Snowmass2021 - Letter of Interest

R&D for low-threshold noble liquid detectors

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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Abstract: Noble liquid detectors using liquid argon and xenon have demonstrated significant potential to search for new physics at low energies, probing energy depositions from particle interactions down to the scale of the atomic ionization threshold. As a result, there is growing interest in deploying noble liquid detectors optimized for low-threshold analyses to study dark matter models and neutrino properties. Most noble liquid detectors built to-date have focused on higher energy signals, where observables and challenges are fundamentally different than at the lowest energies. Optimizing detector technology for this low-energy regime requires a suite of R&D studies geared towards minimizing backgrounds present in this range and lowering the energy threshold as much as possible.

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I. INTRODUCTION

Noble liquid detectors, particularly liquid argon (LAr) and liquid xenon (LXe) time projection chambers (TPCs) have historically shown to be powerful probes for low-mass dark matter candidates with masses in the range of a few MeV/c^2 to $10\,\mathrm{GeV}/c^2$ [1–7]. These candidates include dark matter that scatters on nuclei and atomic electrons [8–12]. Axion-like particles and hidden photons, which may be absorbed by electrons, may also be probed with masses between about $10\,\mathrm{eV}/c^2$ and $1\,\mathrm{keV}/c^2$ [13–15].

The recent observation of Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) with a single-phase liquid argon detector [16] highlights the utility of low-threshold noble liquid detectors for neutrino detection, as well. Due to the high cross section and unique properties of the CEνNS reaction, this channel provides a powerful tool for detecting neutrinos and is a sensitive probe for studying their properties. Other experiments plan to make use of the CEνNS channel to search for more physics beyond the standard model, such as sterile neutrinos and non-standard interactions [17, 18], and simulations have shown that low-threshold LAr and LXe TPCs can observe neutrinos produced in core-collapse supernovae through this channel [19, 20].

These dark matter and neutrino physics goals rely on detecting low-energy signals. To date, the lowest energy thresholds achieved by dual-phase noble liquid TPCs were obtained in studies focusing on the ionizational signal (S2), rather than the scintillation signal (S1). Due to the large amplification of the S2 signal in such detectors, individual electrons may be detected with high efficiency, allowing for energy thresholds below 1 keV. Achieving such thresholds by analyzing signals with S2 but no S1 comes with the loss of discrimination between electronic and nuclear recoils, loss of time resolution, and a class of pathological single- and few-electron backgrounds [21–24].

A number of future noble liquid TPCs are currently being planned to search for these low-energy signals (*e.g.* [25]), capitalizing on the lower energy thresholds achievable with an S2-based analysis. Designing a detector optimized for the particular signals and backgrounds at low energies requires qualitatively different considerations than is needed for TPCs focusing on higher energy signals. The R&D needed to develop such detectors is discussed in the remainder of this document. The two main priorities involve goals to lower the rate of the dominant backgrounds at these energies and to decrease the energy thresholds of these detectors.

II. LOWERING BACKGROUNDS

Two main classes of backgrounds emerge as dominant in low-threshold noble liquid TPCs: spurious electron backgrounds and electronic recoil backgrounds.

Spurious electron backgrounds consist of one- and few-electron events that dominate the lowest energy bins [26] in the low-mass dark matter searches performed by DarkSide-50 [6, 7], XENON1T [5], LUX [22], and ZEPLIN-III [27]. Current studies indicate that these electron events are correlated in time with higher energy deposits, and there are likely multiple origins for such backgrounds, foremost including delayed re-emission of electrons captured on trace electronegative impurities [22, 23]. Photoionization of neutral impurities and of detector components may also contribute to this electron background, as well as charge buildup on the liquid-gas interface [6, 28]. As a result, these backgrounds are sensitive to trace levels of chemical impurities in the bulk liquid, outgassing and photoionization of detector components, and the electric field configuration.

The priorities for reducing spurious electron backgrounds in future detectors can therefore be summarized as:

- Characterize spurious electron backgrounds (*e.g.* using the method described in [27, 29]) and develop techniques to reduce them
- Improve chemical purification techniques to remove electronegative impurities, including *in situ* liquid-phase purification during recirculation
- Optimize electric field configuration for spurious electron backgrounds

The loss of discrimination between electronic and nuclear recoils in S2-only analyses elevates the importance of mitigating electromagnetic backgrounds. These backgrounds can arise from β-emitters mixed uniformly in the bulk liquid, such as ^{85}Kr, ^{39}Ar, and ^{3}H, as well as the ^{220,222}Rn decay chains. Backgrounds resulting from these isotopes can be reduced with R&D identifying their sources and improving radiopurification techniques for noble liquids. Backgrounds may also be produced by γ-emitting isotopes in detector components; improved techniques for mitigating such contaminants and identifying new, radiopure materials will further decrease low-energy background rates. A dominant source of such backgrounds comes from the photo-detectors. The development of scalable, low-noise, and high-efficiency silicon photomultipliers (SiPMs) [30–33] provides a lower background, higher resolution, and higher quantum efficiency alternative to photomultiplier tubes (PMTs). Nevertheless, SiPMs and the associated signal pre-amplification and read-out electronics remain a significant source of γ-emitters. This contribution may be reduced by developing more radiopure packaging substrates and electronic components and by reducing the number of necessary photo-detection modules by means of light focusing technologies such as collectors and/or meta-lenses.

Cosmic rays can also activate radioactive isotopes like ^{39}Ar and ^{3}H in detector materials, which may produce additional low-energy backgrounds. To understand the impact of such nuclides, relevant cross sections are needed, many of wich have not been measured, and have estimates varying by orders of magnitude. For example, this was the case for the cosmogenic production of ^{39}Ar and ^{37}Ar, important for LAr-based detectors, until the production rates were recently measured, resolving tension in theoretical models [34]. Similarly the production of ^{3}H in argon and xenon are not well understood and may pose a significant low-energy background [35], along with several other isotopes in various materials [36]. A program for filling in these nuclear data knowledge gaps is critical.

The priorities for reducing electromagnetic backgrounds can be summarized as:

- Design radiopure detector components with a focus on reducing γ-emitters
- Develop radiopure SiPM photodetector modules with low γ-emitter contamination and high quantum efficiency
- Better quantify the cosmogenic activation of radionuclides in detector materials
- Improve purification of β emitting contaminants from the bulk liquid (e.g. ^{39}Ar, ^{85}Kr, ^{220,222}Rn, and ^{3}H)

III. LOWERING THRESHOLDS

Lowering the energy thresholds for future detectors will significantly enhance their physics reach. Achieving lower thresholds first requires reducing the low-energy backgrounds, as discussed above. Significant uncertainties in the scintillation and ionization yields of noble liquids to low-energy electronic and nuclear recoils hinder the analysis of data at very low energies; measurements of these yields and their intrinsic distributions will enable analysis at these energies. Furthermore, the effects of the drift and extraction fields on low-energy signals should be studied so that the electric field configuration can be optimized.

Finally, the sensitivity of noble liquid detectors can be extended by doping the medium. At low concentrations, additives with low ionization energies can increase the scintillation and ionization yield by allowing energy that would otherwise be lost as heat to translate into additional ionization and excitation. This behavior has been observed by several groups, where improved Fano factors and ionization yields have been reported when doping LAr with xenon [37, 38], allene [39–42], and tetra-methyl-germanium [43], among other dopants [44]. At higher concentrations, additives with low-A nuclei can serve as targets with stronger kinematic couplings to light dark matter particles [45], and additives with odd-A nuclei offer sensitivity to spin-dependent interactions. In order to make use of these additives in a low-threshold, low-background detector, it is necessary to further develop doping and mixing techniques, study the long-term stability of doped noble liquids, and develop mixture purification techniques. It is also necessary to study the effects of these additives on the scintillation and ionization response of the medium to low-energy nuclear and electronic recoils with a dedicated set of calibration measurements.

The main priorities for lowering the energy thresholds of future noble liquid detectors can be summarized as

- Calibrate the detector response to <1 keV electronic and nuclear recoils
- Optimize the electric field configuration to maximize the ionization signal
- Minimize low-energy backgrounds, as discussed above
- Study the effects and develop appropriate techniques for doping noble liquids

IV. CONCLUSIONS

Low-threshold noble liquid detectors promise to provide powerful tools for studying dark matter and neutrinos. This class of detectors largely builds on the very mature technology of dual phase TPCs, already widely adopted in the low-background physics field. However, a concrete and well-defined R&D effort focused on optimizing these detectors for low-energy events is necessary in order to exploit their full potential. Dedicated small-scale experiments are crucial to explore the various goals outlined in this document. In addition to the noble liquid TPCs discussed here, much of this R&D may also support other low-threshold noble liquid detectors, such as the Xe-doped LAr bubble chamber being developed by the Scintillating Bubble Chamber collaboration to study low-mass dark matter and reactor neutrinos [46].

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