

Investigation on the extraction of strontium ions from aqueous phase using crown ether-ionic liquid systems

XU Chao, SHEN XingHai[†], CHEN QingDe & GAO HongCheng

Department of Applied Chemistry, College of Chemistry and Molecular Engineering, Beijing National Laboratory for Molecular Sciences (BNLMS), Peking University, Beijing 100871, China

The extraction of strontium ions using DCH18C6 as the extractant and various ionic liquids (ILs) as solvents has been investigated. The distribution ratio of Sr²⁺ can reach as high as 10³ under certain conditions, much larger than that in DCH18C6/*n*-octanol system. The extraction capacity depends greatly on the structure of ionic liquids. In ILs-based extraction systems, the extraction efficiency of strontium ions is reduced by increasing the concentration of nitric acid and can also be influenced directly by the presence of Na⁺ and K⁺ in the aqueous phase. It is confirmed that the extraction proceeds mainly via a cation-exchange mechanism.

strontium ions, ionic liquid, extraction, crown ether

1 Introduction

⁹⁰Sr, as a major radioactive fission product with a long lifetime, contributes a large part of heat load and radiation in high level liquid wastes (HLLW) during the reprocessing of spent nuclear fuel. Removal of ⁹⁰Sr from HLLW before the final geological disposal provides several advantages, e.g., reducing waste volume and subsurface storage time, facilitating the handling and transportation, and also cutting down the cost of the treatment.

So far, solvent extraction has been regarded as a main method of separating Sr²⁺ from HLLW. Hydrophobic organic compounds are usually used as diluents, while macrocyclic crown ethers are selected as the extractants. Extensive investigations have been carried out in these aspects^[1-4]. However, in traditional solvent extraction processes there exist problems such as low extraction efficiency and environmental problems caused by the vaporous and toxic organic solvents. In recent years, a new kind of compounds, room-temperature ionic liquids (RTILs), is attracting increased attention because of their potential applications as “green” solvents on the extraction of metal ions^[5]. RTILs are compounds com-

posed entirely of ions and with a low melting point usually below room temperature. In contrast to conventional solvents, RTILs hold several excellent properties^[6,7] such as low toxicity, no obvious vapor pressure, wide liquid range, totally ionic environment, good thermal stability, and the ability to dissolve various organic and inorganic compounds. Replacing the toxic and vaporous organic solvents with RTILs for the extraction of metal ions can not only obtain high extraction efficiency but also bring about less harm to the environment. So far, many studies have been focused on the fundamental physicochemical properties of RTILs as well as their applications on catalysis and organic synthesis. However, the work is also performed on the use of RTILs for extraction of metal ions, especially those in nuclear fuel process.

A pioneer study^[8] by Dai et al. in 1999 concerned the extraction of Sr²⁺ by adopting 1-ethyl-3-methyl-imidazolium bis(trifluoromethyl-sulfonyl)imide (C₂mimNTf₂, Figure 1) as solvent and dicyclohexane-18-crown-6

Received July 15, 2009; accepted August 10, 2009
doi: 10.1007/s11426-009-0268-8

[†]Corresponding author (email: xshen@pku.edu.cn)

Supported by the National Natural Science Foundation of China (Grant No. 20871009).

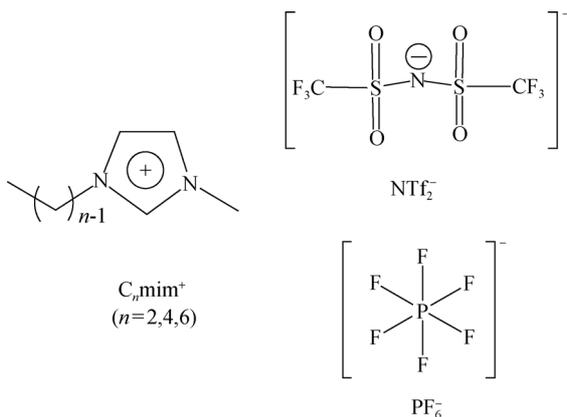


Figure 1 Structures of the cations $C_n \text{mim}^+$ and anions NTf_2^- , PF_6^- of RTILs.

(DCH18C6) as extractant. Much higher extraction capability has been reached as compared with that using toluene as diluent. Visser et al.^[9] further studied the extraction ability of Sr^{2+} by different crown ethers in 1-butyl-3-methylimidazolium hexafluorophosphate ($C_4\text{-mimPF}_6$, Figure 1) and the result indicated that crown ether with higher rigidity structure shows higher extraction efficiency. However, $C_4\text{mimPF}_6$ is unstable under conditions of high acidity. Dietz has also studied the extraction of Sr^{2+} by RTILs based systems and suggested a cation exchange mechanism^[10]. It was found that the extraction mechanisms were influenced by the structures of RTILs used. Yuan et al. reported the γ -radiation effects on hydrophobic RTILs and subsequently their influence on the extraction of Sr^{2+} ^[11,12]. The results showed γ -radiation remarkably reduced the partitioning of Sr^{2+} to the phase crown ether/RTILs. Fortunately, the extraction efficiency can easily be recovered with a simple water-washing method.

While many investigations have carried out on the extraction of Sr^{2+} by RTILs-based systems, it is still worthwhile to perform systematic analysis of the extraction behaviors under various conditions, especially those related with the specialty of HLLW. In this paper, we present a further study on the extraction of Sr^{2+} using DCH18C6 as extractant and various ionic liquids (ILs) as solvents, and thus compare the extraction behaviors with those using conventional solvents. The influences of various aqueous phase conditions, especially the acidity and inorganic salts, on the extraction of Sr^{2+} by crown ether/RTILs are systematically investigated. We also make a preliminary exploration on the extraction mechanism by comparing the extraction behaviors of

RTILs bearing different structures.

2 Experimental

2.1 Reagents

$C_4\text{mimPF}_6$ and $C_n\text{mimNTf}_2$ ($n=2,4,6$) were synthesized and purified according to reported methods^[13–15]. The purity is above 99% as determined by ^1H NMR and Elemental Analysis.

Dicyclohexano-18-crown-6 (DCH18C6) was received as a racemate from INET, Tsinghua University and purified by recrystallization in *n*-heptane. The purity of final product was above 98%.

$\text{Sr}(\text{NO}_3)_2$, SrCl_2 , NaNO_3 , KNO_3 , H_2SO_4 , K_2SO_4 , HNO_3 , *n*-octanol and other reagents were of analytical grade.

2.2 Instruments

HZQ-C Thermostatic Vibrator, LZD4-0.8 Centrifuge, Hitachi 180-80 Atomic Absorption Spectrometry (AAS), Hitachi U-3010 UV-Vis spectrometry, and IKA Genius 3 Vortex Agitator.

2.3 Methods

The extraction experiments were conducted as follows: 0.5 mL of RTIL containing DCH18C6 with different concentrations thoroughly mixed with 1 mL aqueous solution of Sr^{2+} in the vibrator for 30 min (preceding experiments have demonstrated that the equilibrium can be achieved in 10 min), followed by centrifuging to ensure fully phase separation. Then, suitable volume of the upper aqueous phase was removed into 5 mL volumetric flask and diluted with three-distilled water. The concentrations of Sr^{2+} in the diluted solution were determined by AAS and the concentration of Sr^{2+} extracted into the RTILs phase can be calculated by subtraction. Finally, the extraction efficiency E_{Sr} or distribution ratio D_{Sr} was calculated.

Flame (C_2H_2 -Air) AAS was adopted to determine the concentration of Sr^{2+} . The range of working curve was 0–40 $\mu\text{g}\cdot\text{mL}^{-1}$ using 1 $\text{mg}\cdot\text{mL}^{-1}$ $\text{Sr}(\text{NO}_3)_2$ as stock solution. It was worth noting that small quantity of RTILs dissolved in the aqueous phase has obvious sensitization effect on the atomization of Sr^{2+} . To ensure veracity of the results, the quantities of RTILs in every measured sample should be identical and the absorption value should be stable. Therefore, certain volume of aqueous solution saturated by RTILs was added into the samples

before measurement.

3 Results and discussion

3.1 Extraction capability of different RTILs

The extraction results of Sr^{2+} by DCH18C6 in *n*-octanol and four RTILs under same conditions are shown in Table 1.

Table 1 Results of extracting Sr^{2+} by DCH18C6 in various solvents under neutral conditions

	<i>n</i> -Octanol	C_4mimPF_6	$\text{C}_2\text{mimNTf}_2$	$\text{C}_4\text{mimNTf}_2$	$\text{C}_6\text{mimNTf}_2$
$E(\%)$	0	95.5	100	>99.5	90.0
D	0	21.2	>1000	>400	18

[DCH18C6]=0.1 mol·L⁻¹, [Sr²⁺]=0.01 mol·L⁻¹.

As shown in Table 1, the extraction efficiencies with RTILs as solvents are much higher than that with *n*-octanol. In the case of $\text{C}_2\text{mimNTf}_2$, the distribution ratio of Sr^{2+} can be more than 10³, which exceeds all reported results of extraction systems with conventional organic solvent as diluents. This large D value may be attributed to the easy dissolution of the Sr^{2+} /crown ether complex by the total ionic environment of RTILs.

In addition, the extraction efficiency differs largely when different RTILs are used. Generally, E_{Sr} for RTILs with NTf_2^- anion is higher than that with PF_6^- . And with the same anion NTf_2^- , RTILs bearing shorter substituted alkyl chain on the imidazolium ion give higher E_{Sr} .

3.2 Influence of the DCH18C6 concentration

The concentrations of DCH18C6 in RTILs exhibit obvious influence on the extraction of Sr^{2+} . As shown in Figure 2, E_{Sr} increases with increasing the DCH18C6

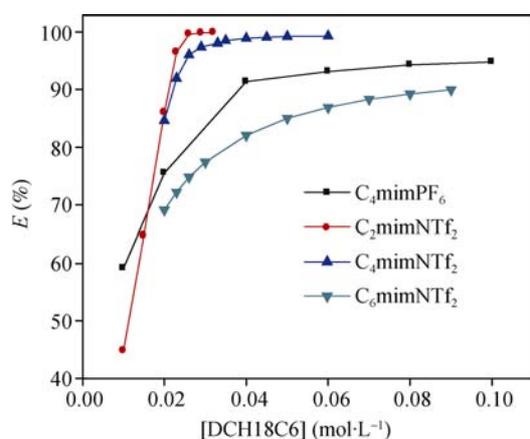


Figure 2 Relation between the extraction efficiency of Sr^{2+} and the concentration of DCH18C6 in various RTILs. [Sr²⁺]=0.01 mol·L⁻¹, $V_{\text{il}}/V_{\text{aq}}=1/2$.

concentration. RTILs show no extraction of Sr^{2+} in the absence of DCH18C6, i.e., RTILs themselves cannot extract Sr^{2+} in the absence of proper extractants.

The results in Figure 2 also indicate that the extraction capability of the four selected RTILs systems follows a general order of $\text{C}_2\text{mimNTf}_2 > \text{C}_4\text{mimNTf}_2 > \text{C}_4\text{mimPF}_6 > \text{C}_6\text{mimNTf}_2$ under given conditions. $\text{C}_2\text{-mimNTf}_2$ matches best with DCH18C6 to extract Sr^{2+} .

3.3 Influence of acidity in the aqueous phase

In HLLW, the extracted Sr^{2+} always exists in the aqueous solution containing HNO_3 at a certain concentration. Therefore, it is quite necessary to study the effects of HNO_3 on the extraction of Sr^{2+} .

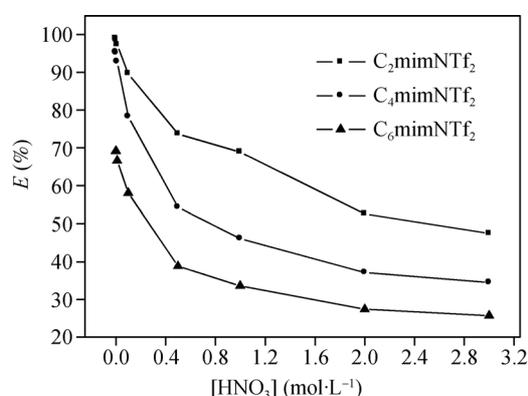


Figure 3 Dependence of the extraction efficiency of Sr^{2+} on the initial HNO_3 concentrations in aqueous phase of DCH18C6/ $\text{C}_n\text{mimNTf}_2$ systems. [DCH18C6]=0.025 mol·L⁻¹, [Sr²⁺]=0.01 mol·L⁻¹.

Figure 3 shows the dependence of the extraction efficiency of Sr^{2+} on the initial HNO_3 concentrations in aqueous phase of DCH18C6/ $\text{C}_n\text{mimNTf}_2$ systems. E_{Sr} in all three systems decreases with the increase of the HNO_3 concentration. Within the acidity range studied, the E_{Sr} values keep an order of $\text{C}_2\text{mimNTf}_2 > \text{C}_4\text{mimNTf}_2 > \text{C}_6\text{mimNTf}_2$.

Notice that the above extraction results are gained at a small concentration of DCH18C6, i.e., 0.025 mol·L⁻¹ in RTILs. HNO_3 will impose less influence on the extraction when higher concentration of DCH18C6 is adopted. In the case of $\text{C}_2\text{mimNTf}_2$, for instance, E_{Sr} is maintained above 95% within the acidity range studied at a DCH18C6 concentration of 0.1 mol·L⁻¹.

The influence of HNO_3 on the extraction of Sr^{2+} by DCH18C6/ C_4mimPF_6 is also investigated. The trend is similar to those of DCH18C6/ $\text{C}_n\text{mimNTf}_2$ systems. The E_{Sr} value descends when the HNO_3 concentration is increased within a range of 0–5 mol·L⁻¹. Further in-

creasing the acidity of aqueous phase to more than $5 \text{ mol}\cdot\text{L}^{-1}$ leads to a rapid decrease of E_{Sr} , which can be attributed to the decompose of C_4mimPF_6 , i.e., PF_6^- is transferred to PO_4^{3-} , caused by the strong oxidation capability of high concentration of HNO_3 . The interface between C_4mimPF_6 and the aqueous phase will disappear after contacting with $8-10 \text{ mol}\cdot\text{L}^{-1}$ HNO_3 for a short time.

The trend of the influence of HNO_3 in RTILs-based extraction systems differs distinctly from that with *n*-octanol as the diluent. In the later case^[2], E_{Sr} increases with the increase of the concentration of HNO_3 and an obvious extraction is achieved only under high HNO_3 concentrations ($> 1 \text{ mol}\cdot\text{L}^{-1}$). The difference between the two extraction systems may indicate a different extraction mechanism involved with RTILs as solvents.

3.4 Effects of inorganic salts

The components in HLLW after removing actinides are very complicated. Besides these radioactive nuclides such as $^{90}\text{Sr}^{2+}$ and $^{137}\text{Cs}^+$, there are also many other co-existing ions such as Na^+ and Al^{3+} . Hence, the effects of some inorganic salts on the extraction of Sr^{2+} by DCH18C6/RTILs should be studied. Herein, we select two salts, NaNO_3 and KNO_3 , to carry out a detailed investigation. The results are shown in Figure 4.

As shown in Figure 4, the addition of the two salts will generally reduce the extraction efficiency of Sr^{2+} , and the detailed trend changes with the variation of the RTIL structure. The salts have less influence on the extraction with a RTIL bearing longer substituted alkyl chain, indicating that the extraction mechanism may be altered due to the variation of the RTIL structure. Notice that for $\text{C}_2\text{mimNTf}_2$ and $\text{C}_4\text{mimNTf}_2$, the addition of NaNO_3 causes the decrease of E_{Sr} , while for $\text{C}_6\text{mimNTf}_2$, E_{Sr} is increased firstly and then reaches a maximum at $0.1 \text{ mol}\cdot\text{L}^{-1}$ NaNO_3 . Evidently, NaNO_3 brings about an obvious salt-out effect on the extraction system containing $\text{C}_6\text{mimNTf}_2$.

The addition of KNO_3 reduces E_{Sr} for all three systems and the decreasing degree is much larger than that of NaNO_3 . This can be explained by the similar radii between K^+ and Sr^{2+} , which causes much more competition when complexing with the crown ether.

Results shown above provide practical guides on how to select appropriate RTILs for extraction of Sr^{2+} . For instance, $\text{C}_6\text{mimNTf}_2$ may be a more suitable selection

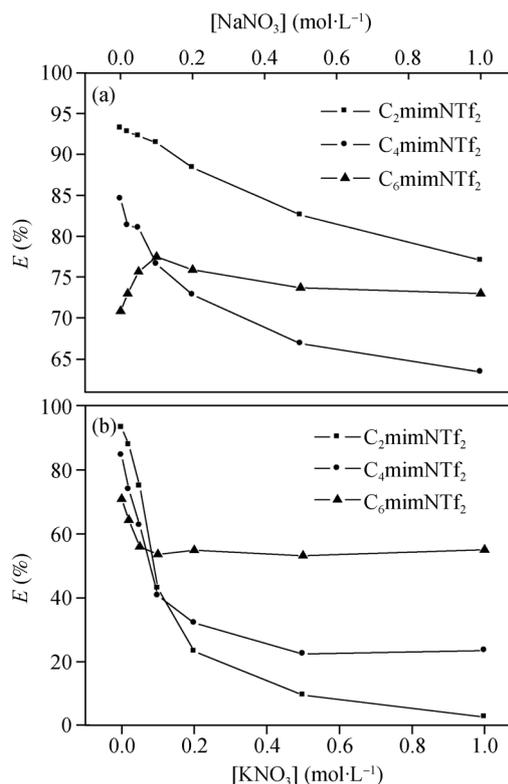


Figure 4 Dependence of the extraction efficiency of Sr^{2+} in DCH18C6/ $\text{C}_n\text{mimNTf}_2$ systems on the concentration of inorganic salts in the aqueous phase (a) NaNO_3 ; (b) KNO_3 . [DCH18C6]= $0.1 \text{ mol}\cdot\text{L}^{-1}$, [Sr^{2+}]= $0.01 \text{ mol}\cdot\text{L}^{-1}$, [HNO_3]= $1 \text{ mol}\cdot\text{L}^{-1}$.

than $\text{C}_2\text{mimNTf}_2$ when high concentrations of salts exist in the aqueous phase.

3.5 Stripping of Sr^{2+} from RTILs

Stripping, as a key step in the extraction process of nuclear fuel cycling, has significant importance for the reusing of RTILs in view of environmental and cost issues. Unfortunately, there has no report of efficient method of stripping Sr^{2+} from RTILs.

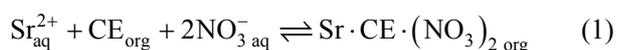
To strip Sr^{2+} , we have selected herein two alternated methods. One way is by ion competition, i.e., by the intense suppression effect of K^+ on the extraction of Sr^{2+} . It was found that Sr^{2+} can be stripped efficiently from C_4mimPF_6 using KCl at a high concentration of $1 \text{ mol}\cdot\text{L}^{-1}$. It is worth noting that this stripping method will cause the exchange of K^+ to the RTILs phase and the Sr^{2+} stripped should be separated again from KCl solutions.

Another stripping way is by precipitation. Sr^{2+} can be precipitated by SO_4^{2-} because SrSO_4 is a hardly soluble salt with K_{sp} of 3.44×10^{-7} . Herein, K_2SO_4 solution is

adopted to precipitate Sr^{2+} from RTIL phase. It is demonstrated that more than 99% of Sr^{2+} can be efficiently stripped by K_2SO_4 solution. The RTIL phase after stripping has been reused to extract Sr^{2+} and the extraction capability is not obviously decreased.

3.6 Exploration of extraction mechanism

As shown above, the extraction behaviors in RTILs based extraction system differ clearly from that of conventional solvent extraction systems. These differences should be related to the different extraction mechanism. In conventional solvent extraction system, the extraction of metal ions mostly proceeds through a neutral complex mechanism, i.e., the metal ions and extractant form neutral complexes with counter anions and then transfer to the organic phase. For the extraction of Sr^{2+} by DCH18C6/octanol, the extraction mechanism can be expressed as follows^[16]:



where CE represents the crown ether DCH18C6.

As reported^[10,17], the extraction mechanism also differs in different RTILs-based extraction systems but usually involves cation exchange. By measuring the UV absorption at 211 nm for imidazolium ions, the concentration of C_2mim^+ in the aqueous phase before and after extraction can be determined. We have performed a study to explore the mechanism of extracting Sr^{2+} by DCH18C6/ $\text{C}_2\text{mimNTf}_2$ and the results are shown in Table 2 and Figure 5. Considering that nitrate ions have intense interference on the UV absorption of imidazolium ions, $\text{Sr}(\text{NO}_3)_2$ is replaced by SrCl_2 in following experiments.

From Table 2, it is found that the decrease of the concentration of Sr^{2+} correlates closely with the increase of the concentration of C_2mim^+ in the aqueous phase. It can be thus deduced that the extraction of Sr^{2+} mainly proceeds via a cation exchange mechanism, which agrees well with that reported by Dietz et al.^[10].

Moreover, it can be seen from Figure 5 that there is a linear relationship between variations of $[\text{Sr}^{2+}]$ and

Table 2 Variations of $[\text{Sr}^{2+}]$ and $[\text{C}_2\text{mim}^+]$ in the aqueous phase before and after extraction of Sr^{2+} by DCH18C6/ $\text{C}_2\text{mimNTf}_2$ (DCH18C6 = 0.1 mol·L⁻¹)

$[\text{Sr}^{2+}]_{\text{initial}} (10^{-3} \text{ mol}\cdot\text{L}^{-1})$	0	5.00	10.0	15.0	20.0
$[\text{Sr}^{2+}]_{\text{aq}} (10^{-3} \text{ mol}\cdot\text{L}^{-1})$	0	-5.00	-10.0	-15.0	-19.4
$[\text{C}_2\text{mim}^+]_{\text{aq}} (10^{-3} \text{ mol}\cdot\text{L}^{-1})$	0	5.94	12.6	19.6	26.3

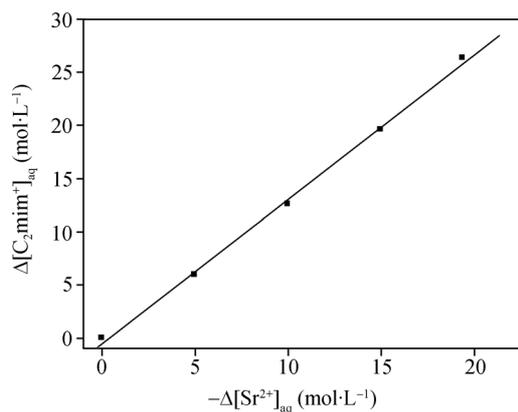
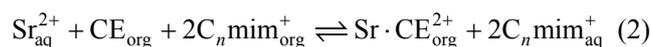


Figure 5 Relation between variations of $[\text{Sr}^{2+}]$ and $[\text{C}_2\text{mim}^+]$ in the aqueous phase before and after extraction of Sr^{2+} by DCH18C6/ $\text{C}_2\text{mimNTf}_2$.

$[\text{C}_2\text{mim}^+]$ in the aqueous phase before and after extraction of Sr^{2+} . Therefore, the degree of ion exchange is independent on the initial concentration and the extracted concentration of Sr^{2+} , i.e., more Sr^{2+} is extracted, more C_2mim^+ is exchanged. Meanwhile, it is noticed that the C_2mim^+ exchanged can not afford charge equilibrium of the two phases, so there must have a part of Cl^- entering the RTILs phase. In other words, the present mechanism is not a total cation exchange process. Dietz et al. have found that the length of substituted alkyl chain has obvious influences on the mechanism of extracting Sr^{2+} by DCH18C6/ $\text{C}_n\text{mimNTf}_2$ ($n = 5, 6, 8, 10$)^[17]. A RTIL with longer alkyl chain makes more NO_3^- enter the RTIL phase and thus increases the ratio of neutral complex mechanism. For instance, the extraction is mainly achieved via the neutral complex mechanism at the n value of 10. In the case of present study, $\text{C}_2\text{mimNTf}_2$ bears a very shorter alkyl chain on the imidazolium ions and, however, only two thirds of Sr^{2+} are extracted by cation exchange with C_2mim^+ . This unusual behavior may be caused by the introducing of SrCl_2 and further research on this aspect is required. All of the above results lead us to conclude that the extraction of Sr^{2+} in present system proceeds mainly via a cation exchange mechanism shown as follows:



We can use the above cation exchange mechanism to explain the effects of HNO_3 on the extraction. For the extraction system using n -octanol, NO_3^- is coextracted to the organic phase as a counter ion to maintain the charge equilibrium due to the neutral complex mechanism. The addition of HNO_3 increases the concentration of NO_3^- in

Table 3 Comparison of the effects of HNO₃ on the extraction of Sr²⁺ by octanol and RTILs systems

	<i>n</i> -Octanol	RTILs
Equilibria existing in the systems	$\text{Sr} \cdot \text{CE}^{2+} + 2\text{NO}_3^- \rightleftharpoons \text{Sr} \cdot \text{CE}^{2+} \cdot 2\text{NO}_{3\text{org}}^-$ $\text{H} \cdot \text{CE}^+ + \text{NO}_3^- \rightleftharpoons \text{H} \cdot \text{CE}^+ \cdot \text{NO}_{3\text{org}}^-$	$\text{Sr} \cdot \text{CE}^{2+} + 2\text{C}_n\text{mim}^+_{\text{org}} \rightleftharpoons \text{Sr} \cdot \text{CE}^{2+}_{\text{org}} + 2\text{C}_n\text{mim}^+$ $\text{Sr} \cdot \text{CE}^{2+} + 2\text{NO}_3^- \rightleftharpoons \text{Sr} \cdot \text{CE}^{2+} \cdot 2\text{NO}_{3\text{org}}^-$ $\text{H} \cdot \text{CE}^+ + \text{NO}_3^- \rightleftharpoons \text{H} \cdot \text{CE}^+ \cdot \text{NO}_{3\text{org}}^-$
Key factor	salt out effect of NO ₃ ⁻	competition effect of H ⁺
Second factor	competition effect of H ⁺	salt-out effect of NO ₃ ⁻
The overall effect	increase of <i>E</i> _{Sr}	decrease of <i>E</i> _{Sr}

the aqueous phase and thus pushes the above equilibrium to the right direction, facilitating the extraction of Sr²⁺[3]. Notice that in this case H⁺ can also be complexed competitively with DCH18C6, however, the dominant effects are caused by NO₃⁻. For RTILs-based extraction system where cation exchange is dominated, NO₃⁻ participates in the extraction to a relatively limited extent and the competition of H⁺ might be the leading factor which causes an overall decrease in the extraction efficiency of Sr²⁺. The effects of HNO₃ on the extraction are summarized in Table 3.

From the mechanism proposed, we can have a deeper understanding of the role of RTILs in the extraction system. RTILs not only act as diluents for the extractant DCH18C6, but also participate in the extraction process directly by exchange of C_{*n*}mim⁺ with Sr²⁺. So, RTILs can be regarded as a special functional media here.

4 Conclusions

The extraction of Sr²⁺ by DCH18C6 in various RTILs has been systematically investigated. RTILs can be used as a good choice for matching with DCH18C6 and higher extraction capability has been achieved. Generally, *E*_{Sr} follows an order of C₂mimNTf₂ > C₄mimNTf₂ > C₄mimPF₆ > C₆mimNTf₂, particularly *D*_{Sr} can be more than 10³ in the case of C₂mimNTf₂.

In RTILs-based extraction systems, *E*_{Sr} decreases with the increase in the concentration of HNO₃ in the aqueous phase. Existence of inorganic salts such as NaNO₃ and

KNO₃ usually reduces *E*_{Sr}, with the detailed trends related to the structure of RTILs selected. Sr²⁺ can be stripped from the RTILs phase by competition or precipitation methods. A cation exchange mechanism has been demonstrated by detecting the variation of C₂mim⁺ concentrations in the aqueous phase before and after extraction.

According to the investigation results shown above and the specialty of RTILs, it can be deduced that RTILs have provided several advantages for the extraction of Sr²⁺ when compared with conventional solvent extraction systems.

(1) Reduce the amount of extractant and RTILs in practical processes as a result of the high extraction efficiency. Therefore, the cost can be saved to some extent. In addition, the process will be much safer and have less influence to the environment because the introducing of RTILs avoids the use of vaporous organic solvents.

(2) Sr²⁺ can be extracted by RTILs-based extraction systems in a wide range of acidity, especially under low acidity. This is of practical significance for the separation of Sr²⁺ from HLLW after the removing of actinides because it is not necessary to adjust the acidity to a high value.

(3) Due to the variety of cations and anions composing RTILs, there is a wide range to select appropriate RTILs and further to match proper extractant.

In conclusion, RTILs-based extraction systems may promise an alternative way for the separation of Sr²⁺ from HLLW.

- 1 He L H, Weng X M, Yang D Z, Jiao R Z, Song C L. Removal of strontium from high-level radioactive waste by crown-ether extraction. *Chin J Nucl Sci Eng* (in Chinese), 1995, 15(3): 259–263
- 2 Yang Q, Han Y D, Liu D M. Extraction of Sr²⁺, Cs⁺ in simulated HLLW with crown ethers. *J Nucl Radiochem* (in Chinese), 1996, 18(01): 61–67
- 3 Ye G A, Luo F X, Jiang Y Q, Ding S D, Chen W J. Study on the ex-

- traction of strontium with amido podand. *Atomic Energy Sci Tech* (in Chinese), 2001, 35(04): 344–350
- 4 Dozol J F, Dozol M, Macias R M. Extraction of strontium and cesium by dicarbollides, crown ethers and functionalized calixarenes. *J Incl Phenom Macrocycl Chem*, 2000, 38: 1–22
- 5 Shen X H, Xu C, Liu X Q, Chu T W. Ionic liquids used in extraction and separation of metal ions. *J Nucl Radiochem* (in Chinese), 2006,

- 28(03): 129–138
- 6 Li R X. Green Solvents-Ionic liquids: Syntheses and Application (in Chinese). Beijing: Chemical Industry Press, 2004. 20–27
 - 7 Rogers R D, Seddon K R. Ionic liquids-solvents of the future. *Science*, 2003, 302(5646): 792–793
 - 8 Dai S, Ju Y H, Barnes C E. Solvent extraction of strontium nitrate by a crown ether using room-temperature ionic liquids. *J Chem Soc, Dalton Trans*, 1999, 8: 1201–1202
 - 9 Visser A E, Swatloski R P, Reichert W M, Griffin S T, Rogers R D. Traditional extractants in nontraditional solvents: Groups 1 and 2 extraction by crown ethers in room-temperature ionic liquids. *Ind Eng Chem Res*, 2000, 39(10): 3596–3604
 - 10 Dietz M L, Dzielawa J A. Ion-exchange as a mode of cation transfer into room-temperature ionic liquids containing crown ethers: Implications for the “Greenness” of ionic liquids as diluents in liquid-liquid extraction. *Chem Commun*, 2001, 20: 2124–2125
 - 11 Yuan L Y, Peng J, Xu L, Zhai M L, Li J Q, Wei G S. Influence of gamma-radiation on the ionic liquid [C₄mim][PF₆] during extraction of strontium ions. *J Chem Soc, Dalton Trans*, 2008, 45, 6358–6360
 - 12 Yuan L Y, Peng J, Xu L, Zhai M L, Li J Q, Wei G S. Radiation effect on hydrophobic ionic liquids [C₄mim][NTf₂] during extraction of strontium ions. *J Phys Chem B*, 2009, 113(26): 8948–8952
 - 13 Bonhote P, Dias A P, Papageorgiou N, Kalyanasundaram K, Gratzel M. Hydrophobic, highly conductive ambient-temperature molten salts. *Inorg Chem*, 1996, 35(5): 1168–1178
 - 14 Huddleston J G, Visser A E, Reichert W M, Willauer H D, Broker G A, Rogers R D. Characterization and comparison of hydrophilic and hydrophobic room temperature ionic liquids incorporating the imidazolium cation. *Green Chem*, 2001, 3(4): 156–164
 - 15 Huddleston J G, Willauer H D, Swatloski R P, Visser A E, Rogers R D. Room temperature ionic liquids as novel media for “clean” liquid-liquid extraction. *Chem Commun*, 1998(16): 1765–1766
 - 16 Horwitz E P, Dietz M L, Fisher D E. Extraction of strontium from nitric-acid solutions using dicyclohexano-18-crown-6 and its derivatives. *Solvent Extr Ion Exch*, 1990, 8(4-5): 557–572
 - 17 Dietz M L, Dzielawa J A, Laszak I, Young B A, Jensen M P. Influence of solvent structural variations on the mechanism of facilitated ion transfer into room-temperature ionic liquids. *Green Chem*, 2003, 5: 682–685