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Study of low-energy nuclear recoils in liquid argon with the ReD experiment

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Abstract: Liquid Argon (LAr) Time Projection Chambers (TPC) operating in double-phase can detect the nuclear recoils (NR) possibly caused by the elastic scattering of WIMP dark matter particles via light signals from both scintillation and ionization processes. In the scenario of a low-mass WIMP (< 2 GeV/c^2), the energy range for the NRs would be below 20 keV, thus making it crucial to characterize the ionization response in LAr TPCs as the lone available detection channel at such low energy. The Recoil Directionality (ReD) project, within the Global Argon Dark Matter Collaboration, aims to measure the ionization yield of a LAr TPC in the recoil energy range of 2–5 keV. The measurement was performed in winter 2023 at the INFN Sezione of Catania and the analysis is ongoing.

Keywords: Noble liquid detectors (scintillation, ionization, double-phase); Time projection chambers; Dark Matter detectors (WIMPs, axions, etc.); Ionization and excitation processes

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Contents

1 Direct Dark Matter searches in liquid argon TPC

Direct searches for Dark Matter (DM) focus on detecting a signal from its interaction with baryonic matter in underground detectors. The so-called Weakly Interactive Massive Particle (WIMP) is a theorized candidate. In recent years, Time Projection Chambers (TPC) filled with a noble element in both liquid and gaseous phases proved to be a promising technology in this field [1, 2].

The signals in a dual-phase TPC are the prompt scintillation light in liquid (S1) and the delayed electroluminescence signal (S2) in gas. The latter is due to ionization electrons that avoid recombination thanks to an electric field (E_D) that drifts them toward the gas-liquid interface on the upper part of the TPC. Two more fields, stronger than the previous, are used to accelerate and multiplicate the electrons extracted in the gas. The S2 signal is proportional to the number of electrons N_e via the gain factor g2, which is defined as the number of photo electrons (PE) per extracted electron, and is an detector-dependent parameter. The time delay between S1 and S2 gives the z coordinate of the interaction point in the detector, while the transverse (x, y) position is obtained from the hit pattern of the S2 signal on the photosensors of the TPC. The DarkSide collaboration, as a member of the Global Dark Matter Collaboration (GADMC), chose argon as the target material for its DarkSide-50 experiment, a 50 kg LAr TPC operated at INFN Laboratori Nazionali del Gran Sasso (LNGS) until 2018 [3]. DarkSide-50 looked for a WIMP particle with a mass at the electroweak scale with an expected recoil energy of the order of tens of keV [1]. Scintillation light allows to distinguish nuclear recoil (NR) events from electron recoil (ER) events of the background using the pulse shape discrimination (PSD) technique, that results in a different time profile of S1 signal for the two different types of events [3].

A relevant result from DarkSide-50 is that a LAr TPC could be optimized for an electron-counting analysis, thus being sensitive also to WIMP particles with a mass of $O(\mathrm{GeV/c^2})$. These so-called *low-mass* WIMPs, are still compatible with the constraints of the theory [4], but more challenging to detect. A low-mass WIMP should produce NRs in the range of a few keV, and at this energy scale scintillation signals are often difficult to detect. The only available detection channel is the ionization one, and the absence of the scintillation signal does not allow PSD method to be used. DarkSide-50 performed a S2-only analysis extending the exclusion region for spin-independent dark matter interactions and improving the current experimental constraints in the [1.2, 3.6] GeV/c^2 WIMP mass range [5]. A comprehensive knowledge of the ionization yield of argon recoil is needed for the analysis, but the literature does not provide a detailed dataset for the energy range of interest. The lowest data points available in the literature are those of Joshi et al. [6] and ARIS [7], which investigate the ionization yield in argon for NRs at 6.7 keV and 7 keV, respectively, while the expected energy E_{Ar} for the argon recoil could be at the sub-keV scale. The ionization yield of the argon has been modeled down to 0.5 keV using the Geant4 tool `g4ds`, providing Monte Carlo simulations fed with the calibration datasets of AmBe and AmC collected by DarkSide-50 to develop a two-parameter model [8]. However, the model is sensitive to the ionization quenching effect, whose fluctuations could change the detection probability of an event over the threshold. For this reason, it is mandatory to measure the ionization yield for low-energy argon recoils applying the two-body kinematic approach.

2 The ReD project: strategy and experimental setup

Among the R&D projects designed by the GADMC in sight of the future multi-tonne experiment DarkSide-20k [9] there is also a project dedicated to the characterization of the ionization signal S2 at low energy argon recoils. The Recoil Directionality (ReD) experiment aims to cover the low energy range of 2–5 keV in the ionization response of LAr by irradiating a miniaturized dual-phase TPC with neutrons from a ^{252}Cf fission source. NR are produced in the TPC via elastic scattering (n,n') of neutrons off argon. Those argon recoils with energy in the region of interest are selected by detecting the outgoing neutrons using a neutron spectrometer with 18 plastic scintillators (Pscis) placed at a fixed angular range to close the kinematics. The E_{Ar} is calculated in a purely-kinematical approach as

$$E_{\mathrm{Ar}} = 2E_n \frac{m_n m_{\mathrm{Ar}}}{(m_n + m_{\mathrm{Ar}})^2}(1 - \cos\theta_{\mathrm{scatt}}), \tag{2.1}$$

where E_n is the kinetic energy of the neutron. ^{252}Cf produces neutrons with an energy up to 10 MeV, so Time of Flight (ToF) measurements are required to calculate E_n event by event from the time interval taken for the neutron to travel the fixed distance between two tagger detectors. The start time is given by one of the two $\mathrm{BaF_2}$ detectors deployed close to the source, while the stop is recorded by the hit Psci in the neutron spectrometer. Figure 1 shows a sketch of the experimental apparatus.

The ^{252}Cf source has an activity of 1.0 MBq ($2.6{\cdot}10^4$ fission/s) and it is kept inside a shield made by layers of boron loaded high-density polyethylene (HDPE), lead and iron. The two $\mathrm{BaF_2}$ detectors are coupled with photomultipliers (PMT) and used as tagger detectors for the accompanying γs of

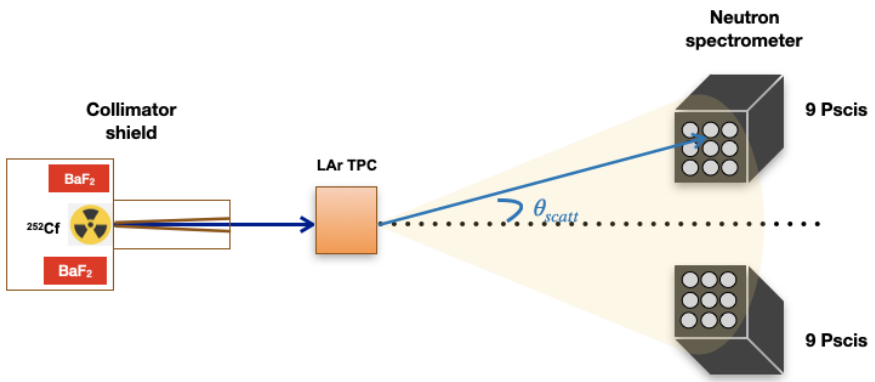

Figure 1. Experimental setup of the ReD experiment. The blue arrow stands for the path traveled by the neutron before scattering elastically inside the TPC, the cyan one is the possible path of the outgoing neutron n' within the solid angle seen by the neutron spectrometer. All elements are described in the text.

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fission events. Neutrons emitted are absorbed by the walls except for a flux collimated by an exit cone of 2° and directed toward the LAr TPC placed at 90 cm from the source. ReD has a small-scale TPC ($5 \times 5 \times 6\,\mathrm{cm}^3$) equipped with Silicon Photomultipliers (SiPM) operated at cryogenic temperature as readout system [10]. SiPMs are mounted on a $5 \times 5\,\mathrm{cm}^2$ tile, and a tile contains 24 channels. The TPC has two tiles, one on the top part and the other on the bottom part of the volume. The SiPMs on the top tile are read out individually to obtain a better spatial resolution for the S2 signals, while the bottom tile has only 4 readout channels (SiPMs summed in four groups of six). The E_D field is set between two acrylic windows coated with indium tin oxide (ITO), a transparent conductive oxide, to make them conductive and act as cathode and anode; the field value is about 200 V/cm, so the maximum drift time for electrons is 55 µs. More details on the TPC of ReD can be found at reference [10].

The neutron spectrometer is placed 100 cm downstream of the TPC. It has two 3×3 matrices of EJ-276 Psci. These scintillators are used to perform n/γ PSD of the particle hitting the spectrometer, while their small diameter (1 inch) allows to obtain a better granularity on the neutron position in the kinematics calculation. The two matrices are outside the direct neutron flux exiting the shield and cover an angular range of $\theta_{\mathrm{scatt}} = 12°–17°$. To control the alignment systematics the matrices are placed symmetrically at about 25 cm above and below the TPC level.

3 Preliminary data analysis

ReD collected data at the INFN Sezione di Catania for three months, from January to March 2023. As already mentioned, the S1 signal is often difficult to detect in low-energy recoil events, so the TPC is not included in the trigger. The trigger logic requires the `AND` between one BaF_2 (the two BaF_2 are in `OR`) and any of the Pscis (Pscis in `OR`). The ToF measurement are used to label an acquired event as a neutron one: the accepted range of ToF for a ^{252}Cf neutron flight from BaF_2 to a Psci is [40,180] ns. The resolution achieved in ToF is 0.7 ns rms, which results in a measurement of the kinetic energy of neutrons better than 5%. Events falling in the same ToF range but that are due to γ rays are rejected via PSD on the light signal seen in the neutron spectrometer. Such events are caused by background γ rays, either from the ^{252}Cf source or from the environment, which accidentally populate the coincidence ToF window. Once this selection step is done at the tagger detectors, the signals recorded by the SiPMs in the TPC are scanned to search for a valid event. The digitized charge pulse of the SiPMs is scrutinized applying a dedicated pulse finder algorithm fully efficient for S2 signal above 70 PE (~4 electrons). The final dataset includes TPC events with a single valid S2 signal within 55 µs from the BaF_2 signal and within the fiducial inner (x,y) region ($4 \times 4\,\mathrm{cm}^2$) of the TPC, for a total of about 600 events. This selection also discards events featuring a S1 signal, mainly originated by multiple neutron scattering, as confirmed also by the Monte Carlo simulation. For these S2-only events the E_{Ar} is calculated event by event according to equation (2.1), with a typical uncertainty of ± 5%. Figure 2 shows the S2 signal as a function of the calculated E_{Ar}. The spread in the data is mostly due to the geometry effect related to the interaction point within the Pscis, including also intrinsic fluctuations, and it is compatible with the expectations from the Monte Carlo simulation. The design goal of populate the energy range of 2–5 keV is met and even improved, as ReD collected data for NRs down to 1 keV. To compare the data collected with the literature, it is necessary to determine the gain factor g2, as done in ref. [10], and the analysis is in progress. Once that the data are scaled from PE to N_e it will be also possible to compare the results with the two ionization yield values reported in [6] and [7].

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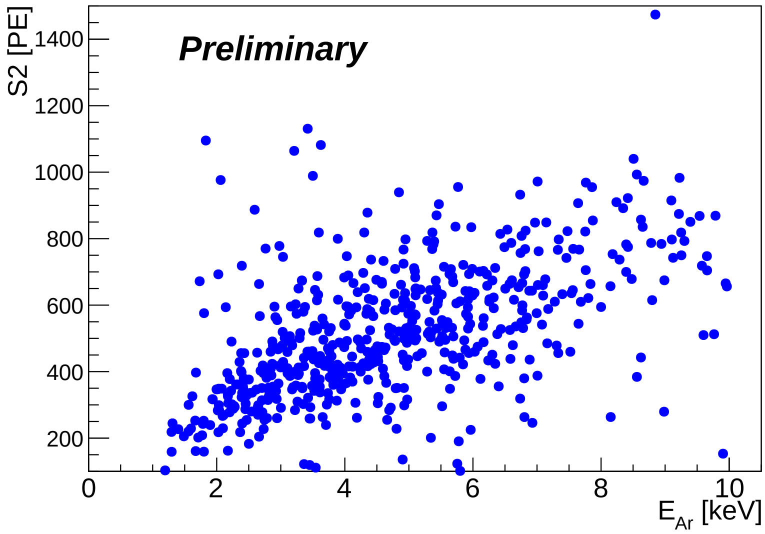

Figure 2. (Preliminary) S2 signal vs. calculated recoil energy E_{Ar} for events with a single neutron scattering in the TPC.

4 Conclusions

Dual-phase argon TPCs can be sensitive to light WIMP particles by exploiting the electroluminescence signal in gas due to the ionization electrons. A detailed S2-only analysis requires better constrains on the ionization response of LAr to low-energy NRs. The ReD experiment succed in cover the gap to 1–2 keV with a two-body kinematic approach. The analysis is ongoing to finalize the measures of the ionization yield and to constrain the parameter of the model developed by DarkSide-50 [11] for the next generation of experiments devoted to the light dark matter searches [12].

References

[1] DarkSide collaboration, *DarkSide-50 532-day Dark Matter Search with Low-Radioactivity Argon*, *Phys. Rev. D* **98** (2018) 102006 [arXiv:1802.07198].

[2] XENON collaboration, *First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment*, *Phys. Rev. Lett.* **131** (2023) 041003 [arXiv:2303.14729].

[3] DarkSide collaboration, *Results From the First Use of Low Radioactivity Argon in a Dark Matter Search*, *Phys. Rev. D* **93** (2016) 081101 [*Addendum ibid.* **95** (2017) 069901] [arXiv:1510.00702].

[4] T. Lin, H.-B. Yu and K.M. Zurek, *On Symmetric and Asymmetric Light Dark Matter*, *Phys. Rev. D* **85** (2012) 063503 [arXiv:1111.0293].

[5] DarkSide-50 collaboration, *Search for low-mass dark matter WIMPs with 12 ton-day exposure of DarkSide-50*, *Phys. Rev. D* **107** (2023) 063001 [arXiv:2207.11966].

[6] T.H. Joshi et al., *First measurement of the ionization yield of nuclear recoils in liquid argon*, *Phys. Rev. Lett.* **112** (2014) 171303 [arXiv:1402.2037].

[7] P. Agnes et al., *Measurement of the liquid argon energy response to nuclear and electronic recoils*, *Phys. Rev. D* **97** (2018) 112005 [arXiv:1801.06653].

[8] DarkSide collaboration, *Simulation of argon response and light detection in the DarkSide-50 dual phase TPC*, 2017 *JINST* **12** P10015 [arXiv:1707.05630].

2024 JINST 19 C04054

[9] DarkSide-20k collaboration, *DarkSide-20k: A 20 tonne two-phase LAr TPC for direct dark matter detection at LNGS*, *Eur. Phys. J. Plus* **133** (2018) 131 [arXiv:1707.08145].

[10] P. Agnes et al., *Performance of the ReD TPC, a novel double-phase LAr detector with silicon photomultiplier readout*, *Eur. Phys. J. C* **81** (2021) 1014 [arXiv:2106.13168].

[11] DarkSide collaboration, *Calibration of the liquid argon ionization response to low energy electronic and nuclear recoils with DarkSide-50*, *Phys. Rev. D* **104** (2021) 082005 [arXiv:2107.08087].

[12] Global Argon Dark Matter collaboration, *Sensitivity projections for a dual-phase argon TPC optimized for light dark matter searches through the ionization channel*, *Phys. Rev. D* **107** (2023) 112006 [arXiv:2209.01177].

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