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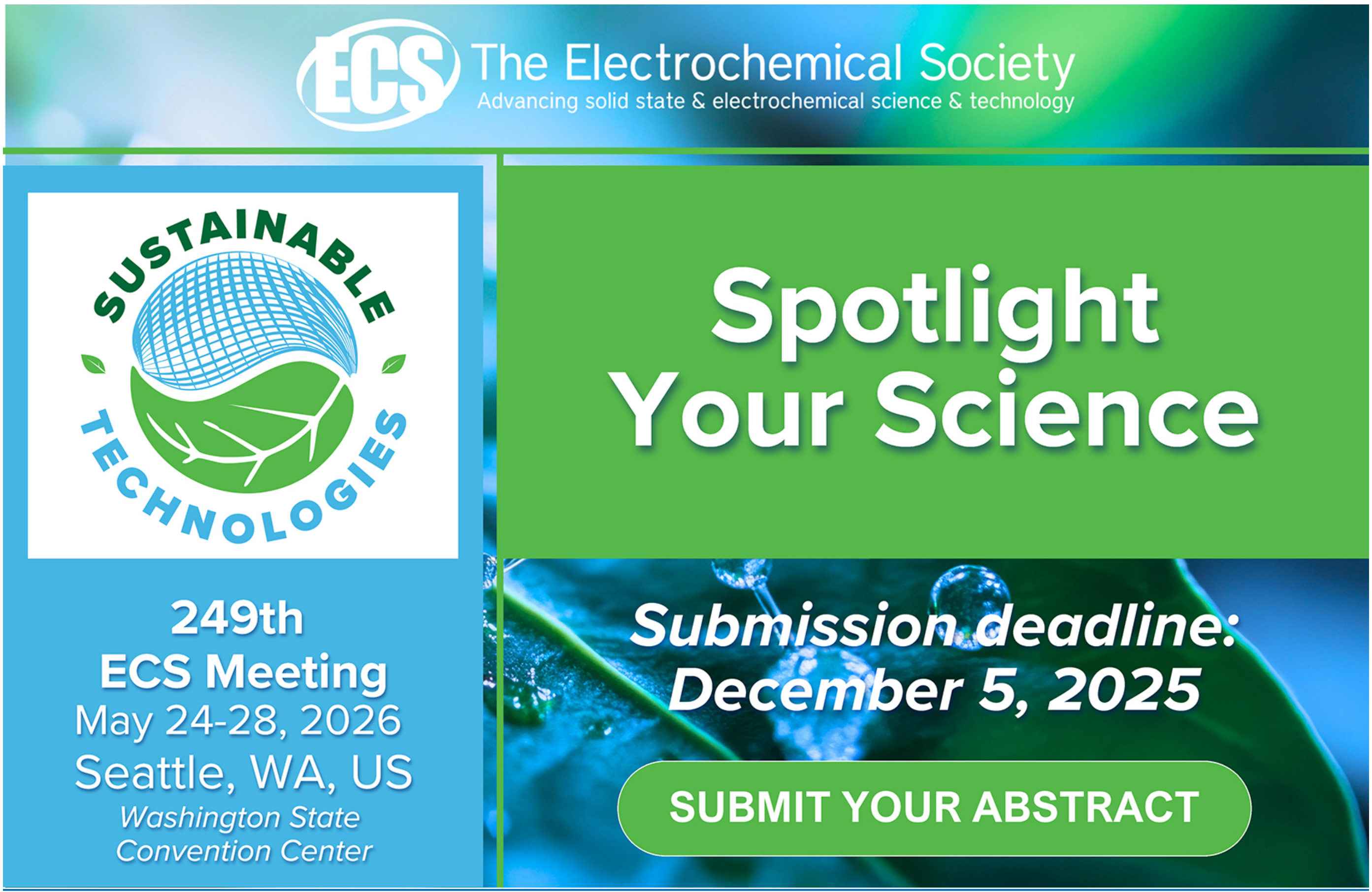

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# Search for neutrinoless double-beta decays in Ge-76 in the LEGEND experiment

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**Abstract.** The search for neutrinoless double-beta decay is the most sensitive technique to establish the Majorana nature of neutrinos. Two operating experiments that look for such decays in Ge-76, GERDA and MAJORANA DEMONSTRATOR have achieved the lowest backgrounds and the best energy resolution in the signal region. These are two of the most important detector characteristics for sensitive searches of this undiscovered decay. The Large Enriched Germanium Experiment for Neutrinoless Double-Beta Decay (LEGEND) Collaboration has been formed to pursue a tonne-scale Ge-76 experiment that integrates the best technologies from these two experiments and others in the field. The Collaboration is developing a phased experimental program that uses existing resources as appropriate to expedite physics results, with the ultimate discovery potential at a decay half-life beyond $10^{28}$ years.

## 1. Introduction

Double-beta decay is the simultaneous beta decay of two neutrons in a nucleus of mass A and charge Z. It is a second order weak process, predicted by the Standard Model: $(A, Z) \rightarrow (A, Z{+}2){+}2e{+}2\nu_e$. This $2\nu\beta\beta$ process has been experimentally observed in even-even nuclei and can be detected only when the single beta decay is energetically forbidden or strongly suppressed because of the large spin difference between the initial and the final state. The typical half-lives of $2\nu\beta\beta$ process are very large in a range between $7 \times 10^{18}$yr and $2 \times 10^{24}$yr[1, 2]. In addition, many extensions of the Standard Model[3], assuming neutrinos to be their own antiparticles (Majorana particles), explains the origin of the low neutrino mass and lead to lepton number violating processes, such as neutrinoless double-beta $(0\nu\beta\beta)$ decay, $(A, Z) \rightarrow (A, Z + 2) + 2e$.

## 2. The hunt for neutrinoless double-beta decay

The $0\nu\beta\beta$ process, yet never observed, has a clear signature with a mono-energetic line in the observed electron sum energy spectrum at $Q_{\beta\beta}$ of the considered element. Under the assumption that $0\nu\beta\beta$ decay is mediated by the exchange of light Majorana neutrinos, an effective neutrino mass ($\mathrm{m}_{\beta\beta}$) can be estimated according to:

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

where $T^{0\nu}_{1/2}$ is the half-life of the $0\nu\beta\beta$ process, $m_e$ the electron mass, while $M_{0\nu}$ and $G_{0\nu}$ are respectively the predictions for the nuclear matrix element[4, 5] (NME) and the phase space factor (PSF). In eq.1 the effective Majorana mass is given by $m_{\beta\beta} = \sum_{i=1}^{3} U_{ei}^2 m_i$ where $U_{ei}$ are the elements of the PMNS mixing matrix and $m_i$ are the neutrino mass eigenvalues.

The sensitivity of a given experiment to $T^{0\nu}_{1/2}$ can be expressed by:

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

where, apart of the obvious quantities, $\varepsilon$ indicates the detection efficiency, $f_{ab}$ is the isotopic abundance of the $\beta\beta$ emitter, $M$ is the target mass, $T$ and $BI$ are respectively the live-time and the background index of the experiment and $\Delta E$ is the energy resolution which is of the adopted detection technique. 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. 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. There are currently a number of experiments working in the field using different $\beta\beta$ isotopes and detection techniques. The most recent results on $0\nu\beta\beta$ decay, including half-life lower limits and sensitivities and corresponding sensitivity ranges on the effective Majorana mass $m_{\beta\beta}$ are reported in Table 1.

**Table 1.** Results from different $0\nu\beta\beta$ decay experiments: lower half-life limits $T_{0\nu}$ and sensitivities $S^{0\nu}$ (both at 90% C.L.). The sensitivities $S_{0\nu}$ have been converted into upper limits of effective Majorana masses $m_{\beta\beta}$ with the corresponding NME[5].

| isotope | $Q_{\beta\beta}$[keV] | experiment | $T^{0\nu}_{1/2}$[$10^{25}$yr] | $S^{0\nu}$[$10^{25}$yr] | $m_{\beta\beta}$[eV] |
|---|---|---|---|---|---|
| $^{76}$Ge | 2039.96(84) | GERDA | 9 | 11 | 104-228 |
| $^{76}$Ge | 2039.96(84) | MAJORANA | 2.7 | 4.8 | 157-346 |
| $^{136}$Xe | 2457.83(37) | EXO-200 | 1.8 | 3.7 | 93-287 |
| $^{136}$Xe | 2457.83(37) | KamLAND-Zen | 10.7 | 5.6 | 76-234 |
| $^{130}$Te | 2526.97(23) | CUORE | 1.5 | 0.7 | 162-757 |

## 3. On-going Ge-76 neutrinoless double-beta decay Ge-76 experiments

The GERDA experiment [7, 8] in Europe and MAJORANA DEMONSTRATOR[9] in the USA use different experimental approaches with germanium detectors, however, they represent the current state of the art experiments in the search for $0\nu\beta\beta$ decay of Ge-76. Two previous experiments, Heidelberg-Moscow [12] (HDM) and IGEX [10, 11], have studied double-beta decay in germanium and set limits on the $0\nu\beta\beta$ half-life: $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr and $T^{0\nu}_{1/2} > 1.6 \times 10^{25}$ yr, respectively. Part of the HDM collaboration [14] claimed evidence for a peak at $Q_{\beta\beta}$ which corresponds to a half-life central value of $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \times 10^{25}$ yr. The result was later refined with pulse shape discrimination (PSD) analysis techniques [13] giving a half-life $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr. However, various inconsistencies in the analysis were pointed out in Ref. [15]. Anyway, these claims have been superseded by the results of next generation experiments GERDA and MAJORANA.

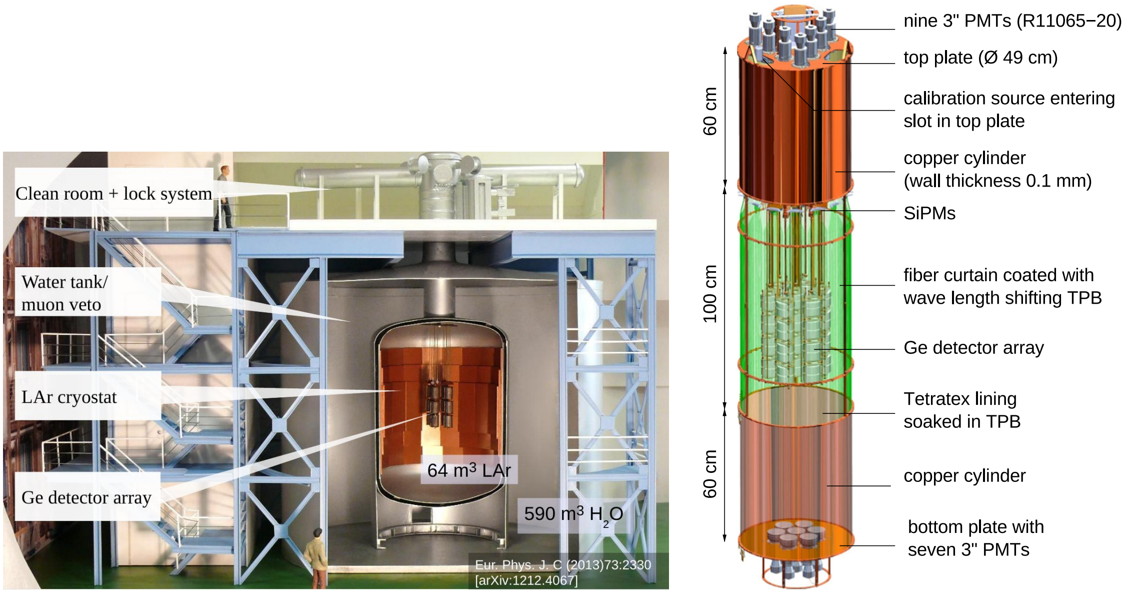

**Figure 1.** Left: setup of the GERDA experiment. Right: assembly of detector array and LAr veto system.

### *3.1. GERDA*

The GERDA experiment 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 panel), has been designed following a multi-layer approach. HPGe detectors enriched to about 87% in Ge-76 are operated bare in liquid argon (LAr). The LAr cryostat is complemented by a water tank with 10 m diameter which further shields from neutron and backgrounds and also works as muon veto. After a first physics data taking campaign carried out from 2011 to 2013, the GERDA setup has been upgraded. The major upgrade is the introduction of 30 BEGe detectors from Canberra[16] with an optimal energy resolution, due to the low input capacitance (pF), and a powerful pulse shape discrimination (PSD). In addition, an active suppression of the background by detecting the LAr scintillation light, using PMTs and wavelength shifting fibers coupled to SiPMs, has been introduced. The core of the GERDA setup is shown in Fig.1 (right panel): the Ge detector array (30 BEGe, 7 enriched coaxial and 3 natural coaxial detectors) is at the center of the instrumented LAr volume. The GERDA background is further reduced by applying PSD cuts[7]. For BEGe detectors the PSD is based on the ratio between the peak amplitude of the current signal A and the total energy E (A/E): low values are typical for multi-site events (i.e $\gamma$-rays and $\beta$ decays on n+ contacts), high A/E values are from surface events due to $\alpha$ decays on p+ contacts. After the A/E cut, the average survival probability of a $0\nu\beta\beta$ event is 87.6 ± 2.5 (see [17]). For coaxial detectors, the PSD between single-site and multi-site events is based on an artificial neural network (ANN) as reported in [7]. Additionally, a cut on the risetime of the pulses is applied to reject fast signals from surface events due $\alpha$ decays occurring near the p+ electrode and in the groove. The estimated combined PSD efficiency for coaxial detectors is 71.2 ± 4.3 (see [17]). In Fig.2 (left panel) the GERDA energy spectra are shown for enriched coaxial (top panel) and BEGe (bottom panel) detectors after the cuts, respectively LAr veto in grey and PSD cuts in red. The total available enriched Ge exposure in GERDA after the last data release is 82.4 kg·yr. The final spectra in the analysis region are shown in Fig.2 (right panel). For the coaxial detectors

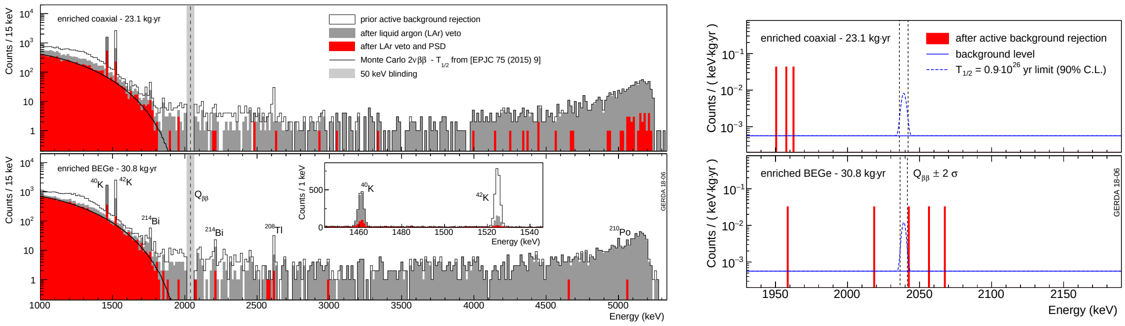

**Figure 2.** Left: GERDA energy spectra for enriched coaxial (top panel) and BEGe (bottom panel) detectors before and after the LAr veto and PSD cuts. Right: events observed in the analysis window for coaxial (top) and BEGe (bottom) detectors. The blue lines show the fit of the background level and the 90% C.L. limit on $0\nu\beta\beta$ decay.

only 3 events survived, corresponding to a background of $5.7^{+4.1}_{-2.6} \cdot 10^{4}$ cts/(keV·kg·yr), while for the BEGe detectors 5 events remain giving a background of $5.6^{+3.4}_{-2.4} \cdot 10^{4}$ cts/(keV·kg·yr). This GERDA result corresponds to the lowest background ever achieved in the field, taking into account the energy resolution. The neutrinoless double-beta decay analysis yielded no signal, setting a new limit on the Ge-76 $0\nu\beta\beta$ decay half-life of $T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$yr (at 90% C.L.) with a median sensitivity of $1.1 \cdot 10^{26}$ yr (at 90% C.L.), thus making GERDA the first experiment to pass $10^{26}$ yr sensitivity (as reported in Tab.1). Despite of this, the presence of an event with an energy of 2042.1 keV and $2.4\sigma$ away from the $Q_{\beta\beta}$, makes the $T^{0\nu}_{1/2}$ limit weaker than the median sensitivity.

### *3.2. MAJORANA DEMONSTRATOR*

The MAJORANA DEMONSTRATOR[9] is operating an array of HPGe detectors at the Sanford Underground Research Facility (SURF) in Lead, South Dakota. The aim of the project is to achive a background low enough to justify the construction of a tonne scale Ge based experiment. The array consists of 58 HPGe detectors, with a total Ge mass of 44.8 kg: 14.4 kg of natural Ge detectors and 29.7 kg of detectors enriched to $88.1 \pm 0.7\%$ in $^{76}$Ge. The enriched detectors are p-type point contact (PPC) detectors with low capacitance and sub-keV energy thresholds, which allow low-energy physics studies. These detectors have achieved an energy resolution of $2.53 \pm 0.08$ keV (FWHM at $Q_{\beta\beta}$), among the best values in the $0\nu\beta\beta$ decay field. The experiment utilizes a number of ultra-low activity materials and methods to reduce environmental backgrounds. The detectors are split between two modules contained in a low-background copper shield. The copper shielding is contained within 45 cm of high-purity lead shielding, separating the low-background environment from the laboratory environment. The lead shield is enclosed within a radon exclusion volume. An active muon veto surrounds the radon exclusion volume. The design of MAJORANA is shown in Fig.3. To further reduce the background two PSD cuts are applied to the data. The relatively low weighting potential of PPC detectors in the bulk of the crystal and peaked in the vicinity of the point contact, allow to discriminate the $\gamma$-ray background (multi-site events in Ge) from possible $\beta\beta$ signal (single-site event) with an efficiency of 90%[18]. A second PSD is successfully used to discriminate $\alpha$ contaminations. Due to the lithium dead layers on PPC detectors, $\alpha$ particles cannot penetrate in the active region but, impinging on the passivated surface, can deposit energy resulting in a potential background close to $Q\beta\beta$. However, the slow collection of the holes can be used to discriminate such events from interactions in the crystal bulk. A high efficiency (99.9%) cut based on the slope of the waveform is implemented[18]. The measured energy spectra above 100 keV from

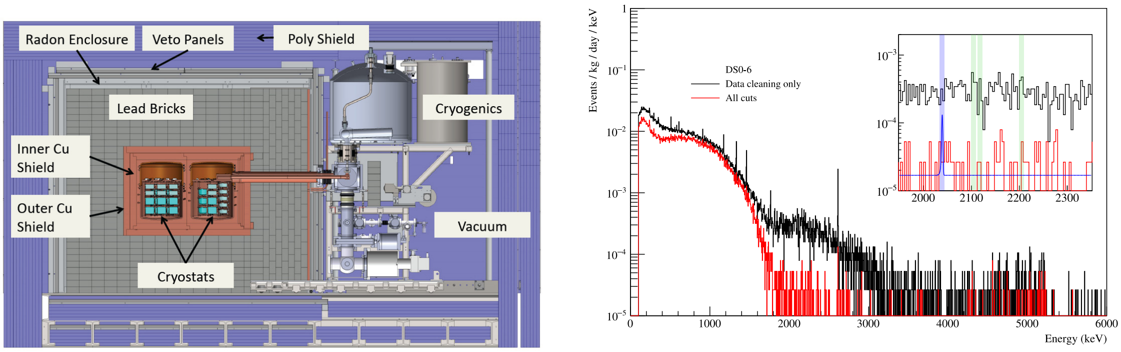

**Figure 3.** Left: design of the Majorana Demonstrator[9]. Right: energy spectrum for the full exposure of 26 kg·yr, a zoom on the range 1950-2350 keV is shown in the inset.

the total enriched Ge exposure of 26.0 kg·yr collected in Majorana until May 2018 are shown in Fig.3 (right panel); in black the spectrum with only data cleaning cuts, while in red when the coincidence between detectors and PSD cuts are also applied. The background spectrum in the energy range 1950-2350 keV is shown in the inset of Fig.3 (right panel). After applying all cuts, the background from the resulting 360 keV window is $(6.1 \pm 0.8) \cdot 10^3$ cts/(keV·kg·yr). A lower background configuration, based on an exposure of 21.3 kg·yr, gives a background of $(4.7 \pm 0.8) \cdot 10^3$ cts/(keV·kg·yr). The observed lower limit on the Ge-76 $0\nu\beta\beta$ decay half-life is $T^{0\nu}_{1/2} > 2.7 \cdot 10^{25}$yr (at 90% C.L.) with a median sensitivity for exclusion of $4.8 \cdot 10^{25}$yr (at 90% C.L.). The half-life limit is weaker than the median sensitivity by $1\sigma$, due to the proximity to Q$\beta\beta$ of one observed event at 2040 keV.

## 4. Next generation Ge-76 experiments: LEGEND

As a result of the successful commissioning and data-taking of both Gerda and Majorana the Ge-76 neutrinoless double-beta decay community is aiming to build, in the next years, Legend[19] (Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay). Legend is a phased project aiming to reach a $0\nu\beta\beta$ decay discovery potential at a half-life beyond $10^{28}$ yr. The best technical solutions developed within Gerda and Majorana experiments, as well as contributions from newcomers groups, will be adopted.

### *4.1. LEGEND-200*

The first phase, i.e Legend-200, will take advantage of the existing Gerda infrastructure at LNGS, which will be modified to deploy 200 kg of Ge-76 detectors in the cryostat. Legend-200 has a background goal of less than 0.6 cts/(FWHM·ton·yr). The achievement of this background rate will allow us to reach a sensitivity above $10^{27}$ yr with 1 ton·yr of exposure. The corresponding discovery potential is shown in Fig.4 (left panel) and physics data taking is expected to start in 2021. Multiple techniques are already planned to achieve the background reduction required for Legend-200, such as the use of the Majorana electroformed copper, the upgrade of the Gerda LAr veto and the improvement of the front-end electronics. A crucial point will be the choice of new detectors geometry. One new option is the Inverted Coaxial Point Contact (ICPC) detector[20], with similar performance to the BEGe and PPC detectors and a mass as large as a coaxial detector. Five enriched ICPC detectors have been already produced and deployed in Gerda during May 2018. The possible design for the arrangement of the detector strings and the LAr veto in Legend are shown in Fig.4 (right panel).

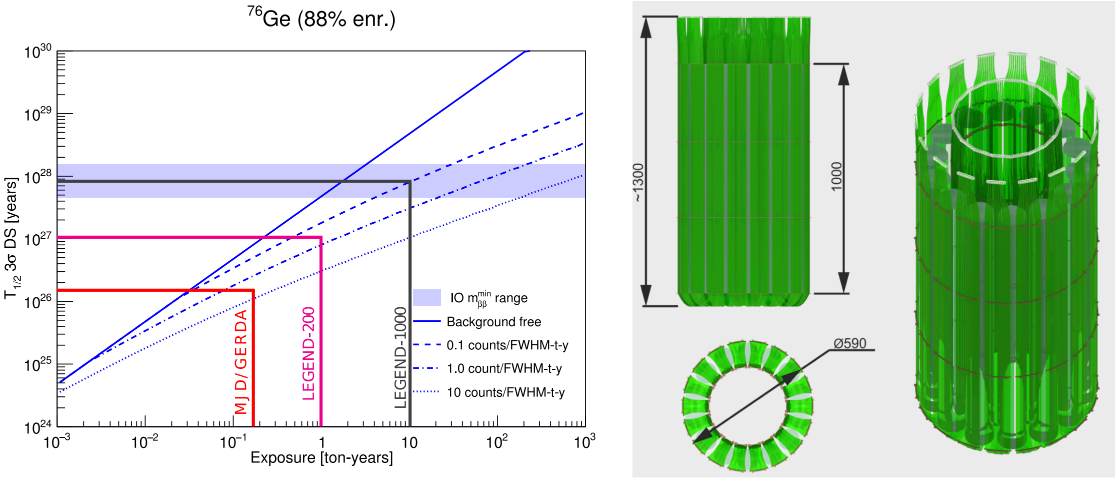

**Figure 4.** Left: $0\nu\beta\beta$ decay half-life $3\sigma$ discovery potential as function of exposure and background rate. Right: Views of a design study of the LEGEND-200 LAr veto system for a 14-string detector configuration.

### *4.2. LEGEND-1000*

The second stage of LEGEND will be deploying 1000 kg of Ge detectors. This increase in detector mass will require a much larger infrastucture for accomodating the cryostat vessel. The background goal for LEGEND-1000 is less than 0.1 cts/(FWHM·ton·yr). This background reduction is required in order to achieve a $0\nu\beta\beta$ decay discovery potential at an half-life greater than $10^{28}$ yr on a reasonable timescale (see Fig.4). The required depth to keep cosmogenic activation backgrounds (e.g. 77 mGe) within the background budget is currently under investigation and will be a contributing factor in the choice of the site where LEGEND-1000 will be located[21].

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