Directionality for nuclear recoils in a Liquid Argon TPC

To cite this article: S Sanfilippo *et al* 2023 *J. Phys.: Conf. Ser.* **2586** 012119

Directionality for nuclear recoils in a Liquid Argon TPC

S Sanfilippo[1], P Agnes[2], I Ahmad[3], S Albergo[4,5], I Albuquerque[6], M Ave[6], W M Bonivento[7], B Bottino[8,9], M Cadeddu[7], A Caminata[9], N Canci[10], G Cappello[4,5], M Caravati[7,11], V Cataudella[10,12], R Cesarano[13,14], C Cicalò[7], G Covone[10,12], A de Candia[10,12], G De Filippis[10,12], G De Rosa[10,12], S Davini[9], C Dionisi[13,14], G Dolganov[15], G Fiorillo[10,12], D Franco[16], C Galbiati[8,17], M Gulino[1,18], V Ippolito[14], N Kemmerich[6], M Kimura[3], M Kuss[19], M La Commara[20,10], X Li[8], S M Mari[21,22], C J Martoff[23], G Matteucci[12], V Oleynikov[24], M Pallavicini[25,9], L Pandola[1], N Pino[4,5], M Rescigno[14], J Rode[16,26], A Sosa[6], Y Suvorov[10,12], G Testera[9], A Tricomi[4,5], M Wada[3], H Wang[27], Y Wang[28,29] and P Zakhary[3]

[1] Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy
[2] Department of Physics, University of Houston, Houston, USA
[3] AstroCeNT, Nicolaus Copernicus Astronomical Centre, Warsaw, Poland
[4] Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy
[5] Istituto Nazionale di Fisica Nucleare Sezione di Catania, Catania, Italy
[6] Instituto de Fìsica, Universidade de São Paulo, São Paulo, Brasil
[7] Istituto Nazionale di Fisica Nucleare Sezione di Cagliari, Cagliari, Italy
[8] Physics Department, Princeton University, Princeton, USA
[9] Istituto Nazionale di Fisica Nucleare Sezione di Genova, Genova 16146, Italy
[10] Istituto Nazionale di Fisica Nucleare Sezione di Napoli, Napoli, Italy
[11] Dipartimento di Fisica, Università degli Studi di Cagliari, Cagliari, Italy
[12] Dipartimento di Fisica, Università degli Studi Federico II, Napoli, Italy
[13] Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[14] Istituto Nazionale di Fisica Nucleare Sezione di Roma, Roma, Italy
[15] National Research Centre Kurchatov Institute, Moscow, Russian Federation
[16] APC, Université Paris Diderot, CNRS/IN2P3, Paris, France
[17] Gran Sasso Science Institute, L'Aquila, Italy
[18] Università di Enna Kore, Enna, Italy
[19] Istituto Nazionale di Fisica Nucleare Sezione di Pisa, Pisa, Italy
[20] Dipartimento di Farmacia, Università degli Studi Federico II, Napoli, Italy
[21] Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, Roma, Italy
[22] Istituto Nazionale di Fisica Nucleare Sezione di Roma Tre, Roma, Italy
[23] Physics Department, Temple University, Philadelphia, USA
[24] Budker Institute of Nuclear Physics (BINP SB RAS), Novosibirsk, Russian Federation
[25] Dipartimento di Fisica, Università degli Studi di Genova, Genova, Italy
[26] LPNHE Paris, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France
[27] Physics and Astronomy Department, University of California, Los Angeles, USA
[28] Institute of High Energy Physics, Beijing, China
[29] University of Chinese Academy of Sciences, Beijing, China

E-mail: sanfilippo@lns.infn.it, pandola@lns.infn.it

Journal of Physics: Conference Series **2586** (2023) 012119 doi:10.1088/1742-6596/2586/1/012119

Abstract. Directional sensitivity to nuclear recoils would provide a smoking gun for a possible discovery of dark matter in the form of WIMPs (Weakly Interacting Massive Particles). A hint of directional dependence of the response of a dual-phase argon Time Projection Chamber (TPC) was found in the SCENE experiment. Given the potential importance of such a capability in the framework of dark matter searches, a new dedicated experiment, ReD (Recoil Directionality), was designed by the Global Argon Dark Matter Collaboration, in order to scrutinise this hint. A small dual-phase argon TPC was irradiated with neutrons produced by the p(^{7}Li,^{7}Be)n reaction using the 15 MV TANDEM accelerator of the INFN - Laboratori Nazionali del Sud, Catania, Italy, so as to produce argon 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. Events were selected by gating of the associated ^{7}Be, which is detected by a telescope of Si 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. Liquid argon (LAr) is particularly well suited for direct DM searches because of its powerful background rejection through pulse shape discrimination [1] and of the possibility to use low-radioactivity active target [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. The first step is the construction at the INFN - Laboratori Nazionali del Gran Sasso, Italy, of the DarkSide-20k experiment [3], a 30 ton dual-phase LAr Time Projection Chamber (TPC). The sensitivity to the direction of the WIMP-induced nuclear recoils (NR) is potentially available in a dual-phase LAr TPC by exploiting the electron recombination effect [4]. Hints of such directional phenomena have been observed by the SCENE collaboration [5]. In such a context, WIMP directional information could 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 possible discovery [6].

2. The ReD Experiment

The main scientific goal of the ReD project is to probe a possible directional dependence of the NR tracks in a LAr TPC in the energy range of interest for direct dark matter search in the framework of columnar recombination models [4]. The minimal requirements for the evaluation of the performance of the detector were studied by means of dedicated Monte Carlo [7] simulations of the experimental setup, by also including a directional signal of the same magnitude as reported in [5]. The latter confirmed that, depending on the achieved angular resolution, a next-generation direction-sensitive Dark Matter experiment could provide a positive 3σ detection for dark matter signal (against isotropic background) with about 100 events in case of ideal angular resolution, or about 250 events in case of a very rough angular resolution of 400 mrad.

The core detector of ReD is a small dual-phase LAr TPC (5 (W) $\times$ 5 (L) $\times$ 6 (H) cm^3) where a volume of liquid argon is in thermal equilibrium with an overlaying thin layer of the same element in the gas phase (the so-called gas pocket). An ionising radiation in the liquid produces a prompt light signal due to scintillation (S1) and residual ionisation electrons. Electrons that escape recombination are then drifted by an appropriate electric field (drift field) towards the liquid-gas boundary, extracted to the gas pocket and then accelerated by a strong electric field. This produces the emission of a delayed (several tens of μs after S1) electroluminescence light signal (S2). The time difference between S2 and S1 is used in order to evaluate the total electron drift time across the liquid phase. The light emitted by scintillation and electroluminescence processes is finally detected by two matrices of 5×5 cm^2 cryogenic Silicon Photomultipliers (SiPMs) each containing 24 devices, placed at the top and at the bottom of the TPC [7]. To investigate the directional phenomena reported in Ref. [5], the ReD detector was irradiated with a neutron beam of known energy and direction, produced via the p(^{7}Li,^{7}Be)n reaction by the 15 MV TANDEM accelerator at the INFN - Laboratori Nazionali del Sud (LNS) in Catania. The outgoing neutron, produced in a two-body reaction together with a ^{7}Be nucleus, has a well defined energy and direction, kinematically constrained by the energy and direction of the charged product. Neutrons can in turn undergo elastic scattering (n, n') with an Ar nucleus, thus producing a nuclear recoil (NR) inside the TPC. The scattered neutron (n') is eventually detected by a neutron spectrometer made by an array of liquid scintillator (LSci) detectors; the detection of the neutron by a specific LSci detector determines the energy and the direction of the Ar NR. The placement of the scintillators is such that they detect neutrons which underwent elastic scattering on Ar at the same recoiling angle and hence produced NRs of the same energy in the TPC. Their momenta form a different angle ϕ with respect to the TPC drift field. The test of the directional effect hence consists in checking if the response of the TPC in terms of scintillation and ionisation differs for NRs of the same energy but different ϕ. Following the recombination model in [4], the electron-ion recombination in LAr, which drives the relative balance between S1 and S2 signals 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 the 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. Beam data analysis

The beam run took place at LNS in February 2020. A primary ^{7}Li beam of 28 MeV was sent on CH_2 targets of thickness between 300 and 500 μg/cm^2, placed inside a vacuum scattering chamber, so as to produce secondary neutrons. 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 [5] and well within the region of interest for WIMP searches. The beam data reported here were collected for a total of 14 days (about 10.7 days live time); 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 nucleus 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.The events of interest are the three-fold coincidences of the Si telescope, the TPC and the neutron spectrometer. They were selected from the whole data sample by the definition of selection cuts based on single S1 and S2 pulses in the TPC, time 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, and pulse shape discrimination (PSD) energy-dependent cuts. The events passing the selections are relatively rare (150 ev/day), so a total of $\sim$ 7000 such events were found with the proper timing and energy, which underwent the final statistical analysis. The residual

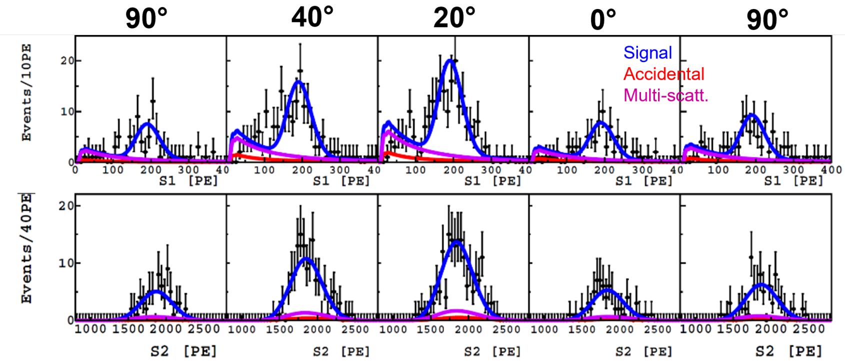

Figure 1. S1 and S2 distributions for triple-coincidence selected events, where the angle between the recoil and the drift field is also displayed. The curves show the best-fit results for the signal in blue, while accidental coincidences and multi-scattering components are the red and the violet lines, respectively. See text for more details.

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 directionality pattern was searched by a statistical approach, using the scintillation-ionisation (S1-S2) anti-correlation as the key observable. The former consisted in an unbinned maximum likelihood fit against the model. [4], 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. The fit model accounted for signal, multi-scattering events and accidental coincidences components, whose distributions were either data-driven or derived from simulations. The output of the fit is displayed in Fig. 1: the parameter R is statistically consistent with the no-directionality hypothesis ($R = 1$) within 2σ and an upper limit on $|R - 1|$ can be set. The sensitivity of this measurement is limited by statistics, i.e. by the dimension of the event samples at different angles.

4. Conclusions

The ReD experiment was designed to investigate the directional sensitivity of liquid argon-based TPC to nuclear recoils in the energy range of interest for WIMP dark matter searches. A compact double-phase liquid argon TPC was constructed, characterised and irradiated with neutrons within a beam run at the INFN LNS in Catania. The experimental layout 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. Data were analysed according to the directional model of Ref. [4]. Future studies on low energy response (few keV) with ^{252}Cf neutron source using the ReD TPC are currently in preparation at INFN - Sezione di Catania.

References

[1] Amaudruz P A et al 2016 *Astropart. Phys* **85** 1–23
[2] Acosta-Kane D et al 2008 *Nucl. Instr. Meth.* A **587** 46
[3] Aalseth C E et al 2018 *Eur. Phys. J.* Plus **133** 131
[4] Cataudella V et al 2017 *JINST* **12** P12002
[5] Cao H et al 2015 *Phys. Rev.* D **91** 092007
[6] Cadeddu M et al 2019 *JCAP* **01** 014
[7] Agnes P et al 2021 *Eur. Phys. J.* C **81** 1014