

# Prompt Gamma Rays in $^{77}\text{Ge}$ after Neutron Capture on $^{76}\text{Ge}$

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**Abstract.** The observation of neutrinoless double beta decay would be proof of the Majorana nature of the neutrino. Half-lives for these decays are very long (for  $^{76}\text{Ge}$ :  $> 10^{25}$  y), so the background reduction and rejection is the major task for double beta experiments.

The GERDA (GERmanium Detector Array) experiment at the Gran Sasso Laboratory of the INFN (LNGS) searches for neutrinoless double beta decay of  $^{76}\text{Ge}$ . The isotope  $^{76}\text{Ge}$  is an ideal candidate because it can be used as source and detector at the same time.

A large remaining contribution to the background arises from the prompt gamma cascade after neutron capture by  $^{76}\text{Ge}$  followed by  $\beta^-$ -decay of  $^{77}\text{Ge}$ . Since the prompt gamma decay scheme is poorly known, measurements with isotopically enriched Germanium samples are carried out at the PGAA facility at the research reactor FRM II (Munich). With the known prompt gamma spectrum it will be possible to improve the overall veto efficiency of the GERDA experiment.

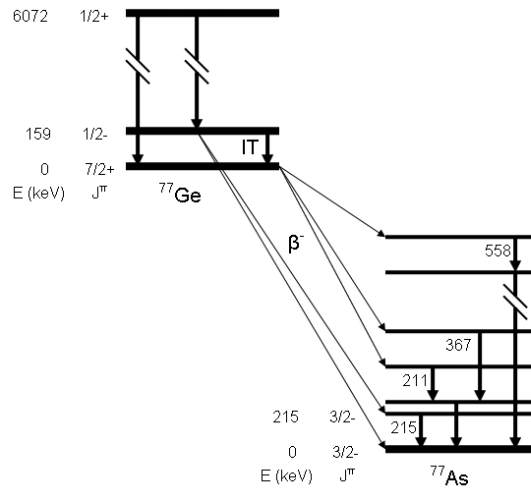
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## INTRODUCTION

GERDA [1] searches for neutrinoless double beta decay ( $0\nu 2\beta$ ) of  $^{76}\text{Ge}$ . Double beta decay can be observed when single beta decay is energetically forbidden but the simultaneous change of two neutrons into two protons is allowed. The half lives of  $2\nu 2\beta$  decaying isotopes are usually longer than  $10^{19}$  y. While  $2\nu 2\beta$  has been observed, the search for  $0\nu 2\beta$  is still a very active field of research. If neutrinoless double beta decay is observed it will prove the Majorana nature of the neutrino, viz., the neutrino is its own anti-particle. If theory provides precise matrix elements the effective neutrino mass can be derived, see e.g. [2].

GERDA uses HPGe detectors made from isotopically enriched Germanium ( $\sim 87\%$  of  $^{76}\text{Ge}$ ) which are source and detector at the same time. The complete reaction energy of  $Q_{\beta\beta} = 2039$  keV is carried by the two emitted electrons and deposited due to their short range in a small volume (few  $\text{mm}^3$ ) of the Germanium crystal. This leads to a single peak at this energy in the energy spectrum. If a previous claim [3] is true, GERDA will detect six  $0\nu 2\beta$  events after 1 year of measurement with 15 kg active mass. This low count rate requires a very efficient background reduction. Though

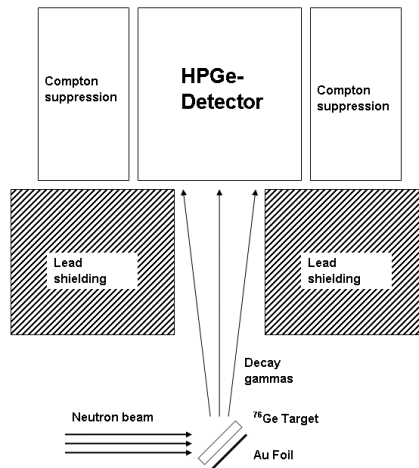


**FIGURE 1.** Decay scheme after neutron capture of  $^{76}\text{Ge}$

the cosmic muon flux is reduced by six orders of magnitude by performing the experiment deep underground (LNGS: 1400 m of rock or 3400 m.w.e) a water "Cherenkov" veto is needed. The water tank with 10 m diameter contains a large cryostat filled with ultra pure liquid Argon. The main design feature of GERDA is to use liquid Argon as shield against gamma radiation, the dominant background in earlier experiments [3]. The HPGe detectors are submerged directly into the cryogenic liquid which also acts as cooling medium.

Muons reaching the laboratory can produce neutrons which may penetrate through the shielding into the Germanium crystals. If a neutron is captured by a  $^{76}\text{Ge}$  nucleus an excited  $^{77}\text{Ge}$  nucleus with  $E^* = 6072$  keV is produced. After deexcitation by prompt gammas to the ground or the metastable state ( $E^m = 159$  keV) it decays further to  $^{77}\text{As}$  by  $\beta^-$ -decay (Figure 1). The  $Q$ -values for the  $\beta^-$ -decay to  $^{77}\text{As}$  are  $Q_\beta \sim 2.7$  MeV ( $t_{1/2} = 11.3$  h) for the ground state and  $Q_\beta \sim 2.9$  MeV ( $t_{1/2} = 52.9$  s) for the metastable state. From the metastable state ( $19 \pm 2$ ) % of the nuclei go by isomeric transition (IT) to the ground state of  $^{77}\text{Ge}$  [4]. The prompt gamma cascade and the beta decay give a contribution to the background in GERDA, part of it in the region of interest around  $Q_{\beta\beta}$ .

After Phase I, with eight unsegmented detectors (17.9 kg of enriched  $^{76}\text{Ge}$ ), another 20 kg of segmented detectors will be added for Phase II. The aim for the background in Phase II is of the order of  $10^{-3}$  cts/(keV kg y) in the region of interest. In a first stage events with energy deposition at multiple sites will be rejected. The  $\gamma$  energies and branching ratio of the prompt cascade if known precisely, can be used to mark the feeding of  $^{77}\text{Ge}^m$  and start the time window searching for the secondary decay. At present only about 15 % of the  $\gamma$  transitions for the  $^{76}\text{Ge}(n,\gamma)$  reaction are known [5]. The values of the cross sections for the neutron capture of  $^{76}\text{Ge}$  stated in literature are not consistent, therefore a new measurement was carried out.



**FIGURE 2.** Schematic view of the experimental setup for the cross section measurement.

## EXPERIMENT

The measurement of the neutron capture cross sections of  $^{76}\text{Ge}$  was carried out at the new PGAA facility at the research reactor FRM II in Munich [6]. The neutron beam had a maximum flux of  $7.3 \times 10^9$  neutrons/(cm<sup>2</sup> s) at the target position. The spectrum at the end of the neutron guide had a Maxwell-like distribution with an average wavelength of  $6.7 \text{ \AA}$  (1.83 meV).

### Cross Section for $^{76}\text{Ge}(n,\gamma)$

The cross section of the  $^{76}\text{Ge}(n,\gamma)^{77}\text{Ge}$  reaction was measured with two samples of isotopically enriched  $\text{GeO}_2$  ( $(87.1 \pm 1.2) \%$  of  $^{76}\text{Ge}$ ). The  $\text{GeO}_2$  powder was pressed into small pills with a diameter of 12 mm and constant thickness of about 2 mm. A gold foil of the same diameter was put behind the germanium pill to obtain the neutron flux (Figure 2). The accumulated activity of  $^{77}\text{Ge}^s$  and  $^{77}\text{Ge}^m$  was measured with HPGe detectors provided by the PGAA setup. Therefore the samples were not moved from the irradiating position. According to their half lives the irradiation times were short for  $^{77}\text{Ge}^m$  (60 s - 180 s) and longer for  $^{77}\text{Ge}^s$  (1200 s - 1800 s). The measurement of the decay spectrum started few seconds after the end of the irradiation for  $^{77}\text{Ge}^m$ . After all  $^{77}\text{Ge}^m$  nuclei decayed ( $\sim 10$  half lifes) the measurement of  $^{77}\text{Ge}^s$  started. To calculate the cross section known  $\gamma$ -rays with energies close to the reference peak of Au at  $E_\gamma = 411 \text{ keV}$  were used. These are the  $\gamma$ -ray energies of 367 keV and 558 keV for  $^{77}\text{Ge}^s$  and 159 keV and 215 keV for  $^{77}\text{Ge}^m$  [7]. The 159 keV  $\gamma$ -ray in the latter case is emitted by IT to the ground state. The counts in the peaks were corrected for gamma-ray self shielding and efficiency. Further corrections were made for the neutron self shielding in the sample. The partial cross sections for the different energies were calculated relatively to the capture cross section of Au, considering the times

**TABLE 1.** Cross sections for the production of  $^{77}\text{Ge}^g$  and  $^{77}\text{Ge}^m$  (preliminary results).

Isomer	Cross Section (mb)	
$^{77}\text{Ge}^g$	$\sigma^e$ experiment	$64.9 \pm 3.5$
	$\sigma^d$ direct	$46.2 \pm 5.5$
$^{77}\text{Ge}^m$	$\sigma^m$ using IT	$98 \pm 12$
	$\sigma^m$ using $\beta^-$ -decay	$112 \pm 14$

for the activation, the measurement itself and the time waited between the irradiation and the measurement. By dividing the partial cross section with the specific emission probabilities [7] a preliminary cross section of  $\sigma^e = (64.9 \pm 3.5)$  mb was obtained, giving the measured overall probability to populate the ground state. Correcting  $\sigma^e$  for the feeding from the shorter lived isomeric state we evaluate the direct cross section to the ground state of  $^{77}\text{Ge}$   $\sigma^d = (46.2 \pm 5.5)$  mb (Tab. 1).

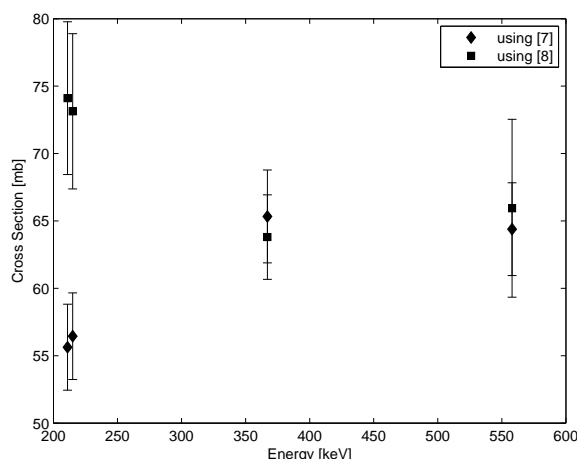
The cross section for the  $^{77}\text{Ge}^m$  state calculated via the  $\beta^-$ -decay is 14 % higher than the one using IT. This effect is due to the rather large uncertainties of the  $\gamma$ -ray intensities or a wrong branching ratio of IT in the literature [7]. The uncertainties are larger than 10 % for IT in  $^{77}\text{Ge}^m$  and larger than 14 % for the  $\beta^-$ -decay of this state. The uncertainties for the gamma ray intensities of the ground state are about 2.5 %. The error of the corrected cross section of the ground state is affected by the large uncertainty of the branching ratio of IT from  $^{77}\text{Ge}^m$  to  $^{77}\text{Ge}$ .

The isomeric ratio  $R$  given by  $R = \sigma_m / (\sigma_m + \sigma_g)$  has a value of  $R = 0.68 \pm 0.14$  using the cross section obtained by IT and  $R = 0.71 \pm 0.15$  for the  $\beta^-$ -decay.

Extracting the cross sections from the measured yields of the gammas of 211 keV and 215 keV and the emission probabilities from [7], about 14 % lower cross sections are obtained than those stated in Tab. 1. This behaviour is shown in Fig. 3 (diamonds). The same was done with the relative gamma ray intensities given in [8]. The cross sections for 367 keV and 558 keV were normalised to the value obtained in the first analysis (64.9 mb) which used the gamma ray intensities from [7]. Here the evaluation for the 211 keV and 215 keV gamma rays give a cross section of 73.7 mb (squares in Fig. 3). Obviously the gamma ray emission probabilities of [7] and [8] are not consistent and both are inconsistent with the experimental data presented here. More precise values for the cross section of the  $^{76}\text{Ge}(n,\gamma)$ -reaction can be achieved only if better data for the gamma ray intensities are provided.

## Prompt Gamma Ray Spectrum

For the determination of the prompt gamma ray energies observed after neutron capture on  $^{76}\text{Ge}$  a target of isotopically enriched material containing 87 % of  $^{76}\text{Ge}$  and 13 % of  $^{74}\text{Ge}$  was used. A second target with 38.9 % of  $^{74}\text{Ge}$  and less than 1 % of  $^{76}\text{Ge}$  was



**FIGURE 3.** Cross sections for  $^{76}\text{Ge}(n,\gamma)$  obtained with gamma ray intensities from [7] and [8].

measured. The different abundances can be used to identify the two isotopes. In both measurements the neutron flux at the target position was  $2 \times 10^9 \text{ n}/(\text{cm}^2 \text{ s})$ . The prompt spectrum was measured by coincidence technique with two Compton suppressed HPGe detectors as well. The data will be used to identify the coincident gamma ray energies that can be measured in the GERDA diodes after neutron capture.

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