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The ReD experiment for the directional sensitivity of a double phase Ar TPC

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Summary. — In the research framework of Weakly Interacting Massive Particle as a Dark Matter candidate, directionality could be a key aspect to flag a signal nuclear recoil event. It could also be a crucial tool to reject isotropic background sources coming from the irreducible neutrino scattering. The Recoil Directionality project within the Global Argon Dark Matter Collaboration aims to characterize the light and charge response of a liquid Argon dual-phase time projection chamber to neutron-induced nuclear recoils to probe the directional sensitivity of the detector in the energy range of interest of 20–100 keV. In this work, such a possibility is investigated with a data-driven analysis involving a Machine Learning algorithm.

1. – Introduction

In the direct searches of a cold Dark Matter candidate, the Weakly Interacting Massive Particle (WIMP), a central role is played by detectors based on noble liquid elements as a target [1, 2]. The Global Argon Dark Matter Collaboration (GADMC) aims to bring together the efforts from more than 100 institutes in a new generation of argon-based detectors. Its near-future goal is the DarkSide-20 k (DS-20 k) experiment [3], that uses a dual-phase time projection chamber (TPC) of about 50 t of mass, currently under construction in the Hall C at INFN, Laboratori Nazionali del Gran Sasso (LNGS). During the R&D phase that preceded of DS-20 k, a dedicated project, the Recoil Directionality (ReD) experiment [4] was elaborated. ReD is named after its scientific objective to investigate the possibility to infer the direction of the nuclear recoil (NR) from the detector response.

2. – Directionality and recombination models

According to the standard halo model, WIMPs are expected to reach Earth-based detectors as a wind with a greater flux from the direction towards which the Solar System is pointing with its revolution motion around the galactic center. Therefore,

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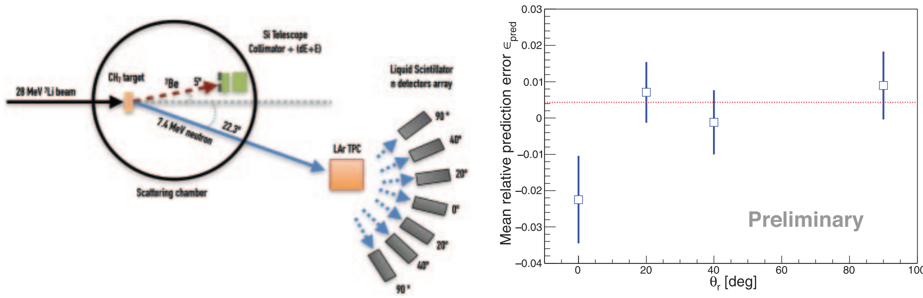
directionality could provide a smoking gun for a possible discovery of a WIMP signal. A TPC filled with argon both in liquid and gaseous phase should in principle allow to infer the direction of the NR exploiting the recombination effect [5]. The first hint of a direction-sensitive effect in the response of a liquid argon (LAr) TPC comes from the SCENE experiment [6]. The mechanisms involved in the signal formation are scintillation and ionization: a particle that interacts in the liquid target of the TPC excites the argon that emits a prompt scintillation light signal (S1). Also, a short ionization track is produced in the liquid target. Under the presence of an electric field, the drift field $\mathcal{E}_d$, electrons which survive recombination travel toward the upper part of the detector where a thin layer of gas is in equilibrium with the liquid part of the target. There, two more intense fields extract and accelerate electrons, giving a delayed electroluminescence signal (S2). However, the electron-ion pairs formed after ionization can also recombine, thus contributing to the S1 signal at the expense of S2. The S2-S1 correlation could in principle be used to derive information about the direction of the momenta of the NR. If the ionization track is parallel to the field, the drifting electrons will pass through the ionization column and will have a higher probability of recombining with Ar ions. A higher S2 signal is instead expected for momenta perpendicular to the field. Therefore, a proper modeling of the electron-ion cloud is needed to investigate the sensitivity of the directional response of the detector through the S2-S1 correlation. The models known in literature, the Thomas Imel model [7] and the Jaffé one [8], lack a proper description of the phenomenon. In the former, the directional sensitivity is zero, since it describes the ionization cloud as an isotropic cubic box, while the latter overestimates the response treating the track as an infinitely long cylinder. For the data collected by the ReD experiment, a novel model, described in [9], has been used. What makes this model promising is that it treats the cloud as an elongated ellipsoid with a single adimensional parameter related to the non-sphericity of the initial electron-ion cloud.

3. – The RED experiment

After the result reported by SCENE, the DarkSide collaboration, within the GADMC, undertook the ReD experiment to design a higher sensitivity experiment to definitely clarify the possible directional sensitivity coming from the correlation between the ionization and scintillation signals. Therefore, a compact, cubic-shape LAr TPC (volume of $5 \times 5 \times 6\,\mathrm{cm}^3$) has been built and characterized in order to evaluate its performance in an energy window similar to the SCENE experiment [6] one but with enough energy resolution on S1 and with a higher granularity for the spatial identification of S2 [4]. ReD was set up with two more goals: the testing of a new readout system performance and stability in a cryogenic environment and the characterization of LAr TPCs response to very low energy nuclear recoils at $\mathcal{O}(5\,\mathrm{keV})$ [4]. ReD is the first experiment with a LAr TPC equipped with new-generation cryogenic Silicon Photomultipliers (SiPMs). The TPC was irradiated for 14 days with quasi-mono energetic neutrons at INFN LNS, in Catania. Neutrons directed toward the detector are produced via the p(^{7}Li,^{7}Be)n reaction, and selected by tagging the paired ^{7}Be ions in a $\Delta E/E$ telescope of silicon detectors. A neutron spectrometer, made of 7 Liquid Scintillators (LSci), detects downstream neutrons from NR at $E_R = 72\,\mathrm{keV}$, thus closing the (n, n') kinematics and allowing deriving also the direction of the recoiling Ar nucleus. The experimental setup (fig. 1(a)) is conceived to select events of NR in the TPC at a chosen recoil energy E_R within the range of interest for WIMPs, but with momenta at different angle θ_r with respect to the direction of the electrical drift field $\mathcal{E}_d$. The scrutinized recoil directions θ_r by the neutron spectrometer



(a) *Setup of ReD* (b) ϵ_{pred} *distributions from triple-coincidences*

Fig. 1. – (a) Schema of the ReD experiment. (b) Mean relative prediction error for the four ϵ_{pred} distribution. The red dotted line marks the $\epsilon_{pred} = 0.0043$ level (no directional effect).

are 0°, 20°, 40° and 90°. The gold-plated events, for which θ_r is reported, are those passing the selection of all the detectors (Si-telescope, TPC and one LSci) and a series of quality cuts. Those events are referred to as triple coincidence events.

4. – A data-driven analysis approach with Machine Learning

A theoretical model describing the phenomenon is mandatory to analyze and understand the collected data, but an alternative approach starting from the dataset itself could provide a new and complementary analysis tool. In this work, Artificial Intelligence techniques and Machine Learning (ML) are used to extrapolate the trend of the recombination effect starting from patterns and correlations in the dataset. A data-driven analysis using ML is performed, in parallel with the statistical analysis carried out with an unbinned maximum likelihood fit [10] according to the electron-ion recombination model in [9].

The strategy aims to train a non-linear regression model using numerical features extracted from NR events produced in the ReD TPC, thus assuming that the angle between the momentum of the recoiling Ar nucleus and the electric field is not relevant for the recombination. If it were true, the effect of recombination would not have privileged regions of θ_r and it should be uniformly distributed among the events of the dataset. Otherwise, if a deviation from the hypothesized behavior were found, one could indirectly prove the recombination dependence of the recoil angle. The derived model aims to extract a pattern from a sample of NR events including all θ_r angles, thus becoming capable of predicting the value of the ionization signal. The chosen algorithm is the Extreme Gradient Boosting (`xgboost`) one, thanks to its good performance and flexibility in multi-field-possible application to various problems [11]. The training paradigm is supervised, where a vector of features (scintillation signal S1 and the spatial coordinates of the event) is passed as an input, together with the corresponding measured S2 signal as the target output. At the end of the training, the model should be able to predict the value of the S2 corrected for TPC non-uniformity effects. To evaluate the accuracy of the derived model, the relative prediction error ϵ_{pred} for the i-th event is calculated as

$$\epsilon^i_{pred} = \frac{S2^i_{measured} - S2^i_{predicted}}{S2^i_{measured}}. \quad (1)$$

At the end of the training phase, the derived model was able to predict the value of the S2 signal for the events in the testing set with relative errors ϵ_{pred} approximately Gaussian-distributed with mean 0.0043(6) and standard deviation 0.09.

Once the model is derived and tested, it is applied on the triple coincidence dataset. First, ϵ_{pred} is calculated event-by-event and the final data sample from all events is divided into four subsets, one for each investigated θ_r, thus obtaining four ϵ_{pred} distributions. From each distribution, the mean value and the error on the mean are calculated (fig. 1(b)). Looking at the obtained values, the ϵ_{pred} value is on average lower for those events with traces parallel to the direction of the drift field. From the definition in (1), this stands for a predicted S2 value greater than the experimentally measured one. This suggests that the derived model tends to overestimate S2 for events with traces parallel to $\mathcal{E}_d$. This result is expected in the case of directionality effects, as traces parallel to $\mathcal{E}_d$ would result in enhanced S1 signals and reduced S2. The statistical significance of this result is evaluated by performing a χ^2 test: the p-value calculated for the null hypothesis of no directional effect is about 23%.

5. – Conclusions

The ReD TPC has such a resolution and working performance to allow for investigating a possible directional effect due to columnar recombination in NRs. Machine Learning techniques have been used to derive a data-driven analysis model as a complementary tool to the likelihood statistical analysis based on a direction-dependent LAr charge recombination model [12]. Even if the observed difference in the behavior of the detector for NRs parallel to the $\mathcal{E}_d$ could possibly hint at a directional sensitivity, the result of the test statistic does not support it within a significant confidence level.

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