Thermal neutron capture cross section of ^{74}Ge

G. Meierhofer,* P. Grabmayr, and J. Jochum
Kepler Center for Astro and Particle Physics, Universität Tübingen, D-72076 Tübingen, Germany

P. Kudejova
Forschungs-Neutronenquelle Heinz Maier-Leibnitz FRM II, Technische Universität München, D-85747 Garching, Germany

L. Canella
Institut für Radiochemie, Technische Universität München, D-85748 Garching, Germany

J. Jolie
Institut für Kernphysik, Universität zu Köln, D-50937 Cologne, Germany
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The thermal neutron capture cross sections of the ^{74}Ge$(n,\gamma)^{75}$Ge and the ^{74}Ge$(n,\gamma)^{75m}$Ge reactions have been measured by the activation method. Cold neutrons were used to activate GeO$_2$ targets depleted in ^{76}Ge. From the decay spectra of ^{75}Ge measured with high-purity germanium detectors, the cross sections relative to ^{197}Au were derived. For the ^{74}Ge$(n,\gamma)^{75m}$Ge reaction, a value of (130.5 $\pm$ 5.6) mb was found and the ground state was populated with a cross section of (497 $\pm$ 52) mb.

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The cross section of ^{74}Ge(n,γ) is of interest in experiments searching for the neutrinoless double β decay in ^{76}Ge. These experiments use high-purity germanium (HPGe) detectors made of germanium, isotopically enriched in ^{76}Ge (GERDA experiment: ~86% ^{76}Ge and ~14% ^{74}Ge [1]). Because of the long half-life of this decay ($T_{1/2} > 10^{25}$ y [2]), the background has to be very low and well understood. Prompt γ rays after neutron capture on Ge contribute to this background. For good background estimations, precise values for the rates of neutron capture, that is, the neutron capture cross sections, are needed. The cross sections for the ^{76}Ge(n,γ) reaction have recently been measured [3].

In previous publications the values for the thermal neutron capture cross sections on ^{74}Ge were obtained using the decay radiation after activation by neutrons. Geiger counters or anthracene crystals were used for β-particle detection [4,5] or NaI detectors for γ rays [6–8]. Other techniques, such as pile oscillation [9] and transmission of neutrons through the target [10], were applied as well. The values from these measurements are in poor agreement, especially those for the isomeric state.

In this work, HPGe detectors were used to detect γ rays from the decay of ^{75}Ge and ^{75m}Ge after neutron activation of ^{74}Ge to determine the cross sections relative to the well-known cross section of ^{197}Au.

The cross sections have been measured at the facility for prompt γ activation analysis (PGAA) at the research reactor Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II) near Munich, Germany [11]. A neutron beam with a flux of 2.9×10^9 n s^{-1} cm^{-2} and a mean neutron energy of 1.8 meV was used for the activation of the targets.

As target material, GeO$_2$ isotopically depleted in ^{76}Ge (~0.6% ^{76}Ge and 38.3% ^{74}Ge) was used. Because both ^{75}Ge and ^{77}Ge emit photons of 264 keV, depletion in ^{76}Ge minimizes the corrections to be made for the corresponding peak area. The GeO$_2$ powder was pressed into pill-shaped targets with diameters of 12 mm. A piece of gold foil of the same diameter was irradiated together with the target to monitor the neutron flux at the target position.

Neutron capture leads to the unstable ^{75}Ge nucleus in the isomeric state (E_m = 139.68 keV) or in its ground state. The isomeric state undergoes an isomeric transition (IT) to the ground state (99.970%) or β decay to ^{75}As (0.03%). The ground state decays via β decay directly to the ground state of ^{75}As (87.1%) or to excited levels, followed by γ emission (see Table I).

The targets were irradiated for a certain time t_a and then, after a period of waiting t_w, the γ rays emitted by ^{75}Ge and ^{198}Au were measured t_m with two HPGe detectors. The target masses and the time spans used to determine the cross section to the ground state are given in Table II; those used to determine the isomeric state can be found in Table III. Comparing the peak areas of emissions during the decay of ^{75}Ge with the reference peak from gold ($E_{\mathrm{Au}} = 411$ keV), the cross sections were derived relative to the well-known cross section of gold $\sigma_{\mathrm{Au}} = (98.65 \pm 0.09)$ b [15].

The cross sections were determined using the relation

$$\sigma_{0,\mathrm{Ge}} = \sigma_{0,\mathrm{Au}} \left(\frac{A_{\mathrm{Ge}}}{A_{\mathrm{Au}}}\right) \left(\frac{n_{\mathrm{Au}}}{n_{\mathrm{Ge}}}\right) \left(\frac{1 - \mathrm{e}^{-\lambda_{\mathrm{Au}} t_a} \lambda_{\mathrm{Ge}}}{1 - \mathrm{e}^{-\lambda_{\mathrm{Ge}} t_a} \lambda_{\mathrm{Au}}}\right), \quad (1)$$

where σ_0 denotes the thermal neutron capture cross section, A the number of activated nuclei after irradiation, and n the total number of nuclei. The last term corrects for the nuclei decayed during activation. A is derived from the experimental peak areas accounting for the emission probability, detector efficiency,

*meierhofer@pit.physik.uni-tuebingen.de

TABLE I. Decay properties of ^{75}Ge [12], ^{77}Ge [13], and ^{198}Au [14].

Nucleus	$T_{1/2}$	E_γ (keV)	I_γ (%)
^{75}Ge	82.78 ± 0.04 m	198.6	1.19 ± 0.12
		264.6	11.4 ± 1.1
^{75m}Ge	47.7 ± 0.5 s	139.68(IT)	39.4 ± 0.8
^{77}Ge	11.30 ± 0.01 h	264.4	53.9 ± 0.5
^{77m}Ge	52.9 ± 0.6 s	264.7	0.022 ± 0.004
^{198}Au	2.69517 ± 0.00021 d	411.8	95.58 ± 0.12

TABLE II. Mass of targets and time spans used for activation t_a, waiting t_w, and measurement t_m in the ^{74}Ge(n,γ)^{75}Ge cross-section experiment.

Target	Mass (mg)	t_a (s)	t_w (s)	t_m (s)
A	435.7	1200	300	14 100
B	401.5	1500	660	10 800

TABLE III. Results for the ^{74}Ge(n,γ)^{75m}Ge measurement and corresponding time intervals used for activation t_a, waiting t_w, and measurement t_w.

Target	t_a (s)	t_w (s)	t_m (s)	Cross section (mb)
A	1200	5	180	132.8 ± 7.3
	60	5	120	132.2 ± 9.7
	60	5	120	129.8 ± 8.2
	180	5	180	129.4 ± 7.2
	180	30	240	132.0 ± 7.7
	120	5	120	131.0 ± 7.6
	120	5	120	134.2 ± 7.8
	120	5	120	132.0 ± 7.7
B	1500	5	180	125.1 ± 6.9
	120	5	120	130.2 ± 7.5
	120	5	120	130.0 ± 7.5
	120	5	120	128.7 ± 7.5
Weighted mean				130.5 ± 5.6

TABLE IV. Cross section of the ^{74}Ge(n,γ)^{75}Ge reaction.

Target	Detector	E_γ (keV)	Cross section (mb)	
			Total	Direct
A	I	264.6	507 ± 52	375 ± 51
	II	198.6	516 ± 57	384 ± 56
		264.6	494 ± 51	362 ± 50
B	I	264.6	492 ± 51	360 ± 50
	II	198.6	498 ± 56	366 ± 55
		264.6	480 ± 50	348 ± 49
Weighted mean			497 ± 52	365 ± 51

TABLE V. Relative uncertainties.

	Relative uncertainty (%)	
	^{75m}Ge	^{75}Ge
Emission probability	2.0	10.0/9.6[a]
Peak area	2.8–5.4	0.8–3.3
Detector efficiency	1.8	1.5–1.8
Correction for decay during activation/waiting/measurement		
Due to beam shutter	1.5–2.3	<0.1
Due to half-life time	0.5–1.1	<0.1
Target inhomogenity	2	2
γ-ray attenuation	$\leqslant$0.2	$\leqslant$0.1
Neutron self-shielding	<0.1	<0.1
Number of ^{74}Ge nuclei	0.2	0.2
Monitored neutron flux (gold reference)	2.7	2.3–2.7[b]

[a]Line dependent.
[b]Detector dependent.

neutron self-shielding, γ-ray attenuation in the target, and decays during the waiting period. Apart from the neutron self-shielding, the neutron flux is the same for target and monitor foil; therefore, the flux cancels out. Though the activation was done with cold neutrons, the thermal values $\sigma_{0,\mathrm{Ge}}$ and $\sigma_{0,\mathrm{Au}}$ can be used because these cross sections follow the same $1/v$ law for cold and thermal neutrons well seperated from any resonance.

To obtain the thermal neutron capture cross section of the ^{74}Ge(n,γ)^{75m}Ge reaction the γ rays of the IT with an energy of $E_m = 139.68$ keV were used (see Table IV). In the spectrum of detector I, energies below 220 keV were cut off by the threshold of the Compton suppression; therefore, only data from detector II were considered. The resulting weighted mean value of all runs is $\sigma_m = (130.5 \pm 5.6)$ mb. The statistical and systematic uncertainties are given in detail in Table V. The target inhomogenity alike the number of nuclei of the two targets were assumed to be independent from each other. The uncertainties induced by the opening and the closing of the beam shutter (correction for the decay during activation waiting and measurement), as well as the uncertainties for the peak areas, were treated as independent for each run.

For the evaluation of the thermal neutron capture cross section to the ground state, the two strongest transitions with energies of 198.6 keV (only detector II) and 264.6 keV were evaluated. For the latter energy, the peak area was corrected for the very small contribution (~0.2%) from the decay of ^{77}Ge. The transition at the same energy due to the decay of ^{77m}Ge can be ignored because of the sufficient waiting time chosen before starting data taking and its small emission probability (Table I).

The experimentally obtained total cross section is $\sigma_t = (497 \pm 52)$ mb. Correcting for the feeding from the isomeric state by IT the direct cross section $\sigma_d = (365 \pm 51)$ mb was derived. The correction includes the delay of the feeding ($T_{1/2} = 47.7$ s) and nuclei in the ground state decaying during activation. To avoid an unnecessary large uncertainty due to double counting of other errors in Eq. (1), the correction was applied to the number of activated nuclei A_{Ge} rather than to the resulting cross section.

TABLE VI. Thermal neutron capture cross sections for ^{74}Ge$(n,\gamma)^{75m}$Ge and ^{74}Ge$(n,\gamma)^{75}$Ge achieved in this work compared with previous publications.

Cross section (mb)			Year	Reference
^{75m}Ge	^{75}Ge			
	Total	Direct		
	380 ± 76		1947	[4]
	600 ± 60		1952	[9]
40 ± 8		180 ± 40	1957	[5]
	550 ± 55		1960	[6]
200 ± 20			1962	[7]
143 ± 16			1968	[8]
	400 ± 200		1987	[10]
130.5 ± 5.6	497 ± 52	365 ± 51	2010	This work

The thermal neutron capture cross section for ^{74}Ge$(n,\gamma)^{75}$Ge is consistent within error bars to those of previous publications (Table VI). The large uncertainties are completely dominated by the poorly known emission probabilities. The detailed information about uncertainties in Table V allows the recalculation of the cross section in case a more precise value for the branching of ^{75}Ge is given in future.

The new value for ^{74}Ge$(n,\gamma)^{75m}$Ge is in the range of the results of Ref. [8], but with a strongly reduced uncertainty.

Alternatively, the total cross section σ_t can be derived from prompt spectra using the partial cross sections σ_γ^p of prompt transitions in a reference isotope and the absolute intensities I_γ of prompt transitions in the isotope examined. In our case, absolute intensities for transitions in ^{75}Ge are given by [16]; however, these absolute intensities were obtained trough normalization by earlier total cross-section values [17]. Because I_γ was determined using σ_t, it is not surprising that the evaluation of our prompt spectra yields cross sections that are consistent with those of Table VI. Normalization to primary γ transitions as done in [18] is not reliable because the prompt decay scheme in ^{75}Ge is not known well enough.

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