IL NUOVO CIMENTO **45 C** (2022) 3
DOI 10.1393/ncc/i2022-22003-2

Colloquia: SoUP 2021

Searching for neutrinoless double beta decay with LEGEND-200 experiment

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received 4 November 2021

Summary. — Experiments searching for neutrinoless double beta ($0\nu\beta\beta$) decay, have the capability to unveil the neutrinos mysteries: defining their absolute scale mass and establishing their nature (Dirac or Majorana particles). The LEGEND collaboration works to develop the largest ^{76}Ge $0\nu\beta\beta$ decay experiment in history. The collaboration was born from the synergy of two collaborations, Gerda and Majorana, and additional institutes. The first phase of the experiment, called LEGEND-200, is under construction at LNGS of INFN: the experiment aims to reach a sensitivity on the half-life of $0\nu\beta\beta$ decay up to 10^{27} yr by operating about 200 kg of HPGe detectors within the upgraded Gerda infrastructure. The experimental setup and the LAr veto system used to actively suppress background events, will be summarized.

1. – Introduction

For decades, neutrinos have been at the forefront of the discovery of particle physics, and the study of their properties has advanced our knowledge of the phenomenology of weak interactions and modern quantum field theory. However, the neutrinos fundamental properties are still open issues in the neutrino sector beyond the Standard Model (SM): we still do not know which is the size and the ordering of the eigenstate masses and if neutrinos are Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu = \bar{\nu}$) particles.

At present, the only known feasible probe of the Majorana nature of the neutrino is an yet unobserved radioactive transition called neutrinoless double beta ($0\nu\beta\beta$) decay [1,2]. The discovery of $0\nu\beta\beta$ decay would prove unambiguously not only the existence of a new lepton-number-violating physics but also its connection to the mysterious origin of the neutrino mass.

(*) On behalf of the LEGEND Collaboration.

2. – Double beta decay: $2\nu\beta\beta$ vs $0\nu\beta\beta$

The double beta ($\beta\beta$) decay is a second-order weak nuclear decay process with very long lifetime (1.93×10^{21} yr for ^{76}Ge [3]). The two-neutrino mode ($2\nu\beta\beta$) of the $\beta\beta$ decay is a nuclear transition in which two neutrons are simultaneously converted into two protons with the emission of two electrons and two anti-neutrinos. In contrast, the neutrinoless version ($0\nu\beta\beta$) of the decay occurs without the emission of the two anti-neutrinos in the final state. Unlike the $2\nu\beta\beta$ decay, the $0\nu\beta\beta$ decay violates the lepton number conservation and requires the exchange of massive Majorana neutrinos. Thus, finding the $0\nu\beta\beta$ decay would imply the presence of new physics beyond the SM and the Majorana nature of neutrinos.

3. – LEGEND: the best of GERDA and MAJORANA

The Gerda [4] and Majorana [5] experiments paved the way for a new-generation experiment, the Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND) [6]. The experiment will be phased: LEGEND-200 and LEGEND-1000 will search for $0\nu\beta\beta$ decay in ^{76}Ge using 200 kg and 1000 kg of enriched germanium detectors, respectively.

The Gerda experiment achieved the lowest background index, 6×10^{-4} cts/(keV·kg·yr), and the highest sensitivity on the half-life, of 1.8×10^{26} yr at 90% C.L. [7]. The Majorana experiment achieved the best energy resolution, FWHM of 2.5 keV in the region of interest (2039 keV) [5]. By combining technological expertise and experience from both previous experiments, LEGEND is expected to reach a design sensitivity two orders of magnitude greater than its predecessors.

In particular, LEGEND-200 aims to reach a sensitivity on the half-life of 10^{27} yr by operating about 200 kg of germanium detectors. The construction of the experiment has already started and LEGEND-200 plans to start data taking at the beginning of 2022. Together with its scientific purpose, it will also serve as a testing ground for all R&D solutions in view of LEGEND-1000. The latter aims for discovery potential beyond 10^{28} yr.

4. – LEGEND-200

The first stage of the experiment, LEGEND-200, takes place at Laboratori Nazionali del Gran Sasso (LNGS), where the overlying rock removes the hadronic components of cosmic ray showers and reduce the moun flux by six orders of magnitude. In this phase High-Purity germanium (HPGe) detectors, organized in strings, will be deployed in the slightly modified Gerda infrastructure.

The LEGEND-200 setup follows a multi-layer approach, as shown in fig. 1, in order to minimize the main background sources: a tank with purified water shields from neutron and gamma background and works also as a muon veto; inside the water tank a cryostat with purified Liquin Argon (LAr) is present, which acts as cooling medium and shielding of the detectors against background radiation; the cryostat contains the LAr veto system, composed of wavelength shifting (WLS) fibers coupled to SiPMs, which surround the detectors array allowing to actively suppress background events.

A new monitoring system, with respect to Gerda, is placed at the bottom of LEGEND-200 cryostat, the LEGEND LAr Monitoring Apparatus (LLAMA) [8]. The

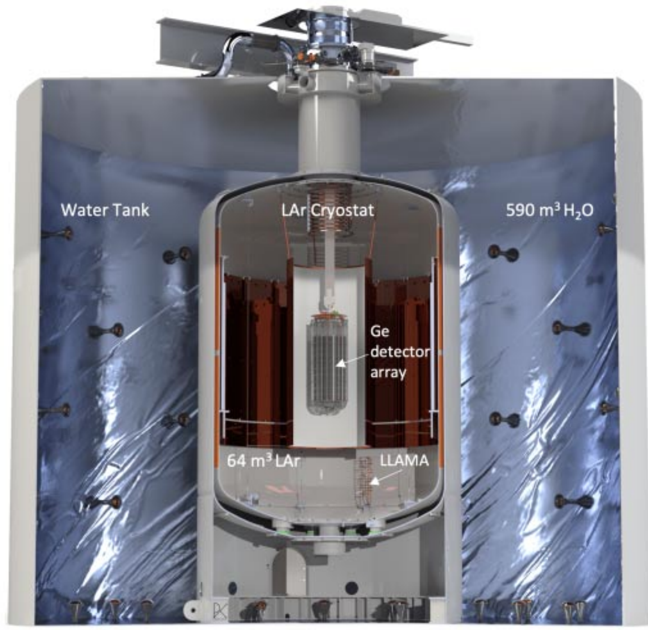

Fig. 1. – Schematic representation of the LEGEND-200 setup at LNGS.

new system allows to monitor continously the LAr quality, providing the triplet lifetime, the relative light yield and the attenuation length.

The germanium detectors form the core of the experiment. They are semiconductor diodes sensitive to ionizing radiation and γ rays, with an excellent energy resolution and a high detection efficiency, being simultaneously the source and the detector of the double beta decay. LEGEND-200 will use P-type germanium detectors deployed in previous experiments, Broad Energy Germanium (BEGe) detectors from Gerda [9], and P-type Point Contact (PPC) detectors from Majorana [10]. In order to reach the 200 kg array, newly developed detectors will be also incorporate, namely the Inverted Coaxial Point Contact (ICPC) detectors, already tested in the last Gerda phase [11].

The LEGEND-200 experiment relies on improved active background reduction techniques, such as the LAr veto and pulse shape discrimination (PSD). The complementarity of the two techniques was efficiently demonstrated in Gerda. The LAr veto is a detector system designed to detect the argon scintillation light near the detector array, due to the energy deposition of background events. The PSD allows to identify background events from γ-rays, which mainly interact via Compton scattering, producing events with multiple energy depositions, and events on the detector surface due to α or β decays, respectively on p^+ or n^+ contact. These background events can be easily discriminated from highly localized events, such as those produced by $0\nu\beta\beta$ and $2\nu\beta\beta$ decays.

5. – LAr veto system

LEGEND-200 adopts an upgraded version of the LAr veto system developed in Gerda [12], one of the key ingredients to achieve the lowest background index and the highest sensitivity on the half-life.

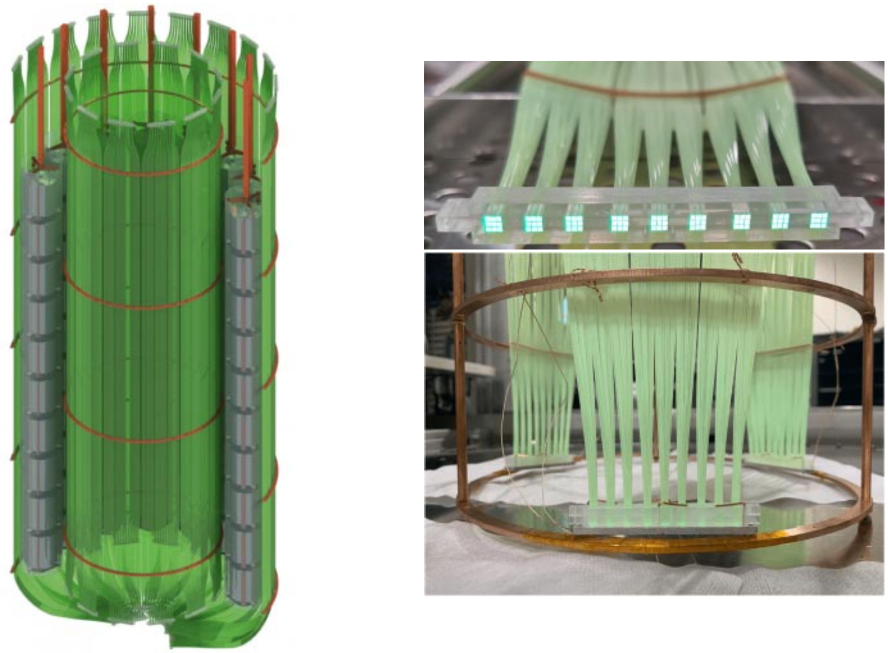

Fig. 2. – The LAr veto system: (left) 60 channels with 9 SiPMs each organized in two concentrical fiber shrouds; (right) detailed view of fibers coupled to SiPM.

The VUV light emitted by the LAr scintillation is shifted towards optical wavelenghts by means of shifting fibers. The wavelenght shifter (WLS) are realized by coating the fibers with tetraphenyl butadiene (TPB). Therefore, TPB first shifts the scintillation light from vacuum ultraviolet (128 nm) to blue light (450 nm), then the WLS fibers shift the light to green light which is read-out by SiPMs, see fig. 2.

As events due to double beta decays have very high probability to release the entire energy within the HPGe detector only, an event is vetoed if the energy is simultaneously deposited in the detector and in LAr, in particular if a scintillation signal with an amplitude greater than the established threshold is found in a narrow time window near the germanium detector pulse.

Monitoring the 1525 keV γ line from the decay of ^{42}K and the line at 1461 keV of the ^{40}K-decay, gives an estimation of the veto acceptance in the region of interest. The decay of ^{42}K, a daughter nuclide of ^{42}Ar which is a long-lived Ar cosmogenic contaminant, can deposits up to 2 MeV in LAr by a β-cascade. The LAr veto system suppresses this line by typically a factor of 5. On the other hand, the γ line at 1461 keV is not suppressed since ^{40}K purely decays via electron capture and therefore deposits no energy in LAr. Hence, no suppression is expected apart from random coincidences so that this line can be used to determine the LAr veto acceptance.

In GERDA the LAr veto acceptance of a $0\nu\beta\beta$ decay signal was 98%, due to accidental coincidences, see fig. 3. In LEGEND we expect a higher acceptance, due to the introduced improvements, such as using improved version of WLS fibers, with minimal background contribution, and new design of the SiPM front-end electronics.

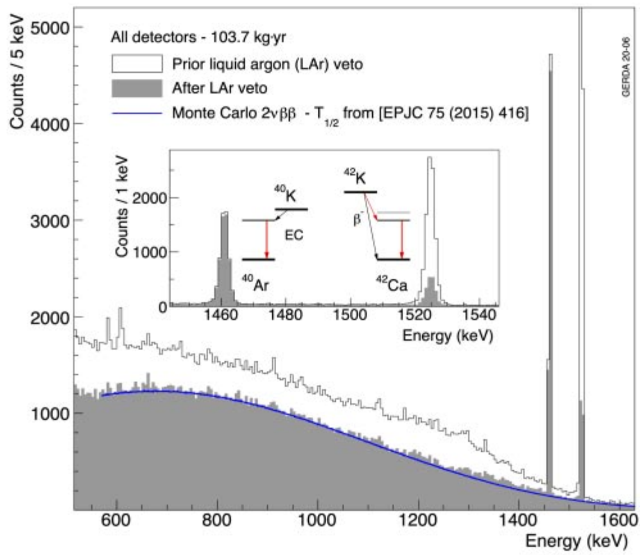

Fig. 3. – GERDA spectrum before and after the application of LAr veto [7, 13]: the Compton continuum below the ^{40}K line is efficiently suppressed; the pure $2\nu\beta\beta$ spectrum is left almost unchanged; the events of the ^{42}K line are suppressed by a factor $\sim$5.

6. – Conclusions

The $0\nu\beta\beta$ decay search is a topic of broad and current interest in modern physics. Its detection would imply the violation of lepton number conservation as predicted to occur in many extensions of the Standard Model. Among many experiments in the field, the GERDA and MAJORANA experiments obtained excellent results, which retrospectively validates their designs and the effectiveness of background suppression techniques.

The detection of the argon scintillation light, with the LAr veto system used in GERDA, was a powerful tool to reach the lowest background index. For this reason it was adopted also in LEGEND experiment which will continue the $0\nu\beta\beta$ decay search, exploiting the technological expertise and experience from both previous experiments.

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