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Conductance Studies of NaCl, KCl, NaBr, NaI, NaBPh$_4$, Bu$_4$NI, and NaClO$_4$ in Water + 2-Butoxyethanol Mixtures at T = 298.15 K

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The electrical conductances of solutions of sodium chloride (NaCl), potassium chloride (KCl), sodium bromide (NaBr), sodium iodide (NaI), sodium tetraphenylborate (NaBPh$_4$), tetrabutylammonium iodide (Bu$_4$NI), and sodium perchlorate (NaClO$_4$) in water (1) + 2-butoxyethanol (2) mixtures containing (0.01, 0.025, 0.05, 0.075, 0.10, 0.15, and 0.20) mole fractions of 2-butoxyethanol have been measured at T = 298.15 K. The conductance data have been analyzed by the Fuoss−Justice equation. The individual limiting ionic conductivities of Na$^+$, K$^+$, Bu$_4$N$^+$, BPh$_4^-$, I$^-$, Cl$^-$, Br$^-$, and ClO$_4^-$ ions have been determined using the Fuoss−Hirsch assumption. The dependencies of the limiting molar conductances, Λ_o, and Walden products, $\Lambda_o\eta$, versus mixed solvent composition have been discussed.

Introduction

Alkoxyethanols and their aqueous mixtures are extensively studied by many research centers. They are commonly used in industry and modern technologies. These amphiphile molecules are known as surfactants. As it is known, in water-rich mixtures, 2-butoxyethanol molecules (BE) exist in molecular dispersion in water, and the further growth of the 2-butoxyethanol content causes a radical change of the mixture structure and then the formation of micelle-like aggregates.[1−6]

The thermodynamic and transport properties of aqueous solutions of 2-butoxyethanol have been studied recently by various physicochemical techniques. Therefore, in the literature, we can find the data of densities, relative permittivities, refractive indices, viscosities, surface tension, ultrasonic speeds, excess molar volumes and enthalpies.[6−12] Because of the nonexistence of the conductometric data in the literature currently available, the present paper presents the electrical conductances of NaCl, KCl, NaBr, NaI, NaBPh$_4$, Bu$_4$NI, and NaClO$_4$ in water-rich (1) 2-butoxyethanol (2) mixtures, which have been measured as a function of the mole fraction at 298.15 K and atmospheric pressure. In earlier papers,[13,14] we have reported the results of the conductance measurements of these salt solutions in water + 2-methoxyethanol and water + 2-ethoxyethanol systems. The same measurements have been also made in water + 2-butoxyethanol mixtures, but only for NaCl and NaI solutions.[15]

Experimental Section

Chemicals. 2-Butoxyethanol (ethylene glycol monobutyl ether) supplied by Fluka (puriss p.a. with a mass fraction purity > 0.995) was dried over freshly activated molecular sieves of type 4A (Sigma) for several days before use, and next it was distilled under vacuum in a dry nitrogen atmosphere. The measured density, viscosity, and refractive index of the pure solvent at T = 298.15 K agreed with those values published in the literature (Table 1).

The salts were of puriss grade and were used without further purification (with the exception of Bu$_4$NI). Sodium chloride (Merck) was dried at T = 373.15 K. Potassium chloride, sodium bromide, and sodium iodide were from Merck and were dried in vacuo at T = 353.15 K. Sodium tetraphenylborate (Fluka) and sodium perchlorate (Aldrich) were dried in vacuo at T = 353.15 K. Tetrabutylammonium iodide was of Aldrich purum grade and was purified by recrystallization from acetone and dried in vacuo at T = 333.15 K.

Double-distilled, deionized, and degassed water with a specific conductance better than $0.5 \cdot 10^{-6}$ S·cm^{-1} was used for the preparation of the mixed solvents. All of the solutions were prepared by mass using an analytical balance (Sartorius RC 210D) with an uncertainty of ± $1 \cdot 10^{-5}$ g. The uncertainty of the composition of the mixtures was 0.0001 in mole fraction.

Measurements. The details of the experimental procedure for conductometric and viscosimetric measurements were described in our previous papers.[16,17] Conductance measurements were

Table 1. Experimental and Literature Densities, ρ, Viscosities, η, and Refractive Indices, n_D, of 2-Butoxyethanol at T = 298.15 K

ρ / g·cm^{-3}		η / mPa·s		n_D	
exptl	lit.	exptl	lit.	exptl	lit.
0.896058	0.89602[a] 0.89581[e] 0.89597[g] 0.8962[b] 0.89625[c]	2.7956	2.786[b] 3.15[c]	1.4172	1.4176[c,d] 1.4173[f]

[a] Ref 26. [b] Ref 28. [c] Ref 29. [d] Ref 8. [e] Ref 1. [f] Ref 9. [g] Ref 27.

Table 2. Densities, ρ, Viscosities, η, and Relative Permittivities, ϵ_r, of Water (1) + 2-Butoxyethanol (2) Mixtures at T = 298.15 K

x_2	ρ / g·cm^3	η / mPa·s	ϵ_r[a]
0.0100	0.995114	1.1217	74.74
0.0250	0.990681	1.5199	68.67
0.0500	0.980926	2.1954	58.85
0.0750	0.972624	2. 7634	50.77
0.1000	0.965618	3.1828	44.78
0.1500	0.954656	3.7113	36.81
0.2000	0.946363	4.0140	30.40

[a] Ref 7.

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Table 3. Molar Conductances, Λ, and Corresponding Molarities, *c*, for NaCl, KCl, NaBr, NaI, $NaBPh_4$, Bu_4NI, and $NaClO_4$ in Water (1) + 2-Butoxyethanol (2) Mixtures at $T = 298.15$ K

$x_2 = 0.0100$		$x_2 = 0.0250$		$x_2 = 0.0500$		$x_2 = 0.0750$		$x_2 = 0.1000$		$x_2 = 0.1500$		$x_2 = 0.2000$	
$c \cdot 10^4$	Λ	$c \cdot 10^4$	Λ	$c \cdot 10^4$	Λ	$c \cdot 10^4$	Λ	$c \cdot 10^4$	Λ	$c \cdot 10^4$	Λ	$c \cdot 10^4$	Λ
$mol \cdot dm^{-3}$	$S \cdot cm^2 \cdot mol^{-1}$	$mol \cdot dm^{-3}$	$S \cdot cm^2 \cdot mol^{-1}$	$mol \cdot dm^{-3}$	$S \cdot cm^2 \cdot mol^{-1}$	$mol \cdot dm^{-3}$	$S \cdot cm^2 \cdot mol^{-1}$	$mol \cdot dm^{-3}$	$S \cdot cm^2 \cdot mol^{-1}$	$mol \cdot dm^{-3}$	$S \cdot cm^2 \cdot mol^{-1}$	$mol \cdot dm^{-3}$	$S \cdot cm^2 \cdot mol^{-1}$
NaCl													
8.402	103.94	9.121	86.28	5.122	69.93	17.864	56.46	10.775	47.85	9.971	35.68	10.862	28.08
15.255	103.04	17.354	85.38	8.548	69.51	24.834	55.97	18.592	47.14	16.244	35.03	18.522	27.28
22.674	102.29	24.201	84.82	16.898	68.58	31.864	55.57	26.082	46.63	23.533	34.47	25.024	26.78
30.495	101.66	31.992	84.30	23.052	68.26	45.833	54.91	33.801	46.20	30.667	34.02	32.179	26.32
46.605	100.57	47.310	83.42	30.944	67.76	63.127	54.25	47.271	45.58	44.474	33.33	45.301	25.66
61.681	99.74	61.585	82.79	46.480	66.95	76.564	53.82	63.259	44.99	58.649	32.77	59.153	25.10
74.882	99.09	76.295	82.21	61.405	66.32	90.402	53.42	76.680	44.59	71.595	32.34	72.451	24.65
89.722	98.42	90.803	81.67	75.753	65.81	104.74	53.05	89.786	44.21	84.953	31.95	84.814	24.30
104.01	97.84	106.69	81.13	89.988	65.35	117.53	52.75	104.96	43.83	97.764	31.63	96.588	23.99
116.50	97.36	119.38	80.73	103.97	64.94	129.95	52.47	118.41	43.53	109.83	31.35	109.63	23.69
130.79	96.83	133.44	80.31	116.78	64.59			129.80	43.29	122.14	31.09	121.78	23.44
				130.50	64.32								
KCl													
8.665	122.47	9.753	101.98	8.583	82.00	21.108	66.12	7.099	55.73	8.774	40.26	12.025	30.71
15.916	121.61	17.923	101.24	15.907	81.13	31.851	65.45	16.322	54.76	16.693	39.46	20.628	29.91
31.421	120.21	34.814	100.06	24.868	80.31	44.013	64.86	23.197	54.25	23.866	38.86	26.415	29.48
46.966	119.15	49.038	99.34	31.687	79.80	56.890	64.34	30.230	53.79	30.860	38.33	35.065	28.92
61.779	118.43	64.174	98.74	46.824	78.81	73.113	63.79	45.026	53.02	46.139	37.45	47.676	28.25
76.429	117.81	77.752	98.26	64.100	77.88	88.116	63.36	59.264	52.41	61.071	36.77	61.888	27.64
91.143	117.24	92.285	97.80	77.069	77.26	102.21	62.99	73.031	51.90	75.326	36.17	75.456	27.14
105.78	116.74	106.88	97.39	91.412	76.63	118.55	62.60	88.166	51.42	89.301	35.67	88.837	26.71
119.47	116.29	120.09	97.04	105.55	76.03	132.24	62.32	102.26	51.02	104.35	35.18	102.00	26.34
		133.35	96.71	118.32	75.52	143.61	62.13	114.70	50.70	117.25	34.80	115.92	25.99
				132.51	75.00			127.86	50.38	129.62	34.46	126.63	25.74
										143.76	34.10	138.76	25.48
										156.48	33.80	150.77	25.24
NaBr													
9.549	105.06	11.616	86.22	11.769	69.24	11.038	57.22	11.831	47.96	9.307	36.46	10.879	28.90
17.739	104.04	20.929	85.34	19.119	68.61	18.186	56.60	18.085	47.41	17.758	35.67	18.679	28.16
24.478	103.41	26.540	84.92	26.515	68.14	25.636	56.11	25.226	47.06	23.638	35.27	25.102	27.71
31.246	102.88	34.114	84.44	34.966	67.70	48.086	55.24	33.489	46.67	31.599	34.83	33.348	27.24
48.551	101.76	50.044	83.59	50.110	67.06	62.377	54.80	47.462	46.14	45.086	34.24	45.814	26.67
65.732	100.95	67.678	82.89	65.333	66.54	77.598	54.41	62.281	45.70	58.822	33.78	59.688	26.17
79.497	100.35	81.981	82.38	80.777	66.08	91.260	54.10	76.486	45.34	72.609	33.39	73.228	25.78
95.156	99.73	96.728	81.89	94.814	65.70	105.29	53.82	90.163	45.04	85.834	33.06	86.048	25.45
111.12	99.13	113.30	81.40	111.67	65.30	119.11	53.57	104.53	44.75	101.96	32.72	99.210	25.15
124.08	98.69	127.50	81.00	125.94	64.98	131.91	53.35	116.50	44.53	112.45	32.52	111.29	24.91
138.32	98.22	140.67	80.65	138.66	64.71			129.52	44.32	126.04	32.29	123.67	24.68
NaI													
6.277	102.18	4.884	82.06	4.452	64.71	5.239	53.14	6.496	44.78	10.903	34.02	8.707	27.93
12.234	101.21	10.368	81.31	10.131	64.06	10.759	52.66	11.357	44.45	18.028	33.64	12.640	27.67
19.196	100.33	18.827	80.51	17.775	63.50	18.946	52.14	18.978	44.03	25.291	33.33	19.366	27.29
27.021	99.53	26.047	79.92	25.481	63.04	26.038	51.79	26.523	43.69	32.693	33.07	25.704	27.00
35.404	98.77	34.928	79.31	33.366	62.64	33.042	51.50	33.916	43.41	46.674	32.66	33.381	26.71
51.553	97.50	49.889	78.44	48.442	62.00	48.866	50.96	49.238	42.94	61.123	32.32	46.470	26.29
65.864	96.52	63.583	77.74	70.267	61.25	62.671	50.57	64.028	42.57	75.388	32.04	60.626	25.94
79.854	95.64	78.645	77.04	78.640	60.99	77.211	50.21	78.198	42.26	87.902	31.83	74.964	25.63
95.568	94.70	94.570	76.35	92.161	60.60	91.365	49.89	92.114	41.99	100.54	31.64	86.441	25.42
109.99	93.90	109.08	75.76	105.06	60.25	104.05	49.62	105.45	41.74	113.61	31.46	99.856	25.20
122.74	93.23	122.20	75.26	118.62	59.90	117.57	49.36	119.48	41.49	126.00	31.30	112.75	25.02
136.76	92.51	136.03	74.76	132.77	59.54	130.95	49.11	131.27	41.32	137.67	31.16	123.92	24.87
						144.93	48.87	145.16	41.11	149.92	31.03		
								156.83	40.95				
$NaBPh_4$													
8.918	54.87			8.861	31.67	9.104	26.88	13.453	23.23	13.829	18.48	13.378	15.74
13.431	54.54			12.005	31.58	13.059	26.81	17.680	23.16	17.923	18.41	17.071	15.65
16.890	54.28			16.496	31.47	17.026	26.73	24.307	23.06	24.297	18.33	24.302	15.56
25.204	53.79			24.538	31.36	23.967	26.64	32.359	22.97	31.793	18.24	31.655	15.45
32.782	53.46			32.664	31.23	31.886	26.55	39.169	22.91	38.949	18.17	38.548	15.37
39.803	53.19			39.809	31.13	39.417	26.48	46.099	22.85	45.456	18.11	44.943	15.31
47.660	52.93			47.770	31.05	45.830	26.43	53.052	22.80	52.318	18.06	52.233	15.21
54.760	52.71			55.351	30.97	52.895	26.37	59.701	22.75	59.021	18.01	58.502	15.16
61.614	52.49			62.070	30.91	60.016	26.32	66.225	22.71	65.175	17.97	64.580	15.14
68.856	52.32			69.743	30.85	66.239	26.28	73.837	22.67	72.014	17.92	71.351	15.08
75.198	52.16			76.510	30.79	73.165	26.24	80.077	22.63	78.519	17.88	77.151	15.05
82.239	51.96			82.995	30.75	79.476	26.20	86.318	22.60	83.677	17.86	83.067	15.01
						85.251	26.17						
Bu_4NI													
4.128	76.24	3.996	58.83	6.249	44.97	6.715	37.10	7.020	32.05	9.224	25.47	10.723	21.50
6.368	75.75	6.586	58.47	9.042	44.65	8.988	36.89	9.372	31.83	11.903	25.25	15.333	21.12
8.971	75.28	8.989	58.14	11.750	44.37	11.766	36.65	12.116	31.59	16.279	24.90	20.231	20.75
11.807	74.85	11.672	57.80	16.685	43.92	16.618	36.25	16.873	31.21	21.222	24.55	25.011	20.44
17.306	74.12	17.243	57.20	21.642	43.52	21.842	35.86	21.589	30.86	26.016	24.25	29.542	20.17
22.198	73.58	22.517	56.73	26.644	43.14	26.688	35.55	26.917	30.51	30.244	24.00	34.927	19.88
27.157	73.07	27.575	56.31	31.412	42.81	31.242	35.29	31.385	30.23	34.743	23.76	39.275	19.66
32.144	72.62	32.499	55.93	36.061	42.51	36.193	35.03	36.150	29.95	39.152	23.54	43.397	19.48
36.933	72.17	37.226	55.59	41.115	42.21	40.685	34.79	40.389	29.72	43.193	23.34	48.825	19.24
41.388	71.80	41.928	55.27	45.344	41.96	44.929	34.56	44.842	29.49	47.417	23.16	52.888	19.08
46.190	71.42	46.700	54.96			49.238	34.28	49.505	29.27	51.769	22.97		
		51.272	54.67			53.702	34.14	54.304	29.05				
		55.591	54.41										

Table 3. Continued

$x_2 = 0.0100$		$x_2 = 0.0250$		$x_2 = 0.0500$		$x_2 = 0.0750$		$x_2 = 0.1000$		$x_2 = 0.1500$		$x_2 = 0.2000$	
$c \cdot 10^4$ mol·dm^{-3}	Λ S·cm^2·mol^{-1}	$c \cdot 10^4$ mol·dm^{-3}	Λ S·cm^2·mol^{-1}	$c \cdot 10^4$ mol·dm^{-3}	Λ S·cm^2·mol^{-1}	$c \cdot 10^4$ mol·dm^{-3}	Λ S·cm^2·mol^{-1}	$c \cdot 10^4$ mol·dm^{-3}	Λ S·cm^2·mol^{-1}	$c \cdot 10^4$ mol·dm^{-3}	Λ S·cm^2·mol^{-1}	$c \cdot 10^4$ mol·dm^{-3}	Λ S·cm^2·mol^{-1}
						$NaClO_4$							
5.909	95.62	9.038	74.51	16.692	56.73	11.140	46.96	19.323	39.65	7.964	31.53	7.096	26.57
11.133	94.90	11.881	74.27	24.844	56.40	17.884	46.68	26.729	39.40	12.872	31.31	13.727	26.23
18.855	94.15	19.487	73.72	31.402	56.18	26.418	46.41	34.640	39.22	20.506	31.00	20.686	25.91
26.257	93.60	27.115	73.34	46.560	55.76	35.435	46.18	47.498	38.95	27.815	30.76	28.856	25.61
34.699	93.01	36.052	73.00	60.706	55.45	47.623	45.92	61.870	38.72	34.951	30.58	42.205	25.22
49.655	92.13	50.173	72.47	74.335	55.18	61.973	45.67	76.149	38.51	48.782	30.27	55.386	24.92
63.329	91.48	65.590	72.00	88.840	54.93	77.036	45.44	89.458	38.34	61.737	30.04	69.780	24.66
77.579	90.88	79.689	71.64	103.41	54.70	89.117	45.28	102.37	38.18	75.456	29.83	82.413	24.46
93.097	90.27	94.124	71.31	116.70	54.50	104.00	45.10	115.99	38.05	88.733	29.66	95.554	24.27
		107.39	71.02	128.95	54.33	116.61	44.97	127.87	37.94	101.88	29.51	107.99	24.11
		121.29	70.76	142.80	54.15	132.04	44.81	140.13	37.83	113.97	29.39	120.00	23.98
		134.74	70.53					152.77	37.72	126.08	29.27	131.53	23.86
												144.04	23.74

Table 4. Limiting Molar Conductances, Λ_o, Association Constants, K_A, Parameters, R, and Walden Products, $\Lambda_o\eta$, for NaCl, KCl, NaBr, NaI, $NaBPh_4$, Bu_4NI, and $NaClO_4$ in Water (1) + 2-Butoxyethanol (2) Mixtures at T = 298.15 K[a]

x_2	Λ_o S·cm^2·mol^{-1}	K_A dm^3·mol^{-1}	R Å	$\Lambda_o\eta \cdot 10^{-2}$ S·cm^2·mol^{-1} ·mPa·s	Λ_o S·cm^2·mol^{-1}	K_A dm^3·mol^{-1}	R Å	$\Lambda_o\eta \cdot 10^{-2}$ S·cm^2·mol^{-1} ·mPa·s
		NaCl				KCl		
0.0000	126.59			1.127	149.95			1.335
0.0100	106.15 ± 0.01	2.08 ± 0.04	3.8	1.191	124.78 ± 0.05	0.85 ± 0.08	3.7	1.400
0.0250	88.18 ± 0.03	2.26 ± 0.06	4.0	1.340	104.06 ± 0.03	0.73 ± 0.04	3.9	1.582
0.0500	71.10 ± 0.04	2.97 ± 0.10	4.3	1.561	83.95 ± 0.02	5.50 ± 0.04	5.1	1.843
0.0750	58.78 ± 0.02	3.56 ± 0.07	4.5	1.624	68.79 ± 0.03	2.10 ± 0.06	4.4	1.901
0.1000	49.57 ± 0.04	5.51 ± 0.15	4.9	1.578	57.27 ± 0.02	5.43 ± 0.08	5.2	1.823
0.1500	37.42 ± 0.04	11.65 ± 0.27	5.4	1.389	42.25 ± 0.01	19.05 ± 0.05	7.6	1.568
0.2000	30.15 ± 0.04	22.32 ± 0.31	6.0	1.210	33.18 ± 0.01	29.33 ± 0.06	8.1	1.332
		NaBr				NaI		
0.0000	128.38			1.143	126.92			1.130
0.0100	107.32 ± 0.04	1.53 ± 0.06	3.8	1.204	104.24 ± 0.02	6.09 ± 0.03	7.8	1.169
0.0250	88.28 ± 0.02	1.61 ± 0.04	3.9	1.342	83.51 ± 0.01	5.29 ± 0.02	7.7	1.269
0.0500	71.08 ± 0.03	1.63 ± 0.07	4.1	1.560	65.80 ± 0.01	4.28 ± 0.03	7.8	1.445
0.0750	58.76 ± 0.02	1.30 ± 0.07	4.5	1.624	54.27 ± 0.01	3.77 ± 0.02	7.6	1.500
0.1000	49.68 ± 0.02	2.52 ± 0.09	4.9	1.581	46.03 ± 0.01	4.39 ± 0.03	8.3	1.465
0.1500	38.03 ± 0.04	7.76 ± 0.27	5.5	1.411	35.60 ± 0.01	5.47 ± 0.04	8.0	1.321
0.2000	30.89 ± 0.03	15.82 ± 0.28	5.9	1.240	29.55 ± 0.02	11.67 ± 0.16	8.5	1.186
		$NaBPh_4$				Bu_4NI		
0.0000	69.98			0.623	96.26			0.857
0.0100	56.63 ± 0.01		5.6	0.635	77.77 ± 0.02	8.49 ± 0.13	4.6	0.872
0.0250	43.52 ± 0.05[b]			0.661[b]	60.11 ± 0.01	9.16 ± 0.05	4.6	0.914
0.0500	32.60 ± 0.01		13.2	0.716	46.67 ± 0.01	11.19 ± 0.09	13.3	1.025
0.0750	27.69 ± 0.01		13.5	0.765	38.41 ± 0.02	17.73 ± 0.20	12.8	1.061
0.1000	24.16 ± 0.01		11.8	0.769	33.43 ± 0.01	24.05 ± 0.14	12.6	1.064
0.1500	19.41 ± 0.01		11.9	0.720	27.10 ± 0.01	32.71 ± 0.17	11.9	1.006
0.2000	16.77 ± 0.02		11.2	0.673	23.43 ± 0.01	46.83 ± 0.20	11.9	0.940
		$NaClO_4$						
0.0000	117.35			1.045				
0.0100	97.41 ± 0.01	1.60 ± 0.02	4.1	1.093				
0.0250	76.21 ± 0.01	0.78 ± 0.02	6.0	1.158				
0.0500	58.50 ± 0.01	1.10 ± 0.03	8.8	1.284				
0.0750	48.32 ± 0.01	0.70 ± 0.02	9.1	1.335				
0.1000	41.34 ± 0.01	1.06 ± 0.03	8.6	1.316				
0.1500	32.78 ± 0.01	3.25 ± 0.10	9.0	1.217				
0.2000	28.03 ± 0.01	8.45 ± 0.06	8.7	1.125				

[a] In all cases, $\Delta R = 0.5 \cdot 10^{-8}$ cm. [b] For $NaBPh_4$ (x_2 = 0.025) the value of $\Lambda_o\eta$ was interpolated from the dependence $\Lambda_o\eta = f(f_2)$, and then the value of $\Lambda_o = \Lambda_o\eta/\eta$ was calculated.

performed in the solutions containing (0.01, 0.025, 0.05, 0.075, 0.10, 0.15, and 0.20) mole fractions of 2-butoxyethanol (2), usually for (9 to 14) molar concentrations of salts, with the use of a precise component analyzer type 6430B (Wayne-Kerr, UK). All conductance values were the results of an extrapolation to infinite frequency. All data were corrected with the specific conductance of the solvent. The temperature was kept constant within 0.003 K (Ultra thermostat UB 20F with through-flow cooler DLK 25, Lauda, Germany). The uncertainty of the measured values of conductivity was 0.03 %.

Viscosities were measured with a AVS 350 viscosimeter (Schott Geräte, Germany). The viscosimeter filled with the liquid was placed vertically in a glass-sided water thermostat. An electronic stopwatch with a precision of 0.01 s was used for flow time measurements. The temperature was kept constant using a precision thermostat Julabo F32 (Julabo Labortechnik GmbH, Germany). The uncertainty in the viscosity measurements was better than 0.05 %.

Densities were measured with an Anton Paar DMA 5000 oscillating U-tube densimeter equipped with a thermostat with a temperature stability within ± 0.001 K. The densimeter was calibrated with extra pure water, previously degassed ultrasonically. The uncertainty in the density measurements was $5 \cdot 10^{-6}$ $g \cdot cm^{-3}$.

The refractive indices (Na-D line, at $\lambda = 589$ nm) were measured using an automatic precision refractometer DR 5000 Krüss. The uncertainty in the refractive index measurements was $2 \cdot 10^{-5}$.

Results and Discussion

The densities, dynamic viscosities, and relative permittivities of water (1) + 2-butoxyethanol (2) mixtures are listed in Table 2. Viscosity and density data were interpolated for the full composition on the basis of our experimental data. The relative permittivities were interpolated on the basis of literature data.[7]

The experimental molar conductances, Λ, as a functions of the electrolyte concentration, *c*, for the investigated salts in the mixed solvent are presented in Table 3.

The conductance data were analyzed using the Fuoss−Justice equation[18,19] in the form

$$\Lambda = \alpha[\Lambda_o - S(\alpha c)^{1/2} + E(\alpha c)\ln(\alpha c) + J(\alpha c) + J_{3/2}(\alpha c)^{3/2}] \quad (1)$$

together with

$$K_A = (1 - \alpha)/(\alpha^2 c y_{\pm}^{\,2}) \quad (2)$$

and

$$\ln y_{\pm} = -(A\alpha^{1/2}c^{1/2})/(1 + BR\alpha^{1/2}c^{1/2}) \quad (3)$$

In these equations, Λ_o is the limiting molar conductance; α is the dissociation degree of an electrolyte; K_A is the ionic association constant; *R* is the distance parameter of the ions; $y_{\pm}$ is the activity coefficient of ions on the molar scale; *A* and *B* are the Debye−Hückel equation coefficients. The analytical form of the parameters *S*, *E*, *J*, and $J_{3/2}$ was presented previously.[20−22] The values of Λ_o, K_A, and *R* were obtained using the well-known procedure given by Fuoss.[19]

The values of density, dynamic viscosity, and relative permittivity necessary for the calculation are collected in Table 2. The values of Λ_o, K_A, *R*, and the Walden products, $\Lambda_o\eta$, for the investigated salts in water (1) + 2-butoxyethanol (2) mixtures are collected in Table 4. The limiting molar conductances for salts in water are the same as in ref 14. The limiting ionic conductanes are taken from ref 23.

As seen from Table 4, the association constant values increase with an increasing amount of 2-butoxyethanol (2) in the mixture, because the relative permittivity of the medium decreases. $NaBPh_4$ is not associated in the mixed solvent media, and for the remaining salts the association constants are practically negligible. The values of Λ_o decrease intensively during the addition of 2-butoxyethanol (2) to water, as in the case of 2-methoxy- (ME) and 2-ethoxyethanol (EE).[13,14] In the case of water (1) + 2-butoxyethanol (2) mixtures the values of Λ_o at $x_2 = 0.2$ are the smallest. It can be easily explained taking into account the changes of viscosity in the order: H_2O + ME < H_2O + EE < H_2O + BE. From simple hydrodynamic models it follows that the ionic mobility decreases as the viscosity increases. The values of Walden product, $\Lambda_o\eta$, increase clearly along with an increase in the mole fraction of 2-butoxyethanol (2) in the very dilute region, and after reaching a maximum (at about $x_2 = 0.075 - 0.10$), the values of $\Lambda_o\eta$ decrease monotonically. It should be noted that the above-mentioned order (H_2O + ME < H_2O + EE < H_2O + BE) also applies to the changes of the Walden product values, which means that the maximum peaks are the highest in water (1) + 2-butoxyethanol (2) mixtures. A comparison of the Walden product for some salts in water + 2-methoxyethanol, water + 2-ethoxyethanol, and water + 2-butoxyethanol is presented in Figure 1.

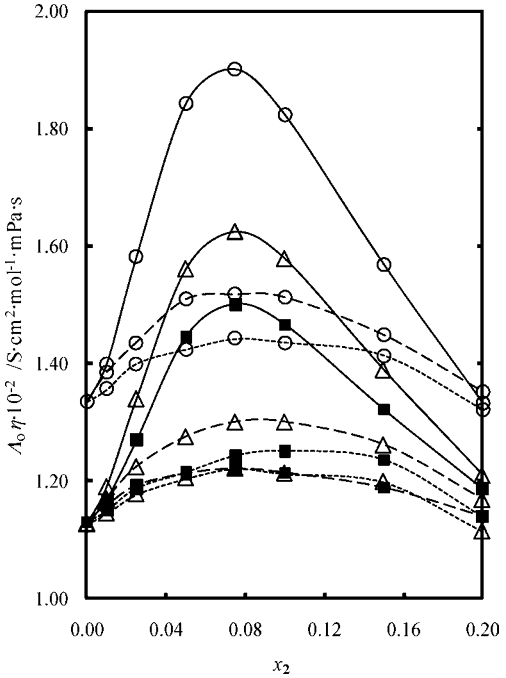

Figure 1. Walden product, $\Lambda_o\eta$, for some salts as a function of the mole fraction, x_2, in water (1) + 2-methoxyethanol (2), water (1) + 2-ethoxyethanol (2), and water (1) + 2-butoxyethanol (1) mixtures at 298.15 K: △, NaCl; ○, KCl; ■, NaI; ···, H_2O + ME (ref 13); ---, H_2O + EE (ref 14); −, H_2O + BE (this work).

The values of Λ_o for NaCl and NaI obtained in this paper are in very good agreement with those values published previously[15] (see Figure 2), and very slight differences between values of $\Lambda_o\eta$ may result from the viscosity data. In this paper, the viscosity measurements were conducted using better equipment.

The single-ion conductances were obtained on the basis of the Fuoss−Hirsch assumption[24]

$$\lambda_o(Bu_4N^+) = \lambda_o(BPh_4^-) = [\Lambda_o(Bu_4NI) + \Lambda_o(NaBPh_4) - \Lambda_o(NaI)]/2 \quad (4)$$

The dependencies $\lambda_o^+ = f(x_2)$ and $\lambda_o^- = f(x_2)$ are presented in Figures 3 and 4, respectively. The factors having an influence on these dependencies are the macroscopic viscosity and the effective size of ions. The values of limiting ionic conductances decrease with an increase of the macroscopic viscosities and of the effective ion size. Therefore, it is no wonder that in the case of the large ions (Bu_4N^+ and BPh_4^-) the values of λ_o are the smallest.

The changes of the values of $\lambda_o^{\pm}\eta$ as a function of the mixed solvent composition are independent from the changes of the macroscopic viscosity. Thus, the difference between the values of $\lambda_o^{\pm}\eta$ for different ions may provide information about the differences in the ion−solvent interactions. The dependencies $\lambda_o^+\eta = f(x_2)$ and $\lambda_o^-\eta = f(x_2)$ are presented in Figures 5 and 6, respectively.

As could be expected, the addition of small amounts of 2-butoxyethanol (2) to water (1) leads to an increase of the values of the ionic Walden product for inorganic ions, but they remain almost constant for Bu_4N^+ and BPh_4^-. The big organic

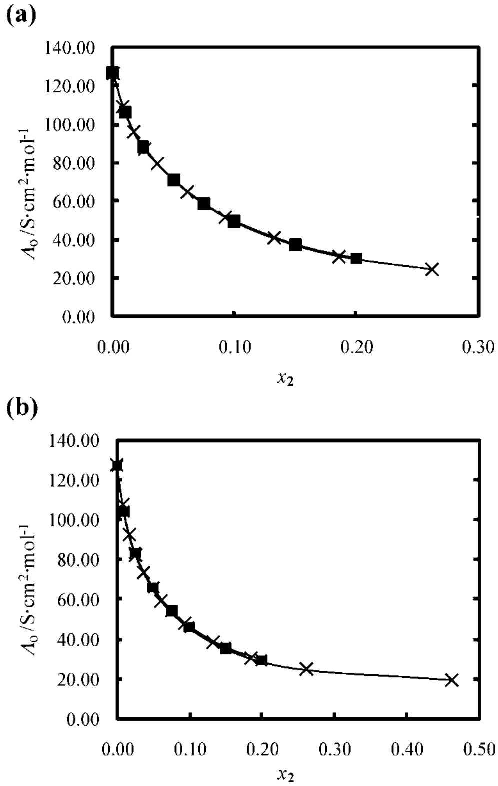

Figure 2. Comparison of the limiting molar conductances, Λ_o, of (a) NaCl and (b) NaI in water (1) + 2-butoxyethanol (2) mixtures at 298.15 K: ×, ref 15; ■, this work.

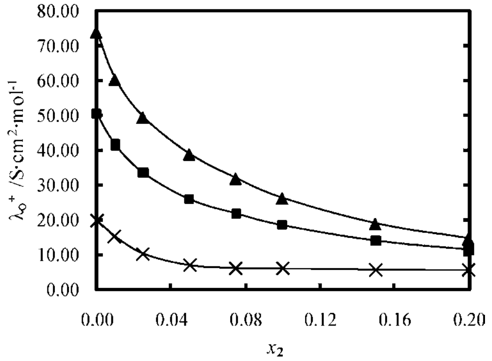

Figure 3. Limiting ionic conductances of the individual cations, λ_o^+, as a function of the mole fraction, x_2, in water (1) + 2-butoxyethanol (2) mixtures at 298.15 K: ▲, K^+; ■, Na^+; ×, Bu_4N^+.

ions having small surface charge densities are practically unsolvated in the solution. The differences between the changes of ionic Walden products (Figures 5 and 6) may result from the differences in the electronegativity of these ions. In the course of the dependence $\lambda_o^\pm\eta = f(x_2)$ for inorganic ions, we can see a maximum, as in the case of aqueous mixtures of 2-methoxy- and 2-ethoxyethanol.[13,14] The similar behavior of electrolyte solutions in water−alcohol mixtures was explained by Kay on the basis of the assumption of the preferential solvation of ions by the water dipoles ("sorting effect").[25] Furthermore, it should be noted that the intensity of the growth of the ionic Walden product values while adding alkoxyethanols to water can be put, for the mixtures examined by us, in the following order: H_2O + ME < H_2O +EE < H_2O + BE.

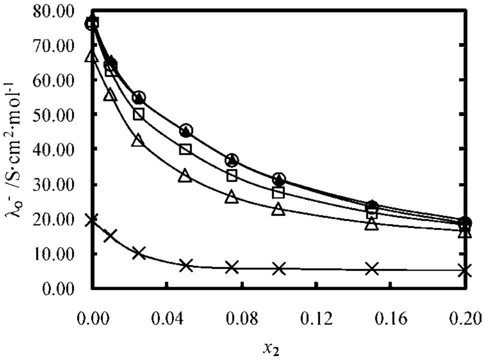

Figure 4. Limiting ionic conductances of the individual anions, λ_o^-, as a function of the mole fraction, x_2, in water (1) + 2-butoxyethanol (2) mixtures at 298.15 K: ○, Cl^-; ▲, Br^-; □, I^-; ×, BPh_4^-; △, ClO_4^-.

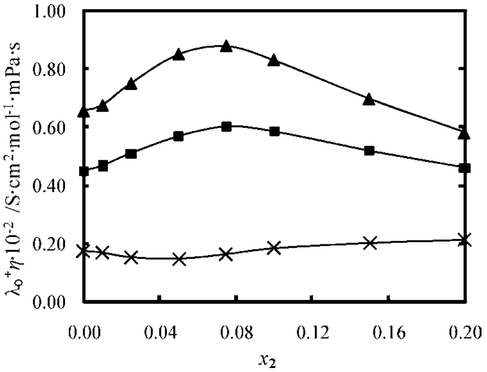

Figure 5. Walden product for cations, $\lambda_o^+\eta$, as a function of the mole fraction, x_2, in water (1) + 2-butoxyethanol (2) mixtures at 298.15 K: ▲, K^+; ■, Na^+; ×, Bu_4N^+.

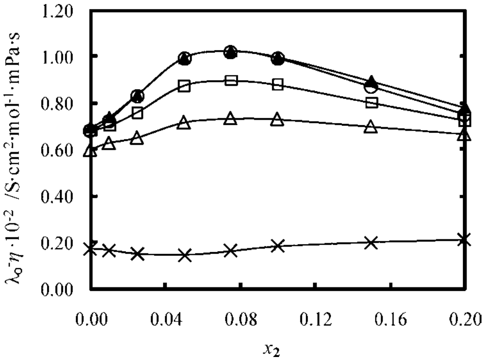

Figure 6. Walden product for anions, $\lambda_o^-\eta$, as a function of the mole fraction, x_2, in water (1) + 2-butoxyethanol (2) mixtures at 298.15 K: ○, Cl^-; ▲, Br^-; □, I^-; ×, BPh_4^-; △, ClO_4^-.

Conclusions

The electrical conductances of solutions of sodium chloride, potassium chloride, sodium bromide, sodium iodide, sodium tetraphenylborate, tetrabutylammonium iodide, and sodium perchlorate have been measured in aqueous 2-butoxyethanol (2) mixtures containing (0.01, 0.025, 0.05, 0.075, 0.10, 0.15, and 0.20) mole fractions of 2-butoxyethanol (2) at T = 298.15 K. The limiting molar conductances, Λ_o, and Walden products, $\Lambda_o\eta$, have been determined. The limiting molar conductances and the limiting ionic conductances decrease along with an increase of 2-butoxyethanol (2) content. The values of the Walden product increase with the increase in the mole fraction of 2-butoxyethanol (2) in the very dilute region and after reaching a maximum decrease monotonically. In the range of composition containing a large amount of water (1), slight additions of 2-butoxyethanol (2) do not cause significant changes in the hydration shells of ions.

Literature Cited

(1) Douhéret, G.; Pal, A.; Davis, M. I. Ultrasonic speeds and isentropic functions of (a 2-alkoxyethanol + water) at 298.15 K. *J. Chem. Thermodyn.* **1990**, *22*, 99–108.

(2) D'Arrigo, G.; Paparelli, A. Sound propagation in water-ethanol mixtures at low temperatures. I. Ultrasonic velocity. *J. Chem. Phys.* **1988**, *88*, 405–415.

(3) Mallamace, F.; Micali, N.; D'Arrigo, G. Dynamical effects of supramolecular aggregates in water-butoxyethanol mixtures studied by viscosity measurements. *Phys. Rev. A* **1991**, *44*, 6652–6658.

(4) D'Arrigo, G.; Mallamace, F.; Micali, N.; Paparelli, A.; Vasi, C. Molecular aggregations in water-2-butoxyethanol mixtures by ultrasonic and Brillouin light-scattering measurements. *Phys. Rev. A* **1991**, *44*, 2578–2587.

(5) Kato, S.; Jobe, D.; Rao, N. P.; Ho, C. H.; Verrall, R. E. Ultrasonic relaxation studies of 2-butoxyethanol-water and 2-butoxyethanol-water-cetyltrimethylammonium bromide solutions as a function of composition. *J. Phys. Chem.* **1986**, *90*, 4167–4174.

(6) Elizalde, F.; Gracia, J.; Costas, M. Effect of Aggregates in Bulk and Surface Properties. Surface Tension, Foam Stability and Heat Capacities for 2-Butoxyethanol + Water. *J. Phys. Chem.* **1988**, *92*, 3565–3568.

(7) Douhéret, G.; Pal, A. Dielectric Constants and Densities of Aqueous Mixtures of 2-Alkoxyethanols at 25°C. *J. Chem. Eng. Data* **1988**, *33*, 40–43.

(8) Shindo, Y.; Kusano, K. Densities and Refractive Indices of Aqueous Mixtures of Alkoxy Alcohols. *J. Chem. Eng. Data* **1979**, *24*, 106–110.

(9) Chu, K.-Y.; Thompson, A. R. Densities and Refractive Indices of Glycol Ether-Water Solutions. *J. Chem. Eng. Data* **1960**, *5*, 147–149.

(10) Davis, M. I.; Molina, M. C.; Douhéret, G. Excess molar volumes and enthalpies of the 2-butoxyethanol + water system at 25°C. *Thermochim. Acta* **1988**, *131*, 153–170.

(11) Douhéret, G.; Pal, A.; Davies, M. I. Excess Thermodynamic Properties of some 2-Alkoxyethanol-Water Systems. *J. Chem. Soc., Faraday Trans. 1* **1989**, *85*, 2723–2736.

(12) Chiou, D.-R.; Chen, S.-Y.; Chen, L.-J. Density, Viscosity, and Refractive Index for Water + 2-Butoxyethanol and + 2-(2-Butoxyethoxy)ethanol at Various Temperatures. *J. Chem. Eng. Data* **2010**, *55*, 1012–1016.

(13) Boruń, A.; Florczak, A.; Bald, A. Conductance studies of NaCl, KCl, NaBr, $NaBPh_4$, Bu_4NI and $NaClO_4$ in water + 2-methoxyethanol mixtures at 298.15 K. *J. Mol. Liq.* **2009**, *149*, 74–80.

(14) Boruń, A.; Florczak, A.; Bald, A. Conductance Studies of NaCl, KCl, NaBr, $NaBPh_4$, and Bu_4NI in Water + 2-Ethoxyethanol Mixtures at 298.15 K. *J. Chem. Eng. Data* **2010**, *55*, 1252–1257.

(15) Piekarski, H.; Tkaczyk, M.; Bald, A.; Szejgis, A. Conductivity Study of NaCl and NaI Solutions in Water-2-Butoxyethanol Mixtures at 298.15 K. The Effect of Ion Pairing on the Standard Dissolution Enthalpies of NaCl and NaI. *J. Mol. Liq.* **1997**, *73−74*, 209–221.

(16) Wypych-Stasiewicz, A.; Szejgis, A.; Chmielewska, A.; Bald, A. Conductance Studies of $NaBPh_4$, NBu_4I, NaI, NaCl, NaBr, $NaClO_4$ and the Limiting Ionic Conductance in Water + Propan-1-ol Mixtures at 298.15 K. *J. Mol. Liq.* **2007**, *130*, 34–37.

(17) Gregorowicz, J.; Bald, A.; Szejgis, A.; Chmielewska, A. Gibbs Energy of Transfer and Conductivity Properties of NaI Solutions in Mixtures of Water with Butan-1-ol at 298.15 K, and Some Physicochemical Properties of Mixed Solvent. *J. Mol. Liq.* **2000**, *84*, 149–160.

(18) Fuoss, R. M. Paired Ions: Dipolar Pairs as Subset of Diffusion Pairs. *Proc. Natl. Acad. Sci. U.S.A.* **1978**, *75*, 16–20.

(19) Fuoss, R. M. Conductance-Concentration Function for the Paired Ion Model. *J. Phys. Chem.* **1978**, *82*, 2427–2440.

(20) Justice, J.-C. An Interpretation for the Distance Parameter of the Fuoss-Onsager Conductance Equation in the Case of Ionic Association. *Electrochim. Acta* **1971**, *16*, 701–712.

(21) Renard, E.; Justice, J.-C. A Comparison of the Conductimetric Behavior of Cesium Chloride in Water-Tetrahydrofuran, Water-Dioxane, and Water-1,2-Dimethoxyethane Mixtures. *J. Solution Chem.* **1974**, *3*, 633–647.

(22) Fuoss, R. M.; Accascina, L. *Electrolytic Conductance*; Interscience: New York, 1959.

(23) Barthel, J. M. G.; Krienke, H.; Kunz, W. *Physical Chemistry of Electrolyte Solutions: modern aspects*; Springer: New York, 1998; Vol. 5.

(24) Fuoss, R. M.; Hirsch, E. Single Ion Conductances in Non-aqueous Solvents. *J. Am. Chem. Soc.* **1960**, *82*, 1013–1117.

(25) Kay, R. L.; Broadwater, T. L. Solvent Structure in Aqueous Mixtures. III. Ionic Conductances in Ethanol-Water Mixtures at 10 and 25°C. *J. Solution Chem.* **1976**, *5*, 57–76.

(26) Rao, N. P.; Verrall, R. E. Ultrasonic velocity, excess adiabatic compressibility, apparent molar volume, and apparent molar compressibility properties of binary liquid mixtures containing 2-butoxyethanol. *Can. J. Chem.* **1987**, *65*, 810–816.

(27) Tamura, K.; Osaki, A.; Murakami, S.; Ohji, H.; Ogawa, H.; Laurent, B.; Grolier, J.-P. E. Thermodynamic properties of binary mixtures {an alkoxyethanol + n-octane}. Excess molar enthalpies and excess molar heat capacities at 298.15 K. *Fluid Phase Equilib.* **1999**, *156*, 137–147.

(28) MacNeil, J. H.; Palepu, R. Viscosities and densities of binary liquid mixtures of 2-butoxyethanol with aniline and N-alkylaniline. *Thermochim. Acta* **1989**, *149*, 275–286.

(29) Riddick, J. A.; Bunger, W. B.; Sakano, T. K. *Organic Solvents*, 4th ed.; Wiley: New York, 1986.

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