Investigation on the production and isolation of ^{149,150,151}Tb from ^{12}C irradiated natural praseodymium target

By M. Maiti[1], S. Lahiri[1,*] and B. S. Tomar[2]

[1] Chemical Sciences Division, Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata 700064, India
[2] Radiochemistry Division, Bhabha Atomic Research Centre, Mumbai 400085, India

Summary. Short lived α-emitting radionuclides have enormous potential to be used in the targeted therapy. ^{149}Tb (4.118 h) is among the few α-emitting radionuclides which are projected for human clinical use. Therefore, direct production of ^{149}Tb was aimed from the ^{12}C induced reaction on natural praseodymium target of 15 mg/cm^2 thickness at 71.5 MeV incident beam energy. No-carrier-added (nca) ^{149,150,151}Tb radionuclides were produced in the target matrix along with ^{149}Gd, which is also the decay product of ^{149}Tb, with relatively high yield of ^{149}Tb. An efficient radiochemical separation method was developed to separate nca $^{149-151}$Tb from bulk praseodymium and coproduced Gd by liquid–liquid extraction (LLX) using aqueous HCl and liquid cation extracting agent di-(2-ethylhexyl)phosphoric acid (HDEHP) dissolved in cyclohexane. Quantitative extraction of nca $^{149-151}$Tb was achieved from bulk target with a high separation factor of 4.7×10^5.

1. Introduction

In the last few decades a group of radio-lanthanides have been proposed both for diagnostic and therapeutic purposes [1, 2]. Diverse decay characteristics of the radio-lanthanides made them appealing for potential applications. The therapeutic radio-lanthanides under consideration may be categorized into three groups: (i) β-particle emitting radionuclides (ii) α-particle emitting radionuclides and (iii) low energy electron emitters, that is, internal conversion or Auger electrons. The β-particle emitting radionuclides deposit energy over a long range, which is ~ 5–150 or more cell dimensions. As a result, the long range electrons can kill the cancerous cells at a relatively long distance, but will deliver high radiation dose to healthy tissues as well. Therefore, small tumors are better treated by electrons of lower energies, such as conversion and Auger electrons which deposit energy in sub-cellular dimensions [1].

The α-particles carry higher energies than β-particles, generally in the range of 4–9 MeV and their range in tissue is only a few cell dimensions. Unlike the low LET (linear

energy transfer) β-particles, α-particles are cytotoxic in hypoxic regions within a tumor. Therefore, use of short-lived α-emitting radionuclides is advantageous in the targeted radioimmuno therapy, especially when localization of dose in the affected cells becomes important. Owing to its moderate half-life and suitable α-particle energy (3.97 MeV), ^{149}Tb is among the few promising α-emitting radionuclides, which are presently projected for human clinical use. Moreover, the trivalent metallic radionuclide, ^{149}Tb offers stable labelling in conjugation with chelating ligands, macromolecules or peptides [3–5].

Clinical application of ^{149}Tb necessitates investigation on the suitable production route as well as the purification method. The possible production routes include the following nuclear reactions:

1. Light charged particle induced reactions:
   ^{152}Gd(p, $4n$)^{149}Tb (direct production);
   ^{152}Gd(α, $7n$)^{149}Dy(EC)^{149}Tb,
   ^{152}Gd(^{3}He, $6n$)^{149}Dy(EC)^{149}Tb (indirect production);
2. Proton induced spallation reaction on heavy targets;
3. Heavy ion induced reactions:
   ^{141}Pr(^{12}C, $4n$)^{149}Tb (direct production);
   ^{144}Sm(^{9}Be, $4n$)^{149}Dy(EC)^{149}Tb or
   $^{142/143}$Nd(^{12}C, $5n/6n$)^{149}Dy(EC)^{149}Tb (indirect production).

Production of ^{149}Tb is difficult by light ion induced reactions as the required 100 MeV α-particle or 50 MeV proton is not available at the common accelerators. Moreover, difficulty lies in the direct production of ^{149}Tb. Compound nuclei of Tb with high spin preferentially decay to the high spin $(11/2^-)$ state ^{149m}Tb (4.16 min), which does not decay to the ground state ^{149}Tb. Only low spin compound nuclei of Tb decay to ^{149}Tb $(1/2^+)$. Thus, ^{149m}Tb exhibits strong shielding towards the production of ^{149}Tb from the high spin compound nuclei. However, ^{149}Tb can be produced in direct reaction or as a decay product of ^{149}Dy (4.2 min).

Alexander and Simonoff [6] studied twelve heavy ion induced reactions, including both direct and indirect reactions to produce ^{149}Tb and measured their excitation functions. The indirect production using Nd target offered about ten times higher production cross section for ^{149}Tb. Later, Kossakowski *et al.* [7] measured cross sections of the individual evaporation residues in ^{12}C and ^{14}N induced reactions on

* Author for correspondence (E-mail: susanta.lahiri@saha.ac.in).

^{141}Pr and ^{144,147,150,152,154}Sm targets in the 5–10 MeV/A energy range.

Allen *et al.* [8] produced nca ^{152}Tb (17.5 h), which has already been established as PET (positron emission tomography) radionuclide, by both heavy ion reactions using 14 UD tandem accelerator at the Australian National University (ANU) and proton induced spallation method at the CERN proton accelerator and online mass separator at the ISOLDE. The nca ^{152}Tb was produced from the decay of its precursor ^{152}Dy (2.4 h), which was produced by ^{12}C induced reactions on natural Nd foil target in the incident energy range 80–110 MeV. In another case, a Ta foil target was bombarded by 1 GeV protons to produce lanthanides by the spallation reaction. The products were separated at the ISOLDE according to mass-to-charge ratio. The products of $A = 152$ were collected on high purity Al catcher. Beyer *et al.* [9] produced nca ^{149}Tb as the decay product of ^{149}Dy by irradiating natural Nd$_2$O$_3$ target by 108 MeV ^{12}C ions of 1 particle μA current for 75 min at the heavy ion cyclotron in the JINR, Dubna and achieved 2.7 MBq at the end of bombardment (EOB). They also produced ^{149}Tb *via* proton ($E_p = 1.4$ GeV, beam current $= 1$–2 μA) induced spallation reaction on the Ta foil target with yield of 500 MBq using the ISOLDE facility at CERN. The mass 149 separated by on-line mass separator was collected on a thin layer of KNO$_3$, which contains nca ^{149}Tb radionuclides, along with other isobars, ^{133}Ce^{16}O$^+$, ^{133}La^{16}O$^+$ and decay products of ^{149}Tb, ^{149}Gd and ^{145}Eu.

Chemical separation of nca Tb radionuclides has mostly been attempted by liquid–liquid extraction (LLX) and column chromatography. In 1999, Lahiri *et al.* produced nca $^{150-153}$Dy and the daughter products $^{150-153}$Tb using the ^{12}C and ^{16}O induced reactions on natural Nd$_2$O$_3$ and CeO$_2$ targets respectively at 80 MeV incident energy. The nca Dy and Tb radionuclides were separated from the natural Nd target matrix by LLX using liquid cation exchanger di-(2-ethylhexyl)phosphoric acid (HDEHP) dissolved in cyclohexane as organic phase and HCl as aqueous phase [10, 11]. The group also reported the production of nca ^{151,152}Tb radionuclides by ^{16}O induced reaction on lanthanum oxide at ~ 78 MeV incident energy. The nca Tb was separated from the bulk target using HDEHP with a radiochemical yield of $\sim 75\%$ [12].

The nca ^{152}Tb produced in the metal Nd target matrix was separated by Allen *et al.* [8] using cation exchange method. The Nd target was dissolved in 6 M HNO$_3$. The solution was evaporated to dryness and the residue was redissolved in 0.16 M α-hydroxyisobutyric acid (α-HIBA). This active solution was then passed through a cation exchange column (AMINEX A5). Tb was eluted with α-HIBA at pH 5. The collected Tb fractions were dried up gently and heated to ~ 450 °C to destroy the Tb-isobutyrate complex. The residue was then dissolved in HNO$_3$/HCl. The chemical yield achieved in this separation was 76%. The group also reported the separation of ^{152}Tb produced in the proton spallation reaction collecting mass 152 on Al foil. The Al foil was dissolved in HCl and ~ 2 mg of La^{3+} carrier was added to it. Lanthanide hydroxide was precipitated by addition of 50% NaOH. The precipitate was dissolved in diluted HCl. The AMINEX A5 resin after the adsorption of active lanthanides was transformed to NH$_4$$^+$- form by NH$_4$Cl

solution and the radionuclides were eluted by α-HIBA of pH 5 through the column with a gradient concentration. The γ- spectrometry of the fractions demonstrates the presence of minute impurity from ^{136}CeO and ^{136}PrO ($< 0.2\%$) with ^{152}Tb. The chemical yield was $\sim 80\%$ in this case [8].

Beyer *et al.* [9] separated nca ^{149}Tb from the other isobars and its decay products using cation exchange chromatography similar to that reported by Allen *et al.* [8], dissolving the layer of KNO$_3$ containing the ^{149}Tb activity in 0.1 M HCl. The radionuclides were adsorbed on the AMINEX A5 resin and were transferred to the top of a small chromatographic column packed with the same resin in NH$_4$$^+$ form. The adsorbed radionuclides were eluted with α-HIBA at pH 5 using a concentration gradient. Nca Tb radionuclides were eluted using 0.145 M α-HIBA. The eluting agent was completely removed from the eluate by heating, and the residue was dissolved in 0.05 M HCl for labelling.

There are large discrepancies among the cross sections for production of ^{149}Tb measured by different groups. For example, Kossakowski *et al.* [7] reported two orders of magnitudes higher cross sections for ^{141}Pr(^{12}C, $4n$)^{149}Tb reaction than the same reported by Alexander and Simonoff [6]. Therefore it was felt necessary to measure the yield of ^{149}Tb using the same reaction under particular experimental condition. Moreover, among the heavy ion induced reactions studied by Alexander and Simonoff and Kossakowski *et al.*, only ^{141}Pr and ^{139}La have 100% and 99.9% natural abundance. However, ^{139}La(^{16}O, $6n$)^{149}Tb reaction has lower cross section compared to that of the ^{141}Pr(^{12}C, $4n$) reaction. Considering all these, we calculated the possibility of production of ^{149}Tb by ^{12}C irradiation on naturally occurring mononuclidic target ^{141}Pr through ^{141}Pr(^{12}C, $4n$)^{149}Tb reaction. The compound nuclear statistical model code PACE-II [13] shows a fairly good cross section for ^{149}Tb along with minute amount of ^{150}Tb at around 71 MeV projectile energy (Fig. 1). Also, there is no report available on the separation of nca Tb from the natural praseodymium matrix. Based on the PACE-II prediction, an attempt has been made to produce nca ^{149}Tb from the natural praseodymium target followed by the development of efficient separation chemistry to isolate them from the bulk target.

2. Experimental

2.1 Production of radionuclides

The irradiation experiments were carried out at the BARC-TIFR Pelletron facility, Mumbai, India. A natural praseodymium (^{141}Pr) foil of 99.9% purity was procured from Alfa Aesar and was used to make a self-supporting foil target of 15 mg/cm^2 thickness by proper rolling. The Pr target was bombarded by 71.5 MeV ^{12}C^{6+} ions for 9.3 h up to a total charge of 1428 μC. The integrated beam current was monitored with the help of an electron suppressed Faraday cup placed downstream of the target assembly. The evaporation residues recoiling in the beam direction, were completely stopped in the aluminum catcher foils.

Pr radionuclides required to monitor the fate of bulk target matrix in radiochemical separation, are hardly produced in the above reaction. Therefore a separate natural Pr foil was irradiated in the neutron flux of 5.0×10^{12} n cm^{-2} s^{-1} for
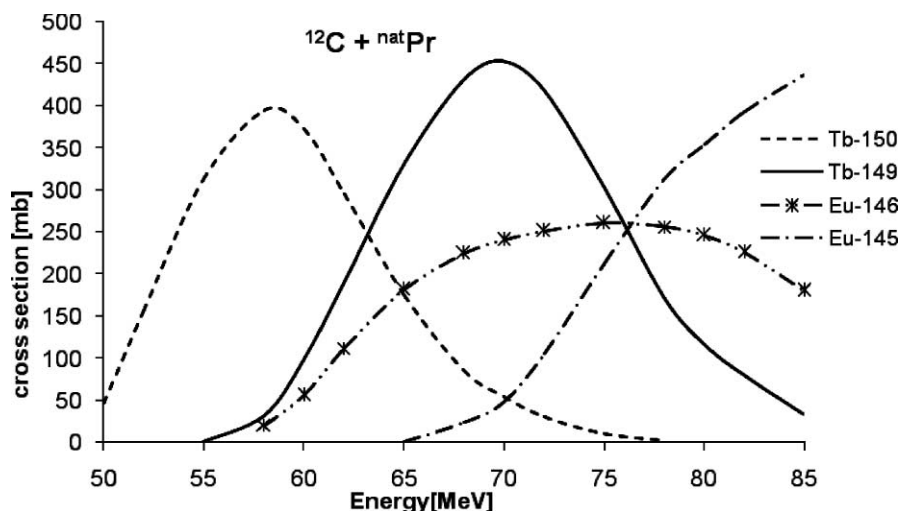
Fig. 1. Theoretical excitation functions of ^{12}C + ^{nat}Pr reaction as predicted by PACE-II.

Table 1. Nuclear reactions, Q values and nuclear spectroscopic data [14] of the product radionuclides.

Nuclear reaction	Product	Q value (MeV)	E_{th} (MeV) (calculated)	$T_{1/2}$	E_γ (keV)	I_γ (%)
^{141}Pr(^{12}C, $4n$)	^{149}Tb	-46.810	50.796	4.118 h	164.98	26.4
					352.24	29.4
^{141}Pr(^{12}C, $3n$)	^{150}Tb	-39.12	42.46	3.48 h	638.05	72
					496.24	14.6
^{141}Pr(^{12}C, $2n$)	^{151}Tb	-30.53	33.13	17.609 h	108.088	24.3
					251.863	26.3
					287.357	28.3
^{141}Pr(^{12}C, $p3n$)	^{149}Gd	-42.39	46.00	9.28 d	149.735	48
					298.634	28.6
^{141}Pr(^{12}C, $4n$) ^{149}Tb (EC/β^+)	^{149}Gd	—	—			
^{141}Pr(n, γ)	^{142}Pr	5.843	—	19.12 h	1575.6	3.7

4 h in the CIRUS reactor, BARC, Mumbai, to produce ^{142}Pr (19.12 h).

After the irradiation, the foils were assayed off line for the γ-ray activity of the product radionuclides using a HPGe detector coupled with a PC based 4096 channel analyzer, PCA2 (OXFORD). The energy resolution of the detector was 2.13 keV at 1332 keV. Efficiency calibration of the detector was performed as a function of γ-ray energy using a standard ^{152}Eu (13.506 y) source of known activity. Nuclear spectroscopic data of the radionuclides studied are listed in the Table 1 [14].

2.2 Radiochemical separation

The ^{12}C activated ^{nat}Pr foil and the neutron irradiated ^{nat}Pr foil were separately dissolved in minimum volume of 0.1 M HCl. The former was then spiked with the ^{142}Pr tracer and evaporated to dryness in order to attain the same chemical form between radioactive ^{142}Pr tracer and bulk Pr. The residue was then re-dissolved into 0.01 M HCl to prepare active uniform mixture of product and target matrix.

Separation of nca Tb, Gd from bulk praseodymium was approached by LLX as well as column chromatographic techniques. A series of LLX experiments were carried out using the cation extracting agent (1% v/v) HDEHP dissolved in cyclohexane as organic phase and dilute HCl as aqueous phase. In each extraction, 3 mL of organic solution

was shaken for 10 min in a mechanical shaker with equal volume of aqueous HCl and 100 μL of activity and was left for the complete phase separation. In order to determine the distribution of activities, 2 mL of aliquot was collected from each phase to carry out γ-spectrometric determination of the radionuclides. In the extraction procedure, concentration of HCl was varied from 10^{-5} M to 1 M keeping the HDEHP concentration fixed to 1% (v/v) and the concentration of HDEHP was varied with respect to fixed 0.1 M HCl. The nca Tb and Gd radionuclides were back extracted to the aqueous phase from HDEHP using 6 M HCl. The active aqueous solution was then evaporated to dryness and re-dissolved in 3 mL 0.1 M HCl solution and LLX was carried out against 0.5% HDEHP in presence of hydrazine sulphate. The nca Tb was recovered from the organic phase by using both 6 M HCl and 0.1 M DTPA in NaOH. The total time required starting from the foil dissolution to final back extraction of nca Tb radionuclides was 90 min.

Column chromatography was also attempted using cation exchange resin, DOWEX-50-8X (The British Drug House Ltd, England) as stationary phase and HCl as eluent to separate nca Tb, Gd from bulk Pr. The column was conditioned using 0.1 M HCl for 30 min. After conditioning, 100 μL of the radioactive mixture was added to the column and was eluted by various strengths of HCl. The flow was controlled to $\sim$ two drops of eluate per minute. The fate of the nca radionuclides and the bulk praseodymium during elution was

monitored by γ-spectrometry of the eluate (10 drops each). All the chemicals used for the chemical separation were of analytical grade.

3. Results and discussion

A series of non-destructive γ-ray spectra of the ^{12}C activated natural praseodymium foil were taken at different time intervals. The corresponding decay data confirm the production of ^{149,150,151}Tb along with ^{149}Gd in the natural Pr target matrix. However, contrary to the PACE-II prediction, no evidence of the production of ^{145,146}Eu was observed in the matrix. The γ-ray spectrum of the ^{12}C activated natural praseodymium foil collected 1.2 h after EOB is presented in Fig. 2. The probable nuclear reactions that occurred under the experimental conditions, along with their Q values, are presented in Table 1. Compound nucleus reaction plays the key role at the selected projectile energy. The batch yield of nca ^{149,150,151}Tb and ^{149}Gd measured at the EOB under the experimental conditions has been tabulated in Table 2. The production of ^{149}Tb was not satisfactory, though it had the highest production among others. The production of nca ^{149}Gd was found to be comparatively high at EOB. The reason is as follows: ^{149}Tb has two decay modes, EC (83.3%) and α (17.7%). The irradiation time in the present experiment was long (9.3 h) wherein ^{149}Tb (4.118 h) lost more than two half-lives, which in turn increased the amount of nca ^{149}Gd (9.28 d) at EOB *via* electron capture. Another important observation to be made is that ^{149}Tb is the low spin $(1/2^+)$ state, and the high initial angular momentum involved in the reaction of 71.5 MeV ^{12}C + ^{141}Pr will result in preferential population of the high spin $(11/2^-)$ isomer (^{149m}Tb). The EC decay of this isomer to ^{149}Gd is responsible for the high yield of the latter as observed in the present experiment. In addition ^{149}Gd will also be produced through direct reaction of ^{141}Pr(^{12}C, $p3n$)^{149}Gd.

In this context, incomplete fusion (ICF) reactions may offer an alternative pathway for production of low spin isomers

Table 2. Batch yield of nca radionuclides under the experimental conditions.

Experimental conditions		Batch yield at EOB	
		Radio-isotope	Yield (kBq/µA h)
Beam	^{12}C^{+6} (71.5 MeV)	^{149}Tb	86
Target	^{141}Pr foil (15 mg/cm^2)	^{150}Tb	37
Dose	1428 µC	^{151}Tb	7
Irradiation	9.3 h	^{149}Gd	70

in heavy ion reactions [15]. For instance bombardment of ^{141}Pr with ^{16}O at beam energy of ~ 6 MeV/A, would result in incomplete fusion of ^{16}O with the target nucleus, wherein an alpha particle is emitted at the forward angle with the same velocity as that of the incident projectile and carrying large angular momentum. The remaining part of the projectile (^{12}C) then fuses with the target nucleus with much lower angular momentum than that in the case of complete fusion of ^{12}C with ^{141}Pr. Thus ICF reaction would produce the low spin isomer of ^{149}Tb with higher yield than complete fusion reaction.

Fig. 3 represents the extraction behavior of nca Tb, Gd and bulk Pr as a function of concentration of HCl at a fixed 1% (v/v) HDEHP dissolved in cyclohexane. At the low concentration of HCl, from 10^{-5} M to 10^{-2} M region, nca Tb and Gd were extracted to the HDEHP phase along with bulk Pr. The high extractability of lanthanides may be attributed to the formation of cationic aquo-complex like, $[Ln(H_2O)_x]^{3+}$ [16] at the lower acidity and extracted to the liquid cation exchanger HDEHP. A significant change in the extraction scenario of the nca Tb, Gd and bulk Pr was observed at 0.1 M HCl, where nca Tb was extracted quantitatively to the organic phase along with $\sim 70\%$ nca Gd leaving bulk praseodymium ($\sim 97\%$) in the aqueous phase, after which (> 0.1 M HCl) the extraction of all the lanthanides sharply decreases. At 0.1 M HCl and 1% HDEHP concentration, about 3% bulk Pr was extracted to the organic phase
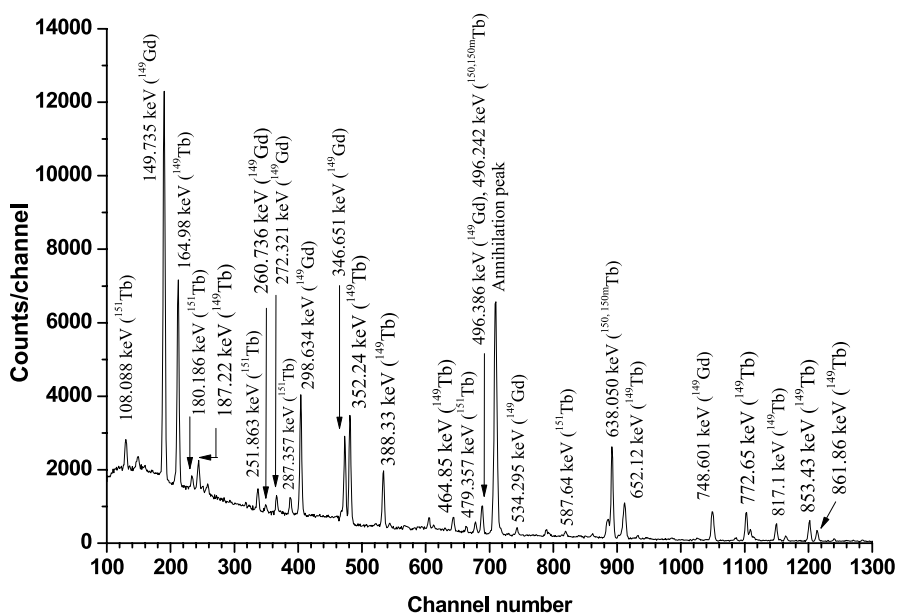
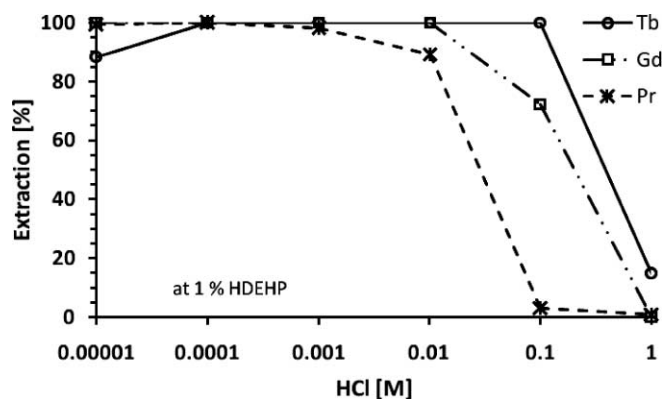**Fig. 2.** Nondestructive γ-ray spectrum of the ^{12}C activated natural Pr foil 1.2 h after EOB.

Fig. 3. Extraction profile of nca Tb, Gd and bulk Pr in LLX as a function of HCl concentration at a fixed strength of HDEHP (1%).
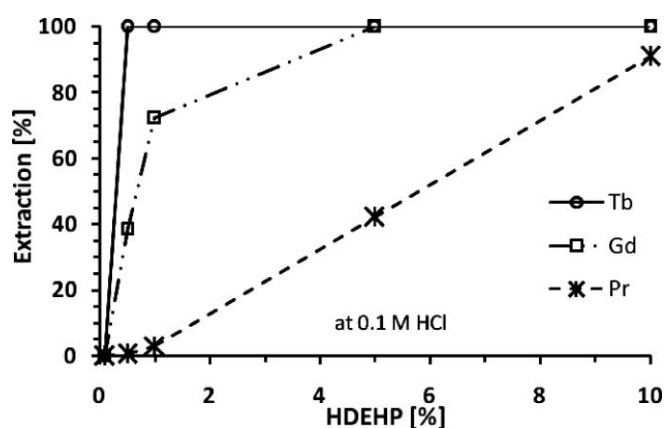

Fig. 4. Extraction profile of nca Tb, Gd and bulk Pr in LLX as a function of HDEHP concentration at a fixed strength of HCl (0.1 M).

with the nca products. In order to improve this situation, a second series of extraction was carried out by varying the concentration of HDEHP with fixed 0.1 M HCl (Fig. 4). It was possible to improve the separation between nca Tb and

bulk Pr at the 0.5% HDEHP and 0.1 M HCl, where nca Tb was extracted quantitatively along with $\sim 40\%$ nca Gd to the HDEHP phase leaving bulk Pr in the aqueous solution. However, in the organic phase, a minute contamination of bulk Pr ($\sim 0.5\%$) was present along with the separated nca products. This situation was further improved and a quantitative separation of bulk Pr and nca Tb was obtained by 0.5% HDEHP against 0.1 M HCl in presence of a pinch of hydrazine sulphate. After the heavy ion irradiation, it is possible that some fraction of Pr remained in higher oxidation state. The use of hydrazine sulfate helped to reduce them to Pr(III) state. A high separation factor (D_{Tb}/D_{Pr}) of 4.7×10^5 was achieved at this experimental condition between bulk Pr and nca Tb. Extraction of nca Gd also reduced in presence of hydrazine sulphate and at the optimum condition, extraction of nca Tb was ~ 3.5 times higher than the nca Gd. Nca Tb and Gd radionuclides were back extracted to the aqueous phase using 6 M HCl. The aqueous solution was then evaporated to dryness twice and finally kept in 0.1 M HCl for the separation of nca Tb and Gd. Nca Tb was extracted quantitatively from the aqueous 0.1 M HCl in presence of a pinch of hydrazine sulphate by 0.5% HDEHP leaving nca Gd to the aqueous solution. This yields a high separation factor (D_{Tb}/D_{Gd}) of 5.2×10^4. The nca Tb was then back extracted to the aqueous phase by both 6 M HCl and 0.1 M DTPA in 1 M NaOH. A schematic of the above separation is presented in Fig. 5. The optimum separation conditions and the corresponding separation factors are presented in Table 3. The extraction patterns of nca and bulk lanthanides are quite confirmative with our earlier experiments for production and separation of nca lanthanides [10–12]. It is noteworthy to mention that due to finer adjustment of HDEHP strength, and addition of hydrazine sulfate in the second step of extraction, we obtained much improved D_{Tb} values, almost 2–3 orders higher, compared to the earlier reported D_{Tb} values. However, the D_{Tb} values in the earlier reported data have been carried out with different set of target-product

Table 3. Distribution ratios (D) and corresponding separation factors (SF) at the optimal experimental conditions.

LLX: Experimental condition in presence of hydrazine sulphate	D_{Tb}	D_{Gd}	D_{Pr}	SF ($= D_{Tb}/D_{Pr}$)	SF ($= D_{Gd}/D_{Pr}$)	SF ($= D_{Tb}/D_{Gd}$)
HCl (0.1 M)/HDEHP (0.5%)	747	0.63	1.6×10^{-3}	4.7×10^5	394	–
HCl (0.1 M) + HDEHP (0.5%)	155	3×10^{-3}	–	–	–	5.2×10^4

Table 4. Comparison of D_{Tb} values of the present work and earlier reported values.

Optimal condition	Separation carried out between the pairs	D_{Tb}	Reference
0.1 M HCl hydrazine sulphate/HDEHP (0.5%)	Tb(nca), Gd (nca) and Pr (target)	747	This work
0.1 M HCl + hydrazine sulphate/HDEHP (0.5%)	Tb (nca), Gd (nca)	155	
0.1 M HCl, 1% HDEHP	Tb (nca), Dy (nca) and Nd$_2$O$_3$ (target)	3.36	[10]
1.5 M HCl, 10% HDEHP	Tb (nca), Dy (nca)	0.51	
0.001 M HCl, 10% HDEHP	Tb (nca), Dy (nca), CeO$_2$ (target)	2.43	[11]
1.5 M HCl, 10% HDEHP	Tb (nca), Dy (nca)	0.51	
0.1 M HCl, 1% HDEHP	Tb (nca), La$_2$O$_3$ (target)	2.776	[12]
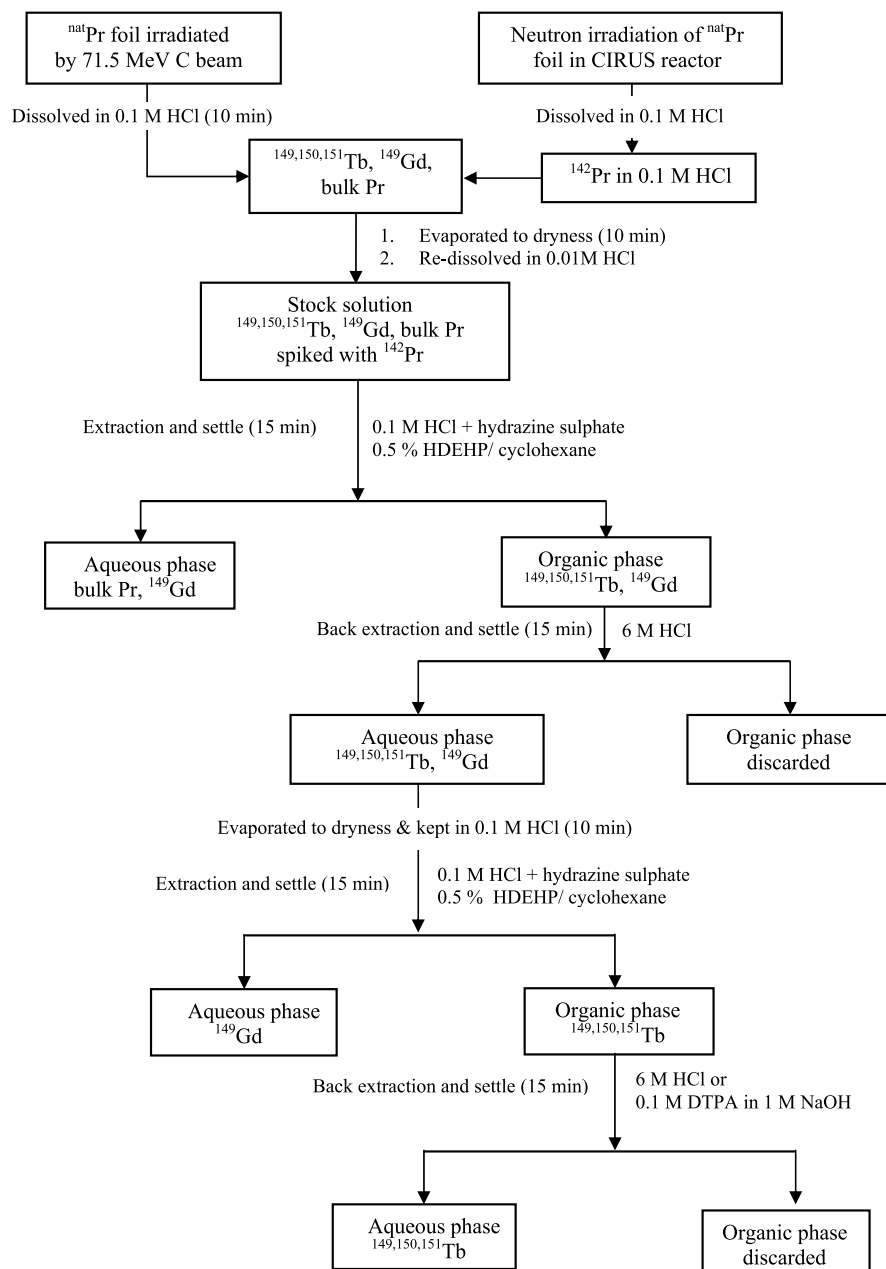
Fig. 5. Schematics of the separation of nca Tb and Gd from natural Pr using LLX.

combination. A comparison of D_{Tb} values with earlier experiments have been tabulated in Table 4.

The separation between nca Tb, Gd and bulk Pr was difficult by column chromatography using DOWEX-50-8X resin. It was observed that at the lower acidity (≤ 0.1 M HCl) all the three elements are strongly sorbed onto the resin, with no sorption at higher acidity (≥ 1 M HCl). Therefore, practically no separation was achieved by the column chromatography.

4. Conclusion

The separation between lanthanides is always a challenging task owing to their similar chemical properties. It is also time consuming in some cases. Moreover, application of short-lived radionuclides requires reliable and faster method for the separation of desired lanthanide with high

purity from the corresponding target matrix. We report a new separation technique, which describes the separation of nca Tb from the bulk praseodymium target matrix and coproduced nca Gd radionuclides by LLX using HDEHP as a cation extracting agent. The reported method is simple, fast and reliable. The high separation factor and $\sim 99\%$ chemical yield of nca Tb essentially indicate the separation efficiency of nca Tb from natural Pr target.

It is true that the yield of ^{149,150}Tb through ^{nat}Pr(^{12}C, xn) reaction is not high enough for clinical application. Nevertheless, it should be kept in mind that many new facilities including high current heavy ion accelerators are coming up. Following our observation (Table 2), it may be extrapolated that 1 mA of ^{12}C current would produce clinical dose of ^{149}Tb in 1 h irradiation time. However, to withstand such a huge dose a rigorous research is required especially with the designing of a target.

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References

1. Roesch, F.: Radiolanthanides in endoradiotherapy: an overview. Radiochim. Acta **95**, 303 (2007).

2. Nayak, D., Lahiri, S.: Application of radioisotopes in the field of nuclear medicine. I. Lanthanide series elements. J. Radioanal. Nucl. Chem. **242**, 423 (1999).

3. Allen, B. J.: Can alpha-immunotherapy succeed where other systemic modalities have failed? Nucl. Med. Commun. **20**, 205 (1999).

4. McDevitt, M. R., Sgouros, G., Finn, R. D., Humm, J. L., Jurcic, J. G., Larson, S. M., Scheinberg, D. A.: Radioimmunotherapy with alpha-emitting radionuclides. Eur. J. Nucl. Med. **25**, 1341 (1998).

5. Allen, B. J., Blagojevic, N.: Alpha- and beta-emitting radiolanthanides in targeted cancer therapy: the potential role of terbium-149. Nucl. Med. Commun. **17**, 40 (1996).

6. Alexander, J. M., Simonoff, G. N.: Excitation functions for ^{149g}Tb from reactions between complex nuclei. Phys. Rev. **130**, 2383 (1963).

7. Kossakowski, R., Jastrzebski, J., Rymuza, P., Skulski, W., Gizon, A., André, S., Genevey, J., Gizon, J., Barci, V.: Heavy residues following 5–10 MeV/nucleon ^{12}C- and ^{14}N induced reactions on Sm and Pr targets. Phys. Rev. C **32**, 1612–1630 (1985).

8. Allen, B. J., Goozee, G., Sarkar, S., Beyer, G., Morel, C., Byrne, A. P.: Production of terbium-152 by heavy ion reactions and proton induced spallation. Appl. Radiat. Isot. **54**, 53 (2001).

9. Beyer, G. J., Comor, J. J., Dakovic, M., Soloviev, D., Tamburella, C., Hagebo, E., Allan, B., Dmitriev, S. N., Zaitseva, N. G., Starodub, G. Y., Molokanova, L. G., Vranjes, S., Miederer, M.: Production routes of the alpha emitting ^{149}Tb for medical application. Radiochim. Acta **90**, 247 (2002).

10. Lahiri, S., Nayak, D., Das, S. K., Ramaswami, A., Manohor, S. B., Das, N. R.: Separation of carrier free dysprosium and terbium isotopes from ^{12}C^{6+} irradiated Nd$_2$O$_3$. Appl. Radiat. Isot. **51**, 27 (1999).

11. Lahiri, S., Nayak, D., Das, S. K., Ramaswami, A., Manohor, S. B., Das, N. R.: Separation of carrier free ^{152,153}Dy and $^{151-153}$Tb from ^{16}O^{7+} irradiated CeO$_2$ by liquid–liquid extraction. J. Radioanal. Nucl. Chem. **241**, 201 (1999).

12. Nayak, D., Lahiri, S., Ramaswami, A., Manohar, S. B., Das, N. R.: Separation of carrier free ^{151,152}Tb produced in ^{16}O irradiated lanthanum oxide matrix. Appl. Radiat. Isot. **51**, 631 (1999).

13. Gavron, A.: Statistical model calculations in heavy ion reactions. Phys Rev. C **21**, 230 (1980).

14. Firestone, R. B., Shirley, V. S.: *Table of Isotopes*. 8th Edn., Wiley, New York (1996).

15. Tomar, B. S., Goswami, A., Das, S. K., Reddy, A. V. R., Burte, P. P., Manohar, S. B., John, B.: Investigations on complete and incomplete fusion in ^{12}C + ^{93}Nb and ^{16}O + ^{89}Y by recoil range measurements. Phys. Rev. C **49**, 941 (1994).

16. Greenwood, N. N., Earnshaw, A.: *Chemistry of the Elements*. Pergamon Press, Oxford (1989).