

Snowmass2021 - Letter of Interest

The LEGEND Double Beta Decay Experiment

NF Topical Groups: (check all that apply ☐/■)

☐ (NF1) Neutrino oscillations

☐ (NF2) Sterile neutrinos

■ (NF3) Beyond the Standard Model

☐ (NF4) Neutrinos from natural sources

■ (NF5) Neutrino properties

☐ (NF6) Neutrino cross sections

☐ (NF7) Applications

☐ (TF11) Theory of neutrino physics

☐ (NF9) Artificial neutrino sources

☐ (NF10) Neutrino detectors

■ (Other) [*Rare Processes and Precision Frontier/ Baryon and Lepton Number Violation*]

Contact Information:

Steve Elliott (LANL): elliotts@lanl.gov

Stefan Schönert (TUM): schoenert@ph.tum.de

Collaboration: LEGEND

Authors: The full author list follows the text and references

Abstract: We propose the 1000-kg phase of the Large Enriched Germanium Experiment for Neutrinoless double beta Decay (LEGEND-1000), for the search of neutrinoless double beta ($0\nu\beta\beta$) decay of ^{76}Ge . The experiment will probe the $0\nu\beta\beta$ decay of ^{76}Ge with a 3σ discovery potential of $T_{1/2}^{0\nu} > 10^{28}$ yr corresponding to a limit on the effective neutrino mass of < 17 meV (worst case matrix element of 3.5). 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 goal of the LEGEND-200 phase is only a factor of 2.5 below the measured levels of MAJORANA and GERDA, reaching a level of $< 2 \times 10^{-4}$ cts/(keV·kg·yr). A scaling toward a 1000-kg phase incorporating a further factor of 20 reduction in background beyond LEGEND-200 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.

The physics case. Since their discovery, neutrinos have been an object of extensive study, and the knowledge of their properties has advanced our understanding of weak interactions significantly. Still unanswered, however, is the very fundamental question as to whether the neutrino is identical to its anti-particle (a Majorana particle), which many extensions of the Standard Model incorporate.

More generally, $0\nu\beta\beta$ decay violates lepton number conservation and, if observed, would establish new physics beyond the Standard Model of particle physics. Though Majorana neutrinos are the prime candidate to mediate this elusive nuclear decay, other lepton number violating non-Standard Model processes could also generate $0\nu\beta\beta$ decay.

Furthermore, Majorana neutrinos are a robust prediction of Leptogenesis, a leading model for explaining the particle-antiparticle asymmetry of the Universe. The study of $0\nu\beta\beta$ decay is the most sensitive approach to test this prediction. If the decay occurs without the emission of neutrinos, then their Majorana nature is established. The motivation of this technique has increased considerably recently since a non-zero mass of the neutrinos has been established by the observation of neutrino flavor oscillation. In fact, the observation of $0\nu\beta\beta$ decay would not only strongly imply the Majorana nature of the neutrino but also help elucidate the effective neutrino mass.

The experimental situation. The $0\nu\beta\beta$ reaction $((A, Z) \rightarrow (A, Z + 2) + 2e^-)$ is only possible if neutrinos are Majorana particles or, equivalently, if lepton number violating interactions occur in nature. There is a long history of searches for $0\nu\beta\beta$ decay with the best current experimental sensitivities at or above 10^{26} yr coming from the isotopes ^{136}Xe ¹ and ^{76}Ge ²⁻⁶. Using calculations for nuclear matrix elements, lifetime limits can be used to constrain the effective Majorana neutrino mass ($\langle m_{\beta\beta} \rangle$). Variations in the nuclear transition calculations introduce about a factor of three uncertainty in the mass limit. The current best limit is in the range $\langle m_{\beta\beta} \rangle < (61 - 165) \text{ meV}$ from Xe and $\langle m_{\beta\beta} \rangle < (80 - 182) \text{ meV}$ from Ge⁴. It is critical to note that the Ge limits are comparable to the Xe limits even though the Ge exposure ($\approx 127.2 \text{ kg}\cdot\text{yr}$ from GERDA) is nearly a factor 4.6 less than that from Xe ($594 \text{ kg}\cdot\text{yr}$).

Experimental Considerations. The parameters determining the sensitivity of a $0\nu\beta\beta$ experiment are the active mass of the relevant isotope, M , the run time, T , and the background index B (often quoted in units of $\text{cts}/(\text{keV}\cdot\text{kg}\cdot\text{yr})$) in the relevant energy range, δE . The kinetic energy spectrum of the outgoing electrons is measured, and the number of events in δE near $Q_{\beta\beta}$ is evaluated. In the case where no events are found, the $\langle m_{\beta\beta} \rangle$ limit scaling can be approximated as $(MT)^{-1/2}$. Once non-zero background is observed, then the $\langle m_{\beta\beta} \rangle$ limit approximately varies as $[(B\delta E)/(MT)]^{1/4}$. A high sensitivity experiment will need maximum detector mass as well as very small backgrounds in order to operate in the “background-free” regime. This is even more relevant to the discovery sensitivity of an experiment.

Germanium is a good choice for such an experiment. The isotope ^{76}Ge can be enriched to greater than 86% in sufficient quantities. Germanium detectors are standard commercial products and act both as source and detector. They exhibit the best energy resolution of any $\beta\beta$ detector and no Th or U contaminations have been found inside a detector so far⁷. Germanium detector experiments (MAJORANA and GERDA) have achieved the lowest background of any $\beta\beta$ experiment - if normalized to δE - and operate in the regime where the half-life sensitivity scales almost linearly with the exposure.

LEGEND will combine the most effective background-mitigating practices employed in GERDA and MAJORANA. The dominant backgrounds in MAJORANA are found to be far away from the detectors and will be reduced with a GERDA-style active LAr shield. The dominant backgrounds in GERDA, other than ^{42}K , are close to the detectors and would be reduced with MAJORANA materials and improved energy resolution. This is why combining the advantages of both experiments can produce the necessary background improvement. Further, the use of underground-sourced LAr will reduce surface ^{42}Ar backgrounds. In total, a background improvement is anticipated for LEGEND-1000 yielding a projected background index of

$$< 1 \times 10^{-5} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr}).$$

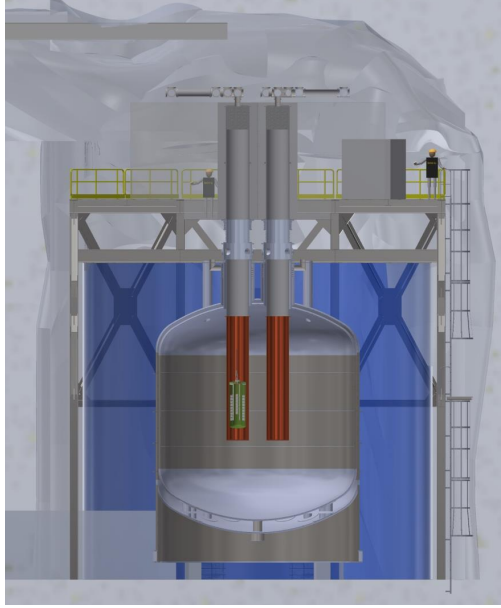


Figure 1: A conceptual design of the LEGEND-1000 ^{76}Ge array showing the four modules within the vacuum-insulated cryostat and water tank.

separate $2\nu\beta\beta$ from $0\nu\beta\beta$ decays. Beyond the tight energy cut, additional cuts based on pulse-shape analysis parameters offer a discrimination of backgrounds from the $0\nu\beta\beta$ signal of interest. A pulse shape analysis of the charge-collection signature from a bulk $\beta\beta$ energy deposition can be distinguished from multiple-interacting γ rays and surface events. The granular nature of the Ge detector array allows discrimination of background interactions that span multiple detectors. Finally, background interactions external to the Ge detectors are signaled by an active liquid Ar (LAr) shield.

The Ge detectors are distributed among four 250-kg modules to allow commissioning of the array in stages and independent operation (Fig. 1). In each module, the detector strings are immersed within the LAr active shield, sourced from radiopure underground Ar, to provide direct reduction of background. Alternative mitigation strategies have been developed if underground Ar is unavailable. Background sources that deposit energy in the LAr create scintillation light that is read out by a curtain of wavelength-shifting (WLS) polystyrene fibers. The TPB (tetraphenyl butadiene) coated fibers are coupled to silicon photomultiplier photodetectors at each end and read out by charge-sensitive amplifiers. Each of the four underground LAr modules are surrounded by natural LAr, with additional light collection, and supported within a vacuum-insulated cryostat, itself inside a water tank providing infrastructure and additional shielding.

As a baseline, we define a reference overburden depth and cavity size to be that of the SNOLAB cryopit for cosmogenic background estimate, the cryostat conceptual design, and infrastructure needs. The impact on the design and background contribution has been considered for shallower depths⁸.

We anticipate construction of LEGEND-1000 to take about 6 years. However, it will begin operation with the first 250-kg payload approximately during year 4, with additional payloads becoming operational over the final 2 years.

Baseline detector design for LEGEND-1000. We have prepared technical designs that are compatible with the leading candidate underground laboratories. The LEGEND-1000 baseline technical design is centered around the demonstrated low-background and excellent energy performance of p-type, point-contact (P-PC) high-purity Ge (HPGe) semiconductor detectors, enriched in ^{76}Ge . The larger mass inverted-coaxial, point contact (ICPC) detectors will be the standard in use for LEGEND-1000. When combined with the LEGEND-200 ICPCs, a total of <400 individual ICPCs with an average mass of 2.6 kg will be instrumented for a total detector active mass of 1000 kg. The detectors are mounted using underground electroformed Cu rods that provide physical support and electrical isolation through plastic insulators. Below each detector is a silicon base plate supporting a wire-bonded signal cable and front-end ASIC board to collect charges at the detector's p^+ electrode. From there, the signal is passed out of the cryostat and tank to a data acquisition system for waveform digitization and offline storage. A separate single conductor flat flex cable wire-bonded to the detector's n^+ electrode provides a high-voltage bias to deplete the Ge semiconductor.

The background rejection power of ICPC-style detectors begins with the superior energy resolution, demonstrated to be as low as 0.12% FWHM at $Q_{\beta\beta}$ ⁶, which is sufficient to

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Full Author List (LEGEND collaboration)

N. Abgrall¹, I. Abt², M. Agostini^{3,4}, A. Alexander⁴, G.R. Araujo⁵, F.T. Avignone III^{8,9},
 A. Bakalyarov⁶, M. Balata¹⁰, M. Bantel¹¹, I. Barabanov¹², A.S. Barabash⁶, P.S. Barbeau^{13,14},
 C.J. Barton¹⁵, P.J. Barton¹, L. Baudis⁵, C. Bauer¹¹, E. Bernieri^{16,17}, L. Bezrukov¹²,
 K.H. Bhimani^{18,14}, V. Biancacci^{19,20}, E. Blalock^{21,14,9}, A. Bolozydynya²², B. Bos^{18,14}, E. Bossio³,
 A. Boston²³, V. Bothe¹¹, S. Boyd²⁴, V. Brudanin²⁵, R. Brugnera^{19,20}, N. Burlac^{26,10}, M. Busch^{13,14},
 A. Caldwell², T.S. Caldwell^{18,14}, R. Carney¹, C. Cattadori²⁷, Y.-D. Chan¹, A. Chernogorov⁶,
 C.D. Christofferson²⁸, P.-H. Chu²⁹, M. Clark^{18,14}, T. Cohen^{18,14}, T. Comellato³, R.J. Cooper¹,
 V. D'Andrea^{26,10}, Z. Deng³⁰, J.A. Detwiler³¹, N. Di Marco^{10,44}, J. Dobson⁴, A. Drobizhev¹,
 M.R. Durand³¹, F. Edzards^{3,2}, Yu. Efremenko³², S.R. Elliott²⁹, A. Engelhardt^{18,14}, L. Fajt³³,
 M.T. Febbraro⁹, F. Ferella²⁶, D.E. Fields²⁴, F. Fischer², M. Fomina²⁵, H. Fox³⁴, R. Gala^{21,14,9},
 A. Galindo-Uribarri⁹, A. Gangapshev¹², A. Garfagnini²⁰, A. Geraci⁴², G.K. Giovanetti⁴³,
 M. Gold²⁴, C. Gooch², K.P. Gradwohl⁷, M.P. Green^{21,14,9}, J. Gruszko^{18,14}, I. Guinn^{18,14},
 V.E. Guiseppe⁹, V. Gurentsov¹², Y. Gurov²⁵, K. Gusev^{25,3}, B. Hackett^{9,32}, J. Hakenmüller¹¹,
 M. Haranczyk³⁵, Z. Harvey¹, L. Hauertmann², C.R. Haufe^{18,14}, C. Hayward^{34,2}, B. Heffron^{9,32},
 R. Henning^{18,14}, D. Hervas Aguilar^{18,14}, J. Hinton¹¹, R. Hodak³³, W. Hofmann¹¹, A. Hostiuc³¹,
 J. Huang⁵, M. Hult³⁶, M. Jeřkovský³⁷, H.T. Jia³⁸, J. Jochum³⁹, R. Jones³⁴, D. Judson²³,
 M. Junker¹⁰, J. Kaizer³⁷, K. Kang³⁰, V. Kazalov¹², Y. Kermaïdic¹¹, H. Khushbakht³⁹, M. Kidd⁴⁰,
 T. Kihm¹¹, I. Kim²⁹, A. Klimenko²⁵, K.T. Knöpfle¹¹, O. Kochetov²⁵, S.I. Konovalov⁶, I. Kontul³⁷,
 L.L. Kormos³⁴, V.N. Kornoukhov²², P. Krause³, V.V. Kuzminov¹², J.M. López-Castaño¹⁵,
 K. Lang⁴¹, M. Laubenstein¹⁰, E. León^{18,14}, B. Lehnert¹, Y. Li³⁰, H.B. Li⁴⁸, S.T. Lin³⁸,
 M. Lindner¹¹, I. Lippi^{19,20}, S.K. Liu³⁸, X. Liu², J. Liu¹⁵, D. Loomba²⁴, A. Lopez³²,
 A. Lubashevskiy²⁵, B. Lubsandorzhiev¹², N. Lusardi⁴², G. Lutter³⁶, Y. Müller⁵, H. Ma³⁰,
 M. Macko³³, C. Macolino¹⁰, B. Majorovits², F. Mamedov³³, W. Maneschg¹¹, L. Manzanillas²,
 R.D. Martin⁴⁵, E.L. Martin^{18,14}, R. Massarczyk²⁹, N. McFadden⁵, D. Mei¹⁵, H. Mei¹⁵,
 S.J. Meijer²⁹, S. Mertens^{3,2}, M. Misiaszek³⁵, B. Morgan⁴⁶, T. Mroz³⁵, D. Muenstermann³⁴,
 J. Myslik¹, I. Nemchenok²⁵, T. Oil¹⁵, G. Orebi Gann^{1,47}, G. Othman^{18,14}, V. Palušova³⁷, L. Papp³,
 L. Pertoldi^{19,20}, W. Pettus³¹, P. Piseri⁴², A.W.P. Poon¹, P. Povinec³⁷, R. Panth¹⁵, A. Pullia⁴²,
 D.C. Radford⁹, Y.A. Ramachers⁴⁶, C. Ransom⁵, L. Rauscher³⁹, A.L. Reine^{18,14}, S. Riboldi⁴²,
 K. Rielage²⁹, S. Rozov²⁵, E. Rukhadze³³, N. Rumyantseva²⁵, J. Runge^{13,14}, N.W. Ruof³¹,
 R. Saakyan⁴, G. Salamanna^{16,17}, F. Salamida^{26,10}, V. Sandukovsky²⁵, S. Schönert³, M. Schütt¹¹,
 J. Schreiner¹¹, A. Schuetz³⁹, O. Schulz², M. Schuster², M. Schwarz³, B. Schwingenheuer¹¹,
 O. Selivanenko¹², M. Shafiee⁴⁵, V. Sharma⁴⁸, E. Shevchik²⁵, M. Shirchenko²⁵, Y. Shitov²⁵,
 H. Simgen¹¹, F. Simkovic³³, M. Skorokhvatov⁶, M. Slavickova³³, K. Smolek³³, A. Smolnikov²⁵,
 J.A. Solomon^{18,14}, I. Stekl³³, D. Stukov^{16,17}, D. Stukov⁶, R.R. Sumathi⁷, K. Szczepanec³⁵,
 L. Taffarello^{19,20}, D. Tagnani^{16,17}, D. Tedeschi⁸, J. Thompson²⁸, Y. Tian³⁰, R.L. Varner⁹,
 S. Vasilyev²⁵, A. Veresnikova¹², K. Vetter^{1,49}, C. Vignoli¹⁰, C. Vogl³, K. von Sturm^{19,20},
 D. Waters⁴, J.C. Waters^{18,14}, W. Wei¹⁵, T. Wester⁵⁰, C. Wiesinger³, J.F. Wilkerson^{18,14,9},
 M. Willers^{3,2}, C. Wiseman³¹, M. Wojcik³⁵, H.T. Wong⁴⁸, V.H.S. Wu⁵, W. Xu¹⁵, E. Yakushev²⁵,
 L. Yang³⁰, C.-H. Yu⁹, Q. Yue³⁰, V. Yumatov⁶, I. Zhitnikov²⁵, D. Zinatulina²⁵, A.-K. Zschocke³⁹,
 A.J. Zsigmond², K. Zuber⁵⁰, and G. Zuzel³⁵

¹*Institute for Nuclear and Particle Astrophysics and Nuclear Science Division, Lawrence Berkeley National*

- Laboratory, Berkeley, California 94720
- ²Max-Planck-Institut für Physik, München
- ³Physik-Department E15, Technische Universität, München
- ⁴University College London, London
- ⁵Physik-Institut, University of Zürich, Zürich
- ⁶National Research Centre “Kurchatov Institute”, Moscow
- ⁷Leibniz Institute for Crystal Growth, Berlin
- ⁸Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina 29208
- ⁹Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
- ¹⁰Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso, Assergi (AQ)
- ¹¹Max-Planck-Institut für Kernphysik, Heidelberg
- ¹²Institute for Nuclear Research of the Russian Academy of Sciences, Moscow
- ¹³Department of Physics, Duke University, Durham, North Carolina 27708
- ¹⁴Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708
- ¹⁵Department of Physics, University of South Dakota, Vermillion, South Dakota 57069
- ¹⁶Roma Tre University and INFN Roma Tre, Rome
- ¹⁷Roma Tre University Istituto Nazionale di Fisica Nucleare, Rome
- ¹⁸Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27514
- ¹⁹Dipartimento di Fisica e Astronomia dell’Università di Padova
- ²⁰Padova Istituto Nazionale di Fisica Nucleare, Padova
- ²¹Department of Physics, North Carolina State University, Raleigh, North Carolina 27607
- ²²National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow
- ²³University of Liverpool, Liverpool
- ²⁴Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131
- ²⁵Joint Institute for Nuclear Research, Dubna
- ²⁶Department of Physical and Chemical Sciences University of L’Aquila, L’Aquila
- ²⁷Istituto Nazionale di Fisica Nucleare, Milano Bicocca, Milano
- ²⁸South Dakota School of Mines and Technology, Rapid City, South Dakota, 57701
- ²⁹Los Alamos National Laboratory, Los Alamos, New Mexico 87545
- ³⁰Key Laboratory of Particle and Radiation Imaging (Ministry of Education) and Department of Engineering Physics, Tsinghua University, Beijing
- ³¹Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, Washington 98195
- ³²Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37916
- ³³Czech Technical University, Institute of Experimental and Applied Physics, CZ-12800 Prague
- ³⁴Department of Physics, Lancaster University, Lancaster
- ³⁵Institute of Physics, Jagiellonian University, Cracow
- ³⁶European Commission, Joint Research Centre, Directorate for Nuclear Safety & Security, Geel
- ³⁷Department of Nuclear Physics and Biophysics, Comenius University, Bratislava
- ³⁸College of Physical Science and Technology, Sichuan University, Chengdu
- ³⁹University Tübingen, Tübingen
- ⁴⁰Tennessee Tech University, Cookeville, TN 38505
- ⁴¹Department of Physics, University of Texas at Austin, Austin, Texas 78712
- ⁴²Milano Univ. and Milano Istituto Nazionale di Fisica Nucleare, Milano
- ⁴³Department of Physics, Williams College, Williamstown, Massachusetts 01267
- ⁴⁴Gran Sasso Science Institute, L’Aquila
- ⁴⁵Department of Physics, Engineering Physics & Astronomy, Queen’s University, Kingston
- ⁴⁶Department of Physics, University of Warwick, Coventry
- ⁴⁷Department of Physics, University of California, Berkeley, California, 94720
- ⁴⁸Institute of Physics, Academia Sinica, Taipei
- ⁴⁹Department of Nuclear Engineering, University of California, Berkeley, California, 94720
- ⁵⁰Technische Universität Dresden, Dresden