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DRIFT: a directionally sensitive dark matter detector

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On behalf of the DRIFT and UK Dark Matter Collaborations

Abstract

Directional Recoil Identification From Tracks-I (DRIFT) is the world's first WIMP dark matter detector with sensitivity to the directions of nuclear recoils. The distribution of WIMP induced nuclear recoil directions offers the most powerful way of positively identifying a WIMP signal. This paper discusses the DRIFT-I detector and considers future high spatial resolution readout schemes.

Keywords: Dark matter; Gas detectors; MWPC; GEM; MICROMEGAS

1. Introduction

The search for dark matter is perhaps the greatest challenge facing particle physics and cosmology at present. Weakly Interacting Massive Particles (WIMPs) are the currently favoured candidates for the dark matter, and a WIMP, the Neutralino, is predicted by Supersymmetric extensions to the Standard Model. Searches for these particles in our galaxy look for the low energy ($<100\,\mathrm{keV}$) nuclear recoils produced by the elastic scattering of WIMPs off atomic nuclei. However, the scattering rate is less than 1event per kg of target per day, and so backgrounds from electron and alpha recoils must be reduced.

In addition, experiments would like to measure some characteristic feature of the WIMP signal that positively identifies it as galactic in origin. Directional Recoil Identification From Tracks-I (DRIFT) is a low-pressure gas Time Projection Chamber designed to detect WIMPs, and is the first detector in the world capable of measuring components of WIMP-induced nuclear recoil track ranges in addition to their energy. This sensitivity to the recoil direction offers significant advantages in positively identifying a WIMP signal compared with other techniques. Whilst several prototype directional detectors based on phonon anisotropy in BaF2 crystals [1] or roton anisotropy in liquid He [2] have been tested, low pressure gas detectors offer the best prospects for a workable detector.

The DRIFT project is a collaboration between the United Kingdom Dark Matter Collaboration (UKDMC: Sheffield University, Rutherford Appleton Laboratory, Imperial College), Occidental College, Temple University and Lawrence Livermore National Laboratory with the purpose of constructing and operating low pressure TPCs for WIMP detection.

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This paper discusses the DRIFT-I detector, presents some preliminary data from underground engineering runs, and considers future high spatial resolution readout schemes.

2. Directional detectors—theory

The standard isotropic sphere model of the WIMP halo believed to surround our Galaxy predicts it to be non-rotating with a Maxwellian velocity distribution of mean speed $\sim 270\,\mathrm{km s^{-1}}$. In contrast, the solar system is orbiting the galactic center, and thus moving through the WIMP halo, at a speed of $\sim 220\,\mathrm{km s^{-1}}$. Thus the WIMP velocity distribution when transformed to the Earth's frame is strongly peaked in the direction of the solar system's motion. In consequence, the distribution of nuclear recoil directions will be strongly peaked in the opposite direction. Thus, a detector capable of measuring the directions of these recoils can positively identify a WIMP signal from two distinct signatures.

As shown in Fig. 1, a detector fixed on the Earth will see the mean recoil direction rotate from downwards to southwards and back again over one sidereal day. Alternatively, one can measure the angle between the solar motion and recoil directions and look for deviations from isotropy. Monte Carlo simulations indicate that a non-isotropic signal could be identified at 90% confidence as few as 100 events. A further advantage of these directional signals is that they cannot be mimicked by background signals (Fig. 2).

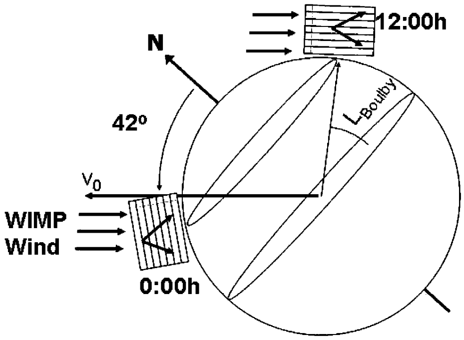

Fig. 1. Diagram showing the orientation of the Earth's spin axis relative to the WIMP wind. Over 12 sidereal hours, the mean recoil direction rotates from downwards to southwards for a detector at the Boulby mine.

Fig. 2. Picture of the DRIFT-I detector, showing the main detector outside and in front of the vacuum vessel.

3. Directional detectors—realization

The sub-100 keV energy scale of WIMP induced nuclear recoils means that their ranges are very short (~ 100 A) in solids and liquids, making directional measurement nearly impossible. Instead, DRIFT uses a gas at low pressure to extend the recoil range to a few millimetres.

Despite the low target mass of a low-pressure gas detector, it is competitive in sensitivity to WIMPs with higher mass solid/liquid detectors through very high background rejection. The difference in range between electrons, alphas and recoils at a given ionization is such that rejection efficiencies as high as 99.9% are possible at 6 keV [3]. This allows a 1 m^3 detector operating with Ar at a pressure of 40 torr to produce a limit on the WIMP mass and scattering cross-section competitive with DAMA and CDMS-I [3].

DRIFT also utilizes an electronegative gas, CS_2, in order to optimize the spatial resolution. By capturing ionization electrons onto CS_2 molecules, the resulting negative CS_2^- ions are drifted, thereby reducing the charge diffusion to thermal levels. Experiments have shown that diffusions of less than 0.5 mm can be achieved over drift length of ~0.5 m [4]. At the readout stage, the captured electrons are field ionized by a high electric field, enabling amplification by electron avalanches.

4. The DRIFT-I detector

DRIFT-I is the first full scale DRIFT detector to be operated at a deep underground, low background site. The detector itself consists of two 0.5 m^3 fiducial volumes defined by 0.5 m long field cages mounted either side of a common cathode plane consisting of 512 20 μm stainless steel wires. Particle tracks are read out with two 1 m^2 MWPCs, one at each end of the field cages. The MWPCs are made up of an anode plane instrumented with 512 20 μm stainless steel wires at a pitch of 2 mm, with grid planes of 100 μm stainless steel wires either side. All field cage and MWPC frames are constructed from Lucite to ensure a low contamination of U/Th. Although the MWPCs only permit a 2D projection of the track range to be measured from reading out signals on the anode wires, background rejection efficiencies >99.9% are still possible via the range/ionization measurement. The detector is housed in a large stainless steel vacuum vessel.

Full engineering runs were performed above ground during spring of 2001 before installation at the Boulby Mine during September/October 2001. Since this time, work has concentrated on characterizing the detector in this low background environment using gamma (^{55}Fe) and neutron (^{252}Cf) sources.

5. Preliminary engineering data

The DRIFT-I DAQ system allows each MWPC anode wire to be read out individually. A veto is also formed from the edge anode wires and the outermost wires on each grid plane. Output is in the form of the voltage traces on each triggered wire, enabling the range and ionization of tracks to be determined as described in Snowden-Ifft [5].

Noise events such as sparks are easily rejected as these are characterized by large pulse height, narrow pulses, often occurring on neighbouring wires. Gamma induced photoelectron events from an ^{55}Fe source are also narrow with small pulse heights. The narrowness of the pulses indicates that these events are occurring in the MWPCs themselves, where electrons are being drifted instead of ions to give a fast pulse. In addition, no gamma events are seen in background data. This lack of gamma sensitivity in the main gas volume is due to the ionization density being much lower for electrons. As a result, these events will produce smaller pulse heights due to both the lower charge density deposited on the wires, and the slower drift of negative ions in the main gas volume. By a suitable choice of pulse height trigger, all gamma events occurring in the main gas volume can be rejected, a major advance for dark matter detectors (see Fig 3).

This lack of gamma sensitivity has also been demonstrated in ^{252}Cf runs, as this source is a copious gamma emitter, but no gamma events are seen in the data. DRIFT-I is continuing to take data at present, with a predicted limit on the WIMP scattering cross-section of $\sim 10^{-6}$ pb after 1 year of operation.

6. DRIFT-II: future readouts

To reach sensitivities to scattering cross-sections below 10^{-7} pb, a scale up in the mass of DRIFT-I is needed. DRIFT-II is proposed to have 30–50 times the sensitivity of DRIFT-I through an increase in the volume and gas pressure. However, increasing the gas pressure means that the recoil range will be shorter, and so a higher spatial resolution detector is required. A further challenge

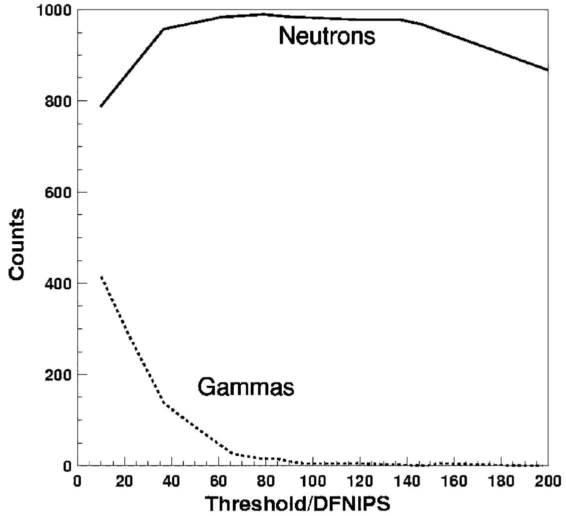

Fig. 3. Graph showing the number of neutron and gamma events seen in one data run as a function of the analysis threshold in DFNIPS (the smallest detectable ionization). Gamma events are strongly suppressed by increasing the threshold, whereas the number of neutrons remains roughly constant.

is that sub-mm resolution is required over areas of 1 m^2 or more. Current research is focusing on three schemes.

Although DRIFT-I reads the anode wires of its MWPCs, the cathode (grid) wires could also be read out. Induced charges on these wires caused by avalanches on the anode allow the centre of the avalanche to be found with high accuracy by fitting a centroid to the distribution of pulse heights on the cathode wires. By taking time-resolved slices through the cathode pulses, the position of the avalanche along an anode wire can be found as a function of time, and thus the range of the track along the anode wire can be determined. The advantage of this method is that large area detectors can be constructed simply and cheaply, but the resolution is still limited in the x-direction by the spacing of the anode wires.

A second scheme envisages using a MICROMEGAS microstructure detector [6]. This device allows high gains (up to 10^4), and the construction is simple and from naturally low background materials. In addition, 2D readouts are possible from crossed anode microstrips or micropixel based detectors. Current research is focused on testing these detectors in low pressure CS_2 gas. MICROMEGAS detectors up to $40 \times 40\,cm^2$ have been constructed, but larger areas are not necessary for DRIFT as it would be possible to tile smaller detectors together over a large area.

Finally, optical imaging of recoil tracks using Gas Electron Multipliers (GEMs) [7] is being investigated. Electroluminescence via electron avalanches and drift in GEM based detectors has already been demonstrated for Ar–CF_4 gas mixtures at atmospheric pressures [7]. Previous work has also demonstrated electroluminescence in a Parallel Plate Avalanche Chamber operated in CS_2 at low pressure, so current tests are focused on testing GEMs in this gas. The significant advantage of an optically based readout is that very few readout channels are needed to image a large surface area at high spatial resolution. As an example, one 4×10^6 pixel CCD camera could image 1 m^2 at a resolution of 0.5 mm.

7. Conclusions

DRIFT-I is the world's first operational WIMP dark matter detector with directional sensitivity. It has demonstrated operational stability underground and continues to take data. Neutron and gamma source calibrations have shown the detector to operate as expected, and insensitivity to gamma backgrounds in the main gas volume has been demonstrated. Detectors for the DRIFT-II detector are also under investigation, with MWPC cathode readout, MICROMEGAS and optically imaged GEMs being studied.

Acknowledgements

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