Snowmass2021 - Letter of Interest

BSM Searches with the LEGEND Double Beta Decay Experiment

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: We propose the 1000-kg phase of the Large Enriched Germanium Experiment for Neutrinoless double beta Decay (LEGEND-1000). Though the main focus of LEGEND-1000 is the search of neutrinoless double beta decay of ^{76}Ge, it will also have a rich program searching for other rare events from beyond standard model (BSM) physics processes that are relevant to the Cosmic and Rare Processes and Precision Frontiers. These searches are enabled by its keV-level thresholds, large mass, low backgrounds, and detector technology. We provide an overview of these opportunities in this LOI.

Baseline detector design for LEGEND-1000.

We propose the 1000-kg phase of the Large Enriched Germanium Experiment for Neutrinoless double beta Decay (LEGEND-1000), based on the successful MAJORANA and GERDA experiments. 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, low-thresholds, low-noise, and excellent energy performance of p-type, point-contact (P-PC) high-purity Ge (HPGe) semiconductor detectors, enriched to over 88% in ^{76}Ge. Specifically, the inverted-coaxial, point contact (ICPC) design is the standard for LEGEND-1000. Approximately 400 individual ICPCs with an average mass of 2.6 kg are instrumented for a total detector active mass of 1000 kg. The detectors are mounted using underground electroformed Cu rods that provide mechanical support. Below each detector is a silicon base plate supporting a wire-bonded signal cable and front-end ASIC board that collects charges from the detector's p^+ electrode. From there, flat flex cables carry the signal 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.

Pulse-shape analysis of detector signals allows discrimination of backgrounds from the BSM signal of interest. The highly 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 detected by an active liquid Ar (LAr) shield.

The HPGe detectors are split among four 250-kg modules to allow commissioning of the array in stages and independent operation. In each module, the detector strings are immersed within the LAr active shield, sourced from radiopure underground Ar. Each of the four underground LAr modules are surrounded by natural LAr, with additional light collection inside a cryostat, itself inside a water tank providing additional shielding.

As a baseline, we use the SNOLAB cryopit overburden depth and cavity size for cosmogenic background estimates, the cryostat conceptual design, and infrastructure needs. The impact on the design and background contribution has been considered for shallower depths[1].

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

LEGEND-1000 BSM Program

Though the main focus of LEGEND-1000 is the search of neutrinoless double beta decay of ^{76}Ge, it will also have a rich program searching for other rare events from beyond standard model (BSM) physics processes. These searches are enabled by its keV-level thresholds, large mass, low backgrounds, and detector technology. A unique benefit is the demonstrated excellent energy resolution of P-PC detectors at low energies (0.4 keV FWHM at 10.4 keV[2]), which makes LEGEND-1000 especially sensitive to BSM physics with sharp features or peaks in the spectrum, such as solar axions, exotic atomic transitions, and bosonic DM. We expect the ICPC detectors in LEGEND-1000 to have similar resolution.

Axions and Axion-like Particles (ALPS): Bosonic pseudoscalar (i.e. ALPs) and vector dark matter, with mass scale of $1-100$ keV, offer explanations for the observed subgalactic structure in the Universe, assuming a large number density compensates for their light mass[3–5]. With suitable electronic coupling strength, they may be detectable via a pseudoscalar or vector-electric effect that is analogous to photoelectric absorption. In this case the particle is absorbed, and its rest-mass energy is passed to atomic electrons in the detector, ultimately producing a peak in the detector energy spectrum at the rest mass of the particle. In 2017 the MAJORANA Collaboration presented several limits on BSM processes, including ALPS, using data acquired during its 2015 commissioning run[2]. The Collaboration presented more recent results using production data at the TAUP 2019 conference[6]. Very recently, the GERDA Collaboration released limits on vector and pseudo-scalar dark matter in the mass region from 60 keV/c^2 to 1 MeV/c^2 [7]. Some of these limits have been surpassed subsequently by the XENON experiment[8].

Another potential axion/ALP source is the solar interior with production mechanisms that include Primakoff interactions of plasma photons, electron interactions, or nuclear transitions. These particles can be detected on earth in germanium detectors when they interact with atomic electrons or a virtual photon from an atomic Coulomb field[9]. Ge detectors are also sensitive to coherent Bragg-like ALP to photon conversion in the Ge-crystal lattice[10], as was demonstrated by the CDMS Collaboration[11]. LEGEND-1000 will be able to significantly improve on these searches by solid-state detectors. LEGEND-1000 could also study the solar axion interpretation of the recently reported excess in the XENON low-energy electron recoil spectrum[8].

Lightly ionizing particles (LIPs): LIPs are hypothetical particles with suppressed electromagnetic interactions when compared to charged hadrons and leptons. Unbound quarks, noninteger-charged bound states of quarks, millicharged particles, or new leptons with a fractional charge are examples that occur in extensions of the SM[12;13]. MAJORANA was able to set a world-leading limit searching for these in cosmic-rays[14], and LEGEND-1000 will further extend our sensitivity.

Baryon number violating nuclear decays: Many BSM theories predict baryon number (B) violating process. For example, the Standard Model with small neutrino masses has an anomaly-free Z_6 symmetry that acts as discrete B[15]. In this model $\Delta B = 1$ or $\Delta B = 2$ processes are forbidden, but $\Delta B = 3$ transitions can arise from a dimension 15 operator. The MAJORANA Collaboration published the first limits for trinucleon decay ($\Delta B = 3$) modes and invisible decay modes for Ge isotopes[16]. LEGEND-1000 will be able to greatly extend these results and look for similar decays in Ar.

Other BSM searches: Other BSM searches include sterile neutrinos, majorons, charge-violating electron decay, Lorentz-violation, and Pauli Exclusion Principle violation. The LAr itself can be used for searches for BSM physics. GERDA performed a search for neutrinoless double-electron (ECEC) capture in ^{36}Ar[17] and similar searches will be possible in LEGEND-1000. Both the Ge and Ar can also serve as targets for supernova neutrinos. HPGe detectors are also sensitive to WIMP-nucleus recoils, though LEGEND-1000 will probably not be competitive with the noble gas experiments. The list in this section is clearly not exhaustive, and it is likely additional opportunities will arise.

Experimental Considerations.

A major challenge to searches for BSM physics with low-energy deposits (below 100 keV) in LEGEND-1000 is ^{39}Ar decay in the LAr. ^{39}Ar undergoes beta decay with a Q-value of 565 keV and a half-life of 268 years. This yields a background spectrum that increases monotonically with decreasing energy below 565 keV, as was shown in GERDA[18]. The use of underground argon depleted in ^{39}Ar is one strategy to mitigate this background. A factor of 1400 reduction of ^{39}Ar has already been demonstrated by the Darkside experiment[19]. Other mitigation strategies include pulse-shape discrimination and increased LAr veto efficiency.

Other sources of background are cosmogenic tritium and ^{68}Ge, ^{42}Ar, energy degraded surface events, and small angle Compton scatters from gamma-ray sources. Cosmogenic backgrounds are mitigated by storing Ge underground and transportation and fabrication protocols to minimize surface exposure[20]. To achieve its physics potential, LEGEND-1000 is developing a detailed model of the low-energy background to help guide design decision, for example to refine the level of ^{39}Ar depletion required and levels of surface exposure that can be tolerated for the Ge.

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