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The ReD experiment for low-energy nuclear recoils in a liquid argon TPC(*)

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Summary. — Time Projection Chambers filled with Ar in double phase are largely employed in the direct detection of Weakly Interacting Massive Particles (WIMPs) as Dark Matter candidates. Models predict WIMP with a mass at the electroweak scale, so the expected energy of the Ar nuclear recoil after a WIMP-induced scattering is in the range of tens of keV. However, if these particles had mass at the GeV/c^2 scale, the deposited energy would drop to a few keV. In this scenario, WIMP direct detection will become challenging but still possible in these detectors, as proved by recent studies on the data collected by DarkSide-50. Since the future generation of multi-tonnes experiments aims to be sensitive also at this low-mass scale, the REcoil Directionality (ReD) experiment underwent a campaign to investigate the ionization response of LAr down to a few keV.

1. – Signals in a LAr TPC and low-mass searches in DarkSide-50

A WIMP could interact in an Earth-based Liquid Argon Time Projection Chamber (LAr TPC) and produce a nuclear recoil which deposits its energy. This energy can be detected via a prompt scintillation signal (S1). Moreover, due to the presence of an electric field, electrons formed after ionization are drifted upward to the liquid-gas interface, extracted and accelerated in gas by two stronger fields, to give a delayed electroluminescence signal (S2). The time profile of the S1 signal can be used to separate the signal of a Nuclear Recoil (NR) event from a background signal due to an Electron Recoil (ER). Together with this Pulse Shape Discrimination (PSD) method, it is also possible to select events of interest within a fiducial volume. The position of an event can be reconstructed using the light pattern of the S2 signal on the (x,y) plane and the time difference between S1 and S2 (z-direction).

WIMPs are expected to have a mass of 100's of GeV/c^2, so the energy range for the NR in Ar is from 10 to 100 keV$_{nr}$. However, a dark matter candidate with a mass $\leq$ 10 GeV/c^2 can be also acceptable according to the constraints of the theory [1]. The LAr TPC of DarkSide-50 [2] was designed to be sensitive to standard WIMPs, but the collaboration tried also to investigate the sensitivity of the detector to lighter dark matter particles, *i.e.*, with a mass of the order of GeV/c^2, the so-called *low-mass* WIMPs.

A NR event from such a particle often does not have enough energy to give a detectable S1 signal and the only detection channel available is the ionization one [5]. This so-called *S2-only* analysis is challenging since requires a detailed knowledge of the background and can not rely on the possibility of applying the PSD technique or reconstructing the vertical position of an event to select the fiducial volume in 3D. However, DarkSide-50 was able to set the current best limit for a WIMP with a mass in the range [1.2,3.6] GeV/c^2 [3].

Future improvements in this research field will be carried out by the DarkSide-20k experiment [4]. A deeper investigation of the response of LAr, especially to learn more about the ionization quenching phenomenon, will be mandatory to optimize the analysis developed by DarkSide-50. Literature is scarce at this low energy scale, so the Recoil Directionality (ReD) experiment aims to collect S2-only events with a nuclear recoil energy (E_{NR}) in the range of 1-5 keV. It will provide an external calibration dataset of the charge yield as a function of the E_{NR} to better constrain the model developed by DarkSide-50 [3].

2. – Low-mass studies with ReD

ReD is an R&D project within the Global Argon Dark Matter Collaboration. It operates a miniaturized LAr TPC with a volume of about 150 cm^3 equipped with cryogenic silicon photomultipliers as readout system. It is designed to characterize the response of LAr to neutron-induced nuclear recoils via (n,n') scattering and, thanks to the two-body kinematic approach, it allows to determine the energy of the nuclear recoil by detecting the outgoing neutron with a neutron spectrometer.

For low-mass studies, the LAr TPC of ReD [6] is irradiated with neutrons of $\mathcal{O}$(MeV). The strategy is to place the neutron spectrometer, which detects the neutrons scattered off Ar, at a desired fixed range of angles. The equation used to retrieve the energy of the NR is

$$E_{NR} = 2E_n \frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - \cos\theta_{scatt}). \quad (1)$$

Neutrons are emitted by a ^{252}Cf source with an activity of 1.0 MBq (26 kBq of fission). In a spontaneous fission event of ^{252}Cf neutrons are emitted with a multiplicity of 3.76. The source is placed in a cubic shield ($\sim 60 \times 57 \times 60$ cm^3) of B-loaded polyethilene, iron and lead. The side facing the TPC has an exit tunnel of about 50 cm length. The neutron flux is collimated through this exit channel, which has a conical opening of 2°.

Since neutrons have a continuous energy spectrum in the range up to 10 MeV, the Time of Flight (ToF) technique is employed to measure the kinetic energy (E_n) of the particle and use it in eq. (1). Two kinds of detectors have been deployed as taggers to measure the neutron time of flight between the Cf source and the neutron spectrometer. The start signal is given by two BaF_2 scintillator crystals placed inside the shield facing the source at both sides. Those are fast detectors, efficient in detecting the γ radiation emitted in the fission event. The time signal for the stop is given by one of the plastic scintillators of the spectrometer hit by the scattered neutron. In this campaign, 18 1-inch plastic scintillators (PScis) EJ-276 have been mounted in a neutron spectrometer placed at $\sim$ 1 m downstream from the position of the TPC. The neutron spectrometer consists in two quadratic matrices, each hosting 9 PScis (3×3). The two matrices are placed in such a way that the PScis covers the range $\theta_{scatt} = 12° - 17°$ and at about 25 cm above and below with respect to the direction of the neutron flux to select mainly neutrons that have interacted inside the TPC and to offer at the same time a control on the alignment systematics. A schematic view of the experimental setup is showed in fig. 1.

The trigger logic for the data acquisition is the `AND` of a signal from one of the BaF_2 (the two BaF_2 are in `OR`) and any of the PScis (Pscis in `OR`). Since scintillation signals in the TPC are low and difficult to detect, the TPC is not included in the trigger logic: signals are searched offline for those events whose ToF and scintillation light seen by the PSci are compatible with a neutron event.

The experiment was conducted at INFN Sezione di Catania and the data taking lasted about three months, from January to March 2023.

3. – Conclusions

The ReD project was designed to collect NR events due to neutrons elastically scattering off Ar atoms that mimic the behavior of a Dark Matter particle. The main goal of this data campaign is to characterize the response of LAr TPC in the energy range of NRs down to a few keV_{nr} at which events from low-mass WIMP are expected. The

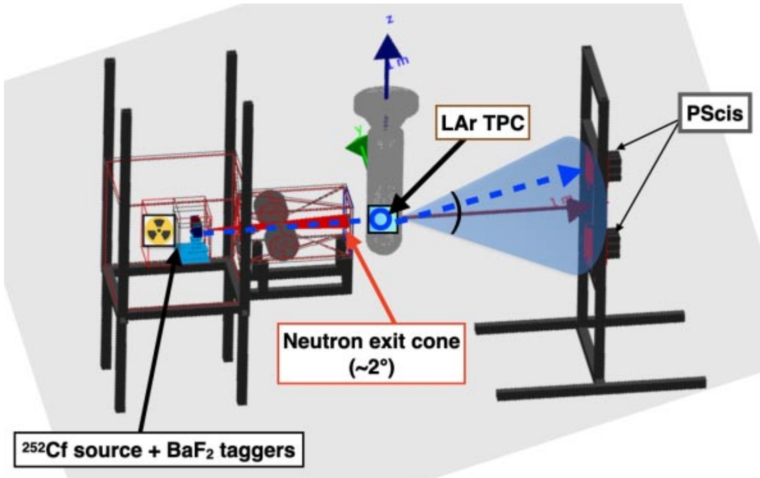

Fig. 1. – Schematic side view of the experimental setup for the campaign with the ^{252}Cf. The dashed blue line represents the path of a neutron emitted from the source in the shield (left) escaping from the exit cone (in red). The neutron scatters elastically (n,n') in the TPC contained in the dewar (grey element in the centre of the image). Finally, the n' hits one of the 18 PScis in the neutron spectrometer (right). More details can be found in the text.

data analysis is ongoing to determine the charge yield in LAr. This will be crucial to constrain the response of a LAr TPC operated in double phase since this technology will be adopted for the next generation of multi-tonnes experiments dedicated to the direct search for Dark Matter.

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