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Development of Background Discrimination Techniques in Liquid Xenon Cold Dark Matter Detectors

T.J. Sumner[1], D. Akimov[2], A. Bewick[1], D. Davidge[1], A.S. Howard[1], W.G. Jones[1], V. Lebedenko[2], and J.J. Quenby[1]

[1]*Physics Department, Imperial College, Prince Consort Rd., London, SW7 2BZ, UK*

E-mail: *t.sumner@ic.ac.uk*

[2]*ITEP, B. Cheremushkinskaya - 25, Moscow, 117218*

Abstract

Liquid xenon is potentially a very powerful cold dark matter (CDM) detector because (a) it provides good timing discrimination between possible WIMP induced scintillation pulses and the local photon background and (b) it provides good amplitude discrimination in the ionisation signals. We describe development work on light collection, timing and prototype construction of a detector for the Boulby mine CDM array using this technique.

1 Introduction:

The UK Dark Matter Collaboration (UKDMC) is deploying detectors based on scintillation in NaI and scintillation and ionisation in Xe to achieve a sensitivity of < 1 count/day/kg to the scattering of weakly interacting massive particles (WIMPs) in the mass range 10-1000 GeV (see Quenby et al. this conf.). The choice of these target materials is based on use of large mass detectors, coverage of a large WIMP mass range favoured for the lightest supersymmetric particle within MSSM (Roszkowski, 1997), and ease of signal discrimination (Sumner, 1999) between the nuclear recoil type interactions expected for WIMPs and the much more abundant electron recoils associated with background γ-ray interactions. Our NaI detectors use pulse shape discrimination to differentiate the signals. This is also possible in liquid xenon (Jones et al., 1997) and the UKDMC is currently developing a 5kg detector along these lines. The time signature depends on the degree of recombination occurring in the initial interaction region. This will happen much more quickly for high linear density nuclear recoil tracks than for the lower linear density electron tracks initiated by γ-ray interactions. Hence γ-ray (electron) interactions show a longer 'time constant' due to slower recombination. A related effect is that the amount of residual ionisation surviving the recombination will differ and Benetti et al. (1993) showed that combining the primary scintillation signal with a delayed 'ionisation' signal is a much more effective discriminator. Wang (1998) and Akimov et al. (1998) independently proposed using two-phase (liquid/gas) systems where the first (scintillation) signal is provided by photomultipliers viewing the liquid interaction volume, and the second (ionisation) signal is obtained by drifting the ionisation to the liquid surface, extracting it into the gas phase, and then causing electroluminescence in a high field region in the gas volume. The luminescence is then viewed, as a delayed signal, by the photomultipliers. The UKDMC is now collaborating with these two groups to develop its own two-phase detector.

2 Prototype design:

In order to set the final detector design parameters a prototype test chamber is being built. The crucial requirements are for the best possible light collection, a long electron path length against loss, efficient electron extraction across the liquid/gas interface and a high electroluminescent yield. To maximise the light collection the prototype will use two photomultipliers; one immersed in the liquid viewing upwards and one in the gas viewing downwards. Between the two photomultipliers is a variable height electrode stack which sets the electric fields in the liquid and gas phases. The liquid level will be set midway between the top and bottom electrodes with viewports to allow accurate levelling of the system. The detector is cooled from the top by a liquid nitrogen cryostat with a heater embedded in the copper conduction path to control the liquid temperature. The xenon containment chamber and gas handling system are of all stainless steel bakeable construction. Copper sleeves are used to provide the thermal control needed to ensure a uniform temperature throughout the detector volume and for the photomultipliers. The two ETL 9829 2-inch diameter photomultipliers have already been tested at low temperature (see later) and high pressure. Science goals which will be studied with this prototype include establishing the electroluminescent yield in the gas phase for a given energy deposit in the liquid phase, as a function of liquid depth and operating voltages. The light collection efficiency for both the primary scintillation and secondary luminescence will also be studied as a function of liquid depth. In addition the use of reflective surfaces, GEM plates, or other types of readout to replace the photomultiplier tubes will be assessed.

3 Xenon purification system:

Figure 2 shows a purification and liquefaction system already developed for use with a smaller test chamber. The gas handling rig is an all stainless construction pumped using a turbo-molecular pump. It includes a liquid nitrogen trap and mass spectrometer. It has a base pressure of < 10^{-8} torr. A stainless pressure vessel is used to store the gaseous xenon at room temperature and a flexible U-tube acts as a distillation volume during xenon purification. An oxisorb stack provides specific removal of oxygen impurities. Purification cycles include slow distillation and pumping on solid xenon. The test chamber itself has a surrounding vacuum jacket which is pumped using a cryogenic sorption pump. It is only used for scintillation tests at the moment and the ETL 9829 quartz windowed photomultiplier in this small system views the liquid xenon volume through a small inner quartz window. It is sealed into the vacuum flange in the outer jacket. Controlled amounts of xenon gas are admitted into the scintillation chamber using a number of all-metal pressure gauges and calibrated pipe volumes. An additional small chamber is now available which has an electrode structure for measuring electron lifetimes.

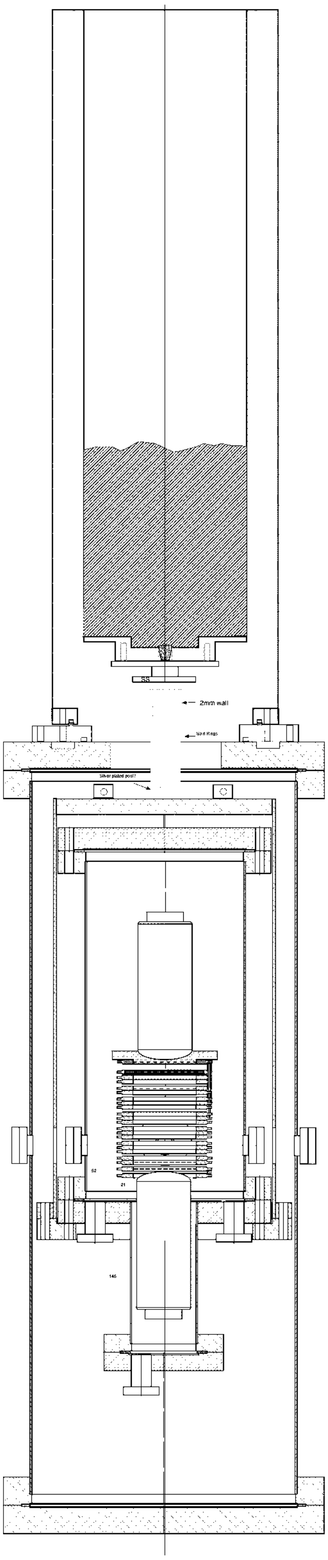

Figure 1: Prototype two-phase test chamber

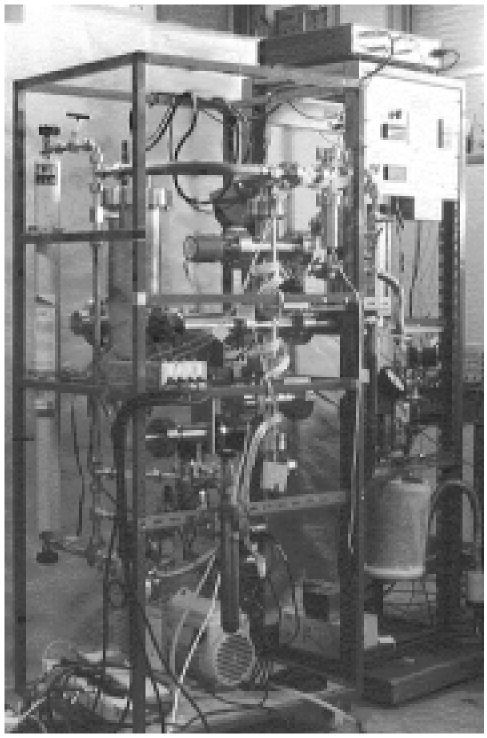

Figure 2: Xenon purification and liquefaction system

3 Development studies:

3.1 Light output and surface reflectivities: The scintillation output from liquid xenon has been measured, using the small test chamber, as a function of depth of liquid by floating a radioactive ^{241}Am source on an aluminium float. Two floats are used; one allows both alphas particles and 60keV γ-rays into the xenon, whereas the other has a thin covering so that only the γ-rays are used. Scintillation spectra are recorded using a pulse-height analyser. The alpha particles are stopped very locally in the xenon and produce a large amplitude peaked spectral distribution (figure 3). The position of the peak is used to study the variation of light collection with xenon depth to evaluate surface reflectivities of chamber wall materials (figure 4). In figure 4 the experimental points shown as solid circles record the variation obtained with an unlined chamber which has an unpolished stainless inner surface. The solid curve is the variation expected purely from solid angle

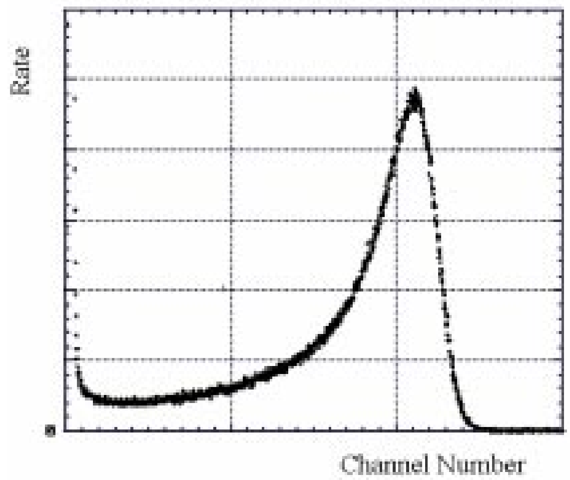

Figure 3: Alpha particle spectrum from 1.7 cm depth of liquid xenon

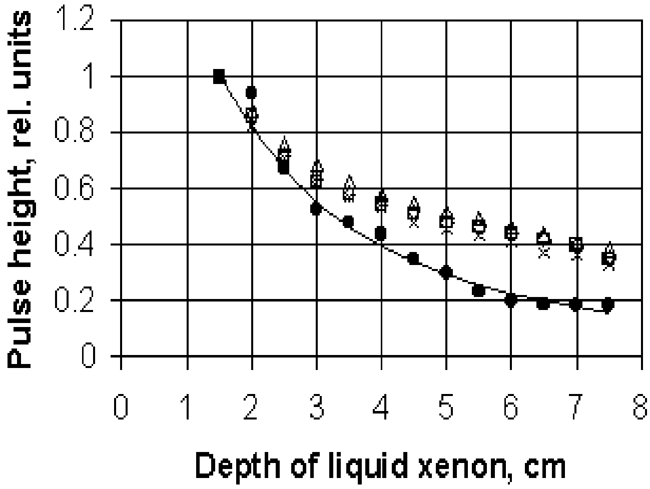

Figure 4: Variation of alpha peak position with depth of xenon

considerations assuming non-reflective surfaces. The other data points show the effect of adding various reflective wall materials and the variation of their effects with depth is an artefact of solid angle and vignetting as the viewing aperture is not the full chamber diameter. Figure 5 shows the spectrum obtained from the 60keV γ-rays. The 60keV photopeak can be clearly seen and resolved as can the single photoelectron peak from the photomultiplier. The additional feature at around channel 125 is probably a combination of the Neptunium line complex and an escape peak from the xenon. The signal amplitude corresponds to 0.15 photoelectrons/keV which converts to a photon output of ~20,000/keV allowing for the viewing solid angle of ~3% and the various window transmission values and the photomultiplier response.

3.2 Low-temperature photomultiplier tests: In order to improve the light collection efficiency we plan to place the photomultipliers in the liquid xenon itself. This imposes two requirements in that they must continue to operate at liquid xenon temperatures (~-100°C) and survive high pressures around 2-2.5bar. We have confirmed high pressure survival up to 4.5bar using a dummy photomultiplier, and ETL can supply photomultipliers proofed to our pressure. To check on the low temperature operation the quantum efficiency (figure 6) and rate response have been tested over a range of temperatures in vacuum. An led was used to provide a standard reference signal in the visible. Our results show that these photomultipliers will be useable for our experiment although we will need to work at a high pressure to keep the temperature in their operating range. Araújo et al. (1997,1998) show similar results from tests on other types of photomultiplier and an interesting feature of their work is an apparent increase in sensitivity for the xenon VUV emission at 170nm, which is partly attributed to improved window transmission at low temperature. We have yet to repeat our test in the VUV. Linearity in pulse counting mode was preserved at low temperature in our tests.

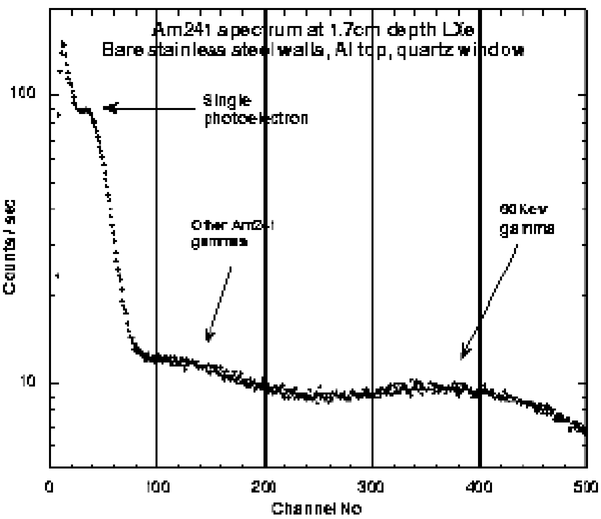

Figure 5: Americium gamma-ray spectrum from liquid xenon

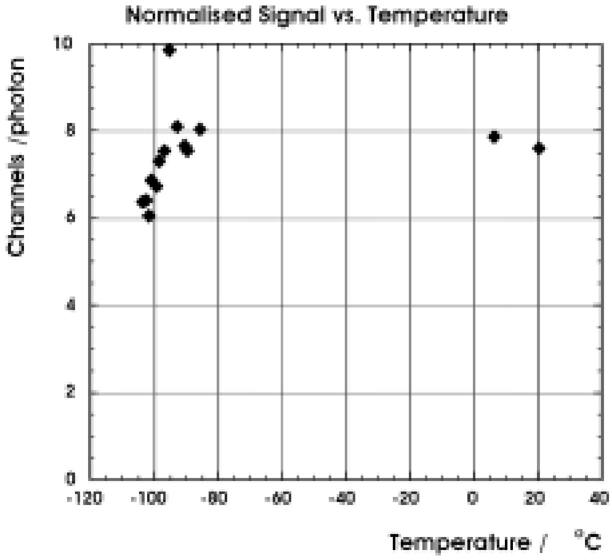

Figure 6: Variation of signal amplitude with temperature for an ETL 9829 PMT

3.3 Pulse shape discrimination: Finally figure 7 shows our measured average pulse shapes for xenon stimulation by ^{241}Am α-particles and ^{60}Co γ-rays. These results are consistent with those measured by other authors (as reviewed in Davies, 1994) but need to be repeated for much lower energies (~10keV). This awaits new reflectors and improved light collection.

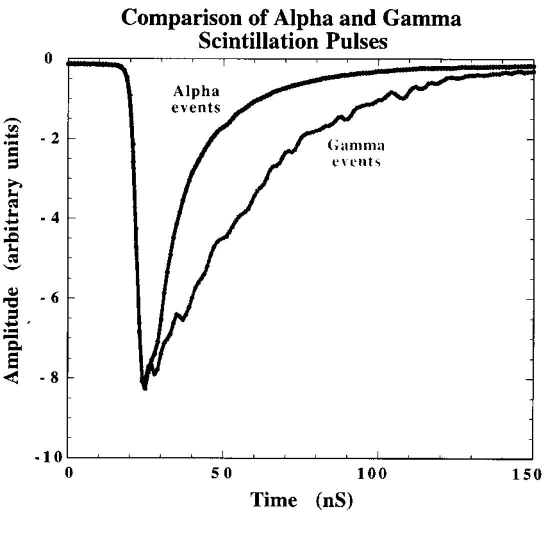

Figure 7: Comparative pulse shapes from alpha particle and gamma-rays

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