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The LEGEND-200 Liquid Argon Instrumentation: From a simple veto to a full-fledged detector

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LEGEND-200 is an experiment designed to search for neutrinoless double beta decay of ^{76}Ge by operating up to 200 kg of enriched germanium detectors in liquid argon (LAr). To achieve ultra-low backgrounds, the LAr is instrumented to detect scintillation light emitted upon interactions with ionizing radiation, thus tagging and rejecting backgrounds. The LAr scintillation light is detected with wavelength-shifting fibers coupled to silicon photomultiplier (SiPM) arrays. In this document, we demonstrate the high photoelectron resolution and low noise level of the SiPM signals. We also present the results of special calibration runs performed to determine the light yield and background suppression factors. We show the background suppression performance of the LAr instrumentation on the LEGEND-200 background spectrum before and after the LAr light coincidence cut. Finally, we present the event topology classifier which enables effective particle discrimination, allowing the identification of background types in LEGEND-200.

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1. Introduction

The observation of a double beta decay with no neutrinos in the final state, referred to as neutrinoless double beta ($0\nu\beta\beta$) decay, would identify neutrinos as Majorana particles and would prove lepton number non-conservation. LEGEND is an experiment designed to search for $0\nu\beta\beta$ decay of ^{76}Ge. It employs germanium (Ge) detectors enriched in ^{76}Ge, where the detector and the double-beta-decaying medium coincide. The experiment will be carried out in two stages, starting with LEGEND-200 and continuing with LEGEND-1000, which will be operated with 1 ton of enriched Ge detectors and is designed to achieve a discovery potential covering the inverted-ordering neutrino mass scale region [1]. LEGEND-200 is currently operating about 140 kg of enriched Ge detectors in the former cryogenic infrastructure of the GERDA experiment at Laboratori Nazionali del Gran Sasso (LNGS) in Italy. This setup consists of a 64 m^3 liquid argon (LAr) cryostat inside a water tank equipped with photomultiplier tubes that provide a water Cherenkov veto. The LAr cryostat provides cooling and additional shielding. As LAr scintillates when exposed to ionizing radiation, detecting this scintillation light is a powerful background suppression technique. The scintillation light with a peak emission wavelength of 128 nm is detected with the LAr instrumentation, which is described in the following section.

2. The LEGEND-200 LAr instrumentation

Figure 1 shows the LEGEND-200 LAr instrumentation. The Ge detector strings are arranged in a circle and are surrounded by two concentric barrels with different diameters, which are equipped with wavelength-shifting fibers. This configuration provides optimal geometrical coverage to collect the vacuum ultra-violet (VUV) photons emitted near the Ge detectors. Light collection from VUV scintillation photons involves two wavelength-shifting stages: tetraphenyl butadiene (TPB)-coated fibers first absorb VUV photons, shifting their wavelength to the blue spectrum. Then, the fibers shift the blue photons to the green spectrum, guiding them through total internal reflections to both ends. At these ends, the fibers are optically coupled to SiPM arrays, where the photons are detected. The LAr instrumentation comprises a total of 58 SiPM arrays, with 18 arrays mounted on the inner barrel and 40 arrays mounted on the outer barrel. Furthermore, the outer barrel is surrounded by a wavelength-shifting reflector (WLSR). As a TPB-coated Copper-Tetratex foil it reflects and shifts photons towards the blue spectrum. It defines the volume of instrumented LAr and shields against scintillation light of ^{39}Ar decays from outside of this volume. Additionally, it reflects photons back toward the center, giving them a chance to be detected by the instrumentation.

3. Data processing

The SiPM signals have a fast rise time of $O(10\,\text{ps})$ and two decay components. The fast decay component is of $O(10\,\text{ns})$ and the slow component is of $O(1-10\,\mu\text{s})$. The decay times vary among the different SiPM arrays and within a SiPM array, as these devices consist of 9 SiPMs read out in parallel. The signals are amplified and read out with a low-noise front-end electronics [2]. The time and charge reconstruction of pulses in a SiPM trace is achieved with two independent methods: The so-called hypercurrent (HC) algorithm and the Digital Penalized Least Mean Squares (DPLMS)

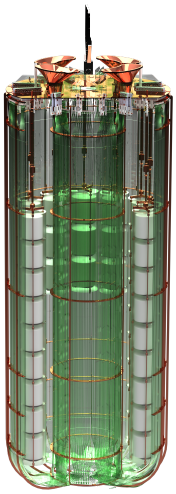

Figure 1: Artistic view of the LEGEND-200 LAr instrumentation and Ge detector strings.

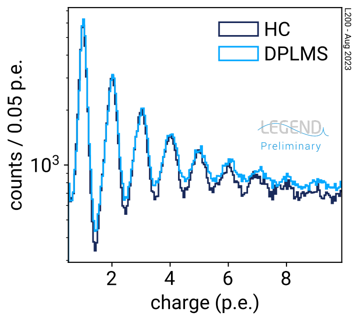

Figure 2: The photoelectron (p.e.) spectra obtained with HC and DPLMS methods show high p.e. resolution.

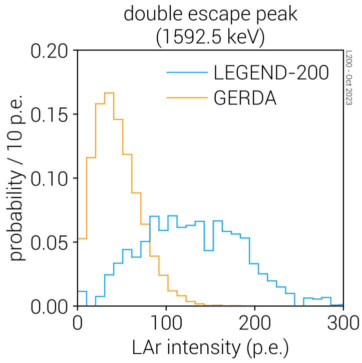

Figure 3: The intensity of scintillation light detected in coincidence to the DEP of the ^{208}Tl line is higher in LEGEND-200 compared to GERDA.

filter algorithm [3]. The HC algorithm is based on the derivative of the waveform and is therefore independent of the decay time of the pulse. With this, a 95% accurate charge reconstruction and a 10 ns pulse onset time reconstruction precision is achieved. The DPLMS filter-based reconstruction algorithm was developed to treat more noisy waveforms and performs equivalently to the HC reconstruction. This can be seen in figure 2 where the photoelectron (p.e.) spectra are shown for both reconstruction algorithms. The spectra show the summed p.e. values over all operational channels, showcasing the high accuracy in charge reconstruction for every channel.

4. Special calibration runs

Special calibration runs were performed during the commissioning of LEGEND-200 with 60 kg of germanium detectors. Three low-activity sources of $O(1)$kBq were used: ^{228}Th, ^{226}Ra and ^{137}Cs. The ^{228}Th run primarily aimed to investigate the LAr light coincidences to the single (SEP) and double escape peak (DEP) of the high-energy gamma line of ^{208}Tl at 2615 keV. The obtained intensities were compared to those of the LAr system of the GERDA experiment [4], on which the LEGEND-200 LAr instrumentation is based. By comparing the normalized p.e. intensity distributions of LEGEND-200 and GERDA in coincidence to the SEP and DEP of the ^{208}Tl line, a factor 3 to 4 higher p.e. yield is obtained compared to GERDA (see figure 3). This was achieved by the improved geometrical and optical coverage of the LAr instrumentation in LEGEND-200 and by the increased LAr purity. Additionally, the light shadowing, defined as the probability of observing less than one p.e. of light in coincidence, is 34 times lower compared to GERDA for the SEP. The ^{226}Ra run was focussed on the LAr instrumentation's suppression power in the region of interest (ROI) around the Q-value of double beta decay (at 2039 keV for ^{76}Ge). The survival probability of events in the ROI is (10.4 ± 0.2) % compared to (30.4 ± 0.2) % in GERDA. Lastly, the ^{137}Cs was used to estimate the p.e. yield. As ^{137}Cs has only one main line at 661 keV, it allows a continuous

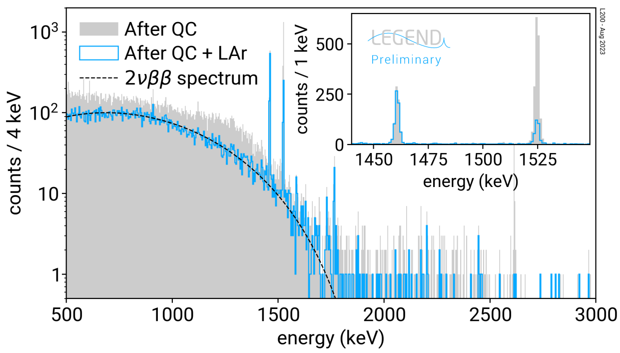

Figure 4: LEGEND-200 background spectrum after quality cuts (QC) and after LAr AC cut. An overlay of a $2\nu\beta\beta$ decay spectrum with fixed half-life is shown. The inset shows the most prominent lines of the spectrum, ^{40}K and ^{42}K.

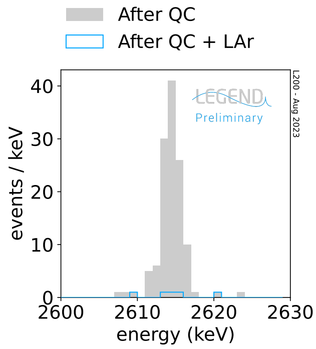

Figure 5: The ^{208}Tl line in the LEGEND-200 background spectrum at 2615 keV is strongly suppressed by the LAr AC cut.

calibration via the Compton continuum. The LAr light intensity was plotted against the coincident Ge energy, and a linear fit was applied with the mean light intensities taken in 5 keV windows. This resulted in a p.e. yield of ~ 0.1 p e /keV. It must be noted that this number is highly dependent on the interaction position in the LAr volume. An optical map for LEGEND-200, similar to the optical map of GERDA [5], is currently under development whereas the measured p.e. yield benchmarks the simulations.

5. Performance in LEGEND-200

The potassium lines of ^{40}K and ^{42}K are the two most intense lines in the LEGEND-200 background spectrum which is shown in figure 4. They can be used to showcase the acceptance of events without and the rejection of events with LAr light coincidences. The ^{40}K decay does not produce coincident β or γ radiation. Therefore, the ^{40}K line at 1461 keV should not be suppressed by the LAr instrumentation. As can be seen in the inset of figure 4, the ^{40}K line survives with a probability of (93 ± 1) %. ^{42}K is a radioactive progeny of ^{42}Ar present in LAr. Thus, there is likely a coincident energy deposition of the initial β decay in the LAr to the ^{42}K line at 1525 keV. In LEGEND-200, the ^{42}K line survives with (19 ± 1) % (see inlet of figure 4). The background spectrum also shows that the Compton continuum is highly suppressed. A two-neutrino double beta ($2\nu\beta\beta$) decay spectrum with fixed half-life was fitted to the spectrum after LAr anti-coincidence (AC) cuts. This shows that the LAr AC cut removes the majority of events that are not double-beta-decay-like. Lastly, the ^{208}Tl line at 2615 keV, accompanied by a minimum of 583 keV, is almost completely suppressed, as shown in figure 5.

6. Particle discrimination

Scintillation light emission of LAr is a superposition of two excimer states: an unstable singlet state with a lifetime of around 6 ns, and a metastable triplet state with a lifetime of approximately 1.3 µs. Excimers in both states emit 128 nm VUV scintillation light. The ratio R of singlet to

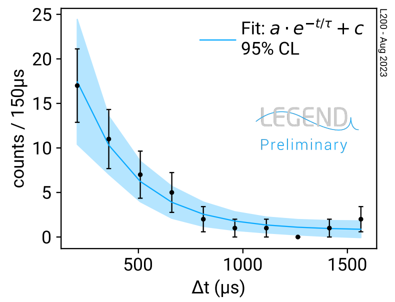

Figure 6: Time difference between prompt and delayed signal for events with ^{214}Bi-Po signature. The β and α decays are tagged by the ETC parameter.

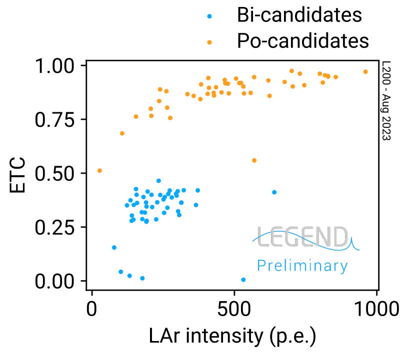

Figure 7: ETC values over LAr intensities for prompt and delayed event, which can be assigned to ^{214}Bi and ^{214}Po decays, respectively.

triplet components in a scintillation events varies with radiation's linear energy transfer (LET) dE/dx. As different particles have different LETs, specific radiation types, like α and γ radiation can be identified by the LAr instrumentation. Therefore, the event topology classifier (ETC) is used, which is defined as ETC$=1/(1+1/R)$. Due to the good light yield of the LEGEND-200 LAr instrumentation and the fact that the LAr instrumentation can detect scintillation pulses in a scintillation event time-resolved, the ETC can be used to identify background types in LEGEND-200.

This can be demonstrated by tagging ^{214}Bi decays contaminating the LAr. ^{214}Bi is a radioactive progeny of ^{222}Rn and decays into the unstable ^{214}Po which has a half-life of 164 µs. Two decays, a prompt and a delayed one, separated in time up to several ^{214}Po half-lives, are therefore likely to originate from the ^{222}Rn chain. This is called the ^{214}Bi-Po coincidence. With ^{214}Bi being a β decay and ^{214}Po an α decay, the ETC can be used to tag the two time-correlated scintillation events. The γ/e^- band was found at ETC values < 0.6 while the α band appears at ETC values > 0.6. Figure 6 shows the time difference between the prompt (^{214}Bi) and the delayed (^{214}Po) event, where the ETC conditions for e^- or α particles were applied. The ETC parameter over the LAr intensity is shown in Figure 7, with ^{214}Bi and ^{214}Po events occurring in the γ/e^- and α bands, respectively. In total, 47 ^{214}Bi-Po candidates were found in a data set of about 20 days. A half-life of (188 ± 46) µs is obtained which agrees with the ^{214}Po half-life of 164 µs. With secular equilibrium between ^{222}Rn and its daughter nuclei, this translates to a ^{222}Rn activity of (23 ± 4) µBq, or (3.8 ± 0.7) nBq/kg of LAr with about 6 tons of LAr in the WLSR-enclosed volume.

7. Conclusion

The LEGEND-200 LAr instrumentation reaches a 95% accurate charge reconstruction and a 10 ns-precise pulse onset reconstruction. Special calibration runs showed significant light yield and shadowing improvements compared to the LAr system of GERDA. The LEGEND-200 background spectrum after the LAr AC cut is dominated by the $2\nu\beta\beta$ spectrum. Various lines, such as ^{42}K and ^{208}Tl, are highly suppressed. The event topology classifier enables the discrimination of different background types, elevating the LAr instrumentation from a simple veto to a full-fledged detector.

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