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GERDA final results on neutrinoless double beta decay search

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Summary. — The GErmanium Detector Array (GERDA) experiment searched at Laboratori Nazionali del Gran Sasso of INFN for neutrinoless double beta ($0\nu\beta\beta$) decay of the ^{76}Ge isotope. The experiment has used 44 kg of bare high-purity germanium detectors, acting simultaneously as source and detector, deployed into ultra-pure liquid argon. The last GERDA results lead the $0\nu\beta\beta$ decay field, reporting the highest sensitivity on the half-life of $0\nu\beta\beta$ decay, 1.8×10^{26} yr, and the lowest background index at the Q-value of the decay, of 5.2×10^{-4} cts/(keV·kg·yr). These achievements are the result of the careful selection of highly radiopure materials and of efficient background suppression techniques. The experimental setup, the active background reduction techniques and the final results of GERDA will be summarized.

1. – Introduction and motivation

In the Standard Model (SM) of Particle Physics neutrinos are elementary spin-1/2 fermions, with no electrical and color charge. Only the lepton number can differentiate the neutrino from its antiparticle, the anti-neutrino. Since there is no gauge symmetry associated with the conservation of the lepton number, this quantum number could be violated, leading to new physics beyond the SM. In those extensions of the SM which do not require the lepton number conservation [1], the neutrinos coincide with their own anti-particles and they are called Majorana neutrinos [2], unlike all other fermions of the SM that have distinct anti-particle states and are known as Dirac particles.

Thanks to the observation of the neutrino oscillation phenomenon [3,4], we know that neutrinos have a mass, but the nature and the size of their mass are still open issues in the neutrino sector beyond the SM. At present the only feasible experiments that have the capability to define the absolute scale of the neutrinos mass and to establish their nature (Dirac or Majorana particles), are those searching for an hypothetical process called neutrinoless double beta ($0\nu\beta\beta$) decay. Its detection would imply the violation of lepton number conservation as predicted to occur in extensions of the SM.

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In recent years, the half-life of the $0\nu\beta\beta$ decay has been established to be higher than 10^{25} yr [5-8].

2. – Neutrinoless double beta decay

The double beta ($\beta\beta$) decay is a second-order weak nuclear decay process with the longest lifetime ever observed. The idea of such a decay was first suggested by Maria Goeppert-Mayer in 1935 [9]. The two-neutrino mode of the $\beta\beta$ ($2\nu\beta\beta$) decay is a nuclear transition in which two neutrons are simultaneously converted into two protons with the emission of two electrons and two anti-neutrinos.

In 1939, Wendell H. Furry presented a new $\beta\beta$ decay mode: the neutrinoless double beta ($0\nu\beta\beta$) decay [10]. As in the $2\nu\beta\beta$ decay, in the $0\nu\beta\beta$ decay a nucleus with Z protons decays into a nucleus with $Z+2$ protons and the same mass number A, accompanied by the emission of two electrons but no anti-neutrinos:

$$(A,Z) \rightarrow (A,Z+2) + 2e^-. \tag{1}$$

Moreover, unlike the $2\nu\beta\beta$ decay, the $0\nu\beta\beta$ decay violates the law of lepton number conservation and requires the exchange of massive Majorana neutrinos.

From the experimental point of view, the most direct approach in the search of a $0\nu\beta\beta$ decay signal consists in the detection of the two emitted electrons. The recoil energy of the nucleus is negligible and the energy is almost entirely carried away by the two electrons. Therefore the $0\nu\beta\beta$ decay signal will manifest as a characteristic peak in the energy spectrum at the Q-value of the decay process ($Q_{\beta\beta}$).

The rate of the $0\nu\beta\beta$ decay, in the assumption that the decay is mediated only by a massive Majorana neutrino, can be factorized as [11]

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

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 and $M^{0\nu}$ is the nuclear matrix element (NME). The expression of eq. (2) features a key quantity: the effective Majorana mass of the electron neutrino $m_{\beta\beta} =\mid \sum_i U^2_{ei} m_i \mid$, where U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix and m_i are the mass eigenvalues of the three neutrinos. In this way, by studying the $0\nu\beta\beta$ decay, it is possible to measure the half-life and then estimate the Majorana mass.

The sensitivity of an experiment searching for $0\nu\beta\beta$ decay is expressed by [12]:

$$S^{0\nu} = \frac{ln(2)\cdot N_A \cdot \epsilon \cdot a}{m_A \cdot n_\sigma}\sqrt{\frac{M\cdot T}{BI\cdot \Delta E}}. \tag{3}$$

This expression highlights the role of the experimental parameters used in the search of the $0\nu\beta\beta$ decay: the detection efficiency ε; the isotopic abundance a of the $\beta\beta$ emitter; the target mass M; the experimental lifetime T; the background index BI, defined as the rate of background events per unity of energy, mass and time; the energy window ΔE around $Q_{\beta\beta}$, proportional to the energy resolution of the detector.

Of particular interest is the situation where BI is so low that the number of expected background events is less than one count in the energy region around $Q_{\beta\beta}$, the so-called "background-free" condition. The advantage of such a condition lies in the linear increase of the sensitivity $S_{0\nu}$ with the experimental exposure (mass × lifetime), instead of the square root as in the expression of eq. (3).

3. – GERDA experiment

The GErmanium Detector Array (Gerda) experiment [13], designed in the search of the lepton number violating $0\nu\beta\beta$ decay of the ^{76}Ge isotope, operated at the underground Laboratori Nazionali del Gran Sasso of INFN (Italy), where the overlying rock removes the hadronic components of cosmic ray showers and reduces the muon flux by six orders of magnitude.

The core of the Gerda experiment was composed of High-Purity Germanium (HPGe) detectors, isotopically enriched in ^{76}Ge up to $\sim 87\%$. The germanium detectors show an excellent energy resolution at $Q_{\beta\beta}$ ($\sim 0.12\%$FWHM) and a high detection efficiency, being source and detector of the $0\nu\beta\beta$ decay.

The Gerda shielding, aimed to the minimization of the background around the Q-value of the $0\nu\beta\beta$ decay in ^{76}Ge ($Q_{\beta\beta} = 2039$ keV), was designed in a multi-layer approach, as shown in fig. 1 (left). A tank with purified water shielded from neutron and gamma backgrounds and also worked as a muon veto. Subsequently a cryostat filled with Liquid Argon (LAr), which contained Ge detectors organized in strings, acted as cooling medium and shielding of the detectors against background radiation.

The first data taking campaign, named as Gerda Phase I, was carried out from November 2011 to June 2013 and showed no indication of a $0\nu\beta\beta$ decay signal: the average background index achieved at $Q_{\beta\beta}$ was 11×10^{-3} cts/(keV·kg·yr) with an exposure of 21.6 keV · yr [14].

Between 2013 and 2015 the Gerda setup was upgraded for the Phase II [15], with the aim of reducing the background index below 10^{-3} cts/(keV·kg·yr) and collecting 100 kg · yr of exposure in a "background-free" regime. The latter was achieved by the introduction of a new active background suppression technique, allowing to detect the

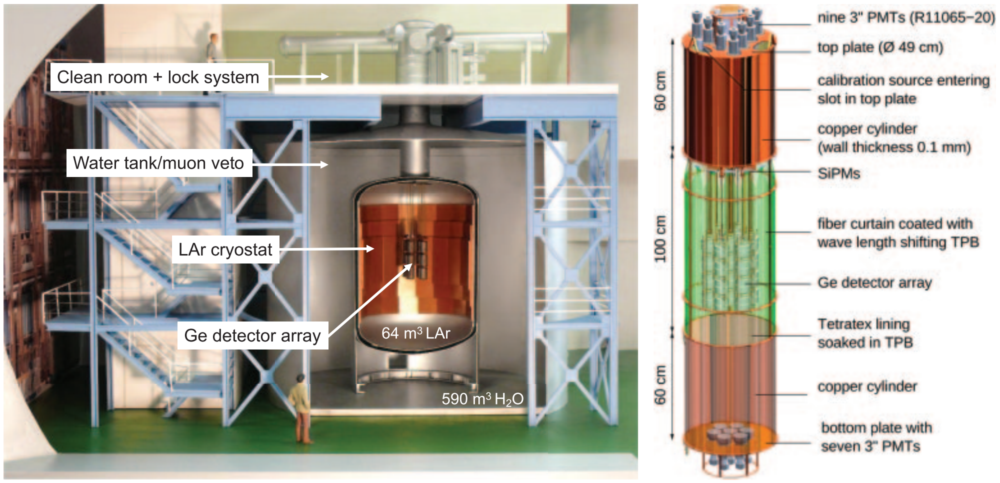

Fig. 1. – Left: artists view of the Gerda setup (Ge detector array not to scale) [13]. Right: the LAr veto system containing the Ge detector array [15].

background energy deposition in the LAr, the so-called LAr veto [16]. This veto is composed of PMTs and wavelength shifting fibers coupled to SiPMs, in order to detect the LAr scintillation light. In fig. 1 (right) the upgraded setup is shown: the Ge detector array are surrounded by the instrumented LAr volume. In addition, 20 kg of Broad Energy Germanium (BEGe) detectors [17, 18], produced by Canberra Olen, were added to 15.6 kg of refurbished coaxial detectors from previous experiments (HdM [19] and Igex [20]), already operated in Gerda Phase I. The main advantages of BEGe detectors are their optimal energy resolution, due to the very low input capacitance (∼pF), and a powerful pulse shape discrimination, due to the particular shape and configuration of the electrodes that produce a highly non-uniform internal electric field.

In December 2015 the data taking started for the Phase II and the data, released in May 2018, reported the lowest background index ever achieved, 6×10^{-4} cts/(keV·kg·yr) [5], with an exposure of about 60 kg · yr. This confirmed that Gerda was in the "background-free" regime. Since July 2018 additional data have been acquired using also 9.6 kg of new type of Ge detectors, the Inverted Coaxial (IC) detectors [21]. The IC detectors have the same performance as BEGe detectors but with a higher mass and were introduced as a test for the next generation experiments.

In November 2019 Gerda stopped the data taking for the Phase II, reaching 103.7 kg· yr of total exposure, and the final results were presented in June 2020.

4. – Front-end electronics and data acquisition

The HPGe detectors used in Gerda are p-type diodes with a large volume (up to hundreds of cm^3), which work with a reverse bias voltage, such that almost the entire volume is depleted of free charge carriers. The high voltage is applied to n$^+$ electrode, a Li-diffused relatively thick (∼ mm) dead layer, while the signal is read-out on the very thin (∼ μm) p$^+$ electrode, obtained via boron implantation.

The front-end electronics selected for the Gerda Phase II Ge detector read-out is the CC3, a 4 channel, hybrid and cryogenic Charge Sensitive Preamplifier (CSP) [23, 22], derived from the CC2 CSP used in Gerda Phase I [24]. Its main function is to extract the signal from the detector, converting a charge into a voltage signal and preserving the intrinsic signal-to-noise ratio.

The signals from HPGe detectors are driven via 10 m long coaxial cables to the outside of the lock where they are digitized by a 14-bit 100 MHz flash analog-to-digital converter. The digital signal processing of the traces is performed within a dedicated software [25], where an optimized cusp-like filter [26] is used to reconstruct the energy deposited in the Ge detectors. In addition, a set of quality cuts suppresses signals originating from electrical discharges or noise bursts.

The energy calibration and the estimation of the detectors resolution are performed by lowering three ^{228}Th sources, with low neutron emission, in the LAr cryostat. The energy resolution at $Q_{\beta\beta}$ is extracted from the summed spectrum of all calibrations for each detector, then compared with the average resolutions of the γ-lines from ^{40}K (at 1461 keV) and ^{42}K (at 1525 keV) in physics spectrum.

5. – Active background reduction techniques

The signal due to a $0\nu\beta\beta$ decay is expected to release an energy amounting to $Q_{\beta\beta} =$ 2039 keV, for ^{76}Ge isotope, in a small volume of the detector (∼ mm^3). The detection

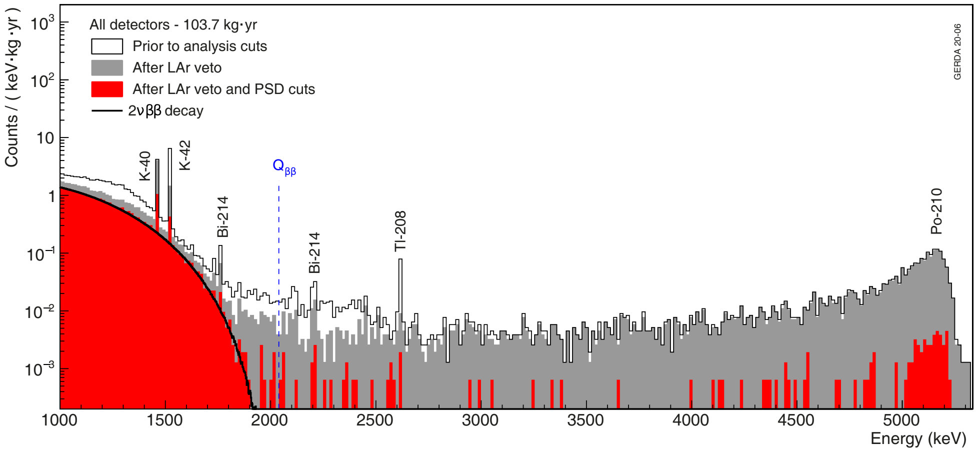

Fig. 2. – GERDA Phase II energy distribution (103.7 kg · yr of exposure) before and after the application of active background reduction techniques (LAr veto and PSD) [27]. The expected $2\nu\beta\beta$ decay spectrum is shown assuming the half-life of 1.93×10^{21} yr measured by GERDA [28]. The γ-lines and the α events around 5.3 MeV are also labeled.

of such a rare decay requires the suppression of any kind of background in the region of interest (around $Q_{\beta\beta}$).

In the GERDA experiment the main background sources are related to the residual contaminations present in the materials used for the experiment construction and located near the detector array. In particular, the γ-rays from ^{214}Bi and ^{208}Tl lines and β-decays from ^{42}K, a daughter nuclide of ^{42}Ar which is a long-lived Ar cosmogenic contaminant, release their energy around $Q_{\beta\beta}$.

The GERDA Phase II energy spectrum, with 103.7 kg · yr of total exposure, is shown in fig. 2. Before applying the LAr veto and the Pulse Shape Discrimination (PSD), the event is rejected if a muon veto trigger occurs within 10 μs or if the signal is detected simultaneously in multiple detectors. In the energy region up to 1700 keV, the events are mostly coming from $2\nu\beta\beta$ decay, as highlighted in fig. 2. The high-energy region (> 3000 keV) contains events coming from ^{210}Po α contamination.

The GERDA experiment relies on improved active background reduction techniques, such as liquid argon veto and pulse shape discrimination, in order to reach a background index below 10^{-3} cts/(keV·kg·yr) at $Q_{\beta\beta}$ and to achieve the $0\nu\beta\beta$ decay half-life of the order of 10^{26} yr.

5·1. *LAr veto.* – The GERDA LAr veto is a detector system designed to detect the argon scintillation light near the detector array, due to the energy deposition of background events. Since the events due to the $2\nu\beta\beta$ and $0\nu\beta\beta$ decays have very high probability to release the entire energy $Q_{\beta\beta}$ within the Ge detector only, an event is vetoed if the energy was simultaneously deposited in the HPGe detector and in the LAr. The PMT and SiPM waveforms are processed off-line to reconstruct the timing and the amplitude of the scintillation signals. If a scintillation signal with an amplitude greater than the established threshold is found in a narrow time window near the Ge detector pulse, the event is rejected. Taking into account the noise level, the dark rate and the time structure of the LAr scintillation process, the threshold and the time window are optimized for each detector.

Figure 2 shows the energy distribution after the LAr veto: the Compton continuum below the ^{40}K line is efficiently suppressed, so almost the pure $2\nu\beta\beta$ spectrum remains; the events of the ^{42}K line are suppressed by a factor ∼5 and the events around $Q_{\beta\beta}$ by a factor ∼2. The LAr veto acceptance of a $0\nu\beta\beta$ decay signal is 98%, due to accidentals.

5·2. *Pulse shape discrimination.* – The Gerda background in the region of interest is further reduced by the application of the PSD cuts [29, 30]. The pulse shape of the output signals from Ge detectors allows to identify background events from γ-rays, which mainly interact via Compton scattering, producing events with multiple energy depositions (multiple site events, MSEs), and events on the detector surface due to α or β decays, respectively on p^+ or n^+ contact. The PSD is used to discriminate this type of events against highly localized events (single site events, SSEs), such as those produced by $0\nu\beta\beta$ and $2\nu\beta\beta$ decays.

Due to the different geometric shapes and electric field configurations, BEGe, coaxial and IC detectors require distinct PSD techniques. For Gerda BEGe and IC detectors a single parameter is used to classify background events: the ratio of maximum current amplitude to energy (A/E). The A/E parameter shows that the amplitude of the current pulse is approximately proportional to the energy deposited in a single interaction. Therefore MSEs and events at the n^+ electrode are characterized by a lower A/E value compared to SSEs, while events at the p^+ electrode have higher A/E value. In this way the PSD with the A/E parameter is an effective method to discriminate signal-like from background-like events. For the coaxial detectors the discrimination between SSEs and MSEs is based on an Artificial Neural Network (ANN), as they are characterized by a more complex time structure of events. Additionally, a cut is applied on the risetime of the pulses to reject fast signals from surface events, due to α decays near the p^+ electrode.

^{228}Th calibration spectrum is used to understand and validate the discrimination of SSEs from MSEs with A/E parameter and ANN: the Double Escape Peak (DEP) at 1593 keV, from the ^{208}Tl line at 2615 keV, is used as a proxy for $0\nu\beta\beta$ events (SSEs), and the full energy peaks, as the one at 1621 keV from ^{212}Bi, are used as samples of MSEs. The lower threshold for rejecting MSEs is chosen such to have a 90% survival fraction of the DEP, while the upper threshold for rejecting the surface events on p^+ contact is optimized using the $2\nu\beta\beta$ and α decays. The $0\nu\beta\beta$ decay signal efficiency is estimated, after all cuts, from the survival fraction of DEP and $2\nu\beta\beta$ decay events: the average survival probability of a $0\nu\beta\beta$ decay event is about 89% for BEGe detectors, 90% for IC detectors and 69% for coaxial detectors.

The results after the PSD cuts combined to LAr veto are reported in fig. 2: at low energy the counting rate is mostly represented by the $2\nu\beta\beta$ decay spectrum; around $Q_{\beta\beta}$ and at high energy most of background events are suppressed. In this way, extremely powerful complementarity between LAr veto and PSD cuts is obtained.

6. – Analysis in the $0\nu\beta\beta$ decay window

The Gerda experiment uses a blind analysis approach to guarantee an unbiased search for $0\nu\beta\beta$ decay. Events within an energy interval corresponding to $(Q_{\beta\beta} \pm 50)$ keV are removed from the data stream until all the analysis parameters are finalized.

For the $0\nu\beta\beta$ decay analysis an energy range from 1930 keV to 2190 keV is considered, without the intervals corresponding to ^{208}Tl and ^{214}Bi lines, as shown in fig. 3. According to the Gerda background model [31], no other γ-lines are expected in this region.

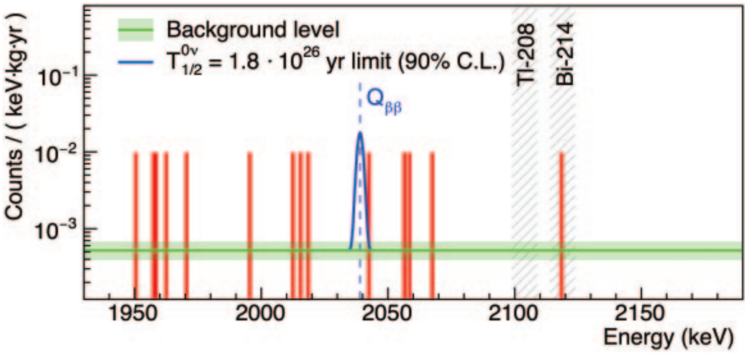

Fig. 3. – Energy of the observed events in the analysis window after analysis cuts. The horizontal line corresponds to the fitted background level and the 90% C.L. limit on $0\nu\beta\beta$ decay [27].

After the application of all background reduction techniques, 13 events are found in the analysis window for the entire Phase II exposure [27], as reported in fig. 3. This result allows GERDA to achieve an unprecedentedly low background index:

$$BI = 5.2^{+1.6}_{-1.3} \times 10^{-4} \quad \frac{\text{cts}}{(\text{keV} \cdot \text{kg} \cdot \text{yr})} \tag{4}$$

and thus to collect an exposure of 100 kg · yr in a “background-free” regime: the mean background expected around $Q_{\beta\beta}$ is 0.3 counts.

The search for a $0\nu\beta\beta$ decay signal consists in the fit of the energy distribution of the found events, as shown in fig. 3: a constant distribution for the background and a Gaussian distribution for the signal expected at $Q_{\beta\beta}$, with a width corresponding to the energy resolution. The statistical analysis followed the procedure described in [32].

Combining all collected data from GERDA Phase I and Phase II, 127.2 kg · yr of total exposure, no signal of a $0\nu\beta\beta$ decay was discovered. The best fit sets a limit on the half-life of the $0\nu\beta\beta$ decay in ^{76}Ge isotope

$$T^{0\nu}_{1/2} > 1.8 \times 10^{26} \text{ yr at } 90\% \text{ C.L.} \tag{5}$$

which coincides with the sensitivity, defined as the median expectation under the no signal hypothesis.

In the assumption that the $0\nu\beta\beta$ decay is mediated only by massive Majorana neutrinos, the lower limit on the half-life leads to an upper limit on the effective Majorana neutrino mass and taking into account the uncertainties on NME, the upper limit interval is set at

$$m_{\beta\beta} < 79 - 180 \text{ meV at } 90\% \text{ C.L.} \tag{6}$$

which is comparable with the upper limits of other isotopes [6-8].

7. – Conclusion and outlook

The neutrinoless double beta ($0\nu\beta\beta$) decay search is a topic of broad and current interest in modern physics. Its detection would imply the violation of lepton number conservation as predicted to occur in the extensions of the Standard Model. Among many experiments in the field, the GErmanium Detector Array (Gerda) experiment obtained the best limit on the half-life of the $0\nu\beta\beta$ decay, 1.8×10^{26} yr (90% C.L.), with 127.2 kg·yr of total exposure collected in a "background-free" regime. This result retrospectively validates the Gerda design and the effectiveness of background suppression techniques, based on powerful pulse shape discrimination and the detection of the argon scintillation light.

Gerda and Majorana [33] experiments pave the way for a new-generation experiment, the Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND) experiment [34]. The experiment will be phased: LEGEND-200 and LEGEND-1000 with 200 kg and 1000 kg of enriched germanium detectors, respectively. LEGEND-200 aims to reach a sensitivity up to 10^{27} yr by operating 200 kg of Ge detectors within the upgraded Gerda infrastructure. The construction of the experiment has already started and under favorable scenarios LEGEND-200 could start the data taking by 2021. It will also be a prototype for LEGEND-1000, which aims to reach the $0\nu\beta\beta$ decay half-life limit of 10^{28} yr.

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