Nonproportional Response and Energy Resolution of Pure SrI_2 and $\text{SrI}_2:5\%\text{Eu}$ Scintillators

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Abstract—Nonproportional response of the scintillation yield of un-doped SrI_2 and $\text{SrI}_2:5\%\text{Eu}^{2+}$ was studied using highly monochromatic synchrotron irradiation ranging from 10.5 to 100 keV. Measurements were performed at 80 K and 295 K for SrI_2 , and at 80 K, 295 K, 450 K, and 600 K for $\text{SrI}_2:5\%\text{Eu}$. By making a dense data sampling around the iodine K-edge and using the recently developed *K-dip spectroscopy* method, the K-shell photoelectron response curves were reconstructed down to 500 eV. Proportionalities of X-ray response and K-shell photoelectron response of both crystals reveal temperature dependence. Energy resolution of the X-ray photopeak was analyzed as a function of temperature and deposited energy. Energy resolution improves with better proportionality.

Index Terms—Electron response, nonproportionality, scintillators, strontium iodide, X-ray response.

I. INTRODUCTION

THE RECENTLY rediscovered scintillator $\text{SrI}_2:\text{Eu}^{2+}$ is a material with a reported very high light yield and excellent energy resolution [1], [2]. Excellent proportionality with a deviation of less than 2% in the 14–1274 keV γ and X-ray energy range [1] makes $\text{SrI}_2:\text{Eu}^{2+}$ one of the most proportional scintillators available.

Currently, there are several methods of measuring nonproportional response (*nPR*). First of all, *nPR* can be studied with a standard set of radioactive sources [3], [4]. However, for energies below, say, 5 keV, the X-ray penetration depth is very small and the scintillator surface may affect the photon yield. The second method is to use the Scintillator Light Yield Nonproportionality Characterization Instrument (SLYNCI). It is based on the Compton Coincidence Technique (CCT) [5] and was developed by Choong *et al.* [6]. This method enables to measure accurate values of *nPR* beginning from 3 keV electron energy from Compton scattered electrons that are not influenced by surface effects. The Compton scattered electron *nPR* data of $\text{SrI}_2:\text{Eu}^{2+}$ obtained with SLYNCI shows very good proportionality in comparison to other well-known scintillators [2]. The next method, the so-called K-dip spectroscopy method, is based on the photon

response to highly monochromatic synchrotron X-ray irradiation in the 9–100 keV energy range. It has been recently developed by Khodyuk [7]. This method enables one to get information on electron response starting from energy as low as 100 eV, avoiding the influence of surface effects. A detailed description of this method can be found in Section III-C.

In this paper, we apply the K-dip spectroscopy method to study *nPR* and energy resolution of pure SrI_2 and $\text{SrI}_2:5\%\text{Eu}$. The arising questions are whether such a good proportionality is an intrinsic property of SrI_2 or due to the doping of Eu, and how *nPR* is affected by temperature. With studies on LaBr_3 scintillators, we discovered for the first time that proportionality can be improved with temperature decrease [10]. Except for [14], no studies on the temperature dependence of *nPR* of $\text{SrI}_2:\text{Eu}$ have been reported so far, which motivated us to perform this research. We studied the *nPR* of scintillation yield and energy resolution of SrI_2 and $\text{SrI}_2:5\%\text{Eu}$ in the 10.5–100 keV X-ray energy range between 80 K and 600 K. Using the K-dip spectroscopy, we obtained electron response data down to 500 eV. Energy resolution is a crucial parameter required for good scintillation performance. Several contributions that worsen the total energy resolution are treated in this paper: 1) the contribution from the photomultiplier tube (PMT) and Poisson statistics; 2) from the nonproportional response of the scintillator; 3) from inhomogeneities in the crystal; and 4) from self-absorption of scintillation photons. We applied the experimental results to analyze the energy resolution and its components as a function of temperature, and we found that better proportionality improves the energy resolution.

II. EXPERIMENT

SrI_2 and $\text{SrI}_2:5\%\text{Eu}$ crystals were grown from commercially available SrI_2 and EuI_2 starting material with a conventional crystal growth method from the melt. For this work, we selected two transparent fragments of the original crystals of about 0.05 cm³ each. The experiment was performed at the X-1 beam line at the Hamburger Synchrotronstrahlungslabor (HASYLAB) synchrotron radiation facility in Hamburg, Germany. A highly monochromatic pencil X-ray beam in the energy range 10.5–100 keV was used as an excitation source. The setup was described in detail in [8]. The sample was fixed at the bottom of a parabolic-like stainless steel reflector covered with Al foil. The reflector was mounted on a cold finger of a Janis VPF-800 Cryostat operated with a LakeShore 331 Temperature Controller [11]. The reflector faced a Hamamatsu R6231-100 PMT, which was placed outside the cryostat and kept at room temperature during all experiments. The PMT was

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Fig. 1. X-ray excited emission of pure SrI_2 and $\text{SrI}_2:5\%\text{Eu}$. Line 1: SrI_2 at 80 K. Line 2: SrI_2 at 295 K. Line 3: $\text{SrI}_2:5\%\text{Eu}$ at 295 K.

connected to a Cremat CR-112 preamplifier and an Ortec 672 spectroscopic amplifier with 10 μs shaping time.

The number of the photoelectrons produced in the PMT $N_{\text{phe}}^{\text{PMT}}$ per MeV of absorbed energy was determined from the ratio of the peak position of the ^{137}Cs 662 keV or ^{241}Am 59.5 keV photopeak to the position of the mean value of the so-called single photoelectron peak in a pulse-height spectrum [12]. For pure SrI_2 , the $n\text{PR}$ at X-ray energy (E_x) was defined as the ratio between the number of photoelectrons per MeV observed at E_x and that observed at 662 keV. For $\text{SrI}_2:5\%\text{Eu}$, we normalized the $n\text{PR}$ to 100% at 100 keV. Energy resolution was defined as the full width at half-maximum (FWHM) intensity over the peak position of the photopeak in a pulse-height spectrum.

III. RESULTS

First, we review some results from previous work [13] that are relevant for understanding of the $n\text{PR}$ data on $\text{SrI}_2:\text{Eu}^{2+}$. X-ray excited emission spectra of pure SrI_2 and $\text{SrI}_2:5\%\text{Eu}$ are shown in Fig. 1. Pure SrI_2 emission at 80 K consists of three broad emission bands at 360, 430, and 570 nm. The emissions at 360 and 430 nm are quenched at 295 K. The relatively narrow $\text{SrI}_2:5\%\text{Eu}$ emission at 430 nm is due to 5d-4f emission in Eu^{2+} . The photoelectron yield, obtained from ^{137}Cs 662 keV γ -ray pulse height spectra recorded with a shaping time of 10 μs at room temperature, is 30 000 phe/MeV for $\text{SrI}_2:5\%\text{Eu}$ and 7000 phe/MeV for undoped SrI_2 . These values correspond to 85 000 and 40 000 photons/MeV, respectively. Scintillation decay time varies from 0.5 μs at 295 K to 1.5 μs at 80 K in SrI_2 , and from 0.5 μs at 80 K to 4.5 μs at 600 K in $\text{SrI}_2:5\%\text{Eu}$. With a shaping time of 10 μs and scintillation decay time of 4.5 μs , ballistic deficit does not exceed 10%.

A. Scintillation Nonproportionality to X-Rays

Fig. 2 shows the $n\text{PR}$ data as a function of X-ray energy E_x in SrI_2 at 80 K and 295 K. The $n\text{PR}$ is measured for E_x between 10.5 and 100 keV with a step size of 5 keV. A much finer step size of 100 eV was used around the K-shell electron binding energies, the so-called K-edges. The K-edge in Sr is $E_{\text{K}_{\text{Sr}}} = 16.105$ keV, and that in I is $E_{\text{K}_{\text{I}}} = 33.169$ keV. As shown in Fig. 2, discontinuities in $n\text{PR}$ appear at both energies. The size of the drop in $n\text{PR}$ at the K-edge is called the K-dip magnitude. Detailed descriptions of $n\text{PR}$ curve shapes

Fig. 2. $n\text{PR}$ of SrI_2 as a function of X-ray energy. Circles: values at 80 K. Triangles: values at 295 K. The solid lines are drawn to guide the eye.

TABLE I
SOME RELEVANT CHARACTERISTICS OF THE X-RAY $n\text{PR}$ AND R CURVES OF PURE SrI_2 AND $\text{SrI}_2:5\%\text{Eu}$

Crystal	T, K	$\Delta n\text{PR}$, %	Kdip, %	R at 15 keV, %	R at 100 keV, %
$\text{SrI}_2:5\%\text{Eu}$	80	8.6	3.1	39	16
	295	7	2	39	13
	450	8.9	3	41	15
	600	17.4	7.5	52	17
SrI_2	80	6.3	2.8	48	19
	295	11	4.8	73	26

Column 3 is $\Delta n\text{PR}$, defined as a difference between minimum and maximum values of $n\text{PR}$ in the 15–100 keV range. Column 4 contains the Iodine K-dip magnitudes. Columns 5 and 6 are the energy resolution R at 15 keV and 100 keV.

and examples obtained with the same method for LuAG , GSO , LSO , LPS , NaI:Tl , $\text{LaCl}_3:\text{Ce}$, and $\text{LaBr}_3:\text{Ce}$ scintillators can be found in [7]–[9]. Fig. 2 shows that the $n\text{PR}$ of SrI_2 improves significantly with decrease in temperature. Together with the improved $n\text{PR}$, the K-dip magnitude decreases. Some relevant $n\text{PR}$ data and characteristics from Fig. 2 are compiled in Table I.

Fig. 3 shows the $n\text{PR}$ as a function of X-ray energy for $\text{SrI}_2:5\%\text{Eu}$ at 80 K, 295 K, and 600 K. The $n\text{PR}$ curve at 450 K was also measured. However, it differs less than 1.5% from that at 80 K along the entire energy range, and therefore it is not included in Fig. 3. Among the scintillators studied in [7]–[9], $\text{SrI}_2:5\%\text{Eu}$ appeared to be one of the most proportional in the 15–100 keV X-ray energy range. In contrast to SrI_2 , the $n\text{PR}$ in $\text{SrI}_2:5\%\text{Eu}$ first improves on heating from 80 K to 295 K, and then worsens with further increase in temperature to 450 K and 600 K. The inset in Fig. 3 shows an enlarged scale K-dip, normalized to 100% at E_{KI} . As in pure SrI_2 , in $\text{SrI}_2:5\%\text{Eu}$ the K-dip magnitude decreases with improved proportionality. This is also shown in columns 3 and 4 of Table I.

B. Energy Resolution of X-ray Total Absorption Peaks

The previous section revealed temperature dependence in the $n\text{PR}$ data. The next goal then is to discover whether improvement of the $n\text{PR}$ results in improvement of the energy resolution R of the X-ray photopeak.

Data connected by curves 1 and 3 in Fig. 4 show the observed energy resolution of pure SrI_2 as a function of X-ray energy on a double-log scale. The resolution at 80 K is on average 1.46 times better than that at 295 K. The insets in Fig. 4 show a step-like

Fig. 3. nPR of $\text{SrI}_2\text{:5\%Eu}$ as a function of X-ray energy. Squares: values at 80 K. Circles: values at 295 K. Triangles: values at 600 K. The solid lines are drawn to guide the eye. Note that the inset and the main graph have different normalization points.

Fig. 4. Energy resolution R of the X-ray photopeak of SrI_2 as a function of X-ray energy—circles (curve 1): values at 295 K; squares (curve 3): values at 80 K. Statistical contribution R_M —pointed-down triangles (curve 2): values at 295 K; pointed-up triangles (curve 4): values at 80 K. The solid lines are drawn to guide the eye.

Fig. 5. Energy resolution of the X-ray photopeak of $\text{SrI}_2\text{:5\%Eu}$ as a function of X-ray energy. Squares: values at 80 K. Circles: values at 295 K. Pointed-up triangles: values at 450 K. Pointed-down triangles: values at 600 K. The solid lines are drawn to guide the eye.

increase of the resolution at the iodine K-edge energy on an enlarged scale.

Fig. 5 shows the energy resolution of the X-ray photopeak as a function of E_x in $\text{SrI}_2\text{:5\%Eu}$. The values of R at 15 and 100 keV are compiled in Table I. The resolution first improves on heating from 80 K to 295 K, and then worsens on further heating to 450 K and 600 K. As in pure SrI_2 , a step-like increase in the energy resolution is observed at the Iodine K-edge energy at 600 K. At lower temperatures an increase was not observed.

Fig. 6. (top) Photoelectron yield as a function of temperature. Squares: data for $\text{SrI}_2\text{:5\%Eu}$. Circles: data for pure SrI_2 . (bottom) Energy resolution R at 662 keV as a function of temperature. Solid squares: data for $\text{SrI}_2\text{:5\%Eu}$. Solid circles: data for pure SrI_2 . Calculated with (2) statistical contribution R_M —open squares: $\text{SrI}_2\text{:5\%Eu}$; open circles: pure SrI_2 .

Fig. 6 shows the photoelectron yield and energy resolution of pure SrI_2 and $\text{SrI}_2\text{:5\%Eu}$ as a function of temperature measured in the cryostat under ^{137}Cs 662 keV γ -ray excitation. In pure SrI_2 , the photoelectron yield gradually quenches from 2000 phe/MeV at 80 K with increase in temperature. In $\text{SrI}_2\text{:5\%Eu}$, the yield increases on heating from 80 K to 100 K, and then gradually decreases with increase in temperature to 600 K. The energy resolution anti-correlates with the photoelectron yield. The energy resolution is optimal at about 150 K, which agrees with the results obtained by Lam *et al.* [14]. Note that because of the 15%–20% scintillation light collection efficiency for a sample mounted in the cryostat in comparison to the almost 100% efficiency for a sample optically coupled to the window of the PMT, the photoelectron yield is rather low and energy resolution is rather poor.

C. Scintillation Nonproportionality to K-Shell Photoelectrons

Because of the short attenuation length, most X-rays with energies below 9 keV are absorbed close to the scintillator surface, which may affect the light yield. Low-energy X-rays also cannot penetrate through the packaging and reflecting covering around the scintillator anymore. This limits the standard method to determine nPR to X-ray energies of about 5 keV. As an alternative to measuring the scintillation response to the low-energy X-rays, one may analyze nPR data at energies just above the K-edge. The method is called K-dip spectroscopy. It enables one to reconstruct the nPR curve down to 100 eV.

The method works as follows. The response of a scintillator to an X-ray photon that has interacted with a K-shell photoelectron is equivalent to the response of a scintillator to a sum of two main interaction products: 1) a K-shell photoelectron, plus 2) electrons and photons emitted due to the sequence of processes following relaxation of the hole in the K-shell, the so-called K-cascade response. Our strategy is to employ X-ray energies just above E_{KI} [7]. The K-cascade response is assumed independent of the original X-ray energy. This response is found by tuning the X-ray energy very close above

Fig. 7. K-shell photoelectron response as a function of the electron energy obtained with the K-dip spectroscopy method. Solid squares: values for $\text{SrI}_2\text{:5\%Eu}$ at 295 K. Solid circles: values for SrI_2 at 80 K. Solid triangles: values for SrI_2 at 295 K. Open circles: data acquired with SLYNCI [15].

Fig. 8. K-shell photoelectron response in $\text{SrI}_2\text{:5\%Eu}$ as a function of the electron energy obtained with the K-dip spectroscopy method. Squares: values at 80 K. Circles: values at 295 K. Pointed-up triangles: values at 450 K. Pointed-down triangles: values at 600 K. Solid lines are drawn to guide the eye.

E_{KI} . By subtracting the K-cascade response from the total X-ray response, we are left with the response in photoelectrons from the K-shell photoelectron alone with energy $E_X - E_{\text{KI}}$. The K-shell photoelectron- nPR curve is then obtained by the $N_{\text{phe}}^{\text{PMT}}/\text{MeV}$ at the energy of the K-photoelectron divided by the $N_{\text{phe}}^{\text{PMT}}/\text{MeV}$ measured at 662 keV. A more detailed description of the K-dip spectroscopy method can be found in [8].

The K-shell photoelectron nPR obtained with the K-dip spectroscopy method is shown in Fig. 7. Going down from 67 keV, the nPR of pure SrI_2 at 295 K and at 80 K in Fig. 7 increases by 3%–4%, reaching a maximum near 10–25 keV. With further decrease in electron energy, the nPR decreases. As for the X-ray response in Fig. 2, the K-shell photoelectron response of SrI_2 is most proportional at 80 K. Going down from 67 keV, the nPR of $\text{SrI}_2\text{:5\%Eu}$ decreases with decrease in electron energy. At 295 K, the K-shell photoelectron response of $\text{SrI}_2\text{:5\%Eu}$ is slightly better proportional than that of pure SrI_2 .

Fig. 8 shows the K-shell photoelectron response of $\text{SrI}_2\text{:5\%Eu}$ at 80 K, 295 K, 450 K, and 600 K. The nPR was obtained by the $N_{\text{phe}}^{\text{PMT}}/\text{MeV}$ at the energy of the K-shell photoelectron divided by the $N_{\text{phe}}^{\text{PMT}}/\text{MeV}$ at 6.8 keV. The normalization point was arbitrarily chosen. The K-shell photoelectron response of $\text{SrI}_2\text{:5\%Eu}$ is the most proportional at 80 K at energies between 500 eV and 67 keV.

IV. DISCUSSION

There are two main observations from the results on the 10.5–100-keV X-ray nPR data in Figs. 2 and 3. First, at room temperature the response of $\text{SrI}_2\text{:5\%Eu}$ is more proportional than that of pure SrI_2 . Second, the nPR of SrI_2 and $\text{SrI}_2\text{:5\%Eu}$ depend on temperature. In both crystals, the K-dip magnitude decreases together with the improved proportionality.

Similar observations are made for the 0.5–66.8-keV K-shell photoelectron nPR data in Figs. 7 and 8. Again, at room temperature the response of $\text{SrI}_2\text{:5\%Eu}$ is more proportional than that of SrI_2 . Second, the K-shell photoelectron nPR of both crystals depends on temperature. The Compton scattered electron nPR of $\text{SrI}_2\text{:6\%Eu}$ obtained with SLYNCI [15] is added in Fig. 7 and can be compared to the K-shell photoelectron nPR data of $\text{SrI}_2\text{:5\%Eu}$. The SLYNCI Compton scattered electron nPR was normalized in [15] at 446 keV, while our K-shell photoelectron nPR is normalized at 662 keV. Both data sets agree within a few percent with each other. Note that the SLYNCI nPR tends to decrease somewhat more strongly with decrease of electron energy than the K-shell photoelectron nPR . The true reason is not yet clear. It may be caused by differences in the methods of data analysis and normalization or by properties of the scintillator such as different Eu concentration.

The energy resolution as shown in Figs. 4–6 is determined by different contributions that in first approximation can be regarded as independent from each another. One may then write for the observed energy resolution

$$R^2 = R_M^2 + R_{\text{nPR}}^2 + R_{\text{inh}}^2 + R_{\text{tr}}^2 \quad (1)$$

where R_M is the contribution from the PMT gain and photon detection Poisson statistics, R_{nPR} is the contribution from the nonproportional response of the scintillator, R_{inh} is the contribution from crystal inhomogeneities, and R_{tr} is the contribution from the transfer of the scintillation photons from the crystal to the PMT.

R_M is given by

$$R_M = 2.35 \sqrt{\frac{1 + \text{var}(M)}{N_{\text{phe}}^{\text{PMT}}}} \quad (2)$$

where $\text{var}(M)$ is the fractional variance in the PMT gain, which is 0.28 for the used Hamamatsu R6231-100 [16] PMT.

Fig. 2 shows that in SrI_2 the X-ray nPR improves with temperature decrease. Fig. 4 shows that the energy resolution of the X-ray photopeak also improves with temperature decrease. However, this does not yet show that the improved nPR results in the improved R . Fig. 6 demonstrates that both for pure and doped SrI_2 , the photoelectron yield versus temperature anti-correlates with the energy resolution, indicating a considerable contribution of R_M to R . To verify whether better proportionality improves R , we calculated the values of R_M and compared them to R . R_M were calculated with (2) and the number of photoelectrons $N_{\text{phe}}^{\text{PMT}}$ produced in the PMT. The values of R_M are shown as the data points connected by curves 2 and 4 in Fig. 4. The values of R and R_M , for example, at 60 keV, are compiled in Table II.

Fig. 4 shows that in SrI_2 , R is 1%–2% larger than R_M at 80 K and about 1%–5% larger at 295 K. The difference between

TABLE II

NUMBER OF PHOTOELECTRONS PRODUCED IN THE PMT $N_{\text{phe}}^{\text{PMT}}$, THE TOTAL ENERGY RESOLUTION R , AND THE CONTRIBUTION FROM THE PMT GAIN AND POISSON STATISTICS R_M DETERMINED AT 60-keV X-RAY EXCITATION OF SrI_2 SCINTILLATORS

Sample	Temperature, K	$N_{\text{phe}}^{\text{PMT}}$	R , %	R_M , %
SrI_2	80 K	135	23.3	22.8
	295 K	70	33.5	32.4
$\text{SrI}_2\text{:}5\%\text{Eu}$	295 K	265	16.7	16.3
	600 K	180	23.9	19.9

Fig. 9. Energy resolution R of the X-ray photopeak of $\text{SrI}_2\text{:}5\%\text{Eu}$ as a function of X-ray energy. Filled triangles (curve 1): values at 600 K. Filled circles (curve 3): values at 295 K. Statistical contribution R_M —open triangles (curve 2): values at 600 K; open circles (curve 4): values at 295 K. The solid lines are drawn to guide the eye.

R and R_M is comparable to the systematic error of R_M , which was caused by relatively small number of produced photoelectrons. Calculation of the contribution from R_{nPR} , R_{inh} , and R_{tr} , which is equal to $\sqrt{R^2 - R_M^2}$ according to (1), is therefore meaningless. However, the average difference between R and R_M at 295 K is larger than that at 80 K. Assuming that R_{tr} and R_{inh} are not temperature-dependent, this larger difference indicates on the higher contribution of R_{nPR} at 295 K than at 80 K. This is in agreement with the worsening nPR in Fig. 2.

The next observation, showing the influence of nPR on R , is the step-like increase of R at E_{KI} , depicted in the insets in Fig. 4. At 80 K, R increases by $\Delta R = 1\%$, whereas R_M increases only by $\Delta R_M = 0.2\%$. At 295 K, $\Delta R = 1.5\%$, whereas $\Delta R_M = 0.6\%$. Since at both temperatures $R \approx R_M$, but the contribution of ΔR_M to ΔR is insignificant, the step-like increase of R at E_{KI} is attributed to R_{nPR} .

Fig. 3 shows that the X-ray nPR curves of $\text{SrI}_2\text{:}5\%\text{Eu}$ are most different when the curve at 295 K is compared to that at 600 K. We therefore select the data taken at those temperatures to compare the measured values of R from Fig. 5 with calculated values of R_M . The result is shown in Fig. 9. Although at both temperatures the contribution of R_M dominates, the difference between R and R_M at 600 K is significantly larger than that at 295 K. This observation agrees with poorer nPR at 600 K in Fig. 3, and it is probably related to higher self-absorption at 600 K [13].

In $\text{SrI}_2\text{:Eu}$, self-absorption might worsen energy resolution. Eu absorbs and re-emits its own emission with very high probability—a probability that increases with increase of sample size, Eu concentration, and temperature [13]. Sturm *et al.* [17]

demonstrated a fluctuation of the light yield depending on the position of the interaction of the γ -ray photon with the $\text{SrI}_2\text{:Eu}$ crystal. When the events, originating from different spots in the same crystal, are accumulated, it will deteriorate the total energy resolution. In $\text{SrI}_2\text{:}5\%\text{Eu}$, X-ray attenuation length increases from 50 μm for 15-keV X-rays to 1.5 mm for 100-keV X-rays. The attenuation length is comparable to the thickness of the sample we used, and might therefore affect the energy resolution.

V. CONCLUSION

The proportionality and energy resolution of pure SrI_2 and $\text{SrI}_2\text{:}5\%\text{Eu}$ were measured using highly monochromatic synchrotron irradiation in the 10.5–100 keV energy range. Both scintillators demonstrate very good proportionality. Using the K-dip spectroscopy method, the K-shell photoelectron response curves were obtained down to 500 eV. Both the X-ray nPR and the K-shell photoelectron nPR depend on temperature and Eu doping.

— At room temperature, $\text{SrI}_2\text{:}5\%\text{Eu}$ is more proportional than SrI_2 .

— In SrI_2 , nPR is better at 80 K than at 295 K.

— The X-ray nPR of $\text{SrI}_2\text{:}5\%\text{Eu}$ improves on heating from 80 K to 295 K, and then worsens with further heating to 600 K. The K-shell photoelectron response demonstrates the best proportionality at 80 K.

Anti-correlation between the photoelectron yield and energy resolution R was observed in both crystals, indicating a considerable contribution of R_M to R for the measurements inside the cryostat. Nevertheless, the analysis of R , R_M , and nPR as function of temperature showed that improved nPR results in improved R .

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REFERENCES

- [1] C. M. Wilson, E. V. D. van Loef, J. Glodo, N. J. Cherepy, G. Hull, S. A. Payne, W.-S. Choong, W. W. Moses, and K. S. Shah, “Strontium iodide scintillators for high energy resolution gamma ray spectroscopy,” in *Proc. SPIE*, 2008, pp. 707917.1–707917.7.
- [2] N. J. Cherepy, S. A. Payne, S. J. Asztalos, G. Hull, J. D. Kuntz, T. Niedermayr, S. Pimputkar, J. J. Roberts, R. D. Sanner, T. M. Tillotson, E. v. Loef, C. M. Wilson, K. S. Shah, U. N. Roy, R. Hawrami, A. Burger, L. A. Boatner, W.-S. Choong, and W. W. Moses, “Scintillators with potential to supersede lanthanum bromide,” *IEEE Trans. Nucl. Sci.*, vol. 56, no. 3, pp. 873–880, Jun. 2009.
- [3] P. Dorenbos, J. T. M. de Haas, and C. W. E. van Eijk, “Non-proportionality in the scintillation response and the energy resolution obtainable with scintillation crystals,” *IEEE Trans. Nucl. Sci.*, vol. 42, no. 6, pp. 2190–2202, Dec. 1995.
- [4] M. Moszynski, A. Nassalski, A. Syntfeld-Kazuch, L. Swiderski, and T. Szczesniak, *IEEE Trans. Nucl. Sci.*, vol. 55, no. 3, pp. 1062–1068, Jun. 2008.
- [5] J. D. Valentine and B. D. Rooney, “Design of a Compton spectrometer for studying scintillator nonlinearity and intrinsic resolution,” *Nucl. Instrum. Methods A*, vol. A353, no. 1–3, pp. 37–40, Dec. 1994.

- [6] W.-S. Choong, K. M. Vetter, W. W. Moses, S. A. Payne, N. J. Cherepy, J. D. Valentine, and G. Hull, "Design of a facility for measuring scintillator non-proportionality," *IEEE Trans. Nucl. Sci.*, vol. 55, no. 3, pp. 1753–1758, Jun. 2008.
- [7] I. V. Khodyuk, J. T. M. de Haas, and P. Dorenbos, "Nonproportional response between 0.1–100 keV energy by means of highly monochromatic synchrotron X-rays," *IEEE Trans. Nucl. Sci.*, vol. 57, no. 3, pp. 1175–1181, Jun. 2010.
- [8] I. V. Khodyuk, P. A. Rodnyi, and P. Dorenbos, "Nonproportional scintillation response of NaI:Tl to low energy x-ray photons and electrons," *J. Appl. Phys.*, vol. 107, p. 113513, 2010.
- [9] I. V. Khodyuk and P. Dorenbos, "Nonproportional response of LaBr₃:Ce and LaCl₃:Ce scintillators to synchrotron x-ray irradiation," *J. Phys. Condens. Matter*, vol. 22, p. 485402, 2010.
- [10] I. V. Khodyuk, M. S. Alekhin, J. T. M. de Haas, and P. Dorenbos, "Improved scintillation proportionality and energy resolution of LaBr₃ at 80 K," *Nucl. Instr. Meth. A*, vol. 642, pp. 75–77, 2011.
- [11] G. Bizarri, J. T. M. de Haas, P. Dorenbos, and C. W. E. van Eijk, "First time measurement of gamma-ray excited LaBr₃:5%Ce³⁺ and LaCl₃:10%Ce³⁺ temperature dependent properties," *Phys. Stat. Sol. A*, vol. 203, pp. R41–R43, Apr. 2006.
- [12] J. T. M. de Haas and P. Dorenbos, "Advances in yield calibration of scintillators," *IEEE Trans. Nucl. Sci.*, vol. 55, no. 3, pp. 1086–1092, Jun. 2008.
- [13] M. S. Alekhin, J. T. M. de Haas, K. W. Kramer, and P. Dorenbos, "Scintillation properties of and self absorption in SrI₂:Eu²⁺," *IEEE Trans. Nucl. Sci.*, vol. 58, no. 5, pp. 2519–2527, Oct. 2011.
- [14] S. Lam, M. Ganson, R. Hawrami, W. Setyawan, S. Curtarolo, R. Feigelson, and R. Gaume, "Nonproportionality and scintillation studies of Eu:SrI₂ from 295 to 5 K," *IEEE Trans. Nucl. Sci.*, 2012, to be published.
- [15] L. Ahle, G. Bizarri, L. Boatner, N. J. Cherepy, W.-S. Choong, W. W. Moses, S. A. Payne, K. Shah, S. Sheets, and B. W. Sturm, "Studies of non-proportionality in alkali halide and strontium iodide scintillators using SLYNCL," in *Proc. Mater. Res. Soc. Symp.*, 2010, vol. 1164, pp. 99–104.
- [16] J. T. M. de Haas and P. Dorenbos, "Methods for accurate measurement of the response of photomultiplier tubes and intensity of light pulses," *IEEE Trans. Nucl. Sci.*, vol. 58, no. 3, pp. 1290–1296, Jun. 2011.
- [17] B. W. Sturm, N. J. Cherepy, O. B. Drury, P. A. Thelin, S. E. Fisher, S. A. Payne, A. Burger, L. A. Boatner, J. O. Ramey, K. S. Shah, and R. Hawrami, "Effects of packaging SrI₂(Eu) scintillator crystals," *Nucl. Instrum. Methods A*, vol. 652, pp. 242–246, 2011.