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Iterative Monte Carlo simulation with the Compton kinematics-based GEB in a plastic scintillation detector

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ABSTRACT

Plastic scintillators have been used for gamma ray detection in the fields of dosimetry and homeland security because of their desired characteristics such as a fast decay time, a low production cost, availability in a large-scale, and a tissue-equivalence. Gaussian energy broadening (GEB) in MCNP simulation is an effective treatment for tallies to calculate the broadened response function of a detector similarly to measured spectra. The full width at half maximum (FWHM) of a photopeak has been generally used to compute input parameters required for the GEB treatment. However, it is hard to find the photopeak in measured gamma spectra with plastic scintillators so that computation of the input parameters for the GEB has to be taken with another way. In this study, an iterative method for the GEB treated MCNP simulation to calculate the response function of a plastic scintillator is suggested. Instead of the photopeak, Compton maximum and Compton edge were used to estimate energy broadening in the measured spectra and to determine the GEB parameters. In a demonstration with a CsI(Tl) scintillator, the proposed iterative simulation showed the similar gamma spectra to the existing method using photopeaks. The proposed method was then applied to a polystyrene scintillator, and the simulation result were in agreement with the measured spectra with only a little iteration.

1. Introduction

In the history of radiation detection, plastic scintillators have been far from ideal for gamma spectroscopy because of their low light output and low density [1]. Nonetheless, they have desired characteristics which differentiate themselves from inorganic scintillators such as a fast decay time, a low production cost, availability in a large-scale, and a tissue-equivalence. For this reason, there have been many approaches to use plastic scintillators for a gamma ray detection, especially in the fields of dosimetry and homeland security [2–5].

Because of their physical and chemical properties, plastic scintillators show quite different gamma responses from that of inorganic scintillators. An absence of a photopeak is the most outstanding feature, and low cross-sections for photoelectric absorption is a main reason for this difference. Fig. 1 shows relative contribution to photon attenuation from the photoelectric absorption, Compton scattering, and pair production in polystyrene used in this study. The XCOM program [6] developed by NIST was used to calculate photon cross-sections for polystyrene (input as C_8H_8).

For gamma energies exceeding 50 keV, the cross-sections of photoelectric absorption are lower than those of Compton scattering so that the Compton scattering becomes predominant over the energy range of interest. As a result, it is hard to find any photopeak in measured gamma spectra except for a low energy gamma ray, i.e., only the Compton continuum is observed. In the Compton kinematics, the energy of Compton edge (E_c) which is the end of Compton continuum is calculated as follows:

$$E_c = E_{e-}|_{(\theta=\pi)} = E_\gamma \left(\frac{2E_\gamma}{m_e c^2 + 2E_\gamma} \right) \quad (1)$$

where E_{e-} is the kinetic energy of a recoil electron, θ is the scattering angle, E_γ is the initial energy of incident gamma ray, and $m_e c^2$ is the rest mass energy of an electron (0.511 MeV) [1]. However, differing from theoretical calculation and the primary result from simulation, this Compton edge is not obviously observed in reality because of a finite energy resolution of a radiation detector. Instead of the Compton edge, a peak is observed at the end of Compton continuum due to overlapped energy broadening effect, and this peak is called a Compton maximum [7,8].

The Monte Carlo method is an effective technique to investigate possible outcomes numerically, and widely applied in the nuclear and radiation fields. The Monte Carlo N-Particle code (MCNP) that has been developed by the Los Alamos National Laboratory is the most representative tool for the Monte Carlo simulation. It traces

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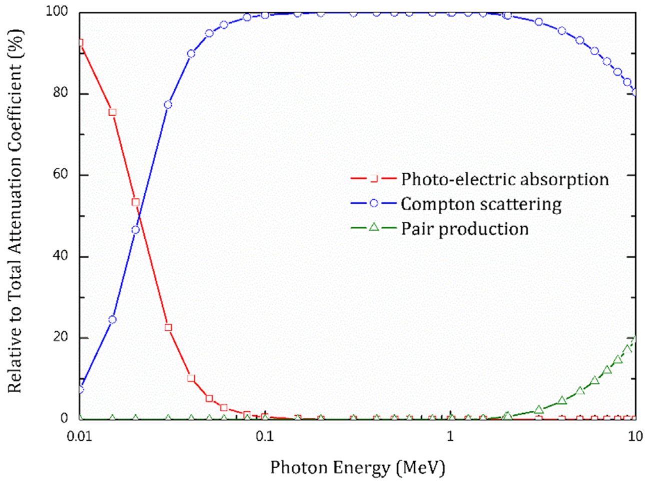

Fig. 1. Relative contribution from photon interactions in polystyrene.

particles in a designated situation and indicates certain tallied results requested by a user. High accuracy and effectiveness of the MCNP simulation has been verified in many studies related to radiation simulation including the studies about response functions of radiation detectors [9–13].

The response function of a detector is defined as the differential pulse height distribution for an incident monoenergetic radiation and it depends on the cross-sections of photon interactions within a detector [1,14]. The initial response function is broadened due to several reasons such as variation in light generation, statistical nature of photon-production in a scintillator, variation of light collection efficiency, fluctuation in the number of generated electrons in a detector, inherent variation of a detector, and electronic noise [13]. To describe the response function close to measured spectra, individual and collective calculations of physical effects on the broadening from each factor are required but it is very complicated. In the recent versions of MCNP (MCNP5, MCNP-X, MCNP6), an alternative way to consider the energy broadening effect has been suggested. Instead of calculating each physical phenomena, a Gaussian energy broadening (GEB) treatment in the MCNP provides a virtual peak-broadening, which includes all broadening effects. The MCNP simulation with GEB shows a broadened gamma spectrum by sampling from the Gaussian function with specified input parameters [15].

Since the introduction of the GEB into the MCNP code, many studies have used it to calculate the response function of various detector materials such as NaI(Tl), $LaCl_3$(Tl), HPGE, BGO, and PVT [4,5,7,9–13,16,17]. In the studies of inorganic scintillators which have high cross-sections for photoelectric absorption, the full width at half maximum (FWHM) of photopeaks in measured spectra has been used to estimate energy broadening and compute input parameters for the GEB treatment [9,10,12,13,16,17]. The simulation results in these studies were in agreement with the measured spectra so that this GEB treated simulation using a photopeak has been validated. Differing from inorganic scintillators, this method using a photopeak is not appropriate for plastic scintillators as well as other organic scintillators because it is hard to observe any photopeak in gamma spectra with plastic scintillators. Therefore, for the simulation of energy-broadened spectra, the GEB treated MCNP simulation has to be taken with another way. Some studies of plastic scintillators have reported the use of MCNP simulation with GEB to calculate the gamma response [4,5,7,11]. In these simulation, the energy resolution at each energy were specified for fitting the simulation results to the measured spectra, and the computed input parameters for the GEB treatment were based on the determined resolution to the energy. This approach requires many runs of the simulation and a long computation time to find the energy resolution which provide the best fit to the measured results.

In this study, the gamma response function for the polystyrene scintillation detector is calculated using the iterative MCNP simulation with the Compton kinematics-based GEB. Estimation of the energy broadening effect in measured spectra and computation of input parameters for the GEB treatment were performed using Compton maxima and Compton edges. Unknown energy of the Compton maxima were assumed at the initial stage and updated with the MCNP simulation results at each stage. In a demonstration with a cubic CsI(Tl) scintillation detector, the proposed method was compared with the existing method using a photopeak. And finally, it was used to calculate the gamma response function for the polystyrene scintillation detector.

2. Materials and methods

This study is a series of measurement, calibration of gamma spectra, computation of input parameters, and the GEB treated MCNP simulation. As previously mentioned, both scintillators of CsI(Tl) and polystyrene were used for this study.

Fig. 2 shows the flow of proposed iterative method. At the initial stage, Compton maximum is used to calibrate the measured spectra and estimate the energy broadening with an assumption on its energy. Based on the acquired FWHM of Compton maxima, the initial GEB parameters are computed and MCNP simulation is performed. In the MCNP simulation results using the initial GEB parameters, the energy of Compton maxima are determined more precisely than the assumed energy and the energy calibration is done again at the second stage. Since the second stage, estimation of energy broadening and computation of the GEB parameters are performed at the calculated energy of Compton edges. Because the Compton edge is located at the outer side of a Compton maximum peak, the estimated energy broadening at Compton edge is less affected by the overlap of energy broadening effect. In the second MCNP simulation results, the energy of Compton maxima are determined again for a next iteration, and the same process is repeated with the updated energy of Compton maxima. With the iteration stages, the energy of Compton maxima approach the exact values so that the spectra from MCNP simulation also approach the measured spectra.

2.1. Measurement and energy calibration of gamma spectra

Considering the energy range of general interest and calculated energy of Compton edges, standard gamma sources are selected for measurement and MCNP simulation. Table 1 is details of the gamma sources [18].

As mentioned earlier, a 1 cm^3 cubic scintillator of CsI(Tl) was used as well as a 1 cm^3 cubic polystyrene scintillator which is the main focus of this study. A PMT (H6410, Hamamatsu), a spectroscopy amplifier (673, ORTEC), and a multichannel analyzer (TRUMP-PCI-2K, ORTEC) followed the scintillators. Optical grease (BC 630, Saint-Gobain) was used for optical coupling between the scintillators and the PMT. Because the area of the PMT is larger than that of the scintillators, the exceed area of the PMT was sealed with Teflon tapes to prevent interference of ambient light as shown in Fig. 3. All measurements were performed in the aluminum dark box whose thickness and length were 1 cm and 70 cm each. A distance between the source and scintillator was fixed as 5 cm enough to get sufficient counts, even this short distance was not a good choice for energy resolution. Each measurement was lasted more than a half hour so that all