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Measurement of Production Cross Sections of Neodymium induced by Proton Beam

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1. Introduction

Nuclear data on proton-induced reactions are normally needed for various applications such as the design of Accelerator-Driven System (ADS), the production of radioisotopes and surface analysis in industrial application. Neodymium (Nd) which is the second most abundant rare earth elements is used as a cryocooler and the permanent magnet. In addition, it can be used as a target material for the production of medically important radioisotopes such as ^{140}Nd and ^{149}Pm as well as the research of biomedical filed via positron emission tomography [1]. Thus, the characteristics of radionuclides produced from the Nd for application in various fields are necessary to study.

In view of this, the production cross sections of the Nd induced by proton beam were determined by the well-known stacked-foil activation method. The ^{149}Pm radionuclide in this research was measured using the proton energy of 45 MeV at the KIRAMS. Furthermore, the production cross section of ^{149}Nd produced from the ^{nat}Nd(p,x) reaction was also measured to understand the contribution for the production of ^{149}Pm. Longer-lived ^{149}Pm (53.08 h) is formed by both direct ^{nat}Nd(p,x) reaction and the decay of ^{149}Nd (1.728 h).

Although some experiments were carried out for the measurement of cross sections on the Nd with charged particle [2], the production cross sections of ^{149}Pm in the ^{nat}Nd(p,x) reaction was only researched by Lebeda *et al*. [3]. The production cross sections of ^{149}Pm and ^{149}Nd from the present work in ^{nat}Nd(p,x) reaction are compared with those from the literature and those calculated theoretically by TALYS 1.4 code [4].

2. Experimental method

The experiment for the production cross sections of ^{149}Pm and ^{149}Nd radionuclides were performed by using the conventional stacked-foil activation technique at the MC-50 cyclotron of KIRAMS. A total of 28 Nd foils (99.9% purity) with thickness of 106.5 μm and size of 1.1 cm × 1.1 cm were used as the target for the irradiation. Twenty-five natural nickel foils (99.9% purity, 50 μm thickness) were also included in the stacks as monitor to check the proton beam flux. The stacked assembly was irradiated with 45 MeV proton beam for 20 minutes in the external beam line of the MC-50 cyclotron. The average proton energy regions of Nd foils were calculated using SRIM code [5]. The induced γ-ray activities of the irradiated Nd foils were measured by the HPGe detector coupled to a PC-based 4K channel analyzer. The γ-ray counting of the irradiated samples based on the half-life of radionuclide was started after enough cooling time. In order to keep the dead time below 10%, the irradiated samples were placed on a suitable distance. The set of standard gamma sources such as ^{133}Ba, ^{152}Eu and ^{137}Cs were used for the energy and efficiency calibration of the detector system.

The production cross section of the radionuclides is determined by the following equation,

$$\sigma = \frac{\lambda \cdot S}{N_0 \phi \varepsilon I_\gamma \left(1-e^{-\lambda t_i}\right) \cdot e^{-\lambda t_w} \cdot \left(1-e^{-\lambda t_m}\right)} \qquad (1)$$

where S is the total counts under photo-peak, λ is the decay constant (s^{-1}), N_0 is the number of target nuclei (atoms), ϕ is the proton flux (protons/cm^{-2}·s), ε is the detector efficiency, I_γ is the γ-ray intensity. The t_i, t_w and t_m denote the irradiation, the waiting and the measuring time (s), respectively. The N_0 value was determined by considering the collimator with a diameter of 1 cm as $N_0 = N_d \times V$, where N_d is the atomic density (protons/cm^3) and V (cm^3) is the target volume associated with proton beam size passing the collimator. For the determination of proton flux, the standard cross section for the monitor reaction, ^{nat}Ni(p,x)^{57}Ni was taken from IAEA recommendation [6]. The average proton flux from the replicate measurements for each nickel foil was obtained as 5.08×10^{11} with the uncertainty of 4.69%.

The nuclear spectroscopic data such as γ-ray energies and half-lives used for the calculation of the production cross section of radionuclides are given in Table 1.

Table 1. Nuclear spectroscopic data of the ^{149}Pm and ^{149}Nd radionuclides [7]

Nuclide	Half-life	Decay mode	E_γ in keV (I_γ in %)
^{149}Pm	53.08 h	β^- (100%)	**285.95 (3.1)**
			859.46 (0.109)
^{149}Nd	1.728 h	β^- (100%)	114.31 (19.2)
			211.31 (25.9)
			270.17 (10.7)

A high-purity natural neodymium foil with a natural isotopic composition (^{142}Nd: 27.2%, ^{143}Nd: 12.2%, ^{144}Nd: 23.8%, ^{145}Nd: 8.3%, ^{146}Nd: 17.2%, ^{148}Nd: 5.7% and ^{150}Nd: 5.6%) was used as the target for the experiment. The ^{149}Pm radionuclide could be produced form two reactions such as (p,γ) and (p,2n), where threshold energies for each of reactions are 0 and 6.5 MeV. In case of the ^{149}Nd nuclide, its production is related to the (p,d) or (p,pn) reactions with threshold energy of 5.2 MeV. In addition, the ^{149}Pm and ^{149}Nd can be produced indirectly from the decay of ^{149}Nd and ^{149}Pr (2.26 m), respectively. Therefore, the measured production cross sections of these radionuclides need to be considered as cumulative values.

3. Results and Discussion

The measured cross sections of ^{149}Pm and ^{149}Nd in the ^{nat}Nd(p,x) reaction are given in Table 2 and are shown in Figs.1 and 2. The uncertainties associated to the cross sections of present work are from the repeated measurements. The overall uncertainty is the quadratic sum of both statistical and systematic errors. The statistical error in the observed activity is primarily due to counting statistics. The systematic errors are due to the uncertainties in the beam energy, the irradiation and waiting time, the detector efficiency and nuclear decay data. The total uncertainty was estimated to be 6.66 ~ 26.73% and 8.43 ~ 14.23% for ^{149}Pm and ^{149}Nd, respectively.

Table 2. Measured production cross sections of the ^{149}Pm and ^{149}Nd radionuclides.

Proton energy(MeV)	Cross section (mb)	
	^{149cum}Pm	^{149cum}Nd
44.72	13.95 ± 0.96	7.52 ± 0.63
43.72	14.74 ± 1.00	7.19 ± 0.61
42.72	14.41 ± 0.99	7.36 ± 0.62
41.72	15.07 ± 1.00	7.82 ± 0.66
40.73	15.55 ± 1.04	7.89 ± 0.67
39.70	12.47 ± 0.85	7.76 ± 0.66
38.62	15.36 ± 1.03	8.02 ± 0.68
37.54	14.66 ± 0.99	7.92 ± 0.67
36.43	15.35 ± 1.05	8.09 ± 0.69
35.31	16.49 ± 1.10	8.61 ± 0.73
34.14	14.15 ± 0.97	7.97 ± 0.68
32.95	14.32 ± 0.99	8.55 ± 0.73
31.72	15.52 ± 1.06	8.65 ± 0.74
30.46	14.05 ± 0.97	7.69 ± 0.66
29.17	15.03 ± 1.01	8.18 ± 0.70
27.86	16.17 ± 1.11	8.17 ± 0.70
26.46	15.17 ± 1.02	7.61 ± 0.66
25.01	15.40 ± 1.06	7.20 ± 0.62
23.46	17.03 ± 1.18	7.50 ± 0.65
21.86	17.94 ± 1.26	6.62 ± 0.58
20.19	23.57 ± 1.65	5.39 ± 0.48
18.39	34.33 ± 2.44	4.04 ± 0.37
16.45	51.64 ± 3.77	2.47 ± 0.24
14.33	57.16 ± 4.44	1.11 ± 0.12
11.95	42.70 ± 3.74	0.34 ± 0.02
9.16	17.17 ± 1.97	
7.32	6.02 ± 0.93	
5.08	1.13 ± 0.30	

It can be seen from Figs. 1 and 2 that most of the production cross sections of ^{149}Pm and ^{149}Nd from the ^{nat}Nd(p,x) reaction are found to be in good agreement with the values by Lebeda *et al*. [3] in the energy range less than 20 MeV.

Beyond 20 MeV, the measured production cross sections of ^{149}Pm and ^{149}Nd from present work are higher than those in literature data. In addition, the experimental data are compared with theoretical calculations by TALYS code [4]. Although the shape calculated by TALYS code as function of proton energy corresponds well to the experimental data, the values of cross section show the some difference. Especially, in case of the cross sections of ^{149}Nd radionuclide, the calculated values show that the starting point of the reaction is greater than the experimental data. This difference may be caused by the use of TALYS with default parameters.

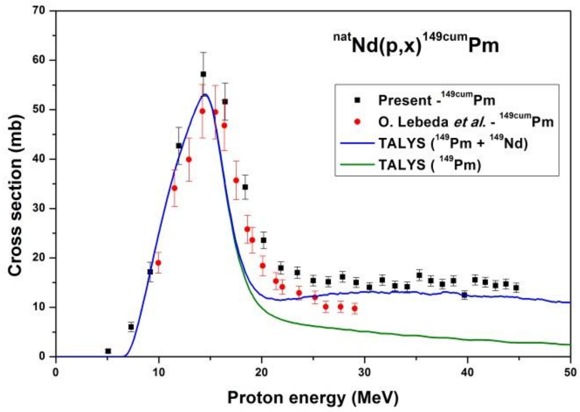

Fig.1. The experimental cross sections for the ^{nat}Nd(p,x)^{149}Pm reaction and a comparison of the values calculated by TALYS code.

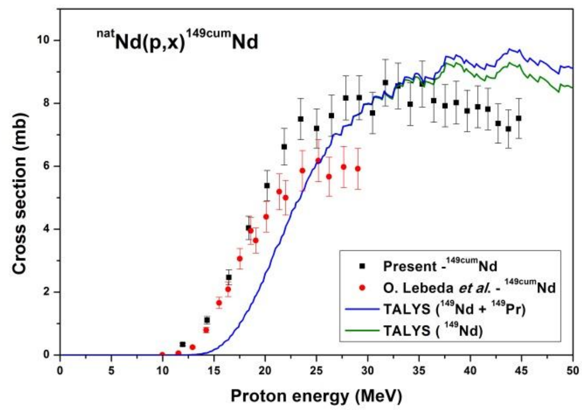

Fig.2. The experimental cross sections for the ^{nat}Nd(p,x)^{149}Nd reaction and a comparison of the values calculated by TALYS code.

4. Conclusions

The production cross sections of ^{149}Pm and ^{149}Nd from the ^{nat}Nd(p,x) reactions within the proton energies of 5.08 ~ 44.72 MeV were determined from present work. It was found that the produced data show a good agreement with other measured data. However, it can be seen that there are slight differences in the high energy region. Moreover, in order to obtain the independent production cross sections of radionuclides, the contribution by a parent radionuclide needs to be researched.

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