MEASUREMENT OF THE SCINTILLATION EFFICIENCY OF Na RECOILS IN NaI(Tl) DOWN TO 10 keV NUCLEAR RECOIL ENERGY RELEVANT TO DARK MATTER SEARCHES

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We present preliminary results of measurements of the quenching factor for Na recoils in NaI(Tl) at room temperature, made at a dedicated neutron facility at the University of Sheffield. Measurements have been performed with a 2.45 MeV mono-energetic neutron generator in the energy range from 10 keV to 100 keV nuclear recoil energy. A BC501A liquid scintillator detector was used to tag neutrons. Cuts on pulse-shape discrimination from the BC501A liquid scintillator detector and neutron time-of-flight were performed on pulses recorded by a digitizer with a 2 ns sampling time. Measured quenching factors range from 19% to 26%, in agreement with other experiments. From pulse-shape analysis, a mean time of pulses from electron and nuclear recoils are compared down to 2 keV electron equivalent energy.

1. Introduction

Thallium activated sodium iodide (NaI(Tl)) crystals are a popular choice as a target material for dark matter experiments. This is because of their relatively high light yield and pulse shape differences between nuclear and electron recoils. Currently three experiments utilise these crystals: ANAIS [1]; DAMA/NaI [2]; and ELEGANT-V [3]. Although better discrimination can be reached with other target media, NaI(Tl) crystal-based detectors remain one of the best at determining spin-dependent WIMP-nucleon limits. For instance, for direct detection techniques, the NaIAD experiment [4] still holds the best spin-dependent limit on WIMP-proton interactions [5]. Hence, NaI(Tl) remains an important detector material in non-baryonic dark matter searches.
2. Measuring Scintillation Efficiencies

An important measurement to determine a scintillating target’s sensitivity to dark matter particles is the ratio of light induced by a nuclear recoil (produced by WIMP/neutron collisions with nuclei) to that by an electron recoil of the same energy. This is known as the quenching factor.

![Schematic view of the detector arrangement used to measure the scintillation efficiency of nuclear recoils in NaI(Tl).](image)

The 2-inch diameter, encapsulated, NaI(Tl) crystal is placed in the path of a 2.45 MeV mono-energetic deuterium-deuterium neutron beam as shown in Figure 1. A 3-inch ETL 9265KB photomultiplier tube is optically coupled to the crystal. Neutrons that interact with the target nuclei scatter off at an angle that is dependent on the deposited neutron energy:

\[ E_R \approx \frac{2m_A E_n m_n}{(m_A + m_n)^2} \cdot (1 - \cos \theta) \]  

where \( E_R \) is the recoil energy, \( m_A \) is the mass of the target nucleus, \( E_n \) is the energy of the neutron beam, \( \theta \) is the scattering angle and \( m_n \) is the mass of the neutron.

A BC501A liquid scintillator detector is placed at various angles around the target to detect scattered neutrons at nuclear recoil energies given by
Eq. (1). Pulses from the target and liquid scintillator that are coincident within a 100 ns time window are sent to a 2-channel, 8-bit, Acqiris digitizer with a 500 MHz sampling rate, and written to disk.

3. NaI(Tl) Response to Electron Recois

It is known that the response of NaI(Tl) to gamma-rays is non-linear at low energies [6, 7]. The crystal is exposed to gamma-rays from a variety of low energy sources, between 29 keV (¹²⁹I Xe Kα X-rays) and 122 keV (⁵⁷Co γ-rays). A decrease in detector response is observed at the iodine K-shell absorption edge at 33.2 keV, consistent with other studies [6, 7]. Therefore, determination of the energy scale must be performed in an energy region where a linear response is observed. The crystal is calibrated with a ⁵⁷Co source, as shown in Figure 2(a). The iodine escape peak at 90 keV is also seen. A light yield of 5.5 photoelectrons/keV is found.

![NaI(Tl) Crystal Calibration with ⁵⁷Co](image)

**Fig. 2.** (a) Results from calibration of detector with 122 keV line from ⁵⁷Co source. (b) Mean time of the pulses as a function of deposited energy for sodium (Na) recoils and Compton electrons. Measurements of Na recoils are performed with the neutron beam. Compton electrons are induced by a ²²Na source.

4. Quenching Factor Measurements

The nuclear recoil energy spectrum measured at each scattering angle is converted to an electron equivalent energy scale (keVee) and compared to the expected nuclear recoil energy (keVnr) at that angle. The ratio between the measured nuclear recoil energy, and that calculated from Eq. (1), is the quenching factor.

In order to eliminate the background from gamma-ray interactions, nuclear recoils are discerned by discrimination of pulse shapes from the
BC501A detector and time-of-flight measurements.

Events that arise from gamma-ray interactions in the BC501A detector have shorter decay times relative to those from neutron collisions. Adequate discrimination between nuclear and electron recoils is achieved by integrating over the tail of the pulse. The ratio between this partial area and the total pulse area is then plotted as a function of the total area. An example is illustrated in figure 3(a).

Unlike gammas, neutrons that scatter off the target in this experiment are non-relativistic. Therefore, after interacting with a sodium nucleus in the crystal, a neutron takes approximately 40 ns to travel the 80 cm distance to the BC501A detector. By taking the time difference between coincident events in the target and BC501A detector, as shown in Figure 3(b), neutron and gamma events are separated.

Better discrimination at energy scales relevant to dark matter searches has been demonstrated in NaI(Tl) crystals using the mean time $\langle t \rangle$ [6,8] rather than the traditional double charge method [9]. The mean time is defined as: $\langle t \rangle = \frac{\sum_i A_i t_i}{\sum_i A_i}$, where $A_i$ is the amplitude of the digitized pulse at the time bin $t_i$. After gamma events have been rejected by performing the cuts outlined above, mean time distributions for each nuclear recoil energy are investigated. An example is shown in Figure 3(c). This is compared with the mean time of Compton recoils induced by a $^{22}\text{Na}$ source in Figure 2(b).

In agreement with previous work [10], it is clear that this difference is less prominent at energies less than 10 keVee, limiting the discrimination power of NaI(Tl) detectors. This cut serves to reduce the background from noise and gamma pulses, leading to a nuclear recoil peak as shown in Figure 3(d).

5. Results

The quenching factor varies between 19% to 26% in the range 10 keV to 100 keV nuclear recoil energy, which agrees with previous experimental results [6,10–12], as shown in Figure 4. From Figure 3(d), a scintillation efficiency of $25.2 \pm 6.4\%$ has been determined for 10 keVnr Na recoils.

6. Summary

Scintillation efficiency measurements have been performed for Na recoils in a NaI(Tl) crystal. The results show an average value of 22.1% at energies less than 50 keVnr, and are in agreement with other measurements. Future plans include simulating nuclear recoils in NaI(Tl) in an effort to decrease the errors in quenching factors.
Fig. 3. (a) Pulse shape discrimination in the BC501A liquid scintillator detector for 10 keVnr Na recoils. The upper neutron event band is clearly distinguishable from gamma interactions. (b) Time-of-flight between the BC501A detector and NaI(Tl) crystal. The peaks at roughly 0 and 40 ns represent gamma and neutron events respectively. (c) Mean time of pulses from 10 keVnr Na recoils in the NaI(Tl) crystal. (d) Recoil energy in electron equivalent scale.

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Fig. 4. Quenching factor measurements for Na recoils in NaI(Tl). Results from this work (closed black squares), Simon et al. [11] (open diamond), Gerbier et al. [6] (open circles), Tovey et al. [10] (open triangles), Spooner et al. [12] (open squares) and the preliminary theoretical estimation from Hitachi [13] (solid black line) are shown.

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