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Galactic dark matter searches in the Boulby Mine

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Abstract.
The current status and planned future developments of galactic dark matter searches in the Boulby mine, N. Yorkshire, UK, are described. A $\sim$ 50 kg array of NaI crystal scintillator detectors is being brought into operation in a low background environment. Many of the sub-units are unencapsulated to allow control of surface contamination sources of background. At present, the spin-independent WIMP-proton cross-section limit is 3×10^{-5} pb at 80 GeV WIMP mass. Improved background discrimination is expected from three detectors based upon liquid Xe. ZEPLIN I, with 4 kg of liquid Xe is already deployed and uses pulse shape discrimination. ZEPLIN II and ZEPLIN III exploit the ionisation to scintillation ratio to discriminate and require an additional gas phase with electric field drift to transfer the ionisation charge to the secondary scintillation region. For ZEPLIN II at 30 kg, the emphasis is on a high mass detector while for ZEPLIN III at 6 kg and a higher electric field, the emphasis is on low detector threshold. A directional, gas-based, electric field drift detector filled with a low A gas (initially CS_2 where drift spread is suppressed) is also under development to allow search for the definitive correlation of any signal found with galactic motion. Initially a 1 m^2 detector is under construction, but a scale-up to 10 m^2 is planned.

1 Introduction

Astronomical studies of the matter distribution within the universe on all scales from galaxies to superclusters indicate that 90-99% is in the form of non-luminous matter. It is likely that this matter is non-baryonic, consisting of a new type of relic particle formed in the early universe and now clustered gravitationally in association with the smaller fraction of baryonic matter. Particle physics offers a natural candidate for cold dark matter, the neutralino of supersymmetry theory. Although this candidate may be revealed in the next generation of accelerator experiments, direct observation of a galactic flux of such particles is necessary to confirm the astronomical significance.

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The UK Dark Matter Collaboration operating in the Boulby Mine set dark matter limits using NaI but is joined by an international team to exploit liquid Xe to obtain improved sensitivity. Collaborating with ICSTM, RAL and Sheffield are UCLA, Torino, ITEP, Temple, Occidental, UCSD, CERN/Padova, Columbia, LLNL and Coimbra. Improvements underway in the 1100 m deep site include extension of the experimental area, increased air conditioning and dust filtration while a surface laboratory for equipment maintenance and assembly is under construction. The collaboration (BDMC) has established two powerful and complementary techniques, potentially capable of reaching the lower end of the range of theoretical prediction of the neutralino scattering cross-section. These are based on liquid xenon technology (ZEPLIN) and gas-based recoil directional technology (DRIFT). A programme of successive improvement in technique is in progress, capable it is expected, to not only set to limits on WIMP events but able to provide a positive signal identification in a background typically 1000 times higher. By employing arrays of different detector types, it is hoped to eliminate systematic errors in the results.

The low temperature ionisation/bolometric technique of CDMS has similar sensitivity objectives to the BDMC ZEPLIN detectors currently under construction and also relies on a background discrimination method differentiating between various types of recoil. Both this experiment and other large detectors which do not have recoil discrimination (DAMA NaI and Heidelberg/Moscow Ge) are essentially single technique programmes.

Considerable controversy surrounds the likely astronomical estimate of the overall matter density parameter Ω_m, which on the basis of the original, supercluster virial theorem estimates could be $\sim$ 1, the closure density. Tegmark et al. (2000) used constraints derived from CMB, large-scale structure and Type Ia supernova data to suggest Ω_m lies between 0.3 and 0.4, with the effect of the cosmological constant bringing about the near flat or closed universe.

Recent work on SUSY suggests that the lightest supersymetric particle is predominantly gaugino rather than higgsino in a superposition of these supersymetric partners and hence is most likely to be seen in spin-independent interactions. 'Naturalness' favours a mass range 20-200 GeV and the range of spin-independent cross-sections favoured by accelerator constraints is $10^{-10} - 10^{-6}$ Pb (Ellis et al. 2000).

2 NaIAD

Based upon the above scenario, one of the core experiments is NaIAD, an array of NaI detectors to cover the WIMP mass range 10-200 GeV. It will complement the ZEPLIN Xe array which covers the WIMP mass range of 50-500 GeV. The low A target, NaI array is being built up to a 50kg mass. It relies on the 30% faster time decays of neutron induced-WIMP like-nuclear recoil scintillation events as compared to electron induced events to discriminate against detector radioactivity background. External radioactive backgrounds are effectively removed by Pb/Cu castles and the muon induced events are small at 1100 mwe. Techniques of limit extraction and previous results are found in Quenby et al. (1996) and Smith et al.(1996). Since these initial results, a 50% increase in light collection by going over to cylindrical rather than tapered light guides and to 5" tubes showed up an anomalous distribution of pulses with a time constant just shorter than those obtained during neutron calibration. Similar pulses and spectra of the anomalous pulses showed up in crystals of other manufacture but appeared not to be present in gamma-ray source calibration. Although the pulses could correspond to the shorter of the two intrinsic scintillation decay times, the relative amounts of which enable neutron/electron discrimination, their apparent absence in the gamma calibration argues against an intrinsic crystal effect. Tests polishing crystal surfaces argue for alpha particles from surface radon contamination (Spooner et al, 2000) although the rate of surface deposition seems rather high. Further improvement in sensitivity has been approached by increasing light collection with thicker PTFE reflector around crystals, unencapsulated crystal operation in dry air or organic liquids to eliminate multiple interfaces and high QE PM selection.

Results of 3 months running with 3 crystals totalling 18 kg mass yield the spin dependent (left) and spin independent (right) cross-sections of figure 1 (Spooner et al., 2000).

Provided there can be certainty that the anomalous events remain excluded from the crystals employed and the improved sensitivities of the crystals used for figure 1 are maintained, we show in figure 2 the likely result of 3 years NaIAD running at the 50 kg detector level. The y axis shows the event rate R_o/r /kg/day normalised by the kinematic factor $r = 4mA/(m+A)^2$ to render the coupling independent of target A and WIMP mass m. $R_o/r = 10$ corresponds roughly to a spin independent WIMP-proton cross-section of 10^{-5} Pb. The upper box for NaI represents the current achievement, the middle box the next 3 years and the lower box the possible consequence of further light collection and detector background improvement.

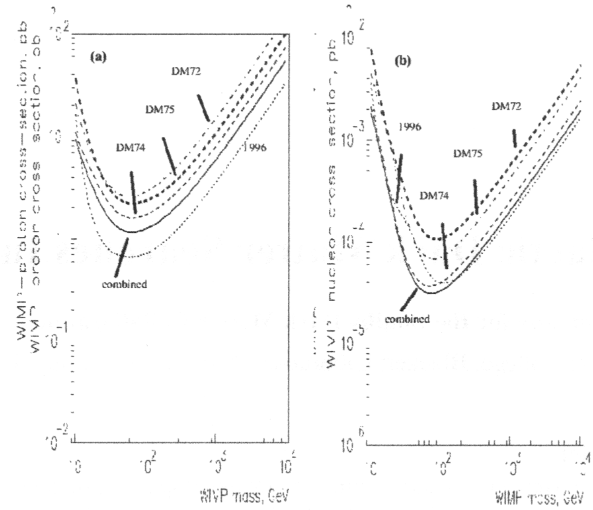

Fig. 1. Preliminary new limits from first $\sim$ 3 months operation of NAID modules DM72, DM74, and DM75 (no anomalous events) for: (a) spin dependent, and (b) spin independent cases.

3 ZEPLIN

Nuclear recoil discrimination in liquid Xe is achieved by measuring the scintillation and ionisation produced. Excited Xe_2 decays with 3ns and 27ns time constants with nuclear recoils favouring the faster one. Ionised Xe_2^+ either recombines in ps for nuclear or in 15 ns for electron events into the excited molecule or an electric field can suppress the recombination and charge, dependent on the excitation event, collected. The three ZEPLIN detectors exploit this physics.

3.1 ZEPLIN I

The ZEPLIN I detector is a 3.6 kg fiducial volume liquid Xe scintillator detector viewed by 3, 3" PM's arranged in turrets to allow some self shielding from PM radioactivity. A low activity Cu vessel houses the Xe and external shielding is by a passive Pb castle and an active, PXE-based liquid scintillator veto. (see fig 3)

A light yield within the fiducial volume, defined by the ra-

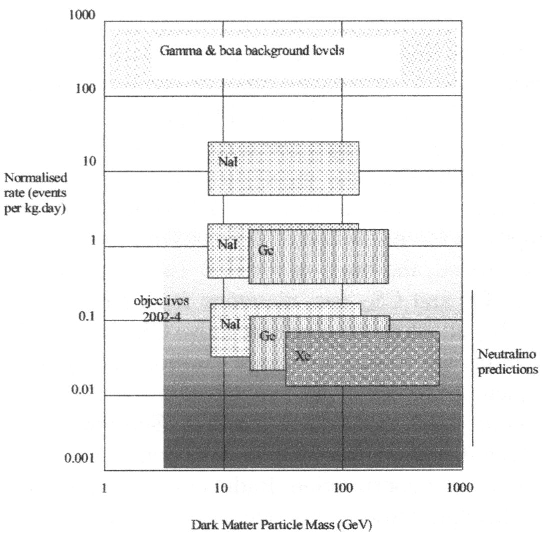

Fig. 2. World progressive improvement in dark matter limits, currently running at 1 order of magnitude per 2 years.

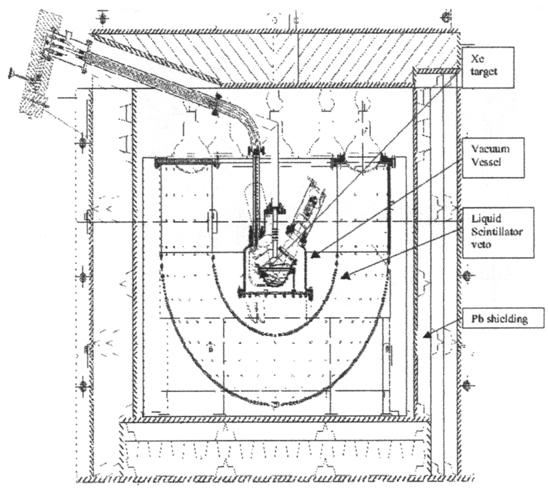

Fig. 3. Layout of the ZEPLIN I detector, illustrating the 4 kg liquid xenon target, the liquid scintillator Compton veto and the passive lead shielding.

tios of the 3 PM's so that the asymmetry between them is low, of 1 pe/KeV has been achieved while the threshold of the veto for gamma-ray background is about 50 keV. Background discrimination is achieved by timing, exploiting the difference seen in neutron and electron induced recoil events where the time constants are 20 ns and 40 ns respectively. Preliminary results obtained underground indicate a performance at the 10^{-6} Pb spin independent level.

3.1.1 ZEPLIN II

The ZEPLIN II detector is based upon the pioneering effort at CERN/UCLA with a 2 phase, 1 kg detector. To discriminate against electron recoil, the primary ionisation is recorded and an electric field used to extract the ionisation from the liquid to a gas phase where secondary luminescence is generated around a multi-wire plane. With a relatively low drift field, the nuclear recoil secondary electro-luminescence is very small and can be neglected, whereas electron recoil ionisation is easily extracted. Using the effective absence of the nuclear recoil ionisation signal requires the ionisation extraction and light collection from the fiducial volume to be very uniform. This is achieved using 7 5" PM's collecting in the gas phase and defining a uniform electric field region with a PTFE cone reflector. The fiducial mass is about 30 kg. A liquid scintillator veto and Pb passive shield will be employed when the detector is ready for mine deployment. The expected sensitivity is in the lowest Xe band shown in figure 2.

3.2 ZEPLIN III

The ZEPLIN III detector is also based on the two phase discrimination principle. As a contrasting design approach, followed in initial development work at ITEP and verified with a prototype constructed at ICSTM, (see Sumner et al, 2001) the emphasis is on a small fiducial volume with best possible light collection and a high drift field to obtain both a low threshold and positive identification of the small secondary nuclear recoil ionisation signal. Figure 4 shows the design of the 6 kg fiducial mass apparatus under construction.

A thin slab geometry is adopted to minimise PM background and maximise secondary drift collection and event location. PM's immersed in the liquid Xe to minimise interface light loss look upwards to collect direct and reflected light from a top mirror. Monte-Carlo simulation suggests the light collection efficiency $\sim$ 30% for the primary scintillation and $\sim$ 25% for the secondary, electro-luminescence. 31 2" PM's view the 3.5 cm liquid and 0.5 cm gas gap. Fields

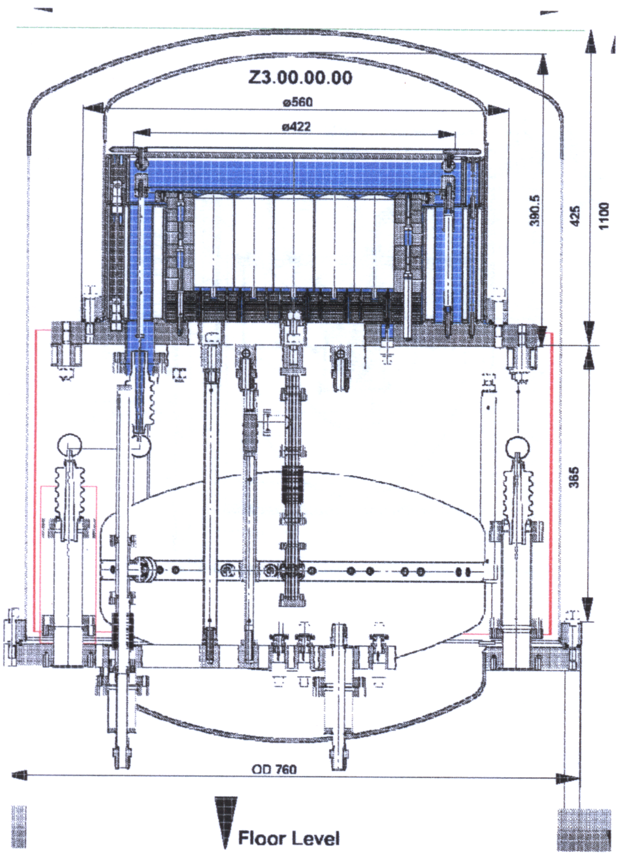

Fig. 4. The Zeplin III Dark Matter Detector.

generated by voltages greater than 10 kV across the detector enhance nuclear recoil ionisation detection and the lack of intermediate electrodes reduces the possible feedback from secondary emission. The top mirror is an electrode and the high field region permeates the whole target volume. A 5 mm reverse field region is provided just above the PM's to both suppress the low energy end of the X-ray background from the PM glass and prevent photoelectric feedback from the PM grid and mirror planes. Event position reconstruction as an additional diagnostic for background is estimated to be within 1 cm in the radial direction while primary to secondary timing gives the third coordinate. Use of low background Cu for most of the vacuum vessels helps to minimise background but a liquid scintillator veto, as in ZEPLIN I is required to suppress about 90% of the Compton background induced by gamma-rays from the PM's and ceramic feedthroughs necessary for the HV supplies. With a threshold expected to approach 1 keV observed energy loss and a vetoed background expected to approach 3 events/keV/kg/day, the sensitivity is likely lie at the bottom part of the lower Xe band of figure 2. Scale-up to a 1000 kg detector is necessary to approach the lower region of theoretical neutralino cross-section predicions.

4 DRIFT

The DRIFT detectors under development are designed to search for a sidereal day signal due to an asymmetry in recoil directions if caused by WIMPs moving on average at 220 km/s with respect to the Sun's galactic rotational velocity. Additionally, further details of galactic infall or clumping in the dark matter distribution funvtion could be probed. DRIFT is based on using low-pressure (50 torr) gas as a target in which the sub-10 mm nuclear recoil directions are imaged. It has been established (Martoff et al., 2000) that negative ion drift improves the resolution of the gas Time Projection Chamber technique, the basis of DRIFT. Using a mixture of target (eg Xe) and CS_2 gas, electrons from target ionisation reversibly attach to the electronegative CS_2 molecules and these anions are drifted to a high electric field region with subsequent avalanching onto an anode where standard MWPC readout yields track reconstruction. Sub mm resolution has been demonstrated for 1 m diffusion paths. A 1 m^3 chamber is under construction. Radioactivity assessment allows a low background stainless steel vessel. Cathode feed design is confirmed for 50 kV. Tests with a small MWPC CS_2 chamber at Occidental with a ^{252}Cf neutron/gamma source found positive identification of neutron induced recoils in the gas, a 99.9% rejection of of electron recoils at 6 keV threshold and using a ^{210}Po source, a 95% rejection of alphas as compared to the neutron scatter events at 10 keV. The lower dE/dx of the background at a given energy, E, allows the discrimination to occur. Background is estimated to be at the level of 0.1/kg/d in the mine with a Pb castle and thin Cu shield. This would allow a cross-section limit $\sim 10^{-6}$ Pb. At this level, if there were a positive signal, 30-50 events would have been seen in 3-20 m^3 yr and a directional asymmetry would have been visible. Plans for a 10 m^3 detector are underway.

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