Cross section measurements for (n, p) reaction on stannum isotopes at neutron energies from 13.5 to 14.6 MeV*

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Abstract: Utilizing the cross sections for ^{93}Nb(n, 2n)^{93m}Nb or ^{27}Al(n, a)^{24}Na reactions as monitors, the cross sections for the reactions ^{115}Sn(n, p)^{115m}In, ^{116}Sn(n, p)^{116m}In, ^{117}Sn(n, p)^{117}In and ^{117}Sn(n, p)^{117m}In have been measured at neutron energy ranging from 13.5 to 14.6 MeV through activation technology. Then, the results of present work were compared with the published experimental data.

Key words: cross section, (n, p) reaction, activation technology, stannum

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1 Introduction

Neutron reaction cross section is one of the most important research subjects in nuclear physics. It is essential for understanding the nuclear phenomenon in materials by neutron irradiation. Experimental data of neutron induced reactions are used to test and verify the accuracy of nuclear models, which are used in the process of calculating cross sections. Stannum is a kind of significant fusion reactor metal, and research on the cross section reaction of stannum isotopes is of importance. The cross-section of stannum isotopes at neutron energy of 14 MeV has been measured by several research groups. Some data are obtained, but relatively large disagreement exists, and the majority of data were obtained before 1990. Therefore, it is necessary to further measure the cross-sections on stannum isotopes with accuracy in order to strengthen the reliability of the database.

In the present work, the cross sections for ^{115}Sn(n,p) ^{115m}In, ^{116}Sn(n,p) ^{116m}In, ^{117}Sn(n,p) ^{117}In and ^{117}Sn(n,p) ^{117m}In reactions were measured in the neutron energy ranging from 13.5 to 14.6 MeV through activation technology. The reaction yields were obtained by absolute measurement of the gamma activities of the product nuclei using a coaxial high-purity germanium detector. The results are discussed and compared with the existing data obtained previously.

2 Experiment

2.1 Sample irradiation

The irradiation of samples was carried out at ZF-300-Ⅱ Intense Neutron Generator at Lanzhou University with a yield of (3–4)×10^{10} n/s. T (d, n) ^{4}He serves as a neutron source with average deuteron beam energy of 135 keV and beam current of 500 μA. The thickness of the tritium-titanium target was 1.35 mg/cm^2. An accompanying α−particle was used to monitor the neutron flux in order to correct some small variations during irradiation. The cross sections for reaction ^{93}Nb(n,2n) ^{92m}Nb or ^{27}Al(n,α) ^{24}Na [1] were selected as monitors to measure the reaction cross section on several stannum isotopes. The neutron energies in these measurements were determined by the cross section ratios for ^{90}Zr(n,2n) $^{89m+g}$Zr and ^{93}Nb(n,2n) ^{92m}Nb reactions [2]. Groups of samples were placed at 0°, 45°, 90°, or 135° angles in relation to the beam direction. The samples in each group were sandwhiched between two Al or Nb foils.

The cross section values of the monitor reaction ^{27}Al(n,α) ^{24}Na were (125.7±1.4) mb, (121.9±1.2) mb,

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(116.1±1.2) mb and (112.9±1.2) mb at neutron energies of 13.5 MeV, 14.1 MeV, 14.4 MeV and 14.6 MeV, respectively. The cross section values of the monitor reaction ^{93}Nb(n,2n) ^{92m}Nb were (451.7±6.2) mb, (457.1±6.5) mb, (460.2±5.6) mb and (459.9±5.6) mb at neutron energies of 13.5 MeV, 14.1 MeV, 14.4 MeV and 14.6 MeV, respectively.

2.2 Gamma activity survey

A CH8403 coaxial high-purity germanium detector (sensitive volume 110 cm^3) (made in China) with a relative efficiency of 20% and an energy resolution of 3 keV at 1332 keV, was devoted to determining the gamma ray activities of ^{92m}Nb, ^{24}Na, ^{115m}In, ^{116m}In, ^{117}In and ^{117m}In. The efficiency of the detector needs to be calibrated precisely using the standard gamma source. The standard reference material 4275 was obtained from the National Institute of Standards and Technology (Washington, D. C. USA). An absolute efficiency calibration curve was obtained at 20 cm from the surface of the germanium crystal. In our situation, however, we needed to calibrate the efficiency at 2 cm. The actual counting position was used because of the weak activity of the sample. For this reason, we placed a set of single γ sources at two positions (20 cm and 2 cm) in succession to measure their efficiency ratios, so that we were able to evaluate the efficiency ratio curve as a function of energy. The absolute efficiency curve at 2 cm can be obtained from the calibration curve at 20 cm and the efficiency ratios curve. The uncertainty of the activity of the standard source was ~1.0%, while the uncertainty of the absolute efficiency curve at 2 cm was estimated to be ~1.5%.

The absolute efficiency curve was

$$\varepsilon = a_0 + a_1 E + a_2 E^2 + a_3 E^3 + a_4 E^4$$

at 2 cm. If $E < 200$ keV, then

$$\begin{aligned} a_0 &= 0.07389381, \\ a_1 &= -0.1465568\times10^{-3}, \\ a_2 &= 0.1383559\times10^{-6}, \\ a_3 &= -0.6226944\times10^{-9}, \\ a_4 &= 0.1073058\times10^{-13}, \end{aligned}$$

or else

$$\begin{aligned} a_0 &= 0.10054, \\ a_1 &= -0.2807773\times10^{-3}, \\ a_2 &= 0.3767462\times10^{-6}, \\ a_3 &= -0.2409134\times10^{-9}, \\ a_4 &= 0.5878159\times10^{-13}. \end{aligned}$$

The decay characteristics of the product radioisotopes and natural abundances of target isotopes under investigation are summarized in Table 1 [3].

Table 1. Reactions and associated decay data of activation products.

reaction	abundance of target isotope (%)	Half-life of product	E_γ/keV	I_γ(%)
^{115}Sn(n, p)^{115m}In	0.34	4.486 h	336.24	45.9
^{116}Sn(n, p)^{116m}In	14.53	54.41 m	818.7	11.5
^{117}Sn(n, p) ^{117}In	7.68	43.2 m	552.9	100.0
^{117}Sn(n, p)^{117m}In	7.68	116.2 m	315.3	19.1
^{93}Nb(n, 2n)^{92m}Nb	100	10.15 d	934.4	99.07
^{27}Al(n, α)^{24}Na	100	14.959 h	1368.6	100

3 Results and discussion

The cross-sections were calculated by the equation proposed by Wang Y C et al. (1990) [4] as follows,

$$\sigma_x = \frac{[\varepsilon_{\rm p} I_\gamma \eta KSMD]_o}{[\varepsilon_{\rm p} I_\gamma \eta KSMD]_x} \bullet \frac{[\lambda AFC]_x}{[\lambda AFC]_o} \bullet \sigma_o,$$

where σ is the reaction cross section, the subscript o represent the term corresponding to the monitor reaction and the subscript x corresponds to the measured reaction, ε is the full-energy peak emerency of the measured characteristics gamma-ray, I_γ is the γ ray intensity, η denotes the abundance of the target nuclide, λ and C describe the decay constant and the measured full energy peak area, respectively, M represents the mass of samples, A is the atomic weight, F denotes the total correction factor of the activity, $F = f_s + f_o + f_g$, here f_s, f_o and f_g represents the factors for 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 fluence fluctuation factor, written as

$$K = \left[\sum_{i=1}^{L} \phi_i \left(1-{\rm e}^{-\lambda\Delta t_i}\right){\rm e}^{-\lambda T_i}\right] \Big/ \phi S,$$

where L denotes the number of time intervals into 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 average neutron flux during $\Delta t_i, \phi$ is the average neutron flux during the total irradiation time T. $S = 1 - e^{-\lambda T}$ describes the growth factor of the residual nucleus. $D = e^{-\lambda t_1} - e^{-\lambda t_2}$ is the counting collection factor. t_1 and t_2 are the time intervals from the end of the irradiation to the start and finish of counting, respectively.

The main error sources in our data measurements are from the counting statistics (0.3%–4.3%), detector efficiency (1.5%), standard cross-sections uncertainties (1%–2%), weight of samples (0.1%), self-absorption of γ-rays (0.4%), coincidence sum effect of cascade γ-rays (0–3%), uncertainties of irradiation, cooling and measuring times (0.1%–0.8%), etc.

The cross sections measured in this work are summarized in Table 2 and plotted in Figs. 1–4, together with the value in the literature for comparison.

Table 2. Summary of the cross section measurements.

reaction	neutron energy/MeV			
	13.5±0.3	14.1±0.2	14.4±0.3	14.6±0.3
	cross sections/mb			
^{115}Sn(n, p)^{115m}In	38±3.3	41±3.1	34±3.3	36±2.8
^{116}Sn(n, p)^{116m}In		5.8±0.8	11±1.8	16±2.1
^{117}Sn(n, p)^{117}In		5.6±0.8	16±2.6	8.1±1.7
^{117}Sn(n, p)^{117m}In	3.4±0.6	5.3±0.7	4.4±0.6	6.9±0.8

Because of the little available experiment data in the case of the ^{115}Sn(n,p) ^{115m}In reaction, there are just two data from Refs. [5, 6] for comparison. The results are shown in Fig. 1. It can be seen that our result is really close to the result from Ref. [6] at the energy of 14.4 MeV, but the value from Ref. [5] is much smaller than those of this work and Ref. [6] at this energy point.

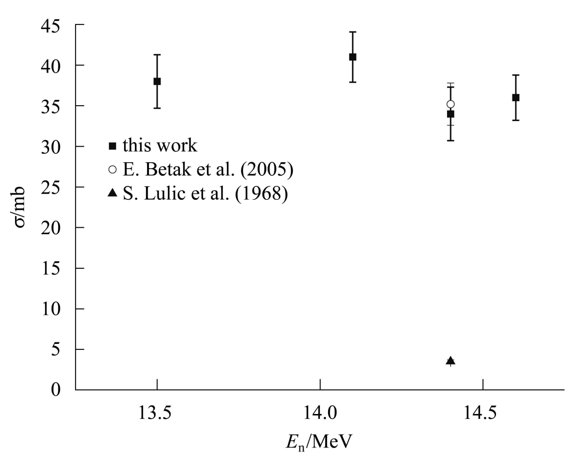

Fig. 1. The cross sections for the ^{115}Sn(n,p) ^{115m}In reaction.

The cross section data for ^{116}Sn(n,p) ^{116m}In are shown in Fig. 2. We can see that the cross section of this reaction channel increases with the increasing neutron energy at the energy of 14.1–14.6 MeV. At the neutron energy 14.1 MeV, our result is in agreement with that of Ref. [7], within experimental uncertainty. At the neutron energy 14.4 MeV, the value of Ref. [6] is basically the same as our result, while the value of Ref. [8] is somewhat lower relative to our result. Values reported by Refs. [7, 9, 10] are much smaller than the present data at the neutron energy of 14.6 MeV.

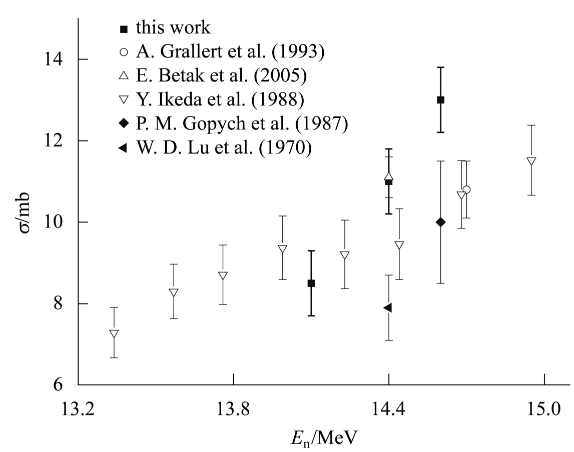

Fig. 2. The cross sections for the ^{116}Sn(n,p) ^{116m}In reaction.

For the ^{117}Sn(n,p) ^{117}In reaction, it can be seen from Fig. 3 that the value obtained by Refs. [11, 12] is a little greater than that obtained by this work at the neutron energy of 14.1 MeV. In the neutron energy of 14.6 MeV，our value is consistent with those given by Ref. [11], within experimental uncertainties, but not consistent with the values published by Refs. [10, 13, 14]. The data of Ref. [13] are somewhat higher than others.

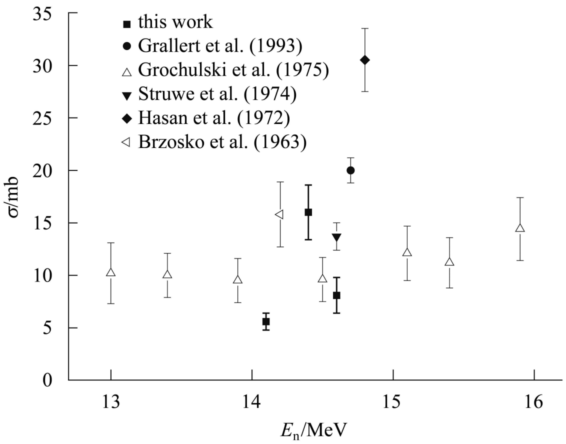

Fig. 3. The cross sections for the ^{117}Sn(n,p) ^{117}In reaction.

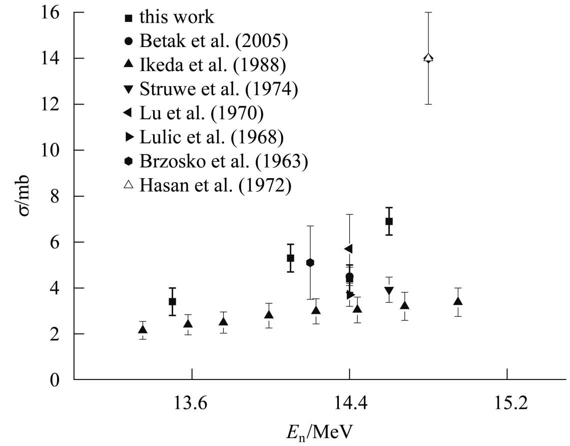

Fig. 4. The cross sections for the ^{117}Sn(n,p) ^{117m}In reaction.

The present cross section values for the ^{117}Sn(n,p) ^{117m}In reaction are shown in Fig. 4. Our results are larger than those of Ref. [7] and Ref. [14] near some experimental energy point measured. It can be seen that our results are in agreement with those of Ref. [12] at the neutron energy of 14.1 MeV, within experimental uncertainties, while at the neutron energy 14.4 MeV, our value is nearly the same as that of Ref. [6], and sandwiched in between those of Ref. [8] and Ref. [5]. The numerical value of Ref. [13] has large discrepancies with others.

In our work, the activation cross sections for the (n, p) reactions on stannum isotopes were measured at the neutron energy of 13.5–14.6 MeV. In general, our measurements agree with the literature data, but some discrepancies are observed among the literature values, which might be attributed to the variations in experimental methods, the nuclear constants used, the use of β-counting or poor-resolution NaI(Tl) crystal γ-spectrometers in this early work.

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