Activation cross section and isomeric cross section ratio for the $^{76}$Ge(n, 2n)$^{75m, g}$Ge process

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Abstract. We measured neutron-induced reaction cross sections for the $^{76}$Ge(n, 2n)$^{75m, g}$Ge reactions and their isomeric cross section ratios $\sigma_m/\sigma_g$ at three neutron energies between 13 and 15 MeV by an activation and off-line $\gamma$-ray spectrometric technique using the K-400 Neutron Generator at the Chinese Academy of Engineering Physics (CAEP). Ge samples and Nb monitor foils were activated together to determine the reaction cross section and the incident neutron flux. The monoenergetic neutron beams were formed via the $^3$H(d, n)$^4$He reaction. The pure cross section of the ground state was derived from the absolute cross section of the metastable state and the residual nuclear decay analysis. The cross sections were also calculated using the nuclear model code TALYS-1.8 with different level density options at neutron energies varying from the reaction threshold to 20 MeV. Results are discussed and compared with the corresponding literature data.

1 Introduction

Activation cross sections of neutron threshold reactions on medium mass nuclei are of considerable interest for testing nuclear models. Furthermore, the data for potential first wall constituents of a fusion reactor are of practical importance, especially for estimating nuclear heating, nuclear transmutation, and radiation damage effects [1].

A lot of experimental data on neutron induced cross sections for fusion reactor technology applications have been reported and great efforts have been devoted to compilations and evaluations [2,3]. We chose to study the neutron-induced reaction cross sections of germanium-76 mainly for four reasons. First, the germanium is an important semi-conducting material for the nuclear technology and integrated circuits; second, the $^{76}$Ge nucleus lies between the magic numbers of 28 and 50; shape coexistence plays a prominent role in its structure [4], and $^{76}$Ge may be a rare example of a nucleus exhibiting rigid triaxial deformation in its low-lying states [5,6]; third, the germanium-75 isomeric pair is an example of the isomeric pair type in which the half-life of the metastable state is shorter than that of the ground state and decays almost entirely by isomeric transition (see fig. 1); fourth, although there are enough data for metastable cross sections for the $^{76}$Ge(n, 2n)$^{75m}$Ge reactions in the energy range from 13 to 15 MeV [7–14], only three direct measurements for the ground state cross section $\sigma_g$ have been performed separately [7,9,14]. The experimental and theoretical data for the $^{76}$Ge(n, 2n)$^{75g}$Ge reaction cross section are inconsistent. In the energy region around 14 MeV, the experimental cross sections [7,9,14] are clustered around 550 mb, while the results of TALYS are centered around 300 mb.

Therefore, we aimed to measure the pure ground state cross section $\sigma_g$ directly by means of the analysis methods of residual nuclear decay [15–17] and to compare the experimental results to those obtained by the statistical model calculation.

2 Experimental

2.1 Samples and irradiations

Two disks, about 0.1 and 0.19 cm in thickness and 20 mm in diameter, were formed by pressing approximately 1.7 and 3.2 g of Ge (99.99% pure) powder (natural isotopic composition) at 980 MPa to form a pellet. The samples were irradiated near the target and sandwiched between two Nb foils (99.99% pure, 0.12 mm thick) with the same diameter which were used to monitor the neutron fluence via the $^{93}$Nb(n, 2n)$^{92m}$Nb reaction.
Irradiation of the samples was carried out at the K-400 Neutron Generator at the Chinese Academy of Engineering Physics (CAEP) and lasted approximately 3 minutes with a neutron yield \((3–4) \times 10^{10}\) n/s in 4π solid angle. Neutrons were produced by the T(d,n)\(^4\)He reaction with an effective deuteron beam energy of 135 keV, beam current of 240 \(\mu\)A, and the diameter of the deuterium beam spot was under 0.6 cm. The groups of samples were placed at 0°, 90° and 135° relative to the beam direction and centered a 0.566 mg/cm\(^2\) thick tritium-molybdenum (T-Mo) target at a distance of \(\sim 50\) mm. In order to avoid the deposition of deuterium in the target, the new T-Mo target is used. The diameter of the active zone of the T-Mo target is 1.2 cm. The sample positions in the experiment are shown in fig. 2. In order to avoid the effect of low energy neutrons, samples were wrapped in cadmium foil. During irradiation, the neutron flux was monitored by accompanying \(\alpha\)-particles so that corrections could be made for small variations of the yield. Cross sections for the \(^{93}\)Nb(n, 2n)\(^{92m}\)Nb monitor reaction were taken from [19].  

2.2 Measurement of radioactivity

High-resolution gamma-ray spectroscopy was applied to the activated disks. The measurements were carried out using low-background high-purity germanium (HPGe) detector (ORTEC, model GEM 60P, crystal diameter 70.1 mm, crystal length 72.3 mm) with a relative efficiency of \(\sim 68\)\% and an energy resolution of 1.69 keV at 1.332 MeV for \(^{57}\)Co. The distance from sample to detector was 2.0 cm. To avoid excessive death time, the sample was cooled for 2 minutes after irradiation. Figure 3 shows the typical spectra acquired from the Ge samples during the measurement of the isomeric and ground state, where the \(\gamma\)-rays of interest have been marked. The \(\gamma\)-ray intensities and half-lives used in the analysis are summarized in table 1 [18]. The detector was pre-calibrated for energy and efficiency by using the standard gamma ray sources \(^{54}\)Mn, \(^{57}\)Co, \(^{60}\)Co, \(^{109}\)Cd, \(^{133}\)Ba, \(^{137}\)Cs, \(^{152}\)Eu, \(^{241}\)Am and \(^{226}\)Ra.

2.3 Calculation of cross sections and their uncertainties

The cross sections were calculated by the following formula [16,17]:

\[
\sigma_x = \frac{[S\varepsilon I_\gamma \eta KMD]_0}{[S\varepsilon I_\gamma \eta KMD]_x} \cdot \frac{[\lambda A FC]_x}{[\lambda A FC]_0} \sigma_0. \tag{1}
\]

where the subscript 0 represents the term corresponding to the monitor reaction and subscript x corresponds to the measured reaction; \(\varepsilon\) is the full-energy peak efficiency of the measured characteristic gamma-ray; \(I_\gamma\) is the gamma-ray intensity; \(\eta\) is the abundance of the target nuclide; \(M\) is the mass of the sample; \(D = e^{-\lambda t_1} - e^{-\lambda(t_1+t_2)}\) is the counting collection factor; \(S = 1 - e^{-\lambda T}\) is the growth factor of the product nuclide, \(T\) is the total irradiation time; \(t_1\) is the total cool time and \(t_2\) is the total measurement time; \(A\) is the atomic weight; \(C\) is the measured full energy peak area; \(\lambda\) is the decay constant; \(K\) is the neutron...
Table 1. Neutron induced nuclear reactions on germanium and niobium and decay data of associated activation products (taken from [18]).

| Reaction | Abundance of target isotope (%) | Half-life of product | E-threshold (MeV) | Mode of decay (%) | E_γ (keV) | I_γ (%) |
|----------|---------------------------------|----------------------|------------------|------------------|-----------|---------|
| 76Ge(n,2n)75m Ge | 7.7312 | 47.75 s | 9.694 | IT(99.97) | 139.68 | 39.51 |
| 76Ge(n,2n)75 Ge | 7.7312 | 82.784 m | 9.552 | β(100) | 264.6 | 11.4 |
| 93Nb(n,2n)92m Nb | 100 | 10.152 d | 8.972 | EC(100) | 934.44 | 99.15 |

Table 2. Correction factors for the self-absorption of the sample at a given gamma-ray energy.

| Gamma-energy (keV) | µ/ρ (cm²/g) | µ(cm⁻¹) | Samples | Correction factors |
|---------------------|------------|--------|----------|--------------------|
|                     | no. | thickness h (cm) |                    |                    |
| 139.68              | 1   | 0.1863 | 1.163    |
| 264.6              | 2   | 0.9948 | 1.081    |

Fig. 4. Sketch map of the time during which the sample is irradiated, cooled, and measured.

While calculating the cross sections of the 76Ge(n,2n) 75m Ge reaction, C_γ in (1) should be the result of the measured full-energy peak area (at 264.6 keV γ-ray) minus the contribution from 75m Ge via 75m Ge IT(99.97%) 75m Ge (counting C''_mg). According to the regulation of growth and decay of artificial radioactive nuclide we can deduce a formula to calculate the number of the daughter nucleus 75m Ge at any moment t during the irradiation (see fig. 4) as follows:

\[ N_m(t) = \frac{\phi_0\sigma_m}{\lambda_m}(1 - e^{-\lambda_m t}), \]

where σ_m is the cross sections for formation of the metastable, λ_m is the decay constant of this state, φ_0 is the mean neutron flux in neutrons/cm²/sec, and N is the number of target nuclei.

At any moment t during the irradiation, the number of 75m Ge from the 75m Ge procedure meets the following equation:

\[ \frac{dN_γ(t)}{dt} = P_{mg}\lambda_mN_m(t) - \lambda_gN_γ(t), \]

where P_{mg} is the fraction of disintegrations of the metastable state that produces ground state nuclides (branching ratio), λ_g is the decay constant of 75m Ge.
Using eqs. (5) and (6) and the initial condition: $t = 0$, $N_g(0) = 0$, and working out $N_g(t)$,

$$
N_g(t) = N_0 \phi \sigma_m P_{mg} \left[ \left( \frac{1}{\lambda_g} - \frac{1}{\lambda_g - \lambda_m} e^{-\lambda_m t} \right) - \left( \frac{1}{\lambda_g} - \frac{1}{\lambda_g - \lambda_m} e^{-\lambda_g t} \right) \right].
$$

(7)

At the moment of the end of the irradiation ($t = T$), the number of $^{75m}\text{Ge}$ and $^{75g}\text{Ge}$ from $^{75m}\text{Ge} \rightarrow ^{75g}\text{Ge}$ are $N_m(T)$ and $N_g(T)$, respectively, which can be obtained by using eqs. (5) and (7).

At any moment $t'$ after the irradiation, the number of $^{75m}\text{Ge}$ is

$$
N_m(t') = N_m(T) e^{-\lambda_m t'} = \frac{N_0 \phi \sigma_m}{\lambda_m} (1 - e^{-\lambda_m T}) e^{-\lambda_m t'}.
$$

(8)

At any moment after the irradiation $t'$, the number of $^{75g}\text{Ge}$ from $^{75m}\text{Ge} \rightarrow ^{75g}\text{Ge}$ meets eq. (6). Using eqs. (6) and (8) and the initial condition $t' = 0$, $N_g(0) = N_g(T)$ (the number of $^{75g}\text{Ge}$ from $^{75m}\text{Ge} \rightarrow ^{75g}\text{Ge}$ is equal at the end of the irradiation and the start of cooling) and working out $N_g(t')$,

$$
N_g(t') = \frac{N_0 \phi \sigma_m P_{mg}}{\lambda_g - \lambda_m} \left[ (1 - e^{-\lambda_m T}) e^{-\lambda_m t'} - \frac{\lambda_m}{\lambda_g} (1 - e^{-\lambda_g T}) e^{-\lambda_g t'} \right].
$$

(9)

Let $t'$ in eqs. (8) and (9) equal $t'' + t_1$, $t_1$ is the time interval from the end of the irradiation to the start of counting. We can obtain the number of $^{75m}\text{Ge}$ at any moment $t''$ after beginning to detect the characteristic $\gamma$ ray of $^{75m}\text{Ge}$

$$
N_m(t'') = \frac{N_0 \phi \sigma_m}{\lambda_m} (1 - e^{-\lambda_m t_1}) e^{-\lambda_m t''}.
$$

(10)

and the number of $^{75g}\text{Ge}$ from the $^{75m}\text{Ge} \rightarrow ^{75g}\text{Ge}$ procedure at any moment $t''$ after beginning to detect the characteristic $\gamma$ ray of $^{75g}\text{Ge}$

$$
N_g(t'') = \frac{N_0 \phi \sigma_m P_{mg}}{\lambda_g - \lambda_m} \left[ (1 - e^{-\lambda_m T}) e^{-\lambda_m t_1} e^{-\lambda_m t''} - \frac{\lambda_m}{\lambda_g} (1 - e^{-\lambda_g T}) e^{-\lambda_g t_1} e^{-\lambda_g t''} \right].
$$

(11)

During the period $t_2$ of detecting the characteristic $\gamma$ ray, the full-energy peak (FEP) counts $C'_m$ of the characteristic $\gamma$ ray of $^{75m}\text{Ge}$ and $C'_{mg}$ of the characteristic $\gamma$ ray of $^{75g}\text{Ge}$ from the $^{75m}\text{Ge} \rightarrow ^{75g}\text{Ge}$ procedure are

$$
C'_m = \int_0^{T_2} \lambda_m I_m \varepsilon_m N_m(t'') dt'' = \frac{I_m \varepsilon_m \phi \sigma_m}{\lambda_m} \left[ (1 - e^{-\lambda_m T}) e^{-\lambda_m t_1} (1 - e^{-\lambda_m t_2}) \right],
$$

(12)

$$
C'_{mg} = \int_0^{T_2} \lambda_g I_g \varepsilon_g N_g(t'') dt'' = \frac{I_g \varepsilon_g \phi \sigma_m P_{mg}}{\lambda_g - \lambda_m} \left( \frac{\lambda_g}{\lambda_m} (1 - e^{-\lambda_m T}) e^{-\lambda_m t_1} (1 - e^{-\lambda_m t_2}) \right. \left. - \frac{\lambda_m}{\lambda_g} (1 - e^{-\lambda_g T}) e^{-\lambda_g t_1} (1 - e^{-\lambda_g t_2}) \right).
$$

(13)

Using eqs. (12) and (13), $C'_{mg}$ can be written as

$$
C'_{mg} = \frac{P_{mg} \varepsilon_g I_g C'_m (\lambda_g - \lambda_m) S_m D_m - \lambda^2_m S_g D_g)}{\lambda_g - \lambda_m} K_m
$$

where $S_m = 1 - e^{-\lambda_m T}$ and $S_g = 1 - e^{-\lambda_g T}$; $I_m$ and $I_g$ are the gamma ray intensities of the measured metastable and ground state, respectively; $\varepsilon_m$ and $\varepsilon_g$ are the full-energy peak efficiencies of the characteristic gamma-rays of the measured metastable and ground state; $D_m$ and $D_g$ can be written as

$$
D_m = e^{-\lambda_m t_1} - e^{-\lambda_m (t_1 + t_2)}, \quad D_g = e^{-\lambda_g t_1} - e^{-\lambda_g (t_1 + t_2)}
$$

3 Nuclear model calculations

The excitation functions for the reactions were studied theoretically using the numerical nuclear model code TALYS-1.8 [21]. The theoretical calculations were computed using the default parameter values and only changing the choice of the level density models. The level density parameters were calculated using the six different choices of level density models available in TALYS-1.8. The six level density models are given in table 3.

4 Discussions

The cross sections measured in this work are presented in table 4. The uncertainty analysis was carried out using the quadrature method [22]. The principal sources of uncertainty and their estimated values are given in table 5. The total uncertainty lies between 4.5 and 8.7%. The small contribution to the gamma ray activity of products from the $^{74}\text{Ge}(n, \gamma)$ reaction could be ignored because of the very small cross section of the $(n, \gamma)$ reaction in the region of 14 MeV. Furthermore, samples were wrapped in a cadmium foil in order to reduce the contribution of thermal and epithermal effects. For the $^{76}\text{Ge}(n, 2n)$ reaction the cross sections slightly increase with the increasing neutron energy. The various reactions are discussed below.
Table 3. The six different level density models.

| Level density model | Describes                                                                 |
|---------------------|---------------------------------------------------------------------------|
| ldmodel 1           | the constant temperature and Fermi gas model, where the constant temperature model is used in the low excitation region and the Fermi-gas model in the high excitation energy region. The transition energy is around the neutron separation energy. |
| ldmodel 2           | the back-shifted Fermi gas model.                                          |
| ldmodel 3           | the generalized superfluid model.                                          |
| ldmodel 4           | composed of microscopic level densities (Skyrme force) from Goriely’s tables [23]. |
| ldmodel 5           | composed of microscopic level densities (Skyrme force) from Hilaire’s combinatorial tables [23]. |
| ldmodel 6           | microscopic level densities (temperature dependent HFB, Gogny force) from Hilaire’s combinatorial tables [23]. |

Table 4. Summary of cross section measurements.

| Reaction | Cross sections (in mb) at various neutron energies (in MeV) |
|----------|------------------------------------------------------------|
|          | 13.5 ± 0.2       | 14.1 ± 0.2       | 14.8 ± 0.2       |
| ⁷⁶Ge(n,2n)⁷⁵mGe | 870 ± 39         | 899 ± 41         | 910 ± 44         |
| ⁷⁶Ge(n,2n)⁷⁸Ge | 376 ± 31         | 380 ± 33         | 381 ± 30         |
| ⁷⁶Ge(n,2n)⁷⁵Ge | 1246 ± 70        | 1279 ± 74        | 1291 ± 74        |
| ⁹³Nb(n,2n)⁹²mNb | 457.9 ± 6.8 [19] | 459.8 ± 6.8 [19] | 459.7 ± 5.0 [19] |

Table 5. Principal sources of uncertainty and their estimated values in cross section measurements.

| Source of uncertainty                  | Uncertainty % |
|----------------------------------------|---------------|
| counting statistics                    | 0.5–3.2       |
| standard cross sections                | 1.1–1.5       |
| isotopic abundance                     | 1.6           |
| detector efficiency                    | 2.0–3.0       |
| weight of samples                      | 0.1           |
| self-absorption of gamma-ray           | ~ 0.5         |
| relative gamma-ray intensity           | ~ 1.0         |
| half-life                              | 0.05–1.1      |
| uncertainties of irradiation, cooling and measuring times | 0.1–0.5 |
| total uncertainty                      | 4.5–8.7       |

4.1 ⁷⁶Ge(n, 2n)⁷⁵mGe reaction

In the present work, an intensity of Iγ = 39.51% of the 139.68 keV gamma-ray emitted in the decay of ⁷⁵mGe was used to deduce the value of the ⁷⁶Ge(n, 2n)⁷⁵mGe reaction cross section. Vanska and Rieppo [9] and Hlavac et al. [12] used Iγ = 34%. Kasugai et al. [10] used Iγ = 38.8% for the same ray (139.68 keV) (see table 6). Thus, these data are normalized with respect to the latest γ-ray branching of 39.51% [18]. For this reaction, it’s threshold energy is 9.694 MeV. In order to avoid the effect of low-energy neutrons, the near threshold ⁹³Nb(n, 2n)⁹²mNb (E_{th} = 8.972 MeV) monitor reaction was selected. Whereas, Vans­ka and Rieppo [9], Kasugai et al. [10], Mangal and Gill [11], Hlavac et al. [12], and Attar et al. [14] used the lower threshold ²⁷Al(n, p)²⁷Mg (E_{th} = 1.896 MeV) and Dzysiuk et al. [13] used ²⁷Al(n, α)²⁴Na (E_{th} = 3.249 MeV) monitor reactions (see table 6). Our results are plotted in fig. 5 along with all the other data [7–14]. In the energy region between 13 and 14 MeV our values are in agreement with those of Bormann et al. [8] within their experimental uncertainties. At 14.8 MeV, present data is in agreement with the results of Kasugai et al. [10], Hlavac et al. [12] and Attar et al. [14] within the experimental uncertainties. The shapes of the excitation curves of the TALYS-1.8 calculation also exhibit a trend similar to Bormann et al. [8], Kasugai et al. [10], Attar et al. [14], and the present data set. Between 13 and 15 MeV the TALYS-1.8 calculations with ldmodels 1, 5, and 6 agree very well with our measured data within the reported data uncertainties.

4.2 ⁷⁶Ge(n, 2n)⁷⁶Ge reaction

Concerning the ⁷⁶Ge(n, 2n)⁷⁶Ge reaction, there are three earlier measurements that can be found in the litera-
Table 6. Summary of $^{76}$Ge(n, 2n) reaction cross sections from previous measurements.

| Reaction $^{76}$Ge(n, 2n)$^{75m}$Ge | Method | Decay data | Detector | Monitor reaction | Reference |
|-------------------------------------|--------|------------|----------|----------------|-----------|
| $^{76}$Ge(n, 2n)$^{75m}$Ge          | activation | no information | GeLi | $^{63}$Cu(n, 2n)$^{62}$Cu | ref. [7] |
| $^{76}$Ge(n, 2n)$^{75m}$Ge          | activation | $T_{1/2} = 48.2\text{ s}$ | Nal | No information | ref. [8] |
| $^{76}$Ge(n, 2n)$^{75m}$Ge          | activation | $T_{1/2} = 49\text{ s}$, $E_{\gamma} = 136.6\text{ keV}, I_\gamma = 34\%$ | GeLi | $^{27}$Al(n, p)$^{27}$Mg | ref. [9] |
| $^{76}$Ge(n, 2n)$^{75m}$Ge          | activation | $T_{1/2} = 47.7\text{ s}$, $E_{\gamma} = 139.5\text{ keV}, I_\gamma = 38.8\%$ | HPGe | $^{27}$Al(n, p)$^{27}$Mg | ref. [10] |
| $^{76}$Ge(n, 2n)$^{75m}$Ge          | activation | $T_{1/2} = 48\text{ s}$ | Nal | $^{27}$Al(n, p)$^{27}$Mg | ref. [11] |
| $^{76}$Ge(n, 2n)$^{75m}$Ge          | activation | $T_{1/2} = 48\text{ s}$, $E_{\gamma} = 139\text{ keV}, I_\gamma = 34\%$ | GeLi | $^{27}$Al(n, p)$^{27}$Mg | ref. [12] |
| $^{76}$Ge(n, 2n)$^{75m}$Ge          | activation | $T_{1/2} = 47.7\text{ s}$ | HPGe | $^{27}$Al(n, p)$^{27}$Mg | ref. [13] |
| $^{76}$Ge(n, 2n)$^{75m}$Ge          | activation | $T_{1/2} = 47.7\text{ s}$, $E_{\gamma} = 139.7\text{ keV}, I_\gamma = 39.4\%$ | HPGe | $^{27}$Al(n, p)$^{27}$Mg | ref. [14] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | no information | GeLi | $^{63}$Cu(n, 2n)$^{62}$Cu | ref. [7] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | $T_{1/2} = 82.8\text{ min}$, $E_{\gamma} = 264.8\text{ keV}$ ($I_\gamma = 11.0\%$, $E_{\gamma} = 199.2\text{ keV}$ ($I_\gamma = 1.4\%$) | GeLi | $^{27}$Al(n, p)$^{27}$Mg | ref. [9] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | $T_{1/2} = 82.78\text{ min}$, $E_{\gamma} = 264.0\text{ keV}$, $I_\gamma = 11.4\%$ | HPGe | $^{27}$Al(n, p)$^{27}$Mg | ref. [14] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | $T_{1/2} = 82\text{ min}$ | Boron counter | No information | ref. [24] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | $T_{1/2} = 82.2\text{ min}$, $E_{\gamma} = 265\text{ keV}, I_\gamma = 11.0\%$ | GeLi | $^{76}$Ge(n, 2n)$^{62}$Ge | ref. [25] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | no information | Nal | counting the associated alpha particles | ref. [26] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | no information | Ge | $^{56}$Fe(n, p)$^{56}$Mn | ref. [27] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | $T_{1/2} = 1.38\text{ h}$, $E_{\gamma} = 264.7\text{ keV}$, $I_\gamma = 11.3\%$ | GeLi | $^{27}$Al(n, α)$^{24}$Na | ref. [28] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | $T_{1/2} = 81.79\text{ min}$ | Nal | $^{63}$Cu(n, 2n)$^{62}$Cu | ref. [29] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | $T_{1/2} = 78\text{ min}$ | GEMUC | $^{56}$Fe(n, p)$^{56}$Mn | ref. [30] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | no information | HPGe | $^{27}$Al(n, α)$^{24}$Na | ref. [31] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | $T_{1/2} = 82.78\text{ min}$, $E_{\gamma} = 264.6\text{ keV}$, $I_\gamma = 11.4\%$ | HPGe | $^{96}$Nb(n, 2n)$^{92m}$Nb | ref. [32] |
| $^{76}$Ge(n, 2n)$^{77}$Ge           | activation | $T_{1/2} = 82.78\text{ min}$, $E_{\gamma} = 264.6\text{ keV}$, $I_\gamma = 11.4\%$ | HPGe | $^{27}$Al(n, α)$^{24}$Na | ref. [33] |

ture [7,9,14]. In the present work, the 264.6 keV ($I_\gamma = 11.4\%$) gamma-ray emitted in the $^{75m}$Ge decay was used to deduce the value of the $^{76}$Ge(n, 2n)$^{75m}$Ge reaction cross section. The contribution of the $^{76}$Ge(n, 2n)$^{75m}$Ge reaction via IT (isomeric transition, 99.97%) was subtracted using eq. (14). Figure 6 shows the excitation function of the $^{76}$Ge(n, 2n)$^{75m}$Ge reaction. Between 13 and 15 MeV, the measured data for the $^{76}$Ge(n, 2n)$^{75m}$Ge reaction cross sections can be grouped into two bands which differ by about 80%. The large discrepancies are probably due to the different deducting methods of excited states. Between 13 and 15 MeV, the Talys-1.8 calculations with ldmodels 1–6 are lower than all the results of papers in the literature [7,9,14], but the TALYS-1.8 calculations with ldmodel 1 (the constant temperature and Fermi gas model) agree very well with our data, whilst the results by Casanova and Sanchez [7], Vanska and Rieppo [9], and Attar et al. [14] are about 60–90% higher than our data and TALYS-1.8 calculations. For this reaction, other previous authors [8,10–13] only reported cross section values of the excited state and did not give cross section values of the ground state.

4.3 $^{76}$Ge(n, 2n)$^{75}$Ge reaction

The present cross section data for the $^{76}$Ge(n, 2n)$^{75}$Ge reaction are shown in fig. 7 together with the results of the TALYS-1.8 calculation with ldmodels 1, 2, 3, 4, 5, and 6 (given as continuous lines) and earlier measurements [9,12,13,24–33]. It can be seen that in the 13 to 15 MeV energy range our data are consistent with the results of TALYS-1.8 calculations using ldmodels 1, 2, 4, 5, and 6 within the experimental uncertainties.

4.4 Isomeric cross section ratio

The isomeric cross section ratio $\sigma_m/\sigma_g$ for the isomeric pair $^{75m}$Ge produced in the (n,2n) reaction on $^{76}$Ge was
measured. The obtained cross section ratios are 2.3 ± 0.2, 2.4 ± 0.2 and 2.4 ± 0.2 at neutron energies of 13.5 ± 0.2, 14.1 ± 0.2, and 14.8 ± 0.2 MeV, respectively. The experimental data and the TALYS-1.8 calculations are shown together in fig. 8. It can be seen that our results agree well with the result of Bhattacharyya et al. [34], and the data from the TALYS-1.8 calculations with ldmodel 1, 2 and 3.

The isomeric cross section ratio determined in this work has a slightly increasing trend with the increasing neutron energy, suggesting that at higher excitation energies the formation of the high-spin isomer ($7/2 \rightarrow 1/2$) is more favored. This trend is similar to that for several other neutron- and charged-particle–induced reactions near thresholds [35–44]. In the range of 13–15 MeV, the calculated isomeric cross section ratio shows the same slightly increasing trend for the six ldmodels. Our data and the results of TALYS-1.8 with ldmodels 1, 2, and 3 are somewhat lower than the data of Hlavac et al. [12], Okumura [26], Birn et al. [28], while they are higher than the results of Vanska and Rieppo [9] and Mangal and Gill [11].

5 Conclusions

In the present paper, a methodical experimental campaign and TALYS-1.8 code calculations with different level density models have been carried out. Activation cross sections for $^{76}$Ge(n,2n)$^{75m}$Ge, $^{76}$Ge(n,2n)$^{75g}$Ge, and $^{76}$Ge(n,2n)$^{75}$Ge reactions as well as isomeric cross section ratios for $^{76}$Ge(n,2n)$^{75m,g}$Ge reactions induced by 13.5, 14.1 MeV, and 14.8 MeV neutrons have been measured using the latest decay data, and by taking into account the contribution of the metastable state in the case of unstable ground state formation cross section. In order to avoid the effect of low energy neutrons, the near threshold $^{93}$Nb(n,2n)$^{92m}$Nb ($E_{th} = 8.972$ MeV) monitor reaction was selected, samples were wrapped in a cadmium...
foil and the new T-Mo target was used. The constant temperature and Fermi gas model (ldmodel 1) is to be preferred for $^{76}$Ge(n, 2n)$^{75m+8}$Ge reactions. The results were compared with previous experimental results reported in the literature and theoretical nuclear model calculations computed using TALYS-1.8. A detailed comparison with previously reported cross sections reveals that the discrepancies in the historic data could be due to: 1) the decay data (half-life and ray intensity) used in the determination of the cross sections; 2) the system difference caused by different measuring methods (radiation detector and neutron monitoring method) and experimental conditions (neutron field characteristics); and 3) interfering reactions. The experimental results presented here may be used to more accurately describe the reaction processes and verify statistical model parameters used in their theoretical representation.

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