The Future of Neutrinoless Double Beta Decay Searches with Germanium Detectors

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Abstract. The observation of neutrinoless double beta (0νββ) decay would establish the Majorana nature of neutrinos and explicitly show that lepton number conservation is violated. In their search for the rare decay in the isotope ^{76}Ge, the GERDA and Majorana Demonstrator (MJD) experiments have achieved the lowest backgrounds and best energy resolutions in the signal region of interest of any 0νββ decay experiment. Building on the successful results of these experiments, as well as contributions from other groups, the Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND) collaboration aims to develop a phased 0νββ decay experimental program with discovery potential at a half-life beyond 10^{28} years. To achieve this goal, the enriched germanium detector mass has to be increased up to the tonne-scale and the backgrounds have to be reduced further. The first phase of LEGEND, a 200 kg measurement utilizing the existing GERDA infrastructure at LNGS in Italy, is expected to start in 2021.

1. Introduction

Typically, a nucleus with an excess of neutrons gradually converts into a more stable nucleus via single beta decay. In some (even-even) nuclei, however, single beta decay is energetically forbidden, while the simultaneous occurrence of two beta decays, the so-called two-neutrino double beta decay (2νββ decay) is allowed. In this rare nuclear decay, two neutrons in one nucleus are converted into two protons via the weak interaction, and two electrons as well as two electron antineutrinos are emitted. Two-neutrino double beta decay is a second-order weak process that was first proposed by M. Goeppert-Mayer in 1935 [1]. So far, it has been observed experimentally in more than ten isotopes (e.g. ^{76}Ge, ^{130}Te, ^{136}Xe, etc.) with half-lives ranging from $T^{2\nu}_{1/2} \sim 10^{18} - 10^{24}$ yr.

Neutrinoless double beta decay (0νββ decay) is a lepton number violating process ($\Delta L = +2$) that is forbidden in the Standard Model of particle physics and has not yet been observed. Currently, the search for 0νββ decay is the only feasible way of establishing that massive neutrinos are Majorana fermions, i.e. the neutrino is identical to its antiparticle ($\nu = \bar{\nu}$) [2–6]. In the decay, two neutrons in one nucleus are converted into two protons and two electrons are emitted. Since there are no (anti)neutrinos in the final state, the emitted electrons share the total energy $Q_{\beta\beta}$ corresponding to the mass difference of the two nuclei. Therefore, the experimental signature of 0νββ decay is a mono-energetic peak centered at the $Q_{\beta\beta}$-value as illustrated in Figure 1. 0νββ decay not only provides information on the nature of the neutrino, but also on its mass scale. Assuming that the decay is mediated by the exchange of light Majorana neutrinos and that only the three known light neutrinos participate in the process, the decay half-life $T^{0\nu}_{1/2}$ can be related to the effective Majorana mass $\langle m_{\beta\beta}\rangle$ via

$$\frac{1}{T^{0\nu}_{1/2}} \propto G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta}\rangle^2 \quad \Leftrightarrow \quad \langle m_{\beta\beta}\rangle \propto \frac{1}{|M^{0\nu}|} \cdot \sqrt{\frac{1}{T^{0\nu}_{1/2} \cdot G^{0\nu}}}. \tag{1}$$

Here, $G^{0\nu}$ describes the phase space factor and $\left|M^{0\nu}\right|$ the nuclear matrix element. While the phase space factor is calculable, the nuclear matrix element is obtained from nuclear theory and its calculation has large theoretical uncertainties [5]. The experimental sensitivity of the decay half-life can be expressed as

$$T^{0\nu}_{1/2} \propto \begin{cases} f_a \cdot \varepsilon \cdot M \cdot t, & \text{background-free,} \\ f_a \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{\mathrm{BI} \cdot \Delta E}}, & \text{with background.} \end{cases} \tag{2}$$

Here, f_a denotes the isotopic abundance of the parent isotope, ε the detection efficiency, M the detector mass, t the measurement time, BI the background index (expressed in units cts/(keV · kg · yr)) and ΔE the energy resolution. Equation (2) shows that it is crucial to stay in a background-free regime, i.e. an environment in which the BI is so low that the expected number of background events is below one count within the energy region of interest at a given exposure $M \cdot t$. In this case, the sensitivity scales linearly with the exposure, whereas in the presence of backgrounds it scales as $\sqrt{M \cdot t}$. Sensitivity estimations for LEGEND are shown in Figure 2.

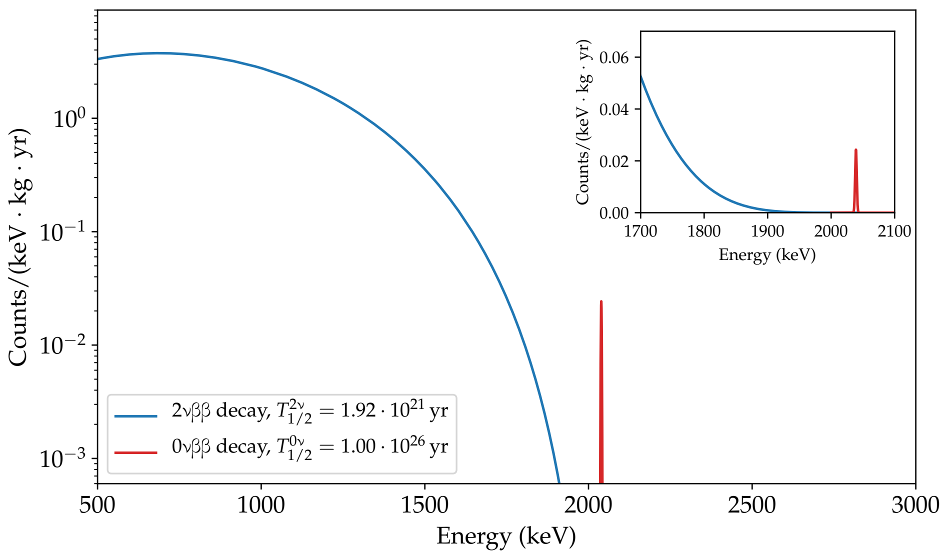


Figure 1. Experimental signature of neutrinoless double beta decay: peak at the $Q_{\beta\beta}$-value ($Q_{\beta\beta} \sim 2039$ keV for ^{76}Ge) for a given half-life $T^{0\nu}_{1/2}$ above the two-neutrino double beta decay (2νββ decay) continuum. The peak width (see inset) is determined by the finite energy resolution of the detectors.

Several isotopes and various experimental techniques are currently pursued to search for 0νββ decay. One of the most promising technologies are high-purity germanium (HPGe) detectors, searching for the decay $^{76}\mathrm{Ge} \rightarrow ^{76}\mathrm{Se} + 2\mathrm{e}^-$. Germanium detectors are intrinsically pure, can be enriched readily from 7.7% to above 92% in the double beta decaying isotope ^{76}Ge, and provide an excellent energy resolution of about 0.1% FWHM in the signal region of interest at the $Q_{\beta\beta}$-value. This is important to effectively suppress the intrinsic background contribution from 2νββ decay. Another advantage is that the detector material is also the source of the 0νββ decaying isotope. This translates into a high signal detection efficiency. In addition, germanium has a high density. Therefore, the topology of a 0νββ decay event in a HPGe detector is an energy deposition at a single site within a volume of about 1 mm^3. This can be exploited to deploy pulse shape discrimination (PSD) methods to powerfully reject background events, see sec. 2.2.

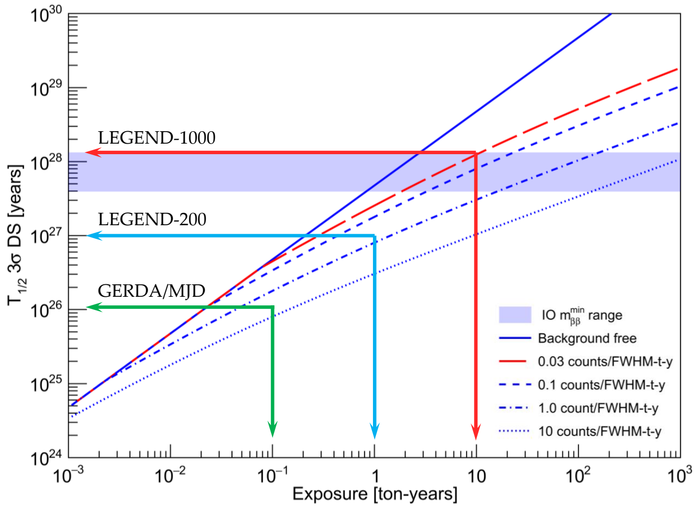


Figure 2. Signal discovery sensitivity for the isotope ^{76}Ge as a function of exposure. To increase the discovery sensitivity, one needs to stay close to the background-free regime (solid blue line). The presence of backgrounds (dashed lines) reduces the sensitivity significantly. The blue band shows the allowed region of the inverted mass ordering corresponding to an effective Majorana mass of $\langle m_{\beta\beta}\rangle = 17\,\text{meV}$ (assuming the worst case matrix element and an unquenched vector coupling g_A). The width of the band is due to the uncertainty of the matrix element. The red lines indicate the goal of LEGEND-1000 with a background goal of $< 0.03\,\text{cts}/(\text{FWHM}\cdot\text{t}\cdot\text{yr})$ and a sensitivity on the half-life of $T^{0\nu}_{1/2} > 10^{28}$ yr. Adapted from [8].

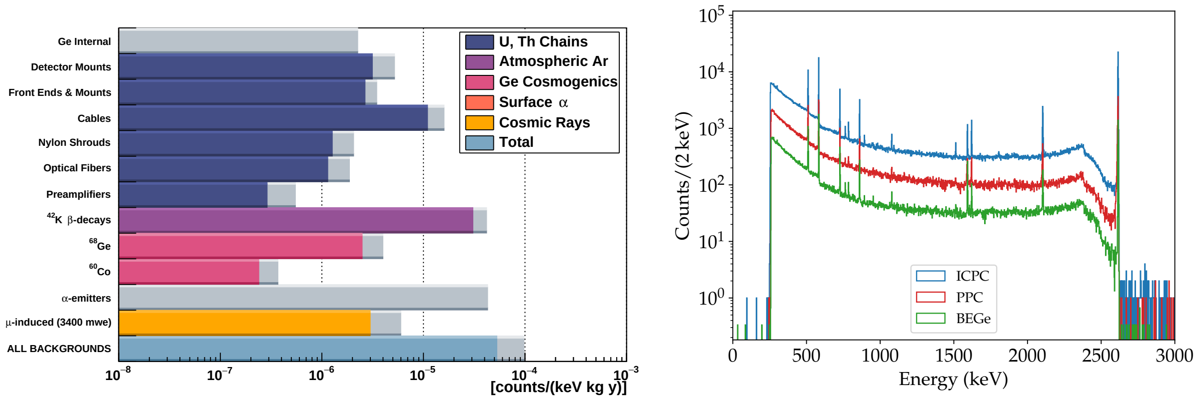
2. LEGEND

2.1. Overview

The Large Enriched Germanium Experiment for Neutrinoless ββ Decay (LEGEND) collaboration has been formed to pursue a ton-scale ^{76}Ge-based 0νββ decay experiment utilizing the best technologies from the GERDA (GERmanium Detector Array) and Majorana Demonstrator experiments, as well as contributions from other groups [7, 8]. GERDA and Majorana Demonstrator (MJD) have achieved the lowest backgrounds ($5.2^{+1.6}_{-1.3}\cdot 10^{-4}$ cts/(keV · kg · yr), held by GERDA) and the best energy resolutions (2.5 keV FWHM at $Q_{\beta\beta}$, held by the Majorana Demonstrator) of all experimental 0νββ decay searches [9–13]. To achieve a signal discovery sensitivity at a half-life of $T^{0\nu}_{1/2} > 10^{28}$ yr, LEGEND pursues a phased approach.

LEGEND-200 In the first phase of the experimental program, LEGEND-200, up to 200 kg of HPGe detectors will be operated in the cryogenic infrastructure previously installed by the

GERDA collaboration at the Laboratori Nazionali del Gran Sasso (LNGS). The detectors will be operated in liquid argon (LAr) which acts both as a cooling medium and as an active shielding. At the same time, ultra-high radiopurity materials for all internal structures and custom-designed low-noise signal readout electronics will be used. The overall background is estimated to improve by a factor of more than two compared to the background achieved in the GERDA experiment to a level of $< 2 \cdot 10^{-4}$ cts/(keV · kg · yr) or equally < 0.6 cts/(FWHM · t · yr), with a targeted signal discovery sensitivity of $T^{0\nu}_{1/2} > 10^{27}$ yr. Background estimations based on Monte Carlo simulations and material screening measurements demonstrate that the background goal is projected to be met: A total background of $\sim 1 \cdot 10^{-4}$ cts/(keV · kg · yr) is anticipated, see Figure 3(a). The commissioning phase of the data acquisition system, the calibration system and the signal readout electronics has started in February 2020 at LNGS. During first test measurements under realistic conditions, the three HPGe detector types to be deployed in LEGEND-200, see sec. 2.2, were operated successfully. An example for the energy spectra acquired during a calibration run with a ^{228}Th source is shown in Figure 3(b). Data taking of LEGEND-200 is intended to start in 2021.



(a) (b)

Figure 3. (a) Anticipated backgrounds in LEGEND-200. Grey bars indicate 1σ uncertainties of the background contributions due to screening measurements and Monte Carlo simulations. A total background of $\sim 1 \cdot 10^{-4}$ cts/(keV · kg · yr) is anticipated. (b) Energy spectra taken during a calibration run with a radioactive ^{228}Th source for the three detector geometries (BEGe, PPC, ICPC) to be deployed in LEGEND-200.

LEGEND-1000 In the final stage of LEGEND, LEGEND-1000, the collaboration plans to operate up to 1000 kg of HPGe detectors for a time period of about 10 years. The detectors will be deployed in several payloads. A completely new infrastructure and a more ambitious background goal of $< 1 \cdot 10^{-5}$ cts/(keV · kg · yr) or equally < 0.03 cts/(FWHM · t · yr) are required to reach the targeted signal discovery sensitivity on the half-life of $T^{0\nu}_{1/2} > 10^{28}$ yr. This sensitivity covers the inverted mass ordering (IO) regime, see Figure 2.

2.2. Background reduction strategy

To maximize the signal discovery sensitivity, the next generation of $0\nu\beta\beta$ decay experiments needs to deploy sophisticated background reduction strategies. The LEGEND collaboration largely follows the background-free experiment design established by GERDA, the Majorana Demonstrator, and contributions from other groups. A simplified graphical representation of the reduction strategy is shown in Figure 4. In the following, a selection of the techniques to be used to achieve the ambitious background goal of LEGEND-200 is discussed.

Bigger HPGe detectors An efficient way to improve the signal discovery sensitivity of 0νββ decay searches is to increase the isotope mass, cf. Equation (2). Detectors with higher masses reduce the number of required channels for a large-scale 0νββ decay experiment with a given total experiment mass, particularly the number of cables, amplifiers, detector holders, etc. and therefore the overall background. Two detector types intensively deployed in the GERDA and the Majorana Demonstrator experiments are the broad energy germanium (BEGe) detector, and the p-type point contact (PPC) detector, respectively. Both detector geometries feature a low capacitance (excellent energy resolution), a low detection threshold (sub-keV regime) and excellent PSD capabilities. Unfortunately, the size of BEGe (average mass: 0.66 kg) and PPC detectors (average mass: 0.85 kg) cannot be increased further since this would result in a region of undepleted material in the center of the active volume when biasing the detector. The inverted coaxial point-contact (ICPC) detector is a novel detector design that was proposed recently [14]. It has the same advantages as BEGe and PPC detectors [15], but at the same time allows for much larger detector masses. Compared to the other detector types, the surface to volume ratio is $30-40\%$ smaller, making them less susceptible to surface effects. Five enriched ICPC detectors (each with a mass of ~ 1.9 kg) have already been deployed successfully in the GERDA experiment [9].

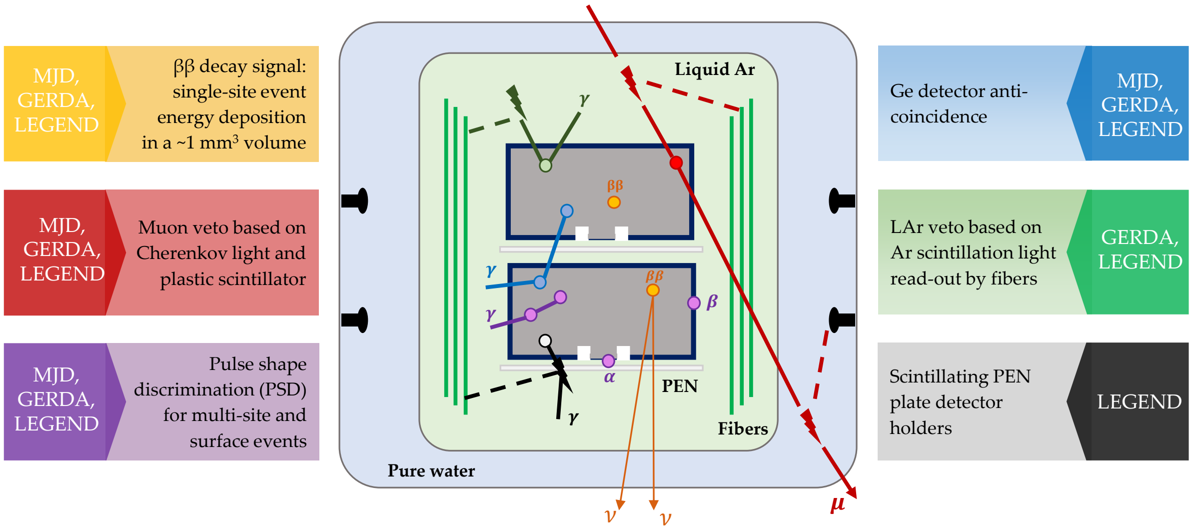


Figure 4. Graphical representation of the background reduction strategy of LEGEND-200. The anticipated backgrounds can be largely rejected by using muon and liquid argon veto systems, as well as scintillating materials, such as detector holders made from polyethylene naphthalate (PEN). These techniques are supported by analysis methods such as detector anti-coincidence cuts and pulse shape discrimination techniques to reject multi-site events, and alpha and beta surface events.

Liquid argon veto system Just as in the GERDA experiment [16], in LEGEND-200, the HPGe detectors will be assembled into several strings and operated in a cryostat filled with LAr. The LAr volume acts as an active shield that can be used to reject external backgrounds via the detection of scintillation light. In particular, events with coincident energy depositions in the cryogenic liquid and in the detectors (e.g. gamma ray events undergoing Compton scattering) can be identified properly. The LAr scintillation light is detected by a system consisting of light-guiding optical fibers surrounding the detector strings read out by silicon photomultipliers. To facilitate the readout of the scintillation light, the fibers, as well as other surfaces are coated with wavelength-shifting material shifting the wavelength of the scintillation light from 128 nm to about 400 nm.

Muon veto system The LAr cryostat is surrounded by a tank filled with purified water. It shields the experiment from external ionizing radiation and neutron backgrounds. Atmospheric muons are identified by the detection of Cherenkov light read out with several PMTs.

Readout electronics In LEGEND-200, electronic components based on previous implementations by the predecessor experiments, GERDA and MJD, will be used. The charge sensitive amplifier consists of two stages: A first stage very close to the HPGe detectors (to minimize electronic noise) is based on Majorana's radiopure low-noise, low-mass front-end (LMFE) readout electronics [17]. The LMFE consists of a junction field-effect transistor (JFET) and an *RC* feedback circuit. Backgrounds due to the LMFE are kept low through its low-mass design and the usage of ultra-pure materials. A second amplification stage farther away (~ 30 cm above the detector array) has been developed based on the preamplifier of the GERDA experiment [18]. For LEGEND-1000, the baseline design is to use an application-specific integrated circuit (ASIC)-based readout scheme for the HPGe detectors. State-of-the art ASIC technology enables the integration and miniaturization of the readout electronics components into a single low-mass chip. The main advantage for $0\nu\beta\beta$ decay searches compared to conventional amplifiers is a potentially higher per-channel radiopurity (e.g. ideally no *RC* components, fewer supply voltages, etc.). Furthermore, a lower electronic noise can be achieved since ASIC technology allows for a high amplification gain close to the detector before sending the analog signal over a long distance to the data acquisition system [19]. First test measurements of a commercially available ASIC together with a HPGe detector show very promising results in terms of energy resolution, PSD capabilities and radiopurity [19, 20].

Pulse shape discrimination techniques A powerful background rejection method in ^{76}Ge-based $0\nu\beta\beta$ decay searches is based on the analysis of the shape of the signal pulses, commonly referred to as pulse shape discrimination (PSD). While signal events deposit energy at a single location in the detector (single-site events), gamma radiation background events typically undergo multiple Compton scattering and deposit energy at various locations in the germanium crystal (multi-site events). This leads to a distinct difference in the signal shape, see Figure 5, that can be exploited to define background rejection cuts [21, 22].

The same holds true for backgrounds originating on the surface of HPGe detectors [23]. As can be seen in Figure 3(a), the anticipated largest single background component in LEGEND-200 is due to beta surface events originating from radioactive beta decays of the isotope ^{42}K in the LAr volume. Since the PPC detector geometry encompasses a large passivated surface (area between p^+ readout contact and n^+ bias voltage electrode) at undefined potential, it is particularly subject to surface effects. Dedicated measurements in various test facilities were carried out to better understand the behavior of this surface with respect to surface backgrounds. In a vacuum environment, it was observed that the passivated surface of a PPC detector can charge up positively or negatively leading to a radial-dependent degradation of the alpha and beta event energy, see Figure 6(a). Independent of this degradation, alpha events have a distinct signal pulse shape that can be used to define efficient background rejection cuts, see Figure 6(b).

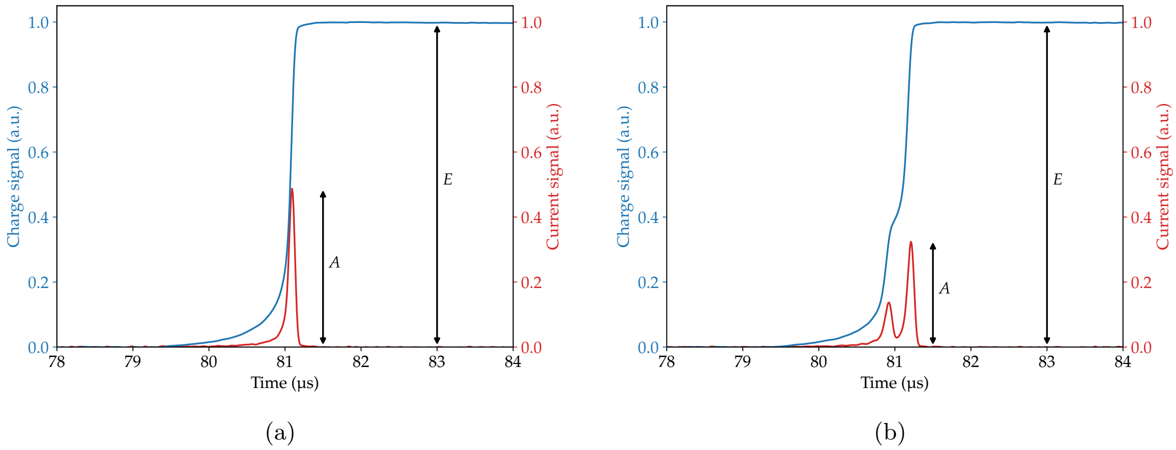


Figure 5. Charge and current signals corresponding to a single-site event (a) and a multi-site event (b). The current pulse (red line) corresponds to the time derivative of the charge pulse (blue line). The different signal shapes of a single- and multi-site event can be clearly identified by the different maximal heights A of the current pulses. Source: [19]

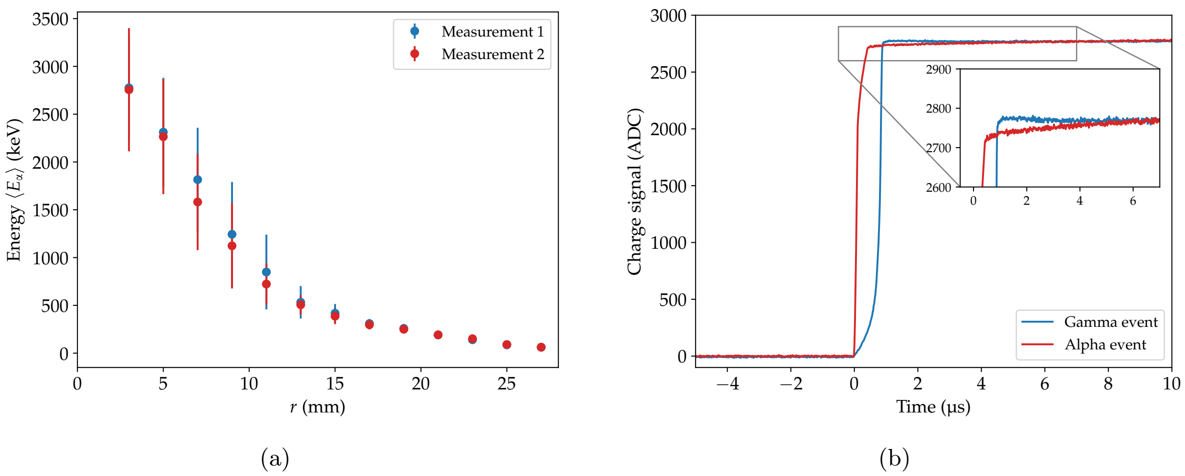


Figure 6. (a) Radial energy dependence of surface alpha events: the mean energy degrades with increasing radial position through the passivated surface (the position $r = 0$ mm corresponds to the center of the point contact). At small radii, the beam spot was shaded by the detector holding structure. (b) Experimental waveform examples for a bulk gamma event and a surface alpha event with the same energy. For the alpha signal, a slow rising waveform tail can be observed (see inset). This slow-rising component can be exploited to define cuts to reject alpha surface backgrounds. Due to its proximity to the readout electrode, the drift time of the surface alpha event is shorter (steeply rising leading edge) than the one of the bulk gamma event.

3. Conclusions

LEGEND, the Large Enriched Germanium Experiment for Neutrinoless ββ Decay, will search for neutrinoless double beta (0νββ) decay in the isotope ^{76}Ge with an unprecedented sensitivity.

Taking the best technologies of the GERDA and Majorana Demonstrator experiments, which have demonstrated the lowest backgrounds and best energy resolutions of all $0\nu\beta\beta$ decay searches, as well as contributions from other groups, LEGEND will proceed in several phases to reach the final discovery potential at a half-life beyond 10^{28} yr. To this end, the experiment requires further reduced background levels and additional mass. In a first phase, LEGEND-200, 200 kg of germanium detectors will be operated. The collaboration has demonstrated that the background goal is feasible and will start taking data in 2021.

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