Ionic Liquids in Polyethylene Glycol Aqueous Solutions: Salting-in and Salting-out Effects

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Summary. Changes of the fluid phase behaviour of polyethylene glycol (*PEG*) aqueous solutions – *viz.* critical solution temperature shifts at atmospheric pressure – were produced by the addition of different ionic liquids, namely 1-ethyl-3-methylimidazolium ethyl sulfate and 1-alkyl-3-methylimidazolium chloride (alkyl = ethyl to decyl). The addition of ionic liquids with long alkyl chains improves the solubility of *PEG* in water (salting-in effect), whereas the impact of short-chain ionic liquids is usually the contrary (salting-out effect). The results are interpreted taking into account the kosmotropic (water-structuring) or chaotropic (water-structure-breaking) nature of ionic liquids, as compared to other inorganic salts.

Keywords. Ionic Liquids; Salting-out effects; Aqueous *PEG* solutions; Kosmotropic and chaotropic salts.

Introduction

In recent years ionic liquids have been publicized as alternative solvents in many different applications ranging from organic synthesis and catalysis [1], to extraction and separation processes [2]. Generally, their negligible volatility [3], low flammability [4], and thermal stability [5] contributed to their recognition as ambient-friendly media. These characteristics, although not universal for the ionic liquids as a class, granted them the common perception that the implementation of a recycling process would be facilitated. Moreover, the potential diversity of ionic liquids (originating from the immense number of cation and anion permutations) allows for their use in a tunable fashion, as tailor-made for specific tasks [1, 6].

Aqueous solutions of polyethylene glycol (*PEG*) exhibit high-temperature, closed-loop liquid–liquid immiscibility phase behaviour, *i.e.* a two-phase region bounded by an upper and a lower critical solution temperature envelopes (UCST and LCST, in which $T_{UCST} > T_{LCST}$). Besides its importance at a fundamental, theoretical level [7], this rare phenomenon also allowed the use of *PEG* aqueous solutions in many separation and extraction processes (Refs. [8, 9] and references therein). In these applications, inorganic water-structuring (kosmotropic) salts are often added to *PEG* aqueous solutions in order to establish another particular type of alternative solvents: aqueous biphasic systems (ABS).

Abraham et al. [10] showed that both aqueous solutions of ionic liquids and ABS might be considered as novel liquid partitioning systems. Several studies [9, 11, 12] have also demonstrated that the addition of kosmotropic inorganic salts can cause liquid–liquid phase demixing in aqueous solutions of ionic liquids, eventually forming ABS. In this paper, we have investigated the effects of the addition of water-miscible ionic liquids (1-ethyl-3-methylimidazolium ethyl sulfate, [C_2mim][$EtOSO_3$], and 1-alkyl-3-methylimidazolium chloride, [C_nmim]Cl with $n = 2, 4, 6, 8$, or 10) on the phase behaviour

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of aqueous *PEG* solutions with a polymer average molecular mass of 35,000 Da (*PEG* 35,000).

Results and Discussion

Cloud-point temperature data – that correspond to the perturbation of the original LCST locus (henceforth called LCST-type of locus) of the binary *PEG* + water mixtures – as a function of the weight fraction of ionic liquid in the (*PEG* 35,000 + water + ionic liquid) solutions are illustrated in Fig. 1 and reported in Table 1. The concentration of the polymer in the initial binary aqueous solution was always 5 wt%, a value close to the critical concentration of *PEG* 35,000 in aqueous solution.
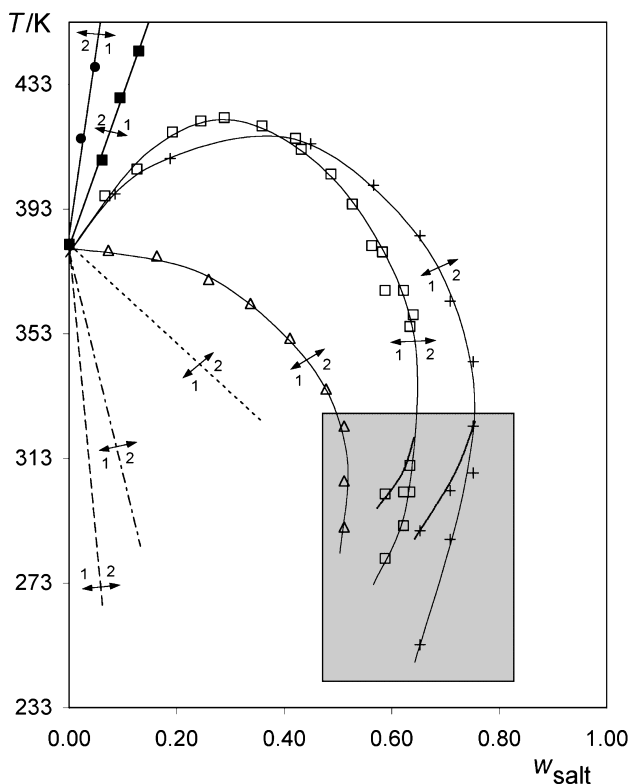
Fig. 1. Salting-in and salting-out effects in (*PEG* 35,000 + water + salt) solutions: cloud-point temperature, T/K, as a function of weight fraction of salt, w_{salt}. Ionic liquids data: ●: [C$_8$*mim*]Cl; ■: [C$_6$*mim*]Cl; □: [C$_4$*mim*]Cl; Δ: [C$_2$*mim*]Cl; +: [C$_2$*mim*][*Et*OSO$_3$]. Lines are merely guides to the eye. Inorganic salts data [8(b)]: dotted line: KI; dash-dotted: NaCl; dashed: Na$_3$PO$_4$. The numerals and double arrows indicate the direction of the demixing process (one-phase (1) and two-phase (2) regions). The shaded area marks the heterogeneous gel-like phase

Table 1. Cloud-point temperature, T/K, as a function of the weight and mole fractions of ionic liquid, w_{IL} and x_{IL}, in (*PEG* 35,000 + water + ionic liquid) ternary solutions

w_{IL}	x_{IL}	T/K	w_{IL}	x_{IL}	T/K
[C$_2$*mim*][*Et*OSO$_3$]			[C$_4$*mim*]Cl		
0.08526	0.00726	397.8	0.06635	0.00749	397.2
0.18820	0.01787	409.2	0.12645	0.01514	405.7
0.44929	0.06018	413.9	0.19199	0.02461	417.7
0.56623	0.09294	400.6	0.24508	0.03332	421.2
0.65252	0.12847	384.4	0.28882	0.04134	422.3
0.65252	0.12847	253.1	0.35918	0.05617	419.6
0.65252	0.12847	289.7	0.42099	0.07166	415.6
0.70888	0.16047	363.4	0.19199	0.02461	417.7
0.70888	0.16047	286.9	0.43162	0.07461	412.1
0.70888	0.16047	302.6	0.48753	0.09174	404.1
0.75197	0.19223	344.0	0.52702	0.10579	394.5
0.75197	0.19223	308.3	0.56295	0.12031	381.2
0.75197	0.19223	323.3	0.58313	0.12931	379.2
			0.58808	0.13163	366.8
[C$_2$*mim*]Cl			0.62218	0.14882	366.8
0.00000	0.00000	381.6	0.63388	0.15528	355.2
0.07273	0.00713	379.7	0.64029	0.15895	359.0
0.16313	0.01752	377.9	0.58795	0.13157	280.8
0.25927	0.03103	370.4	0.58795	0.13157	301.5
0.33737	0.04452	362.6	0.62218	0.14882	291.3
0.41097	0.06001	351.5	0.62218	0.14882	302.1
0.47816	0.07736	335.2	0.63388	0.15528	310.6
0.51137	0.08740	323.3	0.63388	0.15528	302.1
0.51137	0.08740	305.7			
0.51137	0.08740	290.9	[C$_6$*mim*]Cl		
			0.06181	0.00599	408.65
[C$_8$*mim*]Cl			0.09466	0.00948	428.65
0.02167	0.00178	415.65	0.12934	0.01341	443.65
0.04792	0.00403	438.65			

It is immediately evident from the two observed "turnovers" in the shape of the (Δ), (□), and (+) curves represented in Fig. 1 that in those cases (i) the first high-temperature turnover corresponds to the crossover between salting-in and salting out effects, and (ii) the second turnover is related to the appearance of a new low-temperature immiscibility domain. The latter is probably a consequence of a hidden low-temperature UCST, UCST(II), in the *PEG* + water mixtures – thus, henceforth called UCST(II)-type of cloud-points.

For [C$_6$*mim*]Cl, [C$_8$*mim*]Cl, and [C$_{10}$*mim*]Cl, the one-phase region of the ternary solution expands rapidly (raise in the LCST-type of cloud-point temperatures) as the ionic liquid concentration is increased: a dramatic salting-in effect occurs, as depicted in Fig. 1 by the steep, positive slopes of the corresponding (●) and (■) lines. In the case of the (*PEG*

35,000 + H$_2$O + [C$_{10}$*mim*]Cl) system no transition points are presented in Fig. 1 since the solution remains homogeneous up to 200°C, even for very low concentrations of the ionic liquid. For further discussion, it should be noted that [C$_{10}$*mim*]Cl and [C$_8$*mim*]Cl present aqueous solution critical micelle concentrations of 0.014 and 0.051 weight fraction of ionic liquid [13]. On the other hand, one should keep in mind that these values were established at room-temperature, not at the LCST conditions of *PEG* + water.

Smaller salting-in effects occur when [C$_4$*mim*]Cl and [C$_2$*mim*][*Et*OSO$_3$] begin to be added to the *PEG* solutions, *cf.* the gentle and positive initial slopes of the (□) and (+) lines in Fig. 1. However, at higher concentrations of added salt the effect is reversed: a salting-out effect (drop in the cloud-point temperatures) takes over, as evidenced by the negative slopes and the resulting reduction of the one-phase region. The addition of [C$_2$*mim*]Cl produces a salting-out effect, even for small concentrations of added salt, *cf.* the initial negative slope of line (△) in Fig. 1.

As one moves to even higher ionic liquid concentrations, the systems discussed in the previous paragraph cross from a LCST-type of cloud-point locus at high temperature to an UCST-type, UCST(II), at low-temperature. Thus, a new low-temperature two-phase region has emerged. Further addition of ionic liquid in (*PEG* + H$_2$O + [C$_2$*mim*]Cl or [C$_4$*mim*]Cl or [C$_2$*mim*][*Et*OSO$_3$]) mixtures induces the merging of the two demixing loci, meaning that for higher ionic liquid concentrations only a two-phase region is found irrespective of the temperature (right-hand side of Fig. 1).

When these systems are in the low-temperature, two-phase UCST(II)-type region they exhibit metastable gel-like phases (marked by the shaded area in Fig. 1). In this region, the kinetics of the phase-transition are very slow leading to significant hysteresis effects in the cloud-point determinations (*cf.* forked ends of the (□) and (+) lines in Fig. 1 and the Experimental below).

The results can be discussed in a phenomenological way in terms of the kosmotropic *versus* chaotropic nature of ionic salts, *i.e.* their ability to enhance or destroy the structure of water solutions, and how this characteristic affects the fluid phase behaviour of *PEG* aqueous solutions. For comparison purposes, salting-out effects of three inorganic salts (KI, NaCl, and Na$_3$PO$_4$) are also depicted in Fig. 1.

One of the factors causing the existence of LCSTs in *PEG* aqueous solutions is the hydrogen bonding (HB) between the water molecules and the oxygen atoms contained in the ether groups of the polymeric chain. These interactions (and their dependence on temperature) are paramount in defining the enthalpic and entropic contributions to the excess *Gibbs* energy of mixture and determine the phase behaviour of the solutions [14].

The salting-out effect produced by kosmotropic inorganic salts is easy to understand in this context: the addition of a water-structuring salt makes water less available to perform HB with *PEG* (HB is now occurring mainly between "better organized" water molecules) causing an easier demixing of the solution (*cf.* the drop in the cloud point temperatures in Fig. 1 for all inorganic salts). Conversely, the addition of a chaotropic ionic liquid [9], particularly one with a long alkyl chain, makes water more available to perform HB with *PEG* (less water-water HB in "less organized" water) originating a less favourable demixing of the solution. An additional explanation could be rationalized in terms of the tendency of these long alkyl-side-chain ionic liquids to self-aggregate (namely by micelle formation) [13]. Whether these organized structures with enhanced solubility ability persist at the relatively high temperatures of the LCST demixing region of *PEG* + water solutions remains elusive as data are only known for ambient conditions. In this context, it is important to stress that molecules capable of forming micelles and other self-aggregation structures generally also have surfactant and co-solvency properties. In this case, one can easily imagine that the ionic liquid ions with long alkyl side chains can act as a surfactant between water (IL-water interactions *via* the charged parts of the ionic liquid ions) and the *PEG* polymeric chains (IL-*PEG* interactions *via* the long alkyl side chains of the ions) replacing the role of HB between *PEG* and water and avoiding the demixing of the *PEG*-water solutions.

Short-chained ionic liquids are somewhere in between: they can produce some water-structuring effect through the polar parts of the anion or cation that is partially compensated by chaotropic effects caused by the non-polar parts of the alkyl side-chains. This balance between kosmotropic and chaotropic contributions is one of the factors that can help explain the non-monotonic behaviour of the curves corresponding to the solutions containing [C$_2$*mim*]Cl,

[C$_4$mim]Cl, and [C$_2$mim][EtOSO$_3$]. It must be stressed at this point that all salting-out effects induced by the ionic liquids studied in this work are weak as compared to those caused by inorganic salts: even the most "kosmotropic" ionic liquid, [C$_2$mim]Cl, is less so than one of the least "kosmotropic" inorganic salts like potassium iodide (*cf.* Fig. 1).

The other reason why the addition of short-alkyl-chain ionic liquids to the *PEG* aqueous solutions exhibit non-monotonic salting effects and also the existence of the UCST-type of lines is related to the large amount of these ionic liquids that can be added to the *PEG* aqueous solutions. Since the salting effects are quite weak for the short-alkyl-chain ionic liquids one is able to follow the cloud-point lines up to large concentrations of ionic liquid (right hand-side of Fig. 1). This means that the fluid phase behaviour is no longer controlled just by the balance between water-*PEG* and water–water hydrogen-bonding but also by the amount of hydrogen bonding between the ionic liquid and water. In other words, *PEG*-water HB is less frequent not because water is more structured due to the presence of a kosmotropic ionic liquid but simply because there is less water available to perform the HB due to its interactions with large amounts of a water-soluble ionic liquid.

In conclusion, ionic liquids and inorganic salts can be used to fine-tune salting (-in or -out) effects in *PEG* aqueous solutions (*cf.* the branching out LCST-type lines starting at 380 K on the left side of Fig. 1). In fact, strongly chaotropic ionic liquids can be used as switches to trigger miscibility in *PEG* aqueous solutions, in a fashion similar to the use of inorganic salts that are commonly used to trigger the opposite effect. A combination of the two types of salts can thus offer us novel ways to perform partitioning processes.

Experimental

Materials

Polyethylene Glycol with 35,000 average molecular mass (*PEG* 35,000), and 1-ethyl-3-methylimidazolium ethylsulfate ([C$_2$mim][EtOSO$_3$], ECOENG 212®) were purchased from Merck and Solvent Innovation (Germany), respectively. The stated purity of [C$_2$mim][EtOSO$_3$] was better than 98 mass %. 1-Alkyl-3-methylimidazolium chloride ionic liquids ([C$_n$mim]Cl, where $n = 2, 4, 6, 8,$ or 10) were synthesized at QUILL (The Queen's University Ionic Liquid Laboratories, Belfast) according to a recipe found elsewhere [15], where they underwent first-stage purification. All ionic liquid were thoroughly degassed, dried, and freed from small traces of volatile compounds by applying vacuum (0.1 Pa) at moderate temperatures (60–80°C) for typically 48 h. The water content of all ionic liquids (though not relevant for the present study) and chloride content in [C$_2$mim][EtOSO$_3$] were analyzed. In the case of chloride-based ionic liquids, *Karl-Fischer* coulometric titrations revealed water contents in the range of 1500–2000 ppm, whereas for [C$_2$mim][EtOSO$_3$] it was 120 ppm. Potentiometric analyses using a chloride-selective electrode (Cole Parmer) calibrated using [C$_2$mim]Cl have shown a chloride content of 310 ppm in [C$_2$mim][EtOSO$_3$]. This ionic liquid was not further treated to decrease the chloride content since the aforementioned value is acceptable for the present work and its reduction in case of water-miscible ionic liquids is cumbersome, with doubtful efficiency [16]. Water was doubly distilled and deionized (Milipore Co. equipment, Bedford, MA).

Experimental Procedure

The loci of the onset of immiscibility (cloud-points) were determined at a nominal pressure of 0.1 MPa using a visual detection of the phase demixing (naked eye observation of turbidity followed by phase separation). Samples of the solutions were prepared in narrow Pyrex-glass vials equipped with stirring. After the freezing of the solutions under vacuum, the vials were sealed. On warming and melting, the liquid inside the vials always occupied almost its entire internal volume (0.5 cm^3), allowing only for a small dead volume of vapour phase. The vials were placed in a glass thermostat beaker of 2 dm^3 filled with ethanol (from 253 to 293 K), water (from 293 to 333 K), or silicon oil (up to 473 K) as the thermostatic fluid. The solutions were cooled or heated with continuous stirring in order to determine the cloud-points, and three to four independent determinations – with the last run being carried out very slowly (the rate of temperature change near the cloud-point was not greater than 5 K h^{-1}) – were performed. Two modes were used: (i) starting in the one-phase region, upon heating or cooling, the temperature at which the first sign of turbidity appeared was taken as the temperature of the liquid-liquid phase transition; conversely, (ii) starting in the heterogeneous region, upon heating, the temperature at which the last sign of turbidity disappeared was taken as the temperature of the phase transition. Temperature was monitored using a four-wire platinum resistance thermometer coupled to a Keithley 199 System DMM/Scanner.

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