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Search for annual modulation of the event rate generated by dark matter in the DarkSide-50 ionization signal

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DarkSide-50 is a direct detection experiment at LNGS in Italy searching for dark matter. It utilizes a dual-phase argon time projection chamber. On the basis of the ionization spectrum alone, it has established the most stringent exclusion limit for dark matter candidates with masses below 1.4 GeV/c^2. By exploiting the expected variation of the relative velocity between dark matter and Earth, one can search for dark matter in a model-independent manner. We describe the first search for such an event rate modulation with argon using the DarkSide-50 ionization signal. Likelihood and Lomb–Scargle analyses were used to look for a 1 year period peaking at June 2$^{\text{nd}}$. As a result of years of stable operation of the detector and a thorough knowledge of its response, we were able to obtain the lowest energy threshold, 0.04 keV$_{ee}$, ever achieved in this kind of experiments.

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1. Introduction

Within a stationary halo, the Sun's orbit around the galactic center generates a continuous flow of dark matter in Earth's reference frame. Its velocity undergoes annual variations due to Earth's orbit around the Sun. This results in an annual modulation in the observed event rate. The scattering rate can be approximated to

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cos(\omega(t-\phi)),$$

with $\omega = 2\pi/T$, T the time period and ϕ the phase of the modulation. The modulation is expected to peak on June 2$^{\text{nd}}$, with the amplitude S_m predicted to be a fraction of the constant contribution S_0. The amplitude will be contingent upon the exact halo model. This approach enables a straightforward comparison with other experiments (see Fig. 1). With the Lomb-Scargle (LS) analysis (see [4] for an overview) we were able to perform an analysis independent of the phase and period, covering some extension of the Standard Halo Model (e.g. SHM^{++} see [6]).

2. DarkSide-50 ionization signal

The DarkSide-50 Time Projection Chambers (TPC), located at the *Laboratori Nazionali del Gran Sasso* (LNGS), detects scintillation signals (S1) resulting from energy deposition in the liquid target (LAr) and ionization (S2) signals. Electrons are drifted into a thin gas layer above the LAr, then extracted from it, producing a secondary electroluminescence scintillation. It is filled with an active mass of (46.4 ± 0.7) kg of low-radioactivity argon extracted from a deep underground source (UAr) [5]. This study uses data from August 2, 2015 to February 24, 2018. Although the UAr runs began in April 2015, we remove the period required for low energy calibration with higher ^{37}Ar activity. The overall livetime is 693.3 days, spanning 31 months without any break longer than 30 days.

Event reconstruction and selection use the same procedure as the spectrum analysis [2]. Due to the low detection efficiency of the S1 photons (0.16 ± 0.01), the selected events are divided into two categories S2-only or S1 plus S2. In this work, the event position is defined as the location of the top-array photomultiplier tubes (PMT) that detects the greatest fraction of S2 photons. Events that are detected within the outermost ring of PMTs are rejected due to the presence of external radioactive background, notably αs and γs. The signal acceptance for this cut is calculated to be 41.9%. Ne^-, the energy observable utilized in this analysis, refers to the quantity of electrons detected. It is defined as the quotient of the corrected number of S2 PE with the S2 yield, g_2, the mean number of PE per ionization electron. The trigger efficiency is assessed to be 100% across the entire range of interest. The selection of the lower bound of the region of interest (RoI), 4 Ne^-, is motivated by the need to prevent interference from spurious ionization electrons. Dedicated investigation is needed to understand their origins. We hypothesize that some electrons may become caught by trace amounts of impurities in LAr and then released later, becoming S2 only events.

3. Detector stability

This analysis relies on detector performance stability. The assessment involves monitoring sensors in the cryogenic system and the examination of observed events from the TPC. Based on

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the system's radioactive contamination and cumulative exposure, DarkSide-50 is expected to detect and respond to a modulation amplitude of about 1% of the observed event rate. Some critical parameters are g_2 [PE/e^-], stable within 0.5% traced by the S2/S1 ratio of continuous electronic recoil background above the RoI, consistent with measurement from α-ray peaks and to appropriate sensor readings inside the cryogenic system. And the drift field, F_d [V/cm], traced by the drift time, ΔT_{S1-S2} showing 0.01% variation. We performed an examination on all sensors, assessed potential seasonal changes and their non-trivial influence. Correlation coefficients with Pearson, Spearman and Kendall methods, are well-contained between -0.07 and 0.10 (p-values > 0.01) for all Ne^- ranges. Additionally, a time-delayed correlation analysis was conducted; results indicate no significant impact on TPC event rate, with coefficient values ranging from -0.08 to 0.10. Due to the stability and low correlation of the sensors with the TPC event rate, we can confidently say that even tiny observed variations are not significant.

Finally, we did a sanity analysis on all parameters using the LS periodogram. Few parameters exhibit a 1 year periodicity with a 3σ significance, most notably Ar pressure and temperature in the cryostat, nitrogen dewar liquid level, and auxiliary pump temperatures. Due to the stability of Ar pressure and temperature, and the lack of a known mechanism affecting the TPC performance, the few periodic parameters found in the LS analysis do not have an impact on the final result [3].

4. Annual modulation search

We performed a likelihood analysis (see [1] for a full description), defining the dark matter event rate time dependencies with a cosine signal,

$$f(t) = S_m \cos\left(\frac{t-\phi}{T/2\pi}\right) + \sum_l \frac{A_l}{\tau_l} e^{-t/\tau_l} + C, \quad (l = {}^{37}\mathrm{Ar}, {}^{85}\mathrm{Kr}, {}^{54}\mathrm{Mn}, {}^{60}\mathrm{Co})$$

where ϕ is the phase, S_m introduced in Sec.1 and T the 1 year fixed period. The constant term C is the sum of the long-lived backgrounds (such as ^{39}Ar) and time-averaged signal component, A_l and τ_l are the activities and decay time, of the short-lived isotopes. The likelihood fit reveals no evidence of modulation in any of the analysed ranges, the best fit values of S_m as well as the 68% and 95% confidence level contours are depicted in Fig. 1 (Left). Fig. 1 (Right) shows the result of our 2D likelihood fit simultaneously fitting event timestamps and energies, where both ϕ and T are fixed and we employ a smaller binning in order to take advantage of the correlations that exist between Ne^- bins. The data are in agreement with the null hypothesis across all energy ranges. It is important to point out that our experiment achieves the lowest energy threshold of 0.04 keV$_{ee}$ but neither confirm nor reject the DAMA's observation.

Finally, a LS analysis was conducted on the event rate's time-series to detect sinusoidal signals of any period. The analysis is performed on the residual data after subtracting the best-fitted background model. The Bootstrap approach [4] is used to compute the false alarm probability and evaluate the relevance of sinusoidal signals. To assess the sensitivity of this analysis, we used Monte-Carlo simulations with the addition of an annual modulated signal. Adding 0.03 count/d/kg/keV yields a median of 1σ significance for the false alarm probability, Fig. 2 (Left) present our results with 1 and 2 σ bands corresponding to toy-MC data-sets with the addition of 0.02 count/d/kg/keV. Fig. 2 (Right) shows no significant modulation signal within our analyzed intervals.

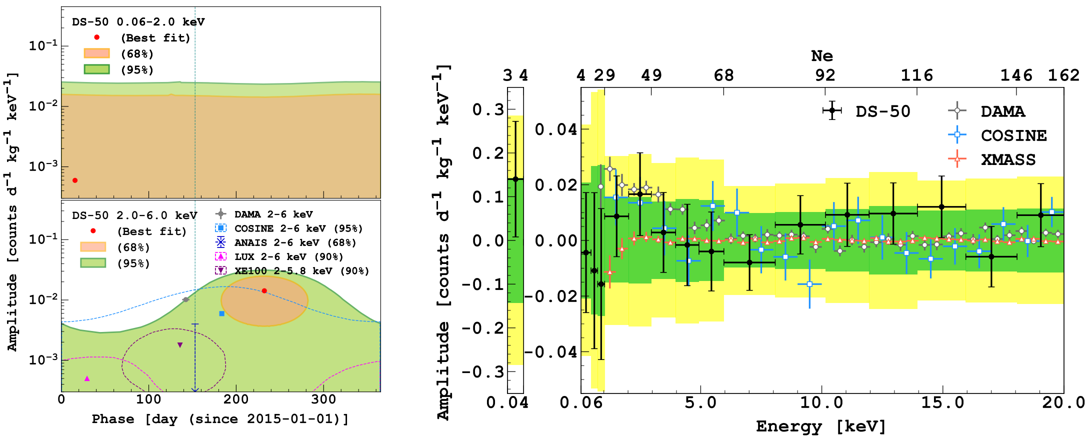

Figure 1: Left: Best fit parameters from the likelihood analysis in the amplitude versus phase space, with a fixed one year period. **Right**: Best fit amplitude of the modulation signal as a function of Ne$^-$. The green and yellow bands represent the expected 1σ and 2σ statistical fluctuations derived by background only Monte Carlo samples.

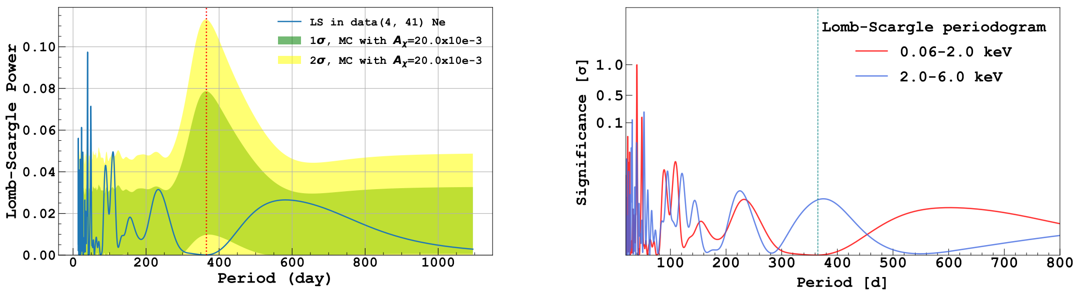

Figure 2: Left: LS periodogram in 4-41 Ne$^-$. The green and yellow bands represent the expected 1σ and 2σ statistical fluctuations derived by background plus signal Monte Carlo samples, with S_m = 0.02 count/day/kg/keV. **Right**: Results of the LS analysis in 4-41 Ne$^-$ and 41-68 Ne$^-$, normalized by the false alarm probability calculated with the bootstrap method (see [4] for further details)

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