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Directionality for nuclear recoils in a LAr TPC

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Abstract. In the direct searches for Weakly Interacting Massive Particles (WIMPs) as Dark Matter candidates, the sensitivity of the detector to the incoming particle direction could provide a smoking gun signature for an interesting event. The SCENE collaboration firstly suggested the possible directional dependence of a dual-phase argon Time Projection Chamber through the columnar recombination effect. The Recoil Directionality project (ReD) within the Global Argon Dark Matter Collaboration aims to characterize the light and charge response of a liquid Argon dual-phase TPC to neutron-induced nuclear recoils to probe for the hint by SCENE. In this work, the directional sensitivity of the detector in the energy range of interest for WIMPs (20-100 keV) is investigated with a data-driven analysis involving a Machine Learning algorithm.

1 Introduction

Directionality should be a key aspect to flag a nuclear recoil (NR) event as a WIMP's one and a crucial tool to reject isotropic background sources, like the irreducible neutrino fog. In a dual-phase argon-based Time Projection Chamber (TPC) signals coming from two different processes are collected: prompt scintillation light (S1) in liquid and electroluminescence light (S2) in gas [1]. The presence of an electric field, the so-called drift field $\mathcal{E}_d$, allows electrons from ionization to avoid recombination. These electrons are drifted into the gas layer of the detector (gas pocket) and originate a delayed signal by electroluminescence. S2-S1 correlation could in principle be used in order to infer information about the initial direction of the nuclear recoils (NRs) with respect to $\mathcal{E}_d$ exploiting the columnar recombination effect [2, 3].

2 The ReD Experiment

The first hint of a direction-sensitive effect in the response of a liquid argon (LAr) TPC comes from the SCENE experiment [4]. To scrutinize it, the DarkSide collaboration, within the Global Argon Dark Matter Collaboration (GADMC), undertook a dedicated project, the Recoil Directionality (ReD) experiment [1]. Therefore, a compact, cubic-shape LAr TPC (volume of 150 cm^3) has been built and characterized to evaluate the performance of the detector system in the same energy range as SCENE[1]. Furthermore, 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 accompanying ^{7}Be ions in a $\Delta E/E$ Silicon telescope. A neutron spectrometer, made by 7 Liquid Scintillators (LSci), detects downstream neutrons from NR at $E_R = 72$ keV, thus closing the (n, n') kinematics and allowing to derive 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 $\mathcal{E}_d$. The scrutinized recoil directions θ_r by the neutron spectrometer are 0°, 20°, 40° and 90°. The golden-plated events, for which θ_r is reported, are those passing the selection of the tagger detectors (Si-telescope, TPC and one LSci) and a series of quality cuts. Those events are referred to as triple coincidence events.

3 Models for Recombination

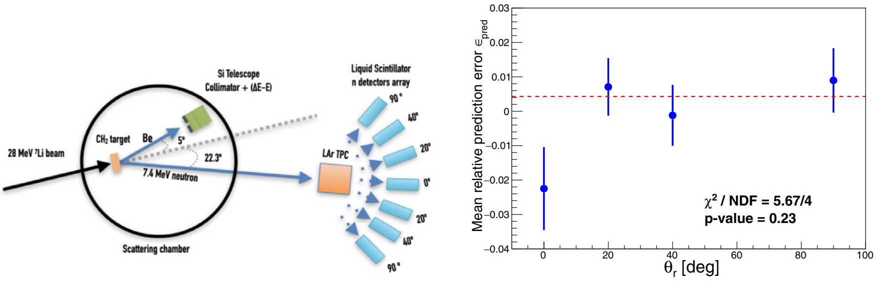
The electron-ion pairs formed in the liquid target after ionization can recombine, thus contributing to the S1 signal at the expense of S2. However, under the presence of $\mathcal{E}_d$, the ionization electrons can be extracted from the interaction site and drifted towards the volume of the TPC up to the gas pocket. Along their travel, if the ionization track is parallel to the field [1], electrons will pass through the ionization column and will have a higher probability to recombine with Ar ions. On the contrary, a higher S2 signal is 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 a LAr-TPC through the S2-S1 correlation. One of the commonly-used models is the Thomas-Imel one [5]. It does not capture the directional sensitivity since it describes the cloud as a uniform cubic volume. On the other hand, the columnar recombination model introduced by Jaffé [2] overestimates the directional response since it treats the ionization cloud as an infinitely long cylinder. The ReD data are finally analyzed following a novel model that describes the cloud as an elongated ellipsoid with a single adimensional parameter R related to the non-sphericity of the initial electron-ion cloud [6, 7]. Starting from the equations describing the evolution of the electron-ion cloud, the dependence of the recombination fraction upon the angle between the track and drift field is described as $f(R, \theta_r) = \sqrt{\sin^2\theta_r + \cos^2\theta_r / R^2}$. An R value higher than 1 stands for a net directional effect, while for $R = 1$ any directional dependence is canceled and the Thomas-Imel configuration is restored.

4 A Data-Driven Analysis with Machine Learning

The absence of a well-established model allows for alternative approaches that do not require a theory as a starting point to describe a phenomenon. Artificial Intelligence techniques and Machine Learning (ML) are well suited to extrapolate the trend of a phenomenon starting from patterns and correlations in a dataset. In parallel with the statistical analysis carried out with an unbinned maximum likelihood fit [8] according to the model of [6], a data-driven analysis is then performed using ML. The strategy aims to train a model using numerical features extracted from NR events produced in the ReD TPC, thus starting from the assumption 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 could 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. Therefore, the S2 signal for each event will be predicted by using only the spatial coordinates of the event and the scintillation signal. The vector of features passed as an input is composed of the scintillation signal S1 and the (x,y,z) position of the ionization signal. The model should be able to predict the value of the S2 corrected for TPC non-uniformity effects. The problem is a supervised non-linear regression one since the model is trained on the vector of features as an input and the measured S2 signal as the target output. The chosen algorithm is the Extreme Gradient Boosting one (`xgboost`), well known in the literature for its good performance and multi-field-possible application to various problems [9]. To evaluate the accuracy of the derived model, the relative prediction error for each event is calculated, ϵ_{pred}, defined as

$$\epsilon^i_{pred} = \frac{S2^i_{measured} - S2^i_{predicted}}{S2^i_{measured}} \tag{1}$$

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 used to make predictions 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. The mean value and the error on the mean are calculated for each distribution (Fig. 1 (b)). It is possible to note that 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 should stand for a predicted S2 value greater than the experimentally measured one. This shows that the derived model tends to overestimate S2 for events with traces parallel to $\mathcal{E}_d$. Such a 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%.



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

Figure 1: (a) Schema of the experimental setup of the ReD experiment. (b) Mean relative prediction error for each ϵ_{pred} distribution obtained by splitting data into the four angular datasets. The red dashed line marks the $\epsilon_{pred} = 0.0043$ level (no directional effect).

5 Conclusion

The directional sensitivity of the ReD TPC is investigated with two complementary approaches, one according to a direction-dependent LAr charge recombination model with a likelihood statistical analysis [7, 8], and another one, described here, developing a data-driven analysis with ML techniques. 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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