Nuclear Instruments and Methods in Physics Research A 821 (2016) 136–141

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Excitation functions of the ^{nat}Cr(p,x)^{44}Ti, ^{56}Fe(p,x)^{44}Ti, ^{nat}Ni(p,x)^{44}Ti and ^{93}Nb(p,x)^{44}Ti reactions at energies up to 2.6 GeV

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ARTICLE INFO

Article history:
Received 1 October 2015
Received in revised form
9 March 2016
Accepted 13 March 2016
Available online 16 March 2016

Keywords:
Cumulative yields
Proton beam
Excitation functions
Codes
Predictive power

ABSTRACT

The paper presents the measured cumulative yields of ^{44}Ti for ^{nat}Cr, ^{56}Fe, ^{nat}Ni and ^{93}Nb samples irradiated by protons at the energy range 0.04–2.6 GeV. The obtained excitation functions are compared with calculations of the well-known codes: ISABEL, Bertini, INCL4.2+ABLA, INCL4.5+ABLA07, PHITS, CASCADE07 and CEM03.02. The predictive power of these codes regarding the studied nuclides is analyzed.

1. Introduction

Accumulation of ^{44}Ti data in different materials can be interesting for various areas of science and technology. For example, the ^{44}Ti activity in meteorites is used effectively in astrophysics to study the century-scale variations of solar activity [1,2]. Natural titanium is also considered as the basic component of the developing low-activated V–Ti–Cr alloys of structural materials for advanced fusion reactors, which should work effectively in conditions of high neutron fluxes and high temperature regimes. ^{44}Ti will be important component of the long-lived residual radioactivity of such materials that will transform in the dominated one after about 3 years of a cooling-down time [3,4].

This paper presents the study of the cumulative production cross-sections of ^{44}Ti for ^{nat}Cr, ^{56}Fe, ^{nat}Ni and ^{93}Nb targets irradiated by protons at the energy range 0.04–2.6 GeV. Irradiations have been performed at the synchrophasotron of the Institute for Theoretical and Experimental Physics (ITEP) during the period from September 1, 2006 to August 31, 2009 within the framework of the International Science Technical Center Project #3266. Irradiation conditions and the measured independent and cumulative cross-sections of the reaction products are presented in Refs. [5–7]. On the whole 31 excitation functions for ^{nat}Cr, 39 excitation functions for ^{56}Fe, 47 excitation functions for ^{nat}Ni, and 109 excitation functions for ^{93}Nb have been determined. However, due to the high activity of the irradiated samples and the low energy gamma-lines from ^{44}Ti, the excitation function of this nuclide has not been determined in the previous measurements.

In order to obtain it, the measurements of gamma-spectra for the previously irradiated samples of ^{nat}Cr, ^{56}Fe, ^{nat}Ni and ^{93}Nb were continued in 2012–2015. The long cooling time provides a significant decrease in the radioactivity background due to the natural decay of the reaction products with short half-lives, and

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http://dx.doi.org/10.1016/j.nima.2016.03.046
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that allowed us to identify ^{44}Ti quite confidently by its distinctive gamma-lines.

2. Methodology

The gamma-ray spectra measurements of residual nuclei were performed by a spectrometer consisting of a low-energy Ge detector of the GUL0110 type with a resolution of 500 eV at the ^{57}Co gamma-line energy of 122 keV and the digital spectrum analyzer DSA1000. The absolute efficiency of the spectrometer was calibrated by means of the validated gamma-sources: ^{55}Fe, ^{241}Am, ^{133}Ba, ^{57}Co, ^{137}Cs, ^{44}Ti, which were certified by the Mendeleev Institute for Metrology (St. Petersburg, Russia). An example of such calibration is shown in Fig. 1. The background spectrum of the room in which the measurements were carried out is shown in Fig. 2.

The yield of ^{44}Ti ($T_{1/2}$=59.1y) was identified in accordance with the intensity of its attendant gamma-lines: 67.868 keV (93.0%) and 78.323 keV (96.4%) [8]. The third gamma-line satelliting the ^{44}Ti decay with energy 146.22 keV (0.092%) is not used because of its extremely low yield. The typical gamma-spectrum of ^{56}Fe sample irradiated by 0.4 GeV protons is shown in Fig. 3, which demonstrates a good separation of the dominant gamma-lines and a very low contribution of the third gamma-line. The gamma-spectra for the ^{nat}Cr, ^{56}Fe, ^{nat}Ni and ^{93}Nb samples measured at about 7 years after irradiation are very similar to the shown one and differ only by some changes of the dominant lines intensities.

The methodology for determining the cross-sections of radioactive reaction products by means of the gamma-ray spectrometry is described in details in Refs. [5–7]. Because ^{44}Ti has only short-lived precursors (see Fig. 4), the formula for the cumulative production rate for the i-th gamma-line (i=1, 2 for 67.868 and 78.323 keV lines, respectively) can be written as

$$R^i_{cum} = \frac{A_i}{N_{Tag}\cdot\eta_i\cdot\epsilon_i\cdot\lambda}\cdot\frac{1}{t_{irr}}, \tag{1}$$

where A_i is the count rate of the corresponding gamma-line reduced to the end of an exposure and adjusted to a self-absorption in the sample in accordance with the data of Ref. [9]; N_{Tag} is the number of nuclei in the sample, η_i is the absolute yield of the gamma-line per decay of ^{44}Ti; ϵ_i is the absolute efficiency of the spectrometer for the analyzed gamma-energy; λ is the decay constant of ^{44}Ti and t_{irr} is the irradiation time (since $t_{irr} << T^{^{44}\mathrm{Ti}}_{1/2}$, a correction for ^{44}Ti decay during irradiation can be ignored).

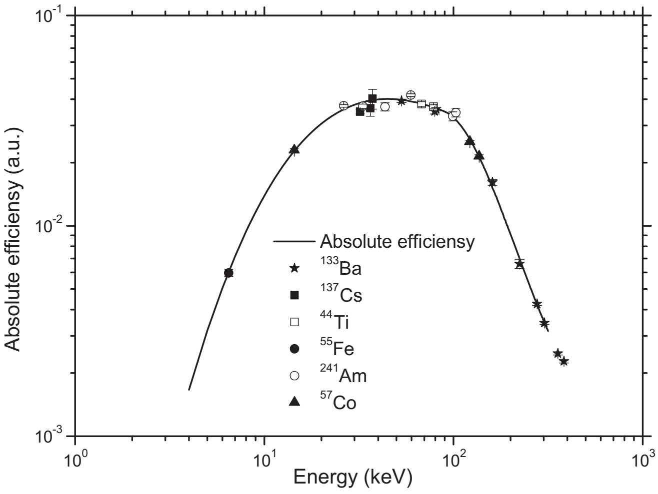

Fig. 1. Efficiency of the gamma-ray spectrometer with the Ge detector.

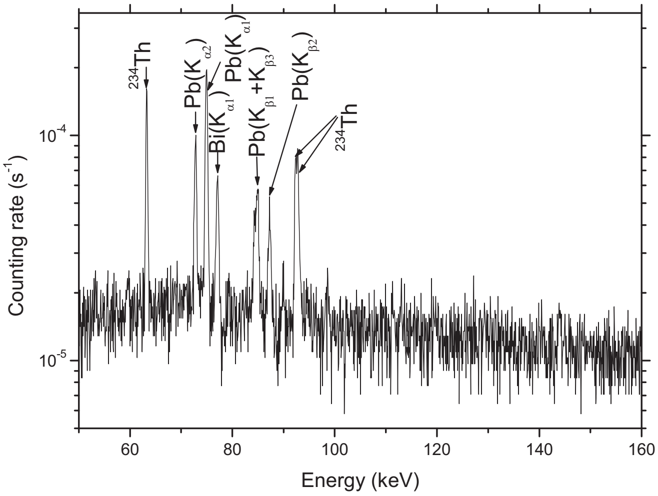

Fig. 2. The laboratory background spectrum. The measuring time was about 18 days.

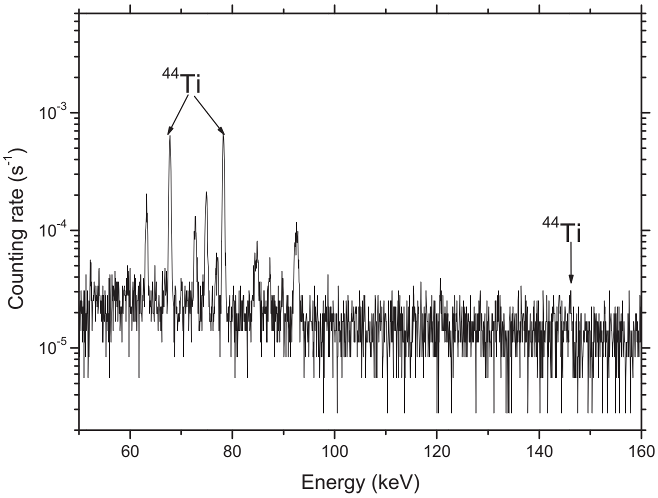

Fig. 3. The measured gamma-spectrum of the ^{56}Fe sample at about 7 years after irradiation by 0.4 GeV protons. The measuring time was about 99 h.

The reaction rate of the ^{44}Ti production was determined for each gamma-line, therefore to calculate the average value of the ^{44}Ti cumulative production rate the Eq. (2) has been applied while Eq. (3) has been used to calculate the corresponding production cross-sections:

$$\overline{R}^{^{44}\mathrm{Ti}}_{cum} = \frac{\sum\limits_{i=1}^{2} R^i_{cum}\cdot W_i}{\sum\limits_{i=1}^{2} W_i}., \text{ where } \quad W_i = \frac{1}{\left(\Delta R^i_{cum}\right)^2}. \tag{2}$$

$$\sigma^{^{44}\mathrm{Ti}}_{cum} = \frac{\overline{R}^{^{44}\mathrm{Ti}}_{cum}}{\Phi_{st}} \tag{3}$$

here $\overline{R}^{^{44}\mathrm{Ti}}_{cum}$ is the averaged value of the cumulative production rate; ΔR^i_{cum} is the uncertainty of the gamma-line intensity estimation; $\sigma^{^{44}\mathrm{Ti}}_{cum}$ denotes the ^{44}Ti production cross section and Φ_{st} is the proton flux presented in Tables 1–4 of Ref. [5].

Uncertainties of ΔR^i_{cum}, $\Delta\overline{R}^{^{44}\mathrm{Ti}}_{cum}$, $\Delta\sigma^{^{44}\mathrm{Ti}}_{cum}$ have been calculated in accordance with formulas given in Ref. [10].