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Pulse Shape Discrimination In NaI And Applications To Cold Dark Matter Detection

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Abstract NaI scintillators are used as cold dark matter (CDM) detectors relying on pulse shape discrimination to separate x-ray and gamma-ray background induced pulses from possible CDM weakly interacting massive particle (WIMP) nuclear recoil events. So far, most techniques have used simplified approximations to the actual pulse shapes. A potentially better way is to analyse the pulses in terms of the fundamental decay rates of the metastable states electron/hole diffusion times. This involves fitting three decay time constants and two amplitudes. Results of using this new techniqueare presented.

1. Introduction

Direct experimental search for a possible WIMP (weakly interacting masive particle) dark matter component, most likely the ground state supersymmetric particle, (eg the photino) as the dominating source of galactic gravity has invovlved sophisticated analysis of underground NaI crystal detectors. The key point is that the expected WIMP-ordinary matter interaction rate is significantly less than one/kg/day and any practical detector, however well shielded, is subject to residual radioactivity in the apparatus. Radioactivity due to beta decay and Compton interactions of gammas is partially distinguished from WIMP type interactions, which are like the recoils induced by neutrons, employing pulse rise time discrimination (Quenby et al., 1996, Smith et al., 1996). While use of this technique has allowed the limits to be significantly reduced, the presence of an apparent population of anomalous rise-times which seem to correspond neither to neutron/alpha or electron induced events, has cast uncertainty on the ultimate sensitivity achievable (Smith et al., 1998, Gerbier et al., 1999). In the following, a new analysis of pulses based on UK Dark Matter Collaboration NaI results is given using a three time constant fit, motivated by the solid state physics process of the scintillation mechanism. The cause of the anomally is assessed under this analysis.

2. Single and Triple Time Constant Analysis

The data was obtained 1100 m underground in the Boulby mine with a 5 kg NaI(Tl) crystal viewed by two 125 mm PM tubes via 18 cm silica light guides, stabilised at $11^\circ \pm 0.5^\circ$ and surrounded by a 6m dia, 6m deep purified water tank. The photo-electric yield was 3.1 photons/keV. Published results were based on a single rise-time analyis employing $f(t) = A(1-exp-(t-t_\circ)/\tau)$. The free parameters, A, τ and $t_\circ$ were fitted to each pulse. It was found that a gamma-ray calibration produces a time constant averaged over the energy range 20-60 keV of 360 ns mean but a small but distinct population of shorter time constants appeared at a mean of about 230 ns, close to the neutron calibration peak (Smith et al., 1998, Quenby et al., this conf.). Both neutron and gamma time constants shorten as the 4 keV threshold is approached, but there is enough difference maintained that a statistical discrimination is possible demonstrating that the background is likely to be electron track induced. The anomalous pulses do not appear to stand out in the gamma calibration. Investigation with a smaller crystal suggests a time constant for the anomalous events still significantly shorter than for alpha particle or neutron induced events (Kudryavtsev et al., 1999).

Indication that a single time constant analysis is insufficient representation of the scintillation process comes from Barton, Blair and Edgington (pre-print). These authors fitted NaI scintillation pulses via the Gatti technique to

$$f(t) \propto (1 - e^{-t/u})(1 + at^{1/2})e^{-t/v} + be^{-t/w}) \tag{1}$$

The parameters u, v and w describe the initial rise, the first fast and the subsequent slow decay while the factor $1 + at^{1/2}$ describes the shape near maximum and can plausibly be associated with diffusion. u,w and w appear to be constants for a particular crystal while a and b vary according to whether the energy loss is due to alphas or betas. We interpret the above equation as due to the two metastable states typical of an alkalihalide. Consider one impurity state close to the valency band. Electron excitation to a near conduction band bound state can arise either directly or by making an exciton somewhere which diffuses to the impurtity centre or causing an electron-hole pair which move until the electron or hole are captured respectively in the upper or lower impurity bands. Scintillation occurs after lattice vibrations move the metastable level to the minimum in the excitation configuration and the subsequent energy loss as the electron jumps levels is less the the size of the initial gap. We see that two decay time constants and a third, diffusion time are expected. Clearly, neutron like recoils favour the shorter time constant as compared with electron induced events and this must depend on the relative number of excitons and electron-hole pairs produced.

3. Results Of A Triple Time Constant Fit

We establish appropriate u,v and w values for our crystal by finding mean pulse shapes for the gamma and neutron calibrations separately. Neutron calibration with a Californium source actually provides a similar number of gamma rays and this contamination should be remembered when interpreting results. A least squares fitting procedure was then carried out to an integral form of equation 1 by varying each parameter separately. The results for a subset of 40-60 keV energy losses;

Gamma calibration; u=25ns, v=205ns, w=445ns

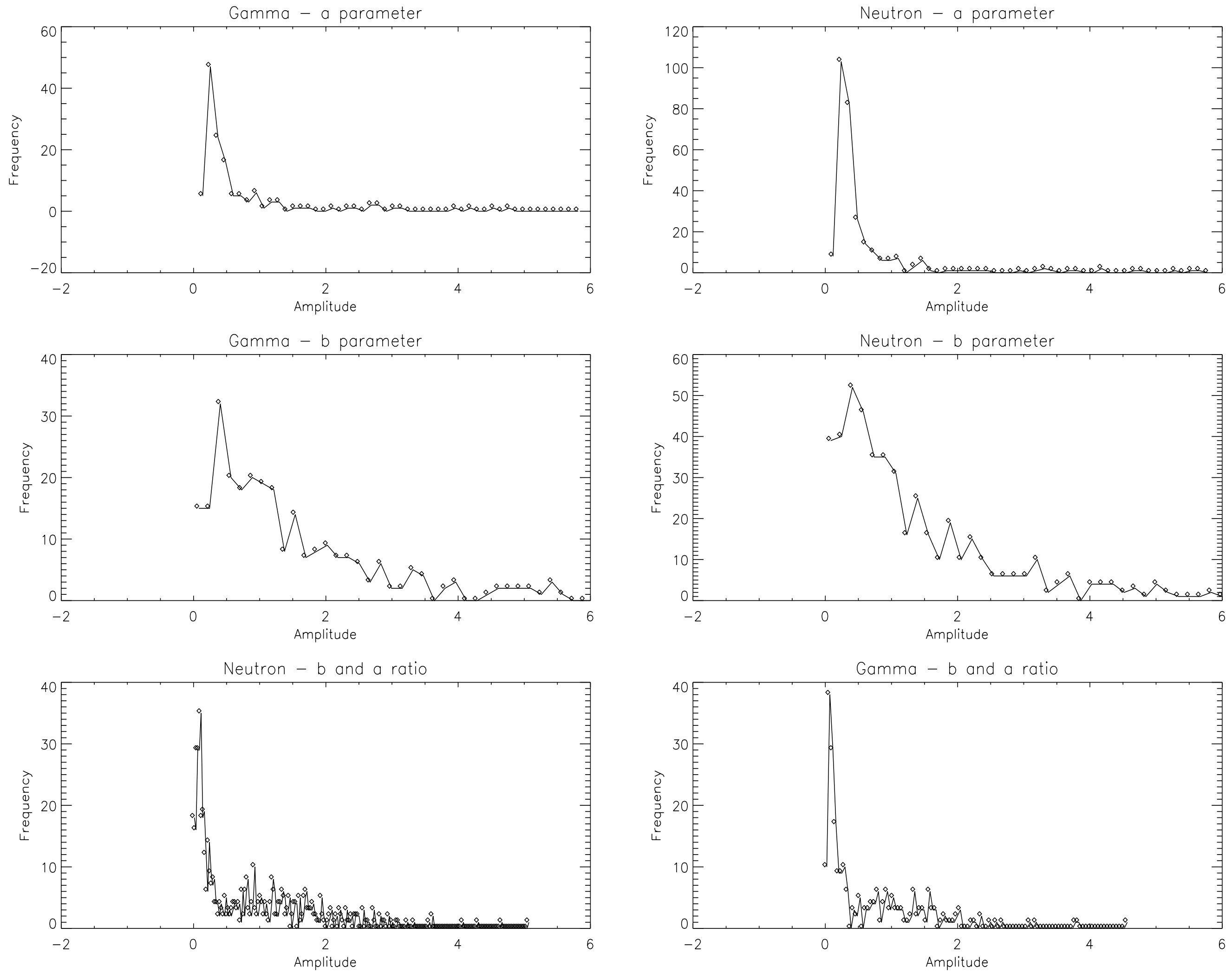
Neutron Calibration; u=25ns, v= 200ns, w= 400ns

The expected similarity of these crystal constants is observed.

Each pulse of the subsets are then fitted separately, first renormalising to the actual instead of mean amplitude and then finding the best fit a and b values. Pulse data was cut at 1500ns because after pulsing and electronic time constants brought in various distortions to the basic crystal scintillation input. The results are shown separately in the figure for the two calibrations where we see the distributions of a and b values, their ratios for a particular calibration source and finally the a to b ratios for neutron and gamma calibration compared. We see there are relatively more lower a/b values in the gamma calibration, corresponding to the greater importance of the shorter time constant in the neutron case and hence the lower single rise time fit seen for recoils. The large overlap of the a/b ratio distributions is due to the admixture of gammas and neutrons from the neutron calibration. The investigation so far, of limited statistical weight, goes to confirm our explanation of the discimination scheme under the Barton et al analysis.

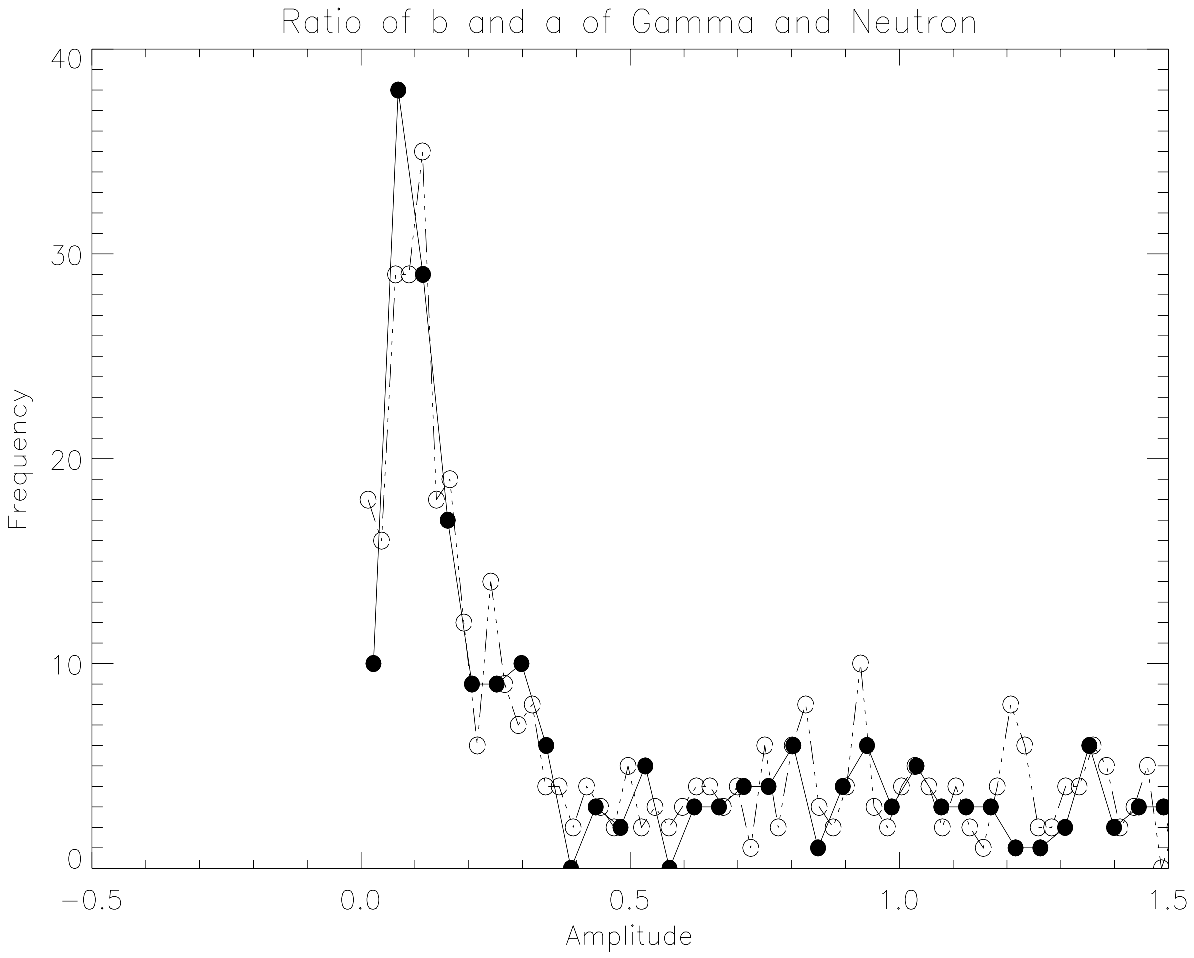
4. Qualitative Explanation Of The Anomalous Rise Times

The major source of background in a well-shielded underground NaI crystal viewed by two PM's in coincidence at low energy losses around the detector threshold is due to coincidence photoluminescence pulses. Without coincidence counting, these single photon events completely swamp all other effects below about 15 keV with the Boulby 5 kg detector. Its exact origin requires further investigation and since it is not necessarily just confined to the central crystal, some large apparent energy losses are possible. We hypothesize that it arises from the high energy tail of the ambient black-body distribution exciting the impurity centres. Experimentally, we have seen that the more distributed electron energy loss process favours the ”w” time constant relative to the ”v” time constant in contrast to the more confined



recoil process. Because we believe that the coincidence background is actually due to single photon photoluminescence, rather than a distribution of photons and excitons,it is reasonable to suppose that the shorter time constant is even more heavilly favoured than the longer time constant. Thus a distinct population of anomalous pulses, apparently shorter than given by neutron recoils when subject to single rise-time analysis, is likely to appear.

If our hypothesis is correct, it is reasonable to subtract the ’anomalous ’pulse set from the background data when deriving a dark matter upper limit. It is neccesary, of course, to confirm the hypothesis with a triple time constant analysis of single PM background above the detector threshold.



5. References

G. Gerbier et al., Astroparticle Phys., to be publ., (1999).
V. Kudryatsev et al., Phys lett. B (to be publ.)
J.J. Quenby et al., Astroparticle Phys., 5 (1966), 249.
J.J. Quenby et al., This Conf.,
P. F. Smith et al., Phys. lett., B, 379 (1966), 299.
P.F. Smith et al., Phys. Rep., 307 (1998), 275.