Production and subsequent separation of ^{47}Sc of nuclear medicine applications using neutron-induced reactions on different natural targets

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Abstract

^{47}Sc can be produced from different three neutron induced nuclear reactions as $^{47}\text{Ti}(\text{n,p})^{47}\text{Sc}$, $^{50}\text{V}(\text{n},\alpha)^{47}\text{Sc}$ and $^{46}\text{Ca}(\text{n},\gamma)^{47}\text{Ca}$, $^{47}\text{Ca}(\beta^-)^{47}\text{Sc}$ using the Egyptian Second Research Reactor. The measured neutron cross-sections (σ) are 62.12 ± 1.93 , 4.51 ± 1.27 and 69.36 ± 2.01 mb from the natural targets of TiO_2 , V_2O_3 and CaO respectively. The carrier-free ^{47}Sc from $^{47}\text{Ti}(\text{n,p})$, was purified using a composite of Alginate–Carboxymethyl cellulose/di-2-ethylhexyl phosphoric acid. The radiochemical separation of ^{47}Sc with a recovery yield of $90 \pm 1.2\%$ was obtained. The eluted ^{47}Sc passed quality control tests (chemical, radionuclide, and radiochemical purities) and was found to be suitable for nuclear medicine applications.

Keywords Nuclear reactions · Gamma spectrometry · Radioisotopes production · Separation · Ion exchanger · Medical applications

Introduction

Due to increased patients who suffer from various cancer diseases, numerous radioisotopes which used in nuclear medicine applications (either in imaging or therapy) have been reported [1, 2]. Scandium is a rare element with a variety of medically useful radioisotopes that can be created in nuclear reactors or cyclotrons. The radioisotopes ^{43}Sc , ^{44}Sc , ^{46}Sc , ^{47}Sc , and ^{48}Sc are used in nuclear medicine for diagnosis and therapy [3, 4]. Due to its favorable emission characteristics, ^{47}Sc is one of the most appealing candidates for radiotheranostic applications, emitting both ideal diagnostic gamma-rays at 159.38 keV (68.4%) and therapeutic electrons ($E = 0.143$ (68%) and 0.204 MeV (32%)), as well as its short half-life ($T_{1/2} = 3.35$ day) [5–7]. The ^{47}Sc can be produced by

fast neutron irradiation ($E_n > 1$ MeV) of titanium target with high energy neutrons from $^{47}\text{Ti}(\text{n,p})^{47}\text{Sc}$ and $^{50}\text{V}(\text{n},\alpha)^{47}\text{Sc}$ nuclear reactions while $^{46}\text{Ca}(\text{n},\gamma)^{47}\text{Ca}$, $^{47}\text{Ca}(\beta^-)^{47}\text{Sc}$ reaction is induced by thermal neutrons ($E_n = 0.025$ eV) [8].

Scandium-47 ($T_{1/2} = 3.35$ days) undergoes beta decay, with β -mean energy of 162 keV to ^{47}Ti , followed by emission of a 159.38 keV gamma-ray (68.4%) [3]. Thus, ^{47}Sc could be used for targeted radionuclide therapy and single-photon emission computed tomography (SPECT). These radionuclides of Sc could be used to create theranostic agents for diagnostic imaging and targeted radiotherapy in the same patient. In today's research, the manufacturing of radioisotopes with appropriate half-lives (for the therapy and diagnosis of various cancers) is important.

For nuclear reactors, the neutron-induced nuclear reaction cross-section data is a key requirement. It depicts the probability of neutrons interacting with the nuclei of the materials through which they pass at various neutron energy. The excitation functions of rapid neutron-induced (n,p) and (n, γ) reactions are critical for nuclear reactor design, evaluation, and construction [9]. For neutron energies up to 20 MeV, the nuclear data available in the IAEA-EXFOR database reveals that significant experimental data is missing in several energy ranges, as well as notable differences between different measurements for numerous activation cross-sectional data [10]. TENDL is a nuclear data library

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that makes the output of the TALYS nuclear model code system available for use in both basic and applied physics. The theoretical predictions for all studied reaction cross sections were carried out using the TENDL-2019 nuclear data library, which is based on the simulation of nuclear reactions using a two-component exciton model (TENDL-2019) [11].

The high purity of radioisotopes is generally recognised to be in high demand and a requirement for possible medical applications. Solvent extraction, adsorption, ion exchange, precipitation, and extraction chromatography are some of the separation processes that can be used [12, 13]. The production and/or separation of Sc radioisotope from various irradiated target have been reported by Aly and El-Haggan [14], Das et al. [15], Lahiri et al. [16], Kolsky et al. [17], Chakravarty et al. [18], Müller et al. [19], Mousa et al. [20] and Gizawy et al. [21]. Among of various separation processes, ion exchange chromatography is easily operated, quick and it considered as one of the significant separation methods to get adequate purity of the desired product. In this regard, much effort has gone into the creation of a new generation of composite materials that could be useful in the separation of a variety of radioisotopes. Alginate and carboxymethyl cellulose was chosen because cheap, abundant, and biodegradable. Also because of its rich hydroxyl and carboxyl groups. Although alginate has many advantages, it has a solubility in water and needs to be solidified. In addition, the mechanical strength of alginate is not high, and it is necessary to improve its mechanical strength in practical application. So, chemical modification (by adding HDEPA) was used to introduce other functional groups to improve their adsorption performance and selectivity [22].

Thus, in this work, the natural TiO_2 , CaO and V_2O_3 powders were used as a target for producing ^{47}Sc by fast neutron at the Egyptian second research reactor (ETRR-2). The neutron cross sections of the produced isotopes were determined experimentally and obtained by TENDL-2019 [11] nuclear data library. The current study also aims to use a newly manufactured composite gel bead to sorb and separate ^{47}Sc for future application as a radiotheranostic isotope from an irradiated Ti target. Batch technique and column chromatography were used to investigate the novel composite's efficiency in separating carrier-free ^{47}Sc from gram quantities of titanium. Finally, for the purified ^{47}Sc , three quality control experiments were performed: radionuclidic, radiochemical, and chemical purity.

Materials and methods

All chemicals and reagents, unless otherwise specified, were of the purest grade. Titanium oxide (TiO_2), calcium oxide (CaO), vanadium oxide (V_2O_3), sodium alginate (SA) and carboxymethyl cellulose (CMC) were supplied from

Table 1 Nuclear decay results of the investigated reactions [24]

Sample	Contributed reactions	Half-life	E_γ (keV)	I_γ (%)
TiO_2	$^{47}\text{Ti}(\text{n,p})^{47}\text{Sc}$	3.35 day	159.38	68.4
V_2O_3	$^{50}\text{V}(\text{n},\alpha)^{47}\text{Sc}$			
CaO	$^{46}\text{Ca}(\text{n},\gamma)^{47}\text{Ca}$ $^{47}\text{Ca}(\beta^-)^{47}\text{Sc}$			
Zr-foil (Monitor)	$^{94}\text{Zr}(\text{n},\gamma)^{95}\text{Zr}$	64.02 day	724.19	44.17
	$^{90}\text{Zr}(\text{n,p})^{89}\text{Zr}$	78.41 h	756.72 909.1	54 99.4

Table 2 Nuclear decay data of the contributed reactions [23]

Sample	Isotope	Contributed reactions	Half-life	E_γ (keV)	I_γ (%)
TiO_2	^{46}Ti	$^{46}\text{Ti}(\text{n,p})^{46}\text{Sc}$	83.79 d	889.27	99.98
				1120.54	99.98
	^{48}Ti	$^{48}\text{Ti}(\text{n,p})^{48}\text{Sc}$	43.67 h	983.51	100
				1037.59	97.6
V_2O_3	^{50}Ti	$^{50}\text{Ti}(\text{n},\alpha)^{47}\text{Ca}$	4.536 d	1312.09	100
				489.23	6.2
	^{51}V	$^{51}\text{V}(\text{n},\alpha)^{48}\text{Sc}$	43.67 h	807.86	6.2
				1297.09	71
CaO	^{46}Ca	$^{46}\text{Ca}(\text{n},\gamma)^{47}\text{Ca}$	4.536 d	983.51	100
				1037.59	97.6
				1312.09	100
CaO	^{46}Ca	$^{46}\text{Ca}(\text{n},\gamma)^{47}\text{Ca}$	4.536 d	489.23	6.2
				807.86	6.2
				1297.09	71

Sigma-Aldrich, Germany. Di-2-ethylhexyl phosphoric acid (DEHPA) was purchased from Merck-Shuchardt, Germany.

Samples irradiation and γ -ray measurements

The irradiation of the powder samples of TiO_2 , CaO , V_2O_3 in high purity (99.9%) and Zr foil monitor were performed by fast neutron flux using the ETRR-2 for 24 h.

The NUDAT-2.8 database provided the decay data for the analysis of ^{47}Sc and Zr isotopes [23], from different neutron induced nuclear reaction are tabulated in Table 1 and the other contributed reactions such as ^{46}Sc , ^{48}Sc and ^{47}Ca isotopes are listed in Table 2.

The γ spectra of the irradiated samples were analyzed using an HPGe detector model Canberra GC-6020 based spectrometer after around 5 days of cooling time. A multi-channel analyzer (MCA) and the software package Gamma vision (Version 5.1, EG&G ORTEC) were used to acquire the data. At the 1332.5 keV gamma line of ^{60}Co , the detector has a relative efficiency of roughly 60% and an energy resolution of 2.2 keV. To reduce pile-up and coincidence effects,

Fig. 1 Gamma-ray spectrum after irradiation and 5-day cooling for **a** ^{nat}TiO target, **b** ^{nat}CaO target **c** $^{nat}\text{V}_2\text{O}_3$ target and **d** ^{nat}Zr -foil monitor

the spectra were determined repeatedly in a cylindrical lead shield at a sufficient distance from the detector. For energy and efficiency calibration of the used gamma-ray spectrometer, standard point gamma-ray sources $^{152,154,155}\text{Eu}$, ^{137}Cs , and ^{60}Co with known gamma-ray energy lines were used.

Cross-sections of monitors were acquired from the literature [24]. From a typical gamma rays' spectrum of the activated samples and monitor, as shown in Fig. 1, it is recognized that there is no interference in the gamma activity measurements for the ^{47}Sc radioisotope production.

Cross-section calculations

The reaction cross sections were calculated using the well-known activation formula as input parameters and the measured activity, flux, and number of target atoms per cm^2 . The uncertainties associated with the measured cross sections include (i) counting statistics of 2–9%, (ii) detector efficiency of 3%, (iii) neutron flux fluctuations of 2%, (iv) monitor cross sections of 2%, (v) decay data of 2%, and dead time of 1.5%. The square root of the total in quadrature of all individual contributions for each of the formula's factors was used to calculate the uncertainty on the cross-section. The experimental neutron cross-section σ_x for the nuclear reaction is calculated relative to that of the natural Zr monitor $^{94}\text{Zr}(n,\gamma)^{95}\text{Zr}$ and $^{90}\text{Zr}(n,p)^{89}\text{Zr}$ neutron induced reactions from this Eq. (1) as follows [25]:

$$\sigma_x = \sigma_m \frac{N_{p(x)} \epsilon_m I_x \lambda_x N_m (1 - e^{-\lambda_m t_i}) e^{-\lambda_m t_d} (1 - e^{-\lambda_m t_c})}{N_{p(m)} \epsilon_x I_x \lambda_m N_x (1 - e^{-\lambda_x t_i}) e^{-\lambda_x t_d} (1 - e^{-\lambda_x t_c})}, \quad (1)$$

where $N_{p(x)}$, $N_{p(m)}$ are the net peak area under the γ -ray peak of interest, ϵ is the detector efficiency, I is the intensity of the γ -ray, $N_{x,m}$ is the number of target or monitor nuclei, $(1 - e^{-\lambda t_i})$ is the saturation factor, λ is the decay constant, t_i is the irradiation time, $(e^{-\lambda t_d})$ is the decay factor where t_d is the cooling time, and $(1 - e^{-\lambda t_c})$ is a term used for correcting the decay during the counting period where t_c is the measuring time. The subscripts x and m represent the target and monitor reactions, respectively.

Activity production calculations

The number of target nuclei, N_x is unknown while irradiation, cooling and measuring times, flux, amount of material, efficiency, correction factors, and the neutron cross section are known. This is achieved by applying the conventional activation equation [26].

The mass of the 'element' in the sample is obtained by the formula:

$$m_x = \frac{N_x M_x}{a N_a}, \quad (2)$$

where N_a is the Avogadro's number, M_x is the atomic mass of the target nucleus, a is the isotope fraction of the target nuclei in the 'element', and m_x is the mass of the sample measured in grams. There are three different routes available for the reactor production of ^{47}Sc , from fast neutrons induced the nuclear reactions $^{47}\text{Ti}(n,p)^{47}\text{Sc}$ and $^{50}\text{V}(n,\alpha)^{47}\text{Sc}$ while $^{46}\text{Ca}(n,\gamma)^{47}\text{Ca}$, $^{47}\text{Ca}(\beta^-)^{47}\text{Sc}$ reaction is induced by thermal neutrons.

The basic equation used to calculate the activity (A) in Bq/Kg of a radioisotope produced by exposure of a target in a reactor is

$$A = N\sigma\phi(1 - e^{-\lambda t_i})e^{-\lambda t_d}, \quad (3)$$

where N is the number of the atoms of the target isotope. Equation 4 can be used to calculate the ^{47}Sc activity from TiO_2 and V_2O_3 targets, while ^{47}Sc activity from CaO target was calculated from Eq. 5 [27]:

$$A^{\text{Sc-47}} = N^{\text{Ca-47}} \sigma_{\text{Ca-46}} \phi \left[(1 - e^{-\lambda_{\text{Sc-47}} t_i}) - \frac{\lambda_{\text{Sc-47}} (e^{-\lambda_{\text{Sc-47}} t_d} - e^{-\lambda_{\text{Ca-47}} t_d})}{(\lambda_{\text{Sc-47}} - \lambda_{\text{Ca-47}})} \right], \quad (4)$$

Chemical separation processing on natural titanium oxide target

Among of the three irradiated targets, the irradiated $^{\text{nat}}\text{Ti}$ target was selected for purification and separation study of carrier-free Sc radioisotopes. With mild heating, the irradiation target was dissolved in 5 mL Conc. HF acid. The resulting solution was almost totally disappeared, and the residue was re-dissolved in deionized water (10 mL).

Preparation of the SA-CMC/DEHPA composite

2.5 gm of SA has dissolved in 100 mL of distilled water under constant stirring at 25 °C. 2.5 gm of CMC was then added into the SA solution under constant stirring to generate a homogeneous dispersion. 5% (W/W) DEHPA was added under magnetic stirring, and the mixed solution was placed into 100 mL of 2% CaCl_2 solution using a 10 mL syringe, and the solution was sealed in the shade to solidify (24 h) [22]. The coagulated beads were then rinsed with distilled water multiple times before being dried at 60 °C.

Batch studies

The batch-wise technique was used to evaluate the sorption studies of Sc(III) and Ti(IV) ions on the produced composite. In a Plate thermo shaker at room temperature with an

agitation speed of 120 rpm, 0.03 g of the composite was mixed with 3 mL solutions of various pH values (from 2 to 5) to conduct the experiment. All of the glass bottles were centrifuged after 24 h of shaking, and the supernatant was tested for residual Sc(III) and Ti(IV) using an HPGe detector and ICP-OES method. The following equation was used to compute the adsorption efficiency percent for Sc(III) and Ti(IV) ions:

$$\text{Adsorption efficiency (\%)} = \left(\frac{C_o - C_e}{C_o} \right) \times 100, \quad (5)$$

While (C_o) and (C_e) are the initial and equilibrium concentrations (mg/L) of the metal ions [Sc(III) or Ti(IV)] respectively. The K_d values (mL/g) of the studied radionuclides is calculated using equations:

$$K_d (\text{mL/g}) = \left(\frac{C_o - C_e}{C_e} \right) \times \frac{V}{m}, \quad (6)$$

where V is the volume (mL) of the sample solution and m is the mass (g) of the prepared sorbent.

Chromatographic column separation of ^{47}Sc

A glass chromatographic column (5 cm (L) × 0.4 cm (i.d.) filled with 0.125 g of Alginate-CMC-/DEHPA composite gel beads was used to investigate the dynamic separation of ^{47}Sc (III). After conditioning the column with a suitable solution, the resulting solution from the dissolving process was placed on the column at a flow rate of 301.4 $\mu\text{L}/\text{min}$, and appropriate fraction sizes of the resulting solution were collected and radiometrically evaluated. The Sc(III) was separated and identified at a flow rate of 301.4 $\mu\text{L}/\text{min}$ with a 0.25 M ammonium acetate solution, and the outflow was recovered and measured.

Quality control measurements of the eluted ^{47}Sc

To guarantee the validity of the eluted ^{47}Sc for nuclear medicine applications, it was put through a series of tests. To evaluate the contribution of any foreign radionuclides associated with ^{47}Sc , the radionuclidic purity was investigated using the gamma spectrometric method. Instant Thin Layer Chromatography (ITLC) was used to determine the radiochemical purity using two developing systems: 10 mM DTPA pH 5 aqueous solution and 10% $\text{CH}_3\text{COONH}_3:\text{CH}_3\text{OH}$ (1:1)

Table 3 The radioisotope ^{47}Sc cross section, mass and activity

Target	^{47}Sc cross section, mb	^{47}Sc mass, gm	^{47}Sc Activity, MBq/g
TiO_2	62.12 ± 1.93	0.0918	$1.812\text{E}+04$
V_2O_3	4.51 ± 1.27	0.0124	$1.414\text{E}+05$
CaO	69.36 ± 2.01	0.1768	$4.906\text{E}+03$

Table 4 Contributed reactions cross section

Target nuclide	Produced radionuclide	Cross section, mb
^{46}Ti	^{46}Sc	1.80 ± 0.09
^{48}Ti	^{48}Sc	2.37 ± 0.11
^{51}V	^{48}Sc	0.18 ± 0.01
^{46}Ca	^{47}Ca	14.30 ± 0.86

[28]. The purity degree for chemical properties was examined using the ICP-AES technique to measure the existence of additional chemical contaminants, particularly Ti ions coupled with the decayed Sc fractions following their separation.

Results and discussion

The samples TiO_2 , V_2O_3 and CaO and Zr monitors were activated with fast neutron energies in the Egyptian second research reactor (ETRR-2). The TiO_2 , CaO , V_2O_3 target and Zr-monitor gamma-ray spectra after 24-h irradiation and 5-day cooling is illustrated in Fig. 1. The radionuclides ^{46}Sc , ^{47}Sc , ^{48}Sc , ^{49}Sc and, ^{50}Sc can be produced by natural titanium irradiation under fast neutron flux, based on the (n, p) nuclear reaction. According to Tables 3 and 4, the production reaction cross-section of ^{47}Sc is higher than other Sc radioisotopes. Therefore, the production of this radionuclide has higher possibility compared with the others. The ^{49}Sc ($T_{1/2} = 57.3$ min) and, ^{50}Sc ($T_{1/2} = 1.71$ min) radionuclides disappear a few hours after irradiation because of their short half-life and only ^{46}Sc ($T_{1/2} = 83.8$ day) ^{47}Sc ($T_{1/2} = 3.38$ day) and ^{48}Sc ($T_{1/2} = 43.7$ h) radionuclides remain.

The neutron flux has been monitored throughout the experiment, and the activity measured from the radioactive decay of ^{95}Zr and ^{89}Zr produced by the neutron induced nuclear reactions using the natural Zr-foil monitor. The flux of the neutron has been measured to be 2.99×10^{13} n/cm² s and 2.36×10^{13} n/cm² s for the nuclear reactions $^{94}\text{Zr}(n, \gamma)^{95}\text{Zr}$ and $^{90}\text{Zr}(n, p)^{89}\text{Zr}$ respectively.

The present results of the experimental neutron cross section of ^{47}Sc are 62.12 ± 1.93 , 4.51 ± 1.27 and 69.36 ± 2.01 mbarn from the reactions $^{47}\text{Ti}(n, p)^{47}\text{Sc}$, $^{50}\text{V}(n, \alpha)^{47}\text{Sc}$ and $^{46}\text{Ca}(n, \gamma)^{47}\text{Ca} (\beta^-)^{47}\text{Sc}$ respectively. The mass of

Fig. 2 ^{47}Sc activities (MBq/g) generated from the irradiation of ^{nat}Ti , ^{nat}V and ^{nat}Ca targets (irradiation time 24 h, decay time 20 days) **Fig. 3** Excitation function for a $^{nat}\text{Ti}(n, p)^{48,47}\text{Sc}$ and $^{nat}\text{V}(n, \alpha)^{48,47}\text{Sc}$ nuclear reactions calculated by TENDL-2019 [11]

radioisotope ^{47}Sc in the sample in grams and its activity were measured as shown in Table 3.

Figure 2 presents the comparison of ^{47}Sc activities (MBq/g) obtained from different natural targets Ti, V and Ca after cooling time varies from the end of irradiation to 20 days cooling time. It is clear from the Fig. 2 that the generated ^{47}Sc activity decreases gradually during the decay period for all the targets and the ^{47}Sc activity obtained from

V target has relatively high values compared to its activities generated from Ti and Ca targets. The studied excitation functions are obtained by using TENDL-2019 library as shown in Fig. 3.

Due to some difficulties in constructing fast neutron reaction experiments, insufficient cross section data for (n,p), (n, α) or (n, γ) reactions are available in the literature. Most of the existing literature data were found for incident neutron energy of about 14 MeV [29–31]. Some formulations for empirical formulae for fast neutron induced reactions were constructed and used to predict the excitation functions for neutron reactions on different existing stable isotopes. The resulted excitation functions are compared with some available experimental data as well as TENDL-2019 data base [32–35].

Figure 3a show the excitation functions for $^{nat}\text{Ti}(n,p)^{48,47}\text{Sc}$ obtained from TENDL-2019 library and compared with the empirical formula [32]. Figure 3b show the excitation functions for $^{nat}\text{V}(n,\alpha)^{48,47}\text{Sc}$ obtained from TENDL-2019 library and compared with some literature data [33–35].

Sorption and purification of ^{47}Sc

In this section, a new radiochemical study for potential separation and purification of carrier free ^{47}Sc is aimed. The irradiated natural Ti target was selected to implement the production and separation of ^{47}Sc for nuclear medicine application. The batch mode was used to investigate the separation percentage (%) for ^{47}Sc on the Alginate–CMC-/DEHPA composite in order to determine the optimal media for a successful separation task.

Effect of the pH on ^{47}Sc adsorption

The batch mode was used to investigate the separation percentage (%) for ^{47}Sc on the Alginate–CMC/DEHPA composite in order to determine the optimal media for separation. The pH factor is considered to be crucial in the adsorption process. It was discovered that increasing the pH from 2 to 5 increases the separation percentage value. Because the Ti is precipitated in mother solution, this study is only for ^{47}Sc . The composite beads' adsorption efficiency % towards Sc(III) ions was calculated, and the findings are given in Table 5. It shows the maximum % S achieved by ^{47}Sc at pH 5. The results showed that ^{47}Sc sorption was higher at lower pH, implying that the synthesized composite material might be used to selectively separate ^{47}Sc from irradiation Titanium targets in a wide range of applications. A batch experiment was used to investigate the selective separation of scandium ions at various pH levels ranging from 2 to 5.

Fig. 4 Elution curve for $^{47}\text{Sc}(\text{III})$ from 0.125 g Alginate–CMC-/DEHPA composite column (0.4 cm *i.d.*) at a flow rate of 301.4 $\mu\text{L}/\text{min}$

Chromatographic separation of ^{47}Sc

In general, the recovery performance of a ^{47}Sc via a chromatographic column is influenced by a number of parameters, including the eluent flow rate, column internal diameter, and the amount of adsorbent stationary phase. These factors must be considered in order to achieve greater separation of the radionuclide in a highly purified yield acceptable for nuclear medical applications.

A small chromatographic column made of Alginate–CMC-/DEHPA composite was used to separate ^{47}Sc from irradiated Ti target based on the results of batch studies, which revealed the optimal parameters for separation of Sc(III) from Ti(IV) matrix. The solution of pH 2 (as optimum pH for Sc separation) was used to prepare the column in the proper conditions, then loaded with the soluble irradiated Ti target after setting the pH to the best condition, allowing Ti ions to pass through the column without sorption, while ^{47}Sc ions were totally sorbed onto composite.

The loading efficiency of ^{47}Sc was extremely high due to the large number of functional groups in the Alginate–CMC/DEHPA composite. As illustrated in Fig. 4, the bound $^{47}\text{Sc}(\text{III})$ ions were recovered using 20 mL of 0.25 M ammonium acetate.

Table 5 Effect of pH on Sc(III) and Ti(IV) adsorption using Alginate–CMC-/DEHPA composite adsorbent

pH	Adsorption %	
	Ti(IV)	Sc(III)
2	15	73.6
3	ND*	58.5
4	ND	62.9
5	ND	81.12

*ND not detected

The current study's results showed that ^{47}Sc recovery was outstanding, with an elution yield of $90 \pm 1.2\%$, which was better than many other compounds examined for this objective, *e.g.* the AG MP-50 cation exchange (Sc recovery = 50–80%) [17], Dowex 50 X8 (Sc recovery > 76%) [36]. As well as in our previous studied an two radiochemical separation were also reported using composite of poly(acrylic acid-Acrylonitrile)-nanoparticles of CuO (Sc recovery was 78%) [20] and AN-PAR (anionic exchanger resin; AN-31 impregnated with 4-(2-Pyridylazo) resorcinol (PAR) (Sc recovery was 89%) [21]. Furthermore, the separation procedure used in this study is much faster than the prior methods at producing Sc radionuclides with a high specific yield. Furthermore, the separation procedure used in this study is much faster than the prior methods at producing Sc radionuclides with a high specific yield.

Quality control tests of the eluted ^{47}Sc

Radionuclidic purity

The radiometric examination was carried out to see if the final eluted ^{47}Sc product contained any possible radionuclides. The results revealed that no foreign radionuclides are connected with ^{47}Sc , with the exception of ^{46}Sc and ^{48}Sc radionuclides, which can only be reduced to acceptable ratios by irradiating an enhanced $^{46}\text{TiO}_2$ target.

Radiochemical purity

As described in the experimental section, two distinct solvents were utilized to test the radiochemical purity of the eluted ^{47}Sc . Just one peak emerged at $R_f = 0.7$, which referring to ^{47}Sc -DTPA for the 10 mM DTPA system, and another peak emerged at $R_f = 0.1$, which referring to $^{47}\text{Sc}^{3+}$ for the $\text{CH}_3\text{COONH}_3:\text{CH}_3\text{OH}$ mixture, indicating that the eluted ^{47}Sc was radiochemically pure.

Chemical purity

Any radiopharmaceutical must be devoid of metallic impurities that compete with the radioisotope for conjugation with the pharmaceutical moiety, reducing labelling efficiency [37]. Using the ICP-OES technique, the existence of any metal ion contaminants in the decaying ^{47}Sc solution was evaluated, and titanium ions were found to be negligible at less than 0.05 ppm.

Conclusion

The radioisotope ^{47}Sc can be produced from different three neutron induced nuclear reactions as $^{47}\text{Ti}(n,p)^{47}\text{Sc}$, $^{50}\text{V}(n,\alpha)^{47}\text{Sc}$ and $^{46}\text{Ca}(n,\gamma)^{47}\text{Ca}$, $^{47}\text{Ca}(\beta)^{47}\text{Sc}$. The neutron cross-section of the nuclear reaction has been measured experimentally relative to the reference reaction by the activation method at ETRR-2. The neutron cross-section results are calculated using the TENDL-2019 nuclear data libraries. The SA-CMC/DEHPA (alginate-carboxymethyl cellulose/DEHPA) composite was effectively produced and used to purify and separate carrier-free ^{47}Sc as a radiotheranostic suitable for nuclear medicine applications. Using the batch approach, the SA-CMC/DEHPA composite demonstrated effectiveness of selective separation % towards Sc^{3+} rather than Ti^{4+} ions at various pH levels, which was confirmed by column chromatography, which provided excellent elution efficiency for ^{47}Sc . The eluted ^{47}Sc exhibited high radionuclidic, radiochemical, and chemical purities, indicating that it might be used safely for cancer theranostics.

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Declarations

Conflict of interest The authors declare no conflicts of interest regarding this article.

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