Snowmass2021 - Letter of Interest

Instrumentation and R&D for the Global Argon Dark Matter Collaboration

Thematic Areas: (check all that apply □/■)
□ IF1: Quantum Sensors
■ IF2: Photon Detectors
□ IF3: Solid State Detectors and Tracking
□ IF4: Trigger and DAQ
□ IF5: Micro Pattern Gas Detectors (MPGDs)
□ IF6: Calorimetry
■ IF7: Electronics/ASICs
■ IF8: Noble Elements
■ IF9: Cross Cutting and Systems Integration
□ (Other) *[Please specify frontier/topical group]*

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Collaboration: The Global Argon Dark Matter Collaboration

Abstract: The Global Argon Dark Matter Collaboration (GADMC) is planning a set of liquid argon-based dark matter experiments that will explore spin-independent WIMP cross sections down to the neutrino floor for WIMP masses in the approximate range of $1\,\mathrm{GeV}/c^2$ to $100\,\mathrm{TeV}/c^2$ and will perform an array of neutrino physics studies. Key to optimizing the sensitivity of these detectors and achieving these goals is the development and implementation of novel instrumentation and infrastructure. These developments will also enable other experiments to expand their physics reach and offer translational impacts in industrial and medical applications. This LoI focuses on the instrumentation efforts of the GADMC. Separate LoIs are submitted to the Cosmic Frontier and Neutrino Frontier to discuss the dark matter and neutrino physics goals of the GADMC experiments. Additional R&D needed for low-threshold noble liquid detectors that would benefit DarkSide-LowMass is discussed in a separate LoI, submitted to the Instrumentation Frontier.

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The Global Argon Dark Matter Collaboration (GADMC) is a union of scientists from the DarkSide [1], DEAP-3600 [2], ArDM [3], and MiniCLEAN [4] collaborations whose goal is to operate a series of liquid argon (LAr) detectors focused on dark matter (DM) direct detection [5], complemented by compelling neutrino physics [6, 7]. The DM and neutrino physics goals of the GADMC program are discussed in separate LoIs submitted to the Cosmic Frontier and Neutrino Frontier. Crucial to meeting these goals is an array of instrumentation and R&D projects that will allow these future detectors to access unprecedentedly low background levels and low energy thresholds. The GADMC instrumentation effort is particularly focused on obtaining chemically and isotopically pure argon, lowering backgrounds, and developing and calibrating novel detector technologies. These developments expand beyond the GADMC and should benefit other LAr-based and low-background experiments as well as finding broader industrial and medical application.

1. UNDERGROUND ARGON

The dominant background in LAr detectors is from ^{39}Ar β-decays, which are present in atmospheric argon (AAr) at an activity of 1 Bq/kg [8]. While pulse shape discrimination (PSD) heavily suppresses electronic recoil (ER) backgrounds in LAr detectors [2], reducing ^{39}Ar below the AAr rate is necessary when operating large detectors or when studying low-energy NRs or ERs below the 565 keV endpoint. Chemically purifying LAr removes radioactive contaminants, including ^{85}Kr and ^{222}Rn, and reduces chemical impurities, which can increase the electron drift lifetime, allowing for more efficient charge collection; increase the S1 yield, thereby improving PSD; and reduce spurious electrons that dominate the lowest-energy S2 signals [9].

The GADMC will procure high-purity LAr using three facilities: (1) Urania: a facility for extracting underground argon (UAr) that is significantly depleted in ^{39}Ar; (2) Aria: a distillation column that will chemically purify and further deplete UAr; and (3) DArT: a facility for measuring the ^{39}Ar activity in UAr. The ultra-pure UAr produced by these facilities is critical for the GADMC program and has application in other experiments using argon.

^{39}Ar is cosmogenically produced and therefore significantly depleted in argon extracted from underground [10]. DarkSide-50 measured the ^{39}Ar activity of UAr extracted from a site in Cortez, Colorado, to be a factor of 1400 lower than in AAr [11]. Urania will extract UAr from the same source at a higher throughput, up to 330 kg/d, with the goal of collecting approximately 60 t for DarkSide-20k by 2022 and supplying UAr to other experiments that would benefit from its use.

Further depleting UAr and improving its chemical purity will allow future detectors to operate with lower pileup rates, will reduce the the trapping and subsequent release of S2 electrons, and will mitigate low-energy ER backgrounds. UAr purification will be performed at the Aria facility, a 350 m-tall distillation column in Sardinia, Italy. The goal of Aria is to demonstrate the separation of ^{39}Ar and ^{40}Ar, exploiting their different vapor pressures, such as to deplete the ^{39}Ar activity by a factor of 10 per pass through the column. At this depletion factor, Aria will be distill about 10 kg/d with a recovery fraction of approximately 50 %. More efficient processing may become available with future upgrades.

A stand-alone, low-background detector is needed to assay the purity of the UAr distilled by Aria. To this end, DArT [12] is being built at LSC. DArT will consist of 1.4 kg of LAr in an acrylic vessel, surrounded by a copper shell. This vessel will be submerged in ArDM, which will be filled with AAr and serve as a γ-ray veto. In this way, DArT will achieve a sufficiently low background rate to measure ^{39}Ar depletion factors up to 6×10^{-4} relative to AAr at the 90 % confidence level.

2. DETECTOR DEVELOPMENT AND CALIBRATION

The continued development of a number of technologies is necessary for the GADMC program, with many of these technologies potentially benefiting other experiments.

One key technology is the development of low-background, cryogenic SiPM-based photodetectors.

The DarkSide collaboration demonstrated that a $50 \times 50\,\text{mm}^2$ SiPM-based photodetector can be operated in LAr with a signal to noise ratio larger than 20, a primary dark count rate below $40\,\text{mcps/mm}^2$, and a total correlated noise probability below 20% [13–17]. The next step is the optimization of the photodetection efficiency at cryogenic temperature. Currently available SiPMs are designed to operate at room temperature, which can be sub-optimal for cryogenic operation where the photon absorption length is longer. A design optimized for cryogenic operation could boost the PDE of SiPMs to values in excess of 60 %, a significant improvement that would benefit many liquid noble-based experiments. Photodetectors for next-generation experiments must be produced cleanly and at large scales. The *Nuova Officina Assergi* (NOA), a dedicated facility for the assembly of SiPM-based detectors under construction at LNGS, will serve the packaging needs of DarkSide-20k and potentially other large-scale experiments using SiPMs for photodetection.

Also central to the success of future detectors is the advancement of techniques for estimating and reducing backgrounds. One of the main sources of instrumental backgrounds for LAr detectors comes from neutrons produced by (α,n) reactions in detector materials. A separate LoI is being submitted to the Cosmic Frontier to discuss efforts to improve (α,n) estimates.

Building on the success of the DarkSide-50 borated liquid scintillator neutron veto [18], the GADMC is designing a LAr-based veto with Gd-loaded PMMA panels in a ProtoDUNE-like cryostat. The TPC will sit within the veto, contained inside of a PMMA vessel. This design exploits the collaboration's experience with large, radiopure PMMA vessels developed for DEAP-3600 [19]. To produce radiopure Gd-loaded PMMA, techniques are being developed in collaboration with industrial partners to load multi-tonne PMMA plates with Gd at 1–2 % mass fractions while maintaining low radioactivity. Panels consisting of polyethylene naphthalate (PEN) wavelength shifter coupled to reflectors are also being developed to improve the detection of LAr scintillation light over large surface areas.

Optimizing the design of GADMC detectors requires detailed simulation and low-radioactivity material identification, which will be achieved through dedicated R&D and assay campaigns. To address challenges related to constructing tonne-scale LAr TPCs and to test technologies that will be used in the DarkSide-20k TPC, the DarkSide-Proto detector is being constructed at CERN [20]. This facility will also be used to investigate techniques to improve *in situ* argon purification.

R&D is also planned to study doping LAr with xenon or other additives. Dopants may extend a LAr detector's sensitivity to light DM by lowering the energy threshold or by introducing kinematically favorable targets. For DarkNoon, LAr doped with a molar fraction of 20 % xenon can achieve competitive sensitivity to $0\nu\beta\beta$. For this, R&D is planned to develop single- and double-electron discrimination techniques using β-induced Cherenkov light, which also requires developing SiPMs with fast timing. In all cases, it will be necessary to study the stability of the mixtures, techniques for mixing and purification, and the effects of doping on the scintillation and ionization signals.

Finally, calibration measurements are needed to support the GADMC program. The DarkSide collaboration has previously performed the SCENE [21, 22] and ARIS [23] experiments to calibrate the response of LAr TPCs to NRs down to about $10\,\text{keV}_{\text{nr}}$. Necessary additional experiments are being planned to measure the ionization yield for lower energy NRs and resolve discrepancies between different measurements of the quenching factors in this energy range. Additionally, the ReD experiment [24] will study correlations between S2 and the direction of the NR relative to the drift field, an effect reported by SCENE [22], which would bolster the claim of any future WIMP detection [25]. ReD is discussed in more detail in a separate LoI.

3. BROADER APPLICATIONS

These projects have broader impacts on society. For example, the UAr extraction facilities in Colorado discovered a significant source of ^{4}He, and the Aria plant will also be capable of producing rare isotopes with medical and industrial applications, in addition to separating argon isotopes. The development of LAr detectors and low-noise SiPMs with good timing resolution has also led to 3Dπ, a project being developed by several GADMC members to develop high-resolution PET scanners.

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