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Characteristics of Alpha, Gamma and Nuclear Recoil Pulses from NaI(Tl) at 10-100 keV Relevant to Dark Matter Searches

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Abstract

Measurements of the shapes of scintillation pulses produced by nuclear recoils, alpha particles and photons in NaI(Tl) crystals at visible energies of 10-100 keV have been performed in order to investigate possible sources of background in NaI(Tl) dark matter experiments and, in particular, the possible origin of the anomalous fast time constant events observed in the UK Dark Matter Collaboration experiments at Boulby mine [1]. Pulses initiated by X-rays (via photoelectric effect close to the surface of the crystal) were found not to differ from those produced by high-energy photons (via Compton electrons inside the crystal) within experimental errors. However, pulses induced by alpha particles (degraded from an external MeV source) were found to be $\sim 10\%$ faster than those of nuclear recoils, but insufficiently fast to account for the anomalous events.

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Keywords: Scintillation detectors; Dark matter; WIMP; Radioactive sources; Pulse-shape discrimination

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1. Introduction

Several NaI-based experiments searching for Weakly Interacting Massive Particles (WIMPs), as possible constituents of galactic dark matter, use pulse-shape discrimination to separate the nuclear recoil signals expected from WIMP elastic scattering from electron recoils due to gamma background (see for example [2, 3, 4]). The feasibility of this technique arises because pulses initiated by nuclear recoils in NaI(Tl) are known to be typically 30% faster than those due to electron recoils [3, 5, 6]. In each case the integrated scintillation pulses can be adequately fitted by assuming an exponential decay of time constant τ . The resulting distribution of τ , can be approximated by a gaussian in $\ln(\tau)$. The shape of the pulses can then be characterised by the mean value of τ , τ_o , in the gaussian [3]. The difference between τ_o values for nuclear and electron recoils is of the order of 30% for measured energies above 20 keV, decreasing almost to zero at 2 keV. This difference, divided by the distribution width, is a measure of the discrimination which can be improved by optimising the crystal operating temperature [1].

Assuming operation of the technique at energies higher than ~ 4 keV [1, 3] then, apart from gammas, other potential sources of background are neutrons and alpha particles. Neutron interactions are expected to yield events indistinguishable from WIMP interactions (hence neutrons are usually used to determine the response of NaI to nuclear recoils since neutron scattering on nuclei is similar to WIMP scattering in terms of nuclear recoil generation). However, neutron background can be sufficiently suppressed by shielding the detectors from neighbouring radioactivity and using deep underground sites to avoid neutrons from cosmic-ray muons. In the case of alpha particles any background at low energies cannot arise from the likely small contamination of uranium and thorium in NaI(Tl) because the alphas from uranium and thorium decay chains have energies exceeding 1 MeV. However, high energy alphas from activity in surrounding materials potentially may penetrate into the crystal and deposit energy in the surface layers. Their path in the sensitive surface layer of a crystal, and hence their energy deposition, can then be small depending on the point of their production. Thus such alphas could be responsible for background events and may be responsible for the anomalous fast time constant events (pulses faster than recoil-like pulses) observed in UKDMC NaI(Tl) experiments undertaken at Boulby mine [1, 7].

In this paper we report characterisation of the shape of pulses induced by neutrons, alphas and electron recoils in NaI(Tl) in order to investigate possible sources of background in NaI(Tl) dark matter experiments. Similar measurements have been performed previously in NaI(Tl) (see, for example, [2, 3, 5] and references therein). However, presented here are results obtained with a single NaI(Tl) crystal at low energies (10-100 keV), allowing direct comparison of the pulses induced by the different particles in the energy range of prime interest for dark matter experiments.

2. Experimental set-up and analysis technique

Measurements were performed using a Hilger Analytical Ltd. unencapsulated NaI(Tl) crystal of dimensions 2 inch x 2 inch diameter cooled, using a purpose-built copper cryo-

stat, to 11°C with control so that variation did not exceed 0.5°C. Further details of the apparatus can be found in [8, 9]. The temperature chosen was close to that of the crystals used in the UK Dark Matter Collaboration (UKDMC) experiments at Boulby mine [1, 7]. The crystal was viewed through a pair of silica light guides by two 3-inch ETL type 9265 photomultiplier tubes (PMTs). Integrated pulses from the PMTs were digitised using a LeCroy 9430 oscilloscope driven by a Macintosh computer running Labview-based data acquisition software identical to that used with the UKDMC dark matter detectors. The digitised pulse shapes were passed to the computer and stored on disk. For the final analysis the sum of the pulses from two PMTs was used. The apparatus was found to yield a total light output corresponded to ~ 5.5 photoelectrons/keV.

Energy calibrations for the tests were performed with a ^{57}Co gamma source (122 keV). A ^{60}Co gamma source was used to obtain pulse shapes from high-energy gammas. These gammas undergo Compton scattering inside the crystal producing electrons which deposit energy measured by the detector. To measure the shapes of the integrated pulses induced by nuclear recoils (sodium and iodine), the crystal was irradiated by neutrons from a ^{252}Cf source. Neutron energies were decreased by shielding the source with a 4 cm thick lead block. All aforementioned sources were placed outside the copper vessel containing the crystal, light guides and PMTs. An ^{241}Am source was used to irradiate the crystal with alpha particles. However, since the path length of alphas does not exceed tens of microns the source was attached to the bare cylindrical face of the crystal inside the cryostat. To decrease the energy of the alphas down to the keV range of interest a few, thin ($\sim 10 \mu\text{m}$), layers of plastic were placed between the source and the crystal. The 60 keV gamma-line from the ^{241}Am source also allowed independent energy calibration of the detector and measurement of the shape of the pulses initiated by electrons near the crystal surface. Such electrons are produced via the photoelectric effect.

Analysis was performed, using the procedure described in [3], by fitting an exponential to each integrated pulse to obtain the index of the exponent, τ - faster pulses (due to nuclear recoils, for example) having smaller values of τ , than slower pulses such as from gammas. For each experiment histograms were generated of the number of detected events versus the value of τ - referred to here as τ -distributions. The τ -distributions are known to be dependent on the measured energy. To reduce such dependence the energy range (0-100 keV) was subdivided into energy bins of 10 keV width. We note that the energy threshold was about 10 keV. As shown in [3] (see also references therein) the τ -distribution for each population of pulses can be approximated by a gaussian in $\ln(\tau)$ (for a more detailed discussion of the distributions see [8] and references therein):

$$\frac{dN}{d\tau} = \frac{N_o}{\tau \sqrt{2\pi} \ln w} \cdot \exp \left[\frac{-(\ln \tau - \ln \tau_o)^2}{2(\ln w)^2} \right] \quad (1)$$

The τ -distributions were fitted with a gaussian in $\ln(\tau)$ with several free parameters as follows. In the case of events from the ^{60}Co gamma source a 3-parameter fit was used with free parameters τ_o , w and N_o . In the experiments with the ^{252}Cf neutron source both neutrons and gammas (from the source as well as from local radioactivity) were detected. The resulting τ -distribution can thus be fitted with two gaussians. However, the parameters $\tau_{o\gamma}$ and w for events initiated by gammas (effectively by Compton electrons) are known from experiments with the ^{60}Co gamma source. Assuming the value of w (called

the width parameter) for the neutron distribution (where the pulses are due to nuclear recoils) is the same as that of the gamma distribution, since the width is determined mainly by the number of photoelectrons, again a 3-parameter fit can be applied. In this case the free parameters are: number of neutrons, N_{on} , number of gammas, $N_{o\gamma}$, and the mean value of the exponent for the neutron distribution, τ_{on} . In practice, for direct comparison of the gamma distributions obtained with different sources, the τ -distribution of gamma events measured with the gamma source was used, instead of the gaussian fit, to approximate the distribution of gamma events measured with the neutron source.

In experiments with the alpha source both alphas and gammas were detected. To approximate the resulting distribution, we again used the τ -distribution of the gamma events measured with ^{60}Co gamma source and a gaussian fit to the alpha distribution with 3 free parameters: number of alphas, $N_{o\alpha}$, number of gammas, $N_{o\gamma}$, and the mean value of the exponent of the alpha distribution, $\tau_{o\alpha}$. Furthermore, by making use of the 60 keV X-rays from the ^{241}Am alpha source it was also possible to evaluate τ_{oX} , attributed to pulses due to X-ray events initiated via the photoelectric effect near the surface of the crystal. Finally, to compare the 4 populations of events (initiated by gammas, neutrons, alphas and X-rays), we compared the values of $\tau_{o\gamma}$, τ_{on} , $\tau_{o\alpha}$ and τ_{oX} .

3. Results and discussion

Measured τ -distributions for events in two example energy bins are plotted in Figure 1a (30-40 keV, alpha source), 1b (55-65 keV, alpha source), 1c (30-40 keV, neutron source) and 1d (55-65 keV, neutron source). Plus signs show the data collected with the aforementioned sources. Open squares correspond to the data collected with the ^{60}Co gamma source normalised using the best fit procedure. Dotted curves show the fits to the neutron (alpha) distributions.

Data collected with the gamma source (squares in Figure 1) match well the right-hand parts of distributions obtained with the neutron or alpha sources (these parts correspond to gamma events detected in the experiments with the neutron or alpha sources). This is true also for the 55-65 keV range with the alpha source where the gamma (right-hand) part of the τ -distribution is dominated by X-rays from the ^{241}Am source. The amplitude of the right-hand peak at 55-65 keV (Figure 1b) is several times more than that at 30-40 keV (Figure 1a) (note the logarithmic scale of the y -axes), showing the presence of the strong 60 keV line superimposed on the background due to Compton electrons. This means that the τ -distribution, and hence the basic shape of the pulses due to the X-rays, does not differ from that of the Compton electrons initiated by high-energy gammas. It is clear also that the positions of the left-hand peaks in the experiment with the alpha source (Figures 1a and 1b) are shifted to the left with respect to the positions of the left-hand peaks in the experiment with the neutron source (Figures 1c and 1d, respectively). This is an indication that $\tau_{o\alpha}$ is less than τ_{on} and, hence, the pulses due to alphas are faster than the pulses due to nuclear recoils (note that it was shown in [5, 8] that pulses due to sodium recoils are indistinguishable from those initiated by iodine recoils at all energies of interest).

Figure 2 shows the fits to the τ -distributions from the gamma- (solid curve), neutron-

(dashed curve) and alpha- (dotted curve) induced events for the energy bin 30-40 keV. The total number of events in each case is normalised to unity.

The results are summarised quantitatively in terms of τ_o in Table 1. The typical error in τ_o is of the order of 2-5 ns (arising from the statistics of the fit), except for the first energy bin in the experiment with the alpha source where the error of $\tau_{o\alpha}$ is 15 ns - being higher due to the smaller number of detected alphas. The value of τ_{oX} , obtained from the fit to the right-hand peak of the τ -distribution at 55-65 keV with the alpha source (see Figure 1), is 322 ± 2 ns, in good agreement with the value of $\tau_{o\gamma}$ (2nd column of Table 1). However, this does not agree with the conclusion of [10], where the shapes of the pulses due to X-rays from an ^{241}Am source and Compton electrons from high-energy gammas were found to be different (the shape of the pulses due to X-rays was found to be similar to that of nuclear recoils). The values of $\tau_{o\alpha}$ (4th column of Table 1) are on average 10% smaller than those of τ_{on} (3rd column of Table 1).

The values of τ_o are known to vary from one crystal to another depending on the growth technology, Tl doping, temperature and other factors [1, 2, 3, 4, 5]. However, the ratios, for instance of τ_{on} to $\tau_{o\gamma}$ are known to be quasi-independent of the crystal for fixed energy and temperature (we found it to decrease from 0.80 down to 0.76 with increasing energy from 10 to 80 keV in the crystal with anomalous events, currently under operation in the Boulby mine). The ratios $\tau_{on}/\tau_{o\gamma}$, $\tau_{o\alpha}/\tau_{o\gamma}$ and $\tau_{o\alpha}/\tau_{on}$ are shown in the 5th, 6th and 7th columns of Table 1, respectively. The first two slightly decrease with increasing energy, while $\tau_{o\alpha}/\tau_{on}$ remains almost constant. The average ratio is $\langle \tau_{o\alpha}/\tau_{on} \rangle = 0.90 \pm 0.01$. The ratio $\langle \tau_{o\alpha}/\tau_{on} \rangle$ is higher than the ratio $\langle \tau_{o\alpha}/\tau_{on} \rangle = 0.79 \pm 0.04$ found for the anomalous fast events (pulses faster than recoil-like pulses) observed in the UKDMC experiment at Boulby mine [1, 7]. This suggests that the anomalous events are not produced by external high energy alphas degraded in energy by a non-scintillating layer of material, assuming the ratio $\langle \tau_{o\alpha}/\tau_{on} \rangle$ does not depend on the crystal.

4. Conclusions

The form of the pulses initiated by gammas, alphas, nuclear recoils and X-rays have been analysed in terms of the mean value, τ_o , of the gaussian distribution of exponent indices (see eq. (1)). The value of τ_{oX} of events initiated by X-rays (using the 60 keV line from an ^{241}Am source) was found to be the same as that of events induced by Compton electrons from high-energy gammas. The values of $\tau_{o\alpha}$ for alpha events are smaller (by $\sim 10\%$ on average) than those of τ_{on} for nuclear recoils induced by neutrons. However, the ratio of $\tau_{o\alpha}/\tau_{on}$ is higher than the corresponding ratio for the anomalous events to nuclear recoil events observed in the UKDMC experiment. This suggests that the anomalous events are not produced by external high energy alphas degraded in energy by a non-scintillating layer of material, assuming the ratio $\tau_{o\alpha}/\tau_{on}$ does not depend on the crystal.

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Table 1: Mean values, τ_o , of gaussian distributions (see eq. (1)) for gamma- (column 2), neutron- (column 3) and alpha- (column 4) induced events, and ratios of the mean values (columns 5, 6 and 7). The typical errors are 2-5 ns (in τ_o , see text for details) and 0.02 (in the ratios).

Energy, keV	$\tau_{o\gamma}$, ns	τ_{on} , ns	$\tau_{o\alpha}$, ns	$\tau_{on}/\tau_{o\gamma}$	$\tau_{o\alpha}/\tau_{o\gamma}$	$\tau_{o\alpha}/\tau_{on}$
10-20	292	242	220	0.83	0.75	0.91
20-30	307	242	220	0.79	0.72	0.91
30-40	314	241	219	0.77	0.70	0.91
40-50	318	240	218	0.75	0.69	0.91
50-60	320	240	214	0.75	0.67	0.89
60-70	320	240	214	0.75	0.67	0.89
70-80	321	240	215	0.75	0.67	0.90
80-90	322	239	216	0.74	0.67	0.90
90-100	322	238	216	0.74	0.67	0.91

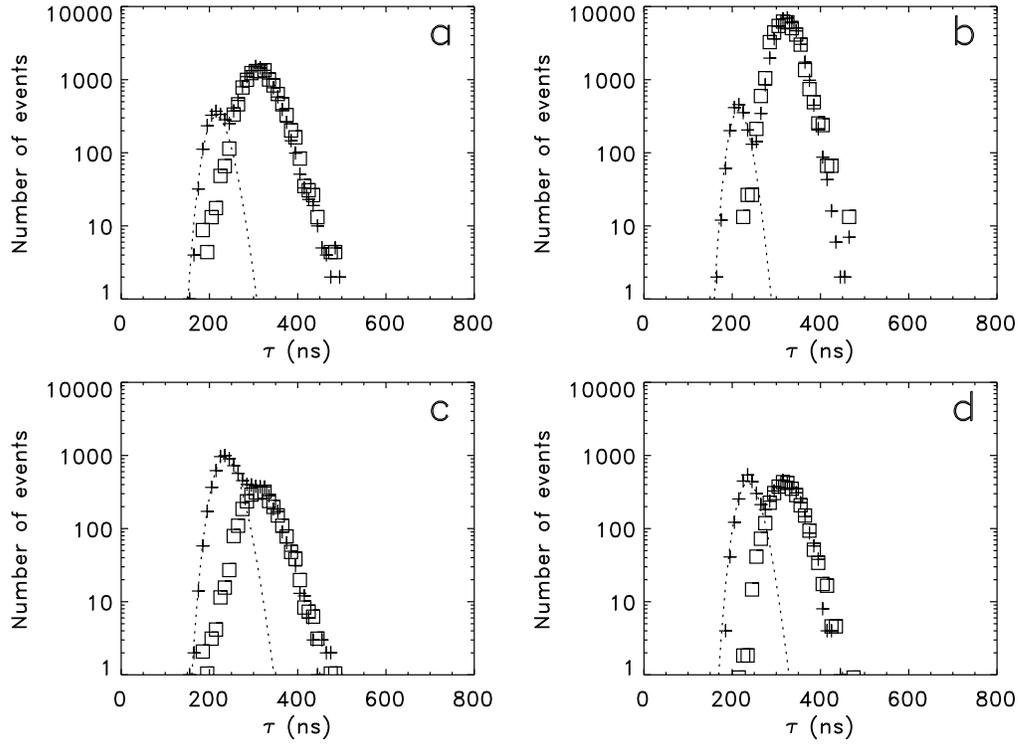


Figure 1: τ -distributions for events collected with different sources: a) alpha source, measured energy 30-40 keV; b) alpha source, measured energy 55-65 keV; c) neutron source, measured energy 30-40 keV; d) neutron source, measured energy 55-65 keV. Plus signs show the data collected with the aforementioned sources. Open squares correspond to the measured distribution of Compton electrons (from ^{60}Co events) normalised using the best fit procedure. Dotted curves are the best fits to the left-hand parts of the distributions (alpha or neutron induced events).

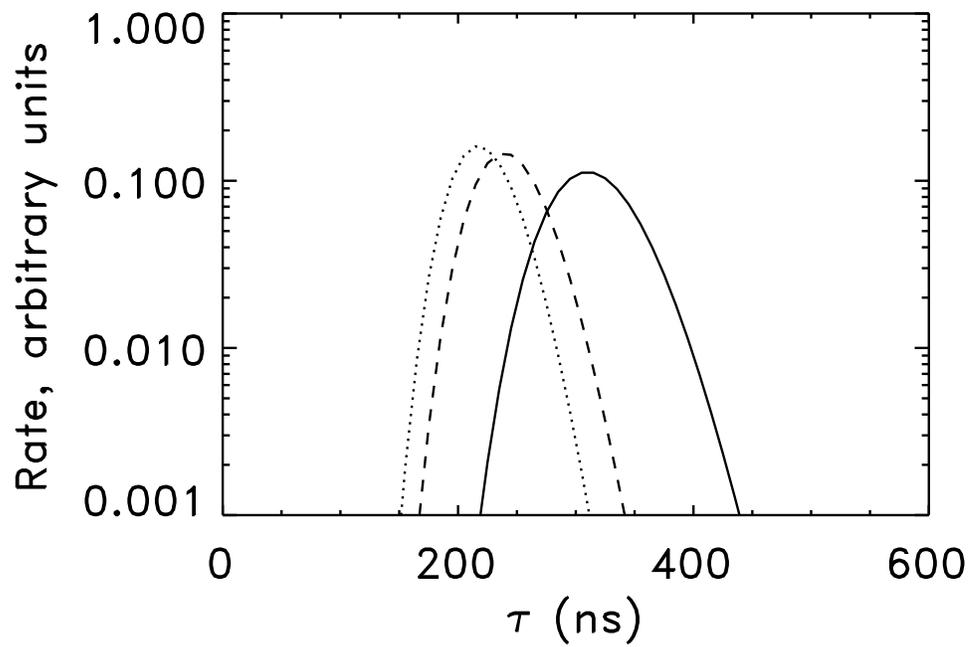


Figure 2: Fits to τ -distributions for gamma- (solid curve), neutron- (dashed curve) and alpha- (dotted curve) induced events for the energy bin 30-40 keV. The total number of events for each fit is normalised to unity.