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Dark matter search at Boulby mine

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Abstract. The Boulby Dark Matter Collaboration is running a WIMP Dark Matter research programme in the underground laboratory of Boulby Mine. The programme is based on (1) liquid Xenon (LXe) as the WIMP target and (2) directional detection in low pressure gas detectors. ZEPLIN-1 is a 3.1kg of LXe scintillation detector with a background discrimination based on Pulse Shape Analysis. Current status of the experiment will be shown. Setups with improved background discrimination tools are commissioned: ZEPLIN-2 and ZEPLIN-3 will be installed underground in early 2004. These are important steps towards the design of a ton-scale LXe Dark Matter detector array. The DRIFT programme relies on discrimination by tracking and directional detection. As the earth's rotation changes the flux angle of Galactic WIMPs, a daily modulation in terms of direction is expected. A low pressure 1m3 chamber (DRIFT-1) is currently taking data. A setup with increased volume and spatial resolution is being designed.

1 Introduction

The search for Dark Matter addresses one of the most fundamental questions in astroparticle physics. The recent measurements of the cosmic microwave background from WMAP[1] suggest that 23% of the matter in the universe is due to Cold Dark Matter (CDM). The SUSY-WIMP model provides an excellent CDM candidate. As new collider physics results appeared, the theoretical predictions for the rates of interaction between WIMPs and targets are down at the level of $\leq 10^{-2}$ events/kg/day. To detect these, very sensitive and massive targets are required.

A Dark Matter programme has been in progress at Boulby Mine for more than a decade. Competitive limits on WIMP cross section were set with NaI targets in 1996[2] and new results with the same target in an improved setup have been published recently[3]. The current programme consists of two axes: (1) detectors based on xenon, which have a high background discrimination potential and (2) gaseous devices with directional detection capabilities.

2 Liquid xenon as a dark matter target

Xenon is very suitable as a target for Dark Matter search: it has heavy nuclei for a large spin-independent coupling and appreciable abundance of isotopes with spin for a large spin-dependent coupling; low background Xe is available in large quantities. LXe is a good scintillator, emitting in the UV region (175 nm): it enables a low energy threshold. Moreover, the interaction process in LXe has characteristics which translate into a potentially high background discrimination. Any recoil in LXe gives rise to both ionisation and excitation of Xe atoms. The excitation results in the emission of a 175 nm photon from either a singlet (with decay time ~ 3 ns) or a triplet state (~ 27 ns). The ratio singlet/triplet is 10 times bigger for nuclear recoil compared to electron recoils. In the absence of an electric field, the ionisation recombines to produce further excited Xe atoms. The recombination time depends on the ionization density: for nuclear recoil, the recombination is very fast, while for electron recoil, the lower density leads to longer times.

2.1 ZEPLIN-1, a single phase detector

The first detector of the ZEPLIN programme is based on a pure scintillator design. The LXe is viewed by 3 PMTs through silica windows (Fig. 1). Between the fiducial volume (3.1 kg) and each window, a volume of LXe which is optically isolated (ie. in which most of the signals appear only in the corresponding PMT) is acting as self-shielding.

The detector is triggered by a 3-fold coincidence of a single photo-electron in each tube. With a light yield of at least 1.5 p.e./keV in the data runs, it gives a 2 keV threshold. The trigger efficiency has been calculated using Poissonian statistics. The signals are digitized using an Acqiris cPCI based DAQ system[10]. The dead-time is smaller than 2 μs, its efficiency is thus bigger than 99.9% during normal data runs.

Daily energy calibration is performed with a ^{57}Co source automatically placed between target and veto. The 122 keV γs convert within the bottom 3 mm in the target, making it a calibration point source. A 30 keV K-shell X-ray is also observed in the spectrum; its presence has been confirmed through a Geant4 simulation. A full light

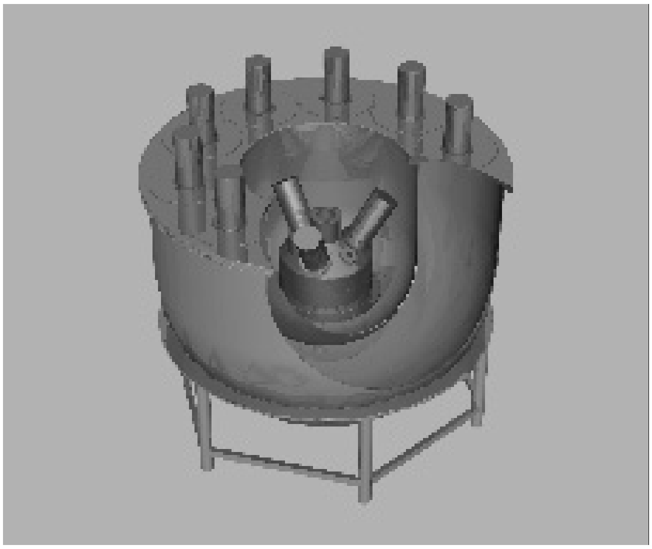

Fig. 1. The ZEPLIN I design: a pure LXe scintillator with 3.1 kg active mass, enclosed in a 1 tonne liquid scintillator Compton veto

collection simulation has been performed, showing variations of efficiencies from a maximum of 18% at the bottom of the target down to 4% just below the Xenon delivery line. This affects the measured energy of an event and has been observed in higher energy gamma calibrations (^{60}Co, ^{137}Cs sources): as different fractions of the target are illuminated, the peak position reflects the reduction in light yield. The observations match well the light collection efficiency simulation.

The light collection study has been extended to each tube separately. This makes it possible to assess the capability of rejecting events occurring in the turrets. A turret parameter (S_3) translates the asymmetry of events into a number. $S_3 = 0.81$ indicates an event with all the signal in a single PMT, while a completely symmetric event would give a null value. In a turret event, in the ideal case of no loss of light within the chamber, one single PMT is expected to get 66% of the light, resulting in S_3 being 0.41.

Purification of the Xe gas is performed by using an Oxisorb[9], as well as by pumping on the frozen Xe and subsequent fractionation of the Xe gas. This removes quencher contamination (O_2, CO_2) to acceptable levels. The Xenon is purified prior to the liquefaction into the target, but not circulated or repurified afterwards. No decrease of light yield has been observed during a 50 day run.

Background discrimination is provided by the difference in time constant of the scintillation pulse induced by nuclear or electron recoils. Neutron and gamma source calibrations done on the surface have shown that a typical nuclear to electron recoil time constant ratio is about 0.6, with signs of decrease with lower energy.

The 90% C.L. limit on nuclear recoil is extracted by studying the monotonically rising edge of the time constant distributions and comparing it with pure gamma data. These come from dedicated high statistic calibration runs (Compton events from ^{60}Co gammas) and from normal data events tagged by the Compton veto. The upper limit on the number of nuclear recoils in each energy bin is then used to calculate the WIMP-nucleon cross section. The limit extracted from 280 kg×days of data in a preliminary analysis is shown in Fig. 2.

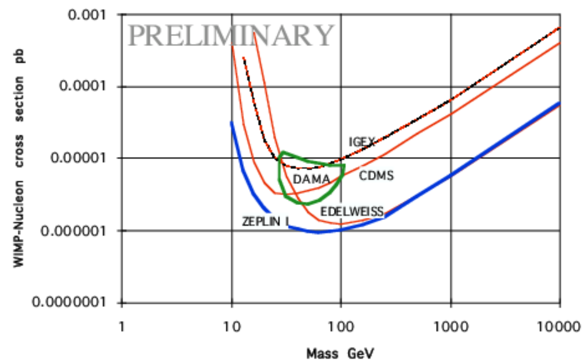

Fig. 2. Preliminary ZEPLIN-1 limit on WIMP-nucleon cross section from 280 kg×days of data, in comparison with CDMS, Edelweiss and the DAMA result (surface)

2.2 Dual phase designs

The two-phase detector measures both the scintillation and the ionization produced by interacting particles. Any particle interacting within the liquid xenon target will produce excitation and ionisation. A vertical electric field partially suppresses recombination; it drifts the ionisation electrons upwards through the liquid to the gaseous phase - where wire planes define a high field region in which an avalanche occurs and electroluminescence is created. Both scintillation and electroluminescence can be recorded by the same PMTs. The proportion of scintillation and electroluminescence released depends on the dE/dx of the particle interaction and differs for an electron recoil (more electroluminescence) and a nuclear recoil (mostly scintillation). For the latter, only a very high electric field may prevent part of the recombination and, thus, induce a secondary signal.

The ZEPLIN-2 design is based on this dual-phase technology. The detector contains a target mass of about 30 kg. It will be surrounded by the liquid scintillator Compton veto from ZEPLIN-1. Sensitivity to rates of about 0.1-0.01 events/kg/day can be reached within 2 years of data-taking. The construction is well underway and commissioning has started. The installation in the Boulby Mine laboratory is scheduled for early 2004.

The ZEPLIN-3 design has been optimised in order to observe both scintillation and ionisation from the nuclear recoil events. As this requires a very high electric field ($\sim$8 kV/cm in the liquid target), the liquid depth is constrained to 3.5 cm, with a radius of 20cm. Both VUV signals are observed by an array of 31 photomultiplier tubes submerged in the liquid. The larger electroluminescence signal is used to determine the position of events, allowing definition of a fiducial volume. The design has a smaller fiducial mass (6 kg), but with an improved background discrimination and a lower threshold, similar sensitivities to ZEPLIN-2 will be reached. More details can be found in [6]. Schedule for installation in Boulby Mine is mid-2004.

2.3 Towards 1 tonne

The sensitivity of ZEPLIN-2 and ZEPLIN-3 in terms of WIMP-nucleon cross section is estimated to be in the region of 10^{-8} pb. Many SUSY models predict lower cross sections, down to 10^{-10} pb. To cover these predictions, a detector mass of 1 tonne might well be needed. We are currently studying different design possibilities for a scale-up towards massive modules, with the constraint of achieving a low energy threshold.

3 DRIFT: A directional detector

The measurement of WIMP induced nuclear recoil directions offers a powerful way of identifying a WIMP signal.. A detector sited at the Boulby Mine will see the mean recoil direction rotate from downwards to southwards and back, within a period of a sidereal day,. It opens also the prospects for directly probing galactic halo structure and dynamics.

DRIFT-1, currently in operation at Boulby mine, consists of a 1 m^3 Time Projection Chamber of low pressure (40 Torr) CS_2 gas, with a drift field of 260V/cm (Fig. 3). In this electronegative gas, the free electrons produced in an ionization track get attached to the CS_2 molecules; these are then drifted towards a Multi-Wire Proportional Chamber readout. The high field detaches the electrons and an avalanche occurs. This negative ion drift technique enables sub mm resolution with 0.5 m drift length[7].

The tracking capability represents also a powerful background rejection tool, as electron recoil and alpha tracks extend significantly more than nuclear recoils for the same energy deposition. The efficiency of this discrimination is such that no passive γ shielding is needed.

DRIFT-1 was installed at Boulby Mine in mid-2001. It represents a proof of feasibility, with an assessment of the sensitivity to tracking, background rejection and directionality. Calibration runs with a neutron source (^{252}Cf) placed on top or on the side of the detector have shown differences in the angular distributions of the nuclear recoil. It is planed to run without any shielding in order to assess the neutron background in the lab. Later this year, neutron shielding will be installed around the detector.

The tracking resolution is limited by the pitch of the MWPC plane (1 mm). The possibility of using alternative read-out techniques with narrower pitch (for instance, MICROMEGAS[8]) is currently being investigated. This would allow an increase in pressure, thus in the target mass, without losing any tracking sensitivity. Alternatives to CS_2 as target gas are being studied. This R&D programme will be the basis of the design of a new generation detector, DRIFT-2.

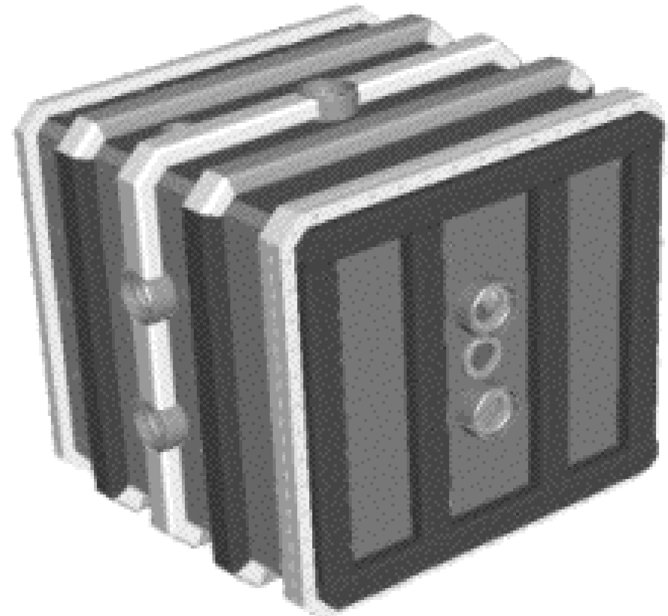

Fig. 3. DRIFT-1: a 1 m^3 Time Projection Chamber

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