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DarkSide-LowMass:
New Detector for Light Dark Matter Search

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Dark matter candidates with masses below 10 GeV/c^2 hold promise, and a new detector, DarkSide-LowMass, is proposed based on the DarkSide-50 detector and progress towards the DarkSide-20k. DarkSide-LowMass is optimized for low-threshold electron-counting measurements, and sensitivity to light dark matter is explored for various potential energy thresholds and background rates. Our studies show that DarkSide-LowMass can achieve sensitivity to light dark matter down to the level of the solar neutrino fog for GeV-scale masses and significant sensitivity down to 10 MeV/c^2, taking into account the Migdal effect or interactions with electrons. Requirements for optimizing the detector's sensitivity are explored, as well as potential gains from modeling and mitigating spurious electron backgrounds that may dominate the signal at the lowest energies.

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1. Introduction

Dark matter (DM), constituting 26 % of the universe's energy density, has been the focus of numerous experiments, primarily targeting Weakly Interacting Massive Particles (WIMPs) with masses ranging from 10 GeV/c^2 to 10 TeV/c^2 [1–5]. In this mass range, planned experiments [6, 7] aim to search for WIMPs with cross sections down to "neutrino fog" [8], below which Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) may obscure DM signals.

Previous experiments have demonstrated the potential for similar technology to be used in dedicated light DM searches [9–11]. DarkSide-50 has shown that a dual-phase liquid argon time-projection chamber (LAr TPC), employing electron-counting analysis, is sensitive to DM with nuclear couplings for masses between 1 GeV/c^2 to 10 GeV/c^2 masses [12, 13], as well as electronic couplings for masses between 0.01 GeV/c^2 to 1 GeV/c^2 [14].

Dual-phase LAr TPC offers scalability, purity, and efficient detection of light DM recoils, which enable it to search for light DM down to the neutrino fog. Maximizing sensitivity requires a dedicated detector optimized for electron-counting analyses by enhancing the signal from the ionization channel and minimizing backgrounds. DarkSide-LowMass aims to employ such a detector. This proceeding is a summary of Ref. [15], where we explore the potential sensitivity of DarkSide-LowMass, considering possible analysis thresholds and background levels.

2. Detector Design & Backgrounds

For high-mass WIMP searches, DarkSide-50 employs primary scintillation (S1) and electroluminescence (S2). However, in low-mass searches using electron-counting analysis, the absence of (S1) compromises the rejection of electronic recoils (ERs) and the reconstruction of vertical positions. DarkSide-50's sensitivity was constrained by ERs originating from γ-rays and β-decays of ^{85}Kr and ^{39}Ar in underground argon (UAr) [16]. Spurious electrons (SEs), dominant in $<4\,e^-$ backgrounds at the lowest energies, impose an effective analysis threshold. Addressing SEs is crucial for enhancing DarkSide-LowMass's sensitivity.

The conceptual DarkSide-LowMass design has a nested structure to isolate and veto against radioactivity. The detector consists of the following elements; **Depleted Argon TPC:** the inner detector is a dual-phase TPC with an active (fiducial) mass of 1.5 t (1 t) of UAr, depleted of ^{39}Ar by cryogenic distillation [17]. Electroluminescence within a 1 cm-thick gas pocket at the top of TPC facilitates the counting of extracted electrons. Reflectors on the inner vessel surfaces, coated with wavelength shifters like TPB (tetraphenyl butadiene), convert VUV photons emitted by argon to ~420 nm. Two planes of photodetector modules (PDMs), positioned 10 cm above and below the TPC capture this light. Each PDM comprises a 5×5 cm^2 array of silicon photomultipliers (SiPMs) utilizing cryogenic pre-amplifiers developed for DarkSide-20k. **γ-ray vetoes:** the TPC is surrounded by two veto volumes. Firstly, the PDM buffer veto utilizes a 10 cm offset between optical planes and the acrylic vessel, acting as a "buffer" against γ-rays emitted by PDMs and related hardware. Additionally, the bath veto employs 4.5 t of UAr in the cryostat, instrumented with PDMs on the cryostat walls, serving as an additional γ-ray veto. **Water shielding:** the cryostat is in a 10 m-diameter water tank that shields against external radiation. If a cosmic-ray veto is desirable, the tank can be instrumented to detect Cherenkov light.

Backgrounds

At the lowest energies, SEs become the primary background. CEνNS from solar and atmospheric neutrinos, along with the Diffuse Supernova Neutrino Background (DSνB), constitutes an irreducible background. Due to space constraints, only selected backgrounds are discussed below; for a comprehensive background consideration, refer to Ref. [15].

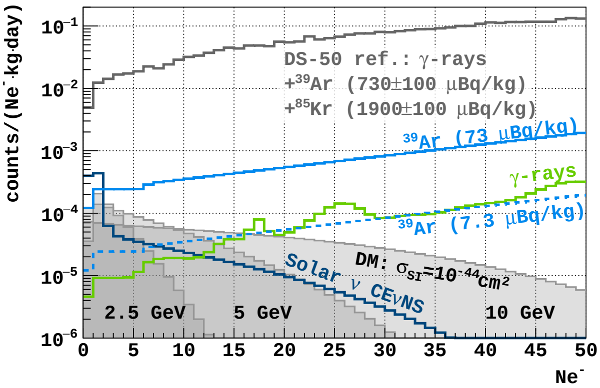

Figure 1: Backgrounds from γ-rays, ^{39}Ar, and CEνNS, compared to DarkSide-50. DM spectra for are shown at 2.5, 5 and 10 GeV/c^2 masses with spin-independent nucleon-scattering cross section $\sigma_{\mathrm{SI}} = 10^{-44}\,\mathrm{cm}^2$. Taken from Ref. [15].

γ-ray backgrounds: Radioisotopes emit γ-rays which scatter in the TPC. Dominant backgrounds encompass X-rays from acrylic and γ-rays from the PDMs, including photosensors and associated hardware–primarily from ^{40}K and the ^{238}U chain (^{238}U to ^{230}Th). Figure 1 illustrates total background rates after selection cuts, compared with DarkSide-50's best-fit backgrounds and example DM signals. Post veto cuts, the γ-ray background rate at $N_{e^-} < 12\,e^-$ falls below that from solar neutrinos.

β-decay backgrounds: Two naturally-present β-emitters, ^{39}Ar and ^{85}Kr, have been observed in UAr [18]. Improvements to the UAr extraction facility are expected to remove ^{85}Kr and significantly reduce the ^{39}Ar content relative to DarkSide-50's measurement. Further suppression of residual ^{39}Ar is achievable through the Aria facility [17], capable of depleting ^{39}Ar by a factor of 10 at a throughput of (8 ± 2) kg/d. The impact of varied ^{39}Ar activity on DM sensitivity is explored in Ref. [15] and is not discussed here.

Spurious electron backgrounds: In DarkSide-50, SEs dominate signals below $4\,e^-$. Leading hypotheses propose their origin from photo- and electrochemical interactions in LAr rather than particle scattering. A significant fraction of SEs follow preceding S2 signals by tens of ms exponential lifetime, with matching horizontal positions. The SE rate correlates with the total event rate, progenitors' drift time, and increases when the purification getter is excluded. Though further investigation is needed, SE properties align with impurities capturing and releasing drifting electrons. Purification methods like Aria and *in situ* improvements offer a potential reduction of SEs with purer LAr. For current studies, the N_{e^-} value determining SE dominance sets the analysis threshold, considering $2\,e^-$ and $4\,e^-$ thresholds.

3. Sensitivity projections & Conclusion

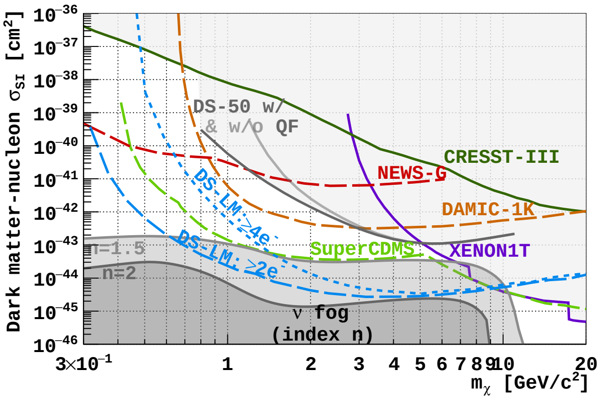

Figure 2: Projected 90% C.L. exclusion curves for the spin-independent DM-nucleon scattering cross section with 73 µBq/kg of ^{39}Ar, compared to (solid) current and (dashed) projected limits. Binomial quenching fluctuations and 1 t yr exposures are assumed. Taken from Ref. [15].

DarkSide-LowMass's sensitivity is assessed using the profile likelihood ratio test statistic, projecting median 90% C.L. upper limits for a 1 t yr exposure. Longer exposures marginally enhance sensitivity, as neutrino backgrounds impose limitations. Conservative reductions in ^{39}Ar and SE backgrounds extend exclusion sensitivity into the neutrino fog for a 1 t yr exposure, illustrated in Fig. 2. Exploring alternative scenarios with additional reductions in SE and ^{39}Ar backgrounds further extends sensitivity down to 1 GeV/c^2.

The study demonstrates that a tonne-scale dual-phase LAr TPC, utilizing current technology, can attain sensitivity to DM with nuclear couplings in the solar neutrino fog with a 1 t yr exposure. This feat can be accomplished by employing a detector akin to DarkSide-50, scaled to a larger target mass, with available UAr further reduced in ^{39}Ar by Aria. However, uncertainties persist in modeling LAr's ionization response to low-energy nuclear and electronic recoils, particularly at lower masses. New measurements, like those from the ReD experiment [19], may alleviate these uncertainties, proving beneficial for DarkSide-LowMass.

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