Cross-section measurement for Ni(n, x)$^{58(m+g)}$Co, Ni(n, x)^{60m}Co, Ni(n, x)^{61}Co and Ni(n, x)^{62m}Co reactions induced by neutrons around 14 MeV

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Abstract The cross sections of Ni(n, x)$^{58(m+g)}$Co, Ni(n, x)^{60m}Co, Ni(n, x)^{61}Co and Ni(n, x)^{62m}Co reactions induced by neutrons around 14 MeV were measured in this work and calculated by a previously developed formula in this work. The neutron flux was determined using the monitor reaction ^{27}Al(n, α)^{24}Na and the neutron energies were measured with the method of cross-section ratios for ^{90}Zr(n, 2n)^{89}Zr to ^{93}Nb(n, 2n)^{92m}Nb reactions.

Key words nickel, (n, x)-reaction, cross-section, activation technique

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1 Introduction

The element (nickel) is very important in many fields, so we need to calculate the total cross sections of several reactions for one element, which produce certain radioactive product nuclide. The cross sections of (n, 2n), (n, γ), (n, p), (n, d), (n, t) $\cdots$ reactions for the isotopes of nickel have been measured by many authors. Here, we adduced several authors[1—8], but the cross sections of Ni(n, x)$^{58(m+g)}$Co, Ni(n, x)^{60m}Co, Ni(n, x)^{61}Co, Ni(n, x)^{62m}Co reactions were measured by few laboratories[9]. Most of the authors neglected the effect of (n, t), (n, d) reactions or deducted the effect indirectly when they calculated the cross section of (n, p) reaction. Thus, we investigate them in order to give the cross section of the element producing certain radioactive product nuclide.

Since the samples we selected are natural abundance, furthermore, the element (nickel) has many isotopes, it is obvious that a radioactive nuclide can be produced by several reactions, such as the reaction Ni(n, x)^{60m}Co is made up of ^{60}Ni(n, p)^{60m}Co, ^{61}Ni(n, d+np)^{60m}Co, ^{62}Ni(n,t+nd+2np)^{60m}Co and so on. In the same way, the other reactions in this work have close resemblance. Surely, each of the reactions producing certain radioactive product has different contribution. So in the calculation we just gave the cross section of the element and didn't import the abundance of the target nuclide into the formula.

In the present work, the four cross sections were measured in the neutron energy of 13.5 to 14.6 MeV. And the reaction yields were obtained by an absolute measurement of the γ-ray activities of the product nuclei using a coaxial HPGe detector. The neutron energies for these measurements were determined by cross-section ratios of ^{90}Zr(n, 2n)^{89}Zr to ^{93}Nb(n, 2n)^{92m}Nb reactions[10].

2 Experiment

All the samples (nickel foils of 99.9% purity) were made into circular disks with a diameter of 2.0 cm. Each of them was sandwiched between two Al foils. The samples were placed at 40° to 135° angles relative to the deuteron beam direction and centered about the T-Ti target at distances of 1.5—3.5 cm.

Irradiations were carried out at the K-400 Intense Neutron Generator at the Institute of Nuclear

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Physics and Chemistry, China Academy of Engineering Physics, and lasted from 0.5 to 1 hour with a fluence rate yield of about 3—4×10^{10} n/s. Neutrons in the 14 MeV region were produced by means of the T(d, n)^{4}He reaction with a deuteron beam of 220 keV and beam current of 350 μA. The solid tritium-titanium (T-Ti) target used in the generator was about 2.18 mg/cm^2 thick. During irradiation, the neutron flux was monitored by accompanying α-particles so that the corrections could be made for small variations in the yield. The neutron energies in the measurements were determined by cross section ratios for ^{93}Nb(n, 2n)^{92m}Nb and ^{90}Zr(n, 2n)^{89m}Zr reactions. The activated samples were studied for their γ-activities by a low background, high efficiency γ-ray spectrometry, using a well calibrated GEM-60P coaxial high-purity germanium (HPGe) detector (crystal diameter: 70.1 mm, crystal length: 72.3 mm) (ORTEC, made in U.S.A) with a relative efficiency of ~68% and an energy resolution of ~1.69 keV FWHM at 1.33 MeV. The efficiency of detector at 5.5 cm was about 1% around the energy 1.33 MeV, and the uncertainty in the absolute efficiency curve at 5.5 cm was estimated to be ~2%, while the uncertainty of the activity of the standard source was ~1%.

The decay characteristics of the radioactive product nuclides and the natural abundances of the target isotopes under investigation are summarized in Table 1.

Table 1. Reaction and associated data of the radioactive products[11].

reactions	half-life of products	E_γ/keV	I_γ(%)
Ni(n,x)$^{58(m+g)}$Co	70.82 d	810.8	99
Ni(n,x)^{60m}Co	10.47 min	1332.5	0.24
Ni(n,x)^{61}Co	1.650 h	67.4	85
Ni(n,x)^{62m}Co	13.91 min	1172.9	96.7
^{27}Al(n,α)^{24}Na	14.959 h	1368.6	100

3 Calculation and discussion

3.1 The calculation

Using the relative activation technique of neutron, each of the samples was sandwiched between two Al foils which were used as monitor. Because the cross section of ^{27}Al(n, α)^{24}Na reaction has been measured by many authors and the value is very accurate, we can select it as a standard. With the irradiation taking place, the neutron flux for the sample was the same as the flux for the monitors. So we can find an equation of neutron flux between them, and avoid importing the neutron flux into the calculation.

The measured cross sections σ_x were calculated by the activation formula[12]:

$$\sigma_x = \frac{[\varepsilon I_\gamma KSMD]_m[\lambda AFC]_x}{[\varepsilon I_\gamma KSMD]_x[\lambda AFC]_m}\ \sigma_m\,. \qquad (1)$$

where σ_m is the monitor reaction cross section, the subscript m represents terms corresponding to the monitor reaction and subscript x corresponding to the measured reaction, ε is the full-energy peak efficiency of the measured characteristic γ-ray, I_γ is the γ-ray intensity, $S=1-e^{-\lambda t}$ is the growth factor of the residual nuclide, λ is the decay constant, t is the total irradiation time, M is the mass of sample, $D=e^{-\lambda t_1}-e^{-\lambda t_2}$ is the counting collection factor, t_1 and t_2 are time intervals from the end of the irradiation to the start and finish of counting, respectively, A is the atomic weight, C is the measured full-energy peak area and F is the total correction factor of the activity:

$$F = f_s f_c f_g\,. \qquad (2)$$

where f_s, f_c and f_g are the correction factors for the self-absorption of the sample at a given γ-energy, the coincidence sum effect of cascade γ-rays in the investigated nuclide and in the counting geometry, respectively. K is the neutron flux fluctuation factor:

$$K = \left[\sum_i^L \Phi_i(1-e^{-\lambda\Delta t_i})e^{-\lambda t_i}\right]/\Phi S\,. \qquad (3)$$

where L is the number of time intervals in which the irradiation time is divided, Δt_i is the duration of the ith time interval, t_i is the time interval from the end of the ith interval to the end of irradiation, Φ_i is the neutron flux averaged over the sample during the Δt_i, Φ is the neutron flux averaged over the sample during the total irradiation time t.

Using this formula, we got the cross-section presented in Table 2.

Table 2. Summary of the cross sections measurements in present work.

reactions	neutron energies/MeV	cross sections/mb
Ni(n,x)$^{58(m+g)}$Co	13.5±0.3	245±9
	14.6±0.3	189±8
Ni(n,x)^{60m}Co	13.5±0.3	38±3
	14.6±0.3	25±2
Ni(n,x)^{61}Co	13.5±0.3	1.29±0.09
	14.6±0.3	1.08±0.08
Ni(n,x)^{62m}Co	13.5±0.3	0.55±0.05
	14.6±0.3	0.78±0.05
^{27}Al(n,α)^{24}Na[13]	13.5	125.7±0.8
	14.6	114.1±0.6

3.2 Discussion

The cross sections measured in this work are shown in Table 2. The errors in our work result from the counting statistics, the detector efficiency, the amendment to dead time of detector, the self-absorbability of gamma rays, the standard cross-section, the weigh of samples and the coincidence sum effect of cascade gamma rays.

There are two reactions which produce short-lived nuclei, to which the International Atomic Energy Agency (IAEA) has attached importance. They are $^{60}Ni(n,p)^{60m}Co$ and $^{62}Ni(n,p)^{62m}Co$ reactions which are used in the evaluation of fusion reactor. Luckily, the two results were gotten in this work by the activation formula above with importing the abundance of the target nuclide into the formula and neglecting the effect of (n, t), (n, d) reactions because of their tiny contribution compared with (n, p) reaction.

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