MONTE CARLO BASED METHOD FOR CONVERSION OF *IN-SITU* GAMMA RAY SPECTRA OBTAINED WITH A PORTABLE Ge DETECTOR TO AN INCIDENT PHOTON FLUX ENERGY DISTRIBUTION

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***Abstract*—A Monte Carlo based method for the conversion of an *in-situ* γ-ray spectrum obtained with a portable Ge detector to photon flux energy distribution is proposed. The spectrum is first stripped of the partial absorption and cosmic-ray events leaving only the events corresponding to the full absorption of a gamma ray. Applying to the resulting spectrum the full absorption efficiency curve of the detector determined by calibrated point sources and Monte Carlo simulations, the photon flux energy distribution is deduced. The events corresponding to partial absorption in the detector are determined by Monte Carlo simulations for different incident photon energies and angles using the CERN's GEANT library. Using the detector's characteristics given by the manufacturer as input it is impossible to reproduce experimental spectra obtained with point sources. A transition zone of increasing charge collection efficiency has to be introduced in the simulation geometry, after the inactive Ge layer, in order to obtain good agreement between the simulated and experimental spectra. The functional form of the charge collection efficiency is deduced from a diffusion model.**
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Key words: Monte Carlo; gamma radiation; photons; exposure, population

INTRODUCTION

Knowledge of radiation levels in buildings is important for the assessment of population exposure. This is because most individuals spend the majority of their time indoors exposed to radiation from the radionuclides (mainly ^{226}Ra, ^{232}Th, their decay products, and ^{40}K) in walls, floors and ceilings. The rest of their time is spent outdoors on roads or near buildings, which exposes them to radiation from materials used for construction.

In-situ gamma spectrometry is a powerful tool to study indoor and outdoor dose rates. A high resolution spectrum allowing analysis of individual photo peaks provides valuable information on the relative contribution of the various nuclides to the total dose rates. *In-situ* techniques for measuring the dose rate, resulting from the gamma radiation and characterizing its sources, with a gamma ray spectrometer have been used successfully in the outdoor environment (Helfer and Miller 1988; Cutshall and Larsen 1986; Gogolak 1982; Beck et al. 1972). The gamma spectrometer, via the analysis of the full absorption peaks, provides a measure of the uncollided flux from the various radionuclides in the soil. Since the open field source geometry can be fairly well modeled by assuming an infinite half-space with a uniform profile with depth for natural emitters and an exponentially decreasing profile with depth for fallout emitters, the measured fluxes can be converted to concentrations or inventories in the soil and also to dose rates in the air above.

In principle, the same methods can be applied to indoor radiation measurements. However, the source distribution can be far more complex and is generally unknown. The sources of indoor exposure are mainly the natural radionuclides contained in building materials. In addition, building materials act also as attenuators of outdoor radiation. Thus, dose rates depend on radionuclide concentration, wall thickness, room shapes, existence of windows and doors, etc. The generally unknown complex source geometry encountered in the indoor environment makes the task of converting full absorption peak count rates in a spectrum to dose rate difficult. For this situation it is desirable to have an independent method of determining the gamma absorbed dose rate that does not require any assumptions of the source geometry. The spectral stripping method described herein provides such a means. Spectrum stripping is used to give a measure of the incident normalized gamma flux energy distribution, which can be converted easily to gamma absorbed dose rate. Conversion of a Ge gamma-ray spectrum to absorbed dose rate has been proposed by several investigators (Terrada et al. 1980; Miller and Beck 1984; Krnac and Ragan 1995; Fehrenbacher et al. 1996). In the present work the method proposed by

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Miller and Beck (1984) is applied with some modifications. The modified Miller method presented in this work is based mainly on Monte Carlo simulations and can be easily adapted to any available commercial portable Ge detector, almost without any particular experiment. The main objective of the present work is therefore the conversion of the measured spectrum by the detector to the incident flux spectrum. Knowledge of the photon flux energy spectrum in a specific indoor environment is of great importance not only for the measurement itself but also as a test of numerical solutions converting the radionuclide inventories in building materials to indoor dose rates.

DESCRIPTION OF THE METHOD

The stripping spectral method was applied to the portable p-type Ge detector of the Nuclear Technology Laboratory of the University of Thessaloniki. A count registered by the detector can be caused by the full or partial absorption of an incident photon or by the passage of a cosmic-ray-produced charged particle. In order to convert to a gamma-absorbed dose rate, the spectrum must be stripped of the partial absorption and cosmic-ray events leaving only the events corresponding to the full absorption of a gamma ray. The resulting spectrum, which represents both primary and scattered photons (from the room's walls, floor and ceiling), can then be converted to the total incident flux spectrum by applying the full absorption curve of the detector.

Concerning the cosmic-ray events induced in the detector we followed the methodology given by Miller and Beck (1984). The events corresponding to partial absorption in the detector make up a large fraction of the counts in the spectrum and are not as simple to strip out. For the most part, these events are the result of Compton scatter in the crystal itself or the surrounding cryostat. For single scatter events, a continuum of counts will form in the spectrum reaching a maximum energy at the Compton edge. Okano et al. (1980) have used a distribution of counts with energy, which is essentially a single step function between the low end of the spectrum and the maximum energy at the Compton edge. In a typical Ge detector spectrum, aside from the nonlinearity of the Compton scattering events in the crystal itself, below the maximum energy at the Compton edge there are a number of counts that lie above the maximum energy at the Compton edge, which are a result of multiple scatter events within the crystal. Based on this, a multi-step function fit to the continuum was introduced by Miller and Beck (1984) into the stripping routine, assuming the shape of the continuum is independent of the incident photon energy and angle, an assumption which is not *apriori* valid for all commercial detectors.

In the present work the events corresponding to partial absorption in the detector are determined by Monte Carlo simulations for different incident photon energies and angles. The GEANT code of CERN was used for this work. The GEANT program describes the passage of elementary particles through matter. The principal applications of the code are a) the tracking of particles through an experimental setup for simulation of detector response; and b) the graphical representation of the setup and of the particle trajectories. In view of these applications the GEANT system allows the user

- to describe an experimental setup in an efficient and simple way;
- to simulate the transport of particles through the various regions of the setup, taking into account the geometrical volume regions of the setup, taking into account the geometrical volume boundaries and all physical effects due to the nature of the particles themselves, and to their interactions with the matter;
- to record elements of the particle trajectories and the response; and
- to visualize the detectors and the particle trajectories.

Using the GEANT program, our task was to assemble the appropriate program segments and utilities into an executable program, to code the relevant subroutines to our specific problem, to provide the data describing the experimental environment, and to compose the appropriate data cards that control the execution of the program.

Knowing the computed shapes of partial absorption continua deduced by the Monte Carlo simulations for different photon energies and angles, it was therefore possible to convert the measured spectra to total incident flux spectra by application of the full absorption efficiency curve of the detector (which was determined by calibrated point sources and by Monte Carlo simulations).

DETECTOR SIMULATION

The studied detector is a p-type coaxial Ge cylinder 44 mm in diameter and 41 mm in length, with an efficiency for a point source at 25 cm of 10% at 1.33 MeV relative to a 7.6 × 7.6 cm NaI(Tl) crystal. It is mounted in a small liquid nitrogen cryostat that features an all-attitude capability. The spectrum is collected in a portable multichannel analyzer. The detector layout, as supplied by the manufacturer, is shown in Fig. 1b.

Other important characteristics are a dead layer of 500 microns and an active volume of 63 cm^3. Simulations were done on the basis of CERN's GEANT library, version 3.21 (GEANT 1993). The programs were executed on a standard PC Pentium 150 MHz computer, using LINUX system. In our calculations, we also used the MS-DOS version of MCNP4A program from the Los Alamos Laboratory (Briesmeister 1993).

The detector structure was reproduced in great detail (Fig. 1a) using GEANT3.21 volumes. Each volume and material was carefully added in order to get acquainted with the influence of each element on the produced spectra. As in any GEANT application, we programmed event generators in order to simulate the photon sources.

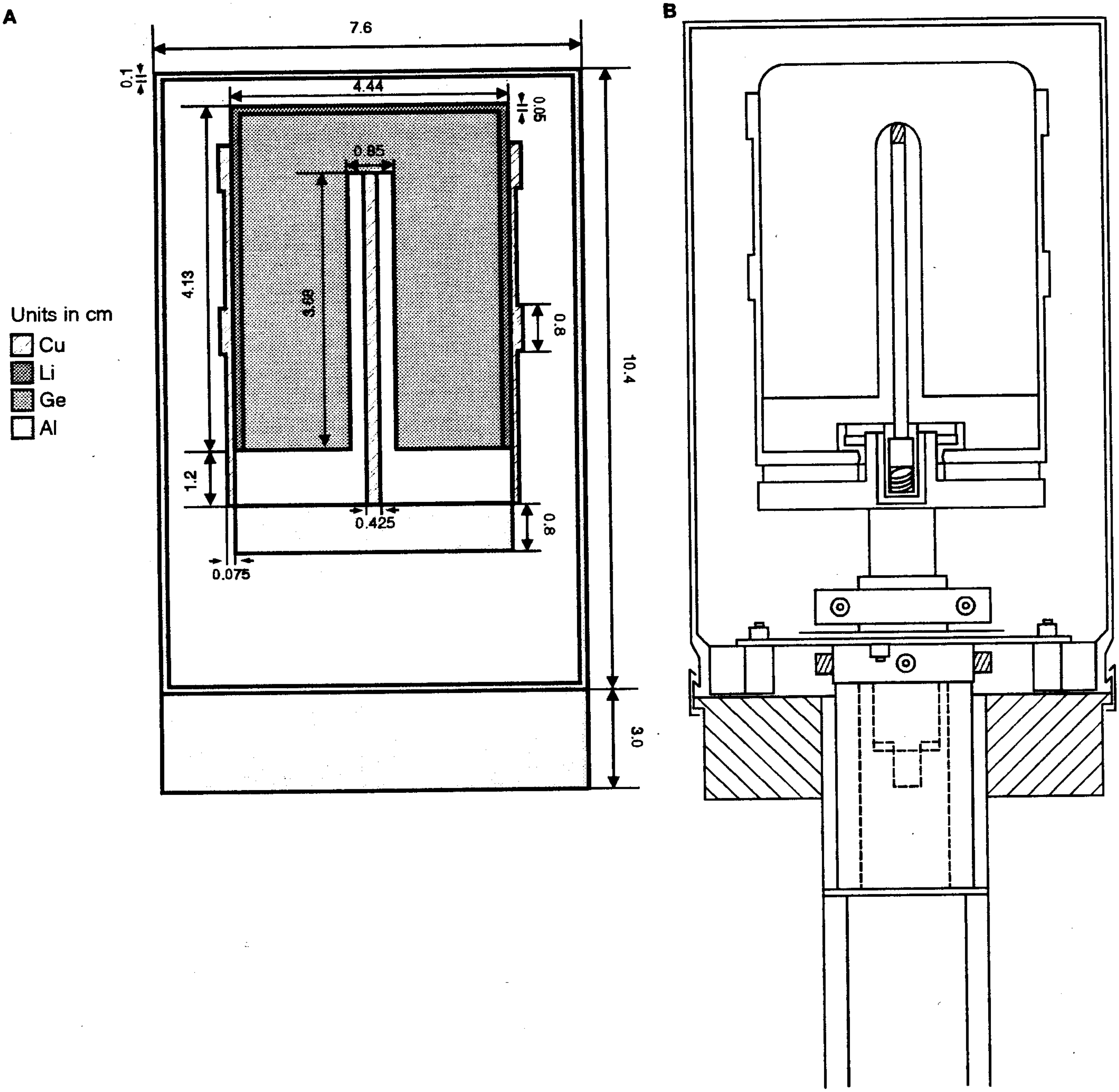


Fig. 1a. Model of the front part of the Ge detector as simulated by the GEANT code. The structure is cylindrically symmetric.
Fig. 1b. Manufacturer's diagram of the Ge detector.

Two kinds of photon sources were implemented: point sources and directional sources. Point sources were used to reproduce, as near as possible, experimental conditions for reference spectra and directional sources to study angle dependence and to generate necessary data needed for the stripping operation. Other sources are easily implemented in the program. The time needed to process one event varies between 1 and 2 ms. This permits the generation of 1 million photons for a typical spectrum and even 10 times more for a more precise one.

The principal geometrical characteristics can be changed without program rebuilding. This fact can be used to evaluate other similar detectors without any change in the program.

Using manufacture's data (dimensions of the detector, thickness of the dead layer) as input, we tried to reproduce by simulation the measured spectra obtained with ^{137}Cs, ^{60}Co, ^{133}Ba and ^{131}I point sources.

The ^{131}I point source, with an activity of 1.85 MBq, has been used for the experimental determination of the detector efficiency. The source was placed several meters from the detector and a spectrum was taken. A shield sufficient to stop essentially all primary gamma rays from the source was then interposed so as to geometrically shadow the detector from the source, and a spectrum was taken and subtracted from the original. In this manner, scattered radiation from the room's walls, floor and ceiling as well as any background radiation is canceled out leaving a spectrum that represents the direct parallel flux from the source. This flux is simply given by

$$\Phi = \frac{S \cdot e^{-\mu r}}{4\pi r^2}, \quad (1)$$

where

Φ = the primary flux incident on the detector (γ cm^{-2} s^{-1});

S = source strength (γ s^{-1});

r = the distance between source and detector (cm); and

μ = the air attenuation coefficient for the source gamma energy.

The observed full absorption peak count rate divided by the flux gives the experimental efficiency of the detector for the specific energy. In view of the important disagreement when using manufacturer's value of the Ge dead layer thickness of 0.5 mm, as shown below, between the experimental and simulated values of the efficiency, it was necessary to modify, in the simulation process, the thickness of the Ge dead layer in order to match the experimental and simulated efficiency values. Fig. 2 presents the experimental efficiency values for different photon energies and the simulated ones obtained by the GEANT code using different inactive Ge layers thickness.

The best agreement between the experimental and simulated efficiency values was found for an inactive Ge layer thickness of 2.5 mm instead of the manufacturer value of 0.5 mm. A similar modification of the Ge dead layer has been also reported previously by Sánchez et al. (1991) where a 1.5 mm dead layer thickness was introduced in the simulation process instead of the 0.8 mm given by the manufacturer.

A good simulated spectra must not only predict the experimental full absorption peak count rate (efficiency of the detector) but also the partial absorption of photons in the detector: in other words, the shape of the continuum. In Fig. 3 we present the experimental and simulated spectra for ^{137}Cs and ^{60}Co point sources placed directly in front of the detector. The contribution of the scattered radiation from the rooms walls, floor, and ceiling is not

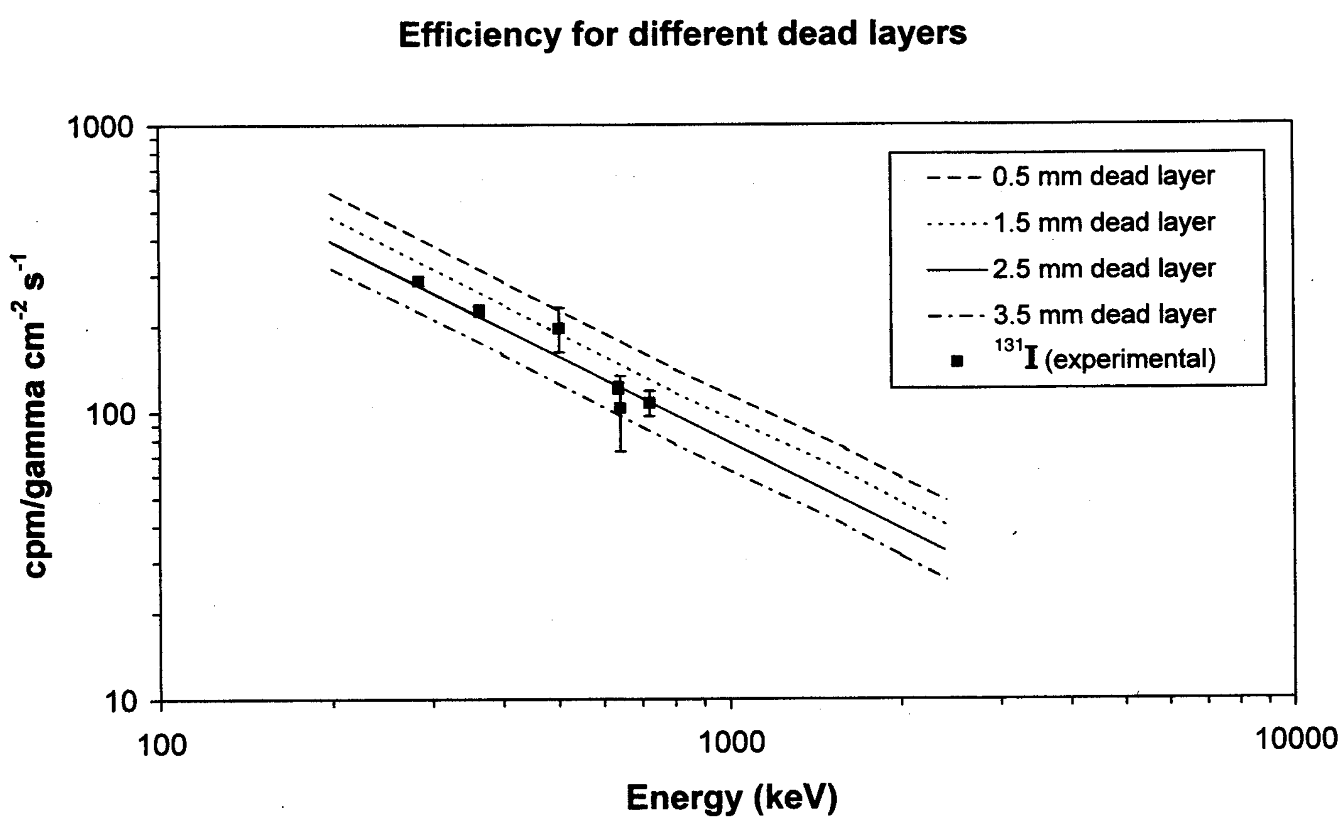


Fig. 2. Simulated detector efficiency for different dead layers.

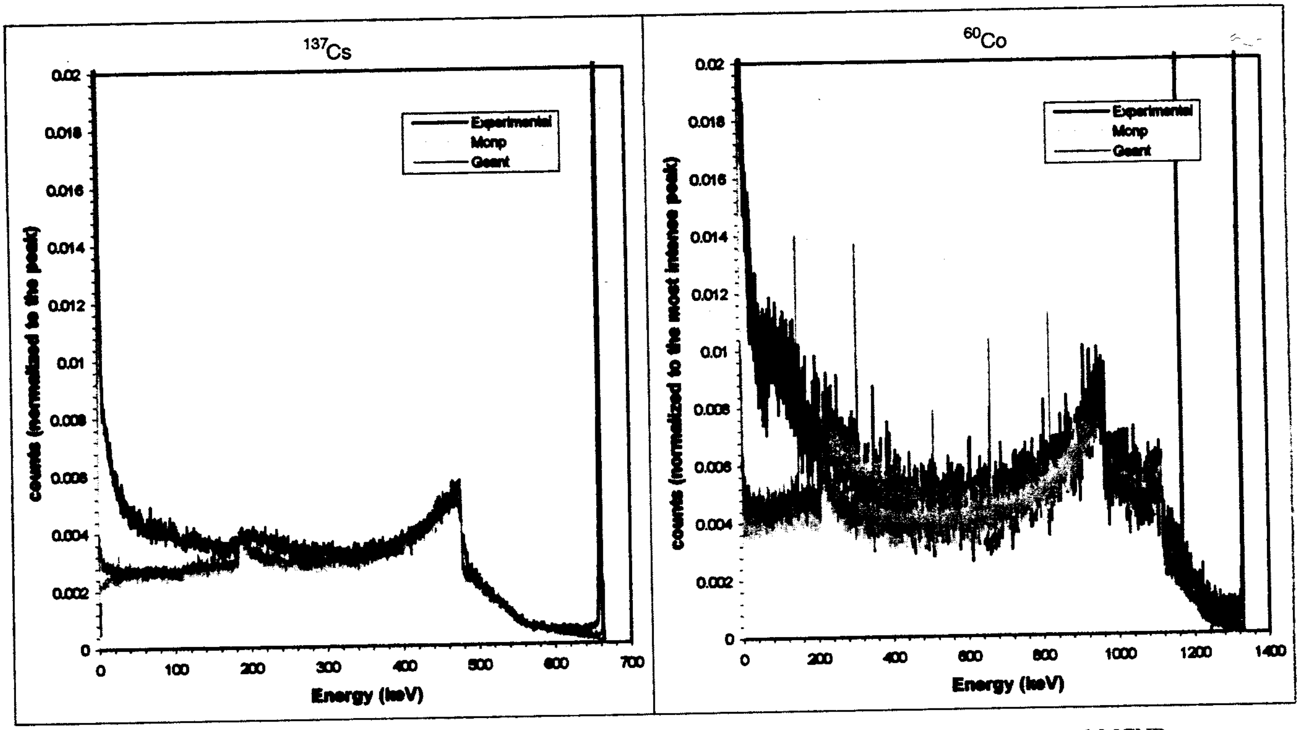


Fig. 3. Comparison between the experimental spectra and a straightforward simulation by GEANT and MCNP.

important when the distance between the source and the detector is small. The simulated spectra were obtained using GEANT and MCNP codes. The detector simulation geometry is as Fig. 1b with a dead layer of 2.5 mm. The difference in the unscattered radiation from the ^{137}Cs point source between the simulated and the experimental spectra was about 12% with an uncertainty in the experimental value of 20%. For this reason, and as we are interested particularly in the comparison between the simulated and the experimental shape of the continuum in Fig. 3, we normalized our spectra (experimental and simulated) to the unscattered peak. It should be noted that for presentation reasons, Fig. 3 (as well as the following) is expanded in the vertical scale. It is observed that the simulation spectra describe satisfactorily the experimental shape of the continuum down to energies 300 keV. A very good agreement between the simulated spectra obtained with GEANT and MCNP codes is observed. However, both of them are unable to describe the experimental shape of the continuum for energies below 300 keV.

In the simulation procedure we considered a charge collection efficiency equal to zero for γ-ray absorption in the zone of the inactive Ge layer and a charge collection efficiency equal to 1 for a γ-ray absorption in the active volume of the detector. However, the crystal entrance window 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 efficiency (Burns et al. 1990). In the simulation procedure we keep the inactive Ge layer thickness equal to 0.5 mm, as given by the manufacturer, and introduce a transition zone in the Ge crystal equal to 2 mm. The choice of 2 mm is based in the following arguments. A γ-ray photon absorbed in the transition zone will not contribute to the full energy peak count rate, and, thus concerning the efficiency of the detector, the transition zone behaves as the inactive Ge layer. In Fig. 2 we observed that the experimental and simulated efficiency values (without taking into account the transition zone) are in good agreement for an inactive Ge layer of 2.5 mm. Taking the inactive Ge layer equal to 0.5 mm, the transition zone must be 2 mm.

Based on the following arguments, a simple model was employed for the charge collection efficiency function. In the p-type coaxial Ge detectors, the traditional method of fabricating the outer contact is the evaporation of lithium into the surface to form an n^+ layer, which represents the dead layer on the surface of the crystal through which the incident radiation must pass. The transition zone is therefore due to the diffusion of lithium from the outer contact (dead layer) in the region of the Ge crystal near the dead layer. In order to estimate the charge collection efficiency function [transition function T(x)] a one-dimensional model is sufficient. Furthermore, we assume that the medium is homogenous; this assumption is well justified in the case of a high purity germanium detector. Let D(T) be the diffusion coefficient of lithium in germanium; D is an increasing function of temperature T; at higher temperatures diffusion is enhanced in comparison to low temperatures. In other words, diffusion 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.

The diffusive translocation of free lithium C is governed by the diffusion equation

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - \Sigma \cdot C, \quad (2)$$

where t is time, x is the distance from the surface of the Germanium, Σ is a macroscopic cross-section accounting for some mechanisms that would possibly trap lithium in the crystal structure of germanium and make it unavailable for further translocation.

The initial condition considered here is that at time $t = 0$ there is uniform concentration of lithium, only within the dead layer of width d and zero concentration of lithium everywhere else.

$$C(x, 0) = S_o \quad 0 \leq x \leq d \quad (3)$$

$$C(x, 0) = 0 \quad x > d. \quad (4)$$

The boundary conditions of the free lithium are as follows:

$$C(\infty, t) = 0 \quad (5)$$

$$\frac{\partial C(0, t)}{\partial x} = 0. \quad (6)$$

With these initial and boundary conditions, the solution of eqn (1) reads

$$C(x, t) = \frac{S_o}{2}\left[erf\left(\frac{d - x}{2\sqrt{D \cdot t}}\right) + erf\left(\frac{d + x}{2\sqrt{D \cdot t}}\right)\right] \cdot e^{-\Sigma \cdot t}, \quad (7)$$

where $erf(x)$ is the error function of x. At this point we may note that neglecting the term $\Sigma \cdot C$ in eqn (2), i.e., setting $\Sigma = 0$ will leave the structure of $C(x, t)$, i.e., its dependence on x, unaltered. The presence of the term $\Sigma \cdot C$ is important for the equilibrium ($\partial C/\partial t = 0$) distribution of C, as can be readily seen from eqn (2), if there is such equilibrium.

For the following qualitative treatment, ignoring the lithium bound in germanium, we assume that the charge collection efficiency function $T(x)$ increases with the inverse of $C(x)$, i.e., it has the following functional form:

$$T(x) = 0 \quad 0 \leq x \leq 0.5 \quad (8)$$

$$T(x) = \alpha + \frac{\beta}{\gamma + f(x)} \quad x > 0.5 \quad (9)$$

$$f(x) = erf\left(\frac{d - x}{L}\right) + erf\left(\frac{d + x}{L}\right), \quad (10)$$

where L is a characteristic length (note that $\sqrt{D \cdot t}$ has dimensions of length) which in general, is a function of time. Function $T(x)$ is a sigmoid. Note that L determines the rate with which the sigmoid rises from 0 to 1 and parameter γ controls the distance from the origin $x = 0$ at which the sigmoid starts significant rising. Parameter γ is empirically determined. Following that, parameters α and β are determined by the boundary requirements

$$T(x = 0.5) = 0, \; T(\infty) = 1. \quad (11)$$

It is clear that in practice infinity is at $x \leq 3L$. The characteristic length is also empirically determined with the requirement that $T(x)$ reaches asymptotically the value of 1 at $x \approx 2.5$, i.e., at the end of the transition zone.

From the comparison between the experimental spectrum obtained with ^{137}Cs point source and simulated spectrum (Fig. 4a) using the transition with different values of γ and L the best agreement has been found for $\gamma = 0.0005$ and $L = 0.5$. At this point it should be noted that the transition function [eqns (8)–(10)] is not the only one which can reproduce the experimental spectra.

From the comparison between the experimental spectrum obtained with the ^{137}Cs point source and the simulated spectrum using different transition functions it has been found that the wanted transition must increase slowly near the dead layer and steeply increase for x values near d. Any function satisfying the above criterion can be used in the simulation procedure.

As an example, Fig. 4b presents the experimental spectrum obtained with ^{137}Cs point source and the simulated spectrum using the following transition function:

$$T(x) = 0 \quad 0 \leq x \leq 0.5 \quad (12)$$

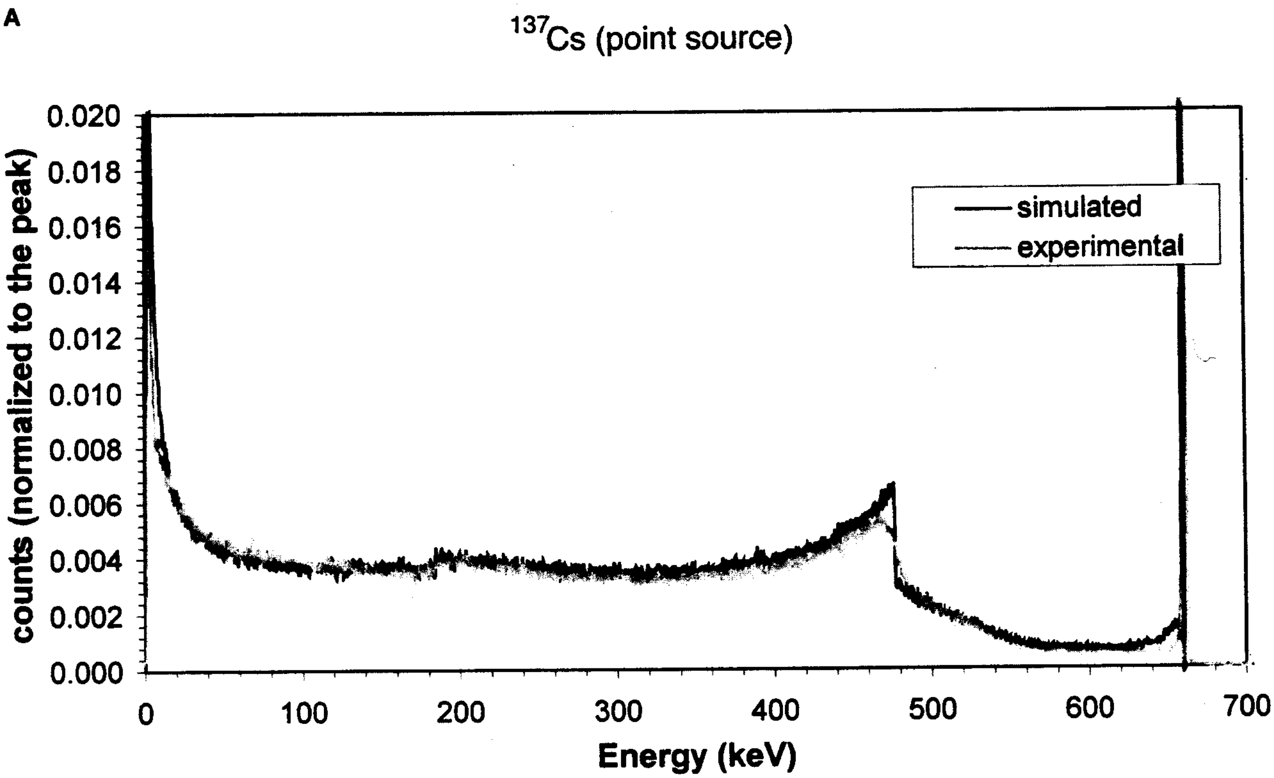
$$T(x) = 2^{\left(\frac{x-0.5}{2}\right)^4} - 1 \quad 0.5 < x \leq 2.5 \quad (13)$$

$$T(x) = 1 \quad x > 2.5 \quad (14)$$

It can be seen that there is very good agreement between the experimental and simulated spectrum. However, the transition function of eqns (12)–(14) is not based on a physical assumption as is the transition function of eqns (8)–(10).

The introduction of the transition zone explains the disagreement observed previously between the experimental and simulated shape of the continuum for energies below 300 keV and avoids the use of "peculiar" inactive Ge layers (much thicker than given by the manufacturer), which are needed in order to reproduce satisfactorily the experimental efficiency curves in the case when no transition zone is used.

In order to check that the simulation procedure used is also valid for other incident photon energies we performed simulated spectra for ^{60}Co and ^{133}Ba point sources placed in front of the detector. The comparison between the simulated and the experimental spectra (Fig. 5) indicates that the simulation procedure used in the present work describes well the experimental spectra in the case of point sources placed in front of the detector. However, in an *in-situ* outdoor or indoor γ-spectrometry measurement the incident radiation is not just a parallel flux normal to the detector face but has all angles of incidence. It is therefore important to examine the re-



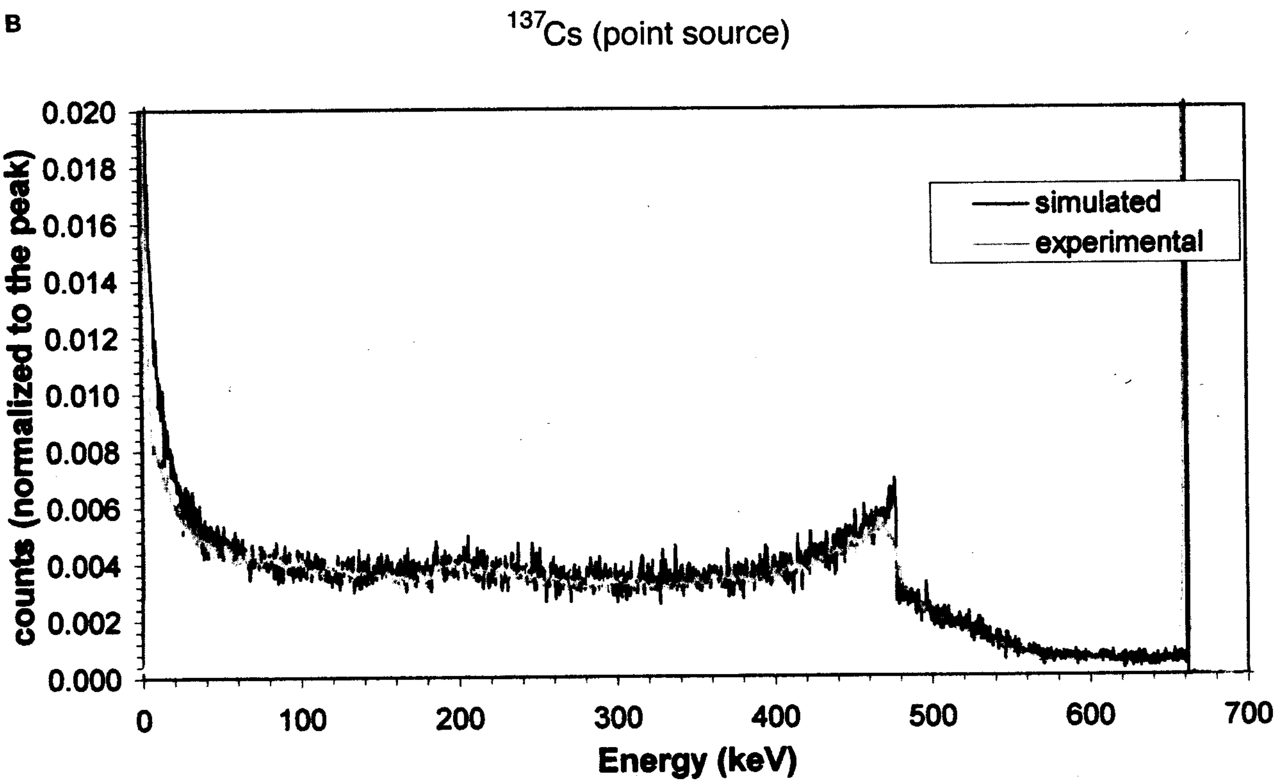


Fig. 4a. Simulated spectrum using the transition function of eqns (8)–(10), compared to the experimental one.
Fig. 4b. Simulated spectrum using the transition function of eqns (12)–(14), compared to the experimental one.

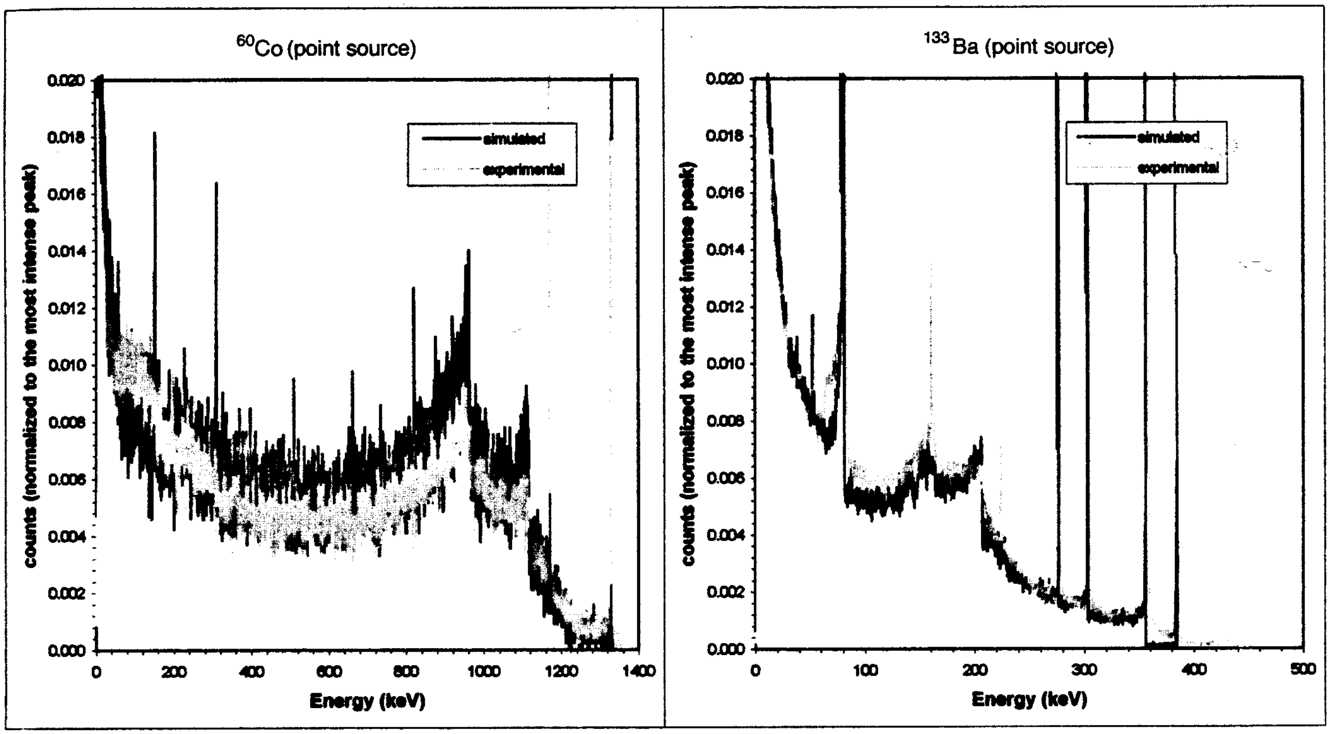


Fig. 5. Simulated spectrum compared to the experimental one.

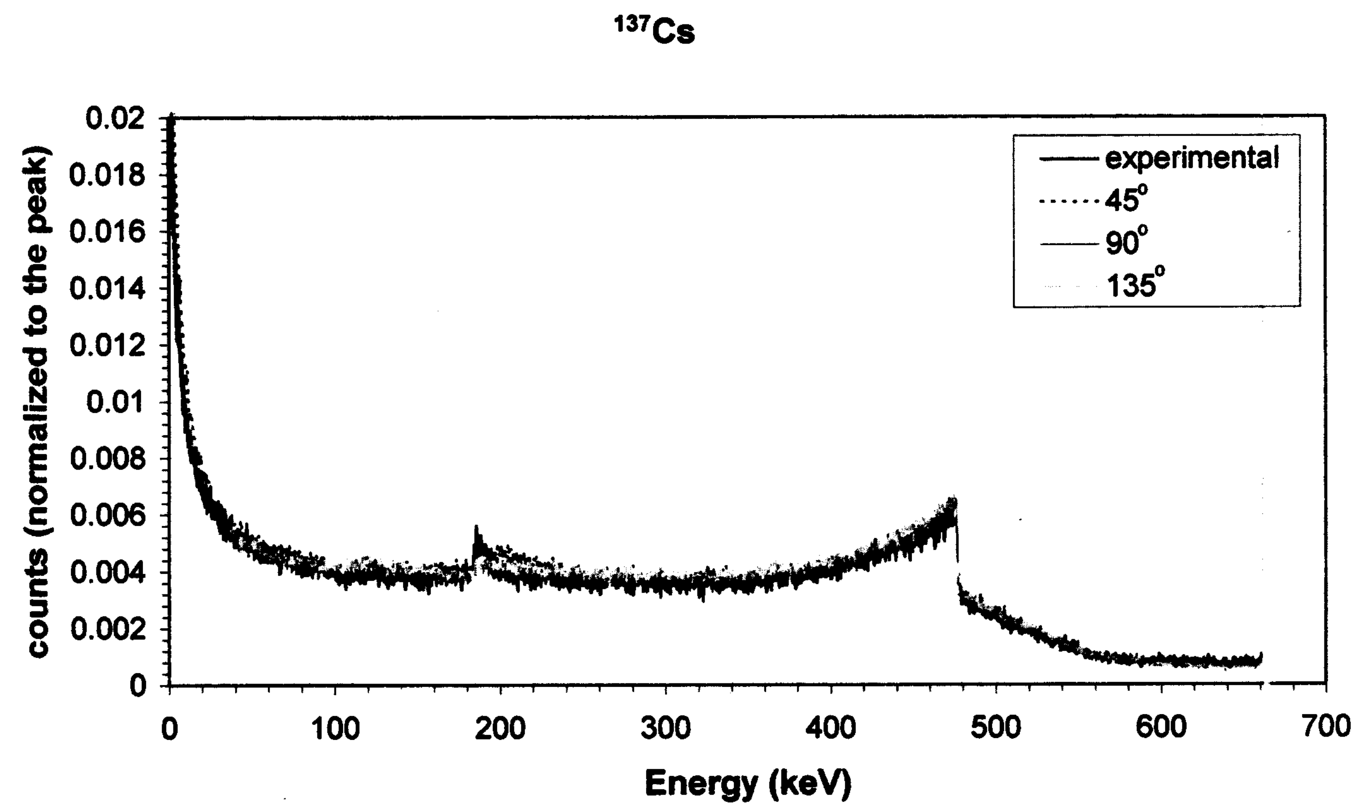


Fig. 6. Angular dependence of spectrum shape.

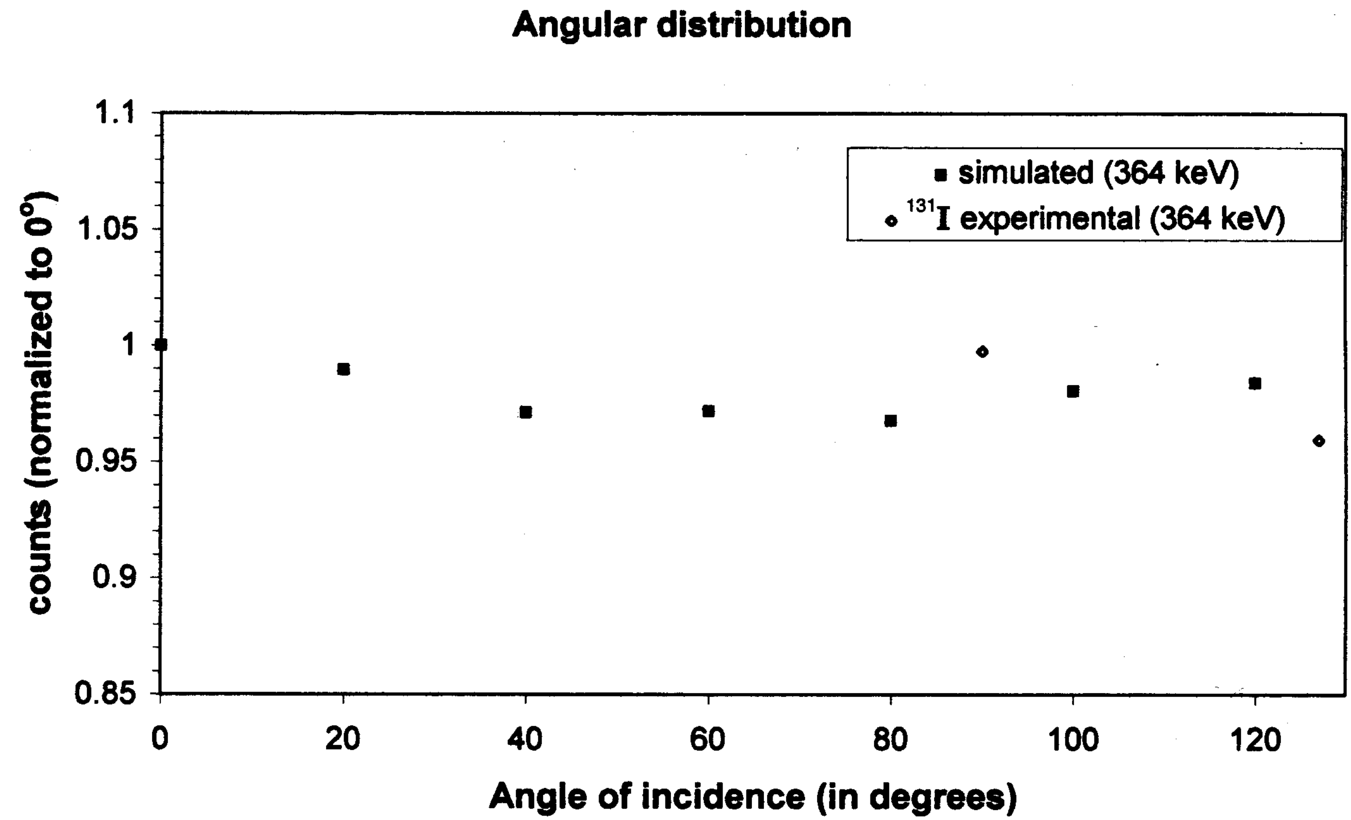


Fig. 7. Angular dependence of efficiency (normalized to 0°).

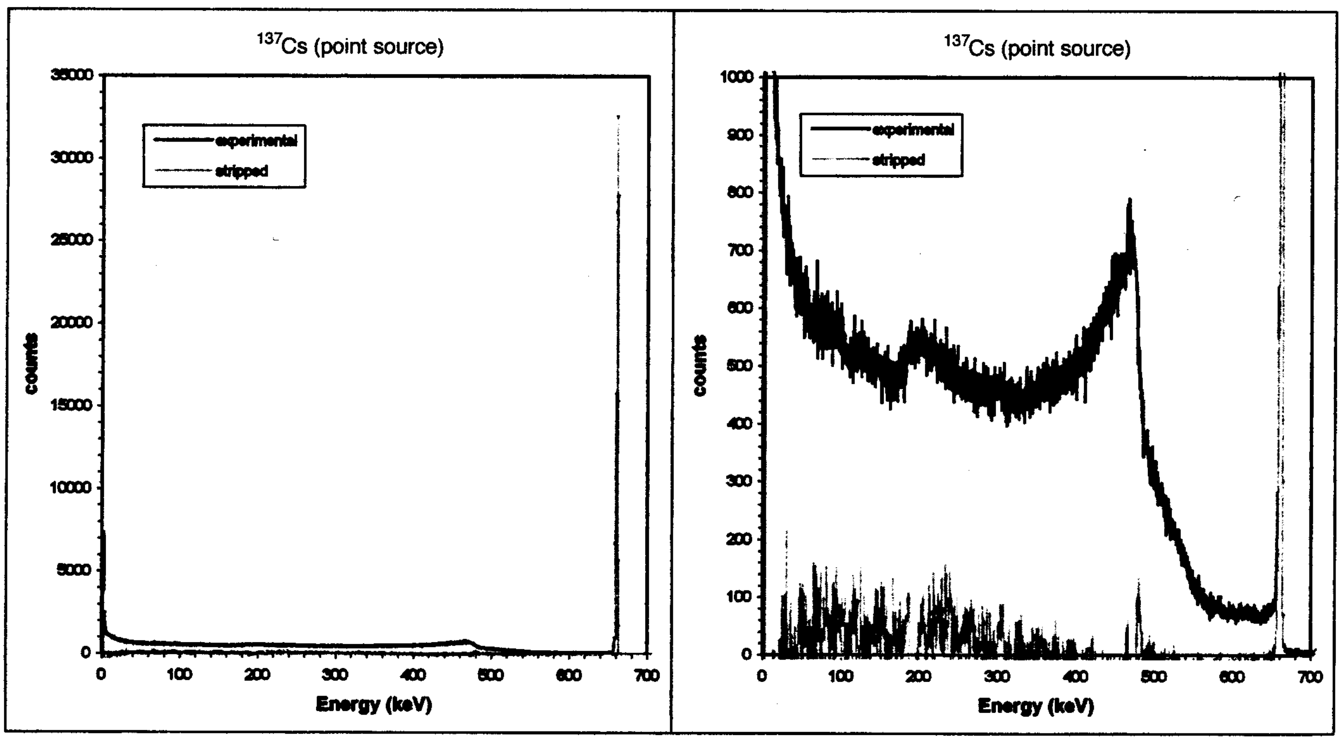


Fig. 8. ^{137}Cs experimental spectrum before and after stripping operation. In the right figure the vertical scale is expanded.

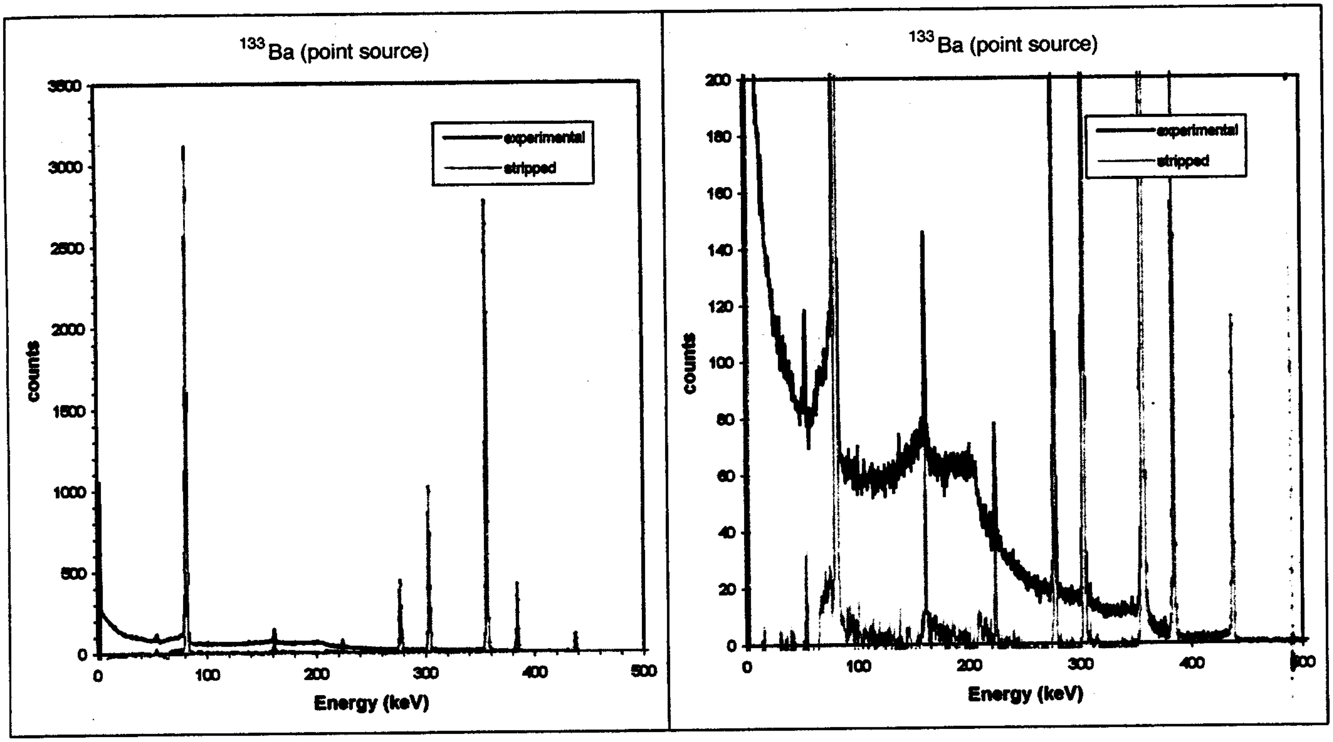


Fig. 9. ^{133}Ba experimental spectrum before and after stripping operation. In the right figure the vertical scale is expanded.

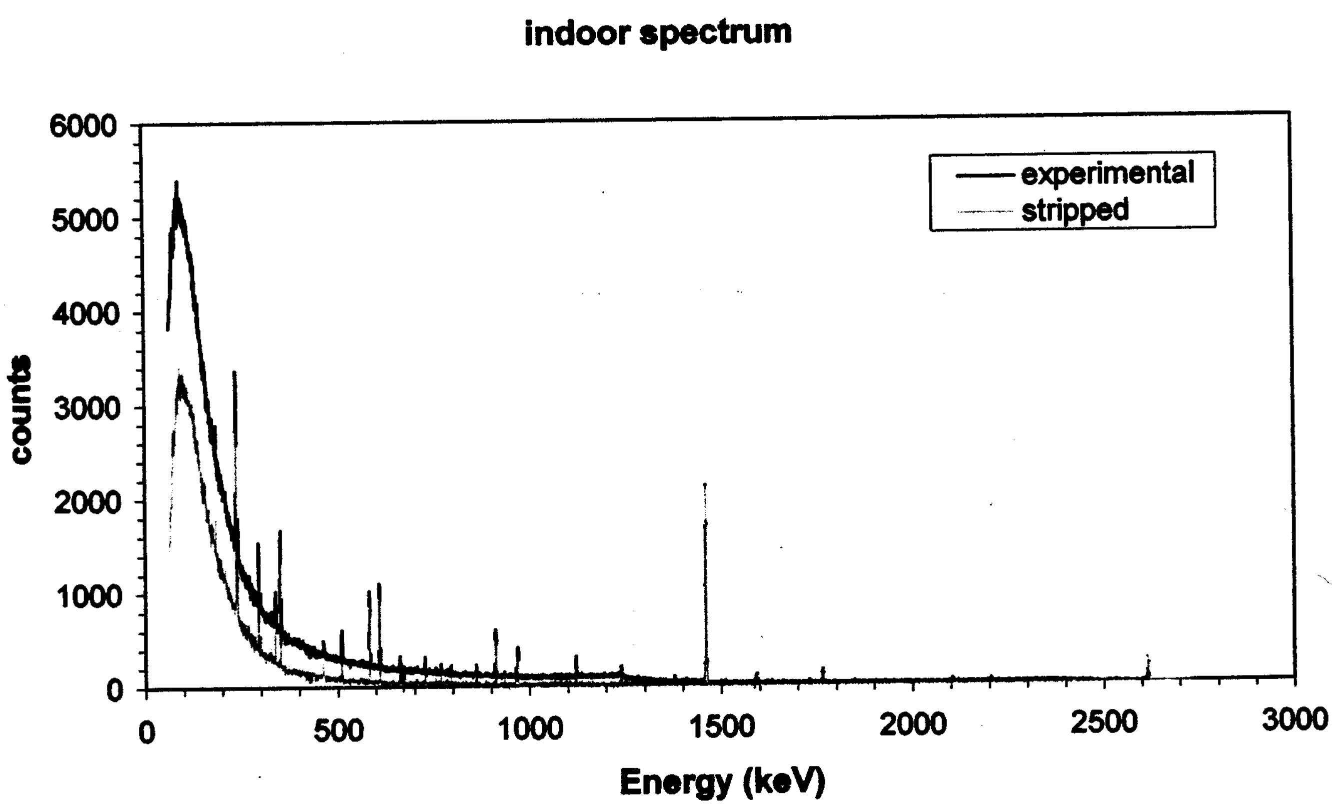


Fig. 10. Indoor spectrum before and after stripping operation.

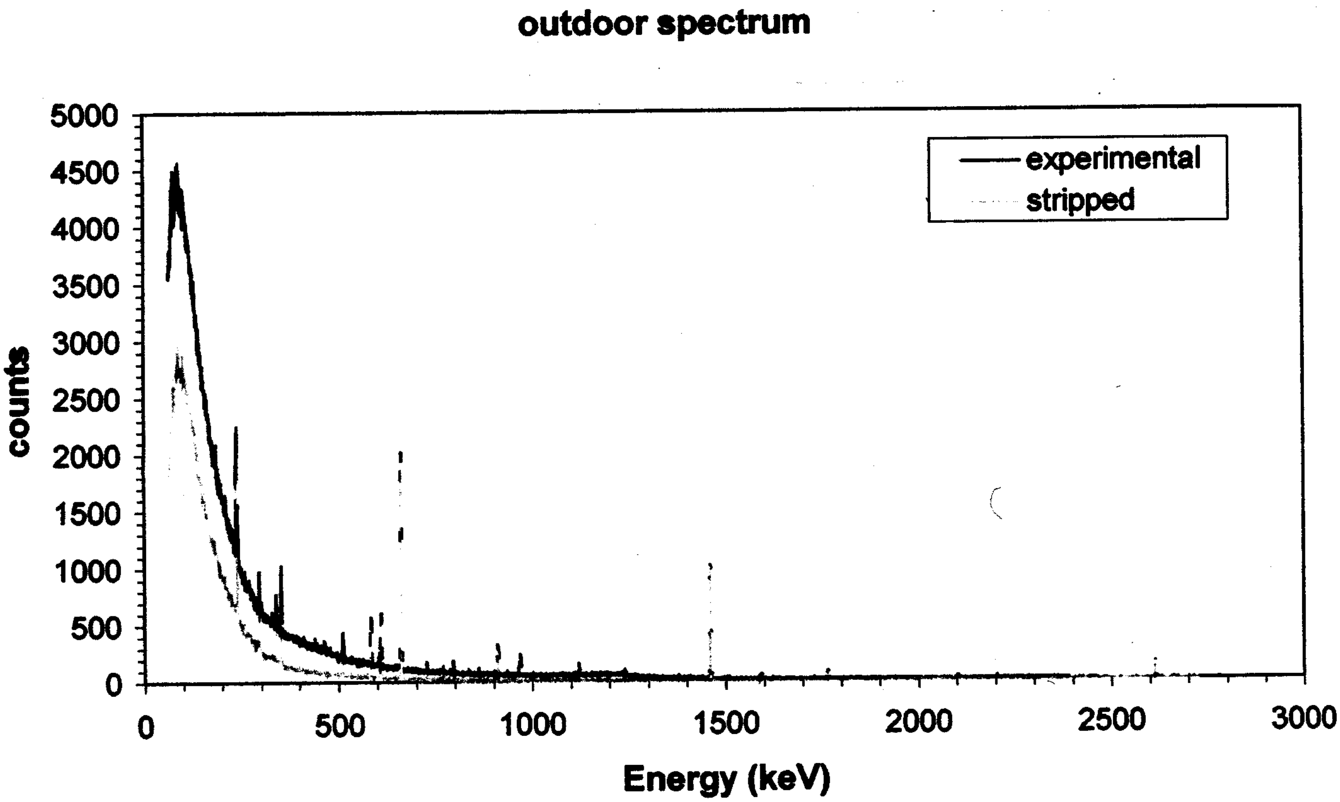


Fig. 11. Outdoor spectrum before and after stripping operation.

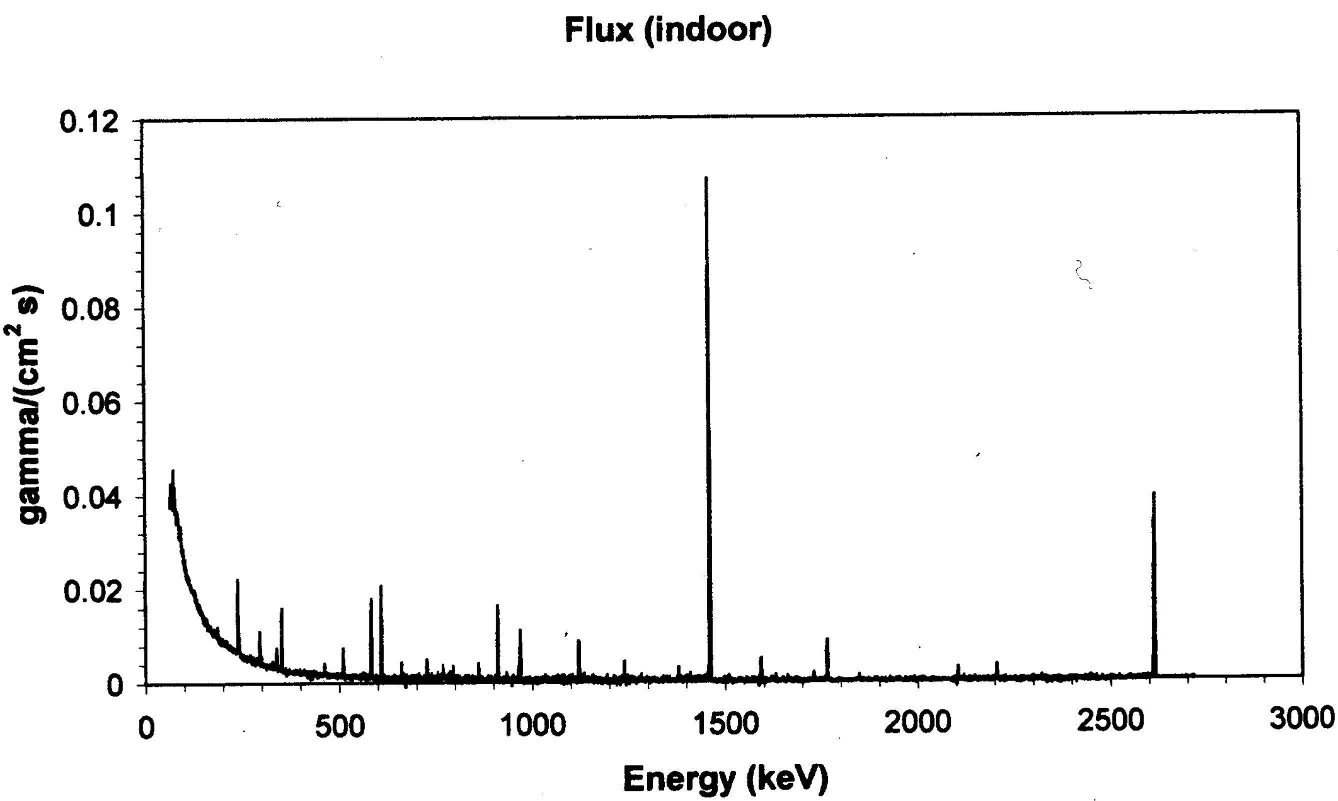


Fig. 12. Photon flux energy distribution in the indoor environment.

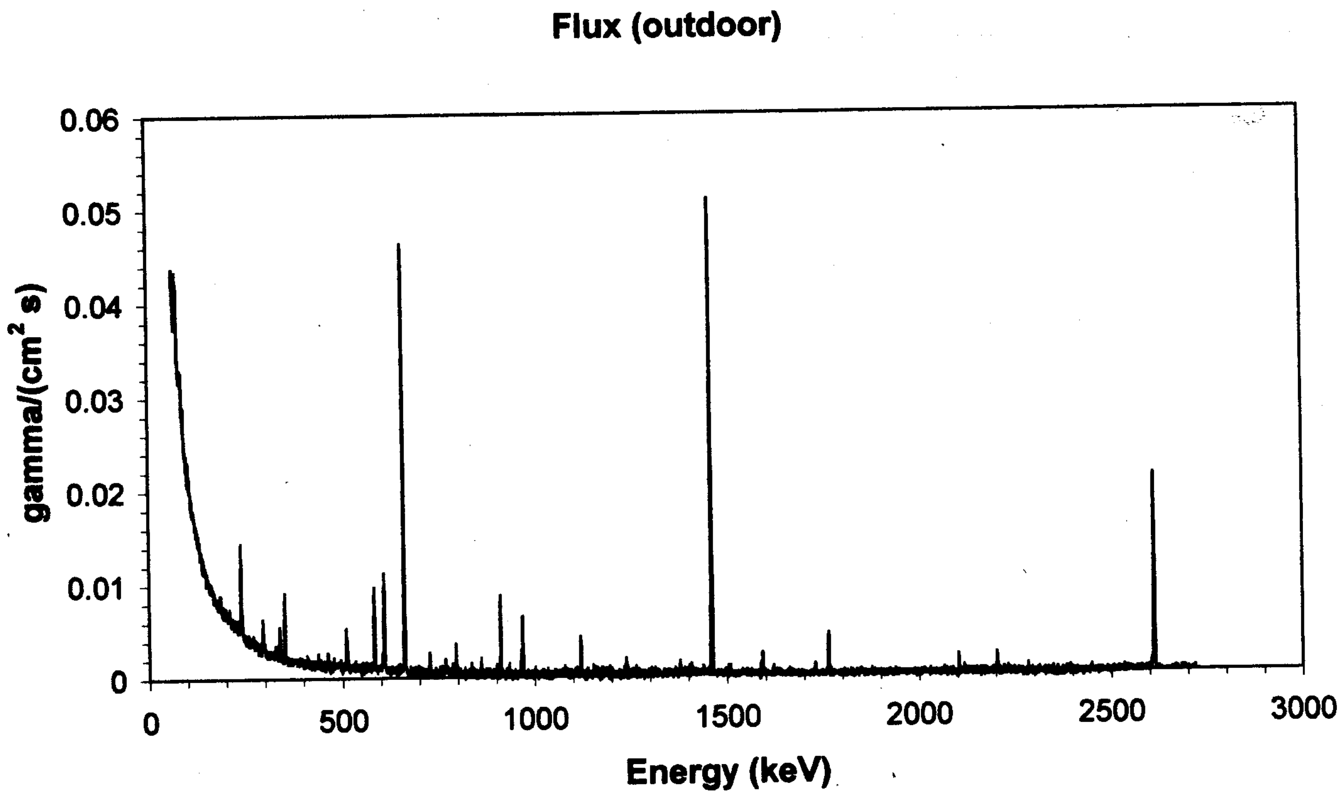


Fig. 13. Photon flux energy distribution in the outdoor environment.

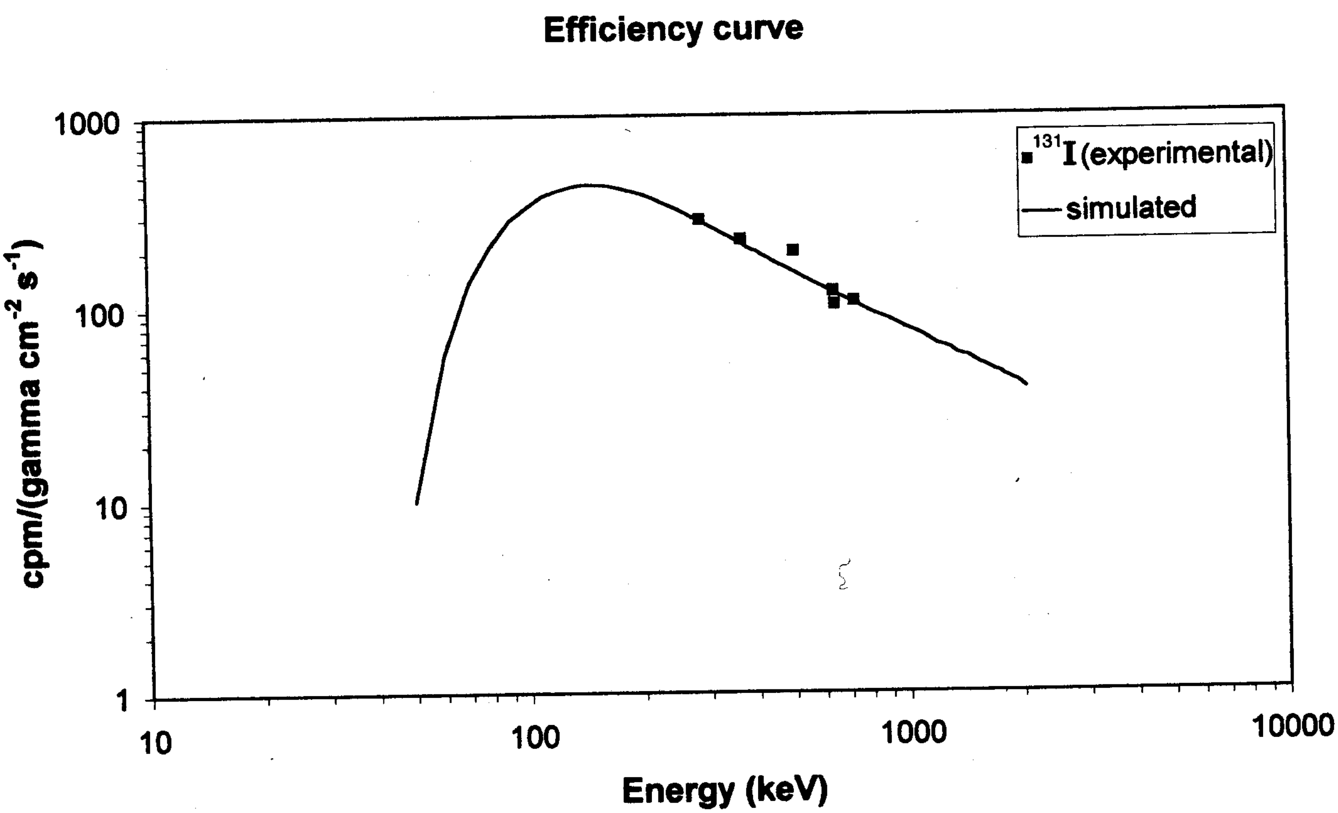


Fig. 14. Detector efficiency.

Table 1. Outdoor absorbed dose rates in air deduced by the stripping operation and the full absorption peak analysis.

	Peak analysis (nGy h^{-1})					
No	U series	Th series	^{40}K	^{137}Cs	Total	Spectrum strip total (nGy h^{-1})
1	6.5	9.3	8.9	14.3	39.0	42.0
2	6.6	11.7	12.0	14.6	44.9	47.8
3	8.5	10.5	9.8	13.6	42.4	44.6
4	8.5	11.3	11.7	7.7	39.2	39.3
5	9.3	15.7	15.6	9.5	50.1	53.8
6	6.2	11.2	10.8	5.4	33.6	35.9
7	7.3	7.3	7.2	10.0	31.8	35.1
8	8.3	11.1	11.6	7.3	38.3	39.7

sponse (shape of continuum and efficiency) of our Ge detector over all angles of incidence.

Fig. 6 presents the simulated shape of continuum for incident photon energy of 661 keV with different angles of incidence normalized to the unscattered peak. The experimental spectra obtained with a point source placed direct in front of the detector is also presented in Fig. 6. Fig. 7 presents the relative efficiency of the detector for photon energy of 364 keV, deduced by simulation, as a function of the angle of incidence. The experimental efficiency was obtained with a ^{131}I source placed 2 m away from the detector. The efficiency is normalized to 1 for incident photons normal to the detector face. From Figs. 6 and 7 it is clear that the angular response of our detector is not a critical factor, and within 5% we can consider that our Ge detector has a uniform response over angles at least up to 120° of incidence.

STRIPPING PROCEDURE

In order to convert a measured spectrum by the detector to the incident photon flux energy distribution, the measured spectrum must first be stripped of the partial absorption and cosmic-ray events leaving only the events corresponding to the full absorption of a gamma ray. Concerning the cosmic-ray events induced in the detector, we followed the methodology given by Miller and Beck (1984). The cosmic ray count rate in the region below 3 MeV in a typical Ge detector is generally small compared to the gamma count rate for an unshielded detector in an environmental application. Since there is no natural gamma line between 3 and 4 MeV (highest natural gamma line 2.615 MeV), this region is used to estimate the cosmic count rate, which is then extrapolated back to 0 MeV and subtracted out from the spectrum. Although there may be some variation in the energy distribution, we have assumed—as have Miller and Beck (1984)—that the cosmic radiation is flat in the region 0–3 MeV, and while there is undoubtedly some build-up at low energies in an outdoor environmental spectrum, this effect can be neglected because most of the counts in this region would come from scattered terrestrial gamma radiation. When a spectrum is taken in a building, the build-up effect becomes even less important due to the filtering out of the soft component of cosmic radiation.

The events corresponding to partial absorption in the detector are simple to strip out when the response function of the detector is known as a function of the incident photon energy and angle of incidence. The angular response of our Ge detector is not a critical factor, and it can be considered to have a uniform response over angles up to 120° of incidence. In order to obtain the response function of the detector as a function of the incident photon energy, we generated about 235 spectra using the simulation procedure described previously for incident photon energies from 50 keV up to 3 MeV with step of 10 keV. For all other incident photon energies between 50 keV and 3 MeV the response function of our Ge detector is determined by interpolation between two simulated spectra.

Using the simulated shapes for the partial absorption continuum we proceeded to a computerized stripping operation which subtracts first out from a measured *in-situ* spectrum those counts that represent cosmic-ray events (a constant number for all energies as described previously) and then the partial absorption of gamma rays in the detector. The stripping operation after subtraction of the constant number for all energies representing the cosmic-ray events is initiated at the highest energy natural gamma line (2.614 MeV) and involves subtracting the simulated continuum of counts, which is lower in energy for this specific photon energy. The operation continues for succeeding lower energies (with step 0.45 keV) down to 50 keV. In order to check our stripping operation we test it for different spectrum obtained with incident γ-rays emitted from ^{133}Ba and ^{137}Cs point sources placed directly in front of the detector.

It can be seen in Figs. 8 and 9 that the computerized stripping operation used subtracts successfully from the measured spectrum the events corresponding to partial absorption in the detector and preserves as it should the full absorption peak.

Examples of a stripped indoor and outdoor spectrum as compared to the original spectrum are shown in Figs. 10 and 11. Typically, about 50% of the counts are removed. These counts are removed from the continuum portion of the spectrum, while the peaks due the full absorption of primary flux are preserved.

After performing the stripping routine, the resultant spectra in Figs. 10 and 11 is converted to incident flux

(Figs. 12 and 13) by applying the full absorption efficiency of the detector, which is shown in Fig. 14.

The good agreement in Fig. 14 between the values deduced from the simulated procedure and the experimental values can be expected from the fact that in the simulation procedure the length of the transition zone was chosen in such a way that the simulated and experimental full absorption efficiency values are in agreement.

Although most of the spectrum in Figs. 12 and 13 is not actually comprised of peaks, it must be remembered that each count represents a fully absorbed gamma ray. The continuum present is a result of scattered radiation of the environment in which the detector is placed. In the case of an indoor measurement this is the floor, ceiling, walls furnishings, etc.

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

$$\dot{D} = \sum_{E=0}^{E=E_{max}} E\Phi(E)\mu(E), \qquad (15)$$

where $\mu(E)$ is the mass absorption coefficient for air at energy E and E_{max} the highest energy gamma line (2.614 MeV). The dose rate in air for the indoor and outdoor measurement was 52.3 nGy h^{-1} and 35.9 nGy h^{-1}, respectively.

In order to check if the dose rate deduced by the computerized stripping operation is sound we performed 8 *in-situ* gamma spectroscopy field measurements (6 h for each one). The results of the dose rate in air deduced by the stripping operation were then compared to the values deduced from the full absorption peak analysis of the measured 8 spectra using the methodology of Beck et al. (1972) and the field calibration factors of Helfer and Miller (1988), which are known to be correct (with an uncertainty of 15%) in the case of field measurements (infinite soil half space). The results are shown in Table 1. The good agreement between the two methods led us to believe that the Monte Carlo based method proposed in the present work is correct.

CONCLUSIONS

A Monte Carlo based method for the conversion of *in-situ* γ-ray spectrum obtained with portable Ge detector to photon flux energy distribution was proposed. In order to deduce from an *in-situ* γ-ray spectrum the photon flux energy distribution, the spectrum was first stripped of the partial absorption and cosmic-ray events leaving only the events corresponding to the full absorption of a gamma ray.

Concerning the cosmic-ray events induced in the detector we followed the methodology given by Miller and Beck (1984). The events corresponding to partial absorption in the detector were determined by Monte Carlo simulations for different incident photon energies and angles using the GEANT code by CERN. Using the detector's characteristics given by the manufacturer as input, it was impossible to reproduce the efficiency and shape of the continuum of experimental spectra obtained with point sources. A transition zone of increasing charge collection efficiency had to be introduced in the simulated geometry, in the Ge crystal entrance window after the Ge dead layer, in order to obtain a good agreement between the simulated and experimental spectra. This result is new and perhaps of practical interest for industries constructing Ge detectors.

Knowing the computed shapes of partial absorption continuum deduced by the Monte Carlo simulation for different incident photon energies and angles, it was therefore possible to convert the measured *in-situ* spectra to total incident flux spectra by applying the full absorption efficiency curve of the detector, which was determined by calibrated point sources and Monte Carlo simulations. Having calculated the flux energy distribution, the absorbed dose rate in air due to the gamma radiation was easily deduced. The good agreement of the dose rate in air deduced by the stripping operation and the full absorption peak analysis method for 8 field measurements is quantitative proof that the proposed technique is valid.

The stripping method reported in the present work has, in comparison to the original one introduced by Miller and Beck (1984), the following advantages:

- Describes better the stripping of the partial absorption in the detector as function of the incident photon energy. More than 235 simulated spectra with incident photon energies from 50 keV up to 3 MeV were used in the stripping routine; and
- Can be easily adapted to any available commercial portable Ge detector. The values of the parameters needed by the program are written in an ordinary text file. The principal geometrical characteristics are given only as default values so the user can change them without program rebuilding.

The spectral stripping method described in the present work is useful in the determination of the absorbed dose rate for situations where the source geometry and resultant spectrum are unknown. Even if a Ge detector and the present method are not the only means to obtain an independent estimate of the absorbed dose rate, a high resolution spectrum can at the same time provide individual photo-peak count rates, which aid in the interpretation of the radiation field. Finally, since one of the final results obtained in executing the stripping procedure is the energy distribution of the incident gamma flux, this method can be used as a test of numerical simulations converting radionuclides concentrations in building materials to dose rates in an indoor environment.

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