J Radioanal Nucl Chem (2012) 292:1325–1328
DOI 10.1007/s10967-011-1601-1

Analytical calculation of the collimated detector response for the characterization of nuclear waste drums by segmented gamma scanning

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Received: 14 December 2011 / Published online: 26 January 2012

Abstract Improved methods for the reconstruction of the isotope specific activity content in nuclear waste drums with data obtained by a gamma scanning system developed at Shanghai Jiao Tong University require an analytical function of the detector response. In this work we derive an analytical detector response function for a collimated HPGe detector with a square collimation window. The model is based on a purely geometric model respecting the configuration of the collimated detector system, the positions of radioactive point sources and the absorption of γ-rays in the matrix as well as in the HPGe crystal. We show that the derived analytical detector response function is in good agreement with data simulated by MCNP5.

Keywords Nuclear waste · Segmented gamma scanning · Detector response

Introduction

Low and intermediate nuclear waste from nuclear power plants (NPP) in China is conditioned in 200 L drums at the NPP sites. The School of Nuclear Science and Engineering of the Shanghai Jiao Tong University develops an improved gamma scanning system to experimentally determine the isotope specific activity contents of nuclear waste drums. The gamma scanning system is mainly composed of a mechanical part to rotate a nuclear waste drum and to lift a detection system for the measurements of γ-rays. The detection system consists of a collimated HPGe detector with a square collimation window. Improved methods for the activity content reconstruction require an analytical description of the detector response to activity point sources in a waste matrix. In this work the analytical response function of the square collimated HPGe detector used at SJTU is derived according to work of Krings and Mauerhofer [1]. For its validation the analytical detector response function is compared to simulated data obtained from MCNP5 (Monte Carlo N-Particle Code).

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Geometric setup

Figure 1 schematically shows the geometric setup of the gamma scanning system developed by the Shanghai Jiao Tong University. A high-resolution n-type coaxial HPGe detector with a relative efficiency of 40% is used to measure the γ-rays. The diameter and length of the detector are 6.20 and 5.95 cm, respectively. The detector is collimated with a lead cylinder that has a square collimation window. The length of the collimator l_{col} is 15 cm and its outer diameter is 16 cm. The side length of the collimation window a_{col} is 6 cm. The distance d_0 from the centre of the radioactive waste drum to the detector window is 53 cm. According to Krings and Mauerhofer [1] and the geometric quantities given in Fig. 1, the photon count rate T measured by the collimated detector system can be calculated by

$$T = \varepsilon(d_n) \cdot I_\gamma \cdot A \cdot \mathrm{e}^{\left(-\frac{\mu_P}{\rho_P}\rho_P l_P\right)} \cdot \mathrm{e}^{\left(-\frac{\mu_w}{\rho_w}\rho_w l_w\right)} \tag{1}$$

where $\varepsilon(d_n)$ is the absolute detector efficiency to a point source located at the distance d_n to the detector, I_γ is the intensity of the considered γ-energy, A activity of the point source, μ is the mass absorption coefficient, ρ is the density and l is the average penetration length of the photon beam. The indices P and W correspond to the different materials in the passive waste matrix (P) and the drum wall (W), respectively.

Detector efficiency

The calculation of the detector efficiency is based on the solid angle that is subtended by the collimated detector system to the point source. Its derivation is analog to the procedure presented by Krings and Mauerhofer [1], who used a collimator with a cylindrical window. Given that the square collimation window is slightly larger than the circular active detector surface, edge penetration effects lowering the absolute efficiency have to be taken into account. Hence, the absolute detector efficiency $\varepsilon(d_n)$ can be calculated by

$$\varepsilon(d_n) = \varepsilon(d_0) \cdot \left(\frac{d_0}{d_n}\right)^2 \cdot \frac{S_{\text{dn}}}{S_{\text{det}}} \cdot C \tag{2}$$

Here, $\varepsilon(d_0)$ is the absolute detector efficiency for a point source located at the drum centre, S_{dn} is the part of the active detector surface illuminated by the photon beam due to the collimation and S_{det} denotes the area of the active detector surface. The factor C corrects the absolute efficiency regarding the edge penetration effect. Parts of the photon beam that pass some collimator material and nevertheless reach the active detector volume unscattered are neglected due to their minor contribution. The next two sections focus on the calculation of S_{dn} and C.

Illuminated active detector surface

Regarding the calculation of the illuminated active detector surface S_{dn}, two trivial cases are considered first. Either the active detector surface is entirely (case 1) or not all (case 2) illuminated by the collimated photon beam resulting to $S_{\text{dn}} = \pi r^2$ or $S_{\text{dn}} = 0$, respectively. Here, r_{d} is the radius of the active detector surface. Figure 2 shows the remaining four cases for the calculation of S_{dn} schematically. The calculation of S_{dn} in those cases requires the calculation of arc segment areas. According the nomenclature in Fig. 2, the area of an arc segment is given by

$$S = \frac{r_{\text{d}}^2 \delta}{2} - \frac{g}{2} \cos\frac{\delta}{2} r_{\text{d}} \tag{3}$$

with g being the length of the chord given by the intersection of the active detector surface and one side of the collimated photon beam. The central angle of the sector is given by

$$\delta = 2 \arcsin\frac{g}{2r_{\text{d}}} \tag{4}$$

and the side length of the photon beam at the plane defined by the active detector surface is given by

$$a = \frac{l_{\text{col}}}{d_x - l_{\text{col}}} \times a_{\text{col}} \tag{5}$$

Here, d_x denotes the projection of d_n to the x-axis. According this equations and Fig. 2, S_{dn} can be calculated for these cases by

$$S_{\text{dn}} = \begin{cases} S_1 + \frac{1}{2}|a_y - b_y||a_z - b_z| & \text{case 3} \\ \pi r_{\text{d}}^2 - (S_1 + S_2) & \text{case 4} \\ S_1 & \text{case 5} \\ \pi r_{\text{d}}^2 - S_1 & \text{case 6} \end{cases} \tag{6}$$

Edge penetration correction

Photons originating from a point source enter the active detector surface under a certain angle with respect to the position of the point source relative to the detector. Path lengths of those photons in the detector volume and hence their detection probabilities strongly vary. Figure 3 schematically shows the different path lengths of photons from a point source in a detector crystal. The correction factor

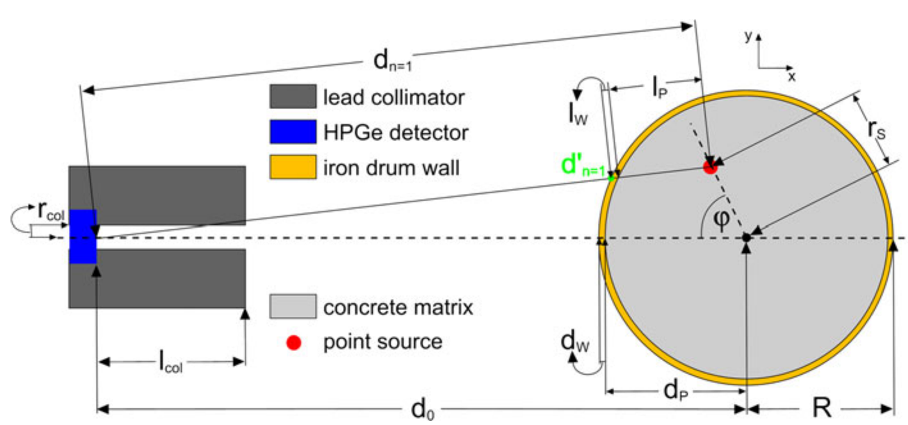

Fig. 1 Geometric model of the collimated detector system for gamma scanning developed at Shanghai Jiao Tong University

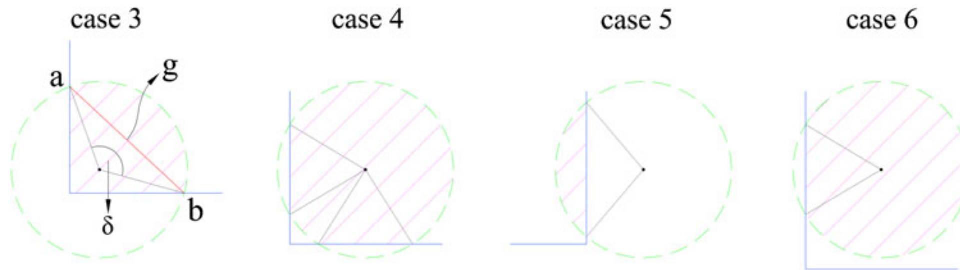

Fig. 2 Active detector surface illuminated by the photon beam using a square collimation

accounts for this edge penetration effect. It is calculated by the averaged absorption probability of the photon beam with respect to the average absorption probability for a photon beam from a point source in front of the detector. The calculation of the average absorption probability relies on a mesh of n_0 virtual points distributed homogenously at the active detector surface. Penetration lengths $l_i(\vec{r}_s)$ of photons from a point source are calculated for each photon beam entering the active detector surface at one of the n points that are within the illuminated part of the active detector surface. The correction factor can hence be expressed by

$$C = \left(1 - \frac{1}{n}\sum_{i=1}^{n} e^{-\frac{\mu}{\rho}\rho l_i(\vec{r_s})}\right) \cdot \left(1 - \frac{1}{n_0}\sum_{i=1}^{n_0} e^{-\frac{\mu}{\rho}\rho l_i(\vec{r_s})}\right)^{-1} \quad (7)$$

Simulations, results and discussions

It has been shown that MCNP5 is suitable for the simulation of efficiencies of HPGe detectors to point sources at various positions [2–4]. Therefore, the detection system as it is used at SJTU is modelled according the specifications of the detector furnisher.

A ^{137}Cs point source ($E_\gamma = 0.661$ MeV) with an activity of 2×10^9 Bq has been simulated in an air environment at a radial position of 15 cm from the centre of the turntable axially to the detector. This source has been rotated with a hypothetical drum in steps of 2° from 0° to 180°. Figure 4 shows the relative deviation between the simulated count rates and the calculated ones according Eq. 1. Without the use of the edge penetration correction the relative deviation in the range of 45–100° exceed 50% with a maximum of about 100% at around 76°. Photons from a point source at that position have the largest incident angle to the active detector surface. Therefore, the edge penetration effect becomes most important in this region. In contrast, the edge penetration corrected values show a significant better agreement with the simulated count rates. Relative errors are between −10 and 2%. Two effects can explain these remaining deviations. First, the calculation do not account for the copper cooling finger, that lowers the active detector volume. Second, the part of the photon beam that passes some collimator material and nevertheless reaches the active detector volume is not taken into consideration. However, these deviations do not influence the activity reconstruction because the main information of the activity point source is given by the measurements at small angles. In this range there is a nearly perfect agreement between the simulated data and the calculation.

Count rate distributions of ^{137}Cs point sources are simulated like they are obtained with a segmented gamma scanning system [1]. The point source is therefore placed in a drum filled with a concrete matrix that has a density of

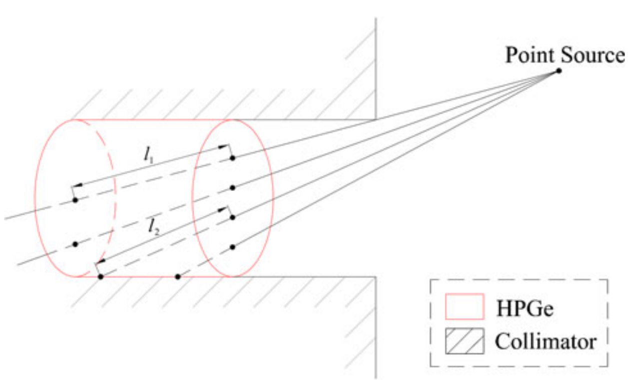

Fig. 3 Scheme of the different penetration lengths of photons from a point source in a collimated detector crystal

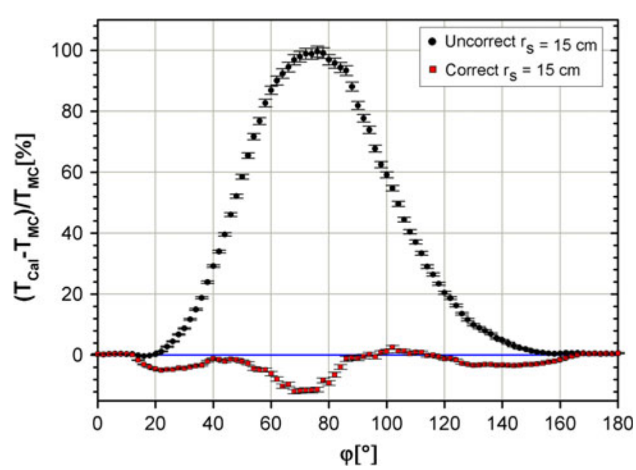

Fig. 4 Relative deviations between the simulated and the calculated count rates with and without edge penetration correction as a function of the angular position of a ^{137}Cs point source ($E_\gamma = 0.661$ MeV)

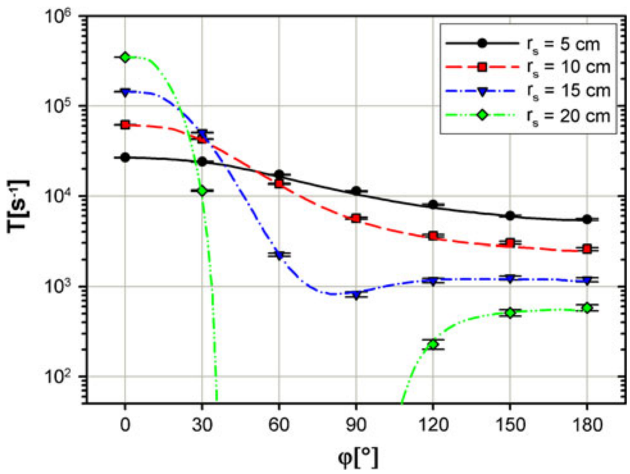

Fig. 5 Comparison of the simulated angular dependent count rate distributions (*symbols*) as obtained by segmented gamma scanning to the calculations according this model (*line*) for a ^{137}Cs point source ($E_\gamma = 0.661$ MeV) positioned at various radial positions in a concrete matrix of a density of 1.6 g/cm^3

1.6 g/cm^3. The drum consists of a 0.15 cm thick iron wall and has an inner radius of 28 cm. In segmented gamma scanning the drum is rotated in discrete steps. At each step a measurement of photon count rates is taken. Here, the drum is rotated in steps of 30°. The simulated and the calculated count rates are shown in Fig. 5 for a source placed at 5, 10, 15 and 20 cm radial position to the drum center. For all simulated source positions, the calculations due to the analytical model are in very good agreement with the simulated data.

Conclusion

It has been shown, that the here used method to analytically calculate the response of HPGe detector in the geometric setup of gamma scanning systems for the characterization of nuclear waste drums is in perfect agreement with simulated data. Thus, this analytical function can be implemented in algorithm for the accurate and reliable reconstruction of the isotope specific activity content in nuclear waste drums.

Acknowledgments This work was supported by the National Natural Science Foundation of China (contract number: 10675084).

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