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Measurements with a two phase xenon prototype dark matter detector

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Abstract.
The two phase Xenon detector principle promises much enhanced background rejection compared with inorganic scintillator dark matter detectors. Scintillation signals from the liquid phase and electroluminescence amplification of the primary ionisation in the gas phase after electron drift are observed. First measurements from a two phase, 5 kg Xe prototype cell have been taken. Signals have been obtained from a variety of radiation sources and results characterised as a function of applied electric field. Electron drift times in excess of 60 μs have been measured. Signals have been observed from both liquid and gas phases. The two phase output from alpha particles and gamma rays are presented. Further experiments on the response to neutrons, simulating dark matter interactions are discussed, emphasising the primary ionisation component. Prospects for the fabrication of a 6 kg fiducial two phase detector by the Boulby Dark Matter Collaboration are mentioned.

1 Introduction

Theoretical predictions of the expected cold dark matter, supersymmetric, weakly interacting massive particle (WIMP) counting rate, R_o/r, lie in the large range of $10^{-4} \rightarrow 1$ /day/kg for detectors of energy loss $\geq$ 10keV. Here R_o/r is an elastic scatter interaction rate normalised by the kinematic factor $r = 4mA/(m + A)^2$ to render the coupling independent of WIMP mass m and target A. Current experimental limits or claimed detections are $R_o/r \sim 1$. The background limitation is by U/Th series γ/β decay background in the case of scintillator detectors and by neutrons from cosmic rays in the case of mK bolometric Ge and Si detectors. The aim of the two phase detector programme, specifically designated ZEPLIN III by the Boulby Dark Matter Collaboration, is to achieve a sensitivity of $\sim 10^{-2}$/d/kg, employing a pulse height ratio rejection technique derived from the two phase output to reduce the radioactivity background. (See Quenby et al, 2001 for further details of the Boulby work) In the two phase system, primary scintillation and ionisation occurs in a particle-target scattering in liquid Xe, followed by immediate recording of the scintillation pulse by PM's while the ionisation electons are drifted into a Xe gas phase where electroluminicent amplification results in a delayed PM pulse. Electron events produce high scintillation and ionisation output while neutron (WIMP-like) events are expected to produce lower scintillation and much lower ionisation output. It is the purpose of the development work with a prototype two phase detector, described here, to verify the discrimination principle and establish the best conditions for the operation of the experiment.

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2 Detector Principles

A detector with a useful threshold to record WIMP recoils will see 2 keV or more energy loss, corresponding in the case of Xe to 10 keV or more actual recoil energy. The recoiling Xe atom can produce scintillation and ionisation via deextitation and self ionisation of the Xe_2^* quasi particles arising in collisions with other Xe atoms. The two lowest states of this excimer decay by 175 nm UV scintillation light with time constants of 2 ns and 27 ns. Ionisation followed by recombination occurs with formation of Xe_2^+. After the electrons lose energy making more excitons or even ionisation, they recombine with Xe_2^+ to form excited molecular states with eventual decay by the scintillation process. The recombination time constant is 15 ns. Application of a $\sim$ 5KV/cm electric field will prevent significant amounts of the electrons from recombining. They are drifted to a liquid/gas Xe interface where at this field magnitude there is almost 95% charge extraction. Electroluminescence multiplication then takes place.

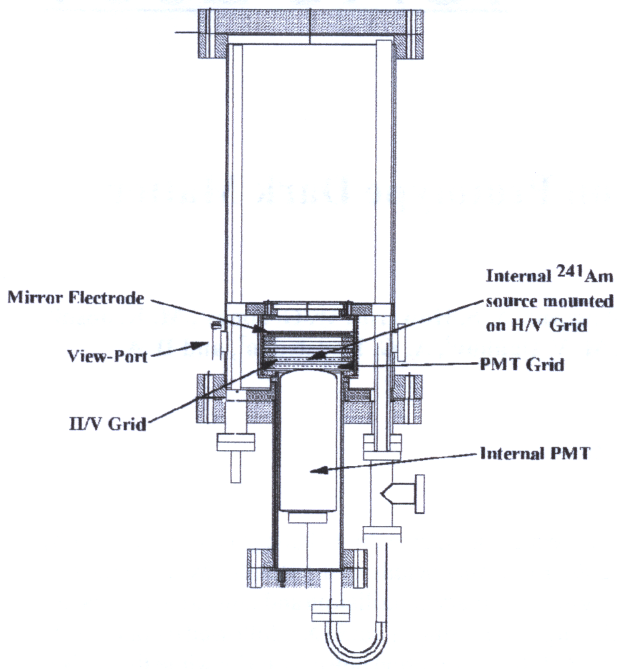

Fig. 1. A schematic of the two-phase protype cell

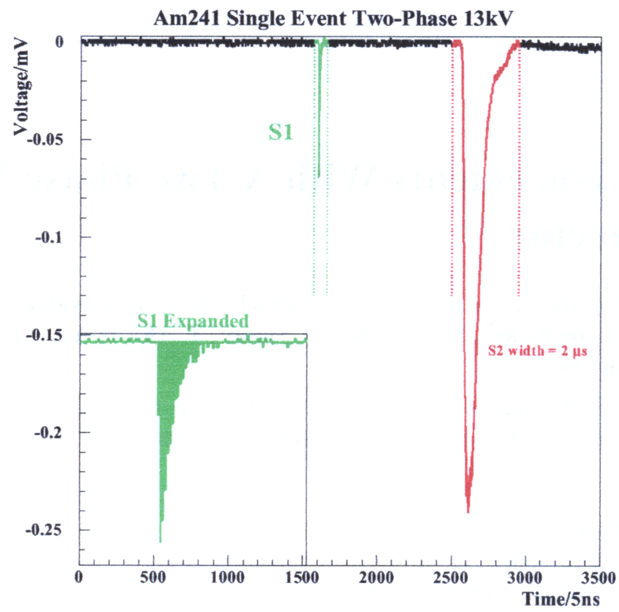

Fig. 2. Two-phase scintillation signal from alpha particles

3 Two Phase Prototype

3.1 Apparatus Description

Figure 1 shows the schematic design of the two phase prototype. Cooling is achieved by LN_2 and a cyro-jacket to achieve temperature uniformity. The single 2" PM with quartz face for UV sensitivity is in contact with the LXe. HV electrodes are capable of supplying up to 20 KV across the liquid and gas phases, between a lower grid which shields the PM from the HV and a mirror at the top acting as an electrode at ground. An internal ^{241}Am α source is located on the wire HV grid, backed by a lead support to prevent α's and most 60 keV γ's causing direct scintillation onto the PM. In normal operation, interactions above the HV grid produce indirect or reflected primary scintillation and free electrons, subsequently seen via electroluminiscence in the gas phase. Typically the LXe is 1.5 cm deep and the gas gap 0.7 cm. Very high Xe purity is required to achieve drift without trapping and thus the purification system was constructed using stainless steel and UHV components throughout. An OXISORB cartridge was employed to remove oxygen and water. Distillation into the detector was via a 0.5μm dust filter. Further details on the apparatus and results are found in Howard et al. (2001).

3.1.1 Prototype Test Results

The PM tube response was checked at room temperature and immersed in LXe and no change in the single electron peak was noticed but the distribution become narrow. Calibration employing the 60 KeV X-ray peak from the built in source yielded a sensitivity of 1.2 amplitude photo electrons/KeV. A charge sensitive amplifier connected to the top mirror electrode was used to measure free electron current at various drift field levels and allowed the establishment of observed drift times in excess of 60 μs. These times remained stable over three months operation.

Two phase output was monitored with via digitisation of the pulses with a Lecroy 7200 oscilloscope. Figure 2.

shows an α event at 4kV/cm in liquid. The secondary (S2) to primary (S1) scintillation yield is plotted in figure 3 and figure 4.

for the internal α source and an external ^{60}Co γ source. The diagonal regions indicate α data sets as the drift voltage increases from 7kV to 12kV. Note the alpha S1 yield should be multiplied x10 because of support shielding. Note all γ signals appear close to the y axis, at all electric field values. The width of the γ distribution (figure 3) is attributed to light collection variability and reduced electric field at the edges.

It has been important to check that neutron induced recoils in liquid Xe produce a similar discrimination to the α particle collision distinction from γ induced events. The neutron (WIMP-like) collision will knock on an Xe atom in the 10's keV KE range which then collides with another Xe atom. Flask (1961) demonstrated Kr atom collisions yield ionisation. We can calculate the cross-section for an energy loss ∇E via the semi-classical Firsov (1959) theory. The relation between ionisation energy, energy E and mass m_1 of moving atom, cross-section radius, R_o and Z_1 and Z_2 atomic number

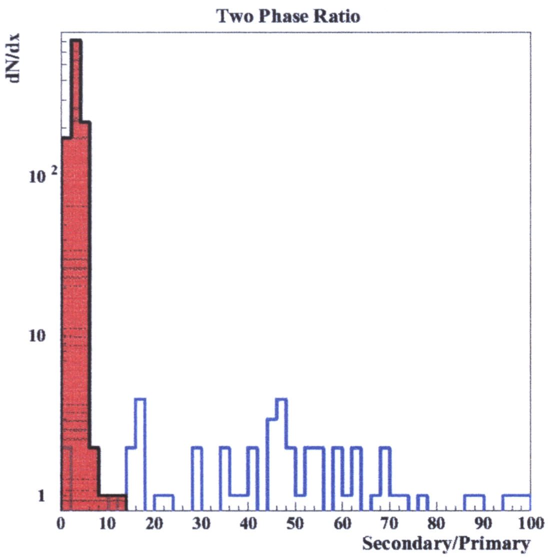

Fig. 3. A plot of the ratio of S2/S1 scintillation. Two distributions can be clearly seen from the gamma (clear) and alpha (shaded) sources

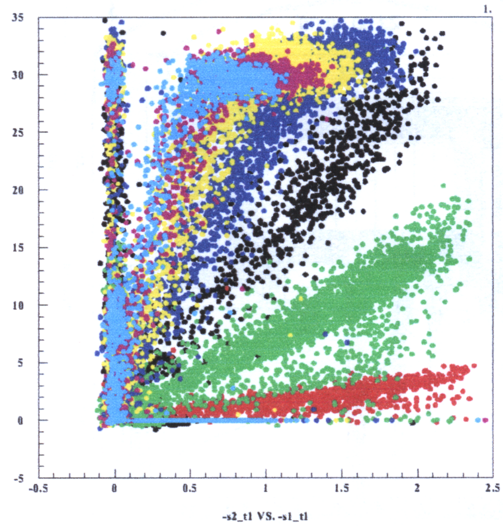

Fig. 4. A plot of S1 (x-axis) vs. S2 (y-axis) scintillation for a range of applied voltages from 7kV to 12 kV. Even at the lowest voltage the gamma distribution is still only observable as a secondary scintillation.

of moving and struck atoms is

$$-\nabla E = \frac{0.05973(Z_1 + Z_2)^{5/3}(E/m_1)^{0.5}}{[1 + 0.31(Z_1 + Z_2)^{1/3}R_o]^5} \tag{1}$$

Tests have been performed with a deuterium z-pinch neutron source where 2 MeV neutrons cause 40-50 keV recoils. To get at least one electron we need about 40 eV and using these numbers in the above equation, we estimate a cross-section $\sim 10^{-16}$ cm^2 for Xe-Xe collision, thus yielding a mean free path smaller than the apparatus dimensions. Experiments with the prototype confirm the detection of neutron induced recoil ionisation via secondary electroluminescence.

A controversial parameter in the detector design is the relative scintillation efficiency for nuclear recoils. Experiments performed at the Sheffield d-d activation neutron beam with the prototype have yielded a value of 0.22 for this parameter (Akimov et al., 2001).

4 Design For ZEPLIN III

The ZEPLIN III design resulting from the prototype work is shown in figure 5.

A slab geometry is adopted with 19, 2" UV sensitive PM's immersed in the liquid and viewing upwards to define the 6 kg fiducial volume. The design allows for a total of 31 tubes to both aid detection of edge events and allow some internal active background shielding. Volume averaged light collection is estimated at $\sim 30\%$ for the primary and $\sim 25\%$ for the secondary scintillation, before the 20% quantum efficiency is taken into account. The liquid is 3.5 cm deep, the gas gap 0.5 cm and the total voltage about 20 KV. A 0.5 cm reverse field region just above the PM's suppresses X-ray PM background and photoelectric feedback. The top mirror is an electrode. 2-D positions are given to within 1 cm by relative PM response while the third D is given by timing. A liquid scintillator veto surrounds the top and sides with a threshold of about 20 keV. Low activity Cu is the main vessel material.

We may estimate the discrimination power of the above design at threshold of about 2 keV observed energy loss seen in primary ionisation of 10 keV nuclear recoil energy. We expect to see 2 Pe at this ionisation. We also expect 1 or 2 electrons from neutron induced ionisation at this energy but to see them with reduced efficiency compared with α events.

From figure 3 we take α's as suitably representative of any nuclear recoil. The alphas are all seen from one location in the centre but the γs suffer from edge effects where the field is reduced. In ZEPLIN III these edge effects should be negligible, but we take a worse case based on figure 3 which demonstrates a factor 100 discrimination in that the α's lie between 0 and 8 and the e/γs between 0 and 75 with roughly equal probability and we remember the S1 α yield should be multiplied by 10. Given that γ calibration will yield this factor accurately, the final limit on possible recoil (WIMP) events will just depend on $N_B^{0.5}$ where N_B is the background in dru (cts/kg/d/keV) at threshold. We would take the WIMP limit as given by $N_B^{0.5}/100$ as the worse case estimate. A rough estimate of the detector background, dominated by PM glass radioactivity, is 100 dru below 20 keV and the active shield is calculated to reduce this to 10 dru. At this backgound, 3 years running yields R$_o$ /r $\sim$ 0.01 interac-

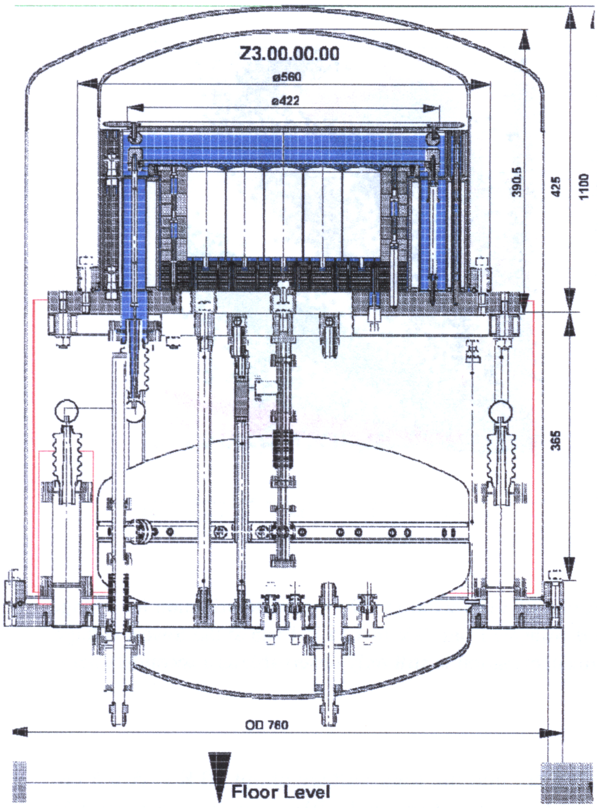

Fig. 5. The Zeplin III Dark Matter Detector.

tions /kg/day for a 2 keV threshold. This figure is consistent with current world-wide objectives in the next three years, but is subject to actual backgrounds to be experienced.

Acknowledgements. PPARC financial support for the development is acknowledged.

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