Formation of Aqueous Biphasic Systems with an Ionic Liquid Induced by Metallic Salts: Nanoscopic Views from Molecular Dynamics Simulations

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Supporting Information

ABSTRACT: The formation of aqueous biphasic systems (ABSs) based on aqueous ionic liquid (IL)/salt mixtures has been investigated via molecular dynamics simulations (with IL butyl-methyl-imidazolium triflate; salts NaCl, CsCl, SrCl₂, and EuCl₃). The analysis of ion distributions, solvation, and mutual interactions during the dynamics reveals the heterogeneity of all solutions due to ion segregation into mutually exclusive IL and salt domains, even in monophasic solutions (“ionic sociology”). Ion segregation and ABS formation are found to increase with (i) the salt content and (ii) the IL content, (iii) in the order Na⁺ < Sr²⁺ < Eu³⁺, and (iv) when the IL ion “polarity” is diminished, following experimental trends. The structuration of the solution is rationalized as a synergistic water transfer from the best donating ion pair (first hydration shell of hydrophobic moieties of IL ions) to the best accepting pair (Mⁿ⁺ and Cl[−] ions, beyond their first shell). In ABSs, the IL- and salt-containing phases are linked by a well-defined “interface” that decreases in width when MCl_n becomes more hydrophilic and/or more concentrated. In the IL-rich phase of ABSs, the hydration of IL ions and their mutual interactions are shown to be similar to those displayed at aqueous interfaces.

1. INTRODUCTION

Aqueous biphasic systems (ABSs), based on water as a single solvent, play an important role in many domains such as the separation, extraction, and purification of biological systems or the treatment of polluted water.^{1,2} Generally, ABSs are formed by mixing two aqueous phases containing either two polymers or a polymer plus a salting-out inducing salt or specific salt–salt combinations at appropriate concentrations and temperature. An interesting class of ABSs is based on aqueous solutions of ionic liquids (ILs) to which salting-out inorganic salts can be added to promote separation into two phases. In practice, such IL-based ABSs have many advantages like low viscosity, resistance to emulsification, quick phase separation, high extraction capabilities, and benefit from a potentially “infinite” panoply of IL components designed for a given use. In 2003, Rogers and colleagues reported that addition of a water-structuring salt, K₃PO₄, to an aqueous concentrated solution of 1-butyl-3-methylimidazolium chloride induced the formation of an upper IL-rich phase and a lower K₃PO₄-rich phase,³ as for classical poly(ethylene glycol) (PEG)-/salt-based ABSs.^{4,5} Since then, many combinations of IL components and salting-out agents have been studied, both to define the underlying driving forces and to establish general guidelines for specific purposes.^{2,6,7} Similar salt-specific effects have also been observed with the related biphasic extraction systems based on hydrophobic ILs.⁸ Generally, for a given M_xX_y salt, ABS

formation is enhanced by the size and hydrophobicity (or reduced hydrophilicity) of ionic components of the IL^{9,10} and by the hydrophilic and salting-out character of the dissolved M_xX_y salt,^{11–14} following the Hofmeister ion series¹⁵ whose interpretation in terms of thermodynamic and structural features remains controversial.^{11,16,17} The hydrophilic/hydrophobic character^{18,19} is often related to the Gibbs free energy of ion hydration²⁰ and to concepts like structure breaking (“chaotropic”)/making (“cosmotropic”) features in water.^{18,21–25} Recently, Shahriari et al.¹⁴ correlated the amount of IL necessary to form an ABS and the entropy of hydration of the salt ions, drawing the implication of a dominant entropic driving force for ABS formation, as for hydrophobic ILs^{11,26,27} or polymer-based ABSs,^{28,29} presumably due to the formation of “water–ion complexes”. Insights into ion solvation and into their mutual interactions have been gained from NMR spectroscopy and simulations in aqueous salt solutions containing IL ions,^{11,27,30,31} but these may not suffice to fully describe the “organization” of the solution, the distribution of all ions, and finally the formation of ABSs in conditions when it occurs. Likewise, the nature of the aqueous–aqueous interface of ABSs has neither been characterized so far nor compared,

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Figure 1. Ternary phase diagram of the [BMI][TfO] IL, water, and MCl_n salts: CsCl (+), NaCl (●), and $SrCl_2$ (■), adapted from ref 14. The simulated solutions are marked B to F (NaCl; red), G to I (CsCl; yellow), and J and K ($SrCl_2$; green).

for instance to aqueous interfaces with hydrophobic (water-immiscible) ILs.^{32–37}

This led us to consider a well-documented case and to explore by molecular dynamics (MD) simulations to what extent homogeneous aqueous mixtures of IL and dissolved inorganic MCl_n salts separate at the nanoscopic level and to analyze what are the related solvation patterns and driving forces. The selected IL, based on BMI^+ (butyl-methylimidazolium⁺) and TfO^- (triflate $CF_3SO_3^-$) ions, is readily soluble in water, as are the MCl_n salts. Their ternary diagrams, adapted from ref 14, are shown in Figure 1; the systems at the right-hand side of a curve are biphasic and those of the left-hand side are monophasic, while a given curve corresponds to the intermediate states (“cloud points”). Here, the ABS formation increases with the IL and/or salt content and in the order $CsCl < NaCl < SrCl_2$, that is, with the M^{n+} charge and hydrophilicity. The simulated solutions are marked B to K in Figure 1. Additionally, a “neat” IL aqueous solution A (without added salt) was studied as a reference, as well as the $EuCl_3$ solutions L to P, expected to display the strongest ABS-promoting effect. Their characteristics are given in Tables 1

Table 1. Characteristics of the Simulated Solutions A to P^a

	IL number of pairs	MCl_n salt number of pairs	[IL] mol kg ^{−1}	[MCl_n] mol kg ^{−1}
A	148	0	1.03	0.00
A2	592	0	1.03	0.00
B	148	148 NaCl	0.97	0.79
C	148	296 NaCl	0.92	1.59
D	148	444 NaCl	0.87	2.38
E	296	296 NaCl	1.83	1.29
F	296	444 NaCl	1.74	1.94
D2	592	1776 NaCl	0.87	2.38
G	148	296 CsCl	0.76	1.59
H	148	444 CsCl	0.68	2.38
I	296	700 CsCl	1.13	3.05
J	148	148 $SrCl_2$	0.88	0.79
K	148	296 $SrCl_2$	0.77	1.59
L	148	296 $EuCl_3$	0.67	1.59
M	148	148 $EuCl_3$	0.81	0.79
N	148	74 $EuCl_3$	0.91	0.40
O	148	50 $EuCl_3$	0.94	0.27
P	148	25 $EuCl_3$	0.98	0.13

^aUnless otherwise specified, the box is “standard” and contains 8000 H_2O ; the “big” box (A2 and D2 systems) contains 32 000 H_2O . An extended version of the table is given in Table S1.

and S1 of the Supporting Information. The simulations were conducted in a consistent manner, in terms of water and ion content and of computational protocol, starting from aqueous solutions of randomly dispersed IL and salt ions (see e.g., Figure S1). During the dynamics, ions segregated and, in some cases, separated into two distinct phases (ABS formation), affording microscopic insights into the ion segregation and solution reorganization presented and analyzed below.

2. METHODS

The solutions were simulated by classical MD simulations using the AMBER16³⁸ software, in which the potential energy U is empirically represented by a sum of bond and angle harmonic deformations, of dihedral torsions, and by pairwise additive 1-6-12 (electrostatic + van der Waals) interactions between nonbonded atoms (eq 1)

$$\begin{aligned}
 U = & \sum_{\text{bonds}} k_r(r - r_0)^2 + \sum_{\text{angles}} k_\theta(\theta - \theta_0)^2 \\
 & + \sum_{\text{dihedrals}} k_\phi[1 + \cos(n\phi + \phi_0)] \\
 & + \sum_{\text{atom } i} \sum_{j \neq i} 4\epsilon_{ij} \left[\left(\frac{\sigma_{ij}}{r_{ij}} \right)^{12} - \left(\frac{\sigma_{ij}}{r_{ij}} \right)^6 \right] + \sum_{\text{atom } i} \sum_{j \neq i} \frac{q_i q_j}{\epsilon_0 r_{ij}}
 \end{aligned} \quad (1)$$

Solute and solvent atom pairs i and j display Coulomb interactions via their charges q_i and q_j , respectively. Cross terms in van der Waals interactions were constructed using the Lorentz–Berthelot rules.

Water was represented with the TIP3P model.³⁹ For the ion parameters, we used the consistent Na^+ , Cs^+ , and Cl^- values from Joung and Cheatham et al.⁴⁰ and Sr^{2+} and Eu^{3+} values from refs 41 and 42, respectively. The BMI^+ parameters are from de Andrade et al.⁴³ and the TfO^- ones are from Baaden et al.⁴⁴ A first set of simulations, conducted with integral ± 1 charges on IL ions (IL ^{± 1} model), produced some instances in conflict with experiment. We thus decided to use reduced charges of ± 0.9 (IL ^{± 0.9} model with atomic charges scaled by 0.9), as in previous work on IL/water biphasic mixtures.^{45–48} Formally reducing the ionic charges to a degree mimics the anion to cation electron transfer in the condensed IL phases (e.g., [BMI][PF₆] or [BMI][Tf₂N])^{35,49} and also better accounts for the solubility of IL ions in an aqueous phase.⁴⁶ The 1–4 van der Waals and 1–4 Coulombic interactions were scaled down by 2.0 and 1.2, respectively. The solutions were simulated with three-dimensional (3D) periodic boundary conditions, using an atom-based cutoff of 12 Å for nonbonded interactions and correcting for the long-range electrostatics by using the Ewald summation method. The characteristics of all simulated systems are given in Tables 1 and S1 of the Supporting Information. The MD simulations were performed at 300 K starting with random velocities. The temperature was monitored via a coupling to a thermal bath using the Berendsen algorithm⁵⁰ with a relaxation time of 0.2 ps. In the (NPT) simulations, the pressure was similarly coupled to a barostat with a relaxation time of 0.2 ps. A time step of 2 fs was used to integrate the equations of motion via the Verlet leapfrog algorithm.

For each system, a “random” mixture of MCl_n and IL ions (M^{n+} , Cl^- , BMI^+ , and TfO^-) was prepared in a box of 8000 or 32 000 H_2O molecules (“standard” box and “big” box,

respectively). After 1000 steps of energy minimization, 0.25 ns of dynamics was performed to allow the solvent to relax around the solute. This was followed by a dynamics run of 0.25 ns at constant volume and of 1 ns at a constant pressure of 1 atm. Note that the relaxed box sizes may somewhat differ from one system to the other (see Table S1 of the [Supporting Information](#)). Furthermore, in some cases, some salt reorganization already occurred at this preparation stage. The evolution of the mixture was then followed for 500 ns of dynamics (NVT ensemble), sometimes extended up to 1000 ns.

2.1. Analysis of Results. The trajectories were analyzed using our MDS software.⁵¹ Snapshots were drawn with the VMD software.⁵² The radial density functions (RDFs) were calculated, unless otherwise specified, between selected atoms, N_{butyl} or C_{TfO} of IL ions, M^{n+} or Cl^- ions, and $O_{\text{H}_2\text{O}}$, $H_{\text{H}_2\text{O}}$ atoms. The distributions of M^{n+} and Cl^- , BMI^+ and TfO^- ions, H_2O molecules in the box, and the corresponding mass-weighted densities d were calculated along the z -coordinate and averaged over different time periods (typically the last 5 or 50 ns) specified in the relevant figures. The total potential energy E_{pot} and interactions between selected neutral groups (IL ions, MCl_n ions, and water) were calculated using Ewald summation. To simply “measure” the extent of ion segregation and phase separation at a given time, a “demixing index” ξ_{demix} defined by $1/\xi_{\text{demix}} = 1/d_{\text{IL}} + 1/d_{\text{wat}}$ where d_{IL} and d_{wat} are the densities of IL and water, respectively, was used, as in previous work,^{46,53} in “nanoboxes” of $0.8 \times 0.8 \times 1.0 \text{ nm}^3$ volume. The simulation box was thus split into such nanoboxes, and the corresponding normalized ξ_{demix} was averaged over all boxes. Thus, in principle, ξ_{demix} ranges from 1 (for randomly dispersed components) to 0 (for two juxtaposed immiscible components, for example, water and “oil”).

3. RESULTS

In the following, we first describe the “neat IL” aqueous solution A as a reference. The effects of salt concentration (mainly focused on NaCl) and of IL concentration are presented in [Section 3.2](#). In [Section 3.3](#), we compare the different MCl_n salts (CsCl , NaCl , SrCl_2 , and EuCl_3) at the same metal and IL content. Ion/ion interactions and hydration in the above series are then analyzed and compared to the purely aqueous solutions ([Section 3.4](#)). Although all simulations have been conducted with both $\text{IL}^{\pm 0.9}$ and $\text{IL}^{\pm 1}$ models, we restrict the presentation of IL/salt mixtures ([Sections 3.2–3.4](#)) to the $\text{IL}^{\pm 0.9}$ results. The $\text{IL}^{\pm 1}$ results are given in the [Supporting Information](#). The ionic content of a simulated box is noted in short, for example, 128 $\text{IL}^{\pm 0.9}/296 \text{ NaCl}$ for 128 BMI^+TfO^- ($\text{IL}^{\pm 0.9}$ charges) and 296 Na^+Cl^- salt ions. The evolution of the demixing index ξ_{demix} during the first 100 ns of the different dynamics is plotted in [Figure 2](#) for the NaCl- and for the MCl_n -containing solutions, and the final average ξ_{demix} values are collected in [Table 2](#).

3.1. “Neat” Aqueous IL Solution is Heterogeneous Due to Hydrophobic Contacts. Solution A was simulated at the same IL and water content (148 BMI^+TfO^- , 8000 H_2O per box) as in salt-containing ones. The main results are shown in [Figures 3](#) and S2 of the [Supporting Information](#). As seen in the final snapshots, in the absence of the MCl_n salt, the solution is monophasic and the IL ions are dispersed in the box. The water density profile along the z -axis of the box, averaged over the last 100 ns, is flat. The BMI^+ and TfO^- density curves are

Figure 2. $\text{IL}^{\pm 0.9}$ salt solutions: demixing index ξ_{demix} as a function of time (0 to 100 ns). Left: NaCl solutions A (148/0 black), B (148/148 orange), C (148/296 red), D (148/444 purple), E (296/296 green), F (296/444 blue). Right: MCl_n solutions C (NaCl red), G (CsCl purple), K (SrCl_2 green), L (EuCl_3 cyan).

quasi-superimposable but not flat, indicative of IL heterogeneities. This feature is also visible by averaging over different time periods: 10–200, 100–200, 150–200, or 190–200 ns ([Figure S3](#) of the [Supporting Information](#)).

According to the RDFs (see integration numbers in S2 of the [Supporting Information](#)), the BMI^+ and TfO^- ions are mostly separated and well hydrated, by ca. 8–10 H_2O molecules in their first shell. They also sometimes form loose pairs, corresponding to a first peak in the $\text{BMI}^+\cdots\text{TfO}^-$ RDFs that integrates to 0.32 (within 5 Å). Of relevance for the formation of ABSs, we note that the shortest $\text{BMI}^+\cdots\text{TfO}^-$ contacts do not correspond to electrostatic but to hydrophobic attractions (between $\text{CF}_3(\text{TfO})$ atoms and either the π -ring or the butyl chain of BMI^+), whereas the more polar SO_3^- and ring-(imidazolium)⁺ moieties are well hydrated and separated. Hydrophobic contacts are likewise observed between TfO^- anions (via their $\text{CF}_3(\text{TfO})$ groups; see snapshots and the $\text{C}_{\text{TfO}}\cdots\text{C}_{\text{TfO}}$ RDF that integrates to 0.27), in spite of their Coulombic repulsions. Similar features are observed in the “standard” (A) and “big” boxes (A2), pointing to the critical role of hydrophobic interactions for IL ion association. On the other hand, there are no π - π stacking contacts between imidazolium cations.

Comparing now the $\text{IL}^{\pm 0.9}$ to the $\text{IL}^{\pm 1}$ models ([Figure S2](#) and [Table S2](#) of the [Supporting Information](#)), we note that there is a little bit more $\text{BMI}^+\cdots\text{TfO}^-$ and $\text{TfO}^-\cdots\text{TfO}^-$ pairing (and hence presumably more IL association) with the less “polar” $\text{IL}^{\pm 0.9}$ one than with the $\text{IL}^{\pm 1}$ one, whereas the $\text{IL}^{\pm 0.9}$ ions are somewhat less well hydrated than the $\text{IL}^{\pm 1}$ ones.

3.2. Adding NaCl, CsCl, or SrCl_2 at Different Concentrations to an Aqueous Solution of BMI^+TfO^- Ions: from Mixed to Separated Phases. In this section, we first compare solutions at a fixed IL content (148 BMI^+TfO^- per box) and different MCl_n salt concentrations and then solutions at different IL concentrations, depicted with the $\text{IL}^{\pm 0.9}$ model.

3.2.1. Effect of Salt Concentration. Three NaCl solutions (B, C, and D, of salt/IL ratios of 1:1, 2:1, and 3:1, respectively) were first considered. As seen from final snapshots ([Figure 4](#)) and average density curves ([Figure 5](#)), all three are heterogeneous and display increased ion segregation from solutions A (without NaCl) to B and from B to D. Accordingly, the ξ_{demix} index decreases in the A–D series: ≈ 0.74 , 0.65, 0.62, and 0.48, respectively.

In solution D, the ions partition into two well-defined slabs, indicating phase separation. At 500 ns, the salt slab contains the majority of the Na^+ and Cl^- ions but only ca. 3 IL ion pairs. In contrast, the IL slab contains only ca. 10 NaCl ion pairs but still much water (≈ 1200 of the 8000 H_2O molecules), supporting the view that the two juxtaposed phases are mainly

Table 2. Final Demixing Index ξ_{demix} for Systems A to L (Averages during the Last 10 ns; Fluctuations are about 0.02)

solution	A	B	C	D	E	F	G	H	I	J	K	L
IL $^{\pm 1}$	0.73	0.74	0.70	0.64	0.71	0.65	0.71	0.68	0.63	0.70	0.65	0.45
IL $^{\pm 0.9}$	0.74	0.65	0.62	0.48	0.56	0.47	0.61	0.53	0.41	0.58	0.49	0.42

Figure 3. Neat IL aqueous solution A (IL $^{\pm 0.9}$ model). Snapshot at 200 ns with the IL only (line 1). Line 2: Average densities along the z -axis of the box (distances in Å) during 100–200 ns (BMI $^+$ orange, TfO $^-$ purple, water blue); C_{TfO}, N_{Butyl} and O_{H₂O} are the reference centers. Line 3: IL...IL RDFs as a function of the distance (in Å): TfO...BMI (purple), TfO...BMI (gray), and BMI...BMI (blue). Line 4: Snapshots of IL...IL contacts. An extended version of the figure, including IL $^{\pm 1}$ results is given in Figure S2. The density curves averaged over different time periods are shown in Figures 5 and S3.

Figure 4. 148 [BMI][TfO] $^{\pm 0.9}$ /NaCl solutions B–D. Snapshots after 500 ns, with either all components (left) or with NaCl hidden (right). Color codes: IL ions green, water cyan, Cl $^-$ orange, and Na $^+$ yellow.

aqueous. This picture is consistent with the density curves: IL and salt (or water) densities, averaged over the last 5 ns, display anticorrelated plateaus. The IL density drops close to zero in the NaCl slab, as does the NaCl density in the IL slab. Note that the distribution curves of individual Na $^+$ and Cl $^-$

ions are superimposable, as are the BMI $^+$ and TfO $^-$ curves (Figure S5 of the Supporting Information), indicating that each phase is overall neutral, with neutral contributions of Na $^+$ Cl $^-$ ions and of IL ions, respectively. Densities averaged over a longer time period (50, instead of 5 ns) afford the same features, but the high IL density profile becomes somewhat “bell-shaped” (Figure S4 of the Supporting Information) because of ion passage across the “interface”.

In the more dilute C and B solutions, ions also segregate, without forming clear slabs, however, because the mutual IL/NaCl exclusion has decreased together with the NaCl concentration. B is overall monophasic but contains distinct NaCl-rich and IL-rich domains: the IL density peak (near $z \approx 120$ Å) correlates with a minimum of salt and water densities. These domains are expected to exchange with each other at timescales longer than the simulated ones, yielding, on average, flat density curves. For solution C, the density profiles are more “D-like” than “B-like”, showing that C, experimentally monophasic, is quite heterogeneous at the nanoscopic scale.

The effect of salt concentration is likewise observed with the CsCl solutions G and H (of CsCl/IL ratios 2:1 and 3:1, respectively) or the SrCl $_2$ solutions J and K (of SrCl $_2$ /IL ratios 1:1 and 2:1, respectively): the ξ_{demix} index decreases from 0.61 (in G) to 0.53 (in H) and from 0.58 (in J) to 0.49 (in K). Snapshots (Figure 6) and density curves (Figure 5) also support enhanced ion segregation and phase separation when the salt gets more concentrated. For instance, in the IL domain from J to K, the IL density profile becomes narrower and of higher amplitude, whereas the water content decreases. The highest IL and lowest salt densities, “bell-shaped” in J, become rather uniform in K where the interfacial domain is sharper, on the average. From J to K, the IL density increases in the IL slab (from ≈ 0.7 to 0.8), whereas the lowest SrCl $_2$ density remains close to zero, supporting full phase separation. This contrasts with the CsCl solutions G and H (experimentally monophasic), where the IL density maxima correspond to a significant CsCl salt content, more in G than in H, and the curves are rather “bell-shaped”. There is thus less IL/salt separation with CsCl than with SrCl $_2$ at both concentrations, following experimental trends.¹⁴

3.2.2. Effect of IL Concentration. Phase separation increases also with the IL concentration. To investigate this feature, we considered the NaCl solutions C and D described above, but doubled their IL content (solutions E and F, respectively). As seen in snapshots (Figure 7) and densities (Figure 5), the IL domain becomes now broader and displays a wider plateau of density. The IL density $d_{\text{IL-max}}$ is higher when NaCl is most concentrated (D and F solutions: $d_{\text{IL-max}} \approx 0.8$) than when NaCl is less concentrated (C and E solutions: $d_{\text{IL-max}} \approx 0.7$). Regarding the ξ_{demix} index, it decreases at the lower NaCl concentration (from 0.62 in C to 0.56 in E), indicating enhanced phase separation. At the higher NaCl concentration, however, ξ_{demix} remains similar (0.48 in D and 0.47 in F) because both simulated solutions are biphasic.

Simultaneously increasing the IL and salt content also enhances segregation: compare the CsCl solution G (148 IL/296 CsCl) to I (296 IL/700 CsCl). They both contain an IL

Figure 5. $IL^{\pm 0.9}/MCl_n$ solutions: densities along the z -axis (in Å) of the box, averaged over the last 5 ns. Color codes: IL green, salt red, and water blue. For each system, the experimental phase behavior is indicated, together with the extrema of water density.

Figure 6. $148 IL^{\pm 0.9}/MCl_n$ solutions at two $CsCl$ or $SrCl_2$ salt concentrations and $EuCl_3$ solution L. Snapshots after 500 ns, with either all components (left) or with salt hidden (right). Color codes: IL ions green, water cyan, Cl^- orange, Cs^+ brown, Sr^{2+} dark blue, and Eu^{3+} blue.

Figure 7. $296 IL^{\pm 0.9}$ solutions with $NaCl$ or $CsCl$. Snapshots after 500 ns with either all species (left) or with the salt hidden (right). Color codes: IL green, water cyan, Cl^- orange, Na^+ yellow, and Cs^+ brown.

slab, but the latter is better structured and contains less $CsCl$ in I than in G (Figures 5 and 7). Accordingly, from G to I, the interface between the two phases becomes sharper, whereas ξ_{demix} decreases (from 0.61 to 0.41).

3.3. Effect of M^{n+} Hardness on Phase Separation: Adding $NaCl$, $CsCl$, $SrCl_2$, or $EuCl_3$ at the Same Concentration to an Aqueous Solution of BMI^+TfO^- Ions. Let us now compare solutions of identical IL and water content to which a fixed amount of salt species ($NaCl$, $CsCl$, $SrCl_2$, and $EuCl_3$) has been added ($148 IL^{\pm 0.9}/296 MCl_n$

solutions C, G, K, and L, respectively). Their M^{n+} metal content is twice the IL content, whereas the Cl^- content is proportional to the M^{n+} charge. The evolution seen from snapshots (Figures 4 and 6) and density curves (Figure 5) fully supports increased phase separation when the M^{n+} charge increases, in accord with experiment.^{14,30} In parallel, the ξ_{demix} index decreases in the order $CsCl$ (0.61) $\approx$ $NaCl$ (0.62) $>$ $SrCl_2$ (0.49) $>$ $EuCl_3$ (0.42).

The $EuCl_3$ solution L is clearly biphasic; at 500 ns, all IL ions concentrate in an IL-rich slab from which $EuCl_3$ ions are excluded, whereas all Eu^{3+} and Cl^- ions are in an aqueous salt phase containing only ca. 3 BMI^+TfO^- ion pairs. On the average, the $EuCl_3$ density in the IL slab is zero, as is the IL density in the $EuCl_3$ slab. In the $SrCl_2$ solution K, ions partition similarly as in L, supporting complete phase separation.

This contrasts with the $CsCl$ solution G that does not display complete phase separation, in agreement with experiment,¹⁴ but the ions still segregate into different domains. Comparing now $CsCl$ to $NaCl$, we observe no clear distinction between the two salts, in spite of the higher ABS-promoting effect of $NaCl$: final snapshots, density curves, and ξ_{demix} values are similar.

The water content of the IL domain also decreases upon ion segregation along the $NaCl$, $SrCl_2$, and $EuCl_3$ series, where the lowest $d_{\text{wat-min}}$ water densities are ≈ 0.5 (in C), 0.4 (in K), and 0.2 (in L), respectively (Figure 6). A similar evolution is observed when the salt concentration increases; for instance, in the $NaCl$ series, $d_{\text{wat-min}}$ drops from ≈ 0.8 (in solution A) to 0.6 (in B), 0.5 (in C), and 0.4 (in D). Compare also solutions J to K or G to H (Figure 5). Thus, the higher the degree of ion segregation, the less humid is the IL phase, reflecting the “water dragging effect” of the salt on aggregation (see Section 3.4).

3.4. IL and Salt Ion Hydration and Mutual Interactions in the MCl_n -Containing Solutions: Comparison with the Pure Aqueous IL or Salt Solutions. In this section, we analyze how the IL segregation induced by MCl_n salts modulates the solvation of the M^{n+} , Cl^- , TfO^- , and BMI^+ ions and their mutual interactions in the final MCl_n/IL mixtures, as compared to the aqueous solutions of MCl_n alone (no IL) and of IL alone (solution A). For consistency, we first select solutions containing same numbers of MCl_n units (296) and of $IL^{\pm 0.9}$ ones (148), that is, solutions C, K, and L.

The M^{n+} and Cl^- ions being quite hydrophilic, their first hydration shell in a given mixture is very similar to the one in pure water (see RDFs in Figure S6 and Table S3 of the Supporting Information). For instance, there are 5.3 OH_2 around Na^+ and 6.8 H_2O around Cl^- in mixture C, versus 5.4 and 6.8, respectively, in pure water. Likewise, there are 6.9 OH_2 around Sr^{2+} and 6.1 H_2O around Cl^- in mixture K, versus 7.2 and 6.3, respectively, in pure water. One also observes some $M^{n+} \cdots Cl^-$ pairs, like in the mixture as in water (ca. 0.3 pairs per Na^+ , 0.9 per Sr^{2+} , and 2.8 per Eu^{3+}). All RDFs display a second peak, also similar in the mixture to the one in water. In the context of ABS formation, note that the $M^{n+} \cdots M^{n+}$ and $M^{n+} \cdots Cl^-$ RDFs have higher intensities in a given mixture (red curves of Figure S6 in the Supporting Information) than in water (blue curves), reflecting the MCl_n salt segregation induced by IL ions.

The hydration of TfO^- and BMI^+ ions and their mutual interactions are markedly modified by the added salts (see Figure 8 and Table 3). Their RDFs with water display a peak,

Figure 8. RDFs of IL ions in 148 $IL^{\pm 0.9}/MCl_n$ solutions A (no salt: yellow), B (148 $NaCl$: orange), C (296 $NaCl$: red), D (444 $NaCl$: purple), J (148 $SrCl_2$: cyan), K (296 $SrCl_2$: green), L (296 $EuCl_3$: black), and P (25 $EuCl_3$: blue). The corresponding integration numbers are given in Table 3.

indicating that they are coordinated to H_2O molecules in their first shell, in a decreasing number, n_{H_2O} , along the $CsCl$, $NaCl$, $SrCl_2$, and $EuCl_3$ salt series. For instance, when going from the $NaCl$ - to the $EuCl_3$ -containing mixture, $n_{H_2O}(BMI^+)$ drops from 14.7 to 9.7, whereas $n_{H_2O}(TfO^-)$ drops from 13.4 to 6.7. Thus, although most M^{n+} and Cl^- ions sit in salt-rich domains, they indirectly influence the hydration of IL ions, in keeping with the diminished water content of the IL domain. As a result, mutual interactions between IL ions (and hence segregation) are also strengthened by the added MCl_n salt: see the evolution of the $TfO^- \cdots BMI^+$ and $TfO^- \cdots TfO^-$ RDFs, where the first peaks (at ≈ 5 –6 Å) increase in magnitude when MCl_n becomes more hydrophilic (see also integration numbers in Table 3).

The influence of the added salt on the “IL structure” is likewise observed in the $NaCl$ series (Figure 8 and Table 3):

Table 3. Characteristics of RDFs of IL Ions in 148 IL^{±0.9}/MCl_n Solutions (See Figure 8): Integration Numbers (up to Indicated Distances)

solution		A	A2	B	C	D	J	K	L	P
	dry IL	0 NaCl	0 NaCl	148 NaCl	296 NaCl	444 NaCl	148 SrCl ₂	296 SrCl ₂	296 EuCl ₃	25 EuCl ₃
BMI...BMI (12 Å)	17.9	3.5	3.7	4.9	5.6	8.6	8.7	8.6	10.3	9.7
BMI...TfO (8 Å)	6.1	1.8	1.8	1.6	1.9	2.7	2.9	2.6	3.1	3.9
TfO...TfO (8 Å)	4.0	1.1	1.1	2.3	2.7	3.6	2.2	3.5	4.1	2.9
BMI...wat (6 Å)		17.6	17.3	15.4	14.7	12.1	13.8	11.9	9.7	10.1
TfO...wat (6 Å)		17.9	17.6	15.3	13.4	9.8	12.4	10.1	6.7	7.5
S _{TfO} ...wat (5 Å)		9.0	9.1	8.5	7.5	6.6	7.4	6.2	4.5	5.1
S _{TfO} ...wat (7 Å)		30.0	30.6	27.5	23.1	19.3	23.1	18.6	12.4	14.8
S _{TfO} ...M ⁿ⁺ (4.5 Å)				0.13	0.16	0.18	0.04	0.04	0.00	0.00
S _{TfO} ...M ⁿ⁺ (7 Å)				0.50	0.65	0.68	0.29	0.25	0.03	0.01
N _{butyl} (BMI)...Cl ⁻ (5.5 Å)				0.08	0.12	0.13	0.09	0.09	0.03	0.00

when going from solutions A (without NaCl) to D, the IL ions lose ca. 5–8 H₂O molecules in their first shell and display more frequent TfO⁻...BMI⁺ and TfO⁻...TfO⁻ contacts, as seen from the increasing magnitude of first peak of the corresponding RDFs.

The cross-interactions between Mⁿ⁺ and Cl⁻ ions and the polar moieties of the IL were analyzed more precisely in the NaCl series B–D and in the MCl_n series C, K, and L, from the S_{TfO}...Mⁿ⁺ and N_{butyl}(BMI)...Cl⁻ RDFs (a summary is given in Table 3). The S_{TfO}...Mⁿ⁺ RDFs display a first peak that integrates within 4.4 Å to less than 0.2 in the Na⁺ series and to 0.04 in the Mⁿ⁺ series, indicating the limited occurrence of direct SO₃⁻...Mⁿ⁺ contacts with the divalent or trivalent ions. The second peaks, corresponding to water-mediated SO₃⁻... (H₂O)...Mⁿ⁺ contacts, increase in intensity when the NaCl salt gets more concentrated (ca. 0.50, 0.65, and 0.68, respectively, within 7 Å in the NaCl series B–D). In the case of SrCl₂ or EuCl₃ salts, the closest interactions are water-mediated and limited (0.25 with Sr²⁺, 0.04 with Eu³⁺ within 7 Å) because their more charged cations increasingly prefer more remote water. One observes also some Cl⁻...BMI⁺ interactions, increasing in the NaCl series (from ca. 0.08 to 0.13 within 5.5 Å), but less obvious with SrCl₂ or EuCl₃ (0.09 and 0.03, respectively) that induce higher segregation.

Comparing now the RDFs along the whole MCl_n salt series at a fixed concentration, one observes no marked discontinuity between mono- and biphasic systems, indicating that short-range (first shell) interactions with the ions are not sufficient to distinguish ABS from heterogeneous monophasic solutions.

3.5. Evolution of Ion Hydration and Mutual Interactions at Different Distances When “Organization” Proceeds. How the IL and salt ions, initially randomly dispersed in the mixtures, progressively segregate and how in parallel water rearranges during the dynamics around these ions have been analyzed at different distances for selected monophasic and biphasic systems. For this purpose, we followed the average number $n_A(X; \text{cutoff})$ of X species around A at different cutoff distances, 5, 10, and 20 Å. The corresponding curves are given in Figures 9, S21, and S22, respectively, of the Supporting Information.

Regarding the hydration of MCl_n salts, the $n_{\text{H}_2\text{O}}(\text{M}^{n+}; 5)$ or $n_{\text{H}_2\text{O}}(\text{Cl}^-; 5)$ curves are rather flat, indicating that the hydrophilic Mⁿ⁺ and Cl⁻ ions rapidly satisfy their first coordination requirements in the different solutions. This contrasts with the $n_{\text{H}_2\text{O}}(\text{BMI}^+; 5)$ or $n_{\text{H}_2\text{O}}(\text{TfO}^-; 5)$ curves that decay rapidly (indicating rapid loss of water) and become flat

after ca. 10 ns. Hydration changes at longer distances (10 or 20 Å) are slower and more spectacular, in keeping with the water migration from (forming) IL domains toward (forming) salt domains. The water transfer increases when MCl_n becomes more salting-out. For instance, during the first 100 ns of dynamics, $n_{\text{H}_2\text{O}}(\text{M}^{n+}; 20)$ increases in the order Cs⁺ ≈ Na⁺ < Sr²⁺ < Eu³⁺, by ≈100 H₂O in the Eu³⁺ case. In parallel, $n_{\text{H}_2\text{O}}(\text{BMI}^+; 20)$ and $n_{\text{H}_2\text{O}}(\text{TfO}^-; 20)$ drops in the same Mⁿ⁺ order, by ≈300 H₂O in the case of Eu³⁺. Ion segregation and phase separation, concomitant with water transfer, are reflected by the populations of BMI...BMI, BMI...TfO, and TfO...TfO “pairs” that increase (at the three distances) when MCl_n becomes more salting-out (Figures 9, S21, and S22 of the Supporting Information), with marked changes at long distances. It is thus crucial to look beyond the first coordination shells of the different partners.

4. DISCUSSION

These MD “demixing” simulations of aqueous solutions of MCl_n and IL, their components initially placed in random positions, have enabled exploration of as to what extent the solutions become mono- or biphasic at the nanoscopic level and thereby provide microscopic insights into ion segregation and ABS formation. To achieve “apples with apples” comparisons, the MD experiments were conducted in a systematic manner, comparing different salt/IL concentrations and MCl_n metallic salts along the Hofmeister series. They reveal in all cases marked heterogeneities, with segregation of the IL ions into a water domain from which the Mⁿ⁺ and Cl⁻ ions tend to be excluded and the converse. Ion segregation (and in some cases, full phase separation) is found to increase (i) when the added Mⁿ⁺ ions are higher charged (and hence more hydrophilic) and (ii) more concentrated and (iii) with the IL content. This is consistent with experimental observations.¹⁴ In the following, we first address computational and related physical issues and compare the calculated to the experimental phase behavior of all systems, comparing the IL^{±1} to IL^{±0.9} models. To discern the driving forces for ABS formation, we then analyze changes in ion hydration, ion–ion interactions, and the water migration, also comparing these concentrated IL mixtures to IL diluted ones. This is followed by a discussion of some related energy features. Ion organization and hydration patterns in the IL phase of ABSs are then discussed, drawing analogies with IL ions at aqueous interfaces. Finally, the main characteristics of liquid–liquid

Figure 9. 148 $\text{IL}^{\pm 0.9}/296 \text{MCl}_n$ solutions: integration number of RDFs up to 5 and 20 Å as a function of time (in ns). Color codes: NaCl blue, CsCl, black, SrCl_2 cyan, and EuCl_3 brown. An extended version is given in Figure S22.

interfaces of ABSs are compared to those of “oil”/water interfaces.

4.1. Computational and Related Physical Issues.

Owing the simplicity of the force field used here, quantitative agreement with thermodynamic partition data is not anticipated. As will be seen below, the charges borne by IL ions critically influence the extent of IL segregation, and the tested $\text{IL}^{\pm 0.9}$ and $\text{IL}^{\pm 1}$ models likely bracket the best compromise. Interactions with water and thereby the segregation behavior, are also influenced by the water and ion models⁵⁴ (see for instance refs^{55–58} for IL ions and ref⁵⁹ for salt ions) and by polarization effects.^{60,61}

Simulation times also matter. Note that those used here (500–1000 ns) are longer than those used to separate classical water/“oil” random mixtures (<0.2 ns when “oil” is an organic molecule or SC-CO_2 ^{53,62} or 20–40 ns when the “oil” is a hydrophobic IL⁴⁶). The purely aqueous mixtures separate more slowly, indicating that the underlying driving forces are weaker, thereby needing to sample more configurations. Short-range reorganization of the random mixtures generally occurs during the first ≈ 10 –20 ns. After that time period, the demixing index ξ_{demix} (Figure 3) and the different energy components (see below) stay fairly constant, indicating that segregation does not significantly change at the nanometer scale. Looking at specific cases illustrates typical steps of ABS formation. For instance, for the EuCl_3 solution L (see S8 of the Supporting Information), the ions form loose aggregates during the first ca. 5–10 ns and then condense (between 10 and 25 ns) into an IL slab and a small IL droplet, ≈ 10 nm apart. At ≈ 225 ns, these collapse into a single IL phase that remains stable until the end. In the case of the NaCl solution D, the two distinct phases formed earlier (at ≈ 160 ns), indicating that the different landscapes obtained at 500 ns are overall meaningful. In the case of the SrCl_2 solution K, cumulated trajectories of individual species during 100 ns (Figure S7) also show that the sampling is sufficient to study ABSs.

Another issue concerns the size of solvent heterogeneities: are they representative of the macroscopic ones or induced by the box size and content? In particular, is the number of IL ion pairs (148) in the “standard” simulations not too small to finally depict a bulk phase? This is clearly not the case for the NaCl, SrCl_2 , and EuCl_3 solutions (D, K, and L, respectively) that form two phases in the “standard box”. For the NaCl solution D, however, we decided to test a “bigger box” (solution D2) of size and content scaled up by 4.0. The snapshots in Figure 10 and density curves in Figure 6 confirm

Figure 10. “Big box” simulations on $\text{IL}^{\pm 0.9}$ solutions with no salt (A2) and with NaCl (D2) after 200 ns (A2) and 500 ns (D2).

the separation of IL and NaCl ions into distinct domains, forming now two slabs per ion type. These differ in size and composition, however; the first one is wider and contains more IL (and hence less water) than the second one, suggesting that the system is metastable. Because these two slabs are ≈ 10 nm apart, there is no driving force inducing their collapse during 500 ns of dynamics.

The shape of ionic phases can also be influenced by the shape of the box, when simulated with 3D periodic conditions: rectangular elongated boxes favor slabs, whereas cubic boxes rather favor cylindrical or “spherical” IL arrangements (see e.g., the case of the EuCl_3 solution L; Figure S9 of the Supporting Information). Whether and how these domains collapse after longer simulations remains to be investigated with bigger systems. Beyond being a computational issue, this may become of importance for experiments carried out in confined conditions. Furthermore, as experimentally observed for the

big “spherical” dicarbollide anions that also form nano-aggregates in water,⁶³ the structure of the solutions (mainly the monophasic ones) may evolve with time and aging.⁶⁴

4.2. Monophasic/Biphasic State of IL/MCl_n Mixtures, Simulated with IL^{±1} Versus IL^{±0.9} Charge Models: Comparison with Experiment. For the MCl_n containing mixtures, increasing the IL ion “polarity” (from the IL^{±0.9} to the IL^{±1} model) diminishes segregation, as indicated by the ξ_{demix} index that decreases by ≈ 0.1 units, on the average (see evolutions with time in Figure S10 of the [Supporting Information](#) and average values in Table 2). See also snapshots (Figures S11–S14 of the [Supporting Information](#)) and density curves (Figures S15–S17 of the [Supporting Information](#)) obtained with the IL^{±1} charges. With the latter, segregation also increases with the salt content (compare ξ_{demix} for NaCl solutions B to D, CsCl solutions G to H, and SrCl₂ solutions J to K) and with the Mⁿ⁺ charge (compare ξ_{demix} for solutions C, K, and L). The effect of the IL content is less clear, however; ξ_{demix} is similar for the C and E NaCl solutions, as for the D to F ones that do not display ion partitioning with that model (Figure S11 of the [Supporting Information](#)).

We now aim at comparing the simulated phase behavior to that experimentally observed (Figure 1). Biphasic and monophasic systems at points near the coexistence curve (and hence the cloud point) are noted “cloud-bi” or “cloud-mono”, respectively, on the different snapshots and density curves. On the simulation side, the distinction is rarely clear-cut, in particular when broad density peaks (also corresponding to some salt/IL mixing), instead of plateaus, are observed. Furthermore, the IL or salt domains are labile and fluctuate with time, as seen from the evolution of density profiles with averaging time (e.g., 50, instead of 5 ns). Notwithstanding these issues, tentative assignments (Table S4 of the [Supporting Information](#)) yield the following trends. With the IL^{±1} charges, most monophasic states (e.g., NaCl solutions B and C, CsCl solutions G and H) are correctly predicted to be so: the density profiles are more or less flat, with significant IL/salt mixing. Most biphasic solutions (e.g., NaCl solution F, SrCl₂ solution K), however, are predicted instead to be monophasic, though with significant IL/salt mixing. Biphasic solutions sitting near the coexistence curve (e.g. NaCl solutions D and D2, CsCl solution I) also look monophasic. The only clear-cut “success” of the IL^{±1} model concerns the EuCl₃ solution L that remains biphasic. On the other hand, with the IL^{±0.9} model, monophasic solutions (e.g., NaCl solution C, CsCl solution H), some of them sitting near the coexistence curve (e.g. NaCl solution E) are instead found to be biphasic, which suggests somewhat exaggerated segregation and phase separation. Thus, to summarize, the IL^{±1} model correctly predicts monophasic states but underestimates segregation and phase separation, whereas the IL^{±0.9} model somewhat magnifies segregation. More fundamentally, the comparison of the IL^{±1} to the IL^{±0.9} results illustrates the subtle influence of IL ion “polarity” in the formation of ABSs. See, for example, the case of the NaCl solution E that becomes biphasic with the IL^{±0.9} charges and monophasic with the IL^{±1} ones.

For the EuCl₃ solution L, there are no experimental data. However, the simulations make clear that this salt has the strongest ABS inducing effect. Even in the more dilute EuCl₃ solutions M, N, O, and P, one observes distinct IL and salt domains, that is, phase separation, with either IL^{±1} or IL^{±0.9} models (see Figures S18 and S19 of the [Supporting Information](#)).

4.3. Water Reorganization and Ion Segregation: Water Migration from the Best “Water-Donating” Ion Pair to the Best “Water-Accepting” Ion Pair. Ion-specific effects on ABS formation phenomenologically follow the Hofmeister series established for the precipitation/solubilization of proteins^{15–17,65} and the order of ion effects on aqueous solubilities of hydrophilic and hydrophobic IL ions,^{14,26} biomolecules,¹¹ or sugars,⁶⁶ for instance. They result from collective phenomena and from the interplay between all ion–water, ion–ion, and solvent–solvent interactions at a given concentration. The formation of ABSs with hydrophilic ILs induced by inorganic salts increases with the salting-out properties of the salt, that is, with its concentration and hydrophilicity.^{7,14,26} It results from the competition between the salt ions and IL ions to capture water, which is won by the most hydrophilic ones.^{3,30} Cross salt/IL interactions may also come into play. Studying the effect of organic and inorganic salts (including alkali and alkaline earth metal chlorides) on the solubility of the (weakly soluble) [BMI][Tf₂N] IL, Freire et al. mentioned “specific ion effects that result from the direct or indirect (water-mediated) interactions between the salt ions and the solute and not from a rearrangement of the water molecules caused by the ions”. They also assigned the resulting favorable effect to the tendency to form “hydration complexes” which cause the “dehydration of the solute”. In another study with the water-soluble [BMI][TfO] IL, Kurnia et al. reported negative NMR chemical shifts on H_{BMI} and F_{TfO} IL atoms upon addition of NaCl, MgCl₂, and AlCl₃ salts, interpreted in terms of “unfavorable interactions between the IL and salt leading to a salting-out phenomenon”.³⁰ Our simulations consider higher IL concentrations, high enough to form ABSs (≈ 1 – 2 , instead of 0.01 mol kg^{-1} in their studies) and cannot be directly compared because at high IL concentration, the IL and salt ions tend to be located in different domains of the solutions.

To analyze what happens prior to segregation (at low IL concentration), we simulated 2 M salt/0.02 M IL aqueous solutions with NaCl, SrCl₂, and EuCl₃ salts and analyzed the corresponding RDFs (their main characteristics are given in Table S5 of the [Supporting Information](#)). There are, as expected, no contacts between the dilute IL ions. Their first hydration shells are similar in the NaCl, SrCl₂, and EuCl₃ solutions (ca. 21 H₂O within 6 Å) and similar to that in the absence of salt, in keeping with the lack of significant IL/salt direct contacts. The closest contacts are water-mediated: the S_{TfO}···Mⁿ⁺ and N_{butyl}···Cl[−] RDFs integrate to ca. 1.5 (at 7 Å) and to ca. 0.3–0.6 (at 5.5 Å), respectively, for the three salts. Looking at longer distances, one finds a similar number of S_{TfO}···Mⁿ⁺ pairs for the three salts (ca. 4.5 Mⁿ⁺ within 10 Å from TfO[−]). The main perturbations of the IL ion environment thus occur mainly via water (e.g., through reorientation and/or polarization of their dipoles and modulation of their H-bonding interactions), in an increasing manner when the Mⁿ⁺ charge (and, accordingly, the Cl[−] concentration and number of Cl[−]···BMI⁺ contacts) increases. This is overall consistent with the reported shifts in the NMR spectra and with their interpretation.³⁰ Such short-range interactions are not sufficient, however, to induce ion segregation (and finally ABS formation). When the IL concentration is increased from 0.02 to 2 M, the IL ions lose much first shell water (ca. 7, 10, and 11 H₂O within 6 Å from BMI⁺, 12, 13, and 18 H₂O around TfO[−], respectively, in the NaCl, SrCl₂, and EuCl₃

mixtures) in keeping with the mutual attractions between IL ions and their segregation.

Overall, the structure of the studied IL/salt mixtures can be represented in terms of synergistic water-donor/water-acceptor interactions between the different ion pairs present in the solution. Here, BMI⁺ and TfO[−] IL behave as water donors (from their hydrophobic butyl and CF₃ moieties, respectively), whereas the more hydrophilic Mⁿ⁺ and Cl[−] ions attract water, in the first shells and much beyond, when the ionic charge increases. Finally, the salt phase contains more water than does the IL phase. Note that ions segregate into distinct IL and salt domains whatever their origin. For instance, the NaCl solution E that contains the same number (296) of Na⁺Cl[−] and BMI⁺TfO[−] ions can alternatively be viewed as a mixture of the NaTfO salt with the BMICl IL, equivalent to “counterion exchange” in water: with both IL^{±0.9} and IL^{±1} models, ions are found to segregate into BMI⁺TfO[−] domains and into Na⁺Cl[−] ones. Interestingly, in the IL domain of solution E, the association of BMI⁺ and TfO[−] ions is reminiscent of BMI⁺ClO₄[−] contacts observed in [BMI][Tf₂N] + NaClO₄ aqueous mixtures, that is, of anion exchange between the IL and salt.²⁷ More generally, instead of focusing on a single ion type, it is worth considering all ion pairs (taking into account the precise speciation of all M_xX_y salts in the case of multicharged ions).^{27,30}

4.4. Evolution of Energy Components When Ion Segregation and Water Transfer Proceed. To follow the energy impact of ion and solvent reorganization occurring along the dynamics, we cut the systems into three overall neutral groups (IL ions, MCl_n ions, and water) and followed their interactions (see curves in Figure 11 and in Figures S23–S25 of the Supporting Information). Regarding interaction energies with water, the salt/water one is fairly constant along the dynamics for the NaCl and CsCl solutions (that remain monophasic) but becomes much more attractive at the beginning of the dynamics for SrCl₂ and EuCl₃ solutions (that become biphasic). In parallel, the IL/water interaction energies, much smaller in magnitude than the salt/water ones, remain stable with NaCl and CsCl, but get destabilized with SrCl₂ and EuCl₃, reflecting water migration from the ions of IL to those of MCl_n. The IL “self-energy” also contributes to the stabilization of ABSs; it is fairly constant along the dynamics in the NaCl and CsCl solutions but becomes more attractive with SrCl₂ or EuCl₃ because of the enhanced BMI⁺/TfO[−] attractions when the IL ions segregate.

On the thermodynamic side, the stabilization of a system corresponds to a decrease in its Gibbs free energy ΔG (in standard conditions), a feature not amenable to simulations. Insights into the evolution of its ΔH component can however be obtained by looking at the total potential energy E_{pot} (Figure 11 and in Figures S23–S25 of the Supporting Information). In the NaCl series B to D, E_{pot} stays fairly constant throughout the dynamics, even for the most concentrated solution (D) that becomes biphasic. In the MCl_n series, E_{pot} first diminishes during ≈ 10 ns with SrCl₂ and EuCl₃ salts and then remains fairly constant. Note that the demixing index ξ_{demix} follows a similar evolution, indicating that during that time period, the initially random solute/solvent mixtures have become more or less homogeneous at the nanometer scale but not yet separated into two phases (for the biphasic ones). Later on, there is thus no dominant enthalpic driving force for further phase separation, which is

Figure 11. 148 IL^{±0.9}/296 MCl_n solutions C and K. Energy component analysis (in 10³ kcal mol^{−1}) as a function of time. Total potential energy E_{pot} during the first 10 ns. Internal IL energy and IL...wat and salt...wat interactions during the first 100 ns. An extended version is given in Figures S23–S25.

consistent with entropy-driven segregation and separation processes.

The origin of any entropic gain is unclear. Experimentally, hydration of metallic salts is an exergonic process (negative ΔG), dominated by high negative ΔH enthalpies, somewhat reduced by unfavorable ΔS entropies.⁶⁷ Enriching the water environment of the salt ions upon ABS formation should thus not be a source of entropic gain. On the other hand, water is also highly structured around hydrophobic species⁶⁸ and displays (weak) attractions with them, overcompensated by an unfavorable entropic cost.⁶⁹ As a result, hydrophobic species tend to “expel” water from their surface and to aggregate with each other, contributing to a favorable entropic gain. The latter likely operates already in IL solution A (without MCl_n salt) where significant hydrophobic contacts (TfO[−]...TfO[−], BMI⁺...TfO[−]) between IL ions are observed. They might explain the ability of this IL to be salted-out, even by weakly salting-out species like NaCl, carbohydrates,⁶⁶ or aminoacids.⁷⁰ On the other hand, like ILs used for ABSs, it does not precipitate in concentrated conditions.

4.5. IL Phase of ABSs: Ion Hydration and Organization into “Dry”/“Humid” Domains. We have seen that the IL-rich phase of ABSs is mainly aqueous: even in the most dramatic cases (NaCl solution D, SrCl₂ solution K, and EuCl₃ solution L), water is in excess over IL ions (more than ≈ 800

H₂O molecules for at most 148 BMI⁺TfO[−] ions). It is thus interesting to look at the state of water in the IL phase, focusing on solution L. Typical snapshots (Figure 12) make

Figure 12. Typical solvated BMI⁺TfO[−] ion arrangements in the IL phase of the biphasic EuCl₃ solution L (left) and at the vacuum/ aqueous-IL interface (right).

clear that water is mainly connected to the SO₃[−] moiety of TfO[−], via three to four strong hydrogen bonds, on the average. Conversely, there are nearly “dry” IL regions where CF₃(TfO) and methyl(BMI) or butyl(BMI) hydrophobic moieties segregate, whereas the polar interactions between SO₃(TfO)[−] and ring(imidazolium)⁺ are most often mediated by water. Hydration of the “IL phase” of these ABSs is thus reminiscent of the one observed in hydrophobic but hygroscopic ILs.^{46,71,72} In particular, the IL anion is better hydrated than the cation because of H-bonding interactions.⁷³ In the IL phase of ABSs, solvating water around polar groups tends to form filaments (in the SrCl₂ solution K) or aggregated fingers (in the EuCl₃ solution L). The remarkable feature of ABSs is the fact that dehydration of the hydrophobic moieties is simply induced by the remote added salt, at a sufficient concentration. When the added MCl_n salt becomes less salting-out (less hydrophilic and/or less concentrated), the water content of the IL phase increases and that phase breaks up into smaller domains, droplets, or aggregates. As mentioned above, dehydration of hydrophobic moieties of the IL is entropically favored,^{11,69} indirectly contributing to the salting-out effect.

In the IL phase of the L solution, IL ions display some “organization”, induced by water. We simulated the pure dry [BMI][TfO] IL for comparison (see Figure S2 of the Supporting Information). In the latter, the apolar groups also aggregate with each other, as do the polar ones. For instance, each SO₃(TfO)[−] is surrounded by a “cage” of 3–4 ring-(imidazolium)⁺ groups, whereas a ring(imidazolium)⁺ is in contact with 2–3 SO₃(TfO)[−] groups. Neither the TfO[−] anion nor the BMI⁺ cation are amphiphilic enough, however, to induce longer range ordering.^{72,74,75} In the presence of water, these polar interactions are disrupted, whereas the apolar ones are strengthened.

4.6. Analogies between IL Patterns in ABSs and at an Aqueous Interface. The analogy between IL ion hydration patterns in ABSs and at aqueous interfaces is striking. First, note that both IL ions prefer the water surface over bulk water.⁷⁶ This feature is illustrated by a MD experiment we performed on the aqueous solution of BMI⁺TfO[−] ions at the air interface: density profiles and snapshots (Figures 13 and S27 of the Supporting Information) show that IL ions are “attracted” by the interface (more with the IL^{±0.9} charges than with the IL^{±1} ones) where they adopt amphiphilic orientations: the hydrophobic Butyl(BMI) and CF₃(TfO) moieties are “dry”

Figure 13. Vacuum/ aqueous-IL interface with 296 [BMI][TfO]^{±0.9}. Line 1: Snapshots highlighting interfacial TfO[−] (left) and BMI⁺ ions (right): CF₃ in blue, SO₃[−] in red, butyl chain in green, and imidazolium ring in black. Line 2: IL and water densities, between 20 and 40 Å of the z-axis (in Å), averaged over 50 ns. Color codes: water blue; IL green; BMI⁺ dotted black; and TfO[−] dotted orange. An extended version is given in Figure S27.

and point toward air, whereas the polar (ring)imidazolium⁺ and SO₃(TfO)[−] ones prefer water. In particular, SO₃[−] is hydrated by 3–4 H₂O molecules, connected to bulk water, as in ABSs.

Calling attention to interfacial properties helps to understand why trends in ABSs formation from IL/salt mixtures follow the surface activity of ions and their Hofmeister series classification.^{16,26,65} The studied IL ions behave as small amphiphiles, as do components of polymers like PEGs, dextrans, or water-soluble macromolecules that also form ABSs. Even “big spherical ions”, some of them being components of ILs (polyoxometallate,^{77,78} dicarbollide,^{63,79} ClO₄[−] anions,⁸⁰ or NR₄⁺ quaternary ammonium cations) display hydrophobic features and surface activity. They also tend to aggregate in water and thus to form ABSs. In contrast, the salting-out Mⁿ⁺Cl[−] ions that increase the surface tension of water are instead “repelled” by the interface and prefer a bulk water environment.

4.7. Liquid–Liquid “Interface” of IL/Salt ABSs.

Generally, liquid–liquid interfaces are defined with respect to the adjacent solvents (e.g., water and a hydrophobic IL).^{35,81–85} In the case of the studied ABSs, the average z-position of the interface ⟨z⟩_{ITF} might be defined by the z-plane where the water density $d_{\text{wat-ITF}}$ is the mean of densities in the IL slab and in the salt slab: $d_{\text{wat-ITF}} = 1/2(d_{\text{wat-IL}} + d_{\text{wat-salt}})$. Because the real partitioning occurs between IL and salt ions, the interface can alternatively be defined by the crossing of the density curves of IL and salt ions. Focusing on the interfaces of D, K, and L biphasic solutions (with NaCl, SrCl₂, and EuCl₃ salts, respectively), one finds similar ⟨z⟩_{ITF} positions from these

two definitions: with the first one, the interface is shifted by only ≈ 0.3 nm from the second one, toward the IL-phase on the average. In the three solutions, the interface is rather sharp and narrow: defining its “width” by the distance between z -planes where the IL-density and the salt-density attain 90% of their values in the bulk adjacent phases, one obtains ca. 2.2, 1.6, and 1.2 nm, respectively, for NaCl, SrCl₂, and EuCl₃ containing ABSs. Thus, the more hydrophilic the metal salt is, the sharper and narrower is the interface. Snapshots (Figure 14) and density curves (Figure 5) show that there is more salt

Figure 14. Snapshots of ions at IL/salt interfaces of biphasic solutions D, K, and L (slices of 3.5 nm width; water hidden for clarity). Color codes: Cl[−] orange, Na⁺ yellow, Sr²⁺ dark blue, and Eu³⁺ cyan.

penetration on the IL side than IL penetration on the salt side of the interface. Near the interface, the IL density slope is much the same with the three salts, whereas the salt slope is weaker and decreases from EuCl₃ to NaCl. Comparing now these ABS interfaces to those of hydrophobic ILs/water solutions, the former ones are found to be comparable in size. The main difference with the studied ABSs is that the BMI⁺TfO[−] ions are better hydrated and that the cohesion forces of the IL phase are induced by the added hydrophilic salt and by water. On the other hand, neither the butyl chain of the BMI⁺ cation nor the trifluoro group of the TfO[−] anion are long enough to induce organized structures like micelles in water.⁸⁶ The simulated interfaces can be viewed as zooms of “flat” ABSs at rest, as well as interfaces of IL droplets formed in the solutions, near the cloud point compositions.

5. CONCLUSIONS

We report MD simulations of concentrated aqueous mixtures of IL and MCl_{*n*} salt ions, selecting solutions that are experimentally monophasic and biphasic. They reveal in all cases collective phenomena yielding marked heterogeneities and segregation features into mutually exclusive neutral IL and salt domains (“ionic sociology”). These domains range, depending on the concentration, from locally fluctuating nanoregions (in monophasic solutions) to completely separated IL and salt aqueous phases (in ABSs). Segregation stems here from two main features: (i) IL ions tend to “attract” each other because of hydrophobic forces (dehydration of their apolar moieties) and to IL/IL attractions upon segregation. Even without added salt, the IL ions display significant anion...cation and anion...anion hydrophobic contacts. (ii) The salt ions trap water, by increasing amounts and at longer distances when their salting-out character (concentration and/or M^{*n+*} hydrophilicity) is increased. The water transfer from the IL to the salt ions can be viewed as a water-donor/water-acceptor synergistic process: MCl_{*n*} ions attract water (mainly in their second coordination shell and much beyond when the cationic charge increases), whereas IL ions release water from their hydrophobic moieties (up to ca. 50% of first hydration shell in

the presence of MCl_{*n*} salts), yielding an entropic gain. Consistent comparisons show that ion segregation and ABS formation increase with the salt concentration, the IL concentration, the M^{*n+*} charge, and the “polarity” of IL ions, in good agreement with experiment. In the ABSs, the aqueous-IL/aqueous-salt interface is found to be quite sharp and of decreasing width when the dissolved MCl_{*n*} salt becomes more “salting-out”. Finally, we point to analogies between ion “organization” in ABSs and the contrasting behavior of IL and MCl_{*n*} salts at aqueous interfaces and thus with the Hofmeister classification of IL and salt ions. From the analysis of snapshots, density curves, the “demixing index” ξ_{demix} , RDFs, and energy components, no clear-cut transition is observed, however, between heterogeneous monophasic systems and biphasic ones, calling for physical and simulation studies on nanoorganization in these phases as well as on their “cloud point” intermediate state, focusing on interactions and structuration at “long distances”. Comparisons with other ILs (e.g., [BMI][BF₄]) or related ABSs (e.g., with PEGs) combining dry ILs⁸⁷ or “humid” ILs⁸⁸ should enable further analysis of the specificity of the presently studied ones.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.jpcb.8b06193.

Description of all simulated systems; characteristics of RDFs; assignment of the different “phases”; final snapshots of the simulated systems with the IL^{±1} and IL^{±0.9} models; density curves along the z -axis; and extended results for the neat solution A, for the aqueous IL/vacuum interface, and for the pure dry IL (PDF)

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Notes

The authors declare no competing financial interest.

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