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Monte Carlo Studies of ZEPLIN III

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A Monte Carlo simulation of a two-phase xenon dark matter detector, ZEPLIN III, has been achieved. Results from the analysis of a simulated data set are presented, showing primary and secondary signal distributions from low energy gamma ray events.

1. Introduction

ZEPLIN III is a two-phase xenon WIMP dark matter detector currently under construction. Once built it will operate in the Boulby Dark Matter Collaboration facility in the Boulby mine. It is optimised to achieve high discrimination, with a low threshold and an active mass of 7 kg. Figure 1 shows the detector design.

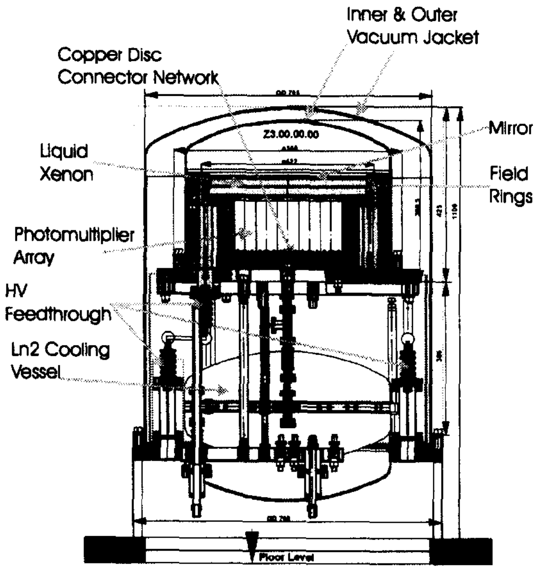

Figure 1. Engineering diagram of ZEPLIN III.

2. Detector Principles

Any interacting particle will produce excitation and ionisation within the liquid xenon target. Fast primary UV scintillation is observed from the excitation and partial recombination of the ionisation. An applied electric field ($\approx$ 8 kV/cm) suppresses a fraction of the recombination by drifting electrons upwards to the gaseous layer. Approximately 95% of the electrons reaching the surface are extracted into the gas. Electroluminescence occurs, giving a delayed broad secondary UV signal as the electrons drift through the gas. Since the ratio of excitation to ionization is indicative of particle energy and interaction process [1], the ratio of primary scintillation to the secondary electroluminescence signal is dependent on the initial particle [7].

3. Monte Carlo Output

ZEPLIN III has an array of photomultiplier tubes within the liquid xenon to observe both primary and secondary UV signals. Figure 2 shows an example of output from a Monte Carlo simulation of ZEPLIN III with 19 photomultiplier tubes. In this event, a single photoelectron is detected in

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tube 19 at 100ns (as shown in the zoomed region). The secondary signal is seen later at 3000ns across all tubes.

The simulation is designed to investigate the gamma ray background due to radioactive decays occuring in the photomultipliers [3]. The liquid xenon depth is 42mm and 5mm for gas. The quantum efficiency of the photomultipliers is 20%. The background rate is estimated to be 9.2 counts kg^{-1} day^{-1} keV^{-1}(dru) including the ZEPLIN III veto and within the fiducial volume [3].

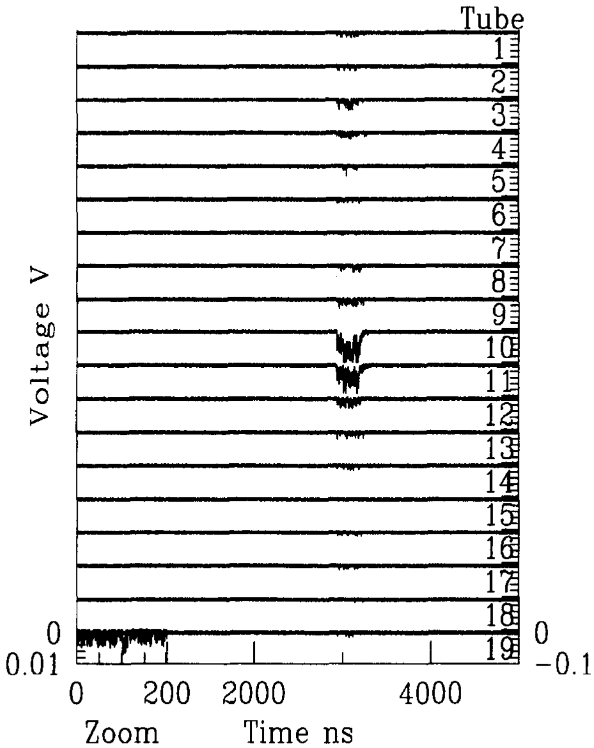

Figure 2. Example output from Monte Carlo simulation with 19 photomultiplier tubes. This event is a 6.5 keV photon. A single photoelectron is detected as the primary scintillation signal in tube 19 shown in zoom(at 100ns). The secondary signal is seen in all tubes at 3000ns.

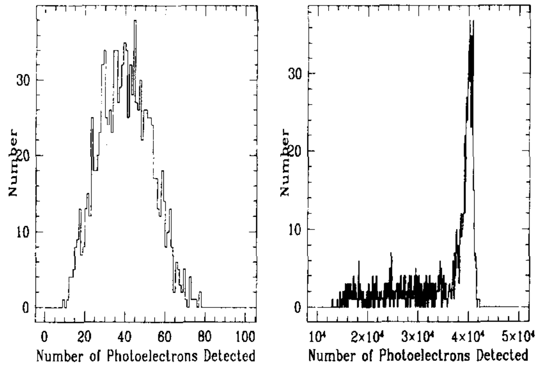

Figure 3. Histograms of the numbers of photoelectrons detected from primary (on left) and secondary signals (on right).

The low energy primary and secondary response distributions are found by simulating 20 keV photon events randomly throughout the liquid volume, see Figure 3. The effect of light collection is the dominant cause of the spread. The mean light collection efficiencies are $40 \pm 5\%$ for the primary signal and $39 \pm 8\%$ with a mode of 45% for the secondary signal within the fiducial volume[4]. The light collection from the gas phase is non-uniform, and decreases from the centre with increasing radius, producing a long tail in the secondary histogram as can be seen in Figure 3. ZEPLIN III will employ a position reconstruction technique to determine the most probable (x,y) event position using the secondary signal. The distribution of detected photoelectrons across the photomultiplier tubes is characteristic of the location of the secondary event. Typically the position of an event can be determined to within 5 mm [4]. Therefore, each secondary signal can be corrected for light collection, eliminating or reducing the long tail of the secondary response distribution.

4. Calibration

With the application of a high electric field, the size of the primary output signal decreases due to the suppression of recombination. This suppression depends on the interaction process, the energy deposited and the strength of the electric field. In this simulation (with an electric field of 8 kV/cm), a 20 keV photon event produces a primary signal equivalent to that of a 9 keV photon event in no field [5]. Conversely, a nuclear recoil event depositing 20 keV visible photon equivalent energy (i.e. including quenching factor) is expected to produce a primary signal similar to that of a no field event; perhaps with only a 5% suppression similar to that observed for alpha particles [6].

The 20 keV photon primary and secondary distributions are used to convert the number of detected photoelectrons to energy. The mode of the primary distribution is 40 photoelectrons which corresponds to 9 keV - recall the electric field is 8kV/cm. The mode of the secondary distribution is 4×10^4 photoelectrons and is set to 11 keV. The sum of primary and secondary now equals the total energy deposited. Using the two calibration factors, the low energy photons are plotted in Figure 4. If nuclear recoil primary signals are assumed to be suppressed by 5%, then a typical distribution is shown as open squares (□) in Figure 4. This calibration assumes that the suppression of recombination is proportional to the number of drifting electrons and hence secondary signal, as observed for 5 MeV alpha particles [6] and ^{207}Bi internal-conversion electrons [2].

The straight line in Figure 4 represents the total energy deposit of 5 keV. Above this energy there is no overlap between the two distributions seen in this simulation.

5. Summary

The majority of the low energy gamma ray background is expected to originate from the photomultipliers of ZEPLIN III. The radioactive decays from the photomultipliers have been simulated and the resulting data set analysed. The expected gamma ray background rate is estimated to be 9.2 dru [3].

A method of calibrating both primary and secondary signals is described and used to show the expected difference between gamma and nuclear recoil events. Future work will be to test this method of calibration with a two-phase prototype detector.

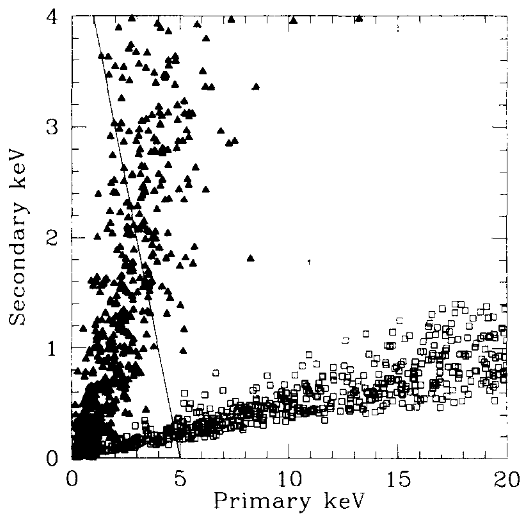

Figure 4. Primary and Secondary calibrated scatter-plot. The filled triangles (▲) are low energy photon events from the simulation of the radioactive decays in the photomultipliers. The open squares (□) are nuclear recoil events assuming 5% suppression of the primary signal. The total visible photon equivalent energy is the sum of both axes for each point. The straight line represents the total energy deposit of 5 keV.

6. Acknowledgements

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