# PULSE-SHAPE DISCRIMINATION IN A MIXED SCINTILLATOR DARK MATTER DETECTOR.

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Results of a study on the reduction of electron recoil induced background in a Dark Matter experiment using range based Pulse-Shape Discrimination techniques are presented. Current progress is reviewed and possible future improvements to the technique are discussed.

## 1 Introduction

Pulse-Shape Discrimination (PSD) in scintillation detectors has been used to discriminate between neutrons and high-energy photons [1] and is now being used in searches for WIMP Dark Matter. Current UK Dark Matter Collaboration NaI detectors use a simple fit of a single exponential function to the digitized integrated scintillation pulse. The fitted time constant of the pulse may be used to discriminate statistically between signal (nuclear recoil) and background (electron recoil) events [2]. Alternative techniques have been proposed involving cooled (160 K) NaI detectors [3] or alternatively organic crystals [4], in which two different decay components are present in the pulse and discrimination is carried out using the ratio of their amplitudes.

Another potentially powerful PSD technique is to make use of the range of the recoiling particle, which is $\sim 10$ times greater for electrons than for nuclei of the same energy [5]. If the Dark Matter target can be segmented on a length scale of the same order as the nuclear recoil range then this range information may be encrypted into the pulse-shape by the use of two different scintillation materials with differing decay time constants $\tau_c$. The resulting pulse then contains two components, the relative amplitudes of which depend upon the nature of the projectile (Figure 1). Hence favourable PSD properties may be engineered into the detector, avoiding reliance upon the (possibly small) pulse-shape differences intrinsic to the scintillation material used.

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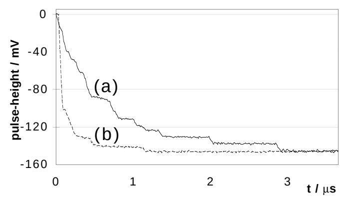


Figure 1: Typical pulses for (a) nuclear recoils within grains and (b) electron recoils.

## 2 The Detector

The detector described here relies upon a technique first proposed by Spooner et al.[6] in which segmentation is achieved by using sub-micron grains of inorganic scintillator suspended in a matrix containing organic liquid scintillator. The requirements for the choice of scintillation materials are that they be of high radiopurity, have high scintillation efficiencies, and have similar refractive indices (r.i.), although very different values of $\tau_c$. The detector material is made by mixing the liquid scintillator with another material of considerably different r.i. in order to match the net r.i. of the mixture to that of the inorganic grains. This ensures that when the grains are added, in addition to some form of suspending gelling agent, the resulting slurry is transparent through the absence of internal reflection at the grain / liquid boundary.

The detector used in this work consisted of grains of Calcium Fluoride $CaF_2$ (Figure 2) suspended in a Dioxan-based liquid scintillator by the addition of a silica gel. $CaF_2$ has a low r.i. (1.44) and large value of $\tau_c$ ($\sim$ 900 ns); the Dioxan scintillator a similar r.i. and a very low $\tau_c$ ($\sim$ 4 ns). Methanol was used to match the refractive index of the liquid to that of the grains. The mean diameter of the grains was found by X-ray diffraction to be $\sim$ 500 nm and a grain volume packing fraction of 10% was used.

The scintillator slurry was held in a 50 mm x 50 mm dia. cylindrical quartz cell wrapped circumferentially in PTFE tape, with an Electron Tubes 9266A 50 mm photomultiplier tube coupled to one end of the cell with optical grease and the other end optically sealed with more PTFE tape. The signal from the PMT was passed into an integrating buffer and thence into a Lecroy 9430 10-bit DSO connected via GPIB to an Apple Macintosh running custom Labview DAQ software. Analysis was performed using in-house IDL routines.

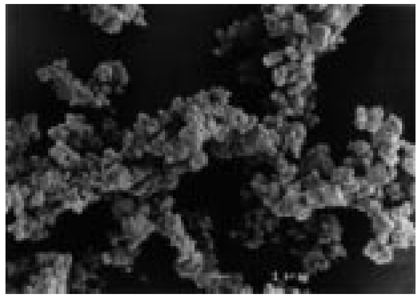

Figure 2: SEM micrograph of $CaF_2$ grains.

## 3 Neutron Scattering Tests

To simulate WIMP events a mono-energetic 5.5 MeV neutron beam at the University of Birmingham Dynamitron facility was used to create nuclear recoils. These were selected by looking for coincidences between detector events and neutron signals observed in NE213 counters, with specific recoil energies being chosen by varying the angle between these NE213 units and the initial beam direction. A more complete description of the apparatus and procedure may be found in Ref.[7] and Ref.[8].

## 4 Results and Discussion

Calibrations with an $^{241}$Am $\gamma$ source were used to determine the response of the detector to electron recoils. Analysis of the data found the scintillation efficiency of the liquid mixture to be $\sim$ 0.45 pe/keV and allowed the event distribution in amplitude-ratio / pulse-height space (Figure 3(a)) to be deduced, where the amplitude-ratio R is defined to be the ratio of the pulse-height of the slow-component to the total pulse-height. The $^{241}$Am photopeak is clearly resolved with a value of R $\sim$ 0.25, consistent with only a small fraction of each electron recoil track passing through the $CaF_2$. A small population of pile-up events is visible at an R of around 1.0.

Figures 3(b), (c) and (d) are equivalent plots for neutrons with scattering angles of $120^o$, $90^o$ and $60^o$ respectively. Considering Figure 3(b), it can be seen that the distribution of events is different from that for the electron recoils. The cluster of events with a pulse-height of around 0.37 V and a low R is due to H recoils, which exceed the maximum measurable pulse-height and appear as events with amplitudes lying around this maximum. The long H recoil range

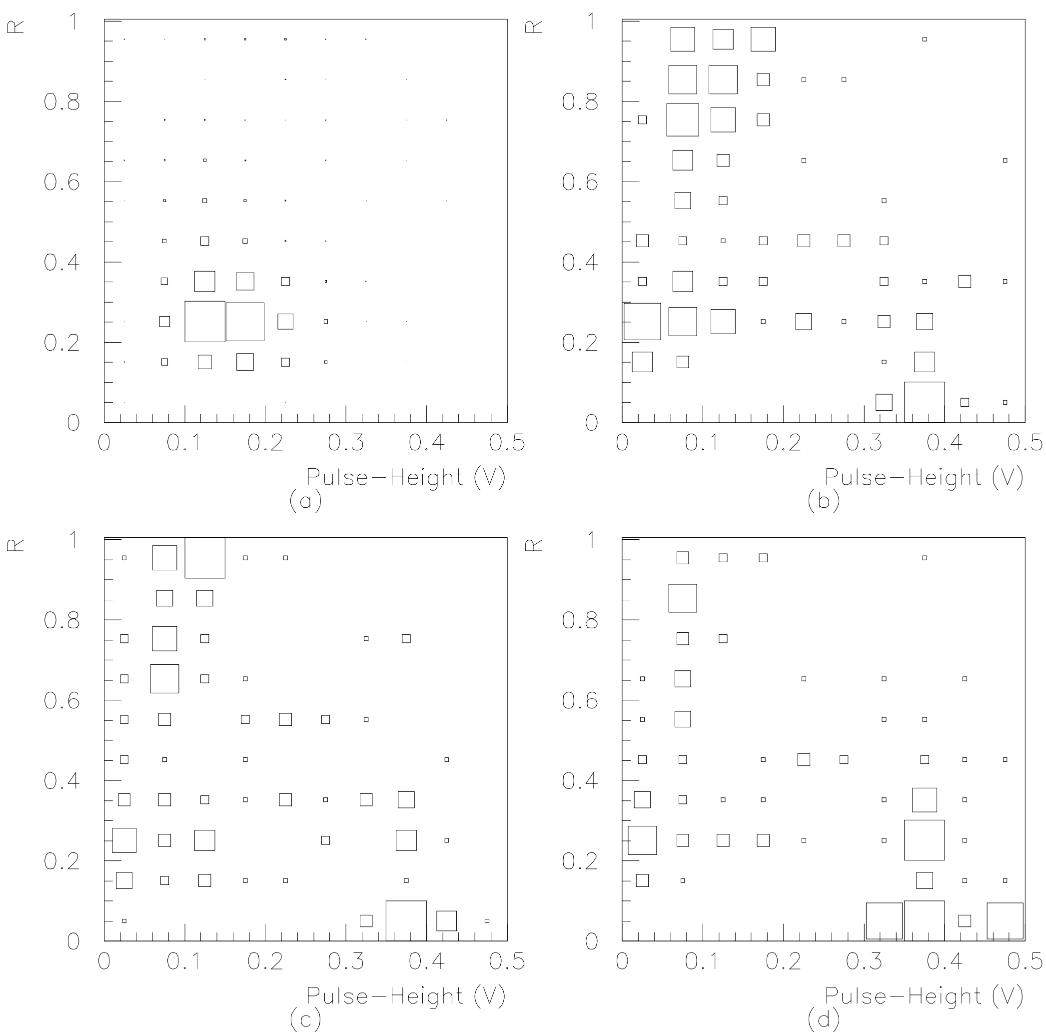


Figure 3: Pulse-height ratio R versus pulse-height (V) for (a) $^{241}$Am $\gamma$ calibration data, (b) 120$^o$ neutron data, (c) 90$^o$ neutron data and (d) 60$^o$ neutron data.

and large pulse amplitude, resulting in only the first part of the pulse shape being recorded before it goes off-scale, gives the extremely low value of R.

The cluster at a pulse-height $\sim$ 0.05 V and an R of 0.25 is consistent with C recoils, which occur within the liquid and so have low R. Given the measured recoil efficiencies of Ca and F of 8% and 12% respectively [7], the more diffuse cluster at R $\sim$ 0.85 and pulse-height between 0.05 V and 0.15 V is consistent with events due to these nuclei recoiling within the grains. These nuclei are expected to provide the best WIMP targets [9] and thus it is this cluster of events which we would expect to correspond to a WIMP signal in an operational detector. A level of discrimination $>$ 90% at 60 keV is achieved between these events and those due to electron recoils, with a corresponding loss of signal events $<$ 5%.

At smaller scattering angles we expect to see the clusters move to lower energy and to see their densities reduced relative to the H clusters, as the distributions are depopulated by the trigger threshold of 2 pe/channel. This behaviour can be seen in Figures 3(c) and 3(d).

Several further points relevant to the application of this detector to a WIMP experiment are revealed by this data. Firstly, electron recoils occurring entirely within grains are so rare that in order to calibrate the scintillation efficiency of the $CaF_2$ neutrons must be used rather than photons. Secondly, owing to the presence of H nuclei in the detector it may be possible simultaneously to monitor any possible neutron background since this is likely to contain a population of neutrons of sufficiently low energy to cause H recoils with a continuous low-energy distribution. These may travel mainly through a single grain, mainly through the liquid, or through both and this in turn may lead to a 'washing-out' of the event distribution in R such that no isolated cluster is observed at R $\sim$ 1.0 . This hypothesise has been tentatively confirmed by tests with a Cf fission source, in which the discrimination between neutron and gamma events was considerably worse than in the tests described here.

## 5 Future Plans

The results obtained thus far indicate that this class of range-based detector has the potential to give good levels of discrimination ($>$ 90%) at energies greater than $\sim$ 20 keV electron-equivalent. In order to take advantage of the predicted exponential rise in WIMP event rate towards lower energy it will be necessary to decrease the energy threshold to below $\sim$ 5 keV. This will require considerably increased light-output and also the ability to produce grains of diameter $\sim$ 100 nm. These problems, and also that of the poor radiopurity of $CaF_2$, may be addressed by the chemical production of powder using radiopurified precursors and the addition of Eu as a doping material.

A number of further improvements are possible. We intend to remove the buffer circuit used to integrate the signal from each PMT, as this limits the minimum measurable $\tau_c$ of the pulse to $\sim 22$ ns, which is an order of magnitude greater than that of the organic scintillator and limits the PSD efficiency. Neural network pattern recognition techniques may be used to analyse the data in order to extract the maximum amount of useful information from each pulse and this in turn will require detailed monte carlo simulation of the detector.

## 6 Conclusions

We have demonstrated that the technique of range-based PSD with an organic / inorganic scintillator mixture is an interesting new possibility in the hunt for a superior detector for WIMP Dark Matter. The results indicate that levels of discrimination $> 90\%$ at low energy may be achievable with further improvements.


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