Neutron beam tests of $CsI(Na)$ and $CaF_2(Eu)$ crystals for dark matter direct search postprint

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Date: 2016-08-31T00:00:00+00:00

Abstract

In recent decades, inorganic crystals have been widely used in dark matter direct search experiments. To contribute to the understanding of the capabilities of CsI(Na) and CaF2(Eu) crystals, a mono-energetic neutron beam is utilized to study the properties of nuclear recoils, which are expected to be similar to signals of dark matter direct detection. The quenching factor of nuclear recoils in CsI(Na) and CaF2(Eu), as well as an improved discrimination factor between nuclear recoils and backgrounds in CsI(Na), are reported.

Full Text

Preamble

Neutron Beam Tests of CsI(Na) and CaF (Eu) Crystals for Dark Matter Direct Search

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Abstract

In recent decades, inorganic crystals have been widely used in dark matter direct search experiments. To contribute to the understanding of the capabilities of

CsI(Na) and CaF (Eu) crystals, a mono-energetic neutron beam is utilized to study the properties of nuclear recoils, which are expected to be similar to signals of dark matter direct detection. The quenching factor of nuclear recoils in CsI(Na) and CaF (Eu), as well as an improved discrimination factor between nuclear recoils and   backgrounds in CsI(Na), are reported.

Keywords: Dark matter direct search, Neutron beam test, CaF (Eu), CsI(Na), Elastic scattering

1. Introduction

According to recent results from Planck [?], normal matter constitutes only 4.9% of the universe’ s mass/energy inventory. Dark matter, which is observed indirectly through its gravitational influence on nearby matter, occupies 26.8%, while dark energy—thought to be responsible for accelerating the expansion of the universe—accounts for 68.3%. The Weakly Interacting Massive Particle (WIMP) is a popular dark matter candidate, and the most promising method for its direct observation is detection of the nuclear recoil signals produced by elastic scattering between WIMPs and target nuclei, for example in inorganic crystals.

In recent decades, neutron beam tests have been performed for various crystals including NaI(Tl) [?, ?, ?, ?, ?, ?, ?], CsI(Tl) [?, ?], CsI(Na) [?, ?] and CaF [?, ?, ?]. According to Ref. [?], CsI(Na) may be a good candidate for dark matter direct detection because of its high neutron/ discrimination ability, though this is not consistent with previous results [?]; we report our findings in this paper. On the other hand, CaF (Eu) is sensitive to spin-dependent dark matter due to its fluorine content [?, ?, ?, ?, ?], but its neutron/ discrimination ability is not well known and will be reported here.

2. Experimental Setup

[Figure 1: see original paper]

Figure 1: The schematic diagram for the experiment.

The experiment is based on a neutron generator at the China Institute of Atomic Energy (CIAE) and the setup is shown in Fig. 1. The neutron beam is obtained from the T(D,n) reaction, which is induced by a 250 keV deuteron beam impinging on a T-Ti target with a frequency of 1.5 MHz and pulse width of 2 ns. Neutrons at an outgoing angle of 32.5 degrees are selected with a 1.5 m thick collimator wall made of concrete, iron, and lead, resulting in a mean kinetic energy of 14.7 MeV with a spread of 0.2 MeV (1). The measured crystal is positioned 0.45 m from the wall, and the neutron flux crossing the crystal is about 1×10^3/s/cm^2.

Two crystals, with all surfaces polished, are both 2.5×2.5×2.5 cm^3 in cubic shape and produced by the Beijing Glass Research Institute. The doping concentrations of Na in CsI(Na) and Eu in CaF (Eu) are both 0.02%. Two photomultipliers (PMTs) directly face the top and bottom surfaces of the crystal, while the other four surfaces are wrapped in a 65 µm thick Enhanced Specular Reflector film. The PMTs, model 9821QB from ET Enterprises, have a very low radioactivity background quartz window [**?**] and are thus particularly suitable for future dark matter direct detection experiments.

To select nuclear recoils with specific energies in the crystal, three neutron detectors (NDs) are positioned at various angles and 1 m away from the crystal. The neutron detectors are made of liquid scintillator (BC501A), which has good neutron/ discrimination ability [**?**], contained in a cylindrical aluminum container of 5 cm diameter. Double checks with laser alignment and a protractor ensure the setup height uncertainty is less than 3 mm and positioning uncertainty less than 1 degree, so the uncertainties of angles are estimated as 1 degree. For each ND, a 2-inch XP2020 PMT is used for readout. The nuclear recoil energy (E_recoil) can be calculated by the kinematical equation with the energy and scattering angle of the neutron:

$$E_{\text{recoil}} = E_{\text{beam}} \left\{ 1 - \left(\frac{m_n \cos\theta - \sqrt{m_N^2 + m_n^2 \sin^2\theta}}{m_n + m_N} \right)^2 \right\}$$

where E_beam is the neutron beam energy, m_n and m_N are the masses of a neutron and the recoiling nucleus (Cs, I, Ca, or F) respectively, and is the scattering angle. Table 1 details the scattering angles and calculated recoil energies, where the recoil energy uncertainties are propagated from the NDs' position uncertainties and neutron beam uncertainties.

Table 1: Estimated recoiling energy of crystal samples.

[Figure 2: see original paper]

Figure 2: Readout diagram of beam test.

Fig. 2 shows the electronics scheme of the experiment. In total there are 7 signal channels: 2 PMTs from the crystal detector named PMT1 and PMT2; 3 PMTs from the 3 NDs named ND1, ND2, and ND3; a pulse shape discrimination (PSD) signal (generated by CANBERRA 2160A) from the 3 NDs; and a time stamp pulse from the neutron beam. The data is recorded by the Flash Analog to Digital Converter (FADC CAEN V1729A, 2 GHz sampling frequency, 1.25 µs readout window). The trigger, which comes from the coincidence of the crystal detector and NDs for background suppression, is about 1 Hz when the neutron beam is on. The sub-trigger of the crystal detector is generated by the coincidence of PMT1 and PMT2, where the single channel threshold is about 0.5 p.e.

The detectors are calibrated with sources, $^{2\ 1}$Am and ^{13} Cs. The $^{2\ 1}$Am spectra of CsI(Na) and CaF (Eu) are shown in Fig. 3. The measured light yields of

CsI(Na) and CaF (Eu) are 5.6 p.e./keV and 2.0 p.e./keV respectively. The effective trigger threshold of the crystal detectors is about 5 p.e. (50% efficiency), which is mainly related to the crystal light emission time constant and coincidence window, and its efficiency is checked by calibration sources, background, and Toy Monte Carlo results; the induced uncertainty will be considered in the following analysis. The NDs are calibrated with ^{13} Cs and their threshold is 0.1 MeV.

[Figure 3: see original paper]

Figure 3: Calibration result with ^{2} ^{1}Am source. Left: CsI(Na). Right: CaF (Eu). The energy resolution is calculated with /Mean of the fitting result. The blue dash lines are the spectra after trigger efficiency correction.

3. Data Analysis

Neutron/ discrimination is key to the analysis. In this section, the analysis procedures for CsI(Na) are described in detail as an example. The fluctuation of time of flight (TOF), one important input, is about 2.5 ns, which is calculated by fitting the - peak in Fig. 4.

TOF distributions of CsI(Na) (Fig. 4, black line) clearly show four peaks from left to right:

1. **The - peak:** This peak is formed by rays generated along with the neutron beam, scattering from the crystal and triggering the NDs. Since rays have the highest and fixed speed, this peak appears on the far left and has the narrowest width.
2. **The n- peak:** Neutrons react with the CsI(Na) crystal via inelastic processes and the secondary rays trigger NDs.
3. **The n-n-elastic peak:** Neutrons elastically scatter with nuclei in the crystal then trigger NDs. Since elastic scattering is mono-energetic at a fixed scattering angle, this peak has a narrow width.
4. **The n-n-inelastic peak:** Neutrons react with the crystal via inelastic processes, for example Cs(n,n)Cs, and the neutrons trigger NDs. Because the inelastically scattered neutrons are not mono-energetic and the energy loss is higher than for elastically scattered ones, this peak appears on the far right and has the widest distribution.

Aside from the four peaks, the wide and nearly flat part in Fig. 4 is due to the direct current component of the pulsed beam and the accidental coincidence of neutrons from room scattering.

[Figure 4: see original paper]

Figure 4: TOF distributions of CsI(Na) from neutron source to NDs. Black line: Raw data. Blue line: After 2-D cut on ND energy and PSD (Fig. 5). Red line: After TOF cut (Fig. 6).

[Figure 5: see original paper]

Figure 5: Distribution of neutron energy deposited in ND3 vs PSD signal amplitude of CsI(Na). The red line shows the discrimination between neutron events on the right and   events on the left.

To select clean scattering neutron samples, a 2-D cut on ND energy and PSD is applied (Fig. 5). Then the neutron events, including elastic and inelastic neutrons, are clearly selected (Fig. 4, blue line). The 2-D cut, compared with the traditional 1-D PSD cut, has higher background rejection efficiency.

To further select elastic scattering neutron events, a TOF cut is utilized as shown in Fig. 6, region A. Region B contains inelastic scattering events and region C contains accidental coincidence events. The cut is determined using a mean value predicted by the - peak plus elastic scattering neutron TOF and ±5 ns (2 times the fluctuation). The prediction is consistent with the data.

[Figure 6: see original paper]

Figure 6: Distribution of TOF vs neutron energy deposited in ND3. Part A: between the two red lines, elastic scattering events; Part B: inelastic scattering events; Part C: random coincident events.

The elastic scattering neutron events are clearly selected (Fig. 4, red line), and the number of photoelectron (N__pe) distributions of CsI(Na) are shown in Fig. 7. A Toy Monte Carlo is constructed to calculate the elastic scattering neutrons, including the effects of beam energy smear, detector geometry, ND efficiency, and crystal response. The elastic scattering cross sections between nucleus and neutron are obtained from the National Nuclear Data Center database [**?**]. The simulation results are also shown in Fig. 7 and Fig. 8, which are basically consistent with the data. Because of the close masses of Cs and I, recoils from Cs or I cannot be distinguished and the fitted results correspond to their averaged energy. For CaF (Eu), the same analysis method is applied and the spectrum can be fitted with a double-Gaussian function for Ca and F recoiling (Fig. 8).

[Figure 7: see original paper]

Figure 7: Recoil energy spectra of CsI(Na) tagged by each ND and fitted with Gaussian function. The labeled energies are the average of Cs and I recoil energies. Black dots are experimental data and blue lines are Monte Carlo simulations.

[Figure 8: see original paper]

Figure 8: Energy spectra of CaF (Eu) tagged by each ND and fitted with double Gaussian function. Black dots are experimental data and blue lines are Monte Carlo simulations.

4.1. Quenching Factor

In a scintillation detector, both organic and inorganic, the energy of heavy ions is always quenched and only part of its energy is released as scintillation photons. This fraction is called the quenching factor and it is an important property of the crystal. Generally speaking, a larger quenching factor value, i.e., higher light yield, results in better neutron/ discrimination. The quenching factor is defined as:

$$QF = \frac{E_{\text{meas}}}{E_{\text{recoil}}}$$

where E_meas is calculated from the measured p.e. normalized by the crystal light yield determined by $^{2\ 1}$Am calibration data, and E_recoil is the recoil energy calculated with Eq. 1. For CsI(Na), E_recoil is the averaged recoil energy of Cs and I. The quenching factors of CsI(Na) and CaF (Eu) (Fig. 9) are consistent with previous measurements [**?**, **?**] within uncertainties.

[Figure 9: see original paper]

Figure 9: Quenching factors for crystal samples. Left: CsI(Na). Right: CaF (Eu). The present results are compared with H. Park et al. [**?**] and R. Hazama et al. [**?**]. Both systematic and statistical errors are included for R. Hazama and our results, while only statistical error is shown for H. Park' s results.

In Fig. 9, the horizontal uncertainties are dominated by the 1 degree scattering angle uncertainties, while the vertical uncertainties include contributions from statistics, trigger efficiency, and systematics, which are dominated by crystal response non-linearity to electrons. In Eq. 2, it is assumed that the light yield is linear at different   energies, but the calibration data shows a 10%-20% nonlinearity, indicating that   rays also quench slightly in the crystal, which is also observed in Ref. [**?**]. The light yield differences for $^{2\ 1}$Am and ^{13} Cs are taken as systematics: 18.6% for CsI(Na) and 15.4% for CaF (Eu). Uncertainties from trigger efficiency are also included in our results.

4.2. Quality Factor of Neutron/ Discrimination

To quantify the discrimination capability between elastic scattering neutrons and   events, a quality factor [**?**] is defined as:

$$Q = \frac{\beta(1-\beta)}{(\alpha-\beta)^2}$$

where   means the fraction of signals passing the selection criteria and   is the fraction of backgrounds passing the same criteria. For an ideal detector,   = 1 and   = 0. Therefore, a smaller quality factor means better discrimination between signal and background events.

A variable A /A [?] is defined to calculate the quality factor, where A is the charge of the first 25 ns of a pulse and A is the total charge of the pulse. Fig. 10 presents the A /A distribution of the CsI(Na) crystal and the quality factors at different energies are obtained (Fig. 11). Our result is better than the previous test, where the quality factor was calculated with the mean time of a pulse [?]. For CaF (Eu), the distribution of A /A is shown in Fig. 12; it is difficult to discriminate elastic scattering neutron events from events.

[Figure 10: see original paper]

Figure 10: A /A distribution of CsI(Na) triggered with ND3.

[Figure 11: see original paper]

Figure 11: Quality factors of CsI(Na). The present results are compared to H. Park et al. [?]. The errors are statistical only.

[Figure 12: see original paper]

Figure 12: A /A distribution of CaF (Eu) triggered with ND3.

5. Conclusion

The nuclear recoils of CsI(Na) and CaF (Eu) crystals are studied with a 14.7 MeV neutron beam. Quenching factors are reported and are consistent with previous work. The quality factor between elastic scattering neutrons and events is obtained for Cs or I in CsI(Na) at various recoil energies, and improved results are achieved by using the new discrimination parameter.

The results indicate that CsI(Na) can discriminate elastic scattering neutrons and backgrounds to a certain extent, while CaF (Eu) does not have sufficient capability for neutron/ discrimination using A /A at low energy. The systematic uncertainties of the quenching factor mainly come from the nonlinearity of the energy response of the crystals. Calibrations of this nonlinearity must be performed to improve measurement accuracy. To extend the measurements to lower nuclear recoil energies, crystals with higher light yield should be used.

Acknowledgements

This work is supported by the Ministry of Science and Technology of the People's Republic of China (No. 2010CB833003). We thank L. Hou, H.T. Chen, and F. Zhao of CIAE for their help during the experiment, and we are grateful to T. Alexander of Pacific Northwest National Lab for assistance with language editing.

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Note: Figure translations are in progress. See original paper for figures.