Measurements of the ^{71}Ga(n, 2n)^{70}Ga cross section in the neutron energy range of 13.5–14.7 MeV

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Cross sections for ^{71}Ga(n, 2n)^{70}Ga reaction have been measured in the neutron energies of 13.5–14.7 MeV using the activation technique, with the gallium sample irradiated under low neutron fluxes and short irradiation time. The data for ^{71}Ga(n, 2n)^{70}Ga reaction cross sections are reported to be 782 ± 80, 896 ± 91, and 1169 ± 120 mb at 13.5 ± 0.2, 14.1 ± 0.1, and 14.7 ± 0.2 MeV incident neutron energies, respectively. The results are discussed and compared with the literature. From the comparison we see that the values show well agreement with the theoretical results calculated from the code STAPRE.

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As an important semiconducting material, gallium has been studied extensively. In 1996 GaAs samples were irradiated with fast neutrons at fluxes 3.93×10^{13} cm^2 s^{-1} by K. Kuriyama *et al.* [1]. Using the Raman scattering and the x-ray diffraction methods, phonon shifts can be related to the defect structure in neutron transmutation doped semi-insulating GaAs. They showed that the changes of GaAs samples in electrical transport properties result from Ge and Se impurities that are transmuted from Ga and As atoms by (n, γ) reactions, respectively. In fact, Ge impurities, when GaAs samples are irradiated with fast neutrons, come from the β^- decay of ^{70}Ga and ^{72}Ga and the electron capture of ^{74}As that are the products of ^{69}Ga(n, γ)^{70}Ga, ^{71}Ga(n, 2n)^{70}Ga, ^{75}As(n, α)^{72}Ga, and ^{75}As(n, 2n)^{74}As, respectively. The threshold energy for ^{71}Ga(n, 2n)^{70}Ga, ^{75}As(n, α)^{72}Ga, and ^{75}As(n, 2n)^{74}As are 9.43, 10.38, and 12.69 MeV, respectively.

In the neutron transmutation doping (NTD) experiment the net concentration of transmuted impurities ($N_{\rm NTD}$) is expressed as $N_{\rm NTD} = \phi t \sum n_i \sigma_c^i$, where ϕ is neutron flux, t is the exposure time, n_i is concentration of the ith isotope, and σ_c^i is its capture cross section. The value of $\sum n_i \sigma_c^i$ in GaAs is estimated to be $\simeq$0.16 cm^{-1} [2–4], $N_{\rm NTD}$ is determined precisely by the thermal neutron fluence (ϕt). But, the samples were irradiated for 3.9 and 19.5 h, respectively, 30 days after irradiation the measured values showed a contribution of nuclear reaction with fast neutrons, i.e., ^{75}As(n, 2n)^{74}As [4]. Because the threshold energy for ^{71}Ga(n, 2n)^{70}Ga is less than the threshold energy for ^{75}As(n, 2n)^{74}As, there is a contribution of the ^{71}Ga(n, 2n)^{70}Ga. The ^{71}Ga(n, 2n)^{70}Ga reaction cross section is very important in research of neutron transmutation doping.

The reaction cross sections of ^{71}Ga(n, 2n)^{70}Ga around the neutron energies of 14 MeV were obtained by various studies, but most were obtained before 1980. Furthermore, there was disagreement in these data thus it is necessary to measure them again and obtain excitation functions around the neutron energies of 14 MeV. Recent detailed work about excitation functions for neutron-induced reactions on some isotopes of gallium in the energy range of 6.2–12.4 MeV was reported by Nesaraja *et al.* [5,6]. The reaction cross sections of ^{69}Ga(n, 2n)^{68}Ga, ^{69}Ga(n, p)^{69m}Zn, ^{71}Ga(n, p)^{71m}Zn, and ^{71}Ga(n, $n'\alpha$)^{67}Cu in the neutron energies of 13.5–14.6 MeV for gallium have been studied by Zhongsheng Pu *et al.* [7].

In the present work, ^{71}Ga(n, 2n)^{70}Ga reaction cross sections in the neutron energies of 13.5–14.7 MeV have been studied. Pure gallium metal was used as the target material. The reaction yields were obtained by an absolute measurement of the γ activities of the product nuclei using a coaxial high-purity germanium detector. The neutron energies for these measurements were determined by cross-section ratios for ^{90}Zr(n, 2n) $^{89m+g}$Zr and ^{93}Nb (n, 2n) ^{92m}Nb reactions [8].

Irradiation of the samples was carried out at the ZF-300-Intense Neutron Generator at Lanzhou University [9] and lasted 20 min to 1 h with a yield of about 2×10^{10}–4×10^{10} n s^{-1}. Neutrons were produced by the ^{3}H(d, n)^{4}He reaction with an effective deuteron beam energy of 134 keV and a beam current of 0.2–0.5 mA. The tritium-titanium (T-Ti) target used in the generator was 1.3–1.4 mg/cm^2 thick. The neutron fluence rate was monitored by the accompanying α particle so that corrections could be made for small variations in the yield. The accompanying α particle monitor is shown in Fig. 1. The Au-Si surface barrier detector used in 135° accompanying α-particle tube was at a distance of 119.7 cm from the target. The groups of samples were placed at 0–135° angles relative to the beam direction and centered about the T-Ti target at distances of 3.8–9.2 cm. Cross sections for the ^{27}Al(n, α)^{24}Na reaction were selected as monitors to measure the ^{71}Ga(n, 2n)^{70}Ga reaction cross section. In this experiment, the samples of aluminum and gallium were always made into circular foils with a diameter of about 2 cm. The samples in each group were sandwiched between two Al foils.

The γ-ray activities of ^{92m}Nb, $^{89m+g}$Zr, ^{24}Na, and ^{70}Ga were determined by a CH8403 coaxial high-purity germanium detector (sensitive volume 110 cm^3) (made in the People's Republic of China) with a relative efficiency of 20% and an energy resolution of 3 keV at 1.33 MeV. The efficiency of the detector was calibrated using a standard γ-ray source. Standard Reference Material 4275 was obtained from the National Institute of Standards and Technology (Washington,

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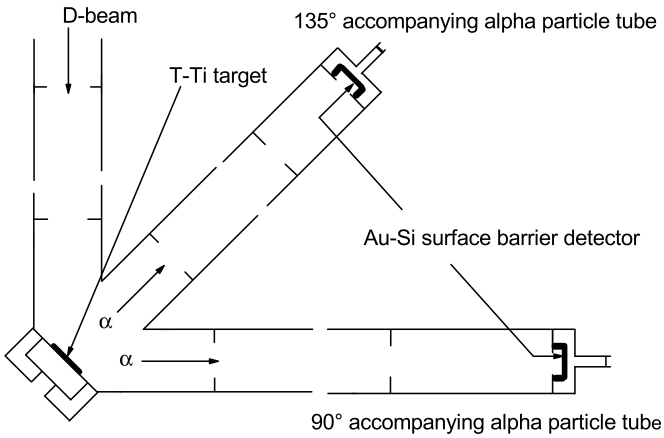

FIG. 1. ZF-300-Intense Neutron Generator neutron flux monitor.

DC, USA). An absolute efficiency calibration curve was obtained at 20 cm from the surface of the germanium crystal. This distance is large enough for the summing loss effects to be negligible. In our case, however, we needed to calibrate the efficiency at 2 cm, the actual counting position that was used because of the weak activity of the sample. Therefore, we selected a set of monoenergetic sources and placed them at two positions (20 and 2 cm) successively to measure their efficiency ratios, so that we were able to evaluate the efficiency ratio curve as a function of energy. The absolute efficiency calibration curve at 2 cm was obtained from the calibration curve at 20 cm and the efficiency ratio curve. The error in the absolute efficiency curve at 2 cm was estimated to be 1.5%, whereas the error of the activity of the standard source is 1%.

The decay characteristics of the product radioisotopes and the natural abundances of the target isotopes under investigation are summarized in Table I [10].

The measured cross sections σ_x were calculated by the following equation [11]:

$$\sigma_x = \frac{[S\varepsilon I_\gamma \eta KMD]_0[\lambda AFC]_x}{[S\varepsilon I_\gamma \eta KMD]_x[\lambda AFC]_0}\sigma_0, \qquad (1)$$

where σ_0 is the monitor reaction cross section, the subscript 0 represents the term corresponding to the monitor reaction and the subscript x corresponds the measured reaction, ε is the full-energy peak efficiency of the measured characteristic γ ray, I_y is the γ-ray intensity, η is the abundance of the target nuclide, M is the mass of sample,

TABLE I. Reactions and decay data of products.

Abundance of target isotope (%)	Reaction	Product half-life	E_γ(keV)	I_γ(%)
39.89	^{71}Ga$(n,2n)^{70}$Ga	21.14m	176.17	0.29
100	^{27}Al$(n,\alpha)^{24}$Na	14.96h	1368.63	100
100	^{93}Nb$(n,2n)^{92m}$Nb	10.15d	934.44	100
51.45	^{90}Zr$(n,2n)^{89m+g}$Zr	78.41h	908.96	99.87

$D = e^{-\lambda t_1} - e^{-\lambda t_2}$ 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, F is the total correction factor of the activity: $F = f_s \times f_c \times f_g$, where f_s, f_c, and f_g are correction factors for self-absorption of the sample at given γ energy and the coincidence sum effect of cascade γ rays in the investigated nuclide and in the counting geometry, respectively, K is neutron fluence fluctuation factor: $K = [\sum_{i=1}^{l} \Phi_i(1 - e^{-\lambda\Delta t_i})e^{-\lambda T_i}]/\Phi S$, where l is the number of time intervals into which the irradiation time is divided, Δt_i is duration of the ith time interval, λ is the decay constant, 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 in Δt_i, Φ is the neutron flux averaged over the sample in the total irradiation time T and $S = 1 - e^{-\lambda T}$ is the growth factor of product nuclide.

The cross sections measured in the present work are summarized and compared with the values given in the literature in Table II.

The values of cross sections for the monitor reaction ^{27}Al$(n,\alpha)^{24}$Na are taken from Filatenkov *et al.* [18]. The errors in our work result from neutron energy (1 ∼ 1.5%), irradiation time (0.1%), counting statistics (5 ∼ 8.2%), decay data (1%), standard cross-sectional uncertainties (1.5 ∼ 2.1%), detector efficiency (1.5%), weight of samples (0.5%), neutron fluence fluctuation (2.0%), self-absorption of γ rays (1.2%), the counting geometry (2.6%) and the coincidence sum effect of cascade γ rays (1.0%).

From Table II and Fig. 2 it can be seen, for our work, that in the neutron energies of 13.5–14.7 MeV, the cross-sections for ^{71}Ga$(n,2n)^{70}$Ga reaction increase with the increasing of neutron energy; at the neutron energy 14.7 MeV, our result is in agreement with Csikai within experimental error, whereas at the neutron energy 14.1 MeV our result is between

TABLE II. Cross sections for ^{71}Ga$(n,2n)^{70}$Ga reaction.

This work σ(mb)	E_n(MeV)	Literature values σ(mb)	E_n(MeV)	
782 ± 80	13.5 ± 0.2			
896 ± 91	14.1 ± 0.1	1166 ± 58	14.1 ± 0.3	Viktorov and Sjablin (1972) [12]
		700 ± 80	14.1	Casanova and Sanchez (1976) [13]
		1085 ± 28	14.5	Bödy and Csikai (1973) [14]
		700 ± 105	14.5	Paul and Clarke (1953) [15]
1169 ± 120	14.7 ± 0.2	961 ± 100	14.7 ± 0.3	Csikai and Peto (1967) [16]
		2180 ± 218	14.8 ± 0.05	Khurana and Hans (1961) [17]

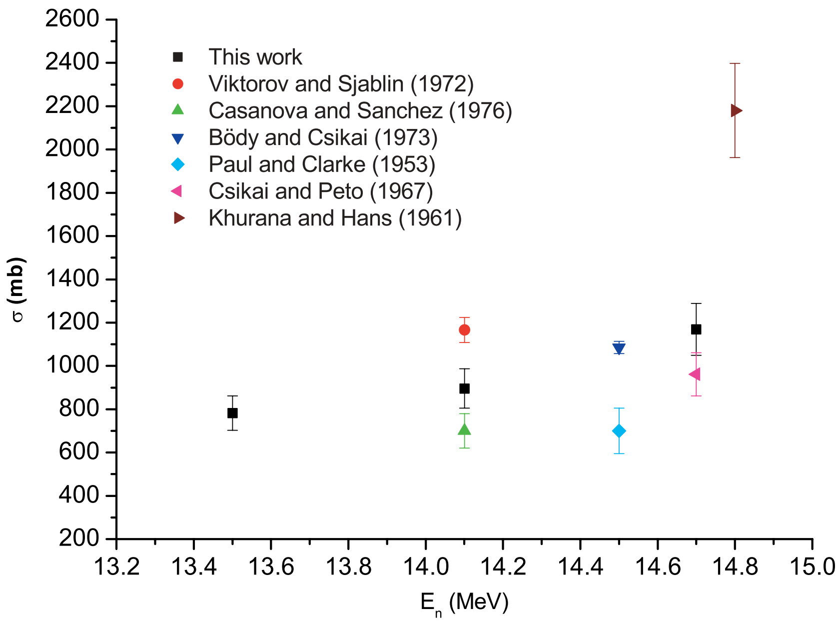

FIG. 2. (Color online) Cross sections of ^{71}Ga$(n, 2n)^{70}$Ga reaction.

those of Casanova and Viktorov. It must be pointed that the cross section for ^{71}Ga$(n, 2n)^{70}$Ga reaction at neutron energy 13.5 MeV is first reported here. The values agree very well with the nuclear model calculations using the code STAPRE [5]. Our experimental values justify the excitation functions for neutron induced reactions ^{71}Ga$(n, 2n)^{70}$Ga in the energy range of 13.5–14.7 MeV.

In summary, in this report under low neutron fluxes and short irradiation time, pure gallium was irradiated and thus the cross sections for the ^{71}Ga$(n, 2n)^{70}$Ga reaction were obtained at the neutron energies of 13.5, 14.1, and 14.7 MeV. Our results may be useful for the research of the neutron transmutation doping of gallium semiconducting material. The results are expected to help in new evaluations of the 14-MeV neutron cross sections.

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