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Constraining the $^{77(\mathrm{m})}$Ge Production with GERDA Data and Implications for LEGEND-1000

Moritz Neuberger,[a,*] **Luigi Pertoldi,**[a] **Stefan Schönert**[a] **and Christoph Wiesinger**[a]
for the GERDA collaboration

[a] *Physik-Department E15*
Technische Universität München
James-Franck-Straße
D-85748 Garching
Germany

E-mail: moritz.neuberger@tum.de

The delayed decay of $^{77(\mathrm{m})}$Ge, produced by neutron capture on ^{76}Ge, is a potential background for Germanium based neutrinoless double beta decay search experiments such as GERDA or the future LEGEND-1000 experiment. In this work we present a search for ^{77}Ge in the full GERDA Phase II data. We employ a delayed coincidence method to identify the decay of ^{77}Ge via the isomeric state of ^{77}As (9/2+, 475.5 keV, $t_{1/2}$ = 114 μs). New digital signal processing methods were employed to select and analyze pile-up signal. We found no signal and are able to set an upper limit on the production rate of ^{77}Ge at < 0.235 nuc/(kg · yr) (90% CL), which translates into < 0.40 nuc/(kg · yr) (90% CL) for the total $^{77(\mathrm{m})}$Ge production assuming equal production of ^{77}Ge and $^{77\mathrm{m}}$Ge. Given the very similar configuration - bare germanium detectors in liquid argon - this limit benchmarks our LEGEND-1000 predictions. Scaled with the production rate obtained from simulations and using a new delayed coincidence cut condition on ^{77}Ge, we estimate a $^{77(\mathrm{m})}$Ge background index contribution in LEGEND-1000 at LNGS (Laboratori Nazionali del Gran Sasso) of $4.0^{+3.0}_{-2.9} \times 10^{-7}$ cts/(keV · kg · yr), which is about 4 % of the target background budget.

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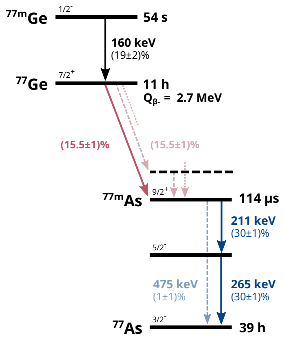

Figure 1: Simplified decay scheme of ^{77}Ge and ^{77m}Ge via the $9/2^{+}$ isomeric state in ^{77}As with $T_{1/2}$ = 114 μs and an excitation energy of 475.5 keV.

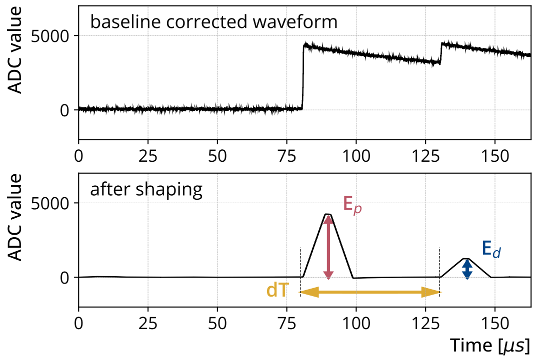

Figure 2: An example of pile-up reconstruction. We shape the waveform with a trapezoidal filter, then estimate the time difference, and finally estimate the pulse heights with a fixed time pick-off.

1. Introduction

The in-situ production of radioactive isotopes by atmospheric muon interactions deep underground can represent a non-negligible background for rare event searches. The muon-induced background for the Gerda (GERmanium Detector Array) experiment [1] looking for neutrinoless double beta decay ($0\nu\beta\beta$) in ^{76}Ge at the Lngs (Laboratori Nazionali del Gran Sasso) has already been studied. The delayed decays of ^{77}Ge and its isomeric state $^{77\mathrm{m}}$Ge, both produced by neutron capture on ^{76}Ge, were identified as the dominant cosmogenic background in Gerda[2]. The Q_{β} value of their decays (2.7 MeV) lies above the $Q_{\beta\beta}$ value of ^{76}Ge (2039 keV), and thus their decays can deposit energy in the region of interest. A Geant4 simulated analysis yielded a $^{77(\mathrm{m})}$Ge* production rate of (0.21 ± 0.01) nuc/(kg · yr) with a systematic uncertainty of 35 % related to the muon-induced neutron production and propagation [3]. This paper summarizes our analysis to quantify the in-situ groundstate ^{77}Ge ($T_{1/2}$ = 11.21 h) isotope production in Gerda by searching for its delayed coincidence characteristic decay through the isomeric state ($9/2^{+}$, 475.5 keV, $T_{1/2}$ = 114 μs) of its progeny ^{77}As. The analysis uses the full data set from the Gerda Phase II experiment.

2. Analysis procedure

In the case of ^{77}Ge, (31 ± 1) % of its decays pass through the isomeric state $^{77\mathrm{m}}$As (see Figure 1). Their maximum energy is 2230 keV. We define the *prompt* transitions as those starting from the ^{77}Ge ground state and ending in the isomeric state of $^{77\mathrm{m}}$As (red). Furthermore, we define the *delayed* transitions as those starting from the isomeric state and ending in the ground state of ^{77}As (blue). Since the half-life of $^{77\mathrm{m}}$As is longer than the charge collection time in Gerda's high purity germanium (HPGe) detector, both transitions can be identified as individual signals, and we call their combined occurrence a *delayed coincidence*. The time difference between the prompt and

*The notation $^{77(\mathrm{m})}$Ge represents ^{77}Ge and $^{77\mathrm{m}}$Ge.

delayed transitions is of the same order as the decay constant of the pulses in the electronics used in GERDA, thus, the delayed pulses most likely appear as pile-up on the prompt pulse.

2.1 Pile-up event reconstruction

A new Digital Signal Processor (DSP) to reconstruct pile-up transforms the original waveform with trapezoidal filters which was not possible in the original GERDA analysis. A filter length is chosen to optimize for energy resolution and detection sensitivity for each waveform individually. Figure 2 shows an example of the DSP, extracting the peak heights and time difference between the pulses. To calibrate the extracted pulse heights, we use a large number events with already estimated energies from the standard GERDA analysis and fit their pulse heights to their previously estimated energy. Since this is a non-standard energy calibration approach, we performed a cross-check using random coincidence pile-up in the GERDA calibration data.

2.2 Candidate selection

Using the MaGe simulation framework [4], we simulated the prompt and delayed decays in the GERDA setup. We define a selection condition for prompt transition candidates by requiring that a single detector has an energy between 200 keV and 2230 keV. We further define a delayed transition selection condition, stating that candidate delayed transitions must occur in the same detector as the prompt transition and have an expected gamma line (211 keV, 264 keV or 475 keV) lying within its energy acceptance region of the Full Width Tenth Maximum (FWTM) range. The combined efficiency to select both the prompt and the delayed transitions with these conditions is 34.5 %. Additionally, we require that the time difference between prompt and delayed transition candidates would be no greater than five times the lifetime (99.3 %) of the isomeric state ($5\,\tau_{^{77\mathrm{m}}\mathrm{As}} = 822\,\mu$s). To remove non-physical events from the event selection, a subset of quality cuts from the standard GERDA analysis as well as additional cuts on new quality parameters from the new DSP were applied. To estimate the resulting event selection efficiency of 94.9 %, we used generated pile-up events. The total selection efficiency of 32.4 % is the product of all previous efficiencies.

3. Result

Figure 3 shows that no candidate delayed coincidence passes the selection criteria ($N_{\mathrm{obs}} = 0$ cts). Random coincidences are the only known background source in this analysis. Using the average event rates in each detector, we calculated $N_{\mathrm{rc}} = 0.04$ cts. With this, we can determine an upper limit of < 2.4 cts (90% CL) on the number of signal events. With the total selection efficiency, and considering that the ^{77}Ge must have been produced in-situ, we can calculate an upper limit on the ^{77}Ge production rate of $r_{^{77}\mathrm{Ge}} < 0.235$ nuc/(kg · yr) (90% CL). ^{77}Ge in GERDA is mainly produced by cosmogenic activation via neutron capture in a muon-induced particle shower, producing either the ground state ^{77}Ge or the isomeric state $^{77\mathrm{m}}$Ge. The ratio for neutron captures to produce the ground state directly was assumed to be $\epsilon_d = (50 \pm 10)$ % [3]. The probability of the internal conversion from the isomeric state into the ground state is $\epsilon_{\mathrm{IC}} = (19 \pm 2)$ %. With this we can calculate the total production rate of $r_{^{77(\mathrm{m})}\mathrm{Ge}} < 0.40$ nuc/(kg · yr) (90% CL). Using a Bayesian approach, we can compute an updated production rate of (0.180 ± 0.072) nuc/(kg · yr) which corresponds to a relative reduction of $0.85^{+0.35}_{-0.34}$.

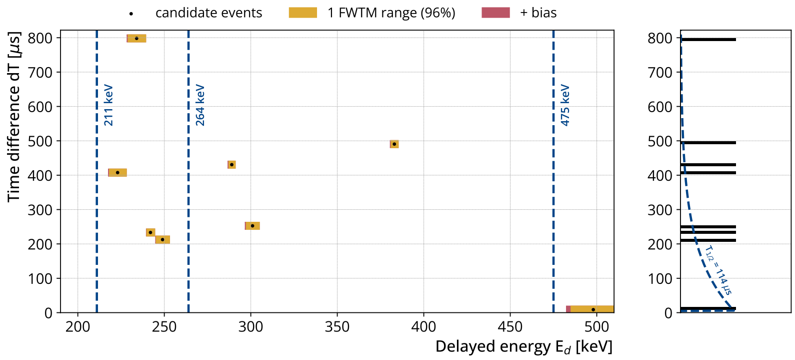

Figure 3: The distribution of all 8 candidate events after the multiplicity and quality cut condition. The energy windows around the points correspond to the linear combination of the FWTM window (yellow) plus the asymmetric bias window from calibration cross-check (red). The blue lines correspond to the gamma energies of the internal transitions from ^{77m}As . An event is rejected if its energy window misses any of the three gamma lines. We find that all candidate events are rejected (N_{obs} = 0 cts).

4. Implications

The LEGEND experiment also searches for $0\nu\beta\beta$ in ^{76}Ge and, like GERDA, uses bare HPGe detectors in LAr. The cosmogenic background is expected to become relevant for LEGEND-1000, using a target mass of 1 ton, when placed at LNGS. A previous simulation found a production rate of (0.33 ± 0.01) nuc/(kg · yr) [5]. By adding neutron moderators and applying additional delayed coincidence cut techniques, a conservative estimate of the cosmogenic background contribution of 1.0×10^{-6} cts/(keV · kg · yr) was found [6]. With the relative reduction from above, we now calculate a scaled cosmogenic background index contribution of $8.5^{+6.4}_{-6.3} \times 10^{-7}$ cts/(keV · kg · yr). In addition to using the delayed coincidence in the decay of ^{77}Ge for estimating its production rate, one can also use it as a veto condition. Using this veto we estimate the total cosmogenic background index contribution to be $4.0^{+3.0}_{-2.9} \times 10^{-7}$ cts/(keV · kg · yr) without adding additional inefficiencies to the $0\nu\beta\beta$ decay analysis. The target for the LEGEND-1000 background index is $<1 \times 10^{-5}$ cts/(keV · kg · yr) [5]. With only 4 % contribution of the in-situ cosmogenic background to the total background budget, LEGEND-1000 can fully realize its science objectives at LNGS.

References

[1] M. Agostini *et al.*, Eur. Phys. J. C 78, 388 (2018)

[2] L. Pandola *et al.*, Nucl. Instrum. Methods A 570, 149–158 (2007)

[3] C. Wiesinger, L. Pandola, S. Schönert, Eur. Phys. J. C 78, 597 (2018)

[4] M. Boswell *et al.*, IEEE Transactions on Nuclear Science, vol. 58, no. 3, pp. 1212-1220, June 2011

[5] Moritz Neuberger *et al.*, 2021 J. Phys.: Conf. Ser. 2156 012216

[6] Moritz Neuberger, Michele Morella *et al.*, Poster, Neutrino 2022, [10.5281/zenodo.6804443]