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Energy Calibration of BC408 Plastic Scintillator Using γ-γ Coincidence Technique

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1. Introduction

Plastic scintillator is an organic radiation sensor that facilitates radiation detection by converting an incident radiation into scintillation lights. It is useful for the medical radiotherapy application because it is composed of low-Z materials (Hydrogen, Carbon) equivalent to components of human tissue. The energy calibration is required for the accurate calculation of absorbed dose to plastic scintillator, but it is difficult to measure energy resolution through a γ-ray photopeak due to very low photoelectric cross section.

In the present paper, for this reason, γ-γ coincidence technique [1] was adopted to calibrate BC408 plastic scintillator (Saint-Gobain Crystal, 30 × 30 × 10 mm^3). The accurate positions of the Compton edge and energy resolution at the position were determined by using the γ-γ coincidence Gaussian peak for various γ-ray sources (^{137}Cs, ^{54}Mn, and ^{60}Co). Energy resolution was analyzed with an empirical fit and the energy calibration was accomplished through the linear fits for the positions of Compton maximum, half of Compton maximum, and Gaussian peak. For the case of the energy calibration using Gaussian peak that showed the smallest variance, the verification was performed with Monte Carlo simulation using the MCNPX code.

2. Methods and Results

2.1 γ-γ Coincidence Technique

The principle of γ-γ coincidence technique is as follows [1]. First, an incident γ-ray on a tested scintillator transmits the maximum energy to Compton electron (E_c) to produce a signal and then it is backscattered at the 180° angle. Secondly, 180° backscattered γ-ray (E_γ) reacts to a monitor detector. The signal of the Compton scattering reaction for maximum energy transfer to Compton electron can be selectively acquired by matching these two signals in terms of signal time. Figure 1 show mechanism of γ-γ coincidence technique.

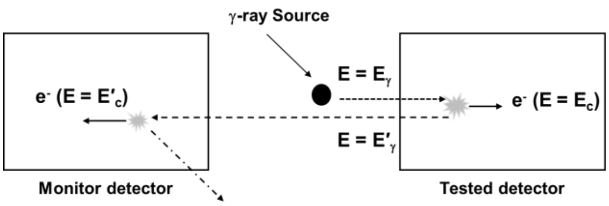

Figure 1. Schematic mechanism of γ-γ coincidence technique

When a photon scattered in the tested detector, the energy of the Compton electron is given by

$$E_e = \frac{E_\gamma^2(1-\cos\theta)}{0.511 + E_\gamma(1-\cos\theta)} \quad (1)$$

so the deposited maximum energy (scattering at 180°) is given by

$$E_c = \frac{2E_\gamma^2}{0.511 + 2E_\gamma} \quad (2)$$

where E_γ is the energy of the incident γ-rays in MeV. The detailed information of the γ-ray sources used for γ-γ coincidence measurement of the tested detector BC408 is listed in Table I.

Table I: Data of the γ-ray sources used for γ-γ coincidence measurement of BC408 plastic scintillator

Source	E_γ [keV]	E_c [keV]	E'_γ [keV]	E'_c [keV]
^{137}Cs	661.659	477.336	184.323	77.247
^{54}Mn	834.855	639.226	195.629	84.833
^{60}Co	1173.24	963.431	209.809	94.604
^{60}Co	1332.508	1118.116	214.392	96.723

2.2 Experimental Setup

The γ-γ coincidence experimental setup is as follows [2]. BC501A liquid scintillator (Saint-Gobain Crystal, D = 50.8 mm, H = 50.8 mm) was used as monitor detector coupled with a photomultiplier (Hamamatsu, R329-02). BC408 plastic scintillator (Saint-Gobain Crystal, 30 × 30 × 10 mm^3) coupled with a photomultiplier (Hamamatsu, H7195) was located at a distance 50 mm from the monitor detector. γ-ray sources listed in Table I were placed at the center of the distance 50 mm.

One of anode outputs of the tested detector was properly amplified through the preamplifier and the main amplifier, and delayed by an ORTEC 427A module, and entered into MCA to measure Compton spectrum without coincidence of the tested detector. The other anode output and the anode output of monitor detector were coupled to the discriminator. The timing output of the discriminator were fed into a TAC whose time range was set to 50 ns. The coincidence spectrum was measured by a gate signal of the SCA output from the TAC module. Figure 2 shows the schematic diagram of the γ-γ coincidence electronic circuit.

Table II: The Gaussian peak (GP), FWHM, and energy resolution (R) for Gaussian curve, the fraction of maximum values at which GP crosses the Compton spectrum, the relative shift of GP to Compton maximum (CM), and the ratio of half of Compton maximum (HM) position and GP position, measured with ^{137}Cs, ^{54}Mn, and ^{60}Co γ-ray sources

Source	E_c [keV]	GP channel	FWHM [ch]	CM channel	Fraction of maximum	$\frac{GP - CM}{GP}$	HM/GP	Resolution [%]
^{137}Cs	477.336	149 ± 0.03	15.61 ± 0.07	140.39 ± 0.04	0.7529	0.058	1.031	9.66 ± 0.04
^{54}Mn	639.226	203.87 ± 0.05	19.53 ± 0.11	194.34 ± 0.08	0.7642	0.047	1.029	9.02 ± 0.05
^{60}Co	963.431	314.76 ± 0.11	24.28 ± 0.26	299.3 ± 0.14	0.8098	0.049	1.035	7.42 ± 0.08
^{60}Co	1118.116	365.57 ± 0.14	26.03 ± 0.34	353.44 ± 0.23	0.6875	0.033	1.018	6.88 ± 0.09

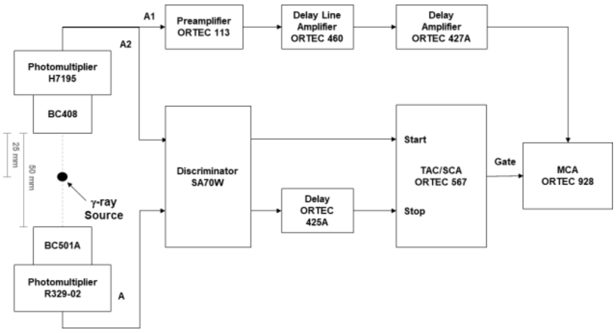

Fig. 2. Systematic diagram of the γ-γ coincidence electronic circuit

The coincidence measurement was performed to determine the position of the Compton edge for the γ-ray sources. Figure 3 shows the measured spectrum and analyzed results for ^{60}Co source. The pulse height spectra with/without coincidence were compared and it was noted that the coincidence spectrum of the ^{60}Co source shows two separated Gaussian peaks. This implies that a good performance can be obtained with the coincidence measurement to determine each Compton edges.

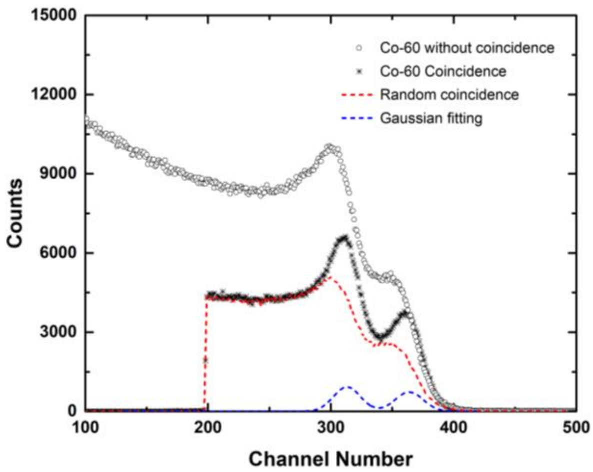

Fig. 3. Direct Compton spectrum (circle) superimposed on the γ-γ coincidence spectrum (star) for ^{60}Co γ-ray source. The smooth dash lines are the fitting results for Compton coincidence (blue) and random coincidence (red).

In order to get the accurate position of the Compton edge and the energy resolution of the tested detector, the coincidence spectrum was subtracted from a random coincidence spectrum and fitted with a Gaussian function. Because the random coincidence was mostly attributed to the γ-ray directly from the source in this experiment, the spectrum was acquired from the pulse height spectrum without coincidence. It was expected that the mean value of the Gaussian distribution represents the accurate position of the Compton edge for each γ-ray source.

2.3 Energy Resolution

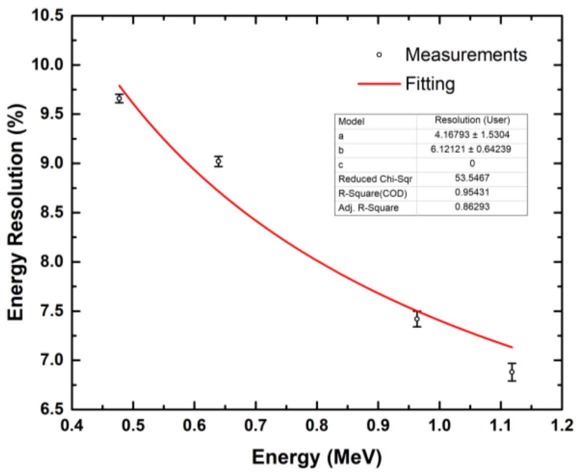

Fig. 4. Empirical fit for energy resolution data of BC408 plastic scintillator

Table 2 shows the fitting results, including Gaussian peak (GP), FWHM, and energy resolution (R) for Gaussian curve, the fraction of maximum values at which GP crosses the Compton spectrum, the relative shift of GP to Compton maximum (CM), and the ratio of half of Compton maximum (HM) position and GP position, measured with ^{137}Cs, ^{54}Mn, and ^{60}Co γ-ray sources. For energy resolution, an empirical fit was performed for the energy resolution data as a function of the Compton eletron energy (E) using the following equation:

$$R\ (\%) = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}} \tag{5}$$

where a, b, and c are the fitting parameters. Figure 4 shows the empirical fit of energy reolustion data for BC408 plastic scintillator.

2.4 Energy Calibration

The energy calibration is accomplished by a linear fitting of the Compton electron maximum energy and pulse height values (channel number) from various γ-ray sources. The linear relationship can be expressed as,

$$E = \alpha(ch - ch_0) \quad (6)$$

α is the calibration constant [keV/ch] and ch_0 is the channel corresponding to E is 0. The intercept energy E_0 (= $\alpha \cdot ch_0$) is regarded as the non-linearity due to the quenching effects in the scintillator. Figure 5 shows the linear fits for the positions of Compton maximum, half of Compton maximum, and Gaussian peak. From the statistical analysis of the linear fit results, the position of Gaussian peak showed the smallest variance to the real Compton edge.

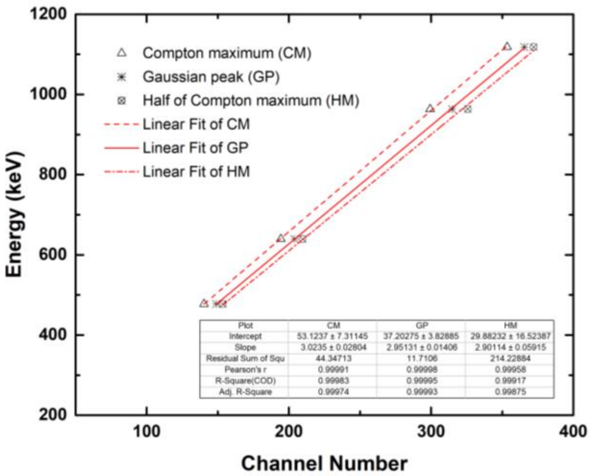

Fig. 5. Linear fit of the pulse height values (channel number) for maximum energy of the Compton electron from various γ-ray sources

To verify the determined position of the Compton edge and the energy calibration based on Gaussian peak, Monte Carlo simulation using MCNPX code [3] was performed. The FT8 geb card in MCNPX code provides energy broadening function. The theoretical spectra for ^{137}Cs, ^{54}Mn, and ^{60}Co were calculated by MCNPX code (as seen in Fig. 6 corresponding to the case of ^{60}Co). The result of MCNPX without geb card was matched to the measured coincidence spectrum, and then the theoretical spectrum was compared to the measured without coincidence spectrum. It was confirmed that the deviation for the position of Compton maximum was about 0.44% (for 1.17 MeV) from the energy spectra of the measurement and MCNPX.

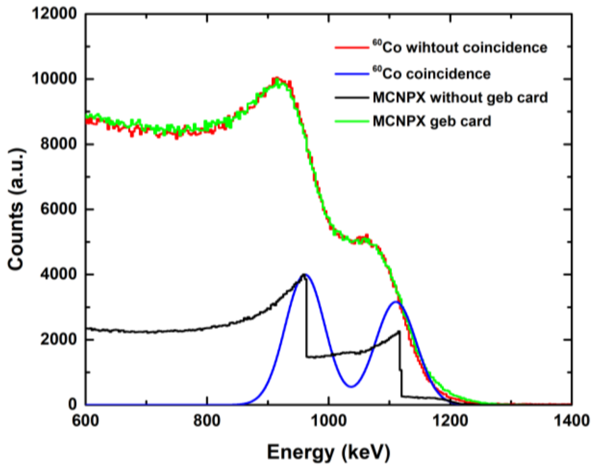

Fig. 6. Comparison between experimental (blue and red) and theoretical (black and green) pulse height spectrum calculated by MCNPX for ^{60}Co source with the energy of 1.17 MeV and 1.33 MeV.

3. Conclusions

The experimental system for γ-γ coincidence was constructed to determine the accurate positions of the Compton edge for the energy calibration of BC408 plastic scintillator. Energy resolution for BC408 was acquired and analyzed by the empirical fit. Also, the linear fits for the positions of Compton maximum, half of Compton maximum and Gaussian peak were compared, and it was confirmed that the energy calibration based on the Gaussian peak was most accurate through the statistical analysis ($R^2 = 0.9995$). To verify this energy calibration, Monte Carlo simulation using MCNPX code was performed and the deviation for the position of the Compton maximum was about 0.44% (for ^{60}Co 1.17 MeV).

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