MEASUREMENTS WITH A TWO-PHASE XENON PROTOTYPE DARK MATTER DETECTOR

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First measurements from a two-phase 3kg Xe prototype cell have been taken. Signals have been observed from a variety of radiation sources and results characterised as a function of applied electric field. Electron drift times in excess of 60μs have been measured. Signals are observed from both phases - primary scintillation in the liquid phase and secondary scintillation due to ionisation drift into the gas phase. The two-phase output from alpha particles and gamma photons are presented. Future prospects for the detection of nuclear recoil ionisation and the fabrication of a 9kg two-phase detector - Zeplin III, are discussed.

1 Introduction

A future UKDMC detector, Zeplin III[1], will comprise a liquid xenon target with combined detection of scintillation and ionisation. This detector will rely upon two-phase operation of xenon utilising the gas phase to "amplify" the ionisation signal and convert it into secondary scintillation via electroluminescence. Amplification results from multiple photoelectrons being detected from the transit of a single electron through the gas region.

Crucial to any two-phase detector based upon ionisation signals is the ability to drift electrons through a few centimetres of liquid and extract them into the gas phase. This requires free electron lifetimes in excess of 100μs which necessitates extreme xenon purity with particular removal of electronegative (electron trapping) impurities such as O_2, N_2O, CO_2 and H_2O. Furthermore careful choice of fabrication materials has to be implemented so that the lifetime can be maintained for a period of months in order to take sufficient data to be useful for the detection of dark matter.

A two-phase detector system is believed to be advantageous due to the inherent differences in the ratio of primary to secondary (ionisation) scintillation depending upon the excitation species. A WIMP interaction should generate a greater proportion of primary scintillation compared to ionisation, whilst a background gamma interaction should produce approximately equal

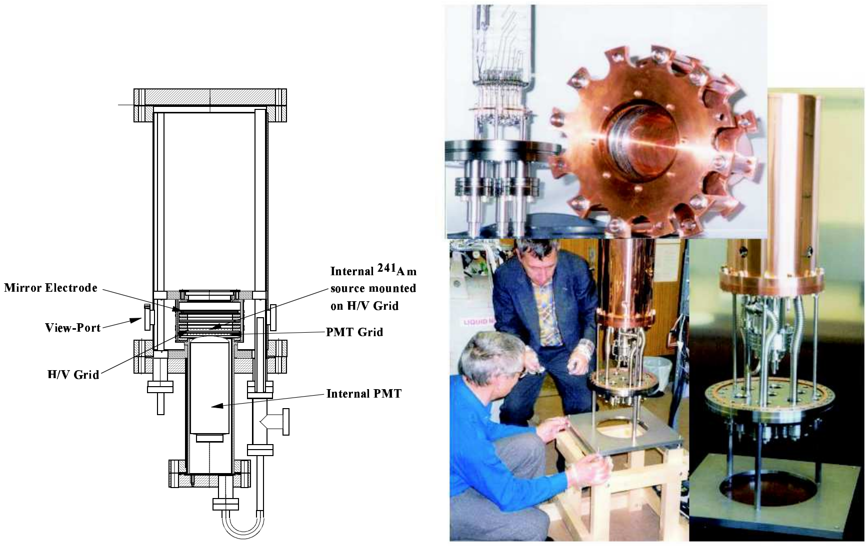

Figure 1. A schematic of the two-phase prototype cell (left). The internal PMT and electrodes can be seen in the picture on the right.

quantities of scintillation and ionisation. Although nuclear recoil ionisation has not so far been observed there is no physical reason why it should not be produced, especially given the observation of nuclear recoil scintillation[2,3]. Its previous non-observation[4] implies that it is greatly quenched (as is the case with alpha particle interaction). Hence the discrimination factor for two-phase liquid xenon detectors could be very large.

2 Two-Phase Prototype Cell

A schematic of the two-phase detector is shown in Fig. 1. It contains an internal PMT and high voltage electrodes capable of operating at up to 20 kV. The lower grid is present to shield the PMT from the HV and also to introduce a zero field region between the PMT face and the grid. In a full-scale dark matter detector with large area read-out this should greatly reduce the background contribution from the PMTs by stopping electrons from this region drifting into the gas phase.

There is an internal ^{241}Am α-source on the wire HV grid backed by a lead support to prevent alphas and most of the 60 keV gammas causing direct scintillation onto the PMT. This increases the proportion of events in the high electric field and also reduces the amount of light on the PMT from the alphas. The light collection is not optimised - the only reflector is a low-grade aluminium mirror forming the top (ground) electrode.

During normal operation interactions occur in the region above the HV grid producing indirect (reflected) primary scintillation and free electrons. The electrons then drift through the liquid to the surface where they are extracted into the gas. Whilst the ionisation drifts through the gas, further (secondary) scintillation is observed due to electroluminescence. The electrons are finally added to the external circuit once they reach the mirror electrode.

For two-phase operation very high xenon purity is required, thus the purification apparatus was constructed using stainless steel and UHV components through-out. Central to the system is an *Oxisorb* cartridge used to remove oxygen and water. The system also has the capability to distil the xenon vapour into the detector through a 0.5μm dust filter. This purification technique has previously been demonstrated by others[5].

3 Results from Prototype Cell

3.1 Light Output Measurements

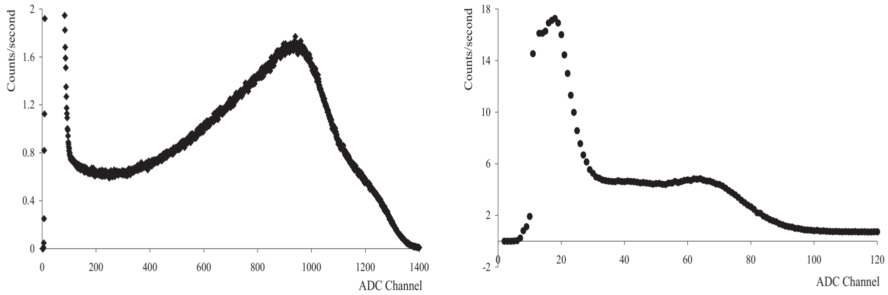

Figure 2. The light output of the detector at zero-field for the internal ^{241}Am source showing the α-spectrum (left) and on an expanded scale the lower energy X-ray lines (right).

The PMT response was characterised by measuring its single photoelectron spectrum at room temperature and whilst immersed in LXe. No detectable difference in the most probable value was observed. In Fig. 2 the detector response to the internal alpha source is clearly shown. The light level is reduced due to shadowing of direct light by the source holder. The X-ray spectrum (right) contains a number of distinguishing features. These are believed to be due to the gamma rays from the source travelling both downwards and upwards. The highest energy peak is due to a downward-going 60keV X-ray (direct light), whilst the intermediary energy is most likely a combination of the neptunium lines going downward and therefore causing direct light onto the PMT. The lowest energy peak is from upward-going 60keV X-rays, which like the alphas, are heavily shadowed by the source and its support, resulting in only reflected light being detected. Taking the highest energy peak as a 60 keV gives a value of 1.22 photoelectrons/keV in the detector.

3.2 Electron Drift Measurements

A charge sensitive Amptek A250 amplifier was connected to the top mirror electrode to quantify the current due to free electrons travelling through the liquid volume. Acquisition was triggered on the primary scintillation from the PMT. Due to high noise levels the amplifier signal was averaged. A typical measurement at 0.7kV/cm is shown in Fig. 3 (top left). The charge is produced from the internal alpha-source. By increasing the scintillation threshold to above that of the α-spectrum it is possible to trigger on higher energy cosmic interactions in the detector. This allows characterisation of electron drift at much lower electric fields than with the alpha-source, as shown in the bottom left of Fig. 3. Drift times in excess of 60μs are clearly observed. The non-linearity in the current as function of time is caused by averaging interactions over the whole sensitive volume, and therefore including drift within the lower electric field at the radial edge of the detector. Nonetheless it is clear that the free electron lifetime must be in excess of 60μs and is most probably closer to $\sim$1ms.

During over 3 months of continuous operation of the two-phase system at high electric field system no degradation was observed in the free electron lifetime either as characterised by the above charge measurement or in terms of electroluminescence output.

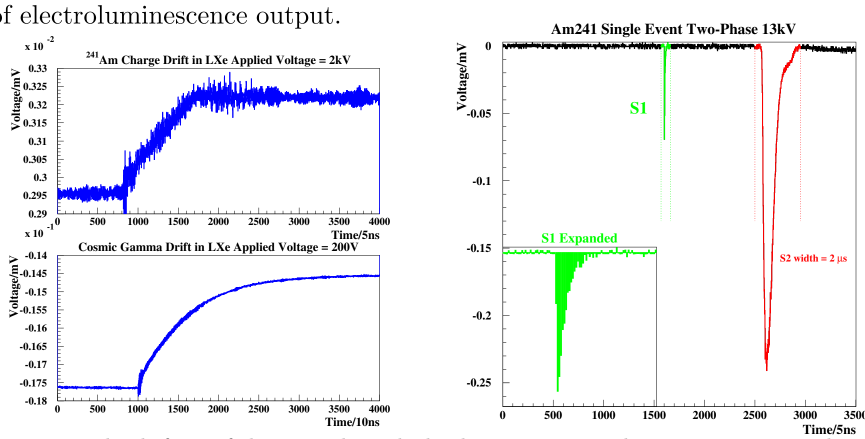

Figure 3. The drifting of electrons through the detector gives a charge measurement due to α-particles (top left) and from cosmic rays (bottom left). By increasing the field electron extraction and electroluminescence can be observed (right).

3.3 Two-Phase Operation

The output of the PMT was digitised using a Lecroy 7200 oscilloscope with individual traces stored to a computer. A typical event at a field of 4kV/cm is shown in Fig. 3. The ratio of primary (S1) to secondary (S2) scintillation is

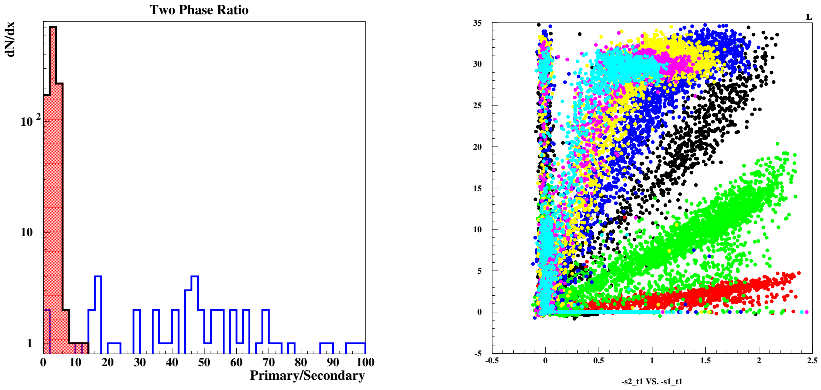

Figure 4. (Left) A plot of the ratio of *S1/*S2 scintillation. Two distributions can be clearly seen from the gamma (clear) and alpha (shaded) sources. (Right) A plot of *S1* (x-axis) vs. *S2* (y-axis) scintillation for a range of applied voltages from 7kV to 12kV. Even at the lowest voltage the gamma distribution is still only observable as a secondary scintillation.

shown in Fig. 4 for the internal α-source and an external ^{60}Co gamma-source. Clear discrimination can be observed between alphas (shaded) and gammas. The variation in the secondary scintillation yield as a function of electric field can be seen on the right of figure. The diagonal regions indicate data sets at a voltage increasing from 7kV to 12kV. At all the electric fields the gamma signals (from a ^{60}Co source) are only seen on the y-axis. This means the secondary scintillation from the gamma interactions is so large that for a deposition that has no observable primary photon, the secondary scintillation actually saturates the data acquisition. At lower electric fields the gamma distribution is particularly broadened compared to theory due to light collection variations and a reduction in electric field (and hence electroluminescence) towards the radial edge of the sensitive region. This is problematic but overcome in the design of the full-scale dark matter detector, Zeplin III (Sec. 4), whereby a multiple PMT array allows position sensitivity thereby defining a fiducial volume within a uniform electric field.

4 Future Dark Matter Detector

Zeplin III, a large scale two-phase system, will be built in the near future and should be operational underground by the end of 2001. A design drawing is shown in Fig. 5. From the prototype work the electrode and HV connection has been adapted. There is also clear definition of a fiducial volume within the electrodes with a uniform electric field. It is hoped that this detector should cover most of the expected SUSY dark matter WIMP parameter space within 2 to 3 years of running, with sensitivities as low as 0.01 interactions/kg/day.

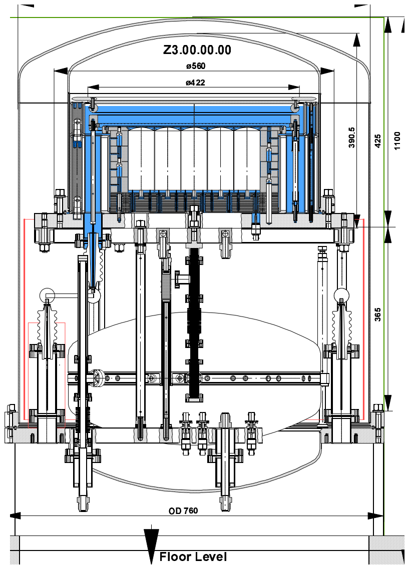

Figure 5. The Zeplin III Dark Datter Detector.

5 Conclusions:

It has been shown that a two-phase liquid-gas xenon prototype dark matter detector can be operated successfully and for long periods of time (>3 months) without re-purification. Successful utilisation of a PMT within liquid xenon has been shown. It has been possible to achieve free electron lifetimes in excess of 60μs and most likely close to $\sim$1ms. By taking the ratio of the primary (direct) scintillation and secondary (ionisation) scintillation clear discrimination between alphas and gammas can be seen. At high electric fields the signals from gammas without any observed primary scintillation produce sufficient secondary scintillation to saturate the PMT and subsequent data acquisition. The next generation UK dark matter detector will be based upon this two-phase work and should be running underground by the end of 2001.

Acknowledgments

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References

1. T. Sumner *et al*, "The Zeplin III Dark Matter Detector", IDM2000, York. These Proceedings.
2. ICARUS Collaboration, Nucl. Instr. and Meth. A 449 (2000) 147
3. R. Bernabei *et al*, Phys. Lett. B436 (1998) 379.
4. H. Wang, Physics Reports 307, (1998) 263-267
5. ICARUS Collaboration, Nucl. Instr. and Meth. A329, (1993), 567.