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Experimental and Simulated Efficiency of a HPGe Detector in the Energy Range of 0.06 ~ 11 MeV

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Abstract

The full energy peak efficiency of a hyper pure germanium (HPGe) detector was calibrated in a wide energy range from 0.06 to 11 MeV. Both the experimental technique and the Monte Carlo method were used for the efficiency calibration. The measurement was performed using the standard radioisotopes in the low energy region of 60 ~ 1408 keV, which was further extended up to 11 MeV by using the $^{14}N(n,\gamma)$ and $^{35}Cl(n,\gamma)$ reactions. The GEANT Monte Carlo code was used for efficiency calculation. The calculated efficiency had the same dependency on the γ-ray energy with the measurement, and the discrepancy between the calculation and the measurement was minimized by fine-tuning of the detector geometry. From the calculated result, the efficiency curve of the HPGe detector was reliably determined particularly in the high energy region above several MeV, where the number of measured efficiency points is relatively small despite the wide energy region. The calculated efficiency agreed with the measurement within about 7%. In addition to the efficiency calculation, the origin of the local minimum near 600 keV on the efficiency curve was analyzed as a general characteristics of a HPGe detector.

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

1. Introduction

The γ-ray spectroscopy system using HPGe detector is widely used for a measurement of radioactivity. The efficiency of a detector is essentially required to determine the radioactivity of an unknown nuclide, and is also important as the fundamental characteristics of a detector[1]. The efficiency calibration is mostly performed by the experimental technique with a check by the Monte Carlo simulation method.

In the exeperimental method, standard radioisotopes with well-known activities are used and the absolute efficiency can be determined accurately. However, the number of available γ-ray energies is typically limited and the calibrated efficiency has little flexibility for different source shapes and source-to-detector distances. In the conventional γ-ray spectroscopy, the maximum γ-ray energy of the radioisotopes being measured stays within a few MeV, and it can be fully calibrated with the standard sources. In the case of the prompt γ-ray spectroscopy, γ-ray energy can reach up to 11 MeV. The extension of the calibration region is usually performed using prompt γ-rays emitted from the $^{14}N(n,\gamma)$ and $^{35}Cl(n,\gamma)$ reactions[2-4]. Although the maximum energy can be extended by these (n,γ) reactions, wide energy gaps occur between the adjacent measured efficiency points and the number of available data points is insufficient for the whole energy range to be calibrated. Therefore, a complementary procedure of a experimental data fitting or a Monte Carlo calculation is strongly required. Currently, the efficiency at an arbitrary γ-ray energy is mainly determined by fitting the measured efficiency data. Typical results using this approach have a common fitting error of 1% and less than 5% at most when the calibrations were performed carefully. Although the fitting method is used for the accurate efficiency calibration, the fitted efficiency may deviate greatly depending on the form of the function used in the energy region outside the measured data. This means that the relevant form of the fitting function can only be investigated by extending the range of measurement at the expense of much experimental efforts· Another fundamental shortage of the fitting method is that the form of the fitting function has no physical basis. When the fitted efficiency function shows unsmooth trend like the local minimum near 600 keV[5], it is difficult to judge whether this trend originates from physical phenomena or from some problems in the spectroscopy system.

On the other hand, the Monte Carlo method reflects a full history of the γ-ray interactions. It can simulate various source-to-detector geometries and produce efficiencies even for the γ-ray energies at which the measurement is not achievable. Hence the relative efficiency curve depending on the γ-ray energy can be determined reliably. Namely, a Monte Carlo method can be complementary to an experimental calibration method. A typical shortcoming of the Monte Carlo method is, however, that the efficiency error can seldom be improved regardless of the effort devoted to the calculation. Seyfarth et al.[6] reported the result of a comparison between the measured efficiency and the indirect Monte Carlo calculation in the beginning of the 1970s. Recently, the γ-ray interaction routines have been further elaborated and the updated cross section data have been used in the general purpose Monte Carlo codes. Therefore, the accuracy improvement of the calculation becomes remarkable. The reduction in calculation time, which is another improvement owing to the development of faster processors, made the importance of the Monte Carlo calculation in a PC or workstation increase furthermore. Shigetome et al.[7] calculated the efficiency up to 30 MeV recently. However, there are few studies on the direct comparison between the measurement and the Monte Carlo calculation in the high energy region above 2 MeV.

In this study, the efficiency of a HPGe detector was calculated using the Monte Carlo method for the γ-ray spectroscopy system of the SNU-KAERI Prompt Gamma Activation Analysis(PGAA) facility[8] at HANARO, a research reactor of the Korea Atomic Energy Research Institute. The calculation was performed in the wide energy range of 0.06 ~ 11 MeV. The calculated efficiency was compared with the measurement. GEANT was chosen as the Monte Carlo code due to its powerfulness and popularity in simulating the response of a HPGe detector. In addition to the efficiency calculation, the origin of the local minimum near 600 keV on the efficiency curve was explained.

2. Efficiency Measurement

The n-type HPGe detector in this study is being used in the SNU-KAERI PGAA facility. The γ-ray spectroscopy system was initially a single mode system using a HPGe detector[8], and has recently been upgraded to a multi-mode system, which includes single, Compton suppression and pair modes[9]. For the multi-mode detection, a BGO/NaI(Tl) guard detector was installed around the HPGe detector. A detailed layout of the detectors and the surrounding shields is shown in Fig. 1. The HPGe detector has a resolution of 2.2 keV for 1332.5 keV γ-rays and a relative efficiency of 43%. The guard detector is comprised of the front and the side parts. The front part is a truncated-cone annular NaI(Tl) scintillator with an inner diameter of 31.6 mm and a thickness of 30 mm. The side part is occupied by a BGO scintillator which is optically isolated into 8 segments. The installed guard detector partly screens the outer sensitive region of the HPGe detector, and accordingly, the opening of the Pb γ-ray collimator was reduced. The solid angle subtended by the HPGe detector at the sample position was reduced to 38% of previous system. The distance from sample to the HPGe detector is 25 cm, which is the same as before. The ^{6}LiF neutron shield[8] positioned in front of the Pb collimator was also the same.

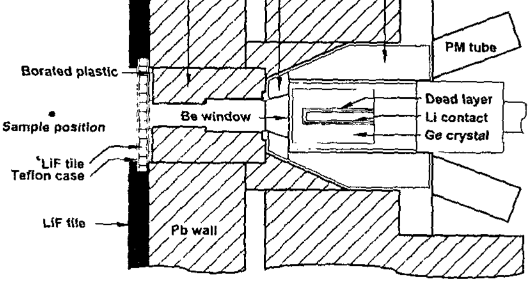

Fig. 1. Schematic Layout of the Multi-mode Assembly of the γ-ray Spectroscopy System

The efficiency was measured using the same procedure described in ref.[8] in the energy range of 0.06 ~ 11 MeV. The standard radioactive sources of ^{241}Am, ^{133}Ba, ^{152}Eu, ^{134}Cs, ^{137}Cs, ^{60}Co were used in the energy range below 1408 keV. The range was extended up to 11 MeV by measuring the prompt γ-rays from the ^{14}N(n,γ) and ^{35}Cl(n,γ) reactions. The data of prompt γ-ray emission intensity required for the calibration were retrieved from the database evaluated recently by Firestone[10]. The area of the full energy absorption peak was obtained using HYPERMET[11].

3. Monte Carlo Simulation

In this study, GEANT[12] was chosen for the Monte Carlo simulation code. The GEANT was developed in CERN as a particle transport code and is widely used for simulating the response of a HPGe detector in parallel with the MCNP and EGS4 codes[13-17]. The GEANT version 4.4.1 was installed on a PC with a 1 GHz clock CPU using the Linux RH 6.2 operating system. In order to calculate the efficiency, a user routine including a description of the detector geometry shown in Fig. 1 was written based on the particle transport functions of GEANT. Among the distributed example routines, the optimum one was chosen and modified to include the experimental conditions in this study.

In the user code, the incident γ-rays were generated with an isotropic angular distribution within the solid angle subtended by the guard detector. The number of generated γ-rays was increased in order to obtain the statistical uncertainty of the full energy peak counts less than 1%. The absolute efficiency was obtained by multiplying the ratio of the counted events to the generated γ-rays by the solid angle fraction. The calculation time was approximately 5 minutes for the 1 MeV γ-rays and approximately 30 minutes for 5 MeV γ-rays.

The full energy peak events were selected by the absorbed energy in the Ge sensitive region. When the amount of absorbed energy was within a finite energy width of the incident γ-ray energy, it was counted in the full energy peak events. Fig. 2 shows the shape of the simulated full energy absorption peak compared with the measured spectrum for 661.7 keV γ-rays emitted from ^{137}Cs. The simulated spectrum shows no background continuum around the full energy peak since only single energy γ-rays are generated without the background. In the measured spectrum, the peak shape follows a Gaussian function due to the finite energy resolution. However, the peak shape in the simulated spectrum is simple because it represents only the distribution of the absorbed energy, and does not include the resolution effects related to the statistical fluctuation in the detection signal formation, noise of electronics, etc. The peak area in the simulated spectrum was determined by a simple summation of the full energy absorption events. The peak width was set to 0.01 keV for the incident γ-ray energies below 6 MeV, and 0.1 keV for the higher energies due to a slight broadening effect.

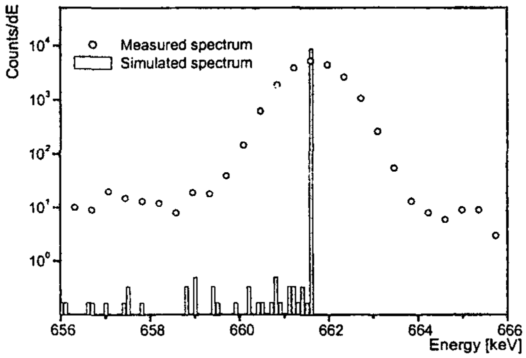

Fig. 2. Measured and Simulated Full Energy Peaks of ^{137}Cs 661.7 keV

4. Results of Measurement and Simulation

In order to validate the accuracy and the reliability of the GEANT simulation, the efficiency of a p-type HPGe detector[18] was calculated in the low energy range of 50 ~ 1408 keV[19] before the simulation in the wide energy range. The calculated results agreed well with the measurement both for the absolute value[18] and for the relative trend in the energy range above 100 keV. However, in the range below 100 keV, the discrepancy between calculation and the measurement was greater than 6%, and it became larger at much lower energies. This discrepancy between the measurement and the Monte Carlo calculation is typical and is believed to be caused by the uncertainty in the detector dimensions, and the non-uniformity of the dead layer thickness, etc. It has been accepted that the detector geometry used in Monte Carlo codes should be fine-tuned from the manufacturer's specification in order to reproduce the measured efficiency values with the best consistency[13-17,20-23]. In this study, the dead layer thickness was finely tuned by considering the severity of the discrepancy in the energy region below 100 keV. The efficiency was calculated by increasing the dead layer thickness in 0.05 mm steps from a nominal value of 0.5 mm, and the result is shown in Fig. 3. In this figure, the calculated efficiency is strongly dependent on the dead layer thickness in the region below 100 keV. The calculated result for 0.55 mm thickness is

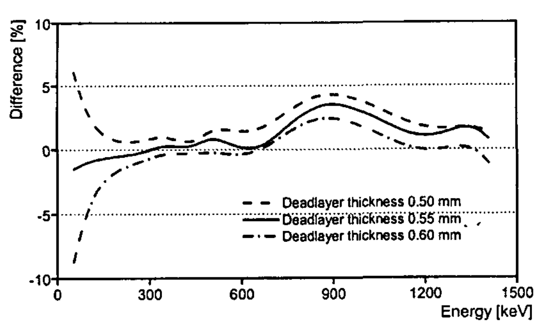

Fig. 3. Difference Between Simulated and Measured Efficiencies for a p-type HPGe Detector. The Simulations were Performed for Several Dead Layer Thicknesses

most consistent with the measurement. The discrepancy is within 6%[19].

On the basis of the test calculation in the low energy range, the efficiency for the detector of the SNU-KAERI PGAA facility was calculated in the wide energy range of 0.06 ~ 11 MeV. The user code written for the p-type detector was modified to take into account the modified detector geometry shown in the Fig. 1. First, the efficiency was calculated for the single mode detection before the upgrade in order to tune the geometric parameters of the HPGe detector. The calculated result using the detector geometry supplied by the manufacturer agreed with the measurement in the relative trend of efficiency. However, the absolute efficiency was higher than the measurement by 15%. The geometry parameters were fine-tuned by the similar procedure used for calculating the p-type HPGe detector. Especially, besides the dead layer thickness, the Ge crystal diameter and the distance from the Be window to the crystal were also tuned[21,22]. In the tuning process, the dead layer thickness, the crystal diameter and the distance from the Be window to crystal were changed from 0.3 to 0.7 mm, from 58.2 to 57.2 mm, and from 3.0 to 9.0 mm, respectively. The final result of the calculation agreed with the measured efficiency[8] within 6% in the energy region below 2 MeV, and within 10% in the total energy range up to 11 MeV[19]. In order to validate the tuned detector geometry using another method, the efficiency for 1332.5 keV γ-rays was calculated for an open geometry without ^{6}LiF tile and Teflon case. The calculated relative efficiency was 44%, which agrees well with the specifications(43%) supplied by the manufacturer. The tuning process was regarded to have been reliably performed.

The measured efficiency curve[9] is shown in Fig. 4. In the figure, the solid line represents the 8th order polynomial fitting of the measured efficiency data. The fitting result shows the deviation within 1% in the energy range of 0.06 ~ 6 MeV, and within 3% in the total energy range. The calculated efficiency was obtained for the geometry of assembled detectors by including the guard detector and the Pb γ-ray collimator. This was compared with the measured efficiency in Fig. 5. The calculated efficiency is consistent with the

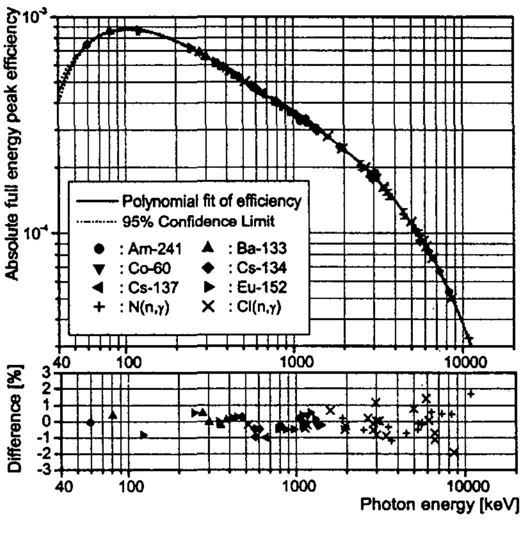

Fig. 4. Measured Absolute Full Energy Peak Efficiency for the SNU-KAERI PGAA Facility

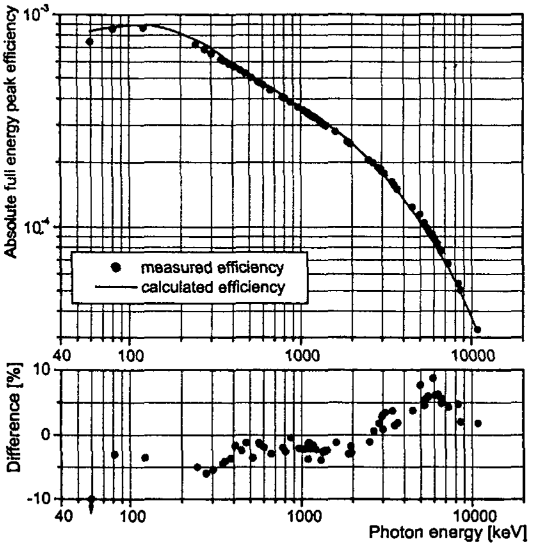

Fig. 5. Comparison of the Measured and Calculated Full Energy Peak Efficiencies

measurement within 7% in most of the energy region, although the measured efficiency deviates a little more from the calculation in the energy region above 3 MeV. Therefore, the Monte Carlo simulation could complement the measured efficiency in the whole energy range, and the detailed energy dependency of the efficiency was determined in the high energy region.

5. Analysis of the Local Efficiency Minimum

In the Figs. 4 and 5, a local minimum is identified near 600 keV on the efficiency curve[3,4,24]. This phenomenon is a common characteristics of a HPGe detector[5], and can be explained by sorting the interaction histories of the full energy absorption events into several classes. During the Monte Carlo simulation, the full energy(FE) absorption histories were classified as follows: the first case is the events undergoing a single photoelectric absorption only. The second case is the events undergoing either single or multiple Compton scattering followed by photoelectric absorption. The third case is the events absorbed by the pair production.

Considering that the local minimum is a general characteristics, the efficiency of each class was simulated by GEANT for the single mode detector geometry before the upgrade. Fig. 6 shows the partial efficiency of each class, with the sum normalized to the full energy absorption efficiency[25]. The single photoelectric absorption is dominant in the energy region below 200 keV. The contribution of the pair production class increases as the γ-ray energy increases, becoming dominant in the region above 11 MeV. In the medium region from several hundred keV to 11 MeV, the dominant class is multiple Compton scattering followed by photoelectric absorption.

The partial efficiency of each case was multiplied by 0.65^{th} power of the γ-ray energy in order to emphasize the local minimum, and the result is shown in Fig. 7[3,4]. In the figure, curve 'a' represents the full energy peak efficiency with

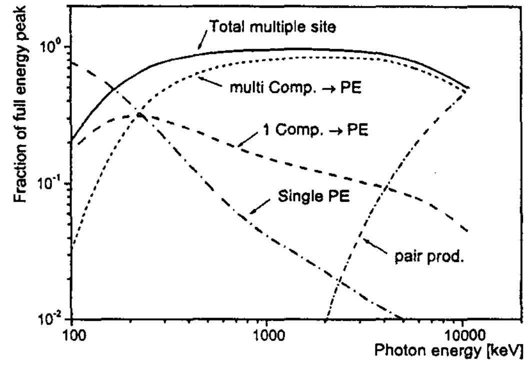

Fig. 6. Fractions of the Full Energy Peak Counts Contributed by the Different Interaction Histories in a Coaxial HPGe Detector. Single PE : Single Photoelectric Absorption, 1 (multi) Comp. → PE : Single (multiple) Compton Scattering Followed by Photoelectric Absorption, Total Multiple Site : Photoelectric Absorption After a Single or Multiple Compton Scattering

the pair production part subtracted. From curve 'a', it can be deduced that the right hill of the efficiency curve near 600 keV originates from the multiple Compton scattering part. Curve 'b' is obtained by subtracting the single Compton scattering part from curve 'a'. Curve 'b' has little effect on the formation of the left hill since it increases monotonously up to approximately 2 MeV. The curve shape of the single Compton scattering part has a maximum near the left hill and therefore it can be deduced that the left hill originates mainly from the single Compton scattering part. Hence, it can be concluded that the characteristics of the local efficiency minimum is caused by the energy dependency of each full energy absorption mechanism.

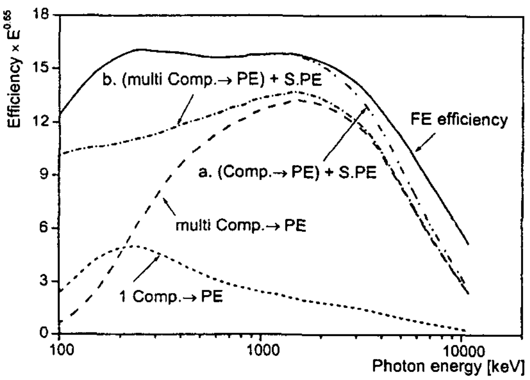

Fig. 7. Efficiency $\times E^{0.65}$ of the Full Energy Absorption by Different Mechanisms. S.PE Denotes the FE Absorption History by a Single Photoelectric Event

6. Conclusion

The efficiency curve of the HPGe detector was measured and calculated using the Monte Carlo method in a wide energy range of 0.06 ~ 11 MeV. The measurement was performed by the SNU-KAERI PGAA detector upgraded recently to multi-mode spectrometer and the Monte Carlo calculation was done using the GEANT code. The calculated and the measured efficiencies agreed with each other within 7% in the whole energy range. From this study, it was confirmed that the Monte Carlo simulation could be applied to an efficiency calibration in the high energy region above several MeV where only an experimental calibration has been tried dominantly up to now. This result is expected to contribute to improving the accuracy of the efficiency calculation using Monte Carlo method, identifying the sensitive tuning parameters, and understanding the efficiency trend dependent on the γ-ray energy. The result will also be a supporting frame for a further calibration study on single and double escape peak efficiencies, which have severer limits on the energy range and the number of data points in the experimental approach. In addition to the absolute efficiency calibration, the physical origin of the characteristic local minimum near 600 keV on the efficiency curve was analyzed. It was concluded to be caused by the energy dependency of the full energy absorption mechanisms.

References

1. K. Derbertin and R.G. Helmer, Gamma- and X-ray Spectrometry with Semiconductor Detectors, pp. 205-244, North-Holland, Amsterdam (1988).
2. Z. Kis, B. Fazekas, J. Östör, Zs. Révay, T. Belgya, G.L. Molá r and L. Koltay, "Comparison of efficiency functions for Ge gamma-ray detectors in a wide energy range", *Nucl. Instr. and Meth.* A 418, 374 (1998).
3. S. Raman, C. Yonezawa, H. Matsue, H. Iimura and N. Shinohara, "Efficiency calibration of a Ge detector in the 0.1-11.0 MeV region",

Nucl. Instr. and Meth. A 454, 389 (2000).

4. G.L. Molnár, Zs. Révay and T. Belgya, "Wide energy range efficiency calibration method for Ge detectors", *Nucl. Instr. Meth.* A 489, 140 (2002).
5. K. Derbertin and R.G. Helmer, Gamma- and X-ray Spectrometry with Semiconductor Detectors, p. 221, North-Holland, Amsterdam (1988).
6. H. Seyfarth, A.M. Hassan, B. Hrastnik, P. Gottel and W. Delang, 'Efficiency determination for some standard type Ge(Li) detectors for gamma-rays in the energy range from 0.04 to 11 MeV", *Nucl. Instr. Meth.* 105, 301 (1972).
7. Y. Shigetome and H. Harada, "Development of twin Ge detector and its performance", *Nucl. Instr. and Meth.* A 469, 185 (2001).
8. S.H. Byun, G.M. Sun and H.D. Choi, "Development of a prompt gamma activation analysis facility using diffracted polychromatic neutron beam", *Nucl. Instr. and Meth.* A 487, 521 (2002).
9. G.M. Sun, C.S. Park and H.D. Choi, "Improvement of the Gamma-ray Spectrometer of SNU-KAERI PGAA Facility", Proceedings of the Korean Nuclear Society Autumn Meeting, Yongpyong, Korea, (2002) (in Korean).
10. R.B. Firestone, Lawrence Berkeley National Laboratory, USA, private communication.
11. G.W. Phillips and K.W. Marlow, "Program HYPERMET for Automatic Analysis of Gamma-Ray Spectra from Germanium Detectors", NRL Memorandum Report 3198, Naval Research Laboratory (1976).
12. GEANT - Detector Description and Simulation Tool, Application Software Group, Computing and Network Division, CERN, Geneva, Switzerland, http://wwwinfo.cern.ch/asd/geant4/geant4.html.
13. M. Korun, A. Likar and T. Vidmar, "Monte-Carlo calculation of the spatial dependence of the coaxial HPGe detector efficiency for point sources", *Nucl. Instr. and Meth.* A 390, 203 (1997).
14. S. Ashrafi, A. Likar and T. Vidmar, "Precise modeling of a coaxial HPGe detector", *Nucl. Instr. and Meth.* A 438, 421 (1999).
15. M. Korun and T. Vidmar, "Monte Carlo calculations of the total-to-peak ratio in gamma-ray spectrometry", *Appl. Radiat. Isot.* 52, 785 (2000).
16. J.-M. Laborie, G.Le Petit, D. Abt and M. Girard, "Monte Carlo calculation of the efficiency calibration curve and coincidence-summing corrections in low-level gamma-ray spectrometry using well-type HPGe detectors", *Appl. Radiat. Isot.* 53, 57 (2000).
17. D. Karamanis, V. Lacoste, S. Andriamonje, G. Barreau and M. Petit, "Experimental and simulated efficiency of a HPGe detector with point-like and extended sources", *Nucl. Instr. and Meth.* A 487, 477 (2002).
18. C.S. Kim, G.M. Sun, J.Y. Lee, S.H. Byun, M.S. Kim, Y.D. Bae and H.D. Choi, "Measurement of the HPGe Detector Efficiencies for γ-rays and a Comparison with Monte Carlo Calculations", *Sae Mulli* 37, 399 (1997) (in Korean).
19. C.S. Park, G.M. Sun, S.H. Byun and H.D. Choi, "Calculation of Efficiency for HPGe Detector by Using GEANT", Proceedings of the Korean Nuclear Society Autumn Meeting, Yongpyong, Korea, (2002) (in Korean).
20. S. Kamboj and B. Kahn, "Evaluation of Monte Carlo simulation of photon counting efficiency for germanium detectors", *Health Phys.* 70, 512 (1996).
21. M.A. Ludington and R.G. Helmer, "High accuracy measurements and Monte Carlo calculations of the relative efficiency curve of

an HPGe detector from 433 to 2754 keV" *Nucl. Instr. and Meth.* A 446, 506 (2000).

22. M.G.-Talavera, H. Neder, M.J. Daza and B. Quintana, "Towards a proper modeling of detector and source characterstics in Monte Carlo simulations", *Appl. Radiat. Isot.* 52, 777 (2000).
23. I.O.B. Ewa, D. Bodizs, Sz. Czifrus and Zs. Molnar, "Monte Carlo determination of full energy peak efficiency for a HPGe detector", *Appl. Radiat. Isot.* 55, 103 (2001).
24. A. Owens, "A comparison of empirical and semiempirical efficiency calculations for Ge detectors", *Nucl. Instr. and Meth.* A 274, 297 (1989).
25. J.F. Knoll, Radiation Detection and Measurement, 3rd ed., p. 430, John Wiley & Sons, Inc., New York (1999).