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Investigation of pulse shapes and time constants for NaI scintillation pulses produced by low energy electrons from beta decay

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Abstract

The scintillation pulse shape in NaI crystals of electrons from beta decay is investigated, as a possible explanation of anomalous pulses seen in dark matter searches based on NaI detectors. The pulse shapes and time constants from beta decay electrons are found not to be significantly different from recoil electrons from Compton scattering and thus do not account for the anomalous shorter pulses. © 1999 Published by Elsevier Science B.V. All rights reserved.

1. Introduction

This work forms part of an investigation of unidentified anomalous pulses observed in low background sodium iodide detectors, running underground in a search for weakly interacting massive particles as a component of the Galactic dark matter.

Such particles would produce low energy nuclear recoils (majority < 50 keV) which could in principle be distinguished from gamma and beta background by the different pulse shape and time constant of the scintillation light. At higher energies, this difference in time constant has been used for 40 years (see, for example, [1–3]) as means of discriminating between gammas and alpha particles. At lower energies, in particular below 30 keV, discrimination becomes more difficult due to a decreasing difference between the time constants and an increasing spread in the measured values (from the smaller number of photoelectrons). Thus at low energies the time constant distributions overlap but the presence of a population of events of different time constant can still be extracted statistically.

The low energy pulse shapes and time constants for nuclear recoils can be observed by using neutrons (from a neutron beam or portable source) to produce the nuclear recoils, and gamma sources to produce electron recoils by Compton scattering. Typical averaged pulse shapes at a selected energy are shown in Fig. 1 (see also [4]). The absolute time constants vary somewhat with temperature and crystal, but the ratio of the decay time constants of nuclear recoil

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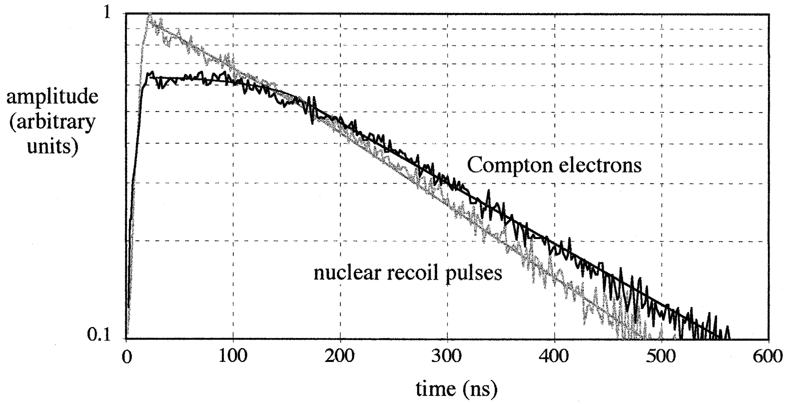

Fig. 1. Averaged pulse shapes (from 1000 pulses) for interactions in Tl-doped NaI crystal. Dark curve: 60 keV Compton electrons from gamma interactions. Light curve: 60 keV (electron-equivalent energy) Na recoils from neutron scattering. Smoothed fits are also shown. The Na recoils may include a small admixture of gamma events, causing the small departure from exponential shape at short times.

pulses and gammas is found to be approximately constant at 0.74 ± 0.03 for energies above about 20 keV.

Using this difference, the UK collaboration was able to set limits for WIMP interactions which were factors 10–40 below the gamma background in the energy range 5–25 keV, using a water-shielded 5 kg NaI crystal assembly in the 1100 m deep Boulby Mine [5]. Subsequently a further reduction in limits, using a larger target mass, was reported by the Rome group [6]

2. Anomalous pulses

By 1998, improvements to the UK system, based on ±0.1 K temperature stability and improved light collection and resolution, yielded data with an order of magnitude gain in sensitivity to nuclear recoil pulses. This could not, however, be translated into improved dark matter signal limits, owing to the presence of a population of pulses with time constant shorter that of gammas, and also apparently shorter than that expected for nuclear recoils [7,8]. A typical observed distribution of fitted time constants, for the energy range 50–70 keV is shown in Fig. 2, together with that obtained for Compton calibration pulses from a ^{60}Co gamma source. This and subsequent distributions in this paper are plotted as a function of the normalised time constant variable $\tau_n = \tau/\tau_{\gamma \mathrm{peak}}$

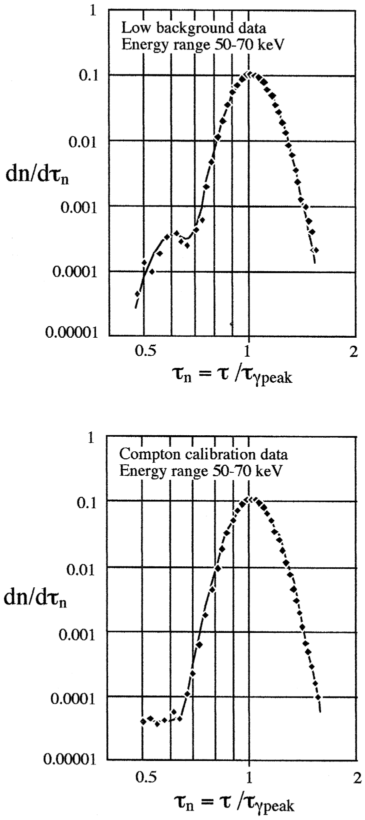

Fig. 2. (upper plot) Pulse time constant distribution from low background NaI crystal in 1100 m deep Boulby Mine, showing additional distribution of shorter pulses [4]. (lower plot) Pulse time constant distribution from Compton calibration data in the same energy range, obtained by irradiation with ^{60}Co source.

, where τ is the fitted time constant for an individual pulse and $\tau_{\gamma \text{peak}}$ is the time constant corresponding to the peak of the (log gaussian) time constant distribution for the ^{60}Co calibration. This normalisation is to eliminate variations in absolute time constant with temperature and crystal. The ratio of the mean anomalous time constant to the mean gamma time constant is in the range 0.62 ± 0.03, compared with 0.74 ± 0.03 for nuclear recoils from neutron scattering. These anomalous pulses are present at energies up to at least 80 keV, forming an spectrum of decreasing amplitude, and we have subsequently seen these at a similar level in other crystals, including two higher resolution crystals with different housing and shielding materials.

The anomalous pulses are randomly distributed in time, and have the pure exponential shape characteristic of nuclear recoils rather than gammas which have an initial flat region (Fig. 1). It was conjectured that these pulses may be due to alphas, but since the usual alphas produced within the crystal by Th and U contamination are in the MeV range, there appears no natural explanation for a significant population of alpha pulses in the keV energy range. A laboratory experiment to simulate keV-range alphas entering the crystal surface from external contamination gave an average time constant which appeared to be significantly higher than the anomalous pulses [9].

3. Investigation of beta decay pulses

The crystal background also includes a significant number of beta decay pulses from the U and Th decay chains, which when summed form a falling energy spectrum similar in form to that observed for the anomalous pulses (see table 14.3 in [10]). Since beta decay pulses are due to electrons emitted from the nucleus, these would be expected to interact with the NaI crystal essentially identically to the recoil electrons of the same energy from Compton scattering, and hence should give pulses of the same time constant (since the accompanying nuclear recoil energy would be negligible). However, this does not appear to have been previously confirmed experimentally. We have therefore carried out a direct test of this by exposing NaI crystals to betas from ^{90}Sr.

Two similar experiments were carried out, independently by the RAL and Sheffield groups. Unencapsulated Tl-doped NaI crystals were used, 2 cm × 2 cm × 2 cm, in one case immersed in paraffin and in the other case in vacuum. They were observed by two photomultipliers, and the ambient gamma background rate was measured. A ^{90}Sr source was placed under the crystal, giving a factor 20 increase in count rate below 100 keV. This ensured that 95% of the counts in the energy range < 100 keV were due to betas from the source. Scintillation pulses which triggered both photomultipliers were digitised and recorded. The Sr source was removed and similar data taken with gamma and neutron sources. Energy calibration was carried out with a ^{57}Co gamma source. Measurements of time constants covered the energy range from 2 keV to 100 keV.

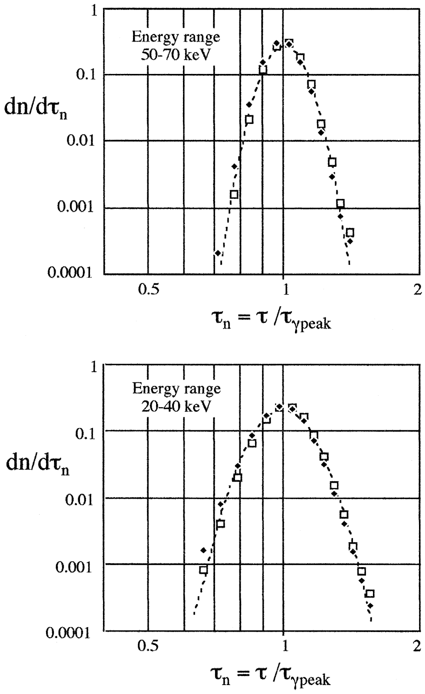

Fig. 3. Comparison of time constant distributions for beta interactions (filled points) and gamma interactions (open points), normalised in each case to the peak of the gamma distribution, showing the beta and gamma pulses to have the same absolute time constant distribution. No significant differences were found in any energy range.

4. Results and conclusions

Simple exponential fits were made to the digitised pulses to give an effective decay constant τ for each pulse, and the differential number distribution ($\mathrm{d}N/\mathrm{d}\tau$ versus τ) of the pulses determined for selected energy ranges of a few keV in width. The width of the $\mathrm{d}N/\mathrm{d}\tau$_distribution arises from Poisson fluctuations in number and emission time of the individual photoelectrons. The distributions were found to be gaussian in $\log(\tau)$ with a width w decreasing with increasing number of photoelectrons, as previously observed [4]. The conclusions were as follows:

(1) The time constant distribution of beta pulses agreed, in both mean time constant and width, with the time constant distribution of gamma pulses of the same energy. This is shown in Fig. 3 for two energy ranges. The precision of the agreement is 0.5%. There was no indication of an additional population of pulses at shorter time constants.

(2) The average pulse shape of the betas was similar to that of the gamma pulses in Fig. 1 – i.e. they had the characteristic initial flatter portion, rather

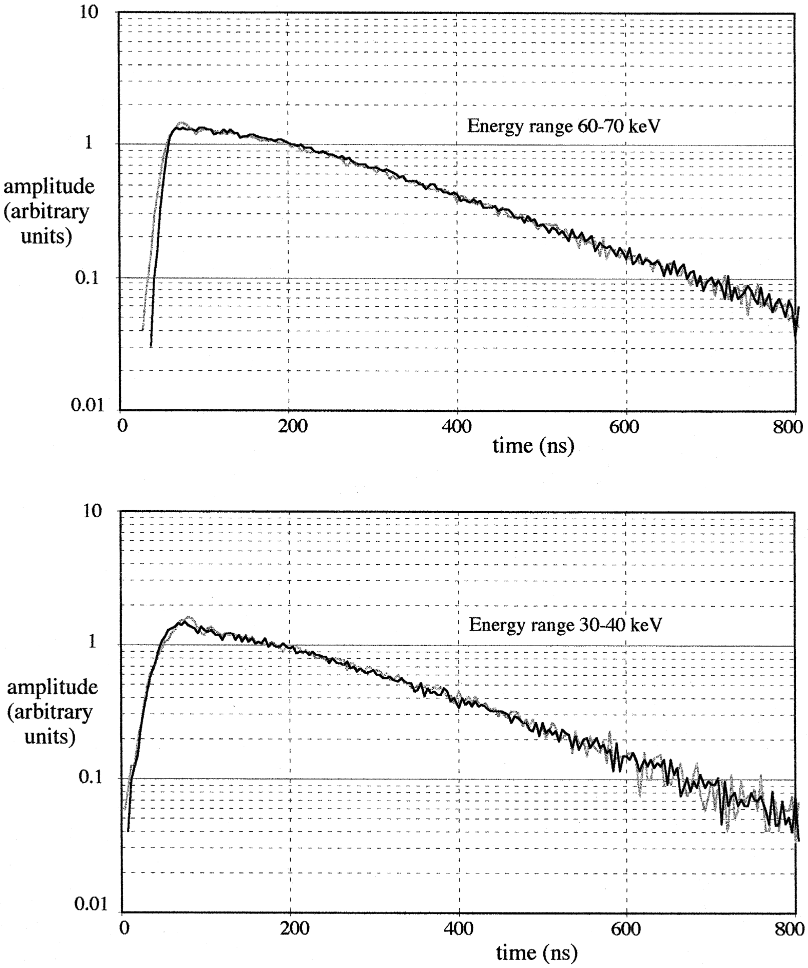

Fig. 4. Comparison of average pulse shapes for beta interactions (light curves) and gamma interactions (dark curves). Differences were negligible ($< 0.5\%$) at all energies.

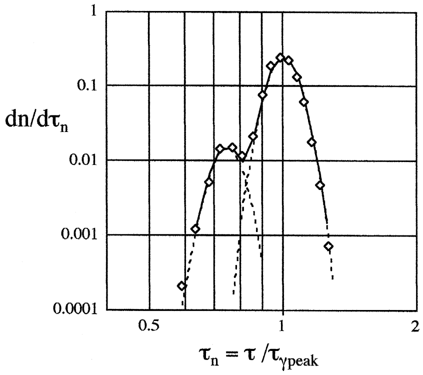

Fig. 5. Distribution of time constants for a mixture of Compton electrons from gamma interactions, and nuclear recoils from neutron scattering, for the electron-equivalent energy range 40–60 keV, again normalised to the peak of the Compton distribution. The points are fitted by two log gaussian distributions of different mean time constants and the same (logarithmic) width.

than the pure exponential form of nuclear recoils. This is shown in Fig. 4. Differences in noise levels affect the initial 10–20 ns pulse rise region but this introduces no more than 0.5% error in the comparison. Our measurements are also consistent with a previous conclusion [9] that the time constant of pulses induced by 60 keV X-rays (from Am–Be) does not differ significantly from the time constant of Compton electrons of the same energy.

(3) The Am–Be neutron source produced a population of nuclear recoils at ~ 0.75 of the gamma time constant, as in previous tests, together with a population of Compton gamma pulses (arising from background and from the accompanying 4.4 MeV gammas from the Am–Be). This is shown in Fig. 5.

Similar results and conclusions were obtained from the two independent sets of tests by the RAL and Sheffield groups, using different crystals (which included the crystal also used for previously-reported alpha particle tests [9]). No evidence was found for a significant difference between the pulse shapes arising from beta decay or Compton scattering, and no second population of pulses with shorter time constants was produced by the beta source.

We therefore conclude that beta decay events do not account for the populations of anomalous short pulses seen in the underground NaI detectors [1].

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[1] After completion of this paper, results have been published by Gerbier et al. [11] which appear to differ from those reported here, showing some differences between beta and gamma pulse shapes. The origin of this discrepancy requires further investigation. However, the magnitude of the differences would still be insufficient to account for the much shorter time constant of the unidentified anomalous events, the existence of which is also confirmed in [11].