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Neutrinoless double beta decay search with the GERDA experiment

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Summary. — The Gerda experiment, located at the Laboratori Nazionali del Gran Sasso (LNGS), searches for the neutrinoless double beta decay of ^{76}Ge. The experiment is using 36 kg of high-purity germanium detectors, simultaneously as source and detector, deployed into ultra-pure cryogenic liquid argon. Gerda is one the leading experiments in the field, reporting the highest sensitivity on the half-life of $0\nu\beta\beta$ decay with $1.1 \cdot 10^{26}$ yr, the lowest background index with $6 \cdot 10^{-4}$ cts/(keV·kg·yr) and an excellent energy resolution of 0.12% (FWHM). The experimental setup, the analysis procedures and the latest results of Gerda are summarized in the present work.

1. – Introduction

The dominance of the matter over the antimatter in our universe is one of the most interesting aspects of cosmology. The favored models to explain this dominance are based on the leptogenesis [1], that includes the violation of the lepton number. In many extensions of the Standard Model [2], neutrinos are assumed to be their own antiparticles (Majorana particles), explaining the origin of the low neutrino mass and leading to lepton number violating processes. At present, the only feasible experiments having the potential of establishing that the massive neutrinos are Majorana particles are the ones searching for the neutrinoless double beta ($0\nu\beta\beta$) decay.

2. – Search for neutrinoless double beta decay

The double beta ($\beta\beta$) decay is a second-order weak nuclear decay process with extremely long half-life, consisting of the transformation of a pair of neutrons into two

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protons as a single process with the emission of two electrons. The standard model includes the $\beta\beta$ decay with two neutrinos ($2\nu\beta\beta$). The neutrinoless mode of this decay is not included by the Standard Model and consists of the emission of only two electrons: $(Z, A) \rightarrow (Z + 2, A) + 2e$. This decay violates the lepton number conservation by two units and has never been observed up to now.

The search for a $0\nu\beta\beta$ decay signal consists of the detection of the two emitted electrons, with total energy corresponding to the mass difference $Q_{\beta\beta}$ of the two nuclei. The rate of the $0\nu\beta\beta$ decay is usually factorized into three terms [3]:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}|M_{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2, \tag{1}$$

where $T^{0\nu}_{1/2}$ is the half-life of the $0\nu\beta\beta$ process, $G_{0\nu}$ is the phase space factor (PSF) and $M_{0\nu}$ is the nuclear matrix element (NME) [4]. In the expression of eq. (1) a fundamental quantity appears, the effective Majorana mass $m_{\beta\beta} = |\sum_{i=1}^{3} U^2_{ei} m_i|$ (where U is the PMNS mixing matrix and m_i are the neutrino mass eigenvalues). The key idea of the experiments is that, by studying the $0\nu\beta\beta$ decay, it is possible to measure its half-life and then estimate $m_{\beta\beta}$. The sensitivity of a given experiment is expressed by [5]

$$S^{0\nu} = \frac{\ln 2 \cdot N_A \cdot \epsilon \cdot f_{ab}}{m_A} \cdot \frac{1}{n_\sigma} \cdot \sqrt{\frac{M \cdot T}{BI \cdot \Delta E}}. \tag{2}$$

This formula emphasizes the role of the experimental parameters needed in the search of the decay: the detection efficiency ϵ, the isotopic abundance f_{ab} of the $\beta\beta$ emitter, the target mass M, the experimental live-time T, the background index BI and the energy resolution ΔE.

Of particular interest is the case in which BI is so low that the expected number of background events is less than one count within the energy region of interest ($Q_{\beta\beta} \pm 0.5$ full-width at half-maximum, FWHM) and a given exposure: this is called "background-free" condition. Next-generation experiments aim for having this condition. The first data release after the upgrade [6] showed that GERDA is the first background-free experiment in the field, since it will remain in this condition up to its design exposure. The advantage of this condition is that the sensitivity $S^{0\nu}$ grows linearly with the experimental mass and time, instead of by square root like in eq. (2).

3. – The GERDA experiment

The GErmanium Detector Array (GERDA) experiment [7] is located at the underground Laboratori Nazionali del Gran Sasso (LNGS) of INFN in Italy. A rock overburden of about 3500 m water equivalent removes the hadronic components of cosmic ray showers and reduces the muon flux at the experiment. The GERDA setup, illustrated in fig. 1(left), has been designed to minimize the main background sources which affected the previous generation experiments. The shielding concept follows a multi-layer approach. High-Purity Germanium (HPGe) detectors enriched to about 87% in the double beta emitter ^{76}Ge are operated bare in liquid argon (LAr), being both source and detector of $0\nu\beta\beta$ decay. The argon cryostat is complemented by a water tank with 10 m diameter which further shields from neutron and γ backgrounds and also works as muon veto.

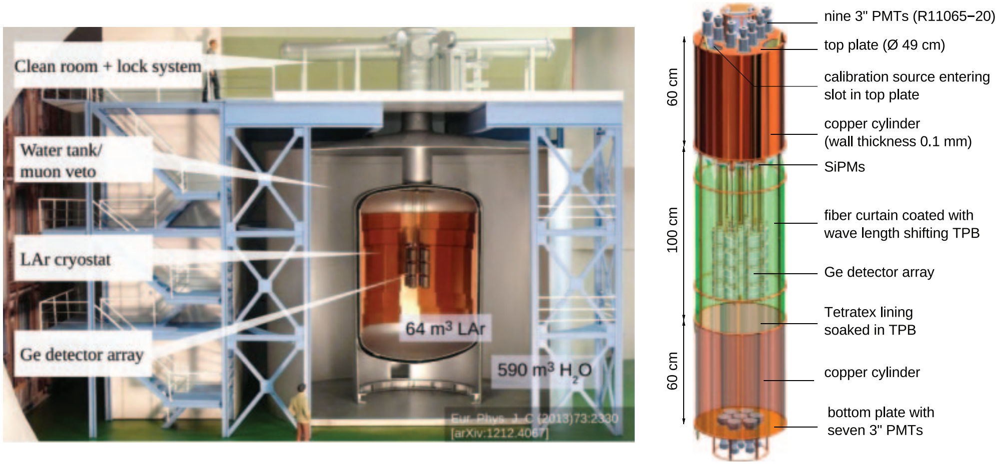

Fig. 1. – Left: setup of the GERDA experiment [7]. Right: assembly of detector array and LAr veto system [9].

A first physics data-taking campaign was carried out from November 2011 to June 2013 and the data showed no indication of a $0\nu\beta\beta$ decay signal [8]. The background index achieved at the Q-value of the ^{76}Ge $0\nu\beta\beta$ decay ($Q_{\beta\beta} = 2039\,\text{keV}$) was 10^{-2} counts/(keV · kg · yr) with an exposure of 21.8 keV · yr.

Between 2013 and 2015, the GERDA setup has been upgraded [9]: the goal was the tenfold reduction of the background with simultaneous increase of the enriched Ge detector mass.

Thirty Broad-Energy Germanium (BEGe) detectors from Canberra [10] were produced. The two main advantages of these detectors are their optimal energy resolution, due to the very low input capacitance ($\sim$ pF), and the powerful pulse shape discrimination (PSD). This is thanks to the particular shape and configuration of the p^+ and n^+ contacts that produce a highly non-uniform electrical field.

In addition, an active suppression of the background by detecting the LAr scintillation light has been introduced [11]. The LAr veto consists of PMTs and wavelength shifting fibers coupled to SiPMs. In fig. 1(right) the core of the upgraded setup is shown: the Ge detector array is at the center of the instrumented LAr volume. The design allows to assemble both the detector array and the surrounding LAr veto system under dry nitrogen atmosphere and to lower both systems together into the cryostat.

The new GERDA detector array consists of 40 HPGe detectors, arranged in 7 strings: 7 enriched coaxial detectors with a total mass of 15.6 kg, 3 coaxial detectors of natural isotopic abundance and 30 enriched BEGe detectors with a mass of 20 kg. The total enriched Ge mass available for the $0\nu\beta\beta$ decay analysis is 35.6 kg.

4. – Data taking and performance

The signals from the Ge detectors are amplified by low-radioactivity charge-sensitive preamplifiers [12] operated 35 cm above the top of the detector array in the LAr. The signals are led via 10 m long coaxial cables to the outside of the lock where they are digitized. The digital signal processing of the traces is performed within a dedicated software framework and the energy deposited in the Ge detectors is reconstructed using a run-by-run optimized cusp-like filter [13].

The calibration of the energy scale and the evaluation of the detector resolution is performed by lowering three ^{228}Th sources of low neutron emission with an activity on the order of 10 kBq into the cryostat. The average duty cycle is 92.9%, mostly due to calibrations and hardware adjustments. Only data recorded in stable conditions are used for physics analysis, corresponding to 80.4% of the total data. In addition a set of quality cuts provide the rejection of the signals originating from electrical discharges in the high voltage line or bursts of noise.

The energy resolution at $Q_{\beta\beta}$ is extracted from the summed spectrum of all calibrations for individual detectors, then compared with the average resolutions of the strongest γ-lines in physics data from ^{40}K (at 1461 keV) and ^{42}K (at 1525 keV). The estimated effective resolution at $Q_{\beta\beta}$ in terms of FWHM is 3.0(1) keV for the BEGe data set and 3.6(1) keV for the coaxial detectors.

5. – Active background rejection

The energy spectra acquired after the GERDA upgrade for BEGe and coaxial detectors are shown in fig. 2. Prior to the application of the LAr veto and the pulse shape discrimination (white spectra), the events are rejected if a muon trigger occurs within 10 μs or signals are detected simultaneously in multiple detectors. In the energy region up to 1700 keV, the events are mostly coming from the spectrum of the $2\nu\beta\beta$ decay (the predicted spectrum with half-life of $(1.926 \pm 0.094) \cdot 10^{21}$ yr [14] is also shown fig. 2). The high-energy region (>3000 keV) shows events coming from ^{210}Po α contamination. At 1461 keV and 1525 keV the γ-lines from ^{40}K and ^{42}K, respectively, are visible.

The LAr veto, as shown in the inset of fig. 2, suppresses by a factor ~5 the ^{42}K line at 1525 keV, due to the β particle depositing energy in the LAr. The Compton continuum below the ^{40}K line is efficiently rejected by the LAr veto. The LAr veto acceptance of a $0\nu\beta\beta$ decay signal is 97.7 ± 1%.

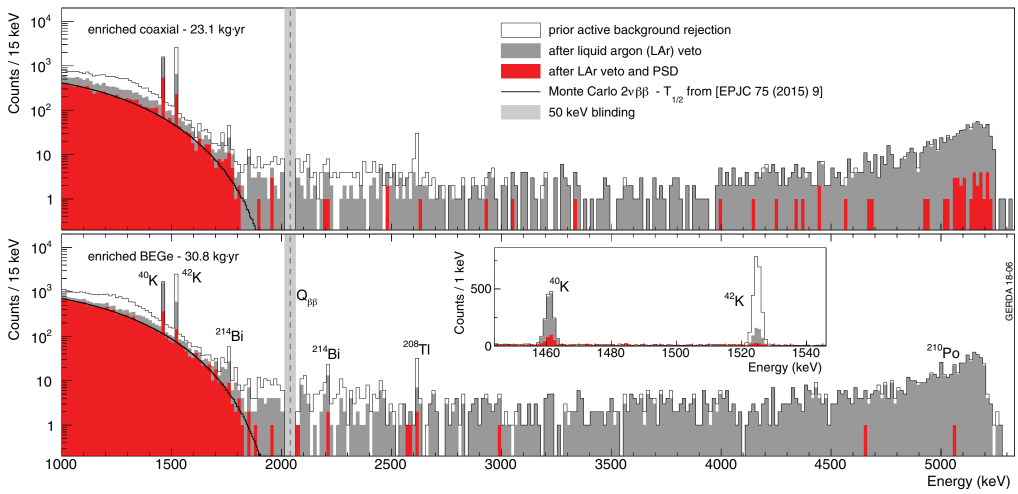

Fig. 2. – GERDA energy spectra for enriched coaxial (top panel) and BEGe (bottom panel) detectors prior the application of active background rejections, after LAr veto (in gray) and after PSD cuts (in red). The inset displays the action of the LAr veto and PSD cuts for the γ-lines from ^{40}K and ^{42}K. The predicted $2\nu\beta\beta$ decay spectrum [14] is also shown.

The GERDA background is further reduced by applying the pulse shape discrimination (PSD) cut [15]. Due to the different geometry and electric field configuration, BEGe and coaxial detectors need distinct PSD techniques. For BEGe detectors the discrimination is based on the ratio between the peak amplitude of the current signal A and the total energy E (A/E parameter). Low values of A/E are typical for multi-site events due to γ-rays and β decays on the detector n^+ contact, high A/E values are from surface events due to α on the p^+ contact. The average survival probability of a $0\nu\beta\beta$ decay event is $(87.6 \pm 2.5)\%$, estimated from ^{208}Tl double escape peak events. For the coaxial detectors the discrimination between single-site and multi-site events is based on an artificial neural network (ANN) [15]. The survival fraction of a $0\nu\beta\beta$ decay event is in this case $(84\pm5)\%$, estimated using pulse shape simulations and $2\nu\beta\beta$ decay events. Additionally, is applied a cut on the risetime of the pulses to reject fast signals from surface events due α decays near the p^+ electrode and the groove. In this case the survival probability of a $0\nu\beta\beta$ decay event is $(84.7\pm1.4)\%$. The combined PSD efficiency for coaxial detectors is $(71.2\pm4.3)\%$. The results of PSD cuts, for both coaxial and BEGe detectors, are reported in fig. 2 (red spectra).

6. – $0\nu\beta\beta$ decay analysis

GERDA adopts a blind analysis strategy to ensure an unbiased search for $0\nu\beta\beta$ decay. An energy region of 50 keV around $Q_{\beta\beta}$ is removed from the data stream until all the analysis parameters are finalized.

The analysis window is from 1930 keV to 2190 keV without the intervals (2104 ± 5) keV and (2119 ± 5) keV of known γ-lines. The final spectra acquired after the GERDA upgrade in the analysis region are shown in fig. 3: the top panel shows the new coaxial detector data ($23.1\,\mathrm{kg}\cdot\mathrm{yr}$) and the bottom panel shows the BEGe detector data ($30.8\,\mathrm{kg}\cdot\mathrm{yr}$). For the coaxial detectors only three events survived all the cuts while in the BEGe data set five events remain. The background index achieved is $5.7^{+4.1}_{-2.6} \cdot 10^{-4}$ cts/(keV · kg · yr)

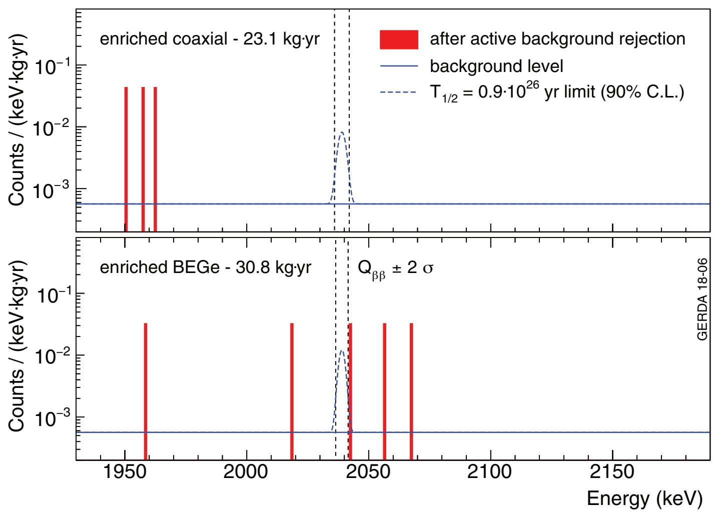

Fig. 3. – Events observed in the analysis window for coaxial (top) and BEGe (bottom) detectors. The blue lines show fitted background level and the 90% CL limit on $0\nu\beta\beta$ decay of $0.9 \cdot 10^{26}$ yr from the likelihood analysis of all GERDA data sets [16].

for coaxial and $5.6^{+3.4}_{-2.4} \cdot 10^{-4}$ cts/(keV · kg · yr) for BEGe detectors [16]. With this result Gerda reached the lowest background ever achieved in the field, taking into account the energy resolution, and will remain in the background-free regime.

A frequentist analysis based on an unbinned extended likelihood function is performed. The best fit yielded no $0\nu\beta\beta$ decay signal, setting a 90% CL limit on the ^{76}Ge $0\nu\beta\beta$ decay half-life of $T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr with a median sensitivity of $1.1 \cdot 10^{26}$ yr (90% CL), thus making Gerda the first experiment to surpass 10^{26} yr sensitivity [16]. The probability to obtain a limit stronger than the actual one in an ensemble of repeated experiments with null signal is 63%. The fact that the actual $T^{0\nu}_{1/2}$ limit is weaker than the median sensitivity is due to the presence of an event close to $Q_{\beta\beta}$ in the BEGe data set (fig. 3, bottom) with energy of 2042.1 keV, 2.4 σ away from the $Q_{\beta\beta}$.

7. – Conclusions

The presented results confirm the high quality of the Gerda design and the effectiveness of background suppression techniques, consisting of the powerful pulse shape discrimination and the detection of the argon scintillation light. Gerda is a background-free experiment and reports a background index of $6 \cdot 10^{-4}$ cts/(keV · kg · yr). Gerda continues to collect data and is projected to reach a sensitivity on the half-life beyond 10^{26} yr with the design exposure of 100 kg · yr.

Based on the success of Gerda and Majorana [17] experiments, the search for $0\nu\beta\beta$ decay in ^{76}Ge will be continued in the next years by the LEGEND-200 experiment [18], that aims to reach a sensitivity up to 10^{27} yr using 200 kg of enriched HPGe detectors. The preparation of this experiment, that will take place at LNGS on the Gerda site, already started.

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