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Monte Carlo Calculations and Measurements of Spectra from a C-14 Source

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Abstract To perform Monte Carlo simulations it is necessary to model the physical geometries i.e., the source and detector geometry. However, a complete model of the physical geometry may not be possible or may result in a very low calculation efficiency. Substituting the complete source model with a simplified model is one way of increasing the calculation efficiency.

In this report, the study of a simplified model of a ^{14}C source is described. Results of Monte Carlo calculations with the EGS4 code are compared with measurements with a β spectrometer consisting of two coaxial Si detectors, and a low-energy photon spectrometer being a Si(Li) detector.

Calculations and measurements show generally good agreement. However, the difference (a factor of 4) between calculated and measured response to electrons for the Si(Li) detector indicates that this detector has a deadlayer about 12 μm thick instead of 0.2 μm as reported by the manufacturer.

The efficiency of the calculations is increased by a factor of 10, when the complete source model is replaced by the simplified source model. This reduces the calculation time of detector responses to a few days instead of weeks on the NRC SGI R4400 computers.

Good agreement between measured and calculated data also verifies that the MC code EGS4 is a reliable and useful tool for simulating coupled electron and photon transport for particles with energies down to a few keV.

Calculations and experiments were performed at Ionizing Radiation Standards, Institute for National Measurement Standards, National Research Council of Canada, with guidance of D. W. O. Rogers and L. van der Zwan. The work is an integral part of the author's Ph. D. project.

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1 Introduction

The β spectrum of ^{14}C can be calculated from well known expressions [1]. However, for the source used in this work the ^{14}C nuclides are distributed in a 50 mm × 50 mm × 1 mm plate of PMMA (see Sect. 4), which will cause moderation of the original β spectrum from the nuclide. The β particles from the ^{14}C nuclide have an average energy of 49 keV and a maximum energy of 156 keV. In PMMA, the CSDA range at these energies are approximately 40 and 250 μm, respectively. This means that only a few percent of the β particles emitted from the nuclides contribute to the electrons at the source surface. Additionally some bremsstrahlung photons are created in the PMMA with average energy about 20 keV. Only a few percent of these photons are stopped in the PMMA.

In this work, spectra for this ^{14}C source have been determined by calculations as well as by experimental methods. The calculations were performed using the Monte Carlo (MC) code EGS4 (Electron-Gamma Shower version 4)[2] with the electron-transport algorithm PRESTA (Sect. 3).

At CEA, France, the spectrum at 5 cm distance from the source was measured with a β spectrometer consisting of 2 coaxial Si detectors (Sect. 2.1). The irradiation set-up of this experiment was simulated with the MC code and the electron and photon fluence spectra at 5 cm distance were calculated (Sect. 5.1). In these calculations the source model was very similar to the real source.

To increase the efficiency of the MC calculations a simplified model of the ^{14}C source was introduced. Calculated electron and photon fluence values obtained by this model were compared with the calculated data obtained by use of the complete source model (Sect. 6). It is concluded that the simplified source model is an acceptable simplification to perform more efficient calculations.

Measurements of the electron and photon spectra from the ^{14}C source were also performed by use of a low-energy photon spectrometer (a Si(Li) detector - see Sect. 2.2) established at NRC, Canada. This detector was covered with a light-tight Be-window and one could expect that the directly measured response provided by this detector would need correction (unfolding) to obtain the real spectra. In this report, "response" refers to the response to the continuous spectra. Using the simplified source model in the MC simulations, the detector responses to the emitted electrons and photons have been calculated and compared with the measured response values (Sect. 7).

An important aim of this work was validation of MC calculations with the EGS4 code of β energy spectra by experimental results. The achievement of good agreement in this work between calculated and measured data is a verification that MC calculation is a reliable and useful tool for β spectrometry, not only for direct determination of spectra, but also for making analyses of the response of β spectrometers and thus also their spectrometric capabilities.

2 Measuring Methods

The two types of spectrometers, used for measuring the electron and photon spectra or responses for the ^{14}C source, are described in this chapter.

2.1 β Spectrometer

The spectrum from the ^{14}C source was measured with a β spectrometer at CEA, France, with 5 cm air between source and detector surface. The measured spectrum includes both electrons and photons. The spectrometer consists of two coaxial Si detectors (an IPT 150-300-16 and a LEC 200-5000 with Si thicknesses of 300 μm and 5000 μm, respectively) and a 2 mm thick Al-collimator with an aperture of 4.0 mm diameter placed in front of the detectors (Fig. 1). Electrons with energy below about 200 keV are detected by the IPT detector only, and electrons with higher energy will reach the LEC detector with a residual energy $E_{res} = E_{inc} - \Delta E$, where E_{inc} is the energy of the incoming electron and ΔE is the energy loss in the IPT detector [3]. Both Si detectors must be calibrated individually, since they do not measure in the same energy intervals. For the energy calibration ^{57}Co (E_γ = 122 keV) and ^{137}Cs (E_γ = 662 keV) were used.

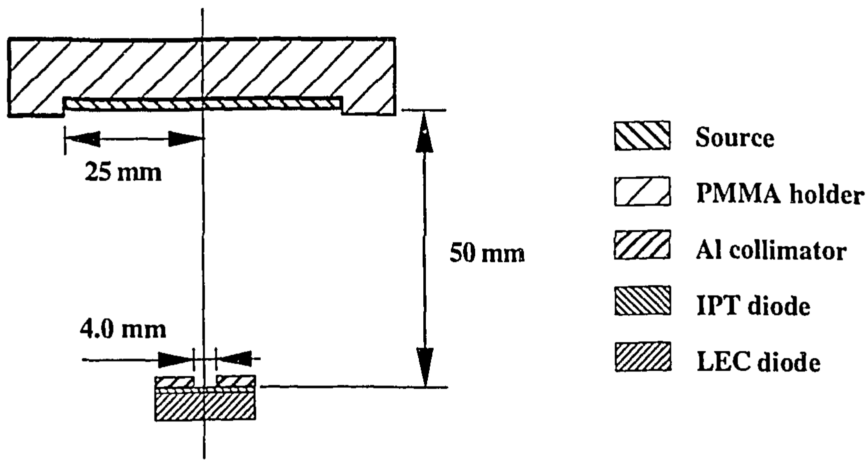

Figure 1. ^{14}C source and β spectrometer consisting of two Si detectors.

The electrons emitted from the ^{14}C source have a maximum energy about 150 keV. All electrons were then stopped in the IPT detector and the LEC detector had no effect in the measurements. The β spectrometer was assumed to measure the kinetic energy of the electrons hitting the Si detectors without any energy loss. Therefore no unfolding of the measured energy spectrum was performed. Measuring time in the experiment was 60000 seconds.

2.2 Low-Energy Photon Spectrometer

A cooled Si(Li) detector established at NRC was used for measuring the energy spectra of the ^{14}C source at 36 mm distance. The cross section of the Si(Li) detector model is shown in Fig. 2. The cylindrical detector has an active region with 6 mm diameter and 5 mm thickness [4]. The Be-window of the detector is 0.0127 mm thick, corresponding to 13 keV energy loss at 50 keV and 8 keV at 100 keV electron energy. The resolution of this detector is 172 eV at 5.9 keV.

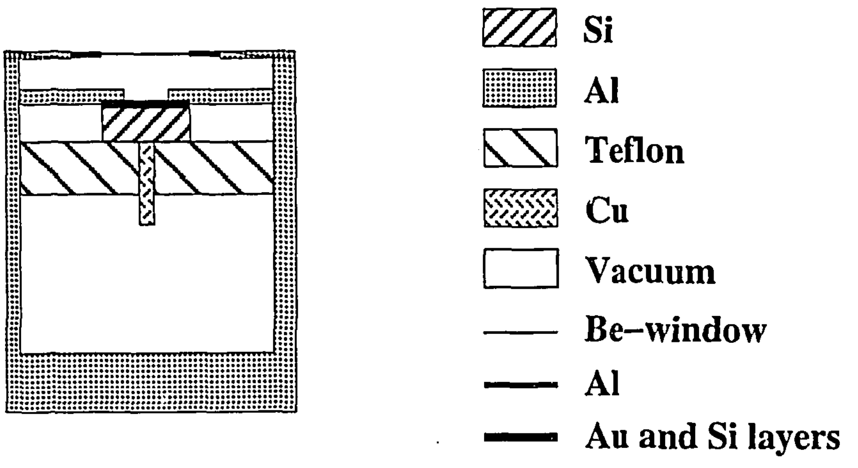

Figure 2. Cross section of the Si(Li) detector model.

First the total response to electrons and photons was measured, and then the photon response alone was measured. In the last case, the electrons were stopped by a 254 μm thick sheet of mylar placed in front of the detector. The measured photon response was then corrected for the attenuation in the mylar sheet and subtracted from the total response to obtain the electron response. Some bremsstrahlung may be created in the mylar sheet. However, based on MC calculations, this will only amount to about 0.2 % of the total number of detected photons and does not need to be corrected for.

The measuring time, Δt, was 12000 s in both experiments.

3 MC Calculations

The EGS4 code is a MC code simulating coupled transport of electrons and photons in an arbitrary geometry for particles with energies above a few keV up to several TeV [2]. The code is an analog MC program i.e., it simulates the actual physical processes as closely as possible and has no variance reduction techniques "built in", which makes it very time consuming. The Parameter Reduced Electron-Step Transport Algorithm, PRESTA, is used in the simulations to avoid step-size artefacts [5]. PRESTA consists of three components: a path-length correction (PLC), a lateral correlation algorithm (LCA), and a boundary crossing algorithm (BCA). The PLC accounts for the differences between the straight path length and the curved path length for each electron step. The curved path of the electron is caused by the elastic scatterings from the nuclei and atomic electrons of the medium in which the transport takes place. The coupling of the Molière multiple scattering theory and the PLC has been shown to be independent of the step-size in it's validity domain [5]. Since the PLC algorithm allows large electron steps, the LCA becomes important. The LCA performs a translation perpendicular to the direction of motion during an electron transport step. Near the interface between regions, the curved path of the electron may result in transport in both regions though the straight path is only taken in one region. For very short steps the difference between the straight path and the curved path is negligible, but for large steps it can be significant. The BCA has been shown to be an efficient and reliable method for treating the electron transport near the interface between regions [5].

Each particle is followed down to a cutoff energy, which includes both rest mass energy (511 keV for an electron) and kinetic energy of the particle. Values for stopping powers were calculated from the data given in ICRU Report 37 [6].

The fluence spectra were calculated by use of the EGS4 usercode FLURZ, which is to be used for fluence calculation in cylindrical geometries only (see below). Similarly the EGS4 usercodes DOSRZ, SPRRZ and PFLURZ[1] calculates the dose, the stopping power ratio, medium to air, and planar fluence, respectively, in cylindrical geometries. All results were calculated per source particle.

The calculations were performed at the NRC SGI R4400 computers, and calculation times stated in this report are for these computers. Energy cutoffs in the calculations were 512 keV for electrons (including the rest mass energy of an electron of 511 keV) and 1 keV for photons unless otherwise stated.

Calculation of Fluence and Planar Fluence

Fluence is a point function formally defined as the number of particles entering a sphere per unit cross-sectional area, when the sphere is reduced to an infinitesimal i.e., a point. From this definition it has been shown that the average fluence in a given region is the sum of the particle track lengths in that region divided by its volume [7, 8].

The planar fluence is defined as the number of particles crossing a fixed plane in either direction per unit area of the plane [9]. It is thus important to distinguish between fluence and planar fluence.

[1] PFLURZ is a modified (Aug. 1991 by D. W. O. Rogers, NRC, Canada) version of FLURZ. It calculates the planar fluence instead of the fluence.

4 The ^{14}C Source

The ^{14}C source used in this work is described in this chapter - both the physical source configuration as well as the modelled source with cylindrical geometry for MC calculations.

4.1 Spectrum for the ^{14}C Radionuclide

The spectrum for the ^{14}C nuclide is calculated using a program made by L. van der Zwan, NRC, based on the work by W. G. Cross et al. [1]. The calculation includes corrections for both the influence of the Coulomb force field and the screening effect. The spectrum can be calculated for different bin-sizes, and in Fig. 3 the ^{14}C spectrum in 10 keV bins is shown. This is the input spectrum used in the MC calculations.

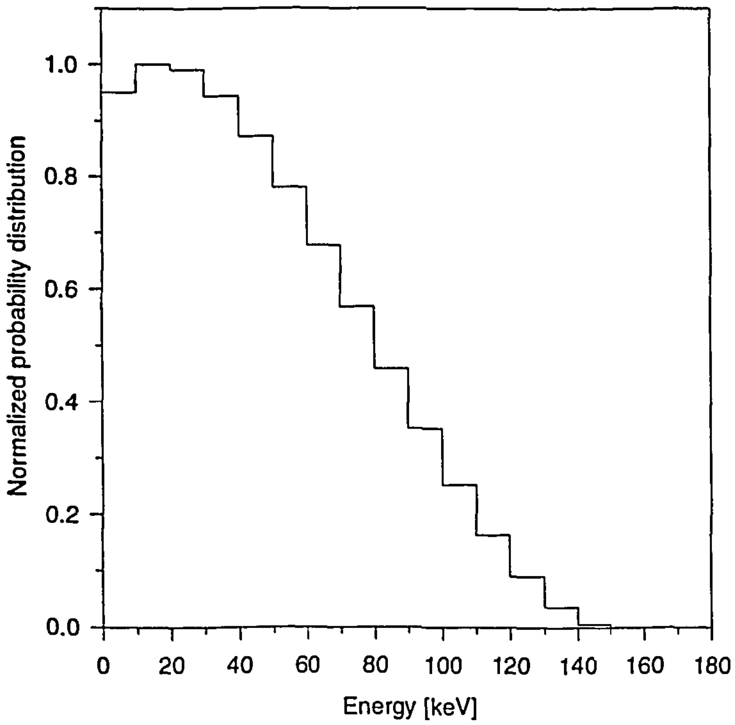

Figure 3. Spectrum for the ^{14}C radionuclide calculated in 10 keV bins.

4.2 The Physical ^{14}C Source Configuration

The source used in this work is a quadratic (50 mm x 50 mm, 1.0 mm thick) sheet of PMMA with the ^{14}C radionuclides uniformly distributed throughout the PMMA. It was purchased from Amersham Company and has a quoted source strength $Q_0 =$ 57 MBq. The half life of ^{14}C is 5730 years, so there is no need for correction due to decay since time of purchase. An emission rate of electrons i.e., the electron planar fluence rate, was measured by Amersham to be $d\phi_{p,e}/dt = 1.5 \cdot 10^6$ electrons cm^{-2} min^{-1} (or $2.5 \cdot 10^4$ electrons cm^{-2} s^{-1}). This type of source is normally used for radiographic examination of paper and similar materials or for use as check sources for multichannel chromatogram analyzers [10].

The source is placed in a 1.0 mm deep recess in a 12 mm thick holder of PMMA. The source is fixed in the holder by a 1.0 mm thick PMMA sheet with a 50 mm diameter hole. The configuration of source and holder is shown in Fig. 4.

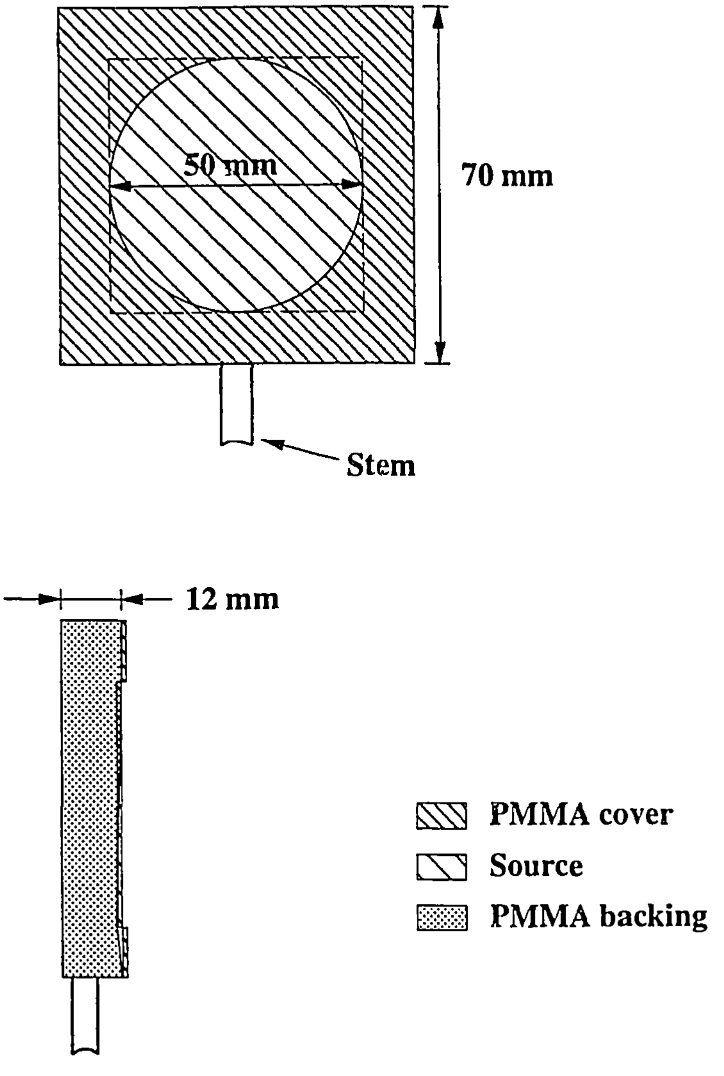

Figure 4. Configuration of physical source including source holder (backing and cover) of PMMA.

All β particles emitted from the covered parts of the source are totally absorbed in the PMMA cover, which simplifies the MC modelling of the source to a cylindrical construction. However, due to production of bremsstrahlung from the covered part of the source, these regions cannot be completely ignored in the calculations.

Since only a circular part of the source is used, the actual source strength, Q, is smaller than for the square source. The actual source strength, being the number of β decays per second from the circular part of the source, is obtained from

$$Q = Q_0 \cdot \pi \cdot (25 \text{ mm})^2/(50 \text{ mm})^2 = 45 \text{ MBq} \quad (1)$$

The planar fluence of electrons (simplified initial electrons), $\Phi_{p,e}$, at the source surface per source electron is then

$$\Phi_{p,e} = (\mathrm{d}\phi_{p,e}/\mathrm{d}t)/Q = 5.6 \cdot 10^{-4} \text{ simp. init. elec. cm}^{-2} \text{ per source elec.} \quad (2)$$

4.3 The ^{14}C Source Model for MC Calculations

The modelled source for the MC calculations is a cylindrical piece of PMMA with diameter 50 mm and 1.0 mm thick. It is placed in a cylindrical PMMA holder - see Fig. 5.

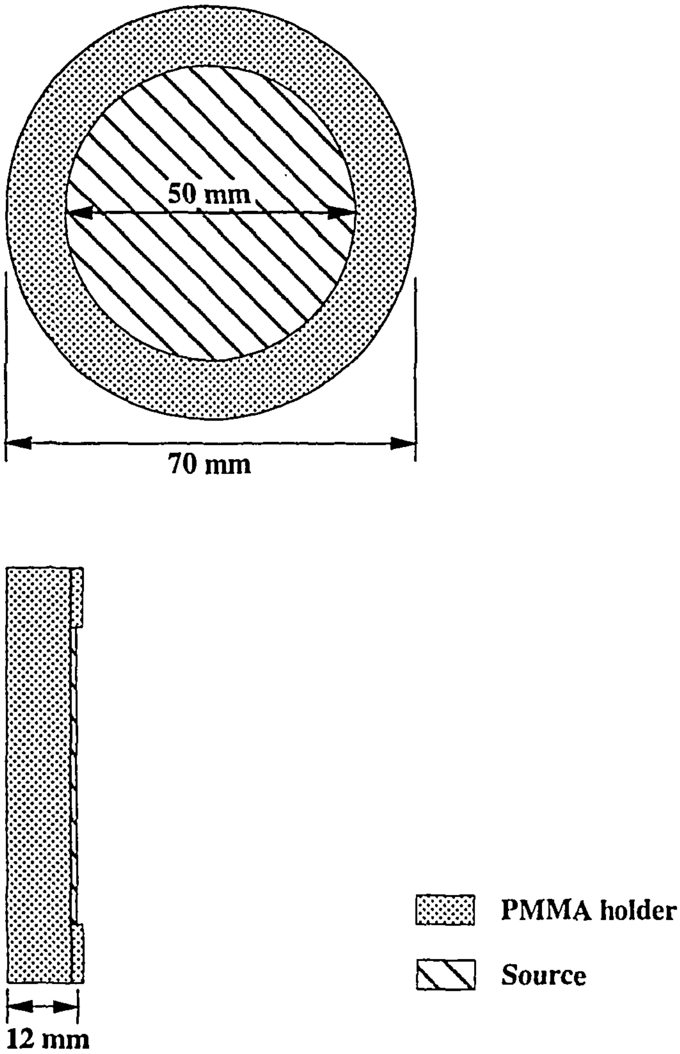

Figure 5. Configuration of complete model of ^{14}C source for calculations including source holder (backing and cover) made of PMMA.

It can be seen from Fig. 4, that a part of the physical source is covered by the sheet of PMMA defining the circular surface area of the source. This is not the case for the modelled source. About 94 % of the bremsstrahlung (average energy approx. 20 keV - see Table 2 in Sect. 5.1) escaping from the part of the source covered with PMMA will pass through this layer of PMMA and thus increase the number of photons to be detected in a measurement.

Assuming that no bremsstrahlung photons are created in the PMMA cover and ignoring attenuation of the photons in the cover, the estimated ratio of photons from the physical source, $N_{ph.phys.}$, to photons from the modelled source, $N_{ph.mod.}$, is:

$$N_{ph.phys.}/N_{ph.mod.} = \frac{(50\ \mathrm{mm})^2}{\pi\cdot(25\ \mathrm{mm})^2} = 1.27 \qquad (3)$$

5 Spectra for the ^{14}C Source

In this chapter the fluences and planar fluences at the source surface are calculated, and the calculated electron planar fluence at 5 cm distance from the source is compared with the result of the β spectrometer measurement.

5.1 Calculated Fluence Spectra

The fluence spectra at the source surface was calculated in 5 keV bins and with a total electron cutoff energy of 512 keV (1 keV kinetic energy) and a photon cutoff energy of 1 keV. The electron and photon fluence per source electron, Φ_e and Φ_{ph}, respectively, at the source surface were calculated for a disc and a ring configuration both 10^{-3} mm high and placed in contact with the source surface. The radius of the disc was 20 mm and the ring was located between radii 20 mm and 25 mm. The results of calculations in 5 keV bins are shown in Table 1 and 2.

Table 1. The fluence at the source surface and the average energy of the fluence spectra. The different values of the fluence in the two scoring regions is due to the edge effect influencing the outer region.

Radii [mm]	0 - 20	20 - 25
Electrons:		
Φ_e [(cm^2 sour. elec.)$^{-1}$]	$1.166 \cdot 10^{-3} \pm 0.6$ %	$1.096 \cdot 10^{-3} \pm 0.4$ %
Average energy [keV]	51.86 ± 0.3 %	52.22 ± 0.1 %
Photons:		
Φ_{ph} [(cm^2 sour. elec.)$^{-1}$]	$4.683 \cdot 10^{-5} \pm 1.8$ %	$3.836 \cdot 10^{-5} \pm 1.9$ %
Average energy [keV]	22.39 ± 1.7 %	21.41 ± 1.3 %

Table 2. The area weighted ($0 \leq r \leq 2.5$ cm) fluence at the source surface and the average energy of the fluence spectra.

Radius [mm]	0 - 25
Electrons:	
Φ_e [(cm^2 sour. elec.)$^{-1}$]	$1.141 \cdot 10^{-3} \pm 0.4$ %
Average energy [keV]	52.00 ± 0.3 %
Photons:	
Φ_{ph} [(cm^2 sour. elec.)$^{-1}$]	$4.378 \cdot 10^{-5} \pm 1.4$ %
Average energy [keV]	22.04 ± 1.2 %

The ratio of electron fluence to photon fluence at the source surface (i.e., at $x = 0$ mm distance from the source):

$$\Phi_e/\Phi_{ph}(0 \text{ mm}) = 26.1 \text{ electron/photon} \pm 1.5\,\% \tag{4}$$

In Fig. 6 the calculated electron and photon fluence spectra at the source surface are shown.

Using FLURZ the total fluence per source particle (i.e., electron) was calculated by Σ(pathlength)/volume (see Sect. 3). In an isotropic field of radiation the planar fluence, Φ_p, is [9]

$$\Phi_p = \Phi/2 \tag{5}$$

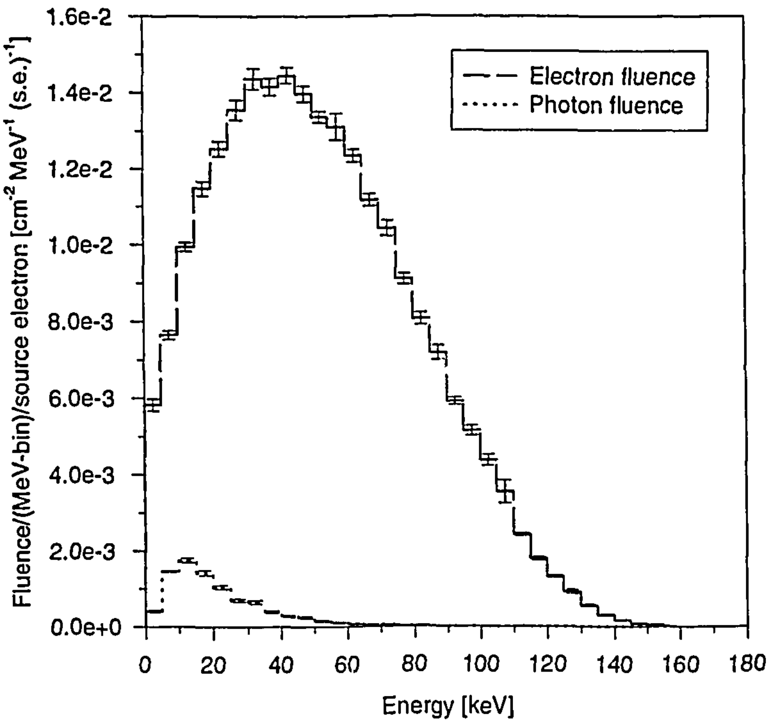

Figure 6. The MC calculated fluence at source surface in 5 keV bins. Average energies are 52 keV for electrons and 22 keV for photons.

For a completely aligned parallel, normal beam $\Phi_p = \Phi$, and for highly angled particles the value of Φ_p/Φ is very small. Using the usercodes PFLURZ and FLURZ the ratios of planar fluence to fluence for both electrons and photons at the source surface were calculated. The ratios were for electrons

$$(\Phi_p/\Phi)_e = 0.511 \pm 1.8\,\% \tag{6}$$

and for photons

$$(\Phi_p/\Phi)_{ph} = 0.34 \pm 4\,\% \tag{7}$$

Almost isotropic fields of electrons and photons were therefore assumed.

From the values in Table 2, the planar fluence of bremsstrahlung photons, $\Phi_{p,ph}$, created in the PMMA cover and the PMMA backing is estimated. The total number, N_{ph}, of photons produced per source electron is then

$$N_{ph} = 2 \cdot A \cdot \Phi_{p,ph} = 7.4 \cdot 10^{-4} \text{ photons per source electron ,} \tag{8}$$

where A is the area of the physical source (25 cm^2). It is assumed that the bremsstrahlung is distributed isotropically meaning that half of it is directed into the positive half plane. The ratio of bremsstrahlung created in the cover and backing to bremsstrahlung created in the source material is then:

$$\tfrac{1}{2} \cdot N_{ph} \cdot \Phi_{p,e} \cdot (A_{back} + A_{cover})/(\Phi_{p,ph} \cdot A) = 1.8\,\% \ , \tag{9}$$

where $A_{back} = A$ and A_{cover} are the area of the back side surface and the covered part of the source, respectively. The contribution of bremsstrahlung photons created in the cover and backing is so small that it has been ignored in the further calculations.

For comparison with the spectrum measured with the β spectrometer at CEA, the fluence spectra were also calculated at 50 mm distance in air from the source

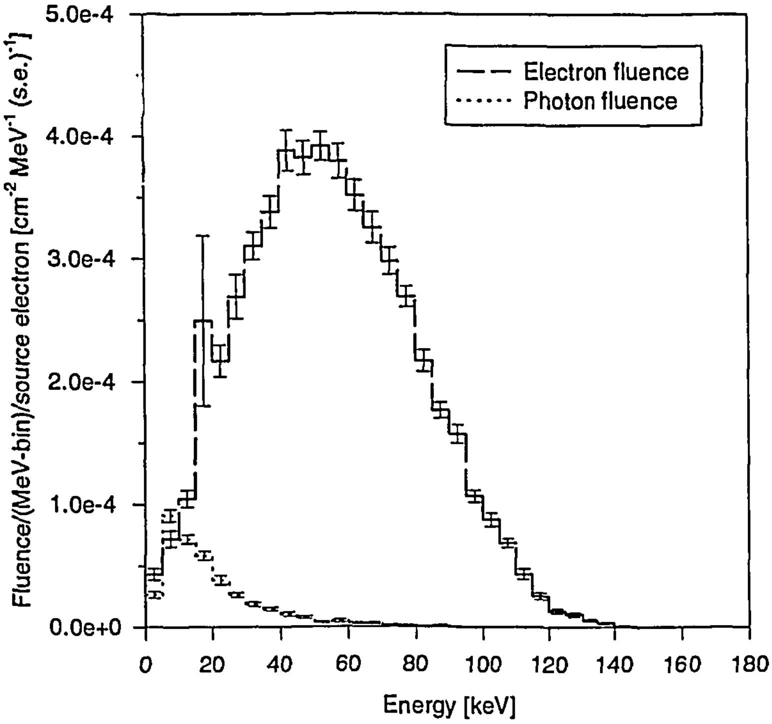

Figure 7. MC calculated on-axis fluence at 50 mm distance in air from the source surface in 5 keV bins. Average energies are 55 keV for electrons and 20 keV for photons.

surface and the results are shown in Fig. 7. The ratio of electron fluence to photon fluence at this distance was:

$$\Phi_e/\Phi_{ph}(50\text{ mm}) = 14.1 \text{ electron/photon} \pm 2.7\,\% \qquad (10)$$

In Fig. 8 the electron and photon spectra on the source surface are compared with the unmoderated spectrum for the ^{14}C nuclide. The electron spectra have been normalized to the peak values for comparison. It is obvious that the spectrum for the ^{14}C nuclide is modified when the β particles travel through the source material.

5.2 Result of β Spectrometer Measurement

The result of the measurement with the β spectrometer at CEA, France, is shown in Fig. 9. The measured average energy is 67 keV. The actual average energy of the spectrum is lower than this value, since the detector has a threshold of about 35 keV. Part of the β spectrum is below this threshold value and is not detected. The normalized measured energy spectrum is compared with the normalized calculated energy spectrum at 50 mm distance in air (the histogram). They show very fine agreement though the spectrometer has a radius $r_{det} = 2.0$ mm, and the calculated result is for a disc with 50 mm diameter. This indicates that the spectrum is essentially homogeneous over the whole area of the disc.

The measurements with the spectrometer include both electrons and photons. However, photons emitted from the source will only contribute with about 1-2 % to the measured spectrum (based on calculated fluence), since the ratio of electron fluence to photon fluence is 14 (Eq. (10)) and nearly 80 % of the photon fluence spectrum is below 35 keV (see Fig. 7).

The total number of detected particles was $n_{total} = 3326175$ particles. Detected electrons per unit area (planar fluence, Φ_p) and per source electron assuming that

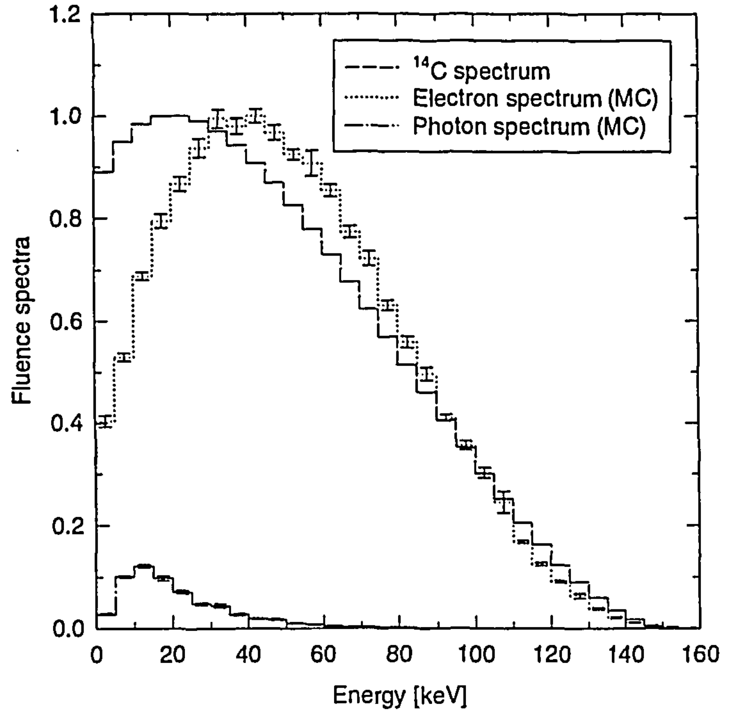

Figure 8. The spectrum for the ^{14}C radionuclide and the MC calculated fluence spectra for electrons and photons at the source surface shown in 5 keV bins. Average β energy for the radionuclide is 49 keV, and for the MC calculated spectra 52 keV for electrons and 22 keV for photons. The electron spectra are normalized to the peak values for comparison. The photon spectrum has been multiplied by the same normalization factor as the MC calculated electron spectrum.

all detected particles were electrons:

$$\Phi_p = \frac{n_{total}}{Q \cdot \Delta t \cdot \pi \cdot (r_{det})^2} = 9.8 \cdot 10^{-6} \text{ electrons cm}^{-2} \text{ per source electron} \quad (11)$$

The planar fluence at $x = 50$ mm distance in air was estimated from MC calculations, too. The estimation was based on fluence calculations in air and vacuum and planar fluence calculations in vacuum, though a direct calculation of planar fluence in air would give a more correct result. The planar fluence in the energy interval 35 to 150 keV amounts to 85 % of the total planar fluence. The MC calculated planar fluence, $\Phi_{p,cal}$, per source electron in the interval 35 to 150 keV was:

$$\Phi_{p,cal}(50 \text{ mm}) = 9.4 \cdot 10^{-6} \pm 10\,\% \text{ electrons cm}^{-2} \text{ per source electron} \quad (12)$$

This agrees well with the detected planar fluence, though there may be some unconsidered effects from the Al-collimator in front of the detector. The agreement between measured and calculated planer fluence shows that the β spectrometer is a good planar-fluence detector.

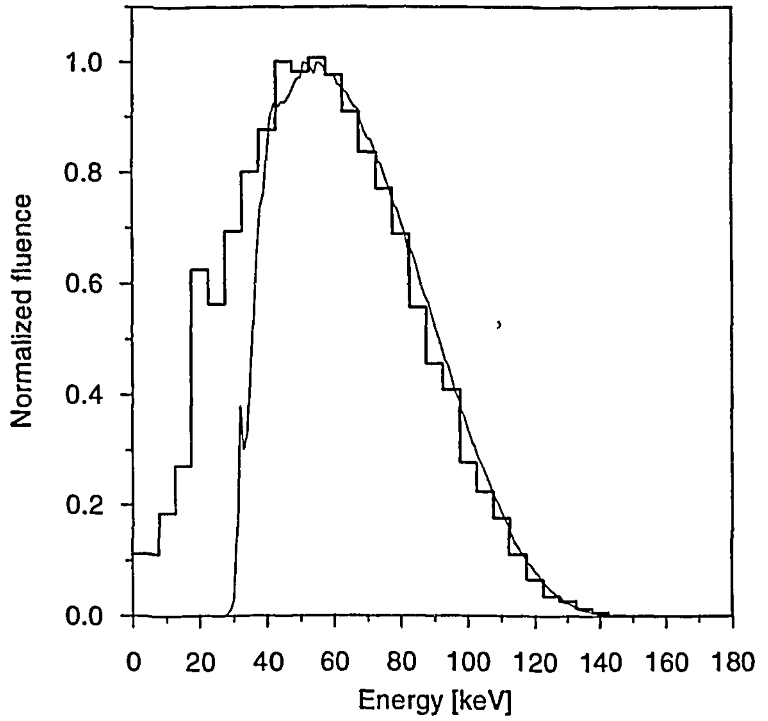

Figure 9. [14]*C spectrum measured at 50 mm distance in air at CEA, France. Average energy is 67 keV. The spectrum is normalized to peak at 1. The histogram shows the calculated energy spectrum also normalized to peak at 1. For uncertainties associated with the histogram, see Fig. 7.*

6 Complete and Simplified Source Models

Performing MC calculations with the complete source model having the ^{14}C nuclides distributed in a 1 mm thick disc of PMMA, most of the source electrons (the β decay of ^{14}C nuclides) are stopped in the source material. To obtain better efficiency in the MC calculations, the whole source configuration is therefore replaced by a 1 μm thick disc of air (Ø 5.0 cm) emitting electrons and photons isotropically - from now on called "the simplified source model". Electrons and photons are distributed uniformly in this disc of air. The calculated electron and photon spectra on the source surface are used as input spectra for the particles in the disc. The source particles for the simplified source model are named "simplified source electrons" (s.s.e.) and "simplified source photons" (s.s.ph.), respectively. The following assumptions and simplifications were made, when making a simplified model of the ^{14}C source to replace the physical source model:

1) The physical source (Fig. 4) is assumed identical to the cylindrical source model (Fig. 5) used in the MC calculations.
2) The cylindrical source model ("complete") is simplified to a thin isotropically radiating disc source ("simplified") to improve the efficiency of the MC calculations. The spectra of the simplified source were the MC calculated spectra on the surface of the complete source.

To verify that using the simplified source model agrees with the calculations performed with the complete source model, the fluence spectra at 5 cm distance from the source was calculated for both cases. The fluences were calculated in 5 keV bins except for the photon fluence calculated for the simplified source model, which was calculated in 10 keV bins. The energy cutoffs were 512 keV and 1 keV for electrons and photons, respectively.

The fluence at a distance from the source will be different for the complete and simplified source models, because the fluence is calculated per source electron, and for the complete model many of the source electrons (s.e.) are "lost" due to the self-absorption in the PMMA source material. Therefore a normalization factor, F_{CS}, is introduced. It is calculated as the ratio of the total on-axis fluences at a distance from the source surface for the complete to the simplified source model:

$$F_{CS} = \Phi_C / \Phi_S \tag{13}$$

The normalization is performed for electrons with energy between 0 and 160 keV and for photons with energy between 10 and 160 keV, because the photon cutoff energy was 10 keV for the calculation of photon fluence for the simplified source model. The factors are calculated for a circular area with diameter 40 mm. The normalization factors for electrons and photons are

$$F_{CS,e} = 2.90 \cdot 10^{-2} \pm 2.5\,\% \tag{14}$$

and

$$F_{CS,ph} = 4.87 \cdot 10^{-4} \pm 3.2\,\% \tag{15}$$

given in (s.s.e. per s.e.) and (s.s.ph. per s.e.), respectively.

The electron and photon fluence rate spectra calculated at 5 cm distance in air for the complete and the simplified source geometry are shown in Figs. 10 and 11.

The calculated electron fluence rate spectra for complete and simplified source models agree for almost the whole energy range. The calculated photon fluence

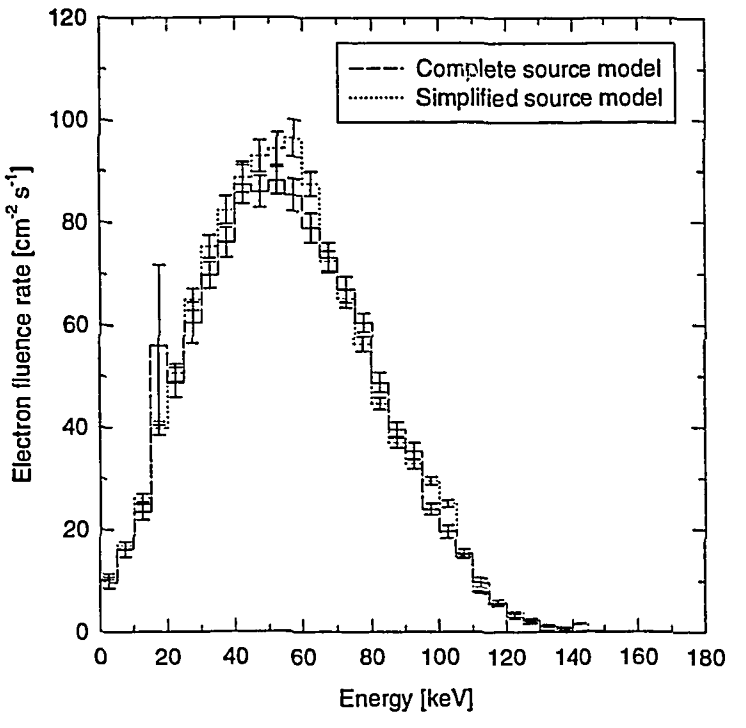

Figure 10. Calculated on-axis electron fluence rate spectra in air at 50 mm distance from the source surface. The spectra were calculated for a region with 25 mm radius. Average energies are 55 keV for both complete and simplified source.

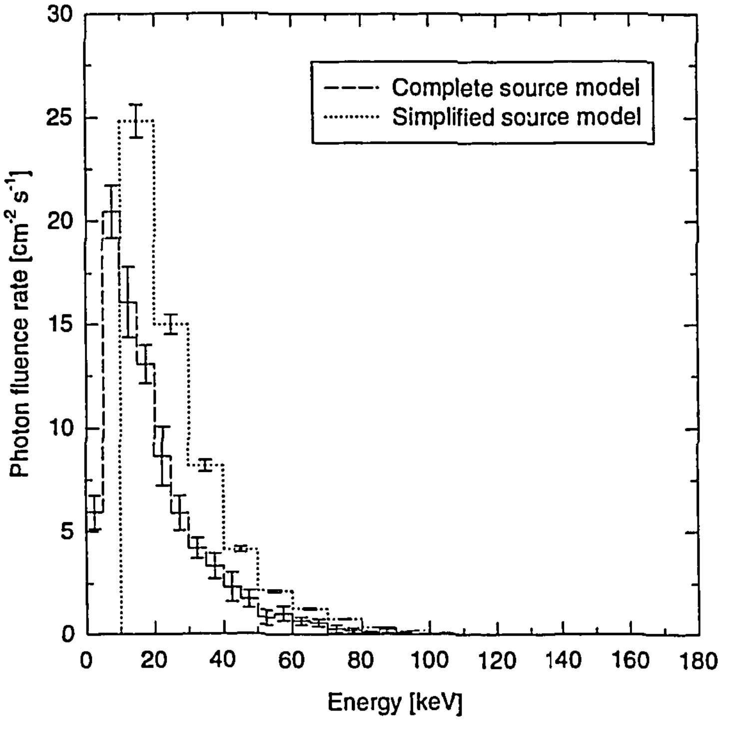

Figure 11. Calculated on-axis photon fluence rate spectra in air at 50 mm distance from the source surface. The spectra were calculated for a region with 25 mm radius. Average energies are 25 keV and 27 keV for complete and simplified source, respectively.

spectrum for the simplified source model has no photons below 10 keV, because the cutoff energy was 10 keV. The difference between the calculated fluence rates is due to the bin-size of 5 keV and 10 keV for complete and simplified source model, respectively. Since the fluence rate spectra agree for both electrons and photons, the simplified source model is accepted to replace the complete source model in the following MC calculations.

Using the complete source model the calculation of electron fluence at 5 cm distance from the source with an uncertainty of 1 % will take about 27 hours ($\sim 3.9 \cdot 10^6$ histories per hour) on the NRC SGI R4400 computers (1994). Similar calculations using the simplified source model takes about 2.6 hours (also $\sim 3.9 \cdot 10^6$ histories per hour). A 10 times increase in efficiency is thus achieved by replacing the complete source model with the simplified source model.

7 Si(Li) Detector Response

In this chapter the calculated and measured responses of the Si(Li) detector are presented, and reasons for the difference between measured and calculated electron responses are discussed.

7.1 MC Calculation of Si(Li) Detector Response

The Si(Li) detector was modelled using given dimensions and dimensions estimated from X-ray photos of the detector. The model is fairly detailed though not exactly equal to the physical detector. The cross section of the modelled detector was shown in Fig. 2. The Be-window of the detector was 12.7 μm (= 0.5 Mil) thick, and the distance from source surface to the Be-window was 3.60 cm (4.30 cm to active Si-material). The simplified source model was used in the calculations. For the modelling of the detector the active Si-material was divided into three regions in accordance with specific construction details of the detector (Fig. 12).

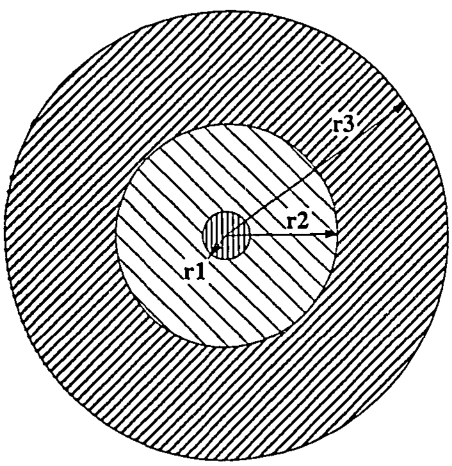

Figure 12. Si-region divided into 3 regions in the calculations. Radii of the regions are r1 = 0.0575 cm, r2 = 0.285 cm and r3 = 0.575 cm.

The detector response is then the sum of responses in each of these three regions. Regions r1 and r2 are covered by air, the Be-window, an Au layer (~200 Å) and a Si layer (~0.1 μm) and region r3 is furthermore covered by an Al layer (0.22 cm), which means that hardly any electrons will get through to this region. The thickness of these regions is 5 mm and the outer radii are 0.0575, 0.2850 and 0.575 cm. MC calculations were performed with the user code DOSRZ and from the result, which is absorbed dose, average pulse height and pulse height distribution, the response (number of particles) is derived. In Table 3 the calculated average pulse height, E', and absorbed dose, D', together with the mass, m, of each region are shown for both electron and photon input spectra.

To obtain the absorbed dose rate, $\dot{D}$, using the complete source model, the normalization factor, F_{CS}, and the source strength, Q, are applied.

$$\dot{D} = Q \cdot F_{CS} \cdot D' \tag{16}$$

The number of electrons and photons detected per second, R_e and R_{ph}, are calculated from the total absorbed dose in the Si, the total mass and the average pulse height by

$$R = \dot{D} \cdot \frac{1}{1.602 \cdot 10^{-16}} \text{ [keV J}^{-1}] \cdot m/E' \ , \tag{17}$$

Table 3. Mass, calculated average pulse height, and absorbed dose in the three Si-regions for electrons and photons, respectively. "Total" refers to the area (or mass) weighted average pulse height and absorbed dose per simplified source particle for the total Si-region. The calculations were made for an air distance of 3.6 cm between the surface of the ^{14}C source and the Be-window.

Region nr.	Mass, m [kg]	Average electron pulse height, E'_e [keV]	Absorbed dose, D'_e [μGy (s.s.e.)$^{-1}$]
r1	$1.288 \cdot 10^{-5}$	51.49	$4.91 \cdot 10^{-9} \pm 8.0$ %
r2	$3.034 \cdot 10^{-4}$	51.88	$3.83 \cdot 10^{-9} \pm 1.7$ %
r3	$9.712 \cdot 10^{-4}$	34.66	$5.97 \cdot 10^{-12} \pm 18$ %
Total	$1.288 \cdot 10^{-3}$	51.74	$9.57 \cdot 10^{-10} \pm 0.41$ %

Region nr.	Mass, m [kg]	Average photon pulse height, E'_{ph} [keV]	Absorbed dose, D'_{ph} [μGy (s.s.e.)$^{-1}$]
r1	$1.288 \cdot 10^{-5}$	19.85	$6.66 \cdot 10^{-9} \pm 1.5$ %
r2	$3.034 \cdot 10^{-4}$	21.52	$5.83 \cdot 10^{-9} \pm 0.2$ %
r3	$9.712 \cdot 10^{-4}$	27.52	$2.51 \cdot 10^{-9} \pm 0.2$ %
Total	$1.288 \cdot 10^{-3}$	24.51	$3.33 \cdot 10^{-9} \pm 0.14$ %

where $\dot{D}$ is in Gy, m in kg, and E' in keV. The calculated total detector response to electrons and photons in the Si at 3.6 cm distance:

$$R_e = 194 \text{ electrons s}^{-1} \pm 2.5\,\% \tag{18}$$

$$R_{ph} = 24.0 \text{ photons s}^{-1} \pm 3.2\,\% \tag{19}$$

The calculated total number of particles detected:

$$R_{total,calc} = 218 \text{ particles s}^{-1} \pm 2.6\,\% \tag{20}$$

7.2 Comparison with Measured Response

The counting rates (particles detected per second) measured without and with the sheet of mylar placed in front of the detector were $CR_{total} = 75.9$ counts s^{-1} and $CR_{ph} = 22.9$ counts s^{-1} in the interval 5 to 140 keV. The background amounted to $CR_{bg} = 0.5$ counts s^{-1}.

Measured total number of detected particles:

$$R_{total,expt} = (CR_{total} - CR_{bg}) = 75.4 \text{ particles s}^{-1} \tag{21}$$

There is a significant difference between the calculated and the measured number of electrons. Assuming that this difference is due to the deadlayer of the detector (a Si layer where particle interactions with energy-loss are not detected), the thickness of this layer can be estimated through MC calculations to be about (more than) 12 μm thick. The manufacturer reports the deadlayer to have a thickness of 0.2 μm, which will not have any significant influence on the MC calculated result.

An explanation for the difference between the measured and the calculated electron response may be that incorrect dimensions for the detector have been reported e.g., the thickness of the Be-window. However, this is not considered very likely. Another reason may be that the EGS4 code is not usable for calculations with low-energy electrons (~1 - 150 keV). This explanation does not seem likely either, since low-energy electron transport has been studied with more agreeable results before [11].

The calculated and measured energy responses are shown in Figs. 13 and 15. It is assumed that the energy distribution of particles detected in regions r1 and r3 is the same as for particles detected in region r2. It must be noted that the MC calculated electron response is multiplied by the ratio of measured electrons to calculated electrons (53/194 = 0.27) to compare the shapes of the energy spectra. Fig. 14 shows the measured and the calculated energy responses assuming a Si deadlayer with a thickness of 12 μm. Furthermore, the calculated electron spectrum is multiplied by the ratio of measured electrons to calculated electrons (53/69 = 0.77) to compare the shapes of the energy spectra.

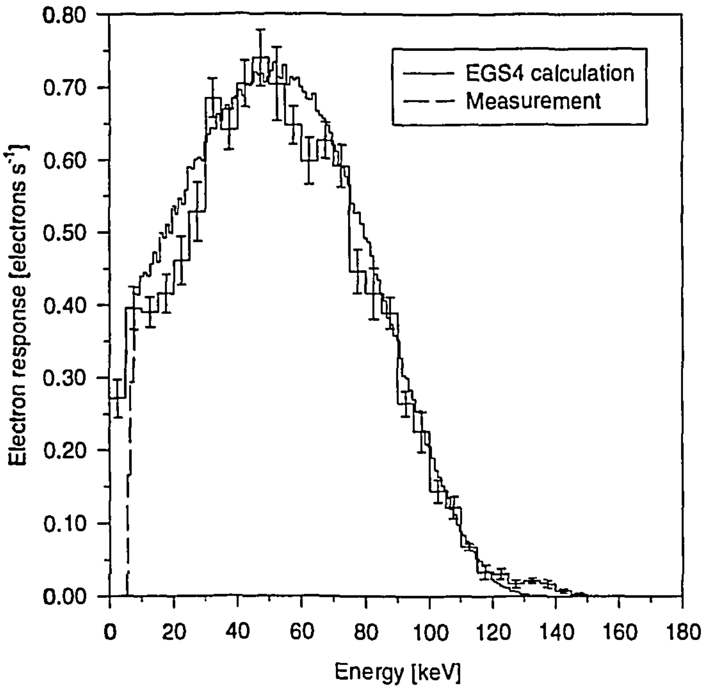

Figure 13. Measured and calculated electron response as a function of energy for the Si(Li) detector. The calculated response in 5 keV bins is divided by 5 to make it comparable with the measured response in 1 keV bins. Furthermore, the calculated response is multiplied by the ratio of measured electrons to calculated electrons (53/194 = 0.27) to compare the shapes of the energy spectra. Average energies are 52 keV and 53.3 keV for calculated and measured response, respectively.

The measured and calculated photon response shows fine agreement. An addition of a 12 μm thick Si deadlayer will not influence the photon response at all. The peak below 5 keV may be caused by the subtraction of the measured photon response corrected for attenuation in the mylar sheet from the measured total response, since the attenuation coefficient is strongly varying at low energies. There will then be some uncertainty on the corrected photon response especially at low energies.

Calculation of the Si(Li) detector response in region r2 with an uncertainty of 1.7 % took about 43 hours on the NRC SGI R4400 computers (1994). A similar calculation with the complete source model would take 10 times longer - about 18 days. Reducing the uncertainty by a factor of 2 would mean an increase in calculation time by a factor 4, since the uncertainty is proportional to $1/\sqrt{N}$, where N is the number of histories. It is thus rather important to simplify the source model.

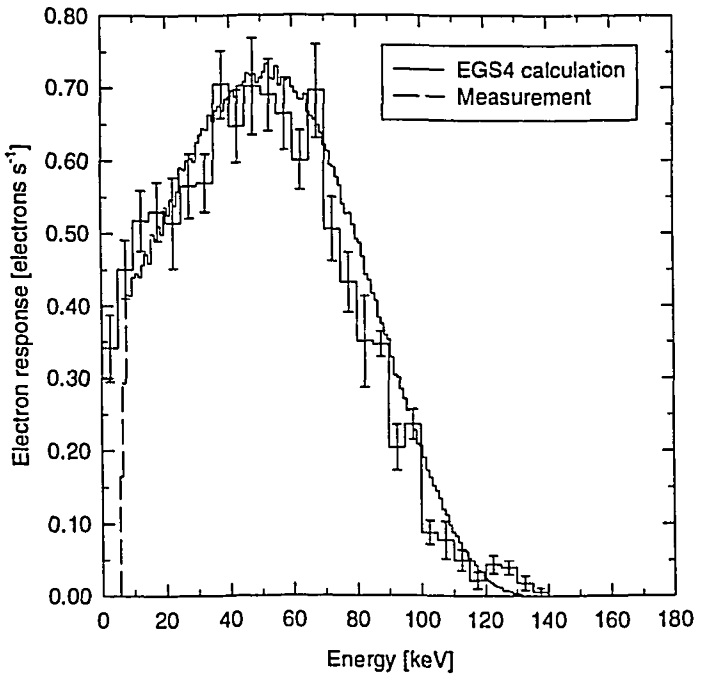

Figure 14. Comparison of measured and calculated electron response as a function of energy for the Si(Li) detector assuming a Si deadlayer 12 μm thick. The calculated response in 5 keV bins is divided by 5 to make it comparable with the measured response in 1 keV bins. Furthermore, the calculated response is multiplied by the ratio of measured electrons to calculated electrons (53/69 = 0.77) to compare the shapes of the energy spectra.

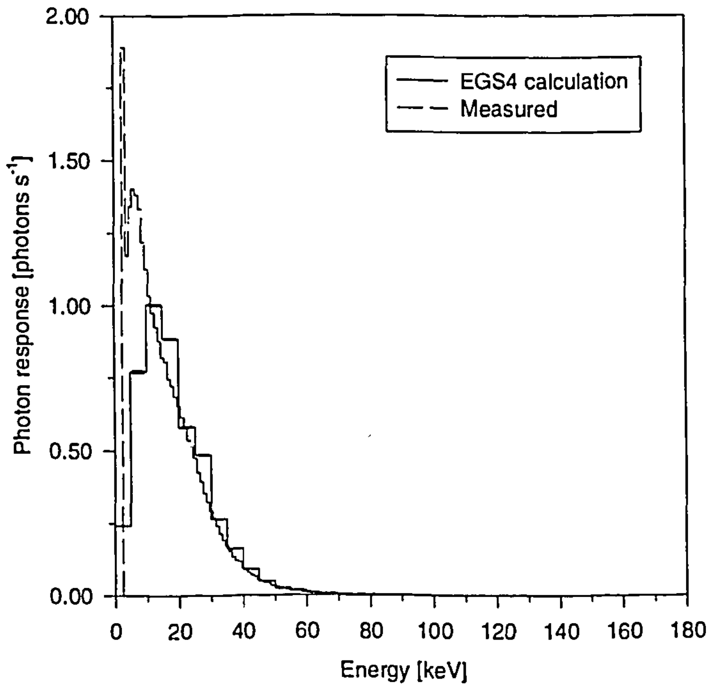

Figure 15. Measured and calculated photon response as a function of energy for the Si(Li) detector. The calculated response in 5 keV bins is divided by 5 to make it comparable with the measured response in 1 keV bins.

8 Conclusions

The Monte Carlo calculated electron spectrum at 5 cm distance from the ^{14}C source has been verified by measurement with a β spectrometer consisting of two Si detectors. A simplified source model which includes the calculated electron and photon spectra at the source surface has been introduced to increase the calculation efficiency, and the normalization factor for complete to simplified source model, F_{CS}, has been calculated for both electrons and photons. It is concluded that the simplified source model is a good simplification of the real source. Using this simplified source model increases the calculation efficiency by a factor of 10, which means that calculations of detector responses will be reduced to a few days instead of weeks.

The measured and calculated photon responses for the low-energy photon spectrometer (the Si(Li) detector) agree well. The measured and calculated electron responses, on the contrary, are different by a factor of 4 for this detector. This may be explained by a Si deadlayer thickness for electron detection of about (more than) 12 μm instead of the 0.2 μm reported by the manufacturer. However, this difference between measured and calculated values should be a subject for further studies.

MC calculations with the EGS4 code has been validated through comparisons with measured data. The achievement of good agreement in this work between calculated and measured data is a verification that MC calculation is a reliable and useful tool for β spectrometry, not only for direct determination of spectra, but also for making analyses of the response of β spectrometers and thus also their spectrometric capabilities.

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Monte Carlo Calculations and Measurements of Spectra from a C-14 Source

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Abstract (Max. 2000 char.)

To perform Monte Carlo simulations it is necessary to model the physical geometries i.e., the source and detector geometry. However, a complete model of the physical geometry may not be possible or may result in a very low calculation efficiency. Substituting the complete source model with a simplified model is one way of increasing the calculation efficiency.
In this report, the study of a simplified model of a ^{14}C source is described. Results of Monte Carlo calculations with the EGS4 code are compared with measurements with a β spectrometer consisting of two coaxial Si detectors, and a low-energy photon spectrometer being a Si(Li) detector.
Calculations and measurements show generally good agreement. However, the difference (a factor of 4) between calculated and measured response to electrons for the Si(Li) detector indicates that this detector has a deadlayer about 12 μm thick instead of 0.2 μm as reported by the manufacturer.
The efficiency of the calculations is increased by a factor of 10, when the complete source model is replaced by the simplified source model. This reduces the calculation time of detector responses to a few days instead of weeks on the NRC SGI R4400 computers.
Good agreement between measured and calculated data also verifies that the MC code EGS4 is a reliable and useful tool for simulating coupled electron and photon transport for particles with energies down to a few keV.

Descriptors INIS/EDB

BETA SOURCES; BETA SPECTRA; BETA SPECTROMETERS; CARBON 14; COMPUTERIZED SIMULATION; E CODES; LI-DRIFTED SILICON DETECTORS; MONTE CARLO METHOD; RESPONSE FUNCTIONS

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