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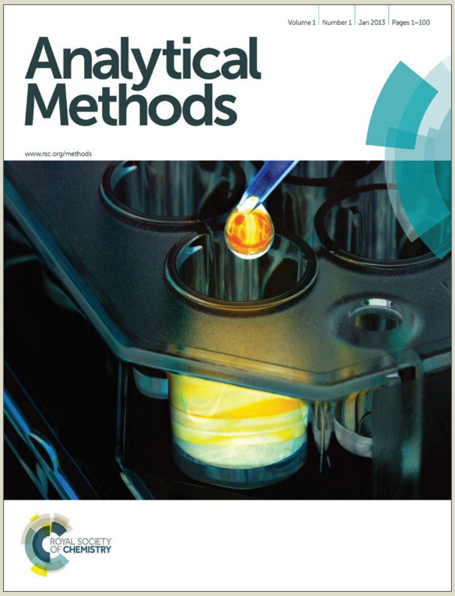

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Rapid determination of plutonium in water samples using vacuum box system separation and low background liquid scintillation counter measurement

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Abstract

An analytical method for rapid determination of $^{239+240}$plutonium in environmental liquid sample was developed. The separation of plutonium from matrix and interfering elements was performed using anion exchange chromatographic columns executed in a vacuum box system. Under the optimized conditions, the chemical yield of plutonium is better than 90% and the decontamination factors for uranium, thorium and americium ranged from 10^3 to 10^4 for 5 L water samples. The concentrations of plutonium were measured by detecting α decay of $^{239+240}$plutonium using low background liquid scintillation counter (LSC). The analytical results of plutonium in water samples were in good agreement with the values obtained by conventional method, indicating that the proposed method is reliable and can be used for low level plutonium analysis in environmental water samples.

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Keywords

Plutonium, environmental liquid samples, vacuum box system, LSC, analysis

1. Introduction

Plutonium (Pu), as an important artificial nuclide, has been released into the environment through human nuclear activities such as reprocessing of spent nuclear fuel, nuclear weapons testing and nuclear accidents[1-4]. Its isotopes are considered as highly radiological and biological toxic pollutants because of their long half-lives (^{236}Pu: 3.5×10^{9} yr, ^{238}Pu: 4.3×10^{10} yr, ^{239}Pu: 5.5×10^{15}yr, ^{240}Pu: 1.2×10^{11}yr, ^{244}Pu: 2.5×10^{10}yr) and α emission associated with their decay[5]. Isotopes of Pu can be migrated into water and soil under the action of monsoon and ocean current, and enter into human body through food chain and cause damage to human[6,7]. Therefore, there is a strong requirement of developing rapid and robust techniques for the determination of Pu in the environment.

Since the 1950s, many methods for separation and purification of Pu from water samples have been developed, including co-precipitation, solvent extraction, and anion exchange and extraction chromatography[8-11]. Based on the high ionic potential and the chemical property of forming anionic complexes, Pu can be easily taken up by anion exchange resins and anion exchange chromatography is thus often used in the determination of Pu in various environmental samples[12,13]. However, in order to obtain the high purity of Pu for accurate analysis, large-size ion exchange columns were often applied for the removal of matrices, which will produce a large amount of radioactive wastes and cause difficulties for subsequent disposal[9-11]. In addition, the traditional anionic chromatography is usually operated under the condition of normal pressure, which is time consuming and labor intensive especially for the samples with complex matrices. The development of a separation system with which a fast column separation can be carried out is significant. Vacuum box executed in chromatography approach is regarded as an appealing tool for convenient separation of trace level of radionuclides from water samples[14,15]. The flow rate of column can be controlled by a vacuum pump. To our best knowledge, the reported methods are mainly related to the vacuum box executed in extraction chromatography[16,17]. The application of anionic chromatography, especially the small sized chromatographic column for the separation of Pu from environmental samples, is still limited.

Both radiometric methods such as α spectrometry and liquid scintillation counting (LSC) and mass spectrometric techniques like inductively coupled plasma mass spectrometry (ICP-MS) can be used for Pu measurement. Based on the advantages of short analytical time and relatively high sensitively, Pu is often measured by ICP-MS[18,19]. The major challenge of this method for Pu measurement is the isobaric and spectrometric interferences of ^{238}U, ^{1}H^{238}U^{+} and ^{241}Am. In addition, high concentration of matrix elements may lead to the signal suppression. The concentration of total dissolved solid in the sample solution generally needs to be kept below 0.1%[20]. Accordingly, effective separation and purification, especially for ^{238}U, is particularly critical for accurate determination of ^{239}Pu, which in some case increase the analytical time and lead to a poor accuracy of measurement. As α-emitter, $^{239+240}$Pu can also be measured by α-spectrometry with advantages of easy application and relatively low instrument expenses[21,22]. However, the detection of Pu with α-spectrometry requires relatively long counting times (usually 1~4 days) and is not suitable for emergency situations. With the improvement of instrument detectors, LSC could offer the function of α/β-discrimination and can be applied for Pu measurement [23-25]. Compared with α-spectrometry, simple source preparation and short counting time are the main advantages and thus LSC can be used for emergency preparedness. In addition, with the aid of scintillation cocktail as the media of radiation energy transfer, the self-absorption of sample source is negligible and the absorption of detector walls, windows and air absorption is also limited. Accordingly, the accurate analysis of trace level Pu in environmental samples using LSC is achievable.

Aiming at rapid determination of trace level Pu in water samples, a vacuum box system executed in small sized anion exchange columns followed by detecting α decay of $^{239+240}$Pu using low background LSC which could discriminate α/β emission was proposed in the present work. The parameters of anion exchange column which affect the separation speed and efficiency of Pu were optimized. The analytical results proved that the proposed method can be used for routine analysis of Pu in daily monitoring and rapid analysis for emergency preparedness.

2. Experimental

2.1. Experimental setup

The vacuum box anion exchange chromatographic setup is composed of a vacuum box system (Eichrom Technologies, Inc., USA) furnished with 24 anion exchange columns (C1-C24). The system consists of a polycarbonate trough with lid and 24 ports and a gauge is used to monitor the vacuum pressure. All the outlets of chromatographic columns were connected through PEEK ferrules with rigid PTFE beaker. Within the system, 24 samples can be separated synchronously.

All measurements of Pu were performed using α/β-LSC (Tri-Carb 3180TR/SL, PerkinElmer LifeScience, Boston, MA, USA) with Optiphase HiSafe3 scintillation cocktails (PerkinElmer LifeScience, Boston, MA, USA). Am and Th were measured by α spectrometer; and U was measured with trace uranium analyzer.

2.2. Standards, reagents and samples

All reagents, including HNO_3, HCl, $NH_3 \cdot H_2O$, $NH_2OH \cdot HCl$, NaOH and $NaNO_2$ used were of analytical grade. High purity water (18 MΩ cm) (Milli-Q 50, Millipore, Bedford, MA, USA) was applied for the solution preparation throughout the experiment.

The Pu standard solution was provided by the 404 Company Limited., China National Nuclear Group (Lanzhou, China). Standard solutions of uranium (U), americium (Am) and thorium (Th) were obtained from China Institute of Atomic Energy (Beijing, China). Simulation solution was prepared by mixing known amounts of Pu, U, Am and Th in water. Three water samples (5 L waste water collected from Yumen Area, China) were analyzed for testing the accuracy of the method.

Anion exchange resins used were of AG 1 series with different crosslinkage and particle sizes, including AG 1-×2 (2% crosslinked, 50-100 mesh), AG 1-×4 (4% crosslinked, 50-100 mesh and 100-200 mesh) and AG 1-×8 (8% crosslinked, 50-100 mesh) in chloride form (Eichrom Technologies LLC., USA). The resins were swelled in water firstly, and then dispersed in 8 mol L^{-1} HCl and transferred into a column which was pre-conditioned with 8 mol L^{-1} HCl. The performance of columns with ratios were investigated and compared, including 10 mm i.d.×20 cm long (ca. 16 mL), 8.8 mm i.d.×20 cm long (ca. 12 mL), 7 mm i.d.×20 cm long (ca. 8 mL), 7 mm i.d.×10 cm long (ca. 4 mL), 5 mm i.d.×10 cm long (ca. 2 mL), 7 mm i.d.×5 cm long (ca. 2 mL) and 5 mm i.d. ×5 cm long (ca. 1 mL).

2.3. Sample pre-treatment

2.3.1. Filtration and acidification

Water samples (e.g., waste water, freshwater and groundwater) were acidized to pH 2-3 immediately after collection. Then the samples were filtered using Millipore MF membrane filters (0.45 mm, 47mm diameter) and a polysulfon filtration unit DSO320 Series (Nalgene, Rochester, NY, USA) before analysis.

2.3.2. Pre-concentration of Pu

The content of Pu is usually at trace level in water sample (typically within the femtograms per litre range). To get accurate analytical results, Pu must be concentrated from sample matrix using some pre-concentration techniques[13]. In the present work, a co-precipitation method was applied for the enrichment of Pu in water samples. The procedure is as follows, a calculated amount of $Al_2(SO_4)_3$ (1 mol/L) and $FeCl_3$ (1 mol/L) were added to the water samples. The pH of sample solution was adjusted to 6 to get $Al(OH)_3$ and $Fe(OH)_3$ precipitates (Pu can be co-precipitated at the same time)[26]. The sample was then kept overnight (>8 h) for settlement. After removal of supernatant, the slurry containing Pu was separated by centrifugation. The residue was finally dissolved with 8 mol L^{-1} HCl for further purification of Pu.

2.4. Valence adjustment to Pu(IV)

Since anion exchange resins have high exchange capacities for Pu(IV) in nitric/hydrochloric acid media[27,28], a two-step valence adjustment method was thus utilized during the separation procedure. 0.1 mol L^{-1} $NH_2OH·HCl$ was firstly added into sample solution with gently stirring for 15 min to reduce the overall Pu to Pu(III), then $NH_3·H_2O$ was used to adjust pH to 9~10. The precipitate obtained was dissolved with concentrated HCl and Pu(III) was oxidized to Pu(IV) using 1.0 mol L^{-1} $NaNO_2$. The sample solution was finally diluted to 8 mol L^{-1} HCl media prior to loading onto anion exchange column.

2.5. Separation scheme and source preparation

The separation procedure contains four steps as following: (i) pre-conditioning anion exchange column with 8 mol L^{-1} HCl; (ii) transferring the sample in 8 mol L^{-1} HCl media (about 10 mL) and loading it on the anion exchange column at 0.8 mL min^{-1} to exchange the target analytes as anionic hydrochloric complexes[29]; (iii) washing column with 5 mL of 1 mol L^{-1} HNO_3 to remove U and Fe ions, and 5 mL of 8 mol L^{-1} HCl to desorb Am and Th as well as other matrix elements respectively; (vi) eluting Pu with 5 mL of 0.5 mol L^{-1} HCl containing 0.1 mol L^{-1} $NH_2OH·HCl$. (v) Regeneration the anion exchange column with 5 mL of 0.1 mol/L $NH_2OH·HCl$-0.5 mol/L HCl

The eluant obtained was evaporated to dryness and the residue was dissolved in 5mL of 0.01 mol L^{-1} HNO_3. The solution contained Pu was then transferred into a 20 mL polyethylene bottle and 10 mL scintillation cocktail was added. The Pu in samples was finally measured by low background LSC.

2.6. Detection of Pu using LSC

In the present work, Pu was determined by detecting α decay of $^{239+240}$Pu using low background LSC. Prior to sample analysis, the LSC instrument was tuned for minimum sensitivity of Am using ^{241}Am standard solution (0.01 mol L^{-1} HNO_3 as media) and the instrumental parameters were further adjusted for Pu. It is important to note that these parameters were optimized each time when the instrument was initialized. The method allows achievement of a detection limit of 1.6×10^{-2} Bq L^{-1} for 5 L water samples in 60 min counting time. The analytical procedure is illustrated in Fig.1.

3. Results and discussion

3.1. Parameters optimization of chromatographic column

In general, sufficient amount of anion exchange resins are often regarded as an essential factor for separation of target radionuclides in water samples. The column volumes of 10-20 mL are usually employed to ensure satisfactory recoveries and appropriate separation efficiencies of radionuclides[30]. In this work, the parameters which affect the separation abilities of chromatographic column were optimized for 5 L water samples. The results (Fig.2) show that the chemical yields of Pu (>85%) and the decontamination factors (>10^3) for U, Th and Am obtained from the anion exchange chromatographic columns (0.5×10 cm, ca. 2 mL) are similar as the larger volumes of 16mL (1.0×20 cm), 12mL (0.88×20 cm), 8mL (0.7×20 cm), 4mL (0.7×10 cm), indicating that the small sized column (containing 2 mL resin) is enough for Pu purification in 5 L water samples. It should be pointed out that when smaller sized column (0.5×5 cm, ca. 1 mL) was explored, the chemical yield of Pu dropped dramatically to less than 40% (Fig.3). Therefore, considering the advantages of low consumption of resins and reagents, an appropriate volume of column (0.5×10 cm, ca. 2 mL resin) was selected for separation and determination of Pu.

Crosslinkage is an important parameter of anion exchange resin, which determines the internal structure of resin and affects its uptake and elution properties. In this work, three kinds of resins with different crosslinkage, namely AG 1-×2, AG 1-×4 and AG 1-×8, were investigated. The results (Fig.4(a)) show that the chemical yields of Pu increased with the increasing of the resin crosslinkage. The main reason for such a phenomenon would be that the higher exchange crosslinkage means there are more functional groups in the interior of the resin and the specific surface area of the resins are larger, leading to higher uptake ability for Pu[31]. Among the three kinds of resins, the decontamination factor of AG 1-×8 for U was reduced obviously (Fig. 4(b)). To overcome the problems, the volumes of washing solutions must be increased to remove the sorbed U from AG 1-×8 columns, which will decrease the chemical yield of Pu because some amount of Pu can be washed with the large volume of solution. For AG 1-×4 resin, different particle size (AG 1-×4(a), 50-100 mesh; AG 1-×4(b), 100-200 mesh) were also investigated (Fig.4(b)). It is found that the chemical yields of Pu with smaller particle size of resin are a little higher than larger ones. However, the decontamination factors for U, Th and Am obtained from the bigger particle size of resins (AG 1-×4(a)) are better. Combining these two factors, we choose AG 1-×4 (a) as the adsorbent for Pu separation.

The flow rate is another important parameter for anion exchange resin during column separation. The high flow rate is in favor for fast separation of nuclides from water samples. However, the chemical yields of Pu and decontamination factors for U, Th and Am were deteriorated when the flow rate is higher than 1.0 mL min^{-1} (see Fig.5). To get high recovery of Pu and fast processing of samples, the flow rate of 0.8 mL min^{-1} was chosen during the sample loading and column washing.

3.2. Media for Pu separation

For Pu separation by anion exchange chromatography, the oxidation state of Pu is very important, which will affect the separation efficiency as well as the accuracy of analytical results. The redox states of Pu can be stabilized by complexation with various ligands[32]. In this case, the choice of suitable media becomes significant. Because the distribution coefficients of Pu on anion exchange resins in concentrated HNO_3 or HCl media are very high, Pu isotopes can generally be separated from other nuclides[33,34]. To our best knowledge, Pu separation has mainly been carried out in HNO_3 media because most of the handling processes of nuclear fuels were dissolved by HNO_3[33]. However, it should be noticed that Th can form strong nitrate complex and U can also form weak complex with NO_3^- in HNO_3 media. Consequently, most of Th and a small quantity of U can be retained on anion exchange column and easily eluted with Pu, which causes the interference for accurate analysis of Pu. It is reported that Th cannot form strong complex like Pu(IV) in HCl media. Furthermore, trivalent actinides show practically no retention (K<1) in HCl solutions of up to approximately 5 mol L^{-1}, while tetravalent actinides remain strongly retained under these conditions, with K $>10^3$ in 4 mol L^{-1} HCl[34]. In this case, all of the retained actinides can be eluted using complexant eluents. To develop the optimal separation procedure, the amount of HCl used during sample loading and column washing was investigated. Our experimental results (see Fig.6(a)) show that the chemical yield of Pu increases gradually (90%~95%) with the increase of HCl concentration from 7 mol/L to 10 mol/L, indicating that Pu can be easily retained on the AG1-×4 resin at high concentration of HCl. Compared to Pu, the retention of Th and Am by AG1-×4 resin in higher concentration of HCl is very limited, and the decontamination factors for these nuclides are all higher than 10^4 (Fig.6(b)). It should be mentioned that the decontamination factor of U is decreased with the increase of HCl concentration (Fig.6(b)). In addition, some amount of Fe^{3+} is also sorbed on the column after sample loading in HCl media. A further washing step with 1 mol/L HNO_3 is thus applied for the removal of U as well as Fe in the analytical procedure. Considering the high recovery of Pu as well as efficient removal of Th and Am, 8 mol L^{-1} HCl was selected as the solution media during sample loading in the present work.

3.3. Elution of Pu

Two types of methods have been reported for Pu elution from anion exchange columns[18,19]. One of them is named direct elution method based on the low adsorptive capacity of Pu(IV) complexes with these eluents (e.g., diluted HF along with HNO_3 or HCl, diluted HCl, or diluted $H_2C_2O_4$ along with HNO_3 solution) on anion exchange chromatography without reducing Pu(IV) to Pu(III). Another is called reduction elution method based on the reduction of Pu(IV) to the non-adsorbable Pu(III), and retrieval of Pu(III) from the column. In our present work, 0.1 mol L^{-1} $NH_2OH{\cdot}HCl$ in certain concentration of HCl was used to elute Pu from anion exchange columns. To get the appropriate concentration of HCl, the concentration range of 0.1~1.0 mol L^{-1} was assessed. The experimental results (Fig.7) show that the decontamination factors of Th and Am were enhanced with the increase of HCl concentration. However, the decontamination factors of U and the chemical yields for Pu were worsened when the concentration of HCl is increased up to 1.0 mol L^{-1}. Accordingly, 0.1 mol L^{-1} $NH_2OH{\cdot}HCl$ in 0.5 mol L^{-1} HCl was selected for Pu elution.

Traditionally, a large amount of reagent (such as 50~100 mL) was used to elute Pu, which makes the analytical procedure time consuming. The analytical cost of samples is also enhanced because more chemical reagents were consumed. In this work, different volumes of eluents were investigated. The results (see Fig. 8) show that 5 mL of eluent is sufficient for Pu desorption from 2 mL column, and the recoveries of Pu are all above 95% for different kinds of anion exchange resins. Compared to AG 1-×2 and AG 1-×4 resins, the elution of Pu from AG 1-×8 is a little difficult, indicating that the sorption abilities of AG 1-×8 for Pu is stronger than others. The result is in good agreement with our experiment data mentioned above (results and discussion section 3.1).

3.4. Sample throughput

Based on the application of the vacuum box system, 5 L water samples can be processed with a 2mL of AG 1-×4 columns within 2 h for total on-column separation. Because the vacuum box used in the system consists of 24 ports and 24 small-size chromatographic columns can be used under the same conditions, 24 water samples can be analyzed at one time (one batch) and 3 batches samples can be successfully processed within one day. As a result, the sample throughput is significantly improved compared with the traditional method, wherein 1~2 days are usually needed for processing a batch of samples[35,36].

The reusability of anion exchange chromatographic column is also investigated (the results are not shown here). It is found that the 2mL of AG 1-×4 column can be reused more than 20 times under the premise of ensure the chemical yield of Pu (>85%) and the decontamination factors of Th, U and Am ($>10^3$).

3.5. Method validation and application

To assess the accuracy and applicability of the proposed analytical method for handling environmental samples with different levels of Pu, three water samples were analyzed. The analytical results of Pu (Table 1) for the samples agree well with the values obtained by the certified method of China G B11225-89, indicating that the proposed analytical method is reliable and can be used for Pu determination in environmental water samples.

With the vacuum box system, column separation can be carried out within 2.0 h and 24 samples were analyzed simultaneously. Compared with the traditional methods, the separation efficiency is improved evidently. The proposed method is therefore better suited for the rapid determination of Pu isotopes in environmental risk assessment and radiological emergencies. Besides the satisfactory recoveries of Pu, appropriate decontamination factors for interferences, and the low cost of analysis, the stability of vacuum box system is another advantage with which the operation can be continuous for a long time (up to 5 months had been confirmed) without any problem.

4. Conclusion

The present paper focused on the development of analytical method for rapid determination of Pu in environmental water samples with vacuum box system separation and LSC measurement. The parameters which affect the separation abilities of anion exchange resins were optimized. Based on our experimental results, the following conclusions can be drown: (i) considering the high recovery of Pu as well as efficient removal of interferences, 8 mol/L HCl was selected as the solution media during sample loading. For Pu elution, 0.1 mol L^{-1} $NH_2OH{\cdot}HCl$ in 0.5 mol L^{-1} HCl was used; (ii) with the application of one small sized chromatographic anion exchange column (AG 1-×4, 2.0 mL), the decontamination factors of $>10^3$ for U and $>10^4$ for Am and Th, and recovery of >90% for Pu was achieved for 5 L water samples, reaching a detection limit of 1.6×10^{-2} Bq L^{-1} in 60 min counting time by low background LSC; (iii) based on the application of vacuum box system and LSC measurement, the developed method remarkably reduced the analytical time, and a batch of samples (n=24) can be analyzed within one day; (iv) the analytical procedure is validated by analysis of the same water samples using a conventional method and can be used for the determination of Pu in routine analysis for daily monitoring and rapid analysis for emergency preparedness.

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Figure captures:

Fig. 1 Analytical procedure for the determination of Pu in environmental water samples;

Fig.2 Chemical yields of Pu (a) and the decontamination factors for U, Th and Am (b) obtained in anion exchange chromatographic columns with different volume;

Fig. 3 Chemical yields of Pu (a) and the decontamination factors for U, Th and Am (b) obtained in anion exchange chromatographic columns with volume of 1-2mL;

Fig. 4 Chemical yields of Pu (a) and the decontamination factors for U, Th and Am (b) obtained in small sized anion exchange chromatographic columns with different crosslinkage and particle size of resin;

Fig. 5 Effects of flow rate of column to chemical yields of Pu (a) and the decontamination factors for U, Th and Am (b) obtained in anion exchange chromatographic columns (2 mL resin);

Fig. 6 Effect of HCl concentration to chemical yields of Pu (a) and the decontamination factors for U, Th and Am (b) obtained in anion exchange chromatographic columns (2 mL resin) during sample loading;

Fig. 7 Chemical yields of Pu (a) and the decontamination factors for U, Th and Am (b) obtained in anion exchange chromatographic column (2 mL resin) with different concentration of HCl contained 0.1 mol L^{-1} $NH_2OH{\cdot}HCl$;

Fig. 8 Accounts of Pu in different stages of eluent obtained in different chromatographic columns (volume: 2 mL).

Fig.1

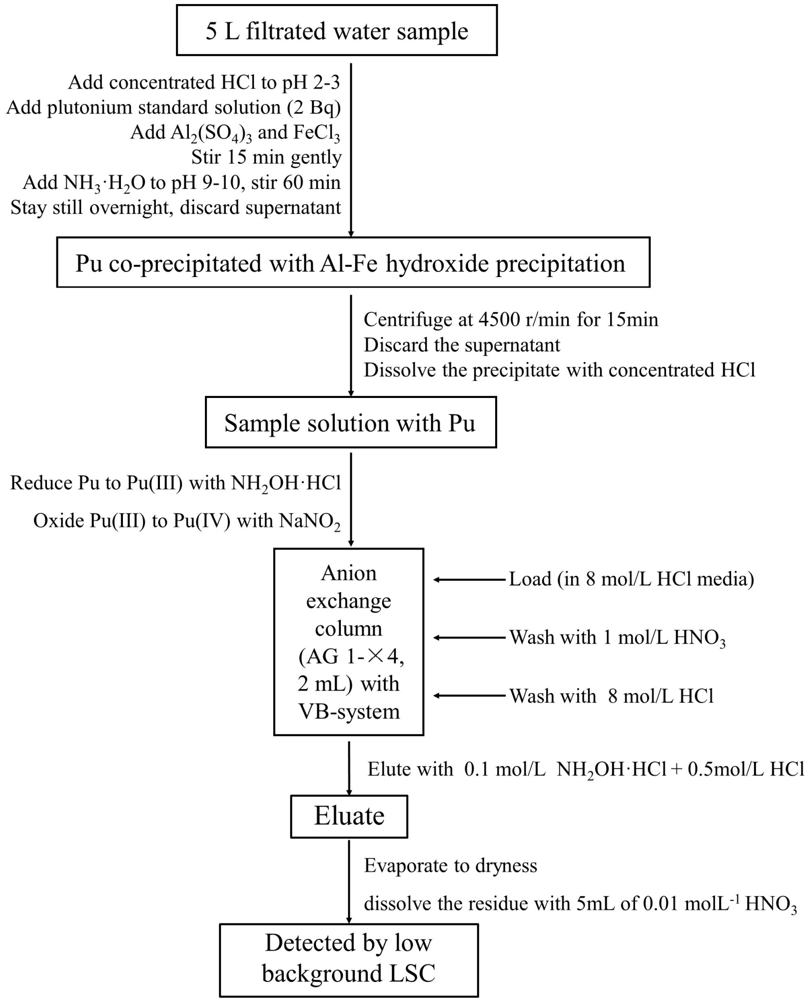
5 L filtrated water sample
Add concentrated HCl to pH 2-3
Add plutonium standard solution (2 Bq)
Add $Al_2(SO_4)_3$ and $FeCl_3$
Stir 15 min gently
Add $NH_3\cdot H_2O$ to pH 9-10, stir 60 min
Stay still overnight, discard supernatant
Pu co-precipitated with Al-Fe hydroxide precipitation
Centrifuge at 4500 r/min for 15min
Discard the supernatant
Dissolve the precipitate with concentrated HCl
Sample solution with Pu
Reduce Pu to Pu(III) with $NH_2OH\cdot HCl$
Oxide Pu(III) to Pu(IV) with $NaNO_2$
Anion exchange column (AG 1-×4, 2 mL) with VB-system
Load (in 8 mol/L HCl media)
Wash with 1 mol/L HNO_3
Wash with 8 mol/L HCl
Elute with 0.1 mol/L $NH_2OH\cdot HCl$ + 0.5mol/L HCl
Eluate
Evaporate to dryness
dissolve the residue with 5mL of 0.01 $molL^{-1}$ HNO_3
Detected by low background LSC

Fig.2

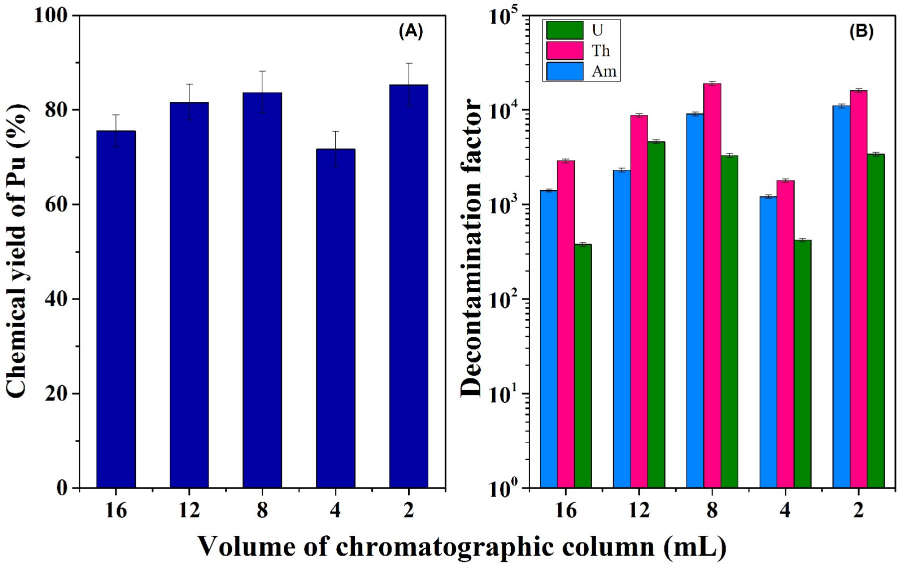
(A)
Chemical yield of Pu (%)
0
20
40
60
80
100
16
12
8
4
2
(B)
U
Th
Am
Decontamination factor
10^0
10^1
10^2
10^3
10^4
10^5
16
12
8
4
2
Volume of chromatographic column (mL)

Fig.3

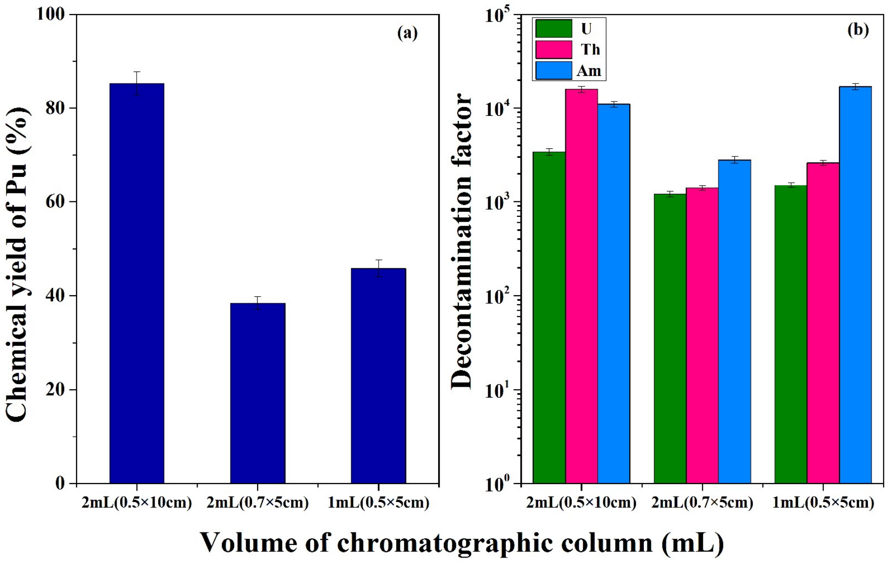
(a)
Chemical yield of Pu (%)
100
80
60
40
20
0
(b)
Decontamination factor
10^5
10^4
10^3
10^2
10^1
10^0
U
Th
Am
2mL(0.5×10cm)
2mL(0.7×5cm)
1mL(0.5×5cm)
Volume of chromatographic column (mL)

Fig.4

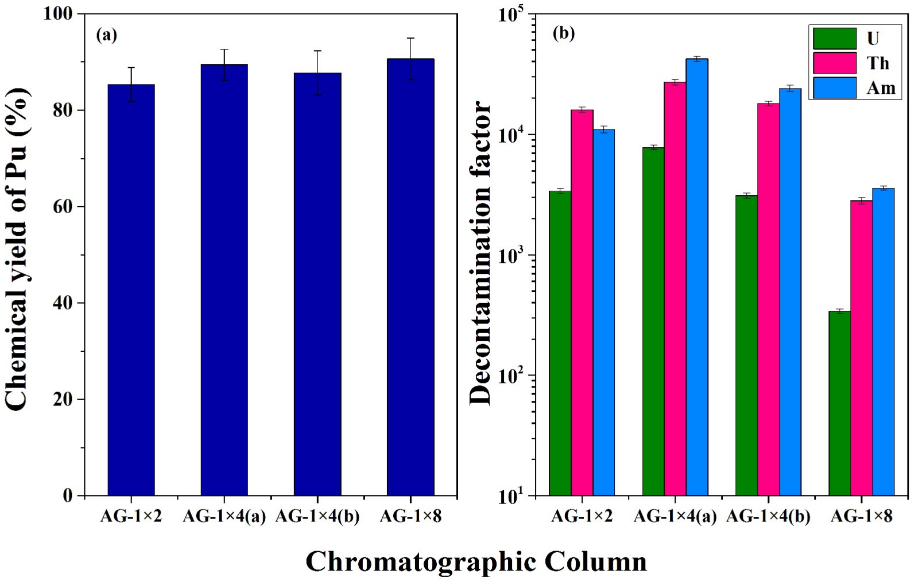
(a)
Chemical yield of Pu (%)
0
20
40
60
80
100
AG-1×2
AG-1×4(a)
AG-1×4(b)
AG-1×8
(b)
Decontamination factor
10^1
10^2
10^3
10^4
10^5
U
Th
Am
AG-1×2
AG-1×4(a)
AG-1×4(b)
AG-1×8
Chromatographic Column

Fig.5

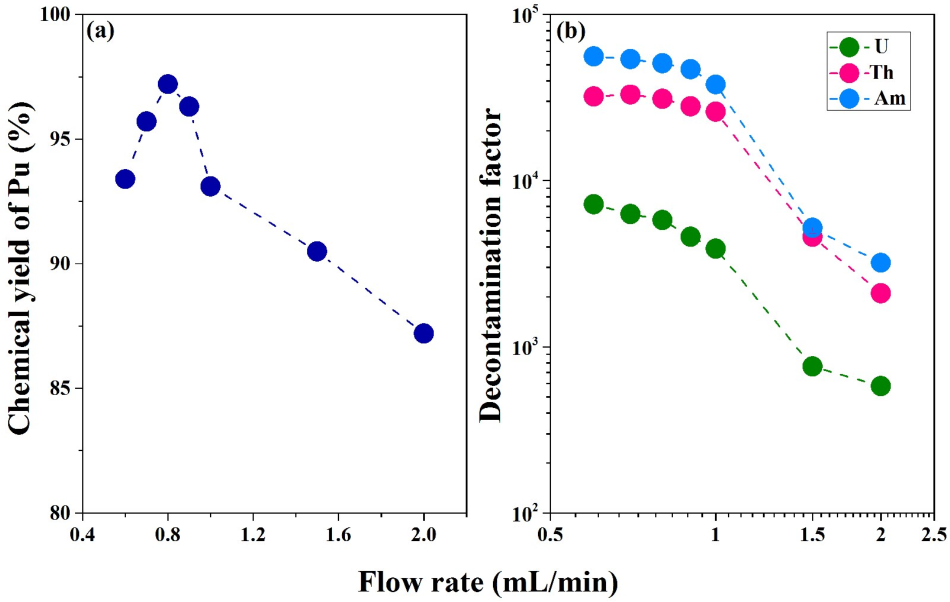
(a)
Chemical yield of Pu (%)
100
95
90
85
80
0.4
0.8
1.2
1.6
2.0
(b)
Decontamination factor
10^5
10^4
10^3
10^2
0.5
1
1.5
2
2.5
U
Th
Am
Flow rate (mL/min)

Fig.6

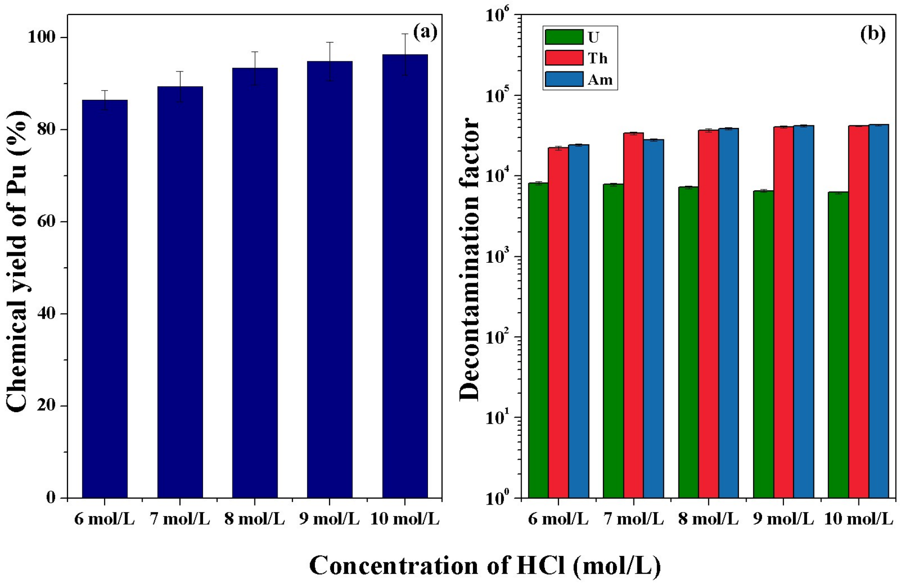
(a)
Chemical yield of Pu (%)
0
20
40
60
80
100
6 mol/L
7 mol/L
8 mol/L
9 mol/L
10 mol/L
(b)
Decontamination factor
10^0
10^1
10^2
10^3
10^4
10^5
10^6
U
Th
Am
Concentration of HCl (mol/L)

Fig.7

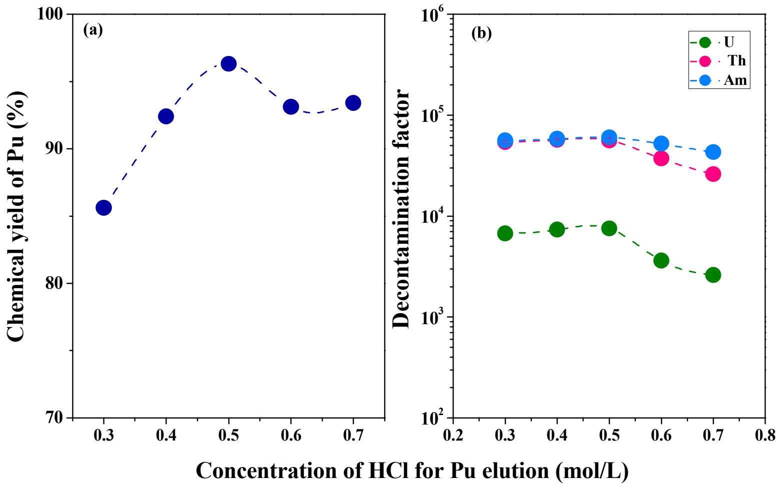
(a)
Chemical yield of Pu (%)
100
90
80
70
0.3
0.4
0.5
0.6
0.7
(b)
Decontamination factor
10^6
10^5
10^4
10^3
10^2
0.2
0.3
0.4
0.5
0.6
0.7
0.8
● U
● Th
● Am
Concentration of HCl for Pu elution (mol/L)

Fig.8

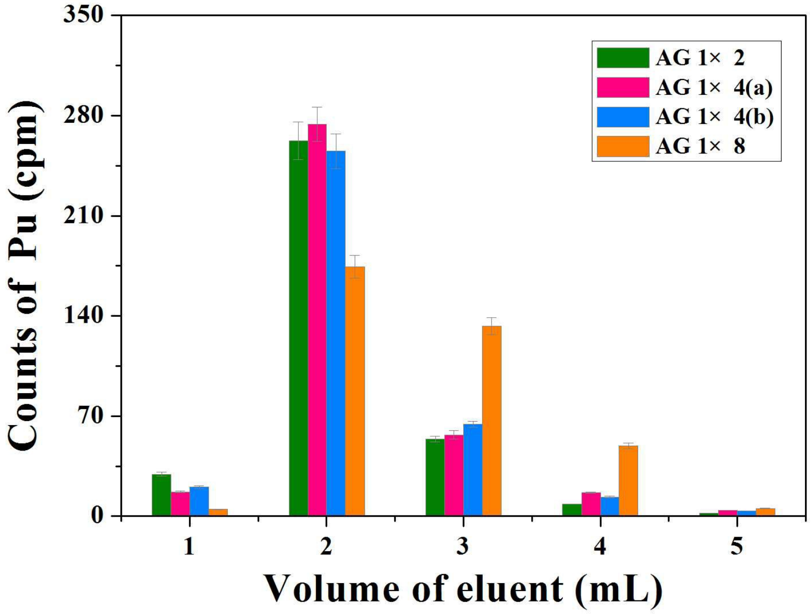
350
280
210
140
70
0
Counts of Pu (cpm)
AG 1× 2
AG 1× 4(a)
AG 1× 4(b)
AG 1× 8
1
2
3
4
5
Volume of eluent (mL)

Table 1, Analytical results of Pu in three water samples using the developed method and conventional method [a]

Samples	Chemical yield, %	Pu measured, Bq L^{-1}	Pu measured by conventional method[b], Bq L^{-1}
1	90.0± 4.6	0.09 ± 0.03	0.10 ± 0.03
3	92.5± 3.8	0.37 ± 0.04	0.40 ± 0.05
5	96.3± 4.2	1.54 ± 0.04	1.60 ± 0.04

a: values are the average of six replicates (±standard deviation) for water samples.

b: values were obtained using a conventional method of China G B11225-89.