The Potential of Liquid Xenon for WIMP Search: the ZEPLIN Diagnostic Array

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A Liquid Xenon based WIMP detector diagnostic array is currently developed by the UKDMC with the help of international collaborators. After a brief reminder on the detection principle in Liquid Xenon, the individual detectors will be described. ZEPLIN I, a detector with a 4 kg fiducial mass with a background discrimination based on Pulse Shape Analysis, is already underground and starting operation. Two setups with improved background discrimination tools (as the ionisation is also recorded) are designed and scheduled to move underground in the second half of 2001. Both of them, ZEPLIN II and ZEPLIN III, are predicted to be sensitive to rate of 0.1-0.01 events/kg/day within 2 years of data taking. Furthermore, new ideas for lower background readout devices are studied, in order to avoid the use of PhotoMultiplier Tubes (PMTs).

1. INTRODUCTION

As part of the WIMP dark matter search programme at Boulby Mine, the UKDMC and new international collaborators are developing a diagnostic array of detectors with Liquid Xenon (LXe) as the target material. The ZEPLIN project (Zoned Proportional scintillation in LIquid Noble gases), takes advantage of the particularly apropriate properties of Xe: heavy nuclei for a large spin-independent coupling and appreciable abundance of isotopes with spin for a large spin-dependent coupling, bigger sensitivity to higher WIMP masses (> 50 GeV) than for instance NaI detectors. Low background Xe is available. LXe is also known as a good scintillator: emitting in the UV region (175 nm), it enables a low energy threshold. Moreover, the interaction process in LXe owns characteristics which translates into a potentially high background discrimination.

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1.1. Interaction in LXe

Any recoil in LXe give rise to both ionisation and excitation of Xe atoms. The excitation result in the emission of a 175 nm photon from either a singlet (with decay time ~ 3 ns) or a triplet state (~ 27 ns). In absence of electric field, the ionisation recombines to produce further excited Xe atoms — with an accordingly increased time for the photon emission[1].

The proportion of ionisation and excitation released depends on the dE/dx of the particle interaction. Electron recoil produces more ionisation, while for nuclear recoils, the excitation is more important. This enables two main discrimination techniques: a) allowing the recombination to occur or b) preventing the recombination by applying an electric field. In case (a), the electron background events are expected to have longer pulses due to the increased contribution of the recombination time, allowing the use of 'classical' Pulse-Shape Analysis (PSA). In case (b), the field which prevents the recombination makes also the ionisation electrons to drift towards a readout plane, so that that this signal can also be measured. The ionisation/scintillation ratio is then used to discriminate the electron background from the nuclear recoils.

1.2. Scintillation characteristics

Studies on the scintillating properties of liquid noble gases goes back to the late 70's. However, there is still controversies about two of its major properties: a) the quenching factor[2] and b) the pulse-shape characteristics. Given the relevance of these respectively to the sensitivity of LXe to WIMP signals and to the potential of background rejection using PSA, it is important to determine them accurately. The UKDMC have done tests with two prototypes in order to evaluate these two characteristics. The response to nuclear recoils has been measured through the elastic scattering of mono-energetic neutrons (2.85 MeV) provided by the Sheffield neutron beam facility. Analysis of the data is in progress but indicates a factor of 0.22 for the relative scintillation efficiency for nuclear recoils in the energy range 40-70 keV. This value is consistent with the expectation from the Lindhard theory[2] and with recently published measurements from the ICARUS collaboration[11], but disagrees strongly with the values published by the DAMA collaboration[10]. Further, the pulses of electron recoils are found to be significantly longer ($\sim$ 30 ns at $\sim$ 15 keV) than nuclear recoil signals ($\sim$ 21 ns). This pulse-shape difference is bigger than the one observed in NaI[9].

2. ZEPLIN I - single phase detector

The first detector of the ZEPLIN array is based on a pure scintillator design. No electric field is applied and, thus, discrimination method (a) is used. The LXe is viewed by 3 PMTs through silica windows (figure 1). Between the fiducial volume, which is containing 4 kg of target, and each windows, there is a volume of LXe which is optically isolated (ie. in which most of the signals appear only in the corresponding PMT), thus acting as self-shielding.

Figure 1. The ZEPLIN I design: a pure LXe scintillator with 4 kg active mass.

The detector is enclosed in a 1 tonne active Compton veto shielding, based on PXE liquid scintillator and view by 10 PMTs. Its function is to veto gamma activities from the PMTs and from the surroundings. Coating the inner surface with Gadolinium would be an option to monitor the neutron background. From Monte-Carlo simulations, a veto efficiency of 80-90% below 100 keV has been estimated.

ZEPLIN I is now underground and data taking has just been started.

3. ZEPLIN II - double phase detector

With collaborators from Columbia, UCLA, Torino, and CERN, we are constructing incorporating a more advanced discrimination technique. The detector ZEPLIN II is based on a technology which has been tested in a 1 kg prototype[3]. An electric field prevents the recombination; the ionisation is drifted out of the liquid into a gas phase, in which wire planes define a

[2] The quenching factor is the ratio between the real photon yield and the ideal yield deduced from the average energy required for the photon production. It can not be measured directly; the scintillation yield for nuclear recoils relative to the one for electron recoils is measured instead.

high field region. Therein, avalanche occurs and electroluminescence is created. The latter is then recorded as a secondary signal by the same PMTs which have already read the primary scintillation. The ratio between the two signal has been shown to be a good tool to discriminate the nuclear recoils from the electron recoils with only very small overlap[4].

The detector consists of a fiducial volume containing about 20 kg (figure 2). It is surrounded by a liquid scintillator Compton veto similar to the one used in ZEPLIN I. Sensitivity to rates of

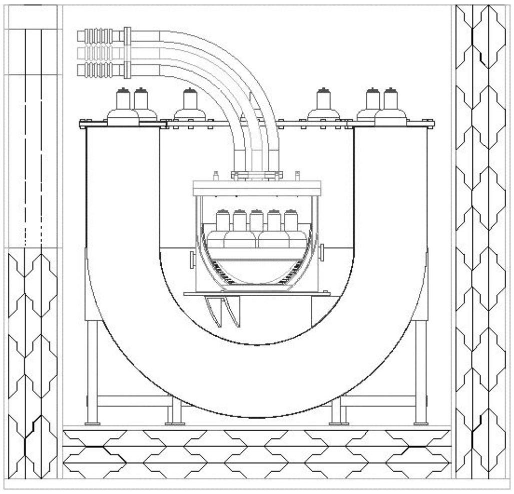

Figure 2. The ZEPLIN II double-phase design, incorporating a more advanced discrimination tool as both the scintillation and the ionisation produced in an event are measured.

about .1-01 events/kg/day can be reached within 2 years. The installation in Boulby mine is scheduled for middle 2001. Further details can be found in ref. [4].

4. ZEPLIN III - double phase, high field detector

The ZEPLIN III experiment (a collaboration with Columbia and ITEP) is an 'upside-down' version of a similar design. The PMTs are submerged in the LXe, what is providing an increased light collection and a decreased noise. In this setup, it is possible to increase the drift field up to levels which enable the detection of the small ionisation signal from the nuclear recoils. This is improving the background discrimination and allowing a lower threshold. Moreover, there

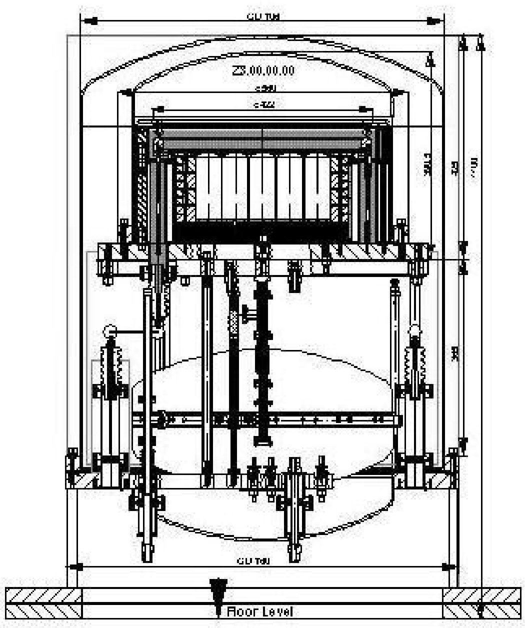

Figure 3. The ZEPLIN III design: a higher drift field allows a lower energy threshold and an increased discrimination factor from the ionisation/scintillation ratio.

are coordinate reconstruction possibilities: to the timing (for z), we can combine a interesting 2D position sensitivity (for x and y). The fiducial volume is limited by the HV requirements (to be reasonnably < 50 kV): with an active liquid depth of 3.5 cm, the design has a fiducial mass of 6 kg. Nevertheless, similar sensitivities as ZEPLIN II will be reached, as the discrimination and the threshold are improved. More details can be found in [5]. Schedule for installation in Boulby is middle 2001.

5. NEW IDEAS

The described detectors are based on PMTs as readout devices. These are known to be radio-contaminated. Thus, the UKDMC has started to study ways of avoiding their use. A promising method includes an internal photocathode and an electron amplification device: CsI photocathodes has been shown to work well in LXe[6,7], while ref. [8] shows recent development of a noble gas PM based on GEMs (Gas Electron Multiplier). The UKDMC is currently working on a prototype incorporating these two devices (figure 4). The primary scintillation light produces

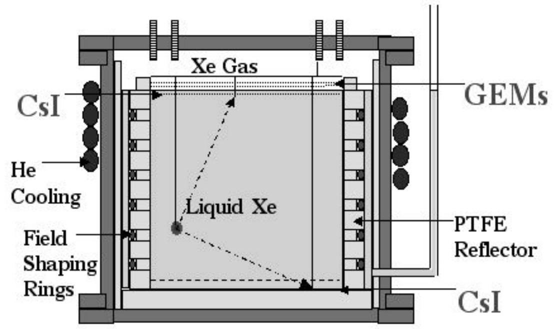

Figure 4. An R&D prototype with internal photocathodes and GEM-based amplification: read-out withou PMTs.

photoelectron on two photocathodes, one on the top, one on the bottom; the photoelectrons and the ionisation electrons are then drifted towards a gas phase, where a GEM-cascade provides amplification. The construction of the prototype is in progress and tests of the response to nuclear recoil should start soon.

6. SUMMARY

A diagnostic array of WIMP detectors with LXe as target material has been developed by the UKDMC with international collaborators. A first design based on a purely scintillation response is installed in Boulby Mine and operation has started. Two further designs are in construction which incorporate more advanced background discrimination tools based on the recording of both ionisation and scintillation of each event, allowing sensitivity to rates of .1-.01 events/day/kg within two years. Installation is scheduled for summer 2001. A new readout technique, which incorporates internal CsI photocathodes and GEM gas phototubes, is currently in development in order to avoid the use of PMTs.

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REFERENCES

1. T. Doke *et al.*, Nucl. Instr. and Meth. A 291 (1990), 617, and Refs. therein.
2. J. Lindhard, *Mat. Fys. Medd. Dan. Vid. Selsk.* 33 (1963),1.
3. H. Wang, Phys. Rep. 307 (1998), 263.
4. H. Wang, proc. of the 4th Int. Symp. on Sources and Detect. of Dark Matter (Marina del Rey, CA, USA, February 2000).
5. D. Akimov, proc. of the 4th Int. Symp. on Sources and Detect. of Dark Matter (Marina del Rey, CA, USA, February 2000).
6. E. Aprile *et al.*, Nucl. Instr. and Meth. A 338, (1994), 328.
7. E. Aprile *et al.*, Nucl. Instr. and Meth. A 343 (1994), 121.
8. A. Buzulutskov *et al.*, Nucl. Instr. and Meth. A 443 (2000), 164.
9. D.R. Tovey *et al.*, Phys. Lett. B 433 (1998,) 150.
10. R. Bernabei *et al.*, Phys. Lett. B 436 (1998), 379.
11. F. Arneodo *et al.*, Nucl. Instr. and Meth. A 449 (2000), 147.