Electronic Supplementary Material (ESI) for Physical Chemistry Chemical Physics

Electronic Supplementary Information

Amide-induced phase separation of hexafluoroisopropanol–water mixtures depending on the hydrophobicity of amide

Toshiyuki Takamuku,[*,a] Hiroshi Wada,[a] Chiemi Kawatoko,[a] Takuya Shimomura,[a] Ryo Kanzaki[b] and Munetaka Takeuchi[c]

[a] *Department of Chemistry and Applied Chemistry, Graduate School of Science and Engineering, Saga University, Honjo-machi, Saga 840-8502, Japan; E-mail: takamut@cc.saga-u.ac.jp.*

[b] *Graduate School of Science and Engineering, Kagoshima University, Korimoto, Kagoshima 890-0065, Japan*

[c] *Fujitsu Limited, Nakase 1-chome, Mihama-ku, Chiba 269-8588, Japan*

Table S1 Compositions of amide–HFIP–D_2O mixtures for SANS measurements and their Ornstein–Zernike correlation lengths ξ determined by SANS measurements at 298 K.[a]

Sample	x_A	x_{HFIP}	x_{Water}	x^S_{HFIP}	$x_A/x^L_{A,298}$	$x_A/x^U_{A,298}$	ξ/Å
				NMF			
$F0_S$	0	0.147	0.853	0.147	0		4.8(1)
$F1_S$	0.00770	0.146	0.846	0.147	35		6.8(1)
$F2_S$	0.0132	0.145	0.842	0.147	60		9.4(1)
$F3_S$	0.0175	0.145	0.838	0.147	80		12.2(1)
$F4_S$	0.0198	0.144	0.836	0.147	90		15.1(1)
$F5_S$	0.199	0.118	0.683	0.147		103	29.2(1)
$F6_S$	0.204	0.117	0.679	0.147		106	22.7(1)
$F7_S$	0.212	0.116	0.672	0.147		110	17.3(1)
$F8_S$	0.222	0.115	0.663	0.147		115	14.1(1)
$F9_S$	0.232	0.113	0.655	0.147		120	11.8(1)
				NMA			
$A0_S$	0	0.147	0.853	0.147	0		4.8(1)
$A1_S$	0.00520	0.147	0.848	0.147	35		7.0(1)
$A2_S$	0.00900	0.146	0.845	0.147	60		9.8(1)
$A3_S$	0.0120	0.146	0.843	0.147	80		13.6(1)
$A4_S$	0.0135	0.145	0.841	0.147	90		16.8(1)
$A5_S$	0.248	0.111	0.641	0.147		103	29.8(1)
$A6_S$	0.256	0.110	0.635	0.147		107	21.3(1)
$A7_S$	0.265	0.108	0.627	0.147		110	17.1(1)
$A8_S$	0.277	0.107	0.617	0.147		115	13.4(1)
$A9_S$	0.289	0.105	0.606	0.147		120	
				NMP			
$P0_S$	0	0.147	0.853	0.147	0		4.8(1)
$P1_S$	0.00440	0.147	0.849	0.147	35		7.3(1)
$P2_S$	0.00750	0.146	0.846	0.147	60		10.1(1)
$P3_S$	0.0100	0.146	0.844	0.147	80		12.7(1)
$P4_S$	0.0113	0.146	0.843	0.147	90		18.2(1)
$P5_S$	0.294	0.104	0.602	0.147		103	19.1(1)
$P6_S$	0.303	0.103	0.594	0.147		106	13.3(1)
$P7_S$	0.315	0.101	0.584	0.147		110	12.2(1)
$P8_S$	0.328	0.0989	0.573	0.147		115	10.6(1)
$P9_S$	0.343	0.0967	0.560	0.147		120	

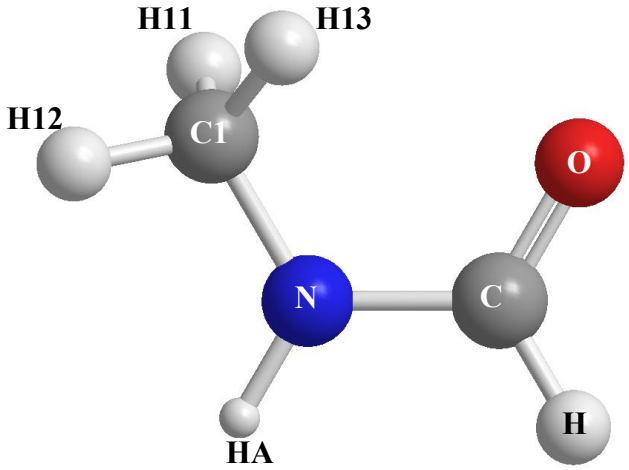
[a] x^S_{HFIP} gives the HFIP mole fractions of HFIP–water binary solvent. $x_A/x^L_{A,298}$ and $x_A/x^U_{A,298}$ represent the ratios of amide mole fraction to the lower and upper phase separation mole fractions, respectively, in percent figures. The phase separation mole fractions $x^L_{A,298}$ and $x^U_{A,298}$ are listed in Table 2. The values in the parentheses are standard deviations.

Table S2 Compositions of amide–HFIP–H_2O mixtures for NMR measurements.

Sample	x_A	x_{HFIP}	x_{Water}	x^S_{HFIP}	$x_A/x^L_{A,298}$	$x_A/x^U_{A,298}$
			NMF			
$F1_N$	0.00832	0.146	0.846	0.147	34	
$F2_N$	0.0139	0.145	0.841	0.147	57	
$F3_N$	0.0210	0.144	0.835	0.147	87	
$F4_N$	0.0235	0.144	0.833	0.147	97	
$F5_N$	0.195	0.118	0.687	0.147		103
$F6_N$	0.197	0.118	0.685	0.147		104
$F7_N$	0.207	0.117	0.676	0.147		110
$F8_N$	0.218	0.115	0.667	0.147		115
$F9_N$	0.237	0.112	0.651	0.147		125
			NMA			
$A1_N$	0.00550	0.146	0.848	0.147	34	
$A2_N$	0.00902	0.146	0.845	0.147	55	
$A3_N$	0.0136	0.145	0.841	0.147	83	
$A4_N$	0.0155	0.145	0.840	0.147	95	
$A5_N$	0.252	0.110	0.638	0.147		105
$A6_N$	0.257	0.109	0.634	0.147		107
$A7_N$	0.266	0.108	0.626	0.147		111
$A8_N$	0.278	0.106	0.616	0.147		116
$A9_N$	0.302	0.103	0.595	0.147		126
			NMP			
$P1_N$	0.00388	0.146	0.850	0.147	28	
$P2_N$	0.00657	0.146	0.847	0.147	54	
$P3_N$	0.00972	0.146	0.845	0.147	80	
$P4_N$	0.0111	0.145	0.844	0.147	91	
$P5_N$	0.298	0.103	0.599	0.147		105
$P6_N$	0.303	0.102	0.594	0.147		106
$P7_N$	0.309	0.102	0.590	0.147		108
$P8_N$	0.324	0.0993	0.576	0.147		114
$P9_N$	0.357	0.0946	0.549	0.147		125

Table S3 Intramolecular atom–atom bond lengths and notation of the atoms in NMF, NMA, and NMP and the potential parameters used for the MD simulations.

Intramolecular Atom–Atom Bond Lengths		
Molecule	Bond	r / Å
NMF	C1–H11	1.090
	C1–H12	1.090
	C1–H13	1.090
	C1–N	1.449
	HA–N	1.010
	C–N	1.335
	C–H	1.080
	C–O	1.229



Bond Angle Potentials			
Molecule	Angle	K_0 / kcal mol^{-1} rad^{-2}	θ_0 / deg
NMF	H11–C1–H12	35	109.5
	H11–C1–H13	35	109.5
	H12–C1–H13	35	109.5
	H11–C1–N	38	109.5
	H12–C1–N	38	109.5
	H13–C1–N	38	109.5
	C1–N–HA	38	118.4
	C1–N–C	50	121.9
	HA–N–C	35	119.8
	N–C–O	80	122.9
	N–C–H	35	119.1
	H–C–O	80	122.9

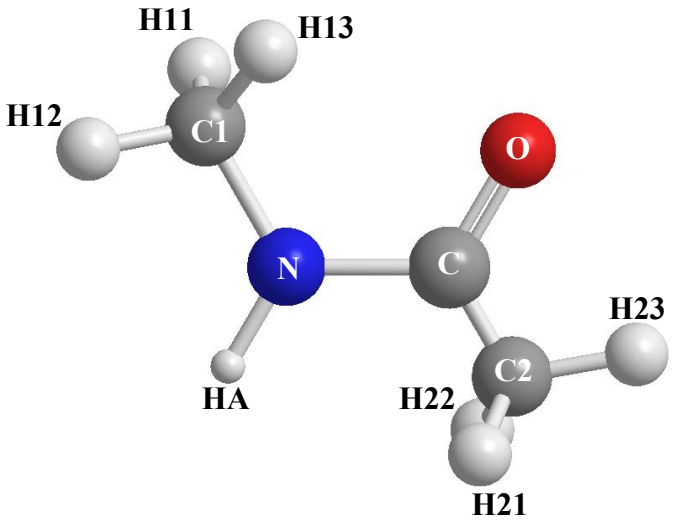
(Cont.)

Torsion Potentials				
Molecule	Torsion	$V_n/2$ / kcal mol^{-1}	n	ϕ_0 / deg
NMF	H11–C1–N–HA	0	3	0
	H12–C1–N–HA	0	3	0
	H13–C1–N–HA	0	3	0
	H11–C1–N–C	0	3	0
	H12–C1–N–C	0	3	0
	H13–C1–N–C	0	3	0
	C1–N–C–O	10	2	180
	HA–N–C–O	10	2	180
	C1–N–C–H	10	2	180
	HA–N–C–H	10	2	180

van der Waals Parameters and Point Charges				
Molecule	Atom	σ / Å	ε / kcal mol^{-1}	q / e
NMF	C1	3.500	0.066	0.020
	HA	0.000	0.000	0.300
	N	3.250	0.170	–0.500
	C	3.750	0.105	0.500
	O	2.960	0.210	–0.500
	H11	2.500	0.030	0.060
	H12	2.500	0.030	0.060
	H13	2.500	0.030	0.060
	H	2.420	0.015	0.000

(Cont.)

Intramolecular Atom–Atom Bond Lengths		
Molecule	Bond	r / Å
NMA	C1–H11	1.090
	C1–H12	1.090
	C1–H13	1.090
	C1–N	1.449
	HA–N	1.010
	C–N	1.335
	C–O	1.229
	C–C2	1.522
	C2–H21	1.090
	C2–H22	1.090
	C2–H23	1.090



Bond Angle Potentials			
Molecule	Angle	K_θ / kcal mol^{-1} rad^{-2}	θ_0 / deg
NMA	H11–C1–H12	35	109.5
	H11–C1–H13	35	109.5
	H12–C1–H13	35	109.5
	H11–C1–N	38	109.5
	H12–C1–N	38	109.5
	H13–C1–N	38	109.5
	C1–N–HA	38	118.4
	C1–N–C	50	121.9
	HA–N–C	35	119.8
	N–C–O	80	122.9
	N–C–C2	70	116.6

(Cont.)

	C–C2–H21	35	109.5
	C–C2–H22	35	109.5
	C–C2–H23	35	109.5
	H21–C2–H22	35	109.5
	H21–C2–H23	35	109.5
	H22–C2–H23	35	109.5
	C2–C–O	87	120.4

Torsion Potentials

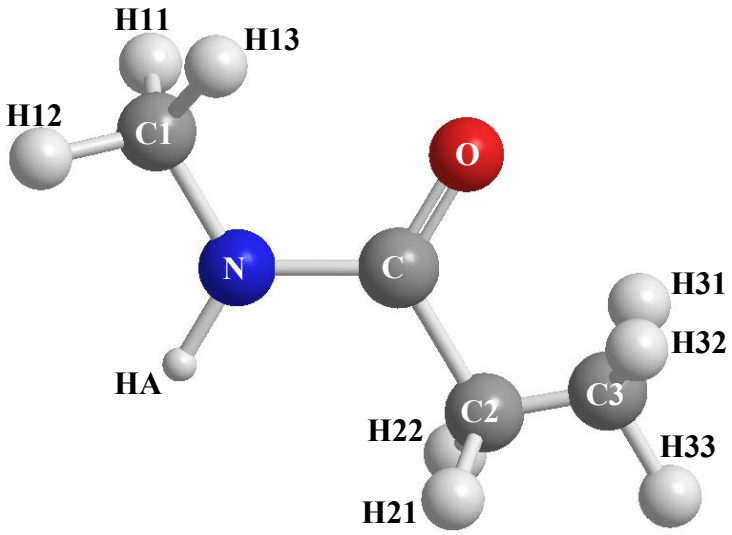
Molecule	Torsion	$V_n/2$ / kcal mol^{-1}	n	ϕ_0 / deg
NMA	H11–C1–N–HA	0	3	0
	H12–C1–N–HA	0	3	0
	H13–C1–N–HA	0	3	0
	H11–C1–N–C	0	3	0
	H12–C1–N–C	0	3	0
	H13–C1–N–C	0	3	0
	C1–N–C–O	10	2	180
	HA–N–C–O	10	2	180
	C1–N–C–C2	10	2	180
	HA–N–C–C2	10	2	180
	N–C–C2–H21	0	2	0
	N–C–C2–H22	0	2	0
	N–C–C2–H23	0	2	0
	O–C–C2–H21	0	2	0
	O–C–C2–H22	0	2	0
	O–C–C2–H23	0	2	0

(Cont.)

van der Waals Parameters and Point Charges				
Molecule	Atom	σ / Å	ε / kcal mol^{-1}	q / e
NMA	C1	3.500	0.066	0.020
	C2	3.500	0.066	–0.180
	HA	0.000	0.000	0.300
	N	3.250	0.170	–0.500
	C	3.750	0.105	0.500
	O	2.960	0.210	–0.500
	H11	2.500	0.030	0.060
	H12	2.500	0.030	0.060
	H13	2.500	0.030	0.060
	H21	2.500	0.030	0.060
	H22	2.500	0.030	0.060
	H23	2.500	0.030	0.060

(Cont.)

Intramolecular Atom–Atom Bond Lengths		
Molecule	Bond	r / Å
NMP	C1–H11	1.090
	C1–H12	1.090
	C1–H13	1.090
	C1–N	1.449
	HA–N	1.010
	C–N	1.335
	C–O	1.229
	C–C2	1.522
	C2–C3	1.526
	C2–H21	1.090
	C2–H22	1.090
	C3–H31	1.090
	C3–H32	1.090
	C3–H33	1.090



Bond Angle Potentials			
Molecule	Angle	K_θ / kcal mol^{-1} rad^{-2}	θ_0 / deg
NMP	H11–C1–H12	35	109.5
	H11–C1–H13	35	109.5
	H12–C1–H13	35	109.5
	H11–C1–N	38	109.5
	H12–C1–N	38	109.5
	H13–C1–N	38	109.5
	C1–N–HA	38	118.4
	C1–N–C	50	121.9
	HA–N–C	35	119.8

(Cont.)

	N–C–O	80	122.9
	N–C–C2	70	116.6
	C–C2–H21	35	109.5
	C–C2–H22	35	109.5
	C–C2–C3	63	111.1
	H21–C2–C3	35	109.5
	H22–C2–C3	35	109.5
	H21–C2–H22	35	109.5
	C2–C3–H31	35	109.5
	C2–C3–H32	35	109.5
	C2–C3–H33	35	109.5
	H31–C3–H32	35	109.5
	H31–C3–H33	35	109.5
	H32–C3–H33	35	109.5
	C2–C–O	87	120.4

Torsion Potentials

Molecule	Torsion	$V_n/2$ / kcal mol^{-1}	n	ϕ_0 / deg
NMP	H11–C1–N–HA	0	3	0
	H12–C1–N–HA	0	3	0
	H13–C1–N–HA	0	3	0
	H11–C1–N–C	0	3	0
	H12–C1–N–C	0	3	0
	H13–C1–N–C	0	3	0
	C1–N–C–O	10	2	180
	HA–N–C–O	10	2	180
	C1–N–C–C2	10	2	180
	HA–N–C–C2	10	2	180

(Cont.)

N–C–C2–C3	0	2	0
N–C–C2–H21	0	2	0
N–C–C2–H22	0	2	0
O–C–C2–H21	0	2	0
O–C–C2–H22	0	2	0
O–C–C2–C3	0	2	0
H21–C2–C3–H31	1.3	3	0
H21–C2–C3–H32	1.3	3	0
H21–C2–C3–H33	1.3	3	0
H22–C2–C3–H31	1.3	3	0
H22–C2–C3–H32	1.3	3	0
H22–C2–C3–H33	1.3	3	0
C–C2–C3–H31	1.3	3	0
C–C2–C3–H32	1.3	3	0
C–C2–C3–H33	1.3	3	0

van der Waals Parameters and Point Charges

Molecule	Atom	σ / Å	ε / kcal mol^{-1}	q / e
NMP	C1	3.500	0.066	0.020
	C2	3.500	0.066	–0.120
	C3	3.500	0.066	–0.180
	HA	0.000	0.000	0.300
	N	3.250	0.170	–0.500
	C	3.750	0.105	0.500
	O	2.960	0.210	–0.500
	H11	2.500	0.030	0.060
	H12	2.500	0.030	0.060
	H13	2.500	0.030	0.060

(Cont.)

H21	2.500	0.030	0.060
H22	2.500	0.030	0.060
H31	2.500	0.030	0.060
H32	2.500	0.030	0.060
H33	2.500	0.030	0.060

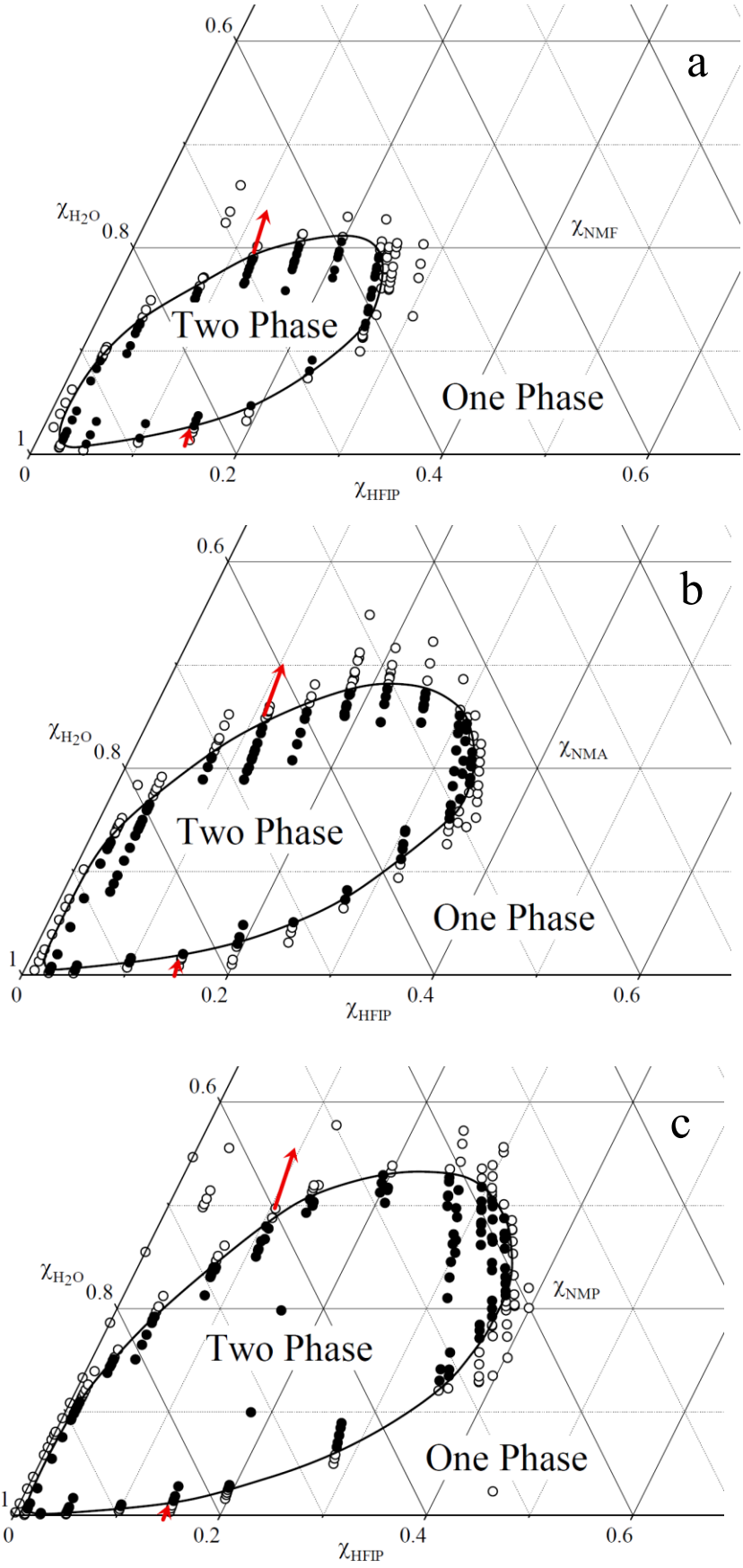


Fig. S2 Phase diagrams of amide–HFIP–water ternary systems at 298.2 ± 0.3 K as a function of mole fractions of amide, x_A, HFIP, x_{HFIP}, and water, x_{H2O}: (a) NMF, (b) NMA, and (c) NMP systems. Compositions of the systems examined are indicated by opened circles (miscible) and filled ones (immiscible). The solid line gives the border between one-phase and two-phase states. The red arrows indicate the variation in the compositions of sample solutions examined by SANS, NMR, and MD.

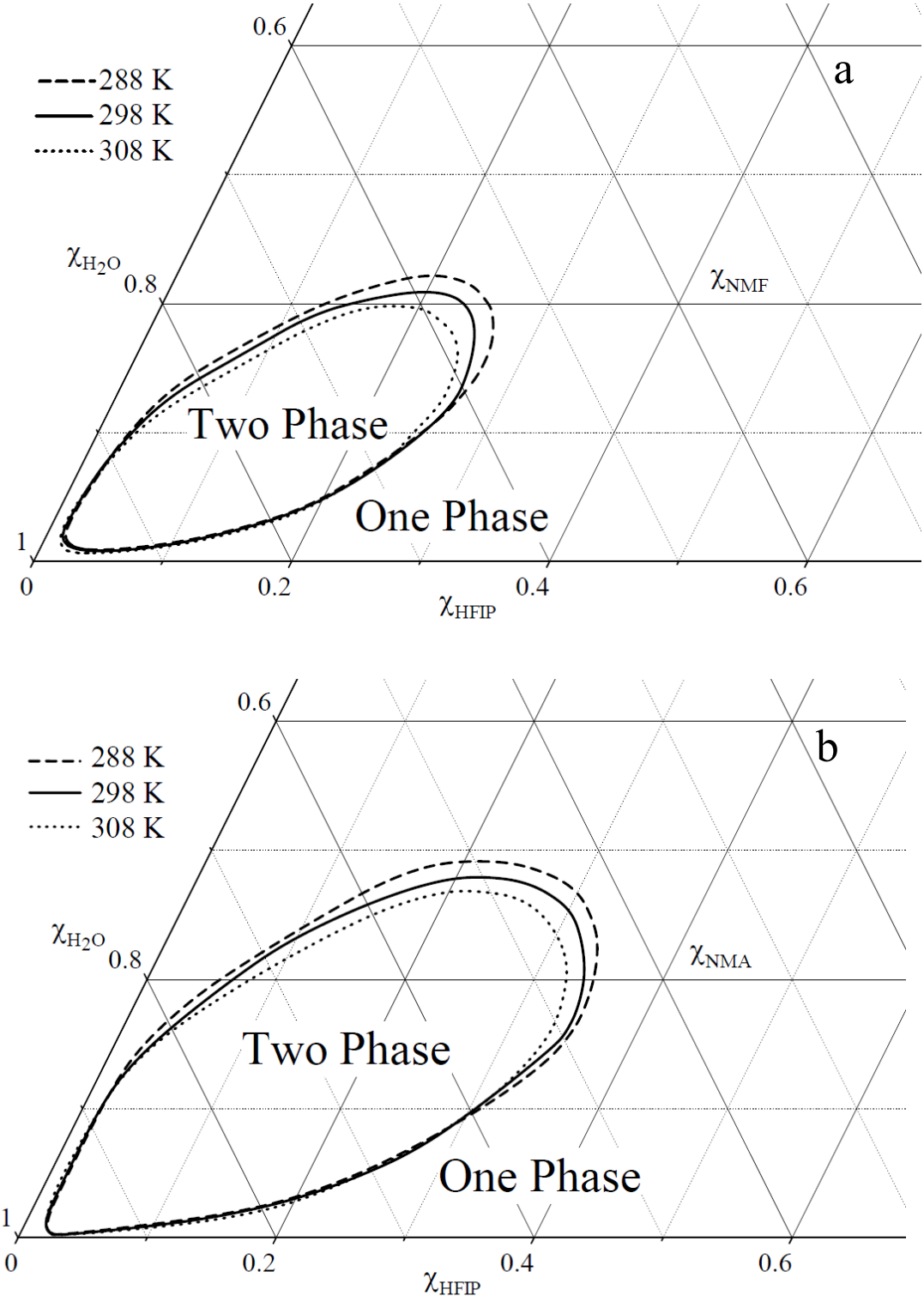


Fig. S3 Temperature dependence of phase diagrams of (a) NMF–HFIP–H_2O and (b) NMA–HFIP–H_2O systems.

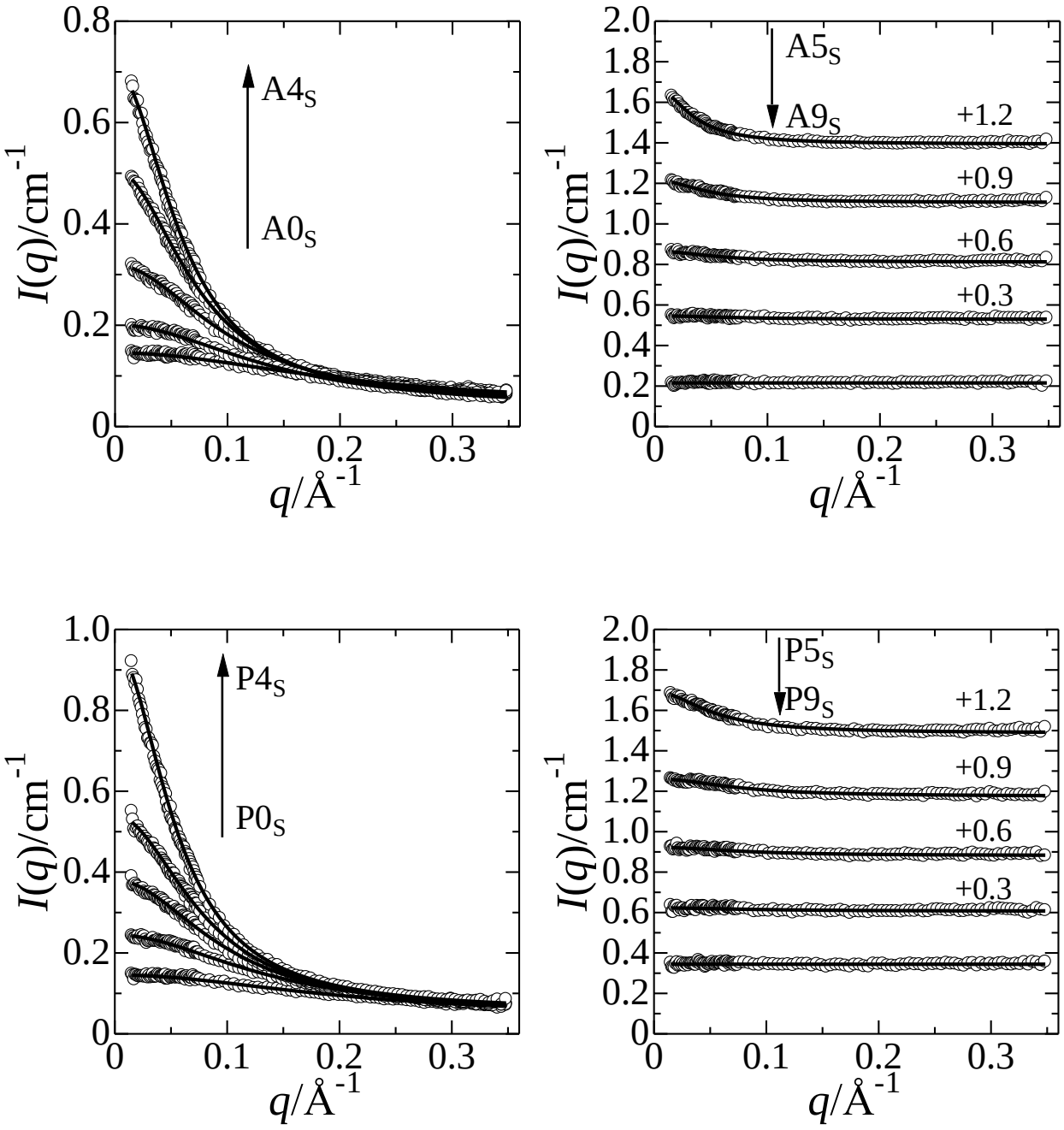


Fig. S4 SANS intensities of NMA–HFIP–D_2O (upper) and NMP–HFIP–D_2O (lower) mixtures: the left panels show the intensities of the mixtures below the $x^{L}_{A,298}$, and the right ones indicate those above the $x^{U}_{A,298}$. The circles are the observed values and the solid lines are the theoretical ones obtained from the Ornstein–Zernike fits using a least-squares refinement procedure. The values in the right panels indicate the intensities shifted from the origin to avoid overlap of the plots. The arrows show the increase in the amide concentration.

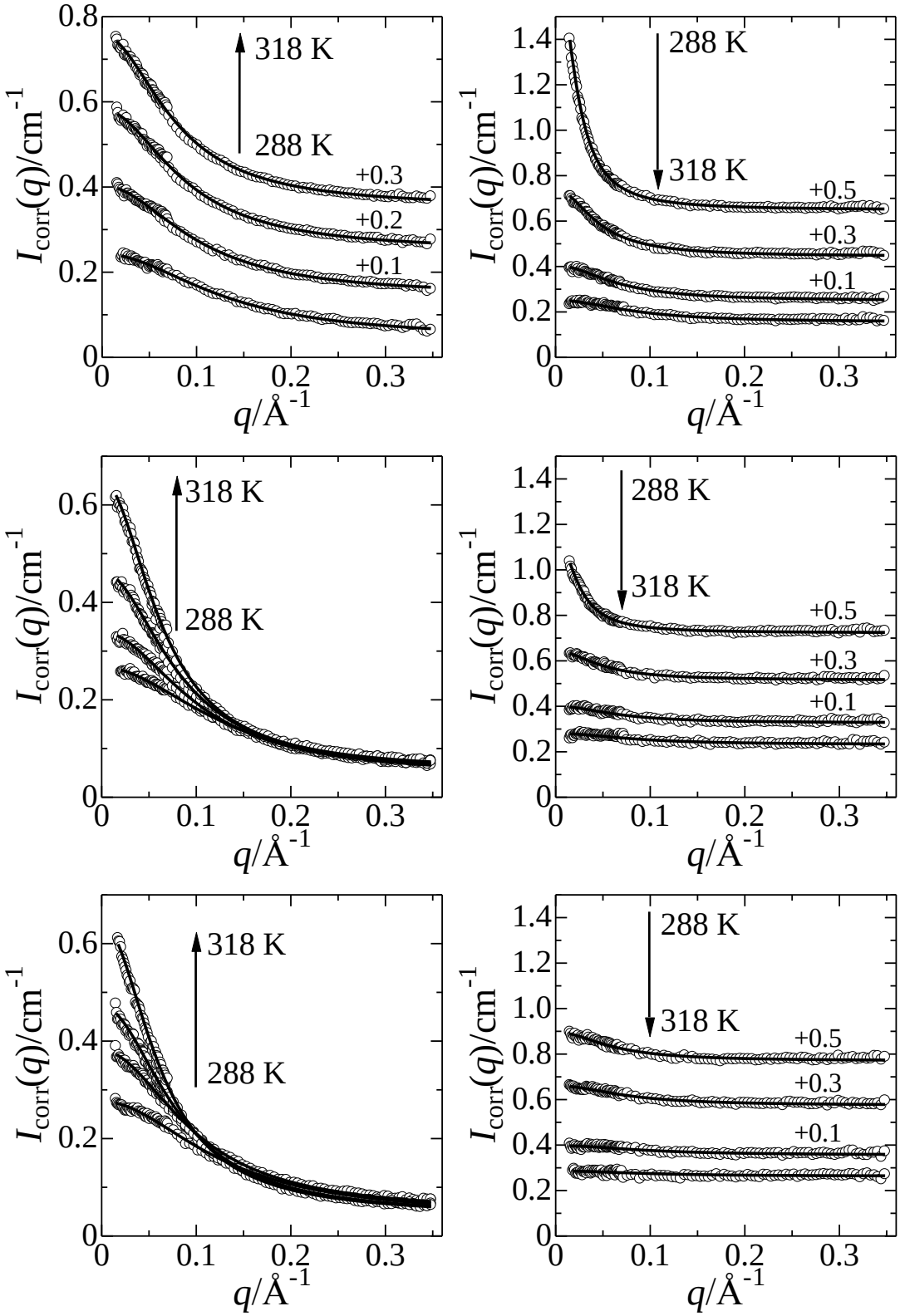


Fig. S6 SANS intensities of amide–HFIP–D_2O mixtures (NMF: upper; NMA: middle; NMP: bottom) as a function of temperature. The left and right panels show the intensities of the NMF systems of $F2_S$ and $F6_S$, the NMA ones of $A2_S$ and $A6_S$, and the NMP ones of $P2_S$ and $P6_S$, respectively. The circles are the observed values, and the solid lines are the theoretical ones obtained from the Ornstein–Zernike fits using a least-squares refinement procedure. The values in the figures indicate the intensities shifted from the origin to avoid overlap of the plots. The arrows show the rise in temperature.

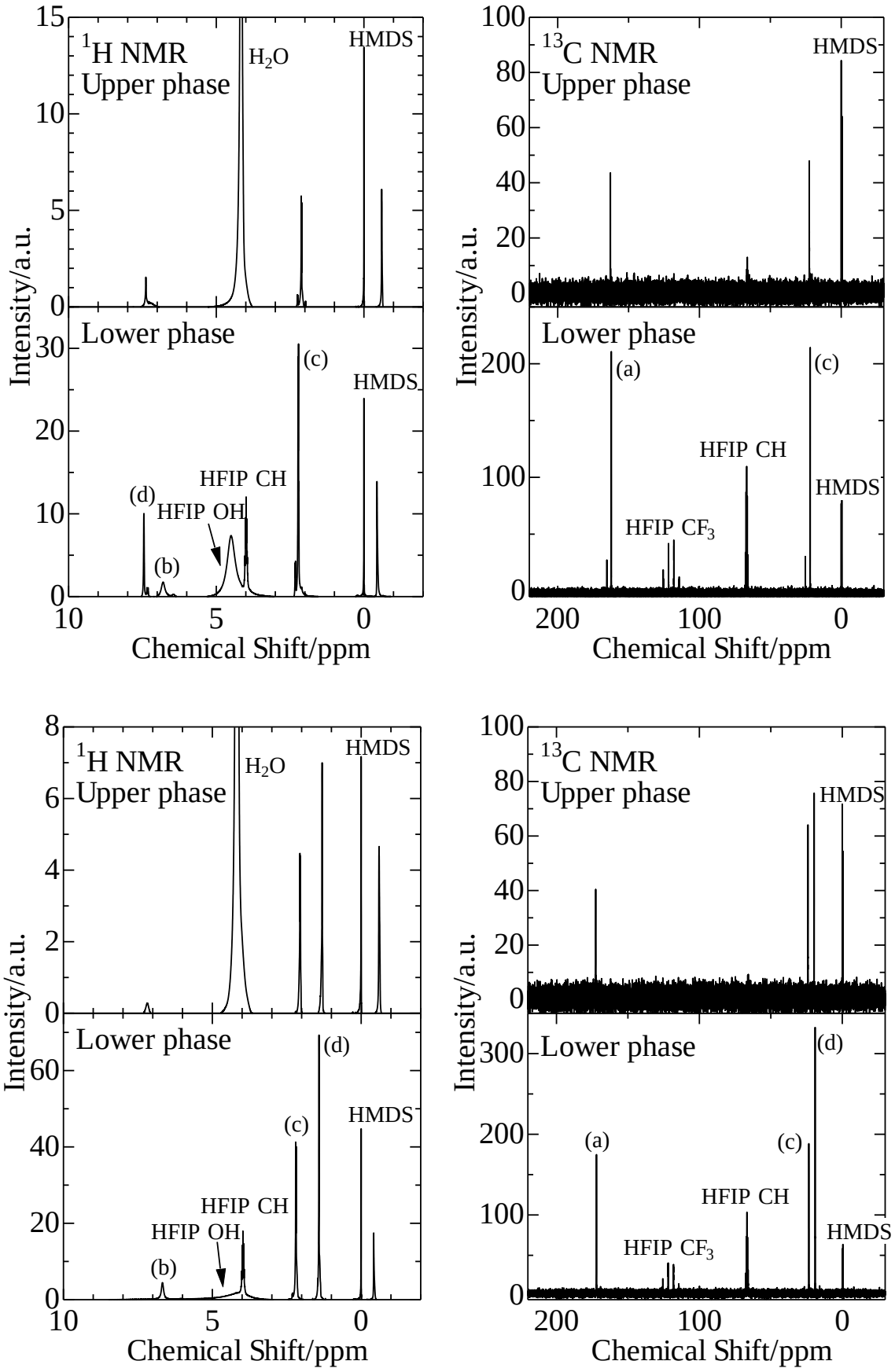


Fig. S7 ^{1}H and ^{13}C NMR spectra of upper and lower phases separated from NMF–HFIP–H_2O (upper) and NMA–HFIP–H_2O (lower) systems at 298 K.

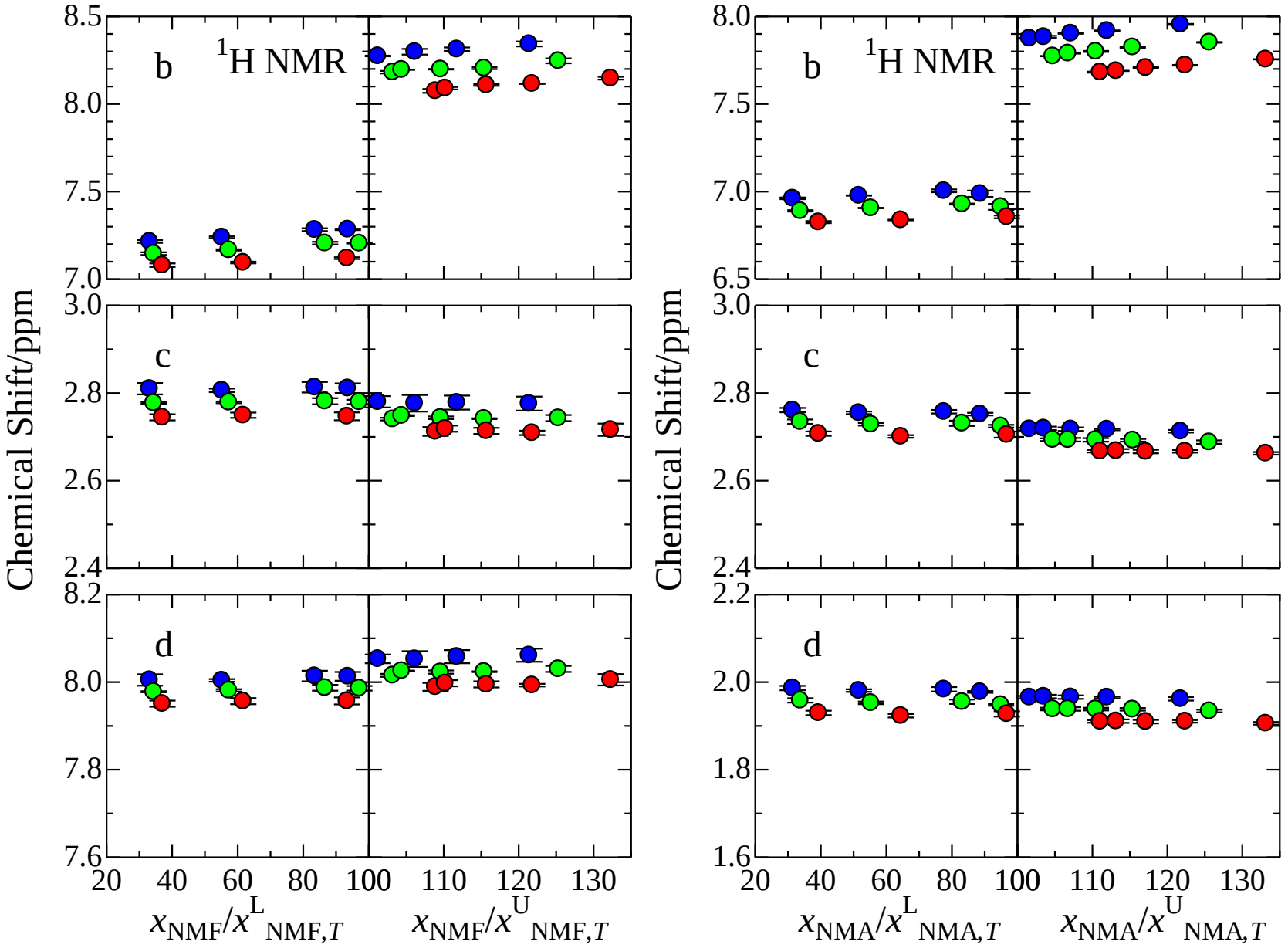


Fig. S8 ^{1}H chemical shifts of amide molecules in NMF–HFIP–H_2O (left, $F1_N$–$F4_N$ and $F5_N$–$F9_N$) and NMA–HFIP–H_2O (right, $A1_N$–$A4_N$ and $A5_N$–$A9_N$) mixtures at 288 (blue circles), 298 (green ones), and 308 K (red ones) as a function of the ratio of amide mole fraction to the phase separation one at each temperature. The standard deviations are shown by error bars.

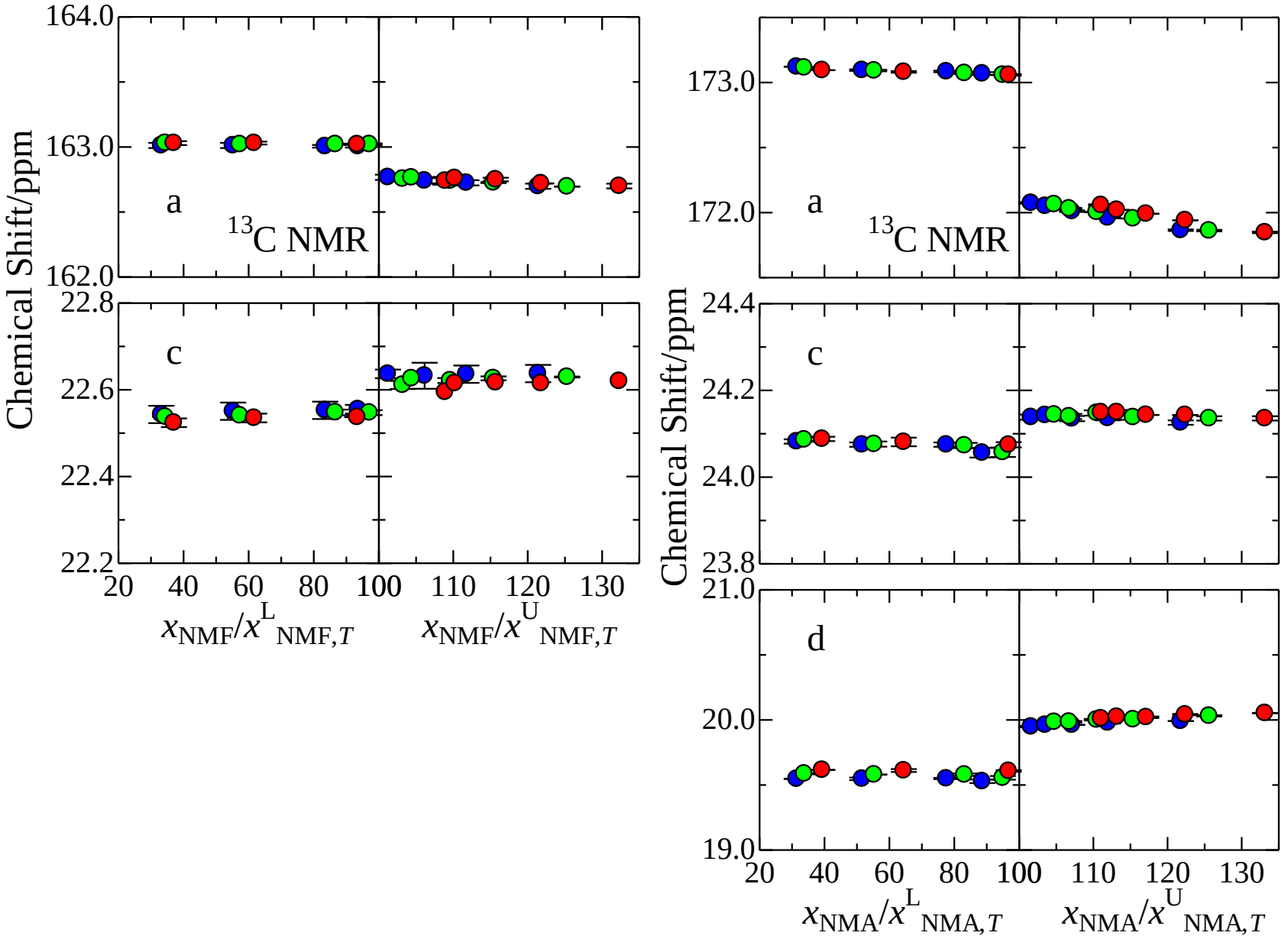


Fig. S9 ^{13}C chemical shifts of amide molecules in NMF–HFIP–H_2O (left, $F1_N$–$F4_N$ and $F5_N$–$F9_N$) and NMA–HFIP–H_2O (right, $A1_N$–$A4_N$ and $A5_N$–$A9_N$) mixtures at 288 (blue circles), 298 (green ones), and 308 K (red ones) as a function of the ratio of amide mole fraction to the phase separation one at each temperature. The standard deviations are shown by error bars.

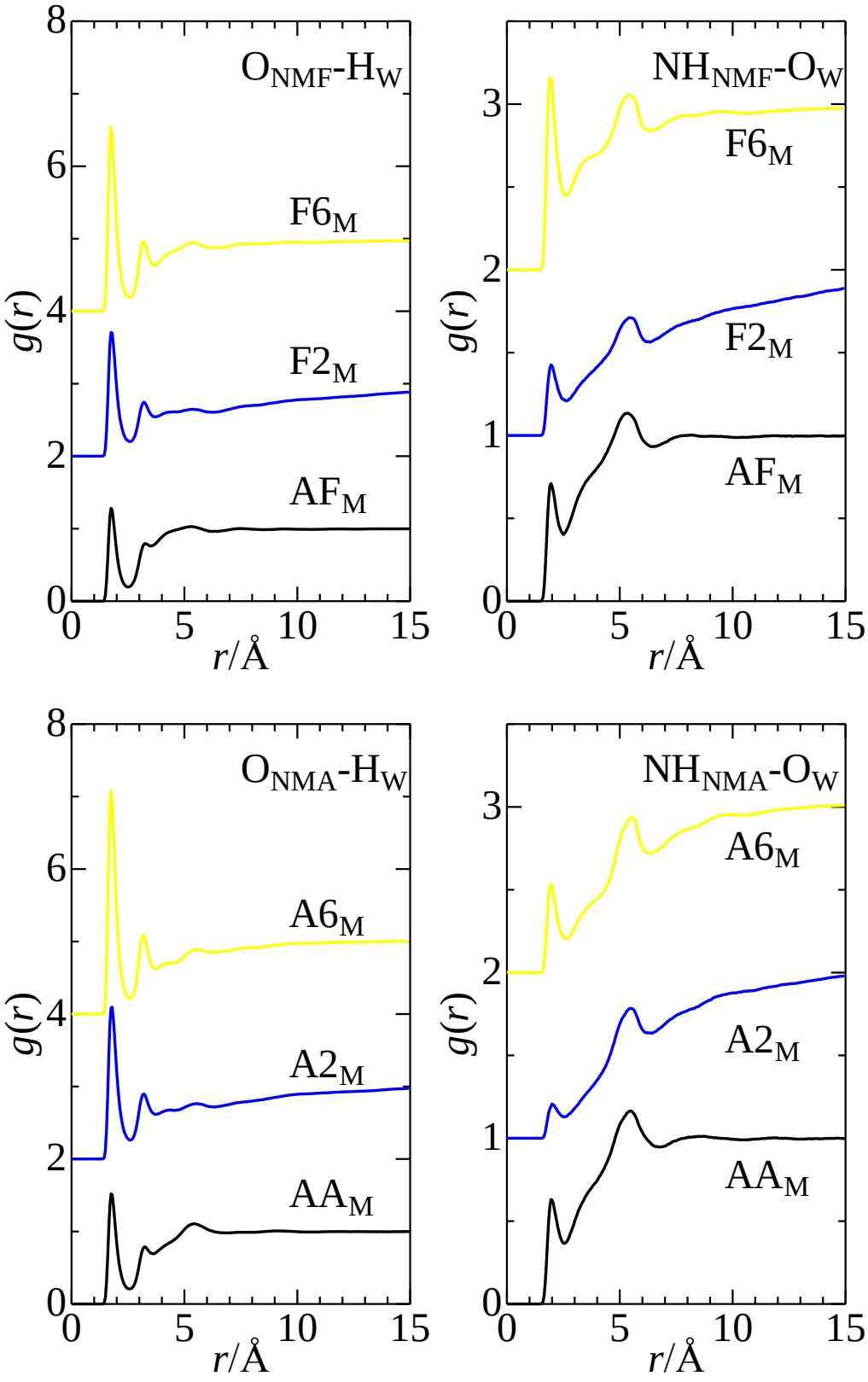


Fig. S10 Intermolecular atom–atom pair correlation functions $g(r)$ for O_A–H_W interaction between the amide carbonyl oxygen and water hydroxyl hydrogen atoms (left) and NH_A–O_W interaction between the amide amino hydrogen and water oxygen atoms (right) obtained from MD simulations on amide–water systems (black line), amide–HFIP–water systems below the $x^{L}_{A,298}$ (blue one) and above the $x^{U}_{A,298}$ (yellow one). The upper and lower panels show the $g(r)$ of the NMF and NMA systems, respectively.

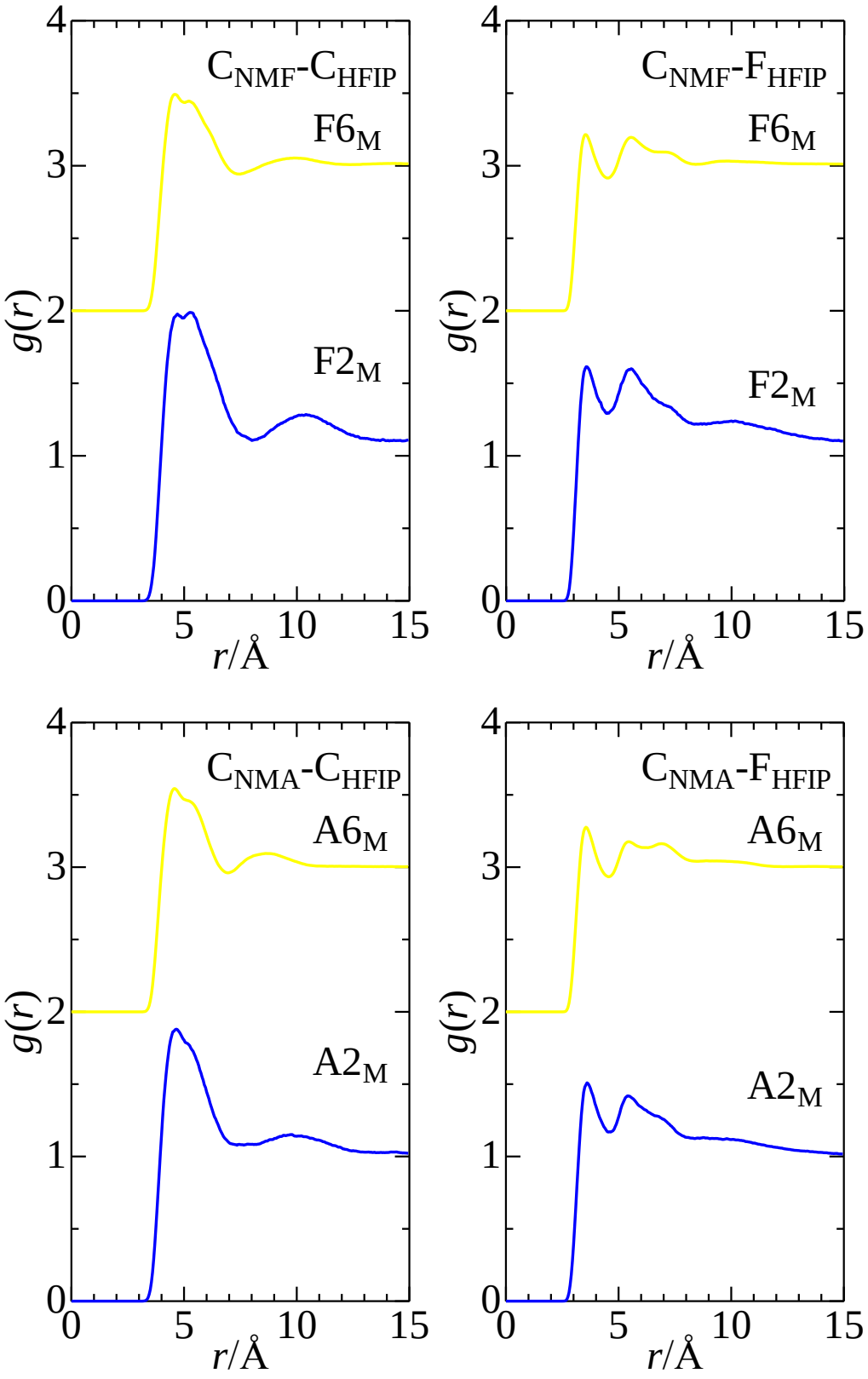


Fig. S12 Intermolecular atom–atom pair correlation functions $g(r)$ for C_A–C_{HFIP} interaction between the amide carbon and HFIP carbon atoms and C_A–F_{HFIP} interaction between the amide carbon and HFIP fluorine atoms obtained from MD simulations on amide–HFIP–water systems. The colors of lines are the same as those used in Fig. S10. The upper and lower panels show the $g(r)$ of the NMF and NMA systems, respectively.

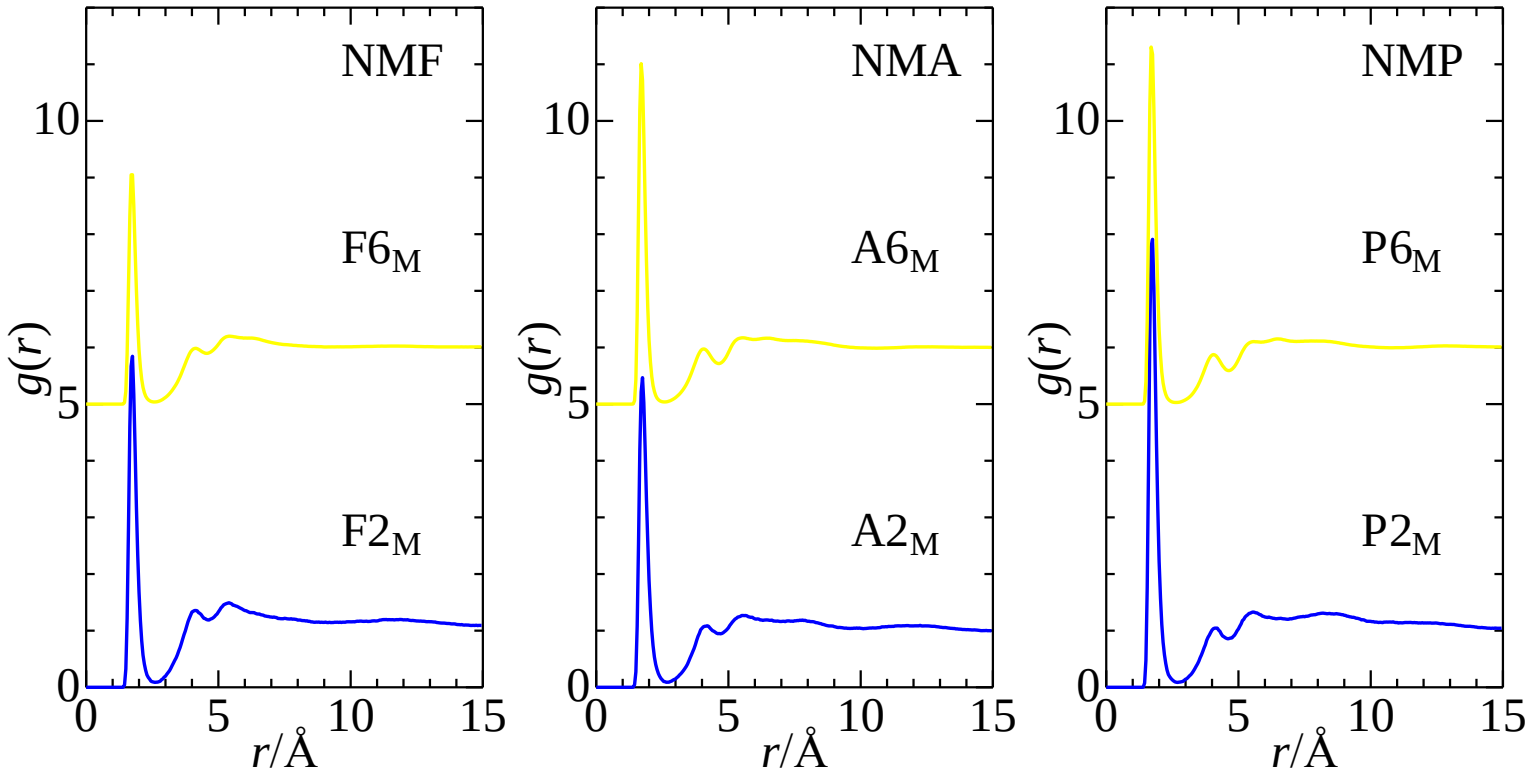


Fig. S13 Intermolecular atom–atom pair correlation functions $g(r)$ for O_A–H_{HFIP} interaction between the amide carbonyl oxygen and HFIP hydroxyl hydrogen atoms obtained from MD simulations on amide–HFIP–water mixtures below the $x^{L}_{A,298}$ (blue) and above the $x^{U}_{A,298}$ (yellow). The left, center, and right panels show the $g(r)$ of the NMF, NMA, and NMP systems, respectively.

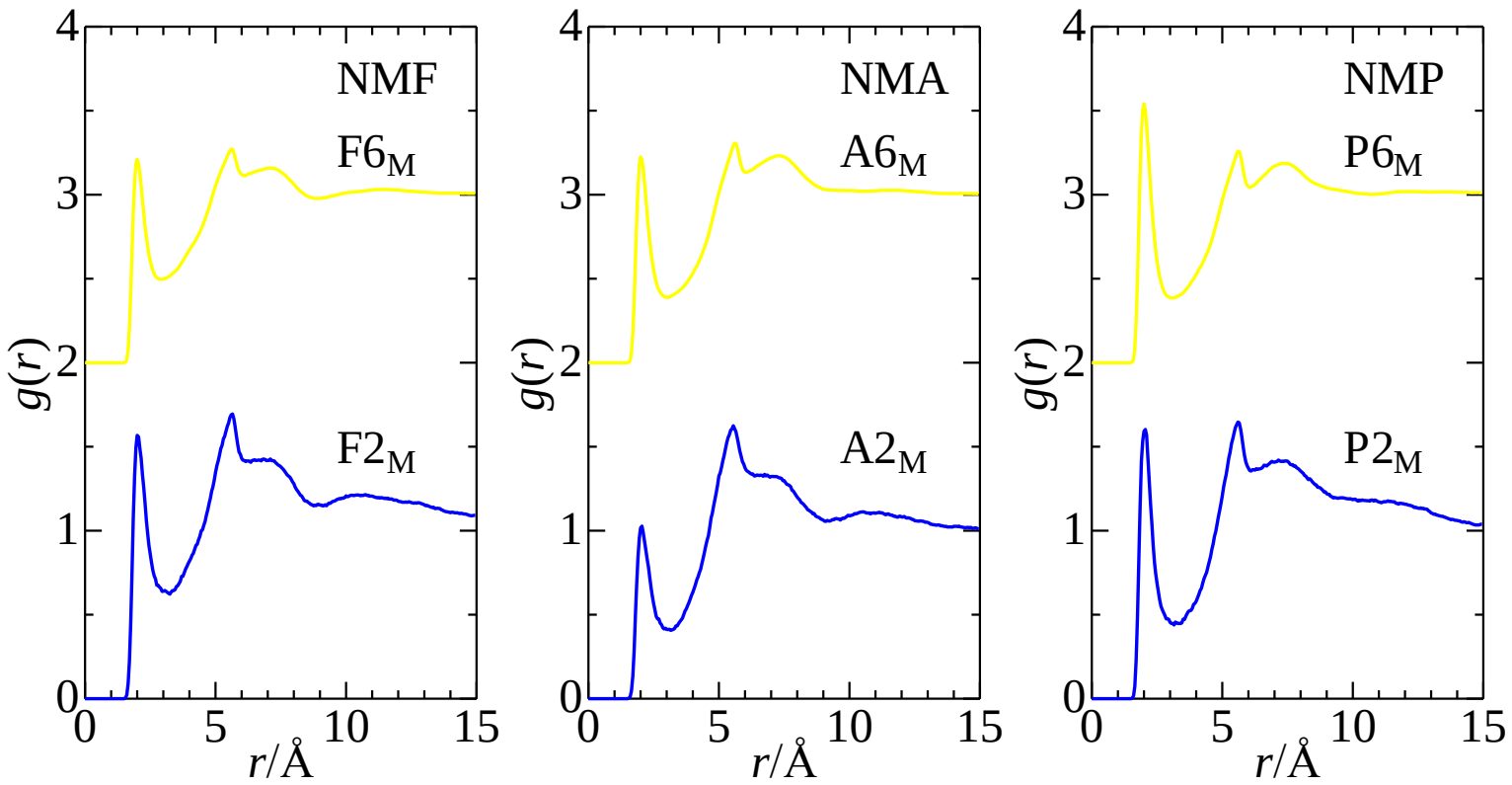


Fig. S14 Intermolecular atom–atom pair correlation functions $g(r)$ for NH_A–O_{HFIP} interaction between the amide amino hydrogen and HFIP hydroxyl oxygen atoms obtained from MD simulations on amide–HFIP–water mixtures below the $x^{L}_{A,298}$ (blue) and above the $x^{U}_{A,298}$ (yellow). The left, center, and right panels show the $g(r)$ of the NMF, NMA, and NMP systems, respectively.

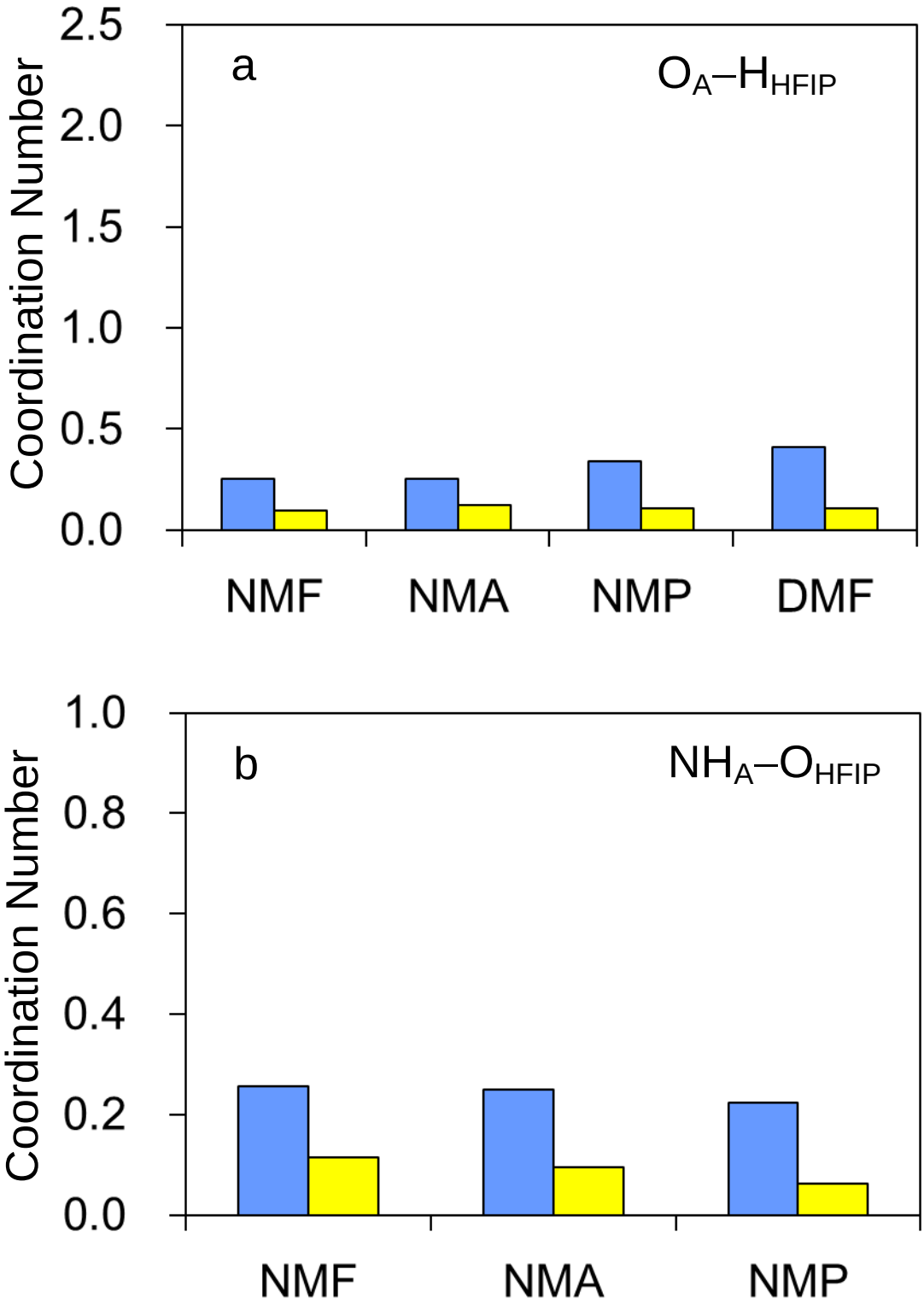


Fig. S15 Numbers of hydrogen bonds for (a) O_A–H_{HFIP} and (b) NH_A–O_{HFIP} estimated from MD $g(r)$. The blue and yellow columns represent those for amide–HFIP–water systems below the $x^{L}_{A,298}$ and above the $x^{U}_{A,298}$, respectively.