**A comparison of methods for determining the total efficiency of HPGe detectors**

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**Abstract** - The total detection efficiency (TDF) of HPGe detectors, calculated using two different codes, MCNP and EFFTRAN, are presented. A comparison with experimentally measured values shows that the two codes produce quite similar results for point sources but very different for disc-shaped ones. Using the TDF calculated with these codes to determine the correction for True Coincidence Summing (TCS), similar results are obtained. This means that this correction is not highly dependent on the TDF, and it is possible to use EFFTRAN to shorten the calculation time.

**INTRODUCTION**

TCS effect occurs when two or more γ-rays are emitted simultaneously during a decay event, and the detector is unable to distinguish these photons independently. This results in distortions in the count rates of γ-peaks, leading to either an increase or decrease in the observed peak intensities [1]. Accurate determination of the TDF is essential for correcting this effect. For this purpose, two methods can be used including experimental and computation. The experimental method [2] is the best method for determining TDF, but it requires the single γ-emitting standard sources, that are not always available in many cases. In addition, the experimental method is not suitable for the sources with complex geometries. Monte Carlo (MC) method, utilizing available codes such as MCNP, can simulate all factors influencing the emission process and γ-ray interactions within the detector material, enabling a detailed reconstruction of the actual geometry and measurement conditions. Therefore, MCNP code is widely used to determine the TDF of HPGe detectors [3, 4]. The primary drawback of this method is its significant computational resource requirements and long calculation time. The EFFTRAN code [5] based on a Monte Carlo integration of the interaction probabilities of γ-ray over the detector and sample volumes is also suitable for calculation of the total efficiency. Very short calculation time is the main advantage of this method, and it is widely used [6, 7]. Nonetheless, the accuracy of this approach relies on standardized performance models, which may not always meet high precision requirements, particularly in complex scenarios involving multiple scattering processes or the effects of shielding components. This report provides a comparison between the TDF of HPGe detectors, calculated with two different codes: MCNP and EFFTRAN. The calculated results are also compared with the experimentally determined values using γ standard sources. The total efficiency curves calculated by two codes were used to determine the correction of TCS effect for 60Co and 99Y γ-ray sources for identification of the strengths and limitations of each approach and offer practical recommendations for their application.

**EXPERIMENTAL PROCEDURE AND CALCULATION METHODS**

***Detector model and calibration sources***

The detector used in this study is a coaxial p-type HPGe GC4018 CANBERRA detector with a relative efficiency of 40% and an energy resolution of 1.8 keV at 1333 keV. The cross section of the used detector is presented in Fig.1. To reduce the influence of environmental radiation on the quality of the measured spectra, the detector is enclosed within a 10 cm thick lead shield. The parameters provided by the manufacturer including the crystal dimensions, material type, and the gap between the crystal and the detector window of the HPGe detector are listed in Table 1. For other parameters where actual data is unavailable, values from a comparable detector of the same model and origin, as reported in reference [8], have been used.

|  |  |  |  |
| --- | --- | --- | --- |
| *Table 1: HPGe detector parameters* | | |  |
| **Components** | **Parameter** | **Value** | **C:\Users\nf-103-41\Desktop\Presentation2.jpg**  *Fig.1. The detector structure model. The dimensions are not scaled.* |
| **Crystal Ge** | Diameter | *59 mm* |
| Length | *61 mm* |
| Dead layer thickness | *0.53 mm* |
| Material | *Ge* |
| **Cavity hole** | Diameter | *42 mm* |
| Length | *10 mm* |
| **Holder** | Thickness | *1 mm* |
| Material | *Aluminum* |
| **Housing** | Diameter | *75 mm* |
| Thickness | *1.5 mm* |
| Material | *Aluminum* |
| **Window** | Thickness | *0.6 mm* |
| Gap to crystal | *6 mm* |
| Material | *Aluminum* |

The set of standard sources used to determine the efficiency curves, along with the γ-ray energies from each radionuclide and their yields, are shown in Table 2 [10], where the numbers in parentheses are corresponding errors. The experimental setup is illustrated in Fig.2, where calibration sources were positioned 5cm from the detector surface along its axis. Additionally, background radiation was continuously recorded over 17 hours.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *Table 2. The radioactive sources used for efficiency determination* | | | |  |
| Nuclide | T1/2 | Eγ, (keV) | Iγ, (%) | *Fig.2. Experimental layout.* *The dimensions are not scaled.* |
| Mono-peak standard point sources | | | |
| 241Am | 432.6 y (6) | 59.54 | 35.9 (4) |
| 109Cd | 461.9 d (4) | 88.03 | 3.644 (16) |
| 139Ce | 137.641 d (20) | 165.86 | 79.7 (5) |
| 137Cs | 30.08 y (9) | 661.66 | 85.1 (2) |
| 54Mn | 312.20 d (20) | 834.85 | 99.976 (1) |
| Double-peak standard point sources | | | |
| 88Y | 106.627 d (21) | 898.04 | 93.7 (3) |
| 1836.06 | 99.2 (3) |
| 60Co | 1925.28 d (14) | 1173.23 | 99.85 (3) |
| 1332.49 | 99.9826 (6) |

***Experimental determination of total detection efficiency***

To determine the TDF of the HPGe detector experimentally, the γ-ray standard sources that emit only one γ-ray listed in Table 2 including 241Am, 109Cd, 139Ce, 137Cs and 54Mn have been used. The total count rate ​ is directly proportional to the TDF , the source activity and the γ-emission intensity . The TDF is calculated by the following equation:

|  |  |
| --- | --- |
|  | (1) |

For 60Co and 88Y γ-ray standard sources, which emit two γ-ray in cascade, the total count rate ​ is calculated as:

|  |  |
| --- | --- |
|  | (2) |
|  |  |

where ​, are the TDF at the energies E1 and E2, and Iγ1, Iγ2 are their intensities.

For the 60Co source (Fig.3a), which emits two γ with Eγ1=1173 keV and Eγ2=1332 keV, intensities of Iγ1≈Iγ2≈1. Since Eγ1 and Eγ2 are quite close to each other, it is possible to assume that the TDF at these two energies are approximately equal and equal to the TDF at their average energy of 1253 keV:

Substituting this approximation into Eq.2, the TDF at 1253 keV can be calculated:

|  |  |
| --- | --- |
|  | (3) |
|  |  |

For the 88Y source (Fig.3b), (898keV) can be determined by extrapolation from the TDF determined by using the γ-ray standard sources of 241Am, 109Cd, 139Ce, 137Cs and 54Mn. Then, the TDF (1836 keV) was calculated from Eq.2 as follows:

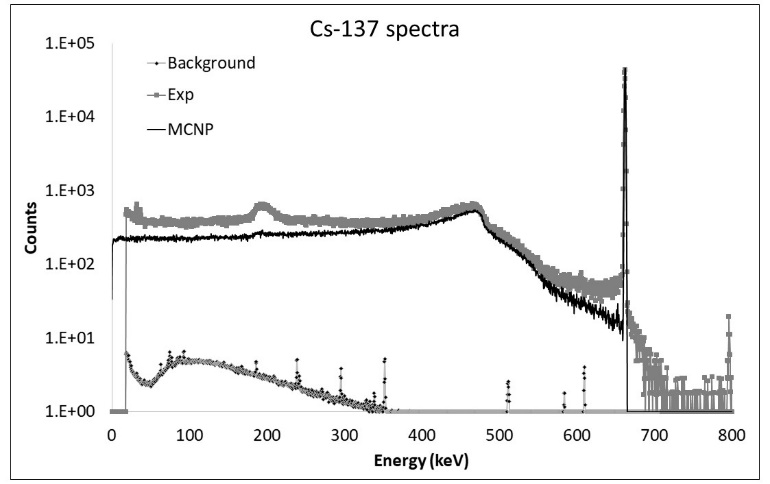
|  |  |  |
| --- | --- | --- |
|  | | (4) |
|  | | | |
| *(a)* | *(b)* | | |
| *Fig.3. γ-decay scheme of 60Co (a) and 88Y (b)* | | | |

The TDF curve can be obtained by fitting the measured values to the following function [11]:

|  |  |
| --- | --- |
|  | (5) |

where are the fitted parameters.

***Calculation of the total detection efficiency using MCNP and EFFTRAN codes***



*Fig.4. 137Cs spectra from experiment and MNCP simulation*

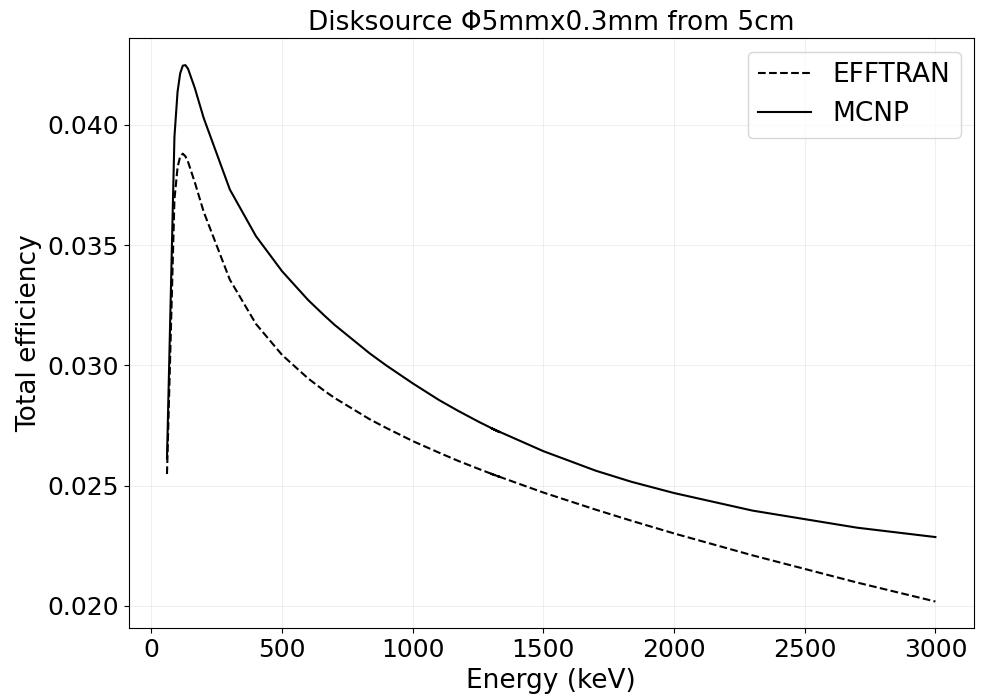
In this study, the TDF for both point and disk sources have been calculated using two codes: EFFTRAN [5] and MCNP6 [9]. The detector configuration presented in Fig.1 and its parameters listed in Table 1 were used for calculation. In EFFTRAN, the code does not account for multiple scattering effects within the sample itself or from surrounding objects, such as lead shielding or chambers. However, in MCNP, all transport processes of γ-rays, especially multiple scattering effects within the sample, detector, and surrounding objects, are considered. A typical simulated γ-ray spectrum by MCNP6 for 137Cs source is shown in Fig.4. The full width at half maximum (FWHM) values were obtained from an experimental calibration curve. The source to detector distance is 5 cm. MCNP6 code was run for 108 events. The simulated γ-ray spectra were then used for determination of the TDF in the same way as in experiment.

**RESULTS AND DISCUSSIONS**

The TDF for a point source, determined by experimental measurement, and calculated by EFFTRAN and MCNP are shown in Fig.5. In Fig.5a, the experimental results are represented by solid circles and its fitting curve is presented by the dashed line while the calculated values by MCNP and EFFTRAN are presented by solid line and dotted line, respectively. The relative differences between the values calculated by MCNP and EFFTRAN and the experimental values ​​are given in Fig.5b. As can be seen from Fig.5b, the results calculated by MCNP agree very well with the experimental values, especially in the energy region below 250 keV. In higher energy range, the values calculated by MCNP are slightly higher than the experimental ones, with an average deviation of 1.7%. In contrast, the TDF calculated by EFFTRAN are always smaller than experimental results with an average deviation of 3.1%. It can therefore be concluded that the TDF calculated by EFFTRAN will be less accurate than that by MCNP. However, the calculation time using EFFTRAN will be much shorter than using MCNP.

|  |  |
| --- | --- |
|  |  |
| *(a)* | *(b)* |
| Fig.5. *Resulted TDF from different methods for point sources with 5cm distance (a), and relative differences (b)* | |

The TDF curves for disc-shaped samples (5 mm of diameter and 0.3 mm of thickness) were also calculated using both MCNP and EFFTRAN codes and the results are listed in Fig.6. The average difference between the values ​​calculated by two codes is about 7%, especially at energies higher than 300 keV, this average difference is up to 13%. These differences are mainly caused by the multiple scattering effect of γ-ray in the sample and surrounding objects. In our opinion, MCNP takes this effect into account while EFFTRAN does not, therefore MCNP should give the better results.



*Fig.6. The total efficiency curves for disk source calculated by MCNP and EFFTRAN*

Using the TDF curves calculated by MCNP and EFFTRAN codes, it is possible to obtain TCS correction factors for extended samples. For illustration, calculated TCS correction factors [2] for the point and disk shaped sources for the principal γ of 60Co and 88Y based on two TDF curves calculated by MCNP and EFFTRAN are listed in Table 3. The results of TCS correction calculated using two different TDF curves are almost similar as can be seen from Table 3.

*Table 3. Correction factor for the TSC effect for 60Co and 88Y*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Type of source** | **Isotopes** | **Energy (keV)** | **EFFTRAN** | **MCNP** | **Difference** |
| Point | 60Co | 1173 | 1.02627 | 1.02785 | 0.154% |
| 1332 | 1.02695 | 1.02875 | 0.175% |
| 88Y | 898 | 1.02432 | 1.02566 | 0.131% |
| 1836 | 1.02679 | 1.02891 | 0.206% |
| Disk | 60Co | 1173 | 1.02602 | 1.02798 | 0.191% |
| 1332 | 1.02670 | 1.02888 | 0.212% |
| 88Y | 898 | 1.02410 | 1.02581 | 0.167% |
| 1836 | 1.02652 | 1.02912 | 0.253% |

**CONCLUSIONS**

The TDF curves for HPGe detectors for point and disk-shaped sources using MCNP and EFFTRAN codes are presented in this paper. These curves are used to determine the TCS correction factors for accurate determination of the γ-ray activity of radioactive samples. The results show that the TDF calculated by two codes for point sources are not significantly different, but for disk sources are quite different. Based on this, the TCS correction factors calculated from the total efficiency results of the MCNP and EFFTRAN codes show almost no difference. This indicates that the TCS correction does not depend too much on the TDF, therefore, it is possible to use EFFTRAN for determination of the TDF of HPGe detector instead of MCNP for data analysis to shorten the calculation time.

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**REFERENCES**

[1]Semkow, T. M., Mehmood, G., Parekh, P. P., & Virgil, M., Coincidence summing in gamma-ray spectroscopy // Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment - 1990 - V. 290 - P. 437-444.

[2] Arnold, D., Debertin, K., Heckel, A., Kanisch, G., Wershofen, H., & Wilhelm, C., Fundamentals of gamma spectrometry.

[3] J. Rodenas et al., Analysis of the influence of germanium dead layer on detector calibration simulation for environmental radioactive samples using the Monte Carlo method // Nuclear Instruments and Methods in Physics Research A: Accelerators, Spectrometers, Detectors and Associated Equipment – 2003 - V. 496 - P. 390-399.

[4] Ba, V.N., Giang, L.T.H., Thien, B.N., Hong Loan, T.T., Huy, N.Q., Verification of physical parameters of insity p-type HPGe detector by scan method using collimated low energy photon beam and MNCP simulation // Applied Radiation and Isotopes- 2020 - V.163.

[5] Vidmar et al., T. EFFTRAN - A Monte Carlo efficiency transfer code for gamma-ray spectrometry // Nuclear Instruments and Methods in Physics Research A: Accelerators, Spectrometers, Detectors and Associated Equipment - 2005 - V. 550 - P. 603-608.

[6] Vidmar et al., Calculation of total efficiencies of extended samples for HPGe detectors // Nuclear Instruments and Methods in Physics Research A: Accelerators, Spectrometers, Detectors and Associated Equipment - 2005 - V. 555 - P. 251-254.

[7] Tim Vidmar et al., Calculation of true coincidence summing corrections for extended sources with EFFTRAN // Applied Radiation and Isotopes - 2011 - V. 69 - P. 908-911.

[8] Pavel Dryak et al., Experimental and MC determination of HPGe detector efficiency in the 40 - 2754 keV energy range for measuring point source geometry with the source-to-detector distance of 25 cm // Applied Radiation and Isotopes - 2006 - V. 64 - P. 1346-1349.

[9] Kulesza, Joel A., et al., MCNP® code version 6.3. 0 theory & user manual - No. LA-UR-22-30006 // Los Alamos National Laboratory (LANL), Los Alamos, NM (United States) - 2022.

[10] Live Chart of Nuclide // available at https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

[11] Genie™ 2000 Spectroscopy Software Operations.