Low-Temperature Performance of CsI(Na) Crystals for WIMPs Direct Searches (Postprint)

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Abstract

Previous studies showed that CsI(Na) crystals have significantly different waveforms between alpha and gamma scintillations. In this work, the light yield and PSD capability of CsI(Na) scintillators as a function of the temperature down to 80 K has been studied. As temperature drops, the fast component rises and the slow component decreases. By cooling the CsI(Na) crystals, the light yield of high ionization events are enhanced significantly, while the light yield of background gamma events are suppressed. At 110 K, CsI(Na) crystal achieves the optimal balance between low threshold and good background rejection performance. The different responses of CsI(Na) to gamma and alpha at different temperatures are explained with self-trapped and activator luminescence centers.

Full Text

Preamble

Low Temperature Performance of CsI(Na) Crystals for WIMPs Direct Searches

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Abstract

Previous studies demonstrated that CsI(Na) crystals exhibit significantly different scintillation waveforms between alpha and gamma radiation. In this work, we investigated the light yield and pulse shape discrimination (PSD) capability of CsI(Na) scintillators as a function of temperature down to 80 K. As temperature decreases, the fast component of the scintillation signal increases while the slow component decreases. By cooling CsI(Na) crystals, the light yield for high-ionization events is significantly enhanced, whereas the light yield for background gamma events is suppressed. At 110 K, the CsI(Na) crystal achieves an optimal balance between low detection threshold and effective background rejection. The distinct responses of CsI(Na) to gamma and alpha particles at different temperatures are explained through the interplay of self-trapped exciton and activator luminescence centers.

Keywords: CsI(Na), Crystal, Dark matter, Nuclear recoil, Particle discrimination, Self-trapped exciton

1. Introduction

It is widely accepted that dark matter constitutes approximately 27% of the universe' s mass-energy content [**?**]. If dark matter consists of Weakly Interacting Massive Particles (WIMPs), these particles could scatter off nuclei in detector materials, depositing nuclear recoil energies in the range of 1–100 keV. Consequently, detector materials must have sufficiently low energy thresholds to detect such small energy depositions.

Since nuclear recoil events are extremely rare (estimated at less than 0.1 events/kg/day), it is essential to construct shields using materials with very low radioactivity. However, some internal background gamma events from the shielding or detector materials themselves are inevitable. Therefore, a background rejection capability better than 10 is critical for distinguishing nuclear recoils from electron recoil backgrounds.

Cesium iodide is a well-studied and widely used crystal scintillator. Doped CsI crystals such as CsI(Tl) and CsI(Na) exhibit high light yield and excellent PSD capability. Previous research has shown that CsI(Na) displays very different responses to nuclear recoils and electron recoils [**?**]. The fast scintillation light in CsI(Na) originates from self-trapped exciton (STE) luminescence, which is significantly enhanced by high-ionization-density particles such as nuclear recoils. In contrast, the slow light component is attributed to activator luminescence (Na emission), which is primarily excited by low-ionization-density particles like electron recoils. At room temperature, the decay time of the fast component is approximately 20 ns, while that of the slow component is 670 ns. This substantial difference in pulse shapes between nuclear and electron recoils makes CsI(Na) a promising candidate for dark matter detection.

Since nuclear recoils are dominated by STE emission, the detection threshold for these events depends on the light yield of the fast component. It is possible to enhance STE emission by cooling the crystal. For pure CsI crystals, the scintillation light yield is below 5,000 photons/MeV at room temperature but reaches 100,000 photons/MeV at 77 K [**?**, **?**]. The present work aims to investigate the influence of low temperature (80 K to room temperature) on the light yield and PSD capability of CsI(Na) and to determine the optimal operating temperature for applications such as direct WIMP detection. Pure CsI crystals were also tested for comparison.

2. Experimental

In this study, we measured the response of CsI(Na) and pure CsI crystals to gamma and alpha particles at low temperatures. Scintillation was excited by 661.7 keV gamma rays from a 0.5 Ci ^{13} Cs source and 5,244 keV alpha particles from a 5 Ci ^{23} Pu source. The samples were placed in a homemade cryostat cooled with liquid nitrogen.

2.1. Experimental Setup

The experimental apparatus is illustrated in [Figure 1: see original paper]. A cubic crystal sample (25 mm × 25 mm × 25 mm) was placed inside a cold copper base within the homemade cryostat. Both CsI(Na) and pure CsI crystals had these dimensions, with a Na doping concentration of approximately 0.02% in the CsI(Na) sample. The left and right surfaces served as light-emitting faces, while the other four surfaces were in contact with the cooled base. A layer of Enhanced Specular Reflector (ESR) film was inserted between the crystal and cold base to minimize light loss during internal reflection. The cold base was continuously cooled by a copper rod whose bottom end was immersed in liquid nitrogen in a dewar. A heater with PID power control was mounted at the junction between the cold base and copper rod. A Pt100 thermal sensor attached to the bottom surface of the crystal monitored temperature and provided feedback to the temperature control system, which achieved a precision of ±0.1 K. The crystal and cold base were enclosed in a 2 mm-thick fused quartz vessel with 80% transmittance across a wide spectral range. Since CsI(Na) is hygroscopic, the sample surfaces were polished to remove the deliquescent outer layer. The interior of the quartz vessel was continuously evacuated to maintain low temperature and prevent further deliquescence. Two 2-inch photomultiplier tubes (PMTs, Hamamatsu R8778) were positioned outside the quartz vessel, facing the two light-emitting sides of the crystal to collect scintillation light. The R8778 PMTs feature high quantum efficiency (>30%) and ultra-low background [?], with similar quantum efficiency at 310 nm and 410 nm.

2.2. Data Acquisition

The data acquisition system is shown in [Figure 2: see original paper]. Signals from the two PMTs were split using a linear fan-in/fan-out module (CAEN N625). One set of the two-channel signals was sent to a waveform acquisition device, while the other set was fed into a discriminator (CAEN N840) and converted to logical pulses. The discriminator threshold was set to 0.5 times the single-photon voltage level. The two-channel logical pulses from the discriminators were input to a gate generator, which produced two-channel 1000 ns gate signals. The coincidence of these two gate signals triggered acquisition of the two-channel PMT signals by the waveform acquisition device. Full waveforms were transferred to a PC and saved to hard disk. The waveform acquisition device was either four synchronized digitizers (CAEN V1729a) or an oscilloscope (Tektronix DPO3054C), depending on the required acquisition window width. Each digitizer had a memory depth of 1.26 s with a sampling frequency of 2 GS/s; the four synchronized digitizers could acquire 5 s-long waveforms at 800 Hz. The oscilloscope could acquire 400 s-long waveforms at 2.5 GS/s with a rate of less than 1 Hz.

3. Results

The temperatures of both pure CsI and CsI(Na) samples were first lowered to 80 K and then gradually increased to room temperature.

3.1. Waveform of CsI(Na)

[Figure 3: see original paper] shows the waveforms of gamma scintillations (661.7 keV) and alpha scintillations (5.2 MeV) from the CsI(Na) crystal. The alpha scintillation waveforms consist of both fast and slow components, while the gamma scintillations are dominated by the slow component at higher temperatures. As temperature decreases, the fast component of alpha scintillations increases significantly, and both alpha and gamma scintillations become slower.

For alpha scintillations, both fast and slow components slow down with decreasing temperature. The decay time of the fast component increases from 16 ns at 298 K to 700 ns at 80 K. The profile of the slow component becomes flat and difficult to distinguish from the fast component below 190 K.

For gamma scintillations from CsI(Na), the slow component dominates the waveforms at higher temperatures. As temperature decreases, the slow component becomes lower and flatter while the fast component emerges. In [Figure 3: see original paper]a, a notable fast component appears on the leading edge of gamma scintillations below 210 K. At 80 K, the decay time of the fast component is 750 ns.

3.2. Waveform of Pure CsI

[Figure 4: see original paper] shows the waveforms of gamma scintillations (661.7 keV) and alpha scintillations (5.2 MeV) from the pure CsI crystal. In both cases, only fast components are observed, and the waveforms slow down and broaden as temperature decreases. At 80 K, the decay time is 620 ns for alpha scintillations and 700 ns for gamma scintillations. The alpha and gamma scintillations from pure CsI are very similar to the fast components of scintillations from CsI(Na).

This comparison indicates that CsI(Na) waveforms contain both fast and slow components, while pure CsI waveforms contain only the fast component, suggesting that the slow component can be attributed to Na activators. As a dopant, Na activators have larger average spacing than in pure CsI. The observation that gamma events produce significantly more slow component than alpha events is consistent with the mechanism discussed in our previous papers [**?**, **?**].

3.3. Light Yields

We integrated the waveforms from the trigger point to 5 s after the trigger as a measure of the fast component light yield. Integration over a 400 s range was used to measure the total light yield, including both fast and slow components.

[Figure 5: see original paper] plots the light yield of CsI(Na) and pure CsI crystals as a function of temperature. The first 5 s of the scintillation waveform is dominated by the fast component, while the full 400 s waveform includes both components. As temperature decreases, the light yield of both fast and slow components from alpha scintillations in CsI(Na) rises, while the gamma scintillation light yield drops. From 298 K to 80 K, the alpha scintillation light yield increased by factors of 8.25 and 5.56 for the fast component window and full waveform, respectively, while the gamma scintillation light yield decreased by 9.2% and 10%, respectively. For pure CsI, the light yield of both alpha and gamma scintillations increases as temperature falls. At 80 K, the alpha and gamma scintillation light yields were 62 and 30.4 times higher, respectively, compared to those at 298 K.

3.4. Pulse Shape Discrimination

We characterized the PSD capability using the ratio of the fast component to the total light yield in CsI(Na). Since the decay time of the fast component varies with temperature, the integration window width for the fast component was optimized to maximize the difference in the fast/total ratio between particle types.

The optimal time window is plotted as a function of temperature in [Figure 6: see original paper]. As temperature decreases, the optimal window time increases, with a rapid change between 120 K and 180 K.

Using the determined time window widths, the background rejection ratio was calculated for different temperatures with a minimum signal efficiency of 60%. The results are shown in [Figure 7: see original paper] as a function of the number of photoelectrons. CsI(Na) achieves its best background rejection performance at 150 K, reaching as low as 10   at 10 photoelectrons. However, as shown in [Figure 5: see original paper], further temperature decreases significantly increase the fast component light yield. We must therefore balance the benefit of a lower threshold for nuclear recoil events against the cost of reduced background rejection performance. Given the low energies of nuclear recoil events, 110 K may be the optimal operating temperature for future CsI(Na)-based dark matter detectors.

[Figure 8: see original paper] shows the PSD scatter plot at 160 K with a fast component integration window of 1.26 s. Alpha and gamma scintillation events form two separate bands. Electron recoil events bend upward sharply below 10 photoelectrons and cross into the nuclear recoil event zone, consistent with [Figure 7: see original paper]. Moreover, a small but non-negligible number of electron events are mixed within the nuclear recoil event zone.

4. Discussion

According to Payne et al. [**?**] and Gridin et al. [**?**], after the creation of electron-hole pairs, multiple interaction pathways exist for electrons and holes to recombine with each other and with activators. Electrons and holes can form excitons, or holes can become self-trapped and recombine with electrons to form self-trapped excitons (STEs). Activators can capture electrons and holes and transition to excited states.

In pure CsI, STEs dominate the luminescence centers. If the distance between an electron and a hole is r, the electron diffuses under the Coulomb field and recombines with the hole with probability p = 1 - e^(-R_Ons/r), where R_Ons = e^2/(4 k_BT) is the Onsager radius (e is electron charge, is static dielectric permeability, k_B is Boltzmann constant, and T is temperature). As temperature decreases, the Onsager radius increases, allowing electrons at greater distances from holes to diffuse and recombine. This results in more exciton formation, enhancing STE emission and the fast component as temperature drops.

In CsI(Na), both STE and activator (Na) luminescence can occur. To form an excited activator state, the activator must capture an electron and a hole (or sequentially capture a hole and then an electron), which limits the production rate of excited activator states. The slow component originates from activator luminescence. Since the total number of electrons and holes is fixed, STE and activator luminescence are competing processes. The dominant process depends on the concentrations of activators (n_A), electrons (n_e), and holes (n_h). Electrons and holes are created in pairs, so n_e = n_h. For high-ionization-density particles, n_h n_A, so electrons are most likely captured by self-trapped holes, making STE luminescence dominant. This explains why alpha scintillation waveforms are dominated by the fast component and closely resemble waveforms from pure CsI.

For low-ionization-density particles like gamma rays or electrons, n_h n_A, giving electrons a much higher probability of being captured by activators than of recombining with self-trapped holes to form STEs. Consequently, the slow component dominates in gamma scintillation waveforms from CsI(Na).

The activator capture radius changes little with temperature because it is determined by dipole polarization of the neutral activator center in the electron Coulomb field [**?**]. As temperature decreases, the Onsager radius increases while the activator capture radius remains essentially constant, causing STE emission to increase and activator emission to decrease. By cooling CsI(Na) crystals, we can enhance the quenching factor for high-ionization-density events while suppressing it for gamma background, significantly lowering the energy threshold for detecting nuclear recoil events.

5. Conclusions

CsI(Na) crystals demonstrate discriminability between alpha and gamma scintillations at temperatures as low as 80 K. As temperature decreases, the light yield for alpha scintillations increases while that for gamma scintillations decreases. The responses of CsI(Na) and pure CsI to gamma and alpha particles at different temperatures can be explained by the competition between STE and activator luminescence formation channels. Cooling CsI(Na) crystals enhances the light yield for high-ionization-density (nuclear recoil) events while suppressing the light yield for gamma background events. The PSD capability of CsI(Na) peaks at 110 K, which represents the optimal operating temperature for future CsI(Na)-based dark matter detectors.

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Figure Captions

[Figure 1: see original paper] Experimental setup

[Figure 2: see original paper] Data acquisition system

[Figure 3: see original paper] Waveforms of CsI(Na). (a) Gamma scintillation waveforms at different temperatures. Each waveform is the average of 50 events at the 661.7 keV peak. (b) Alpha scintillation waveforms at different temperatures. Each waveform is the average of 50 events at the 5.2 MeV peak.

[Figure 4: see original paper] Waveforms of pure CsI. (a) Gamma scintillation waveforms at different temperatures. Each waveform is the average of 50 events at the 661.7 keV peak. (b) Alpha scintillation waveforms at different temperatures. Each waveform is the average of 50 events at the 5.2 MeV peak.

[Figure 5: see original paper] Light yield of pure CsI and CsI(Na) as a function of temperature. The light yield values have been multiplied by a factor of 3.86 to account for the difference in light collection efficiency between PMTs directly coupled to crystals and those placed outside the quartz vessel. Black squares: light yield from the first 5 s integration of gamma scintillations from pure CsI. Red dots: light yield from the first 5 s integration of alpha scintillations from pure CsI. Blue and cyan triangles: light yield from 400 s integration of scintillation waveforms from CsI(Na). Magenta and yellow triangles: light yield from the first 5 s integration of scintillation waveforms from CsI(Na).

[Figure 6: see original paper] Optimized fast component window time at different temperatures. The window time is defined as the intersection point of the normalized gamma and alpha scintillation waveforms from CsI(Na).

[Figure 7: see original paper] Background rejection ratio at different temperatures

[Figure 8: see original paper] PSD scatter plot of gamma and alpha events at 160 K. Red dots represent gamma events; blue dots represent alpha events.

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