Directionality for nuclear recoils in a liquid argon TPC with the ReD experiment[1]

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Abstract. Directional sensitivity to nuclear recoils would provide a smoking gun for a possible discovery of dark matter in the form of weakly interacting massive particles. A hint of directional dependence of the response of a dual-phase argon time projection chamber was reported by the SCENE experiment. Given the potential importance of such a capability, a new dedicated experiment, Recoil Directionality (ReD), was designed to scrutinize this hint. A small dual-phase liquid argon TPC was irradiated with neutrons produced by the p(^{7}Li,^{7}Be)n reaction at the TANDEM accelerator of the INFN - Laboratori Nazionali del Sud, Catania, Italy, such to produce Ar nuclear recoils in the range (20 - 100 keV) of interest for dark matter searches. Energy and direction of nuclear recoils are inferred by the detection of the elastically-scattered neutron by a set of scintillation detectors.

1. Introduction

The existence of dark matter (DM) in the Universe is nowadays commonly accepted as the explanation of many astrophysical and cosmological phenomena, ranging from internal motions of galaxies to the large scale inhomogeneities in the cosmic microwave background radiation and the dynamics of colliding galaxy clusters. In the framework of particle astrophysics, experiments searching for weakly interacting massive particles (WIMPs) play a central role in the studies on the nature and properties of DM in the Universe. Liquid argon (LAr) is particularly well suited for the direct DM searches because of its powerful background rejection through pulse shape discrimination [1] and of the possibility to use low-radioactivity Ar from underground sources [2]. The Global Argon Dark Matter Collaboration (GADMC) is pursuing a multi-staged program to operate a sequence of argon-based detectors, aiming to improve the sensitivity to WIMPs by several orders of magnitude with respect to the current generation of experiments. The first step is the DarkSide-20k experiment [3], a double-phase argon time projection chamber (TPC) currently under construction at the INFN - Laboratori Nazionali del Gran Sasso, Italy. The sensitivity to the direction of the WIMP-induced nuclear recoil (NR) would be a key asset for LAr-based detectors, as signal directionality would be an unmistakable signature for WIMP dark matter and hence a "smoking gun" to support a discovery.

2. The ReD Experiment

Directional information is potentially available in a dual-phase LAr TPC by exploiting the columnar recombination effect [4, 5]. Hints of such directional phenomena were reported by the SCENE experiment [6]. Given the importance that a potential directional sensitivity of a dual-phase LAr TPC would have in the entire field of WIMP dark matter searches [7], an experimental program called Recoil Directionality (ReD) was designed and implemented within the GADMC in order to unambiguously verify the hint by SCENE and to provide information on the recombination mechanism in argon. The ReD TPC was irradiated in February 2020 with a neutron beam of known energy and direction, produced via the p(^{7}Li,^{7}Be)n reaction by the TANDEM accelerator at the INFN - Laboratori Nazionali del Sud (LNS) in Catania. The neutron is produced in association with a ^{7}Be nucleus, and its energy and direction are kinematically constrained by the energy and direction of the charged product. The neutron can undergo elastic scattering (n, n') with an Ar nucleus inside the TPC, thus producing a nucler recoil and a neutron, whose energies and momenta are correlated by two-body kinematics. The scattered neutron is eventually detected by a neutron spectrometer made by an array of liquid

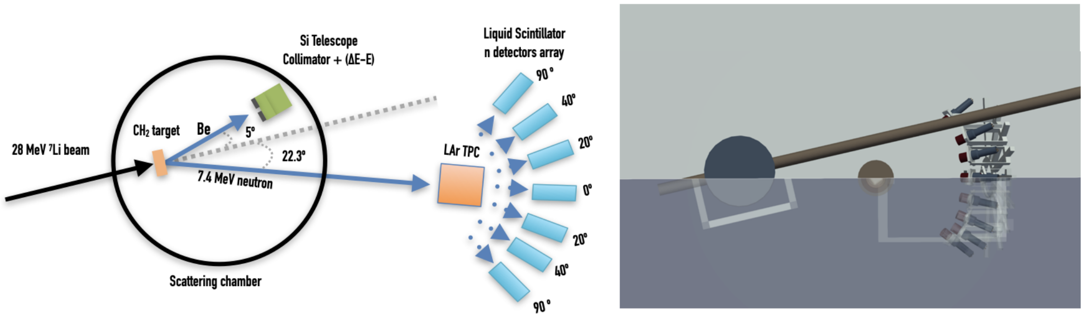

Figure 1. Sketch of the conceptual layout (left) and rendering (right) of the ReD experiment at LNS (top view).

scintillator (LSci) detectors; the detection of the neutron by a specific LSci detector determines the energy and the direction of the Ar NR.

The conceptual layout of ReD is sketched in Fig. 1. The experiment deploys three detector systems: (1) a ΔE-E telescope made by Si detectors to identify Be nuclei associated with neutrons; (2) the TPC to detect NRs; (3) a neutron spectrometer made by 7 LSci detectors to detect the neutrons scattered off Ar. The placement of the scintillators is such that they detect neutrons which underwent elastic scattering on Ar at the same angle and hence produced NRs of the same energy E_r in the TPC. While the NRs tagged by the LSci detectors all have the same energy E_r, their momenta form a different angle ϕ with respect to the TPC electric field (z-axis). The test of the directional effect hence consists in checking if the response of the TPC in terms of scintillation and ionization differs for NRs of the same energy but different angle ϕ. Following the recombination model from Ref. [4], the electron-ion recombination in LAr, which drives the relative balance between the scintillation signal (S1) and the ionization signal (S2) of the TPC, depends on the angle ϕ with the following functional form:

$$f(R, \phi) = \sqrt{\sin^2 \phi + \cos^2 \phi / R^2}. \tag{1}$$

The model depends on a single parameter R, which measures the non-sphericity of the initial electron cloud. If $R > 1$ there is a net directional effect: at a given kinetic energy of the NR, the ratio S2/S1 will also depend on the angle ϕ between the NR momentum and the drift field. When $R = 1$, spherical symmetry is instead restored: $f(R, \phi) = 1$ and any directional dependence cancels.

3. The ReD TPC

The core detector of ReD is a small dual-phase argon TPC: it consists of a volume of liquid argon, having dimensions $5 \times 5 \times 5$ cm^3, above which lies a thin layer of gaseous argon. The passage of ionizing radiation in the liquid produces a prompt light signal due to scintillation (S1) and residual ionization electrons. Unrecombined electrons are then drifted by an appropriate electric field (drift field) towards the liquid-gas boundary, extracted to the gas and then accelerated by a strong electric field. This produces the emission of an electroluminescence light signal (S2): it is delayed with respect to S1 by several tens of μs, which is the electron drift time across the liquid phase. The light emitted by scintillation and electroluminescence is detected by two tiles of Silicon Photomultipliers (SiPMs), of size 5×5 cm^2. Each tile contains 24 SiPMs. The tiles are placed at the top and at the bottom of the TPC, and are coupled with a front-end board electronics. A full technical description of the TPC, of its operational parameters and of its performance can be found in Ref. [8].

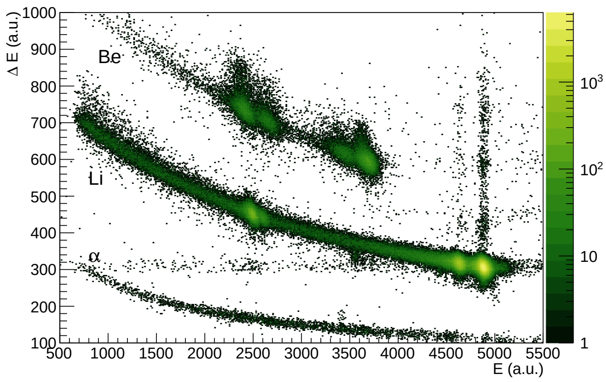

Figure 2. ΔE-E scatter plot for the ^{7}Li+p reaction. The *loci* due to the p(^{7}Li,^{7}Be)n reaction are visible, together with band due to the elastic scattering of the ^{7}Li primary beam and α events from other Li-induced reactions.

The TPC was characterized prior of the irradiation in a dedicated campaign performed in 2019 at the INFN Naples [8]. Specifically, the scintillation gain and ionization amplification of the TPC were measured to be $g_1 = (0.194 \pm 0.013)$ photoelectrons/photon and $g_2 = (20.0 \pm 0.9)$ photoelectrons/electron, respectively. The total scintillation light yield at null field, corrected for the effect of after-pulsing and cross-talk of the SiPMs, was measured to be (9.80 $\pm$ 0.13) photoelectrons/keV using 60-keV γ-rays from ^{241}Am. Calibrations with ^{241}Am were also regularly taken after the redeployment of the system at LNS for the measurement with the TANDEM beam. The light yield was measured to be (8.53 $\pm$ 0.19) photoelectrons/keV at the drift field of 150 V/cm: this is consistent with the null-field measurements taken in Naples, once the scintillation quenching due to the electric field is accounted for [8].

4. Beam data analysis

The beam run designed to search for a possible directional sensitivity took place at LNS, Catania, in February 2020, immediately before the outbreak of the COVID-19 pandemic. A primary ^{7}Li beam of 28 MeV accelerated by the TANDEM accelerator was sent on CH_2 targets of thickness between 300 and 500 μg/cm^2, hosted inside a vacuum scattering chamber. Secondary neutrons are produced by the p(^{7}Li,^{7}Be)n reaction on protons. Given the ^{7}Li beam energy and the relative placing of target, TPC and spectrometer, the ReD system was tuned to detect nuclear recoils in the TPC of $\sim$ 72 keV kinetic energy: this energy is comparable with that of the SCENE hint [6] and well within the region of interest for WIMP searches. The beam data reported here were collected at LNS for a total of 14 days (about 10.7 live days); a typical current of 10-15 nA was achieved for the primary ^{7}Li beam. Neutrons traveling in the direction of the TPC, with kinetic energy of about 7 MeV, were selected by detecting the associated ^{7}Be reaction product with a ΔE-E telescope of Si detectors (ΔE $\sim$ 20 μm and E $\sim$ 1000 μm thick, respectively). The telescope was placed inside the vacuum chamber, at an angle of 5° with respect to the beam direction at a distance of 46.5 cm from the target. An example of ^{7}Be identification by means of the ΔE-E technique is displayed in Fig. 2. The upper part of the spectrum is populated by the ^{7}Be particles, while ^{7}Li from the elastic scattering of the primary beam is visible in the central part.

The golden-plated events of interest are the three-fold coincidences of the Si telescope, the TPC and the neutron spectrometer. Firstly, good events from the TPC with only one S1 pulse and only one S2 pulse were selected. The requirement was also made for the signal detected

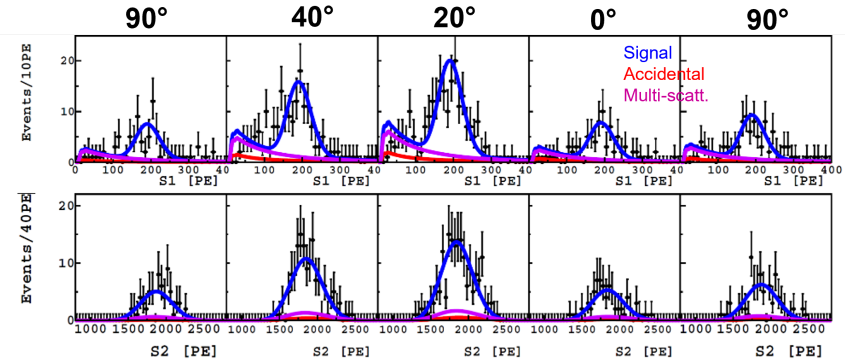

Figure 3. S1 and S2 distributions for triple-coincidence golden events, subdivided in samples according to the angle between the recoil and the drift field. The curves show the best-fit results for the signal (blue), accidental coincidences (red) and multi-scattering (violet) components, respectively. See text for more details.

by the Si telescope to be compatible with a ^{7}Be nucleus (see Fig. 2). The sample of interesting events was further cleaned by requiring the times of flight (ToF) between the Si telescope and the TPC and between the TPC and the spectrometer to be compatible with a few-MeV neutron; time of flights can be measured with resolution of 1-2 ns. Finally, given the high rate of γ events detected by the neutron spectrometer under the beam environment, NR events were selected based the pulse shape discrimination (PSD), using energy-dependent cuts. A similar selection was not applied for the TPC because the PSD resolution gets worse below $\sim$ 10 keV and this would introduce an energy-dependent signal efficiency. The golden-plated events passing the selection cuts are relatively rare (150 ev/day): a total of $\sim$ 7000 such events were found with the proper timing and energy (about 70 keV$_{nr}$), which underwent the final statistical analysis. The residual background was mostly due to accidental coincidences, to inelastic interactions $(n, n'\gamma)$ in the TPC or to neutrons undergoing multiple interactions in the active and passive volumes. The rate and the energy distribution for background events were estimated from the experimental data, using side-bands in ToF, and/or through a dedicated `Geant4` Monte Carlo simulation. The same simulation was also used to calculate the expected energy distribution for signal events.

The directionality pattern was searched by a statistical approach, using the scintillation-ionization (S1-S2) anti-correlation as the key observable. If the directional effect is confirmed with the magnitude as reported by the SCENE hint [6], a 8% difference is expected between the samples with parallel and perpendicular recoil tracks with respect to the drift field taken in ReD: ReD was designed to be sensitive to such a difference with high statistical confidence [8]. The statistical analysis consisted in an unbinned maximum likelihood fit, using the data samples of three-fold coincidence events at four different track angles with respect to the drift field (0°, 20°, 40°and 90°) and a large sample of NR events in the TPC (selected from the coincidence between the Si telescope and the TPC). The fit model accounted for signal, multi-scattering events and accidental coincidences components, whose distributions were either data-driven or derived from simulations. The fit had a number of nuisance parameters (e.g. the TPC gains g_1 and g_2), some of which constrained with Gaussian pull terms by using independent measurements. The only fit parameter of interest is the directional coefficient R of Eq. 1. Due to the complexity of triggering and event selection efficiency below 100 photoelectrons ($\sim$ 30 keV$_{nr}$), the fitting region was limited to 100-350 photoelectrons (PE). The output of the fit on the three-coincidence samples is displayed in Fig. 3. The statistical analysis on R is currently being finalized.

5. Conclusions

The ReD experiment was designed to investigate the directional sensitivity of argon-based TPC to nuclear recoils in the energy range of interest for WIMP dark matter searches. A compact double-phase argon TPC, equipped with innovative readouts by cryogenic SiPMs, was constructed, characterized and eventually irradiated with neutrons within a 14-day beam run at the INFN LNS in Catania. The experimental layout of the beam run was conceived in order to select NR in the TPC having about 72 keV kinetic energy and different directions with respect to the drift field. Sample of NR events at different angle with respect to the TPC electric field are being analyzed according to the directional model of Ref. [4].

Future studies on low energy response (a few keV) with ^{252}Cf neutron source using the ReD TPC are currently in preparation at INFN - Sezione di Catania.

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