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Measurements of quenching factors for NaI(Tl) scintillating crystal

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Understanding nuclear recoil quenching factors, the ratio of the scintillation light yield produced by nuclear and electron recoils of the same energy, is critical for rare event searches, such as dark matter and neutrino experiments. Because NaI(Tl) crystals are widely used for dark matter direct detection and neutrino-nucleus elastic scattering measurements, the low-energy quenching factor of the NaI(Tl) crystals is substantially important. The quenching factor for NaI(Tl) scintillating crystals has been measured by several experimental groups for energies above 5 keVnr for Sodium and 10 keVnr for Iodine. We have developed a NaI(Tl) detector with a high light yield of approximately 25 photoelectrons per keVee and an event-selection and analysis method based on waveform simulations that are specialized for studies of events with energies as low as a sub keVee region. As part of these efforts, we have measured quenching factors for nuclear recoil energies below 5 keVnr and 10 keVnr for Na and I, respectively. This talk presents the results and prospects for future quenching-factor measurements for NaI(Tl) crystals.

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PoS(TAUP2023)047

1. Introduction

The quenching factor, defined as the fraction between electron equivalent energy and deposited nuclear recoil energy, is essential for understanding interactions via nuclear recoil deposition in searches such as WIMP or neutrino elastic scattering. In the parameter space of WIMP mass cross-sections, the exploration of regions is influenced by the quenching factors [1]. These factors also impact the expected number of events in the CEvNS signal [2]. To investigate the unexplored region of these rare event searches, knowledge of the quenching factors at low energies is crucial. While several measurements have been performed, none have extended below 5 keV for sodium and 18 keV for iodine until now. Furthermore, our prior measurements [3] revealed a swifter energy drop at lower levels compared to other studies. To address this, we conducted measurements of quenching factors at lower energies and revisited our earlier findings.

2. Measurements and analysis

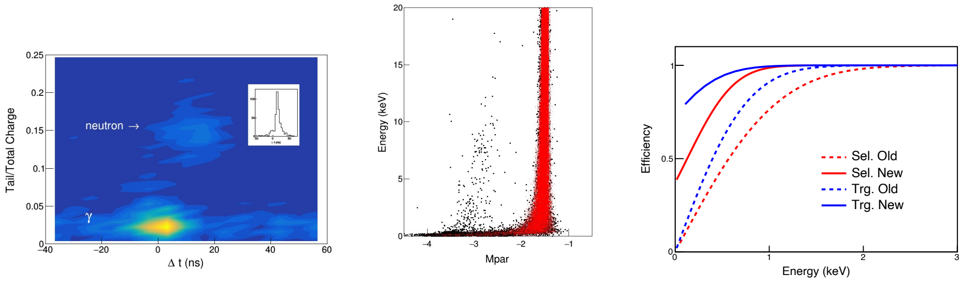
Since the nuclear recoil is a function of incident neutron energy, accurate estimation of neutron energy is crucial for quenching factor estimation. Our measurements utilized a deuteron-based neutron generator, and induced variation in neutron energy via deuteron acceleration power. Earlier quenching factors were established with a neutron energy of 2.43 MeV, measured using ^{3}He detector. Previously, quenching factor measurements were conducted using a 60 keV deuteron energy setup, estimating neutron energy at 2.43 MeV, while this estimation was made at 85 keV. This choice was influenced by the fact that dependency of neutron energy on deuteron energy is limited at collinear angles [4]. This time, we measured neutron energy using the time-of-flight of neutrons with two liquid scintillator neutron detectors by varying deuteron energy. It indicates a slight discrepancy, where the recent measurement at 85 keV deuteron energy with a neutron energy of 2.43 MeV aligns well with the previous measurement, while it has become apparent that for the 60 keV deuteron energy, the appropriate neutron energy is 2.34 MeV. Utilizing these incident neutron energy values and an updated analysis method, we reexamined previous quenching factor measurements. The details of this reexamination will be provided after introducing the new measurements with the updated analysis approach.

New measurements employed distinct crystals from previous experiments. Crystals grown from the same powder as COSINE crystals number 6 and 7 were employed for this time, while crystals from the same ingot as COSINE crystals number 2 and 5 were used for previous measurements [5]. In addition, we introduced new setups yielding higher light yields, similar to the NEON experiment methodology [2]. Previously, crystals were encapsulated and optically coupled using an optical pad and quartz inside the crystal encapsulation, then attached to PMTs. In the novel design, crystals are directly attached to the PMTs, minimizing optical coupling and resultant light loss. The new setup enhances light yield for this detector, increasing it from 18 to 26 photoelectrons/keV (PE/keV). This increased light yield permits lower energy thresholds in the detector. The detector was installed in the collinear direction to the incident neutron. The neutron generation relied on a deuteron-based neutron generator, operational at 100 keV deuteron energy yielding an estimated neutron energy of 2.48 MeV. Eleven liquid scintillator neutron detectors were positioned for neutron tagging. These measurements were specifically designated to investigate lower recoil angles, 10.5 degrees, with

PoS(TAUP2023)047

a 1-inch diameter detector providing enhanced angular resolution along collinear angles. For the electron equivalent energy calibration, the 59.54 keV gamma ray from ^{241}Am radioactive source was used for.

Neutron events were identified by selecting neutrons based on distinct pulse shapes in the neutron detector, distinguishing them from gamma events. Coincidence timings with the NaI detector were also used in the identification process. These separations are depicted in Fig. 1 (a). To suppress PMT noise, a parameter related to mean decay time was employed, effectively segregating noise from scintillation events, even down to the 0.5 keV region as shown in Fig. 1 (b). This event selection, coupled with efficiency and trigger efficiency assessments, was evaluated using waveform simulations [6] developed to characterize low-energy scintillation events. Data prepared



(a) (b) (c)

Figure 1: (a) neutron-γ selections using charge ratio in the waveform, (b) noise rejection selections, (c) selection (red) and trigger (blue) efficiencies of previous and updated one shown in dashed and solid line, respectively.

with this analysis was fitted using a simulated nuclear recoil energy distribution as shown in Fig. 2. Recoil energy distributions were fitted with simulated distributions, accounting for efficiencies.This was performed by varying quenching factor values to achieve the best fit. For the smallest angle and lowest recoil energy cases, events below 0.2 keV, which could be contaminated by noise, were excluded from the fitting. Using the same event selection, updated efficiencies, and revised neutron

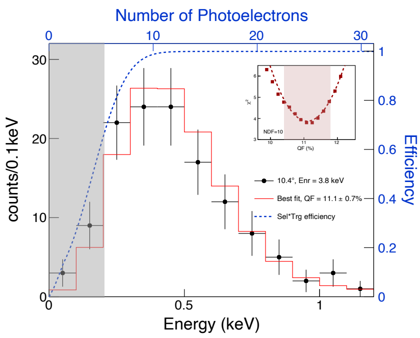


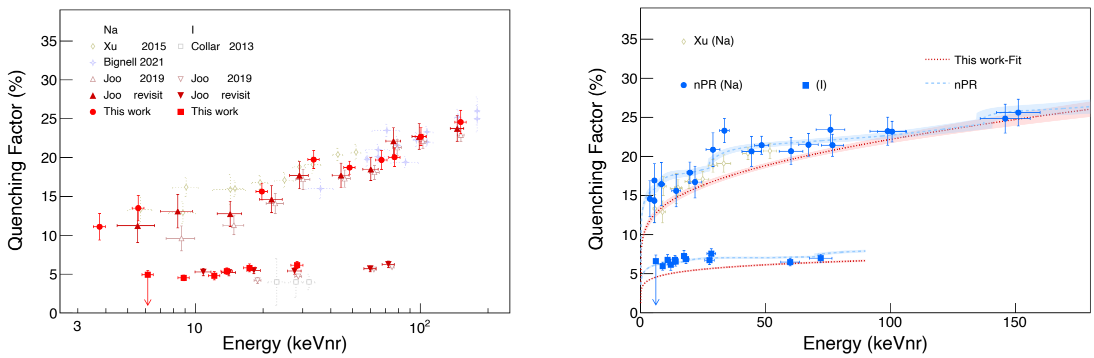
Figure 2: Nuclear recoil spectrum (Na, 10.47°) in NaI(Tl) crystal and its best-fit simulation spectrum. The correction based on the trigger efficiency was applied to the simulation spectrum.

PoS(TAUP2023)047

energy values, we revisited previous measurements. This allowed us to explore lower energies via new event selections and updated efficiencies. As a result, quenching factor values have experienced a slight increase from prior findings shown as a red-ish open triangles to closed triangles in Fig. 3 (a).

3. Results

The new results, obtained using the high light yield detector and a novel analysis, estimate quenching factors plotted as closed circles in Fig. 3 (a). The overall tendency is consistent with the revisit of the previous measurements shown as closed triangles in Fig. 3 (a). The measurements are particularly noteworthy at exceptionally low energies, measuring 3.75 keV for sodium and 8.87 keV for iodine. While this result utilizes the 59.54 keV gamma ray solely for electron equivalent energy calibration, it is crucial to consider the impact of non-proportionality present in the light output of scintillation detectors for a comprehensive understanding. We have extensively studied the non-proportionality phenomenon using X-rays and gamma rays from external source measurements, as well as internal and cosmogenic peaks [7]. Combining all data allowed us to determine the non-proportionality and assess its impact on the quenching factor. The data subjected to fitting using the modified Lindhard model [1, 8], and were adjusted considering non-proportionality. In Figure 3 (b), the blue data points represent the quenching factors considering non-proportionality point by point, while the dashed blue line with the band reflects the quenching factor adjusted for non-proportionality using the model fitted with the modified Lindhard. Accounting for non-proportionality, the quenching factor increases by approximately 30% at 5 keVnr for sodium, and it rises to about 15% from the initial 11%.



(a) (b)

Figure 3: (a) Newly measured QFs (closed circle for sodium, square for iodine), along with re-analyzed QFs for sodium (closed normal triangle) and iodine (inverted triangle) recoils (b) QFs accoungint non-proportionality.

PoS(TAUP2023)047

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PoS(TAUP2023)047