• ARTICLES •

# A further understanding of the cation exchange mechanism for the extraction of Sr<sup>2+</sup> and Cs<sup>+</sup> by ionic liquid

SUN TaoXiang, SHEN XingHai<sup>\*</sup> & CHEN QingDe

Beijing National Laboratory for Molecular Sciences (BNLMS), Radiochemistry and Radiation Chemistry Key Laboratory of Fundamental Science, College of Chemistry and Molecular Engineering, Peking University, Beijing 100871, China

Received October 15, 2012; accepted November 23, 2012; published online March 15, 2013

The cation exchange mechanism was further investigated during the extraction of  $Sr^{2+}$  and  $Cs^+$  using the extractant dicyclohexano-18-crown-6 (DCH18C6) in an ionic liquid (IL) 1-ethyl-3-methyimidazolium bis[(trifluoromethyl)sulfonyl]imide ( $C_2mimNTf_2$ ). The concentrations of both the cation  $C_2mim^+$  and the anion  $NTf_2^-$  in aqueous phase were detected. The concentration of  $NTf_2^-$  in the aqueous phase decreased as  $Sr^{2+}$  or  $Cs^+$  exchanged into the IL phase. Addition of  $C_2mim^+$  or  $NTf_2^-$  as well as the variation of the solubility of  $C_2mimNTf_2$  influenced the extraction efficiency of  $Sr^{2+}$  or  $Cs^+$ .

ionic liquids, extraction, cation exchange, Sr<sup>2+</sup>, Cs<sup>+</sup>

#### 1 Introduction

Room-temperature ionic liquids (ILs) have been considered as alternative solvents in the last decade for synthetic, catalytic, electrochemical and separation sciences due to their unique properties such as low melting point, non-flammability, negligible vapor pressure, thermal and radiation stability [1-4]. Hydrophobic ILs such as 1-alkyl-3-methyimidazolium hexafluorophosphate (CnmimPF6) and bis (trifluoromethyl)sulfonyl]imide (CnmimNTf2) were extensively used in the liquid-liquid extraction of metal ions [5-20]. Because of the ionic compositions and therefore the corresponding physicochemical properties and characteristics of ILs, the ionic species (metal ions and metal-extractant complex) are much more favored thermodynamically solvated in ILs than in conventional solvent and cations/anions of ILs can exchange with metallic complexes into aqueous phase.

The cation or anion exchange mechanism leads to high extraction efficiency in the extraction of metal ions using ILs as solvents [6, 17–22]. The anion exchange mechanism

was indicated in the extraction of lanthanides by 2-thenoyltrifluoroacetone (Htta) into the  $NTf_2^-$  based ILs (eq. (1)) [20].

$$\begin{array}{ccc} Ln^{3+}{}_{(aq)} & 4Htta_{(IL)} & NTf_{2}^{-}{}_{(IL)} & Ln(tta)_{4}^{-}{}_{(IL)} \\ & 4H_{(aq)} & NTf_{2}{}_{(aq)} \end{array}$$

<sup>\*</sup>Corresponding author (email: xshen@pku.edu.cn)

<sup>©</sup> Science China Press and Springer-Verlag Berlin Heidelberg 2013

imidazolium cations in aqueous phase was usually calculated as the IL solubility plus the exchanged amount of C<sub>n</sub>mim<sup>+</sup> [23]. Several researchers reported a linear relationship between the amount of the IL cations increased in the aqueous phase and that of the extracted metal ions. In the extraction of sodium ions by DCH18C6 in C5mimNTf2, Dietz et al. found a linear dependence of [C<sub>5</sub>mim<sup>+</sup>]<sub>ac</sub> upon the concentration of extracted sodium ions with a slope of 0.88 [18]. A slope of approximate 1.8, far from the theoretical value of 3, was found between the amount of C₄mim<sup>+</sup> in the aqueous phase and that of La3+ extracted into the IL phase during the extraction by C₄mimNfO in the absence of extractants, where NfO is nonafluorobutanesulfonate [24]. In a recent work, a linear relationship was also reported by Bell et al. between the mole number of uranium transferred from the aqueous phase to the IL phase and that of IL cations transferred from the IL phase to the aqueous phase [22]. It is noticed that there is always a deviation between the experimentally obtained slope and the theoretical value. This deviation is usually attributed to the coexistence of another extraction mechanism, e.g., the neutral complex extraction mechanism.

On the other hand, although the cation exchange mechanism enhances the extraction efficiency, this extraction procedure induces a further loss of the IL cations besides the dissolution of ILs in aqueous phase, which is considered as a drawback for ILs in the application of extraction or catalysis. To attempt minimizing this drawback, Dai and coworkers adopted sodium tetraphenylborate (NaBPh<sub>4</sub>) as a sacrificial cation exchanger during the extraction of Cs<sup>+</sup> by calix[4]arene-bis(tert-octylbenzo-crown-6) (BOBCalixC6) in C<sub>4</sub>mimNTf<sub>2</sub> and decreased the loss of C<sub>4</sub>mim<sup>+</sup> by about 24% [14]. They also utilized ILs with a more hydrophobic anions bis(perfluoroethanesulfonyl)imide (BETI-) in the extraction of Sr<sup>2+</sup> and Cs<sup>+</sup> [23]. The dissolution of ILs was reduced and the extraction was improved [23]. While the variation of the amount of IL cations in aqueous phase attracted almost all attentions in the research of cation exchange mechanism, the detection of the anion of ILs (e.g., NTf<sub>2</sub>) was neglected. To evaluate the loss of ILs during extraction, both cations and anions should be quantitatively measured.

In this work, we gave a precise detection of the concentrations of both  $C_2 \text{mim}^+$  and  $\text{NTf}_2^-$  in aqueous phase after the extraction of SrCl<sub>2</sub> and CsCl by DCH18C6 in  $C_2 \text{mimNTf}_2$ . The cation exchange mechanism was further discussed and the loss of both the cation and anion of an IL during the cation exchange was quantitatively evaluated.

#### 2 Experimental

#### 2.1 Materials

 $LiNTf_2$  and  $C_2mimCl$  were purchased from TCl Chemical Co. and used without further purification.  $C_2mimNTf_2$  was

synthesized and purified according to the reported method [25–27], and its purity is over 99% as detected by NMR and element analysis. The extractant bis(2-propyloxy)calix[4] crown-6 (BPC6, > 95%) and DCH18C6 (95%) were ob-

UV-vis measurement was performed on a Hitachi 3010 UV-vis Spectrometry to obtain the spectrum of  $C_2 \text{mim}^+$  in the aqueous phase and the absorbance at 211 nm was used to calculate the concentration of  $C_2 \text{mim}^+$ . Figure 2 shows a linear relationship between the absorbance at 211 nm and the equilibrium concentration of  $C_2 \text{mim}^+$  in the aqueous phase ( $[C_2 \text{mim}^+]_{aq}$ ).

<sup>19</sup>F-NMR spectra were recorded on a Bruker AV400 MHz NMR spectrometer and the concentration of NTf<sub>2</sub><sup>-</sup> in the aqueous phase were obtained by the area ratio of <sup>19</sup>F NMR signal of NTf<sub>2</sub><sup>-</sup> to the –CF<sub>3</sub> peak of benzotrifluoride (C<sub>6</sub>H<sub>5</sub>CF<sub>3</sub>). In detail, approximate 300 μL samples were added to an NMR tube within a stem coaxial capillary tube containing benzotrifluoride dissolved in d-acetone as external reference. Area integral of each peak near –80.70 ppm, which referred to the assigned value 1.00 of –63.90 ppm, was proportional to the NTf<sub>2</sub><sup>-</sup> concentration (Figure 3).

Water content in the IL phase after extraction was detected using the Mettler-Toledo DL31/38 Karl-Fischer titrator. The water content in the IL phase is about 1.6×10<sup>4</sup> ppm in all samples. The detection by UV absorption showed that  $C_2$ mimNTf<sub>2</sub> has a solubility of about 0.0479 mol dm<sup>-3</sup> in water. The dissolution of water in the IL phase induces a 1.6% decrease of the volume of the aqueous phase. The dissolution of C<sub>2</sub>mimNTf<sub>2</sub> in the aqueous phase induces a 1.2% decrease of the volume of the IL phase. The water dissolution in the IL phase and the IL dissolution in the aqueous phase induced the volume of the IL phase increment and decrement, respectively. These two effects on the volume change of the IL phase were both very slight and could be compensated, so that the volume of the IL phase was considered constant. Similarly, the volume of the aqueous phase was also considered constant.



Figure 2 Dependence of the absorbance at 211 nm on the equilibrium concentration of C<sub>2</sub>mim<sup>+</sup> in the aqueous solution ([C<sub>2</sub>mim<sup>+</sup>]<sub>aq</sub>). Inset: a typical absorbance curve of C<sub>2</sub>mimNTf<sub>2</sub> (0.15 mmol dm<sup>-3</sup>) in aqueous phase.



Figure 3 Relative integral area of the peak near -80.70 ppm of  $^{19}F$  NMR signal depending on the concentration of NTf<sub>2</sub><sup>-</sup> in the aqueous solution ([NTf<sub>2</sub><sup>-</sup>]<sub>aq</sub>). Inset: A typical <sup>19</sup>F NMR spectrum of C<sub>2</sub>mimNTf<sub>2</sub> in aqueous solution using benzotrifluoride dissolved in d-acetone as external reference.

#### **3** Results and discussion

### 3.1 Variation of $[C_2mim^+]$ and $[NTf_2^-]$ in the aqueous phase

DCH18C6 in C<sub>2</sub>mimNTf<sub>2</sub> can efficiently extract both Sr<sup>2+</sup> and Cs<sup>+</sup>. The concentrations of both C<sub>2</sub>mim<sup>+</sup> and NTf<sub>2</sub><sup>-</sup> in the aqueous phase were detected after extraction. According to the cation exchange mechanism, the concentration of C<sub>2</sub>mim<sup>+</sup> in aqueous phase ([C<sub>2</sub>mim<sup>+</sup>]<sub>aq</sub>) would increase as metal ions extracted into the



Figure 4 Dependence of the concentration of  $C_2 \text{mim}^+$  ([ $C_2 \text{mim}^+$ ]<sub>at</sub>) and  $NTf_2^-$  ([ $NTf_2^-$ ]<sub>at</sub>) in the aqueous phase on the concentration of (a)  $S^{2+}$  ([ $S^{2+}$ ]<sub>1L</sub>) and (b)  $Cs^+$  ([ $Cs^+$ ]<sub>1L</sub>) in the IL phase after extraction using DCH18C6 in  $C_2 \text{mim}NTf_2$ . Symbol: experimental data, line: fitting result.

nomenon. The hydrophobic IL  $C_2$ mimNTf<sub>2</sub> can be dissolved in water and the equilibrium is depicted as

$$C_2 minNTf_{2(IL)} \rightleftharpoons C_2 minNTf_{2(aq)}$$
 (4)

$$C_{2}\min NTf_{2(aq)} \rightleftharpoons C_{2}\min^{+} + NTf_{2(aq)}^{-}$$
(5)

in which the equilibrium constant is depicted as  $K_1$  and  $K_2$ , respectively. Thus

$$\mathbf{K} = \mathbf{K}_1 \cdot \mathbf{K}_2 = [\mathbf{C}_2 \operatorname{mim}^+]_{\operatorname{aq}} \cdot \gamma_+ \cdot [\operatorname{NTf}_2^-]_{\operatorname{aq}} \cdot \gamma_-$$
(6)

where  $\gamma_{+}$  and  $\gamma_{-}$  are the activity coefficients of C<sub>2</sub>mim<sup>+</sup> and NTf<sub>2</sub><sup>-</sup> in the aqueous phase. The  $\gamma_{+}$  and  $\gamma_{-}$  values in each sample can be calculated by the extended Debye-Hückel equation

$$\log \gamma = \frac{-A\sqrt{I}}{1+aB\sqrt{I}}$$
(7)

where a and I are the ion size parameter and the ionic strength, respectively, while the constants A, B at 293.2 K are 0.5070 (mol kg<sup>-1</sup>)<sup>-0.5</sup> and 0.3282×10<sup>10</sup> (mol kg<sup>-1</sup>)<sup>-0.5</sup> m<sup>-1</sup>, respectively [28]. The a value for univalent ions was evaluated from the limiting ionic molar conductivity ( $\lambda^{\circ}$ ) at 298.2 K according to the empirical equation by Brüll [29, 30].

$$a/(10^{-10} \,\mathrm{m}) = \frac{216}{\lambda^{\circ}/(\mathrm{S} \,\mathrm{cm}^2 \,\mathrm{mol}^{-1})} \tag{8}$$

The  $\lambda^{\circ}$  values for C<sub>2</sub>mim<sup>+</sup> and NTf<sub>2</sub><sup>-</sup> are 31.3 and 32.2 S cm<sup>2</sup> mol<sup>-1</sup>, respectively, according to the literature [31, 32]. The values of a for the organic ions are usually between 5 and 8 [30], and they are calculated to be 6.9, 6.7 for C<sub>2</sub>mim<sup>+</sup> and NTf<sub>2</sub><sup>-</sup>, respectively. Using the extended Debye-Hückel equation, Kielland calculated the individual activity coefficients of 130 inorganic and organic ions in water at concentrations up to I = 0.2 mol dm<sup>-3</sup>, and the calculated results are in sufficient accordance with experimental values [30]. For the corresponding sample in the extraction of Sr<sup>2+</sup> (Figure 4(a)), the ionic strength varies from 0.216 to 0.208 mol dm<sup>-3</sup>, and the values of  $\gamma_{+}$ ,  $\gamma_{-}$  vary from 0.768 to 0.770 and from 0.765 to 0.767, respectively. For the Cs<sup>+</sup> system -3Bld...F44VVRy, 0pu\Q÷CÂfz16†s1"0GÀQFkáÔ5öHd, Df9p‰À!%

reported previously between the experimentally obtained slope and the theoretical value is now explained reasonably. Same treatment is also performed in the case of the extraction of Cs<sup>+</sup> by DCH18C6 in C<sub>2</sub>mimNTf<sub>2</sub> (Figure 4(b)), and the fitting result of K' is 0.00224 (mol dm<sup>-3</sup>)<sup>2</sup>.

## **3.2** Effect of adding IL cation or anion on the extraction

The cation exchange procedure opposes the dissolution of anions of ILs in aqueous phase and induces relative small loss of cations, indicating a relative low loss of ILs during extraction. Moreover, adding cations/anions of ILs into aqueous phase can also affect the cation exchange of metal ions. Thus, we have tried to add C<sub>2</sub>mimCl and LiNTf<sub>2</sub> into the aqueous phase during the extraction of Sr<sup>2+</sup> by DCH18C6 in C<sub>2</sub>mimNTf<sub>2</sub> to examine their effects on the extraction, and LiCl was used to subtract the influence of Li<sup>+</sup> (Figure 5(a)). The addition of C<sub>2</sub>mimCl leads to a reduction in the extraction efficiency, implying that C<sub>2</sub>mim<sup>+</sup> indeed decreases the extraction of Sr<sup>2+</sup>. This phenomenon can be easily understood, for the addition of C<sub>2</sub>mim<sup>+</sup> op-



Figure 5 Influence of LiNTf<sub>2</sub>, LiCl and C<sub>2</sub>mimCl on the extraction of (a)  $S^{2+}$  (5 mmol dm<sup>-3</sup>) by DCH18C6 (3 mmol dm<sup>-3</sup>) and (b) Cs<sup>+</sup> (10 mmol dm<sup>-3</sup>) by BPC6 (3 mmol dm<sup>-3</sup>) in C<sub>2</sub>mimNTf<sub>2</sub>.

poses the cation exchange. On the contrary, the extraction efficiency increases upon the addition of LiNTf<sub>2</sub>. For example, adding 1 mol dm<sup>-3</sup> LiNTf<sub>2</sub> induces the extraction efficiency an increase from 49.6% to 53.0%. The addition of NTf<sub>2</sub><sup>-</sup> makes the dissolution of C<sub>2</sub>mim<sup>+</sup> in the aqueous phase decrease, which facilitates C<sub>2</sub>mim<sup>+</sup> exchanged into the aqueous phase from the ILs phase, leading to an increase of E<sub>S</sub>. One can see that the addition of LiCl induces a decrease of the extraction efficiency of Sr<sup>2+</sup>, due to the competition of Li<sup>+</sup> with Sr<sup>2+</sup> in complexing with DCH18C6.

The added salts, C<sub>2</sub>mimCl and LiNTf<sub>2</sub>, induce the extraction efficiency of Sr<sup>2+</sup> decrease and increase, respectively, but Li<sup>+</sup> competes with Sr<sup>2+</sup> in complexing with DCH18C6. The extraction of Cs<sup>+</sup> by BPC6 in C<sub>2</sub>mimNTf<sub>2</sub> was subsequently employed due to the extraordinary high selectivity of Cs<sup>+</sup> by BPC6 so that the influence of Li<sup>+</sup> on the extraction would be reduced [6]. Figure 5(b) shows the effects of the addition of LiCl, C<sub>2</sub>mimCl and LiNTf<sub>2</sub> on the extraction of Cs<sup>+</sup> by BPC6 in C<sub>2</sub>mimNTf<sub>2</sub>. Apparent decrease and increase are found in the variation of extraction efficiency upon the addition of C<sub>2</sub>mimCl and LiNTf<sub>2</sub>, respectively. For example, the extraction efficiency is 91.1% at the LiNTf<sub>2</sub> concentration of 1 mol dm<sup>-3</sup>, while it is 28.0% upon the addition of 1 mol dm<sup>-3</sup> of C<sub>2</sub>mimCl, which are both far from the value of 54.1% in the absence of salts. The addition of LiCl shows little influence on the extraction, suggesting the high selectivity of Cs<sup>+</sup> by BPC6.

### **3.3** Effect of the variation of the IL solubility on the extraction

The variation of the IL solubility, in which the concentrations of C<sub>2</sub>mim<sup>+</sup> and NTf<sub>2</sub><sup>-</sup> in the aqueous phase vary simultaneously, also affects the cation exchange of metal ions. The solubility of hydrophobic ILs C<sub>n</sub>mimNTf<sub>2</sub> in water or in aqueous solution has been studied [33-35], and it is influenced by several facts such as temperature and salt concentration. For instance, the solubility of imidazolium based ILs in water increased and achieved a highest value upon the addition of 0.1 mol dm<sup>-3</sup> of alkaline earth metal ions, e.g., MgCl<sub>2</sub>, CaCl<sub>2</sub> and SrCl<sub>2</sub>, and then decreased as salts further added [33]. We tried to add different salts into the aqueous phase during extraction of Sr2+ or Cs+ to examine the effect of the variation of the solubility of C<sub>2</sub>mimNTf<sub>2</sub> on the extraction efficiency. However, the added salts would complex more or less with the extractants. In the absence of extractants, it was found that C<sub>2</sub>mimNTf<sub>2</sub> can extract Cs<sup>+</sup> to some extent whereas no Sr2+ was extracted [5, 6, 15]. It was found that the mechanism in the extraction of Cs<sup>+</sup> by C<sub>2</sub>mimNTf<sub>2</sub> is cation exchange, which is the same as that in the extraction of  $Cs^+$  by BPC6 in  $C_2$ mimNTf<sub>2</sub>[6]. Therefore we added  $SrCl_2$  in the extraction of  $Cs^+$  by  $C_2mimNTf_2$  in the absence of extractants. Figure 6 shows the variation of the extraction efficiency as salt added. The extraction efficiency of C<sub>2</sub>mimNTf<sub>2</sub> extracting 10 mmol dm<sup>-3</sup> Cs<sup>+</sup> is



Figure 6 Influence of SrCl<sub>2</sub>, NaCl and KCl on the extraction of Cs<sup>+</sup> (10 mmol dm<sup>-3</sup>) by C<sub>2</sub>mimNTf<sub>2</sub> in the absence of extractants.

42.5% and decreases as SrCl<sub>2</sub> added, achieving a lowest value of 40.2% as the concentration of SrCl<sub>2</sub> is 0.1 mol dm<sup>-3</sup>. One can see that the concentration of SrCl<sub>2</sub> at the lowest value of the extraction efficiency of Cs<sup>+</sup> is in good agreement with that at the highest value of the solubility of ILs in aqueous phase. The extraction efficiency is further enhanced by the addition of more SrCl<sub>2</sub>, and achieved a value of 48.7% at 1.5 mol dm<sup>-3</sup> of SrCl<sub>2</sub>. The dependence of the extraction efficiency of Cs<sup>+</sup> by C<sub>2</sub>mimNTf<sub>2</sub> on the concentration of SrCl<sub>2</sub> just reflects that the variation of the solubility of C<sub>2</sub>mimNTf<sub>2</sub> does affect the cation exchange in the extraction of KCl and NaCl induces a decrease of the extraction efficiency due to the competing extraction of K<sup>+</sup> and Na<sup>+</sup> by C<sub>2</sub>mimNTf<sub>2</sub>.

#### 4 Conclusion

The concentration of the anions of C<sub>2</sub>mimNTf<sub>2</sub> in aqueous phase decreases as metal ions (Sr<sup>2+</sup> and Cs<sup>+</sup>) extracted via a cation exchange mechanism. The equilibria of the dissolution and dissociation of C<sub>2</sub>mimNTf<sub>2</sub> in the aqueous phase coexist with the cation exchange. After knowing the extracted amount of metal ions, one can calculate the loss of both the cation and anion of an IL induced by the cation exchange. The addition of C<sub>2</sub>mim<sup>+</sup> decreases whereas addition of NTf<sub>2</sub><sup>-</sup> increases the extraction efficiency of Sr<sup>2+</sup> or Cs<sup>+</sup>. Variation of the solubility of C<sub>2</sub>mimNTf<sub>2</sub> also alters the extraction efficiency of metal ions. Our results help cognize the cation exchange mechanism more deeply and also suggest a method to promote the extraction of metal ions using ILs as solvents.

This work was supported by National Natural Science Foundation of China (20871009) and the Fundamental Research Funds for the Central Univer-

sities. The authors thank Mr. Jingxin Yang for his help with NMR measurement.

- 1 Hallett JP, Welton T. Room-temperature ionic liquids: Solvents for synthesis and catalysis. 2. Chem Rev, 2011, 111(5): 3508–3576
- 2 Armand M, Endres F, MacFarlane DR, Ohno H, Scrosati B. Ionic-liquid materials for the electrochemical challenges of the future. Nat Mater, 2009, 8(8): 621–629
- 3 Han XX, Armstrong DW. Ionic liquids in separations. Accounts Chem Res, 2007, 40(11): 1079–1086
- 4 Sun XQ, Luo HM, Dai S. Ionic liquids-based extraction: A promising strategy for the advanced nuclear fuel cycle. Chem Rev, 2012, 112(4): 2100–2128
- 5 Xu C, Shen XH, Chen QD, Gao HC. Investigation on the extraction of strontium ions from aqueous phase using crown ether-ionic liquid systems. Sci China Ser B-Chem, 2009, 52(11): 1858–1864
- 6 Xu C, Yuan LY, Shen XH, Zhai ML. Efficient removal of caesium ions from aqueous solution using a calix crown ether in ionic liquids: Mechanism and radiation effect. Dalton Trans, 2010, 39(16): 3897–3902
- 7 Sun TX, Wang ZM, Shen XH. Crystallization of cesium complex containing bis(2-propyloxy)calix-4-crown-6 and bis (trifluoromethyl) sulfonyl imide. Inorg Chim Acta, 2012, 390: 8–11
- 8 Sun XQ, Bell JR, Luo HM, Dai S. Extraction separation of rare-earth ions via competitive ligand complexations between aqueous and ionic-liquid phases. Dalton Trans, 2011, 40(31): 8019–8023
- 9 Marin TW, Shkrob IA, Dietz ML. Hydrogen-bonding interactions and protic equilibria in room-temperature ionic liquids containing crown ethers. J Phys Chem B, 2011, 115(14): 3912–3918
- 10 Wang JS, Sheaff CN, Yoon B, Addleman RS, Wai CM. Extraction of uranium from aqueous solutions by using ionic liquid and supercritical carbon dioxide in conjunction. Chem-Eur J, 2009, 15(17): 4458–4463
- 11 Shimojo K, Kurahashi K, Naganawa H. Extraction behavior of lanthanides using a diglycolamide derivative TODGA in ionic liquids. Dalton Trans, 2008, 37(37): 5083–5088
- 12 Dietz ML, Jakab S, Yamato K, Bartsch RA. Stereochemical effects on the mode of facilitated ion transfer into room-temperature ionic liquids. Green Chem, 2008, 10(2): 174–176
- 13 Dietz ML. Ionic liquids as extraction solvents: Where do we stand? Sep Sci Technol, 2006, 41(10): 2047–2063
- 14 Luo HM, Dai S, Bonnesen PV, Buchanan AC, Holbrey JD, Bridges NJ, Rogers RD. Extraction of cesium ions from aqueous solutions

14 LuoPV, BonnesPV ons. S5()]TJ11.203 0 TD..002 Tc.1552 Twolvsed ext.44.3(action of D.)4()-7Sext.4

788

682–685

- 22 Bell TJ, Ikeda Y. The application of novel hydrophobic ionic liquids to the extraction of uranium(vi) from nitric acid medium and a determination of the uranyl complexes formed. Dalton Trans, 2011, 40(39): 10125–10130
- 23 Luo H, Dai S, Bonnesen PV, Haverlock TJ, Moyer BA, Buchanan AC. A striking effect of ionic-liquid anions in the extraction of Sr2+ and Cs+ by dicyclohexano-18-crown-6. Solvent Extr Ion Exch, 2006, 24(1): 19–31
- 24 Kozonoi N, Ikeda Y. Extraction mechanism of metal ion from aqueous solution to the hydrophobic ionic liquid, 1-butyl-3-methylimidazolium nonafluorobutanesulfonate. Mon Chem, 2007, 138(11): 1145–1151
- 25 Bonhote P, Dias AP, Papageorgiou N, Kalyanasundaram K, Gratzel M. Hydrophobic, highly conductive ambient-temperature molten salts. Inorg Chem, 1996, 35(5): 1168–1178
- 26 Dzyuba SV, Bartsch RA. Influence of structural variations in 1-alkyl(aralkyl)-3-methylimidazolium hexafluorophosphates and bis(trifluorormethyl-sulfonyl)imides on physical properties of the ionic liquids. ChemPhysChem, 2002, 3(2): 161–166
- 27 Paul A, Mandal PK, Samanta A. How transparent are the imidazolium ionic liquids? A case study with 1-methyl-3-butylimidazolium hexafluorophosphate, [Bmim][PF6]. Chem Phys Lett, 2005, 402(4-6): 375–379

28