



# Article Imidazolium-Modified Silica Gel for Highly Selective Preconcentration of Ag(I) from the Nitric Acid Medium

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Abstract: The ion-exchange behavior of an organomineral material with an imidazolium (1-methyl-3-(prop-2-yn-1-yl)-1H-imidazol-3-ium bromide)-modified silica gel was studied for the extraction of Ag(I) from nitric acid media. The extraction from multicomponent systems containing Fe(III), Co(II), Ni(II), Cu(II), Pb(II), and Mn(II) in 100- and 1000-fold molar excesses with respect to Ag(I) was shown to occur with high selectivity. Based on the data of X-ray diffraction and X-ray fluorescence spectroscopy for samples of modified silica gel, a mixed ion exchange–adsorption mechanism for the extraction of Ag(I) was proposed. The effect of the phase contact time and the concentration of nitric acid on the distribution coefficient of Ag(I) was studied. The selectivity factors of the extraction of Ag(I) from multicomponent systems containing foreign cations in 100- and 1000-fold molar excesses under steady-state and dynamic concentration conditions were calculated.

Keywords: ionic liquid; mechanism of preconcentration; silica gel



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# 1. Introduction

The first examples of using ionic liquids for the extraction of organic compounds and metal ions appeared in the late 20th century [1-3] and since then this trend has progressed extensively. Ionic liquids have become ingrained in the practice of hydrometallurgy, analytical chemistry, electrochemistry, catalysis, organic synthesis, and other fields [4–9]. The convenience of compounds of this type is that the nature of cations and anions can be varied with ease, which makes it possible to change the hydrophobicity, hydrolytic stability, and solubility of an ionic liquid and some of its specific interactions with an analyte. The use of ionic liquids in extraction is mainly associated with two general approaches [10]. The first is extraction with chemical reaction considering the addition of special reagents to a system (ionic liquid–organic solvent–water), which are responsible for the formation of a coordinatively solvated adduct with an analyte [11–17], or the use of functionalized ILs (ionic liquids), the molecule of which contains coordinatively reactive groups [18–20]. The second approach is extraction with the addition of further reagents to a system (ionic liquid–organic solvent–water) [21–24]. Both of these approaches are implemented through extraction mechanisms that include processes such as the extraction of ion associates, the extraction of neutral coordinatively solvated adducts, and the exchange of cations or anions [25]. All of this specifies having a low extraction selectivity as a result of competitive ion-exchange processes and a loss of ionic liquids due to water solubility.

The problem of dissolution and loss of classic ionic liquids, for example, based on imidazolium salts, is solved through the use of perfluorinated substituents or through immobilization of the cationic moiety of the molecule onto the matrix surface [26–30]. The choice of the matrix's nature is often governed by two important factors: the presence of reactive centers on its surface capable of efficiently forming covalent "modifier–surface" bonds and structural morphological features of the surface. The possibility of covalent grafting of such compounds to the surface of silica gel opens the way to the design of new,

efficient, stationary phases for ion chromatography, materials for the solid-phase extraction of different-nature analytes, and solid-state reagents for the design of heterogeneous catalysts. Currently, there is growing interest in the preparation of such materials based on different forms of silica [31–34]. Covalent immobilization of ionic liquids is often carried out on the surface of commercially available pre-functionalized silica gels to obtain new stationary chromatographic phases for the separation of amino acid mixtures and different organic and inorganic anions [35–38].

At the present time, three main approaches to the synthesis of matrix surface-immobilized ionic liquids can be distinguished [39]:

- Covalent immobilization of a cation or an anion on the surface of silica gel;
- The design of adsorption layers of ionic liquids on the surface of silica gel pores;
- The hydrolytic polycondensation of silicon-containing precursors and in situ encapsulation of ionic liquids in the resulting porous framework of the matrix.

Despite the fact that covalent immobilization is the most labor-consuming process among the above-mentioned ones, it remains to be most preferred in the design of materials since it provides high chemical stability and good reproducibility.

The multivalent ions can be adsorbed specifically on the  $SiO_2/Al_2O_3$  [40] or zirconium phosphate surface [41] on one or two surface sites (hydroxyl groups) via hydrogen exchange, but the number of sites usually occupied by a single ion is smaller than two; adsorption of Ag(I) is a result of the non-stoichiometric cation exchange according to the reaction.

For efficient solid-phase extraction of Ag(I), materials are widely used consisting of an organic or inorganic substrate and an organic reagent with donor atoms, which form stable complexes with Ag(I) [42–44]. Most of the matrices used for Ag(I) preconcentration are modified with sulfur-containing agents such as thiol- [45], 2-mercaptobenzothiazole- [46], and thiourea-group [47], which, as soft bases, form stable complexes on the surface with silver. To further increase the Ag(I) recovery selectivity, Cl<sup>-</sup> is introduced into the aqueous phase. S- and N-containing ligands are most often used as organic reagents, for example, the use of 2,6-diaminopyridine makes it possible to extract Ag(I) and Pd(II) with a low Kd = 120 at pH 4 [48], and the use of a material containing a chelating group makes it possible to extract Cu(II), Pd(II), and Ag(I) at pH 6.0, 6.0, and 5.0 [49]. Sufficiently high pH (4.0, 5.0, 6.0) values used for extraction indirectly indicate the low stability of the developing complexes, as well as the occurrence of hydrolytic processes in the system.

The present work describes features of the nonspecific high-selectivity solid-phase extraction of Ag(I) by an organomineral material—imidazolium (1-methyl-3-(prop-2-yn-1-yl)-1H-imidazol-3-ium bromide)-modified silica gel under steady-state and dynamic conditions, and proposes a mixed ion exchange–adsorption mechanism of extraction.

#### 2. Materials and Methods

A standard stock solution of Ag(I) was prepared using a dissolving technique. The accurately weighed amounts of analytical grade  $AgNO_3$  were dissolved in distilled water with the addition of  $HNO_3$  (ultra-pure grade).

Solutions of Fe(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O, Co(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O, Ni(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O, Cu(NO<sub>3</sub>)<sub>2</sub>·3H<sub>2</sub>O, Pb(NO<sub>3</sub>)<sub>2</sub>, and Mn(NO<sub>3</sub>)<sub>2</sub>·4H<sub>2</sub>O were prepared through the dissolving of the corresponding salt (analytical grade) in 0.1 M HNO<sub>3</sub>.

The sorbent was prepared using Kieselgel 60 (0.040-0.063 mm) (Macherey-Nagel).

All equilibrium experiments were performed in a temperature-controlled stirring device at 298 K. The extraction efficiency was estimated by calculating the distribution coefficient (under static conditions) using Equation (1).

$$K_d\left(mL \times g^{-1}\right) = \left(\frac{A_0 - A_e}{A_e}\right) \times \left(\frac{V}{m}\right) \tag{1}$$

where  $A_0$  is the maximum sorption capacity;

 $A_e$  is the equilibrium sorption capacity;

*V* is the volume of the solution;

*m* is the sorbent weight, g.

The experiment included equilibration of the sorbent (0.05 g) with nitric acid (50 mL) (the concentration varied from 0.01 to 0.1 M). The equilibration experiment was performed in triplicate and the concentration of Ag (I) in the sample in each extraction experiment was determined three times to minimize experimental and statistical errors. Aliquots were sampled from the aqueous phase prior to and after equilibration.

The separation factor (*Sf*) was determined by Equation (2).

$$Sf = \frac{K_d \ of \ Ag(I)}{K_d \ of \ Me}$$
(2)

where *Me* = Fe(III), Co(II), Ni(II), Cu(II), Pb(II), and Mn(II).

The absorbances of solutions were measured on a Leki SS2107 spectrophotometer (Finland) using a standard cell with an optical path length of 10 mm. Solutions were stirred using a KS 4000i control incubator shaker (IKA). The residual concentration of Ag(I) after extraction was determined using the spectrophotometric procedure with brilliant green [50].

The qualitative elemental composition was determined on an EDX-8000 energydispersive X-ray fluorescent spectrometer (Shimadzu, Japan). The sample of modified silica gel was pre-dried at 50 °C (prior to and after extraction of Ag(I)) and was placed as a powder in a cell and fixed using a 4 µm-thick mylar film. Measurement conditions: the X-ray tube anode was made of rhodium, the detector was SDD, the atmosphere was air, the channel was Ti–U, U = 50 kV, I = 100 µA, and the scan range was 0–40 keV. The obtained data were processed using the PCEDX Pro software.

Concentrations of all metal ions were determined using ICP-AES using an iCAP-6000 Series atomic emission spectrometer (Thermo Scientific, Waltham, MA, USA) under optimum instrument parameters providing the maximum assay sensitivity. The main emission lines of elements free of spectral overlaps of matrix components of a sample were chosen based on the analysis of their entire spectra.

Diffractometer Shimadzu XRD-7000 in Bragg-Brentano geometry with a fixed sample and a vertical goniometer and CuK $\alpha$  radiation ( $\lambda$  = 1.5406 Å) were used in the work. The voltage on the X-ray tube was 40 kV, and the current strength was 30 mA.

Adsorption isotherm

The isotherm of Ag(I) adsorption on Sil-Im was studied by equilibration of the sorbent (0.05 g) with a solution of nitric acid (50 mL) containing different amounts of AgNO<sub>3</sub>. The equilibration experiments were performed for 2 h at 298 K. The amount of Ag(I) extracted by Sil-Im was calculated as the difference between the initial and equilibrium concentration of Ag(I) in a solution. Adsorption capacity was calculated by Equation (3)

$$A_e = \frac{(C_0(\text{Ag}(\text{I})) - C_{einsolution}(\text{Ag}(\text{I})) \cdot V}{m}$$
(3)

where  $C_0$  is the initial concentration of Ag(I), mmol·L<sup>-1</sup>;

 $C_e$  is the equilibrium concentration of Ag(I) in a solution, mmol·L<sup>-1</sup>;

*V* is the solution volume, mL;

*m* is the sorbent weight, g.

**Dynamic Sorption Experiment** 

To perform a dynamic experiment, the microcolumn (d = 6 mm) was packed with modified silica gel (m(sorbent) = 0.2 g). A solution was pumped using the peristaltic pump, allowing one to vary the volumetric flow rate from 1.5 to 5 mL·min<sup>-1</sup>. The solution was pumped in aliquots (V = 5 mL) through the packed column, the effluent was collected, and the residual concentration of Ag(I) was determined using spectrophotometry and ICP-AES. Distribution coefficients (Kd) and effective dynamic capacity (Q) were calculated from the shown dynamic curves. For each i-th fraction of a passed solution (corresponding to single

point on the dynamic elution curve), the total amount of sorbed Ag (I) was calculated using Equations (4) and (5).

The effective dynamic capacity Q was calculated as follows

$$Q = \sum_{i} n_{i \text{ (adsorbed)}} / m_{\text{(sorbent)}}$$
(4)

where  $m_{(\text{sorbent})}$  is the weight of sorbent packed into a microcolumn. The distribution coefficient was estimated at the point where  $C_i(\text{Ag}(I)) = 0.5 C_0(\text{Ag}(I))$ :

$$K_{\rm d} = V_{\rm r} / m_{\rm (sorbent)} \tag{5}$$

where  $V_r$  is the retention volume corresponding to  $C_i(Ag(I)) = 0.5 C_0(Ag(I))$ . The equilibrium volume corresponded to the plateau of the dynamic elution curve where  $C_i(Ag(I)) = 0.95 C_0(Ag(I))$ .

#### 3. Results

The most common method for the preparation of silica gels with covalently immobilized moieties of ionic liquids includes the quaternization of 3-halopropyl silica gel with tertiary nitrogen bases, such as trialkylamines, pyridines, and 1-alkylimidazoles.

Since in many cases the properties of a material are governed not only by the nature of the matrix and a functional group but also by the spacer separating them from each other, we used an approach where covalent immobilization is achieved through the azide–alkyne cycloaddition click reaction to form a triazole ring (Figure 1).





The success of the chosen strategy for attachment of the ionic liquid and preparation of the material having a structure as shown in Figure 1 was confirmed by the data of IR and <sup>13</sup>C NMR spectroscopy, and thermogravimetric and elemental analysis [51].

The elemental analysis of the Sil-Im sorbent showed that it contains 6.15% of C and 2.23% of N [51]. Based on the data of the elemental analysis for nitrogen, the amount of the immobilized bromide 1-methyl-3-(prop-2-yn-1-yl)-1H-imidazol-3-ium on silica gel was  $0.32 \pm 0.04$  mM g <sup>-1</sup>. The total ion-exchange capacity of the obtained material was determined using titrimetry, determining bromide ion released in the anion-exchange reaction with HNO<sub>3</sub> as described in [52]. The averaged total ion-exchange capacity of the modified material was  $0.26 \pm 0.02$  mM g <sup>-1</sup> (n = 6, *p* = 0.95). Thus, the number of functional groups calculated from the data of elemental analysis agrees well with the calculated total exchange capacity.

The vacuum-dried (1 Torr, 50 °C, 6 h) silica gel sample was analyzed using X-ray fluorescence spectroscopy. The XRF spectrum displayed an intense K $\alpha$  line of bromine (Figure 2), which also confirms a successful immobilization.

As mentioned above, the presence of a grafted ionic liquid on the surface suggests three types of low-selectivity interactions with an analyte. The specificity of interactions between the grafted ionic liquid and the analyte can be controlled through providing the possibility of simultaneous occurrence of several processes, such as the ion exchange and formation of a low-solubility compound with the ionic liquid anion. In the literature, there is only one example of the selective separation of Am(III)/Eu(III) on 1-methyl-3-(3-(triethoxysilyl)propyl)-1H-imidazol-3-ium bis(2-ethylhexyl)phosphate—modified silica gel. It is assumed that the separation relies on sequential proceeding of the ion exchange and

formation of poorly soluble Am(III) and Eu(III) phosphates [53]; the selectivity of their separation is controlled by the stability constant of compounds that was formed.

In the present work, the possible contribution of two extraction mechanisms, ion-exchange and adsorption ones, providing high-selectivity sorption on material Sil-Im was studied by the example of Ag(I), since the solubility product constant is  $K_{sp}(AgBr) = 5.35 \times 10^{-13}$  [54].



Figure 2. X-ray fluorescence spectrum Sil-Im.

#### 3.1. Distribution Coefficient

The choice of  $HNO_3$  as a supporting solution allowed us to prevent side competitive reactions involving the analyte and to minimize the possibility of the formation of foreign complex anions capable of undergoing ion-exchange equilibria in a solution. Table 1 shows the sorption behavior of Ag(I) as a function of the  $HNO_3$  concentration in the aqueous phase.

**Table 1.** Distribution coefficient of Ag(I), when the concentration of nitric acid varied from 0.01 to 5 M at 298 K (n = 4, p = 0.95).

Concentration of Nitric Acid (M)	log(Distribution Coefficient of Ag(I)), $\log K_d$			
0.01	2.7			
0.1	2.8			
0.5	1.8			
1	1.7			
3	1.5			
5	1.3			

It is seen that the distribution coefficient of Ag(I) decreases with an increase in the concentration of nitric acid, which suggests its participation in the competitive ion-exchange reaction (Equation (6)).

$$\left\{ (Sil - Im)^{+}Br^{-} \right\}_{ad} + HNO_{3 aq} \Leftrightarrow \left\{ (Sil - Im)^{+}NO_{3}^{-} \right\}_{ad} \times HBr_{aq}$$
(6)

For 0.1 M nitric acid, the achieved distribution coefficient was 726.

Figure 3 shows the effect of the phase contact time on the distribution coefficient of Ag(I) in 0.1 M HNO<sub>3</sub>; the distribution coefficient is seen to slightly vary in a time interval from 10 to 60 min, which indirectly suggests the absence of kinetic limitations upon the extraction of Ag(I).



**Figure 3.** Distribution coefficient Ag(I) as a function of phase contact time at 298 K (equilibrium nitric acid concentration 0.1 M).

#### 3.2. Adsorption Isotherm

The sorption capacity of Sil-Im as a function of the equilibrium concentration of Ag(I) in 0.1 M HNO<sub>3</sub> is shown in Figure 4.



**Figure 4.** Adsorption isotherm for the sorption of Ag(I) on Sil–Im at 298 K (equilibrium nitric acid concentration 0.1 M, m (Sil–Im) = 0.05 g), (n = 4, p = 0.95).

The conventional sorption capacity with respect to Ag(I) under steady-state conditions was determined to be  $0.1 \pm 0.01$  mM g<sup>-1</sup>, which is lower than the sorption capacity of Sil-Im determined from the data of elemental analysis (0.3 mM g<sup>-1</sup>) and the data on the total exchange capacity (0.26  $\pm$  0.02 mM g<sup>-1</sup>). Such a result can be due to the presence of HNO<sub>3</sub> in the aqueous phase, which is likely to be involved in the competitive reaction (Equation (6)).

The recording of diffraction patterns of modified silica gel after being pre-equilibrated with a solution of Ag(I) in 0.1 M HNO<sub>3</sub> (silica gel samples after obtaining the sorption isotherm) was carried out in the range of  $2\Theta$  angles of 5–70° with a scanning step of 0.02°. On the radiograph processed by the software HighScore Plus Ver. 3.0, there are reflections on the absolute values of the inter-planar pacing and intensity ratio, which are responsible for the crystalline phase of AgBr (Figure 5).



Figure 5. X-ray diffraction spectrum Sil-Im (2)-pre-equilibrated with a solution of Ag(I) in 0.1 M HNO3.

For the Sil-Im samples that have been pre-equilibrated with a solution of Ag(I) in 0.1 M HNO<sub>3</sub>, separated, and dried at 50 °C, the qualitative composition was determined using X-ray fluorescence (XRF) analysis. Figure 6 shows the XRF spectra for the Sil-Im samples. The spectra for both silica gel samples display the K $\alpha$  line of bromine, the intensity of which remains almost unchanged. For the Sil-Im sample after equilibration with a solution of Ag(I) in 0.1 M HNO<sub>3</sub>, one can observe the appearance of K $\alpha$  and K $\beta$  lines of Ag.



**Figure 6.** X-ray fluorescence spectrum Sil-Im (1) and Sil-Im (2)—pre-equilibrated with a solution of Ag(I) in 0.1 M HNO<sub>3</sub>.

Analysis of X-ray diffraction and X-ray fluorescence spectrum indicates a mixed extraction mechanism (Equations (6) and (7)).

Taking into account the sorption capacity with respect to Ag(I) under selected conditions, we imitated multicomponent systems (n(Ag):n (number of functional groups of Sil-Im) = 1:100) containing Fe(III), Co(II), Ni(II), Cu(II), Pb(II), and Mn(II) in the 100- and 1000-fold molar excesses with regard to Ag(I). For the imitated and equilibrated systems, the residual concentrations of metals, the distribution coefficients, and the selectivity factors were determined using ICP-AES (Table 2).

The obtained data suggest the extraction of Ag(I) to be a selective process that cannot only be provided by the ion-exchange mechanism, allowing us to assume a scheme reflecting the extraction of Ag(I) on Sil-Im (Equation (7)):

$$\left\{ (Sil - Im)^{+}Br^{-} \right\}_{ad} + AgNO_{3 aq} \Leftrightarrow \left\{ (Sil - Im)^{+}NO_{3}^{-} \right\}_{ad} \times AgBr_{ad}$$
(7)

## 3.3. Selection of Dynamic Ion-Exchange Conditions

Slight changes in the distribution coefficient under steady-state conditions of extraction for a period of 10 to 60 min is indicative of quite a fast distribution of Ag(I) between phases, which allows us to assume the absence of loss in efficiency in going to the dynamic conditions of extraction. This assumption was verified taking into account the total ion-exchange capacity of the material under steady-state conditions (0.1 mM g<sup>-1</sup>) and maintaining  $C_0(Ag(I)) = 0.25 \text{ mM} \cdot \text{L}^{-1}$  (V = 100 mL). Upon variation in the flow rate of a Ag(I) solution from 1.5 to 5 mL·min<sup>-1</sup> passed through the modified silica gel cartridge, the percentage extraction of Ag(I) does not decrease; therefore, the flow rate of 5 mL·min<sup>-1</sup> was used in subsequent experiments.

Under selected conditions, we obtained dynamic elution curves as the ratio of the Ag(I) concentration determined in the eluate to its initial value against the volume of passed solution (Figure 7).



**Figure 7.** Frontal dynamic elution curve for Ag(I) in system (0.1 M HNO<sub>3</sub>; V = 5 mL·min<sup>-1</sup>, and m(sorbent) = 0.1 g), (n = 4, p = 0.95).

The calculated dynamic capacity of Sil-Im with respect to Ag(I) was found to be equal to  $0.22 \pm 0.03$  (n = 4, *p* = 0.95) mM g<sup>-1</sup>, which corresponds to the total exchange capacity of Sil-Im ( $0.26 \pm 0.02$  mM g<sup>-1</sup>), and the distribution coefficient was 2037.

Using the method of frontal dynamic elution curves, we estimated the selectivity of Ag(I) extraction on the modified silica gel under selected extraction conditions with the addition of 100- and 1000-fold molar excesses of Fe(III), Co(II), Ni(II), Cu(II), Pb(II), and Mn(II) with respect to Ag(I). It is seen that, for the imitated systems, the values of the dynamic distribution coefficient of Ag(I) remain almost unchanged (Table 3) and a high concentration selectivity is maintained which confirms the mixed ion exchange–adsorption mechanism, the direction and selectivity of which are governed by the solubility product constant, Ksp (AgBr).

**Table 2.** Separation factor (*Sf*) obtained between Ag(I) and Fe(III), Co(II), Ni(II), Cu(II), Pb(II), and Mn(II) (concentration of nitric acid 0.1 M) at 298 K, in static conditions (n = 4), p = 0.95.

n(Ag(I)): n(Me)	$K_{\rm d}$ Ag(I)X $\pm$ ts/ $\sqrt{n}$	$Sf_{Ag(I)/Fe(III)}X\pm ts/\sqrt{n}$	$Sf_{Ag(I)/Co(II)}X \pm ts/\sqrt{n}$	$Sf_{Ag(I)/Ni(II)} x \pm ts/\sqrt{n}$	$Sf_{Ag(I)/Cu(II)} x \pm ts/\sqrt{n}$	$Sf_{Ag(I)/Pb(II)} x \pm ts/\sqrt{n}$	$Sf_{Ag(I)/Mn(II)}X\pm ts/\sqrt{n}$
1:100 1:1000	$\begin{array}{c} 2855\pm51\\ 3088\pm43 \end{array}$	$\begin{array}{c} 62\pm 3\\ 57\pm 2\end{array}$	$\begin{array}{c} 58\pm 4\\ 58\pm 3\end{array}$	$\begin{array}{c} 67\pm3\\ 64\pm2 \end{array}$	$\begin{array}{c} 49\pm 2\\ 52\pm 2\end{array}$	$53 \pm 3 \\ 58 \pm 3$	$\begin{array}{c} 67\pm3\\ 69\pm3 \end{array}$

**Table 3.** Separation factor (*Sf*) obtained between Ag(I) and Fe(III), Co(II), Ni(II), Cu(II), Pb(II), and Mn(II) (concentration of nitric acid 0.1 M) at 298 K, in dynamic conditions (n = 3, p = 0.95).

n(Ag(I)): n (Me)	KdAg(I) x $\pm$ ts/ $\sqrt{n}$	$Sf_{Ag(I)/Fe(III)} \ge ts/\sqrt{n}$	$Sf_{Ag(I)/Co(II)} x \pm ts/\sqrt{n}$	$Sf_{Ag(I)/Ni(II)} x \pm ts/\sqrt{n}$	$Sf_{Ag(I)/Cu(II)} x \pm ts/\sqrt{n}$	$Sf_{Ag(I)/Pb(II)} x \pm ts/\sqrt{n}$	$Sf_{Ag(I)/Mn(II)} x \pm ts/\sqrt{n}$
1:100	$2015\pm38$	$64\pm2$	$52\pm3$	$57\pm3$	$51\pm2$	$51\pm3$	$46\pm3$
1:1000	$1995\pm35$	$57\pm2$	$48\pm2$	$52\pm3$	$52\pm1$	$48\pm3$	$49\pm3$

A recently developed organomineral material with immobilized ionic liquid is proposed for the extraction, separation, and concentration of Ag(I) from nitric acid media. The equilibrium in the sorbent–solution system is attained after 10 min. The distribution coefficient of Ag(I) decreases with an increase in the concentration of nitric acid and reaches X when the concentration of nitric acid is 0.1 M. For multicomponent systems containing 100- and 1000-fold molar excesses of Fe(III), Co(II), Ni(II), Cu(II), Pb(II), and Mn(II) with respect to Ag(I), a separation factor (for both steady-state and dynamic systems) of more than 45 is found to be achieved without the addition of further complexing agents to the aqueous phase, which is usually required for selective separation and achieving high separation factors upon application of ionic liquids. The obtained data suggest a mixed ion exchange–adsorption mechanism for the extraction of Ag(I).

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