Snowmass2021 - Letter of Interest

Advanced Germanium Detectors and Technologies for Underground Physics

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

■ (CF1) Dark Matter: Particle Like
■ (NF05) Neutrino Properties
■ (NF06) Neutrino Interaction Cross Sections
■ (IF03) Solid State Detectors and Tracking
■ (CompF02) Theoretical Calculations and Simulation
■ (CompF03) Machine Learning
■ (CommF05) Public Education and Outreach
■ (UF03) Underground Detectors
■ (UF04) Supporting Capabilities

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Abstract: Next-generation dark matter (DM) experiments aim to detect low-mass DM (MeV to sub-GeV). For a germanium (Ge) based DM detector this requires an energy threshold in the range of $\sim$sub-eV to 100 eV, a technical challenge. The planned ton-scale neutrinoless double-beta decay ($0\nu\beta\beta$) experiment, LEGEND, is exploring the development of a new technology, large-size high purity Ge (LHPGe) ring-contact detectors. These detectors are designed to have masses of $>$3 kg and have excellent e/γ discrimination. Developing these new technologies requires significant research and development (R&D) on the advancement of crystal materials and detector contact technologies. Partnerships for International Research and Education (PIRE) GErmanium Materials And Detectors Advancement Research Consortium (PIRE- GEMADARC) is a global consortium created to accelerate the Ge material platform used in R&D for new generation DM and $0\nu\beta\beta$-decay experiments while educating the next generation of scientists. PIRE-GEMADARC provides in-house capabilities to grow crystals, develop detectors, and study detector performance. PIRE-GEMADARC's valuable experience with processing and testing crystals will help pave the way for these methods to be performed in an underground lab, minimizing cosmogenic production and hence further increasing the sensitivity for a new generation of experiments. In addition, PIRE-GEMADARC is partnering with several vendors that produce detector-grade crystals and detectors in our R&D efforts. In summary, PIRE-GEMADARC is focused on basic research to advance Ge technology to meet the specific needs of next generation experiments enabling new discoveries.

Science-Driven New capacity

Low-mass dark matter searches: Light dark matter (LDM) in the MeV-scale has become a prominent DM candidate in the past decade[1–4]. Correspondingly, new detector technology has been evolving to push the detection threshold down to below $\sim$ 100 eV. Kadribasic et al. have reported the use of solid state detectors with directional sensitivity to detect low-mass Weakly Interacting Massive Particles (WIMPs) below 1 GeV/c^2 [5]. SuperCDMS has obtained a 3 eV phonon energy resolution with a 0.93 gram Si detector[6]. Mirabolfathi et al. achieved 7 eV resolution with a 250 g Ge detector[7]. CRESST has achieved a threshold of 20 eV with a gram-scale prototype sapphire detector[8]. DAMIC has claimed a sensitivity to ionization $<$ 12 eV with silicon CCDs and consider their method to be able to reach 1.2 eV[9]. High-purity germanium (HPGe) detector technology has been used for DM searches since 1987 due to its high radio-purity[10]. Two main advantages of HPGe detector technology are excellent energy resolution and high detection efficiency, allowing Ge detectors to potentially reach a low-energy threshold of $\sim$0.7 eV, the bandgap energy of Ge. This low threshold puts Ge detectors in a unique position for detecting LDM. Recently, a Ge detector utilizing internal charge amplification (GeICA) for the charge carriers created by the ionization of impurities has been proposed as a promising technology for detecting MeV-scale DM[11]. PIRE-GEMADARC aims to develop GeICA technology for detecting single electron-hole pairs[12].

Neutrino properties: The discovery of neutrino mass has revealed that the Standard Model of particle physics is incomplete. A fundamental question that arises is whether neutrinos are Dirac or Majorana in nature? The only experimentally viable approach to establish the Majorana nature of neutrinos is to look for $0\nu\beta\beta$ decay, a postulated form of nuclear decay. If $0\nu\beta\beta$ decay is observed, then it would demonstrate that neutrinos are Majorana particles and demonstrate lepton number violation. Ge detectors are ideal for a ton-scale $0\nu\beta\beta$ experiment[13] with discovery potential due to their excellent energy resolution, the best among all $0\nu\beta\beta$ experiments. In addition, studying phenomena such as coherent elastic neutrino-nucleus scattering (CEνNS) and testing properties such as neutrino magnetic moments, and millicharge could lead to a better understanding of the origin of the Universe and supernovae energy transport. GeICA detectors with extremely low-energy threshold may open a fresh opportunity in exploring cross section for CEνES, neutrino magnetic moments and milli-charges.

New discovery requirements: The next generation of large-scale experiments aims to achieve: (a) an extremely low-energy threshold to detect LDM particles with sub-eV to 100 eV of energy deposition[14,15] and (b) an extremely low-level background rate, $< 1 \times 10^{-5}$ cts/(keV·kg·yr) in the region of interest (ROI)[13], for $0\nu\beta\beta$ decay. This requires large-size high purity Ge (LHPGe) crystals with sufficient purity for developing detectors with either: (i) internal charge or internal Neganov-Trofimov-Luke (NTL) phonon amplification of charge signals for LDM or (ii) the capability to differentiate a two-electron signature from $0\nu\beta\beta$ decay from Compton scatters and other background events. PIRE-GEMADARC leverages established global infrastructure and expertise to innovate new LHPGe detectors with the necessary thresholds and capability to identify backgrounds for discovering DM and $0\nu\beta\beta$ decay. Furthermore, the PIRE-GEMADARC's capacity of crystal growth and detector development can be performed in an underground facility for detector production to further reduce cosmogenic backgrounds and ensure the sensitivity for discovering new physics.

PIRE-GEMADARC Research and Development Activities

Material advancement for developing novel Ge detectors: PIRE-GEMADARC possesses a unique Ge crystal growth facility that enables zone refining, crystal growth, and characterization[17–20]. Zone refining is a prerequisite for growing detector-grade single crystals. Currently, we are able to purify the commercially-available, 99.999% pure Ge to a purity of one part in 10^{13}, which is required for raw materials for detector-grade crystal growth. The cleaning procedures for ingots, boats, and the quartz tube were well established. PIRE-GEMADARC can provide about 6-kg of qualified ingots per month. Crystal growth is the key point for providing qualified crystals for detector fabrication. After a 10-year effort, the detector-grade Ge crystal with an impurity level $\sim 10^{10}$ cm^{-3} and dislocation density in the range of 100 - 10,000 cm^{-2} has been achieved[17–20]. The size of detector-grade crystals ranges from a few hundred grams to about 2.9 kg. The zone-refined ingots and grown crystals are characterized using Hall Effect system. The dislocation density is measured by optical microscopy. The shallow-level impurity is identified by photothermal ionization spectroscopy while the deep-level impurity is measured by deep-level transit spectroscopy.

Development of novel detectors: Utilizing the in-house grown crystals at USD, PIRE-GEMADARC has developed and tested planar detectors with internal charge amplification; a 1.4 kg detector with charge readout similar to those employed by SuperCDMS and EDELWEISS operated at millikelvin temperature; and miniPPC detectors for LEGEND-type detectors[13]. Using the USD detector fabrication facility, we fabricated 16 planar detectors that not only verified the quality of USD-grown crystals, but also demonstrated amorphous Ge contact detector sensor technology. This milestone allows us to start the process of fabricating Ge detectors with internal charge amplification to achieve $\sim$eV detection threshold for LDM searches. We have also fabricated three miniPPC detectors. One was fabricated at TAMU; one of them was fabricated by USD in collaboration with LBNL; and a third one with a unique geometry – planar point contact detector, was fabricated at USD. The variety and number of detectors fabricated couple with fabrication capabilities at multiple PIRE-GEMARDARC facilities enables PIRE-GEMADARC to study the process of fabricating kg-scale detectors using USD-grown Ge crystals.

Emerging detector technology: In the past two years, the search for dark matter and $0\nu\beta\beta$ decay has been evolving. Novel detector technologies and new knowledge about the detector response to nuclear recoils have been proposed. To meet the field's new demands, PIRE-GEMADARC has developed two new technologies and a new low-energy nuclear recoil measurement. A contact-free detector with millikelvin transition-edge sensors similar to those employed by SuperCDMS has been developed at TAMU with a new partner in France[7]. This detector is intended to address the low-leakage current and electrical breakdown issues observed with the high-voltage detectors SuperCDMS employed at the Soudan Underground Laboratory. Additionally the contact free geometry allows for rapid crystal pre-screening prior to any electrode deposition for ionization collection and crystal breakdown performances. A ring contact detector proposed by David Radford at ORNL is intended for potential development of large-size Ge detectors ($>$ 6 kg) for ton-scale $0\nu\beta\beta$ decay to further reduce background by reducing cables and small parts. A group at UNC has performed the field calculation and accomplished the design ideas for a couple of crystals. The response of Si and Ge detectors to low-energy (below 1 keV) nuclear recoils is important knowledge in searching for low-mass dark matter in sub-GeV. UMN has started low-energy nuclear recoil measurements using high-energy gamma rays produced by thermal neutron captures.

PIRE-GEMADARC Education and Career Development Program

PIRE-GEMADARC is developing the next generation of diverse scientists and engineers through its integrated research and education program and is meeting the following educational objectives: (1) Providing graduate and undergraduate students with international experiences and workforce development training thereby increasing the number, quality, and diversity of students, including those from underrepresented groups, who pursue careers at the frontiers of science; (2) Improving students' leadership, international collaboration, and communication skills in order to relate scientific knowledge to the broader community, develop international collaborations and cultivate interactions among students and faculty of different academic departments; and (3) Through international collaborations, train a new generation scientists and young leaders skilled in Ge detectors and technology. To achieve these objectives, PIRE-GEMADARC: (1) offers an annual summer school, a virtual summer exploration series and online mini courses for exploring Ge technology and its applications, Monte Carlo simulation and data analysis; (2) supports international research projects at the international partner sites; (3) recruits and retains graduate and undergraduate students from under-represented groups in STEM as well as attracts K-12 students into STEM; (4) develops and mentors early career researchers for leadership positions; and (5) ensures effective international coordination and logistics. PIRE-GEMADARC is well positioned to recruit and educate a diverse cadre of young scientists who will lead future development of physics beyond the Standard Model.

References

[1] R. Essig, J. Mardon and T. Volansky, *Direct detection of sub-GeV dark matter*, *Phys. Rev. D* **85** (2012) 076007.

[2] R. Essig et al., *Direct detection of sub-GeV dark matter with semiconductor targets*, *J. High Energ. Phys.* **2016** (2016) 46.

[3] C.M. Ho and R.J. Scherrer, *Limits on MeV dark matter from the effective number of neutrinos*, *Phys. Rev. D* **87** (2013) 023505.

[4] G. Steigman, *Equivalent neutrinos, light WIMPs, and the chimera of dark radiation*, *Phys. Rev. D* **87** (2013) 103517.

[5] F. Kadribasic et al., *Directional Sensitivity In Light-Mass Dark Matter Searches With Single-Electron Resolution Ionization Detectors*, *Phys. Rev. Lett.* **120** (2018) 111301.

[6] D. W. Amaral et al. (SuperCDMS Collaboration), *Constrains on low-mass, relic dark matter candidates from a surface-operated SuperCDMS single-charge sensitive detector,* arXiv: 2005.14067v1.

[7] N. Mirabolfathi et al., *Toward Single Electron Resolution Phonon Mediated Ionization Detectors*, Nucl. Instrum. Meth. A, 855 (2017) 88-91. 10.1016/j.nima.2017.02.032.

[8] G. Angloher et al., *Results on MeV-scale dark matter from a gram-scale cryogenic calorimeter operated above ground*, *Eur. Phys. J. C* **77** (2017) 637.

[9] A. Aguilar-Arevalo et al. (DAMIC Collaboration), *First Direct-Detection Constraints on eV-Scale Hidden-Photon Dark Matter with DAMIC at SNOLAB*, *Phys. Rev. Lett.* **118** (2017) 141803.

[10] S. Ahlen et al., *Limits on cold dark matter candidates from an ultralow background germanium spectrometer*, *Phys. Lett. B* **195** (1987) 603.

[11] D.-M. Mei et al., *Direct detection of MeV-scale dark matter utilizing germanium internal amplification for the charge created by the ionization of impurities*, *Eur. Phys. J. C* **78** (2018) 187.

[12] PIRE-GEMADARC Collaboration: pire.gemadarc.org.

[13] LEGEND Collaboration, *The large enriched germanium experiment for neutrinoless double-beta decay (LEGEND),* arXiv:1709.01980.

[14] R. Essig, J. Mardon, and T. Volansky, *Direct Detection of Sub-GeV Dark Matter,* Phys. Rev. D 85 (2012) 076007.

[15] SuperCDMS Collaboration, *Search for Low-Mass WIMPs with SuperCDMS,* Phys.Rev.Lett. 112 (2014) 241302.

[16] EURECA Collaboration, *EURECA Conceptual Design Report,* Physics of Dark Universe, Volume 3, (2014) 41-47.

[17] G. Wang et al., *Crystal growth and detector performance of large size high-purity Ge crystals Matter. Sci. Semiconductor Process*,**39**, (2015): 54–60.

[18] G Yang et al., *Investigation of influential factors on the purification of zone-refined germanium ingot*, *Crystal Research Technology* (2014).

[19] G Yang et al., *Zone Refinement of Germanium Crystals*, *J. Phys.: Conf. Ser. 606 012014* (2015).

[20] G. Wang et al., *High purity germanium crystal growth at the University of South Dakota*, *J. Phys. Conf. Ser. 606 012012*, (2015).

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