

## Precise Determination of the Intrinsic Relative Light Yield of CsI(Tl) Crystals from $-40\text{ }^{\circ}\text{C}$ to $40\text{ }^{\circ}\text{C}$

**Authors:** Sun, Dr. Yu, Tang, Dr. Shuwen, Yu, Dr. Yuhong, Wang, Dr. ShiTao, Zhang, Dr. Xueheng, Zhang, Prof. Huai qiang, Zeng, Dr. Qi, Huang, Dr. Feng Jin, Huang, Mr. Xing, Li, Mr. Long Wen, Sun, Prof. Zhiyu 孙志宇, Liu, Mrs. Yu-Min, Sun, Dr. Yu

**Date:** 2026-02-04T10:12:42+00:00

### Abstract

Thallium-doped cesium iodide (CsI(Tl)) crystals are widely used in nuclear radiation detection and high energy physics experiments, but their scintillation light yield is highly temperature-dependent, which impairs detector stability and accuracy in variable-temperature environments. To address this issue, we propose a high precision method for determining the intrinsic relative light yield of CsI(Tl) crystals. Geant4 simulations confirm that the photon collection efficiency of small-sized CsI(Tl) crystals ( $1\text{cm}^3$ ) can be treated as a constant, eliminating wavelength interference and simplifying the measurement system. We decompose the photodiode (PD) quantum efficiency into wavelength-dependent ( $Q1(\lambda)$ ) and temperature-dependent ( $Q2(\lambda)$ ) components, and systematically characterize their temperature behaviors as well as the wavelength-averaged quantum efficiency ( $Q(T)$ ). Using this method, we measure the intrinsic relative light yield of CsI(Tl) crystals over the temperature range of  $-40\text{ }^{\circ}\text{C}$  to  $40\text{ }^{\circ}\text{C}$ . The results show a non-monotonic temperature dependence: the relative light yield increases quadratically by 16% from  $-40\text{ }^{\circ}\text{C}$  to  $24\text{ }^{\circ}\text{C}$  (peaking near  $24\text{ }^{\circ}\text{C}$ ), and then decreases slightly by 0.8% as the temperature rises to  $40\text{ }^{\circ}\text{C}$ . Compared with conventional methods using photomultiplier tubes or silicon photomultipliers, our approach avoids temperature coupling interference from readout devices, achieving higher measurement accuracy with simplified procedures. This study provides accurate key parameters and a reliable theoretical basis for the design, calibration, and optimization of CsI(Tl)-based energy-spectrum detectors applied in complex temperature-varying scenarios such as space exploration and deep-sea surveys.

## Full Text

### Preamble

Precise Determination of the Intrinsic Relative Light Yield of CsI(Tl) Crystals from  $-40^{\circ}\text{C}$  to  $40^{\circ}\text{C}$  \* Yu Sun,<sup>1, 2, 3</sup> Shu-Wen Tang,<sup>4</sup> † Yu-Hong Yu,<sup>4</sup> Shi-Tao Wang,<sup>4</sup> Xue-Heng Zhang,<sup>4</sup> Huai-Qiang Zhang,<sup>1, 2, 3</sup> Qi Zeng,<sup>1, 2, 3</sup> Jin-Feng Huang,<sup>1, 2, 3</sup> Xing Huang,<sup>1, 2, 3</sup> Weng-Long Li,<sup>1, 2, 3</sup> Zhi-Yu Sun,<sup>4</sup> and Yu-Min Liu<sup>1, 2, 3, ‡</sup> <sup>1</sup>Engineering Research Center of Nuclear Technology Application (East China University of Technology), Ministry of Education, Nanchang ,330013, China <sup>2</sup>Jiangxi Engineering Technology Research Center of Nuclear Radiation Detection and Application, Nanchang 330013, China <sup>3</sup>School of Nuclear Science and Engineering, East China University of Technology, Nanchang 330013, China <sup>4</sup>Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China Thallium-doped cesium iodide (CsI(Tl)) crystals are widely used in nuclear radiation detection and high- energy physics experiments, but their scintillation light yield is highly temperature-dependent, which impairs detector stability and accuracy in variable-temperature environments. To address this issue, we propose a high- precision method for determining the intrinsic relative light yield of CsI(Tl) crystals. Geant4 simulations confirm that the photon collection efficiency of small-sized CsI(Tl) crystals ( $1\text{cm}^3$ ) can be treated as a constant, eliminating wavelength interference and simplifying the measurement system. We decompose the photodiode (PD) quantum efficiency into wavelength-dependent ( $Q_1(\lambda)$ ) and temperature-dependent ( $Q_2(\lambda)$ ) components, and systematically characterize their temperature behaviors as well as the wavelength-averaged quantum efficiency ( $Q(T)$ ). Using this method, we measure the intrinsic relative light yield of CsI(Tl) crystals over the temperature range of  $-40^{\circ}\text{C}$  to  $40^{\circ}\text{C}$ . The results show a non-monotonic temperature dependence: the relative light yield increases quadratically by 16% from  $-40^{\circ}\text{C}$  to  $24^{\circ}\text{C}$  (peaking near  $24^{\circ}\text{C}$ ), and then decreases slightly by 0.8% as the temperature rises to  $40^{\circ}\text{C}$ . Compared with conventional methods using photomultiplier tubes or silicon photomultipliers, our approach avoids temperature coupling interference from readout devices, achieving higher measurement accuracy with simplified procedures. This study provides accurate key parameters and a reliable theoretical basis for the design, calibration, and optimization of CsI(Tl)-based energy-spectrum detectors applied in complex temperature-varying scenarios such as space exploration and deep-sea surveys.

Keywords: CsI(Tl) scintillator, relative light yield, temperature dependence, photon collection efficiency, quantum efficiency decoupling

## INTRODUCTION

Thallium-doped cesium iodide (CsI(Tl)) crystals are widely employed in nuclear radiation detection and high- energy physics experiments due to their high atomic number, high density, and excellent luminescent properties, particularly their high light yield and emission spectrum well- matched to semi-

conductor photodetectors. Coupling CsI(Tl) with photodiodes (PDs) or silicon photomultipliers (SiPMs) to form compact, high-performance energy-spectrum detection systems has become a standard technique for radiation measurements at room temperature[1]. However, the performance stability of such detectors faces significant challenges in applications involving wide temperature variations, such as space science missions and deep-sea exploration, where temperature cycles can range from extremely low (e.g., in shadowed regions) to high (in sunlit areas)[2, 3]. The temperature dependence of the scintillation light yield of CsI(Tl) is a critical factor leading to energy-response instability and calibration drift, ultimately compromising the accuracy and reliability of the measurements. This work is supported by National Science Foundation of China (No:12275050), Jiangxi Provincial Natural Science Foundation (No:20252BAC240175, 20252BAC240171) and Jiangxi Province Engineering Research Center of Nuclear Technology Application, Ministry of Education Funded Project (No:HJS-JYB2022-3) Foundation. † Corresponding author, tangsw@impcas.ac.cn ‡ Corresponding author, liuyumin@ecut.edu.cn

bility of spectral data[4, 5]. Extensive research has been conducted to characterize the temperature-dependent scintillation properties of CsI(Tl). Studies have covered a broad temperature range, from near liquid nitrogen temperatures  $-182^{\circ}\text{C}$  up to  $+400^{\circ}\text{C}$ [6, 7], investigating parameters such as absolute light yield, energy resolution, non-proportionality, and decay kinetics. For instance, Grodzicka et al. characterized CsI(Tl) from  $-40^{\circ}\text{C}$  to  $+22^{\circ}\text{C}$  using a large-area avalanche photodiode (LAAPD), analyzing light output and resolution versus peaking time[8]. Similarly, Swiderski et al. employed a SiPM to study relative light yield and non-proportionality from  $-182^{\circ}\text{C}$  to  $+152^{\circ}\text{C}$ , revealing a strong decrease in light yield at both low and high temperatures[9]. A fundamental limitation persistent in these studies is the temperature sensitivity of the photodetectors themselves. When photomultiplier tubes (PMTs) or SiPMs are used, their gain, photon detection efficiency (PDE), and breakdown voltage are all temperature-dependent[10, 11]. This introduces a coupled temperature effect where the measured “system light output” conflates the response of the crystal and the readout device, making it difficult to extract the intrinsic temperature dependence of the crystal’s light yield. Although photodiodes (PDs) operate with minimal gain and exhibit superior temperature stability in responsivity[12], their quantum efficiency (Q) still varies with both wavelength ( $\lambda$ ) and temperature (T).

Prior works using PDs often neglected these dependencies or treated Q as constant[13], introducing systematic errors that obscure the true crystal behavior.

II. THEORETICAL DESCRIPTIONS constant  $\beta$  into Eq.(1), and integrating over the entire time domain yields:

To accurately extract the intrinsic relative scintillation light yield of CsI(Tl) crystals from experimental measurements, it is necessary to establish a complete physical model describing the entire chain from gamma-ray energy deposition in the crystal to the generation of a usable electrical signal from the photodiode (PD). This process can be decomposed into three sequential stages: (1) A

gamma ray deposits energy  $E_\gamma$  in the crystal, generating scintillation photons characterized by a specific temporal decay and spectral distribution; (2) These photons are collected and transmitted to the photosensitive surface of the PD; (3) The PD absorbs the photons and generates electron-hole pairs, which are subsequently converted into a measurable voltage signal. The mathematical modeling of this complete process is developed below. When a gamma ray with energy  $E_\gamma$  is fully absorbed by the CsI(Tl) crystal, the total number of electron-hole pairs  $N_{eh}(E_\gamma, T)$  generated in the depletion region of the PD can be expressed by the integral:

$$N_{eh}(E_\gamma, T) = \int_0^{E_\gamma} N(E_\gamma, \lambda, T, t) \eta(\lambda, T, t) Q(\lambda, T, t) d\lambda dt$$
 Here,  $N(E_\gamma, \lambda, T, t)$  represents the number of scintillation photons at time  $t$ , temperature  $T$ , and wavelength  $\lambda$  produced by the deposited energy  $E_\gamma$ [14]. This function fully describes the temporal decay and spectral characteristics of the scintillation light. The light pulse shape of CsI(Tl) is commonly described by a multi-exponential decay model. Specifically considering two main components,  $N(E_\gamma, \lambda, T, t)$  can be expressed as:

$$N(E_\gamma, T, t) = E_\gamma [N_1(T) e^{-t/\tau_1(T)} + N_2(T) e^{-t/\tau_2(T)}] \epsilon(\lambda, T)$$
 where  $N_1(T)$  and  $N_2(T)$  represent the total number of scintillation photons produced per unit deposited energy via decay mode 1 and 2, respectively.  $\tau_1(T)$  and  $\tau_2(T)$  are the temperature-dependent decay time constants.  $\epsilon(\lambda, T)$  is the normalized scintillation emission spectrum, satisfying  $\int_0^\infty \epsilon(\lambda, T) d\lambda = 1$ . The factor  $\eta(\lambda, T, t)$  in Eq.(1) is the photon collection efficiency, defined as the probability that a scintillation photon of wavelength  $\lambda$  is absorbed by the PD.

Given a fixed detector geometry and optical coupling, and for a sufficiently small crystal size, the variation of  $\eta$  with time  $t$  and temperature  $T$  can be neglected. Furthermore, within the limited emission spectrum of CsI(Tl), its variation with wavelength  $\lambda$  is also significantly reduced for small crystals, as will be quantitatively verified by Geant4 simulations in Section III. Therefore,  $\eta$  can be simplified as a constant  $\eta_0$ . The factor  $Q(\lambda, T, t)$  is the quantum efficiency of the PD, defined as the average probability that an absorbed photon creates one electron-hole pair. This efficiency is primarily governed by the material properties of the PD and can be defined as  $Q(\lambda, T, t) = Q(\lambda, T)$ . The quantum efficiency depends on both the photon wavelength (via the absorption coefficient) and the temperature (via carrier transport and recombination rates). These dependencies are approximately separable, allowing the decomposition:

$$Q(\lambda, T) = Q_1(\lambda) Q_2(T)$$
 where  $Q_1(\lambda)$  captures the spectral response and  $Q_2(T)$  captures the temperature-dependent factor. Substituting Eq.(2) and the simplified  $N_{eh}(E_\gamma, T) = E_\gamma [N_1(T) + N_2(T)] \int_0^\infty Q(\lambda, T) \epsilon(\lambda, T) d\lambda$  Let  $N_{Abs}(T) = N_1(T) + N_2(T)$ , defined as the absolute scintillation light yield (photons per MeV). To comprehensively account for the spectral overlap between the crystal emission and the PD response, we introduce the wavelength-averaged quantum efficiency at temperature  $T$ : 
$$\bar{Q}(T) = \int_0^\infty Q(\lambda, T) \epsilon(\lambda, T) d\lambda = \int_0^\infty Q_1(\lambda) Q_2(T) \epsilon(\lambda, T) d\lambda$$
 Thus, Eq.(4) simplifies to the core

expression linking the measured electron-hole pairs to the crystal's intrinsic light yield:

$N_{eh}(E_\gamma, T) = E_\gamma * N_{Abs}(T) * Q(T)$  In the experiment, the signal amplitude  $V(T)$  from the readout electron (T). Considering measurements at two temperatures T and a reference temperature  $T_{ref}$  (e.g., +25 °C), their ratio is:

$\frac{V(T)}{V(T_{ref})} = \frac{N_{Abs}(T) * Q(T)}{N_{Abs}(T_{ref}) * Q(T_{ref})}$  Defining the relative light yield as  $N_{ref}(T) = N_{Abs}(T)$  relative signal as  $V_{ref}(T) = V(T)$  from Eq.(3) and (5), we obtain the final working formula:

$N_{Abs}(T_{ref})$  and the  $V(T_{ref})$ , and using the decomposition  $N_{ref}(T) = V_{ref}(T) * Q_{ref}(T)$  where  $V_{ref}(T) = \frac{V(T)}{V(T_{ref})}$  is the measured relative signal amplitude.  $Q_{ref}(T) = \frac{Q(T)}{Q(T_{ref})}$  is the relative temperature-dependent component of the PD quantum efficiency, determined independently via an LED-based calibration described in SectionIV.  $Q_{ref}(T) = \frac{Q(T)}{Q(T_{ref})}$  is the relative wavelength-averaged component, with  $Q_1(T) = \frac{Q(T)}{Q(T_{ref})} \propto$

**$\int_0^\infty Q_1(\lambda) \epsilon(\lambda, T) d\lambda$ . This term is calculated using the**

PD's spectral response  $Q_1(\lambda)$  and the temperature-dependent emission spectrum  $\epsilon(\lambda, T)$  of CsI(Tl), as detailed in SectionV.

In summary, Eq.(8) provides the foundation for extracting the crystal's intrinsic relative light yield  $N_{ref}(T)$ . The experimental determination requires: (1) measuring the relative signal amplitude  $V_{ref}(T)$  from the CsI(Tl)-PD detector; (2) calibrating the PD's temperature factor  $Q_{ref}(T)$  (SectionIV); (3) calculating the spectral factor  $Q_{ref}(T)$  using characterized emission and response spectra (SectionV). The critical assumption of a constant photon collection efficiency  $\eta = 1$  is validated separately by Geant4 simulation for small crystals in SectionIII. This methodology effectively decouples the temperature effects of the readout device from the intrinsic property of the scintillator crystal.

**III. VERIFICATION OF CONSTANT PHOTON COLLECTION EFFICIENCY VIA SIMULATION** This section aims to verify the key assumption made in Chapter II, namely that "the photon collection efficiency  $\eta$  can be regarded as a constant  $\eta = 1$ ", through Geant4 simulation. In particular, the wavelength dependence of this assumption is negligible for small crystals.

The photon collection efficiency ( $\eta$ ) is defined as the ratio of the number of photons absorbed by the photodetector to the total number of photons generated within the scintillator. After their generation, the transport of scintillation photons involves multiple mechanisms: some photons undergo multiple reflections at the interfaces between the scintillator and external reflective layers or the detector before ultimately being absorbed by the scintillator material; another portion may be refracted at the scintillator-detector interface and enter the photodetector to be absorbed, or be directly absorbed at the interface. According to Fresnel's laws, the reflection and transmission of photons at an interface

depend on their angle of incidence, polarization state, and the refractive indices of the media on both sides of the interface. Since the refractive index of a material is typically dependent on the photon wavelength, the photon collection efficiency is closely related to the wavelength for a fixed detector geometry.

However, if the scintillator size is sufficiently small, such that photons of different wavelengths, after experiencing multiple reflections at the optical interfaces, can still overwhelmingly enter the photodetector and be absorbed, the influence of wavelength on the collection efficiency may be significantly reduced. To investigate this relationship, we used Geant4 to simulate the variation of photon collection efficiency with wavelength for CsI(Tl) scintillator crystals of different sizes. The selected crystal sizes included  $1 \times 1 \times 1 \text{ cm}^3$ ,  $2 \times 2 \times 2 \text{ cm}^3$ ,  $5 \times 5 \times 5 \text{ cm}^3$  and  $10 \times 10 \times 10 \text{ cm}^3$ . Photon wavelengths were uniformly selected at seven points within the range of 400 nm to 700 nm for simulation. The reflective layer was a 0.01 mm thick aluminum film with its reflectivity set to 100%. The photodetector was made of silicon, with its receiving surface identical in size to the photon-readout end face of the crystal and a thickness of 2 mm, sufficient to prevent photon transmission. Data for the refractive index and absorption length of silicon at different wavelengths were sourced from the website REFLECTIVRIDO.IF[15]. Table 1 lists the refractive index and absorption length of silicon at different wavelengths. The scintillator material was CsI(Tl), and its refractive index of the crystal was approximated by a series expansion for undoped CsI:  $n(\lambda) = (a_0 + \sum_{i=1}^2 \frac{a_i}{\lambda^{2i}} - b_2)$  where the parameterization in  $a_i$  and  $b_i$  are given in Ref.[16]. The absorption length was extracted from Ref.[17]. The interface between the CsI(Tl) crystal and the silicon detector was set as a LogicalBorderSurface, employing the UNIFIED model with the interface type defined as dielectric-dielectric, and was processed to be smooth. In the simulation, randomly polarized photons were generated uniformly and randomly within the crystal. Due to a lack of data correlating interface absorption efficiency with wavelength, we assumed no photon absorption occurs at the interface. Fig.1 illustrates the relationship between photon collection efficiency and wavelength for the four crystal sizes. The solid line represents a Fig. 1 [Figure 1: see original paper]. The variation of photon collection efficiency with wavelength under different crystal sizes smooth curve connecting the data points. The results show that larger crystal sizes correspond to lower photon collection efficiencies, and the efficiency increases with longer wavelengths. This wavelength dependence weakens as the crystal size decreases. For instance, in the  $10 \times 10 \times 10 \text{ cm}^3$  crystal, the maximum deviation from the average in  $\eta$  with wavelength can reach 18.78%. When the crystal size is reduced to  $1 \times 1 \times 1 \text{ cm}^3$ , this variation is less than 2%.

Wavelength(nm)	Refractive index	Absorption length (cm)
4.967e-4	3.359e-4	2.213e-4
1.405e-4	8.044e-5	4.023e-5
1.16e-5		

The primary reason is that in large crystals, photons incident on the crystal-silicon interface have a higher probability of being reflected and failing to return

to the silicon detector, eventually being self-absorbed by the crystal, and this probability increases with shorter wavelengths. In contrast, in small crystals, photons reflected at the crystal-silicon interface travel a limited distance within the crystal before potentially reaching the detector interface again and being absorbed, experiencing less influence from crystal self-absorption.

Consequently, the collection efficiency shows insignificant dependence on wavelength. The significant wavelength dependence of  $\eta$  for large crystals (such as  $10 \times 10 \times 10\text{cm}^3$ ) (with a variation of approximately 19%) is one of the sources of errors in traditional measurements.

The change in  $\eta$  of the  $1\text{cm}^3$  crystal is less than 2%. Therefore, this size was chosen for the subsequent experiments, which eliminated a major interfering variable systematically and laid the foundation for high-precision measurements.

#### IV. CALIBRATION OF THE PD'S TEMPERATURE-DEPENDENT QUANTUM EFFICIENCY

The objective of this section is to provide experimental calibration data for  $Q_{\text{ref}}$  response of the PD itself.

The temperature-dependent component of the silicon photodiode (PD) quantum efficiency, denoted as  $Q_2$ , is characterized by measuring the output signal amplitude of the PD in response to a blue LED light source at different temperatures. When the blue LED illuminates the PD, the number of generated electron-hole pairs can be expressed as:  $400450500550600650700$  Wavelength (nm) 00.10.20.30.40.50.60.70.80.91h3 cm313 cm323 cm353 cm310

4 Fig. 3 [Figure 3: see original paper]. Input LED blue light, PD outputs the signal amplitude in response to temperature. All ADC values have been normalized to the amplitude at  $25^\circ\text{C}$ . indicate that the output amplitude of PD increases by nearly 8.24%, when the temperature changes from  $-40^\circ\text{C}$  to  $40^\circ\text{C}$ , and exhibits an approximately linear relationship with temperature. It can thus be inferred that the  $Q_2$  component of the quantum efficiency increases by approximately 8.24% relative to its value at  $25^\circ\text{C}$  as the temperature rises from  $-40^\circ\text{C}$  to  $40^\circ\text{C}$ . Moreover,  $Q_{\text{ref}}$  exhibits an approximately linear dependence on temperature over this range, providing direct input for Eq.(8). This change is much smaller than the typical temperature drift of the PMT gain or the PDE of the SiPM (which can be as much as several percent), which is the primary reason for selecting the PD as the readout device for temperature testing.

#### V. CALCULATION OF THE WAVELENGTH-AVERAGED QUANTUM EFFICIENCY

The objective of this section is to provide a calculation basis for another key factor,  $Q_{\text{ref}}(T)$ , in Eq.(8). Fig.4(b) shows the luminescence spectra of CsI(Tl) at different temperatures (data source as referenced in literature[14]). It can be observed that the wavelength range of the luminescence spectra changes only slightly under different temperatures, with the most prominent feature being the decrease in light yield near the peak wavelength

as the temperature rises. The PD device provides the radiant sensitivity parameter  $S$  in its official specifications[18]. According to Eq. (11), this radiant sensitivity has a clear conversion relationship with the quantum efficiency at each wavelength[19]. Further analysis reveals that the quantum efficiency of the PD exhibits a three-segment characteristic: it changes approximately linearly in the 300 to 500 nm range, remains essentially stable in the 500 to 700 nm range, and gradually decreases above 700 nm with increasing wavelength as illustrated in the Fig.4(a) Fig. 2 [Figure 2: see original paper]. Electronic block diagram for PD temperature effect test (cid:90)  $\propto$  (cid:90)  $\propto$   $N_{LED}(T) = N_{LED}(\lambda, T, t)\eta_{LED}(\lambda)Q(\lambda, T, t) d\lambda dt$  where  $N_{LED}$  is the number of photons emitted by the LED,  $\eta_{LED}$  is the photon collection efficiency, and  $Q$  is the total quantum efficiency of the PD. The LED emission spectrum is very narrow and can be approximated as a single wavelength. Under the model where the total quantum efficiency can be decomposed into a wavelength-dependent component  $Q_1(\lambda)$  and a temperature-dependent component  $Q_2(T)$  (i.e.,  $Q = Q_1(\lambda)Q_2(T)$ ), and where  $Q_1$  and the photon collection efficiency  $\eta_{LED}$  are constants at the measurement wavelength, the temperature variation of the PD output signal amplitude solely reflects the temperature dependence of  $Q_2$ . Therefore, in the PD temperature response test based on the LED light source, the change in its output signal amplitude is proportional to the change in  $Q_2$ . The test system is shown in Fig.2. A blue LED (wavelength approximately 460 nm) is driven by a 5 V electrical signal from a pulse generator, with the light intensity controlled by adjusting the duty cycle. To eliminate the influence of ambient temperature on the LED luminous intensity, the LED is placed in a constant temperature chamber maintained at  $T = 20^\circ\text{C}$  for stability. The optical signal is transmitted via an optical fiber to the PD surface. The current signal output from the PD is first preliminarily amplified and converted into a voltage signal by a charge-sensitive preamplifier, then fed into a spectroscopic amplifier for further amplification. The bipolar output signal from the spectroscopic amplifier is processed by a fan-in/fan-out module (Philips 744) to extract a fast negative leading-edge pulse, which is then discriminated by a constant fraction discriminator (CF8000). The discriminator output is widened by a logic coincidence module (CO4020) and used as the gate signal for ADC triggering. The input signal acquired by the ADC comes from the unipolar output of the spectroscopic amplifier. A PT100 platinum resistance thermometer is attached to the CsI(Tl) crystal to monitor the temperature precisely. To avoid ice formation inside the temperature chamber below  $0^\circ\text{C}$ , a set of air drying system is employed to deliver dried air into the chamber.

Fig.3 shows the normalized change in the PD(hamamatsu s3590) output signal amplitude (each temperature point normalized to its value at  $25^\circ\text{C}$ ) over the temperature range of  $-40^\circ\text{C}$  to  $40^\circ\text{C}$ . The solid line is the straight line fitted by a linear function. The results CF8000CO402040-20-02040C(cid:176)Temperature(0.940.960.9811.02C)(cid:176)Relative ADC channel(/25

1 Based on the aforementioned luminescence spectra of CsI(Tl) and the spec-

tral response characteristics of the PD quantum efficiency, we calculated the wavelength-averaged quantum efficiency at different temperatures; the results are presented in Fig.5. The solid line is the straight line fitted by a linear function. Based on the fitted function, can calculate  $Q_{ref}$  at any temperature, thereby providing another input parameter for Eq.(8). Overall, the wavelength-averaged quantum efficiency shows a slight downward trend as temperature increases, though the magnitude of change is relatively limited. A noticeable deviation from the linear trend is observed at  $-25^{\circ}\text{C}$ .

We attribute this anomaly primarily to the increased uncertainty in the extracted emission spectrum at this temperature point, possibly stemming from the original referenced data. Crucially, a sensitivity analysis confirms that the impact of this outlier is negligible: its inclusion or exclusion alters the fitted value of ( $Q_{ref}(T)$ ) by less than 0.25% across the temperature range of interest, which translates to a completely insignificant effect on the final derived light yield. Over the temperature range of  $-50^{\circ}\text{C}$  to  $50^{\circ}\text{C}$ , the wavelength-averaged quantum efficiency decreases by only about 1.38%, which is a small variation rate. Therefore, approximating the wavelength-averaged quantum efficiency as varying linearly with temperature within this interval introduces an acceptable level of systematic error. This slight change indicates that within the temperature range of  $-40^{\circ}\text{C}$  to  $+40^{\circ}\text{C}$ , the net effect resulting from the combined influence of the slight shift in emission spectrum and PD spectral response is very small. Even if it is regarded as a constant, the introduced systematic error is much smaller than the change in the crystal light yield itself (40%). However, in the calculation of the relative light yield of CsI(Tl) in the SectionVI, its influence was still eliminated.

S × 1240 VI. EXTRACTION AND ANALYSIS OF THE INTRINSIC RELATIVE LIGHT YIELD Based on the previously determined  $Q_{ref}(T)$  (SectionIV), ( $T$ ) (SectionV), and the validated assumption of a constant photon collection efficiency  $\eta_0$  (SectionIII), this chapter substitutes the experimentally measured relative voltage signal  $V_{ref}(T)$  into the theoretical Eq.(8) to extract the temperature-dependent curve of the intrinsic relative light yield  $N_{ref}(T)$  of the CsI(Tl) crystal. For this purpose, a measurement system structurally similar to that shown in Fig.2 was constructed, with the excitation source replaced by a  $^{137}\text{Cs}$  radioactive source to provide stable ionizing radiation input.

During the experiment, the temperature of the climate chamber was decreased stepwise from  $40^{\circ}\text{C}$  to  $-40^{\circ}\text{C}$  in increments of  $5^{\circ}\text{C}$ . At each temperature point, the system was allowed to thermally equilibrate for one hour before recording the output signal amplitude. The values of  $Q_{ref}(T)$  corresponding to each temperature were obtained via interpolation using the linear fitting relationships established in Fig.3 and Fig.5 ( $T$ ) and  $Q_{ref}$  Fig.6 shows the variation of the crystal's relative light yield with temperature (normalized to the value at  $25^{\circ}\text{C}$ ). The experimental data are well described by a quadratic fit. The results reveal a distinct non-monotonic temperature dependence of the CsI(Tl) light in the range below  $24^{\circ}\text{C}$ , the relative light yield increases yield: with ris-

ing temperature, accumulating a growth of approximately 16% from  $-40^{\circ}\text{C}$  to  $24^{\circ}\text{C}$ , and peaking near  $24^{\circ}\text{C}$ . Between  $24^{\circ}\text{C}$  and  $40^{\circ}\text{C}$ , the light yield shows a slight decreasing trend with a total reduction of about 0.8%. This behavior can be explained by the Fig. 4 [Figure 4: see original paper]. (a) represents the variation relationship of the quantum efficiency of PD with wavelength, (b) shows the emission spectra of CsI(Tl) at different temperatures evolution of the crystal's luminescence mechanisms with temperature. Low-temperature region ( $-40^{\circ}\text{C}$  to  $24^{\circ}\text{C}$ ): The increase in light yield with temperature is primarily attributed to improved carrier mobility and energy transfer efficiency. At low temperatures, reduced carrier mobility promotes the formation of V<sub>k</sub> centers from holes and the trapping of electrons by activator centers, which suppresses the self-trapped exciton (STE) luminescence channel. Moreover, only spatially correlated electron-hole pairs can recombine radiatively via tunneling, while the remaining carriers lose energy through non-radiative channels. As temperature rises, enhanced carrier mobility improves the energy transfer efficiency from STEs to activator centers, increasing the proportion of radiative recombination and thus raising the light yield. Peak region (near  $24^{\circ}\text{C}$ ): The maximum light yield indicates a dynamic balance between the efficiency of energy transfer from STEs to activator centers and the thermal quenching of activator luminescence. At this temperature, the radiative recombination process reaches its optimum efficiency.

High-temperature region ( $24^{\circ}\text{C}$  to  $40^{\circ}\text{C}$ ): The slight decrease in light yield is mainly due to the enhanced thermal quenching effect.

Further temperature increase raises the probability of non-radiative transitions, dissipating part of the excitation energy through lattice vibrations and other channels, thereby reducing the luminescence efficiency[20].

In summary, CsI(Tl) crystals exhibit relatively stable light-output performance near room temperature while showing clear potential

Fig. 5 [Figure 5: see original paper]. Average quantum efficiency at different temperatures Fig. 6 [Figure 6: see original paper]. Temperature dependence of the relative light yield of CsI(Tl), normalized to its value at  $25^{\circ}\text{C}$  for light-yield enhancement in the low-temperature region. This characteristic provides important guidance for the performance calibration and optimization of detectors operating over a wide temperature range.

VII. DISCUSSION The temperature-dependent behavior of CsI(Tl) light yield observed in this work is contextualized by comparing it with selected prior studies, as shown in Fig.7 While a non-monotonic trend is a common feature, the reported peak position and the magnitude of variation differ considerably. These discrepancies can be primarily attributed to the varying degrees of temperature coupling from the readout devices and photon collection systems employed in differ- Fig. 7 [Figure 7: see original

paper]. Relative Light Yield as a function of temperature from different research groups ent experimental setups.

For instance, the notably lower peak temperature (between approximately  $-10^\circ\text{C}$  and  $0^\circ\text{C}$ ) reported by Valentine et al.[14] is likely due to the significant temperature dependence of the photo-multiplier tube (PMT) gain under low-temperature conditions. Similarly, Grodzicka et al.[8], who used a Multi-Pixel Photon Counter (MPPC), may have introduced considerable error because the temperature effect of the MPPC itself outweighs that of the crystal.

Kobayashi[21] and Bedere[5] coupled large-sized crystals with photodiodes (PDs) but did not apply temperature correction to the PDs. Our simulations (Section III) indicate that for such crystal dimensions, the photon collection efficiency ( $\eta$ ) exhibits non-negligible temperature and wavelength dependence, which could further compromise the accuracy of the extracted light yield. In contrast, Swiderski et al.[9] used a very small crystal and a temperature-stabilized SiPM, yet reported a distinctly different low-temperature trend. This divergence likely stems from the fundamental characteristics of the SiPM itself. Even when temperature-stabilized, the photon detection efficiency (PDE) of an SiPM has a strong inherent dependence on the wavelength of incident light. Since the emission spectrum of CsI(Tl) shifts with temperature[14], the wavelength-averaged PDE of the SiPM is not constant, introducing a temperature-dependent systematic effect that is not present in our PD-based method with explicit spectral correction.

In summary, the comparison underscores that achieving an accurate measurement of the intrinsic property requires carefully decoupling the readout system's response. The methodology developed in this work provides a systematic solution to this challenge.

VIII. SUMMARY This study establishes a high-precision decoupling method to determine the intrinsic relative light yield of CsI(Tl) crystals over 60-40-20-0204060C)(cid:176)Temperature(0.8240.8260.8280.830.8320.8340.8362Q40-30-20-10-010203040C)(cid:176)Temperature(0.70.750.80.850.90.9511.051.1refN50-40-30-20-10-010203040C)(cid:176)Temperature(0.50.60.70.80.911.11.2Relatvie light yieldKobayashiValentineBedereGrodzickaSwiderskiThis work[Csi(Tl)+PD]This work[Pure Csi(Tl)]

432 a wide temperature range ( $-40^\circ\text{C}$  to  $40^\circ\text{C}$ ). The core innovation lies in the systematic isolation of the scintillator's intrinsic response from the temperature effects of the readout chain. This was achieved through two key design elements: (1) employing a small-volume crystal (1 cm<sup>3</sup>) to validate a constant photon collection efficiency ( $\eta$ ), and (2) using a photodiode (PD) and decomposing its quantum efficiency into explicitly calibrated temperature-dependent (Qref Applying this method, the intrinsic relative light yield was measured to exhibit a distinct non-monotonic temperature dependence: it increases quadratically by approximately 16% from  $-40^\circ\text{C}$ , reaches a maximum near  $24^\circ\text{C}$ , and then slightly decreases by about 0.8% up to  $40^\circ\text{C}$ . This behavior is interpreted in terms of com-

peting processes: the enhancement of carrier mobility and energy transfer efficiency at lower temperatures, and the onset of thermal quenching ( $T_q$ ) and calculated spectral ( $Q_{ref}(T)$ ) components. [1] Hong-Yu Zhu, Jian-Ling Lou, Yan-Lin Ye et al., Two annual CsI(Tl) detector arrays for the charged particle telescopes.

Nucl. Sci. Tech. 34, 159 (2023). doi: 10.1007/s41365-023- [2] Cunhui Li, Shuwen Tang, Xiangyu Hu et al., Design and Realization of China Tianwen-1 Energetic Particle Analyzer. Space Sci. Rev. 217, 26 (2021). doi: 10.1007/s11214-021-00803-0 [3] Jeong Ho Kima, and Koan Sik Joo, Feasibility of underwater radiation detector using a silicon photomultiplier (SiPM). J. Instrum. 15, P04013 (2020). doi: 10.1088/1748-0221/15/04/P04013 [4] S.D. Park, J. Lee, H.S. Lee et al., Investigation of scintillation properties of a CsI(Tl) crystal at low temperature for dark matter search. J. Instrum. 19, P07011 (2024). doi: 10.1088/1748-0221/19/07/P07011 [5] D. Bédérède, E. Bougamont, Ph. Bourgeois et al. Performances of the CsI(Tl) detector element of the GLAST calorimeter, Nucl. Instrum. Methods Phys. Res. A 518, 15-18 (2004). doi: 10.1016/j.nima.2003.10.011 [6] M. Kobayashi and P. Carlson, Temperature dependence of CsI(Tl) scintillation yield for cosmic muons, 5 and 1.25 MeV  $\gamma$ -rays, Nucl. Instrum. Methods Phys. Res. A 281, 192-198 (1989). doi: 10.1016/0168-9002(89)91241-7 [7] L.A. Boatner, J.S. Neal, J.A. Kolopus et al., The characterization of scintillator performance at temperatures up to 400 degrees centigrade, Nucl. Instrum. Methods Phys. Res. A 709, 95-101 (2013). doi: 10.1016/j.nima.2013.01.061 [8] M. Grodzicka, M. Moszyński, T. Szczeniak et al., Characterization of CsI:Tl at a wide temperature range ( $-40^\circ\text{C}$  to  $+22^\circ\text{C}$ ), Nucl. Instrum. Methods Phys. Res. A 718, 103-108 (2013). doi: 10.1016/j.nima.2013.01.062 [9] L. Swiderski, M. Moszyński, W. Czarnacki, et al., Scintillation response to gamma-rays measured at wide temperature range for Tl doped CsI with SiPM readout. Nucl. Instrum. Methods Phys. Res. A 916, 32 (2019) doi: 10.1016/j.nima.2018.10.149 [10] N. Dinu, C. Bazin, V. Chaumat et al., Temperature and bias voltage dependence of Nucl. Sci. Symp. Conf. Rec. p215(2010) doi: 10.1109/NSS-MIC.2010.5873750 the MPPC detectors, [11] LI Gang, WANG Yaoqi, WANG Xiaopeng, Adaptive compensation method for photomultiplier tube counting temperature at higher temperature.

Compared to conventional methods using PMTs or SiPMs, the present approach avoids the significant temperature coupling inherent in those devices. The analysis of discrepancies with prior literature confirms that such coupling is a major source of variation in reported data, highlighting the necessity and advantage of the decoupling strategy demonstrated here.

The accurate temperature-dependent curve and the robust methodology provided in this work deliver reliable key parameters and a solid theoretical foundation. These are essential for the performance prediction, calibration, and optimization of CsI(Tl)-based energy-spectrum detectors destined for applications in environments with severe thermal fluctuations, such as space exploration and deep-sea surveys.

ature drift, J. Meas. Sci. Instrum., 15, 244-252 (2024). doi: 10.62756/jmsi.1674-8042. 2024025 [12] Yu Sun, Zhi-Yu Sun, Yu-Hong Yu, et al., Temperature dependence of CsI:Tl coupled to a PIN photodiode and a silicon photomultiplier. Nucl. Sci. Tech. 30, 27 (2019). [13] John D. Valentine, David K. Wehe, Glenn F. Knoll, et al., Temperature dependence of CsI (Tl) absolute scintillation yield, IEEE Trans. Nucl. Sci. 40, 4, 1267-1274 (1993). doi: 10.62756/jmsi.1674-8042. 2024025 [14] John D. Valentine, William W. Moses, Stephen E. Derenzo et al., Temperature dependence of CsI(Tl) gamma-ray excited scintillation characteristics, Nucl. Instrum. Methods Phys. Res.

A 325, 147-157 (1993). doi: 10.1016/0168-9002(93)91015-F [15] Refractive index database. Accessed <https://refractiveindex.info/> [16] H. H. Li, Refractive index of alkaline earth halides and its wavelength and temperature derivatives, J. Phys. Chem. Ref. 9, 161-290 (1980). doi: 10.1063/1.555616 [17] A. Knyazev, J. Park, P. Golubev, et al., Simulations of light collection in long tapered CsI(Tl) scintillators using real crystal surface data and comparisons to measurement, Nucl. Instrum. Methods Phys. Res. A 1003, 165302 (2021). doi: 10.1016/j.nima.2021.165302 [18] Hamamatsu Si PIN photodiode. S3590-08/-09/-18/-19 Manual.

Accessed 14 Jan 2026. [https://www.hamamatsu.com.cn/content/dam/hamamatsu-photonics/sites/documents/99\\_{{SALES}}\\_{{LIBRARY}}/ssd/s3590-08\\_etc\\_kpin1052e.pdf](https://www.hamamatsu.com.cn/content/dam/hamamatsu-photonics/sites/documents/99_{{SALES}}_{{LIBRARY}}/ssd/s3590-08_etc_kpin1052e.pdf) [19] Hamamatsu Technical note Si photodiodes. Accessed 14 Jan 2026. [https://www.hamamatsu.com.cn/content/dam/hamamatsu-photonics/sites/documents/99\\_{{SALES}}\\_{{LIBRARY}}/ssd/si\\_{pd}kspd9001e.pdf](https://www.hamamatsu.com.cn/content/dam/hamamatsu-photonics/sites/documents/99_{{SALES}}_{{LIBRARY}}/ssd/si_{pd}kspd9001e.pdf) [20] Sergii S. Gridin, Andrei N. Belsky, Natalia V. Shiran, et al., Channels of Energy Losses and Relaxation in CsI:A Scintillators (A=Tl, In), IEEE Trans. Nucl. Sci., 61, 1 (2014). doi: 10.1109/TNS.2013.2283316 [21] M. KOBAYASHI and P. CARLSON, Temperature dependence of CsI(Tl) scintillation yield for cosmic muons 5 and 1.25 MeV  $\gamma$ -rays, Nucl. Instrum. Methods Phys. Res. A, 281, 192-196 (1989). doi: 10.1016/0168-9002(89)91234-5

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

*Source: ChinaXiv – Machine translation. Verify with original.*