June 2001

Measurements of Scintillation Efficiency and Pulse-Shape for Low Energy Recoils in Liquid Xenon.

D. Akimov[a], A. Bewick[b], D. Davidge[b], J. Dawson[b], A.S. Howard[b], I. Ivaniouchenkov[b], W.G. Jones[b], M. Joshi[b], V.A. Kudryavtsev[c], T.B. Lawson[c], V. Lebedenko[b], M.J. Lehner[c], P.K. Lightfoot[c], I. Liubarsky[b], R. Lüscher[c], J.E. McMillan[c], C.D. Peak[c], J.J. Quenby[b], N.J.C. Spooner[c], T.J. Sumner[b], D.R. Tovey[c*], C.K. Ward[c]

[a] *Institute for Theoretical and Experimental Physics, B. Cheremushkinskaja 25, 117259 Moscow, Russia.*
[b] *Physics Department, Blackett Laboratory, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BZ, UK.*
[c] *Department of Physics and Astronomy, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, UK.*

Abstract

Results of observations of low energy nuclear and electron recoil events in liquid xenon scintillator detectors are given. The relative scintillation efficiency for nuclear recoils is 0.22 ± 0.01 in the recoil energy range 40 keV - 70 keV. Under the assumption of a single dominant decay component to the scintillation pulse-shape the log-normal mean parameter T_0 of the maximum likelihood estimator of the decay time constant for 6 keV $< E_{ee} <$ 30 keV nuclear recoil events is equal to 21.0 ns $\pm$ 0.5 ns. It is observed that for electron recoils T_0 rises slowly with energy, having a value $\sim$ 30 ns at $E_{ee} \sim$ 15 keV. Electron and nuclear recoil pulse-shapes are found to be well fitted by single exponential functions although some evidence is found for a double exponential form for the nuclear recoil pulse-shape.

PACS: 95.35.+d, 29.40.Mc, 61.25.Bi
Keywords: liquid xenon; dark matter; WIMP; quenching factor; pulse-shape

*e-mail: d.r.tovey@sheffield.ac.uk

1 Introduction

Searches for Weakly Interacting Massive Particles (WIMPs) which may constitute the galactic dark matter are currently being carried out by a number of groups world-wide [1, 2]. These experiments generally seek evidence for anomalous populations of low energy (< 50 keV) nuclear recoil signals caused by elastic scattering of WIMPs [3]. Efficient searches require targets which both couple strongly to WIMPs, to give measurable event rates, and give a high energy transfer. These requirements tend to favour heavy nuclei with significant coherent spin-independent coupling and a nuclear mass comparable to that of the most likely WIMP candidate, the SUSY neutralino. In addition, a good experiment requires a low electron equivalent energy threshold, as the predicted spectrum falls exponentially with energy, and the ability to discriminate nuclear recoil signals from the dominant background, which tends to be electron recoil events.

Liquid xenon scintillator detectors fulfill all of these criteria. In particular the quenching factor of xenon recoils, defined as the ratio of the numbers of photons emitted from pure xenon by nuclear and electron recoils of the same energy, is expected to be higher than those of heavy nuclei in other scintillators [4]. Further, the scintillation pulse-shapes of low energy nuclear recoils are expected to be faster ($\lesssim 20$ ns) than those of electron recoils of the same energy and this permits some level of background rejection using Pulse-Shape Analysis (PSA) [5].

The nuclear recoil quenching factor cannot be measured directly. Instead it must be approximated by the nuclear recoil relative scintillation efficiency, defined as the ratio of the observed scintillation pulse-height from a nuclear recoil to that from a gamma-ray interaction depositing the same total amount of energy. The scintillation pulse-height is commonly measured in 'electron equivalent' energy units by calibration with a mono-energetic gamma-ray source producing electron recoils. The nuclear recoil relative scintillation efficiency is then given by the ratio of the measured electron equivalent energy E_{ee} to the calculated nuclear recoil energy E_R. In the limit where negligible recoil energy (electron or nuclear) is lost through detector dependent secondary processes (such as the absorption of ionisation by impurities, which prevents emission of recombination photons) the quenching factor and nuclear recoil relative scintillation efficiency are identical.

There has been some disagreement in the literature surrounding the value of the nuclear recoil relative scintillation efficiency/quenching factor in liquid xenon. Theoretical and experimental work has suggested values ranging from $\simeq 0.2$ up to 0.8 [4, 6, 7]. Given the relevance of this quantity to the sensitivity of liquid xenon detectors to WIMP signal events it is important that the true value is measured accurately. It is also crucial that the scintillation pulse-shape properties of nuclear and electron recoils in liquid xenon are determined in order to permit the use of PSA with data from operational detectors such as that proposed by the UK Dark Matter Collaboration (ZEPLIN-I [8]).

The response of dark matter detectors to nuclear recoils can be determined through the elastic scattering of monoenergetic neutrons. This technique has been used in previous work to measure relative scintillation efficiencies and pulse-shapes in NaI(Tl) and CaF_2(Eu) [9, 10, 11, 12, 13]. In this letter we describe studies of nuclear recoils in liquid xenon using the same technique.

2 Detector Apparatus

Data from two different liquid xenon detectors were used in this study. The first detector (A) consisted of a cylindrical xenon volume 30 mm (L) $\times$ 30 mm (diam.) viewed from below through a single Spectrasil A quartz window by an Electron Tubes 9829 QA bialkali photomultiplier tube. High efficiency for collection of 175 nm xenon scintillation photons was obtained by using a 5 mm thick PTFE reflector lining the cylindrical wall of the chamber, together with a PTFE float on the liquid surface. Stable light output of 0.90 $\pm$ 0.02 photoelectrons per keV and energy resolution $\sigma(E)/E = 20.0$ % $\pm$ 0.7 % was measured through calibration with the 122 keV line from a 10 μCi ^{57}Co source. Calibration with the 662 keV line from a 1 μCi ^{137}Cs source showed no evidence for significant non-linearity. Further details regarding detector A can be found in Ref. [14].

The second detector (B - designed by Chase Research Ltd.) consisted of a xenon volume of dimension 78 mm (L) $\times$ 22 mm (diam.) defined by a 27 mm thick annular PTFE reflector. The liquid xenon was viewed by two ETL 9849 QB bialkali PMTs through Spectrasil A windows set at the top and bottom of the chamber. Stable light output of 0.62 $\pm$ 0.02 photoelectrons per keV and energy resolution $\sigma(E)/E = 22.9$ % $\pm$ 0.9 % was measured using the same ^{57}Co calibration procedure as for detector A. Again no evidence for significant non-linearity was found with higher energy sources.

Before use the xenon was purified using three processes: distillation, passing through Oxisorb granules (supplied by Messer Griesheim GmbH) and pumping out vapour present over the solid xenon formed at liquid nitrogen temperature. Both detectors were baked and pumped out to a pressure below 10^{-7} Torr before filling with xenon. During tests the liquid xenon was maintained at a temperature of -105 ^{o}C $\pm$ 0.5 ^{o}C and a pressure of 1.3 bar (A) or 2 bar (B).

3 Neutron Beam and Data Acquisition (DAQ) System

The monoenergetic neutron beam used for the nuclear recoil measurements was an Activation Technology Corporation d-d device at the University of Sheffield, producing $\sim 10^9$ neutrons/s isotropically with energy 2.85 MeV. A double-wedged iron collimator of mean diameter 19 mm, passing through borax, lead, iron and wax shielding, was used to define the beam. Further details of the neutron beam facility can be found in Ref. [12].

For each test the liquid xenon detector was placed in the beam 0.2 m from the collimator. A 75 mm diameter NE213 counter with pulse-shape discrimination was placed at a distance of 400 mm from the target and moved to a variety of angles θ to the beam direction. This was surrounded by $\sim$ 200 mm of wax on all sides except that facing the target detector so as to absorb wall-scattered neutrons. In this way those events caused by the scattering of neutrons from xenon nuclei in the target detector could be tagged with coincident nuclear recoil events in the NE213 counter, and the xenon nuclear recoil energy determined by kinematics from the neutron angle-of-scatter θ. Further details of the procedure can be found in Refs. [9, 10, 11].

The data acquisition system used was similar to that described in Ref. [12]. Pulses from the liquid xenon target detector went to a discriminator with a trigger level set to accept single photoelectrons. The signals from the discriminator were used to provide start signals for a Time-to-Amplitude Convertor (TAC). A LINK Systems 5020 pulse-shape discrimination unit was used to identify nuclear recoil events in the NE213 counter and the output signals from this were then used to stop the TAC. TAC pulses corresponding to time differences less than 500 ns between the two signals triggered a LeCroy Digital Sampling Oscilloscope (DSO), which digitised the event pulse-shapes with 1 ns and 2 ns sampling times (for detectors A and B respectively) with an 8 bit resolution. These data, together with the TAC amplitude, were passed to a Macintosh PC running LabView DAQ software for storage and off-line analysis.

4 Data Analysis

Data were taken at neutron scattering angles θ of 120^o, 105^{o}and 90^o. Peaked TAC amplitude distributions were observed indicating low levels of background due to random coincidence between gamma-ray induced events in the liquid xenon and the NE213 signals. In subsequent software analysis data for study were selected using cuts applied to the TAC amplitude distributions.

Scintillation events from the liquid xenon target detectors were analysed by estimating the arrival times of photoelectrons in the events. The procedure used involved integrating the event pulse-shapes and then noting the times of equal pulse-height increment, using an increment set at the mean expected pulse-height for a single photoelectron. The mean photoelectron arrival time for each event ($\bar{t}$), calculated relative to the arrival time of the first photoelectron in the event, was then used to estimate the event time constant. Under the assumption that the pulse-shape is predominantly a single exponential the $\bar{t}$ value provides the maximum likelihood estimator of the decay time constant of the pulse [12].

5 Relative Scintillation Efficiency

Values of the relative scintillation efficiency for each scattering angle are given by the ratio of the mean electron equivalent energy of nuclear recoils and the expected nuclear recoil energy at that angle. The mean electron equivalent energies of nuclear recoils were determined by fitting gaussian curves to the observed energy distributions of events (Fig. 1). Only those events with electron equivalent energies < 30 keV were considered so as to avoid contamination with high energy events from inelastic excitation and decay of the 39.6 keV and 80.2 keV levels in ^{129}Xe and ^{131}Xe . Cuts on the $\bar{t}$ values of events (12 ns $< \bar{t} <$ 30 ns) were also used to reduce this source of contamination. The electron equivalent energy scale for the fits was determined from energy calibrations with a ^{57}Co source (122 keV line) according to the calibration procedure described in [12]. The scintillation efficiency was thus measured with respect to this high energy electron recoil calibration point.

Results of the relative scintillation efficiency measurements are presented in Fig. 2 as a function of nuclear recoil energy E_R. The mean values obtained from both detectors are consistent within errors with a constant value of 0.22 $\pm$ 0.01 over the recoil energy range 40 - 70 keV. The errors on the individual points include both statistical errors determined from the fits and systematic effects due to the finite solid angle acceptance of the NE213 counters, possible fluctuation in the neutron beam energy and variation in fitted means with event selection parameters, histogram binning etc.

The value of the liquid xenon relative scintillation efficiency obtained from this work is in agreement with that obtained from recent measurements carried out by the ICARUS collaboration [7], but contrasts strongly with values reported by the DAMA collaboration [6].

6 Scintillation Time Constant

Scintillation time constants for liquid xenon were estimated from the distributions of event $\bar{t}$ values, which are approximately log-normal for a single exponential pulse-shape [15]. The fitted log-normal mean-parameters [1] (here denoted by T_0 - note that this is not the true mean of the log-normal) of these distributions provide an estimate of the exponential time constant of the parent scintillation pulse-shape [15].

T_0 values are plotted in Fig. 3 for both nuclear recoils and electron recoils. Nuclear recoil $\bar{t}$ distributions for each scattering angle were constructed from events in the range 6 keV $< E_{ee}$ $<$ 30 keV (error bars not shown) but the plotted E_{ee} values correspond to the fitted means of the E_{ee} distributions determined when measuring the relative scintillation efficiency. Electron recoil $\bar{t}$ distributions were constructed from pulses acquired during exposure of detector B to a 1 μCi ^{60}Co source generating low energy Compton scattering events. This data extends down to electron equivalent energies of 12 keV below which the presence of significant numbers of fast ($\bar{t}$ < 9 ns) noise events (due to lack of an NE213 coincidence requirement) prevents measurement of T_0. Note however that these events are not present in the electron equivalent energy distributions used to calculate relative scintillation efficiencies due to the application of the $\bar{t}$ cut (12 ns $< \bar{t} <$ 30 ns). Vertical error bars on all points include both statistical errors and a constant systematic error (estimated to be $\sim$ 0.5 ns) due to uncertainties in fitted values caused by event selection and binning.

The data show strong evidence for significant differences in T_0 and hence scintillation time constant between nuclear and electron recoils of the same electron equivalent energy. The T_0 values for nuclear recoils from both detectors are consistent within errors with a constant value of 21.0 ns $\pm$ 0.5 ns, while the values for electron recoils vary from 29.1 ns $\pm$ 0.6 ns at $\sim$ 13.5 keV to 34.0 ns $\pm$ 0.6 ns at $\sim$ 37.5 keV.

7 Scintillation Pulse-Shape

In order to further investigate the scintillation pulse-shape of low energy recoil events in liquid xenon normalised distributions were constructed of the arrival times of photoelectrons relative to the first photoelectron for events in the electron equivalent energy range 12 keV - 30 keV. These distributions are shown in Fig. 4 for electron recoils (Fig. 4(a)) and nuclear recoils (Fig. 4(b)). Due to poor event statistics in the latter case distributions obtained from data taken at all three neutron scattering angles have been summed. In both cases the data are well fitted by single exponential functions, although the nuclear recoil data are marginally better fitted by a sum of two exponentials (e.g. χ^2/dof = 1.117 for a double exponential fit to detector B data with τ_1 = 11.3 ns $\pm$ 4.1 ns and τ_2 = 28.9 ns $\pm$ 5.3 ns, as opposed to χ^2/dof = 1.386 for a single exponential fit with τ = 21.5 ns $\pm$ 0.76 ns). Such a double exponential pulse-shape is expected on general grounds due to the action of at least two different emission processes within the scintillator [4]. It should be emphasised however that sensitivity to the fastest components of such a pulse-shape is limited by the non-zero transit-time jitter of the PMTs.

8 Conclusions

A 2.85 MeV mono-energetic neutron beam has been used to measure the relative scintillation efficiency and the log-normal mean parameter T_0 of the maximum likelihood time constant estimator for nuclear recoils in liquid xenon. A mean value for the relative scintillation efficiency of 0.22 $\pm$ 0.01 in the recoil energy range 40 keV - 70 keV was obtained. A T_0 value of 21.0 ns $\pm$ 0.5 ns was found for nuclear recoil events with electron equivalent energy in the range 6 keV - 30 keV. Electron recoils were found to possess T_0 values rising from 29.1 ns $\pm$ 0.6 ns at $\sim$ 13.5 keV to 34.0 ns $\pm$ 0.6 ns at $\sim$ 37.5 keV thereby indicating significant pulse-shape discrimination potential. Electron and nuclear recoil pulse-shapes were found to be well fitted by single exponential functions although some evidence was found for a double exponential form for the nuclear recoil pulse-shape.

Acknowledgements

The authors are grateful for discussions with P.F. Smith, N.J.T. Smith, S. Chase and H. Wang. They would also like to thank R. Nicholson and the staff of the University of Sheffield Central Mechanical Workshop for their assistance. The authors wish to acknowledge PPARC (DRT - Post-Doctoral Fellowship, RL - Royal Society ESEP grant), Zinsser Analytic Ltd. (PKL, JEM), Electron Tubes Ltd. (JEM, JWR) and Hilger Analytical Ltd. (JWR, CKW) for support.

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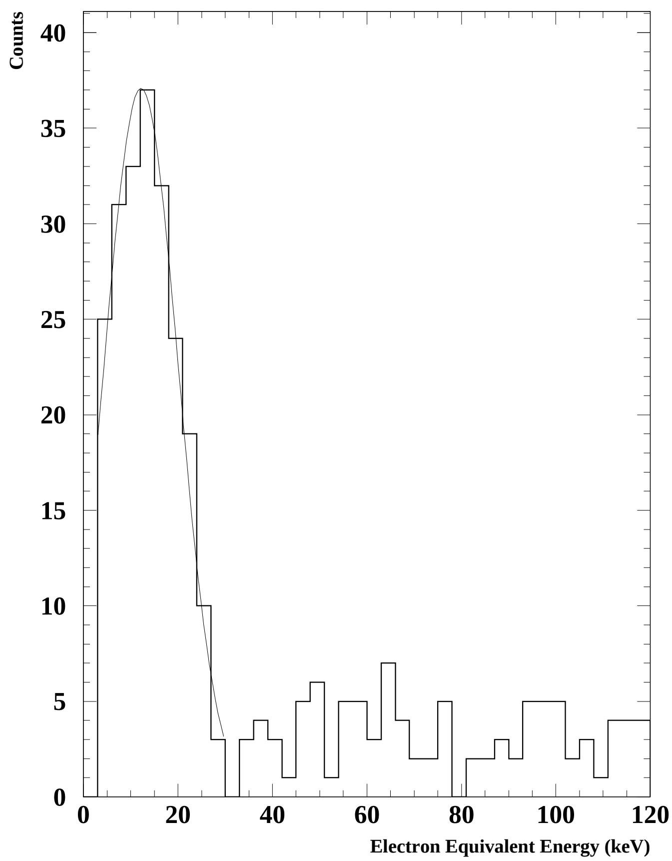
Figures

Figure 1: Electron equivalent energy spectrum of events taken with detector A at neutron scattering angle $\theta = 120^o$ following TAC preselection only. The large peak at $E_{ee} \simeq 14$ keV contains events with $\bar{t} \sim 20$ ns. Events in the broad distribution at energies $\gtrsim 30$ keV possess $\bar{t} \gtrsim 30$ ns characteristic of electron recoil events. These events are consequently interpreted as being due to inelastic scattering of neutrons. Elastic nuclear recoil peaks corresponding to relative scintillation efficiencies of 0.45 and 0.65 (values quoted in Ref. [6]) would lie at electron equivalent energies of 28.9 keV and 41.8 keV respectively.

Figure 2: Nuclear recoil relative scintillation efficiencies E_{ee}/E_R in liquid xenon as a function of nuclear recoil energy E_R. Vertical error bars are dominated by statistical effects but include both statistical and systematic contributions. Nuclear recoil energies for points corresponding to data from detector B (open circles) have been offset by 0.5 keV for clarity. The mean value is 0.22 ± 0.01. The dotted line corresponds to the expected value from Lindhard theory [16].

Figure 3: Fitted T_0 values for nuclear recoil and electron recoil events as a function of electron equivalent energy. Vertical error bars correspond to total errors obtained by adding statistical and systematic errors in quadrature. Nuclear recoil E_{ee} values are those obtained when measuring the nuclear recoil relative scintillation efficiency. Nuclear recoil points correspond to all events in the electron equivalent energy range 6 keV $< E_{ee} <$ 30 keV, although horizontal error bars are not shown for clarity.

Figure 4: Photoelectron arrival time distributions for (a) electron recoils (detector B) and (b) nuclear recoils (detectors A and B) in the electron equivalent energy range 12 keV - 30 keV. Bin widths of 2 ns have been used and nuclear recoil data have been summed over all three scattering angles. Vertical error bars show errors due to finite photoelectron statistics. Also shown (dashed curves) are fits to a single exponential function (Figure 4(a)) and a sum of two exponential functions (Figure 4(b) - detector B data).



Counts
40
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
Electron Equivalent Energy (keV)

Figure 1:

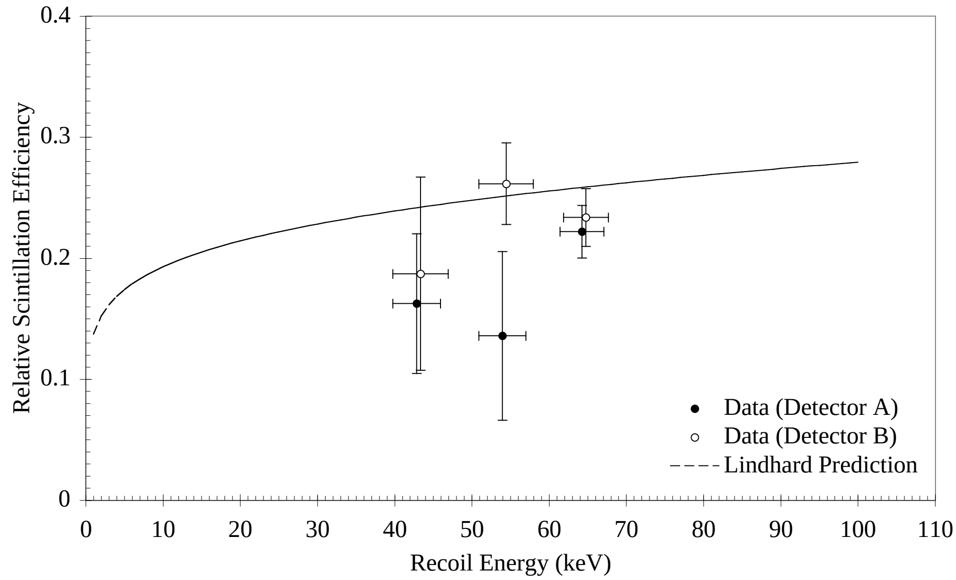


Figure 2:

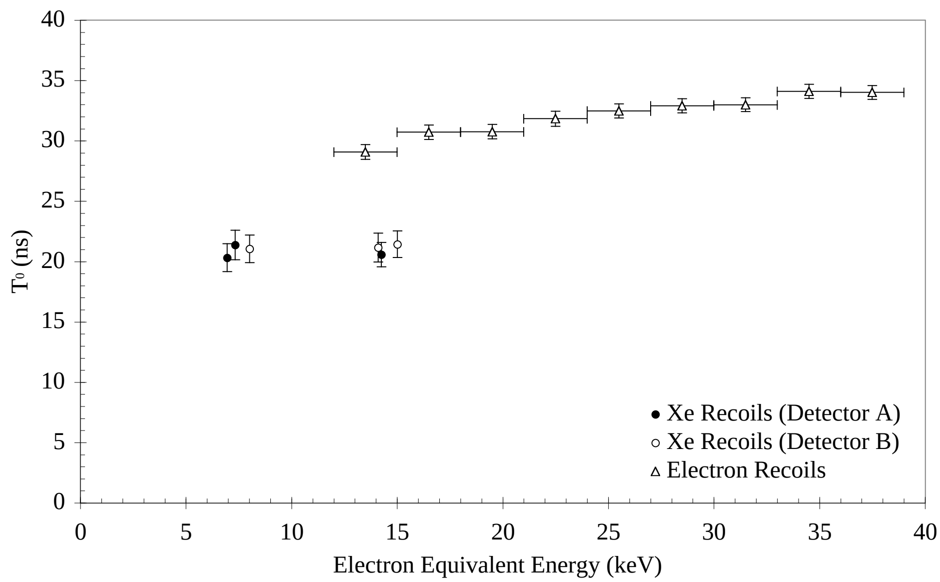


Figure 3:

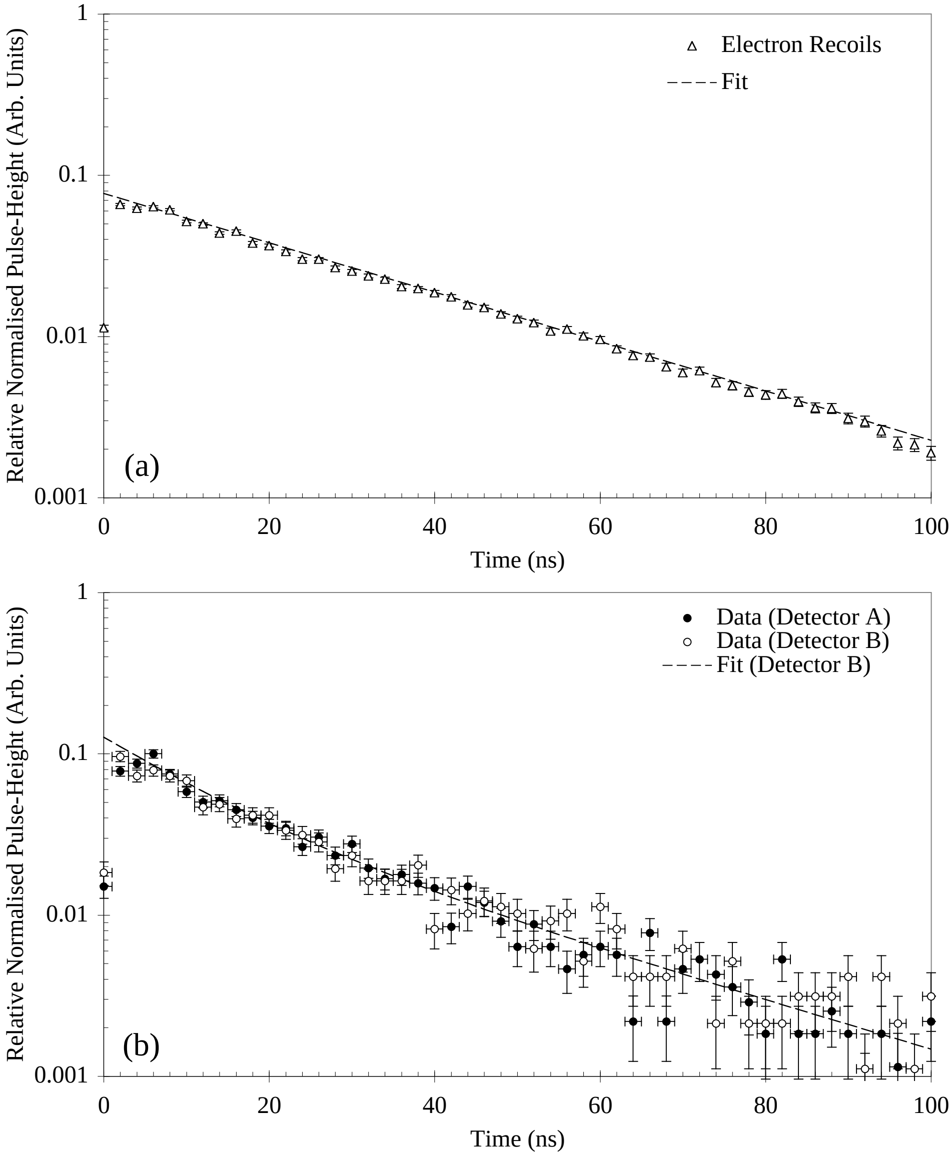

Electron Recoils
Fit
(a)
Relative Normalised Pulse-Height (Arb. Units)
Time (ns)
Data (Detector A)
Data (Detector B)
Fit (Detector B)
(b)
Relative Normalised Pulse-Height (Arb. Units)
Time (ns)

Figure 4: