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A Study on Non-proportionality of Phoswich Detector Using Monte Carlo Simulation

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몬테칼로 전산모사를 이용한 Phoswich 계측기의 비선형성 연구

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Abstract - Using the Monte Carlo simulation, a study on the non-proportionality of the prototype phoswich detector with 2″×2″ CsI(Tl) and plastic scintillator, which was made by KAERI, has been carried. The detector response functions (DRFs) calculated by simulations were compared with the experimental measurement on the ^{137}Cs and ^{60}Co. To precisely simulate the DRF for the phoswich, the CsI(Tl) non-proportionality was calculated using the electron response and the simplified electron cascade sequence for treating the photoelectric absorption event. The resulting DRFs of ^{137}Cs and ^{60}Co sources obtained by simulations were compared with experiments for verification. For ^{137}Cs, gamma-ray responses simulated by MCNP5 are generally good agreement with the measured ones. But the DRF of ^{60}Co does not match well with the results of experiment in the energy region below second peak due to the coincidence effect of two gamma-rays (1.17 MeV and 1.33 MeV). Through the analysis of the non-proportionality of CsI(Tl) in the prototype phoswich, the improved DRFs considering non-proportionality were produced and the simulation results were verified using the experimental measurements. However, to more precisely reproduce the DRF for the phoswich, further studies in relation to the electron channeling effect and the Doppler broadening effect of a scintillator are still needed as well as considering that effect of the transfer contribution.

Key words : Non-proportionality, Phoswich, Detector, Monte Carlo Simulation, Photon response

요약 - 한국원자력연구소에서 감마선과 전자를 동시측정하기 위한 목적으로 제작된 Prototype phoswich를 이용하여 감마선에 대한 섬광체의 비선형성에 대한 연구를 수행하였다. 제작된 Prototype phoswich는 2″×2″ CsI(Tl)와 Plastic scintillator 그리고 하나의 PMT로 구성되어 있다. 몬테칼로 방법을 이용하여 ^{137}Cs과 ^{60}Co 선원의 Prototype phoswich 계측기의 반응함수(Detector Response Function, 이하 DRF)를 구하였으며 이를 검증하기 위하여 제작된 Prototype phoswich를 이용, 실험을 통하여 DRF를 구한 뒤 비교하였다. 계측기의 DRF를 정확하게 모사하기 위하여 CsI(Tl) 섬광체의 Electorn response와 섬광체 내에서의 광전효과를 고려하는

Simplified electron cascade sequence 정보를 이용하여 CsI(Tl) 섬광체의 감마선에 대한 비선형성을 계산하였다. ^{137}Cs 선원의 경우 전산모사를 통하여 구한 DRF 결과는 실험값과 비교적 잘 일치함을 알 수 있었으나 ^{60}Co의 경우에는 ^{137}Cs 선원의 결과와는 달리 전산모사 결과와 실험값에 약간의 차이가 남을 알 수 있었다. 이는 ^{137}Cs 선원과는 달리 ^{60}Co은 1.17 MeV와 1.13 MeV 두 개의 광자를 동시에 방출하기 때문에 동시효과에 의한 불확실성 등이 그 외 다른 불확실성 등과 함께 증폭되어 나타나기 때문이다. 본 연구를 통해 Phoswich내 CsI(Tl)의 감마선 비선형성에 대한 분석을 수행하였으며 이를 통하여 비선형성이 고려된 개선된 Phoswich DRF를 생산하고 이를 실험값과 비교 검증할 수 있었다. 섬광체의 Electron channeling effect, Doppler broadening effect 및 Transfer resolution 등과 같은 후속연구가 추가된다면 좀더 정확한 Phoswich의 DRF를 전산 모사하는 것이 가능해질 것이다.

Introduction

Since Valentine (1998) proposed a new method to describe the precise characteristics of the inorganic detector response function (DRF) [1], much attention has been paid to accurately simulate the gamma-ray response function. A development of Compton Coincidence Technique (CCT) to provide a means for estimating the electron response for monoenergetic electrons promoted the work in relation to accurately reproducing the response function for inorganic scintillation detectors. In recent years, The accurate reproduction of the gamma-ray response is important especially for the prompt gamma-ray neutron activation analysis (PGNAA), since the response functions greatly influence the analysis results.

In principle, it is possible to accurately reproduce the DRF using Monte Carlo simulation, but there are many features of interest that cannot be easily determined and simulated. Generally, the detection process of gamma-ray in a scintillation detector can be described by a chain of subsequent processes, which introduce uncertainty in the measured energy spectra as a result of gamma-ray absorbed in the detector. These processes can be identified as: 1) gamma-ray absorption and light generation in the crystal, 2) light collection at the photocathode, 3) photoelectron production at the photocathode, 4) photoelectron collection at the first dynode, and 5) multiplication by the PMT dynodes.

Methods and Results

The total resolution of a detector coupled to a photomultiplier can be described by three categories such as intrinsic, transfer, and PMT resolution. The intrinsic resolution of a crystal is connected with many effects such as inhomogeneities in the scintillator, non-uniform reflectivity of the reflecting cover of the crystal, as well as the non-proportional response of a scintillator. The transfer resolution is associated with the probability that a photon from the scintillator results in the arrival of photoelectron at the first dynode and then is fully multiplied by the PMT. The total energy resolution of the full-energy peak measured with a scintillator coupled to a photomultiplier can be written as

$$(\delta_{\text{total}})^2 = (\delta_{\text{intrinsic}})^2 + (\delta_{\text{transfer}})^2 + (\delta_{\text{PMT}})^2 \qquad (1)$$

where $\delta_{\text{intrinsic}}$ is the intrinsic resolution of the crystal, δ_{transfer} is the transfer resolution, and δ_{PMT} is the PMT contribution to the resolution.

1. Intrinsic Resolution of the Crystal

Numerous studies suggest that the non-proportional response of the crystal is mainly responsible for the intrinsic resolution even though many characteristics of the crystal contribute to the intrinsic energy resolution. The non-proportionality of a crystal can be described by electron response and photon response of it. While the fundamental characteristic of a crystal is dependent on the electron energy, the knowledge of the photon response is typically more useful to identify the characteristics of the detector. Electron response $R_e(E_e) = L_e(E_e)/E_e$, where $L_e(E_e)$ is light output as function of electron energy E_e, is dependent on the scintillation material while the photon response $R_\gamma(E_\gamma) = L_\gamma(E_\gamma)/E_\gamma$, where $L_\gamma(E_\gamma)$ is light output as function of photon energy E_γ, is dependent on the crystal size and shape. Discrete electron energies $E_{e,i}$, which were obtained by Monte Carlo simulation, together with the measured electron response enable the photon response calculation using the discrete convolution:

$$R_\gamma(E_\gamma) = \frac{K}{E_\gamma}\sum_i \Psi(E_\gamma, E_{e,i})\, R_e(E_{e,i})\, E_{e,i} \qquad (2)$$

where K is a normalization constant and $\Psi(E_\gamma, E_{e,i})$ is an electron energy distribution.

To calculate the photon response of a scintillator for light yield non-proportionality, three step procedures were used and is illustrated in Fig. 1. First, photon transport was simulated using MCNP5 to the produce histories of photon interactions. Using this result of the first step, an electron energy distribution at single photon energy was calculated in the second step. For the third step, the relative photon response $R_\gamma(E_\gamma)$ was calculated by convolving the electron energy distribution with the electron response.

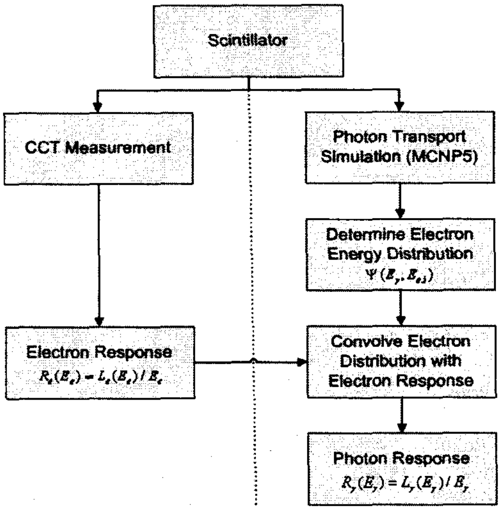

Fig. 1. Diagram showing the steps involved in calculating photon response.

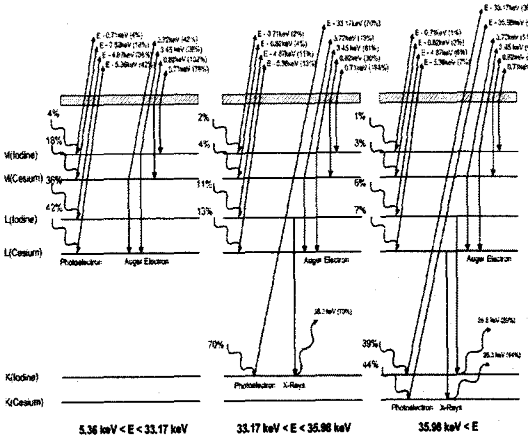

Fig. 2. Simplified electron cascade sequence for CsI(Tl) in phoswich.

To determine the number and the energy of the photoelectrons and Auger electrons produced by a photoelectric absorption interaction for a specific photon energy, a simplified electron cascade sequence for the CsI(Tl) was used. The electron cascade sequences used for determining the energetic electron distributions following the photoelectric absorption are shown in Fig. 2.

Previously, Mengesha [2] measured the electron and photon response for a 2 cm thick and 1 cm diameter right cylindrical CsI(Tl) crystal. In this work, the CsI(Tl) electron response measured by Mengesha was used for calculating the photon response of the phoswich detector. The relative measured electron response for CsI(Tl) is shown in Fig. 3. The relative CsI(Tl) electron response were fitted as following:

$$\begin{aligned} R_e(E_e) &= y_0 + \frac{y_1}{w\times\sqrt{\pi/2}}\times e^{-2\times\frac{(R_e-x_c)^2}{w}} && \mathrm{E_e} \le 13\ \mathrm{keV} \\ R_e(E_e) &= A_2 + \frac{(A_1-A_2)}{\left\{1+(E_e/x_0)^p\right\}} && \mathrm{E_e} > 13\ \mathrm{keV} \end{aligned} \qquad (3)$$

where E_e is electron energy in MeV, y_0 is 0.7537, x_c is 10.8761, y_1 is 9.1924, A_1 is 1.3040, A_2 is 0.9819, x_0 is 22.1807, and p is about 0.9759. The electron response has a maximum at about 10 keV, and then monotonically decreases by about 20% as the electron energy increases from 10 keV to 442 keV.

The CsI(Tl) photon response calculated by using the measured electron response is shown in Fig. 4. The CsI(Tl) intrinsic resolution by the ^{137}Cs source (0.66 MeV) was about 4.48 %, which was obtained by calculating the standard deviation σintrinsic(^{137}Cs). For a ^{60}Co, 1.17 MeV gamma-ray source was about 2.84 % and 1.33 MeV about gamma-ray 2.54 %, respectively.

2. Generation of the DRF Using Monte Carlo Simulation

The transfer component depends on the quality of the optical coupling of the crystal and PMT. The transfer contribution was, in this work, not considered for the total energy resolution of the phoswich since the transfer component is negligible compared to the other components of the energy resolution in the modern scintillation detectors [3]. Thus, the total energy resolution that describes the spread of the spectra in CsI(Tl) consists of the contributions from both the intrinsic resolution due to the CsI(Tl) non-proportionality and the PMT resolution due to the probability of electrons arriving at the first dynode of the PMT.

In general, the PMT contribution can be determined experimentally based on the measured number of photoelectron. But in this work, the PMT resolution was indirectly obtained by using the intrinsic resolution and the total energy resolution of the phoswich measured by the experiment. The PMT resolution can be described as

$$(\delta_{\mathrm{PMT}})^2 = (\delta_{\mathrm{total}})^2 - (\delta_{\mathrm{intrinsic}})^2 \qquad (4)$$

The prototype phoswich detector, which was fabricated by KAERI, was used to reproduce the DRF using the Monte Carlo method and to compare the DRF generated by Monte Carlo code with the measured response function. The phoswich detector consists of CsI(Tl) and plastic scintillator for detecting the gamma and beta-ray, respectively. The plastic layer is 0.22 cm thick and the CsI(Tl) is 5.08 cm (2 inch) thick. The diameter of both crystals is 5.08 cm (2 inch). For generation of the DRF, the

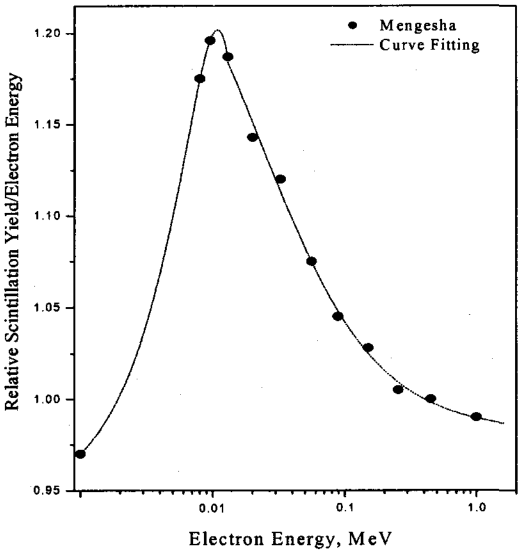

Fig. 3. CsI(Tl) electron response measured by Mengesha with curve fitting.

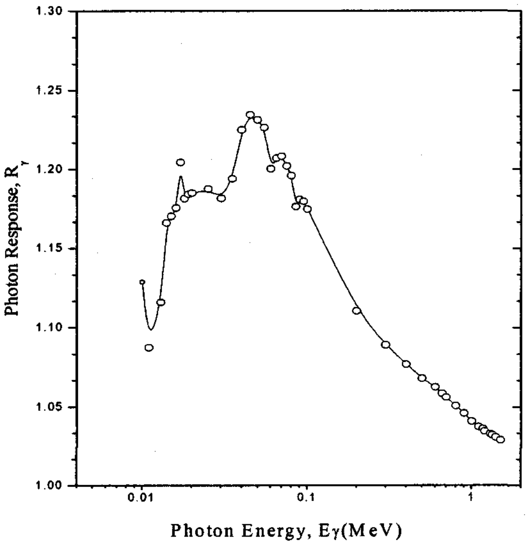

Fig. 4. CsI(Tl) photon response calculated by using measured electron response.

gamma-ray source was located vertically above and 100 cm away from the window of the phoswich detector. Fig. 5 shows the cross sectional view of the phoswich detector used for this study.

Fig. 6 shows the DRF generated by spreading the pulse height distribution of MCNP5 applying the non-proportionality of a CsI(Tl) crystal and the usual PMT resolution. First, the pulse height distribution calculated by MCNP5 was broadened by using the intrinsic resolution and then, the non-proportional response was broadened once again by using the PMT resolution.

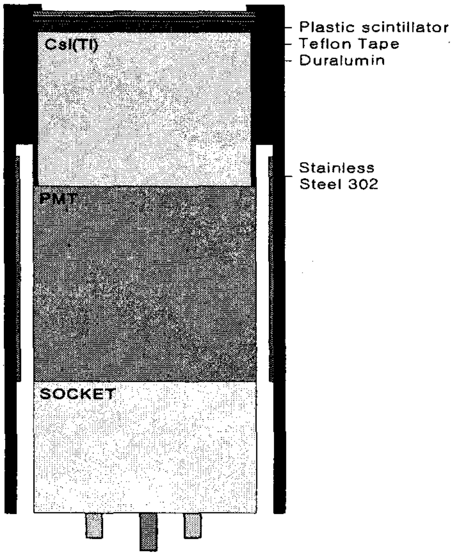

Fig. 5. The cross sectional view of the prototype phoswich detector made by KAERI.

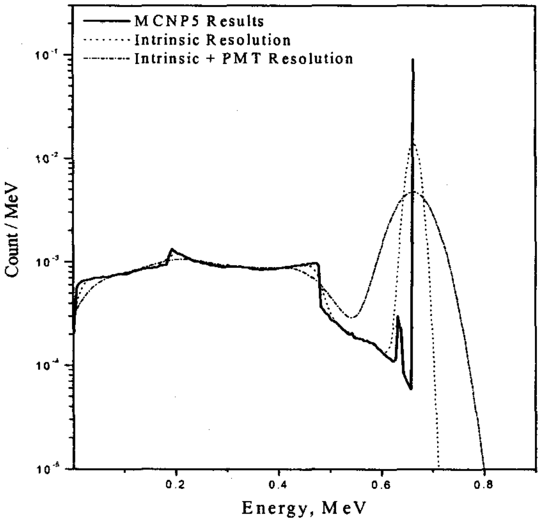

Fig. 6. The comparison between unspread spectrum and spread spectrum using the intrinsic resolution and the PMT resolution.

3. The Comparison of Experiment and Simulation

The ^{137}Cs and ^{60}Co sources were used for the comparison between the DRF measured by experiment and the one calculated by Monte Carlo simulation. Both of the final broadened results and the measured spectra were normalized. As shown in Fig. 7, for ^{137}Cs, gamma-ray responses of the phoswich detector simulated by the MCNP5 are generally good agreement with the measured values. But, the DRF of a ^{60}Co source, which emits the two gamma-rays (1.17 MeV and 1.33 MeV) at the same time, is a little different with that of ^{137}Cs. As shown in Fig. 8, while the results of the simulation agree well with the measured response in the first main peak around 1332.5 keV, it is not good agreement with experiment around the lower second peak. It is found that the discrepancies tend to increase with decreasing the energy.

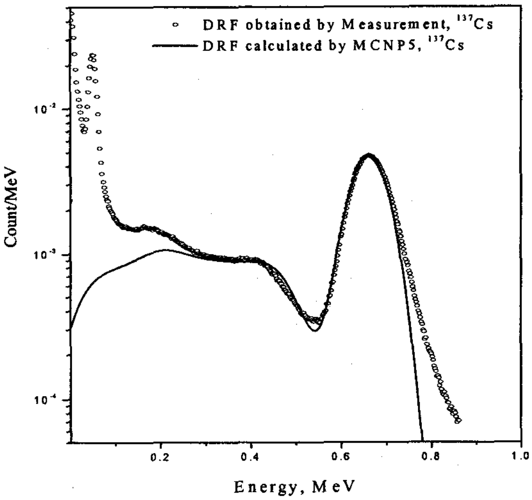

Fig. 7. The comparison between Monte Carlo spread spectrum and the measured spectrum for ^{137}Cs.

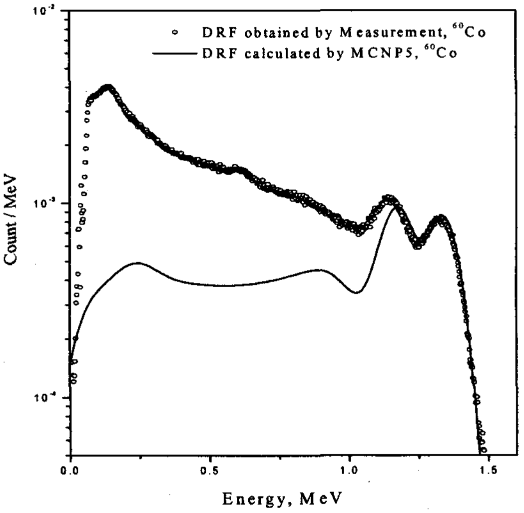

Fig. 8. The comparison between Monte Carlo spread spectrum and the measured spectrum for ^{60}Co.

Conclusion

Using the Monte Carlo simulation, a study on the non-proportionality of the prototype phoswich detector with 2"×2" CsI(Tl) and plastic scintillator, which was made by KAERI, has been carried out and its detector response functions (DRFs) were compared with the measured values of ^{137}Cs and ^{60}Co. To obtain the accurate gamma-ray response of the phoswich detector, the non-proportionality of a CsI(Tl) was calculated and the PMT resolution was also introduced by using the total energy resolution measured by experiment. Through the comparison between the simulations and measurements, the DRF of ^{137}Cs was well agreement with the experiment but the simulated DRF of ^{60}Co was a little different with the measured ones.

Further studies are needed to precisely reproduce the electron channeling effect, the Doppler broadening of Compton scattered electrons in low energy region [4], and the transfer resolution.

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