Low-Background kTon-Scale Liquid-Argon Time-Projection Chambers

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Abstract. It is possible to increase sensitivity to low-energy physics in a third or fourth DUNE-like module with better radiopurity measures and suitable modifications to a detector similar to the DUNE Far Detector design. In particular, sensitivity to supernova and solar neutrinos can be enhanced with improved MeV-scale reach, and with ^{136}Xe doping in the liquid argon, the detector can also be used for neutrinoless double beta decay searches. Furthermore, sensitivity to weakly interacting massive particle dark matter becomes competitive with the planned world program in such a detector.

INTRODUCTION

A dedicated low-background module could enhance the physics reach of next-generation rare-event-search experiments such as the Deep Underground Neutrino Experiment (DUNE). Such a low-background DUNE-like module can be a candidate for the third or fourth far-detector module, the so-called "Module of Opportunity" in DUNE. Modifications to a DUNE-like vertical-drift (VD) time-projection chamber (TPC) (discussed in [1]) can make the module a multi-purpose detector that can carry out a wide range of neutrino measurements and search for Weakly Interacting Massive Particle (WIMP) dark matter. Major features of the module compared with the generic VD DUNE are increased shielding, better light coverage, use of low-radioactivity argon, and stringent radiopurity controls. Readers should consult Refs. [2, 3] to learn more about the proposed low-background module and its capabilities.

DETECTOR FEATURES

The working design for the low-background module is shown in Figure 1. The water shield acts as a shield for the neutrons originating in the cavern rock and shotcrete. Also, certain improvements in the light-detection system are proposed to enhance the light collection. SiPM tiles are mounted on the acrylic box and cathode plane to increase light coverage. Also, to the same end, reflective coatings are applied to the inner acrylic walls and anode planes. Further, Argon purity will be enhanced to < 1.5 ppm nitrogen level so that a photo-attenuation length of $\sim$50 m is achievable [4]. The enhanced light collection enables us to achieve a low energy threshold, improved energy resolution at low neutrino energies, and improved pulse-shape discrimination (PSD) for radioactive-background rejection. Enhancing the light collection and satisfying the argon-purity requirements, the energy resolution of 2% at 1 MeV (when combining the information from the TPC charge signal) can be achieved, which allows efficient pulse discrimination to reject radioactive backgrounds.

BACKGROUND-CONTROL MEASURES

Certain background-control measures are necessary for the proposed low-background module to achieve its physics goals. Neutron-induced backgrounds are particularly problematic. In neutrino searches above a 3.5-MeV threshold, important backgrounds from gammas result from the capture of neutrons, particularly on ^{40}Ar and ^{36}Ar. For a WIMP dark matter search, neutrons themselves are sources of background, as they can induce nuclear recoils in argon. A study in [5] shows that a 40-cm water shield, located within the I-beam support structure, can reduce the external neutron-background rate by three orders of magnitude. In the low-background module, the water shield primarily reduces the rate of neutrons from the cavern and

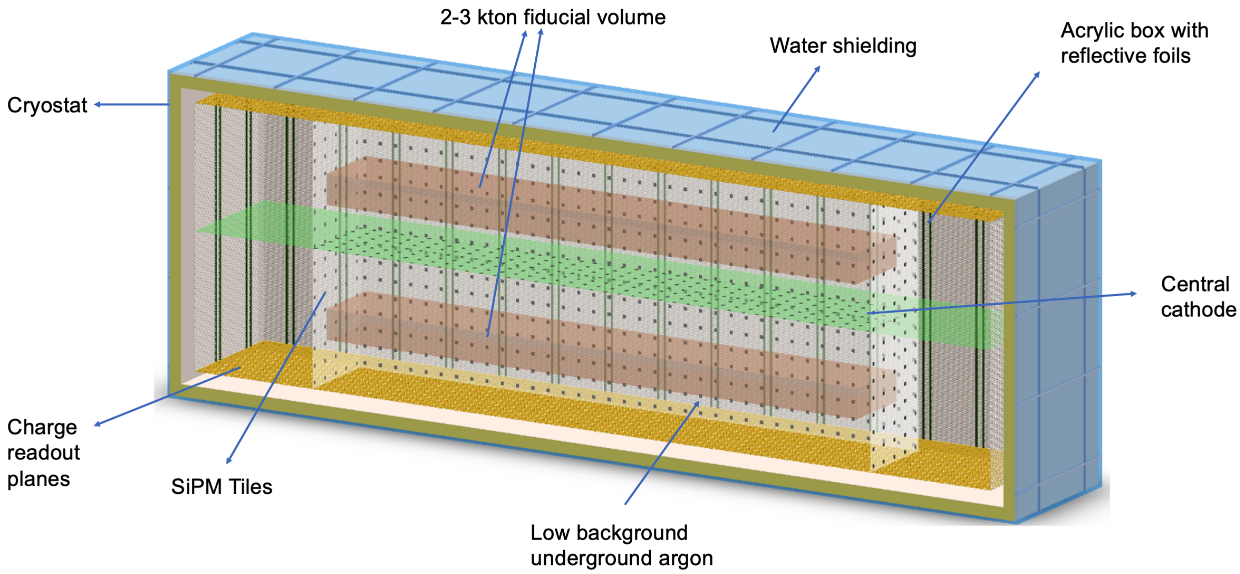


FIGURE 1. The design for the proposed low-background detector is shown. It is adapted from DUNE's Module-2 Vertical-Drift detector design, allowing minimal modifications to suit the low-background purposes. The top and bottom charge-readout planes (in yellow) remain unchanged from the Vertical Drift design. The central cathode is in green. An added shield of water "bricks" (around the outside in blue) is supported by the I-beam structure. An acrylic box (shown in white) mounts SiPM modules and reflective WLS foils. The fiducial volumes (shown in biege) consist of 1–1.5 kTon at 1.5 m stand-off on either side of the cathode central plane. The whole acrylic box holds underground argon (UAr). Figure taken from [2].

the shotcrete. These neutrons are the result of spontaneous fission or (α,n) interactions from uranium and thorium decay chains present in those materials. To achieve the physics goals (listed in the next section), radioactive backgrounds from the cryostat and detector materials need to be reduced by a factor of 10^3 compared to the baseline DUNE radiopurity levels. This reduction can be achieved through a material-assay campaign and selection of radio-pure cryostat and detector materials. Radon and its progeny are another source of background. For the low-background module, the target radon level in liquid argon is 2 µBq/kg. Although this value is three orders of magnitude below the expected DUNE level, it has been achieved or surpassed by the liquid-argon-based dark matter experiments DarkSide-50 [6] and DEAP [7]. Radon removal and other radon-mitigation techniques that will be implemented are discussed in [2].

One limitation of a detector based on atmospheric argon (AAr) is the decays from ^{39}Ar ($Q = 565\,\mathrm{keV}$, $T_{1/2} = 269\,\mathrm{y}$) and ^{42}Ar ($Q = 599\,\mathrm{keV}$, $T_{1/2} = 32.9\,\mathrm{y}$) in the argon bulk. ^{39}Ar activity in AAr is $\sim$1 Bq per kg of argon, and ^{42}Ar activity is four orders of magnitude smaller. ^{42}K, the progeny of ^{42}Ar, has a Q-value of 3.5 MeV. In a kton-scale argon detector, backgrounds and the data trigger rate from the radioactive decays are problematic. Particularly, ^{42}K decays are problematic and make it difficult to probe MeV-scale physics. Argon extracted from underground sources is cosmogenically shielded and so known to be of much lower radioactivity than AAr. DarkSide-50 demonstrated significant reduction ($\times 1400$) [8] of ^{39}Ar in the UAr extracted from CO_2 gas wells in southwest Colorado. The actual ^{39}Ar concentration in UAr could be even lower [9]. ^{42}Ar production is expected to be even more suppressed underground primarily because the most likely nuclear reactions that could produce ^{42}Ar have high energy thresholds beyond the reach of neutrons and alphas originating in natural decay chains of uranium and thorium. So, we expect UAr to be significantly depleted of ^{39}Ar and ^{42}Ar. PNNL is working with a major US gas supplier to procure UAr. 5000 ton/yr production rate is expected to be achievable with an estimated cost on the order of $34\times$ the cost of AAr [2]. The use of UAr will allow the low-background module to reach much lower threshold ($< 100\,\mathrm{keV}$), and the sensitivity of the detector to solar neutrino and supernova-collapse neutrino measurements is significantly enhanced.

PHYSICS GOALS

With a low level of backgrounds and an enhanced light collection, the physics reach of the low-background module is greatly enhanced. Some of the physics goals that the module can achieve are briefly summarized below. For greater details on the capabilities of the low-background module, see Ref. [2]. Capabilities of the low-background module TPC to carry out dark matter searches are discussed in greater detail in [3]. Readers are also encouraged to consult Ref. [10] to learn about the scientific opportunities with detection and event-reconstruction of low-energy ($<$ 100-MeV) neutrino signals with LArTPCs.

Supernova neutrino physics

A much wider supernova energy spectrum is accessible to this low-background module. Detection of early- and late-time supernova explosions and efficient reconstruction of the position of the supernova (as far as from the Magellanic Cloud) is possible with this module with an energy threshold of sub-MeV or lower, which can be achieved primarily by control of neutron and radon backgrounds and the use of UAr. With an energy threshold of a few hundred keV or lower, CEνNS "glow" can be observed as an excess rate of photons detected over the ^{39}Ar-decay background. Finally, low thresholds also give access to elastic neutrino-electron scattering and thus allow pointing back to the supernova in the sky.

Solar neutrino physics

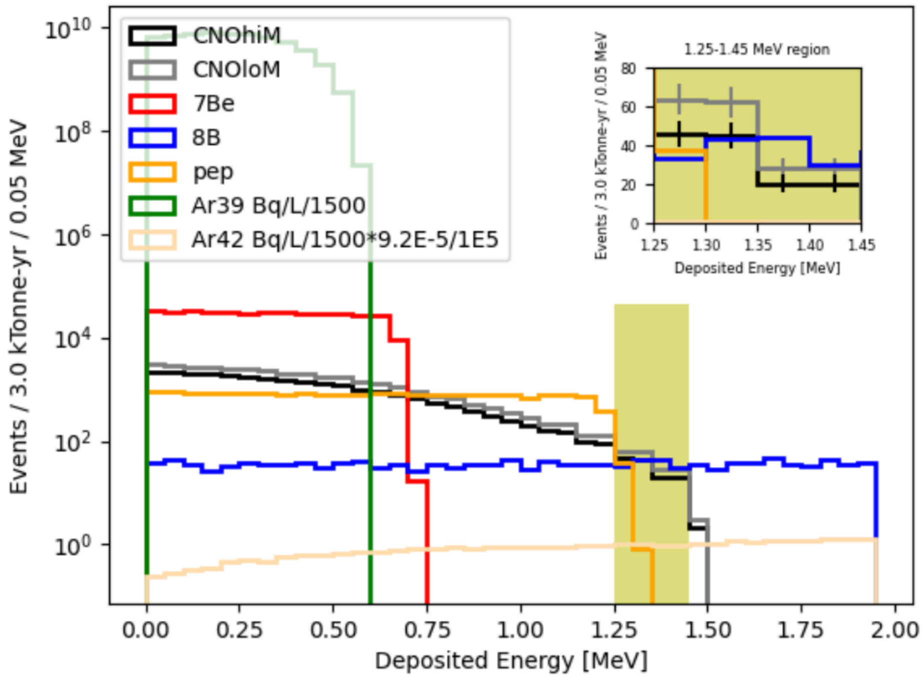
With an energy threshold of $\sim$ 1 MeV, pep neutrinos and CNO neutrinos become observable, making a determination of the high- and low-metallicity solar solutions possible. With low thresholds and increased energy resolution, the neutrino mixing parameter Δm^2_{21} can be measured with increased sensitivity (see Figure 2). This measurement will also help test the solar/reactor neutrino anomaly and improve constraints on non-standard interactions.

^{136}Xe Neutrinoless double beta decay search

The greater energy resolution achievable with a LArTPC with both charge and photon read-out system allows a search of neutrinoless double beta decay ($0\nu\beta\beta$) physics with a few percent-level ^{136}Xe doping in argon. Since xenon-doping would compromise with the Pulse Shape Discrimination (PSD), ($0\nu\beta\beta$) searches with Xenon-doping can be planned following the completion of the baseline physics program. Discovery potential for 2.435-MeV $0\nu\beta\beta$ signal from ^{136}Xe is also enhanced by the use of UAr (such that ^{42}Ar/^{42}K backgrounds are suppressed) and suppression of radon backgrounds.

Dark matter physics

The potential of the low-background module to make sensitive WIMP-dark-matter searches is discussed in greater detail in [3]. The study considers a dual-phase TPC design with a single fiducial volume at the center of the detector. Low-energy thresholds are necessary to measure low-energy nuclear recoils from WIMP interactions in argon. Enhanced light collection and dual-phase TPC design allow efficient rejection of electron/gamma backgrounds by PSD. Measures to mitigate the neutron-induced backgrounds for sensitive WIMP searches are discussed in [3]. This includes shielding and rejection of multi-site nuclear recoil events with efficient position reconstruction achievable for the LArTPC. For a 3-kton-year exposure, the sensitivity of a DUNE-like module able to keep nuclear-recoil event rates to O(1) per year will be competitive to other next-generation direct-detection dark-matter experiments like DarkSide-20k (see Figure 3). The spin-independent DM-nucleon cross-section exclusion curves for different NR thresholds for the module are shown in the Figure. Assumptions are background events of O(10) over the exposure and O(100) photons detected per event to allow PSD.



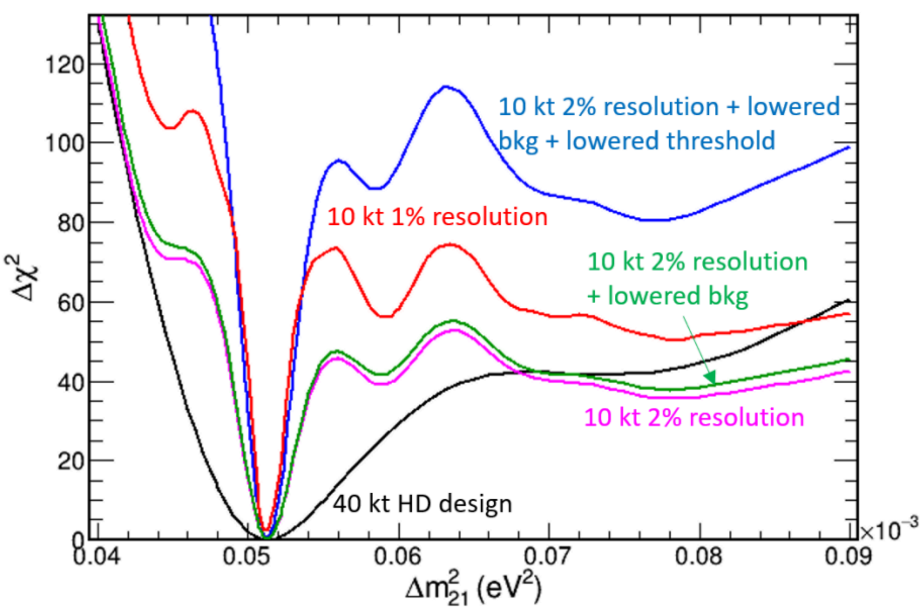


FIGURE 2. Top: CNO solar neutrinos, with radon backgrounds and neutron backgrounds considered negligible. Energies are smeared by 2% for the inner 3 kT fiducial volume for a year's exposure. Inset is the zoomed-in view of the 1.25 – 1.45 MeV region relevant for CNO neutrinos. Low ^{42}Ar/^{42}K rates in UAr allow CNO neutrinos to be measured over the backgrounds, permitting a test of low/high metallicity solar models. **Bottom:** Sensitivity of the low-background module to the neutrino mixing parameter Δm^2_{21} is shown, assuming the true value to be the global solar fit reported in [11]. Sensitivities for various detector configurations are shown in comparison to a 400-kton-year exposure of the baseline DUNE horizontal drift (HD) design. Figures are taken from [2].

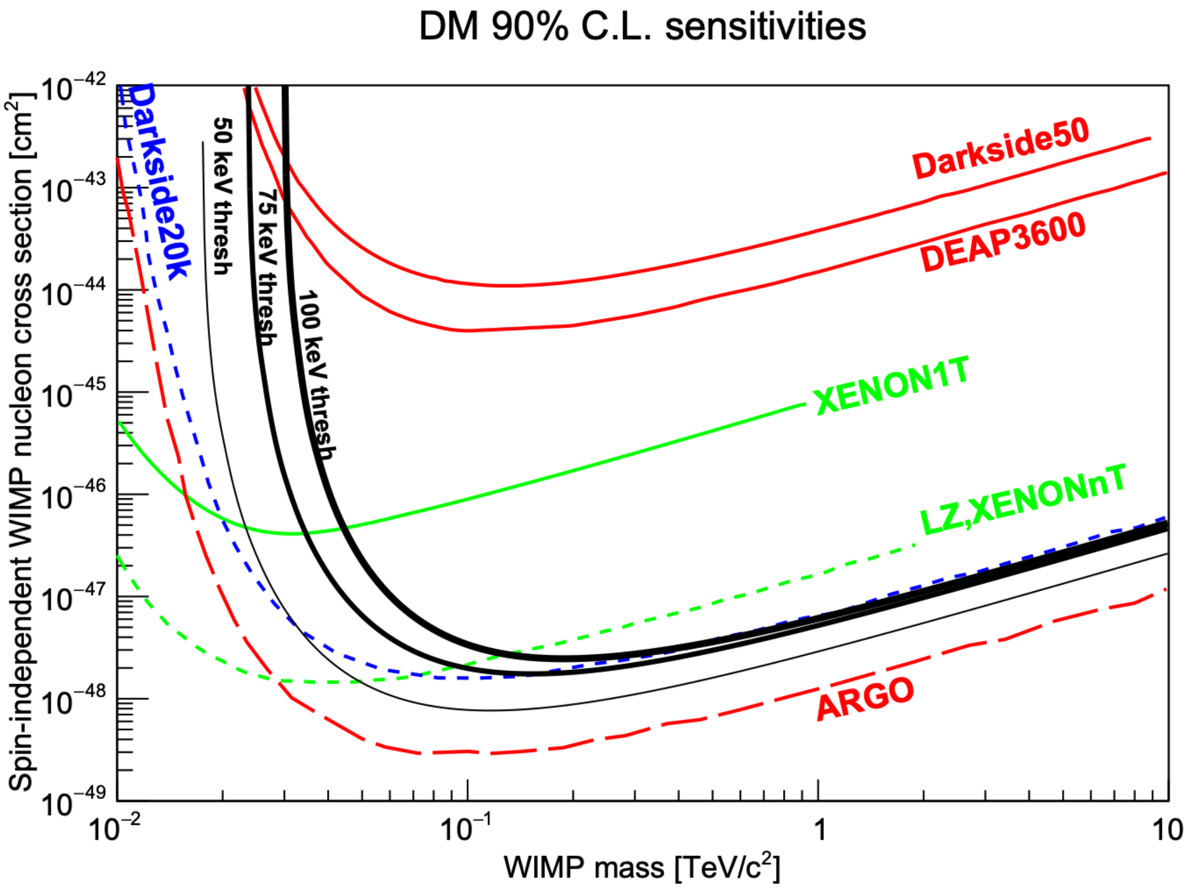


FIGURE 3. The spin-independent DM-nucleon cross-section 90 % C.L exclusion limits, showing in black the projected sensitivity of the low-background module for a 3 kton-year exposure for different thresholds compared to the sensitivities achieved (solid lines) or projected (dashed lines) by other argon-based (red or blue) or xenon-based (light green) experiments. Figure from [3].

The low-background module would also have excellent potential to detect annual modulation of a WIMP dark matter signal. The sun's rotation in our galaxy and the earth's motion around the sun causes the annual modulation of the WIMP flux impinging on terrestrial detectors. The low-background module will be particularly advantaged to measure the expected annual (and seasonal) modulation of the WIMP detection rate given the large fiducial mass (of 3 kTon) and anticipated long DUNE operation spanning a decade or longer. The ability of the low-background module to detect annual modulation and seasonal variation of the WIMP event rate is described in details in [2].

CONCLUSION

The concept of a low-background kton-scale detector with certain modifications to the proposed DUNE Vertical Drift (VD) design is presented. The detector could be a candidate for the third or fourth DUNE far detector module. With increased shielding, added radiopurity considerations, and an enhanced light-collection detection system, the detector is capable of carrying out a wide range of neutrino and dark matter searches. In particular, sensitivity to supernova neutrinos, solar neutrinos, neutrinoless double beta decay, and WIMP dark matter is greatly enhanced.

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