
0.5000	−44.83 (1.72)	−197.00 (269.73)	208.97 (287.62)	0.9998	0.0282
0.6000	−35.79 (2.56)	−65.36 (192.12)	71.44 (212.76)	0.9994	0.0292

[a] The data in the parentheses are the estimated deviations, which are given by the computer during the multiple linear regression analysis. R^2 = correlation coefficients for eq 3. SD = standard derivation.

Table 4. Enthalpic Interaction Coefficients of *N*,*N*-Dimethylformamide with *myo*-Inositol in Water and Aqueous Sodium Chloride Solutions at 298.15 K

m(NaCl) / mol·kg^{-1}	h_{xy} / J·kg·mol^{-2}	h_{xxy} / J·kg^2·mol^{-3}	h_{xyy} / J·kg^3·mol^{-4}	R^2	SD
0.0000	826.38 (7.80)	−351.81 (899.71)	598.85 (914.93)	0.9999	0.0793
0.1000	859.57 (7.73)	−761.73 (489.28)	769.32 (508.80)	0.9999	0.0694
0.2000	898.43 (15.79)	826.94 (1076.46)	−881.20 (1123.55)	0.9998	0.1292
0.3000	954.31 (11.17)	1719.76 (638.00)	−2046.28 (666.85)	0.9999	0.0958
0.4000	1003.16 (43.88)	−4798.78 (8600.77)	3809.89 (9075.01)	0.9995	0.4781
0.5000	1074.65 (60.32)	4492.69 (8200.29)	−5207.65 (8069.93)	0.9994	0.5890
0.6000	1125.62 (15.24)	−6037.41 (829.97)	4847.54 (929.35)	0.9999	0.0838

inositol vs the molality of sodium chloride in aqueous solutions, respectively.

For the acylamide−inositol−sodium chloride−water system discussed here, there are three types of interactions:

(i) partial dehydration of the hydration shell of the acylamide molecule (an endothermic process leading to a positive contribution to h_{xy});

(iii) partial dehydration of the hydration shell of the *myo*-inositol molecule (an endothermic process also leading to a positive contribution to h_{xy}); and

(iii) direct interaction between the acylamide and *myo*-inositol molecules. Generally speaking, the types of interactions occurring between the acylamide and *myo*-inositol molecules can be classified as follows:

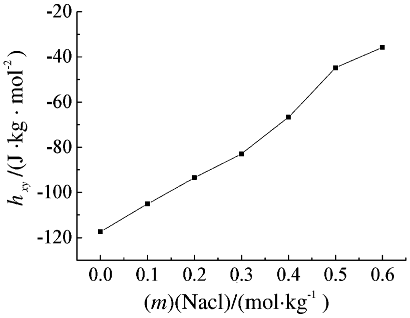

Figure 1. Enthalpic pair interaction coefficients (h_{xy}) of formamide with *myo*-inositol vs the molality of sodium chloride in aqueous solutions at 298.15 K.

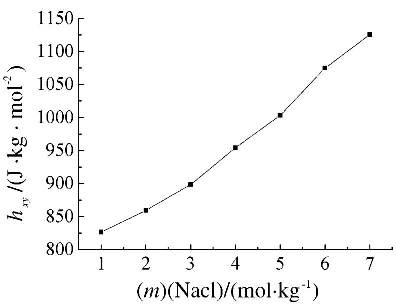

Figure 2. Enthalpic pair interaction coefficients (h_{xy}) of *N*,*N*-dimethylformamide with *myo*-inositol vs the molality of sodium chloride in aqueous solutions at 298.15 K.

(a) dipole−dipole interaction between the polar group of the acylamide and the hydroxyl group of the *myo*-inositol molecule (an exothermic process leading to a negative contribution to h_{xy}); and

(*b*) hydrophobic−hydrophilic interaction between the apolar group of acylamide and the hydroxyl group of the *myo*-inositol molecule (an endothermic process leading to a positive contribution to h_{xy}).

The resulting sign of h_{xy} is a consequence of the competitive equilibrium between the above effects. Among these effects, the direct interactions between acylamide and *myo*-inositol molecules are considered to be the most important interaction and play the dominant role during the overall interaction processes. The discrepancies of h_{xy} between the formamide−inositol system and the DMF−inositol system are mainly dependent on the differences in the structure of formamide and DMF.

Heterotactic Enthalpic Interactions of Formamide with Inositol in Water and Aqueous Sodium Chloride Solutions. From Figure 1, it can be seen that the h_{xy} values between formamide and *myo*-inositol are all negative over the whole concentration of the aqueous salt solutions investigated and become less negative with an increase of salt concentration or ionic strength.

The negative values of h_{xy} indicate that the mutual approach of a formamide molecule and *myo*-inositol molecule in water and aqueous sodium chloride solutions is an exoergic process. Formamide molecules have no alkyl groups, so interaction b cannot exist in the interactions between formamide and *myo*-inositol. The thermal effect is mainly caused by the interaction a. *myo*-Inositol is a cyclic hexahydric alcohol (all of the six hydroxyl groups have a chance to interact with the formamide molecules); therefore, the heat evolved in interaction a surpasses the heat caused by the partial dehydration of the hydration shell of the two molecules (formamide and *myo*-inositol). This conclusion is in accordance with the experimental results of Lu et al.[25] They studied the interactions of formamide with alkan-1-ol in water at 298.15 K and gave the corresponding enthalpic interaction coefficients h_{xy} (methanol 317.3 ± 3 J·kg·mol^{-2}; ethanol 517.6 ± 4 J·kg·mol^{-2}; propanol 670.8 ± 6 J·kg·mol^{-2}), which are all positive. This is because these alkanols have only one hydroxyl group, which can only lead to a relatively weak dipole−dipole interaction between the polar group of formamide and the hydroxyl group of alkanol molecules. Consequently, the partial dehydration of the hydration shells dominates in the solute−solute interaction process.

The enthalpic pairwise interaction coefficients h_{xy} of formamide with *myo*-inositol become less negative with increasing concentration of sodium chloride, which can be attributed to the influence of salt on the enthalpic pairwise interaction. In the acylamide−inositol−sodium chloride−water system, hydration sheaths with defined water molecules are formed around dissolved molecules or ions. Mutual interaction between the molecules or ions of the electrolyte may cause some water molecules to be squeezed out from the hydration sheaths into the typical bulk water.[26] So, the direct interaction between two solute molecules provokes partial dehydration of ions near them, which is an endothermic process. Therefore the partial dehydration of solutes gives a positive contribution to h_{xy}. The higher the concentration of sodium chloride is, the stronger is the associating force of an ion or solute molecule with the water molecules, the more difficult it is for water molecules to depart from the ion or solute molecule, and the more positive the contribution to the enthalpy will be. But the dominant thermal effect is still the dipole−dipole interaction. Consequently, the values of h_{xy} between formamide and *myo*-inositol are all negative over the whole concentration of the salt aqueous solutions investigated and become less negative with an increase of salt concentration.

Heterotactic Enthalpic Interactions of DMF with Inositol in Water and Aqueous Sodium Chloride Solutions. Figure 2 shows that the h_{xy} values for the interaction between DMF and *myo*-inositol are all positive over the whole concentration of the aqueous salt solutions investigated, which is contrary to the corresponding values for formamide. This indicates that the process of a DMF molecule approaching a *myo*-inositol molecule in aqueous sodium chloride solutions is endoergic. This experimental result can be interpreted as follows: The two NH protons of formamide are replaced by methyl groups in DMF. Therefore, in the enthalpic pairwise interaction between DMF and *myo*-inositol, interaction b (i.e., the hydrophobic−hydrophilic interaction between the methyl group of the DMF molecule and the hydroxyl group of the *myo*-inositol molecule) cannot be ignored. The positive value of h_{xy} implies that the cooperative effects of interaction b and that the partial dehydration of the two solutes can surpass the dipole−dipole interaction between the polar group of the DMF molecule and the hydroxyl group of the *myo*-inositol molecule.

The reason for the value of h_{xy} between DMF and *myo*-inositol increasing positively with an increased concentration of the sodium chloride solutions is similar to the influence of salt on the interaction of formamide and *myo*-inositol. The higher the concentration of sodium chloride is, the stronger is the associating force of ion or solute molecule with water molecules. Therefore, the values of h_{xy} between DMF and *myo*-inositol become more positive with an increase of salt concentration.

Conclusions

(1) The heterotactic enthalpic pairwise interaction coefficients h_{xy} between formamide and *myo*-inositol in water and aqueous sodium chloride solution of different concentration are all negative, which shows that the value of h_{xy} is mainly dependent on the dipole−dipole interaction between solute molecules.

(2) The h_{xy} values for the interaction between DMF and *myo*-inositol are all positive over the whole concentration of the salt aqueous solutions investigated. This indicates that the cooperative effects of the hydrophobic−hydrophilic interaction between the methyl groups of DMF molecule and the hydroxyl groups of the *myo*-inositol molecule as well as the partial dehydration of the two solutes can surpass the dipole−dipole interaction between the polar groups of DMF molecule and the hydroxyl groups of *myo*-inositol molecule.

(3) In aqueous sodium chloride solution of different concentration, the heterotactic enthalpic pairwise interaction coefficients (h_{xy}) between formamide and *myo*-inositol become less negative with an increase in the concentration of sodium chloride. In contrast, the values of h_{xy} between DMF and *myo*-inositol become more positive with increasing concentration of sodium chloride solutions. This mainly due to the increase of dehydration effects of solute molecules caused by the increase of the concentration of sodium chloride.

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