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Activation cross sections for reactions induced by 14 MeV neutrons on natural copper

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Abstract The cross sections for the $^{63}Cu(n,\alpha)^{60(m+g)}Co$, $^{65}Cu(n,2n)^{64}Cu$, and $^{65}Cu(n,p)^{65}Ni$ reactions have been studied in the neutron energy range of 13.5–14.8 MeV using the activation technique. The neutron beams were produced via the $^{3}H(d,n)^{4}He$ reaction. The neutron energies of different directions in the measurements were determined beforehand by the method of cross section ratios for the $^{90}Zr(n,2n)^{89m+g}Zr$ and $^{93}Nb(n,2n)^{92m}Nb$ reactions. The results in the present work were discussed and compared with measurement results found in the literatures.

Keywords Copper · Activation · Neutron · Cross section · Nuclear reaction

1 Introduction

The copper and its alloys are widely used in the electronic industry, atomic energy industry, aerospace industry, etc. The accurate and reliable nuclear reaction cross-section data around 14 MeV neutrons on copper are necessary data for nuclear reactor design, radiation shielding calculation, and other nuclear engineering calculations. Because in the operation of a future fusion reactor, the 14 MeV neutron from deuterium and tritium fusion reaction not only causes very serious dislocated damage in structural materials of the fusion reactor such as the first wall and cladding shell, but also participates in nuclear transformed reactions with them, which make the material form cavities or bubbles. This causes its properties become worse, they shortening not only the service life of the fusion reactor material, but also impacting to the safe operation of the reactor. In addition, the experimental cross-section data around 14 MeV neutrons can well reveal the interactional mechanism between incident particle and target nucleus, and deepen the understanding of nuclear force and nuclear structure. The cross sections of the $^{63}Cu(n,\alpha)^{60m+g}Co$, $^{65}Cu(n,2n)^{64}Cu$, and $^{65}Cu(n,p)^{65}Ni$ reactions around 14 MeV have been obtained by many investigators who can be found in experimental nuclear reaction data (EXFOR) [1], but most of them were obtained before 1980 and there were large discrepancies in those data. Furthermore, there were also discrepancies in the results of different investigators obtained after 1980. Thus it is necessary to make further precision measurements for the cross sections of the copper isotopes around 14 MeV neutrons. In the present work, the cross sections for the $^{63}Cu(n,\alpha)^{60(m+g)}Co$, $^{65}Cu(n,2n)^{64}Cu$, and $^{65}Cu(n,p)^{65}Ni$ reactions have been studied in the neutron energy range of 13.5–14.8 MeV using the activation technique. The obtained results in present work are discussed and compared with the previous works.

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2 Experimental

Nuclear reaction cross-section values were measured by activation and identification of the radioactive products. The details have been described in many publications [2–5]. Here we give only some salient features relevant to the present measurements.

The natural copper foils of 99.99% purity and 2 mm thickness were made into circular samples with a diameter of 2.0 cm. Each of them was sandwiched between two disks of thin niobium (purity better than 99.99% and 1 mm thickness) of the same diameter, and was then wrapped in 1 mm thick cadmium foil (purity better than 99.95%) to avoid the effect of the ^{63}Cu(n,γ)^{64}Cu reaction induced by thermal neutron to the ^{65}Cu(n,2n)^{64}Cu reaction.

The irradiation of the samples was carried out at the K-400 Neutron Generator at the Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics. Neutrons in the 14 MeV region with a yield of about 5×10^{10} n/s, were produced by the ^{3}H(d,n)^{4}He reaction with a deuteron beam energy of 255 keV and a beam current of 350 μA. The solid tritium–titanium (T–Ti) target used in the generator was about 2.19 mg/cm^2 thick. The neutron flux was monitored by the accompanying α-particles during the irradiation so that corrections could be made for small variations in the yield. The groups of samples were placed at 0°, 45°, 90°, and 135° angles relative to the deuteron beam direction and the distances of samples from the T–Ti target were about 3–5 cm. The neutron energies in the measurements were determined beforehand by the method of cross section ratios for the ^{90}Zr(n,2n)$^{89m+g}$Zr and ^{93}Nb(n,2n)^{92m}Nb reactions [6].

The activated samples were studied for their γ-activities by using a well-calibrated GEM-60P coaxial high-purity germanium (HPGe) detector, of which the crystal diameter is 70.1 mm, the crystal length is 72.3 mm, the relative efficiency is 68%, and the energy resolution is 1.69 keV FWHM at 1.33 MeV for ^{60}Co. The efficiency of the detector was pre-calibrated using various standard γ sources. Activities of decay γ-rays from the product radionuclides were recorded 9 cm away from the detector.

The decay characteristics of the product radionuclides and the natural abundance of the target isotopes are summarized in Table 1 [7]. But the abundance of ^{93}Nb came from Firestone et al. [8] because no abundance is given in literature [7].

3 Results and discussion

The cross sections were calculated using the equation proposed by Kong et al. [9].

The cross sections of the ^{63}Cu(n,α)$^{60(m+g)}$Co,^{65}Cu(n,2n)^{64}Cu, and ^{65}Cu(n,p)^{65}Ni reactions were obtained relative to those of the ^{93}Nb(n,2n)^{92m}Nb reaction. The cross section values of the monitor reaction ^{93}Nb(n,2n)^{92m}Nb were 457.9 ± 6.8, 459.8 ± 6.8, 459.8 ± 6.8 and 459.7 ± 5.0 mb at neutron energies of 13.5, 14.1, 14.4 and 14.8 MeV, respectively [10]. Our results obtained in this work are summarized in Tables 2, 3, and 4 and plotted in Figs. 1, 2, and 3. The cross sections of the ^{63}Cu(n,α)$^{60m+g}$Co,^{65}Cu(n,2n)^{64}Cu, and ^{65}Cu(n,p)^{65}Ni reactions around 14 MeV neutrons have been obtained by about 20, more than 40, and 30 laboratories, respectively [1]. The previous measurements for which only the results published after 1980 are selected are also summarized in Tables 2, 3, and 4 and plotted in Figs. 1, 2, and 3 for comparison.

In this work, corrections were made for the fluctuation of the neutron flux during the irradiation, γ-ray self-absorption in the sample, the sample geometry. The main uncertainties in our work come from the counting statistics (0.3–2.8%), the standard cross sections uncertainties (1.1–1.5%), detector efficiency (2%), the weight of samples (0.1%), the sample geometry (1%), the self-absorption of the γ-ray (1.0%), and the fluctuation of the neutron flux (1%), and so on.

For the ^{63}Cu(n,α)$^{60(m+g)}$Co reaction, it can be seen from Table 2 and Fig. 1 that the results in the present work decrease with increasing neutron energy around 14 MeV. Our results are in excellent agreement with the values of Semkova et al. [12], Meadows et al. [13], Ikeda et al. [14], Konno et al. [15], Csikai et al. [16], and Greenwood [19] within the experimental uncertainties at the neutron energy range of 13.5–14.8 MeV, and with the values of Filatenkov [11] at the neutron energies 13.5 MeV and 14.1 MeV. The results of Lu et al. [17] are in agreement, within the experimental uncertainties, with those of Wang et al. [18], and these values are 20–25% higher than the other results. The possible reasons of a large difference between the

Table 1 Reactions and associated decay data of activation products

Reaction	Abundance of target isotope (%)	Half-life of product	E_γ (keV)	I_γ (%)
^{63}Cu(n,α)$^{60(m+g)}$Co	69.15	1925.28 d	1332.492	99.9826
^{65}Cu(n,2n)^{64}Cu	30.85	12.701 h	1345.77	0.475
^{65}Cu(n,p)^{65}Ni	30.85	2.51719 h	1481.84	23.59
^{93}Nb(n,2n)^{92m}Nb	100[a]	10.15 d	934.44	99.15

[a] We used the value given by Firestone et al. [8]

Table 2 Summary of the cross section for the $^{63}Cu(n,\alpha)^{60(m+g)}Co$ reaction around 14 MeV neutrons

Reaction	This work		Literature values		
	E_n (MeV)	σ (mb)	E_n (MeV)	σ (mb)	References
$^{63}Cu(n,\alpha)^{60(m+g)}Co$	13.5 ± 0.2	44.8 ± 2.2	13.47	47.6 ± 2.6	[11]
	14.1 ± 0.2	43.9 ± 2.4	13.64	45.9 ± 1.5	[11]
	14.4 ± 0.2	41.4 ± 2.1	13.88	45.9 ± 2.5	[11]
	14.8 ± 0.2	38.4 ± 1.9	14.05	45.7 ± 1.3	[11]
			14.28	45.9 ± 1.3	[11]
			14.44	46.1 ± 1.6	[11]
			14.63	43.3 ± 1.4	[11]
			14.86	42.8 ± 1.2	[11]
			13.35	45.07 ± 2.16	[12]
			14.7	41.6 ± 2.3	[13]
			14.5	43.8 ± 2.5	[14]
			14.8	40.4 ± 2.3	[14]
			13.32	46 ± 2.6	[15]
			13.56	45.6 ± 2.5	[15]
			13.75	45.8 ± 2.5	[15]
			13.98	45.1 ± 2.4	[15]
			14.22	43.3 ± 2.4	[15]
			14.42	41.8 ± 2.3	[15]
			14.66	41.1 ± 2.2	[15]
			14.91	39.8 ± 2.2	[15]
			14.5	45 ± 2	[16]
			14.09	50.2 ± 1.9	[17]
			14.58	49 ± 1.7	[17]
			14.8	46.6 ± 1.7	[17]
			13.64	58.3 ± 3.1	[18]
			13.79	56.3 ± 2.4	[18]
			14.03	53.4 ± 2	[18]
			14.33	50.8 ± 1.9	[18]
			14.6	48.4 ± 1.7	[18]
			14.8	47.4 ± 1.7	[18]
			14.5	41.2	[19]
			14.65	40.4	[19]
			14.8	38.4	[19]
			14.85	38.8	[19]
			14.9	40.1	[19]

results in Fig. 1 are due to the differences in experimental methods, equipments, monitor reactions, nuclear parameters, and datum processing methods.

The $^{65}Cu(n,2n)^{64}Cu$ reaction cross-section values were presented in Table 3 and Fig. 2. It shows that the results in the present work increase with increasing neutron energy around 14 MeV. Our results are in excellent agreement with values of Mannhart and Schmidt [20], Harun et al. [22], Ikeda et al. [26], Meadows et al. [27], and Ghanbari and Robertson [28] within the experimental uncertainties at the neutron energy range of 13.5–14.8 MeV, and with the values of Filatenkov [11], Hafiz [21], Ikeda et al. [23] and Csikai [30] at some experimental energy point. The results of Filatenkov [11] are in agreement, within the experimental uncertainties, with those of Hafiz [21], Molla et al. [24], Winkler and Ryves [29] and Csikai [30] at the neutron energy range of 14.1–14.8 MeV, and these values are higher than the other results.

For the $^{65}Cu(n,p)^{65}Ni$ reaction, it can be seen from Table 4 and Fig. 3 that the cross section values in the present work decrease with increasing neutron energy around 14 MeV and our results are in agreement with those of Mannhart and Schmidt [20], Harun et al. [22], Ercan et al. [25], Ikeda et al. [26], Meadows et al. [27], Uwamino

Table 3 Summary of the cross section for the $^{65}Cu(n,2n)^{64}Cu$ reaction around 14 MeV neutrons

Reaction	This work		Literature values		
	E_n (MeV)	σ (mb)	E_n (MeV)	σ (mb)	References
$^{65}Cu(n,2n)^{64}Cu$	13.5 ± 0.2	781 ± 33	13.56	834 ± 49	[11]
	14.1 ± 0.2	842 ± 36	13.74	865 ± 37	[11]
	14.4 ± 0.2	850 ± 36	13.96	921 ± 62	[11]
	14.8 ± 0.2	898 ± 37	14.19	865 ± 37	[11]
			14.42	948 ± 43	[11]
			14.61	900 ± 38	[11]
			14.78	967 ± 50	[11]
			13.395	785.3 ± 28.8	[20]
			13.531	807.6 ± 33.2	[20]
			13.699	823.6 ± 34.7	[20]
			13.967	846 ± 32.9	[20]
			13.984	836.8 ± 37.3	[20]
			14.327	909.2 ± 42.6	[20]
			14	826 ± 62.4	[21]
			14.31	913.5 ± 64.8	[21]
			14.57	914.8 ± 62.9	[21]
			14.69	979.3 ± 67.9	[21]
			14.71	960.7 ± 63.2	[21]
			14.8	850.41 ± 103.66	[22]
			13.4	760 ± 10	[23]
			13.6	800 ± 20	[23]
			13.8	820 ± 10	[23]
			14	840 ± 10	[23]
			14.2	870 ± 10	[23]
			14.4	920 ± 10	[23]
			14.7	920 ± 10	[23]
			15	960 ± 20	[23]
			13.9	922 ± 50	[24]
			14.1	929 ± 52	[24]
			14.51	1001 ± 47	[24]
			14.71	1006 ± 63	[24]
			14.6	971 ± 200	[25]
			13.33	751 ± 49	[26]
			13.57	803 ± 52	[26]
			13.75	809 ± 52	[26]
			13.98	839 ± 54	[26]
			14.22	872 ± 56	[26]
			14.43	885 ± 57	[26]
			14.67	902 ± 58	[26]
			14.94	961 ± 62	[26]
			14.74	924 ± 46	[27]
			14.8	970 ± 56	[28]
			13.692	823.4 ± 20.6	[29]
			14.473	931.8 ± 13.1	[29]
			14.822	961 ± 14.4	[29]
			13.5	840 ± 50	[30]
			13.77	862 ± 52	[30]

Table 3 continued

Reaction	This work		Literature values		
	E_n (MeV)	σ (mb)	E_n (MeV)	σ (mb)	References
			14.1	905 ± 54	[30]
			14.39	955 ± 57	[30]
			14.66	975 ± 59	[30]
			14.78	980 ± 59	[30]

Table 4 Summary of the cross section for the $^{65}Cu(n, p)^{65}Ni$ reaction around 14 MeV neutrons

Reaction	This work		Literature values		
	E_n (MeV)	σ (mb)	E_n (MeV)	σ (mb)	References
$^{65}Cu(n, p)^{65}Ni$	13.5 ± 0.2	19.9 ± 1.0	13.56	22.4 ± 0.7	[11]
	14.1 ± 0.2	19.8 ± 0.9	13.74	20.4 ± 1.3	[11]
	14.4 ± 0.2	18.9 ± 0.7	13.96	21.6 ± 0.9	[11]
	14.8 ± 0.2	18.4 ± 0.8	14.19	20.5 ± 1.2	[11]
			14.42	20.4 ± 0.7	[11]
			14.61	21.5 ± 0.6	[11]
			14.78	20.7 ± 0.9	[11]
			13.395	20.48 ± 0.93	[20]
			13.967	20.66 ± 0.82	[20]
			14.8	18.83 ± 1.7	[22]
			13.9	22.4 ± 2.3	[24]
			14.1	22.7 ± 2.3	[24]
			14.51	22.5 ± 2.3	[24]
			14.71	22.7 ± 2.3	[24]
			14.6	14 ± 5	[25]
			13.34	17.4 ± 1.4	[26]
			13.57	20.2 ± 1.8	[26]
			13.76	17.7 ± 1.8	[26]
			13.99	17.7 ± 1.5	[26]
			14.23	21 ± 1.6	[26]
			14.43	19.4 ± 1.8	[26]
			14.67	20.1 ± 1.7	[26]
			14.93	18.8 ± 1.5	[26]
			14.74	19.16 ± 0.88	[27]
			13.5	17 ± 9.7	[31]
			14.5	24.01 ± 13	[31]
			14.7	20 ± 1	[32]
			14.8	21 ± 2	[33]

et al. [31], Pepelnik et al. [32], and Gupta et al. [33] within the experimental uncertainties at the neutron energy range of 13.5–14.8 MeV, and with the values of Filatenkov [11], and Molla et al. [24] at some experimental energy points.

4 Conclusion

We have measured the cross sections for the $^{63}Cu(n,\alpha)^{60(m+g)}Co$, $^{65}Cu(n,2n)^{64}Cu$ and $^{65}Cu(n,p)^{65}Ni$ reactions at neutron energies of 13.5–14.8 MeV. In our experiment, the new T-Ti target and natural high-purity copper foils were used, the samples were wrapped in thin cadmium foil during the irradiation so the influence of the (n,γ) reactions of thermal neutrons was reduced.

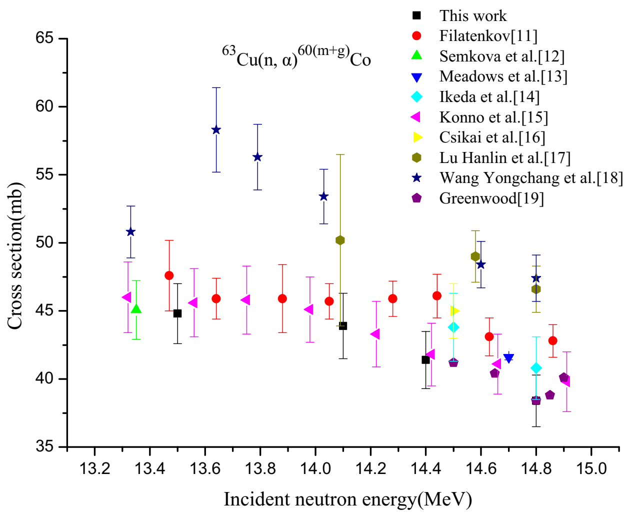

Fig. 1 (Color online) Cross section of the ^{63}Cu(n,α)$^{60(m+g)}$Co reaction

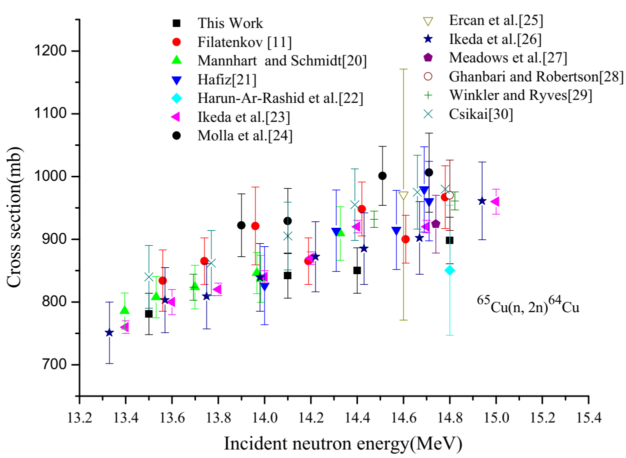

Fig. 2 (Color online) Cross section of the ^{65}Cu(n, 2n)^{64}Cu reaction

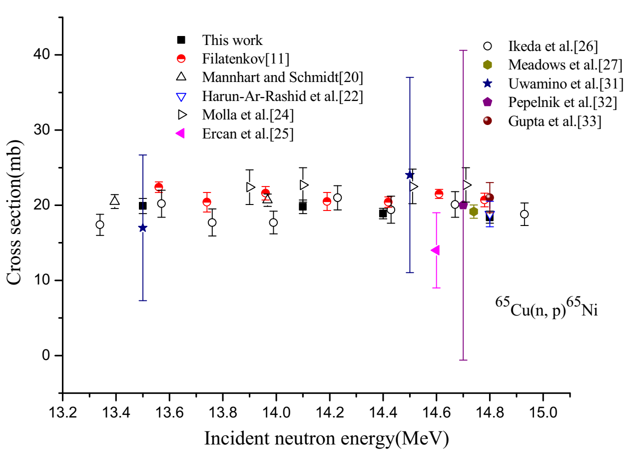

Fig. 3 (Color online) Cross section of the ^{65}Cu(n, p)^{65}Ni reaction

Furthermore, while the measured cross sections were calculated the most recent and accurate nuclear data so far were adopted. All these mentioned above make the measured results reliable and credible. The new data measured in this work are useful for further strengthening the database and giving new evaluations of the 14 MeV neutron cross sections.

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