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Characterization of low-energy argon recoils with the ReD experiment

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The Recoil Directionality project (ReD) within the Global Argon Dark Matter Collaboration aims to characterize the response of an argon dual-phase 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 Ar below 10 keV are scarce in the literature. ReD was designed to cover this gap, by irradiating a miniaturized TPC with neutrons produced by an intense ^{252}Cf fission source, such to generate Ar recoils in the energy range of interest. Data were collected during the Winter of 2023 at the INFN Sezione di Catania. The energy of the nuclear recoils produced within the TPC by (n,n') scattering was determined by detecting the outgoing neutrons by a neutron spectrometer made of 18 plastic scintillators. The neutron kinetic energy was evaluated event-by-event by using a time-of-flight approach. The ionization signal was measured for Ar recoils down to 2 keV.

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1. Introduction

The DarkSide program within the Global Argon Dark Matter Collaboration (GADMC) is searching for dark matter in the form of Weakly Interacting Massive Particles (WIMPs) by using argon dual-phase Time Projection Chambers (TPC) at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN. The experiment DarkSide-50 [1] took data at LNGS until 2018 using a 50-kg Ar TPC. The next generation detector DarkSide-20k [2] features a 50 ton TPC readout by cryogenic Silicon Photomultipliers (SiPMs) and is currently under construction at LNGS. The signal in a dual-phase TPC has two components: the prompt scintillation (S1) and the delayed electroluminescence (S2). The S2 signal is proportional to the number of electrons surviving recombination in argon, which are drifted from the interaction site by an electric field, extracted to a gas layer above and finally accelerated to produce electroluminescence. The delay between S1 and S2 is due to the time spent by the electrons to drift from the production point to the gas phase.

In the standard scenario in which the WIMP mass is O(100's) GeV, the WIMP-induced nuclear recoils (NRs) in Ar have kinetic energy of a few tens of keV. Recently, interest raised on an alternative dark matter scenario, in which WIMPs are much lighter, O(1) GeV. In this case, the NR energy is as low as a few keV in Ar. As the S1 signal is often too low to be detected, the search for low-mass WIMPs must be performed by using the S2 signal only [3]: being the gain g_2 for the S2 signal ~ 20 photoelectrons (PE) for each extracted electron [1], Ar dual-phase TPCs are potentially sensitive to few-electron signals, i.e. to sub-keV Ar recoils. A dedicated S2-only analysis of the DarkSide-50 data was carried on in Ref. [3] in order to constrain low-mass WIMPs. This data analysis is very sensitive to the knowledge of the ionization yield of Ar recoils: literature data are scarce in the energy range of interest, the lowest direct data points available being at about 7 keV [4, 5]. The data of calibrations runs taken in DarkSide-50 with AmBe and AmC neutron sources were compared against detailed Monte Carlo simulations from the tool `g4ds` [6] in order to model the ionization yield of Ar down to 0.5 keV, within a dedicated two-parameter model [7]. The availability of different screening models for the nuclear quenching and the possibility of an unconfirmed low-energy suppression of the electronic quenching (see discussion in Ref. [7]), makes a strong case for a direct measurement of the ionization yield of Ar recoils based on two-body kinematics, at energies below the data points from Joshi et al. [4] (6.7 keV) and ARIS [5] (7.1 keV).

2. ReD conceptual design and experimental setup

The Recoil Directionality (ReD) project within the GADMC was designed to measure the ionization yield of Ar recoils down to 2 keV, by using a dedicated miniaturized dual-phase TPC [8]. Argon recoils of known energy are produced in the TPC by elastic scattering (n,n') of neutrons from an intense ^{252}Cf fission source. Neutrons elastically scattered off Ar are detected by a neutron spectrometer made of plastic scintillator (PSci) detector, thus fixing the neutron scattering angle. Furthermore, two BaF_2 detectors are deployed close to the ^{252}Cf source, such to detect accompanying γ-rays of fission events and then to provide an event-by-event fission tagging. The kinetic energy of Ar recoils is hence determined on a purely-kinematical basis as

$$E_r = 2E_n \frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - \cos\theta_s) \tag{1}$$

which depends on the neutron and Ar masses (m_n and m_{Ar}), on the neutron kinetic energy E_n and on the scattering angle θ_s. The energy E_n is evaluated event-by-event by the time of flight (ToF), while the scattering angle θ_s is fixed geometrically by the placement of the neutron spectrometer.

The core of the system is the 5x5x6 cm^3 ReD dual-phase Ar TPC, which is described in detail in Ref. [8]. The light readout is made by two 5x5 cm tiles of cryogenic SiPMs, each containing 24 devices. The tiles are located on the top and on the bottom of the TPC, beyond two transparent acrylic windows that are operated as anode and cathode. A drift field of 200 V/cm is set between cathode and anode which causes ionization electrons to drift in the TPC, with a maximum time of 55 μs. The TPC is irradiated with the O(MeV) neutrons emitted by a 1.0-MBq ^{252}Cf source ($2.6 \cdot 10^4$ fissions/s), placed at about 90 cm distance and collimated at 2° opening angle. The ^{252}Cf source is shielded and collimated by a structure made by boron-loaded polyethylene, iron and lead. Two BaF$_2$ detectors are placed inside the shielding, close to the source, in order to tag the fission products and to provide a START for the ToF measurement. The neutron spectrometer, which provides the ToF STOP, is placed 100 cm downstream the TPC: it is made by two 3x3 arrays of 1-inch EJ-276 PScis, which feature n/γ pulse shape discrimination (PSD). The arrays cover a range of $\theta_s = 12° - 17°$ and they are outside the direct neutron cone from the collimator. The two arrays are deployed symmetrically, about 25 cm above and below the level of the TPC, in order to offer a better control on the alignment systematics. The layout was optimized in order to achieve a sensitivity down to 1-2 keV for Ar recoils.

3. Data taking and preliminary results

The data taking campaign with the ^{252}Cf source was carried on between January and March, 2023 at the INFN Sezione di Catania. The trigger logic was based on the coincidence between any BaF$_2$ detector and any PSci detector: this was chosen to avoid any possible loss of events in the TPC due to the low trigger efficiency for small S1 signals. Data are complemented by a very detailed end-to-end Monte Carlo (MC) simulation: it produces synthetic data, which undergo the same analysis flow as the real data. The MC was tuned and validated on calibration data and it was extensively used to benchmark the reconstruction algorithms.

Selection of the candidate signal events primarily requires that the BaF$_2$-PSci ToF and the PSci PSD are both compatible with neutron events: the range of ToF taken for the selection of ^{252}Cf neutrons goes from 40 to 180 ns. The resolution achieved in ToF is 0.7 ns rms, allowing an event-by-event measurement of the neutron kinetic energy at better than 5%. A valid TPC signal is then searched for, using a dedicated pulse finder which runs over the digitized charge pulse of the SiPMs; it is fully efficient for S2 signals above 70 PE (~ 4 e$^-$). The selected TPC events are those in which a single valid S2 signal is found within 55 μs from the BaF$_2$ signal and the estimated x-y position of the interaction (based on the pattern of the S2 signal on the top SiPMs) is in the central 4x4 cm^2 region of the TPC. The events in which an S1 signal is also found are discarded because they are mostly originated by multiple neutron scattering, as confirmed by the MC simulation. The final sample of events surviving the selection cuts is made by about 600 S2-only events. The Ar recoil energy E_r is evaluated event-by-event from Eq. 1 using the measured ToF, with a typical uncertainty of ±5%. The scatter plot of the measured S2 signal vs. E_r is displayed in Fig. 1; the S2 signal is proportional to the number of electrons N_e via the gain factor g_2. Fig. 1 also shows the

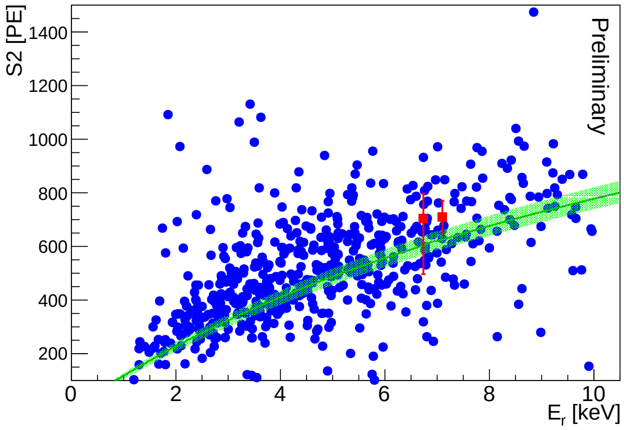

Figure 1: (Premininary) Measured S2 signal vs. E_r for the sample of single-scattering neutron events in the TPC, superimposed with the predictions from the model of Ref. [7] (green band, representing the best-fit with uncertainties). The red points are the experimental measurement from Refs. [4] and [5] at 6.7 and 7.1 keV, respectively. See text for more details.

prediction of the model of Ref. [7] and the experimental measurements[1] of Refs. [4, 5], calculated by taking a preliminary estimate of g_2 based on a cross-calibration with DarkSide-50 data. A final evaluation of g_2, self-consistently based on the ReD data alone, is currently in progress.

In conclusion, the ReD campaign performed with the ^{252}Cf source at INFN Catania achieved its design goal to study the response of an Ar dual-phase TPC to NRs down to 1-2 keV, with a direct two-body-kinematics approach. Data analysis is in progress to finalize the measurement of the ionization yield and to update the parameters of the model of Ref. [7]. The ReD+ project will extend the coverage of the measurements down to 0.4 keV, by using a new optimized TPC and a deuterium-deuterium neutron generator.

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