Form No. 24

GERDA ("G&M") PROJECT: SEARCHING FOR NEUTRINOLESS DOUBLE BETA DECAY OF GE-76

GERDA (“G&M”)

03-2-1100-2010/2018

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PROJECT ENDORSEMENT LIST

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03-2-1100-2010/2018

K.N.GUSEV

APPROVED BY JINR DIRECTOR	SIGNATURE	DATE

ENDORSED BY

JINR VICE-DIRECTOR	SIGNATURE	DATE
CHIEF SCIENTIFIC SECRETARY	SIGNATURE	DATE
CHIEF ENGINEER	SIGNATURE	DATE
HEAD OF SCIENCE ORGANIZATION DEPARTMENT	SIGNATURE	DATE
LABORATORY DIRECTOR	SIGNATURE	DATE
LABORATORY CHIEF ENGINEER	SIGNATURE	DATE
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PROJECT DEPUTY LEADERS	SIGNATURE	DATE

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RESPECTIVE PAC	SIGNATURE	DATE

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Abstract

The GERDA experiment is designed to search for neutrinoless double beta (0νββ) decay of ^{76}Ge. GERDA operates with bare germanium detectors (enriched in ^{76}Ge) directly immersed in liquid argon (LAr). First phase of the experiment (GERDA Phase I) started in 2010 and has been completed in 2013. The new limit on the half-life of ^{76}Ge > 2.1 x 10^{25} years has been set.

In 2014-2015 years the upgrade of GERDA experiment to the second phase were being performed. In GERDA Phase II detector mass is doubled by adding novel germanium detectors with improved energy resolution and pulse shape discrimination capability. Moreover, in Phase II the LAr is instrumented to readout liquid argon scintillations for vetoing background events. As the result, the background level is reduced down to the unprecedented value of 10^{-3} counts keV^{-1} kg^{-1} yr^{-1}. Thus an average background less than 1 count expected in the ROI up to the design exposure of 100 kg yr (in ~2019). This implies that GERDA is the first background-free 0νββ experiment.

GERDA Phase II data taking has been started in December 2015. In June 2016, data accumulated during first 5 months were unblinded for analysis. The new limit on the 0νββ decay half-life > 5.3 x 10^{25} years has been derived. This result has been published in Nature. In 2017, new set of data collected so far has been unblinded. The world best half-life sensitivity of 5.8 x 10^{25} years has been achieved and improved limit > 8.0 x 10^{25} years has been set. The projected GERDA sensitivity exceeds 10^{26} years.

At the same time, the R&D on the next generation ton-scale ^{76}Ge experiment LEGEND is ongoing. This project will have two phases. The first one plans to operate up to 200 kg of enriched detectors in the modified GERDA setup.

The GERDA collaboration consists of more than 100 physicists from 16 institutions of six countries. JINR scientists are playing significant roles in all key parts of the project. DLNP JINR was responsible for design, production, testing and installation of plastic muon veto system. JINR specialists actively participated in the development of LAr instrumentation. Physicists from our institute are strongly involved in the analysis of GERDA data and play the central and leading roles in the core of GERDA experiment – operations with bare germanium detectors.

The requested financing for completion of the project is 621 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 GERDA (GERmanium Detector Array) project designed to search for neutrinoless double beta decay of ^{76}Ge. GERDA employs semiconductor diodes made from Ge enriched in ^{76}Ge so a detector acts also as a source. In GERDA for the first time ever detectors are directly immersed in liquid argon that works as a cooling medium and simultaneously as an additional 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 ROI close to decay energy. GERDA Phase II is the first background free search for $0\nu\beta\beta$ decay because of achieved unique background level of 10^{-3} counts keV^{-1} kg^{-1} yr^{-1}. It will allow GERDA to reach planned sensitivity of > 10^{26} years already in 2019. Building on the experience with the background reduction technique, the next generation project LEGEND will be advanced. The experiment is foreseen to proceed in at least two phases. The first phase plans to operate up to 200 kg of enriched Ge and to reach the sensitivity of 10^{27} years, the second phase – 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:

2018-2019: The upgrade of the GERDA experiment by adding novel enriched detectors and exchanging of the existing liquid argon veto by improved version. Achieving of design sensitivity of 10^{26} years.

2019-2020: Reaching of planned GERDA exposure of 100 kg yr. Preparation of the first phase of next generation experiment LEGEND (procurement of enriched ^{76}Ge, production and testing of new Ge detectors, R&D of low background materials and electronics).

2020-2021: Completion of the GERDA experiment, publication of results. Modification of GERDA cryostat for LEGEND Phase I. Integration and start data taking of the LEGEND experiment.

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 information about electron tracks. Today there many projects aiming to look for neutrinoless double beta decay and it is nearly impossible to mention all of them here. Hence, in the following only most sensitive experiments will be mentioned. 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.

Until recently 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 $> 1.9 \times 10^{25}$ and $> 1.6 \times 10^{25}$ 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. Until a few years ago, the claim has not been scrutinized. However, the results of recent sensitive experiments like GERDA Phase I [3] and KamLAND-Zen [4] have strongly disfavored this claim.

Actual most stringent half-life limits are $> 1.07 \times 10^{26}$ years for ^{136}Xe [4] (KamLAND-Zen, half-life sensitivity of the experiment 5.6×10^{25} years) and for ^{76}Ge $> 8.0 \times 10^{25}$ years (GERDA Phase II [5, 6], sensitivity: 5.8×10^{25} years). The last result has been achieved in 2017 and presented at several conferences including TAUP 2017. It has to be noted, that GERDA half-life sensitivity exceeds KamLAND-Zen despite of the fact that in GERDA Phase II an order of magnitude less mass of 0νββ decay isotope is being used.

Last few years became very exciting in the field of double beta researches. Two new abovementioned half-life limits have been acquired, data taking have been started in CUORE [7] and MAJORANA [8] experiments. The new Phase of EXO-200 [9] has begun. The SuperNEMO Demonstrator [10] is also ready to start data taking at the end of 2017. Thus, one can expect to get very impressive results of 0νββ decay searches with different isotopes in the near future.

The progress of competing projects:

The MAJORANA Collaboration is constructing the DEMONSTRATOR [8], an array of Ge detectors, to search for neutrinoless double-beta decay of ^{76}Ge. Despite of the fact that the isotope candidate is the same as in GERDA this experiment is using traditional approach to operate Ge detectors – they are mounted in vacuum cryostats made from ultrapure electroformed copper. Since the very beginning, there was a close connection between GERDA and MAJORANA projects with the ultimate goal to collaborate for a future tonne-scale ^{76}Ge 0νββ search. MAJORANA has designed a modular instrument composed of two cryostats, with each cryostat capable of housing over 20 kg of novel P-PC detectors. P-PC detectors were chosen after extensive R&D by the collaboration and each has a mass of about 0.6–1.0 kg. The baseline plan calls for 30 kg of the detectors to be built from Ge material enriched to 86% in ^{76}Ge and 10 kg fabricated from natural Ge (7.8% ^{76}Ge). The modular approach allows MAJORANA to assemble and optimize each cryostat independently, providing a fast deployment with minimum interference on already-operational detectors. Data taking with MAJORANA DEMONSTRATOR has been started in December 2015. Recent results of the experiment presented at the several conferences in 2017 show that MAJORANA DEMONSTRATOR managed to achieve similar to GERDA background index. This means that GERDA and MAJORANA both operate in background free regime. Therefore, a combined analysis will boost available exposure and thus sensitivity. Having two experiments of similar low background obtained by different methods opens the way for a more ambitious Ge experiment LEGEND, which will be joint G&M effort.

The Cryogenic Underground Laboratory for Rare Events ("CUORE") [7] is an experiment located at the Gran Sasso National Laboratory in Assergi, Italy. CUORE uses bolometers to search for 0νββ decay and other rare processes. The bolometers are ultra-cold tellurium dioxide (TeO_2) crystals containing the candidate 0νββ isotope ^{130}Te. Every time a tellurium nucleus decays or a particle interacts in the crystal, it releases a minute amount of energy (less than a few MeV), causing the temperature of the crystal to rise slightly. This rise in temperature is then converted into an electrical signal using temperature-dependent resistors (thermistors). For this temperature rise to be measurable, the baseline temperature of the crystals must be very low. CUORE uses ultra-cold cryogenic temperatures: a few thousandths of a degree above absolute zero. CUORE is the largest bolometric experiment ever built. The detector consists of 988 TeO_2 bolometers for a total mass of 741 kg (206 kg of ^{130}Te). To cool these detectors, the CUORE cryostat creates the coldest cubic meter in the known universe. The experiment has completed the installation on August 2016 and has reached its operating temperature on January 2017. The latest CUORE results are following: the median statistical sensitivity is 7.0×10^{24} years, a lower limit on the decay half-life of ^{130}Te > 1.3×10^{25} years or, combining this result with those of two earlier experiments, Cuoricino and CUORE-0, > 1.5×10^{25} years.

EXO-200 [9] is a prototype to develop techniques for working with liquid xenon in a time projection chamber (TPC). One possibility for tonne-scale EXO is a liquid TPC, so familiarity with EXO-200 technologies will contribute to the design of tonne-scale EXO. Additionally, EXO-200 provides a testing ground for developing and procuring extremely radiopure materials and removing backgrounds. EXO-200 has provided fundamental measurement of the double beta decay of ^{136}Xe and improved limit on the rate of 0νββ decay. It is using 200 kg of liquid xenon enriched to 80% ^{136}Xe. The first phase of the project has been successfully finished; a half-life limit of 1.1×10^{25} years has been set. The obtained half-life sensitivity is 1.9×10^{25} years. New round of data taking has been started in 2016.

The KamLAND-Zen [4] detector consists of 13 tons of Xe-loaded liquid scintillator (Xe-LS) contained in a 3.08-m-diameter spherical inner balloon (IB) located at the center of the KamLAND detector. The IB is constructed from 25-μm-thick transparent nylon film and is surrounded by 1 kton of liquid scintillator (LS) contained in a 13-m-diameter spherical outer balloon (OB). The outer LS acts as an active shield. The scintillation photons are viewed by 1,879 photomultiplier tubes (PMTs) mounted on the inner surface of the containment vessel. The isotopic abundances in the enriched xenon were measured to be (90.77±0.08)% ^{136}Xe. The two electrons emitted from ^{136}Xe double beta decay produce scintillation light and their summed energy is observed. Combining the results from the first and second phase they published a lower limit for the 0νββ decay half-life of ^{136}Xe > 1.07×10^{26} years with the half-life sensitivity of 5.6×10^{25} years. It should be mentioned, that as evaluated by an ensemble of toy Monte Carlo realizations of the experiment, the chance to have a stronger limit is 12% only whereas in GERDA Phase II is 30%. KamLAND-Zen collaboration plans to increase the volume of detector and at the same time decrease the background of the experiment.

References

1. «Latest results from the Heidelberg-Moscow double beta decay experiment», Eur.Phys.J. A12 (2001) 147.

2. «The IGEX ^{76}Ge neutrinoless double beta decay experiment: Prospects for next generation experiments», Phys.Rev. D65 (2002) 092007.

3. «Results on Neutrinoless Double-β Decay of ^{76}Ge from Phase I of the GERDA Experiment», Phys. Rev. Lett 111 (2013) 122503.

4. «Search for Majorana Neutrinos Near the Inverted Mass Hierarchy Region with KamLAND-Zen», Phys. Rev. Lett. 117 (2016) 082503.

5. «Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA», Nature 544 (2017) 47.

6. «Searching for neutrinoless double beta decay with GERDA», to be published in the proceeding of TAUP 2017, arXiv:1710.07776.

7. «First Results from CUORE: A Search for Lepton Number Violation via $0\nu\beta\beta$ Decay of ^{130}Te», arXiv:1710.07988.

8. «The MAJORANA DEMONSTRATOR Neutrinoless Double-Beta Decay Experiment», Adv. in High Energy Phys. (2014) 365432.

9. «Search for Majorana neutrinos with the first two years of EXO-200 data», Nature 510 (2014) 229.

10. «SuperNEMO – a new generation of underground experiments for double beta-decay investigations», Proceeding of 14th Vienna Conference on Instrumentation 2016.

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 0νββ decay to be larger than 10^{25} years, and hence its detection requires the utmost suppression of any kind of background.

The GERDA collaboration searches for 0νββ decay of ^{76}Ge, $^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^-$. The experimental facility is located at the Laboratori Nazionali del Gran Sasso of INFN in Italy. It is placed underground below a rock overburden of about 3500 m water equivalent that reduces the muon flux to ~1.25/(m^2 h). GERDA uses high purity germanium detectors enriched in ^{76}Ge, which are arranged in strings inside a cryostat filled with 64 m^3 of liquid argon (Fig. 1a). The liquid argon (LAr) acts both as cooling and shielding medium. 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 MΩ) 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 GERDA 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. GERDA has been proceeded in two phases.

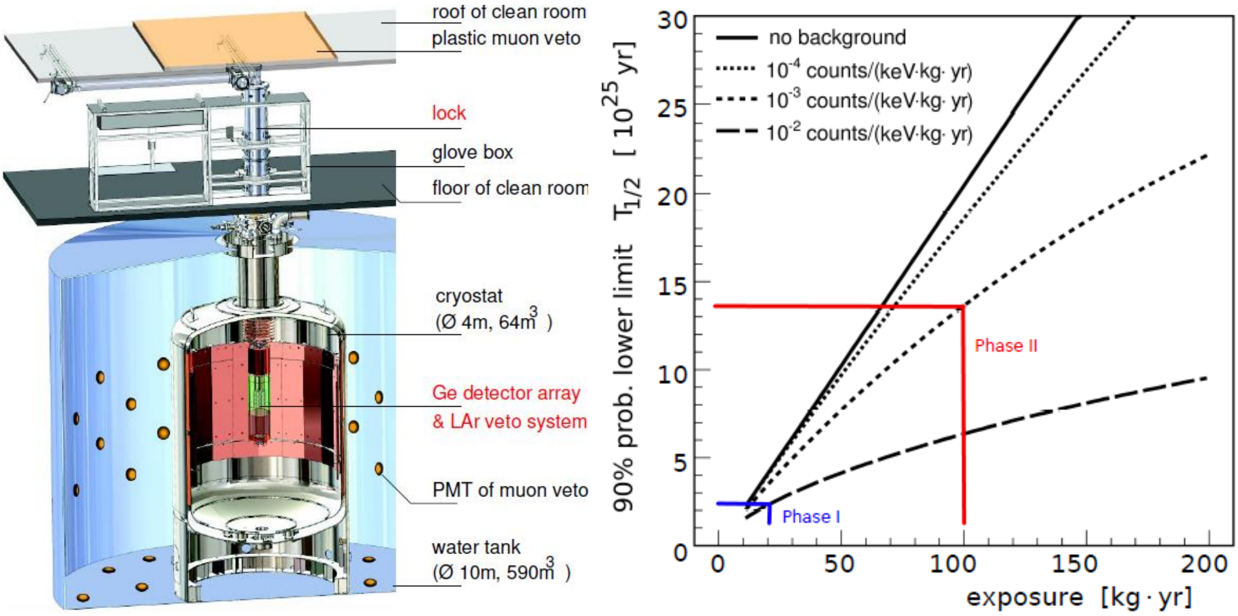

Fig 1. a) Left: GERDA setup. The new Phase II components are marked in red; b) right: estimated sensitivity of the GERDA experiment as a function of exposure for various background indices. The scenarios for GERDA Phase I and II are indicated.

The detailed description of Phase I is presented in [1], here it is only the short overview. The Phase I detector array, 4 strings in total, consisted of 8 enriched semi-coaxial Ge detectors with a total mass of 15.6 kg and 3 semi-coaxial Ge detectors from low-background natural material. The one string of natural Ge detectors was replaced in

July 2012 by 5 Broad Energy Germanium (BEGe) detectors with a total mass of 3.6 kg; these diodes used as prototypes for Phase II.

The physics results of Phase I [2] were based on an exposure of 21.6 kg yr. The energy scale was monitored by (bi) weekly calibrations with ^{228}Th sources. In the region of interest (ROI) around $Q_{\beta\beta}$ = 2039 keV, the average energy resolution of the enriched semi-coaxial and BEGe detectors was 4.8(2) keV and 3.2(2) keV in terms of FWHM, respectively. A background index (BI) of about 10^{-2} counts keV^{-1} kg^{-1} yr^{-1} was achieved, one order of magnitude lower than in the best previous 0νββ decay experiments. No signal was found for 0νββ decay, and a new 90% confidence level (CL) limit of $T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ years was derived (median sensitivity 2.4×10^{25} years) that strongly disfavored a previous claim of observation. Further Phase I results include an significantly improved half-life for 2νββ decay of ^{76}Ge and improved limits for Majoron decay modes [3], as well as 2νββ decays of ^{76}Ge into excited states of ^{76}Se [4].

Phase II of GERDA was aimed to improve the sensitivity on the half-life of 0νββ decay by about one order of magnitude. At the end of Phase I Gerda had left the background-free regime where sensitivity scales linearly with exposure, the product of detector mass and measurement period, and entered the background i.e. statistical fluctuation limited scenario where it scales approximately with the square root of exposure. Hence, an efficient upgrade required to re-enter the background-free regime that means to not only increase exposure (detector mass) but also to reduce correspondingly the background (Fig. 1b). Improvements of the already excellent resolution are possible but limited to a factor of about two for the given technology. So, GERDA has to achieve a BI of 10^{-3} counts keV^{-1} kg^{-1} yr^{-1} in Phase II to reach the expected sensitivity more 10^{26} years at an exposure of about 100 kg yr (Fig. 1b).

The analysis of the Phase I data showed that most background events were due to radioactive isotopes in materials close to the detectors [5]. The obvious consequence was to further reduce the amount of such materials and/or to replace it by material of better radiopurity. The major BI reduction had to come, nevertheless from a largely improved discrimination of background events taking full advantage of their different event topology. While 0νββ events normally deposit energy in a small volume (a few mm^3) of the detector, the background events can also deposit energy in the LAr around the detector, at the detector surface, or scatter at several locations in the detector. Hence, events can be identified as background by coincident scintillation light in the LAr, by coincidences within the detector array and/or by the analysis of the signal pulse shape. GERDA has taken an advantage of all these options in Phase II. The additional batch of 20 kg of enriched Ge detectors consists of diodes of the novel BEGe type shows superior pulse shape discrimination (PSD) [6] and energy resolution. A larger and more densely packed detector array provides enhanced efficiency for detector-detector (anti-) coincidences. The most important feature of Phase II is the LAr instrumentation surrounding the detector array to readout of scintillation light creating an effective active LAr veto system. The usefulness of this approach has been fully proven by the first results obtained with the upgraded GERDA experiment. Started in December 2015, the Phase II physics run reached in June 2016 the exposure of 10.8 kg yr. These accumulated data have been already sufficient to ensure that the projected background level of 10^{-3} counts keV^{-1} kg^{-1} yr^{-1} has been achieved and, to set in combination with the Phase I data a new lower limit for the 0νββ decay half-life of ^{76}Ge of $> 5.3 \times 10^{25}$ years at 90% CL [7]. The modifications of the GERDA experimental setup for Phase II including the new detector components and their performance are described in the following.

The GERDA Phase II detector array consists of 40 detectors mounted in 7 strings. There are three groups of detectors: the newly produced novel BEGe detectors, the semi-coaxial ANG and RG detectors, and the semi-coaxial GTF detectors [1]. The first two groups of the detectors include the diodes made of germanium enriched in ^{76}Ge (^{enr}BEGe,

^{enr}Coax). The last group are made of germanium with natural isotopic abundance (^{nat}Coax). The properties of the individual detectors are listed in the Appendix (Table 1).

The optimization of the detector holders for Phase II was needed to reduce the amount of construction materials and/or to improve their radiopurity. Fig. 2a demonstrates the baseline Phase II BEGe detector module, which consists of 2 BEGe Ge diodes that are mounted back-to-back. The new design uses 25 μm Al wire bonds to contact to the detector. This allowed to replace a main part of the Phase I copper and PTFE material (and PTFE) by monocrystalline silicon which is intrinsically extremely radio-pure. The silicon plate fixes the position of the vertical copper bars that take the weight of the Ge detectors and provides the substrate where signal and high voltage cables are attached with bronze clamps. The top and bottom of the copper bars have bolts and nuts to put together neighboring detector modules.

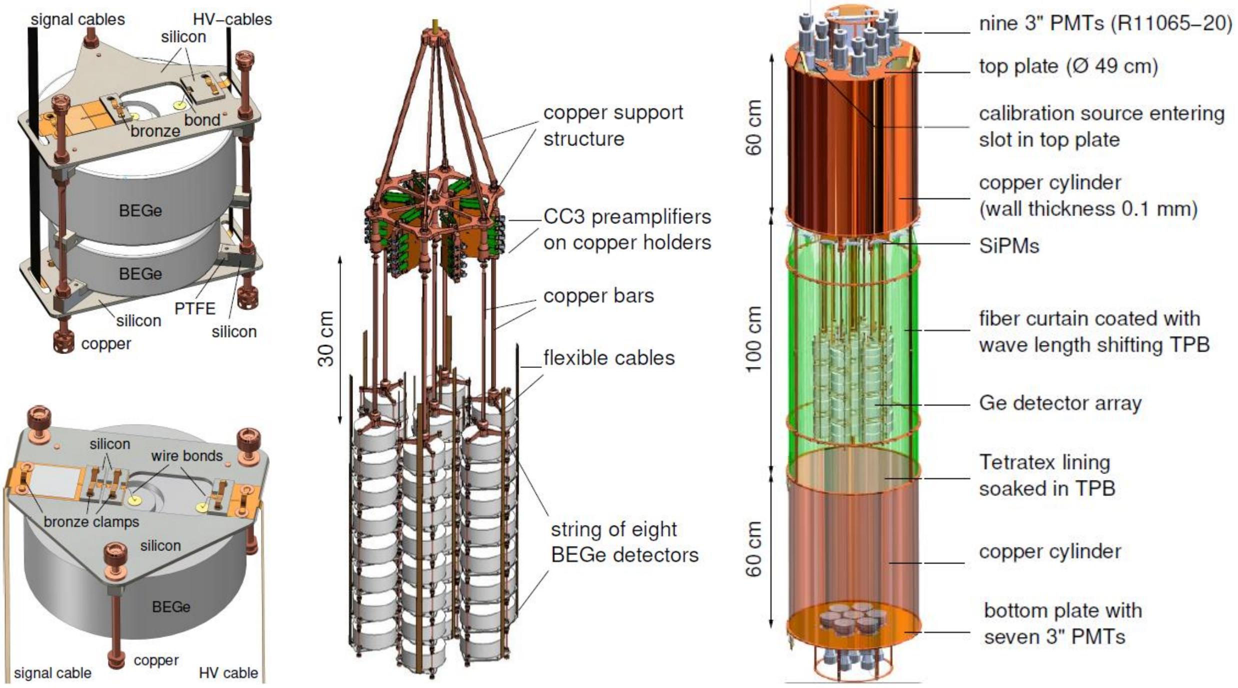

Fig. 2. a) Left: alternative mounts for pairs of and single BEGe detectors; b) center: view of the seven detector strings with preamplifiers; c) right: the LAr veto system with the Ge detector array inside.

The serious advantage of the new detector holder is that the detector mounting procedure becomes easier and safer than in Phase I, since all mounting steps except bonding are being done without touching the very sensitive p^+ contact surface. Some detectors have been mounted and dismounted in Phase II holders several times without any deterioration of their performance. Bonding also solved the Phase I issue of irreproducible quality of HV contact. During commissioning for Phase II, unexpected problem with detector leakage currents (LC) showed up. The strong correlation between the orientation of BEGe detector and dark current has been found. Detectors with the groove looking upwards, the `top' detectors in the mount, were more affected than the `bottom' detectors (Fig. 2a) with the groove pointing downwards. In Phase I all detectors had been mounted with the groove facing down. The explanation of the problem can be the following: some microscopic particulates fell into the groove during the mounting procedure or during operation in the LAr and cause the LC. As the result, the concept of BEGe detectors pair was abandoned and single BEGe detectors were mounted in the single holders similar to the semi-coaxial detectors. This avoids having grooves faced up (Fig. 2a). By the start of the Phase II physics run, all problematic BEGe pair were disassembled and mounted in the new single holders. It is planned to exchange the holders of the 6 remaining BEGe pairs during possible GERDA upgrade in 2018-2019.

After mounting and bonding, every detector was tested for leakage current in the Gerda Germanium Detector Laboratory (GDL), which is also located underground at LNGS. All detectors that passed this test were integrated in the GERDA setup. However, about half of the diodes showed high leakage currents already in the GDL test bench. They were dismounted from their holders and sent to the producer for reprocessing. On return, they were mounted again in the holders, tested in GDL and added to GERDA at the final stage of integration.

The Ge detectors are connected to custom-produced preamplifiers, which are cryogenic, low radioactivity, 4-channel charge sensitive amplifier (Fig. 2b).

The Ge detector array together with the electronic front-end boards placed in about 30 cm distance from the detectors is demonstrated on Fig. 2b. The height of the array is 40 cm; its diameter is about 30 cm. There are 7 strings with 40 detectors in total. Six strings include either 8 BEGe or 3 semi-coaxial (enriched or natural) detectors. One string consists of 1 semi-coaxial and 6 BEGe detectors. A photo of the detector array is shown in Fig. 4 (see Appendix). Another figure in the Appendix demonstrates the detailed arrangement of all detectors (Fig. 5). Detectors labeled with blue are passivated. It should be noted that, contrary to Phase I experience, no leakage current increase has been found for neither passivated nor non-passivated diodes after about 2 years of operation. Detailed information about detector LC stability, energy and A/E resolutions can be also found in the Appendix (Fig. 6 and Fig. 7). It has to be noted that DLNP JINR physicists were strongly involved in all operations with bare Ge detectors from the very beginning until the final integration in the GERDA cryostat. The leader of JINR GERDA team is a head of integration task group of the Project. Recently the GERDA collaboration gave confidence to him to be the technical coordinator of the GERDA experiment.

The background due to ^{42}Ar is essential for GERDA. ^{42}Ar decays into ^{42}K, which is a β emitter with an endpoint energy of 3.5 MeV. A copper cylinder, called 'mini-shroud' (MS), enclosed the space around the detector string was used to reduce the ^{42}K background in Phase I [1]. The MS screens the electric field of the detector and creates a mechanical barrier, which prevents the collection of ^{42}K ions on the detector surface. However, the copper MS is not a solution for Phase II since the LAr is instrumented and scintillation light generated inside the copper MS would not be visible by the LAr veto. Therefore, it will significantly reduce the efficiency of LAr veto. Moreover, copper MS would not fit with the increased requirements to radiopurity in GERDA Phase II. That is why for Phase II a new MS made from ultrapure nylon was developed [8]. A photo of the detector array with each string enclosed by its individual transparent MS is shown in Fig. 4 of the Appendix. Such a nylon MS does not screen the electric field of the detectors like a copper one, but provides a physical barrier to stop the drift of ^{42}K ions to the detectors. The investigation and development of the background suppression methods were done at the low-background test facility LArGe [9] in GDL with strong and leading participation of JINR specialists.

The LAr veto of GERDA is a detector system designed to detect argon scintillation light close to the Ge detector array. It was developed from studies of scintillation light detection in LAr in the abovementioned test facility LArGe and silicon photomultipliers (SiPMs) coupled to wavelength shifting fibers for increasing light detection efficiency. A technical drawing depicting the complete LAr veto system is shown in Fig. 2c.

The muon veto system [10] was slightly upgraded during Phase II preparations. Since the lock has been replaced, the plastic muon veto system, provided by DLNP JINR, had to be removed from the roof of the clean room. This has been done by JINR team. After reinstallation, a broken amplifier of the plastic veto was replaced. By now the plastic veto works well without any deterioration of its performance.

Latest results:

The energy spectrum of Phase II exposure of BEGe detectors collected so far is presented at Fig. 3. The blinded region around the Q$_{\beta\beta}$ is marked by the vertical band. Up to 500 keV the spectrum is mainly consisting of ^{39}Ar events, up to 1.8 MeV by events from 2νββ decays of ^{76}Ge and Compton scattered events – mostly from the ^{40}K and ^{42}K γ lines. For the energies higher than 2.62 MeV the events come from α decays at the p^{+} electrode or at the detector groove – generally from ^{210}Po. The origin of the ^{40}K γ line is an electron capture therefore no energy left in the LAr and only PSD is effective to cut these events. The ^{42}K γ line comes from a β decay and up to 2 MeV are deposited in argon that allows the LAr veto to reject more than 80% of such events. At Q$_{\beta\beta}$ the spectrum consists of degraded α, ^{42}K decays at the detector surface and Compton scattered γ's from ^{214}Bi and ^{208}Tl decays. The background index for BEGe detectors, reported earlier, was based on a single event in the analysis window of 230 keV. Today is fully confirmed with a three times more exposure and equal to $1.0^{+0.6}_{-0.4} \times 10^{-3}$ counts keV^{-1} kg^{-1} yr^{-1}. 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.

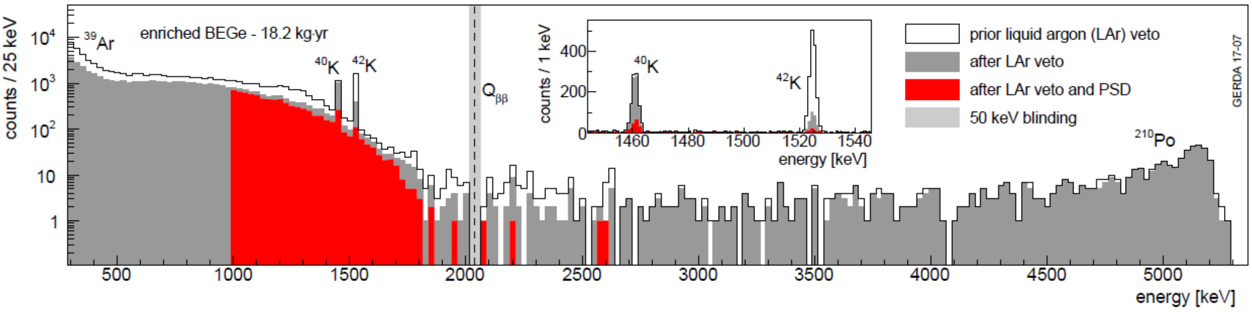

Fig.3. Energy spectra of Phase II BEGe detectors. On the inset the spectrum at the energy of the potassium lines is shown. The vertical grey line band shows the blinded region.

The total exposure used for the last analysis is 23.5 kg yr and 23.2 kg yr for Phase I and Phase II, respectively. No event close to Q$_{\beta\beta}$ has been found and a 90% C.L. lower limit of $T^{0\nu}_{1/2} > 8.0 \times 10^{25}$ years has been set for a frequentist analysis, with a median sensitivity of 5.8×10^{25} years. This is the best half-life sensitivity amongst all existing 0νββ experiments.

GERDA data taking is ongoing until the designed exposure of 100 kg yr will be achieved. It is planned to be reached in 2019-2020. Then the half-life sensitivity will be well above 1.0×10^{26} years. The sensitivity of GERDA can be additionally improved by reducing the background of the experiment and adding of novel enriched Ge detectors. Such an upgrade of GERDA is going to be performed in 2018-2019. It should include not only the increase of enriched isotope mass by adding of new enriched detectors but also the replacement of existing active liquid argon veto by improved version. DLNP JINR members will be strongly involved in all activity concerning the upgrade.

The GERDA experiment design sensitivity will not allow to get an information about neutrino mass hierarchy. In order to address this issue the new generation experiment LEGEND is being built. It is foreseen at least two phases of the project. The first phase will operate with ~ 200 kg of enriched isotope and the expected sensitivity will be 10^{27} years. The second phase will use 1000 kg and reach 10^{28} years respectively. This project will allow answering the question about neutrino mass hierarchy. The first phase of new experiment is going to use the existing GERDA infrastructure at LNGS. Our goal is to start data taking in the first phase of LEGEND in 2021. Scientists from JINR plan to actively participate or even take the lead in the key parts of this ambitious project.

GERDA (“G&M”) publications and talks

1. «The GERDA experiment for the search of $0\nu\beta\beta$ decay in ^{76}Ge», Eur. Phys. J. C 73 (2013) 2330.
2. «Results on Neutrinoless Double-β Decay of ^{76}Ge from Phase I of the GERDA Experiment», Phys. Rev. Lett 111 (2013) 122503.
3. «Results on $\beta\beta$ decay with emission of two neutrinos or Majorons in ^{76}Ge from GERDA Phase I», Eur. Phys. J. C 75 (2015) 416.
4. «$2\nu\beta\beta$ decay of ^{76}Ge into excited states with GERDA Phase I», J. Phys. G: Nucl. Part. Phys. 42 (2015) 115201.
5. «The background in the $0\nu\beta\beta$ experiment GERDA», Eur. Phys. J. C 74 (2014) 2764.
6. «Pulse shape discrimination for GERDA Phase I data», Eur. Phys. J. C 73 (2013) 2583.
7. «Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA», Nature 544 (2017) 47.
8. «Mitigation of ^{42}Ar/^{42}K background for the GERDA Phase II experiment», submitted to Eur. Phys. J. C, preprint: https://arxiv.org/abs/1708.00226.
9. «LArGe: active background suppression using argon scintillation for the Gerda $0\nu\beta\beta$-experiment», Eur. Phys. J. C 75 (2015) 506.
10. «The performance of the Muon Veto of the GERDA experiment», EPJC 76 (2016) 298.
11. «Status of the GERDA experiment: on the way to Phase II», K.Gusev at TAUP 2015, Torino, Italy
12. «Status of preparations for the Phase II of the GERDA experiment aimed for the $0\nu\beta\beta$ decay search», A.Lubashevskiy at PATRAS 2015, Zaragoza, Spain.
13. «First results from Phase II of the GERDA experiment», K.Gusev at INPC 2016, Adelaide, Australia.
14. «Neutrinoless double beta decay: First results of GERDA Phase II and the status of other experiments», A.Lubashevskiy at PASCOS 2016, Quy Nhon, Vietnam.
15. «Double Beta Decay Experiments», K.Gusev at ICSSNP 2016, Dubna, Russia.
16. «Double beta decay experiments and neutrino mass investigation: Past, Present and Future», A.Smolnikov at QUARKS 2016, Pushkin, Russia.
17. «From Baksan to worldwide experiments searching for neutrinoless double beta decay», A.Smolnikov at ICSSNP 2017, Nalchik, Russia.
18. «Neutrinoless double beta decay search with the "background free" GERDA experiment», A.Lubashevskiy at ICSSNP 2017, Nalchik, Russia.
19. «GERDA: first background free search for neutrinoless double beta decay», K.Gusev at ICNFP 2017, Crete, Greece.
20. «LEGEND: new opportunity to discover the neutrinoless double beta decay», K.Gusev at ICNFP 2017, Crete, Greece.

Estimation of human resources

K.N.Gusev – Project Leader (technical coordination of the GERDA experiment, project coordination at JINR, Ge detectors), 1.0 FTE
A.V.Lubashevskiy – Deputy Leader (analysis coordination, ultrapure materials, Ge detectors), 0.4 FTE.
D.R.Zinatulina – Deputy Leader (muon veto coordination, Ge detectors), 0.5 FTE
V.B.Brudanin – Participant (^{76}Ge procurement, ultrapure materials), 0.1 FTE
D.Borowicz – Participant (Ge detectors), 0.8 FTE
V.G.Egorov – Participant (active veto systems), 0.1 FTE
M.V.Fomina – Participant (active veto systems), 0.2 FTE
A.A.Klimenko – Participant (analysis), 0.5 FTE
O.I.Kochetov – Participant (ultrapure materials, active veto systems), 0.1 FTE
I.B.Nemchenok – Participant (ultrapure materials, active veto systems), 0.2 FTE
S.M.Nepochatich – Participant (Ge detectors, analysis), 1.0 FTE
N.S.Rumyantseva – Participant (Ge detectors, analysis), 0.7 FTE
V.G.Sandukovsky – Participant (Ge detectors), 0.5 FTE
E.A.Shevchik – Participant (active veto systems), 0.2 FTE
M.V.Shirchenko – Participant (active veto systems, Ge detectors), 0.3 FTE
A.A.Smolnikov – Participant (active veto systems, ultrapure materials, analysis), 0.8 FTE
I.V.Zhitnikov – Participant (active veto systems, Ge detectors), 0.2 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 can try to estimate benefits and risks of the future upgrade of the GERDA experiment by adding novel enriched Ge detectors and replacement of the existing LAr veto system by improved version. In addition, all signal and high voltage cables have to be exchanged by new ones with better radiopurity. The upgrade will possibly happen in 2018-2019 and take about 3 months. All Ge detectors and LAr veto system have to be fully dismounted and mounted again.

Benefits:

- Reaching of the planned exposure of 100 kg yr earlier than without upgrade. This will improve the competitive ability of GERDA compared with other 0νββ decay experiments.
- Showing the possibility to additionally improve the background index. The background might go down by ~30% assuming that Th/Ra background now is dominating in the cables. The sensitivity for a discovery will be also increase because of improving the background index.
- Testing of novel detectors that look as good candidates for tonne-scale experiment in GERDA environment, which is very close to the first phase of the LEGEND project.
- Availability of most personnel who performed final integration of the GERDA experiment (detector handling, mounting, bonding; LAr veto mounting; usage of the lock system).
- The improvement of the background needed for the first phase of LEGEND relative to GERDA will be not a factor of 3 but only a factor of 2.
- Earlier start of cryostat preparation for the first phase of the LEGEND experiment.
- Possibility to show the robustness and reproducibility of GERDA approach which can strongly affect the decisions concerning the second phase of the LEGEND project with ~1 ton of ^{76}Ge.

Risks:

- Possibility to delay the completion of the GERDA experiment due to unexpected problems arise during upgrade. However, many cooling/warming cycles and mounting/dismounting procedures during Phase I and Phase II have been performed. So based on our experience the risk of ‘failure’ of the upgrade is low.
- The unsuccessful upgrade will create a bad impression for physic society that will significantly influence on all stages of LEGEND experiment.

Appendix

Table 1. Main parameters of all detectors used in Gerda Phase II. The GD, ANG and RG detectors are made of germanium enriched in ^{76}Ge from 85.5% to 88.3 %. The three GTF detectors are made from natural germanium. The operational voltages recommended by the manufacturer are quoted. A ‘y’ marks in column 4 the detectors with a passivation layer (PL) in the groove. The position number in a given string increases from top to bottom. The active masses of the newly produced BEGe detectors include a correction that considers a full charge collection depth growth occurred during storage at room temperature in the three years before deployment in GERDA. In the last column, the full energy peak detector efficiencies for the 0νββ decay in ^{76}Ge are quoted.

Nr.	Detector	V_{rec} [kV]	With PL	String & Position	f_{Ge76}	M_{diode} [g]	$M_{av}\ {}^{+ucorr+corr}_{-ucorr-corr}$ [g]	$\epsilon_{fep} \pm ucorr \pm corr$
13	GD32A	3.0		III-2	0.877 ± 0.013	458	404^{+10+4}_{-10-2}	0.888 ± 0.001 ± 0.002
12	GD32B	4.0		III-1	0.877 ± 0.013	716	632^{+10+4}_{-10-2}	0.900 ± 0.001 ± 0.002
14	GD32C	4.0		III-3	0.877 ± 0.013	743	665^{+10+4}_{-10-2}	0.901 ± 0.001 ± 0.002
34	GD32D	4.0		VI-4	0.877 ± 0.013	720	657^{+10+5}_{-10-2}	0.900 ± 0.001 ± 0.002
24	GD35A	4.0		IV-5	0.877 ± 0.013	768	693^{+13+3}_{-13-2}	0.904 ± 0.001 ± 0.002
1	GD35B	4.0		I-1	0.877 ± 0.013	810	740^{+11+5}_{-11-2}	0.902 ± 0.001 ± 0.002
19	GD35C	3.5	y	IV-0	0.877 ± 0.013	634	572^{+9+4}_{-9-3}	0.893 ± 0.001 ± 0.002
4	GD61A	4.5	y	I-4	0.877 ± 0.013	731	652^{+12+4}_{-11-3}	0.902 ± 0.001 ± 0.002
26	GD61B	4.0	y	IV-7	0.877 ± 0.013	751	666^{+12+5}_{-12-2}	0.899 ± 0.001 ± 0.002
16	GD61C	4.0		III-5	0.877 ± 0.013	634	562^{+10+5}_{-10-3}	0.892 ± 0.001 ± 0.002
17	GD76B	3.5	y	III-6	0.877 ± 0.013	384	326^{+7+3}_{-7-2}	0.883 ± 0.001 ± 0.002
20	GD76C	3.5	y	IV-1	0.877 ± 0.013	824	723^{+12+5}_{-12-2}	0.902 ± 0.001 ± 0.002
32	GD79B	3.5		VI-2	0.877 ± 0.013	736	648^{+13+5}_{-13-2}	0.897 ± 0.001 ± 0.002
23	GD79C	3.5		IV-4	0.877 ± 0.013	812	713^{+11+5}_{-11-2}	0.900 ± 0.001 ± 0.002
35	GD89A	4.0		VI-5	0.877 ± 0.013	524	462^{+10+3}_{-9-2}	0.893 ± 0.001 ± 0.002
5	GD89B	3.5	y	I-5	0.877 ± 0.013	620	533^{+12+4}_{-12-2}	0.890 ± 0.001 ± 0.002
15	GD89C	4.0	y	III-4	0.877 ± 0.013	595	520^{+12+5}_{-11-2}	0.889 ± 0.001 ± 0.002
21	GD89D	4.0		IV-2	0.877 ± 0.013	526	454^{+9+5}_{-9-2}	0.884 ± 0.001 ± 0.002
0	GD91A	3.5		I-0	0.877 ± 0.013	627	557^{+10+3}_{-11-2}	0.898 ± 0.001 ± 0.002
25	GD91B	3.5		IV-6	0.877 ± 0.013	650	578^{+10+5}_{-10-2}	0.897 ± 0.001 ± 0.002
7	GD91C	4.0	y	I-7	0.877 ± 0.013	627	556^{+11+4}_{-11-2}	0.896 ± 0.001 ± 0.002
33	GD91D	4.5		VI-3	0.877 ± 0.013	693	615^{+12+5}_{-12-2}	0.899 ± 0.001 ± 0.002
30	GD00A	2.5	y	VI-0	0.877 ± 0.013	496	439^{+8+3}_{-9-2}	0.888 ± 0.001 ± 0.002
3	GD00B	3.5		I-3	0.877 ± 0.013	697	613^{+12+5}_{-12-2}	0.897 ± 0.001 ± 0.002
18	GD00C	3.5	y	III-7	0.877 ± 0.013	815	727^{+14+5}_{-13-2}	0.903 ± 0.001 ± 0.002
22	GD00D	3.5	y	IV-3	0.877 ± 0.013	813	723^{+13+5}_{-13-2}	0.902 ± 0.001 ± 0.002
11	GD02A	2.5	y	III-0	0.877 ± 0.013	545	488^{+8+3}_{-8-2}	0.893 ± 0.001 ± 0.002
2	GD02B	3.0		I-2	0.877 ± 0.013	625	553^{+10+4}_{-10-2}	0.895 ± 0.001 ± 0.002
31	GD02C	3.5		VI-1	0.877 ± 0.013	788	700^{+13+5}_{-13-2}	0.901 ± 0.001 ± 0.002
6	GD02D[a]	4.0	y	I-6	0.877 ± 0.013	662	552^{+11+0}_{-11-2}	not defined, see remark
36	ANG1	4.0		VI-6	0.859 ± 0.029	958	795^{+43+26}_{-43-26}	0.889 ± 0.018
27	ANG2	4.0	y	V-0	0.866 ± 0.025	2833	$2468^{+121+80}_{-121-80}$	0.918 ± 0.018
10	ANG3	3.5	y	II-2	0.883 ± 0.026	2391	$2070^{+118+60}_{-118-67}$	0.916 ± 0.018
29	ANG4	3.0	y	V-2	0.863 ± 0.013	2372	$2136^{+116+69}_{-116-69}$	0.916 ± 0.018
8	ANG5	2.5		II-0	0.856 ± 0.013	2746	$2281^{+109+74}_{-109-74}$	0.918 ± 0.018
9	RG1	5.0		II-1	0.855 ± 0.015	2110	$1908^{+109+62}_{-109-62}$	0.915 ± 0.018
28	RG2	4.0		V-1	0.855 ± 0.015	2166	1800^{+99+58}_{-99-58}	0.912 ± 0.018
38	GTF32	3.5	y	VII-1	0.078 ± 0.001	2321	2251^{+116}_{-116}	0.92 ± 0.018
39	GTF45_2	3.5		VII-2	0.078 ± 0.001	2312	1965	0.92 ± 0.018
37	GTF112	3.5	y	VII-0	0.078 ± 0.001	2965	2522	0.92 ± 0.018

Remark: detector GD02D does not deplete due to an unsuitable impurity concentration. The material is rather a *pn*-junction than of *p*-type.

Fig. 4. Photo of GERDA Phase II detector array. Each of the seven strings is enclosed by a transparent mini-shroud.

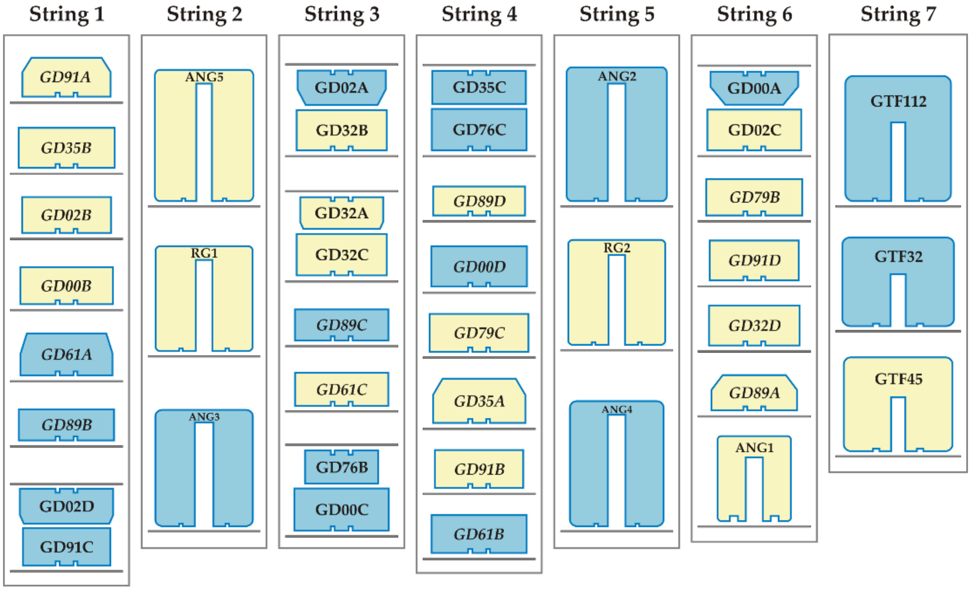

Fig. 5. Distribution of the enriched BEGe (GDxxx) and semi-coaxial (RGx and ANGx) detectors in the various strings of the GERDA Phase II detector array; the natural low-background semi-coaxial detectors carry the labels GTFxx. Blue colored detectors have passivation on the insulating groove between the p^+ and n^+ contact; the yellow colored ones have this layer removed.

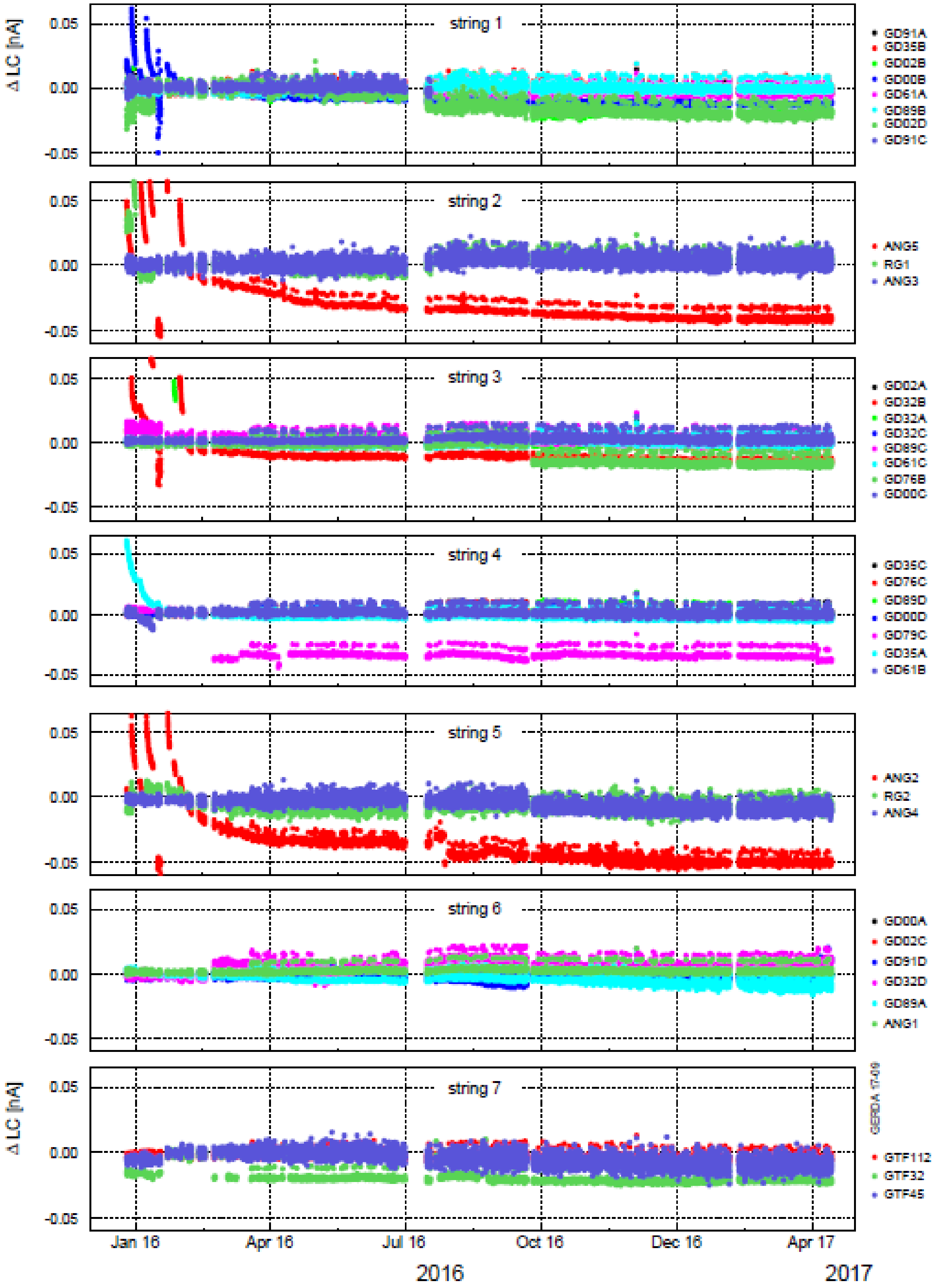

Fig. 6. Leakage currents of GERDA detectors in the period from December 2015 to April 2017.

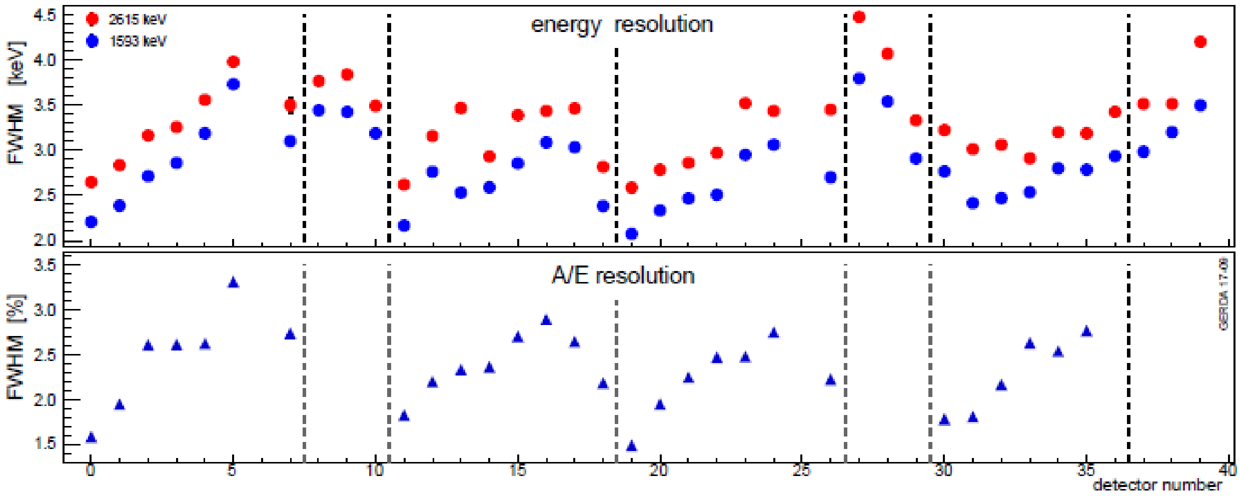

Fig. 7. FWHM energy resolutions (top) of the 2615 keV line and its double escape peak (DEP) at 1593 keV, and A/E resolutions (bottom) of individual Ge detectors deduced from the DEP. The dashed lines separate the 7 detector strings; within each string the detector number increases from top to bottom detector.

Form No. 26

Schedule proposal and resources required for the implementation of the Project GERDA (“G&M”)

Expenditures, resources, financing sources			Costs (k$) Resource requirements	Proposals of the Laboratory on the distribution of finances and resources		
				1st year	2nd year	3rd year
Expenditures		1. Production of the test stand for Ge detectors	40	30	10	
		2. R&D of ultrapure materials	30	10	10	10
		3. Procurement of ^{76}Ge detectors	150	50	50	50
		4. R&D of low background electronics	30	10	10	10
		5. R&D of active veto systems	30	10	10	10
		6. Procurement of prototype detectors	60	60		
		Construction/repair of premises				
		Materials:				
		1. Enriched ^{76}Ge	150	50	50	50
		2. Scintillating materials	30	20	7	3
		3. Chemicals for Ge detectors	5	2	2	1
Required resources	Standard hour	Resources of – Laboratory design bureau; – JINR Experimental Workshop; – Laboratory experimental facilities division; – accelerator; – computer. Operating costs.				
Financing sources	Budgetary resources	Budget expenditures including foreign-currency resources.	621	274	181	166
	External resources	Contributions by collaborators. Grants. Contributions by sponsors. Contracts. Other financial resources, etc.	30	10	10	10

PROJECT LEADER

Form No. 29

Estimated expenditures for the Project GERDA ("G&M"): 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			
5.	Experimental Workshop	standard hour			
6.	Materials	185 k$	72	59	54
7.	Equipment	340 k$	170	90	80
8.	Construction/repair of premises	k$			
9.	Payments for agreement-based research	k$			
10.	Travel allowance, including:	90 k$	30	30	30
	a) non-rouble zone countries				
	b) rouble zone countries				
	c) protocol-based				
	Total direct expenses	621	274	181	166

PROJECT LEADER

LABORATORY DIRECTOR

LABORATORY CHIEF ENGINEER-ECONOMIST