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Nuclear Instruments and Methods in Physics Research A 513 (2003) 215–221

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Dark matter detectors and the use of interaction location information for background suppression

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Abstract

Detector requirements, particularly the need for background rejection, in the search for weakly Interacting Massive Particles, one of the possible solutions to the cold dark matter problem, are broadly reviewed. The use of liquid Xenon as a target material is discussed in detail for the ZEPLIN I detector, a single phase scintillation detector operated by the UK Dark Matter Collaboration. The use of position sensitive information to remove photomultiplier based events, reduce backgrounds and help identify potential signal events is outlined.

Keywords: Dark matter; Liquid xenon; Position sensitivity

1. Introduction

Over the last decade growing observational evidence has emerged that up to 90% of the matter in the Universe is in the form of non-relativistic, non-baryonic, non-luminous material [1–3]. One possible solution to the cold dark matter problem, supported by theoretically favoured supersymmetric extensions to the standard model of particle physics [4], is that this material comprises Weakly Interacting Massive Particles (WIMPs). Examples of such particles are the neutralino of the CMSSM [5–8], the lightest stable admixture of the neutral supersymmetric particles, with expected masses in the 100 GeV range. The direct observation of a neutralino population within the Galaxy would impart information to the fields of cosmology and astrophysics allowing refinement and confirmation of the current standard paradigm, and also to the field of particle physics providing complementary information to accelerator investigation of the supersymmetric extensions to the standard model by investigating spin dependence, target mass dependence and, uniquely, testing R-parity conservation—a multiplicative quantum number prohibiting the decay of supersymmetric particles into 'normal' ones.

The Galactic component of this cold dark matter may be directly observed through the elastic scattering off target nuclei, a near-maximal process due to the comparable masses of the dark matter WIMP and the target nuclei in many detector systems [9]. Many experiments are currently being undertaken to search for these WIMP interactions [10], using many different detector technologies. All detector technologies require a high degree of background rejection, to remove events due to local radio-isotopic contaminations and cosmic rays.

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0168-9002/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2003.08.035

Position sensitivity is used in several of these detectors to identify and remove surface contaminants, events due to detector components such as photomultipliers and, ultimately, to confirm the uniform nature of any WIMP interactions throughout the detector volume. An additional use of position and direction information is to correlate the WIMP induced recoil events with that expected due to the motion of the Earth through the Galactic dark matter halo. Such a directional detector being developed by a UK/US collaboration is discussed in greater detail in these proceedings [11].

2. Dark matter detector requirements

The expected scalar interaction cross section for neutralino dark matter elastic scattering is in the range 10^{-8} to 10^{-10} pb, see Fig. 1 [12]. This translates to an expected event rate in a target material of between 0.01 and 0.0001 events/kg/day, i.e. of order events/tonne/day for the lower bound. The expected recoil energy deposition for a WIMP interaction is below 50 keV, with an essentially exponential energy spectrum. The low interaction rate and small energy deposition require detectors with high signal to noise capability ($>10^5$), low energy threshold (keV), ultimately high mass (tonne scale), and low intrinsic background levels (event/kg/day of target).

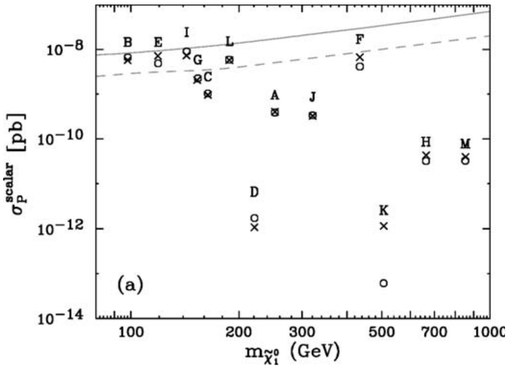

Fig. 1. Expected spin independent elastic interaction cross section of the neutralino WIMPs on protons for CMSSM (constrained minimal supersymmetric) benchmark models proposed in [12], which are indicative of allowed regions in CMSSM parameter space. This illustrates the range of expected interactions between 0.01 and 0.0001 events/kg/day of target, with WIMP masses between 100 GeV and 1 TeV. Figure taken from Ref. [12]. Letters refer to benchmark models described in Ref. [12] with crosses and circles referring to different calculations. Solid and dotted lines are predictions from CDMS and GENIUS experiments.

Detector technologies currently affording the best limits on the WIMP cross sections, at about 10^{-6} pb, are based on two technologies—cryogenic semiconductor devices and scintillation based detectors. The key requirement for these detectors, following maximal background reduction, is the ability to differentiate the nuclear recoils initiated by WIMP collisions and the more frequent electron recoils due to gamma and beta backgrounds. In addition nuclear recoils due to neutrons must be clearly quantified and sufficient shielding or active veto be in place to reduce these events well below the expected WIMP rate.

In these detector technologies position sensitivity is used in two ways. Firstly, localization of events allows a mapping of all events throughout the detector volume to be constructed, which allows the definition of a fiducial volume, rejecting surface events from betas and low energy gammas, and the removal of any 'hot-spots' from localized radioactivity or reduced shielding. Secondly, the distribution of WIMP interaction locations throughout the volume will be uniform, whereas the distribution of background events from radioisotopic contaminants will be gradated, or, in the case of background ambient neutrons, may have secondary scattering locations allowing their removal. The latter effect may be utilized in different ways dependent on the target material. For the cryogenic semiconductor devices multiple interactions are currently identified by scattering between segmented or separated detectors, whereas for the more massive scintillation detectors the segmentation will arise ultimately through imaging of the scattering loci.

3. Dark matter detectors

As outlined above, detectors used in direct dark matter searches need to have low energy thresholds, high species discrimination potential and low intrinsic backgrounds. The main sources of backgrounds are radio-isotopic impurities within the detector materials, giving rise to gamma, beta and neutron backgrounds (from alpha-n reactions), radio-isotopic impurities within the surroundings and neutrons from cosmic ray spallation. Low backgrounds are derived through the use of radiopure materials for detector construction, radiopure gamma shielding of the detector from its surroundings and the operation of the detectors deep underground to shield from cosmic rays. Position sensitivity is most useful in rejection of internal background events through the definition of a fiducial volume, and the rejection of neutrons through segmentation or multiple scattering.

3.1. Cryogenic semiconductor detectors

The EDELWEISS [13] and CDMS [14] collaborations employ detectors based on cryogenic semiconductor devices where the ionisation and phonon signals produced in a particle interaction are observed. The CDMS collaboration uses two different detector designs, both designs are described below. The EDELWEISS design is similar to the CDMS BLIP detector.

The BLIP detectors [15] consist of 165 g cylindrical crystals of high purity, undoped Ge. Phonon production is measured by the temperature change during a particle interaction, measured with two NTD Ge thermistors bonded to the crystal. Ionisation production is measured by electrodes on the top and bottom surfaces of the cylinder, each of which comprises an annular outer electrode and a circular inner electrode to allow definition of a fiducial volume for charge collection. This allows the rejection of events due to particles incident on the sides of the detector, which, in operation, are less well shielded that the upper and lower surfaces [16].

The ZIP detectors [17] utilize the collection of athermal phonons to determine both phonon production and *x–y* position of the particle interaction. They consist of 100 g crystals of high purity Si with two concentric charge collection electrodes. One side of the detector has an aluminium/tungsten film defining four phonon sensors in a quadrant pattern, with phonon readout through transition edge sensors.

Position sensitivity in the ZIP detector is achieved through measurement of the relative phonon amplitudes in the four quadrants of the detector and also in the relative delay between the phonon arrival times [18]. The phonon signal from the quadrant in which the interaction took place is both greatest in amplitude, and also delayed least in comparison to the ionisation signal read directly from the electrode structures. Fig. 2, from Ref. [18], illustrates the ability of the ZIP detector to identify x–y location of an interaction, using a

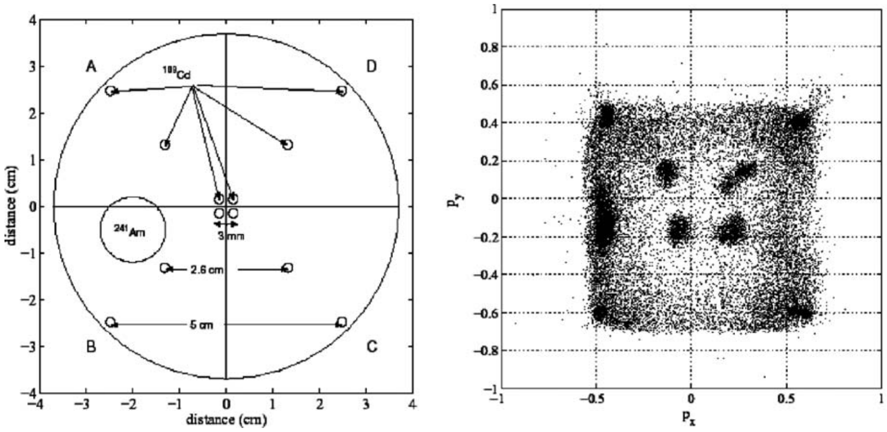

Fig. 2. Illustration of position sensitivity with the CDMS ZIP detector. Left shows the mask of collimated gamma sources, right shows the reconstructed *x–y* position using the relative amplitude observed within the four phonon detector quadrants. The collimator holes closest to the detector edge are discarded in the analysis. Figure taken from Ref. [18].

mask of collimated low energy gammas from two sources.

In addition to the ability to define a fiducial volume within the bulk of the cryogenic detectors to allow rejection of background events from less well shielded directions, the multiple scattering from neutron interactions is also identified by the CDMS group [19]. The semiconductor detectors are operated in a stack of several detectors, with no interleaved shielding. This arrangement allows multiple scattering of background neutrons between adjacent detectors, a process that would not occur for the weakly interacting neutralino interactions. The CDMS detectors have initially been run at a shallow site in Stanford where high energy neutrons have been produced through cosmic ray spallation, outside the muon veto surrounding the detector, which then 'punch through' the hydrogenous shielding. These high energy neutrons have been clearly identified by the multiple scattering between detectors [19], and have required a relocation of the CDMS experiment to a deep mine site at Soudan.

3.2. Liquid xenon detectors

The UK Dark Matter Collaboration is developing a series of detectors based on liquid xenon [20], in collaboration with US, EU and Russian collaborators. The first stage detector, ZEPLIN I, utilizes the scintillation light produced in particle interactions and is currently operating. More advanced detectors, ZEPLIN II and III, utilising two phase operation where both scintillation light and ionisation produced in interactions are detected, are currently under construction.

The ZEPLIN I detector is a single phase, 3.1 kg fiducial mass, liquid xenon scintillation detector [21]. The configuration of the detector and underground installation is illustrated in Fig. 3. The target mass is housed in a Cu-101 oxygen free copper vessel, shaped to maximise light collection, which provides a uniform temperature environment through the use of a cryo-liquid jacket maintained by a Polycold cryo-generator.[1] A 5 mm PTFE reflector, giving diffuse scattering of the 175 nm scintillation photons to again maximise light collection, surrounds the fiducial volume of xenon. This volume is viewed through 3 mm silica windows by three quartz windowed EMI9265QA photomultipliers through optically isolated 'turrets' of liquid xenon which act both as light guides and passive shielding for the X-ray emission from the photomultipliers. The turrets are lined with specular UV reflective Ano-Fol[2] to maximise photon transport to the photomultipliers.

Fig. 3. Cut-away illustration of the single phase ZEPLIN 1 liquid xenon detector showing target arrangement within the liquid scintillator Compton veto. Not shown is the lead gamma shielding.

A 1 tonne multi-purpose phenyl-ortho-xylylethane (PXE) based liquid scintillator shield and an outer passive lead shield enclose the liquid xenon target. The liquid scintillator shield acts as: a Compton veto for low energy events produced by low angle scattering of high energy gammas from the photomultipliers, a muon veto, an active shield for external gammas, a high purity inner passive shield and, through the optional use of an internal gadolinium coated surface, a neutron monitor. The use of this anti-coincidence veto to reject the low angle Compton scattered gammas from the photomultipliers illustrates a trivial use of detector segmentation.

Position sensitivity within the ZEPLIN I target is afforded through the relative scintillation amplitudes seen within the three photomultiplier

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[1] IGC Polycold Systems, Petaluma, CA 94954.

[2] Ano-Fol Metalloxyd GmbH, Germany.

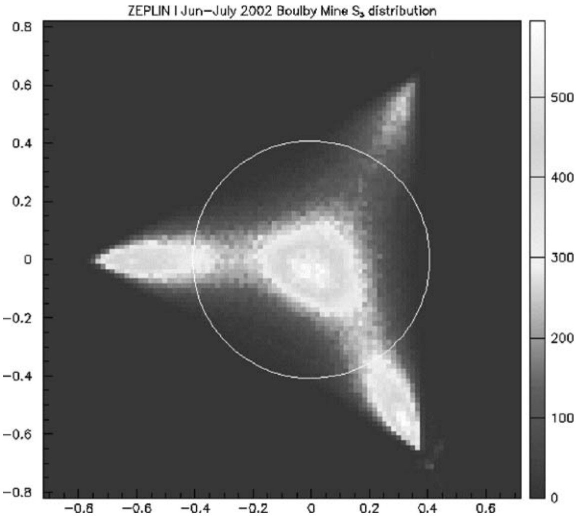

Fig. 4. The S_3 distribution for ZEPLIN I data from 2002, showing a constant energy projection of the relative amplitudes observed in each photomultiplier. Events seen in a single photomultiplier would arise beyond the three 'arms' of the trefoil, events from the fiducial volume would be located at the origin. Events located within the turret volumes are observed as three distinct populations, allowing rejection of these events and definition of a fiducial volume.

tubes. Scintillation light produced in the turret regions will be seen predominantly by the nearest tube, which allows the rejection of the photomultiplier X-ray events and the definition of a fiducial volume through a comparison of the light seen by each tube.

The assessment of the capability to reject turret events in ZEPLIN I is shown in Fig. 4. This shows the normalised relative signals observed in each photomultiplier projected onto a plane, which has been translated such that the origin is an event where all three photomultipliers record identical signals. The radial length of an event on this transformed plot, S_3, defines the asymmetry of the event, with an $S_3 = 0.81$ indicating an event where the entire signal is in one photomultiplier (an event which should not trigger the system). The central peak in the relative amplitude distribution corresponds to events from the fiducial volume. The S_3 value at the minimum of the 'ridge' is where 66% of the signal is seen in one photomultiplier, corresponding to an ideal case for a turret event if there was no absorption or reflective loss within the chamber $(0.5 + 0.5/3)$. The S_3 value used to cut turret data is set at 0.41. Fig. 5 illustrates the S_3 values for simulated scintillation events within the main body of the detector volume, showing the effect of the cut at 0.41 is to reject events within the turret and 1 cm below. These simulations allow the efficiency of the S_3 cut to be evaluated and the fiducial volume of the target to be calculated as 3.1 kg.

The two phase liquid xenon detectors currently under construction by the UK Dark Matter Collaboration and international collaborators improve the discrimination power between nuclear and electron recoils by measurement of both the scintillation and ionisation created during a particle interaction. The scintillation light is measured directly by photomultipliers, with the ionisation being measured by drifting the electrons created through the liquid xenon target, extracting them into a gaseous phase and observing them optically through the production of electroluminescence.

ZEPLIN II [22] and ZEPLIN III [23] differ in detail as each explores different options of two phase operation of liquid xenon. However both utilize the same readout mechanisms and operate through an array of photomultipliers observing the liquid target and electroluminescence regions. In a similar way to the ZEPLIN I target the interaction location information in the two phase detectors will arise from a comparison of observed signals within the photomultiplier array, but will also have information related to the depth of interaction from the time delay between primary and secondary light pulses. This delay will be dependent on the applied drift electric field, as the ionisation is extracted for the secondary electroluminescence signal, but will be uniquely defined against the prompt primary scintillation signal.

Fig. 6 shows the result of a Monte Carlo simulation for ZEPLIN III [24] which has a hexagonal array of 31 photomultipliers immersed in liquid xenon viewing upwards. Immediately above the tubes is a 0.5 cm reverse field region to trap ionisation from photomultiplier initiated X-rays. Above this region is a 3.5 cm liquid target volume, and above that is a 0.5 cm gas gap before

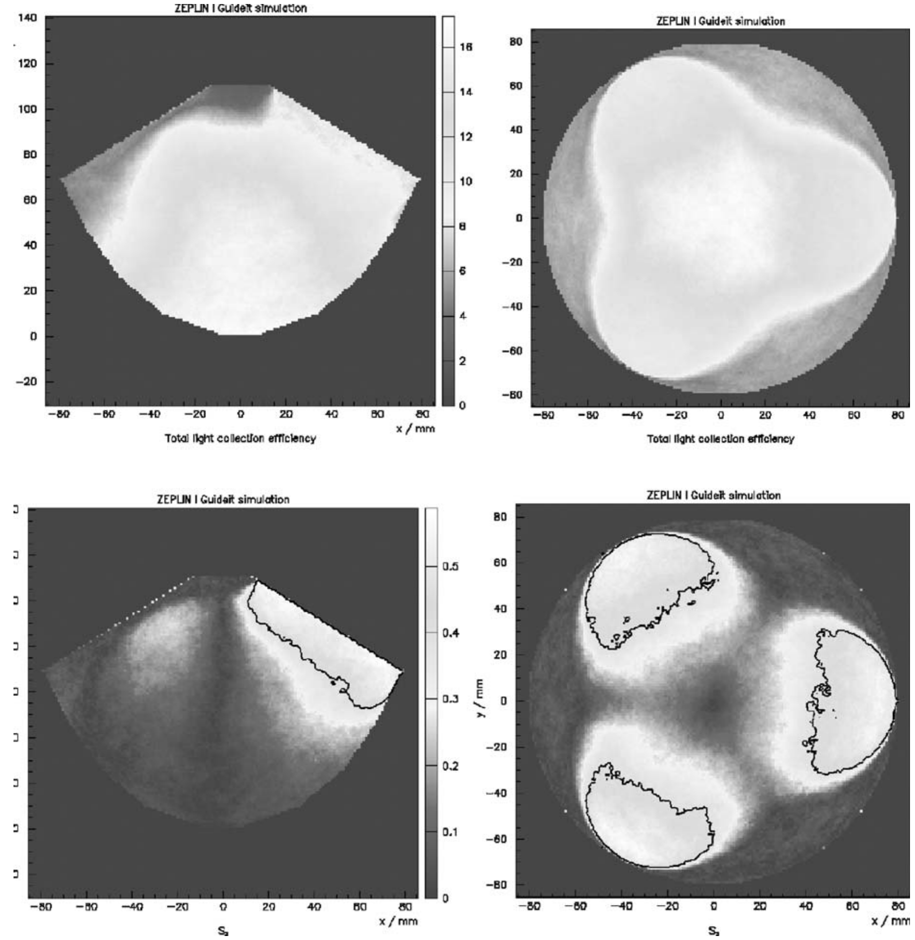

Fig. 5. Light collection simulations of ZEPLIN I and subsequent S_3 values. The simulations are scans through the detector in a horizontal and vertical slice. The horizontal slice is through the girth of the detector, the vertical through a plane containing one photomultiplier. The upper plots show the light collection efficiency, the lower plots show the S_3 value for events with a large number of photons. The contour on the S_3 plots shows the effect of using the $S_3 < 0.408$ cut within the analysis. The volume of the detector excluded by such a cut allows the fiducial mass of the detector to be calculated as 3.1 kg.

the top mirror plane. The simulation indicates that, even for single electrons extracted from the liquid surface, the relative electroluminescence signal size allows the interaction *x–y* location to be identified with sub-cm accuracy. The *z* location may be derived from the delay between primary and secondary scintillation pulses, giving a full 3D location. Such information may then be used to define a fiducial volume within the target volume, but also to potentially identify multiple scatters from background neutrons.

4. Summary

The direct detection of WIMPs within the Galactic dark matter halo is made possible by their elastic coherent scatter from target nuclei. The problems associated with this detection are the low rate and low energy of the recoil, and the high background rate in the detectors. The use of position sensitivity and the location of the particle interaction site help in the reduction of the background through the removal of surface and

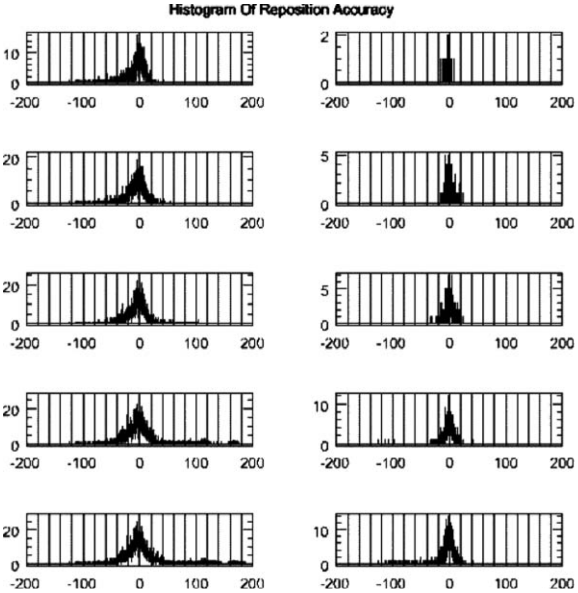

Fig. 6. Monte Carlo simulation of the reconstruction accuracy of ZEPLIN III using the inner 19 photomultipliers only for single electrons extracted from the liquid target. The relative ratio of the electroluminescence signal to primary scintillation is used to determine position, shown here in mm, for ten annular sections of equal radial increment.

edge events, segmentation of the target volume and identification of multiple scattering due to neutron initiated events.

Acknowledgements

The author would like to gratefully acknowledge the contribution and support of the UK Dark Matter Collaboration and PPARC in the production of the UKDMC liquid xenon detectors, the data and its interpretation. In particular the invaluable contribution of Peter Smith, Simon Hart, Igor Liubarsky, Roy Preece and Roland Lüscher to the realization of the ZEPLIN I detector.

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