DARK MATTER EXPERIMENTS AT BOULBY MINE

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The Boulby Dark Matter Collaboration (BDMC) is running several experiments for particle (WIMP) dark matter search in the Underground Boulby Laboratory. These include a liquid xenon detector (ZEPLIN I) and a low pressure gas TPC with directional sensitivity (DRIFT I). Next stage double-phase xenon detectors ZEPLIN II and ZEPLIN III, and a new TPC DRIFT II will be installed at Boulby in a few months. Recent results from the running experiments are discussed and future programme towards large-scale detectors is presented.

1 Introduction

It is believed that 20% of the Universe may consist of non-baryonic dark matter. Supersymmetric theories provide a good candidate – neutralino or Weakly Interacting Massive Particle (WIMP). Due to very small cross-section of WIMP-nucleus interactions, very sensitive and massive detectors are required to detect WIMPs. There are three key requirements for direct dark matter detection technology: (1) low intrinsic radioactive background from detector and surrounding components; (2) good discrimination between electron recoils produced by remaining gamma background and nuclear recoils expected from WIMP interactions; (3) low energy threshold to achieve maximal sensitivity to WIMP-induced nuclear recoils.

The UK Dark Matter Collaboration has been running a Dark Matter programme at Boulby Mine (North Yorkshire, UK) at a vertical depth of 2800 m w.e. for more than a decade. Three major programmes were pursued so far: i) NAIAD experiment (an array of NaI(Tl) crystals) is almost completed and the resources have been moved to other projects, more sensitive to the particle non-baryonic dark matter; ii) detectors based on liquid xenon, which have high
background discrimination power, have been developed and are either running or being commissioned, iii) a low pressure gas Time Projection Chamber (TPC) with a potential of directional sensitivity has been constructed and is operating at Boulby. Two later projects are carried out in collaboration with international groups from Europe and USA.

2 Liquid xenon experiments

Nuclear recoil discrimination in liquid xenon is feasible by measuring both the scintillation light and the ionisation produced during an interaction, either directly or through secondary recombination. Meanwhile, the chemical inertness and isotopic composition of liquid xenon provide intrinsically high purity and routes, in principle, to further purification using various techniques. The heavy nuclei of xenon also have the advantage of providing a large spin-independent coupling.

Any recoil in liquid Xe gives rise to both ionisation and excitation of Xe atoms. The de-excitation result in the emission of 175 nm photons from either singlet (with decay time $\sim 3$ ns) or triplet ($\sim 27$ ns) states. The ratio single/triplet is several times higher for nuclear recoils compared to electron recoils. In the absence of an electric field, the ions recombine with electrons to produce excited Xe atoms again. The recombination time depends on the ionisation density: for nuclear recoils, it is very high and the recombination is very fast. For electron recoils, the lower density leads to longer times.

The ZEPLIN I detector (ZonEd Proportional scintillation in LIquid Noble gases – shown in Figure 1) consisted of liquid Xe with 3.2 kg fiducial mass incased in a copper vessel and viewed by 3 PMTs through silica windows. PMT signals were digitised using a digital oscilloscope driven by a Labview based software at the beginning of the experiment or using an Acqiris CompactPCI based DAQ system later on. The detector itself was enclosed in a 0.93 tonne active scintillator veto, its function being to veto gamma events from the PMTs and the surroundings.

The detector was triggered by a 3-fold coincidence of single photoelectron pulses in each tube. With a light yield of at least 1.5 photoelectrons/keV in the data runs, this gave a 2 keV threshold. The trigger efficiency was calculated using Poissonian statistics. Daily energy calibration was performed with a $^{57}$Co source automatically placed between target and veto. The 122 keV $\gamma$-s were absorbed within $\approx 3$ mm of their path in the bottom part of the target, making it a calibration point source. A 30 keV K-shell X-ray was also observed in the spectrum, its presence was confirmed through the GEANT4 simulation. A full light collection simulation was performed, showing non-uniform of light collection efficiency. This affected the measured energy of an event and was observed in higher energy gamma calibrations ($^{60}$Co, $^{137}$Cs sources): as different parts of the target were illuminated, the peak position was shifted, which reflected the reduction in light yield. The observations matched well the light collection efficiency simulation.

ZEPLIN I had better sensitivity than NaI detectors due to its improved discrimination at low energies. Background discrimination was possible due to the difference in the characteristic time between nuclear and electron recoil pulses. Our standard procedure of data analysis involved calculation of the mean time for each scintillation pulse. The mean times of these pulses followed a gamma density distribution with characteristic times, which were very much different (by about a factor of 2 at low energies) for electron and nuclear recoils. Electron and nuclear recoils thus gave rise to two populations with different characteristic times. Calibration of the detector was done using neutron source and ambient neutrons, which produce nuclear recoils, and gamma-ray source, which produces electron recoils via Compton scattering. Nuclear recoils were also expected from WIMP-nucleus interactions, whereas electron recoils from gammas constituted the main background. Based on the absence of the nuclear recoils in underground data, the 90% C.L. on the number of nuclear recoils was extracted and used to calculate the limit on the WIMP-nucleon cross-section as a function of WIMP mass. The preliminary limit on the
spin-independent WIMP-nucleon cross-section from 293 kg×days of data is shown in Figure 2 in comparison with the NAIAD limit and some other world-best limits. Work is now underway on ZEPLIN II and ZEPLIN III detectors. ZEPLIN II (Figure 1) is a two-phase detector with a target mass of about 30 kg and a sensitivity to WIMP-nucleon cross-section down to $10^{-7}$ pb or better at the minimum of the sensitivity curve. In ZEPLIN II, recoils produce both excitation and ionisation in liquid xenon. Recombination of electrons and ions produced via ionisation is prevented by the strong electric field. Electrons, drifting in this field towards gas phase, produce a secondary luminescence signal in the gas. For a given primary amplitude an electron recoil will produce a much larger secondary than a nuclear recoil. This provides ZEPLIN II with greater discrimination power over ZEPLIN I. ZEPLIN III aims to increase background discrimination by increasing electric field through the liquid xenon and, with a fiducial mass of 6 kg, should achieve similar or better sensitivities to ZEPLIN II.

The ZEPLIN projects described above can be viewed as a development programme aimed at determining the optimum design for a large-scale (about one tonne) xenon detector capable of reaching the sensitivity below $10^{-9}$ pb in 1 year of operation. Such a large mass is required to achieve sufficient signal counts (10 - 100 events). ZEPLIN MAX – a tonne scale liquid xenon experiment – is at the R&D stage at present.

3 The DRIFT Experiment

The DRIFT (Directional Recoil Identification From Tracks) detector adopts a different approach to identifying a potential WIMP signal. DRIFT I uses a low pressure CS$_2$ gas TPC capable of measuring the components of recoil track ranges in addition to their energy. The use of negative ions, notably CS$_2$, to capture and drift the ionisation electrons reduces diffusion. The detector 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 (Figure 4). Particle tracks are read out with two 1 m long MWPCs, one at either end of the field cages. The difference in track range between electrons, alpha particles and recoils is such that rejection efficiencies as high as 99.9% at 6 keV measured energy are possible. After 1 year of operation DRIFT I is expected to reach a sensitivity of $\sim 10^{-6}$ pb. The power of DRIFT comes from its ability to determine the direction of a WIMP induced nuclear recoil. The Earth’s motion around the galactic centre means that the Earth experiences a WIMP “wind”. As the Earth rotates through this wind, the nuclear recoil direction is modulated over
a period of one sidereal day, making it a strong signature of a galactic WIMP signal.

Building on DRIFT I the long term objective of the DRIFT programme is to scale-up detectors towards a target mass of 100 kg (DRIFT III) through development of several intermediate scale modules (DRIFT II), which can be replicated many times. DRIFT II is proposed to have 30-50 times the sensitivity of DRIFT I through an increase in the volume (several modules) and gas pressure. A higher gas pressure means that the recoil range will be shorter requiring higher spatial resolution. Alternative read-out schemes are currently being investigated including Gas Electron Multipliers and a MICROMEGAS microstructure detector.

Figure 3: Computer view of ZEPLIN II. Figure 4: Schematic of the inner part of DRIFT I.

4 Conclusions

Liquid xenon has been demonstrated as an excellent technology for dark matter searches with ZEPLIN I already producing significant sensitivity using pulse shape discrimination. The collaboration is now progressing to two phase operation which shows promise for substantial improvement in sensitivity towards $10^{-8}$ pb. There is a route with this technology to reach $10^{-10}$ pb with an one tonne liquid xenon detector. Directional detectors based on low pressure gas provide a unique means of determining the galactic origin of an observed WIMP signal, a significant advantage over conventional dark matter experiments. The DRIFT programme based on this concept is underway to approach this possibility, complementing also the liquid xenon programme through the use of entirely different technology with different target nuclei. More on the Boulby programme can be found in recent reviews.

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References

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