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Status of the Boulby dark matter programme

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Abstract. We give a status report on three experiments aiming at the direct detection of dark matter. ZEPLIN II is a two phase xenon ionization/scintillation detector currently undergoing commissioning at the Boulby underground laboratory. ZEPLIN III is a two phase xenon ionization/scintillation detector currently being tested at a UKDMC surface facility. DRIFT II is a low pressure CS_2 gas time proportional chamber currently taking data at the Boulby underground laboratory.

1. Introduction

Weakly interacting massive particles of mass in the range $[10, 1000]$ GeV/c^2 could be the cold dark matter thought to form halos around this and other spiral galaxies [1]. Numerous experiments aiming at direct detection and study of WIMPs in our own galactic halo have published results, are currently underway, or are proposed [2,3,4,5,6,7,8,9,10,11,12,13]. These experiments rely on detection of the energy, typically a few keV, transferred when a WIMP undergoes an elastic collision with a nucleus of the detector material.

Null results of earlier experiments to detect WIMPs have placed upper limits on the cross section for their couplings to nuclei at the 10^{-6} pb level, and detectors of mass at least a few kg, and perhaps as high as several tonnes, are required to probe the parameter space of possible smaller WIMP-nucleon cross sections.

The most problematic backgrounds are neutrons released as a result of cosmic ray muon showers, and neutrons and gammas due to decays of radioactive isotopes in the detector or the surrounding environment. Deep underground operation of the apparatus is required to reduce the cosmic ray background to acceptable levels. The Boulby underground facility is described briefly in Section 2. Rejection of gamma backgrounds is possible because gammas cause recoil of electrons rather than nuclei. Discrimination power between nuclear and electron recoils is a key requirement of sensitive WIMP detectors. Reduction of the gamma ray flux is achieved by surrounding the detector with shielding, typically lead, copper, or iron. Neutron backgrounds cause nuclear recoils, mimicking the expected signature of WIMPs. Sensitive detectors are surrounded by neutron moderators and constructed out of materials having low concentrations of neutron-producing isotopes, such as those of uranium and thorium.

An additional difficulty associated with direct dark matter searches is that of establishing an unambiguous WIMP signature. The motion of the detector through the halo due to the orbit of the Earth around the sun gives rise to an annual modulation of the event rate in a given recoil

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energy range. The DAMA collaboration [11,12] measure an annual modulation in the event rate from their detector, which they attribute to annual modulation in the nuclear recoil rate induced by WIMP interactions. Another method is to measure the relative event rates with different target materials. An additional degree of freedom that could be used as an improved signature for WIMPs is the direction of incidence of the WIMP. In Section 5 the second of a series of operational dark matter detectors having potential sensitivity to the direction of incidence of WIMPs is described.

2. The Boulby underground laboratory

The UKDMC operates the Boulby underground laboratory, located at a depth of 2800 M.W.E. [14]. The measured muon flux is 4.09×10^{-8} cm^{-2} s^{-1} [14]. Simulations yield a muon induced neutron flux at the laboratory walls of 8.7×10^{-10} cm^{2} s^{-1} above 1 MeV [15]. The neutron background from decay of radionuclides in the cavern walls is estimated at about 2×10^{-6} cm^{-2} s^{-1} above 100 keV [16,17]. The main underground laboratory is a HEPA-filtered cleanroom of dimensions 80 m × 5 m × 3 m. The laboratory is located in a working potash and salt mine operated by Cleveland Potash, Ltd. The ZEPLIN II detector, described in Section 3, and the DRIFT II detector, described in Section 5, are currently installed and operational underground.

3. ZEPLIN II

ZEPLIN II is a two phase liquid/gaseous xenon scintillation/ionization dark matter detector. Figure 2 is a photograph of the apparatus installed underground. Figure 1 is a cross section through the xenon target, which is enclosed in a copper pressure vessel. The lower, liquid phase of the xenon is 15 cm deep, and is threaded by an electric field of up to 450V/cm. The liquid surface is between two wire mesh grids that define a higher electric field of up to 8 (4) kV/cm in the xenon vapour (liquid).

The detector yields signals proportional to the energy deposited in two channels, prompt scintillation light and ionization charge. A WIMP, neutron, or gamma event causes recoil of an atomic electron or a nucleus. Nuclear recoil energies in the range a few keV to around 100 keV are expected from WIMP interactions. The rate of nuclear recoils falls rapidly with increasing recoil energy, therefore the detector sensitivity increases rapidly if the lowest detectable recoil energy, or threshold, can be made smaller. The recoil energy is transferred to surrounding xenon atoms, causing ionization. Recombination of the ionized atoms gives rise to VUV scintillation photons at 175 nm, resulting in a primary pulse from the photomultiplier tubes (PMTs), typically tens of nanoseconds long. The electric field threading the dielectric liquid suppresses recombination for some fraction of the ionization electrons. These liberated electrons drift upwards at a terminal velocity of $1 - 2$ mm/μs. The electrons reach the liquid surface, where the high electric field imparts sufficient energy for them to enter the gaseous phase, where they accelerate. This acceleration gives rise to electroluminescence, which is detected as a secondary pulse from the PMTs of duration around 1 μs. The integral of the voltage pulse corresponding to the primary (secondary) light pulse is referred to as S1 (S2). Increasing the electric field suppresses recombination and increases the charge released, thereby increasing S2 and decreasing S1. Decreasing the electric field causes the opposite effect.

Discrimination between nuclear recoils that could be due to WIMPs or neutrons, and electron recoils that could not, is achieved using the ratio S2/S1. This ratio should be smaller for nuclear recoils than electron recoils. At a given recoil energy, the velocity of a recoiling nucleus is smaller than that of a recoiling electron. Therefore the ionization density along the track of the recoiling nucleus will be larger, and more of the ions will recombine than in the case of the faster electron recoil.

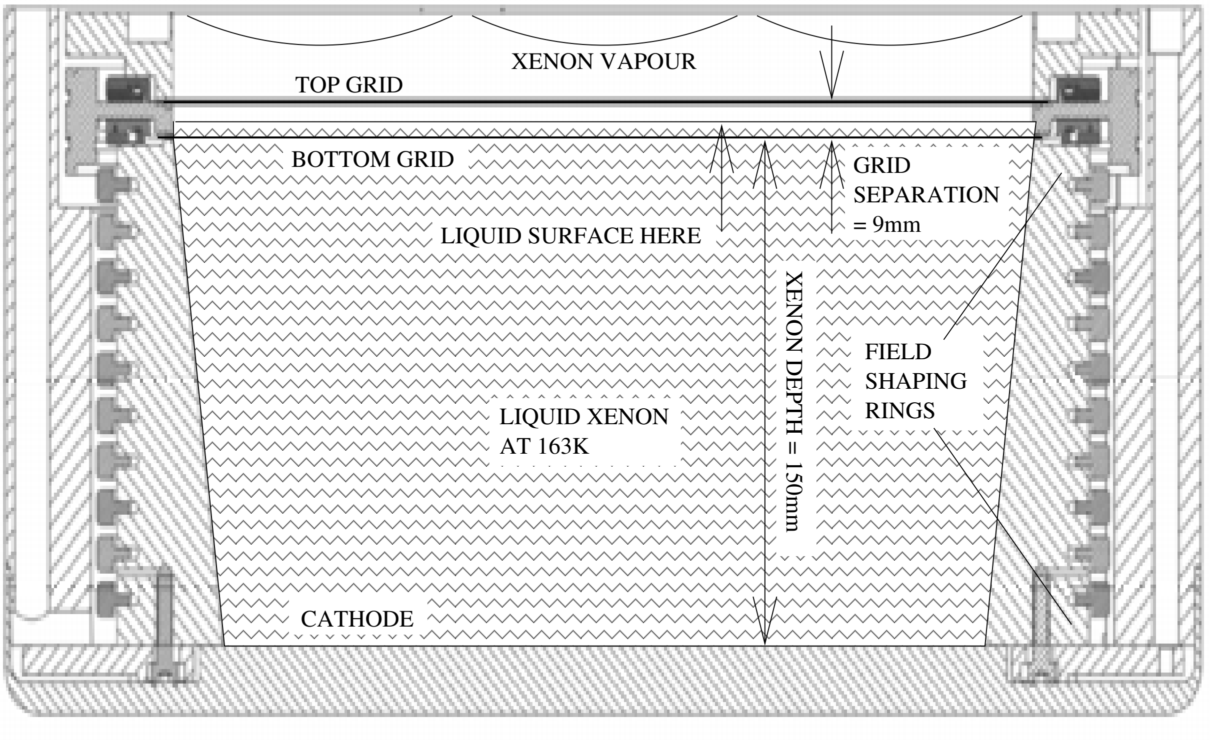

Figure 1. A cross sectional elevation of the ZEPLIN II target. The three curved arcs close to the top represent the front faces of three of the seven photomultiplier tubes facing down into the xenon vapour region above the top grid. The cross-hatched material surrounding the liquid xenon is PTFE. The field shaping rings and the pressure vessel enclosing the xenon are all copper. The mass of the xenon target is 30 kg.

Signals from the 7 PMTs are passively split, each signal being passed to an input of an 8 channel 8 bit Acqiris waveform digitizer having 2ns sampling, and to the trigger hardware. For the trigger, each channel is amplified, and the amplified signal drives a discriminator. The discriminator output from each of the 7 PMTs feeds an input of a majority logic unit, which sends a trigger to the DAQ if some number (currently 3) of the PMTs exceed their discriminator thresholds. The DAQ system keeps up to 100 microseconds of data after the trigger pulse. Figure 3 shows an event display from data taken in a surface test run on 17th May 2005.

The target sits in an organic scintillator active veto read out by 10 PMTs. The top of the target is not covered by this veto, so a 20cm thick hydrocarbon shield completes the 4π coverage of the detector with neutron moderator. Gd loaded paint, resin, and wax shielding surround the detector to convert neutrons into gammas, which may subsequently be detected and discriminated against in the target. The neutron moderator is encased in a 4π, 20 cm thick passive lead shield.

At the time of TAUP 2005, the detector had recently been moved underground, and cooling of the target had started. As I write these proceedings the following November, the target is cold and full of xenon, and we are analyzing our first underground data.

4. ZEPLIN III

ZEPLIN III, like ZEPLIN II, is a two phase liquid/gaseous xenon scintillation/ionization detector. Its basic principles of operation are similar to those described for ZEPLIN II, but with

Figure 2. The ZEPLIN II detector running underground. The lead shielding and moderator have been partially removed. The target is surrounded by an organic liquid scintillator veto read out by 10 photomultiplier tubes, 3 of whose housings are visible in the foreground. The outer vacuum jacket is made of stainless steel, the inner pressure vessel housing the xenon is made of copper. All electrical and gas connections are to a manifold on top of the target volume. The black insulated line connected to this manifold is the return line for the refrigerant. The target is maintained at 163K by a commercial refrigerator, visible immediately behind the edge of the shielding. The rack behind the refridgerator contains the slow control and trigger electronics. The events are digitized in a 2ns sampling Acqiris ADC visible on the table in the background.

some key design differences that are intended to improve the maximum sensitivity. Figure 4 is a photograph of Zeplin III in the final stages of assembly. The detector is currently undergoing surface tests.

First, the PMTs are in the liquid, facing upwards. This should result in much improved light collection compared to a geometry with the PMTs in the gas, since in the gas phase design, photons can be totally internally reflected off the liquid vapour interface and never reach the PMT photocathodes. The projected light collection is 3.5 photoelectrons per keV. Secondly, the high voltage feeds to the electrodes are through the liquid, greatly reducing the probability of sparks that could contaminate the xenon, and allowing for higher voltages, up to 35kV, on the electrodes. The design field is 8 kV/cm in the liquid bulk. Thirdly, the flat geometry and large number of tubes should allow full 3d reconstruction of event position, so that the detector volume can be fiducialized, a powerful way of rejecting background events due to surface effects [24]. Finally, the detector is built almost entirely out of copper and quartz for low background and to preserve the purity of the xenon.

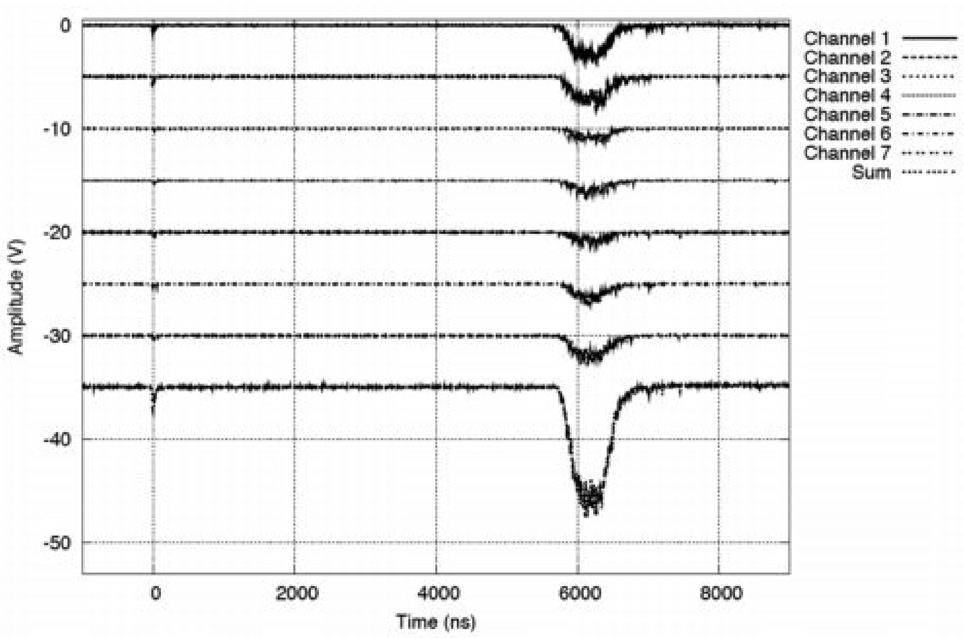

Figure 3. An event display from the 17th May 2005 surface data run. The short, small primary and broader secondary is visible on all 7 tubes. The time delay between primary and secondary indicates that the event vertex was round 10mm below the xenon surface for this event.

5. DRIFT II

DRIFT II is a time projection chamber containing the electronegative gas CS_2 at a pressure of 40 torr. Figure 5 shows the detector being assembled prior to shipment and installation underground, where it is currently taking production data. The detector consists of two back to back time projection chambers (TPCs) on either side of a central photocathode. An electric field of 560kV/cm threads both chambers. WIMPs collide with CS_2 molecules and ionize them. The ionization electrons combine with electronegative CS_2 molecules to form CS_2^- ions, which drift towards the anode plane, where two dimensional grid of wires is read out to allow track reconstruction. The large mass of the CS_2^- ions limits diffusion along the track to 0.1% of the drift distance, so reconstruction of tracks only a few mm long is possible.

The direction of the track gives information about the direction of incidence of the WIMP. DRIFT also has very good discrimination power. Gamma background produces electron recoils, and the resulting tracks have lower ionization density than the denser ionization tracks from nuclear recoils. Alpha particles have longer tracks than would be possible for nuclear recoils from WIMPs. The idea is to utilize this efficient discrimination and operate this as a background free detector, so the sensitivity increases linearly with time.

Operating at 40 torr, the target mass in a single DRIFT II module is 167 grams. However, the directional advantage, combined with the simplicity of the detector, make this a technology very suitable for scale up to larger masses. DRIFT 2 is a modular design, and a second 1 m^3 module is currently being installed underground. Production data from the first module is currently being analyzed.

6. Summary

The Boulby dark matter programme currently consists of 3 experiments, DRIFT II and ZEPLIN II which are running at a deep site, and ZEPLIN III which is filled with xenon and undergoing tests at a surface facility. The design sensitivity of ZEPLIN II assuming a year of running in

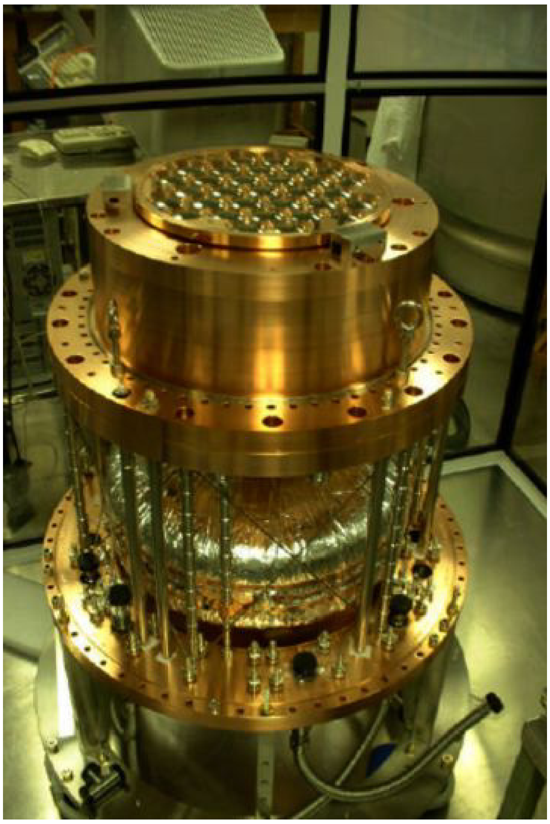

Figure 4. The ZEPLIN III detector before the inner and outer vacuum jackets were bolted on. The top faces of the 31 PMTs are visible, facing upwards towards the 4 cm deep xenon lake. A fiducial mass of 6-8 kg should be achievable. The liquid nitrogen reservoir, used for regulating the temperature of the liquid xenon volume, is visible between the two large flanges. The detector is constructed almost entirely out of copper and quartz. No PTFE or plastics are in contact with the liquid xenon.

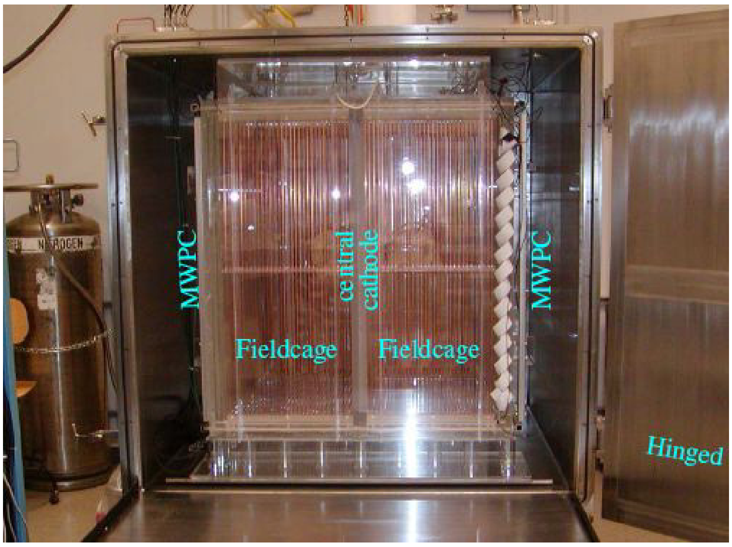

Figure 5. The first DRIFT II module during test assembly. The completed detector is now taking production data underground at Boulby.

its current configuration is 10^{-7} pb [19, 20]. ZEPLIN III, running underground with passive gamma and neutron shielding would achieve a similar sensitivity in two months [22]. With an active neutron veto to tag internal neutrons in coincidence with the target, running for one year, ZEPLIN III should achieve sensitivity at the 10^{-8} pb level [22,20,21]. Replacement of the PMTs with lower background types should improve its sensitivity further. A single module of DRIFT II is sensitive at the 10^{-6} pb level assuming a year of running with zero background [18].

The field of direct searches for dark matter continues to be interesting, challenging, and competitive. We look forward to the next generation of experiments.

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