Journal of Physics: Conference Series **2156** (2022) 012117 doi:10.1088/1742-6596/2156/1/012117

GERDA: Final Results and Physics Beyond Neutrinoless Double-Beta Decay

P. Krause for the GERDA collaboration

Department of Physics, Technical University of Munich, James-Franck-Straße 1, Garching, DE.

Abstract. The GERDA experiment searched for the lepton number violating neutrinoless double-beta $0\nu\beta\beta$ decay of ^{76}Ge. Observation of this decay would provide answers to fundamental problems in particle physics and cosmology, including the origin of neutrino masses and baryon asymmetry in the universe. The GERDA experiment achieved the most stringent lower limit on the half-life of the $0\nu\beta\beta$ decay of $1.8 \cdot 10^{26}$ yr at 90% C.L. (which coincides with the sensitivity) by operating high-purity germanium (HPGe) detectors enriched in ^{76}Ge submerged in liquid argon (LAr). The collaboration could achieve this breakthrough by reducing the background event rate to $5.2 \cdot 10^{-4}$ counts/(keV kg yr) at the end-point energy. This unprecedented background index could be achieved by developing unique technologies like utilizing the scintillation light of the LAr to reject efficiently background events that deposit energy simultaneously in the HPGe detectors and in LAr, and the pulse shape discrimination which exploits specific event topologies of backgrounds and signal candidates. Due to the ultra-low background approach the GERDA data is also suited for other rare event searches beyond the $0\nu\beta\beta$ decay like the search for super-WIMPs.

1. Introduction

Neutrinoless double-beta decay ($0\nu\beta\beta$ decay) is a matter formation process beyond the standard model with a lepton number violation of two. This hypothetical nuclear transition $(Z, A) \rightarrow (Z, A + 2) + 2e^-$, unlike the usual two-neutrino double beta decay ($2\nu\beta\beta$ decay), is not accompanied by 2 antineutrinos, hence the lepton number violation. Due to the absence of neutrinos, all the energy of the $0\nu\beta\beta$ decay is carried by the electrons. Therefore, an experimental observation of the $0\nu\beta\beta$ decay would show a discrete peak at the endpoint energy ($Q_{\beta\beta}$) of the $2\nu\beta\beta$ decay [1]. An observation of the $0\nu\beta\beta$ decay could provide answers to fundamental questions in particle physics and cosmology, including the origin of neutrino masses and baryon asymmetry in the universe [2]. For this reason, significant experimental efforts are currently underway to detect the $0\nu\beta\beta$ decay in various isotopes (e.g. ^{76}Ge [3, 4], ^{82}Se [5], ^{100}Mo [6], ^{130}Te [7], ^{136}Xe [8, 9]).

2. Experimental Setup

The GERDA experiment searches for the $0\nu\beta\beta$ decay decay in ^{76}Ge (endpoint energy of $Q_{\beta\beta} = 2039$ keV) using germanium detectors enriched to 87% in the ^{76}Ge isotope [10]. This has the advantage that the detector is identical to the source, maximizing detection efficiency and reducing the background contribution from non-active material. In addition, germanium detectors offer excellent energy resolution, providing a clear signal for events at $Q_{\beta\beta}$. The GERDA experiment is located in the underground laboratory of the Laboratori Nazionali del Gran Sasso

(LNGS) of INFN. Its 3500 m.w.e. rock cover reduces the muon flux by six orders of magnitude. The experiment is constructed according to the onion-shell principle, with several subdetectors that further reduce the background. The outermost layer consists of a 590 m^3 water tank equipped with photomultipliers that detect Cherenkov radiation from residual cosmic muons [11]. Inside the water tank resides a cryostat containing 60 m^3 of liquid argon (LAr). The LAr serves as a coolant for the germanium detectors and, together with its instrumentation, provides an active background suppression system. The next layer, the LAr instrumentation, consists of a wavelength-shifting fiber curtain and are read out by 135 silicon photomultipliers (SiPM), arranged in 15 channels. In the vertical direction, the LAr volume is observed by 16 PMTs. Inside the fiber curtain the germanium detector array is located. The 41 germanium detectors with a total mass of 44.2 kg are arranged in 7 strings [12]. Each string is surrounded by a Tetraphenyl butadiene (TPB) coated nylon tube, which limits the LAr volume around the detectors from which the electric fields could collect radioactive ions [13]. In GERDA Phase II, 3 different types of germanium detectors were used: Broad-energy germanium (BeGe) detectors, which have excellent performance but are quite small (less than 1 kg per detector) [14, 15], requiring many detectors and thus potentially radioactive cables for readout to achieve a large germanium mass. The second type of detector is the coaxial detector. It has a large mass (more than 2 kg per detector), but is not as performing as the BeGe detector. The latest type of detector operated in GERDA is the so-called inverted coaxial detector, which has a large mass and good performance at the same time [16]. An overview of the experimental setup can be found in figure 3.

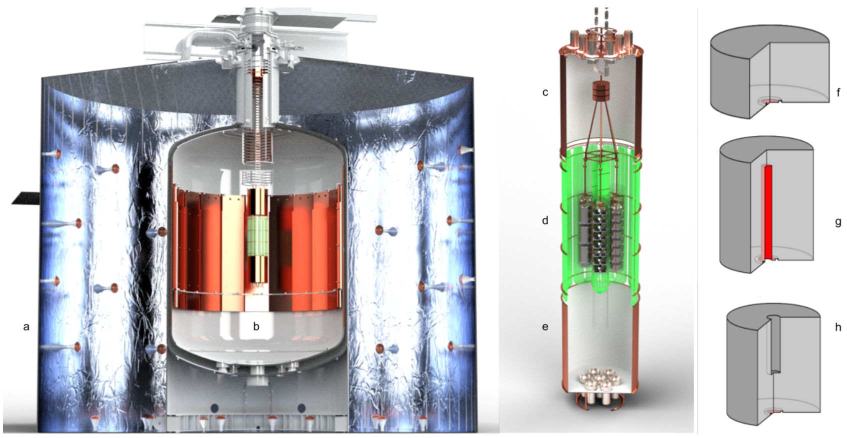

Figure 1: Overview of the GERDA experiment. **a:** 590 m^3 watertank with PMTs. **b:** 60 m^3 LAr cryostat. **c:** Top TetraTex-lined copper shroud and its 9 PMTs. **d:** Wavelength shifting fiber barrel surrounding the germanium detector array. **d:** Bottom TetraTex-lined copper shroud and its 7 PMTs. On the right the detector types deployed in GERDA; **f:** BeGe, **g:** coaxial, **h:** inverted-coaxial.

3. Background Mitigation Strategies

Background reduction is the key consideration in GERDA. In addition to careful material selection, other strategies based on the event topology of the germanium detectors are used to suppress background events. The main parameter used in GERDA to parameterize the pulse shape of an event is the A/E parameter [17]. Here A denotes the maximum current amplitude and E the energy. It is known that the energy deposition of a $0\nu\beta\beta$ decay in the germanium detector is contained in a very small volume, so-called single-site events (SSE). This is reflected in a fixed A/E value. SSEs can be caused by background events as well, for example by α or β decays on the surface of the detector. α events on the p^+ electrode create signals dominated by electron drifts. This leads to a larger A/E value due to the faster movements of electrons. β events on the n^+ electrode result in a time delayed charge collection since holes need to diffuse from the transition layer into the bulk volume, this reduces the A/E value. Gamma rays can Compton scatter multiple times within the detector, so-called multisite events (MSE). Here the A/E is smaller [17]. Energy deposition from background events can occur in multiple detectors, so another background mitigation approach used by GERDA is to require that only one germanium detector in the coincidence window has triggered. Last but not least, the instrumentation of the liquid argon provides a further powerful tool for background suppression. When interacting with ionizing radiation, LAr scintillates with a peak wavelength of 128 nm [18]. This light is then shifted to blue light (450 nm peak wavelength) by the chemical TPB. The TPB is vapor deposited onto wavelength shifting fibers. The blue light from the TPB couples into the fibers, is shifted to green light and is there read out by SiPMs coupled to the fiber ends (see fig. 2). If a signal from the SiPMs or the PMTs occurs in coincidence with the germanium detectors, the events are discarded as background. A crucial aspect of the

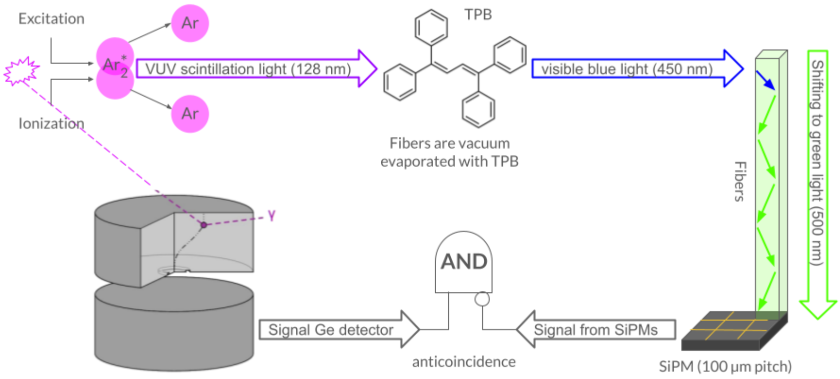

Figure 2: Working principle of GERDAs LAr instrumentation.

liquid argon instrumentation is the quality of the LAr. Impurities in the ppm range can greatly reduce the amount of scintillation light [19]. A major indicator of reduced LAr quality is a reduced triplet lifetime [20]. The triplet lifetime was monitored throughout the data acquisition in GERDA. Stable 1 μs were measured over two and a half years. In 2018, a mandatory safety valve check reduced the lifetime to 0.9 μs, which remained stable until the end of data collection in November 2019.

4. Final Results

With the GERDA Phase II data collected between December 2015 and November 2019, a total exposure of 103.7 kg/year was obtained. For the analysis of the $0\nu\beta\beta$ decay, an energy range from 1930 to 2190 keV is considered. The two known background peaks at 2104 ± 5 and 2119 ± 5 keV are excluded. In accordance with the background model [21], no other background structures are observed in the analysis window. After unblinding and applying all background mitigation cuts, 13 events are found (see Fig. 3). These are due to decays of the ^{238}U and ^{232}Th series. A Gaussian model is fitted in the analysis window, centered in $Q_{\beta\beta}$ with the width of the energy resolution and a flat prior distribution for the background. The 103.7 kg/yr exposure of the GERDA Phase II data does not indicate a signal and a lower limit for the half-life of $T_{1/2} > 1.5 \cdot 10^{26}$ yr at 90% C.L. can be given. Combining the Phase I and Phase II data, the total exposure is 127.2 kg/yr. The combined analysis also supports the null signal strength fit and yields a halflife limit of

$$T_{1/2} > 1.8 \cdot 10^{26} \text{ yr at } 90\% \text{ C.L.}$$

This result coincides with the sensitivity (median expectation under the no signal hypothesis). An unprecedented background index of $B = 5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ counts/(keV kg yr) is obtained. With the assumption of a constant prior distribution between 0 and 10^{-24} 1/yr, the Bayesian analysis yields $T_{1/2} > 1.4 \cdot 10^{26}$ yr (90% C.I.). An upper limit on the effective neutrino Majorana mass is obtained to $m_{\beta\beta} < 79$-180 meV [22].

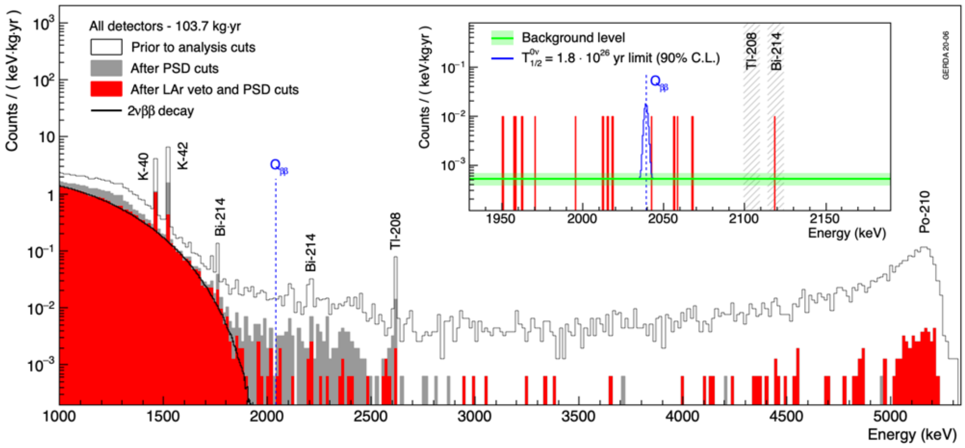

Figure 3: Final Spectrum after unbinding. Inset: Zoom into the $0\nu\beta\beta$ decay analysis window.

5. Physics Beyond Neutrinoless Double-Beta Decay

The extremely low background of GERDA enables the search for rare events beyond neutrinoless double-beta decay. One example is the search for superweakly interacting massive particles (super-WIMPs). Super-WIMPs are a type of dark matter with a mass range on the keV scale and ultraweak coupling to the standard model. They can be cosmologically viable and produce the required relic abundance [23, 24]. In GERDA, it is possible to search for pseudoscalar and vector super-WIMPs. Their energy is transferred to an electron that emits its energy in the germanium detector, where a full absorption peak in the energy spectrum corresponding to the mass of the particle is expected (the kinetic energy is negligible). In GERDA, an exposure of 58.9 kg/yr was used to search for super-WIMPs (mass range 200 - 1000 keV/c^2). A lowering of the germanium detector threshold in October 2017 allowed additional searches for super-WIMPs with masses from 60 to 200 keV/c^2 in an exposure of 14.6 ky yr. Figure 4 shows the limits that GERDA can set on the coupling strengths for super-WIMPs compared to other experiments [25]. Another example is the ongoing search for physics beyond the standard model in the $2\nu\beta\beta$ spectrum, which is almost free of background distortions in GERDA. This is of vital importance since new physics in the $2\nu\beta\beta$ spectrum would affect its shape [26, 27]. Figure 5 shows how possible Majoron emission, Lorentz violation, and sterile neutrino emission would affect the shape of the $2\nu\beta\beta$ spectrum.

6. Conclusion

Due to the extremely low background ($B = 5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ counts/(keV kg yr)), GERDA was able to achieve a half-life limit of the $0\nu\beta\beta$ decay in ^{76}Ge of $T_{1/2} > 1.8 \cdot 10^{26}$ yr at 90% C.L.. While the GERDA infrastructure has now been handed over to the LEGEND collaboration, the GERDA data will be used to search for physics beyond the $0\nu\beta\beta$ decay. Limits on the coupling strengths of super-WIMPs have already been determined. In the meantime, other studies such as searches for exotic physics (Majoron emission, Lorentz violation, and sterile neutrino emission) in the $2\nu\beta\beta$ spectrum are underway.

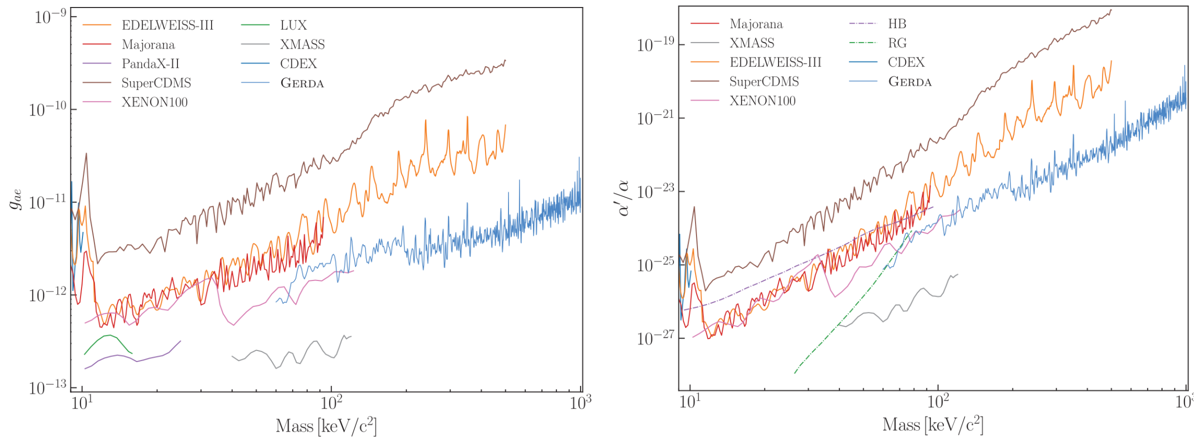

Figure 4: Upper limits (at 90% C.I.) on the coupling strengths of pseudoscalar (left) and vector (right) super-WIMPs.

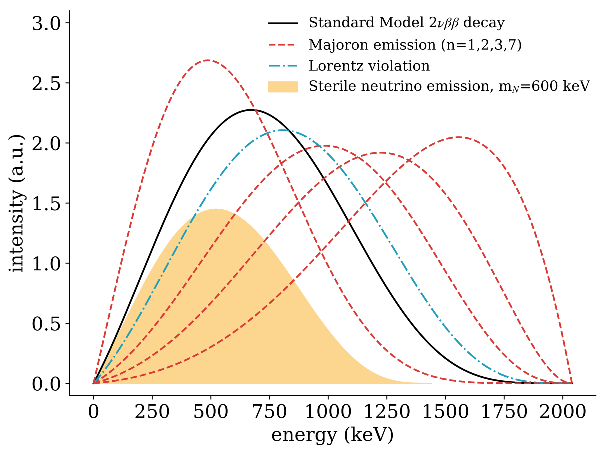

Figure 5: Influence on the shape of the $2\nu\beta\beta$ spectrum by different physics processes beyond the standard model (adapted from [26]).

References

[1] Schechter J and Valle J W F 1982 *Phys. Rev. D* **25**(11) 2951–2954
[2] Davidson S et al. 2008 *Phys. Rep.* **466** 105–177
[3] Agostini M et al. 2019 *Science* **365** 1445–1448
[4] Alvis S I et al. 2019 *Phys. Rev. C* **100**(2) 025501
[5] Azzolini O et al. 2019 *Phys. Rev. Lett.* **123**(3) 032501
[6] Arnold R et al. 2015 *Phys. Rev. D* **92**(7) 072011
[7] Adams D Q et al. 2020 *Phys. Rev. Lett.* **124**(12) 122501
[8] Gando A et al. 2016 *Phys. Rev. Lett.* **117**(8) 082503
[9] Anton G et al. 2019 *Phys. Rev. Lett.* **123**(16) 161802
[10] Ackermann K H et al. 2013 *Eur. Phys. J. C* **73** 2330
[11] Freund K et al. 2016 *Eur. Phys. J. C* **76** 298
[12] Agostini M et al. 2018 *Eur. Phys. J. C* **78** 388
[13] Lubashevskiy A et al. 2018 *Eur. Phys. J. C* **78** 15
[14] Agostini M et al. 2015 *Eur. Phys. J. C* **75** 39
[15] Agostini M et al. 2019 *Eur. Phys. J. C* **79** 978
[16] Agostini M et al. 2021 *Eur. Phys. J. C* **81** 505
[17] Agostini M et al. 2013 *Eur. Phys. J. C* **73** 2583
[18] Heindl T et al. 2010 *Eur. Phys. Lett.* **91** 62002
[19] Acciarri R et al. 2010 *JINST* **5** P06003–P06003
[20] Neumeier A et al. 2012 *Eur. Phys. J. C* **72** 2190
[21] Agostini M et al. 2020 *JHEP* **03** 139
[22] Agostini M et al. 2020 *Phys. Rev. Lett.* **125** 252502
[23] Pospelov M et al. 2008 *Phys. Rev. D* **78** 115012
[24] An H et al. 2015 *Phys. Lett. B* **747** 331–338
[25] Agostini M et al. 2020 *Phys. Rev. Lett.* **125** 011801
[26] Bossio E 2021 Poster, WIN Conference.