Head-Tail in the DRIFT-II Dark Matter Detector

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We introduce the concepts and techniques relevant to determining evidence for the so-called Head-Tail asymmetry from neutron-induced nuclear recoil tracks in the DRIFT-II dark matter detector. The back-to-back dual TPC arrangement in DRIFT makes this detector ideal for Head-Tail tests, allowing systematic errors to be reduced. The detection of Head-Tail asymmetry can open a powerful new means of searching for a galactic signature from WIMPs.

1 Introduction

A world-wide effort to observe WIMP-induced nuclear recoils in terrestrial materials is underway [1]. Annual modulation [2] provides one route towards a galactic signature based on the non-terrestrial nature of WIMPs but it is known that a more powerful galactic signal, impossible to mimic by terrestrial backgrounds, could come from a device capable of tracking the direction of WIMP-induced recoil ions, down to low (∼1 keV/amu) energies, event by event [3]. The only method established for observing these powerful but difficult to extract signatures, is to use a low density, large volume, target with sufficient spatial resolution to do the necessary tracking [4]. The DRIFT (Directional Recoil Identification From Tracks) experiment at Boulby mine [5], is designed to achieve this using a low pressure CS_2 gas Negative Ion Time Projection Chamber (NITPC) [6]. Previous studies have shown that only ∼100 WIMP events are, in principle, needed to demonstrate the galactic nature of such a range component signature [7]. However, reconstruction of the full recoil direction vector, to distinguish the "tail" from the "head", as opposed to the direction axis alone, critically influences this sensitivity, lowering the required number of events to ∼10. Confirmation that this is possible would open prospects for a new generation of experiment sensitive to the galactic WIMP velocity distribution.

To achieve this signature requires measurement of the variation in ionization density along the track. Based on use of a $1\,m^3$ DRIFT module with realistic energy threshold and size for WIMP searches, we present here a new technique for achieving such a measurement. Results from application of the methods introduced here will be published in the near future. The technique is based on measuring the integrated ionization loss split between the head and tail of sulfur recoil tracks down to 1.5 keV/amu, induced by ^{252}Cf neutrons [8]. We show how the energy loss can be measured and hence how it is possible to measure track orientation.

2 DRIFT concept and dead-tail experiment

The idea behind DRIFT is to make use of the Earth's motion through the stationary Galactic WIMP halo which will tend to produce a WIMP wind from the direction Cygnus, declination $\sim 45°$. Recoil tracks produced will preferentially be aligned with this wind vector [3]. A detector on Earth at a latitude $\sim 45°$, like Boulby, will thus see the WIMP wind vector oscillate over a sidereal day, from pointing south to pointing to the Earth's center, repeating each sidereal day and going rapidly out of phase with the terrestrial day. The recoils produced are extremely low energy with the electronic stopping power, energy loss to electrons, expected to decrease from tail to head [9], (more ionization at the tail than head). However, as the ion slows the energy loss to nuclear recoils also becomes important. Also, ions at the end of their range scatter frequently and so tend to ball up, losing their last energy over a small region, possibly creating an ionization spike at the track-head, observable depending on the topology relative to the readout [10]. Even if these effects yield a theoretical head-tail asymmetry, the detector resolution and diffusion to a readout could swamp the effect.

Descriptions of the DRIFT-II design, operation and analysis are given in [11, 12], the specific module used here, DRIFT-IIc, being essentially identical to IIa,b. The device comprises a 1.5 m^3 low background stainless steel vessel filled with 40 Torr CS_2 and containing two identical back-to-back TPCs with a common 1 m^2 central cathode plane. Recoil events can form in two identical drift regions of 1 m^2 by 50 cm depth. Ionization tracks are drifted in each TPC away from the central cathode, to be read out by either of two MWPCs. We defined here the direction perpendicular to the MWPCs as the z-direction, this being horizontal, the +z direction defined as left to right viewed from the front with the origin on the central cathode. Each MWPC comprises 448 grid (y-direction) and 448 anode wires (x-direction) of 2 mm pitch, grouped into 8 signal lines per readout plane. 52 wires at the edges provide veto signals against, for instance, alphas [12]. The fiducial volume is 0.80 m^3 (134 g of CS_2) and each drift volume has a retractable $\sim$100 μmCi ^{55}Fe source for gain monitoring.

The head-tail technique here is based on use of a 202 μCi ^{252}Cf source to produce neutrons headed in the +x, -y, +z and -z directions. Simulations [13] have shown such exposures mimic WIMPs quite well. For instance, Figure **??** compares the S recoil spectrum from ^{252}Cf neutrons (using GEANT) and 1000 GeV WIMPs. Thus the head-tail signature in either +z or -z neutron exposure, should if present be seen through production of a different degree of ionization at the head or tail revealed as an asymmetry in the time distribution of ionization arrival at the MWPC planes. For instance, if the effect produces more ionization at the head then for a -z directed neutron run, events on the right TPC will have, on average, more ionization earlier than later. Events on the left TPC will have the reverse. For the +z run the effect will be opposite. For x and y runs, with neutrons parallel to the MWPCs, the ionization on average will appear the same at the beginning and end.

3 Head-tail analysis procedure

A simple event-by-event analysis has been developed to quantify this, where the voltage integral over the first and second half of each accepted ionization time profile is calculated and the ratio taken as an asymmetry measure. In DRIFT, the voltage integral is proportional to the Number of Ionizing Pairs (NIPs), convertible to event energy using source calibrations. For instance, 1000 NIP S recoils have energies of 47 keV [13]. We thus introduce a so-called asymmetry quantity given by: $NIPsRatio = NIPs_1/NIPs_2$, where indices refer to the first and second half of the pulse. Determination of NIPsRatio follows by locating the highest voltage and using this to find the first time that the waveform crosses 25% of this value on either side (to minimizes potential biases from waveform noise and baseline shifts). The middle of the track is defined as midway between these times. $NIPs_1$ is the integral voltage above 25% of the peak value at minimum time to the middle and $NIPs_2$ the integral from there to 25% of peak value at maximum time. Prior to this a first stage analysis is used to extract the recoil signals from unwanted backgrounds, like sparks and alphas see [14] and for general concepts see [15]. Figure 2 shows a typical NIPs energy spectrum for neutron-induced S recoils selected by the analysis. Here, the hardware threshold and the analysis cuts produced an effective threshold of ∼1000 NIPs, 47 KeV S recoil [13].

Experiments can proceed using this technique with neutrons alternately directed along the +x, -y, +z and -z directions. For a given number of events passing cuts for each exposure and direction, the means of the NIPsRatio distribution for left and right TPC can be recorded along with their difference and the significance (difference divided by combined error). It is expected, for instance, that for the +x run the average NIPsRatio=1.0 since equal numbers of events are headed towards or away from the detectors. It is likely however that in practice the mean ratio is not 1.0 because there will be amplifier overshoot that tends to shorten the second half of the event. However, because we have two detectors, identical except for the opposing electric drift fields, with identical electronic shaping on both sides, the left and right mean NIPsRatios should be in statistical agreement. The +y run should show the same result within the errors. The technique will then allow the +z run to be compared with the +x and -y runs to determine whether the events on the left side have, for instance, a larger NIPsRatio and events on the right, smaller. The sign here is of course a signature that indicates if there is more ionization at the tail than head or vice-versa. As a check the -z run results for the left should agree with those for the right from the +z run.

As a better measurement of the effect events on the left(right) of the +z(-z) runs for which the NIPsRatio measures the ratio of the ionization at the head of the track to the tail, can be combined, as also for the events on the right(left) of the +z(-z) runs for which the NIPsRatio measures the ratio of the ionization at the head to the tail. The difference in these average ratios can be used as a better measure of the effect. As a further check the same procedure can be applied to the +x and -y runs, where a null result is expected.

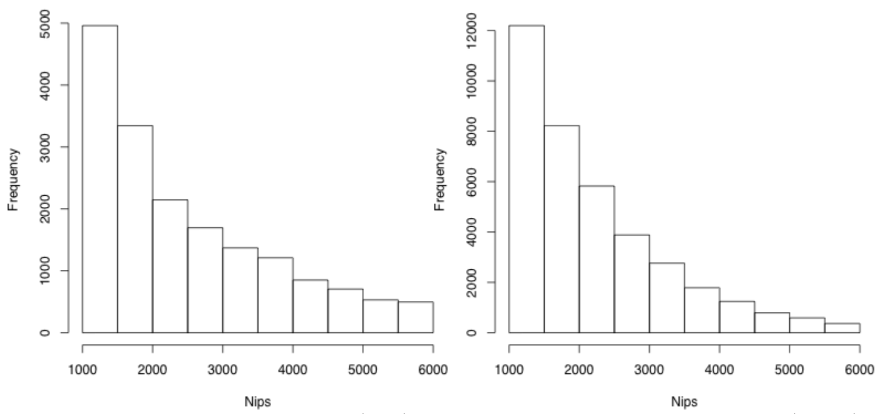

Figure 1: Predicted NIPs spectrum for (left) neutron induced S recoils; and (right) from 1000 GeV WIMPs (using GEANT).

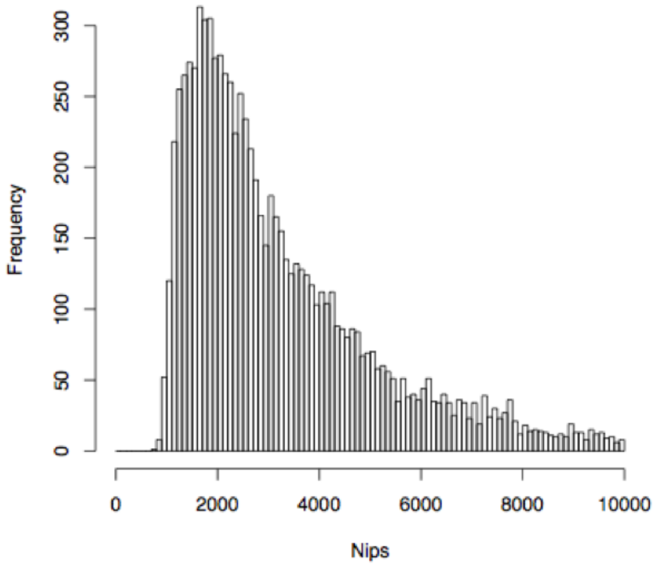

Figure 2: Example neutron S recoils NIPs spectrum.

4 Conclusion

In summary, we have developed a new technique for determining the existence or not of a head-tail asymmetry in nuclear recoils at low energy in DRIFT. The DRIFT II detector is designed well for this type of measurement since it comprises two detectors identical except for the direction of the drift field. Results form a directed neutron run using the technique are expected to be published soon [16]. We thank J. Martoff for useful discussions, CPL for access to Boulby and NSF and ILIAS EU contract RII3-CT-2004-506222 for support.

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