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Characterization of low energy argon recoils with ReD and ReD+

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Abstract: The Recoil Directionality project (ReD) within the DarkSide-20k Collaboration characterized the response of a liquid argon (LAr) dual-phase Time Projection Chamber (TPC) to neutron induced nuclear recoils, to measure the ionization yield at low-energy. The ionization 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 the gap down to 2 keV. The ReD data taking took place in 2023 at the INFN Sezione di Catania. The TPC was irradiated by neutrons from an intense ^{252}Cf fission source in order to produce Ar recoils in the energy range of interest. The energy of the nuclear recoils produced within the TPC by $(\mathrm{n}, \mathrm{n}')$ scattering was determined by detecting the outgoing neutrons with a dedicated neutron spectrometer made of 18 plastic scintillators. The kinetic energy of neutrons interacting in the TPC was evaluated event-by-event by measuring the time of flight. ReD collected and characterized a sample of nuclear recoils down to 2 keV, thus meeting its design goal.

The ReD effort will be further extended by a new project, ReD+, funded by a PRIN grant from the Italian Ministry of Research. ReD+ is designed to push the sensitivity down to 0.5 keV, by using the same conceptual design of ReD and improved components. A new TPC is being re-designed and optimized in order to increase the signal rate and the signal-to-background ratio, which limited the sensitivity of ReD.

Keywords: Dark Matter detectors (WIMPs, axions, etc.); Instrumentation and methods for time-of-flight (TOF) spectroscopy; Neutron detectors (cold, thermal, fast neutrons); Time projection chambers

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1 Context

The so-called Weakly Interactive Massive Particle (WIMP) is a generic name for non-Standard Model stable particles with masses from a few GeV up to few TeV that have been proposed as Dark Matter (DM) candidates. The increasingly required fine tuning of WIMP models to fulfill experimental constrains is leading to contemplate other theoretical possibilities, with DM masses in the GeV scale.

Direct DM detectors targeting the mass range from GeV to TeV constrain the coupling of DM with Baryonic Matter using the WIMP-Nuclear scattering channel. Liquid noble elements such as argon and xenon offer excellent media for building large detectors with low background [1–3]. The detection of low-mass WIMPs of mass of ∼1 GeV is challenging due to the fact that the mean Nuclear Recoil (NR) energy resulting from scattering interactions is about 100 eV in Ar (30 eV in Xe). In fact, the rather large ionization energy (19.5 eV for Ar) and the nuclear quenching effects lead to a small number of ionization electrons produced in average.

This does not pose a problem to predict the expected WIMP spectrum as long as the response function to NRs is known down to the sub-keV region. The lowest data points available in the literature for the mean ionization yield in Ar are the ones by Joshi et al. [4] and ARIS [5], at about 6.7 and 7 keV, respectively. The DarkSide-50 collaboration developed a model for the NR ionization yield tuned to external data sets and AmC/AmBe DarkSide-50 calibration data [6]. The model relies in theoretical calculations of the nuclei stopping power. Moreover, the data used to tune the model are insensitive to the fluctuations of the ionization yield, so two extreme assumptions were adopted to set WIMP limits [7–9]. The precise modeling of the Ar ionization yield in the few-keV region is hence a critical parameter for the sensitivity to low-mass WIMPs [10] of the DarkSide-20k experiment [2], which is currently being constructed at INFN Laboratori Nazionali del Gran Sasso.

The ReD and ReD+ experiments within the DarkSide-20k Collaboration aim to measure or constrain the response functions down to 2 and 0.5 keV, respectively. NRs are produced by neutron elastic scattering and the NR kinetic energy is reconstructed by kinematics with ∼10% resolution; this is the key feature of the experiment that makes it sensitive to both the mean and fluctuations of the ionization yield.

2 Strategy, ReD experimental setup and preliminary results

The conceptual layout of the experimental setup is displayed in figure 1: neutrons are emitted from a ^{252}Cf fission source and are tagged via the accompanying fission γ emission by close Barium Fluoride (BaF) detectors. Neutrons scatter off Ar nuclei in the target dual-phase Ar Time Projection

Chamber (TPC), thus producing NRs in the energy range of interest, and are eventually detected by a set of Plastic Scintillator detectors (PSci) with Pulse Shape Discrimination (PSD) capability (EJ-276 by Scionix). The neutron kinetic energy is reconstructed event-by-event on the basis of the time of flight (ToF) from source to TPC and from TPC to PSci. The interaction vertex within the TPC, the (fixed) PSci position and the neutron energy are then used to calculate the NR energy (E_{Ar}) 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, m_n and m_{Ar} are the neutron and argon masses, and θ_{scatt} is the scattering angle.

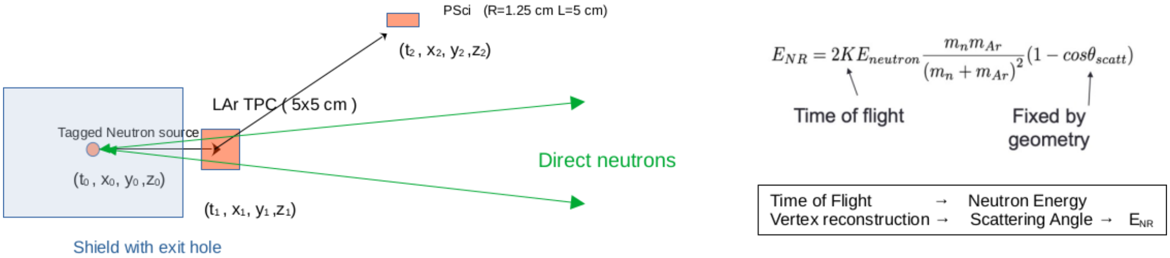

Figure 1. Experimental setup of the ReD experiment. The black arrows indicate a tagged neutron at production that undergoes (n,n') elastic scatter in the TPC and is detected by the PSci downstream. The green arrows indicate the cone of Direct Neutrons from the collimator.

The relative distances (92.1 cm source to TPC and 103.3 cm TPC to PSci), the alignment requirements (< 1 cm) and the size of the PSci were tuned to guarantee a E_{Ar} energy resolution better than 10%. The interaction vertex within the TPC needs to be reconstructed with a ~cm accuracy, which is challenging due to the smallness of the detector signals at this energy. The E_{Ar} energy resolution also depends on the accuracy of the ToF measurements. All BaF, PSci and TPC signals are acquired and digitized by FADCs at 500 MHz sampling rate. A resolution of 0.7 ns (rms) was achieved in the BaF-PSci ToF by interpolating the FADC traces.

The ^{252}Cf source, with activity of 1.0 MBq (corresponding to $26{\cdot}10^3$ fission/s), was placed inside a shield made by boron-loaded polyethylene, lead and iron. The shielding has a conical collimator of total opening of 2.6°. Two BaF detectors were placed next to the source, inside the shield, to tag neutron emission through the detection of the accompanying γ-rays emitted in spontaneous fissions. The BaF detectors are calibrated with ^{60}Co, ^{137}Cs and ^{152}Eu γ sources. Their response to nuclear recoils was derived using internal radioactive α contaminants. The tagging efficiency for ^{252}Cf spontaneous fission events when the two BaFs are operated in OR is estimated with Monte Carlo (MC) simulations to be ~39% (~53%) for a hard threshold of 200 (100) keV. The trigger efficiency vs. energy was inferred individually for the two detectors by matching the experimental data with the expected MC spectra. One of the BaFs exhibits a weak prompt component in the light signal which induces a strong energy-dependent and non-gaussian effect on the ToF accuracy: this dependence was modeled in detail by considering the sample of γ-rays emitted from the ^{252}Cf source and detected directly by the PSci (“gamma flash”).

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The neutron spectrometer of ReD was made by 18 1-inch PSci, placed to detect those neutrons that, upon elastic interaction in the center of the TPC, are scattered by approximately $\theta_{\mathrm{scatt}} \sim 15°$. In order to constrain systematic uncertainties due to a possible mis-alignment of the setup, the Pscis are arranged in two 3x3 arrays, which are deployed symmetrically 27.2 cm above and below the source-TPC axis. The neutron/γ discrimination capability of the PSci is fundamental in the experiment: direct γ-rays coming from ^{252}Cf can be easily distinguished by ToF, but the rate of accidental coincidences between PSci and BaF in the ToF range of interest (40–180 ns) is a factor of >10 larger than the neutron scattering rate. The PSD discrimination was tuned and characterized using experimental data: the selection cuts are set in order to limit the expected leak of mis-identified γ events to less than 1% of the total selected sample. The PSci response to proton recoils, which is needed for a detailed full MC simulations, was derived in a set of dedicated runs in which the detectors were exposed directly to the neutron beam at 105 cm from the source. Results are in agreement with literature values for EJ-276 [11–13]. The PSci trigger threshold for ^{252}Cf data was set at $\sim$ 200 keV. The detectors were calibrated in energy using an ^{241}Am source (59.5 keV).

ReD operated a small dual-phase TPC (5×5×5 cm^3) readout by Silicon Photomultipliers (SiPM) at cryogenic temperature [14] using the technology developed for the DarkSide-20k experiment [2]. The signals from the TPC are the prompt scintillation light in liquid (S1) and the delayed electroluminescence signal (S2) in gas. The S2 signal is proportional to the number of ionization electrons that avoid recombination thanks to an electric field (E_d = 200 V/cm) that drifts them toward the gas-liquid interface on the upper part of the TPC. Two stronger fields are set to extract the electrons from the liquid to the gas phase and to accelerate them in the gas. The SiPMs were mounted on a 5×5 cm^2 tile, each containing 24 devices. 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 were read individually to obtain a better spatial resolution for the S2 signals, while the bottom tile had only four readout channels (SiPMs summed in four groups of six). The time response of the SiPM to the Single Photoelectron (SPE) exhibits a prompt and a delayed component (with a τ ~600 ns and f_{delay} = 0.9). This response function was deconvolved from the signals acquired by the FADC in order to produce Gaussian-shaped SPEs, for each of which the total charge was evaluated and stored. This method preserves all relevant charge and time information, while reducing the global size by a factor of 70. The time delay between S1 and S2 gives the z coordinate of the interaction point in the detector. NRs in the energy range of interest of this work (< 10 keV) often produce a S1 signal which is too weak to be detected: the majority of signal events is hence made of S2 only. For the events lacking the prompt S1, the z position was estimated using the BaF time instead. The xy position was estimated with a likelihood method that uses the hit pattern detected by the SiPM of the top tile. The procedure was calibrated using events from environmental background, which are uniformly distributed within the TPC. The accuracy for low-S2 events (~100–200 PE) was evaluated by re-sampling the light fraction from higher energy events. The energy calibration of the TPC was done with a ^{241}Am γ source and repeated weekly: the time stability in S1 is about 2.5%. The S2 gain g_2, namely the number of SPE in the S2 signal detected on average for each electron extracted in the gas phase, depends on the interaction coordinates; the dependence is estimated using the S2/S1 ratio for a sample of environmental background events. The absolute value of g_2 at the center of the TPC was evaluated by cross-calibrating against the DarkSide-50 data and checked independently with "echo" signals (i.e. electrons produced by photo-ionization of the cathode that follow the S2 signal) [15]. The setup was simulated with a Geant4-based MC simulation [16–18], coupled with a detailed model of the detector response and of the scintillation light profiles. Simulated

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data are reconstructed using the same reconstruction chain as in data. The pulse finder for S2 is found to be fully efficient above ~ 70 SPE with a reconstruction accuracy <5% and a 2% bias due to late SPE.

The trigger logic required the `AND` between one of the BaF detectors and any of the PScis. The TPC was acquired in follower mode, so that weak S1 and S2 pulses could be searched offline. The total acquisition window was 80 µs, which is large enough to contain S1-S2 events with the maximum drift time of ~54 µs, with a 500 MHz sampling rate (40 kSamples/trace).

The first step of the data selection is the identification of *tagged neutron* events, namely PSci+BaF coincidences with a ToF in the range [40,180] ns which is expected for a ~ MeV neutron flight over a distance of 200 cm, and PSD compatible with a neutron. For those events, a TPC signal is searched. The rate of tagged neutrons is ~40 cph, of which only ~2 cph are found to have signals in the TPC. The majority of tagged neutron events without TPC signal is originated by neutrons leaking from the front face of the shield and which hence do not pass through the collimator. Within the candidate sample (tagged neutrons with a coincident TPC signal) about ~ 50% of events are the clean scatters: neutrons through the collimator that interact once in the TPC and are absorbed in one PSci. The contamination of accidental events, i.e. events in which the PSci+BaF signal is in coincidence with an uncorrelated event in the TPC, was estimated to be < 1% by dedicated runs with random triggers. The sample of candidate events is further cleaned by applying a fiducial cut (> 1 cm from the border of the TPC) and requesting that the S2 time is in the range [5,80] µs with respect to the BaF. For the events in which a S1 pulse was found, it was also requested that the S1 time is consistent with the neutron ToF, within a 15 ns tolerance.

ReD collected data at the INFN Sezione di Catania for three months, from January to March 2023. Figure 2 shows the S2 signal as a function of the calculated E_{Ar} after final event selection (events with S1 are not shown). The data sample contains about 800 events between 1 and 10 keV, thus confirming that ReD could meet its design goal (E_{Ar} down to 2 keV). The absolute scale (g_2) which is necessary to convert S2 in N_e is being finalized and will be reported in a future publication. The spread in the points is mainly due to E_{Ar} reconstruction accuracy and intrinsic fluctuations of the ionization yield.

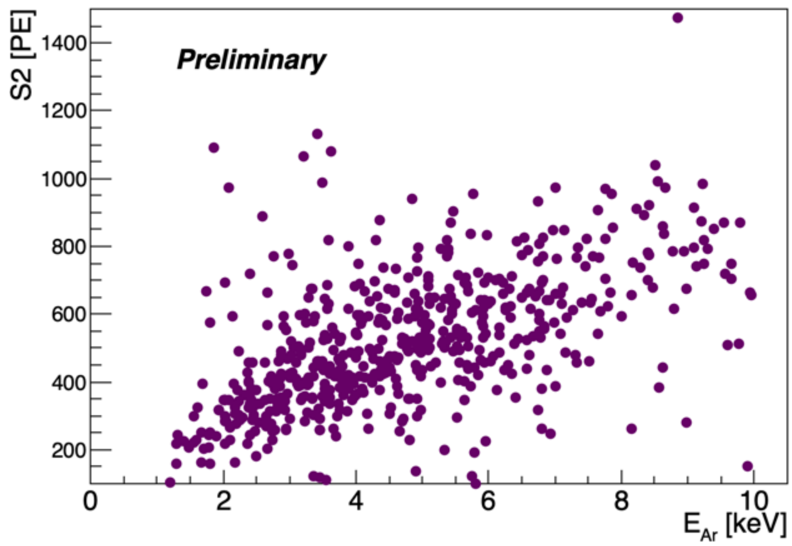

Figure 2. S2 signal vs. calculated recoil energy E_{Ar} for events with a single neutron scattering in the TPC.

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3 Future improvements with ReD+

The project ReD+, supported under a two-year PRIN grant from the Italian Ministry of Research, is designed to extend the measurements performed by ReD down to 0.5 keV and to increase the statistics by a factor of >10.

The conceptual design of ReD+ is the same as for ReD, with improved components and capitalizing the lesson learnt from ReD. Since ReD+ is targeting NR events of lower energy with respect to ReD, the neutron spectrometer will be deployed at a smaller scattering angle (about 9°). Furthermore, the spectrometer will be doubled by deploying two more 3x3 arrays of PSci, placed in the left/right direction: this is meant to increase the statistics and to constrain the horizontal alignment. A new TPC is being re-designed and optimized to overcome the factors which limited the ReD sensitivity at low energy. The new TPC, which will be deployed in the existing cryostat, will be cylindrical in shape and with a larger size, in order to increase the signal rate and to minimize the passive volumes which caused the sub-optimal signal-to-background ratio in ReD. The signal rate will also be increased by using a stronger ^{252}Cf source ($\sim$ 2 MBq); this will require to replace the current BaF taggers with faster detectors (e.g. NaI), such to minimize pile-up and accidental coincidences, and to improve the ToF resolution. A higher number of ^{252}Cf tagger detectors is also being considered, aiming to increase the neutron tagging efficiency and the signal rate. The ReD+ data taking with the ^{252}Cf source is foreseen in early 2026 at the INFN Laboratori Nazionali del Sud, targeting the energy region down to 0.5 keV.

As a further step, the ^{252}Cf source will be replaced by a Deuterium-Deuterium neutron generator, which is able to deliver mono-energetic 2.4 MeV neutrons via the reaction d(d,^{3}He)n, with fluence of $10^5 - 10^7$ n/s. The generator was already purchased and it is being characterized and commissioned at the University of Sao Paulo (USP). The detection of the accompanying ^{3}He nucleus by a dedicated Si detector allows for the neutron tagging with an expected efficiency of $\sim$ 20%. The goal of this second phase is the characterization of NRs down to 0.2 keV, thanks to the higher rate and the mono-energetic source.

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