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Latest results from GERDA Phase II experiment on ^{76}Ge double-beta decay and exotic decay searches

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The GERmanium Detector Array (GERDA) experiment at the Laboratori Nazionali del Gran Sasso (LNGS, Italy) had, as main goal, the search for the lepton-number-violating neutrinoless double-beta ($0\nu\beta\beta$) decay of ^{76}Ge. The potential discovery of such phenomenon would have significant implications in cosmology and particle physics, helping unrevealing the Majorana nature of neutrinos. The main feature of the GERDA design consisted in operating an array of bare germanium diodes enriched in ^{76}Ge in an active liquid argon shield. The Phase II physics run (December 2015 - November 2019) reached an unprecedentedly low background index of 5.2×10^{-4} counts/(keV kg yr) in the signal region, collecting an exposure of 103.7 kg yr while operating in a background-free regime. No signal was observed after a total exposure of 127.2 kg yr for a combined analysis of Phase I (November 2011 - September 2013) and Phase II data. A lower bound on the half-life of $0\nu\beta\beta$ decay in ^{76}Ge was set at $T_{1/2} > 1.8 \times 10^{26}$ yr (90% C.L.), which coincides with the median expectation under the no signal hypothesis. This contribution will review the GERDA experiment design and its final results, both on ^{76}Ge double-beta decay searches with and without neutrinos, and recent results on searches for tri-nucleon decay of ^{76}Ge and search for new exotics physics.

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1. Introduction

Double beta decay is the simultaneous beta decay of two neutrons in a nucleus. The process, called two neutrino double beta decay ($2\nu\beta\beta$), can be calculated in the Standard Model of Particle Physics as a second order process $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu}_e$ and it has been observed in 11 nuclei, where single beta decay is energetically forbidden; very high half-lives, between 7×10^{18} yr and 2×10^{24} yr, have been measured [1]. Several models extending the Standard Model of Particle Physics predict that a neutrinoless double beta decay ($0\nu\beta\beta$) should also exist: $(A, Z) \rightarrow (A, Z+2) + 2e^-$. The observation would imply that lepton number is violated by two units and that neutrino is its own antiparticle, developing a Majorana mass component. The standard mechanism for $0\nu\beta\beta$ assumes that the process is mediated by light and massive Majorana neutrino and that other mechanisms potentially leading to neutrinoless double beta decay are negligible. The main experimental signature of the $0\nu\beta\beta$ decay is a characteristic peak in the measured energy distribution, which is centered at the Q value of the decay, while for the $2\nu\beta\beta$ decay, the total decay energy is shared among the two final-state electrons and antineutrinos produced in the decay. A rich experimental program is underway to search for this rare nuclear trasition employing various candidate isotopes. This paper describes the status of the art in double beta decay searches in ^{76}Ge with the results achieved by the GERDA experiment.

2. The GERDA experiment

The GERmanium Detector Array (GERDA) [2] is an experiment employing isotopically modified germanium detectors (enriched in ^{76}Ge at about 87% level) to search for neutrinoless double-β decay ($0\nu\beta\beta$) of ^{76}Ge and other possible decays of the the same isotope. The experiment has been located at the Gran Sasso National Laboratories of INFN (LNGS), in Italy, under a mountain that with an overburden of 3500 m of water equivalent provides a high reduction of the cosmic muons, suppressing them by six order of magnitude with respect to the above ground flux. GERDA operated in two distinct phases: Phase I from November 2011 to December 2015, and Phase II from December 2015 to November 2019. The same infrastructure has been upgraded and is now operating the LEGEND-200 experiment [3]. A distinctive feature of the experiment has been the operation of bare high-purity germanium detector in a cryostat containing 64 m^3 of liquid argon (LAr), the latter providing both detectors cooling and shielding from environmental backgroud. The cryostat is immersed in a water tank filled with 590 m^3 of purified water and instrumented with photomultipliers to detect the residual cosmic muons that reach the experiment. Both water and LAr serve as shield for the germanium detector arrays from external radioactivity and neutrons. GERDA Phase II operated 41 high purity germanium detectors assembled into seven strings which were surrounded by a nylon cylinder to limit the LAr volume radioactivity coming from β decays of ^{42}K, produced from the long-lived ^{42}Ar, and effectively reducing this type of background. The detector arrays were sorrounded by a cilyinder made by a curtain of instrumented wave-length-shifting fibers connected to cyogenically operated SiPMs and PMTs.

This experimental approach is very efficient in detection since both source and detector coincide. Moreover, the excellent energy resolution of germanium detectors allows to measure with high precision the signature of the $0\nu\beta\beta$ decay signal. The two electrons emitted in a $\beta\beta$ decay have a limited range in germanium (about 1 mm) and therefore deposit their energy in a small volume producing a highly localized event (also called single-site event, or SSE). On the contrary, γ rays in the same energy range interact mainly via Compton scattering and multiple interactions inside one detector, but well separated in space, or in multiple detectors in the strings may happen, originating well separated energy depositions (these are the so-called multiple-site events, of MSE). Morevover, these events could provide energy depositions both in multiple germanium detectors or in the instrumented LAr region, allowing to clearly identify them and to reject them as background events. The time structure of the germanium detector signals can be used to identify MSEs in a single detector and also recognize events due to α or β decays close to the detector surface. This technique is referred to as pulse shape discrimination (PSD) [4] and it has been a very important ingredient in all the analyses performed by GERDA to minimize the background contaminations in the final samples.

2.1 Neutrino-less Double Beta Decay

GERDA has published the final result on the search for $0\nu\beta\beta$ decay of ^{76}Ge with a total exposure of 103.7 kg yr [5]. The plot of Figure 1 shows the energy distribution of all the events

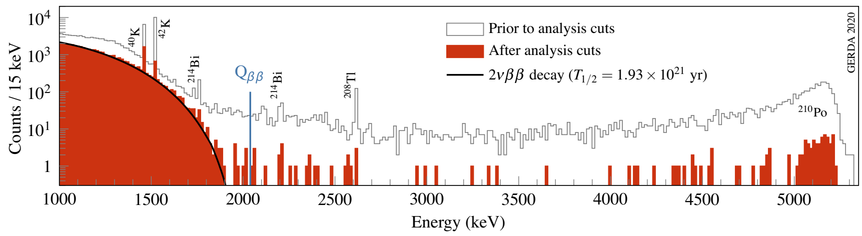

Figure 1: GERDA Phase II energy spectrum in the 1 to 5.3 MeV region before and after the analysis cuts. The $Q_{\beta\beta}$ and the prominent γ lines and α decays around 5.2 MeV are shown. Taken from [5].

before and after applying the analysis cuts. As can be clearly seen, the counting rate at low energy (below 1.9 MeV) is mostly due to $2\nu\beta\beta$ decay of ^{76}Ge. The search for $0\nu\beta\beta$ decay of ^{76}Ge gives a half-life limit of

$$T_{1/2} > 1.8 \times 10^{26} \text{ yr at 90\% CL.}$$

As can be seen from the right plot of Figure 2, the limit coincides with the sensitivity, defined as the median expectation under no signal hypothesis. GERDA achieved an unprecedentedly low background of $B = 5.2^{+1.6}_{-1.3} \times 10^{-4}$ counts/(keV kg yr) which confirms that GERDA performed a background-free search in the Region of Interest (ROI) ($Q_{\beta\beta} \pm 2\sigma$) with a mean expected background of 0.3 counts. In the right plot of Figure 2 the improvement achieved by GERDA as a function of the exposure for both the measured $0\nu\beta\beta$ lower limit and expected sensitivity is shown. The achieved background-free regime results in a nearly linear improvement of the sensitivity as a function of the exposure.

As can be seen from the left plot of Figure 2, the energy range that has been considered for the $0\nu\beta\beta$ decay analysis is 1930 keV - 2190 keV with the exclusion of two small intervals containing two known background peaks.

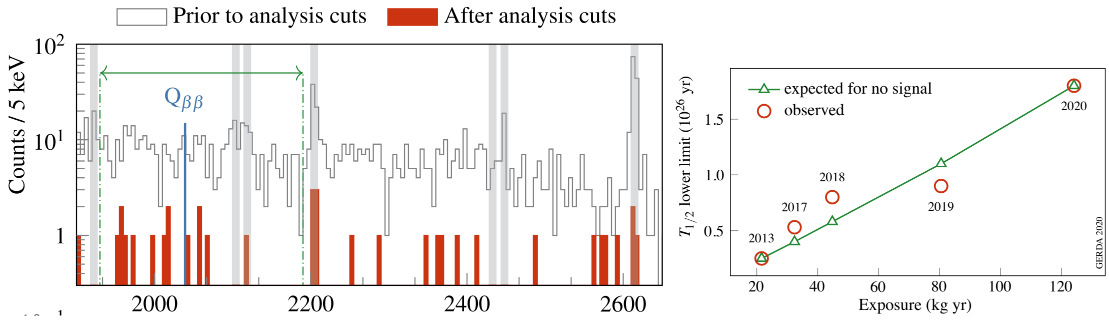

Figure 2: Left: GERDA Phase II enlarged energy spectrum in the 1900 - 2650 keV region, before and after the analysis cuts. The regions of expected γ lines are marked in grey. Right: lower limit (90% C.L.) on the $0\nu\beta\beta$ decay half-life of ^{76}Ge as a function of the exposure. Taken from [5].

2.2 Two neutrino Double Beta Decay

The GERDA Collaboration has recently published [6] a precise measurement of the two-neutrino double-β decay of ^{76}Ge. Only a subset of the full exposure of the GERDA Phase II experiment (103.7 kg yr) and only data collected with nine BEGe detectors have been used, corresponding to an exposure of 11.8 kg yr. These detectors were selected because they have been carefully characterized before deployment in the GERDA cryostat and after the end of the GERDA data taking. These measurements allowed to determine the dead layer thickness and the active volume fraction, which is one of the most critical sources of uncertainty in the half-life determination. The measured half-life,

$$T^{2\nu}_{1/2} = (2.022 \pm 0.018_{\text{stat}} \pm 0.038_{\text{syst}}) \times 10^{21} \text{ yr},$$

is the most precise measurement of this double-β decay process, to date. Apart from the detectors active volume determination (still dominating the systematic uncertainty), an enhanced signal-to-background condition due to the excellent background subtraction capability of the GERDA LAr veto system was crucial for the result.

Figure 3 shows the experimental data after having applied the LAr veto cut and the total best fit model, superimposed. As can be seen, the residual backgound, after the LAr veto cut, is extremely low, and excluding the two γ lines coming from ^{40}K and ^{42}K is 22:1. Summing in quadrature, both statistical and systematic uncertainties, the total 1σ uncertainty on the $T^{2\nu}_{1/2}$ measurement is 2.1%. The systematic uncertainty dominates with a majour contribution from the active volume estimate (1.8%). Further improvements on the precision of the ^{76}Ge two-neutrino double-β decay would require a more precise determination of the Ge detectors active volume, which will be the challenge for the LEGEND experiment [7], the next generation experiment for double-β decay physics with ^{76}Ge.

2.3 Beyond Standard Model decay searches

The existence of new particles in Beyond the Standard Model (BSM) theories can lead to $\beta\beta$ decay modes with different final states, in which the exotic particles are emitted along with the two electrons. The experimental quantity that allows to distinguish the exotic decays from the SM $2\nu\beta\beta$

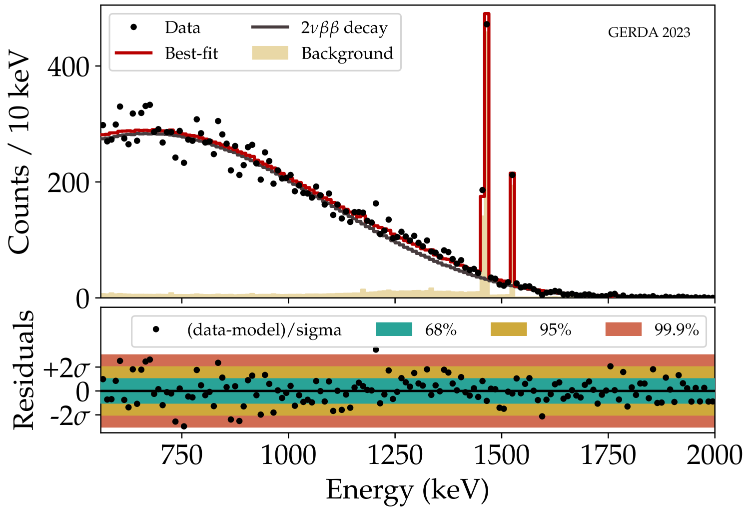

Figure 3: GERDA energy spectrum in the $2\nu\beta\beta$ region. Taken from [6].

decay is the shape of the predicted distribution of the summed energy of the two emitted electrons. In a recent paper [8], the GERDA collaboration performed a search for new physics in the ^{76}Ge $\beta\beta$ decay that manifests as a deformation of the continuous $2\nu\beta\beta$ spectrum, such as decays involving Majorons, light exotic fermions, and Lorentz violation. No indication of deviations from the SM $2\nu\beta\beta$ decay distribution was found for any of the considered decay modes.

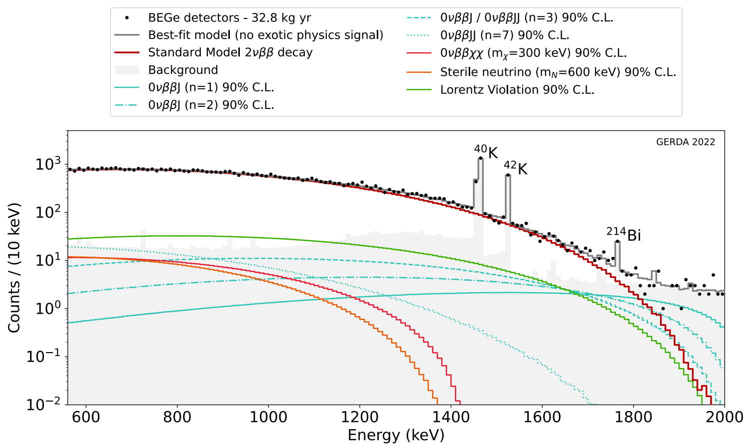

Figure 4: Data energy spectrum and best-fit model, corresponding to the absence of any new physics signal. Taken from [8].

In Figure 4 the analyzed data set is shown, together with the best fit model, corresponding to the absence of any new physics signal. The contributions from the SM $2\nu\beta\beta$ decay and other backgrounds are also shown separately. The limits at 90% C.L. on the different new physics contributions obtained from the individual analysis are shown. All the results presented in this work represent the most stringent limits obtained with ^{76}Ge to date.

2.4 Search for tri-nucleon decays of ^{76}Ge

The GERDA experiment has very recently published [9] the results of a search for tri-nucleon decays of ^{76}Ge in the full GERDA dataset. The ^{76}Ge nucleus may decay via *ppp*, *ppn*, and *pnn* to ^{73}Cu, ^{73}Zn and ^{73}Ga, respectively. These final state nuclei are unstable and eventually proceed by a sequence of β decays until ^{73}Ga which further decays β to ^{73}Ge. The analysis searched for ^{73}Ga decay exploiting the fact that it populates the 66.7 keV ^{73m}Ga state with an half-life of 0.5 s. The analysis was also applied to the invisible *nnn* decay of ^{76}Ge to bound states of ^{73}Ge. No candidate events were found, setting the lower limit on the sum of the decay widths of the tri-nucleon decays to 1.2×10^{26} yr, improving the current limits by one to three orders of magnitude.

3. Conclusion

GERDA has been a pioneering experiment in the search for neutrinoless double beta decay. The published results have improved the sensitivity by one order of magnitude with respect to previous searches in ^{76}Ge and demonstrated that a background-free experiment using germanium detectors is feasible. The superior background rejection with the active LAr veto system and pulse shape discrimination allowed to achieve extremely low background conditions and perform leading measurements in the two neutrino double beta decay and set new limits in Beyond the Standard Model searches. While the LEGEND Collaboration is preparing a next generation experiment with challenging sensitivity to the neutrinoless double beta decay in ^{76}Ge up to 10^{28} yr and beyond, the LEGEND-200 experiment has taken over the GERDA infrastructure at LNGS and has started new measurements with increasing target mass and improved background control.

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