PROCEEDINGS OF SCIENCE

The GERDA enterprise in the search for matter creation

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The GERDA experiment has searched for the neutrinoless double-beta decay of ^{76}Ge from 2011 to 2019, accumulating an exposure of 127.2 kg yr. Thanks to the novel experimental concept of operating bare germanium detectors in an instrumented liquid argon bath, it reached a background level of $(5.2^{+1.6}_{-1.3}) \cdot 10^{-4}$ cts/(keV · kg · yr), which is the lowest value ever achieved in a double-beta experiment. No hint for a discovery was found, and the limit on the half-life of the process was set to $T_{1/2}^{0\nu\beta\beta} > 1.8 \cdot 10^{26}$ yr at 90% C.L.. In addition to this result, the GERDA collaboration has provided the most precise determination of the half-life of the standard double-beta decay of ^{76}Ge, which has been preliminarily set to $T_{1/2}^{2\nu\beta\beta} = (2.022 \pm 0.041) \cdot 10^{21}$ yr. The existence of beyond the Standard Model physics has also been investigated through the emission of exotic particles and no evidence for a signal was found.

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1. Double-beta decay and the creation of matter

Single $\beta-$decays are a standard mean for nuclei to proceed towards stability. In a few cases, single β-decay cannot occur, and the only way nuclei can reach stability is through the simultaneous β-decay of two nucleons. Goeppert-Mayer conceived such a process in 1935 and named it *double beta-disintegration* [1], though nowadays is commonly referred to as two-neutrinos double-beta decay ($2\nu\beta\beta$). A few years later, Furry combined it with the theory of Majorana for neutrinos [2] and proposed the *neutrinoless* double-beta decay ($0\nu\beta\beta$), a particular double-beta decay where no (anti)neutrinos are emitted in the final state [3]. Since in this process two matter particles are created without compensation of anti-matter, it has also been named *creation of matter* [4], and its observation would be a hint for the existence of Beyond the Standard Model (BSM) physics.

As neutrinos are more likely to elude detection, the experimental signature of both $2\nu\beta\beta$ and $0\nu\beta\beta$ consists in the energy deposition of two electrons. If no neutrinos are emitted, the energy of the electrons will be precisely that of the Q-value of the decay, which is typically referred to as $Q_{\beta\beta}$ and ranges from 1 to 4 MeV, according to the isotope. When the two neutrinos are present in the final state, the energy of the electrons will be lower than $Q_{\beta\beta}$ by the amount which is carried away by neutrinos, and therefore ranges from zero to $Q_{\beta\beta}$.

2. The GERDA enterprise

The GERDA experiment has searched for the $0\nu\beta\beta$ decay of ^{76}Ge from 2011 to 2019, and accumulated a total exposure of 127.2 kg yr. The experimental apparatus was located in Hall A of the Laboratori Nazionali del Gran Sasso (LNGS), shielded by 1400 m of rock overburden, and used the novel experimental concept of operating HPGe detectors in an instrumented Liquid Argon (LAr) bath, acting both as cooling material as well as a passive and active shield. A detailed description of the setup can be found in [5].

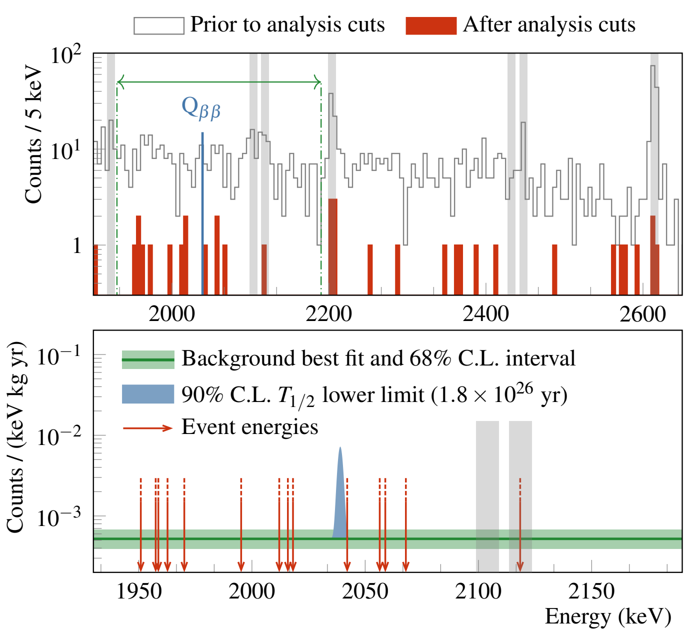

Figure 1: Final energy spectrum around $Q_{\beta\beta}$ (top) and result of the unbinned extended likelihood fit (bottom) on GERDA data. Figure taken from [6].

2.1 Results on the search for $0\nu\beta\beta$ decay

The final energy spectrum of the GERDA experiment around $Q_{\beta\beta}$ is shown in Fig. 1. The statistical analysis assumes a gaussian signal on a flat background and is carried out as an unbinned extended likelihood fit, in the energy window between 1930 and 2190 keV (excluding the two regions around the expected γ lines from the decays of ^{208}Tl and ^{214}Bi at 2103 and 2119 keV, respectively). In a frequentist framework, the best fit for the number of signal events is zero, and the lower limit on the half-life is: $T_{1/2}^{0\nu\beta\beta} > 1.8 \cdot 10^{26}$ yr at 90% C.L., which is also the result shown in Fig. 1. The best fit result for the background is: $BI = (5.2^{+1.6}_{-1.3}) \cdot 10^{-4}$ cts/(keV · kg · yr), which is the lowest background level ever achieved in a double-beta experiment [6].

2.2 Results on the physics below $Q_{\beta\beta}$

Thanks to the unprecedentedly low background level in the energy range below $Q_{\beta\beta}$, the GERDA experiment provided the most precise measurement of the half-life of ^{76}Ge $2\nu\beta\beta$ decay. A preliminary estimation, which will be the subject of a dedicated publication, is $T_{1/2}^{2\nu\beta\beta} = (2.022 \pm 0.041) \cdot 10^{21}$ yr [7].

In the same energy range, the GERDA collaboration also performed searches for BSM physics. BSM theories which predict the existence of exotic particles can lead to different double-beta decays where such exotic particles are also emitted in the final state. This implies a different repartition of the energy of the decay, hence a deformation of the energy spectrum of the electrons with respect to the Standard Model $2\nu\beta\beta$ decay. Specifically, the GERDA collaboration has searched for Majoron-involving $0\nu\beta\beta$ decays, Lorentz violating $2\nu\beta\beta$ decay and emission of light exotic fermions (sterile neutrinos and Z_2-odd fermions). This has been pursued using a subset of 32.8 kg yr of the total exposure, which allowed for a minimization of the systematic uncertainties. The statistical analysis lead as a best fit the null signal strenght for all the considered decay modes. The results of the fit are shown graphically in Fig. 2 as 90% C.L. limit, and the numerical results of such exotic decays are listed in Tab. 1 and can be found in more details in [8].

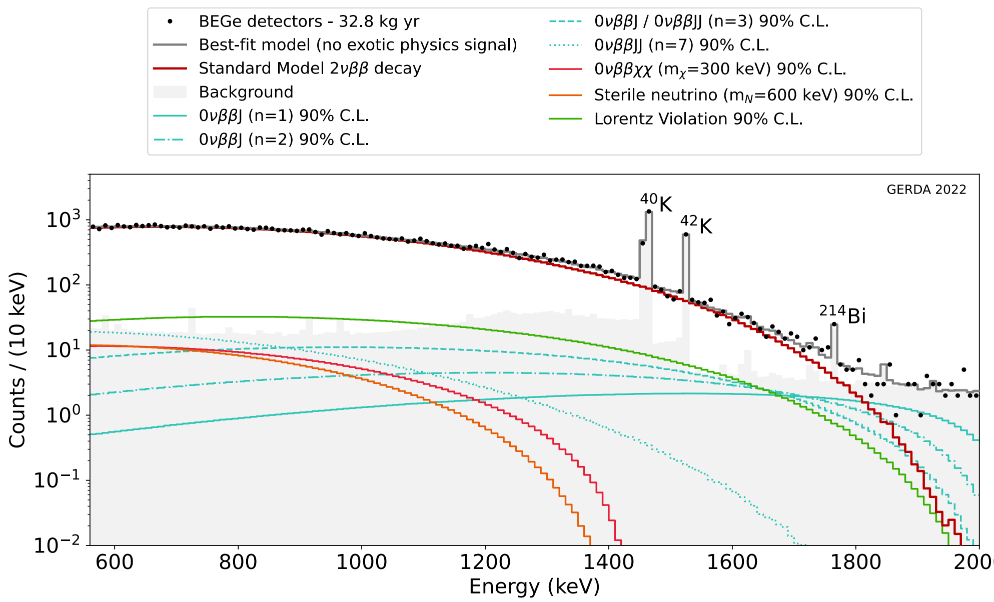

Figure 2: Data energy spectrum from the 32.8 kg yr exposure of GERDA and best-fit model for $2\nu\beta\beta$ decay and for exotic double-beta decays. The contributions from the underlying backgrounds is also shown with the shadowed histogram. The most prominent γ-lines are labeled. Figure taken from [8].

Exotic double-β decay mode	Observed limit at 90% C.L.	
Decays with Majorons	$T_{1/2}(yr)$	g_J
$0\nu\beta\beta J$ (n=1)	$> 6.4 \cdot 10^{23}$	$< (1.8 - 4.4) \cdot 10^{-5}$
$0\nu\beta\beta J$ (n=2)	$> 2.9 \cdot 10^{23}$	-
$0\nu\beta\beta J$ (n=3)	$> 1.2 \cdot 10^{23}$	$< 1.7 \cdot 10^{-2}$
$0\nu\beta\beta JJ$ (n=3)	$> 1.2 \cdot 10^{23}$	< 1.2
$0\nu\beta\beta JJ$ (n=7)	$> 1.0 \cdot 10^{23}$	< 1.1
Lorentz-violating $2\nu\beta\beta$	$(-2.7 < \mathring{a}^{(3)}_{of} < 6.2) \cdot 10^{-6}$ GeV	
Decay into sterile neutrino / $m_N = 600$ keV	$sin^2\theta < 0.013$	
Decay into Z_2*-odd fermions*	$T_{1/2}(yr)$	g_χ (MeV^{-2})
$m_\chi = 300$ keV	$> 1.6 \cdot 10^{23}$	$< (0.6 - 1.4) \cdot 10^{-3}$

Table 1: Summary of the results obtained for the search of exotic double-β decay modes of ^{76}Ge with the Gerda experiment. Results and discussion can be found in [8].

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