A design study of the Ge crystal for a pair-spectrometer system by using the EGS-4 code

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A Ge crystal dimension of a pair-spectrometer system was optimized to improve its performance for the prompt gamma ray spectroscopy. To demonstrate the performance of the pair-spectrometer system, it was applied to the measurement of prompt gamma rays which are emitted from ^{15}N produced in thermal neutron capture reaction, in the energy range up to 10.8 MeV.

1 Introduction

For the transmutation study of radioactive wastes, it is important to obtain precise thermal neutron capture cross section of long-lived fission products and minor actinides. However, the capture cross sections for some nuclides have not yet been obtained or are poor in accuracy, because they can not be measured by conventional activation methods. Therefore, we have started the development of a measurement method of the thermal neutron capture cross section by prompt gamma ray spectroscopy.

The cross sections are determined on the basis of energy equivalence between Q-value and an energy sum of cascading gamma rays per a neutron capture reaction. However, prompt gamma ray spectra of isotopes in the medium and heavy mass region, even though measured with a Ge detector, tend to be so complicated that each peak of gamma rays can not be resolved. To deduce the sum of gamma ray energy from raw spectrum of gamma rays, unfolding is needed which enables to extract the full energy deposition from continuum component of spectra. To minimize the error in the unfolding process, the pair-spectrometer system is developed since it was expected that double escape peaks (DEP) were clearly enhanced and then high DSP to total ratio obtained especially for high energy prompt gamma rays.

In this work, a coaxial Ge crystal dimension of the pair-spectrometer system was optimized to improve its performance for the prompt gamma ray spectroscopy. To demonstrate the performance of the pair-spectrometer system, it was applied to the measurement of prompt gamma rays emitted from ^{15}N

produced in thermal neutron capture reaction using a Ge detector with a similar shape as the optimized one.

2 Optimization of crystal shape using EGS-4 code

A pair-spectrometer consists of a Ge detector and multisected BGO annulus surrounded by the Ge detector. When an energy of incident gamma ray exceeds pair creation threshold, an electron-positron pair within the central Ge detector can be created. The two 511-keV gamma rays from annihilation of the positron are emitted in opposite directions. When these gamma rays are detected simultaneously in each of opposite BGO detectors, the event in a Ge detector is recorded. By using this method, peak(DEP)-to-total ratio is improved dramatically which strongly affects the accuracy of spectrum unfolding method. Peak-to-total ratios were calculated by using the EGS-4 code [1] in the case of a pair-spectrometer using a bisected BGO annulus, 17 cm in length, 11 cm in inner diameter and 21cm in outer diameters. A schematic view of the pair-spectrometer is shown in Fig. 1.

The dimension of the Ge crystal affects on the peak-to-total ratio strongly. In case of pair-spectrometer mode, peak-to-total ratio is defined as ratio of DEP counts to total counts. The calculated peak-to-total ratios are shown in Fig.2 as a function of the length of Ge crystal for three operation mode: pair-spectrometer mode, Compton suppression mode and singles mode. A diameter of Ge crystal was fixed at 5 cm and an energy of incident gamma ray was fixed at 10 MeV. As its length increases, the ratio increases. The ratio in the pair-spectrometer mode is about 10 times higher than that in singles mode, about 5 times higher than that in Compton suppression mode. The correlation of peak-to-total ratio relative to diameter of Ge crystal is shown in Fig. 3. In this calculation, a length of Ge crystal was fixed at 12 cm and an energy of incident gamma ray was fixed at 10 MeV. The ratio reaches its maximum at a diameter of 5 cm. The dependence of an energy of incident gamma ray on peak-to-total ratios are shown in Fig. 4. When irradiated with 10 MeV gamma rays, in the case of 5-cm diameter and 12-cm length, peak-to-total ratio of about 80 % is achieved in the pair-spectrometer mode. The ratios in the singles mode and in the Compton suppression mode are 7% and 14% for the same crystal size.

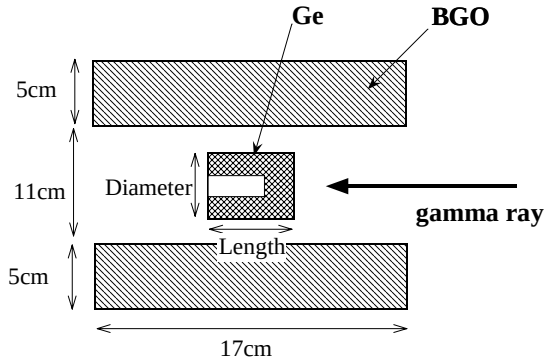

Fig. 1 The schematic view of pair spectrometer.

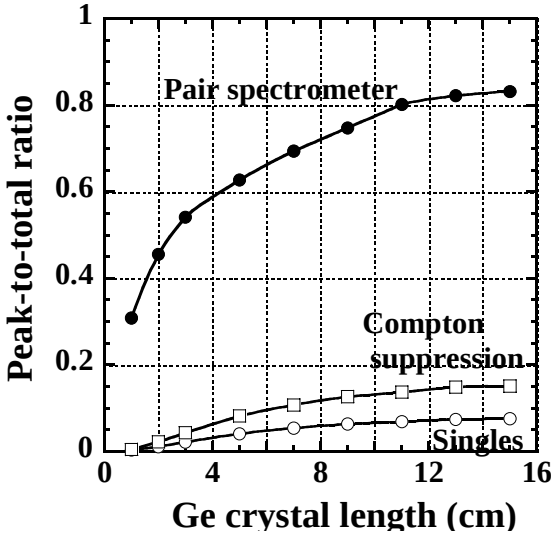

Fig. 2 The correlation peak-to-total ratio relative to Ge crystal length.

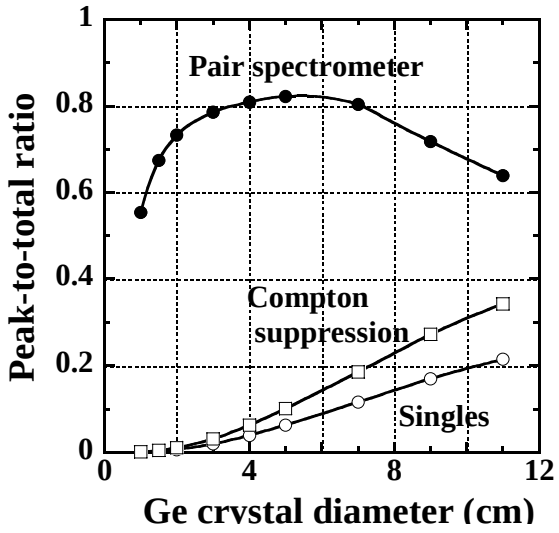

Fig. 3 The correlation of peak-to-total ratio relative to Ge crystal diameter.

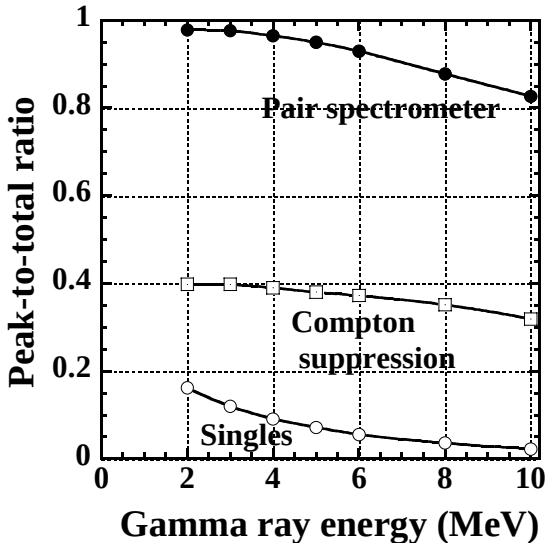

Fig. 4 The correlation of peak-to-total ratio relative to energy of gamma ray

3 Experiment

To demonstrate the performance of the optimized pair-spectrometer system, it was applied to the measurement of prompt gamma rays emitted from ^{15}N produced in thermal neutron capture reaction using a Ge detector with a approximately dimension as the optimized one. The irradiation by thermal neutron was carried out using the B4 neutron guide tube facility in the Kyoto University Research Reactor Institute. The neutron flux at the irradiation position was about 2×10^{7} n・cm^{-2}・s^{-1}. The irradiated sample was D-substituted melamine ($C_3D_6N_6$) [2] to reduce the strong background gamma-ray from the $^{1}H(n,\gamma)$ reaction. The setup of the experiment was shown in Fig. 5. The pair-spectrometer system consists of an n-type Ge detector and the BGO detector described in chapter 2. Relative detection efficiency of the Ge detector is 90% of that of 3 inch×3 inch NaI. The neutron flux at the sample position was measured by detecting a decay gamma ray emitted form ^{28}Al produced in the $^{27}Al(n,\gamma)$ reaction. To subtract the contribution of background gamma rays originated from scattering neutrons, gamma rays generated by irradiate Carbon foils were measured.

The prompt gamma ray spectra were obtained in singles mode, Compton suppression mode and pair-spectrometer mode, simultaneously. These spectra were shown in Fig. 6. Closed circles show the position of full-energy peaks. The peak-to-total ratio for 10.8 MeV gamma ray was about 4% in pair-spectrometer mode, 0.1% in singles mode and 0.2% in Compton suppression mode. The pair-spectrometer system was demonstrated to have the high ability to measure high-energy gamma rays with high peak-to-total ratio.

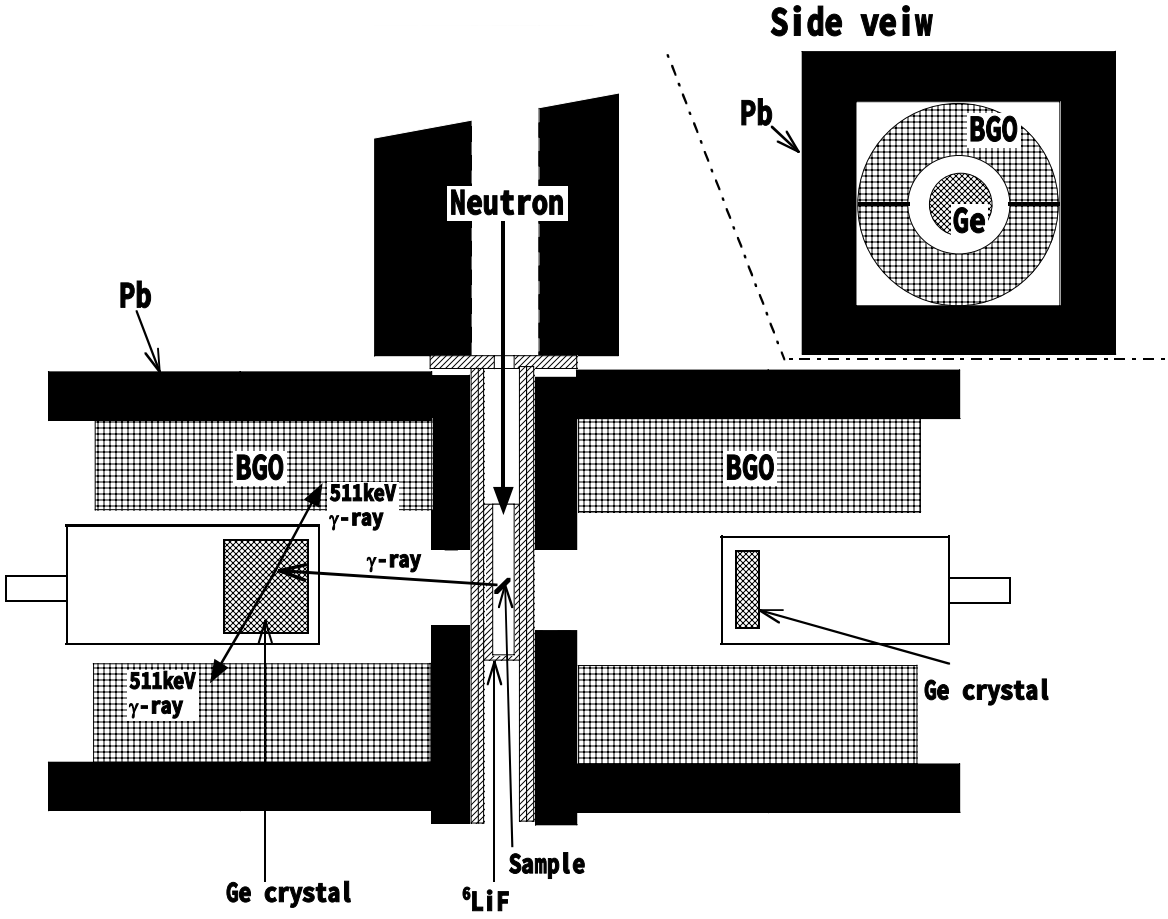

Fig. 5 The setup of the experiment.

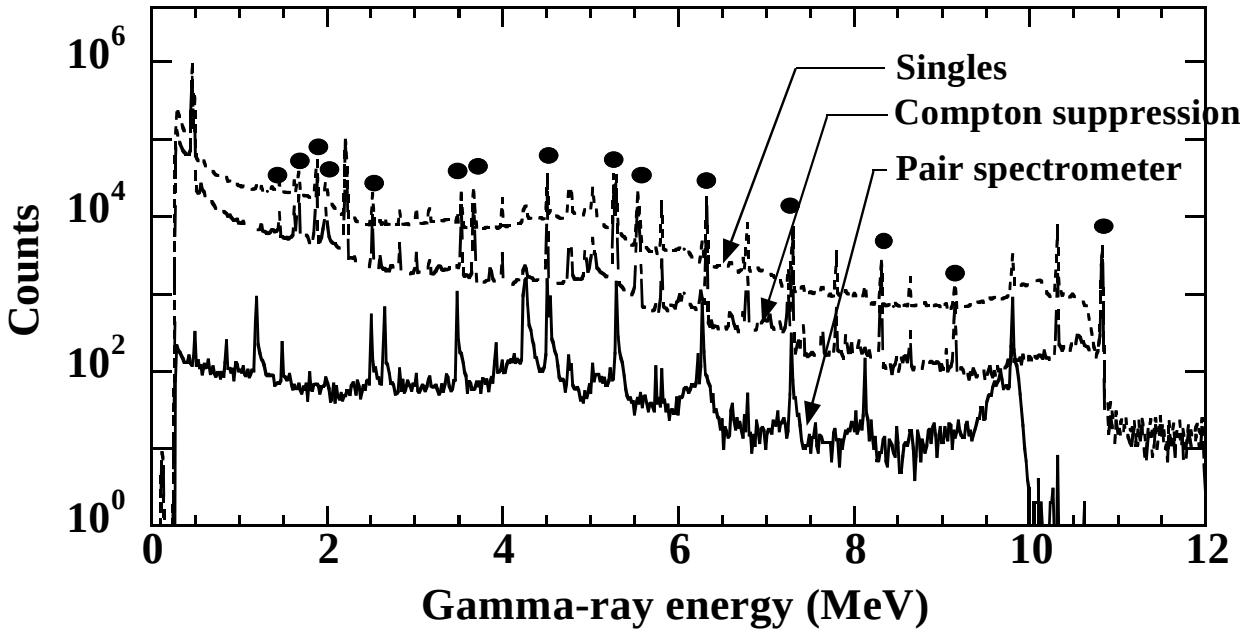

Fig. 6 The spectrum of prompt gamma ray emitted from ^{15}N. Closed circles show the position of full energy peaks.

4 Response of the pair-spectrometer

The response of the pair-spectrometer was studied by comparing the calculated spectra with experimental one. The comparison between calculation and experiment in pair-spectrometer mode is shown in Fig. 7. Solid and dashed lines in the figure represent the calculated spectra and experimental one, respectively. The calculated spectrum agrees with the experimental one above 7 MeV, however, the calculation is lower than the experimental one below 7 MeV. Further study of the response function is required.

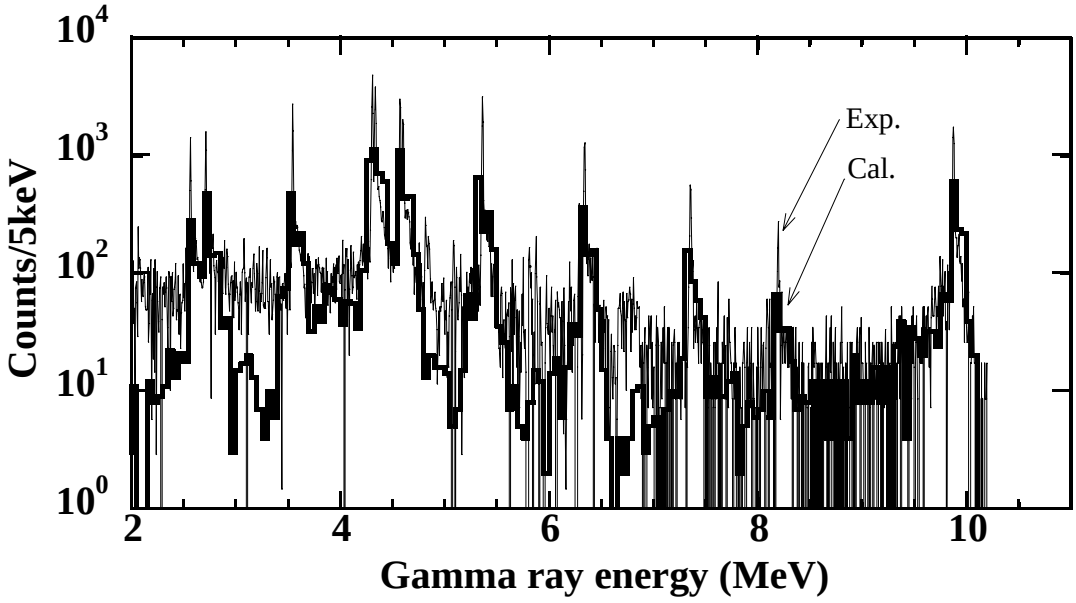

Fig. 7 Comparison between calculation spectrum and experiment ones.

5 Conclusion

In the course of the development of a method of thermal-neutron capture cross section measurement by unfolding prompt gamma ray spectra, a coaxial Ge crystal dimension of the pair-spectrometer system was optimized to improve the pair-spectrometer's performance for the prompt gamma ray spectroscopy. The pair-spectrometer system was demonstrated to have the high ability to measure high-energy gamma rays with high peak-to-total ratio.

References

[1] W.R. Nelson, H. Hirayama and W.O. Rogers: The EGS4 Code System SLAC-265 （December 1985）.

[2] S. Nakamura, H. Harada, H. Takayama, K. Kawade: The development of melamine-D for the precise measurement of detection efficiencies of high energy γ-rays, JAERI-Conf 2003-006 (2003) pp.237.