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Determination of Single Escape and Double Escape Peak Efficiency for a HPGe Detector

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Abstract

The efficiencies of single escape and double escape peaks were calculated by using Monte Carlo method and compared with measured efficiencies. The efficiency was obtained from the area ratio of escape peak to full energy absorption peak and the full energy absorption peak efficiency. For the escape peak interfered with other γ-ray peaks, the net area was obtained by area correction. The GEANT code developed in CERN was used for the Monte Carlo calculation. The calculated efficiencies of the escape peaks agreed with the measurement within 12%.

Key Words : escape peak efficiency, HPGe detector, monte carlo method, GEANT, prompt gamma activation analysis

1. Introduction

The single escape(SE) and double escape(DE) peaks that appear on γ-ray spectra are due to the escapes of the annihilation γ-rays produced subsequent to pair production from incident γ-rays of energy higher than 1022 keV. The interaction probability of pair production is larger than that of Compton scattering for the energy range higher than several MeV during absorption in a germanium detector of typical size. Therefore, the escape peak can be more important than the full energy absorption(FE) peak in the energy range over several MeV[1,2]. On the prompt γ-ray spectrum, there are many interfered peaks because of complex decay scheme subsequent to the nuclear reaction. Particularly, interferences induced by escape peaks are noticeable for the incident γ-rays with high energy. For these interferences, resolving both peaks can be achieved if the escape peak efficiency is well known. Therefore, escape peak efficiency is required for accurate analysis of prompt γ-ray spectrum. The efficiency of escape peak($\varepsilon_{SE(or\ DE)}$) can be obtained by both measurement and Monte Carlo method. It is determined from the area ratio($A_{SE(or\ DE)}/A_{FE}$) of the escape peak to the FE peak according to Eq. (1),

$$\varepsilon_{SE(orDE)} = \frac{A_{SE(orDE)}}{A_{FE}} \times \varepsilon_{FE} \ . \qquad (1)$$

The measurement is limited by very low efficiency in the energy range under 2 MeV or over 10 MeV. The efficiency at an arbitrary energy is typically obtained by a functional fit to the measured dataset. Otherwise, an interpolation or extrapolation from the measured data is also used. The interpolation is a reasonable method to employ when there are enough measured points, while the extrapolated values fluctuate severely outside of the measured energy range as the choice of model formula is changed. Besides, the typical polynomial model has no physical basis while it is widely used for generating the efficiency function. The Monte Carlo method, however, can be used to calculate ε_{SE} or ε_{DE} for γ-rays of arbitrary energy with sufficient statistics since the algorithm in the calculation code simulates transport and absorption of particles according to physical models. Hence, it can produce a result that reflects the physical meanings. Therefore, the Monte Carlo method can complement the measurement.

In this study, the efficiencies of SE and DE peak were determined by both the measurement and the Monte Carlo method. The GEANT code[3] was adopted for the Monte Carlo method, which is widely used for simulating γ-ray interactions in a HPGe detector. The measurement and calculation were carried out for the n-type HPGe detector of the SNU-KAERI PGAA(Prompt Gamma Activation Analysis) facility[4] at HANARO in the Korea Atomic Energy Research Institute. Based on the previous study of the FE peak efficiency over a wide energy range (0.06 ~ 11 MeV) performed by GEANT[5], the calculated escape peak efficiency was compared with the measurement.

2. Measurement of Escape Peak Efficiency

To compare with Monte Carlo calculated result, the escape peak efficiency was obtained in relation to the FE peak efficiency according to Eq. (1). The HYPERMET code[6] was used to extract the net peak area. The shape of escape peak is slightly different from that of the FE peak due to Doppler effect superposed on the statistical variation of absorbing annihilation γ-rays. Hence, escape peaks must be analyzed with more care[1,7].

For the interfered peaks closer than the energy resolution of the detector, the multiplet peak analysis with HYPERMET code is limited. For these cases, the net peak area was obtained by area correction method. The FWHM(Full Width at Half Maximum) of FE peak of the detector is shown in Fig. 1. The interfered peaks can be easily identified by comparing the single mode spectrum with the pair mode one[2]. Fig. 2 shows a case that escape peaks are interfered on the measured prompt γ-ray spectrum for melamine sample. In the single mode spectrum, escape peaks appear as well as FE peak, but in the pair mode one, only escape peaks do[2,4]. In the figure, while 6322.43 keV FE peak was seen only in the single mode spectrum, 5297.82 keV FE peak was seen in the pair mode spectrum as well as single mode one. Therefore, it can be concluded that the DE peak of 6322.43 keV γ-ray appeared at the position of 5300.43 keV and

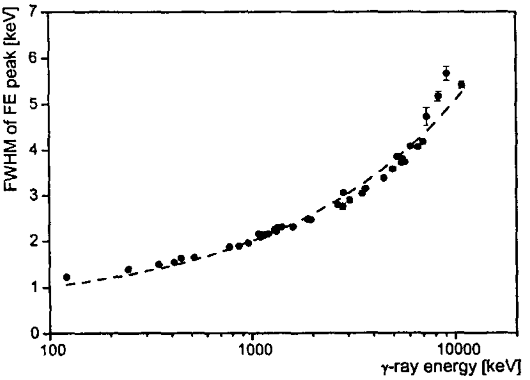

Fig. 1. The FWHM of the FE Peak for the HPGe Detector Used in this Study

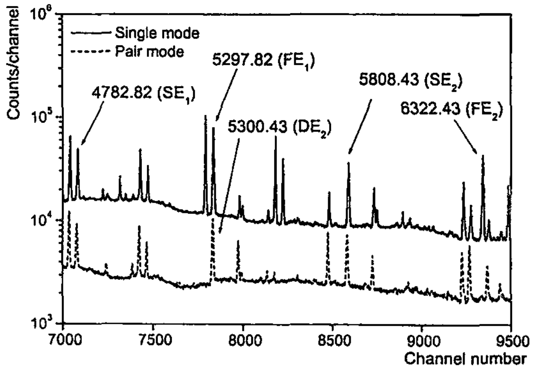

Fig. 2. Single Mode and Pair Mode Spectra of Prompt γ-rays Emitted from Melamine ($C_3H_6N_6$)

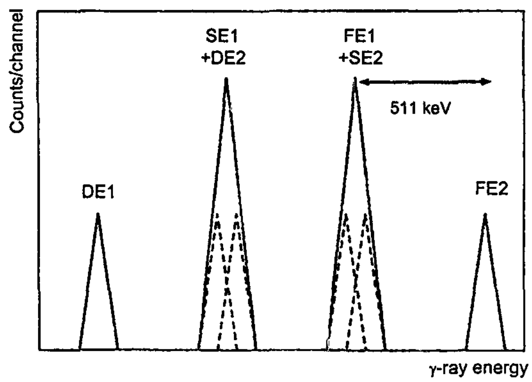

Fig. 3. Schematic Diagram of Interfered Escape Peaks

hence interfered the 5297.82 keV FE peak. Fig. 3 simplifies the interference case. In the figure, the FE_1 and SE_1 peak are interfered with the SE_2 and DE_2 peak, respectively. If they are emitted from the same nuclide, the net area of FE_1 peak(A_{FE1}) is determined from FE_2 peak area(A_{FE2}), each FE peak efficiencies (ε_{FE1}, ε_{FE2}) and prompt γ-ray emission probabilities(Γ_1, Γ_2)[8] by using the following relation :

$$A_{FE1} = A_{FE2} \cdot \frac{\varepsilon_{FE1}}{\varepsilon_{FE2}} \cdot \frac{\Gamma_1}{\Gamma_2} \quad . \tag{2}$$

Hence the net area of SE_2 peak(A_{SE2}) is determined by subtracting the net area of FE_1 peak(A_{FE1}) from the combined area of the interfering peaks ($A_{(FE1+SE2)}$) as Eq. (3),

$$A_{SE2} = A_{(FE1+SE2)} - A_{FE1} \quad . \tag{3}$$

Also for the case that the interference with γ-ray peak originating from the different nuclide, the correction can be carried out by similar method, considering the activity ratio. Conversely, by obtaining the net area of escape peak from the accurate escape peak efficiency, the net area of FE peak can be determined from the interfered peak area through the relation of Eq. (3). This correction process is very important for the analysis of prompt γ-ray spectrum, because there are many interfered peaks as mentioned above.

3. Calculation of Escape Peak Efficiency

There are two methods to obtain the escape peak efficiency by using GEANT. One method is to analyze the net area of escape peak on the simulated spectrum. Fig. 4 shows the simulated spectrum and the measured one for 6760.08 keV prompt γ-ray emitted from Ti. The net area of escape peak can be obtained from the total counts subtracted by background continuum on the simulated spectrum. This method is, however, very tedious because the net area of each escape peak must be analyzed on each simulated spectrum.

The other method is to count directly the events of escape peak formation during the calculation process. The efficiency is calculated by counting the events only when two specific conditions are fulfilled; one is that a positron is produced and the other is that the total absorbed energy is smaller than the incident γ-ray energy by 511 or 1022 keV. The efficiencies calculated using these two methods have agreed within 2%, and hence the

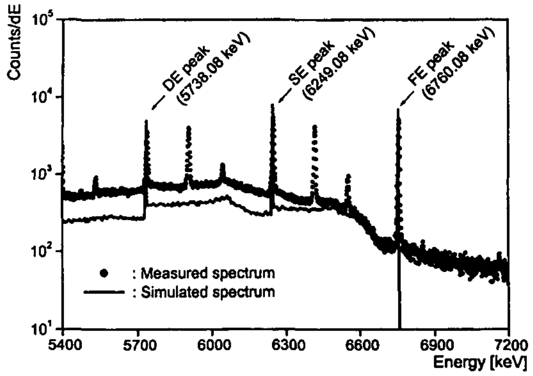

Fig. 4. Simulated Spectrum for 6760.08 keV γ-ray and Measured Prompt γ-ray Spectrum for Ti

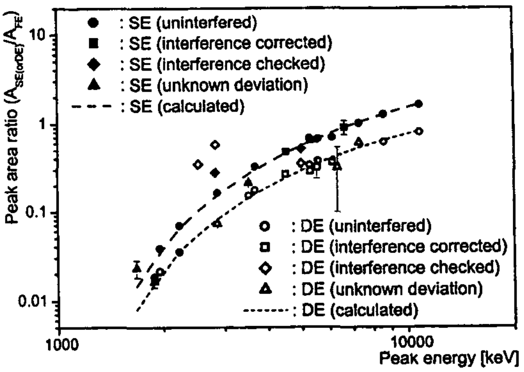

Fig. 5. Measured and Calculated Ratios of Escape Peak to Full Energy Peak Efficiency

latter method was adopted in this study due to its greater convenience.

The escape peak efficiency was calculated for the prompt γ-ray peaks originating from thermal neutron capture reactions of ^{1}H, ^{14}N and ^{35}Cl, in the energy range between 1678 and 10829 keV. The geometric description of the detector in GEANT calculation is unchanged from that in the previous work on FE peak efficiency[5]. The total number of generated γ-ray histories was set so as to obtain a statistical uncertainty of efficiency of less than 1%. The efficiency was obtained from the ratio of the number of counted escape peak events to that of total generated γ-rays.

4. Results of Measurement and Simulation

The calculated ratios of escape peak area to that of FE peak are compared with the measurements in Fig. 5. There are four different cases of measurement analyses in the figure. In the first case, the escape peak has no interference and consists with the general tendency ('uninterfered'). In the second case, the interference is corrected by using Eqs. (2) and (3) for the peaks originating from the same nuclide ('interference corrected'). In the third case, the interference with another peak is identified, but is difficult to correct, so it is only checked for interference ('interference checked'). In the last case, the obtained efficiency does not follow the general tendency and a check was made to verify that there was no interference ('unknown deviation'). Due to difficulties encountered in the area analysis, the peak areas of the last case have a relative uncertainty of about 15 ~ 25%.

In Table 1, the escape peaks are listed for a few nuclides, whose efficiencies could be influenced by interference with FE peak or are not consistent with the general tendency. The peaks are identified by their incident γ-ray energy and type of escape(SE or DE). The interfered peaks influencing the efficiency of escape peaks are shown in the fourth column, where the number in the parentheses indicates the actual energy of the escape peak. For example, in the first row, the 4508.73 keV FE peak and 5533.40 keV DE peak (4511.40 keV) differ from each other by only 2.7 keV. This is smaller than the FWHM at this energy, which is about 3.5 keV in Fig. 1. So they are interfered at almost same position. And the efficiencies of SE and DE peak of 4508.73 keV γ-

Table 1. List of Escape Peaks which are Subject to Interference and Unknown Deviation Cases

Case	Nuclide	Influenced peaks	Unresolved peaks
Interference corrected	^{14}N	4508.73 SE, DE, 5533.40 DE	4508.73 FE + 5533.40 DE(4511.40)
		5297.82 SE, DE, 6322.43 DE	5297.82 FE + 6322.43 DE(5300.43)
	^{35}Cl	6110.84 DE, 6619.62 SE	6110.84 FE + 6619.62 SE(6108.62), 6110.84 SE(5599.84)+ 6619.62 DE(5597.62)
Interference checked	^{14}N	2830.79 SE, DE	2830.79 SE(2319.79) + background 2321 FE
	^{35}Cl	4979.76 SE, DE	4979.76 FE + background 5999.80 DE(4977.80)
Unknown deviation	^{14}N	1678.28 SE, 1884.82 SE, 3531.89 SE, 7298.98 DE	-
	^{35}Cl	2863.82 DE	-

ray and DE peak of 5533.40 keV γ-ray are influenced by interference, if the corresponding unresolved peaks are taken for a single FE peak.

The ratios of the SE peak to DE peak areas are shown in Fig. 6, excluding the cases classified as interference checked'. Most of the measurements and calculations are fairly consistent with the general tendency. The area ratios are almost constant, because the probability of the 511 keV annihilation γ-ray escaping from Ge crystal is almost constant[1,9,10]. The slightly increasing effect of the peak ratio as the incident γ-ray energy increase is shown in the figure. This is because that the positions of pair production are skew-distributed to the backward and outward regions for higher incident γ-ray energies, so that the escape probability of the annihilation γ-ray is increased accordingly.

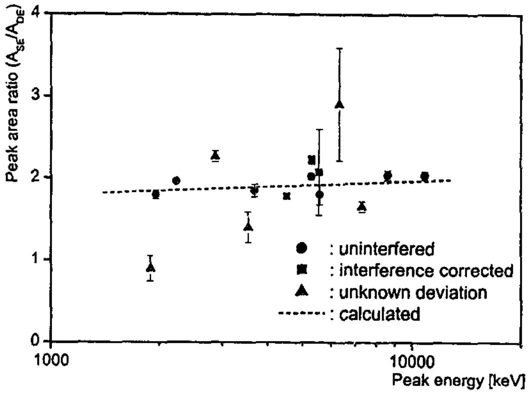

Fig. 6. Measured and Calculated Ratios of Single Escape Peak to Double Escape Peak Area

The measured and the calculated efficiencies are compared in Fig. 7. In the case of 'unknown deviation', the difference is over 12%, and this may be caused by unknown interfered peak or error in the area analysis with insufficient statistics. With the exception of this case, the measured and the calculated results agreed with each other within 12%.

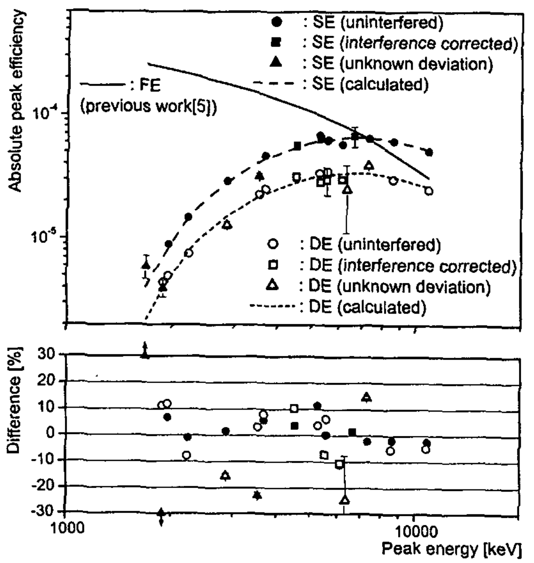

Fig. 7. Measured and Calculated Efficiencies of Single and Double Escape Peaks

5. Conclusions

The SE and DE peak efficiencies were calculated by Monte Carlo method and compared with the measurement. The cases of interference were corrected using the peak area ratio, the FE peak efficiencies and the prompt γ-ray emission probabilities. The measured and calculated escape peak efficiencies were found to agree with each other within 12% both in the case of 'no interference' and 'corrected interference' and were consistent with the general tendency. In this study, the escape peak efficiency in high energy prompt γ-ray spectrum was presented. These can be used as reference data in analysis of high energy γ-ray measurement. For those escape peaks which do not agree with the general tendency, the further examination of measurement is required.

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