Available online at www.sciencedirect.com
ScienceDirect

NUCLEAR SCIENCE AND TECHNIQUES

Nuclear Science and Techniques 19 (2008) 358–364

Method for converting *in-situ* gamma ray spectra of a portable Ge detector to an incident photon flux energy distribution based on Monte Carlo simulation

Boubaker ASKRI[1, *] Adel TRABELSI[1, 2] Brahim BACCARI[1]

[1]*Unité de Physique Nucléaire et des Hautes Énergies, Faculté des Sciences de Tunis, 2092 Tunis, Tunisia*

[2] *Centre National de Sciences et de Technologies Nucléaires, Sidi Thabet, Tunisia*

Abstract A matrix stripping method for the conversion of *in-situ* gamma ray spectrum, obtained with portable Ge detector, to photon flux energy distribution is proposed. The detector response is fully described by its stripping matrix and full absorption efficiency curve. A charge collection efficiency function is introduced in the simulation to take into account the existence of a transition zone of increasing charge collection after the inactive Ge layer. Good agreement is obtained between simulated and experimental full absorption efficiencies. The characteristic stripping matrix is determined by Monte Carlo simulation for different incident photon energies using the Geant4 toolkit system. The photon flux energy distribution is deduced by stripping the measured spectrum of the partial absorption and cosmic ray events and then applying the full absorption efficiency curve. The stripping method is applied to a measured *in-situ* spectrum. The value of the absorbed dose rate in air deduced from the corresponding flux energy distribution agrees well with the value measured directly *in-situ*.

Key words Monte Carlo simulation, Ge detector, Gamma radiation, Geant4, Stripping

CLC numbers TL817, TL814, O242.2

1 Introduction

In-situ gamma spectrometry is a powerful tool to study indoor and outdoor gamma dose rates [1-3]. An important tool in environmental applications is the portable germanium detector used for *in-situ* measurements to collect information from an enormous sample. But generally, the source geometries are of inhomogeneities and complex configurations. Experimental approaches and theoretical calculations are employed to obtain adequate calibration efficiency curves which permit expression of the measurement results in the quantity of interest [3,4].

Methods based on Monte Carlo simulation have been widely used in radiation field calculation [5-7] and for full-energy peak efficiency calibration of germanium detector in particular [8-10]. For these methods, the main component of uncertainty in the detector response is incomplete knowledge of the dimensions of the detector parts. In particular, the calculated efficiency is very sensitive to thickness of the germanium dead layer [11, 12]. When the thickness provided by detector manufacturers is used in a simulation, strong discrepancies arise between calculated and measured efficiencies. The thickness of this inactive layer is not well known due to the existence of a transition zone where photons are increasingly absorbed. In previous works, sensitivity analysis on effective thickness of the inactive Ge layer was performed by varying this thickness in the detector model to obtain the highest accordance between experimental and simulated efficiencies [13]. A model has been proposed by Clouvas *et al.* [11] for

* Corresponding author. *E-mail address:* nliu720@scu.edu.cn
Received date: 2008-09-17

the charge collection efficiency function in the crystal, taking into account the transition zone. This function has been used in the Monte Carlo simulation of Ge detectors. A better agreement between experimental and simulated values of the efficiency was achieved.

For outdoor measurement, analysis of the full absorption peaks provides a measure of the uncollided flux from radionuclides distributed in the soil. The measured flux can be converted to gamma dose rate in the air above if we assume the source geometry to be an infinite half-space of uniform profile with depth for natural emitters and an exponentially decreasing profile with depth for fallout emitters. For unknown complex source geometry, it is important to have an independent method to determine the absorbed dose rate that does not require any assumptions of the source geometry. An important approach consists of a stripping operation to a Ge detector spectrum collected in free air in order to obtain the incident gamma flux energy distribution [14], which can be converted easily to gamma absorbed dose rate.

In the present work, a Monte Carlo simulation of a portable Ge(Li) detector response is performed. Based on the model developed by Clouvas *et al.* [11], a charge collection efficiency function in the Ge crystal is used in the simulation code to get accurate calibration efficiency curve. A new matrix stripping method is developed, based on the Miller approach [14], to transform *in-situ* collected spectra to normalized gamma flux energy distribution, which is then converted to gamma absorbed dose rate.

2 Matrix stripping procedure

A count registered by the detector can be triggered by the full or partial absorption of an incident photon or by the passage of a cosmic ray produced charged particle. In order to obtain a measure of the incident photon flux spectrum, the partial absorption and cosmic-ray events must be subtracted out and then the full absorption efficiency curve of the detector can be applied. The stripping operation can be expressed as [14]

$$N'_i = N_i - \sum_{j=i+1}^{l} f_{ij}(r_j - 1)N'_j - N_c \qquad (1)$$

where N'_i is the number of counts in the energy band i due to the total absorption of incident γ flux, N_i is the observed counts in the energy band i due to all sources, l is the energy band containing the highest energy γ line (generally 2.614 MeV), f_{ij} is the fraction of the continuum counts at energy band i due to the partial absorption of incident γ flux at energy band j, r_j is the ratio of total counts to full absorption peak counts for incident flux at energy band j, and N_c is the counts due to cosmic ray events, assumed to be constant in any energy band. For simplicity, we suppose $N_c = 0$, which does not affect the results as N_c is constant. Let $\Delta N = N'_i - N_i$, then Eq.(1) can be rewritten as

$$\Delta N_i = -\sum_{j=i+1}^{l} f_{ij}(r_j - 1)\Delta N_j - \sum_{j=i+1}^{l} f_{ij}(r_j - 1)N_j \quad 0 \le i \le l \qquad (2)$$

yielding a system of l equations

$$\begin{cases} \Delta N_1 = -\sum_{j=2}^{l} f_{ij}(r_j - 1)\Delta N_j - \sum_{j=2}^{l} f_{ij}(r_j - 1)N_j & (eq\,1) \\ \Delta N_2 = -\sum_{j=3}^{l} f_{ij}(r_j - 1)\Delta N_j - \sum_{j=3}^{l} f_{ij}(r_j - 1)N_j & (eq\,2) \\ \vdots & \\ \Delta N_i = -\sum_{j=i+1}^{l} f_{ij}(r_j - 1)\Delta N_j - \sum_{j=i+1}^{l} f_{ij}(r_j - 1)N_j & (eq\,i) \\ \vdots & \\ \Delta N_l = 0 & (eq\,l) \end{cases} \qquad (3)$$

which can be written in matrix form

$$\boldsymbol{\Delta N} + \boldsymbol{M} \cdot \boldsymbol{\Delta N} = -\boldsymbol{MN} \qquad (4)$$

where $\boldsymbol{\Delta N} = \begin{pmatrix} \Delta N_1 \\ \Delta N_2 \\ \vdots \\ \Delta N_i \\ \vdots \\ \Delta N_l \end{pmatrix}$, $\boldsymbol{N} = \begin{pmatrix} N_1 \\ N_2 \\ \vdots \\ N_i \\ \vdots \\ N_l \end{pmatrix}$

and $\boldsymbol{M}$ is the matrix having elements as

$$M_{ij} = f_{ij}(r_j - 1) \qquad (5)$$

In consequence, Eqs. (3) can be reduced to

$$\boldsymbol{L} \cdot \boldsymbol{\Delta N} = -\boldsymbol{MN} \qquad (6)$$

L is the matrix given by

$$\boldsymbol{L}=\boldsymbol{M}+\boldsymbol{I} \tag{7}$$

where ***I*** is the identity matrix.

Matrices ***M*** and ***L*** have the following forms:

$$\boldsymbol{M}=\begin{pmatrix} 0 & f_{12}(r_2-1) & f_{13}(r_3-1) & \dots & f_{1i}(r_i-1) & \dots & f_{1l}(r_l-1) \\ 0 & 0 & f_{23}(r_3-1) & \dots & f_{2i}(r_i-1) & \dots & f_{2l}(r_l-1) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & f_{ii+1}(r_i-1) & f_{il}(r_l-1) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 0 & \dots & 0 \end{pmatrix}$$

and

$$\boldsymbol{L}=\begin{pmatrix} 1 & M_{12} & M_{13} & \dots & M_{1i} & \dots & M_{1l} \\ 0 & 1 & M_{23} & \dots & M_{2i} & \dots & M_{2l} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & M_{ii+1} & M_{il} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 0 & \dots & 1 \end{pmatrix}$$

The matrix ***L*** is an upper triangular matrix. It is an invertible matrix.

The solution of the matrix Eq.(6) is given by

$$\boldsymbol{\Delta N}=-\boldsymbol{L}^{-1}\cdot\boldsymbol{M}\cdot\boldsymbol{N} \tag{8}$$

Remember that N is a known vector. The vector N' is simply deduced

$$N'=\Delta N+N \tag{9}$$

Matrix ***L*** is characteristic of the detector as it defines its response. By determining ***L*** it is possible to transform any measured spectra to an incident gamma flux energy distribution as described below.

3 Detector simulation

A Canberra p-type coaxial Ge(Li) detector of Φ58 mm×56 mm was used, with a relative photo-peak efficiency of 30% at 1332 keV. Its layout as supplied by the manufacturer is shown in Fig. 1. The detector has a dead layer of 0.84 mm. For computer simulation we use the Geant4 toolkit system, an M-C code based on Object Oriented technology. It provides the transparency of the physics implementation. Particle energy of 1 keV is set as the ultimate cut-off for the simulation [15]. Geant4 geometry package allows a set of geometric shapes along with some boolean operations, such as intersection and union, to build more complex geometries. It was used to reproduce in great detail the detector structure. Volumes and materials are carefully added in order to deduce the influence of each element on the produced results.

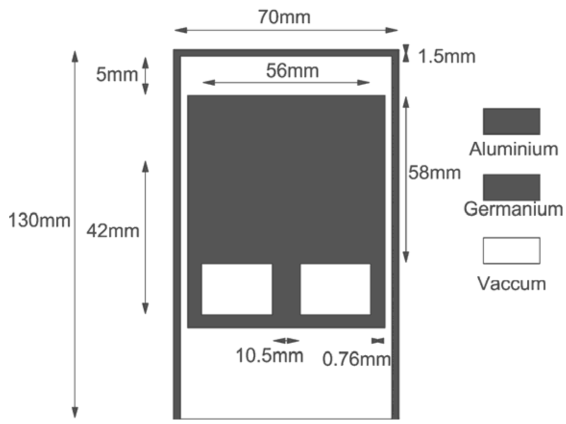

Fig. 1 Detector geometry. The structure is cylindrically symmetric.

The semiempirical method based on full absorption peak analysis [4] states the efficiency calibration as the product of separate factors, which can be independently determined on experimental or theoretical basis. The main objective of this work is to transform a collected spectrum to gamma flux energy distribution. The efficiency of the detector is then given by

$$\frac{N_f}{\Phi}=\frac{N_0}{\Phi}\left(\frac{N_f}{N_0}\right) \tag{10}$$

where N_f/Φ is the efficiency calibration expressed as the full-absorption peak count rate in the spectrum at the incident γ-ray energy normalized to the incident gamma flux originated from the source, N_0/Φ is the fluence response of the detector and corresponds to the peak count rate per unit uncollided flux for a parallel beam of γ-rays of the same energy that is incident-normal to detector front face, and N_f/N_0 is the angular correction factor of the detector at that energy.

3.1 Term N_0/Φ

The detector efficiency was determined with a ^{137}Cs point source placed at 1.5 m from the detector. This distance is sufficient when considering the incident flux to the detector as a direct and parallel flux. A shield was interposed to geometrically shadow the detector from the source. A spectrum was taken and subtracted from the original. In this manner, scattered radiation as well as any background radiation is cancelled out. The resultant spectrum represents the direct parallel flux, which is simply given by

$$\Phi = \frac{S\mathrm{e}^{-\mu r}}{4\pi r^2} \tag{11}$$

where Φ is the primary flux incident on the detector; S is source strength; r =150 cm; and μ is the air attenuation coefficient for the γ-ray.

The observed full absorption peak count rate divided by the flux gives the experimental efficiency of detector for the specific energy.

The experimental value (4.00±0.01 $\mathrm{g^{-1}\cdot cm^{-2}\cdot s^{-1}}$) disagreed the simulated value (4.40±0.09 $\mathrm{g^{-1}\cdot cm^{-2}\cdot s^{-1}}$) of the efficiency when we used the manufacturer's value of the Ge dead layer thickness of 0.84 mm in the simulation. This is due to the fact that, in the simulation, the charge collection efficiency is considered equal to zero for γ-ray absorption in the zone of the inactive Ge layer and equal to 1 for γ-ray absorption in the active volume of the detector. However, the crystal entrance windows can be considered as two contiguous layers: a Ge dead layer from which no charge is expected to be collected, and an underlying transition zone of increasing charge collection.

A simple model was employed by Clouvas *et al.* to explain the origin of this transition zone [11]. It states that the diffusion of the lithium, which composes the outer contact, in the Ge crystal is expected to be significant when the germanium is not cooled and thus lithium concentration is expected to depend on the particular history of the Ge detector. This phenomenon is described by the diffusion equation containing the diffusive translocation of free lithium in germanium, $C(x)$, where x is the distance from the surface of germanium [11]. In order to estimate the charge collection efficiency, a one-dimensional transition function $T(x)$ is introduced. The function $T(x)$ increases with the inverse of $C(x)$; this permits the deduction of its functional form [11]. $T(x)$ is a sigmoid function having its values in the interval [0, 1]. It begins to increase at the distance $x= d_0$, where d_0 is the dead layer thickness provided by the manufacturer. It saturates at the distance $x = d$, where d is the dead layer thickness including d_0 and the transition zone thickness. Moreover, it was shown by Clouvas *et al.* [11] that any function that increases slowly near d_0 and steep increase for x values near d can be used in the simulation procedure.

In this work we use the following charge collection efficiency function

$$\begin{cases} T(x) = 0 & \text{if} \quad 0 \le x \le d_0 \\ T(x) = 2^{\left(\frac{x-d_0}{\delta l}\right)^4} - 1 & \text{if} \quad d_0 \le x \le d_0 + \delta l \\ T(x) = 1 & \text{if} \quad x \ge d_0 + \delta l \end{cases} \tag{12}$$

where δl is the transition zone thickness which verifies $d = d_0+\delta l$.

In the simulation process, the parameter δl was modified in order to match the experimental and simulated efficiency values for the photon energy of 662 keV specific to the ^{137}Cs source emission. The best agreement between the experimental and simulated efficiency values was found for δl = 1 mm (Fig. 2).

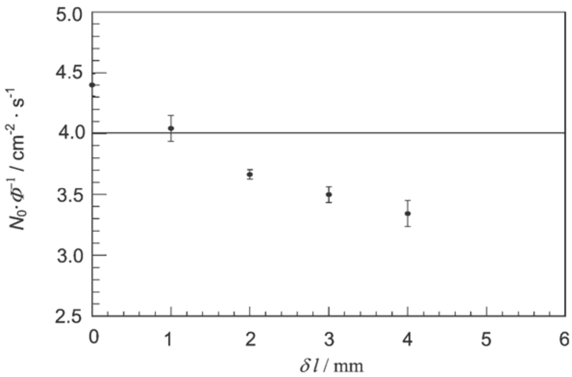

Fig. 2 Adjustment of the transition zone layer δl to match the experimental and simulated values of the efficiency for the ^{137}Cs source. The horizontal line represents the experimental value of the efficiency.

The charge collection efficiency function $T(x)$, corresponding to the parameter δl =1mm, was used in the simulation in order to determine the detector response. The $T(x)$ is shown in Fig.3. The simulated efficiency curve $N_0/\Phi = f(E)$ is shown in Fig. 4 with some experimental values of the efficiency. It can be seen that the experimental and simulated efficiencies agree within the statistical uncertainty of 5% in the simulation.

This study provides strong evidence that the main source of discrepancy between the experimental and simulated response of the detector arises from the uncertainty in the dead layer thickness. The introduction of the transition zone and the charge collection efficiency function in the simulation effectively reduces this discrepancy.

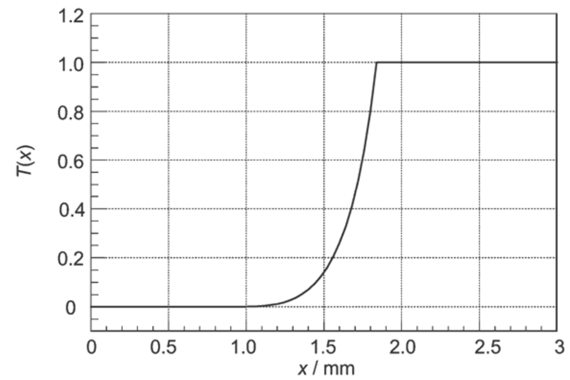

Fig. 3 Graph of the charge collection efficiency function $T(x)$ used in simulation.

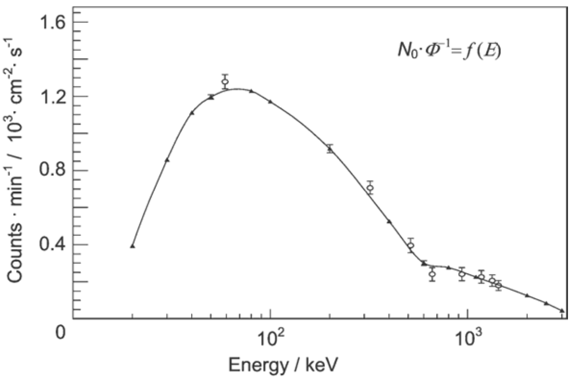

Fig. 4 Simulated efficiency curve of the detector. The circles represent the experimental efficiencies corresponding to the sources.

3.2 Term N_f / N_0

The angular correction factor is estimated experimentally by measuring the peak count rates for point sources of various energies positioned at different angles at a fixed distance to the detector. In general, a more uniform angular response is achieved with a Ge crystal of diameter close to the length dimension [4]. The angular response of our detector was simulated for 100 keV and 1000 keV photons. The source was placed at different angular positions at 1 m from the detector. It is clear from the results shown in Fig.5 that the angular response of our detector is not a critical factor. We can consider it as uniform over angles of at least 60° incidence. The uniformity of the angular response was checked with the ^{137}Cs source. The results are also shown in Fig. 5.

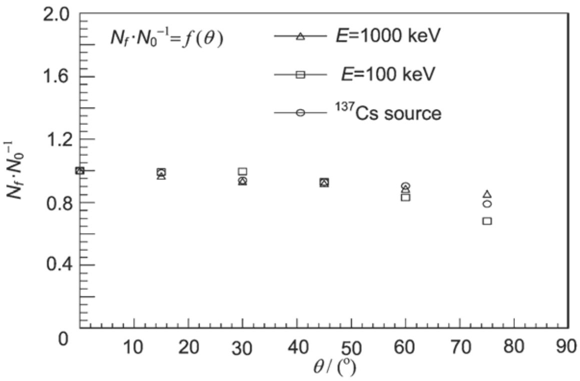

Fig. 5 Angular response of the detector.

4 Application of the matrix stripping method

The energy interval (0, 3000 keV) is divided into 600 equal size energy bands of 5 keV. The matrix L is a 600×600 matrix. The 5 keV subdivision yields a sufficient precision over the measured spectra.

The terms f_{ij} and r_i were determined by an M-C simulation where a point source was placed at 25 cm from the detector on its axis. Each emission corresponded to the mean energy of a 5 keV interval from the previous subdivision. To reduce the calculation time necessary to determine the elements of the matrix $\boldsymbol{L}$, only 21 primary photon energies scanning the whole energy interval were taken in the simulation. By analyzing the corresponding spectra, 21 columns of $\boldsymbol{L}$ were completely determined with 21 elements of each row of the matrix. The other elements of a row were determined by linear interpolation over the set of known elements of the same row. Using the ROOT analysis package [16], the matrix $\boldsymbol{L}$ was inverted and stored in the memory for eventual treatment of a measured spectrum.

Fig.6 is the real spectra and the stripped spectra for a simulated monoenergitic source after applying the matrix method. It is clear that the used stripping method eliminates almost entirely the continuum due to partial absorption. Fig.7 shows the real and the stripped spectra for a ^{137}Cs source. The widening of the full absorption peak is due to the energy resolution of the detector. It is important to notice that the full absorption peak is conserved after the stripping operation whereas the partial absorption events are considerably reduced.

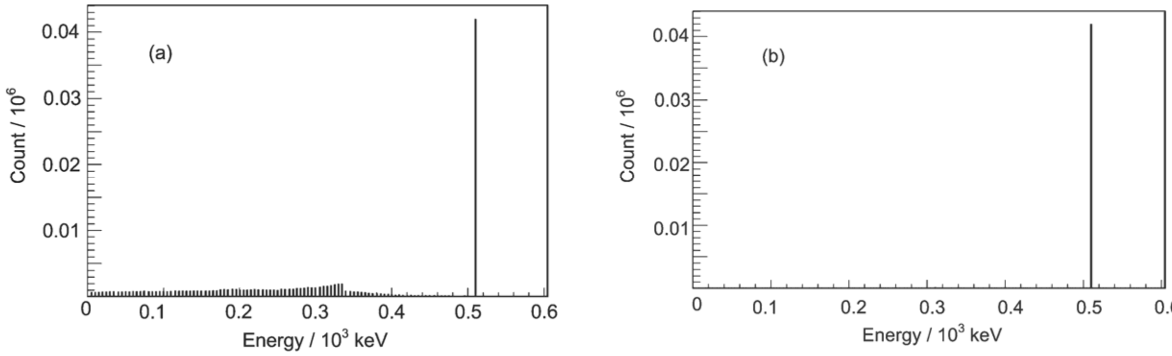

Fig. 6 Spectra of simulated monoenergitic source before(a) and after (b) applying the stripping matrix to the spectrum.

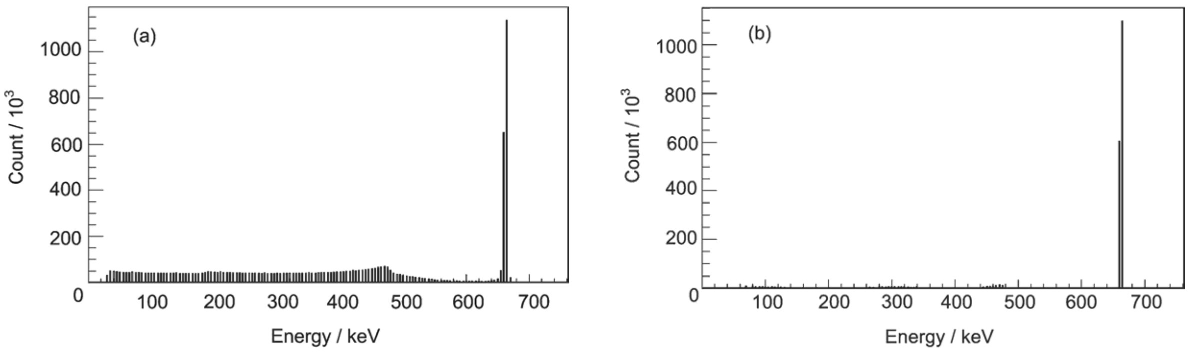

Fig. 7 Experimental spectra of the ^{137}Cs source before (a) and after (b) stripping.

A spectrum was taken in the soil of the National Center of Nuclear Sciences and Technologies in Sidi Thabet (CNSTN) in Tunisia. The portable Ge detector was used in this work. The duration of acquisition was fixed to 7200 s. At the same location, a measurement of the gamma absorbed dose rate was performed with the radiation meter FH 40 of the CNSTN mobile laboratory.

In order to convert the measured spectrum to the incident photon flux energy distribution, the spectrum must be stripped of cosmic ray and partial absorption events. Concerning the cosmic-ray events, we have assumed, as had Miller [14], that the cosmic radiation is flat in the region 0~3 MeV. Since there is no natural γ-rays in 3 ~ 4 MeV, this region was used to estimate the cosmic count rate, which was then extrapolated back to 0 MeV. For the partial absorption events, the matrix $\boldsymbol{L}$ is applied to the resultant spectrum after eliminating the cosmic ray counts. The results are shown in Fig. 8. After performing the stripping operation, the resultant spectrum was converted to an incident gamma flux by applying the full absorption efficiency of the detector (Fig.4). The angular response of our detector is not a critical factor, and it can be considered as uniform over angles up to 60° as shown previously. The gamma flux energy distribution is shown in Fig.9.

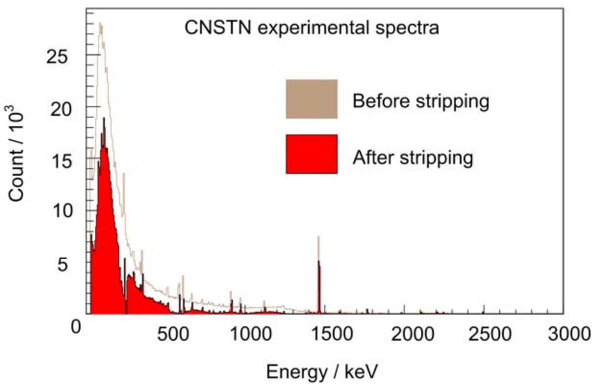

Fig. 8 Measured *in-situ* spectrum, before and after applying the stripping procedure.

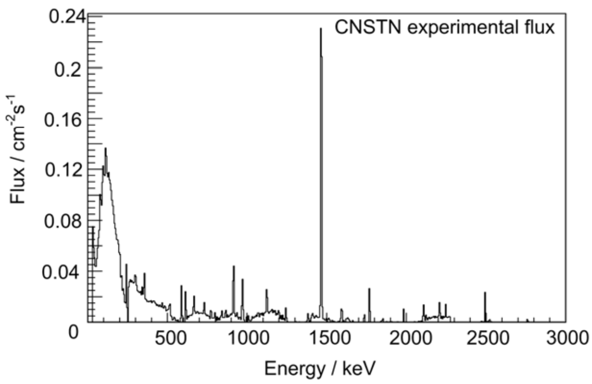

Fig. 9 *In-situ* gamma flux energy distribution.

Having calculated the flux energy distribution $\Phi(E)$, the absorbed dose rate D in air due to gamma radiation can be easily calculated by

$$\dot{D} = \sum_{E=0}^{E=E_{\max}} E\Phi(E)\left(\frac{\mu}{\rho}\right) \tag{13}$$

where $E_{\max}$ =2.614 MeV is the highest energy γ-ray and μ/ρ is mass absorption coefficient for air at E.

The resulting dose rate was D=47.2 nGy/h, which agrees with the *in-situ* measurement performed with the radiameter FH 40 (42.9 nGy/h with an uncertainty of 10%). This agreement led us to believe that the matrix stripping method proposed in this work is accurate.

5 Conclusion

A matrix stripping method for converting *in-situ* γ-ray spectrum, obtained with a portable Ge detector, to photon flux energy distribution was proposed. The detector response is fully described by its stripping matrix and a full absorption efficiency curve. The stripping matrix elements were determined by Monte Carlo simulations for different incident photon energies.

A function of charge collection efficiency was introduced in the simulation based on the methodology described by Clouvas *et al*. [11] to calculate the full absorption peak efficiency curve. Sufficient agreement was achieved between simulated and experimental efficiencies. The procedure is faster than the classical approach based on the variation of dead layer thickness to match simulated and experimental efficiencies.

The measured spectrum was stripped of the partial absorption by applying the stripping matrix. When dealing with the cosmic-ray events induced in the detector, we followed the procedure given in Ref.[14]. Having calculated the flux energy distribution, the absorbed dose rate in air was easily deduced. Good agreement was achieved between the dose rate deduced from the stripping procedure applied to an *in-situ* spectrum collected in the soil of the National Center of Nuclear Sciences and Technologies in Sidi Thabet-Tunisia (CNSTN) and the measured dose rate by the FH 40 radiation meter of the mobile laboratory of the CNSTN. This successfully validated the proposed technique.

The matrix stripping method described in this work is useful for determining dose rates when dealing with unknown source geometry, and helps to interpret the radiation field by providing a high resolution flux energy distribution.

References

1 Helfer L, Miller K. Health Phys, 1988, **55**: 15-29.

2 Cutshall N, Larsen J. Health Phys, 1986, **51**: 53-59.

3 Beck H L, De Campo J, Gogolak C V. *In-situ* Ge(Li) and NaI(Tl) gamma-ray Spectrometry. New York: US Department of Energy, 1972. HASL-258.

4 Miller K M, Shebell P. In situ gamma-ray spectrometry. A tutorial for environmental radiation scientists. New York: Department of Energy, 1993. Report EML-557.

5 Askri B, Manai K, Trabelsi A, *et al*. Radiat Prot Dosimetry, 2007, doi:10.1093/rpd/ncm426.

6 Clouvas A, Xanthos S, Antonopoulos-Domis M, *et al*. Health Phys, 2000, **78**(3): 295-302.

7 Saito K, Jacob P. Radiat. Protect. Dosim, 1995, **58**:29-45.

8 Rodenas J, Rius V. Application of Monte Carlo method to the simulation of Ge-detector calibration, in Proceedings of the Topsafe'98, Valencia, Spain. 1998.15-17.

9 Hurtado S, Garcia-León M, García-Tenorio R. Nucl. Instrum. Methods A, 2003, **518**: 764-774.

10 Korun M, Likar A, Vidmar T. Nucl Instrum Methods A, 1997, **390**: 203-208.

11 Clouvas A, Xantos S, Antonopoulos-Domis M. Health Phys, 1998, **74**(2): 216-230.

12 Ródenas J, Ortiz J, Ballesteros L, *et al*. Analysis of the simulation of Ge-detector calibration for environmental radioactive samples in a Marinelli beaker source using the Monte Carlo method, in Proceedings of the International Conference on Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications-MC2000, Lisbon: Springer, 2001, 517-522.

13 Ródenas J, Pascual A, Zarza I, *et al*. Nucl Instrum Methods A, 2003, **496**: 390-399.

14 Miller K M, Beck H L. Radiat Protect Dosim, 1984, **7**: 185-189.

15 Agostinelli S, Allison J, Amako K, *et al*. Nucl Instrum Methods A, 2003, **506**: 250-303.

16 ROOT. An object-oriented data analysis framework, http:www.root.cern.

Available online at www.sciencedirect.com

ScienceDirect

Nuclear Science and Techniques 19 (2008) 358–364

NUCLEAR
SCIENCE
AND
TECHNIQUES

* Corresponding author. *E-mail address:* nliu720@scu.edu.cn

Received date: 2008-09-17