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Energy calibration of thin plastic scintillators using Compton scattered γ-rays

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ABSTRACT

A practical method of using the Compton scattered photons for the energy calibration of thin plastic scintillators is described. The location of the Compton edge in the measured energy spectrum was obtained by matching this spectrum with the Monte Carlo simulated spectrum near the Compton maxima. The simulated spectrum was broadened by a Gaussian-type function. The γ-ray energy spectrum calculation was carried out by employing the MCNP4C simulation code. The natural degradation of the light yield within the scintillator was experimentally investigated and the observed non-uniform yield across the scintillator was taken into account in the simulation. A χ^2 fit between the measured and the simulated γ-ray spectra provided the Compton edge positions for γ energies of 511, 662, 1173 and 1275 keV. The calibration approach can be simply applied to any thin organic scintillator with an arbitrary shape.

1. Introduction

Plastic scintillation materials are widely used in particle physics experiments. For β-spectrometry purposes, the plastic detectors have a great advantage over the semiconductors: there are fewer electrons backscattering for the plastics because of their lower atomic number. However, the energy calibration of a plastic scintillator is not an easy task because the electron sources with clearly specified energy are not available. Mono-energetic electrons are provided by accelerators and by the radioisotopes emitting internal-conversion (IC) electrons. The accelerators have two important drawbacks, namely, their expensive operation, and the fact that the spectrometer has to be moved to the accelerator beam. On the other hand, the IC electron emitters are relatively inexpensive to obtain and very easy to handle, but the IC electrons suffer from the energy loss in source cover and detector window [1]. γ-rays can also be used to calibrate the energy scale of the plastic scintillators output. In the γ-ray spectrum taken with a plastic scintillator, the only distinguishable features are Compton edge (CE) energies. Due to low atomic number of these detectors, photo peaks do not appear in the spectrum [2]. Studies describing the energy calibration of these scintillators using Compton scattering of γ-rays have been published in the literature [3–5]. In all of the above-mentioned studies, it is assumed that both scintillation process and light collection are uniform across the scintillator.

In fact, some chemical and physical structure degradations occur in the polymeric base with time. They are manifested in the appearance of dotty defects on the surface and in the bulk of the scintillator, as well as micro-voids, silver and minute cracks. Originally, free radicals may appear in the plastic under the effect of the external destabilization factors such as temperature, UV light, oxygen, humidity and radiation. Each of the free radicals, which is created under the effect of the oxygen and the other external factors, can initiate the polymeric degradation, including the oxidation chain process [6]. The structure degradation could significantly worsen the light yield, the detection efficiency, and the energy resolution of the scintillator. The decline in the energy resolution leads to a shift of Compton maximum in the measured γ-ray spectrum [7]. Thus for the high precision energy calibration, it is necessary to account for the possible degradation in the light output of the scintillator.

In this work, the possible non-uniformity in the light yield of a thin plastic scintillator was determined. The main objective of the study was to develop amethod for the energy calibration of a thin scintillator with non-uniform light output. We used the MCNP simulation code of the Los Alamos National Laboratory [8] for constructing the detector model and calculating the response of the scintillator to the collimated beam of γ-rays. By matching the Compton peak of the convoluted form of the calculated spectrum with the measured one, the actual position of the Compton edge was determined. Finally, we repeated the procedure for the different energies of γ-ray and calibrated the energy output of the scintillator.

2. Methods

2.1. Experimental setup

The scintillator was made from the polystyrene plastic activated by paraterphenyl (ATOMTEX Corp. [9]). It was a right circular cylinder with the diameter of 128 mm and the thickness

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of 8 mm, and had a thin film as an entrance window for electrons. The scintillator was optically coupled to a photomultiplier. A 1024 channel MCA and a PC with an appropriate software acquired the energy spectra from the scintillator.

2.2. Scanning with β-ray

Both the production and the collection efficiency of light may vary from one region of the scintillator to another. Therefore, possible changes in the light output of the scintillator were investigated before simulating the plastic scintillator response to γ-rays. Fig. 1 shows the experimental setup. A 2 cm thick lead collimator with a ∅5 mm hole was placed between a ^{90}Sr pure beta source and the scintillator. The collimator localized the beam of β-rays to each of the 37 different regions of the detector surface.

By comparing the total counts (integrated surface under the measured β-spectra) for the different source locations, the spatial distribution of the scintillator light output was determined. The front view of the scintillator and a counter plot of the light output in terms of the total counts of the β-rays is shown in Fig. 2. The region which is labeled as 100% and limited to $2 \le x \le 4$, $-1 \le y \le 2$ had the maximum total count. The light output in the other regions of the scintillator ranged from 98.8% to 94.4%.

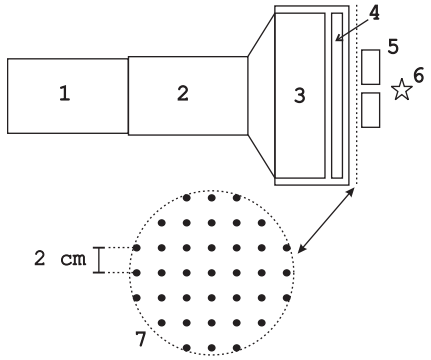

Fig. 1. (1) Amplifier, (2) voltage divider, (3) PM tube, (4) plastic scintillator, (5) Pb collimator, (6) β-ray point source and (7) grid of 37 positions of point source.

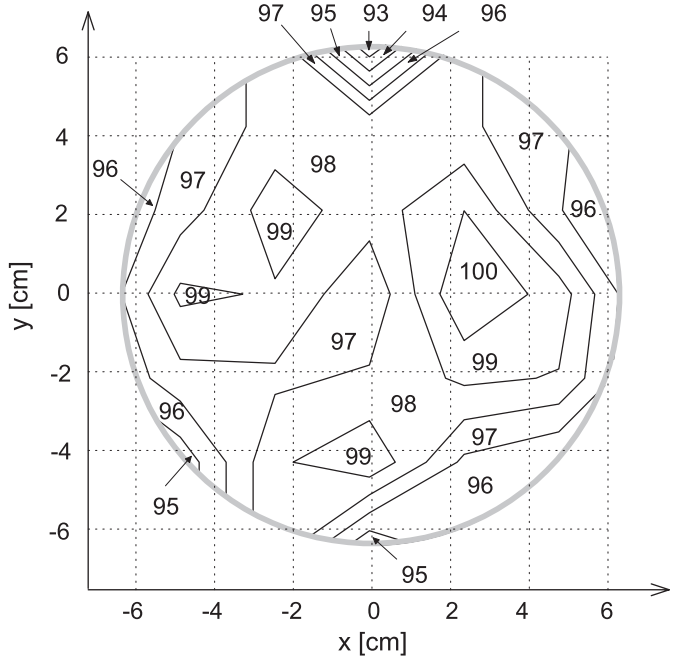

Fig. 2. Non-uniform distribution of light output across the scintillator.

The non-uniform response of the detector could also be caused by the variation of the phototube efficiency over the face. To estimate the importance of this effect, the phototube was rotated on its symmetry axis by 90°, 180°and 270°, all the while keeping the source-scintillator arrangement unchanged. Then, we repeated the experiment for the different rotation angles and got almost the same results. This suggested that the non-uniform response of the detector was mainly influenced by the scintillator rather than the phototube. In the Monte Carlo calculation of the scintillator response to the γ-ray, the sensitive volume of the scintillator must be defined based on both the geometrical data and the light yield distribution.

2.3. Measuring γ-ray energy spectrum

The experimental setup for the γ-ray measurement is shown in Fig. 1. A ^{60}Co point source was placed in front of the plastic scintillator. The source was located on the symmetry axis of the detector, at the distance of 1 cm from the front end of the detector. To avoid any interference between scattered and original γ-rays, the point source (without the collimator) should be placed as close as possible to the detector. Otherwise, the CM peak would be broadened, and it would be difficult to find the position of the Compton maxima in the measured spectrum.

2.4. Monte Carlo simulation of γ-ray interactions in the plastic scintillator

Because of the low atomic number of plastic materials, in the energy range of 50–3000 keV the primary interaction mechanism for the γ-rays is the Compton scattering. In a thick plastic, multiple scattering events tend to broaden the scintillator response function in the region of the CM by extending pulse height distribution to the higher energies. However, for a thin scintillator the multiple scattering is negligible and the energy spectrum of γ-rays is mainly due to the single Compton scattered electrons. The energy distribution of the electrons can be calculated from the Klein–Nishina formula [10]:

$$\frac{d\sigma}{dT} = \frac{\pi r_e^2}{m_e c^2 \gamma^2}\left[2 + \frac{s^2}{\gamma^2(1-s)^2} + \frac{s}{1-s}\left(s - \frac{2}{\gamma}\right)\right] \quad (1)$$

where r_e is the classical electron radius, $\gamma = h\nu/m_e c^2$ and $s = T/h\nu$. The maximum electron energy allowed by kinematics, known as the Compton edge (CE) energy, is given by

$$T_{max} = h\nu\left(\frac{2\gamma}{1+2\gamma}\right). \quad (2)$$

The energy calibration of the plastic scintillator can be made using the CE energies of several mono-energetic γ sources. Dietze and Klein [11] calculated the resolution-free γ-ray spectra by the Monte Carlo techniques, and systematically broadened them with known resolutions. Then they found a relationship between the true position of the CE, and the positions of the measured spectral features, namely the CM peak position and the half-height position. The relationship depends strongly on the size of detecting volume of the scintillator and the γ-ray energy. The non-uniform light yield changes the effective size of the scintillator. Therefore, in order to achieve higher precision calibration, we took into account the non-uniform light output of the scintillator by introducing a variable density for plastic. We modified the plastic density across the scintillator to reproduce the light output pattern as shown in Fig. 2. The Monte Carlo simulation of spectral response of the scintillator was carried out using the MCNP code.

The simulation code determined the total energy deposited in the scintillator. Each spectrum simulation was carried out for 10^6 of the photons. This number provided a good compromise between statistics and computer time.

2.5. Comparison between simulated and measured γ-ray spectra

The simulated and the measured spectra for the γ-rays of 1173.2 and 1332.5 keV from a ^{60}Co source are shown in Fig. 3. Due to the poor energy resolution of the detector, the CM peaks for the two closely spaced γ-lines from the ^{60}Co-isotope overlapped in the measured spectrum. The Compton edge energies of these lines are 963.4 and 1118 keV, respectively. Prior to comparing the simulated spectrum with the measured one, it was necessary to add the effects of the statistical fluctuations caused by the processes of light production and collection, as well as photomultiplication and electronic pulse analysis. For this purpose, the simulated γ-ray spectrum was broadened using a Gaussian-type energy resolution function. If S_0 is the number of events within an energy channel between E_1 and E_2 in the simulated spectrum, then these events will be distributed over the neighboring energy channels according to the following equation [1]:

$$M(E) = S_0 \int_{E_1}^{E_2} \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(E-E')^2}{2\sigma^2}\right] dE'$$

$$= \frac{S_0}{2}\left[erf\left(\frac{E_2-E}{\sqrt{2}\sigma}\right) - erf\left(\frac{E_1-E}{\sqrt{2}\sigma}\right)\right] \quad (3)$$

where σ is the standard deviation of the Gaussian distribution and it is related to the photon energy as: $\sigma \propto \sqrt{E}$ [12]. The energy resolution of the scintillator R is defined as

$$R = \frac{FWHM}{E} = \frac{2.35\ \sigma}{E} \propto \frac{a}{\sqrt{E}}. \quad (4)$$

Parameter a was adjusted to obtain the best shape agreement between the simulated and the measured γ spectra. Fig. 4 compares the measured γ-ray spectrum with the simulated (Gaussian broadened) spectrum for the ^{60}Co source. Whereas the shape of the experimental spectrum has been fairly well reproduced in the simulation, the locations of the Compton maxima (CM) are still different. To fit the positions of the CMs, the arbitrary energy axis at the top of Fig. 4 was re-scaled. This was achieved by increasing the width of the energy bins in the Monte Carlo calculations.

The light output of a plastic scintillator, in general, depends on the nature and the energy of the incident charged particles. For the electrons at energies above 100 keV, the light yield of the plastic scintillator is linear [13]. In the linear region, it is convenient to relate MCA channel number to the Compton recoil electron energy as

$$Ch = c(E-E_0) \quad (5)$$

where Ch is the channel number in the measured spectra, E is the energy of electron, E_0 is the energy intercept and c is an energy scaling parameter. The offset energy E_0 is sufficiently small compared to typical light output values [14].

The simulated spectrum was broadened and then scaled using different values of the broadening parameter a (ranging from 1.2 to 3.2) as well as the energy scaling parameter c (ranging from 3.205 to 3.291). The best values of these parameters were then found by least-square fitting of the simulated spectrum to the measured one in the vicinity of Compton maxima. The fitting procedure was carried out by minimization of χ^2 function which is defined by

$$\chi^2 = \sum_{Ch} [S_{exp}(Ch) - S_{sim}(Ch)]^2 \quad (6)$$

where $S_{exp}(Ch)$ and $S_{sim}(Ch)$ are the number of events in channel Ch of the measured and the simulated spectra, respectively. In Fig. 5, the calculated values of the χ^2 for different resolutions and the channel numbers are shown for ^{60}Co γ-rays. The minimum χ^2 value occurs in channel 226 and the energy resolution of 14%. The parameter search was made in the range of 20 channels around the observed Compton maxima.

3. Results and discussion

The Monte Carlo simulation of response of the plastic scintillator for ^{60}Co γ-ray is presented in Fig. 6. The measured and the simulated spectra are in good agreement. The deviation for small energies of $E_e < 100$ keV may be mainly attributed to *bremsstrahlung* of electrons [15]. Since the scintillator was thin, escape of X-rays from the scintillator was very likely. This effect was not

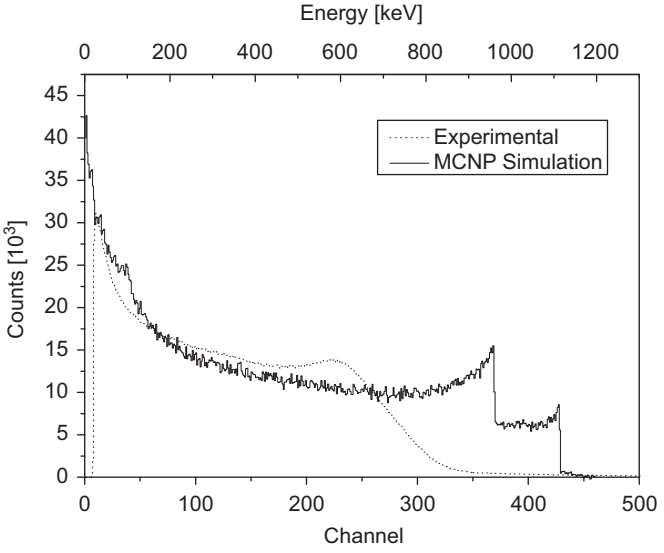

Fig. 3. Solid line presents simulated spectrum of ^{60}Co γ-rays. The dashed line shows measured spectrum of the same γ-rays.

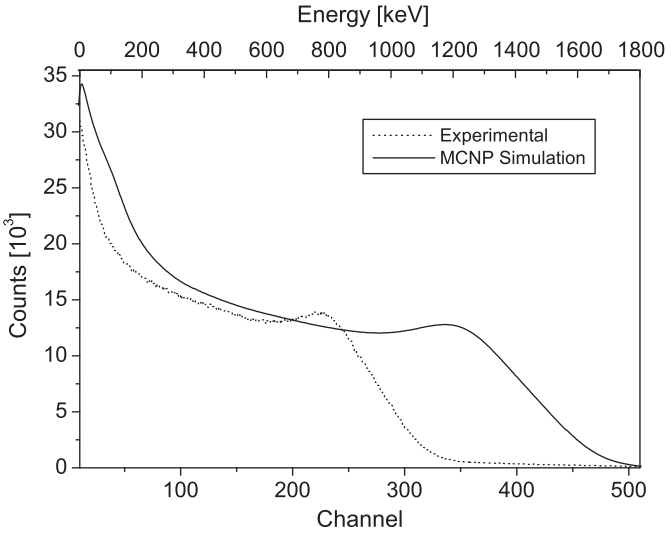

Fig. 4. Dashed line presents measured spectrum of ^{60}Co γ-rays. Solid line shows simulated spectrum which is only broadened. The broadening parameter is $a = 1.63$.

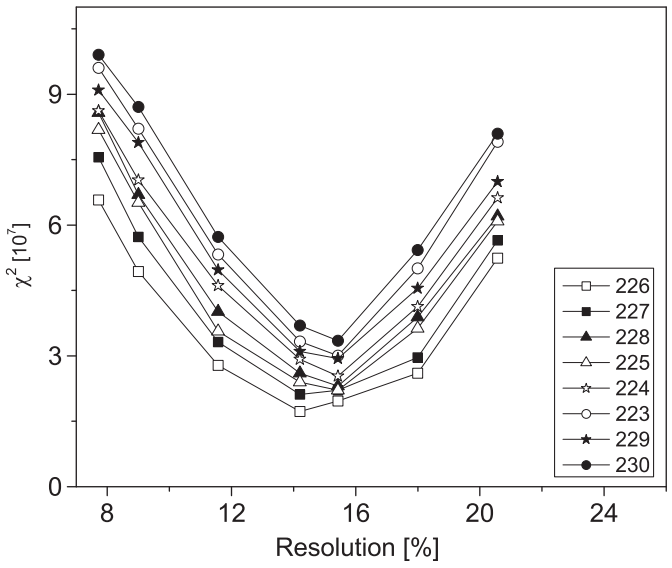

Fig. 5. χ^2 values are shown for ^{60}Co γ-rays. Channel numbers vary from ch=223 to 230. The minimum value has been obtained for ch=226.

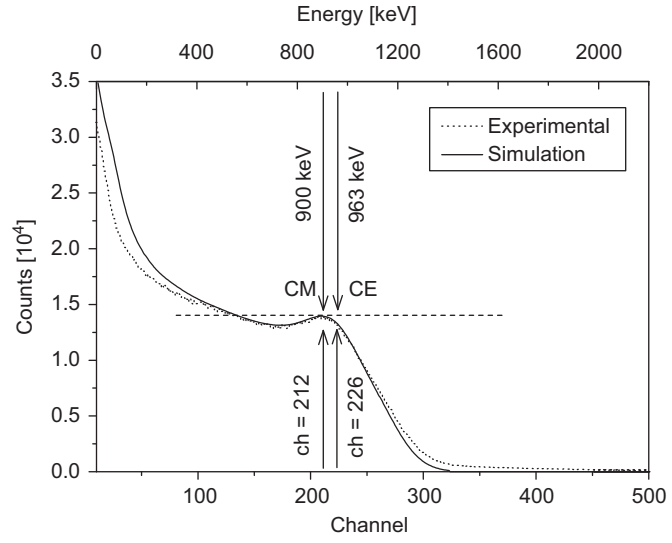

Fig. 6. The simulated ^{60}Co γ-ray spectrum after broadening and scaling is compared to the measured spectrum. The corresponding energy value and channel number for Compton edge are shown.

taken into account in the simulation. The simulated spectrum was folded with a Gaussian-type resolution function. The result of the simulation that matters most to us is how well it reproduces the CM in the γ-ray spectrum.

The χ^2 minimization procedure was performed separately for ^{60}Co, ^{137}Cs and ^{22}Na γ-ray point sources. The positions of the CE for γ-rays of 511, 662, 1173 and 1275 keV were found. The energies of the corresponding CEs are 341, 477.4, 963.4 and 1061 keV, respectively. Finally, as shown in Fig. 7, a linear energy calibration plot with a slope of 4.53 ± 0.01 keV per channel and an energy intercept of 8.18 keV was established. In addition to the energy calibration, the energy resolution of the scintillator at a given γ-ray energy can be determined by choosing proper radioactive source.

The calibration method can be applied to any source-detector geometry, including distributed sources. In our previous study [16] on the same plastic scintillator, we used the Compton edge calibration method for two different geometries, namely a point

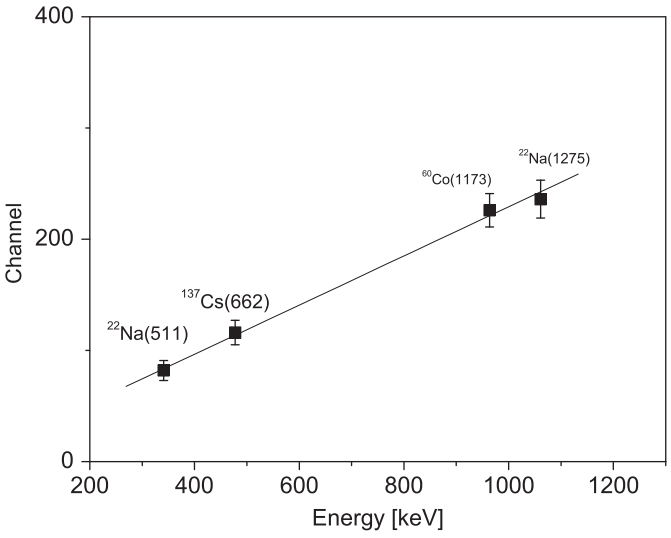

Fig. 7. Energy calibration line of plastic scintillator.

source without the collimator and the distributed source (a 1 l Marinelli beaker). The Monte Carlo simulations of the scintillator's response for these geometries were carried out using GEANT4 code [17]. Very good agreements between simulated and measured energy spectrum of the scintillator were found. This suggests that the proposed calibration method can be generalized to the wider choice of source-detector geometries.

4. Conclusion

We have investigated the light output characteristics of a thin scintillator by measuring the detector response to the collimated beam of β-rays. A 7% decrease in the light yield was observed over the scintillator surface which is mainly due to the inefficiency of the polystyrene plastic. Following the method proposed by Kudomi [3] and Hohara [15] but taking into account the non-uniformity in the light output, we have calibrated a thin plastic scintillator. Good agreement has been obtained between the measured and the MCNP simulated γ-ray spectra. Applying the Chi-squared method for the thin plastic detector, we have determined the position of the Compton edge in the experimental spectrum with a reasonable accuracy. The discrepancy in the channel number assignment amounts to ± 4.5 keV at 477 keV. This energy calibration approach is particularly important for the low-Z scintillation material, where no photopeaks are observed due to the poor γ-ray detection efficiency of the light material.

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