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Neutron Activation of ^{74}Ge and ^{76}Ge

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Abstract. The upcoming Gerda and Majorana experiments will use germanium crystals, isotopically enriched in ^{76}Ge to search for the neutrinoless double beta decay ($0\nu2\beta$). The very long half-life of $0\nu2\beta$ ($> 10^{25}$ y for ^{76}Ge) requires an extremely low background level. Neutrons induced by cosmic muons can be captured after thermalization by ^{74}Ge or ^{76}Ge, followed by β^--decay of ^{75}Ge and ^{77}Ge respectively. The prompt γ-cascade after neutron capture and the β-decay contribute to the total backround in these experiments. For a good estimation of the background the poorly known cross-sections for the ^{74}Ge(n,γ)^{75,75m}Ge reactions were measured using targets, isotopically depleted in ^{76}Ge. Furthermore the prompt γ-rays in ^{77}Ge were measured with isotopically enriched germanium targets. The results of the latter measurement were combined with the results of a dedicated coincidence measurement to reconstruct the prompt γ-ray decay scheme.

1 Introduction

The question of the Majorana nature of the neutrino, i.e. if the neutrino is its own anti-particle, can be answered by the observation of the neutrinoless double beta decay ($0\nu\beta\beta$). Moreover this decay leeds towards physics beyond the standard model because it violates lepton number conservation. If the $0\nu\beta\beta$-decay will be observed, the effective neutrino mass can be derived using matrix elements provided from theory [1].
While the search for $0\nu\beta\beta$-decay is still a very active field of research the two neutrino double beta decay has been observed in several isotopes (^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd etc.). Amongst others these nuclei are used in different experiments for the $0\nu\beta\beta$-decay search. ^{76}Ge is an ideal candidate because it can be used for the production of HPGe detectors, that act as source and detector at the same time. Previous experiments have shown, that the half-life of $0\nu\beta\beta$ decay in ^{76}Ge is longer than 10^{25} y [2,3]. Therefore the background suppression and rejection are the major tasks in the search for $0\nu\beta\beta$-decay. Only very radiopure materials are used in these experiments that are performed underground to reduce the flux of cosmic muons.
^{76}Ge will be used by the Gerda experiment (GERmanium Detector Array) that is built at the moment at the LNGS (Italy) [4]. Isotopically enriched in ^{76}Ge germanium diodes (14 % ^{74}Ge, 86 % ^{76}Ge) will be operated directly in liquid argon that acts as cooling fluid and shielding against γ-rays. The cryostat filled with liquid argon (diameter: 4 m) is centered in a water tank (diameter: 10 m, height: 9 m) used as Cherenkov muon veto.

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Electrons emitted by $0\nu\beta\beta$ deposit their discrete energy ($Q_{\beta\beta} = 2039$ keV) in a very small volume of a few mm^3 (single-site event). So part of the background can be rejected by suppressing multi-site events using segmentation and pulse shape analysis.

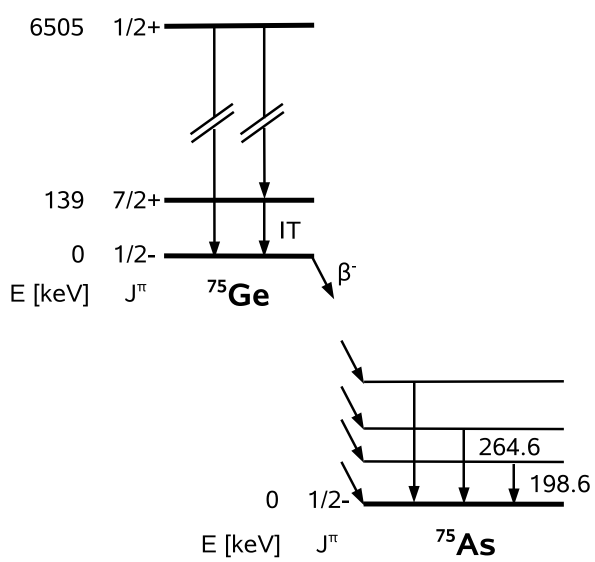

Fig. 1. Simplified decay scheme of ^{75}Ge. β-decay from the isomeric state to ^{75}As (0.03 %) is not shown.

Table 1. Half-lives ($t_{1/2}$) and emission probabilities per neutron capture I_γ of ^{75}Ge [5] and ^{198}Au [6] for transitions used in this experiment.

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	(IT) 139.68	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

Fast neutrons produced by cosmic muons outside the experiment can propagate through the water tank to the germanium diodes undetected. After being moderated by inelastic scattering in water or liquid argon they can be captured by the nuclei of ^{74}Ge or ^{76}Ge in the germanium crystals. The binding energy gained is released via a prompt γ-cascade leading in both nuclei to a population of the groundstate or an isomeric state. The isomeric state in ^{75}Ge undergoes an isomeric transition (IT) to the groundstate (99.970 %) or β-decay to ^{75}As (0.03 %). The groundstate decays with a half-life of $t_{1/2} = 82.78$ m to ^{75}As. Similar processes with different branching and half-lives are observed in ^{77}Ge. All half lives and emission probabilities used to derive the cross-sections are shown in table 1.

While for ^{75}Ge only the prompt γ-rays have sufficiently high energies to deposit energy in the region of interest at 2039 keV, the γ-rays and electrons emitted by the delayed decay of ^{77}Ge and ^{77m}Ge may contribute to the background as well. Energy deposition by electrons has the same signature as $0\nu\beta\beta$-decay and therefore can not be rejected by pulse shape analysis.

For a precise background prediction the neutron capture cross-sections and the prompt decay schemes of these two germanium isotopes have to be known well. The data provided in the literature do not meet this requirement [7,8], therefore new measurements were carried out. The prompt γ-rays in ^{77}Ge were measured with GeO_2 targets of different isotopical composition using the facility for prompt gamma activation analysis (PGAA) at the research reactor "Forschungs-Neutronenquelle Heinz Maier-Leibnitz" (FRM II) near Munich (Germany) [9]. The thermal neutron capture cross-section of ^{74}Ge and ^{76}Ge have been measured at the same instrument.

2 Experiment

2.1 Thermal cross-section of ^{74}Ge(n,γ)

The thermal neutron capture cross-section of ^{74}Ge was determined relative to the well known cross-section of ^{197}Au ($\sigma_{\mathrm{Au}} = (98.65 \pm 0.09)$ b [7]).

Two pills of 12 mm diameter and mass of (435.7 ± 0.6) mg (target A) and (401.5 ± 0.6) mg (target B) respectively were pressed from GeO_2 powder, isotopically depleted in ^{76}Ge (^{76}Ge: 0.6 %). The pills were activated together with a thin gold foil to monitor the flux of cold neutrons at the target position. After activation (20 min. for A and 25 min. for B) the γ-rays emitted by ^{75}As after β-decay of ^{75}Ge were measured together with the spectrum of ^{198}Au using two HPGe detectors (target A: $t_m = 14\,100$ s, target B: 10 800 s). The cross-section of ^{75}Ge was calculated using the measured peak areas and emission probabilities of the most intense lines in the spectra. These were the peaks at 198.6 keV and 264.6 keV for ^{75}Ge and the gold reference peak at 411.8 keV. The decay of ^{77}Ge has a peak at 264.4 keV that overlaps with the one of ^{75}Ge at 264.6 keV. Due to the small abundance of ^{76}Ge and the long half-life of ^{77}Ge this contribution is less than 0.1 %. Contributions to the same peak from ^{77m}Ge (table 1) were avoided by waiting a few half-lives after irradiation before starting the measurement. The experimentally obtained value for the cross-section of ^{74}Ge(n,γ)^{75}Ge is $\sigma_e = (499 \pm 53)$ mb. For the measurement of the ^{74}Ge(n,γ)^{75m}Ge reaction the time for activation and measurement was short ($t_a = t_m = 120$ s), accounting for the short half-life of the isomeric state ($T_{1/2} = 47.7$ s). Using the IT line to the ground state, a cross-section of $\sigma_m = (131.4 \pm 6.8)$ mb was found. To determine the cross-section directly to the ground state a correction for the feeding from the isomeric state was applied to the experimental value σ_e, resulting in the direct cross-section of $\sigma_d = (368 \pm 52)$ mb.

All preliminary results are listed in table 2. The uncertainties include contributions from statistics, emission probabilities, detector efficiency, target inhomogenity, γ-ray attenuation, gold reference, neutron self-shielding, half-live times and target mass. The uncertainties for the cross-sections to the ground state are dominated by the large uncertainties of the γ-emission probabilities.

A more detailed description of the analysis and the results of the cross-section measurement of the ^{76}Ge(n,γ) reactions can be found in [10].

2.2 Prompt γ-rays in ^{77}Ge

After thermal s-wave neutron capture on ^{76}Ge the nucleus is highly excited ($E = 6072$ keV, $J^\pi = 1/2^+$). This energy is lost in a complex cascade of γ-rays to the isomeric state at 159.7 keV ($J^\pi = 1/2^-$) or to the ground state ($J^\pi = 7/2^+$).

To determine the prompt γ-ray decay scheme in ^{77}Ge after neutron capture on ^{76}Ge two targets of GeO_2 powder

Table 2. Preliminary values for the thermal cross-sections of the ^{74}Ge(n,γ)^{75}Ge and ^{74}Ge(n,γ)^{75m}Ge reactions.

Reaction	Cross-section [mb]
^{74}Ge(n,γ)^{75}Ge	
σ_e (experimental)	499 ± 53
σ_d (direct)	368 ± 52
^{74}Ge(n,γ)^{75m}Ge	
σ_m	131.4 ± 6.8

Table 3. Isotopical abundances of the germanium targets used.

Isotope	Enriched target [%]	Depleted target [%]
70	0.0	22.77
72	0.03	30.06
73	0.13	8.32
74	12.1	38.27
76	86.9	0.60

were used. One target was isotopically enriched, the other depleted in ^{76}Ge (table 3). The GeO_2 powder was sealed in FEP (Fluorinated Ethylene-Propylene) bags and positioned in the beam of cold neutrons with a mean energy of $E_n = 1.8$ meV. The thermal equivalent neutron flux was $\Phi = 2.9 \times 10^9$ $n_{th}/(cm^2\,s)$ at the target position. The prompt γ-rays were measured using two well shielded HPGe detectors at a distance of 35 cm and 30 cm respectively from the target position (fig. 2). Both detectors were equiped with aCompton suppression system. The target chamber was evacuated to reduce background from interactions of neutrons with nitrogen in air.

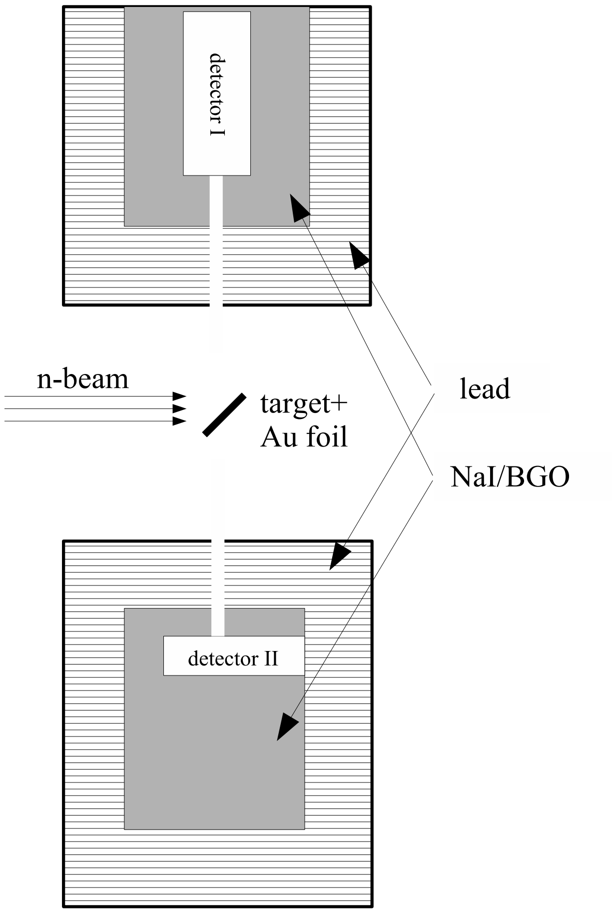

Fig. 2. Experimental setup. The neutron shield consisting of ^{113}Cd and ^{6}Li is not shown. The gold foil was used only for the cross-section measuremnts.

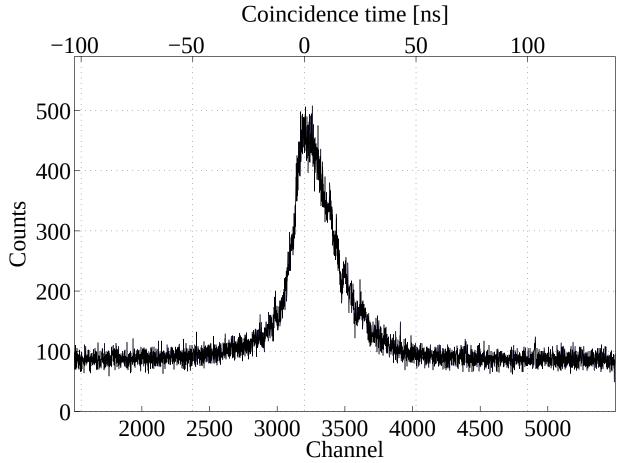

Fig. 3. Time difference between events in detector I and II. True coincidences are located in the peak sitting on a flat contribution from random coincidences.

Spectra were taken of isotopically enriched and depleted material, the background spectrum was measured by irradiation of an empty target, consisting only of the FEP foil. Analyzing the spectra of the three targets the transitions in ^{77}Ge could unambiguously be identified.

To place the transitions in the decay scheme correctly the two HPGe detectors were operated in coincidence mode in a second run. For each coincident event the corresponding energies and the time difference between the two events were recorded. The time difference was used to distinguish true coincidences from background due to random coincidences (fig. 3).

Combining the information from the single spectra with the coincidence data a preliminary decay scheme was reconstructed. All transitions that could be placed in the decay scheme are shown in fig. 4 (90 % C. L.). In total 34 new transitions were found.

3 Conclusions

This work delivers (preliminary) values for the thermal neutron capture cross-sections of ^{74}Ge. For the cross-section to the isomeric state a value of $\sigma_m = (131.4 \pm 6.8)$ mb was obtained. The cross-section for the ^{74}Ge(n,γ)^{75}Ge reaction was found to be $\sigma_e = (499 \pm 53)$ mb. Correcting this value for the feeding from the isomeric state the direct cross-section obtained is $\sigma_d = (368 \pm 52)$ mb. The uncertainties of the cross-sections σ_e and σ_d to the ground state can be significantly decreased only if the accuracy of the emission probabilities is improved.

Our coincidence measurement of prompt γ-rays in ^{77}Ge after neutron capture on ^{76}Ge allows to reconstruct a decay scheme much more complex than the decay schemes found in the literature. The data obtained in this work will be usefull for better understanding of background in ^{76}Ge based $0\nu\beta\beta$ experiments.

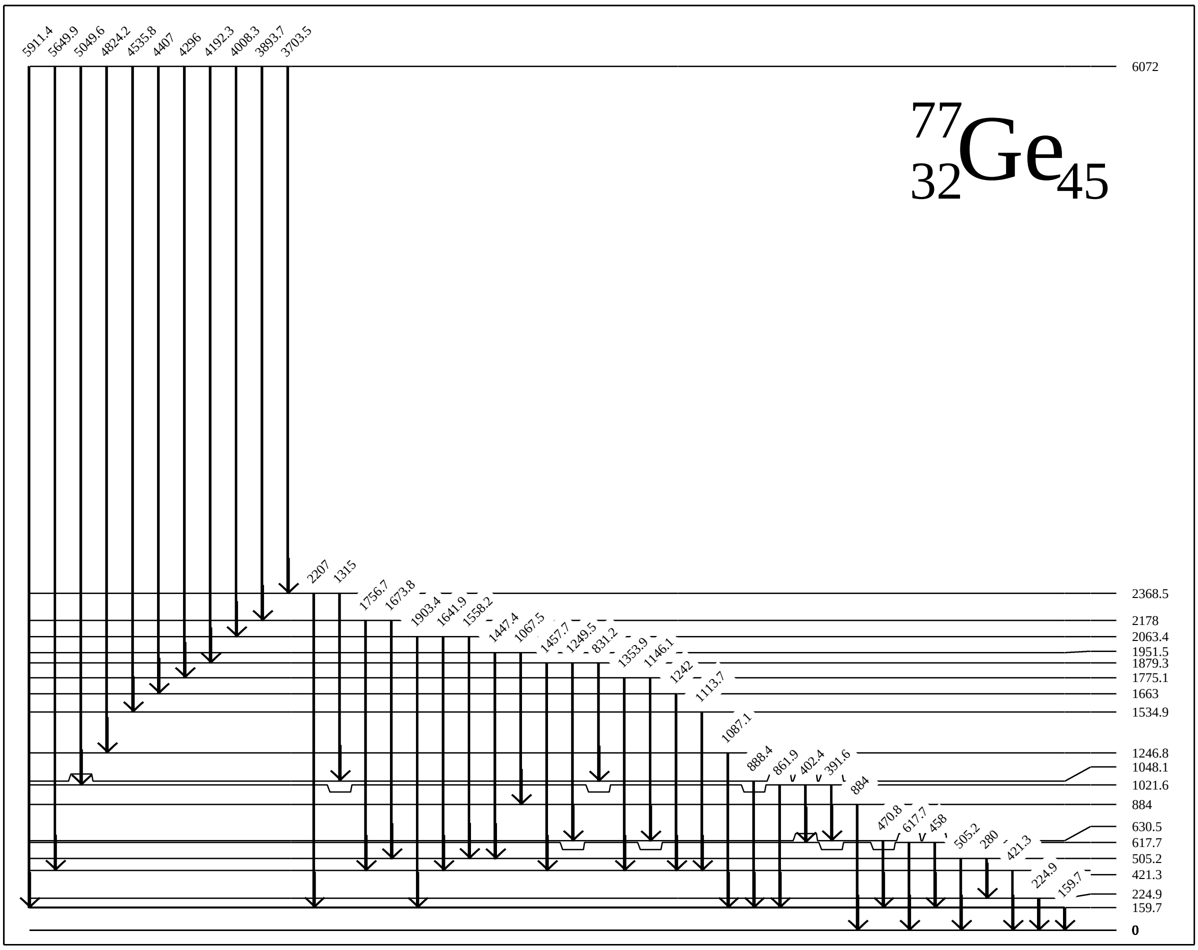

Fig. 4. Decay scheme of prompt γ-rays in ^{77}Ge after neutron capture by ^{76}Ge (preliminary).

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