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

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Summary. — The Recoil Directionality project (ReD) within the Global Argon Dark Matter Collaboration aims to characterize the response of a liquid argon (LAr) Time Projection Chamber (TPC) to neutron-induced nuclear recoils and to measure the charge yield for low-energy recoils. The charge yield is a critical parameter for the experiments searching for dark matter in the form of low-mass WIMPs and measurements in argon below 10 keV are scarce in the literature. This project covers the gap down to 2 keV.

1. – Direct searches for Dark Matter in dual-phase Time Projection Chambers

One of the most pressing open questions in physics regards the 27% of our Universe that seems to behave like a dark and massive amount of matter. Since the 1930s, Zwicky called it *dunkle materie* [1], literally Dark Matter (DM), to underline the difficulty to detect it with traditional methods. The presence of DM in the Universe has been suggested by observational evidence at different scales, like rotation curves of galaxies, mass profile of colliding clusters [2] and discrepancies in the distributions of galaxy cluster mass estimated from luminosity as a function of gravitational lensing [3]. Models indicate a non-relativistic and non-baryonic particle, the so-called Weakly Interactive Massive Particle (WIMP), as a possible DM candidate, with a theorized mass of the order of 100 GeV/c^2. WIMP particles should reach Earth and interact with the baryonic matter which the detectors are made of. The goal of the direct detection of the DM experiment is to see a signal formed after the energy deposit of WIMP-induced scattering off nuclei.

Among the technologies employed to detect WIMPs, Time Projection Chambers (TPCs) filled with a noble element in double phase are largely employed. The detection channels in a dual-phase TPC are the scintillation light and the ionization charge. Once the WIMP scatters off the target there is a momentum transfer that originates a Nuclear Recoil (NR). After the NR, excited Ar atoms emit scintillation light (S1) while de-exciting, and an ionization track is formed. The electrons formed from ionization can contribute to the S1 signal when recombining with the ions. However, most electrons avoid recombination since are drifted away by an electric field and reach the upper part of the detector. In equilibrium with the noble liquid scintillator, there is the gaseous layer where electrons are extracted and accelerated. Once extracted in gas the electrons give a delayed light signal S2. Both scintillation and electroluminescence signals are collected by photosensors.

In a two-phase TPC it is possible to reconstruct the z position of the event using the time difference between S2 and S1 signals, while the x-y position is given by the light pattern of S2 seen by photosensors.

2. – Searches for WIMPs with the LAr TPC of DarkSide-50

DarkSide-50 [4] was a dual-phase TPC filled with 50 kg of liquid argon (LAr) as a target. It operated at Laboratori Nazionali Del Gran Sasso (LNGS) of INFN from 2013 to 2018. LAr allows a good separation of NR events of interest from Electron Recoils

(ERs) using the time profile of the scintillation signal. This Pulse Shape Discrimination (PSD) technique is efficient in LAr with a rejection of background at the 10^7 level [4].

DarkSide-50 also employed argon extracted underground from a mine in Colorado to reduce the background due to the contamination of cosmogenic ^{39}Ar. Underground argon (UAr) showed an activity for ^{39}Ar reduced by a factor of 1400 relative to atmospheric argon [4]. Using this low-radioactivity UAr, DarkSide-50 performed a blind analysis on a 532-day dataset and set an upper limit on the spin-independent DM-nucleon cross-section at $1.14{\cdot}10^{-44}$ cm^2 for 100 GeV/c^2 WIMPs [5].

Even if optimized for a DM particle with a mass at the electroweak scale, DarkSide-50 studied also the case of a low-mass WIMP. One scenario that recently gained more interest foresees DM particles with a mass of the order of GeV/c^2. At this mass scale, a WIMP could give a NR with an energy of a few keV, lower than the tens of keV expected from a WIMP with a mass at O(100's) GeV/c^2. This search for low-energy signals is challenging: since the S1 signal is often low, it is difficult to detect in the case of low-energy recoils, and the possibility of using the PSD technique is lost. DarkSide-50 was able to set a 90% C.L. exclusion limit for the spin-independent cross-section of 3 GeV/c^2 mass WIMP on nucleons at $6{\cdot}10^{-43}$ cm^2 [6]. Further studies on this low-mass case will be conducted also by the future experiment DarkSide-20k [7], a 50-ton LAr TPC designed within the Global Argon Dark Matter Collaboration (GADMC). The analysis of the data is strongly affected by quenching fluctuations in the ionization process and literature is scarce in describing this phenomenon at energies below 7 keV. Therefore, a calibration dataset covering this gap is necessary to constrain the analysis of future experiments.

3. – The Recoil Directionality experiment

The Recoil Directionality (ReD) project within the GADMC was designed to measure the ionization yield of Ar recoils down to 2 keV in a small-scale LAr TPC. The TPC of ReD [9] was irradiated with neutrons produced by a ^{252}Cf fission source, and NRs of known recoil energy were obtained by a two-body kinematics approach. Neutrons elastically scattered (n,n') off Ar nuclei inside the TPC, and the outgoing neutron was detected downstream by a neutron spectrometer made of plastic scintillators (PScis), that have been placed to cover a fixed range of angles to close the kinematics. The recoil energy (E_{Ar}) has been derived using the equation

$$E_{Ar} = 2E_n \frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - \cos\theta_s), \quad (1)$$

where m_n and m_{Ar} refers to the masses for the neutron and the Ar respectively, θ_s is the fixed angle of scattering and E_n is the kinetic energy of the neutron. The ^{252}Cf source emits neutrons with a continuum energy spectrum, so E_n has been calculated event-by-event via Time of Flight (ToF) measurements. The STOP signal was given by the neutron spectrometer, while the START time was given by one of the two BaF_2 scintillators deployed close to the source to detect the accompanying γ rays in the fission event. The distances traveled by the neutrons between the source and the TPC and then from the TPC to the neutron spectrometer were 90 cm and 100 cm, respectively. The trigger logic required the coincidence between the two tagger detectors used for ToF (any BaF_2 in coincidence with any PSci), while the light signals collected by the TPC have been searched for during offline analysis, as they were too low to be efficiently used as a trigger signal.

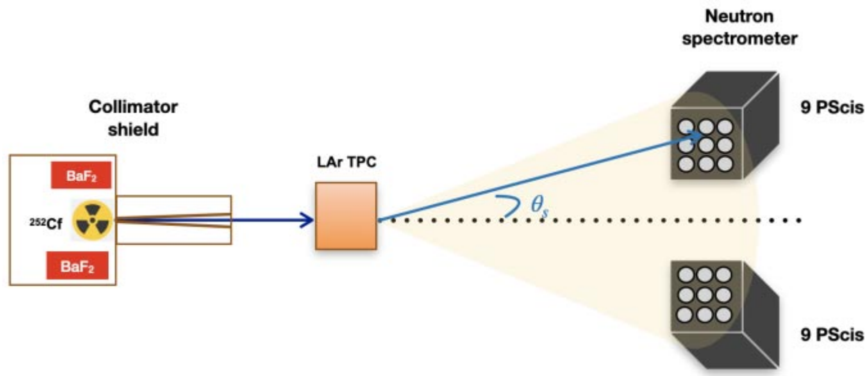

Fig. 1. – Schematic view of the experimental setup for the campaign with the ^{252}Cf source. The blue arrow represents the path of a neutron emitted from the source in the shield (left) escaping from the collimator. The neutron scatters elastically in the TPC and afterwards (in cyan) hits one of the 18 plastic scintillators (PScis) in the neutron spectrometer (right). More details can be found in the text.

A sketch of the experimental layout is shown in fig. 1. Each component of the setup is described below.

3˙1. *The TPC*. – ReD had a LAr TPC of 5×5×6 cm^3, with a gas argon layer of about 7 mm. Two acrylic windows coated with ITO were operated as anode and cathode, thus establishing an electric field of 200 V/cm responsible for the drift of the electrons. Cryogenic Silicon Photomultipliers (SiPMs) were used as readout system to collect light signals. Two 5×5 cm^2 tiles of SiPMs were mounted on the windows (24 SiPMs in each tile). Further details of the TPC can be found in ref. [9].

3˙2. *The fission source and the* BaF_2 *detectors*. – The TPC was irradiated with neutrons of $\mathcal{O}$(2 MeV) emitted by the ^{252}Cf source, which had an activity of 1.0 MBq (of which 26 kBq for spontaneous fission). Two 3 cm cubic BaF_2 crystals coupled to Hamamatsu PMTs were deployed equidistant on either side of the source and used as fast scintillators to detect the γ rays. Both the source and the BaF_2 detectors were housed in a shielding structure. The walls of the shield were made of layers of boron-loaded high density polyethylene (HDPE), iron, and lead to moderate most of the neutrons, except for an exit channel designed to collimate the neutrons into a 2° exit cone and direct them to the TPC.

3˙3. *The neutron detector*. – Downstream of the TPC was a neutron spectrometer. The custom-built structure contained 18 1-inch EJ-276 PScis, divided into two symmetrical (3 Pscis × 3 Pscis) arrays. The arrays were placed to cover θ_s between 12° and 17°, and shifted vertically by about ± 25 cm with respect to the direction of the exiting hole to select neutrons that have interacted inside the TPC. The PScis were also used to perform the PSD in order to mark the good neutron events from the γ rays.

4. – Conclusions

The ReD experiment was located at the INFN Sezione di Catania and the data acquisition campaign with the source was carried out during the winter of 2023, from

January to March. As predicted by the detailed end-to-end Monte Carlo simulation, the good neutron event rate was of a few counts per hour. The project was designed to collect argon recoils of known energy using a two-body kinematic approach to characterize the response of the LAr TPC, and the goal of being sensitive in the energy range up to 1-2 keV was achieved. This energy range is under investigation since a possible low-mass WIMP event is expected at this scale. The analysis is still ongoing to determine the charge yield in LAr, strongly affected by ionization quenching fluctuations. The contribution of ReD will be crucial in constraining the response model of a LAr TPC for the next generation of multi-ton experiments dedicated to the direct search for dark matter.

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