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## Polymeric Vesicles and Micelles Obtained by Self-Assembly of Ionic Liquid-Based Block Copolymers Triggered by Anion or Solvent Exchange

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**ABSTRACT:** The solution properties of IL-based block copolymers (IL BCs) of the type PAm-*b*-PIL-1Br, PMAA-*b*-PIL-2Br, and PMAA-*b*-PIL-3Br, where PIL, PAm and PMAA stand for polymeric ionic liquid, poly(acrylamide), and poly(methacrylic acid), respectively, are manipulated and made to self-assemble into nanoparticles in water or in organic media. This can be achieved not only by simply exchanging the bromide ( $\text{Br}^-$ ) counteranion of IL blocks for  $^-\text{N}(\text{SO}_2\text{CF}_3)_2$ , but also by the choice of a selective solvent or by methylation of the hydrophilic PMAA blocks into hydrophobic poly(methyl methacrylate) (PMMA) ones. Investigations into the behavior of self-assembled IL BCs aggregates by  $^1\text{H}$  NMR spectroscopy, light scattering and transmission electron microscopy evidence that anion or solvent exchange or chemical modification induce the formation of polymeric vesicles referred to as polymersomes, for IL BCs of hydrophilic mass fraction ( $f$ ) of around 40. The size and shape of the self-assembled aggregates formed can be altered by changing the composition of the blocks or by a partial exchange of the anion. In addition, the anion sensitivity of these IL BCs occurs reversibly. For instance, anion exchange of the PIL block, from  $\text{Br}^-$  to  $^-\text{N}(\text{SO}_2\text{CF}_3)_2$  leads to a vesicular morphology consisting of  $^-\text{N}(\text{SO}_2\text{CF}_3)_2$ -based IL blocks as the hydrophobic membrane stabilized by water-soluble PAm (or PMAA). As for PAm<sub>135</sub>-*b*-(PIL-1N( $\text{SO}_2\text{CF}_3)_2$ )<sub>12</sub> IL BC possessing a hydrophilic mass fraction higher than 45, it is found to self-assemble into spherical polymeric micelles.

### Introduction

Ionic liquids (ILs) are attracting much attention for potential applications in various fields due to their unique physicochemical properties: chemical stability, thermal stability, low vapor pressure, and high ionic conductivity.<sup>1–6</sup> Overall, the solubility of ILs can be tuned by a simple exchange of their counteranion, which is called the anionic sensitivity. Not only have ILs been promoted as “green solvents”, they have also been investigated as media for extraction processes. ILs are being used in catalysis,<sup>2</sup> organic synthesis,<sup>2,7,8</sup> chemical separation,<sup>9</sup> chemical storage, and/or transportation.<sup>10</sup> In recent years, they have also found applications in polymer science,<sup>11–14</sup> mostly as media of polymerization processes or as selective solvents for the self-assembly of block copolymers into micelle-like nanostructures.<sup>15</sup> However, ILs have also been incorporated in polymeric matrixes, for instance as high performance plasticizers,<sup>16</sup> as compatibilizers in nanocomposites and functional polymers.<sup>16–22</sup> Finally, polymeric ionic liquids (PILs) made out of ILs are described as a novel class of materials combining the properties of ILs mentioned above and the specificities of polymers. PILs are finding innovative applications in emerging areas such as biosensors,<sup>23</sup> in support of catalysts,<sup>24</sup> as polymeric surfactants for the construction of porous polymers,<sup>25</sup> as high CO<sub>2</sub> absorbing resins,<sup>26</sup> as polymer electrolytes for electrochemical devices,<sup>18,27,28</sup> as microwave absorbing materials,<sup>29</sup> in solid phase microextraction,<sup>30</sup> and as a polymerization template and phase transfer medium.<sup>31</sup> The solvent sensitivity and

the anion sensitivity of PILs or of IL-based random copolymers have already been amply demonstrated.<sup>14,25</sup> In contrast, only a few reports have described block copolymers consisting of a PIL block, referred to as IL-based block copolymers (IL BCs).<sup>32–34</sup> For instance, Waymouth et al. reported that imidazolium-functionalized block copolymers constituted of a polystyrene backbone self-assembled in toluene into elongated micelles with the IL block at the core.<sup>32</sup> More recently, we have reported for the first time the synthesis of double hydrophilic IL BCs<sup>33</sup> by sequential reversible addition–fragmentation chain transfer (RAFT) polymerization. In the same vein, Sun et al. have derived IL BCs by RAFT and have investigated their magnetic properties after complexation of the methacrylic IL-based blocks with metals.<sup>34</sup> IL BCs thus combine the known anionic sensitivity of PILs with the self-assembly properties of block copolymers.

In our previous report, we have capitalized on the anion sensitivity of our IL BCs which were found to self-assemble into micellar aggregates in water after anion exchange of  $(\text{SO}_2\text{CF}_3)_2\text{N}^-$  for bromide ( $\text{Br}^-$ ).<sup>33</sup> We now wish to thoroughly investigate the self-assembly properties in solution of these IL BCs, which can be triggered by anion or solvent exchange. This leads to polymeric vesicles referred to as polymersomes or to spherical polymeric micelles as a function of the overall composition of the IL BC. Due to their structural resemblance with primitive biological cells, polymersomes have a great potential,<sup>35–38</sup> for instance as nanosensors, in controlled drug delivery, in bioseparation,<sup>39–42</sup> and as a microreactor to carry out the chemical reactions at molecular level.<sup>43</sup> This is related to their very unique features which include stability, ability of encapsulating hydrophilic or hydrophobic actives in their membranes and/or in their

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**Table 1.** Hydrodynamic Radius ( $R_H$ ) of Different IL BCs of Type PIL-*b*-PMAA and PIL-*b*-PMMA

sample	IL BC <sup>a</sup>	$M_n$ <sup>b</sup> (g·mol <sup>-1</sup> )	$f$ <sup>c</sup>	$R_H$ (nm) in water (after anion exchange from Br <sup>-</sup> to <sup>-</sup> NTf <sub>2</sub> ) <sup>e</sup>	$R_H$ (nm) in THF <sup>e</sup>
1	(PIL-3) <sub>27-b</sub> -PMMA <sub>110</sub>	7800 + 9470	41.7 <sup>d</sup>	110	-
2	(PIL-3) <sub>27-b</sub> -PMMA <sub>110</sub>	7800 + 11015	41.5	insoluble	45 <sup>f</sup>
3	(PIL-2) <sub>43-b</sub> -PMMA <sub>80</sub>	11825 + 8010	59.6	Nd	insoluble
4	(PIL-2) <sub>8-b</sub> -PMMA <sub>80</sub>	2200 + 8010	21.5	insoluble	17.3 <sup>g</sup>

<sup>a</sup>The numbers in subscript indicates the degree of polymerization of the block, as determined by <sup>1</sup>H NMR (see ref 33). <sup>b</sup>Molar mass of both blocks determined by <sup>1</sup>H NMR spectroscopy, knowing the molar mass of the first block (see ref 33). <sup>c</sup>*f* = hydrophilic mass fraction. <sup>d</sup>Hydrophilic mass fraction of PMAA in the IL BC after anion exchange from Br<sup>-</sup> to <sup>-</sup>NTf<sub>2</sub> of the PIL block. <sup>e</sup>Hydrodynamic radius ( $R_H$ ) calculated by DLS. <sup>f</sup>After anion exchange from Br<sup>-</sup> to <sup>-</sup>NTf<sub>2</sub>. <sup>g</sup>With Br<sup>-</sup> as a counteranion.

**Table 2.** Hydrodynamic Radius ( $R_H$ ) of Different IL BCs of Type PIL-1-*b*-PAm

sample	IL BC <sup>a</sup>	$M_n$ <sup>b</sup> (g·mol <sup>-1</sup> )	$f$ <sup>c</sup>	$R_H$ (nm) in water after anion exchange from Br <sup>-</sup> to <sup>-</sup> NTf <sub>2</sub> <sup>d</sup>	$R_H$ (nm) in methanol (for IL BCs with Br <sup>-</sup> as a counteranion) <sup>d</sup>
5	(PIL-1) <sub>20</sub> - <i>b</i> -PAm <sub>86</sub>	6040 + 6115	37.8	135	150
6	(PIL-1) <sub>20</sub> - <i>b</i> -PAm <sub>113</sub>	6040 + 8030	44.4	95	insoluble
7	(PIL-1) <sub>16</sub> - <i>b</i> -PAm <sub>38</sub>	4830 + 2700	25.0	127	116
8	(PIL-1) <sub>16</sub> - <i>b</i> -PAm <sub>64</sub>	4830 + 4550	36.0	112	148
9	(PIL-1) <sub>12</sub> - <i>b</i> -PAm <sub>135</sub>	3625 + 9595	61.4	25	insoluble

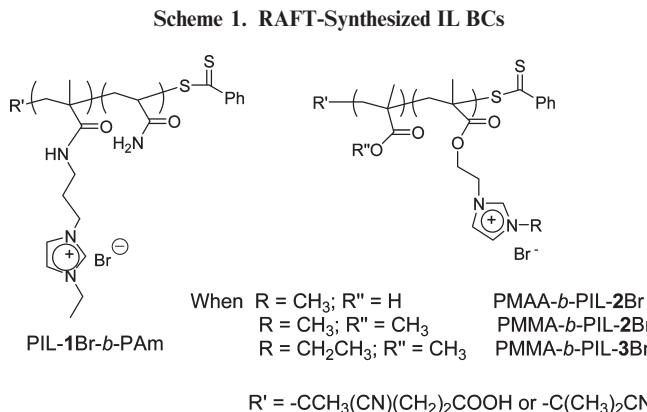
<sup>a</sup>The numbers in subscript indicates the degree of polymerization of the block, as determined by <sup>1</sup>H NMR (see ref 33). <sup>b</sup>Molar mass of both blocks determined by <sup>1</sup>H NMR spectroscopy, knowing the molar mass of the first block (see ref 33). <sup>c</sup>f = hydrophilic mass fraction of PAm in the copolymer after anion exchange from Br<sup>-</sup> to <sup>-</sup>NTf<sub>2</sub> of the PIL block. <sup>d</sup>Hydrodynamic radius ( $R_H$ ) calculated by DLS.

shell and tunable surface functionalization. As for the so-called polymeric reverse vesicles—or reverse polymersomes—generated in non aqueous media,<sup>44</sup> they are constituted with outer hydrophobic blocks while their internal membrane is made out of the hydrophilic blocks. These polymeric reverse vesicles are also potential candidates in control drug delivery system.<sup>36,44–49</sup> Here we discuss the self-assembly of IL BCs directed not only by anion or solvent exchange, but also by chemical modification of one block so as to generate water-soluble (direct) and organosoluble (reverse) polymersomes. The influence of parameters such as the type of the counteranion, the block copolymer composition and the choice of the selective solvent on the nanostructures formed has been examined by means of proton nuclear magnetic resonance, dynamic and static light scattering, and transmission electron microscopy.

## Experimental Section

**Materials.** All chemical manipulations were carried out under inert conditions. The ionic liquid-based homo and block copolymers were prepared by RAFT process as described in our previous report.<sup>33</sup> Trimethylsilyldiazomethane (2 M solution in diethyl ether) and LiBr were purchased from Aldrich and used as received. LiN(SO<sub>2</sub>CF<sub>3</sub>)<sub>2</sub>, also denoted as LiNTf<sub>2</sub>, was purchased from Fluka and used without further purification.

**Instrumentation.**  $^1\text{H}$  NMR spectra were recorded on a Bruker AC-400 spectrometer in appropriate deuterated solvents. Dynamic light scattering (DLS) experiments were performed at four different angles (120, 90, 70 and 50°) with a sample concentration of 1 g/L, using an ALV laser goniometer, which consists of a 22 mW He–Ne linear polarized laser with 632.8 nm wavelength and an ALV-5000/EPP multiple  $\tau$  digital correlator with 125 ns initial sampling time. Data were acquired with ALV correlator control software, and the analysis time was fixed for each sample as 180 s. DLS experiments were carried at a constant temperature of 25 °C and measurements were evaluated by fitting the normalized time autocorrelation function of the scattered light intensity. The data were fitted with the help of the constrained regularization algorithm (CONTIN), which provides the distribution of relaxation times  $\tau$ ,  $A(\tau)$ , as the inverse Laplace transform of the  $g^{(1)}(t)$  function:



Apparent diffusion coefficients  $D$  were obtained by plotting the relaxation frequency,  $\Gamma$  ( $\Gamma = \tau^{-1}$ ) versus  $q^2$  where  $q$  is the wave vector defined as

$$q = \frac{4\pi n}{\lambda} \sin\left(\frac{\theta}{2}\right) \quad (2)$$

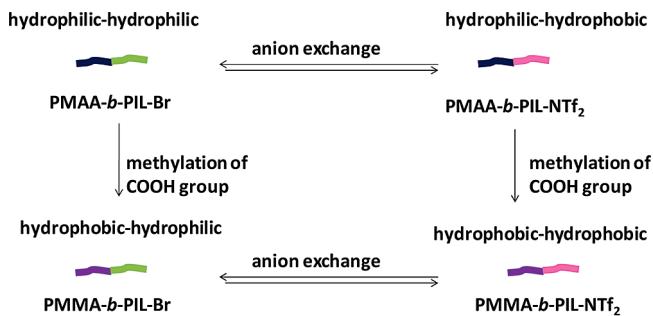
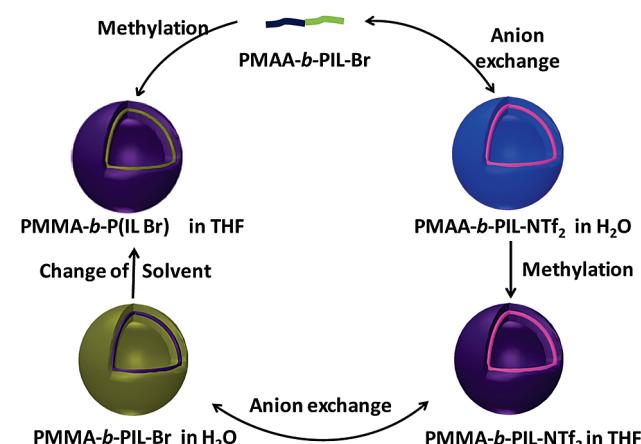
and  $\lambda$  is the wavelength of the incident laser beam (632.8 nm),  $\theta$  is the scattering angle, and  $n$  is the refractive index of the media. Single nanoparticle diffusion coefficients were determined by extrapolation to zero concentration, and the hydrodynamic radius ( $R_h$ ) was calculated from the Stokes–Einstein relation

$$R_H = \frac{k_B T}{6\pi\eta\Gamma} q^2 = \frac{k_B T}{6\pi\eta D_{real}} \quad (3)$$

where  $k_B$  is the Boltzmann constant,  $\Gamma$  the relaxation frequency,  $T$  is the temperature, and  $\eta$  is the viscosity of the medium. TEM images were recorded on HITACHI H7650 microscopy with a working voltage of 80 kV.

Static light scattering (SLS) experiments were performed at 25 °C using the same ALV Laser Goniometer in a range of scattered angle from 50° to 120°, with an interval of 10° at three different concentrations (1.0, 1.5, and 2.0 mg/mL). Triple distilled water was filtered through 0.1 μm filter and used for solution preparation.

**Sample Preparation.** All of the samples were prepared by direct dissolution of 1 mg of IL-BCs in 1 mL of the appropriate solvent (used after filtering through 0.1  $\mu\text{m}$  filter) and stirred over and used as such for DLS and SLS analysis. The same sample solutions used for SLS or DLS measurements (1 mg/mL)

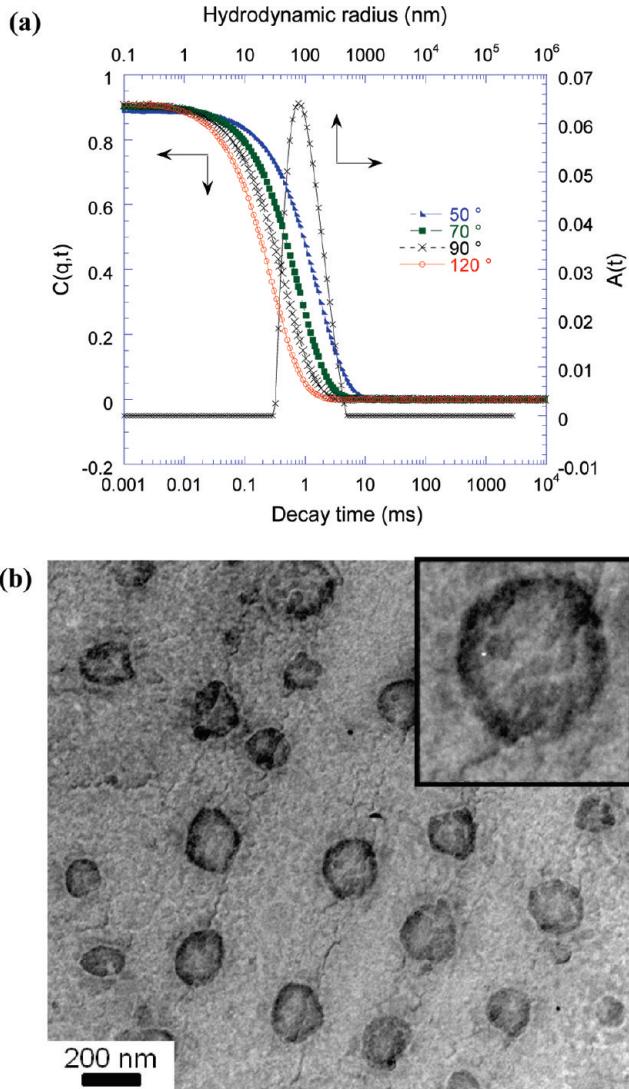
**Scheme 2. Chemical Manipulation of IL-Based Block Copolymers****Self-directed assembling of PMAA-*b*-PILs in Solution**

were used for TEM analysis. A small drop of the sample solution was placed on carbon coated Cu grid and left for several minutes. The excess of the solution on the sample grid was removed by wiping off with a filter paper and the sample grid was dried at room temperature for a couple of hours before analysis.

**Chemical Modification of PMAA-Based Compounds.** The carboxylic acid groups in PMAA-based polymers were modified into methacrylate units using trimethylsilyldiazomethane.<sup>50,51</sup> In a typical experiment, 50 mg of PMAA-based polymer was dissolved in a mixture of methanol and THF. To this solution was added a large excess of trimethylsilyldiazomethane (2 M stock solution in diethyl ether) dropwise, and the reaction mixture was stirred at room temperature for 3–4 h.

**Results and Discussion**

The ionic liquid-based block copolymers (IL BCs) used for self-assembly in solution were derived by reversible addition-fragmentation chain transfer (RAFT) polymerization, as described previously.<sup>33</sup> Three types of imidazolium-functionalized IL BCs whose molecular features are summarized in Tables 1 and 2 were studied: PAm-*b*-PIL-1Br, PMAA-*b*-PIL-2Br, and PMAA-*b*-PIL-3Br, where PILBr, PAm, and PMAA are abbreviations for polymeric ionic liquid (of methacrylamido or methacrylate-type) with bromide (Br<sup>−</sup>) as counteranion, poly(acrylamide) and poly(methacrylic acid), respectively (see Scheme 1). PAm, PMAA, and PILBr are water-soluble polymers. PAm is neutral whereas PMAA is responsive to pH and to cations or can be chemically transformed into hydrophobic poly(methyl methacrylate) (PMMA), as discussed further. As for the PIL blocks, they are anion responsive and each type of anion can selectively modify the aqueous behavior of the PIL block<sup>52</sup> and hence that of the corresponding IL BCs. To the best of our knowledge, only Waymouth et al. have reported on the self-assembly of IL BCs,

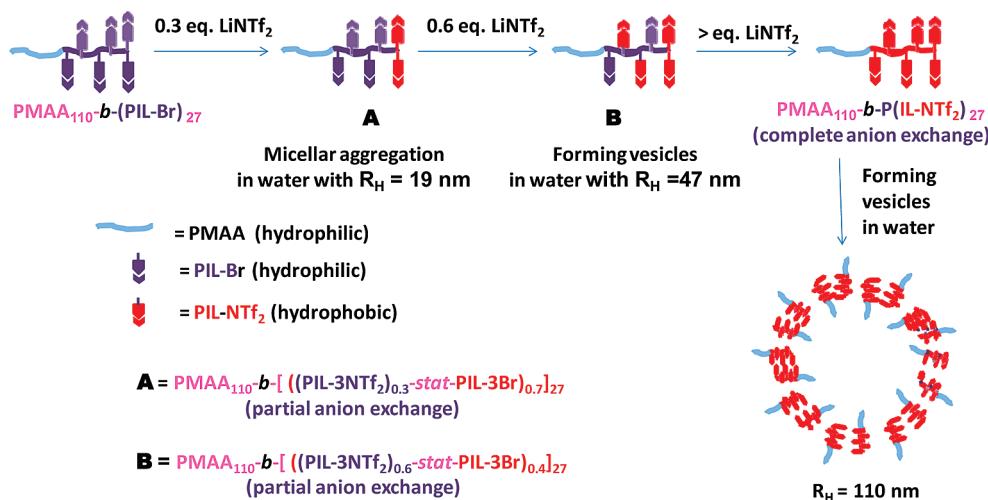


**Figure 1.** (a) Intensity auto correlation function at 50, 70, 90, and 120° and CONTIN plot at 90° for PMAA<sub>110</sub>-*b*-P(IL-3NTf<sub>2</sub>)<sub>27</sub> in water free from LiBr. The sample was washed with acetone after anion exchange to remove LiBr. (b) TEM image of PMAA<sub>110</sub>-*b*-P(IL-3NTf<sub>2</sub>)<sub>27</sub> from a water solution.

which were imidazolium-functionalized block copolymers constituted of a polystyrene backbone that self-assembled in toluene into elongated micelles.<sup>32</sup> Due to their multiresponsiveness, the solution properties of our IL BCs can be manipulated by several means, including chemical modification of the hydrophilic PMAA block into a hydrophobic PMMA one or anion exchange on the PIL block to make it hydrophobic, or solvent exchange. This is highlighted in Scheme 2.

**1. Self-Aggregation in Solution of PMAA-*b*-PILBr and Related IL BCs.** With bromide (Br<sup>−</sup>) as the counteranion, all these PIL BCs are highly soluble in water. On the basis of <sup>1</sup>H NMR investigations, we have previously shown that these diblock copolymers exhibit salt-responsive behavior in aqueous solutions: anion exchange from Br<sup>−</sup> to <sup>−</sup>NTf<sub>2</sub> induced the formation of aggregates consisting of hydrophobic <sup>−</sup>NTf<sub>2</sub>-based IL blocks stabilized by PMAA blocks (Scheme 2).<sup>33</sup> For instance, the double hydrophilic PMAA<sub>110</sub>-*b*-(PIL-3Br)<sub>27</sub> block copolymer precursor is transformed into an amphiphilic PMAA<sub>110</sub>-*b*-(PIL-3NTf<sub>2</sub>)<sub>27</sub> IL BC after anion exchange. However, the latter compound remained water-soluble thanks to the stabilizing

**Scheme 3. Variation of the Size and Shape of Polymeric Vesicles Formed by Self-Assembly in Water of PMAA-*b*-PIL-NTf<sub>2</sub> Triggered by Partial Anion Exchange**



PMAA blocks forming the shell of the micelle-like structure. The self-assembled aggregates have been here further investigated by dynamic light scattering (DLS) and transmission electron microscopy (TEM) to get an insight into their size and shape. Given the composition of most of our IL BCs, formation of polymeric vesicles (polymersomes) by self-assembly in solution was expected. Indeed, Discher and Eisenberg<sup>35</sup> have proposed that amphiphilic block copolymers consisting of a hydrophilic mass fraction (*f*) higher than 45% form spherical micelles while those with *f* < 25% are expected to self-assemble into reverse nanostructures, polymeric vesicles being observed for block copolymers with *f* around 35 ± 10%.

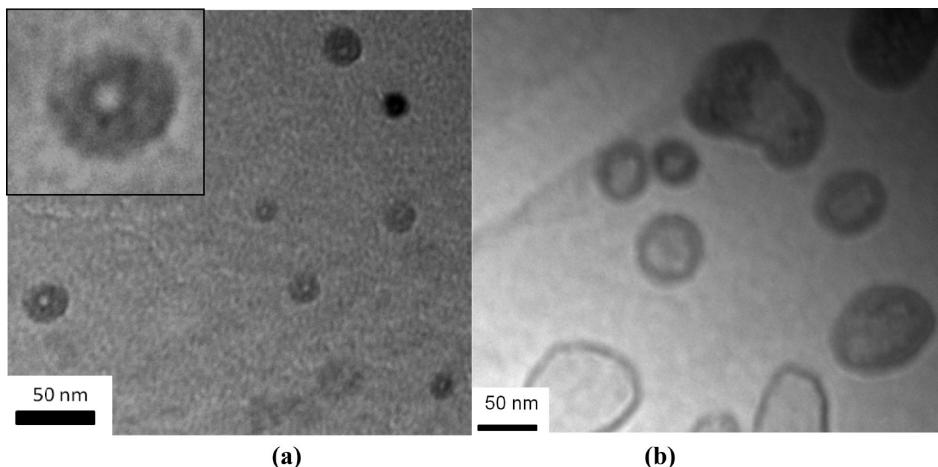
The hydrodynamic radius ( $R_H$ ) of the aggregates formed in water from PMAA<sub>110</sub>-*b*-(PIL-3NTf<sub>2</sub>)<sub>27</sub> was found to be 110 nm by DLS, with relatively narrow distribution of relaxation times (Figure 1a). TEM images obtained from an aqueous solution of this IL BC revealed the formation of polymersomes, with a good correlation of the size of the vesicles between DLS and TEM techniques (Figure 1b). In this particular example, the hydrophilic mass fraction is 41.7%, and observation of polymersomes is consistent with the predictions of Discher and Eisenberg.<sup>35</sup>

As illustrated in Scheme 3, the hydrophobic content in these amphiphilic PMAA-*b*-PIL-3 IL BCs can be adjusted by varying the extent of anion exchange, from partial to complete modification. The size and shape of the corresponding aggregates can thus be manipulated. In our previous contribution, we have shown by DLS that the size of the aggregates formed in water increases by increasing the extent of anion exchange, from Br<sup>-</sup> to NTf<sub>2</sub>.<sup>33</sup> It is believed that partial anion exchange leads to IL-based copolymer exhibiting a random distribution of Br<sup>-</sup> and NTf<sub>2</sub> anions, resulting in a lowering of the surface tension between the PIL block and the PMAA one. For instance, partially exchanging the Br<sup>-</sup> anion of the parent PMAA<sub>110</sub>-*b*-(PIL-3 Br)<sub>27</sub> IL BC for 0.3 equiv of LiNTf<sub>2</sub> resulted in a IL BC that can be noted as PMAA<sub>110</sub>-*b*[(PIL-3NTf<sub>2</sub>)<sub>0.3</sub>-stat-(PIL-3Br)<sub>0.7</sub>]<sub>27</sub>, where the second block is an IL-type statistical copolymer. This IL BC self-assemble in aggregates of lower  $R_H$  value ( $R_H = 19 \text{ nm}$  by DLS) than that of the PMAA<sub>110</sub>-*b*-(PIL-3 NTf<sub>2</sub>)<sub>27</sub> obtained by complete anion exchange ( $R_H = 110 \text{ nm}$ ), as shown in Figure 1. Analysis by TEM of PMAA<sub>110</sub>-*b*[(PIL-3NTf<sub>2</sub>)<sub>0.3</sub>-stat-(PIL-3Br)<sub>0.7</sub>]<sub>27</sub> showed a micellar morphology resembling vesicles with an average size  $R_H = 19 \text{ nm}$  (Figure 2a),

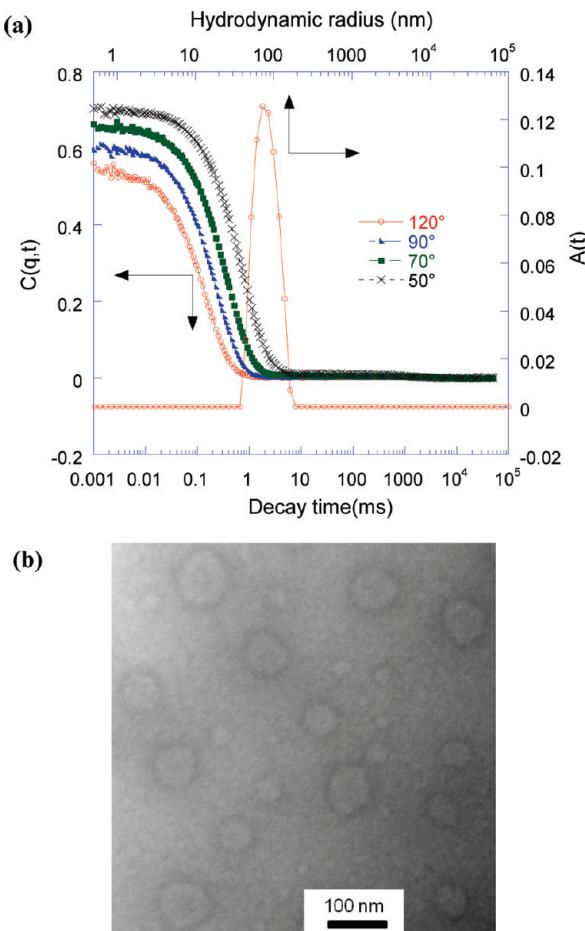
though clear conclusions can not be drawn. Analysis by static light scattering (SLS) in water did not give reliable results, likely because of the formation of micellar aggregates. We imaged another sample for which the extent of anion exchange was 60%, denoted as PMAA<sub>110</sub>-*b*-(PIL-3NTf<sub>2</sub>)<sub>0.6</sub>-stat-(PIL-3Br)<sub>0.4</sub>]<sub>27</sub>. In this case, the observation of polymeric vesicles is less ambiguous (Figure 2b). Thus, the trend seems to be that the higher the extent of anion exchange is, the higher the size of the aggregates is. However, a more systematic study would be necessary to gain an insight into how the morphology and the size of the aggregates are impacted by varying the extent of anion exchange.

As reported earlier,<sup>33</sup> chemical modification by methylation of the hydrophilic PMAA blocks of PMAA-*b*-PIL-3NTf<sub>2</sub> IL BCs into hydrophobic PMMA ones led to doubly hydrophobic PMMA-*b*-PIL-3NTf<sub>2</sub> IL BCs. For instance, PMMA<sub>110</sub>-*b*-(PIL-3NTf<sub>2</sub>)<sub>27</sub> aggregated in THF solution into micelle-like nanostructures, with PIL-3NTf<sub>2</sub> blocks forming the membrane protected by a THF-soluble PMMA part. DLS investigations, indeed, gave a hydrodynamic radius of 45 nm (Figure 3a) while polymeric vesicles were again observed by TEM (Figure 3b).

Further manipulation of these PMMA-*b*-PIL-3NTf<sub>2</sub> IL BCs by anion exchange using LiBr afforded an amphiphilic block copolymer PMMA-*b*-PIL-3Br, as depicted in Scheme 2. The latter compounds were found to self-assemble either in water or in THF, depending upon the molar mass and the overall composition of the copolymer. For instance, they could be dissolved in THF for short IL block compared to the PMMA chain length: PMMA<sub>80</sub>-*b*-(PIL-2Br)<sub>8</sub> is thus soluble in THF whereas PMMA<sub>80</sub>-*b*-(PIL-2Br)<sub>43</sub> is not. Characterization by <sup>1</sup>H NMR in THF-*d*<sub>8</sub> revealed that the former compound (*f* fraction = 21.5%) gave rise to micellar aggregates with a PIL-2Br-based membrane stabilized by PMMA. Further investigations by DLS and TEM indicated the formation of reverse polymeric vesicles, with  $R_H$  of 17.3 nm. Figure 4b shows such reverse polymersomes by TEM image obtained from a THF solution of PMMA<sub>80</sub>-*b*-(PIL-2Br)<sub>8</sub>, with a uniform size distribution. The vesicular morphology in THF was confirmed from SLS experiments: the radius of gyration ( $R_g$ ) is equal to 17.7 nm and the  $R_g/R_H$  value is close to one ( $R_g/R_H = 1.02$ ).<sup>36,38</sup> From SLS data, it is found that the number of copolymeric chains self-aggregating into vesicles in THF from PMMA<sub>80</sub>-*b*-(PIL-2Br)<sub>8</sub> is equal to 156, with a weight-average molar mass of  $1.6 \times 10^6 \text{ g/mol}$ .

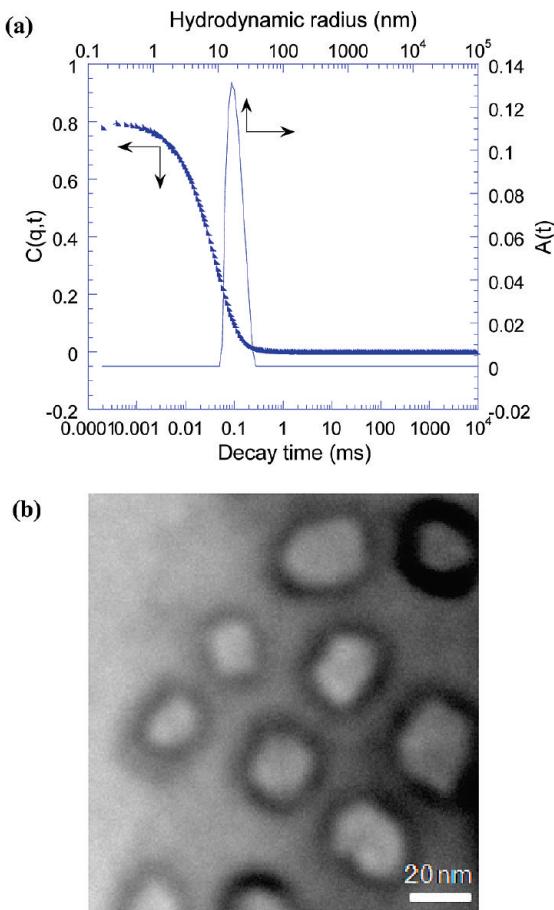


**Figure 2.** (a) TEM images of (a)  $\text{PMAA}_{110}\text{-}b\text{-[PIL-3NTf}_2\text{]}_{0.3}\text{-stat-(PIL-3Br)}_{0.7}]_{27}$  and (b)  $\text{PMAA}_{110}\text{-}b\text{-[PIL-3NTf}_2\text{]}_{0.6}\text{-stat-(PIL-3Br)}_{0.4}]_{27}$  in water obtained after partial anion exchange to  $\text{PMAA}_{110}\text{-}b\text{-P(IL-3Br)}_{27}$  with 0.3% and 0.6% of  $\text{LiNTf}_2$ , respectively.



**Figure 3.** (a) Intensity auto correlation function at 50, 70, 90 and 120° and CONTIN plot at 90° for  $\text{PMMA}_{110}\text{-}b\text{-P(IL-3NTf}_2\text{)}_{27}$  in THF and (b) TEM image in THF.

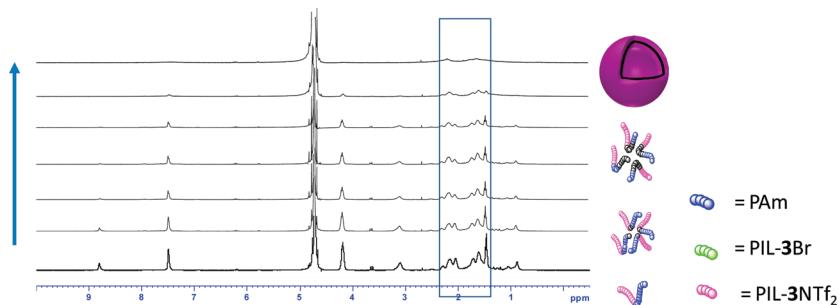
As recently highlighted by Raghavan et al. concerning molecular surfactants,<sup>48</sup> no general rules or guidelines have been laid out for the formation of reverse vesicles, in contrast to the extensive knowledge of the same for normal (direct) vesicles generated in water. One can reasonably believe that it is also true for reverse vesicles formed from block copolymers (reverse polymersomes). Propositions made by Discher and Eisenberg mentioned above are only valid for self-assembly of block copolymers in water. Thus, three different IL BCs—two being



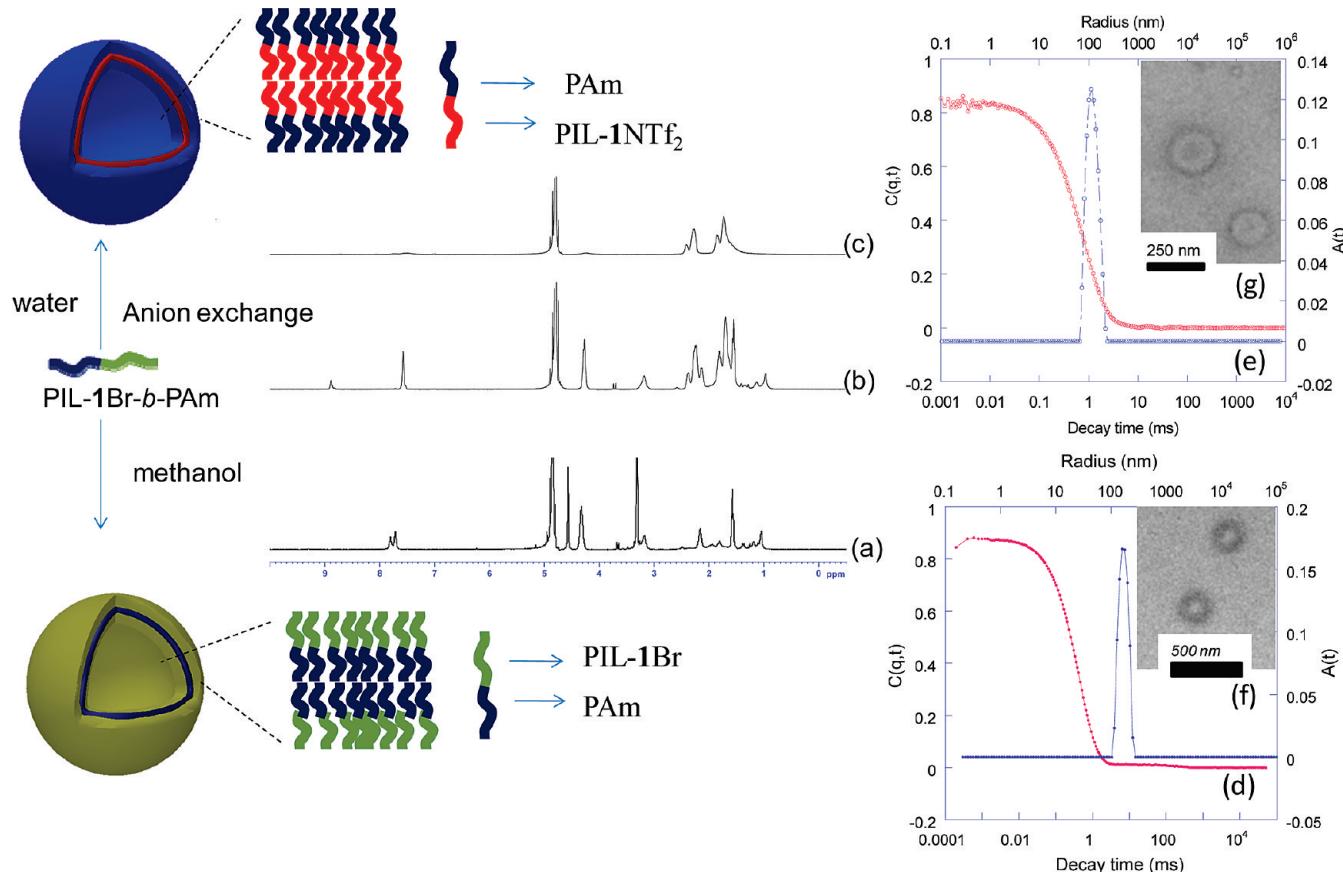
**Figure 4.** (a) Intensity auto correlation function and CONTIN plot at 90° for  $\text{PMMA}_{80}\text{-}b\text{-P(IL-2Br)}_8$  in THF. (b) TEM image of  $\text{PMMA}_{80}\text{-}b\text{-P(IL-2Br)}_8$  in THF.

amphiphilic and one doubly hydrophobic—could be derived by a simple methylation reaction or by anion exchange from  $\text{PMAA-}b\text{-PILBr}$  IL BCs; this allowed us to trigger their self-assembly into direct or reverse polymersomes (Scheme 2).

**2. Self Aggregation of PAm-*b*-(PIL-1 Br) in solution.** Anion exchange from  $\text{Br}^-$  to  $^-\text{NTf}_2$  of PAm-*b*-PIL-1Br led to PAm-*b*-PIL-1NTf<sub>2</sub> compounds with amphiphilic properties. The ability of these IL BCs with water-soluble stabilizing PAm blocks to self-associate into micelles was also investigated. In contrast to the case of homo PIL-1NTf<sub>2</sub>,



**Figure 5.**  $^1\text{H}$  NMR of  $\text{P}(\text{IL-1Br})_{20}\text{-}b\text{-PAm}_{86}$  in  $\text{D}_2\text{O}$  with gradual addition of  $\text{LiNTf}_2$  to induce anion exchange from  $\text{Br}^-$  to  $\text{NTf}_2^-$ . Protons corresponds to PAm block resonate between 1.5 to 2.5 ppm as marked in the figure and the other signals correspond to the ionic liquid block. The gradual disappearance of signals corresponding to the IL part is due to their micellization.

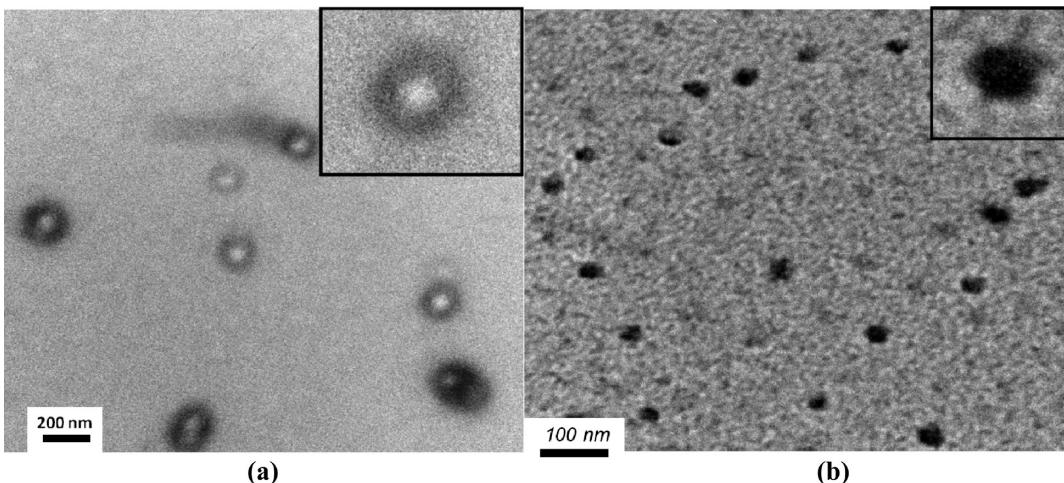


**Figure 6.** Overlay of  $^1\text{H}$  NMR spectra of block copolymer  $\text{P}(\text{IL-1Br})_{20}\text{-}b\text{-PAm}_{86}$  in  $\text{MeOD}$  (a) and in  $\text{D}_2\text{O}$  before (b) and after (c) anion exchange from  $\text{Br}^-$  to  $\text{NTf}_2^-$ . (d and e) Intensity auto correlation function and CONTIN plot for  $\text{P}(\text{IL-1Br})_{20}\text{-}b\text{-PAm}_{86}$  ( $R_{\text{H}} = 150 \text{ nm}$ ) and  $\text{P}(\text{IL-1NTf}_2)_{20}\text{-}b\text{-PAm}_{86}$  ( $R_{\text{H}} = 135 \text{ nm}$ ) in methanol and water respectively. (f and g) TEM images of  $\text{P}(\text{IL-1Br})_{20}\text{-}b\text{-PAm}_{86}$  and  $\text{P}(\text{IL-1NTf}_2)_{20}\text{-}b\text{-PAm}_{86}$  in methanol and water, respectively.

the corresponding PAm-*b*-PIL-1NTf<sub>2</sub> IL BC remained water-soluble after anion exchange, aggregating into nanostructures with a PAm-based corona stabilizing the hydrophobic part made of the PIL-1NTf<sub>2</sub> blocks. A series of  $^1\text{H}$  NMR spectra were recorded in  $\text{D}_2\text{O}$  for the PAm<sub>86</sub>-*b*-(PIL-1Br)<sub>20</sub> sample, with a gradual addition of LiNTf<sub>2</sub> solution to induce anion exchange. A progressive decrease -until complete disappearance- of the intensity of protons of PIL block can be seen, as a result of their aggregation (Figure 5). DLS measurements gave a hydrodynamic radius  $R_{\text{H}}$  equal to 135 nm (Figure 6e) and visualization by TEM showed that aggregates formed in water corresponded to polymeric vesicles (Figure 6g). This observation is again in accordance with the empirical rule proposed by Discher and Eisenberg,<sup>35</sup> given the overall composition of such a IL BC (here  $f = 37.8$ ).

Not only the anion exchange, the choice of a selective solvent such as methanol also triggers the self-assembly of these IL BCs. For instance, the  $^1\text{H}$  NMR spectrum of PAm<sub>86</sub>-*b*-(PIL-1Br)<sub>20</sub> in methanol-*d*<sub>4</sub> shows only peaks corresponding to the protons of PIL-1Br (Figure 6a), the peaks corresponding to the protons of PAm being not detected. This is indicative of a self-association with PAm chains that are protected from precipitation by the PIL-1Br blocks. The hydrodynamic radius  $R_{\text{H}}$  of these aggregates in methanol was found to be 150 nm by DLS (Figure 6d), while TEM images obtained from a methanol solution of the PAm<sub>86</sub>-*b*-(PIL-1Br)<sub>20</sub> IL BC again revealed polymersomes (Figure 6f).

Next, DLS measurements were performed with different PAm-*b*-PIL-1Br IL BCs, both in water (after anion exchange) and in methanol, at an angle of 90° with a concentration of



**Figure 7.** TEM image of (a)  $\text{P}(\text{IL-1NTf}_2)_{20}$ -*b*- $\text{PAm}_{113}$  and (b)  $\text{P}(\text{IL-1NTf}_2)_{12}$ -*b*- $\text{PAm}_{135}$  in water.

1 mg/mL (Table 2). As the molar content of PAm increased, the size of the self-assembled aggregates in methanol increased; however, the opposite trend was noted in water. For example, the  $R_H$  of  $\text{PAm}_{38}$ -*b*-(PIL-1Br)<sub>16</sub> and  $\text{PAm}_{64}$ -*b*-(PIL-1Br)<sub>16</sub> in methanol are 116 and 148 nm, respectively. Since methanol is nonselective for PAm, the solubility of these IL BCs in this solvent depends upon the molar mass and molar ratio of the PAm block. For instance  $\text{PAm}_{86}$ -*b*-(PIL-1Br)<sub>20</sub> is freely soluble in methanol whereas  $\text{PAm}_{113}$ -*b*-(PIL-1Br)<sub>20</sub> is not. In most cases, the PAm-*b*-(PIL-1NTf<sub>2</sub>) IL BCs formed by anion exchange from Br<sup>-</sup> to <sup>-</sup>NTf<sub>2</sub> proved to self-assemble in polymersomes in water. In contrast, when the molar content of PIL-1NTf<sub>2</sub> as well as the molar ratio between PAm to PIL-1NTf<sub>2</sub> was low enough, these IL BCs gave rise to spherical micelles, as is the case of  $\text{PAm}_{135}$ -*b*-(PIL-1NTf<sub>2</sub>)<sub>12</sub> whose  $R_H$  value is equal to 25 nm (Figure 7b). In this example, the hydrophilic mass fraction (*f*) is higher than 45 and observation of spherical micelles is again consistent with Discher and Eisenberg's empirical law.<sup>35</sup>

## Conclusion

We have demonstrated here that the self-assembly of ionic liquid-based block copolymers (IL BCs) can be readily triggered by different stimuli, including anion exchange of the polymeric ionic liquid block, proper choice of the selective solvent of one block or chemical modification of carboxylic acid groups of methacrylic acid units-containing IL BCs. Triggering self-assembly by anion exchange is reversible and a given self-assembled morphology can be unassembled and/or reassembled into another nanostructure. In this work, the option was to investigate the morphology in solution before and after complete anion exchange of miscellaneous IL-based diblock copolymers (IL BCs), rather than to examine the entire phase diagram of a particular type of IL BC by varying its molar mass. However, self-assembled aggregates of several IL BCs could be imaged by TEM and analyzed by DLS and/or SLS revealing the type of nanostructures generated in solution. Compounds consisting of a hydrophilic mass fraction (*f*) around  $35 \pm 10$  are found to self-organize into direct or reverse polymersomes, as a function of the selective solvent used (water, methanol or THF). The characteristic hydrodynamic radius of the obtained polymeric vesicles is in the range 17 to 150 nm, depending on the composition of the IL BC. Some IL BCs possessing *f* values higher than 45 self-assemble into polymeric spherical micelles. All these observations are consistent with the empirical classification of Discher and Eisenberg referring to the type of nanoparticles obtained by

self-assembly of amphiphilic block copolymers of coil-coil type, as a function of the hydrophilic mass fraction.

Moreover, preliminary investigations into the morphology of aggregates induced by partial anion exchange have shown the formation of bigger aggregates as the extent of anion exchange progressively increases, but this should be investigated further. Therefore, the solution behavior of IL BCs cannot be generalized at this stage and more variation of the block copolymer composition would be necessary for the different systems described in this work. Work is also in progress to achieve IL BCs which could combine both thermosensitivity and anion responsiveness, where temperature and anion concentration can be independently varied to tune the overall solubility. This could facilitate the access to multiresponsive, robust, and stable polymersomes.

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