Background reduction and spin-dependent limits using DRIFT - a directionally sensitive dark matter detector

Mark Pipe on behalf of the DRIFT collaboration
Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, UK
E-mail: m.pipe@sheffield.ac.uk

Abstract. The DRIFT (Directional Recoil Identification From Tracks) collaboration operates a 1m$^3$ low pressure gaseous negative ion time projection chamber (NI-TPC) WIMP dark matter search experiment in the Boulby Underground Laboratory. Recent progress from the DRIFT collaboration is presented that includes a series of background reduction work and the addition of CF$_4$ to the target volume. A preliminary limit on the spin-dependent WIMP-proton interaction cross-section is presented from a non-blind analysis of 47.2 days live time with a 0.8 m$^3$ 30 Torr CS$_2$ - 10 Torr CF$_4$ target. The preliminary limit has a minimum of 1.1 pb for a 100 GeV WIMP.

1. Introduction

Weakly Interacting Massive Particles (WIMPs) are a particularly well-motivated candidate for cold dark matter. Dark matter halo models suggest that WIMPs may exist in the form of an isothermal sphere that encompasses our galaxy, resolving the problem of flat galactic rotation curves [1]. WIMPs are predicted to interact with baryonic matter such that sufficiently sensitive particle detectors should be able to detect the rare (<1 event/kg/day), low energy (∼keV) nuclear recoil that would result. The nuclear recoil energy spectrum expected from WIMP interactions is exponential and featureless making it very difficult to discern above the many backgrounds that exist at this energy level. However, WIMPs arrive from a fixed point in the galactic rest frame (roughly from the constellation Cygnus) and this directionality offers a uniquely powerful signature for a directionally sensitive dark matter detector on Earth [2]. The DRIFT collaboration is attempting to utilise this powerful discriminant against terrestrial backgrounds with the development of a directionally sensitive dark matter detector.

The DRIFT-II detector (described in detail in [3]) is a 1 m$^3$ low pressure gaseous negative ion time projection chamber (NI-TPC). WIMP-nucleon interactions in the 40 Torr CS$_2$-CF$_4$ target gas are expected to create tracks of ionisation a few mm in length, and with an orientation biased in the direction opposite to that of the incoming WIMPs [4]. The DRIFT detectors use a novel negative ion drift concept to reduce diffusion of this track for drift distances up to 50 cm. Electronegative CS$_2$ gas is used in the target volume so that primary ionisation electrons quickly attach to the CS$_2$ molecules creating a track of negative CS$_2$ ions. These heavy ions drift with far less diffusion than electrons drifted alone, reducing diffusion to thermal levels and preserving the track’s directional information.
There are currently two, essentially identical, DRIFT-II modules in operation. DRIFT-IId is located at a depth of 2805 m.w.e. at the Boulby Underground Laboratory, UK. DRIFT-IIc is located in a surface laboratory at Occidental College, Los Angeles, CA, USA. Results presented here are from the DRIFT-IId detector.

2. Background suppression

The current dominating background in the underground DRIFT-IId detector is from a class of events known as radon progeny recoils (RPRs). A schematic showing the source of these events can be seen in Figure 2. Radon gas (\(^{222}\text{Rn}\) and \(^{220}\text{Rn}\)) is known to be present in the DRIFT-IId detector target volume, emitted from trace levels of U and Th in the detector components. \(^{222}\text{Rn}\) is unstable and decays to \(^{218}\text{Po}\) via the emission of a 5.49 MeV alpha, producing an ionisation track of length \(\sim 400\) mm in the detector volume. The long track length allows these events to be discriminated from WIMP interactions with high efficiency so this background has little affect on detector performance. However, \(\sim 80\%\) of the time this decay results in an unstable, positively charged \(^{218}\text{Po}^+\) ion that, in the electric field, drifts to, and plates out on, the surface of the 20\(\mu\)m stainless steel central cathode wires \([5]\). This unstable \(^{218}\text{Po}\) atom then decays by emission of an 6.11 MeV alpha, which has a range of only 14\(\mu\)m in stainless steel. The geometry of this decay on the surface of the wire means that there is a \(\sim 37\%\) chance that the alpha will become completely embedded in the cathode wire leaving only the recoil of the \(^{218}\text{Po}\) into the fiducial volume. The result is a detection of a nuclear recoil of energy \(\sim 100\) keV, potentially mimicking the expected WIMP signal. Furthermore, this decay chain results in \(^{210}\text{Pb}\) plating out on the central cathode wires. \(^{210}\text{Pb}\), unstable with a half life of 22.3 years, can then be a source of further RPR background events long after the radon has been eliminated from the detector volume.

2.1. Radon reduction

Eliminating radon from the detector volume is the first crucial step in reducing the RPR background. The ambient radon background in the Boulby Underground Laboratory is low (< 3 Bq m\(^{-2}\)), so it is known that the high levels of radon contamination in the DRIFT-IId detector must be emanating from the components of the detector itself. Results from extensive radon emanation tests of all detector components are shown in Table 2. It is seen that the RG58
coaxial cables (PVC coated) and ribbon cables (PVC coated) were the dominant source of radon emanation. PTFE coated coaxial signal cables and FEP coated ribbon cables were tested and found to be suitable replacements for these with significantly lower radon emanation. The radon measurements in Table 2 show the total number of Rn atoms per second emitted by all detector components is reduced from 0.95±0.06 to 0.09±0.03 by replacing these cables.

An analysis of data from the DRIFT detector before and after replacing the components with high radon emanation shows a reduction in the rate of fully contained alpha events by a factor of 10±1, consistent with the expected reduction from the Rn emanation results. A reduction in the residual RPR rate by a factor of 12.5±0.8 is also seen and is also consistent with the removal of radon from the detector volume.

In March 2008 the 1 m$^2$ central cathode from the DRIFT-IIId detector was etched in nitric acid in an attempt to remove long lived radon progeny (e.g. $^{210}$Pb) and any other contaminants from the 512 20 µm wires of the central cathode wire plane. The cathode was placed in a clean plastic lined container that was then filled with 3 molar dilute nitric acid until all of the wires were covered. It was left to soak for 30 minutes. The water was then drained from the container and replaced with triply de-ionised water in which the cathode was left to soak for 48 hours. The water was then drained and the cathode allowed to dry for one week before being put back in the detector. The cathode was allowed to outgas in the vacuum vessel for two weeks before data taking was started again.

Analysis of data from before and after this procedure showed that the level of background events was reduced further, by a factor of 6.7±1.0, to the current level of 12±1 background
Table 1. Table caption.

| Sample                        | Emanation time | Adjusted result |
|-------------------------------|----------------|-----------------|
| (emanating into vacuum)       | (days)         | (Rn atoms s\(^{-1}\)) |
| RG58 coaxial cables (72m)    | 12.5           | 0.36±0.03       |
| Electronic boxes              | 12             | 0.05±0.02       |
| Ribbon cables                 | 6.5            | 0.50±0.04       |
| Electronics                   | 10             | <0.02*          |
| Coax cables                   | 7              | 0.04±0.02       |
| Field cage parts              | 7              | <0.03*          |
| PTFE signal cables            | 20             | <0.02*          |
| FEP ribbon cables             | 12.5           | <0.02*          |

Table 2. Radon emanation results of various components from DRIFT-IIa. Measurements marked with ‘∗’ are below the level of sensitivity of the radon emanation setup used.

2.2. Analysis techniques

Despite the significant reduction in RPR events achieved with the techniques above, the remaining rate of 12±1 RPR events per day needs to be addressed. RPRs create ionisation tracks in principle indistinguishable from WIMP/neutron induced tracks. However, RPR events occur solely on the surface of the central cathode. Thus all RPR tracks will have drifted the full 50 cm drift distance to the MWPC readout plane and will have suffered maximum diffusion of ∼0.7 mm. Although there is not sufficient resolution in the x and y dimensions of the detector to measure the 3-dimensional diffusion at this level, the high resolution in the z axis (from the ∼60 m s\(^{-1}\) ion drift velocity and the 1 MHz digitisation rate) is sufficient to determine some measurement of the diffusion. This measurement is challenging because the charge arrival of a track is affected not only by diffusion but by the orientation of the original track. Nevertheless, the track range in the z direction will generally be greater for events that occurred on the central cathode because of the diffusion of the track. The RMS time (RMST) of the event waveform was found to be the best measure of this. We show in the left hand side plot of Figure 5 the RMST vs equivalent F recoil energy in keV for background data remaining after all cuts (blue points) compared to the neutron data that has been through the same set of cuts (red points). For neutrons we expect an isotropic distribution in the detector. A clear separation can be seen with the background RPR events in a region ∼25-65 keV equivalent F recoil energy with RMST ∼15 µs and the neutron events spread out between ∼10-20 µs. This separation in neutron data vs background data allows a signal region to be derived that has zero background and a neutron efficiency that can be calculated using Monte Carlo simulations. The left hand side plot of Figure 3 shows the background events remaining, after cuts, from 47.2 days live time with a 0.8 m\(^3\) fiducial volume of a 30 Torr CS\(_2\) - 10 Torr CF\(_4\) gas mixture in the underground DRIFT-IIId detector. A signal region has been marked (tan line) that contains zero background events but in which events are seen in neutron calibration data. The right hand side plot of Figure 3 shows data from a Monte Carlo simulation, which has been verified by comparison to real neutron data. In this simulation 10000 100 GeV WIMP interactions were produced in the DRIFT-IIId detector. The output data from the simulation was processed by the same analysis package and with the same cuts as the real data. The plot shows the 2742 simulated WIMP
events that remain after all cuts, 228 of which are in the zero background signal region. A range of WIMP masses are simulated and analysed in this way in order to determine the response of the detector to WIMPs of all relevant masses.

Figure 3. Plots of event RMST vs equivalent F recoil energy in keV. The left plot shows the remaining 6132 background events, after cuts, from 47.2 days of live time with a 30 Torr CS$_2$ - 10 Torr CF$_4$ gas mixture. A signal region has been chosen (tan line) that has zero background. The right plot shows the distribution of events from Monte Carlo data of 100 GeV WIMP recoils. From 10000 WIMP recoils generated, 2742 events pass all analysis cuts, 228 of which are in the zero background signal region. The Monte Carlo simulation has been verified by comparison to real neutron data.

3. Spin-dependent WIMP-proton limit
A target material of 30 Torr CS$_2$ - 10 Torr CF$_4$ was chosen to maximise fluorine content (where fluorine, with a nuclei of spin 1/2, is an ideal target material to detect spin-dependent WIMP interactions [6]) whilst maintaining negative ion drift and detector stability [7]. The detector was run for 47.2 days live time with a continuous flow of this gas mixture (to minimise radon buildup in the gas) giving 1.47 kg·days of fluorine fiducial mass. Preliminary limits on the SD WIMP-proton cross-section were produced using the zero background signal region and the WIMP detection efficiency determined in Section 2.2. These limits are shown in Figure 4. It should be noted that this first analysis is not blind, the signal region being chosen after analysis of the data and study of the background events. Further data is currently being taken that will be used in a fully blind analysis.

3.1. Thin film cathode
As described above, the WIMP-like RPR background is a result of unstable radon progeny on the surface of the central cathode wires recoiling into the fiducial volume, with the tell-tale alpha becoming embedded in the central cathode wire. A simple, short-term solution to drastically reduce this background could be to make the cathode more transparent to alphas so that the alpha particle does not get lost in the central cathode, but escapes and can be used to reject the event.
To study this possibility a number of potential cathodes were modelled and tested for structural integrity. 0.9 µm mylar sheet, evaporation coated with aluminium was found to be a suitable solution. The range of alphas in a sheet of this thickness is such that only ∼1% of decays on the surface would result in a WIMP-mimicking RPR event compared to 37% of radon progeny decays on the wire central cathode. This suggests a potential reduction in background of a factor ∼40.

A 1 m² cathode constructed from 0.9 µm mylar sheet was tested at Occidental College on DRIFT-IIc and was shown not to have adverse effects on detector operation or stability. It was subsequently installed on the DRIFT-IIId detector underground at the Boulby mine in March 2010 and the detector has been operating stably since the installation. Figure 5 shows a preliminary analysis of this data. The left hand side plot shows 12.25 days of background data (blue points) on top of 0.43 days of neutron data (red points) with the wire central cathode. The right hand side plot shows background and neutron data of similar live times with the new thin film central cathode. The rate and distribution of neutron events remains constant as expected, whereas the number of background events has reduced significantly, by a factor ∼15. The expected full factor ∼40 reduction is not seen suggesting there may be other backgrounds within the RPR region, or that there may be new backgrounds introduced by the thin film central cathode. These backgrounds will have to be understood and changes to cuts may be necessary to maximise WIMP efficiency and remove further of the background events. This job is underway as part of the preparation for the proposed blind analysis.

4. Summary
A 47.2 day run of the DRIFT-IIId detector in the Boulby Underground Laboratory has been used to set a preliminary limit on SD WIMP-proton cross-sections ∼3 orders of magnitude below published limits from other directional detectors and comparable to that achieved by
Figure 5. Plots of event RMST vs equivalent F recoil energy in keV. The left plot shows 0.43 days of neutron data (red points) that produce an isotropic distribution of tracks in the detector volume, and 12.25 days of background data (blue points) that occur on the surface of the wire central cathode and thus all suffer maximum diffusion. The right plot shows 0.44 days of neutron data (red points) and 12.22 days of background data with the new thin film central cathode. The neutron efficiency is seen to remain constant whilst a factor of $\sim 15$ reduction is seen in events in the RPR region.

non-directional detectors of much larger target mass.

The DRIFT-IIId detector is currently running underground with the 20 $\mu$m wire plane cathode replaced by a 0.9 $\mu$m thin film cathode, which has been shown to reduce the RPR background by a factor of at least $\sim 15$. Preliminary analysis has shown a significant reduction in background but further work is required to fully understand the data with the new cathode.

The RMST parameter used here to reject RPRs in analysis has allowed competitive limits to be set but it is clear that a more accurate and efficient way of rejecting these events is required. To achieve this the current focus of the DRIFT collaboration is to develop a way of determining the absolute Z position of events in the detector by detecting the positive ions that drift to the central cathode from a particle interaction, as well as the negative charge at the MWPC. So far R&D work has succeeded in detecting $\sim 1000$ ion pairs ($\sim 45$ keV equivalent F recoil energy) that arrive at the central cathode of a test device with similar conditions to the DRIFT detectors.

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