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Compton-edge-based energy calibration of double-sided silicon strip detectors in Compton camera

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ABSTRACT

Accurate energy calibration of double-sided silicon strip detectors (DSSDs) is very important, but challenging for high-energy photons. In the present study, the calibration was improved by considering the Compton edge additionally to the existing low-energy calibration points. The result, indeed, was very encouraging. The energy-calibration errors were dramatically reduced, from, on average, 15.5% and 16.9% to 0.47% and 0.31% for the 356 (^{133}Ba) and 662 keV (^{137}Cs) peaks, respectively. The imaging resolution of a double-scattering-type Compton camera using DSSDs as the scatterer detectors, for a ^{22}Na point-like source, also was improved, by $\sim$9%.

1. Introduction

Double-sided silicon strip detectors (DSSDs) are considered to be the most suitable scatterer detectors for Compton cameras. The energy calibration of DSSDs is, however, very challenging in the case of high-energy photons (of > a few hundred keV) because, given the low-Z material of which DSSDs are composed, the probability of photoelectric absorption is very low. Furthermore, DSSDs normally are very thin (< 2 mm), and as such, the likelihood of forming a full-energy peak from multiple interactions is negligible.

Several authors have suggested that for organic scintillation detectors, which, like DSSDs, are composed of low-Z material, accurate energy calibration is possible if the Compton edge in the measured spectrum is utilized [1–3]. In the present study, the accuracy of the energy calibration of a DSSD semiconductor detector was improved by considering the Compton edge in addition to the existing low-energy calibration points. The improvement was then evaluated by predicting the locations (=channel numbers) of two peaks (of 356 and 662 keV) before and after considering the Compton edge in the energy calibration. Finally, the Compton-edge-based calibration was applied to a Compton camera using DSSDs as the scatterer detectors in order to determine the effect of the improved energy calibration on the imaging resolution.

2. Material and methods

First, a number of theoretical energy spectra with different energy resolutions were calculated, by Geant4 [4] Monte Carlo simulations, and compared with the measured spectrum in order to find the theoretical spectrum that best matched the measured spectrum. Then, the information of that best-matching theoretical spectrum was used to determine the location (=channel number) of the Compton edge in the measured energy spectrum, which edge subsequently was used, in addition to the existing low-energy calibration points, in the energy calibration.

The most challenging task, in fact, was finding that best-matching theoretical spectrum. The shape of the Compton edge strongly depends on the energy resolution of the DSSD. Therefore, a number of theoretical energy spectra were calculated for a ^{137}Cs source with energy resolutions varying from 0.5% to 20% in 0.5% intervals (=40 cases). In the simulations, it was assumed that the DSSD had a constant percent energy resolution regardless of the deposited energies in the detector [1–3]. Each of the theoretical energy spectra, one at a time, was then compared with the measured spectrum to find the best-matching spectrum (see Fig. 1).

The theoretical and measured energy spectra were compared for the energy channels equal to or greater than 1000 in the measured spectrum, which corresponded to $\sim$250 keV, in order to compare only the upper part of the Compton continuum and edge. For this, different cutting channels, varying from 200 to 320 in 1-channel intervals (=120 cases), were applied to the theoretical spectrum. Finally, different amplitude gains, varying from 2 to 5 in 0.05 intervals (=60 cases), were applied to the

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theoretical energy spectrum to find the best-matching energy spectrum.

3. Results and discussion

The measured energy spectrum was obtained by counting a 9.28-μCi ^{137}Cs check source for 1 h. A total of 288,000 cases of theoretical spectra, that is, 40 (energy resolutions) × 120 (cutting channels) × 60 (amplitude gains), were then calculated and compared with the measured spectrum, using an in-house program, in order to find the best-matching theoretical energy spectrum. The comparisons were repeated for each of the strips to find the best-matching energy spectrum minimizing the χ^2-value

$$\chi^2 = \sum_i (N_{\mathrm{measured},i} - N_{\mathrm{theoretical},i})^2 \tag{1}$$

where $N_{\mathrm{measured},i}$ and $N_{\mathrm{theoretical},i}$ are the normalized counts in channel i for the measured spectrum and the theoretical spectrum, respectively. Fig. 2 shows the best-matching theoretical energy spectra found for the 16 strips of the DSSD under investigation. The results show that the best-matching theoretical spectra did, in fact, well match the measured spectra.

The improvement of energy calibration was evaluated for the 356 (^{133}Ba) and 662 keV (^{137}Cs) peaks by considering the Compton edge (=477 keV) of the ^{137}Cs source in addition to the low-energy calibration points, 59.5 (^{241}Am) and 88 keV (^{109}Cd). The energy spectra of the ^{133}Ba and ^{137}Cs sources were obtained separately by counting these two sources over a very long time (=12 h), after which the peak energies appearing in the measured spectrum were compared with the true values (356 and 662 keV). Fig. 3 shows the energy-calibration errors of the 16 strips

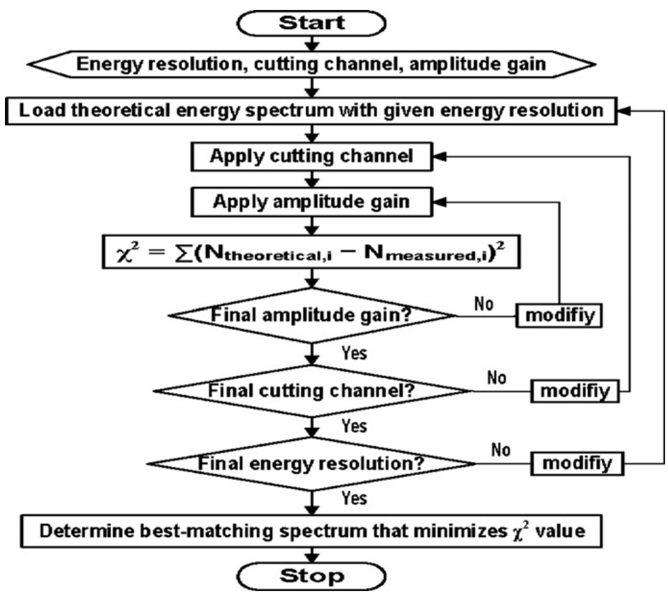

Fig. 1. Flow chart for finding best-matching theoretical energy spectrum.

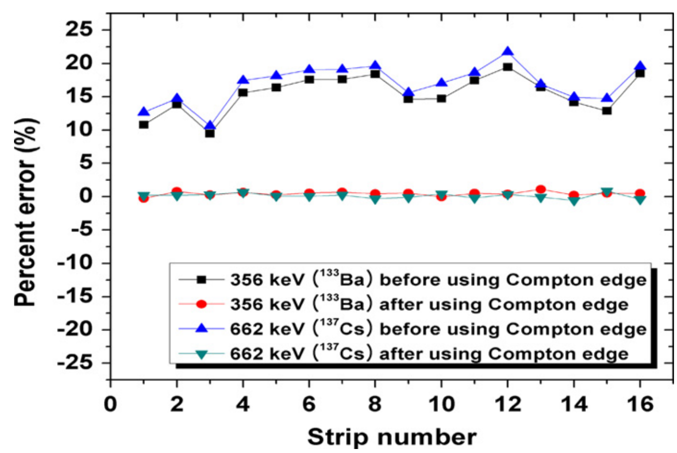

Fig. 3. Energy-calibration errors of 16 strips in DSSD for 356 and 662 keV peaks of ^{133}Ba and ^{137}Cs sources, respectively, before (squares and triangles) and after (circles and reverse triangles) use of Compton edge in energy calibration. The error was calculated as [(observed peak energy − exact peak energy)/exact peak energy] × 100%.

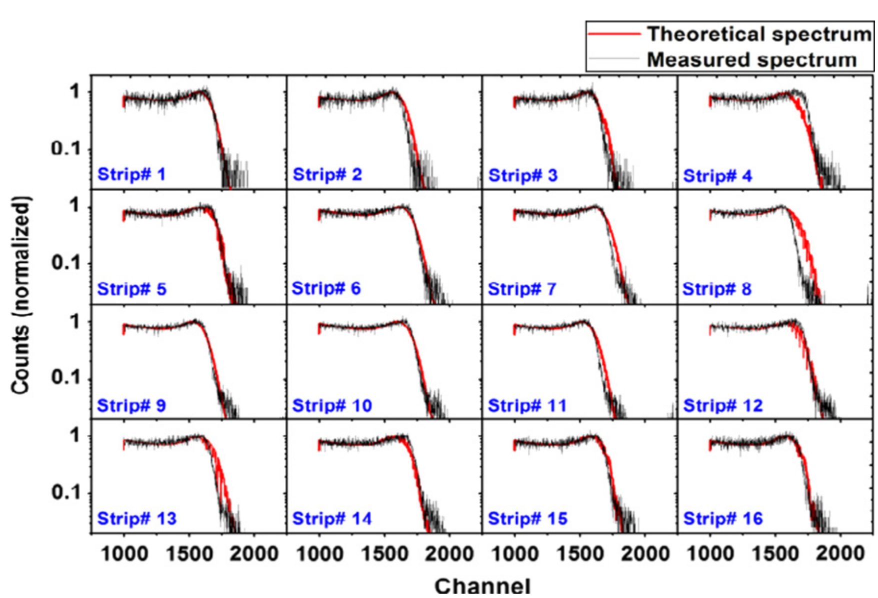

Fig. 2. Comparison of best-matching theoretical energy spectra (red) and measured energy spectra (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the DSSD for the 356 and 662 keV peaks. The results show that the inclusion of the Compton edge in the energy calibration dramatically improved the accuracy, reducing the energy-calibration errors from, on average, 15.5% and 16.9% to 0.47% and 0.31% for the 356 and 662 keV peaks, respectively. The energy resolutions for the 16 strips in the DSSD were determined to fall in the 7–10% range.

Finally, the Compton-edge-based energy calibration was applied to a double-scattering-type Compton camera (DOCI: DOuble-scattering Compton Imager) that uses two DSSDs as the scatterer detectors and one NaI(Tl) scintillation detector as the absorber detector. With the DOCI, accurate energy calibration of the first DSSD is very important, as it directly affects the imaging resolution. The imaging resolution of the DOCI, by additionally considering the Compton edge in the energy calibration of the DSSDs, was improved, for a ^{22}Na point-like gamma source (511 keV), by $\sim$9%, from 9.3 to 8.5 mm FWHM. The improvement of the imaging resolution was not very significant, due to the fact that it is affected also by other factors such as the spatial resolution of the scatterer detectors, Doppler broadening, and electronic noise.

4. Conclusions

In the present study, energy calibration of a DSSD was dramatically improved by considering the Compton edge in addition to the existing low-energy calibration points. The result, indeed, was very encouraging. The imaging resolution of a double-scattering-type Compton camera, or DOCI, also was improved by $\sim$9%. Based on all of the results, Compton-edge-based energy calibration is believed to be very useful for accurate energy calibration of small and/or low-Z-material detectors.

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