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Measurement of nuclear recoil responses of NaI(Tl) crystal for dark matter search

Hanwool Joo*
on behalf of the KIMS-NaI collaboration
Department of Physics and Astronomy, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea
E-mail: hwjoo1240@gmail.com

In direct detection of WIMP dark matter particles, scintillation crystals such as NaI(Tl) are commonly used as targets/detectors. In this experiment, nuclear recoil responses of a small NaI(Tl) crystal were measured with 2.43 MeV mono-energetic neutrons from deuterium-deuterium fusion. The quenching factors of sodium and iodine recoils and pulse shape discrimination power of the crystal were measured with those nuclear recoils and electron recoils produced by Compton scattering of 662 keV gamma-rays from a ^{137}Cs source.

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*Speaker.

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1. Introduction

Direct detection of WIMP particle is based on detection of nuclear recoil energies in a target detector material and therefore complete understanding of detector response of nuclear recoils is necessary. [1, 7, 8] In scintillation crystals, such as NaI(Tl), the light yields from electron and nuclear recoils of the same energy are different. Typically, due to the small fraction of energy transfer to electrons, nuclear recoils gives less scintillation light yields compared with electron recoils of the same energy deposition. Since calibrations are done with monochromatic gamma sources that produce electron recoils while WIMP interactions are expected to produce nuclear recoils, in order to predict the response to WIMP-induced nuclear recoils, measurements of these light yield ratios - quenching factors (QF) - are necessary. This is typically accomplished using neutron-induced nuclear recoils.

In this experiment, the quenching factors for sodium and iodine recoils for small (2 cm x 2 cm x 1.5 cm) NaI(Tl) crystal were measured with 2.43 MeV mono-energetic neutrons generated from deuterium-deuterium nuclear fusion reaction. The neutron generator "DD-109" model from Adelphi technology in Korea Research Institute of Standards and Science(KRISS) was used as an neutron source. The crystal was made from the same Alpha Spectra-grown ingot as a large crystal used for KIMS-NaI experiment. [11] BC501a liquid scintillators are placed in various angles to tag neutrons that scatter off sodium or iodine nuclei.

On the other hand, nuclear recoil events and beta/gamma-induced events can be discriminated based on their differences in scintillation characteristics. By using a pulse shape discrimination(PSD) analysis, discrimination between WIMP-induced recoils and the background beta-gamma events can be possible. To measure this PSD power, the responses to nuclear recoils are compared to the response to electron recoils produced by Compton scattering of 662 keV gamma-rays from a ^{137}Cs source.

2. Experimental setup

The measurements of the quenching factors for sodium and iodine and PSD power of the NaI crystal were performed with 2.43 MeV mono-energetic neutron beam from deuterium-deuterium nuclear fusion reaction. The neutrons emitted at a scattering angle of 90° have an energy of 2.43 MeV for an accelerating potential of 60kV. Neutrons produced from the reaction are emitted in every direction and are directed to the target crystal by a small hole with 2.5 cm diameter in the 40-cm-long polyethylene shielding material. The collimated neutron beam produced nuclear recoil scintillation events in the crystal. Scintillation lights from the interactions were collected by two 3-inch photomultiplier tubes (PMTs) at each side of the crystal. After the interactions, some of the neutrons are tagged by one of the neutron detectors at a fixed recoil angles. Quenching factor was measured for 16 nuclear recoil energies (10 for sodium recoils and 6 for iodine recoils) with 12 different recoil angles. The measurements were performed with 3 different setups with 4 neutron detectors in various angles and the fixed NaI(Tl) crystal, 1.5 m from the neutron generator. Goal of each measurement was 1,000 recoil events per each recoil event. As a result, data was taken for 70, 55, 25 hours for each setup.

On the other hand, in measurement of PSD power of the crystal, neutron generation power of the neutron generator was too strong and single trigger rate of the NaI crystal was too high, so we installed the crystal at 3 m from the neutron generator. In addition to this, precise calculations of nuclear recoil energies are not necessary in PSD power measurement, so neutron detectors are installed more closer to the crystal (30 cm from the crystal) at 30° and 75°.

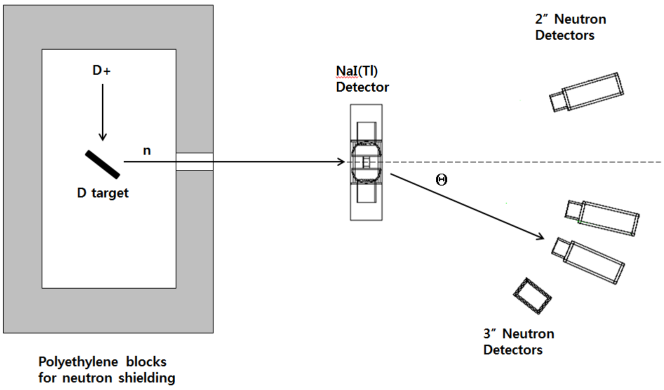


Figure 1: Experimental setup for quenching factor measurement

2.1 NaI crystal

To minimize the probability of neutron multiple scattering in the NaI(Tl) crystal and energy uncertainty of neutrons come into the crystal, a small dimension($2\times2\times1.5$ cm^3) of the crystal was used. [11] Because NaI(Tl) crystals are highly hygroscopic, the crystal was encapsulated with 1.52 mm aluminum housing and was coupled to two 3-inch PMTs with high quantum efficiency (R12669SEL, Hamamatsu Photonics). Between the crystal and the PMTs, 5 mm thickness quartz were attached at each side of the crystal to minimize loss of scintillation lights.

2.2 Neutron Detectors

To identify neutrons that elastically scatter in the crystal, neutron-tagging detectors were located from 13° to 170°. Corresponding recoil energies for sodium recoil is 6 to 100 keVnr and iodine recoil is between 10 to 75 keVnr. In a quenching factor measurement, two types of neutron detectors were used for the measurement: 2” (D) x 1” (L) and 3”(D) x 3.54”(L) liquid scintillator detectors. In some directions, uncertainties in observed recoil energy were larger than our expectation due to finite size of 3” neutron detector and so 2” neutron detectors were installed with further distances in those directions. Both type of neutron detectors were made of BC501A liquid scintillator, which has high pulse-shape discrimination capability, contained in cylindrical stainless-steel containers. Scintillation lights from the liquid scintillators are collected with PMTs. The distances between the crystal and the neutron detectors were chosen in order to obtain enough event rates and reduce uncertainty in recoil energy due to finite detector size. More details about distance and installed angle of the detectors are listed in Table 1.

In PSD power measurement, only 3” detectors are used and two detectors are installed at 30° and another two at 75°. The distances between the crystal and each detectors were 30 cm.

Setup	Detector number	Detector size	Scattering angle (deg)	Distance (cm)
1	ND1	2"(D) × 1"(L)	13.2	82.3
	ND2	2"(D) × 1"(L)	16.4	83.6
	ND3	2"(D) × 1"(L)	26.6	84.4
	ND4	3"(D) × 3.54"(L)	38.2	84.0
2	ND1	2"(D) × 1"(L)	21.3	84.6
	ND5	3"(D) × 3.54"(L)	59.0	46.3
	ND6	3"(D) × 3.54"(L)	75.0	45.0
	ND7	3"(D) × 3.54"(L)	126.9	38.0
3	ND4	3"(D) × 3.54"(L)	31.0	46.3
	ND5	3"(D) × 3.54"(L)	45.0	44.6
	ND6	3"(D) × 3.54"(L)	51.3	52.0
	ND7	3"(D) × 3.54"(L)	159.4	30.7

Table 1: Information of installed neutron detector for quenching factor measurement.

3. Data Analysis

For the triggered events, to remove gamma-induced background events or non-scintillation noise events from PMTs and treat only nuclear recoil events,additional event selection for the crystal and the neutron detectors is applied in offline analysis. For the crystal, a charge asymmetry of two PMT signals and a charge ratio of fast and slow components of the signal waveforms were used to remove noise-like events. On the other hand, for the neutron detectors, the PSD method was used to discriminate neutron-induced events from gamma-induced events, and time of flight was considered to removed the background noise-like events.

3.1 PMT charge asymmetry and charge ratio

The noise events usually appear in only one side of PMT and has no correlation with PMT on the other side. As a result, the noise events show asymmetry in charge sum of each side of PMT. The asymmetry is defined as below.

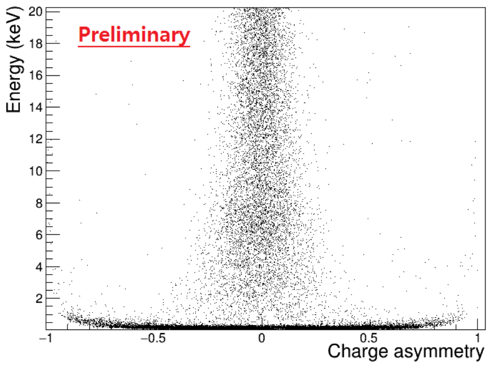
$$Asym = \frac{Q_{pmt1} - Q_{pmt2}}{Q_{pmt1} + Q_{pmt2}} \tag{3.1}$$

where Q_{pmt} means charge sum of the signals in each PMT. Figure 2 shows deposit energy on the crystal as a function of the charge asymmetry below 20 keV. Events with the absolute value of asymmetry is larger than 0.5 are considered as noise events and removed.

In addition to the PMT charge asymmetry, a partial charge fraction of PMT signal waveforms was used to remove remaining PMT noise events based on the fact that noise pulses are generally decaying faster than normal scintillation signals. This was originally developed by the DAMA group and they defined ratios of the pulse areas for different time characteristics of fast noise pulses and relatively slow scintillation pulses. The slow and fast charge ratios are denoted by X1 and X2 respectively and defined as below.

$$X1 = \frac{Q_{100to600ns}}{Q_{0to600ns}}, X2 = \frac{Q_{0to50ns}}{Q_{0to600ns}} \tag{3.2}$$

where, Q means an integrated charge in specific time range from the start of trigger position. Here we used the difference x1 - x2 as a selection parameter.



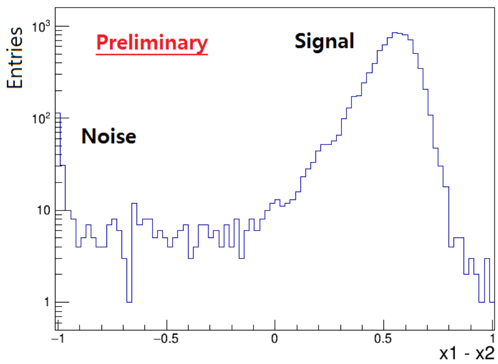


Figure 2: (left) Charge asymmetry distribution below 20 keV. Events with large asymmetry values are considered as noise events. (right) x1 - x2 distribution. Large positive value indicates high fraction of the slow component while low negative indicates high fraction of the fast charge, a typical of noise-like events.

3.2 Neutron detector PSD and Time of Flight

For the signals from the neutron detectors, to pick out expected nuclear recoil events, event selection with pulse shape discrimination power of neutron detector is performed. Because neutron-induced signals in the neutron detectors have longer decay time, PSD against gamma backgrounds was performed with ratio of charge sum of tail part (from 50 ns to 200 ns from leading edge) and charge sum over 200 ns.

In addition to the PSD analysis, an event selection with time of flight, time difference between the NaI(Tl) signal and the triggered neutron detector signal, was performed. For the neutron energy used in this measurement (For 2.43 MeV neutrons, corresponding to a speed of about 2 cm / ns), the time required for the neutrons to travel from the NaI(Tl) detector to the neutron detectors is about 30 ns, depending on the detector positions. This well-defined time correlation made the neutron events distinct from the nearly instantaneous gamma coincidence background and random coincidence backgrounds.

3.3 Calculation of quenching factor

The quenching factors of sodium and iodine recoil events were evaluated by comparison between the simulated and observed recoil energies. The ratio between the centroids of Gaussian fits to the observed recoil energies and those to the simulated recoil energies are identified as the sought quenching factor. In this analysis, to simulate nuclear recoil energies of each event, the Geant4 4.9.6 p2 was used. Initial states of generated neutrons (positions, momentums, kinetic energies, etc) from deuterium-deuterium nuclear fusion reaction was calculated from the kinematics and used as an input. Calculated quenching factors are drawn in Figure 4.

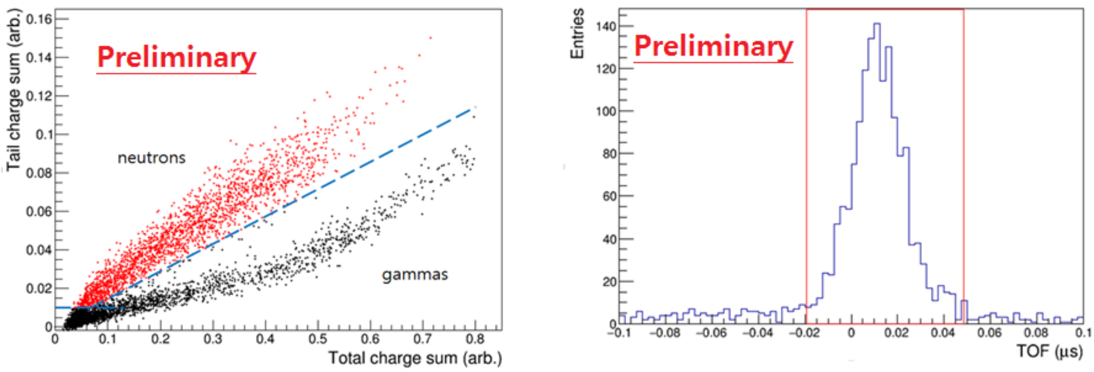


Figure 3: (left) Discrimination of neutron and gamma events in neutron detector with pulse shape discrimination method. Red and black dotted points indicates neutron events and background gamma events, respectively. (right) Event selection with time of flight cut. Events in red box are assumed as real coincidence events.

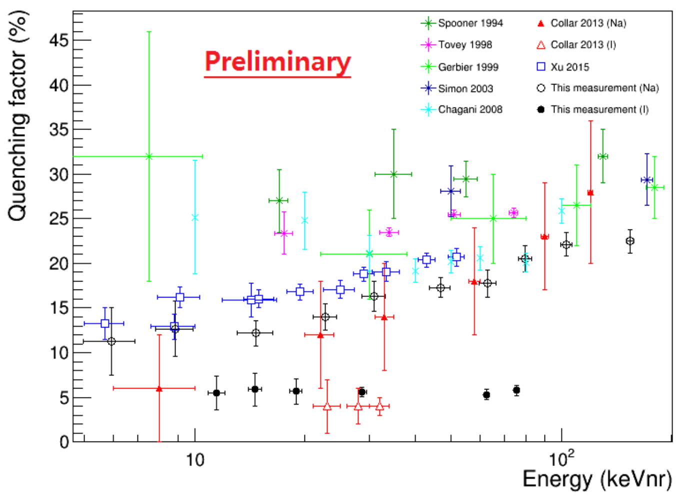


Figure 4: Measured quenching factors for Na and I recoils in this work and comparison with previously measured results. [2–8] Black opened/closed circles indicate quenching factors of this measurement for sodium/iodine recoils, separately.

3.4 PSD analysis for the NaI crystal

To study the PSD power of the NaI crystal, electron recoil events were taken from Compton scattering of 662 keV gamma-rays from a ^{137}Cs source. To discriminate nuclear and electron recoil events based on differences in scintillation characteristics, natural logarithm of mean decay time calculated within in 1.5 μs waveform window was used.

$$ln(MT) = ln(\frac{\sum A_n t_n}{\sum A_n} - t_0) \tag{3.3}$$

Here, A_n and t_n means charge and time of nth photon clusters. Figure 5 shows mean time distributions of nuclear and electron recoil events for 3 to 4 keV energy bin and most probable values of ln(MT) for each energy bin for electron and nuclear recoil data.

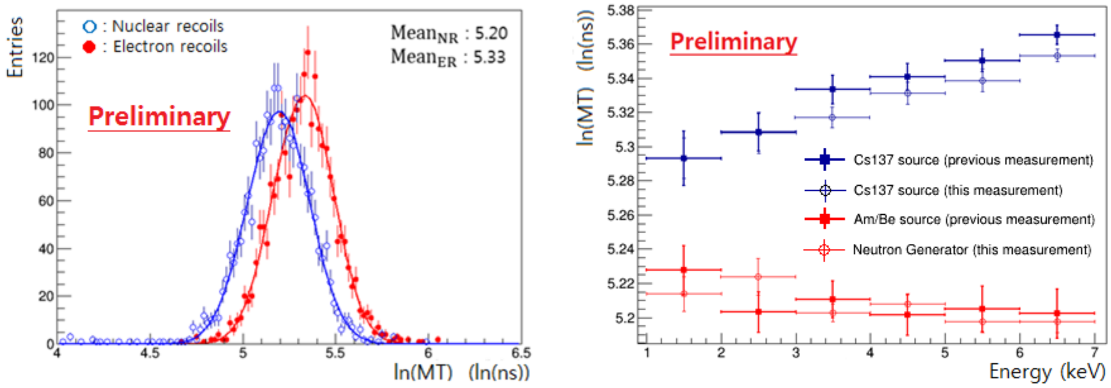


Figure 5: (left) Mean decay time distribution of (blue opened circle) nuclear and (red closed circle) electron recoil events for (left) 3 to 4 keV. (right) The most probable values of ln(MT) from the asymmetric Gaussian fits for each energy bin for (blue) nuclear recoils and (red) electron recoils.

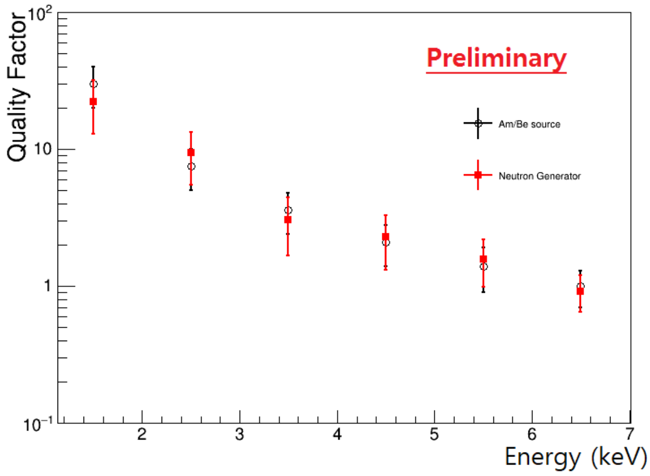


Figure 6: Calculated quality factor for each energy bin for (red closed square) previous measurement with Am/Be neutron source at SNU and (black opend circle) this measurement with the neutron generator at KRISS.

From the mean decay time, PSD power of the crystal was characterized using a quality factor [9, 10] defined as

$$K = \frac{\beta(1-\beta)}{(\alpha-\beta)^2}, \tag{3.4}$$

where α and β are fractions of the nuclear and electron recoil events that satisfy the selection criteria, respectively. The criteria was chosen for the best (i.e., the minimum) value of the quality factor. In Figure 6, the quality factors below 7 keV were compared with previous measurement with Am/Be as a neutron source at Seoul National University(SNU) and with same crystal and same model of PMT was used. [11]

4. Summary

Measurements of the quenching factors for sodium and iodine recoils in the small NaI(Tl) crystal have been performed with 2.43 MeV mono-energetic neutrons. Depending on the scattering angle of the neutron, energies of recoiled ions range from 6 to 100 keVnr for sodium and 10 to 75 keVnr for iodine. Quenching factors of sodium are measured at 10 points and those range from 11% to 22% and those of iodine are measured at 6 points and it range from 5 to 7%.

On the other hand, PSD power of the NaI crystal was studied from mean decay time of nuclear and electron recoil events and characterized using quality factor from 1 keV to 7 keV. Result of this measurement was compared with previous measurement with Am/Be neutron source at SNU.

Acknowledgments

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