Status of Dark Matter Searches in the Boulby Mine

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We present the current status and future plans for dark matter searches in the Boulby Mine. A 50 kg array of NaI(Tl) crystals is under construction and a method of suppressing anomalous, fast signals in such detectors is described. Liquid Xe based detectors, with improved background rejection, are under development. The first of these, ZEPLIN I, is already deployed and uses pulse shape discrimination. ZEPLIN II and III measure the ratio of ionisation to scintillation by use of an electric field to extract ionisation from the liquid into a gas phase. Finally a low pressure gas drift chamber with directional sensitivity has been installed, larger versions of which will enable a search for correlations between any WIMP signal and galactic motion.

1. NaI(Tl)

In scintillators such as NaI or liquid Xe the nuclear recoils, expected from elastic scattering of WIMPs, produce signals with faster mean decay time than for the large background of electron recoils[1]. Pulse shape analysis can be used to discriminate between these processes.

Improvements on our previous limits from NaI(Tl) data[2] have been prevented by the discovery of anomalous events which are faster than nuclear recoils[3]. This characteristic of NaI(Tl) has been confirmed by the Saclay group[4] and could be due to contamination of the crystal surface by an alpha emitting isotope[5–7]. Recoil nuclei from Radon decay can be implanted into the surface creating a thin ($\ll \mu$m) alpha-emitting layer resulting in a spectrum of fast events that matches observations.

Tests on an 800 g CsI(Tl) crystal, which also exhibits the anomalous behaviour, have shown that surface polishing can suppress anomalous events[8]. Subsequent tests were performed with an 8.5 kg NaI(Tl) crystal (referred to as DM74) which was polished and then operated un-encapsulated and suspended in mineral oil to exclude water. Figure 1 shows the rate of anomalous events in two encapsulated NaI(Tl) crystals and limits at the 90% confidence level for DM74. Encapsulation precludes polishing and the two such crystals show behaviour typical of NaI(Tl) whereas the rates in DM74 are greatly suppressed.

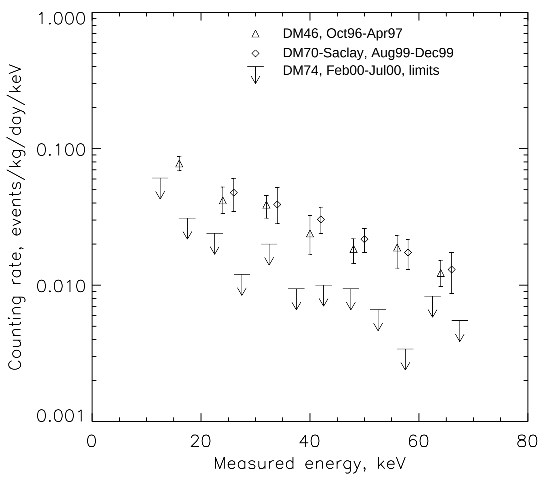

Figure 1. Anomalous event rates in NaI(Tl) crystals: △ - DM46 (encapsulated); ⋄ - DM70 (Saclay encapsulated crystal see also[6]); ↓ - DM74 (un-encapsulated) limits at 90% confidence level

An array (called NaIAD) of un-encapsulated

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crystals is now under construction. Each crystal, enveloped in dry N_2 gas, is viewed by 2 5" photomultipliers (PM) and has a high light yield of 6-9 photoelectrons (p.e.) per keV. Currently 5 crystals, of total mass 31 kg, are operating with 50 kg expected to be operational by early 2002.

2. Liquid Xe

Excited Xe_2 dimers relax with time constants of 3 and 27 ns with nuclear recoils favouring the faster one by a factor of ∼10 over electron recoils. In addition electron recombination of the ionisation channel extends electron-recoil time constants and can be suppressed by use of an electric field to separate and extract the ionisation.

2.1. ZEPLIN I

ZEPLIN I consists of a 3.6 kg fiducial mass liquid Xe target viewed by 3 3" PMs. Shielding from PM radioactivity is by turrets of liquid Xe which separate the PMs from the target. Target construction is from low activity Cu lined with a PTFE reflector and the whole is surrounded by a 1 tonne PXE-based liquid scintillator Compton gamma veto, which doubles as an hydrogenous shield, and a passive Pb castle.

The detector is triggered by 3-fold coincidence of a single p.e. in each PM. Events in the fiducial volume are selected by demanding low asymmetry between the three signals. Light yield is 1.4 p.e./keV at 122 keV. Nuclear recoil discrimination is achieved through pulse shape analysis of the summed, integrated signal from the PMs which is recorded by a digital oscilloscope. Single exponential functions are fitted to each signal to determine the time constant.

Ground level calibrations with Compton-gamma and neutron sources show the gamma time constants are distributed log-normally with a mean ∼twice that for neutrons. Distribution widths are close to statistical limits (see figure 2). By comparison the neutron to gamma time constant ratio in NaI(Tl) is 0.75. 3 months of underground data are currently being analysed.

2.2. ZEPLIN II

ZEPLIN II has a high fiducial mass of 30 kg and is a development of work at CERN and UCLA[9].

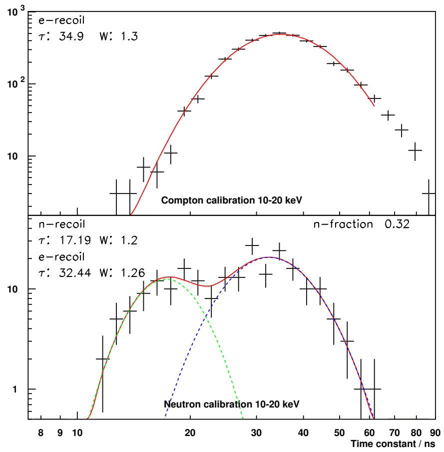

Figure 2. ZEPLIN I Time constant calibrations with gamma and neutron sources. Gamma data is log-normally distributed. Neutrons appear as a 2nd component of faster time constants.

Interactions in the liquid Xe are first detected by scintillation. Electric fields are used to extract ionised electrons into a gaseous phase where a 2nd electro-luminescence signal is recorded. A relatively low drift field is used so that the secondary signal for nuclear recoils is negligible, whereas for electron recoils the ionisation is easily extracted. Discrimination requires that extraction and light collection be highly uniform which is achieved by using seven, 5" PMs in the gas phase and defining a uniform electric field region with a PTFE reflector.

2.3. ZEPLIN III

Based on development work at ITEP and a working prototype at ICSTM[10], ZEPLIN III is also a 2 phase system with a lower fiducial mass of 6 kg but an emphasis on low threshold. 31, 2" PMs are housed inside the liquid Xe to maximise the primary scintillation signal. A high electric field (2.5 kV/cm) allows the ionisation from nuclear recoils to be extracted. A reverse field directly in front of the PMs suppresses secondary signals from X-ray and β contamination. The primary/secondary signal ratio, which varies by 3 orders of magnitude between nuclear and electron recoils, is used for discrimination. The designs of ZEPLIN II(see figure 3) and III have been finalised, and construction has begun for installation in 2002.

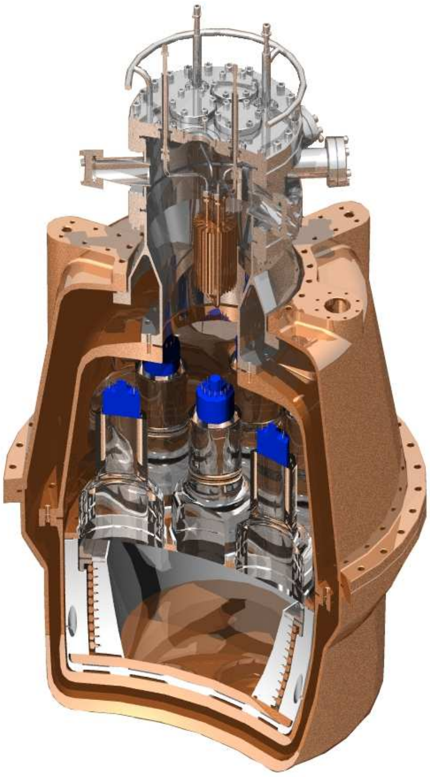

Figure 3. ZEPLIN II Engineering design, cutaway to show interior.

3. DRIFT

The DRIFT concept is designed to search for a sidereal variation of nuclear-recoil directions that would be a definitive WIMP signature. The current prototype, DRIFT 1, is operating at Boulby mine and consists of a 1 m^3 chamber of low pressure (50 Torr) CS_2 gas with a 1kV/cm field applied across one axis. Free electrons in ionisation tracks combine with electro-negative CS_2 to produce -ve ions which are then drifted towards a MWPC readout. Negative ion drift has been shown[11] to reduce track diffusion and enable sub mm track resolution for 1 m of drift. Electron recoil tracks extend much further than for nuclear recoils. Tests on a smaller prototype chamber at Occidental with a ^{253}Cf source showed positive identification of nuclear recoils and 99.9% rejection of electron recoils at a threshold of 6 keV. When combined with shielding underground this results in an estimated background for DRIFT 1 of 0.1 events/keV/kg/day. Plans exist for a 10 m^3 detector.

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