CHARACTERIZATION OF THE COAXIAL n-TYPE HPGe DETECTOR FOR ACTIVITY MEASUREMENTS OF ITER MATERIALS IRRADIATED IN JET*

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A model describing the ORTEC GMX-30190-P coaxial n-type HPGe detector with a thin beryllium window was created. The absolute full-energy peak efficiency calibration for measurements of activated ITER materials was performed in the gamma-energy range from 60 to 1836 keV using a semi-empirical approach employing Monte-Carlo-based efficiency transfer method. The validity of the model was shown by cross-checking against the experimental data obtained with a calibration standard of the same geometry. The additional correction factors for a self-absorption of gamma rays in different sample matrices were also calculated.

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1. Introduction

Samples of structural materials, used for the construction of the International Thermonuclear Experimental Reactor (ITER), will be irradiated in the Joint European Torus (JET) during the next D–D (deuterium–deuterium) and D–T (deuterium–tritium) experimental campaigns. This will be done to validate, in fusion-relevant operational conditions, the radiation transport and activation calculation predictions based on state-of-the-art codes and nuclear data used in ITER nuclear analyses [1, 2].

The quality of gamma spectrometry measurements, carried out with HPGe (High-Purity Germanium) detectors, depends on the knowledge of a full-energy photopeak efficiency (FEPE) for a specific source-detector configuration. In case the measured activity is low, the positioning of the sample as close as possible to the detector's end-cup window is necessary in order to reduce the counting times. However, the appropriate corrections for a true

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coincidence summing effect for radionuclides with complex decay schemes are then needed to accurately determine the sample activity. Introducing such correction factors is extremely important especially for a coaxial n-type HPGe detector with 0.3 μm boron-implanted contact and thin beryllium entrance window allowing photons of energy down to 3 keV to enter the active volume of the detector. Obtaining equivalent calibration standards that match the samples to be measured (by shape, size, density, chemical composition) can be difficult. Therefore, computational methods such as Monte Carlo techniques can be used to take into account the dimensions of the sample and self-absorption within it.

The aim of this work was to apply the MCNP5 code to develop a detailed model for a calibration of the coaxial n-type HPGe detector used in the measurements of dosimetry foils and ITER material samples irradiated in JET. The validity of the model was shown by cross-checking against experimental data obtained with a gamma-ray reference source having the same disk-shaped geometry.

2. Materials and methods

2.1. Experimental set-up

The detector to be characterized was an ORTEC coaxial n-type HPGe detector (model No. GMX-30190-P) having a relative photopeak efficiency of 30%. It has a resolution of 715 eV for 5.9 keV and 1.9 keV for 1.33 MeV and a Peak-to-Compton ratio of 52:1. An HPGe crystal and a front end of a charge-sensitive preamplifier are mounted inside a vacuum enclosure of a PopTop capsule. The rest of the preamplifier and a HV filter are a part of the capsule but they are outside the vacuum chamber. Some key dimensional data for the detector and its assembly are given in Table I. The detector is surrounded by a box-like shield, made of 17 cm-thick 19^{th}-century steel (free from Co-60 traces present in all modern steels), which inner walls are covered by a 3 mm-thick copper lining. The detector is connected to the amplifier (model 2026, Canberra) with Pileup Rejection/Live time correction (PUR/LTC) feature. The amplifier output is fed directly into a computer controlled NIM multichannel analyzer, manufactured by Canberra, with a 13-bit ADC.

The point-like gamma-ray sources, used for experimental FEPE determination, were prepared from standard solutions containing radionuclides of certified activity provided by the Czech Metrology Institute. The accurately measured quantity of the active solution of Am-241, Ba-133, Cs-137, Mn-54, Co-60 and Y-88 was deposited on a filter paper. The filter paper had a diameter of 3 mm and was placed on a Scotch tape. After drying under an IR lamp, the source was heat sealed in a thin plastic foil. The sources placed

in the holders made of Plexiglas were measured at two source-to-detector window distances (SDD): 0.90 cm (hereafter called as a close geometry) and 10.75 cm (where the coincidence summing effect for low-activity sources can be considered as negligible in practice). The sources activity was kept low in order to avoid too high count rates when measuring in close proximity to the detector. Additionally, to check the accuracy of the efficiency transfer method (see Section 2.2.1) a disk-shaped multi-gamma source AK-4546 supplied by Eckert&Ziegler (Germany) was also measured at the same distances. The active area of this calibration standard was identical to the one of activated ITER materials and dosimetry foils that is 18 mm in diameter. The gamma spectra were acquired using the Genie^{TM}2000 software (Canberra) and analysed using in-house software developed at IFJ PAN. The acquisition time was set so that the net peak area uncertainty was below 1%. The measured FEPEs for a close geometry were corrected for a true-coincidence summing.

TABLE I

Manufacturer detector specification. All dimensions are given in millimeters [mm] unless otherwise stated.

Basic detector dimensions	
Detector diameter	54.5
Detector length	67.5
Detector end radius	8 (nominal)
Hole diameter	10.2
Hole depth	59.8
Hole bottom radius	5.1 (nominal)
Detector assembly dimensions and materials	
Mount cup length	94, aluminium
Mount cup base	3.2, aluminium
Mount cup wall	0.76, aluminium
Insulator/shield	0.05, aluminized Mylar
Outside contact layer	0.3 μm, Ge with B ions
Hole contact layer	700 μm, Ge with Li ions
End cap to crystal gap	3, n/a.
End cap window thickness	0.5, beryllium
End cap wall thickness	1.3, aluminium
End cap diameter	70

2.2. Monte Carlo modelling

Monte Carlo simulations were performed using the MCNP5 code [3] in order to predict the FEP efficiency of the HPGe detector. Initially, nominal detector dimensions provided by ORTEC (Table I) were used to create a

detector model. The "bulletization" of the front "corners" of crystal, which influences the most the efficiencies for lower gamma-ray energies, was also taken into account. The certified point-like gamma-ray sources and their holders were implemented in detail in the code. The photon intensities per decay were taken from Bé *et al.* [4]. In order to determine the energy deposited in the crystal active volume, in a specified energy bin, and predict detector FEP efficiency, a pulse height tally (F8 tally) was used [3]. In each run, 10^9 photons were sampled to reduce the statistical uncertainty. Relative errors of the obtained results did not exceed 1%.

2.2.1. Efficiency transfer method

The efficiency transfer (ET), originally proposed by Moens *et al.* [5], was used to calculate FEPEs for a sample with a geometry of ITER materials and dosimetry foils irradiated in JET (18 mm diameter and 0.5 mm thickness). The FEPEs for the sample of interest were computed as a ratio of an MC simulated FEPE for the sample and for a reference standard (point-like source) multiplied by the experimentally determined FEPE for the standard [6]. The experimentally determined FEPE for a reference standard geometry (point-like source) was transferred to a geometry of the sample of interest by scaling the ratio of an MC simulated FEPE for the sample and for a reference standard. A great advantage of the ET method is that the reference standard does not have to be of the same shape, size, density and chemical composition as the sample of interest. The method is based on the assumption that the transfer factors between Monte Carlo computed FEPEs using the nominal detector dimensions and measured FEPE depend only on photon energy and not on a measurement geometry. Moreover, the ET method is insensitive to the uncertainty related to the detector characterization [7, 8].

2.2.2. Self-absorption corrections

In order to account for a self-absorption within each ITER sample and dosimetry foil to be analysed, the ratio of simulated efficiency values between the sample and a calibration source was calculated using the MCNP model of the detector. The chemical composition of the ITER materials was taken from [9]. In the case of dosimetry foils, a pure metal sample was considered.

3. Results and discussion

The experimental results were compared to the corresponding values of FEPE calculated using the MCNP5 code for a point-like source geometry. Figure 1 shows this comparison. It can be observed that the FEPEs obtained with MCNP5 are higher than the experimentally determined and differ from

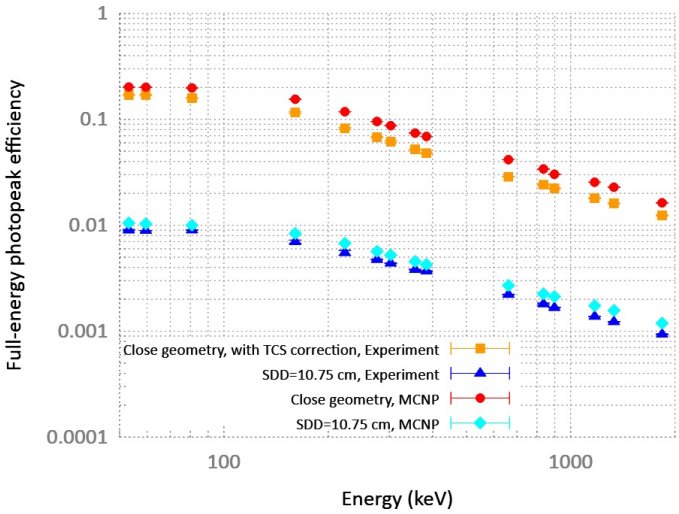

Fig. 1. Measured and calculated FEPE at two source-to-detector distances for point-like sources: Am-241, Ba-133, Cs-137, Mn-54, Co-60 and Y-88.

the measured efficiencies by a factor between 1.21 and 1.47 for a close geometry and by a factor between 1.11 and 1.28 for a SDD = 10.75 cm. These discrepancies arise mainly from insufficiently accurate information on the detector's dimensions and its housing. Among uncertain detector parameters reported by other authors [10, 11] there are the thickness of dead layers, the crystal active volume (crystal length and radius) and the crystal-to-window distance. These parameters can be adjusted to get a better agreement between the simulated and experimental efficiency values. However, it is a time-consuming task. In order to reduce the number of unknown parameters in the model, one has to use *e.g.* X-ray radiography, computed tomography (CT) or a collimated gamma-ray source to scan a detector and experimentally check the detector dimensions. This will be a subject of our future studies. In the present work, the non-optimized detector model and the efficiency transfer method were used to calculate the theoretical FEP efficiency curve (polynominal fit in log(FEPE) against log(Energy)) for a geometry of ITER materials and dosimetry foils used during the activation experiments at JET. The validation of the obtained calibration curve was performed with the use of a mixed nuclide gamma-ray source AK-4546 (having the same disk-shaped geometry). The activity of radionuclides present in the source reported in the source certificate was compared against the decay corrected activity calculated using the theoretical FEPEs. The results of this comparison are given in Table II. The reported and calculated activity shows good agreement for all radionuclides. The certified activity is

found within the combined standard uncertainty of the activity calculated with the use of the ET method. The mean of the ratio of calculated (C) and reported (R) activity is 0.983 ± 0.019 ($\pm$ standard deviation).

TABLE II

Comparison between calculated (C) and reported activity (R) of mixed nuclide gamma-source AK-4546.

Nuclide	Energy [keV]	Activity R* [Bq]	Activity C [Bq]	C/R activity	RD [%]
Am-241	60	3430±103	3264±288	0.952	−4.84
Cd-109	88	16700±835	16136±1231	0.966	−3.38
Co-57	122	629±19	613±42	0.974	−2.59
Ce-139	166	827±25	817±45	0.988	−1.18
Hg-203	279	2120±64	2113±48	0.997	−0.35
Sn-113	392	2950±89	2968±149	1.006	0.63
Sr-85	514	3850±116	3746±123	0.973	−2.69
Cs-137	662	2880±86	2907±174	1.009	0.94
Y-88	898	6330±190	6291±246	0.994	−0.61
	1836				
Co-60	1173	3250±98	3161±133	0.973	−2.73
	1333				
			Mean:	0.983	
			Std. dev.:	0.019	

*Reference date: 1st of September, 2017 12:00 UTC.

Following the completion of the experimental campaign at the JET tokamak, samples of ITER materials and dosimetry foils will be measured in the same geometry as the AK-4546 source was presently measured. Since the irradiated samples and the calibration standard are different in terms of the chemical composition and density, the self-absorption correction factors are required to account for a difference in self-absorption of gamma rays. The correction factors for the analysed samples were evaluated at energies listed in the mixed nuclide gamma-calibration source AK-4546 (Table III). For low-energy gamma rays (below 100 keV), the mass attenuation coefficients, and hence the self-absorption correction factors significantly vary in different materials. Except for tungsten (Fig. 2), which is a high-Z element ($Z = 74$) and has a density of 19.25 g/cm^3, the calculated self-absorption correction factors with respect to the calibration standard does not exceed 35%. Since the self-absorption correction factor is a ratio of efficiency for a standard and a sample, the possible errors in the efficiency determination cancel out (the proper optimization of the detector dimensions has no importance).

TABLE III
Self-absorption correction factors for selected ITER materials and dosimetry foils.

Isotope	Energy [keV]	SS316L	EUROFER	XM-19	Sc
Am-241	60	0.773(11)	0.716(16)	0.776(11)	0.9420(17)
Cd-109	88	0.8940(12)	0.8310(13)	0.8969(12)	0.9737(11)
Co-57	122	0.9414(12)	0.9153(12)	0.9426(12)	0.9836(16)
Ce-139	166	0.9598(13)	0.9520(13)	0.9602(13)	0.9866(13)
Hg-203	279	0.9739(17)	0.9765(17)	0.9738(17)	0.9904(13)
Sn-113	392	0.9785(19)	0.9827(19)	0.9784(19)	0.9923(16)
Sr-85	514	0.9821(21)	0.9864(21)	0.9820(21)	0.9941(18)
Cs-137	662	0.9836(24)	0.9878(24)	0.9835(24)	0.9944(24)
Y-88	898	0.9832(28)	0.9869(28)	0.9831(28)	0.9925(28)
Co-60	1173	0.9866(31)	0.9899(31)	0.9866(31)	0.9946(31)
Co-60	1333	0.9855(33)	0.9887(33)	0.9854(33)	0.9931(33)
Y-88	1836	0.9910(38)	0.9936(38)	0.9909(38)	0.9972(38)
Isotope	Energy [keV]	Al bronze	CuCrZr	Nb_3Sn	Y
Am-241	60	0.753(13)	0.710(16)	0.7093(16)	0.689(19)
Cd-109	88	0.8867(12)	0.8621(12)	0.8615(12)	0.8548(12)
Co-57	122	0.9392(12)	0.9263(12)	0.9261(12)	0.9314(12)
Ce-139	166	0.9597(13)	0.9521(13)	0.9520(13)	0.9628(13)
Hg-203	279	0.9748(17)	0.9705(17)	0.9704(17)	0.9827(16)
Sn-113	392	0.9796(19)	0.9761(19)	0.9760(19)	0.9875(19)
Sr-85	514	0.9830(21)	0.9800(22)	0.9800(22)	0.9904(21)
Cs-137	662	0.9845(24)	0.9819(24)	0.9818(24)	0.9914(24)
Y-88	898	0.9840(28)	0.9817(28)	0.9816(28)	0.9900(28)
Co-60	1173	0.9873(31)	0.9854(31)	0.9853(31)	0.9925(31)
Co-60	1333	0.9862(33)	0.9843(33)	0.9842(33)	0.9911(33)
Y-88	1836	0.9916(38)	0.9898(38)	0.9898(38)	0.9954(38)

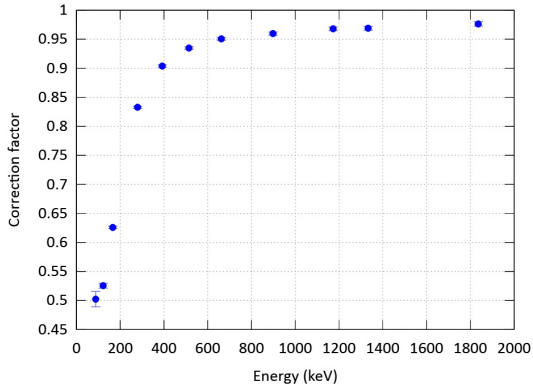

Fig. 2. Self-absorption correction factors for tungsten.

4. Conclusions

Reliable measurements of the radionuclide activity using an HPGe detector require the knowledge of the absolute photo-peak efficiency. In the case when a standard radioactive source of the same geometrical dimensions, chemical composition and density is not available or when low-level counting is required, Monte Carlo (MC) calculations can be used for efficiency calibration and self-absorption corrections.

The efficiency values for the GMX-30190-P HPGe detector obtained experimentally and by MC simulation based on nominal values of the parameters provided by ORTEC show significant differences due to the inaccuracy in the detector geometrical parameters such as the thickness of a dead layer, the crystal active volume (crystal length and radius) and the crystal-to-window distance. Nevertheless, the semi-empirical method of an HPGe detector calibration based on the efficiency transfer function from a reference point-like source configuration appears to be a very practical method in the measurements of samples with complex matrices and different geometries. In this investigation, the accuracy of radionuclide activity determination of better than 5% was achieved which is an acceptable level for analytical purposes.

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