Progress on the Boulby Mine Dark Matter Experiments

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Abstract. We summarise here the present status of searches for Weakly Interacting Massive Particles at the Boulby site using NaI, liquid Xe and low pressure gas.

1 Introduction

The UKDMC programme of WIMP dark matter searches at Boulby Mine has recently undergone significant expansion. Working with new international collaborators the project now involves three interleaved experiments: (i) NAIAD (NaI Advanced Detector) - plus associated small diagnostic array based on pulse shape discrimination in NaI and CsI, (ii) ZEPLIN (Zoned Proportional scintillation in LIquid Noble gases) - currently comprising three experiments based on liquid xenon, and (iii) DRIFT (Directional Recoil Identification From Tracks) - a development towards the first dark matter detector with direction sensitivity. In the following sections we describe recent progress in each project. To fulfil the objectives of the experiments a major upgrade of facilities at the Boulby underground laboratory has been sought and successfully obtained. We describe here the new laboratories being built at the Boulby site, now renamed the British Underground Facility for Dark Matter and Neutrino Studies.

2 Diagnostic Scintillator Array

2.1 NaI(Tl)

The base-line technique of the UKDMC programme has been the use of pulse shape discrimination (PSD) in NaI [1]. In this technique each scintillation pulse decay resulting from a particle interaction in low background NaI is individually fitted to a single exponential to extract a decay time constant τ. The distribution of accumulated τ values can be shown to have the form:

$$\frac{dN}{dt} = \frac{N_0}{t\sqrt{2p}\ln w} \exp\left[\frac{-(\ln t - \ln t_0)^2}{2(\ln w)^2}\right] \qquad (1)$$

where τ_0 is the mean time constant and *w* the width [1,2]. The mean time is know from neutron calibrations to be typically 30% lower for Na and I recoils than for background electron recoils arising from gamma interactions (ratio $\tau_{neutron}/\tau_{gamma}$ ~0.70). This enables a statistical search for nuclear recoils to be performed, the sensitivity of which depends on the width of the τ distribution, *w*, and the event energy. Values for *w* depend on the number of photoelectrons/keV (pe/keV) obtained from the crystal and a factor associated with the quality of the crystal. Further, details of the techniques can be found in refs. [1-6].

First limits on weakly interacting massive particles based on this PSD technique in NaI where reported in 1996 using a 6 kg low background NaI detector operating in a high purity water shield at Boulby [1]. Subsequently, the detector (DM46) was upgraded by installation of improved lightguides and larger photomultipliers (PMTs). This increased the light collection to ~3.5 pe/keV. The resulting improved sensitivity (from a decrease in *w*) allowed discovery of a previously undetected population of fast time constant events in the NaI - the time constant ratio being τ_{anom}/τ_{gamma} ~0.75 [4]. Fig. 1 shows a typical plot of the spectrum of these events from various data runs.

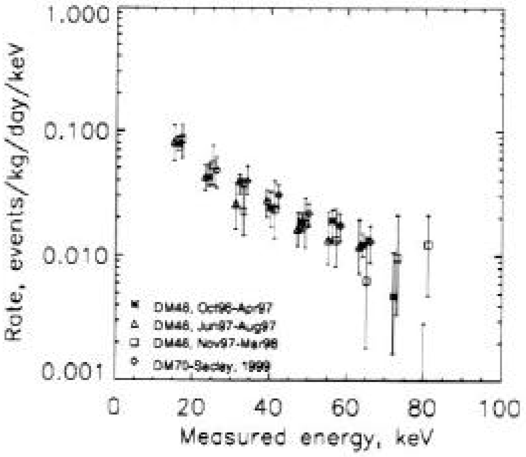

Fig. 1. Energy spectra of anomalous fast time constant events from 3 runs of the UKDMC DM46 NaI experiment and the Saclay crystal (DM70) originally part of the DAMA NaI array

Subsequently an array of new NaI crystals (total mass 20-30 kg) from different manufacturers with different geometries and in various shielding arrangements, was built to investigate the origin of the anomalous events. Results have been extensively reported [4,7]. In all these crystals anomalous events were detected at the same rate and with the same exponentially decreasing spectral form, within statistics. In 1999, in collaboration with the Saclay group [8] one of the original batch of 9.7 kg Crysmatec NaI crystals currently used by the DAMA collaboration [9] was obtained and installed at Boulby. This crystal, after removal from the DAMA array, had been previously operated at the Modane underground site by the Saclay group where a population of anomalous events was detected [10]. New data from this crystal (DM70) from runs at Boulby using different electronics, shielding and analysis techniques, has now confirmed the presence of the events in this crystal and now demonstrated that their characteristics are comparable with those of the events detected in the other NaI crystals. Fig. 1 shows the latest anomalous event spectrum from DM70 for comparison with DM46. The results suggest that these unidentified events could also be present in the DAMA NaI array and would likely be revealed by pulse shape discrimination if applied to that detector.

Extensive laboratory tests of unencapsulated NaI crystals with alpha and beta sources have now also been performed to investigate the origin of the anomalous events. These experiments have revealed the possibility that extra-fast scintillation events can be produced by interactions near the crystal surfaces (down to a few μm) [5,6]. There is evidence that the effects vary from crystal to crystal and depend on the surface treatment applied. The studies have concluded that surface beta or x-ray events are unlikely to be responsible for the anomalous events. However, it appears possible that alphas interacting in the surfaces may be capable of inducing fast scintillation events [11]. It has been shown that alpha emitters could be implanted in a thin sub-μm surface layer by exposure to ^{222}Rn and that such alphas could produce an energy spectrum of form compatible with that observed from the anomalous events [12], whereas alphas firing into the crystal from external surface contamination produce a spectrum that may be too flat. However, in both cases the count rate observed requires a contamination level equivalent to $\sim 10^{-6}$ g/g U, Th which is many orders of magnitude higher than the known contamination in the bulk NaI and surrounding materials, and incompatible with radon levels. It is also unclear how the mechanism of radioactive contamination could produce event rates so similar in crystals that have widely differing history, come from different manufacturers and are operated in different environments.

2.2 CsI(Tl)

Like NaI(Tl), CsI(Tl) is known also to have PSD capability at high energy [13]. This makes CsI potentially viable as a WIMP detector with the interesting diagnostic characteristic as a target of behaving like NaI but without the low-A Na component. It also provides an alternative route to investigating the origin of the anomalous events seen in NaI. To investigate the potential of CsI for these tasks a series of neutron scattering experiments have been performed to assess the recoil discrimination capability below 100 keV (including measurement of the neutron to gamma τ ratio and distribution widths *w*) and the quenching factor Q (the efficiency of conversion of recoil energy into scintillation light relative to electrons of the same energy). Similar studies have recently been performed by Kim et al. [14] and Pecourt et al. [15]. Measurements of pulse shape characteristics were performed using a crystal of size 3 inch diameter x 1.5 inches close-coupled to two 3 inch ETL 9265KB photomultiplier tubes and exposed to ^{57}Co, ^{60}Co and ^{252}Cf sources. For quenching factor tests a 1 inch diameter x 1 inch crystal was mounted in the UKDMC 2.9 MeV neutron beam at Sheffield University. Both crystals were previously polished and side surfaces wrapped in PTFE. A light yield of about 5.5 pe/keV was achieved for the larger crystal. Further details of the apparatus and procedures can be found in [16,17].

Shown in Fig. 2 are the measured quenching factors $Q = E_m/E_r$, where E_m is the measured energy and E_r is recoil energy (for Cs and I), as a function of E_r together with the measurements reported in [15]. Both results show an increase in quenching factor with decreasing recoil energy (from ~11% at 60 keV to ~17% at 12 keV). The ratio of time constants was found to be well fitted by the equation: R_t (E < 4 keV) = 1 and R_t (E > 4 keV) = $a + b$ x exp[(c-E)/d] where: a = 0.65, b = 0.35, c = 3 keV and d = 4.5 keV for CsI(Tl) and a = 0.75, b = 0.25, c = 3 keV and d = 5 keV for NaI(Tl). The width *w* of the distribution is a function of the number of photoelectrons and can be parameterised as: $w = 1 + f\,(N_{pe})^{-1/2}$, where N_{pe} is the number of photoelectrons and f = 2.4 for CsI(Tl) and f = 1.7 for NaI(Tl) at 10^0 C.

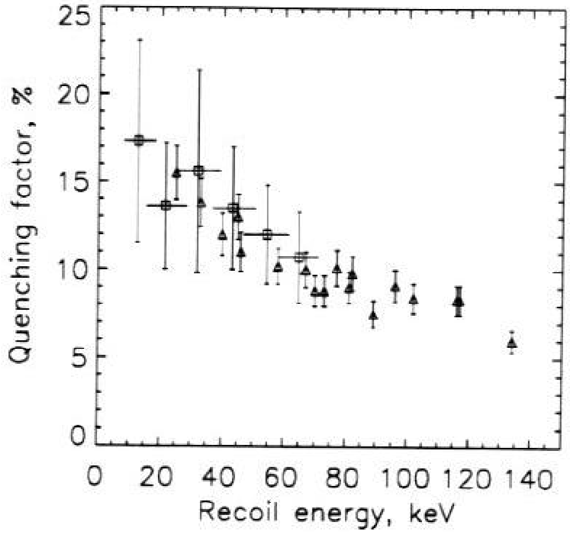

Fig. 2. Quenching factor of nuclear recoils in CsI(Tl) crystal vs. recoil energy (squares) shown together with results from [15] (triangles)

Based on these measurements it is possible to calculate the potential sensitivity of CsI(Tl) to WIMP-proton spin-dependent and WIMP-nucleon spin-independent interactions, for instance for a Higgsino-type neutralino. Fig. 3 shows results for the latter case compared with sensitivity predictions for NaI. An A^2-enhancement of the spin-independent cross-section has been assumed. The Halo parameters have been taken as follows: local dark matter density r_{dm} = 0.3 GeV/cm^3, parameter of Maxwellian dark matter velocity distribution v_o = 220 km/s, local galactic escape velocity v_{esc} = 650 km/s and Earth velocity relative to dark matter distribution v_{Earth} = 232 km/s. It can be seen from Fig. 3 that even assuming a higher background rate than in NaI(Tl) a CsI(Tl) detector is potentially more sensitive to spin-independent interactions than NaI(Tl) for a given light yield. This is found not to be true in the spin-dependent case where high suppression occurs in CsI(Tl) due to the Cs and I form factors. Further details can be found in [17].

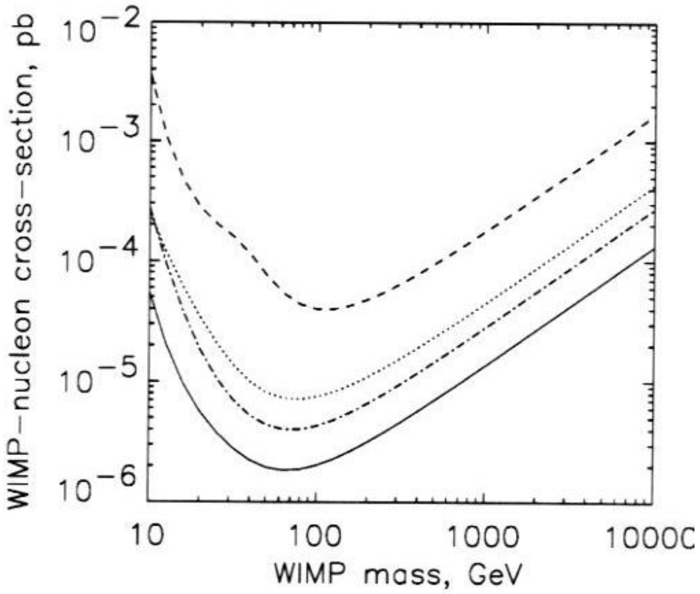

Fig. 3. Estimates of the sensitivity of Cs(Tl) to spin independent WIMP-nucleon interactions compared with NaI(Tl) [18]: solid curve - estimate for 10 kg.yrs with background rate of 2 dru and light yield 3 pe/keV, dash-dotted curve - estimate for 10 dru and 3 pe/keV, dashed curve - UKDMC limits from [1] recalculated [18], dotted curve - estimate for NaI with 8 pe/keV [18]

In practice it is known that CsI(Tl) can suffer from very high background levels, resulting particularly from contamination by ^{137}Cs [17]. Nevertheless based on the results above a 0.8 kg CsI(Tl) detector has been installed at Boulby. Preliminary results suggest that a population of anomalous fast time constant events is again present. Fig. 4 shows the spectrum of these events.

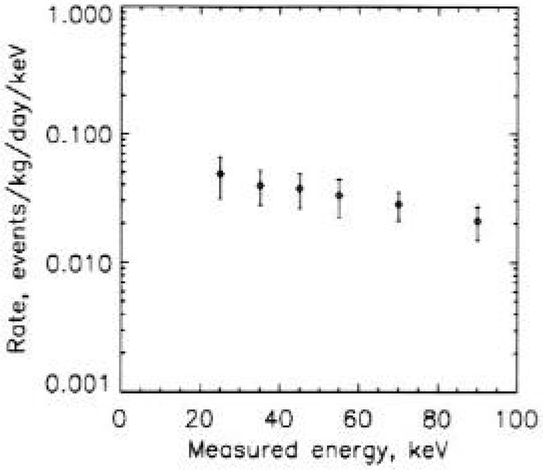

Fig. 4. Preliminary spectrum of anomalous fast time constant events from a 0.8 kg CsI(Tl) crystal (DM71) operated at Boulby - events extracted using PSD

3 NAIAD - Advanced NaI Array

If the hypothesis that surface contamination can produce anomalous low-τ events is correct then using NaI with surfaces pre-cleaned underground and run without the usual encapsulation may be expected to remove the effect. This would also have the potential advantage of further increasing the light collection, and hence discrimination (lower *w* value) and threshold, due to the elimination of optical boundaries. Light collection as high as 10 pe/keV has previously been reported using unencapsulated crystals [19]. Such light collection also provides an improved route to searching for possible time modulations in the discriminated anomalous event spectrum. These factors have provided the motivation for construction of the NAIAD detector, comprising 50 kg of unencapsulated NaI in 5 and 8.5 kg crystals mounted in an array. Sensitivity predictions for NAIAD are reported in [18].

The NAIAD array is designed to be flexible enough to allow various modes of operation with crystals from several manufacturers (presently Hilger Analytical Ltd., Bicron, Amcrys-H and VIMS). To-date two types of module have been constructed, a “vertical” module filled with high purity mineral oil or hexadecene to protect the crystal from moisture, and a “horizontal” module in which either liquid or dry nitrogen is used around the crystal. Fig. 5 shows a schematic of one vertical module. Pre-installation tests have confirmed >8 pe/keV is possible in the best 8.5 kg crystals in dry air.

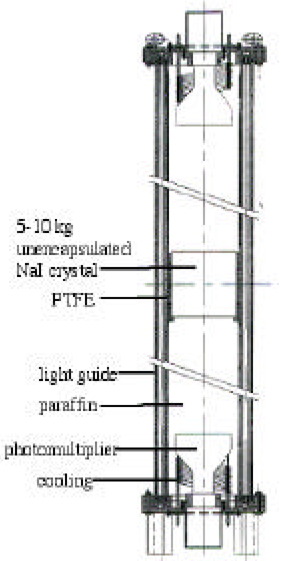

Fig. 5. Schematic of a single NAIAD module

4 ZEPLIN - Advanced Liquid Xe Array

Liquid Xe provides a dark matter target with the potential for combing excellent recoil discrimination, sensitivity to higher mass WIMPs (>50 GeV) and low background [20]. Interactions in liquid Xe give rise to both ionisation and excitation of Xe atoms. The latter result in the emission of 175 nm photons from a singlet state (decay time ~3 ns) and a triplet state (~27 ns). Xe^+ ions from the former can recombine with electrons in a recombination time of ~45 ns to produce further excited Xe atoms that can again produce singlet and triplet state photons. It is found that the proportion of energy released through the two routes, ionisation and excitation, depends on the dE/dx of the particle interaction such that more ionisation is produced in the case of electron recoils than nuclear recoils. This fact, combined with the various mechanisms above, provides several routes towards implementing recoil discrimination in liquid Xe. One route is to allow recombination of the ionised Xe to occur and rely on pulse shape discrimination of the scintillation photons. In this case electron background events are expected to have longer time constant due to the increased proportion of 45 ns recombination time in those events. A second route is to prevent the recombination by applying a high electric field to sweep the charge to a second readout region. In this case two pulses can be recorded per event, a primary and a secondary. The ratio of these will be higher for nuclear recoils since there is less ionisation for those and hence a lower secondary pulse height [21,22].

The successful philosophy with NaI of building a diagnostic array of detectors has led the UKDMC towards constructing a similar Xe array. Currently three experiments are under construction or operation based on the ideas above as follows:

4.1 ZEPLIN I - single phase xenon detector

ZEPLIN I is a single phase liquid xenon detector with discrimination based on pulse shape analysis. The Xe is viewed by three photomultipliers through silica windows and optically isolated, self shielding, liquid xenon turrets (see Fig. 6). This design allows comparison to be made of signal sizes in the three photomultiplier tubes and hence the definition of a fiducial volume (amounting to 4 kg), excluding events in the turret regions where the majority of observed signal appears in a single tube.

Recently neutron calibrations at 10-30 keV observed energy have been completed. These show a clear discrimination between the neutron events, log normally peaked at 20 ns, and the gamma events, log normally peaked at 40 ns. The width (w) of both distributions follows the theoretical minimum of $(N_{pe})^{-1/2}$, (the factor f = 1 c.f. ~1.7 for NaI(Tl) (see sec. 2)). The pulse shape due to gamma interactions is found to match the theoretically motivated one with two exponential decays and a recombination time. The designed light yield of 1 pe/keV has been exceeded at below 500 keV incident gamma energy.

The target is enclosed by a multi-purpose, 1 tonne, PXE-based liquid scintillator shield viewed by 10 PMTs (see Fig. 6). The liquid scintillator shield is designed to act as a Compton veto for events produced by high energy gammas from the photomultipliers, an active shield for external gammas, a high purity inner shield and, through the use of an optional internal gadolinium coated surface, a neutron monitor. Gamma response tests using a ^{137}Cs source show an integrated signal from the ten photomultipliers of 10-15 keV/pe. Using a majority logic of three from ten PMTs firing at the one photoelectron level the veto achieves a hard threshold of 30 keV with a soft threshold of 50 keV. Monte Carlo simulations indicate this will yield a veto efficiency of 80-90% below 100 keV.

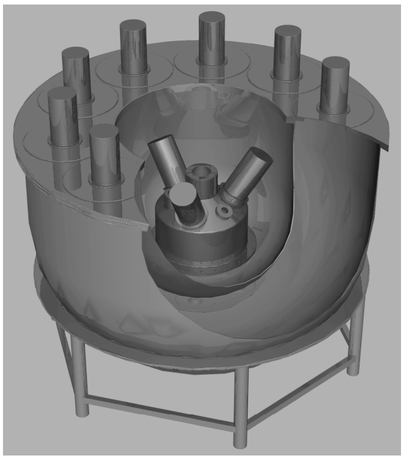

Fig. 6. Schematic of the ZEPLIN I detector showing inner liquid xenon chamber with three PMTs above, surrounded by liquid scintillator Compton veto

4.2 ZEPLIN II - two phase xenon detector

The ZEPLIN II experiment (being constructed with collaborators from UCLA, Torino, Columbia and CERN) incorporates the more advanced discrimination technique described above in which event ionisation is drifted in a high field to a second readout region. The device is based on technology originally proven at CERN [21] in which the secondary signal amplification occurs in a region of Xe gas above the liquid phase. Fig. 7 shows a schematic of the detector. Primary scintillation and secondary electroluminescence signals are detected by an array of photomultipliers situated above the gas phase that define a fiducial volume of typically 20 kg. The detector is designed to work inside a liquid scintillator Compton veto similar to that used with ZEPLIN I. Installation at Boulby is currently on schedule for summer 2001. Further details are provided by Wang et al. [23].

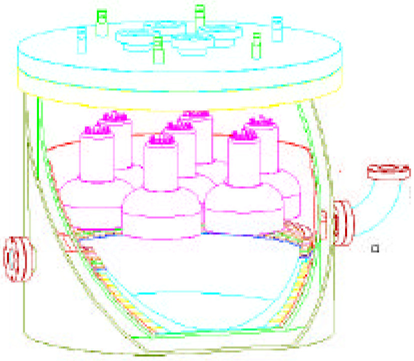

Fig. 7. Schematic of the ZEPLIN II two phase xenon detector

4.3 ZEPLIN III - two phase high field xenon detector

The ZEPLIN III detector is a more advanced intermediate mass (6 kg fiducial volume) xenon experiment currently being built in collaboration with ITEP. Further details are provided in Akimov et al. [24]. Fig. 8 shows a schematic design for ZEPLIN III. The main difference between this detector and ZEPLIN II is the additional capability of detecting the small ionisation signal from nuclear recoil events by incorporation of a high field region in the liquid phase part of the detector. This improves background discrimination and allows lower threshold. The basic design uses 19 photomultipliers of 2 inch diameter facing upwards into the liquid. The use of PMTs submerged in the liquid Xe provides excellent light collection and a level of position sensitivity, which will allow reconstruction of x and y co-ordinates with the z co-ordinate coming from timing measurements. The active liquid depth is 3.5 cm, to keep the HV requirements manageable (< 50 kV). The design phase of ZEPLIN III was recently completed and construction is underway aimed for installation in the xenon array in summer 2001.

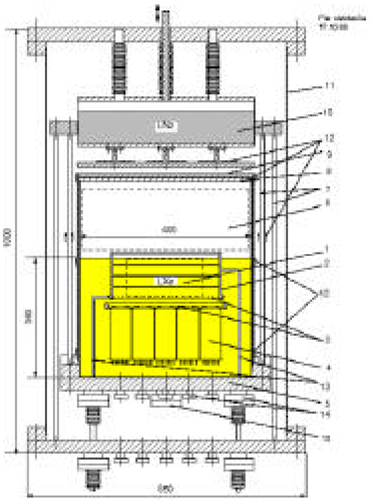

Fig. 8. Schematic of the ZEPLIN III detector

An important aspect of the design phases for ZEPLIN III and the other Xe detectors has been measurement of fundamental liquid xenon parameters. In particular, the scintillation pulse shape characteristics (see sec. 4.1) and the recoil quenching factor, Q. Several prototype detectors have been constructed for this purpose. A 1 kg Xe detector has been successfully built and operated for two phase tests and has been used to verify operation of PMTs in liquid Xe. Tests are continuing with this to optimise electric fields, operation at HV (10s kV), control of Xe bubbling, mirror reflectivity, gas luminescence and electron drift path length. Two further smaller chambers have been used for neutron scattering tests. Fig. 9 shows recent measurements of the quenching factor as a function of Xe recoil energy, taken using the 2.9 MeV neutron beam (see sec. 2). The mean value obtained is 0.218 +/- 0.015

in the visible energy range 40 - 70 keV_{ee}. A scintillation time constant value of 19.6 +/- 0.6 ns was found for recoils of 12 keV_{ee}, consistent with measurements in ZEPLIN I. The quench factor is consistent with that expected from Lindhard theory and with recent measurements by Wang et al. [23], though appear ~x2.5 lower than for beam results reported in [25].

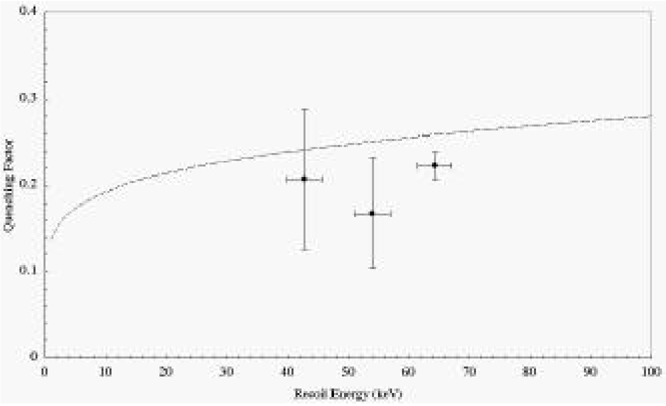

Fig. 9. First results from measurements of the quenching factor for liquid Xe vs. recoil energy using the UKDMC 2.9 MeV neutron beam

5 DRIFT - directional detector array

The DRIFT detector (under construction with collaborators from Temple, Occidental College and Surrey University) is designed to make use of the predicted asymmetry in the direction of WIMP induced recoils due to the motion of the Earth through the Galactic halo [26]. The concept is to use a low pressure gas (20-40 torr of Ar or Xe) in which recoil events produce ionisation tracks of sufficient length (> mm) that they can be imaged, following drift on to a readout plane, and their orientation determined. This provides a potentially unique signal for dark matter since no background source is likely to yield events with orientations varying in the same diurnal manner. Furthermore, the low pressure has the additional advantage that electron background can anyway be rejected with near 100% efficiency due to the lower dE/dx and x10 greater track length of these events [27,28].

Based on this concept the collaboration is constructing a 1 m^3 detector (DRIFT-1) comprising two back to back field regions in each of which charge is drifted onto a MWPC readout plane comprising 500 wires. Fig. 10 shows a schematic of the detector vessel. Further details are provided in [29]. A key design feature will be the use of negative ion drift via the addition of CS_2 to the chamber. Electrons produced by events are captured by CS_2 molecules which are then drifted in the field, in preference to electrons. On reaching the high field region at the anodes the electrons are then stripped to produce an avalanche signal. The large mass of the drifting CS_2 ions greatly limits both the lateral and perpendicular diffusion that would otherwise result if electrons where the charge carriers. This allows sub-mm resolution to be maintained over long drift lengths (0.15 mm has been measured over 15 cm [30]). The latter is a crucial requirement since the use of low pressure means a full DRIFT detector must be of large volume (>10 m^3).

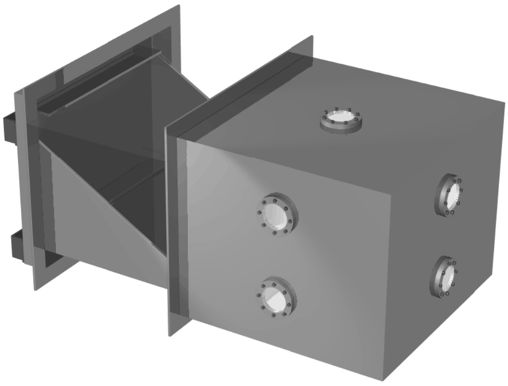

Fig. 10. Schematic of the outer detector vessel for the DRIFT-1 directional detector

6 The Boulby Facility

Expansion of the Boulby facility is now underway as part of a programme to encourage new particle astrophysics and dark matter activity. Over the next year a new underground laboratory will be constructed in a cavern of ~300 m by 8 m wide and 4.5 m high. This will be fitted with air conditioning and filtering. Existing underground labs will also be upgraded. Meanwhile a new surface building will be constructed to house workshops, clean room, experiment construction area, laboratory space, changing rooms and office space.

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