Search for Dark Matter Induced Event Rate Modulation in DarkSide-50 Ionization Signal

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19th July 2023 | 31st Lepton Photon at Melbourne





Annual Modulation Signal

- The Sun moves toward the Cygnus, leading to a boost of the dark matter velocity distribution: "*Dark Matter Wind*"
- The Earth's rotation around the Sun increases the boost around June and decreases around December

Event rate in terrestrial detectors above the energy threshold modulates annually

• The DAMA/LIBRA's observation with NaI(TI) crystal

- Modulation signature above the energy threshold of 0.75 keV
- Traditional WIMP model faces challenges from the null-detection in many other experiments

—This talk (arXiv:2307.07249) Model-independent modulation search down to 0.04 keV with Argon





Dual-Phase Argon TPC

S2 light fraction

GAr

LAr

Photo-

detectors

Z position

from ΔT_{51-52}

fel

(Drift field)

• $M_{Ar} = 40 \text{ GeV/c}^2$:

Gaining recoil-energy from ~10 GeV/c² DM w.r.t. Ge, Xe, ..(kinematics)

- Two time-separated light signal, primary scintillation and secondary electroluminescence (from ionization e⁻)
- Efficient ER rejection from NR thanks to the Scintillation Pulse Shape Discrimination and S2/S1 Ratio



Dual-Phase Argon TPC Vc²:

GAr

_Ar

Photo-

detectors

(Drift field)

Z position from $riangle T_{S1-S2}$

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- Efficient electron extraction (~100%) and electroluminescence amplification (g₂, >20 PE/e-)



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Bosnia and Genoa Herzegovina **Rn-Free** Saraievo San Marino Florence Monaco o Clean Room Italy Monter onal Institute uclear Physics Полгориц Naples Materao Taranto Lecce Pompei Sardegna Cagliari Reggio Paler Calabria Trapanio Gran Sasso þ ostat containing U ON

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The DS-50 Results

100 150 200 250 300 350 400 450

S1 [PE]

"High-Mass" WIMP Seach "Low-Mass" Dark Matter Seach **Ionization Only Pulse Shape Discrimination** -466 No requirement on S1 E 90 Atmospheri WIMP Expected Region (- Detection efficiency g1 ~ 16%) Argon 456 No NR/ER discrimination Ο. 0 (2015) 25000 0.6 20000 0.5 300 ~100% detection efficiency for 3e- (0.04 keV) 15000 743 0.3 10000 Select single-scatter S2 pulse 1.5x10⁷ events of ³⁹Ar 0 5000 Electron Recoil Energy [keVer] Underground 0.04 0.13 0.20 0.55 1.10 450 Argon day) Energy [keVnr] Underground 80 100 120 140 160 180 2 ğ RD 98 (2018) 102006 Argon 0.9 Ne +S2/S150 40 0.5 Background free over 30 0.4 Inner Lume re than 530 days 0.3 20 0.00 0.2 100 170 10 Number of Electrons

This work is based on the preceding analysis

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DS-50 UAr Run History



(PRD 107 063001, PRL 130 101001, PRL 130 101002. EPJC 83 322)

- Filled at 04/2015, ended at 02/2018
- Continuous data taking without significant breaks
- This work uses the full dataset except the initial one for the lowenergy calibration
- Total livetime = 693 days (over the 2.5 years)

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Detector Stability

- The critical parameters : g_2 [PE/e-] and F_d [V/cm]
 - 1% of fluctuation could lead to a fake signal
- g₂ is traced by the S2/S1 ratio of continuous ER above the region of interest:
 0.5% variation at most
 - Consistent to the measurement from α-ray peaks (limited by statistics)
 - Consistent to sensor readings inside the cryogenic^{$\frac{1}{4}$} system that are sensitive to g_2
- *F_d* is traced by ΔT_{S1-S2} from the bottom:
 0.01% variation



Likelihood Fit

- Four radioactive isotopes decaying in 3 years are taken into account
- Event rate as a function of time is modeled with a cosine signal:

$$f(t) = \underbrace{A_{\chi}}_{\substack{\text{Signal} \\ \text{amplitude}}} \cos\left(\frac{t-\phi}{\underline{T}/2\pi}\right) + \sum_{l} \frac{A_{l}}{\tau_{l}} e^{-t/\tau_{l}} + \underbrace{C}_{\substack{\text{Inclust} \\ \text{(no c})}}$$

ncluding long-lived isotope no constrain)

• Likelihood fit to the model with 7-d time bin:

$$\mathscr{L} = \prod_{i \in t_{\text{bins}}} \mathscr{P}\left(n_i | m_i(A_{\chi}, \phi, C, \Theta)\right) \times \prod_{\theta_k \in \Theta} \mathscr{G}(\theta_k | \theta_k^0, \Delta \theta_k).$$

- The nuisance parameters come from the spectrum analysis

lsotope (/)	t _{1/2}	Place	Constrained by	
³⁷ Ar	35 d	LAr	Initial dataset	
⁸⁵ Kr	10.8 y	LAr	Same dataset above Rol	
⁵⁴ Mn	312 d	PMT	Screening	
⁶⁰ Co	5.3 y	PMT&Cryostat	Screening	

Parameter	$ heta_k^0$	$\Delta \theta_k$
Т	$1{ m yr}$	0
Fiducial volume	$19.4\mathrm{kg}$	1.5%
$ au_{ m 37Ar}$	$35.0\mathrm{d}$	0
$ au_{ m ^{85}Kr}$	$10.8\mathrm{yr}$	0
$ au_{54}{ m Mn}$	$312.1\mathrm{d}$	0
${ au_{ m Co}}_{ m Co}$	$5.27\mathrm{yr}$	0
$A_{ m 37Ar}$	$2.1 \mathrm{counts}/(\mathrm{dkg})^{\dagger}$	14%
$A_{ m ^{85}Kr}$	$1.7 \mathrm{counts}/(\mathrm{dkg})^\dagger$	4.7%
$A_{^{54}\mathrm{Mn}}$	$0.02 \mathrm{counts}/(\mathrm{dkg})^{\dagger}$	40%
$A_{^{60}\mathrm{Co}}$	$0.58 \mathrm{counts}/(\mathrm{dkg})^{\dagger}$	12%
85 Kr β -decay spectrum	$1.7\mathrm{counts}/(\mathrm{dkg})^\dagger$	0.7%
Ionization response	$4.4\rm{counts}/(\rm{dkg})^\dagger$	0.4%

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- Neither confirm nor reject the DAMA's observation

Periodogram Analysis



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- Lomb-Scargle periodogram is applied to look for any periodical signal
 - Residuals of the background-only fit are converted into the frequency space

No significant signal is observed

Analysis in 3e- Bin

- More events than the expectation from the radioimpurities,
 - They have been suppressed by a 20-ms veto after each trigger
 - No a priori prediction on their properties
- For this analysis, they are characterized with sideband samples



umber of Electron

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 The relative change of the SE rate in N_e=3 is traceable from the time-correlated rate below 3e-:

$$R_{\rm SE}(t_i, N_e = 3) = \alpha \times \left(\sum R_i(t_i)\right)$$

- Added to this term only in the first bin (N $_{\rm e}{=}3)$ of the model



Sourious

Electron Recoil Energy [keVer]

Observed

Results from 2D Fit

• Simultaneous fit in both time and energy bins:

$$\mathscr{L} = \prod_{i \in t_{\text{bins}}} \prod_{j \in E_{\text{bins}}} \mathscr{P}\left(n_i^j | m_i^j(A_{\chi}^j, C^j, \tilde{\Theta})\right) \times \prod_{\tilde{\theta}_k \in \tilde{\Theta}} \mathscr{G}(\tilde{\theta}_k | \tilde{\theta}_k^0, \Delta \tilde{\theta}_k),$$

- Fixed the phase φ (June 2nd) and period T (1-yr)
- Amplitudes of the short-decayed component for each energy bin are correlated



Summary



- Oark-matter-induced event rate modulation search using the 2.5 years dataset from the DarkSide-50 ionization signal →arXiv:2307.07249
 - Owing to the stable operation of the detector over years, grounded in the matured S2-only analysis technique
 - The lowest energy threshold of **0.04 keV** is achieved
 - First such search using argon as target material
- In none of the analyzed intervals, a modulation signal is observed
 - Neither confirm nor reject the DAMA/LIBRA's positive observation
- The next generation, DarkSide-20k, is coming
 - x400 mass, 10-y exposure, less instrumental background level
 - Data taking expected in 2026



Backup





The DarkSide Program - Direct Dark Matter Search with Argon TPC -



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Event Selection

Fiducialization

- Select event with max fraction of detected S2 photoelectron in one of the 7 central top PMTs
- Acceptance ~ 41%

Alpha-induced S2

- Reject events with
 "anomalous" S2/S1 ratio,
 originated from α-decay on
 the detector surface
- Cut tuned on calibration data
- Acceptance ~ 99%





Spurious electrons

- Reject time-correlated events if within 20 ms from the previous one
- Acceptance ~ 97%



Background



Ionization-Only Results





NuSTAR (2020

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20

 m_{ν} (keV/ c^2)

25

30

35

10

10-4

20





