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Quenching factor measurement of low-energy Na recoils in ultra-pure NaI(Tl) crystal

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The Weakly Interacting Massive Particles (WIMPs) are considered to be the hypothetical particles that have been the leading candidate for dark matter for decades. The PICOLON project is directly searching for WIMPs dark matter using ultra-pure NaI(Tl) crystals at the Kamioka underground laboratory. To determine the WIMP sensitivity, it is necessary to know the quenching factor (QF) of NaI(Tl), which is the scintillation light yield ratio of nuclear recoil and electron recoil at the same energy deposit. Several groups reported the QF absolute values and its energy dependence in the low energy region (less than 100 keV), however the results are not in good agreement. It is still unsolved whether the disagreement is due to the individual crystal differences or the effect of systematic errors. In this paper, we report the QF of ultra-pure NaI(Tl) crystal developed by PICOLON group. To measure the QF, the crystal was irradiated with 2.45-MeV monochromatic neutrons generated by a discharge-type compact D-D fusion neutron source at the Institute of Advanced Energy, Kyoto University. The QFs of Na were obtained at six points in the range of 19–101 $\mathrm{keV_{nr}}$.

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1. Introduction

The search for cosmic dark matter is an important issue in modern physics. WIMPs (Weakly Interacting Massive Particles) [1], which only interact via gravity and weak interaction, are considered to be one of the most promising candidates for dark matter. The PICOLON (Pure Inorganic Crystal Observatory for LOw-energy Neutr(al)ino) group has succeeded in producing the high-purity NaI(Tl) crystals [2] and is directly searching for WIMP dark matter at the underground laboratory in Kamioka observatory.

To determine the sensitivity of the WIMP, it is necessary to obtain the quenching factor (QF) of the NaI(Tl) scintillator to be used. The QF is experimentally determined by the ratio of the electron-equivalent recoil energy $E_{\rm ee}$ to the nuclear recoil energy $E_{\rm nr}$.

$$\mathrm{QF} = E_{\rm ee}/E_{\rm nr} \tag{1}$$

The DAMA group reported QF results measured using ^{252}Cf [3]. To measure more precisely, experiments have been performed by various groups using monochromatic neutrons [4–13]. However, the QF absolute values and its energy dependence in the low-energy region (less than 100 keV) have been discrepant. It is still unsolved whether the variation is due to the individual crystal differences or the effect of systematic errors. Impurity may be one of the causes of variation. In general, the higher the impurity concentration in the crystal, the lower the light output.

In this study, we have experimented with monochromatic neutrons to measure the QF of the ultra-pure NaI(Tl) scintillator developed by PICOLON group.

2. Experiment

2.1 Setup of this experiment

The crystal used in the experiment was developed by PICOLON group. The size of the crystal was 2.54 cm diameter × 2.54 cm height as shown in Fig. 1. The concentration of radioactive impurities of the crystal was 0.4 ± 0.5 ppt for ^{232}Th, 4.7 ± 0.3 ppt for ^{238}U, and 29.4 ± 6.6 μBq/kg for ^{210}Pb respectively.

Figure 1: NaI(Tl) crystal.

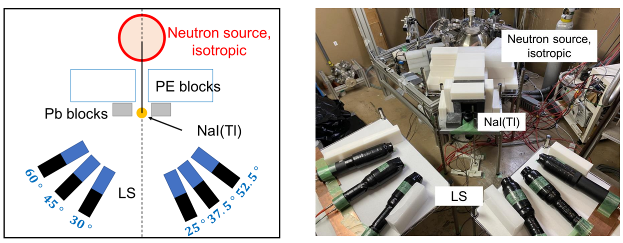

Figure 2: Schematic view (left) and photograph (right) of the experimental setup.

We used 2.45-MeV monochromatic neutrons to simulate low-energy nuclear recoil by WIMPs. The neutron source was a glow discharge fusion neutron source [14] developed at the Institute of Advanced Energy, Kyoto University. By applying high voltage to the electrode coated with diamond-like carbon inside the deuterium atmosphere, a nuclear fusion reaction occurs and 2.45-MeV neutrons are isotropically generated.

The experimental setup is shown in Fig. 2. Monochromatic neutrons with an intensity of 6.0×10^6 s^{-1} at the neutron source were irradiated to the NaI(Tl) crystal which was placed at a distance of 90 cm from the neutron source. Neutron events scattered by the NaI(Tl) crystal were obtained by placing a liquid scintillator (EJ-301) at a distance of 50 cm from the NaI(Tl) crystal and taking a coincidence with the NaI(Tl) crystal. Since the nuclear recoil energy depends on the neutron scattering angle, in this experiment, liquid scintillators were placed at 25, 30, 37.5, 45, 52.5 and 60 degree scattering angles. The NaI(Tl) crystal and liquid scintillator were read out by Hamamatsu Photonics photomultiplier tubes (PMT) H11284-100 and R6091 respectively. The data were collected by two cascaded DRS4 (Domino-Ring-Sampler 4) evaluation board V5 [15] units operated with 700 MHz sampling rate.

2.2 Data analysis

The NaI(Tl) detector was energy calibrated separately at 0–6.5 keV and 6.5–35.1 keV using a ^{133}Ba source. Nuclear recoil events are identified by pulse shape discrimination (PSD) and time of flight (TOF) analysis. For PSD analysis, the Mean Arrival Time $< t >$ was defined with t_i as the photon arrival time of ith sampling and a_i as the voltage value at time t_i [16].

$$< t >= \frac{\Sigma_{i=0}^{2047} t_i a_i}{\Sigma_{i=0}^{2047} a_i} \tag{2}$$

In Fig. 3, background gamma-ray events were confirmed in the area above ~190 ns, and nuclear recoil events were confirmed in the area below ~190 ns. The energy peak around 50 keV$_{\text{ee}}$ is due to the bremsstrahlung X-rays from the neutron source. The TOF results are shown in Fig. 4. The timing peak around 23 ns, the same as the calculated theoretical neutron TOF was confirmed after the PSD selection.

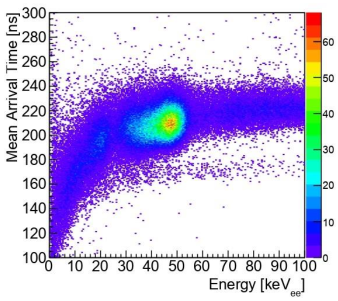

Figure 3: PSD for the NaI(Tl) detector.

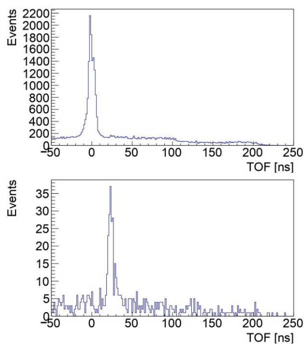

Figure 4: TOF distribution of all events (top) and after PSD selection (bottom).

Energy spectra of nuclear recoil events at each neutron scattering angle after analysis by PSD and TOF are shown in Fig. 5. For each spectrum, the mean and error were obtained by fitting with a Gaussian function. The same setup, detector size, and neutron beam structure as in the present experiment were reproduced by Geant4 simulations to calculate nuclear recoil energies without quenching effects.

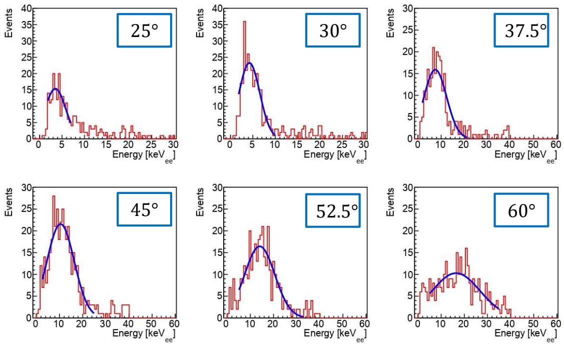

Figure 5: Nuclear recoil energy spectra for each neutron scattering angle.

3. Result and Discussions

From the experimental and simulated values, the QFs of Na were obtained at six points in the range of 19–101 keV$_{\mathrm{nr}}$. Systematic errors such as energy calibration errors and liquid scintillator placement errors were also taken into account.

Figure. 6 shows the results in this work and comparison with previous studies. The blue circles represent the results of this experiment. Similar values are obtained as in the previous studies, however no clear dependence on energy was observed. Although more precise measurement with higher statistics is needed for a precise discussion, one factor contributing to this discrepancy may be the effect of different energy calibration methods. Nonlinear response of NaI(Tl) is particularly pronounced at photon energies 10 keV or less [17]. In fact, the radiation sources used in previous studies were different, and the energy ranges used for calibration were also varied. The effect of these differences might be significant in the less than 100 keV range, which is important for WIMP searches.

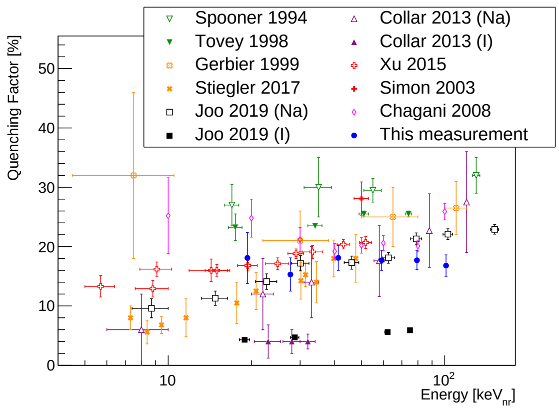

Figure 6: The results in this work and comparison with previous studies of QF.

4. Conclusions

We have experimented to measure the QF of the ultra-pure NaI(Tl) scintillator developed by PICOLON group. We have succeeded in calculating the QF_{Na}. No clear energy dependence of QF was identified, which is different from several previous studies. NaI(Tl) has been reported to have a pronounced nonlinear dependence on photon energy [17], which may be one factor contributing to the discrepancy in the QFs. Accurate methodology is needed when comparing QF results from previous studies.

Precise measurement of the QF dependence of Tl concentration, temperature, readout photodetector, radioactive impurity and energy calibration method remains a future work.

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