Status of Direct Dark Matter Detection Experiments at the Boulby Mine

Nigel Smith[1] for the Boulby Dark Matter Collaboration

[1] Particle Physics Department, Rutherford Appleton Laboratory,
Chilton, Didcot, Oxon, OX11 0QX, UK

Abstract. This paper presents the current status and future plans for the dark matter experiments being undertaken at the Boulby mine. An array of surface controlled NaI(Tl) crystals has been constructed, which control previously observed fast anomalous signals. A series of detectors based on xenon, which has a better background discrimination potential, is under development. The first of these detectors based on liquid xenon pulse shape discrimination is in operation at the Boulby site. Second generation detectors which are based on two phase detectors where both scintillation and ionisation are observed, are under construction. A low pressure CS_2 gas TPC detector has been installed and is operating at Boulby with the intention of developing directional detectors to enable correlations between nuclear recoils and Galactic motion.

1 Inorganic crystal scintillation detectors

The UK Dark Matter Collaboration has been operating dark matter scintillation detectors based on twin photomultipliers viewing NaI(Tl) crystals at the Boulby mine for a decade[1]. The technique of pulse shape discrimination is utilised to set limits on the nuclear recoil interactions expected in these detectors from interactions due to the flux of weakly interacting massive particles (WIMPs), which may constitue up to 90% of the Galactic mass. This discrimination is possible as the time constant of the scintillation due to these nuclear recoils is faster than that due to the electron recoils due to gamma and beta background events[2], see Fig. 1.

1.1 Event population with fast anomalous time constants

Competitive limits on the WIMP cross section were set by the UK Collaboration during 1996[3] but due to the emergence at low rate of an anomalous population of events with scintillation time constants faster than electron recoils but not comparable to nuclear recoils the detector sensitivities were limited[1,4]. The mechanism for the production of these anomalous events is unknown, however it is demonstrably related to surface contamination as evidenced by tests performed on an 800g Harshaw CsI(Tl) crystal on which

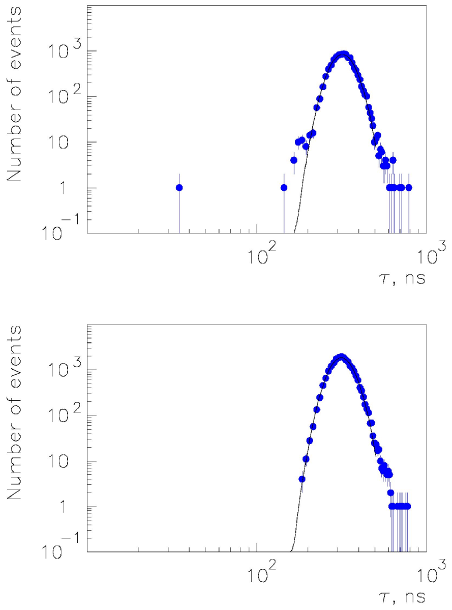

Fig. 1. The distribution of time constants for scintillation light from NaI. The top plot shows the scintillation time constant distribution for underground data showing the presence of an anomalous, fast, population of events. The lower plot shows the time constant distribution for electron recoil events due to Compton scattered gamma events from a calibration source. Both plots are in the range 35-40keV observed energy and have an illustrative log Normal distribution drawn

surface polishing was performed[5]. Although the time constant of scintillation light from a CsI crystal differs from that of NaI(Tl) the CsI(Tl) crystal, utilised due to the hygroscopic nature of NaI, showed evidence of the fast population of events when operated underground. The rate and spectrum of these anomalous events was found to be comparable to that of the NaI(Tl) crystals. The crystal was subsequently surface polished and replaced in a dry nitrogen atmosphere. The rate of the anomalous events was found to be reduced by at least a factor of 4, see Fig. 2.

Several hypotheses have been investigated to explain this population of fast events[1,6–8], including beta and alpha contamination. The favoured being a link between the anomalous events and the high energy alpha emitting radioisotopic contamination, although to reproduce the observed spectrum and time constant the alpha radiation must be exiting the crystal, with an associated small energy deposition[9,6].One possible source for these alpha events may be due to the implantation of nucleii from radon decay, the re-

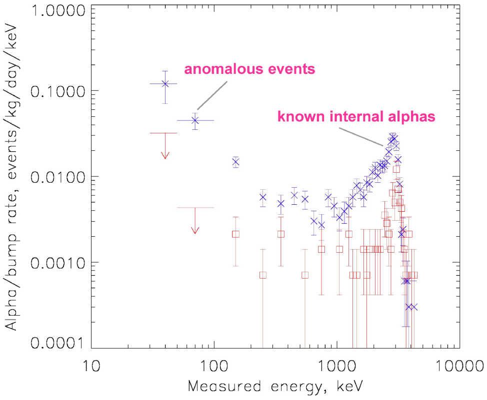

Fig. 2. Rate of fast events observed in an 800g CsI(Tl) crystal, showing the effect of surface polishing. The rate of anomalous and high energy alpha events is shown prior to polishing (crosses) and after polishing (squares)

coiling nucleii being embedded into the crystal surface in a 0.1 micron layer[6] with a subsequent alpha decay. To recreate the spectrum observed the concentration of nucleii embedded needs to be higher than can be reasonably explained due to radon contamination on the bare crystal surface, especially in the case of the hygroscopic NaI crystals.

1.2 The NaIAD Array

Based on the results of the surface treatment of the CsI(Tl) crystal and the removal of the anomalous fast events an array of NaI(Tl) scintillation detectors has been designed and is now operating at the Boulby mine. This array comprises a series of eight NaI(Tl) crystals ranging from 5-10kg in mass, viewed by two 5” low background photomultipliers through silica light guides to shield the crystal from X-ray, alpha and low energy gamma radiation from the photomultipliers. The crystals are surface treated and maintained in a dry nitrogen atmosphere to maintain surface quality. The crystals are surrounded by a 10mm PTFE reflector to enhance the light collection efficiency. First results from this array indicate that the fast anomalous events have indeed been suppressed, allowing an estimate that 100 kg.years of data will provide a sensitivity of $2x10^{-6}pb$[10].

2 Noble gas scintillation and ionisation detectors

Xenon is well suited to use as a dark matter target due to the high mean nuclear mass which is well matched to the expected WIMP mass[13]. Xenon

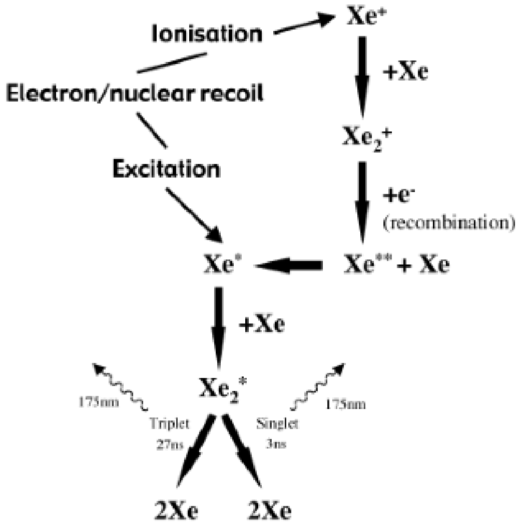

Fig. 3. Schematic of the scintillation and ionisation process in xenon. The primary scintillation is generated through an excited dimer. With no applied electric field the ionisation recombines to form further excited dimers. Discrimination occurs due to a factor 10 difference in the ratio of 3ns and 27ns decay modes, and also due to the recombination time introduced in electron recoils.

also has a well understood response to electron and nuclear recoils, which yields good discrimination between the background and WIMP signal. A recoil produces both scintillation and ionisation, see Fig. 3. When no electric field is applied the primary discrimination between nuclear and electron recoils occurs due to the recombination time introduced into the scintillation pulse of 45ns. For nuclear recoils this time is a few picoseconds.

2.1 ZEPLIN I - single phase scintillation detector

The ZEPLIN I detector[15] is a single phase liquid xenon scintillation detector of 3kg fiducial volume, viewed by three 3 quartz photomultipliers through silica windows and optically isolated, self shielding, liquid xenon turrets. The target is enclosed by a multi-purpose, 1 tonne, PXE-based liquid scintillator shield and an outer passive lead shield. The liquid scintillator shield acts as a veto for PMT events and also provides a Compton gamma calibration contemporaneous with the data collected, an active shield for external gammas, a high purity inner shield and, through the use of an optional internal gadolinium coated surface, a neutron monitor.

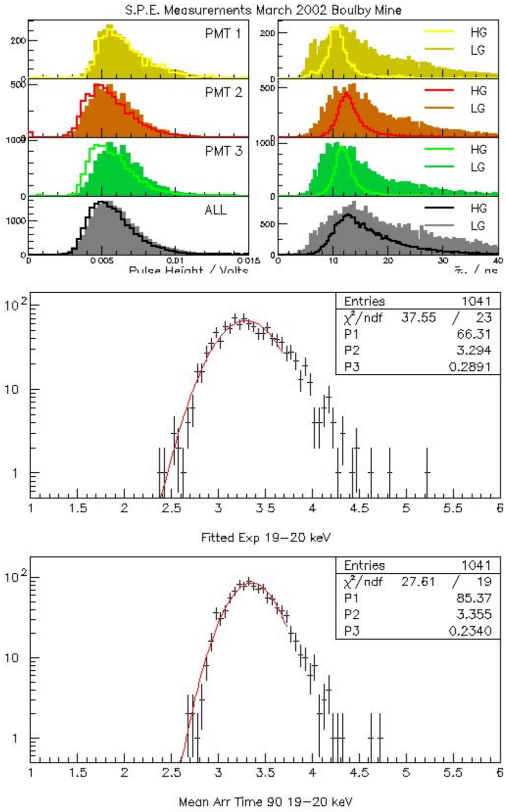

Fig. 4. The time constant distributions for single photo-electrons in the three photomultipliers of ZEPLIN I, showing the log normal (or gamma density) distribution of the events. The lower plots show the characteristic gamma density distributions for electron recoils in liquid xenon at 10-20keV visible energy for two different analysis techniques

Discrimination between nuclear recoil and electron recoil events is provided by the time constant of the scintillation light from the liquid xenon. There is no electric field applied to the fiducial volume, thus recombination of the ionisation yield is allowed. For nuclear recoils initiated by neutrons or WIMPs the scintillation has a characteristic time of approximately 55% that of electron recoils due to beta and gamma backgrounds, currently measured down to 10keV electron equivalent observed recoil energy.

To calculate the limit on WIMP interactions in the detector the scintillation time constant distribution is studied as a function of energy, with the 90% upper limit of nuclear recoils being deduced[16,14]. The optimisation of

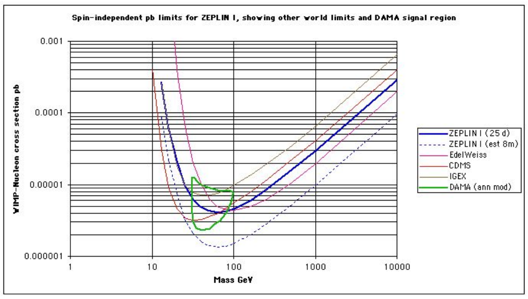

Fig. 5. The preliminary limit set by ZEPLIN I from 25 days on-time compared to other direct dark matter detection experiments[11]. The central region is the claimed WIMP detection by the DAMA collaboration using the predicted annual modulation signature[12]

the extraction of the nuclear recoil limit remains the key statistical question within the ZEPLIN I analysis.

Several different analyses techniques have been applied to the scintillation pulse fitting routines based on single exponential fits, mean and median times. Although the time structure is well defined for large events, the events of interest are measured in tens of photo-electrons for which the model independent fits to the pulses are equivalent. The characteristic distribution of the scintillation time constants is a gamma density distribution in 1/time, Fig. 4. The underlying process for the generation of this distribution in the photomultiplier signals is not well understood the natural generation of gamma density distributions arises from non-consecutive time interval distributions. It is also noted that the time constant distributions for single photo-electrons from the photomultipliers, ie disconnected from the xenon scintillation, is well fitted by either a log normal or gamma density distribution.

The extraction of the 90% upper limit of nuclear recoils is usually achieved by comparison of the time constant distributions for the run data and calibration data generated by gamma sources or known gamma backgrounds. The latter is generated in ZEPLIN I through the use of the Compton veto signal where coincidental events in the chamber and veto are generated by high energy Compton scattered gammas from the photomultipliers. A delta-chisquared analysis can then be used to compare the sum of gamma and neutron calibration data with the run data to extract the 90% upper limit of observed signal. An alternative to the comparison to gamma calibration data is to assume the functional form of the time constant distributions of the scintillation data are true gamma density distributions or, less stringent, are smooth monotonically rising distributions. An analysis can then be performed by comparing the expected distribution for the sum of signal and background against the functional form of the calibration data, or searching for the expected gradient break in the monotonic distribution. The validity of comparison with the functional form of the calibration data is in question when the underlying process for the generation of such a distribution is unknown. The rigour of the statistical test utilised to extract the 90% upper limit to the nuclear recoils, and hence the dark matter cross section, is of importance in present dark matter experiments which are beginning to exclude the claimed WIMP signal inferred from the annual modulation seen in the DAMA NaI detector array[12], Fig. 5.

2.2 ZEPLIN II - two phase scintillation/electroluminescence detector

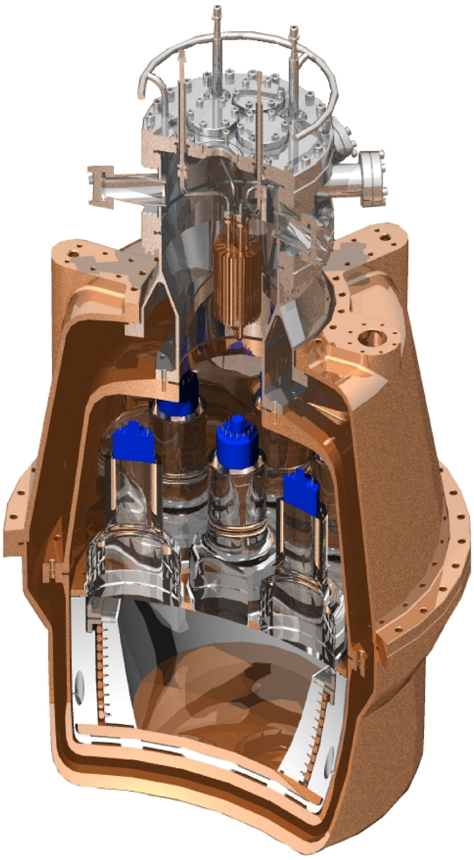

Fig. 6. Engineering drawing of the ZEPLIN II detector illustrating the 30kg fiducial volume of liquid xenon viewed by seven 5” photomultipliers through the gas phase. Electroluminescence is generated in an electric field below the photomultipliers

ZEPLIN II (see Fig. 6) is a two phase xenon detector which utilises discrimination between the nuclear and electron recoils through a comparison of the scintillation and ionisation yields and is a development of work performed at CERN, UCLA and the UK[17]. The detector is currently under construction for deployment at Boulby in 2002/3. The primary scintillation is measured directly by seven 5" photomultiplier tubes which are located in the gas phase but view the liquid xenon target volume directly. The ionisation is extracted from the target mass of liquid xenon through an electric field into the gaseous phase where it is measured by viewing the electroluminescence generated in a high field region with the same photomultipliers. For nuclear recoils where the high rate of energy loss produces electrons co-located with the xenon ions the electric field is low enough to allow recombination of the ionisation. The characteristic signature of a nuclear recoil is therefore a single pulse due to the primary scintillation. The characteristic signature of a background event is a double pulse due to the observation of both the primary scintillation but also the ionisation associated with the electron recoil. The fiducial mass of ZEPLIN II is 30kg, with a PTFE reflector having the the three purpose of increasing the light collection yield, allowing a uniform electric field to be produced within the fiducial volume of xenon and removing areas of xenon without an electric field where gamma events may mimic single pulse events. The information related to large xenon mass and long electron drift lengths gathered from operating the ZEPLIN II detector will allow the development of large scale two phase xenon detectors.

2.3 ZEPLIN III - two phase scintillation/electroluminescence detector

ZEPLIN III (see Fig. 7) is a two phase xenon detector which utilises discrimination between the nuclear and electron recoils through a comparison of the scintillation and ionisation yields and is a development of work performed at ITEP and the UK[18]. The detector is currently under construction for deployment at the Boulby mine in 2003. The emphasis of the ZEPLIN III detector is to maximise the light yield from the liquid xenon and to investigate the maximum discrimination possible through the use of a high (2.5kV/cm) field within the fiducial volume. This high field is expected to allow separation of the ionisation from both electron and nuclear recoils, an effect demonstrated for recoils due to the more energetic and ionising alpha particles[18] and recently demonstrated for nuclear recoils due to neutrons[19]. To maximise light yield and allow position measurement the ZEPLIN II target has 31 fast 2" photomultipliers located within the liquid xenon target. A reverse field is maintained directly in front of the cathodes to prevent the collection of ionisation fom the beta and alpha activity within the photomultipliers. Again the ionisation is extracted from the 6kg fiducial volume and measured through the generation of an electroluminescence signal, with the primary/secondary signal size ratio being the discriminant varying by three orders of magnitude

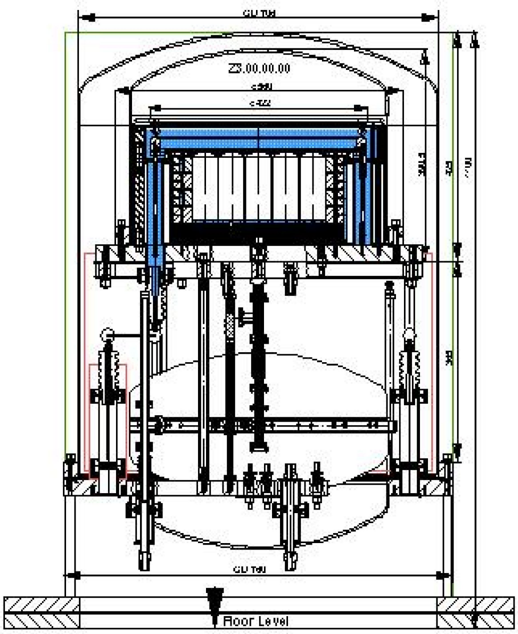

Fig. 7. Engineering drawing of the ZEPLIN III detector illustrating the 6kg fiducial volume of liquid xenon viewed by 31 2” photomultipliers from within the liquid phase. Electroluminescence is generated in an electric field within the gas field from ionisation extracted under high drift and extraction fields

for electron and alpha induced nuclear recoils. The information related to high light yield, low background and maximum discrimination gathered from operating the ZEPLIN III detector will allow the development of large scale two phase xenon detectors.

3 Directional detectors

One of the signatures for a WIMP detection is the correlation between the direction of the nuclear recoils observed in a detector and the sidereal variation in Galactic motion. The DRIFT detector concept is based on a 50 torr low pressure CS_2 gas time projection chamber where a 1kV/cm field is applied across one axis to drift negative ions to MWPC readout planes at each end of the detector. The free electrons produced from ionisation due to nuclear and electron recoils combine with the electronegative CS_2 molecule to produce the negative ions. Negative ion drift has been shown to reduce track diffusion to enable mm tracks to be resolved at 0.5m drift lengths [20]. In addition to the discrimination potential due to resolving and correlating track directions the DRIFT detector allows discrimination through the different charge densities due to electron and nuclear recoils. Tests on a foot-cube prototype chamber show positive identification of nuclear recoils with a 99.9% rejection of electron recoils at 6keV[20]. A 1m^3 detector has been constructed and installed at Boulby mine with confirmation of the nuclear recoil discrimination potential of the DRIFT concept[21].

The support of Cleveland Potash Ltd., the operators of the Boulby mine, and PPARC and NSF funding are gratefully acknowledged.

References

1. P. F. Smith *et al Phys Reports (1998)* **307** 275.
2. D. R. Tovey *et al Phys. Lett. B (1998)* **433** 150.
3. P. F. Smith *et al Phys. Lett. B (1996)* **379** 299.
4. G. Gerbier *et al Astroparticle Physics (1999)* **11** 287.
5. V. A. Kudryavtsev *et al Astroparticle Physics* (2002) **17** 401.
6. N. J. T. Smith *et al Phys. Lett. B (2000)* **485** 9.
7. G. Chardin *et al* Proc. 4th Int. Symp. Marina del Rey 2000 p.340.
8. S. Cooper *et al Phys. Lett. B (2000)* **490** 6.
9. V. A. Kudryavtsev *et al Phys. Lett. B (1999)* **452** 167.
10. N. J. C. Spooner *et al Phys. Lett. B (2000)* **473** 330.
11. References summarised at http://dendera.Berkeley.EDU/plotter/entryform.html
12. R Bernabei *et al Phys. Lett. B (2000)* **480** 23.
13. G. J. Davies *et al* , *Phys. Lett. B (1994)* **320**395-399
14. N. J. T. Smith, C. H. Lally, G. J. Davies. *Nucl. Phys. B (proc. supp.) (1996)* **48** 67-69
15. I. Ivaniouchenkov et al., IEEE 2000 Nuclear Science Symposium and Medical Imaging Conference
16. J. D. Lewin, P. F. Smith, *Astroparticle Physics 6 (1996)* 87-112
17. D. Cline *et al Astroparticle Physics (2000)* **12** 373.
18. T. J. Sumner *et al Proc 27th ICRC (2001)*
19. F. N. Beg *et al* Applied Physics Letters (2002) **80** 16
20. C. J. Martoff *et al Nucl. Instrum. Methods A (2000)* **440**.
21. B. Morgan *et al* Proc Xenon Workshop, Tokyo *(2001)*