Form No. 24

GERDA (“LEGEND”) PROJECT: SEARCHING FOR NEUTRINOLESS DOUBLE BETA DECAY OF GE-76

GERDA (“LEGEND”)

03-2-1100-2010/2024

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K.N.GUSEV

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RESPECTIVE PAC

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Abstract

The **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless double beta **D**ecay (**LEGEND**) experiment (the successor of the GERDA experiment) is designed to search for neutrinoless double beta ($0\nu\beta\beta$) decay of ^{76}Ge. In the experiment germanium detectors fabricated from isotopically enriched material will be operated inside a cryogenic fluid shield. The experiment will probe the $0\nu\beta\beta$ decay of ^{76}Ge with a sensitivity of $> 10^{28}$ years at 90% confidence level (C.L.).

The 200-kg phase (LEGEND-200), currently under construction in the existing GERDA infrastructure at LNGS, is using the enriched detectors from the previous Majorana and GERDA experiments as well as new detectors for a total mass of up to 200 kg. The background projection of the LEGEND-200 is a factor of 5 below the measured levels of GERDA, reaching a level of $< 10^{-4}$ counts/(keV kg yr). A scaling toward a 1000-kg phase incorporating a further factor of 10 reduction in background beyond LEGEND-200 at a level of $< 10^{-5}$ counts/(keV kg yr) will provide discovery potential that encompasses the inverted hierarchy mass region for the light left-handed Majorana neutrino exchange mechanism. LEGEND-1000 will probe a large/relevant part of the parameter space even if the ordering is normal.

At the time of writing, the LEGEND collaboration consists of 240 members from 47 institutions worldwide. JINR scientists are playing significant roles in all key parts of the project. So far JINR provided to the collaboration ~ 15 kg of enriched ^{76}Ge and this contribution is increasing on annual basis. Common JINR+TUM team is responsible for design and production of new liquid argon veto system for LEGEND-200 phase of the experiment and also for the R&D of such a system for LEGEND-1000. JINR is designing the glove box for the operations with bare germanium detectors as well as nylon mini-shrouds needed to mitigate the background form ^{42}Ar in LEGEND-200. Physicists from our institute are strongly involved in the analysis of LEGEND data and playing the central and leading roles in the core of LEGEND experiment – operations with bare germanium detectors.

The requested financing for completion of the project is 737 k$.

Introduction

The evidence for neutrino flavor oscillations has convincingly shown that neutrino has a finite mass. However, the fundamental question whether neutrino is Majorana (particle is equal to its own antiparticle) or Dirac particle is still unanswered. The only known practical way to probe the Majorana nature of neutrinos experimentally is via the discovery of the neutrinoless double beta ($0\nu\beta\beta$) decay. Moreover, this process violates lepton number conservation. Hence, it is forbidden within the Standard Model (SM) of particle physics. Therefore, the discovery of $0\nu\beta\beta$ decay will confirm the existence of New Physics beyond SM.

The experimental signature for discovery of $0\nu\beta\beta$ decay is a peak in the electron sum spectrum at the decay energy of the isotope under consideration. This makes the energy resolution very essential and gives the advantage to the experiments exploited Ge detectors.

The **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless double beta **D**ecay (**LEGEND**) project (the successor of the GERDA experiment) designed to search for neutrinoless double beta decay of ^{76}Ge. These experiments employ semiconductor diodes made from Ge enriched in ^{76}Ge so a detector acts also as a source. The detectors are directly immersed in liquid argon that works as a cooling medium and simultaneously as an additional passive and active shield against external radioactivity.

The half-life sensitivity of $0\nu\beta\beta$ experiments grows linearly with the exposure (kg yr) as long as there are no background counts in the region of interest (ROI) close to decay energy. GERDA Phase II was the first background free search for $0\nu\beta\beta$ decay because of achieved unique background level of 10^{-3} counts/(keV kg yr). It allowed GERDA to reach planned sensitivity of > 10^{26} years. Building on the experience with the background reduction technique, the next generation project LEGEND is being advanced. The experiment is foreseen to proceed in at least two phases. The first phase (LEGEND-200) plans to operate up to 200 kg of enriched Ge and to reach the sensitivity of 10^{27} years, the second phase (LEGEND-1000) – up to 1000 kg and 10^{28} years respectively. The aim of the new project is to answer the question about neutrino mass hierarchy. It is also very essential, that ultra-low background germanium-based experiments have better $0\nu\beta\beta$ discovery potential compared with all competitors thanks to the excellent energy resolution of Ge detectors.

Plan of the Project implementation:

2021-2022: Modification of GERDA cryostat for LEGEND-200. Integration of the first strings and start data taking of the LEGEND experiment. Working on the conceptual design of LEGEND-1000.

2022-2023: Taking data in LEGEND-200. Finalizing the array by adding the rest of the enriched Ge detectors. Publication of the first results of LEGEND-200. Preparation of the LEGEND-1000 (procurement of enriched ^{76}Ge, production and testing of new Ge detectors, R&D of low background materials and electronics).

2023-2024: Taking data in LEGEND-200. Adding the new detectors strings in the center of the LEGEND-200 array. Publication of improved results of LEGEND-200. Completion the design of LEGEND-1000. Continuation of preparation of the LEGEND-1000 (procurement of enriched ^{76}Ge, production and testing of new Ge detectors, R&D of low background materials and electronics).

State-of-the-art of the science case

During decades, the search for neutrinoless double beta decay remains worldwide ranked amongst the top research priorities. There are two experimental approaches in this field. Experiments of the first type so-called “active source” projects are utilizing the idea to use a detector at the same time as a source of double beta decay events. The main advantage of such an experiment is high registration efficiency. It should be mentioned, that the most part of state-of-art 0νββ projects are using active source approach. Second way to look for double beta processes is to have an external source (thin film source made of 0νββ isotope is placed between neighboring detectors). In this case, there is a possibility to measure several different isotopes simultaneously and to get an information about electron tracks. Today there many projects aiming to look for 0νββ decay and it is nearly impossible to mention all of them here. However, authors fully appreciate the projects that are not the list and understand that the serious progress could be achieved by any experiment in the near future. In any case, the importance of 0νββ search is additionally confirmed by numbers of such projects in modern physics.

At the end of last century, the two most sensitive experiments were Heidelberg-Moscow (HdM) [1] and IGEX [2]. They both used ^{76}Ge, found no evidence for the 0νββ decay and set lower limits on the half-life > 1.9×10^{25} and > 1.6×10^{25} years respectively. The leader of the HdM experiment and his group had further continued their investigations and had published a claim on an observation of the 0νββ decay in ^{76}Ge. However, the results of present experiments have disfavored this claim.

In the initial decade of the new century, Cuoricino [3] and NEMO-3 [4] provided new limits on $T_{1/2}^{0\nu}$. Cuoricino used bolometric TeO_2 crystals to set a lower limit of $T_{1/2}^{0\nu}$ > 2.8×10^{24} yr (at 90% C.L.) for ^{130}Te. In NEMO-3, thin foils made out of seven different ββ-isotopes were located in a drift chamber embedded in a magnetic field. The 90% C.L. limits are $T_{1/2}^{0\nu}$ > 1.1×10^{24} yr for ^{100}Mo and $T_{1/2}^{0\nu}$ > 3.2×10^{24} yr for ^{82}Se.

The present time is characterized by the limits obtained by the following five experiments: GERDA [5] [6], Majorana [7], EXO-200 [8], KamLAND-Zen [9] and CUORE [10].

GERDA (located at the LNGS, Italy) operates an array of germanium detectors enriched in the isotope ^{76}Ge immersed in liquid argon. The cryogenic liquid serves simultaneously as coolant, high-purity shield and active veto system. Similarly, Majorana Demonstrator (located in the SURF underground facility in the USA) investigates the 0νββ decay of ^{76}Ge. The germanium detector array is deployed in vacuum cryostats and shielding produced from ultra-pure copper. The EXO-200 collaboration operates at the WIPP facility in USA a liquid Xe TPC with xenon enriched in the isotope ^{136}Xe. KamLAND-Zen, located in the Kamioka mine in Japan, is a follow-up of the neutrino experiment KamLAND. It was converted into an apparatus capable to study 0νββ decay by dissolving Xe gas enriched in the isotope ^{136}Xe in an organic scintillator. CUORE, located at the LNGS, Italy, is a natural expansion of Cuoricino investigating the 0νββ decay of ^{130}Te. An array of natural TeO_2 bolometers is operated at 10 mK in a specially designed cryostat.

The aim of all these five experiments is to fully explore the quasi-degenerate neutrino mass spectrum and in case of no positive signal, to prepare the path for a substantial increase of their sensitivities in order to explore the parameter range predicted for the inverted mass ordering and for a large fraction in case of normal ordering. Table I shows the most recent results from the five aforementioned experiments. The lower limits can be converted to upper limits on the effective Majorana mass $\langle m_{\beta\beta} \rangle$ assuming the light neutrino exchange as dominant mechanism. In Table 1 such upper limits on $\langle m_{\beta\beta} \rangle$ are shown using the standard value of g_A = 1.27, phase space factors [11] and the set of nuclear matrix elements discussed in the recent review [12].

Table 1. Comparison of lower half-life limits (90% C.L.) and corresponding upper Majorana neutrino mass limits for the present generation experiments. The limits results from each collaboration's choice of matrix element.

Experiment	Isotope	Isotope mass (kg)	$T^{0\nu}_{1/2}$ (× 10^{25} yr)	$\langle m_{\beta\beta} \rangle$ (meV)
GERDA [13]	^{76}Ge	31	18	79 – 180
Majorana [14]	^{76}Ge	26	2.7	200 – 433
KamLAND-Zen [9]	^{136}Xe	343	10.7	61 – 165
EXO [15]	^{136}Xe	161	3.5	93 – 286
CUORE [16]	^{130}Te	206	1.5	110 – 520

Table 1 manifests that ^{76}Ge experiments reach competitive sensitivities with much smaller isotope masses compared to the other experiments. The reason is that they acquire data free of background in the signal region and have excellent energy resolution and no ββ-isotopes are 'lost' through a fiducial volume cut. As a result, experiments using ^{76}Ge have been historically impactful in 0νββ. It is important to note that the most stringent half-life limit $T^{0\nu}_{1/2}$ > 1.8 × 10^{26} yr has been recently achieved in our project – GERDA.

The next generation of 0νββ experiments aims for probing $\langle m_{\beta\beta} \rangle$ down to about 10 meV, i.e. to completely cover the parameter range predicted in case of inverted mass ordering. Many different isotopes and detector concepts have been suggested. Here, we briefly discuss the more advanced projects as listed in Table 2 in the Appendix. The two phases of new ^{76}Ge project LEGEND, proposed here, are shown for comparison.

SuperNEMO [17], located at the Modane underground laboratory in France, is a project based on the NEMO-3 tracking concept. It will use approximately 100 kg of foils enriched in ^{82}Se, with an improved energy resolution respect to the predecessor.

CUPID [18], is a proposed future ton-scale bolometric 0νββ experiment built on experience, expertise and lessons learned in CUORE [16], and will exploit the current CUORE infrastructure at LNGS as much as possible. The background index will be reduced by about two orders of magnitude with respect to CUORE thanks to an active background suppression obtained through the use of scintillating bolometers. Various isotopes were under study but recently the collaboration decided to use ^{100}Mo.

SNO+ [19] is a large liquid scintillator-based experiment located at SNOLAB, Sudbury, Canada. It reuses the SNO detector, consisting of a 12-m diameter acrylic vessel which will be filled with about 780 tons of ultra-pure liquid scintillator. In Phase 1, the scintillator will be loaded with 0.5% natural tellurium and in phase 2, this percentage will be increased up to 3%. With the second phase the entire inverted mass hierarchy will be scrutinized.

KamLAND-Zen [9] is a multi-staged program that uses the kiloton-scale liquid scintillator detector KamLAND, retrofitted with a balloon containing xenon-doped liquid scintillator to search for the 0νββ decay of ^{136}Xe. The next phase of the experiment will increase the mass of ^{136}Xe to 750 kg using a new low-background balloon. Following this phase, a major upgrade of the detector will take place including improvements in the photon collection and the liquid scintillator in addition to increasing the mass to 1 ton.

nEXO [20] is a proposed experiment to search for 0νββ decay in ^{136}Xe with a target sensitivity of approximately 10^{28} yr using 5 tons of isotopically enriched liquid xenon in a time projection chamber (TPC). A possible experiment's location is the Sudbury Neutrino Laboratory (SNOLAB), Canada. The project is based on the present EXO-200 experiment and the large improvement in performances are obtained by a significant increase of the ^{136}Xe mass, the monolithic and homogeneous configuration of the active medium, and the multi-parameter measurements of the interactions enabled by the TPC.

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Project description

Neutrinoless double beta decay is a hypothetical lepton number violating process, $(\mathrm{A,Z}) \rightarrow (\mathrm{A,Z{+}2}) + 2e^{-}$, where inside a nucleus two neutrons convert into two protons and two electrons. Its observation would establish the neutrino to be its own anti-particle (Majorana particle), provide access to the absolute mass scale of neutrinos, and support extensions of the Standard Model of particle physics, which try to explain the dominance of baryonic matter over anti-matter in our universe. Recent experiments have established the half-life of $0\nu\beta\beta$ decay to be larger than 10^{26} years, and hence its detection requires the utmost suppression of any kind of background.

The LEGEND collaboration (the successor of the GERDA and Majorana experiments) searches for $0\nu\beta\beta$ decay of ^{76}Ge, $^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^{-}$. It employs semiconductor diodes made from Ge enriched in ^{76}Ge so a detector acts also as a source. The detectors are directly immersed in liquid argon (LAr) which cools the detectors and is used as an active and passive shield against external radioactivity. It is foreseen at least two phases of the project. The first phase (LEGEND-200) will operate with ~ 200 kg of enriched isotope and the expected sensitivity will be 10^{27} years. The second phase (LEGEND-1000) will use 1000 kg and reach 10^{28} years respectively.

A main feature of LEGEND-200 is the reuse of the existing GERDA infrastructure [1] located at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN in Italy. It is placed underground below a rock overburden of about 3500m water equivalent that reduces the muon flux to ~1.25/(m^2 h). Fig. 1 shows a cross section through the current installation. LEGEND-200 as well as GERDA is using germanium detectors enriched in ^{76}Ge, which are arranged in strings inside a cryostat filled with 64 m^3 of liquid argon. The cryostat is located inside a water tank of 10 m in diameter. Only very small amounts of LAr are lost as it is cooled via a heat exchanger by liquid nitrogen. The 590 m^3 of high purity (>0.17 MΩm) water moderate ambient neutrons and γ radiation. It is instrumented with 66 PMTs and operates as a Cherenkov muon veto to reduce further cosmic induced backgrounds to insignificant levels for the LEGEND experiment. Muons traversing through the opening of the cryostat without reaching water are detected by plastic scintillator panels on top of the clean room. A glove box and the lock for integration and deployment of the Ge detectors is placed in a clean room on top of the cryostat and water tank. The main relevant items of the current configuration are the cryostat with its infrastructure (a few modifications are needed, see below), the water tank with the muon veto instrumentation and purification plant, the clean room and the germanium detector laboratory. The latter is a grey room which houses glove boxes for detector assembly, a chemical hood and a cryostat for testing detectors before deploying them.

The main new hardware activities for LEGEND-200 are

- fabrication of inverted-coax detectors from enriched germanium,
- design and fabrication of detector holders,
- design and fabrication of very low-radioactivity front-end electronics working at the detectors in liquid argon,
- design and production of a new lock for the insertion of the detector strings including a cable chain and feedthroughs,
- data acquisition with increased channel count and rate,
- liquid argon instrumentation for the detection of scintillation light,
- replacement of the piping inside the cryostat,
- glove boxes for detector handling and jigs for detector mounting.

Most these items we discuss in more detail in the following.

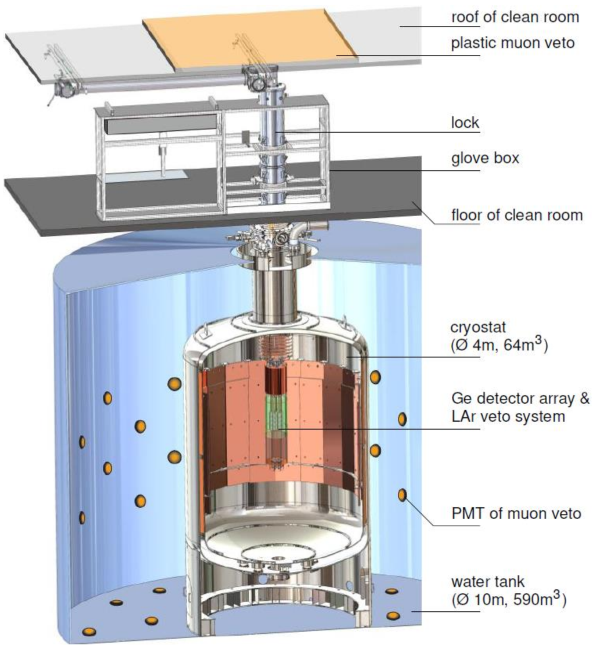


Fig. 1. Schematic cross section of the GERDA experiment. The main components are labelled.

Cryostat piping

The piping internal to the GERDA cryostat limits the usable aperture to currently less than 530 mm. For a larger detector array consisting of 14 strings and the new LAr veto, this is not sufficient. The design of the piping was therefore modified to increase the nominal cross section to 610 mm in diameter. Stricter control of alignment and eccentricity should reduce the required safety clearance to less than 10mm in radius such that the usable diameter is 590 mm.

Fig. 4 in the Appendix shows a cross section of the cryostat piping (below the DN630 shutter). The compensator allows for relative movements between the clean room and the cryostat in case of an earth quake. The manifold is mounted on the cryostat and contains all feedthroughs. The right part of the figure shows the lower part of the piping with the two copper coil heat exchanges for the cooling of the LAr with LN_2 and a swimmer as fill level sensor. The production of the new piping is finishing at the time of writing.

Lock

The DN630 shutter separates the cryostat gas volume from the lock. When the shutter is closed the lock can be opened for operation on the germanium detectors and the LAr veto. Fig. 5 in the Appendix shows a cross section through the current lock.

The vertical piping layout follows the existing solution: the lower pipe can slide to the side inside the glove box to open the lock (after compressing the compensators). The detector string and veto will be in the upper pipe during opening and closing which is at a fixed position. Since the height of the clean room limits the height of these pipes and hence the argon veto and detector array to about 1.2 m, it was decided to increase the clean room height in order to adopt longer strings and the new LAr veto (1.5 m).

Detector mounting

Detector mounts must provide physical support and electrical isolation of each detector. Additional requirements are that the design must accommodate nylon shrouds, light collection fibers, electronics mounting, routing, and termination. Detector mounts must not damage the detectors and provide some level of protection from damage during handling and installation. Mounts must be made from ultrapure materials to minimize contribution to background, and have low volume in order to minimize any reduction in light collection efficiency for the active veto system.

The default design for LEGEND detector mounts is based on the GERDA design with elements of the Majorana design and refinements. Fig. 6 in the Appendix shows schematically what is meant by the term “detector module” and how they are configured in the overall experiment. The base plate of the GERDA detector mount is a high purity silicon wafer. This material is intrinsically free of radio contamination, has a reasonable high strength, but is brittle and thus must be handled with care. The vertical support rods are machined from commercial copper. The termination for HV and signal contact are simple pads and bronze spring latches to provide a stable surface for wire bonding. Bond wires are applied in the glovebox to connect this constrained cable end to the detector. All active electronics and removable connectors for GERDA are located about 40 cm above the top detector. Fig. 7 (Appendix) shows a GERDA detector mount in a protective assembly fixture. The Majorana detector mount is much more massive, but the main difference is the location of the first stage of preamplifier. This unit names a low-mass front-end circuit (LMFE) and provides the initial stage of signal amplification very near to the detector. This also allows for the use of coaxial cables to reduce noise. So, the LEGEND design uses the Si base plates on which there is a place for LMFE circuit. Moreover, all Cu elements will be made from electroformed copper (UGEFCu) produced underground in the Majorana facilities.

Tooling in the glovebox for LEGEND were designed by JINR specialists. It is based on the GERDA design but some serious modifications to deal with longer strings were needed. Fig. 8 (Appendix) shows a few key stages of string assembly for the GERDA experiment. In LEGEND it will be similar however the main idea was to mount the detectors in strings close to the lock in order to avoid moving of assembled string along the glove box. The design of the new glove box is depicted on Fig. 9 in the Appendix.

Front-end electronics

The most expedient approach to implement the readout electronics for LEGEND-200 is to deploy a system that comprises improved Majorana LMFE and GERDA charge-sensitive preamplifier (CSA) with new interconnects that can be deployed by the lock. Fig. 10 (Appendix) shows the photos of these components. Before this unified design could be implemented for a sub-10 keV threshold, successful R&D in several areas had to be realized. These areas included the demonstration of LMFE operation in liquid argon; improvements in LMFE fabrication; improvements in the designs of CSA and LMFE-CSA interconnects to reduce noise; and the design and selection of cables from the CSA to the top of the glovebox. All these steps were done and at the time of writing we are ready to start the LEGEND LMFE and CSA mass production.

Liquid argon veto system

LEGEND-200 LAr veto system builds on the successful liquid argon instrumentation pioneered by the GERDA collaboration [1, 2]. While $0\nu\beta\beta$ decays typically have point-like energy depositions in a single Ge detector, background events often have multi-site energy depositions in one or several Ge detectors, or in the surrounding liquid argon.

To detect the scintillation light following the energy deposition in the liquid argon, the GERDA collaboration operates a hybrid design consisting of two arrays of photomultipliers at the top and at the bottom of the cylindrical instrumented volume, and wavelength shifting (WLS) fibers coupled to silicon photomultipliers (SiPM) on the cylindrical part, as displayed in Fig. 11 in the Appendix. In the upgrade of GERDA in 2018 (performed by common JINR+TUM team) the SiPMs (in die) are mounted on mirco-machined fused silica substrates, as shown on the bottom right of the same figure.

The baseline design of LEGEND-200 will adopt WLS-fibers which will be read out with SiPMs as developed and tested in GERDA. Improved geometrical fiber coverage will increase the photo electron yield together with an improved liquid argon quality of a factor of two or more while keeping the trigger threshold to discard a background event at the single photo electron level. Given the increased number of detector strings in LEGEND-

200 with respect to GERDA, the scintillation light emitted inside the Ge detector array has a reduced likelihood to reach an outer WLS-fiber element. For this reason, it is planned to deploy also the internal WLS-fiber shroud. The final design of LEGEND-200 LAr veto, developed by JINR and TUM specialists, is displayed in Fig. 12 (Appendix).

Nylon mini-shrouds

The background due to ^{42}Ar stays essential for LEGEND-200. ^{42}Ar decays into ^{42}K, which is a β emitter with an endpoint energy of 3.5 MeV. So in GERDA we had to create a mechanical barrier, called 'mini-shroud' (MS), enclosed the space around the detector string, which prevents the collection of ^{42}K ions on the detector surfaces. This barrier should be transparent otherwise the LAr veto system couldn't register the scintillation light from the area close to the detectors. For GERDA Phase II a new MS made from ultrapure nylon was developed [3]. A photo of the GERDA Phase II detector array with each string enclosed by its individual transparent MS is shown in Fig. 13 in the Appendix. The investigation and development of the background suppression methods were done at the low-background test facility LArGe [2] in GDL with strong and leading participation of JINR specialists. For LEGEND-200 the JINR team stays responsible for the R&D and production of all nylon MSs. They are going to be made in the dedicated glove box situated in the clean room in our department at DLNP JINR.

Enriched detectors

When available, Majorana has 29.7 kg of P-PC detectors that can be directly installed in LEGEND-200. GERDA has already have 20.0 kg of BEGe detectors and, after the upgrade in 2018, 9.6 kg of newly produced inverted-coax LEGEND detectors. Another six detectors of new inverted-coax type (about 2 kg each) have been fabricated and delivered to LNGS in order to immerse them in the GERDA cryostat after the end of the GERDA data taking to test their performance together with LEGEND-like electronics and data acquisition system. This action named post GERDA test (PGT) and was organized with the strong involvement of JINR team. In addition it worth to note that about 15 kg of the enriched isotope used to produce abovementioned new detectors has been provided by JINR. The 17.6 kg of semi-coax detectors will be considered as part of ^{76}Ge to be recycled. In addition, Majorana and GERDA have 2.2 kg and 14.2 kg respectively of unprocessed ^{76}Ge left over from previous detector production.

It is our intent to install up to 200 kg of enriched ^{76}Ge in the existing GERDA infrastructure at LNGS. Presently we have ~ 80 kg of detectors that can be used directly and 34 kg of enriched material which will be converted in ~ 20 kg of detector mass. Hence to reach our 200 kg goal, an additional ~ 100 kg of detectors is required. With the expected detector mass yield (~75%), we require about 135 kg of ^{76}Ge. LEGEND-200 has ordered or has orders in place for this material. Five detectors were produced in 2018 and used during the upgrade of the GERDA Phase II. So the process for acquiring the enriched ^{76}Ge and production of enriched detectors has begun. Thus about 230 kg of enriched Ge has been obtained, funded, or proposed at this time, providing an estimated 190 kg of detectors. A summary of the ^{76}Ge inventory is given in Table 3 (Appendix).

Physics sensitivity

The sensitivity to a 0νββ decay signal as a function of exposure and background is shown in Fig. 2, separately for a 3σ discovery and a 90% C.L. upper limit analysis. The calculation assumes a total signal efficiency of 60%, accounting for the enrichment level, the PSD signal survival probability, the active volume fraction, and the containment efficiency for neutrinoless double-beta decay events to have their full energy deposited within a crystal's active volume. If an experiment's background is zero both the discovery sensitivity as well as the limit sensitivity scale linearly with the exposure, while in the background-dominated regime both sensitivities scale with the square root. For signal discovery a low background is especially important because as the expected number of background counts increases, the signal level required to obtain a 3σ excess grows rapidly. Even assuming a conservative background of 0.2 cts/(keV t yr) or 0.6 cts/(FWHM t yr), LEGEND-200 would reach a 3σ discovery sensitivity of > 10^{27} yr for an exposure of 1 t yr.

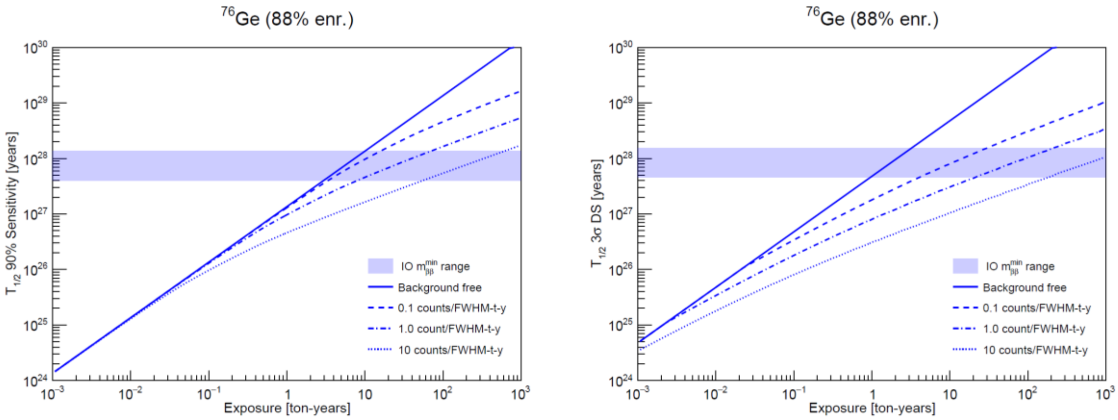


Fig. 2. Sensitivity for setting a limit (left) or a signal discovery (right).

Latest results

Since the final results of the GERDA experiment, achieved recently, opened the bright future for the LEGEND project, it is worth to discuss them here. Moreover these results show the success of the GERDA project supported by JINR. The energy spectrum of full Phase II exposure is presented at Fig. 3. The background index is equal to $5.2^{+1.6}_{-1.3} \times 10^{-4}$ counts/(keV kg yr). If normalized to the energy resolution and signal efficiency this value is more than factor of five lower compared with any non-^{76}Ge competitors.

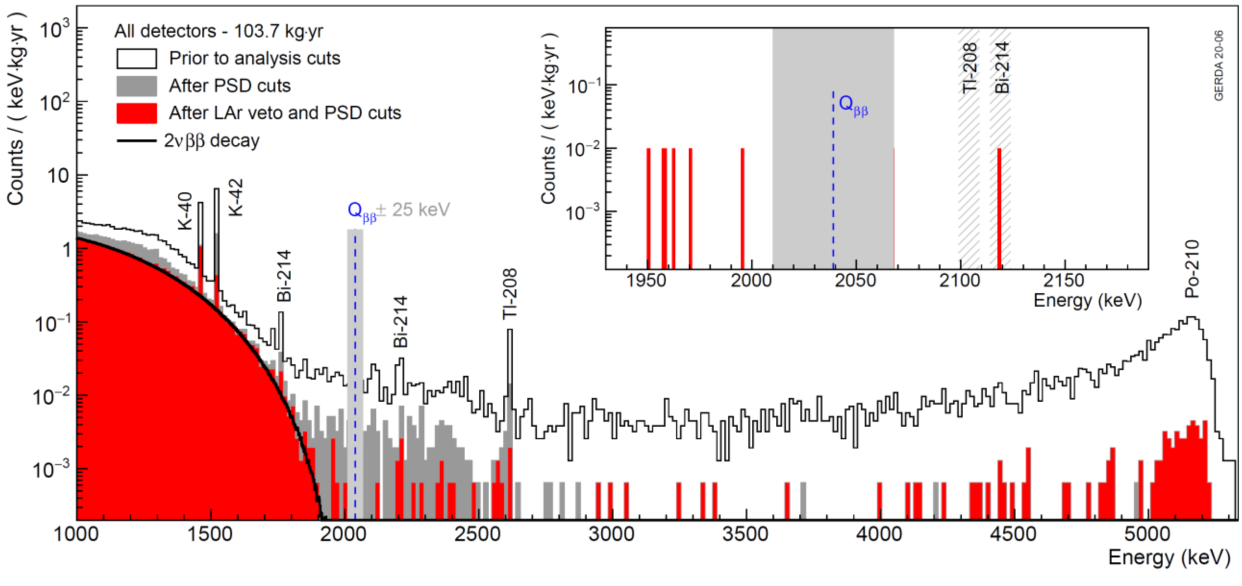


Fig. 3. Final energy spectra of GERDA Phase II. On the inset, the spectrum the spectrum in the ROI is shown. The vertical grey line band shows the blinded region.

With a total exposure of 127.2 kg yr (103.7 kg yr in Phase II), we observed no 0νββ signal and derived a world best lower half-life limit of $T_{1/2}^{0\nu}$ > 1.8 × 10^{26} yr (90% C.L.) at the unprecedented median sensitivity of 1.8 × 10^{26} yr. The linear increase of sensitivity with exposure, achieved by GERDA (Fig. 14 in the Appendix), proves that we were taking data in background free regime. JINR scientists were playing significant roles in the GERDA experiment and plan to do the same or even take the lead in the key parts of the LEGEND project.

GERDA (LEGEND) publications and talks

1. «Upgrade for Phase II of the GERDA Experiment», Eur. Phys. J. C 78 (2018) 388.
2. «LArGe: active background suppression using argon scintillation for the Gerda 0νββ-experiment», Eur. Phys. J. C 75 (2015) 506.
3. «Mitigation of ^{42}Ar/^{42}K background for the GERDA Phase II experiment», Eur. Phys. J. C 78 (2018) 15.
4. «The GERDA experiment for the search of 0νββ decay in ^{76}Ge», Eur. Phys. J. C 73 (2013) 2330.
5. «Results on Neutrinoless Double-β Decay of ^{76}Ge from Phase I of the GERDA Experiment», Phys. Rev. Lett 111 (2013) 122503.
6. «Pulse shape discrimination for GERDA Phase I data», Eur. Phys. J. C 73 (2013) 2583.
7. «The background in the 0νββ experiment GERDA», Eur. Phys. J. C 74 (2014) 2764.
8. «Results on ββ decay with emission of two neutrinos or Majorons in ^{76}Ge from GERDA Phase I», Eur. Phys. J. C 75 (2015) 416.
9. «2νββ decay of ^{76}Ge into excited states with GERDA Phase I», J. Phys. G: Nucl. Part. Phys. 42 (2015) 115201.
10. «The performance of the Muon Veto of the GERDA experiment», EPJC 76 (2016) 298.
11. «Flux modulations seen by the muon veto of the GERDA experiment», Astroparticle Physics 84 (2016) 29.
12. «Limit on the radiative neutrinoless double electron capture of ^{36}Ar from GERDA Phase I», Eur. Phys. J. C 76 (2016) 652.
13. «Limits on uranium and thorium bulk content in GERDA Phase I detectors», Astroparticle Physics 91 (2017) 15.
14. «Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA», Nature 544 (2017) 47.
15. «The Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND)», AIP Conference Proceedings 1894 (2017) 020027.
16. «Improved Limit on Neutrinoless Double-β Decay of ^{76}Ge from GERDA Phase II», Phys. Rev. Lett. 120 (2018) 132503.
17. «Characterization of 30 ^{76}Ge enriched Broad Energy Ge detectors for GERDA Phase II», Eur. Phys. J. C. 79 11 (2019) 978.
18. «Probing Majorana neutrinos with double-β decay», Science 365 (2019) 1445.
19. «Modeling of GERDA Phase II data», Journal of High Energy Physics 03 (2020) 139.
20. «First Search for Bosonic Superweakly Interacting Massive Particles with Masses up to 1 MeV/c2 with GERDA», Phys. Rev. Lett. 125 (2020) 011801.
21. «Final Results of GERDA on the Search for Neutrinoless Double-β Decay», submitted to Physical Review Letters, arXiv: 2009.06079.
22. «Status of the GERDA experiment: on the way to Phase II», K.Gusev at TAUP 2015, Torino, Italy
23. «Status of preparations for the Phase II of the GERDA experiment aimed for the 0νββ decay search», A.Lubashevskiy at PATRAS 2015, Zaragoza, Spain.
24. «First results from Phase II of the GERDA experiment», K.Gusev at INPC 2016, Adelaide, Australia.
25. «Neutrinoless double beta decay: First results of GERDA Phase II and the status of other experiments», A.Lubashevskiy at PASCOS 2016, Quy Nhon, Vietnam.
26. «Double Beta Decay Experiments», K.Gusev at ICSSNP 2016, Dubna, Russia.
27. «Double beta decay experiments and neutrino mass investigation: Past, Present and Future», A.Smolnikov at QUARKS 2016, Pushkin, Russia.

28. «From Baksan to worldwide experiments searching for neutrinoless double beta decay», A.Smolnikov at ICSSNP 2017, Nalchik, Russia.
29. «Neutrinoless double beta decay search with the "background free" GERDA experiment», A.Lubashevskiy at ICSSNP 2017, Nalchik, Russia.
30. «GERDA: first background free search for neutrinoless double beta decay», K.Gusev at ICNFP 2017, Crete, Greece.
31. «LEGEND: new opportunity to discover the neutrinoless double beta decay», K.Gusev at ICNFP 2017, Crete, Greece.
32. «Neutrinoless double beta decay: Experimental challenges», K.Gusev at NOW 2018, Brindisi, Italy.
33. «Fifty Years of Searching for Neutrinoless Double Beta Decay with Ge Detectors», A.Smolnikov at History of Neutrinos, Paris, France.
34. « New results of the search for neutrinoless double beta decay from GERDA Phase II», N.Rumyantseva at Nucleus 2018, Voronezh, Russia.
35. «GERDA searches for $0\nu\beta\beta$ and other $\beta\beta$ decay modes of ^{76}Ge», A.Smolnikov at MEDEX 19, Prague, Czech Republic.
36. «Status of the search for neutrinoless double-beta decay with GERDA», A.Lubashevskiy at WIN 2019, Bari, Italy.
37. «Upgrade of the GERDA Phase II experiment», E.Shevchik at Nucleus 2019, Dubna, Russia.
38. «Latest results from the first background free search for neutrinoless double beta decay – GERDA Phase II», K.Gusev at INPC 2019, Glasgow, UK.
39. «Status of the GERDA Phase II experiment», N.Rumyantseva at ICNFP 2019, Crete, Greece.
40. «Results of the GERDA Phase II experiment», K.Gusev at ICHEP 2020, Prague (virtual conference).

Estimation of human resources

K.N.Gusev – Project Leader (technical coordination of the GERDA experiment, project coordination at JINR, Ge detectors, active veto systems), 0.6 FTE
A.V.Lubashevskiy – Deputy Leader (analysis coordination, ultrapure materials, Ge detectors), 0.3 FTE.
N.S.Rumyantseva – Deputy Leader (Ge detectors, analysis), 0.4 FTE
V.B.Brudanin – Participant (^{76}Ge procurement, ultrapure materials), 0.1 FTE
M.V.Fomina – Participant (active veto systems), 0.2 FTE
S.A.Evseev – Participant (Ge detectors), 0.1 FTE
D.V.Filosofov – Participant (ultrapure materials), 0.1 FTE
L.Grubchin – Participant (Ge detectors), 0.1 FTE
Yu.B.Gurov – Participant (Ge detectors), 0.2 FTE
Zh.H.Hushvaktov – Participant (ultrapure materials), 0.2 FTE
I.I.Kamnev – Participant (active veto systems), 0.2 FTE
A.A.Klimenko – Participant (analysis), 0.7 FTE
F.Mamedov – Participant (ultrapure materials, analysis), 0.2 FTE
I.B.Nemchenok – Participant (ultrapure materials, active veto systems), 0.2 FTE
A.V.Rakhimov – Participant (ultrapure materials), 0.1 FTE
S.V.Rozov – Participant (Ge detectors), 0.1 FTE
V.G.Sandukovsky – Participant (Ge detectors), 0.5 FTE
K.V.Shakhov – Participant (ultrapure materials), 0.1 FTE
E.A.Shevchik – Participant (active veto systems), 0.3 FTE
Yu.A.Shitov – Participant (analysis), 0.1 FTE
A.A.Smolnikov – Participant (active veto systems, ultrapure materials, analysis), 0.7 FTE
S.I.Vasilev – Participant (active veto systems, analysis), 1.0 FTE
V.P.Volnikh – Participant (technical support), 0.1 FTE
E.A.Yakushev – Participant (Ge detectors, analysis), 0.1 FTE
I.V.Zhitnikov – Participant (analysis), 0.1 FTE

SWOT analysis

The major strength of the Project compared with other 0νββ experiments is the highest possibility for discovery of this process thanks to the excellent energy resolution of Ge detectors and extremely low background.

Here we are trying to estimate benefits and risks of the first phase of the tone-scale experiment searching for neutrinoless double-beta decay of ^{76}Ge – LEGEND-200. A main feature of LEGEND-200 is the reuse of the existing GERDA infrastructure located at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN in Italy. The main relevant items of the current configuration are the cryostat with its infrastructure (a few modifications are needed), the water tank with the muon veto instrumentation and purification plant, the clean room and the germanium detector laboratory.

The main new hardware activities for LEGEND-200 are

- fabrication of inverted-coax detectors from enriched germanium,
- design and fabrication of detector holders,
- design and fabrication of very low-radioactivity front-end electronics working at the detectors in liquid argon,
- design and production of a new lock for the insertion of the detector strings including a cable chain and feedthroughs,
- data acquisition with increased channel count and rate,
- liquid argon instrumentation for the detection of scintillation light,
- replacement of the piping inside the cryostat,
- glove boxes for detector handling and jigs for detector mounting.

Going through these bullets we can discuss benefits and risks of the LEGEND-200 experiment.

Benefits:

- **Existing infrastructure**

The construction of the large infrastructure items required major resources and time. Alone the discussion of the safety aspects of the experiment lasted several years and motivated major redesigns. The reuse of the GERDA facilities is therefore a very economical and time efficient option and is therefore pursued by the LEGEND collaboration. Two main features allow to proceed with LEGEND-200:

  - The background of GERDA is dominated by sources close to the detectors like cables, ^{42}Ar and detector surface contaminations. External sources of radiation are efficiently reduced by the water and the liquid argon shield to ensure sufficiently low background rates for LEGEND-200. Muon induced events are tagged efficiently by the water Cherenkov detector and the liquid argon instrumentation.
  - The cryostat, especially the aperture of the neck, is large enough to house 14 detector strings with 200 kg of mass

- **Existing enriched detectors and secured funding for new detectors**

As described above, the LEGEND collaboration can directly immerse in the modified cryostat about 80 kg of enriched germanium detectors as soon as they will not be used anymore by GERDA (which is the case at the time of writing) and Majorana (will be the case soon) experiments. In addition the production of new detectors in ongoing and needed funding is mostly secured.

- **Well-established technology of detector fabrication**

Majorana and GERDA have accumulated experience in crystal and detector fabrication with Canberra (now part of Mirion Technologies) and ORTEC (AMETEK) over the past decade. For LEGEND-200, we plan to consider both of these companies. At the time of writing these companies are producing new enriched detectors. Some of them have been already provided to the collaboration (9 from Mirion and 2 from ORTEC), tested in vacuum cryostats and delivered to LNGS for the first test in liquid argon, which most of them have been successfully passed.

- **Existing design of the detector holders**

  The baseline design of the detector holders is slightly modified GERDA Phase II design. In addition several samples of LEGEND-200 holders were produced and tested in the abovementioned post GERDA test (PGT). Since we didn't find any unexpected problems we decided to start the mass production of the LEGEND-200 holders. They should be ready in time.

- **Well-developed design of electronics**

  The design of LEGEND-200 FE electronics is the merging of two well-developed designs from GERDA (charge sensitive preamplifier) and Majorana (low mass front-end (LMFE) – first stage of preamplifier). However the increased number of channels compared to GERDA and new LMFE components (taken from Majorana design) required the serious modification of the preamplifier design. It was done, and the new preamplifier was successfully tested together with LEGEND-200 LMFE during PGT.

- **Well-advanced production of the new lock and new piping in the cryostat**

  At the time of writing the modification of the cryostat piping, performed to adopt bigger array in the existing cryostat, is ongoing as well as the production of the new lock.

- **Existing design of liquid argon instrumentation**

  The design of liquid argon instrumentation for LEGEND-200 is based on the design used in the upgrade of GERDA Phase II. The fabrication of needed components has been already started, fibers have been delivered. It is very important to mention, that people who produced the modified veto for GERDA in 2018 (common JINR+TUM team) are available and ready to start the production of instrumentation for LEGEND-200.

- **Existing design of the glove box and detector fixtures**

The design of the glove box for assembling of detector strings and liquid argon veto has been finished, most of new parts were ordered or being ordered now. Most part of pieces needed for detector fixture have been already produced and delivered to LNGS.

- **Availability of most personnel who performed final integration of the GERDA experiment in 2015 as well as GERDA Phase II modification in 2018 (detector handling, mounting, bonding; LAr veto mounting; usage of the lock system).**

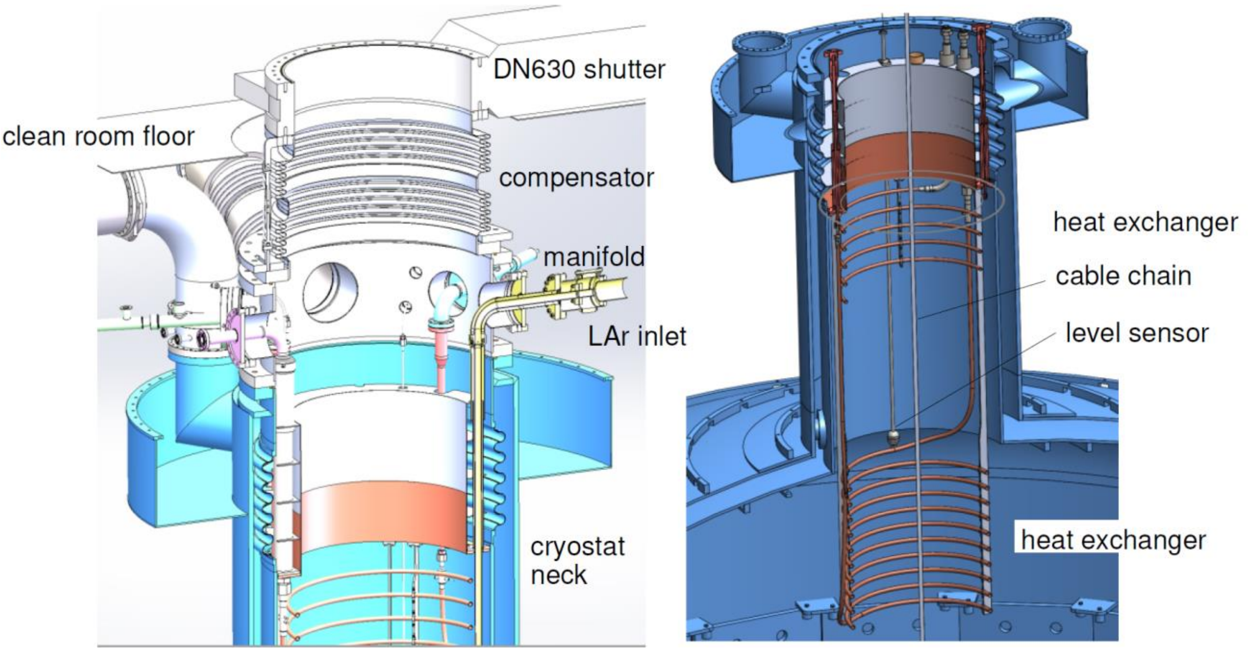
Risks:

- Possibility to delay the start of LEGEND-200 data taking due to the actual situation with COVID-19 pandemic especially in case of new travel restrictions. However, the main activities which were stopped in spring 2020 is ongoing again now.
- Another problem can be connected to the high failure rate of the new detector production which will not allow us to have total needed enriched germanium mass. However this risk is pretty low due to well-established detector technology. Moreover the fabrication capability of two existing companies has been checked already – more than 10 newly produced detectors are available and performing well.
- The last but not least problem is the possibility to not reach the desired background level, but very careful assay of materials as well as the unique background level achieved by GERDA, significantly reduce this risk.

Appendix

Table 2. Experimental parameters for next-generation experiments. The quoted masses refer to the isotope. The background indices (BI) are normalized to the FWHM without correcting for cut efficiencies.

Experiment	Isotope	Isotope mass (kg)	Run Time (yr)	FWHM (keV)	BI (cts/(FWHM t yr))	$T^{0\nu}_{1/2}$ ($\times 10^{27}$ yr)	$\langle m_{\beta\beta} \rangle$ (meV)
LEGEND-200	^{76}Ge	180	5	2.5	0.6	1.4	29 – 65
LEGEND-1000	^{76}Ge	880	10	2.5	0.1	15	9 – 20
SuperNEMO	^{82}Se	100	5	120	6	0.1	58 – 144
CUPID	^{100}Mo	253	10	5	0.02	1.5	10 – 17
SNO+ Phase I	^{130}Te	1357	5	193	23	0.2	31 – 139
SNO+ Phase II	^{130}Te	7960	5	134	5.4	1	16 – 71
KamLAND-Zen 800	^{136}Xe	750	5	268	64.3	0.5	24 – 77
KamLAND2-Zen	^{136}Xe	1000	5	141	3.3	1.4	14 – 44
nEXO	^{136}Xe	4038	10	58	0.14	9.2	5.7 – 17.7



g. 4. Cross section through the cryogenic infrastructure at the cryostat. Left: between the DN630 shutter and the cryostat (compensator and manifold with feedthroughs). Right: inside the cryostat (heat exchanger, fill level measurement).

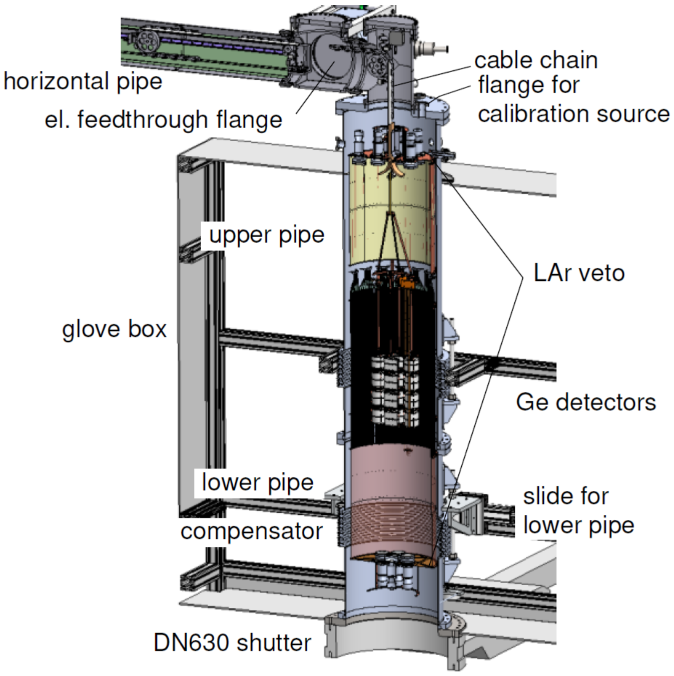


Fig. 5. Schematic cross section of the GERDA lock and glove box. The Ge detector array is in the center surrounded by the LAr veto system. The weight is supported by the cable chain. The vertical lock is separated into an upper and a lower pipe. Both can be compressed due to compensators and the lower one then slides to the side inside the glove box to open the lock.

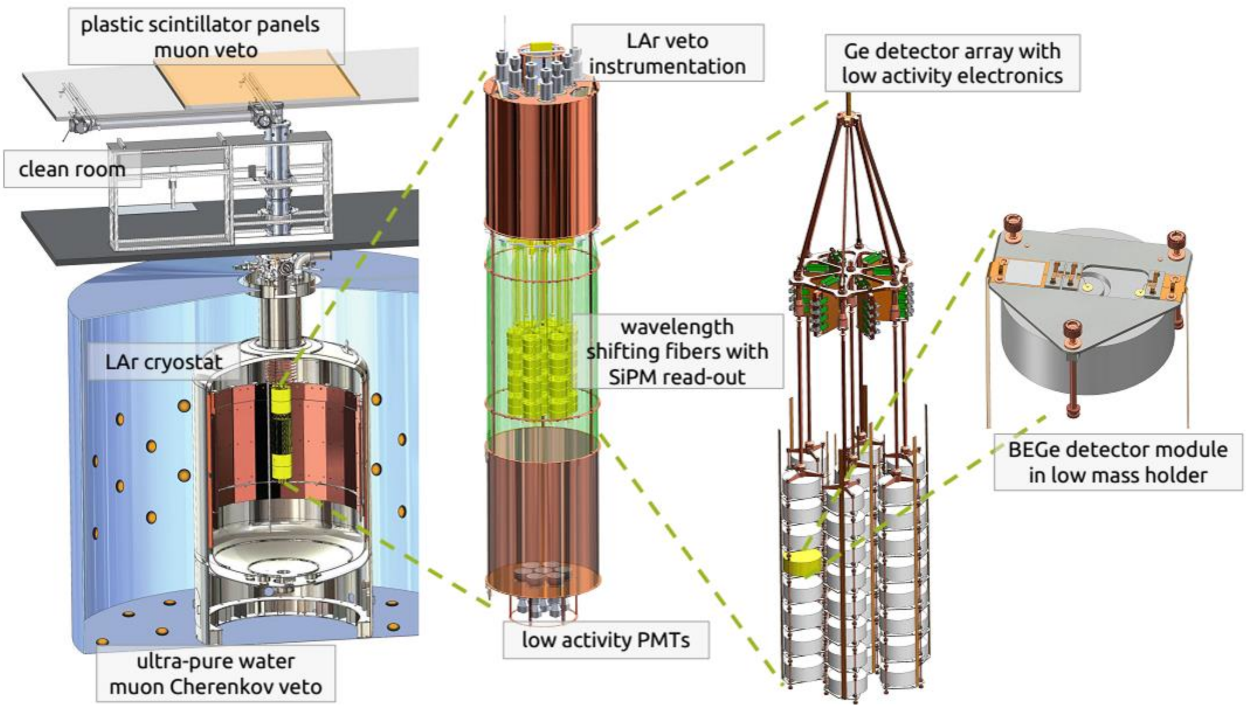


Fig. 6. Detector mounts, strings and LAr veto for the GERDA experiment.

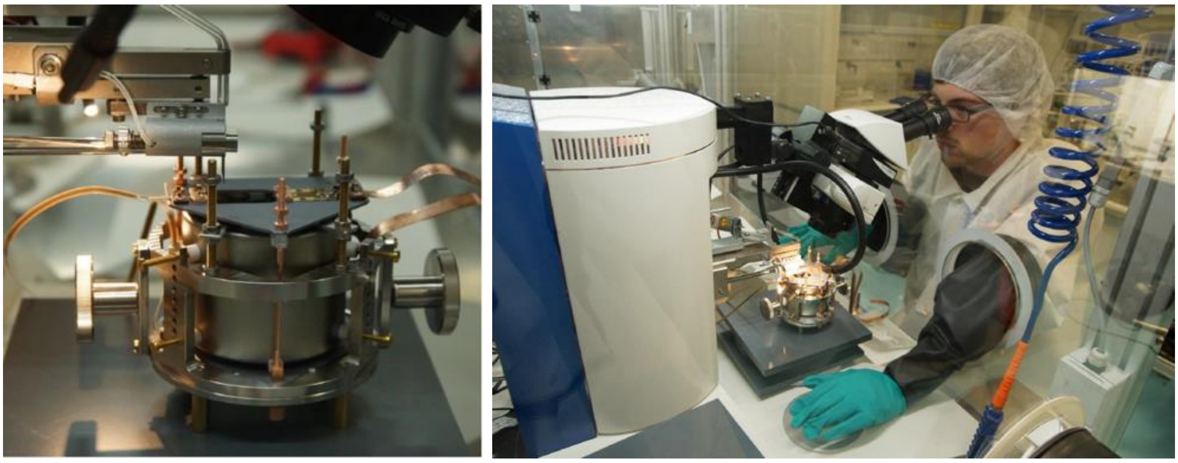


Fig. 7. Left: a detector mount for the GERDA experiment in a protective assembly frame. Right: the wirebond machine used to terminate to the detector for signal and HV.

Fig. 8. The GERDA string building process.

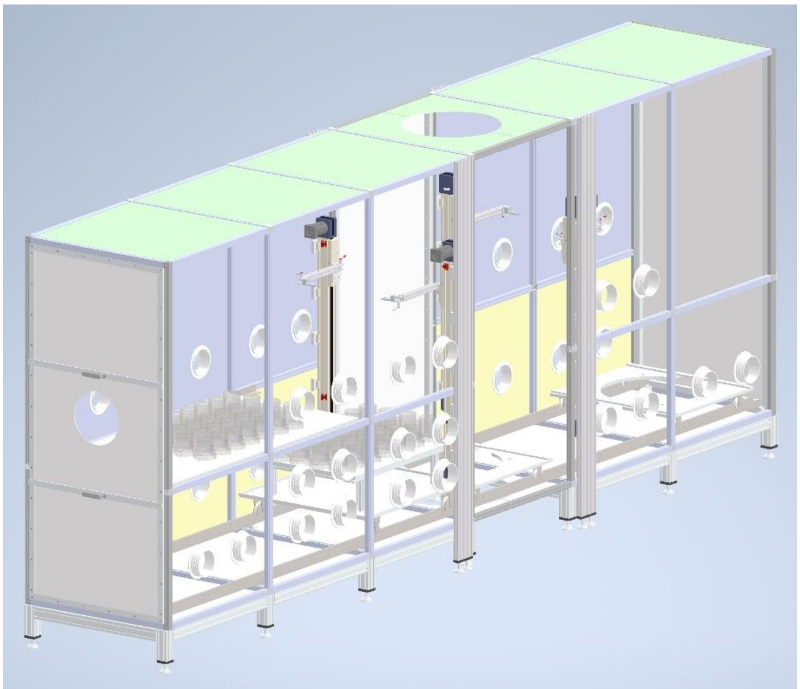


Fig. 9. Design of the glove box for LEGEND-200.

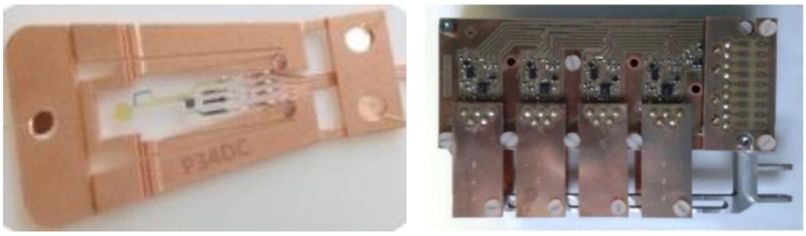


Fig. 10. Photos of Majorana low-mass front-end mounted on an electroformed copper clip (left) and GERDA Phase II charge-sensitive preamplifier (right).

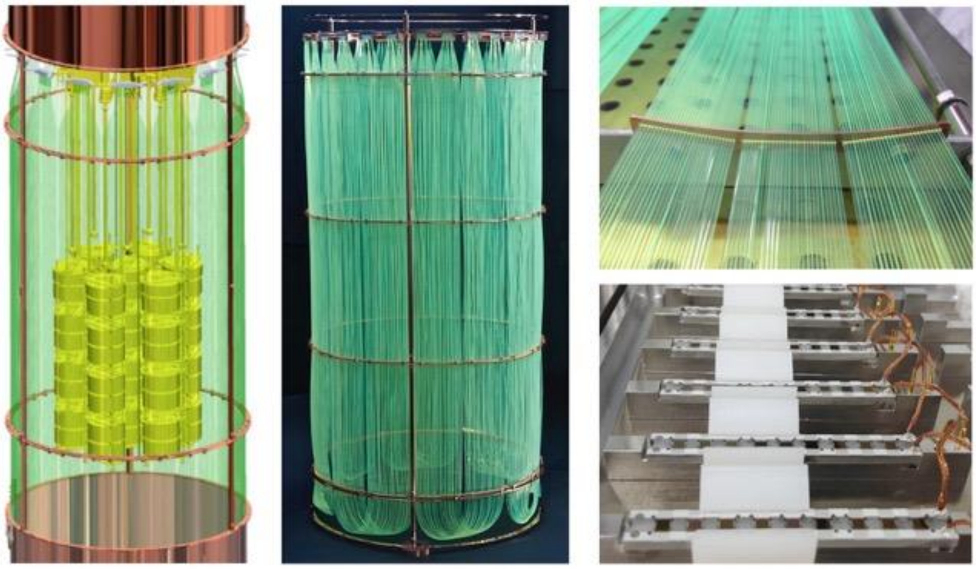


Fig. 11. Wavelength shifting (WLS) fiber shroud with SiPM readout of GERDA. Left: artist's view with germanium detector array; middle/right top: photo of WLS shroud during production; right bottom: SiPMs in die mounted on mirco-machined fused quartz substrates. All materials are selected and screened for their intrinsic radio purity.

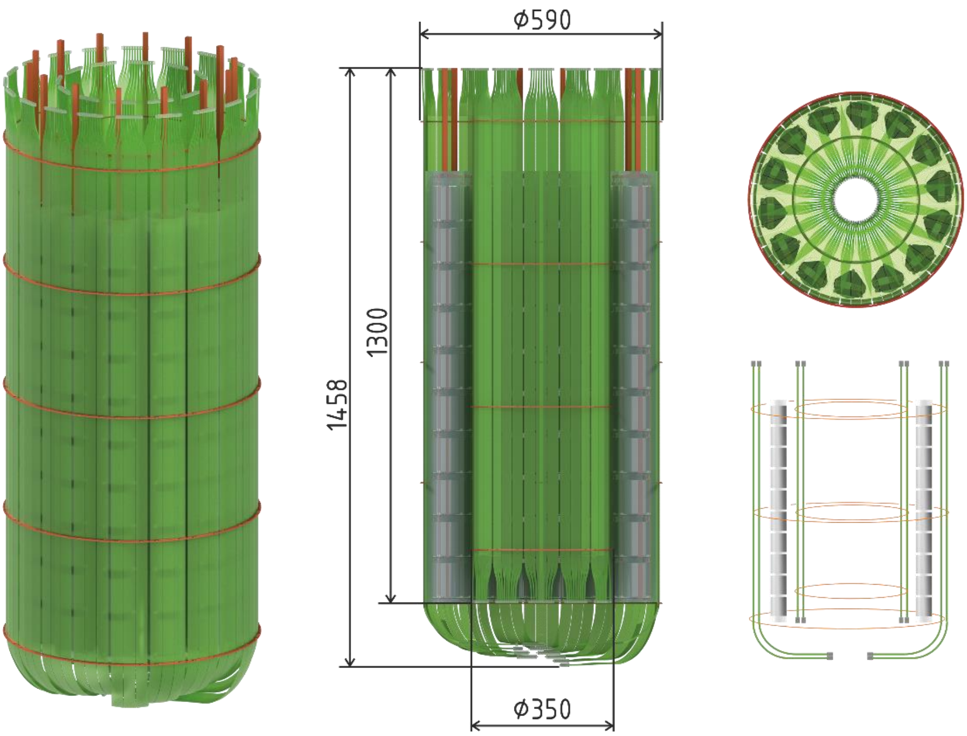


Fig. 12. Latest design of LEGEND-200 LAr veto system, developed by JINR and TUM specialists.

Fig. 13. Photo of GERDA Phase II detector array. Each of the seven strings is enclosed by a transparent mini-shroud.

Table 3. Legend-200 ^{76}Ge inventory.

Source	Mass (kg)	Salvage yield	Fabrication yield	Estimated detector mass (kg)
Re-purposed detectors	77	1.00	1.00	77
Recycle from previous detector production	16	0.80	0.75	9.6
Recycle from existing semi-coax detectors	18	0.85	0.75	11.4
Purchased or funded fresh material	120	1.00	0.75	90
Total	231			188

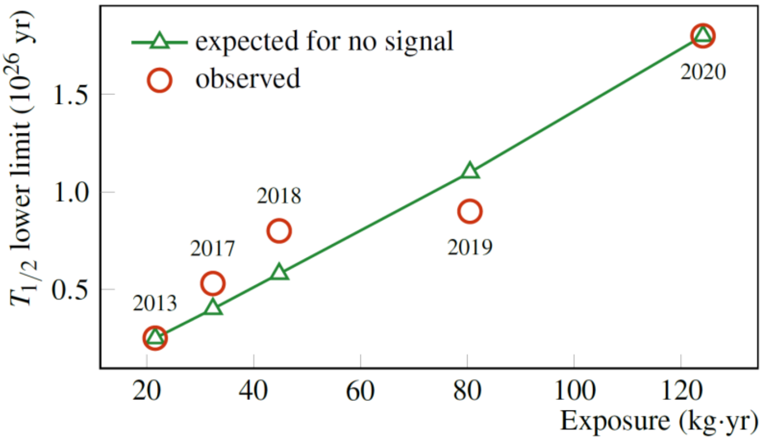


Fig. 14. Increase of sensitivity with exposure measured in the GERDA experiment.

Form No. 26

Schedule proposal and resources required for the implementation of the Project GERDA (LEGEND)

<table>
<tr><td colspan="3" rowspan="2">Expenditures, resources, financing sources</td><td rowspan="2">Costs (k$)
Resource requirements</td><td colspan="3">Proposals of the Laboratory on the distribution of finances and resources</td></tr>
<tr><td>1st year</td><td>2nd year</td><td>3rd year</td></tr>
<tr><td colspan="2" rowspan="3">Expenditures</td><td>1. R&D of ultrapure materials
2. Procurement of ^{76}Ge detectors
3. R&D of active veto systems
4. R&D on Ge detectors
5. R&D of ^{42}Ar/^{42}K background mitigation</td><td>30
150
30
140
30</td><td>10
50
10
60
10</td><td>10
50
10
20
10</td><td>10
50
10
60
10</td></tr>
<tr><td>Construction/repair of premises</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Materials:
1. Enriched ^{76}Ge
2. Scintillating and clean materials
3. Chemicals for Ge detectors</td><td>150
45
6</td><td>50
15
2</td><td>50
15
2</td><td>50
15
2</td></tr>
<tr><td>Required resources</td><td>Standard hour</td><td>Resources of
– Laboratory design bureau;
– JINR Experimental Workshop;
– Laboratory experimental facilities division;
– accelerator;
– computer.
Operating costs.</td><td>300
600</td><td>100
200</td><td>100
200</td><td>100
200</td></tr>
<tr><td rowspan="2">Financing sources</td><td>Budgetary resources</td><td>Budget expenditures including foreign-currency resources.</td><td>581</td><td>207</td><td>167</td><td>207</td></tr>
<tr><td>External resources</td><td>Contributions by collaborators.
Grants.
Contributions by sponsors.
Contracts.
Other financial resources, etc.</td><td>30</td><td>10</td><td>10</td><td>10</td></tr>
</table>

PROJECT LEADER

Form No. 29

Estimated expenditures for the Project GERDA (LEGEND): searching for neutrinoless double beta decay of Ge-76

	Expenditure items	Full cost	1st year	2nd year	3rd year
	Direct expenses for the Project				
1.	Accelerator, reactor	h			
2.	Computers	h			
3.	Computer connection	6 k$	2	2	2
4.	Design bureau	standard hour	100	100	100
5.	Experimental Workshop	standard hour	200	200	200
6.	Materials	201 k$	67	67	67
7.	Equipment	380 k$	140	100	140
8.	Construction/repair of premises	k$			
9.	Payments for agreement-based research	k$			
10.	Travel allowance, including:	150 k$			
	a) non-rouble zone countries		30	30	30
	b) rouble zone countries				
	c) protocol-based		20	20	20
	Total direct expenses	737	259	219	259

PROJECT LEADER

LABORATORY DIRECTOR

LABORATORY CHIEF ENGINEER-ECONOMIST