



Temperature-responsive alkaline aqueous biphasic system for radioactive wastewater treatment



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ABSTRACT

The treatment of anionic $^{99}\text{TcO}_4^-$ in the waste tank with high alkalinity is still very challenging. In this work, a new temperature-responsive alkaline aqueous biphasic system (ABS) based on (tri-*n*-butyl)-*n*-tetradecyl phosphonium chloride ($\text{P}_{44414}\text{Cl}$) was developed to remove radioactive $^{99}\text{TcO}_4^-$. The phase transition mechanism was studied by cloud point titration, small-angle X-ray scattering, dynamic light scattering, and molecular dynamic simulations. As the NaOH concentration or temperature increased, the P_{44414}^+ micelle could grow and aggregate. This micelle showed a particularly high affinity toward $\text{ReO}_4^- / ^{99}\text{TcO}_4^-$ compared to other competing anions and could directly extract more than 98.6% of $^{99}\text{TcO}_4^-$ from simulated radioactive tank waste supernatant. Furthermore, the loaded $^{99}\text{TcO}_4^-$ could be easily stripped by using concentrated nitric acid rather than metal salt-based reductants. This work clearly demonstrates that the alkaline ABS is a promising separation system for solving the technetium problem in the alkaline waste tank.

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Liquid-liquid extraction is widely applied in environmental engineering, hydrometallurgy, petrochemical industry, pharmacy, and fine chemicals engineering [1–5]. In this process, one compound is separated from others due to their different solubility in two immiscible liquid phases [6]. Traditionally, organic solvents like kerosene are adopted as an immiscible phase. However, the high volatility, inflammability, and inherent unsustainability of these solvents make them the source of pollution and danger in many chemical engineering processes [7]. Furthermore, the hydration energy and mass transfer on the interface which need to be overcome during the extraction make it an energy-intensive process. For this, various green solvents, such as ionic liquid (IL), supercritical fluids, deep eutectic solvent (DES), and aqueous biphasic system (ABS), have been developed to replace the traditional organic solvents [8–11]. Among them, the ABS, which consists of two immiscible aqueous-rich phases, is regarded as a non-denaturing

and highly efficient separation media without the need of dehydration [12,13]. However, the interfacial mass transfer problem still impedes the extraction efficiency of ABS.

The homogeneous liquid-liquid extraction process is considered to be a solution to the mass transfer problem. This technique has extremely fast kinetics because there is no obstacle of mass transfer by the liquid interface and is mainly applied to extract metals or natural products [14,15]. The phase separation of homogeneous liquid-liquid extraction is achieved by the thermomorphic behavior of the solute in water, which are often organic salts or ILs. Recently, some novel phosphonium-based IL ABSs have been developed to separate transition metals and rare earths, showing the advantages of both ABS and homogeneous liquid-liquid extraction [16–18]. However, to the best of our knowledge, there is still lack of alkaline ABSs that may have huge particular applications in hydrometallurgy and nuclear waste treatment.

Taking the ^{99}Tc problem for an example, as a long-lived β -emitting radionuclide, it is generated from the fission of ^{235}U and ^{239}Pu in nuclear reactors [19,20], and is stored in the waste tanks with high alkalinity after recovery of nuclear materials [21]. The long half-life (2.13×10^5 years) and high thermal neutron fission yield (6.1%) make this radionuclide a long-term threat to human health [22]. What is more, the major species of ^{99}Tc (*i.e.*, $^{99}\text{TcO}_4^-$)

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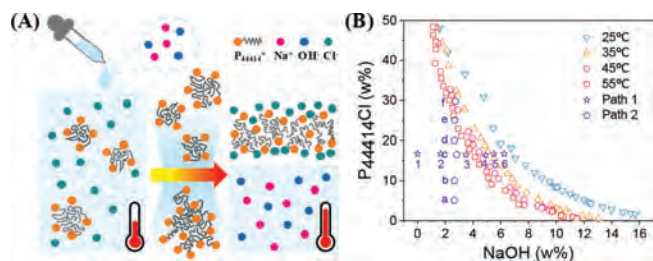


Fig. 1. (A) Phase separation process of the $P_{44414}\text{Cl-NaOH-H}_2\text{O}$ system, (B) the binodal curves for the $P_{44414}\text{Cl-NaOH-H}_2\text{O}$ system at various temperatures and the composition of mixture points in paths 1 and 2 studied.

has a vast solubility in water and high environmental mobility, leading to severe leakage of this hazardous anion [23,24]. To avoid this pollution, it is highly desired to treat $^{99}\text{TcO}_4^-$ in the alkaline tank waste. However, the content of ^{99}Tc in the waste tank is very low (5 ppm) and the alkalinity is very high, making the treatment of $^{99}\text{TcO}_4^-$ very challenging [25]. The state of art ^{99}Tc removal techniques are mainly focused on the adsorption process based on novel cationic materials which were operated under pH ranges that might not be suitable for treating waste water with OH^- concentration as high as 2 mol/L [26–30].

In this work, we developed an alkaline ABS system based on $P_{44414}\text{Cl}$ to extract $^{99}\text{TcO}_4^-$ from waste tank water with high selectivity. The phase separation and extraction mechanism were studied through cloudy point titration, small-angle X-rays scattering (SAXS), dynamic light scattering (DLS), and molecular dynamic simulations (MD).

The phase transition of ABS is a thermodynamically driven process, where the temperature plays a significant role in the critical concentrations [31]. A simple illustration of the phase separation process is provided in Fig. 1A. As the NaOH concentration or temperature increases, the P_{44414}^+ micelles tend to aggregate and result in a new phase. The binodal curves of $P_{44414}\text{Cl-NaOH-H}_2\text{O}$ systems at 25, 35, 45 and 55 °C, shown in Fig. 1B, were obtained by cloudy point titration. The biphasic domain is located at the right for each binodal curve, while the monophasic domain is at the left, indicating that this system is a low critical temperature system (LCTS) [32]. In this kind of colloid solution, the critical concentration of the solute decreases as the temperature increases. So, the $P_{44414}\text{Cl-NaOH-H}_2\text{O}$ system is a homogeneous aqueous solution at room temperature and become ABS when the temperature exceeds to a certain degree. This temperature-responsive property is endowed with the surface activity of the long side chain on P_{44414}^+ and salting-out effect of NaOH [33,34]. Compared with the HCl ABS, the concentration of NaOH needed to induce ABS under the same condition is smaller, but the distance between isothermal binodal curves of NaOH is much closer [16], which gives NaOH a more moderate phase transition condition but narrower adjusting range than HCl ABS.

Due to quite similar size and physico-chemical properties between ReO_4^- and $^{99}\text{TcO}_4^-$, ReO_4^- is used as a surrogate for $^{99}\text{TcO}_4^-$ in most of our batch experiments. The effect of NaOH concentration on the extraction of ReO_4^- was first studied. From Fig. 2A, when the NaOH concentration increases from 2 mol/kg to 6.5 mol/kg, the ReO_4^- could be extracted quantitatively by the $P_{44414}\text{Cl}$ with extraction efficiency larger than 99.9%. The extraction equilibrium could be accomplished in 3 min due to the strong reaction between ReO_4^- and $P_{44414}\text{Cl}$. As a comparison, the extraction efficiency of ReO_4^- dramatically decreases with increasing HNO_3 concentration (Fig. 2A), which indicates the $P_{44414}\text{Cl}$ ABS is suitable to extract ReO_4^- from NaOH solution rather than HNO_3 solution and the HNO_3 might be applied in the stripping of $\text{ReO}_4^-/^{99}\text{TcO}_4^-$.

Traditionally, the loaded $\text{ReO}_4^-/^{99}\text{TcO}_4^-$ on the ABS or IL could not be stripped directly. Reduction precipitation was adopted to

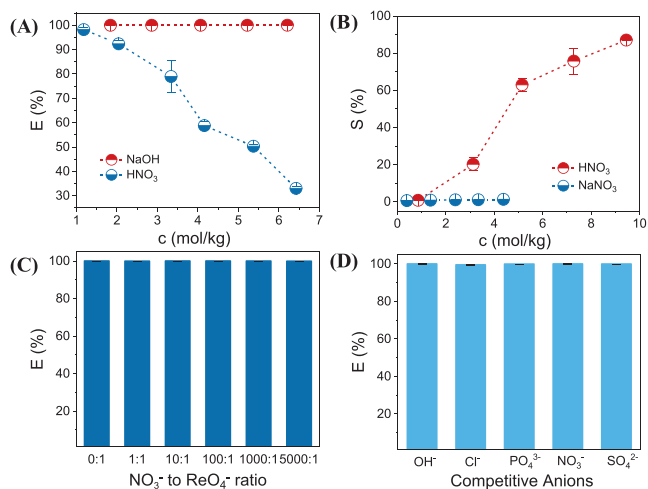


Fig. 2. (A) Extraction efficiency of ReO_4^- by $P_{44414}\text{Cl-NaOH}$ and $P_{44414}\text{Cl-HNO}_3$ ABS, (B) stripping ratio of ReO_4^- using HNO_3 and NaNO_3 , (C) effect of competing NO_3^- anions on the extraction of ReO_4^- by $P_{44414}\text{Cl-NaOH}$ ABS, and (D) effect of different competing anions (1000 times) on the extraction of ReO_4^- by $P_{44414}\text{Cl-NaOH}$ ABS.

recover $\text{ReO}_4^-/^{99}\text{TcO}_4^-$ from the extract [35–37]. This procedure would consume extra reduction agents and lack continuity or flexibility. Whereas, as shown in Fig. 2B, the maximum stripping ratio of ReO_4^- by HNO_3 from $P_{44414}\text{Cl}$ phase could reach 85%, which promises the recovery of ReO_4^- in the practical process. It should be noted that only HNO_3 could obtain such high stripping ratio of ReO_4^- . The NaNO_3 solution did not exhibit any stripping capability (Fig. 2B). This result indicates both NO_3^- anion and H^+ play an important role in the stripping step.

The influence of NO_3^- on the extraction also verified this hypothesis. From Fig. 2C, the extraction efficiency of ReO_4^- could keep over 99.5% even the ratio of NO_3^- to ReO_4^- increased from 0 to 5000. Comparing with other extraction and adsorption systems, in which the presence of large amount of NO_3^- would greatly reduce the removal of $\text{ReO}_4^-/^{99}\text{TcO}_4^-$ [36,37], the $P_{44414}\text{Cl}$ ABS exhibited stronger selectivity towards $\text{ReO}_4^-/^{99}\text{TcO}_4^-$. The influence of Cl^- , SO_4^{2-} , OH^- , PO_4^{3-} and NO_3^- , which are main competing anions in practical tank waste, on the extraction of ReO_4^- was also tested and is shown in Fig. 2D. All the anions had no influence on the extraction efficiency of ReO_4^- with a molar ratio of 1000:1.

The extremely high selectivity toward $\text{ReO}_4^-/^{99}\text{TcO}_4^-$ by $P_{44414}\text{Cl-NaOH}$ ABS could be interpreted by the Hofmeister series [38,39]. The $P_{44414}\text{Cl}$ acts as a chaotrope in the alkaline ABS, so the P_{44414}^+ is inclined to form an IL-rich phase with hydrophobic anions [36,40]. The anions adopted in this work follow the Gibbs free energies of hydration ($\Delta_{\text{hyd}}G^0$): PO_4^{3-} (−2773) < SO_4^{2-} (−1090) < Cl^- (−347) < NO_3^- (−306) < ReO_4^- (−251) [28]. Not surprisingly, the ReO_4^- with monovalent and largest ion radii is the most hydrophobic anion; thus, it is easy to be extracted into the IL-rich phase even from large amounts of competing anions. The high stripping ratio by HNO_3 might be the resulting formation of HReO_4 , which had strong interaction with water molecules and increased the solubility of ReO_4^- in the acid-rich phase [41,42].

Nevertheless, as shown in Table S6 (Supporting information), the H_2SO_4 and HCl showed almost no stripping effect on ReO_4^- which suggests both H^+ and an anion with high $\Delta_{\text{hyd}}G^0$ are indispensable in stripping.

Another important parameter in the extraction process is the loading capacity of the target anion, which influences the operation efficiency of the extraction process. As Fig. S1 (Supporting information) illustrated, the maximum Re content in the IL-rich phase could reach 160,000 ppm which has reached 50% of the the-

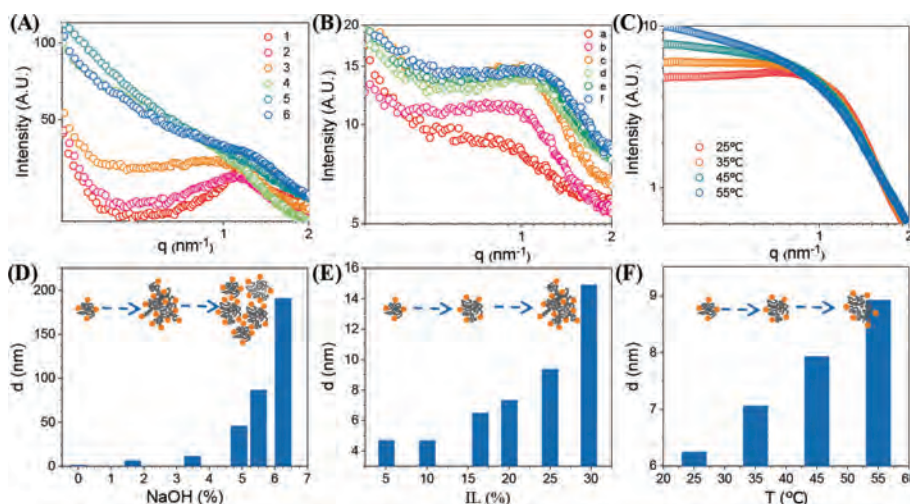


Fig. 3. SAXS patterns of mixtures taken from Fig. 1: (A) path 1, (B) path 2, (C) point c in path 2, and average dynamic diameter of the mixtures that was taken from DLS, (D) path 1, (E) path 2, (F) point c in path 2. The scheme in (D), (E), and (F) represent the growth and aggregation process of P_{44414}^+ micelle.

oretical concentration of Re in $P_{44414}ReO_4$. Because of the strong extraction ability of $P_{44414}Cl$ to ReO_4^- , the $P_{44414}Cl$ concentration had very little influence on the extraction efficiency of ReO_4^- (Fig. S2 in Supporting information), which indicates this parameter could be adjusted flexibly according to the sample composition.

SAXS, DLS and MD were combined to interpret the phase transition mechanism of $P_{44414}Cl$ -NaOH ABS. The compositions of mixtures used in the measurements were based on the points marked in the phase diagram (Fig. 1B). Points 1 to 6 in path 1 were used to study the effect of NaOH concentration and the corresponding SAXS patterns are shown in Fig. 3A. Taking the curve of mixture 1 as an example, from the peak around 1.14 nm^{-1} , the short-range order structure diameter was calculated to be 5.51 nm from the equation: $d = 2\pi/q$, which represented the size of micelle that the P_{44414}^+ aggregated into [43]. With the increasing NaOH concentration, the peak position around 1.14 nm^{-1} almost did not change, but the shape became smooth and vanished. The DLS measurement supported the change in SAXS curves. From Fig. 3D, the dynamic diameter of each mixture increased with increasing NaOH concentration, indicating the aggregation of P_{44414}^+ micelle [44]. It should be noted that the dynamic diameter of each mixture followed by the Gaussian distribution (Figs. S4–S6 in Supporting information) which suggested that the $P_{44414}Cl$ -NaOH ABS was a polydisperse system. When the NaOH concentration increased, the micelles grew larger and started to aggregate, resulting in a larger and more dispersed size range. As the dispersity of the system increased, the peaks of SAXS patterns became smooth and finally resulted in a slash.

Similar but weaker changes in the SAXS patterns and micelle diameter could be observed with increasing temperature (Figs. 3C and F) and $P_{44414}Cl$ concentration (Figs. 3B and E). The mixture used in the temperature study was referred to the point c, path 2 in Fig. 1B. The SAXS patterns also became smooth as the temperature increased from 25°C to 55°C , accompanying with the increase of micelle size. The experiments of $P_{44414}Cl$ concentration were carried out according to mixtures a–f from path 2 in Fig. 1B, whose SAXS patterns kept their peaks around 1.14 nm^{-1} . The dynamic diameter varied from 5 nm to 14 nm when the $P_{44414}Cl$ concentration changed from 5% to 30% . Comparing the results of the three variables, we can conclude that the NaOH concentration has a much stronger effect on the trigger of the micelle aggregation than temperature and IL concentration for its stronger effect on the change of critical micelle concentration. The growth and aggregation of phosponium micelle would finally connect the separated

micelles and generate a new aqueous phase immiscible with the NaOH solution [44,45].

We first studied the selective extraction behavior of the $P_{44414}Cl$ -NaOH system towards ReO_4^- using all-atom MD simulations. The geometric structures of $P_{44414}Cl$ optimized based on density functional theory (DFT) is shown in Fig. S7A (Supporting information). Figs. S7B and C (Supporting information) show the snapshots of initial and final configurations of the MD trajectory for the $P_{44414}Cl$ system, respectively. At the initial state, all the chemical components are randomly distributed at a relatively low density in order to avoid the atom overlap. However, as shown in Fig. S7C, the aggregation behavior of P_{44414}^+ appears after equilibrium in the molecular scale, forming P_{44414}^+ micelles. Then we analyzed the spacial distribution of ReO_4^- , Cl^- , and OH^- as the simulation time increases. As revealed in Fig. S7D (Supporting information), the formed P_{44414}^+ micelles have significantly stronger affinity towards ReO_4^- rather than Cl^- , which is in good accordance to our experimental results. All the ReO_4^- ions are selectively extracted by the P_{44414}^+ micelles from aqueous solution, either being attached on the surface or moving into the interior. In contrast, Na^+ , Cl^- and OH^- ions prefer to reside in aqueous solution instead of penetrating into the interior. Fig. S7E (Supporting information) clearly shows the relative distribution of various ions at the micelle–aqueous interface and within channels between neighboring micelles. We can deduce that the positive charges of P_{44414}^+ may be shielded by surrounding anions to different extents, and thus the observed P_{44414}^+ micelles can be formed via strong enough van der Waals interaction. The effect of ReO_4^- on the aggregation of P_{44414}^+ has also been studied via MD simulations. Our results indicated that the P_{44414}^+ micelles can still be formed without the absence of ReO_4^- at room temperature, as displayed in Fig. S7F (Supporting information). The connected micelles predict the forming of $P_{44414}Cl$ -NaOH ABS that is in accordance with the SAXS and DLS analysis.

We also compared the influence of various counterions like Cl^- , SO_4^{2-} and NO_3^- on the extraction in MD simulations. It is surprising that all the counterions have negligible influence on the formation of the P_{44414}^+ micelles as well as the extraction efficiency towards ReO_4^- . As presented in Fig. S8 (Supporting information), the average interaction energies of the P_{44414}^+ micelles with each counteranion reveal that the P_{44414}^+ micelles show significantly higher affinity to ReO_4^- over Cl^- , SO_4^{2-} , and NO_3^- , which explains the high selectivity to ReO_4^- of the $P_{44414}Cl$ ABS.

The practical application of the $P_{44414}Cl-NaOH$ ABS was tested with a simulated tank waste supernatant. The composition of elements was listed in Table S1 (Supporting information). The extraction efficiency of $^{99}TcO_4^-$ is larger than 98.6%. In addition, over 73.8% of loaded $^{99}TcO_4^-$ could be directly stripped by 65% HNO_3 . The $P_{44414}Cl$ based ABS extraction process could be regarded as an efficient and green method to prevent the environmental risk from $^{99}TcO_4^-$ in the tank waste. The reusability of $P_{44414}Cl$ from HNO_3 stripping was tested by extracting ReO_4^- with three repeated cycles. As shown in Table S13 (Supporting information), the extraction efficiencies of recycled $P_{44414}Cl$ in all three cycles are 99.9% which is only 0.07% less than original $P_{44414}Cl$ and suggests that this extractant could be reused.

In summary, a homogeneous liquid-liquid extraction process based on $P_{44414}Cl-NaOH$ ABS was developed to treat $^{99}TcO_4^-$ from tank waste supernatant. The phase diagram suggests this ABS is a LCTS. The NaOH concentration strongly affected the phase separation by changing the critical micelle concentration. The $P_{44414}Cl-NaOH$ ABS could quantitatively extract ReO_4^- with high concentration of competing anions because the interaction energy between P_{44414}^+ micelles and ReO_4^- was much lower than that of other anions. However, the P_{44414}^+ micelle still has relative strong affinity to NO_3^- , resulting in the high stripping ratio (85%) of loaded ReO_4^- by HNO_3 . The practical test of extracting $^{99}TcO_4^-$ from simulated waste tank water by the $P_{44414}Cl$ ABS indicate that this system provides an efficient and green option for recovering hazardous anions from alkaline solutions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ccl.2022.02.024.

References

- [1] C.Y. Liu, L. Chen, J. Chen, et al., *J. Rare Earths* 37 (2019) 1002–1008.
- [2] J. Chen, S.K. Spear, J.G. Huddleston, R.D. Rogers, *Green Chem.* 7 (2005) 64–82.
- [3] L. Li, F. Liu, X.X. Kong, et al., *Chin. Chem. Lett.* 13 (2002) 349–350.
- [4] J.X. Huang, D.H. Lu, K. Wan, F.H. Wang, *Chin. Chem. Lett.* 25 (2014) 635–639.
- [5] S.B. Yu, H.J. Zang, X.L. Yang, et al., *Chin. Chem. Lett.* 28 (2017) 1479–1484.
- [6] N. Schaeffer, J.H.F. Conceição, M.A.R. Martins, et al., *Green Chem.* 22 (2020) 2810–2820.
- [7] Y.H. Chen, H.Y. Wang, Y.C. Pei, et al., *ACS Sustain. Chem. Eng.* 3 (2015) 3167–3174.
- [8] L. Chen, J. Chen, H.L. Li, et al., *Sep. Purif. Technol.* 207 (2018) 179–186.
- [9] N. Schaeffer, M. Gras, H. Passos, et al., *ACS Sustain. Chem. Eng.* 7 (2019) 1769–1777.
- [10] Y.X. Yao, N.F. Farac, G. Azimi, *ACS Sustain. Chem. Eng.* 6 (2018) 1417–1426.
- [11] C.Y. Liu, Q.B. Yan, X.W. Zhang, et al., *Environ. Sci. Technol.* 54 (2020) 10370–10379.
- [12] M.G. Freire, A.F.M. Claudio, J.M.M. Araujo, et al., *Chem. Soc. Rev.* 41 (2012) 4966–4995.
- [13] L.L. Zhang, Y.B. Tian, Y.Y. Wang, L.Y. Dai, *Chin. Chem. Lett.* 32 (2021) 2233–2238.
- [14] S. Igarashi, T. Kyuwa, M. Matsuura, T. Yotsuyanagi, *Chem. Lett.* 23 (1994) 1189–1190.
- [15] T. Vander Hoogerstraete, B. Onghena, K. Binnemans, *J. Phys. Chem. Lett.* 4 (2013) 1659–1663.
- [16] M. Gras, N. Papaiconomou, N. Schaeffer, et al., *Angew. Chem. Int. Ed.* 57 (2018) 1563–1566.
- [17] D. Depuydt, L.W. Liu, C. Glorieux, et al., *Chem. Commun.* 51 (2015) 14183–14186.
- [18] C.Y. Liu, Q.B. Yan, X.W. Zhang, et al., *Chin. Chem. Lett.* 33 (2022) 953–956.
- [19] S. Chatterjee, V. Holfeltz, G.B. Hall, et al., *Anal. Chem.* 92 (2020) 13961–13970.
- [20] C.X. Lu, Z.W. Wang, Q.F. Jiang, et al., *Chin. Chem. Lett.* 22 (2011) 1309–1312.
- [21] K.R. Ashley, G.D. Whitener, N.C. Schroeder, et al., *Solvent Extr. Ion Exch.* 16 (1998) 843–859.
- [22] L. Wang, H. Song, L.Y. Yuan, et al., *Environ. Sci. Technol.* 53 (2019) 3739–3747.
- [23] N.N. Shen, Z.X. Yang, S.T. Liu, et al., *Nat. Commun.* 11 (2020) 5571.
- [24] H.D. Ji, Y.M. Zhu, J. Duan, et al., *Chin. Chem. Lett.* 30 (2019) 2163–2168.
- [25] W.D. King, N.M. Hassan, D.J. McCabe, et al., *Sep. Sci. Technol.* 38 (2003) 3093–3114.
- [26] L. Zhu, C.L. Xiao, X. Dai, et al., *Environ. Sci. Technol. Lett.* 4 (2017) 316–322.
- [27] L. Zhu, D.P. Sheng, C. Xu, et al., *J. Am. Chem. Soc.* 139 (2017) 14873–14876.
- [28] C.L. Xiao, A. Khayambashi, S. Wang, *Chem. Mater.* 31 (2019) 3863–3877.
- [29] D.P. Sheng, L. Zhu, X. Dai, et al., *Angew. Chem. Int. Ed.* 58 (2019) 4968–4972.
- [30] X.J. Chen, X. Dai, R.Z. Xie, et al., *Chin. Chem. Lett.* 31 (2020) 1974–1977.
- [31] M. Dilip, N.J. Bridges, H. Rodriguez, et al., *J. Solut. Chem.* 44 (2015) 454–468.
- [32] P.H.J. Kouwer, P. de Almeida, O. ven den Boomen, et al., *Chin. Chem. Lett.* 29 (2018) 281–284.
- [33] N. Schaeffer, H. Passos, I. Billard, et al., *Crit. Rev. Environ. Sci. Technol.* 48 (2018) 859–922.
- [34] Y.B. Xie, L.F. Yang, Y.Q. Ke, et al., *ACS Sustain. Chem. Eng.* 8 (2020) 3253–3260.
- [35] R.D. Rogers, J.H. Zhang, A.H. Bond, et al., *Solvent Extr. Ion Exch.* 13 (1995) 665–688.
- [36] T.E. Phelps, N. Bhawawet, S.S. Jurisson, G.A. Baker, *ACS Sustain. Chem. Eng.* 6 (2018) 13656–13661.
- [37] M. Chotkowski, D. Polomski, *J. Radioanal. Nucl. Chem.* 314 (2017) 87–92.
- [38] P.A. Gurnev, T.C. Roark, H.I. Petrache, et al., *Angew. Chem. Int. Ed.* 56 (2017) 3506–3509.
- [39] X.L. He, K.L. Zhang, Y. Liu, et al., *Angew. Chem. Int. Ed.* 57 (2018) 4590–4593.
- [40] N.J. Bridges, K.E. Gutowski, R.D. Rogers, *Green Chem.* 9 (2007) 177–183.
- [41] P. Moeyaert, L. Abiad, C. Sorel, J.F. Dufrière, P. Moisy, *J. Chem. Thermodyn.* 85 (2015) 61–67.
- [42] R.R. Srivastava, J. Lee, M. Kim, *J. Chem. Technol. Biotechnol.* 90 (2015) 1752–1764.
- [43] C. Shi, S.X. Xi, Y.C. Han, et al., *Chin. Chem. Lett.* 30 (2019) 305–310.
- [44] N. Schaeffer, G. Perez-Sanchez, H. Passos, et al., *Phys. Chem. Chem. Phys.* 21 (2019) 7462–7473.
- [45] Q.W. Yang, D. Xu, J.Z. Zhang, et al., *ACS Sustain. Chem. Eng.* 3 (2015) 309–316.