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# Production of $^{149}$Tb in nuclear reactions induced by alpha-particles

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$^{149}$Tb is the only known isotope decaying both by emission of alpha-particles and positrons. This unique feature makes it possible to unite in one radionuclide two main tools of nuclear medicine: cancer therapy by $\alpha$-particles and diagnostics using positron emission tomography. This new direction in nuclear medicine is called theranostics.

A half-life of $^{149}$Tb is $T_{1/2} = 4.12$ h and the energy of emitting alpha particles is 4.08 MeV. The existing ways of production of $^{149}$Tb are far from being practical. They exploit either the high energy accelerators allowing usage of the spallation reactions [1] or the targets made of the isotope with very low abundance in Nature: the $^{152}$Gd whose content is 0.2 % with the $(p, 4n)^{149}$Tb reaction [2].

In this paper we propose using the nuclear reactions $^{151}$Eu$(\alpha, 6n)^{149}$Tb and $^{153}$E$(\alpha, 8n)^{149}$Tb having the thresholds 50.5 and 65.7 MeV respectively. The both target isotopes are the only stable Europium isotopes and exist in Nature approximately in equal parts (47.8 % and 52.2 %, correspondingly). This feature allows using the targets made from natural Europium.

This work is the evolution of the ideas proposed in [3]. The experiment performed in [3] was dedicated to measuring the yields of different Terbium radioisotopes including the reaction $^{151}$Eu($^3$He,5$n$)$^{149}$Tb $^{149}$Tb one. This reaction has, apparently, the lowest threshold among the well-known nuclear reactions that produce $^{149}$Tb . The threshold is equal to Tr = 29.3 MeV, and can be used with accelerators possessing quite modest parameters. The saturation yields measured in [3] are sufficient for many preclinical studies [3, 4]. However, one may expect much higher cross-sections of the alpha-particle induced reactions due to the larger probability of the mechanism of the compound nucleus formation in the latter ones.

The aim of this work was: 1) simulating of the excitation functions of the reactions $^{151}$Eu$(\alpha, 6n)^{149}$Tb and $^{153}$Eu$(\alpha, 8n)^{149}$Tb; 2) estimation of the expected yields; 3) obtaining some information about the mechanisms of these reactions; 4) their comparison with other reactions suitable for the production of $^{149}$Tb. At present time there are neither theoretical nor experimental data on the properties of these reactions.

We simulated the excitation functions of the $(\alpha, xn)$ – reactions, where $x$ lies in the range from 3 to 8, at the targets made of $^{151}$Eu and $^{153}$Eu (Fig. 1). The cross-sections in the maxima (approximately 65 and 80 MeV correspondingly) are predicted to approach one barn. The targets could be made from natural Europium. Calculations were carried out using TALYS-1.8 [5] code.

We compared our data with known cross sections of the reactions $(\alpha, xn)$, $x = 2{-}4$, at the neighbor nucleus $^{159}$Tb [6].

The obtained results confirm the acceptability of the TALYS code for discussed reactions in the chosen energy range. Opens up prospects for creating a new technology for use in one of the most important directions of nuclear medicine – theranostics.

The yields in saturation of $^{149}$Tb in different nuclear reactions induced by $\alpha$-particles were estimated as well and compared with those in the reaction $^{151}$Eu($^3$He, $5n$)$^{149}$Tb [3].

The $^{152}$Gd$(p, 4n)$-reaction has a fairly low threshold (28.4 MeV). The expected yield in saturation of $^{149}$Tb exceeds 1000 MBq/$\mu$a at the proton energy over 50 MeV (the data taken from [8]). This value suits quite satisfactory for applications and is typical for the reactions with protons. However, the main disadvantage of its use is that the target should be done from a rare $^{152}$Gd isotope. This fact dramatically increases the cost of its use. The same considerations apply also to the reaction $^{152}$Gd$(\alpha, 7n)^{149}$Dy $\to$ $^{149}$Tb where $^{149}$Tb is formed as a result of the of $^{149}$Dy decay. The predicted yield of $^{149}$Tb in this reaction, calculated by the code ALICE1 [8] is also not inferior to that of the reaction $(p, 4n)$ and is in good agreement with our estimates of yields.

The expected yields of $^{149}$Tb in the $(\alpha, 6n)$- and $(\alpha, 8n)$-reactions on Europium isotopes studied in this paper, are practically the same as in the case of reactions on Gadolinium.

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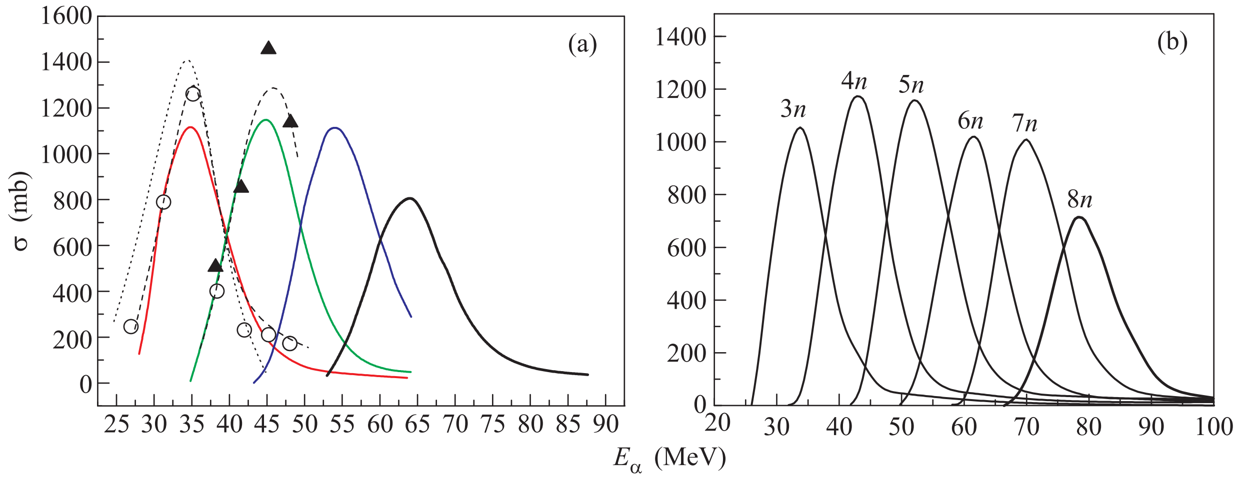


Fig. 1. (Color online) (a) – Excitation functions of the $^{151}$Eu($\alpha, xn$) $^{(155-x)}$Tb reactions. Solid curves were calculated by the code TALYS. The number $x$ of emitted neutrons varies from 3 to 6 corresponding to the curves from left to right. The curve for the reaction $^{151}$Eu($\alpha, 6n$)$^{149}$Tb is highlighted by the line thickness. Circles and triangles denote the experimental cross sections [6] of the reactions $^{159}$Tb($\alpha, 3n$) and $^{159}$Tb($\alpha, 4n$) correspondingly. Dashed curves calculated in [6] describe these data under the assumption of contributing both reaction mechanisms: formation of the compound nucleus and pre-equilibrium process. A point curve denotes only the formation of the compound nucleus. (b) – The same as in (a) for the reactions $^{153}$Eu($\alpha, xn$)$^{(157-x)}$Tb. The number x of emitted neutrons varies from 3 to 8 and is shown above the curves. The curve for the reaction $^{153}$Eu($\alpha, 8n$)$^{149}$Tb is highlighted by the line thickness

Comparison with the data on the reaction $^{151}$Eu($^3$He$, 5n$)$^{149}$Tb [3] shows that the latter really are inferior to those with alpha-particles and may be used predominantly for tests which do not require large activities of Terbium.

To conclude, a simulation of the excitation functions of the $^{151}$Eu($\alpha, 6n$)$^{149}$Tb and $^{153}$E($\alpha, 8n$)$^{149}$Tb reactions not studied before has been carried out. Verification of the calculations was done by comparing them with some existing data on neighbor nuclei. The predicted cross-sections reach their maxima close to one barn at the energies of about 65 and 80 MeV correspondingly. These cross-section values are similar to those of the proton induced reactions normally used for the radioisotopes production. As both Europium isotopes are presented in a natural mixture with approximately equal quantities, the targets made of natural Europium together with alpha-particle beams at the energies about 100 MeV seem to be the mostly effective tool for production of $^{149}$Tb.

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