Application of Geant4 for efficiency calculations of a scintillating plastic β-detector

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In a separate report [1], we describe Monte Carlo (MC) studies of the efficiency of a 1-mm-thick plastic detector to few-MeV positrons with three MC programs: Geant4 [2], EGSnrc [3] and Penelope [4]. Simulated results have previously been compared with measured data from standard conversion-electron sources: ^{133}Ba, ^{137}Cs and ^{207}Bi [5]. These MC studies of our β-detector efficiency are important for the measurement of precise β^+-branching-ratios since there is a slight difference in the efficiency of the β-detector for different β-branches. This has an effect on the number of observed β-γ coincidences, over and above the well known efficiency of our γ-ray detector. We report here the final comparison between Geant4 MC simulations and experiment for the three sources, including an absolute efficiency measurement for the ^{207}Bi β-source. A manuscript describing this work has been submitted for publication [6].

The realistic geometric model that was chosen for the simulation is shown in Figure 1 of Ref. [5]; the material composition is also described there. Figure 1 of this report shows the energy deposition into the β-detector generated by the radioactive decay module (RDM) of Geant4 in the case of the decay of ^{137}Cs. Three different electromagnetic (EM) packages were used: standard, low-energy and Penelope (see ref. [1] for more details); normalized residuals in standard-deviation units also shown in the lower panel of the figure for the differences between the low-energy EM package and the other two packages. The resulting total β-efficiencies for three EM physics packages are 15.18(3)%, 15.16(3)%, and 15.11(3)%, respectively, for the low-energy, standard, and Penelope packages, with a low-energy threshold of 50 keV and at a distance of 13 mm from the surface of the radioactive source to the front face of the β-detector. For our superallowed β-decay measurements, our low-energy threshold is set at about 75 keV. Under these conditions, the total β-detector efficiency is 13.80(3)% in all three models. Obviously, it makes no

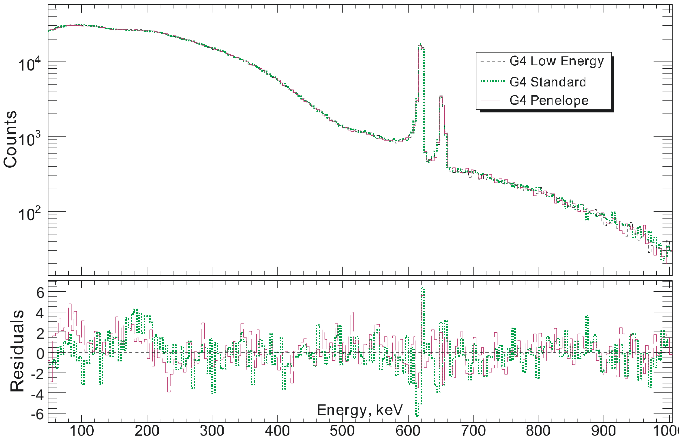

Figure 1. Geant4 MC-generated energy deposition into the β-detector for the decay of ^{137}Cs. Three different EM physics models are used: standard, low-energy and Penelope.

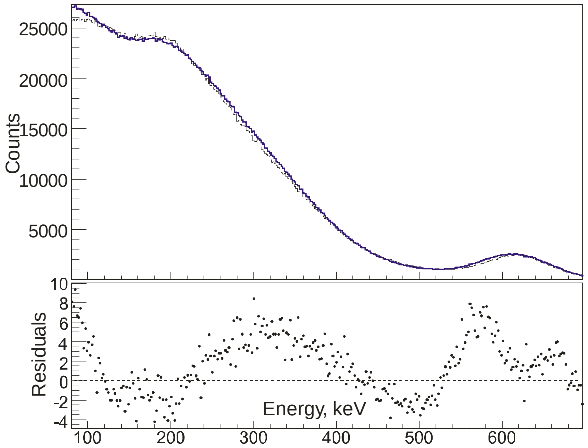

Figure 2. Measured spectrum for the decay of ^{137}Cs, compared to the Geant4 result simulated with the low-energy EM package (thin dashed line – Geant4; thick solid line - experiment).

difference which EM physics model we choose in making our Geant4 MC simulations. For all further simulations reported here, we used the low-energy EM package.

To generate the MC emission spectra we began by programming Geant4 based on the RDM. Although the primary electron spectrum generated by the RDM for ^{207}Bi showed no obvious problems, when we repeated the procedure for ^{133}Ba, to our surprise we found that the electron spectrum produced by the RDM was simply not correct, yielding relative conversion-electron intensities in significant disagreement with ENSDF data. The emission spectrum from ^{137}Cs also turned out to be incorrect, but here the main problem was more subtle: there are two β-decay branches from ^{137}Cs, which are both treated by Geant4 as allowed. In fact both transitions are forbidden, with shape-correction factors that have been determined experimentally by Behrens and Christmas [7]. In addition, the RDM gave the incorrect intensity for one of the conversion electron lines of ^{137}Cs. In both decays - of ^{133}Ba and ^{137}Cs - we bypassed the RDM and inserted each decay mode and transition individually, with the correct intensities for the conversion electrons and the correct shape for the forbidden β-transitions. We did this with the General Particle Source module available in Geant4, which allows the user to define standard energy, angle and space distributions of the primary particle.

Based on a primary spectrum thus generated for each source, the MC code then determined the total energy deposited into the scintillator. However, before this result could be compared with the experimental spectrum, it was necessary to add the effects of statistical fluctuations introduced by the processes of light production and transmission, as well as by photo-multiplication and electronic pulse analysis. For this purpose, we looked to a published study of the response of a plastic scintillator to mono-energetic beams of positrons and electrons [8], which tabulated the width of the full-energy Gaussian peak as a function of energy between 0.8 and 3.8 MeV. Since we also needed to deal with energies lower than that, we made a linear extrapolation to β-energies below 0.8 MeV. All MC spectra were corrected for the resolution of the plastic scintillator by applying this resolution function to the MC data.

In comparing the experimental data with the MC results, we treated two energy-calibration coefficients (*y*-intercept and slope) in each measured spectrum as adjustable fit parameters. For this purpose we used a special C++ ROOT program to fit the shape of the MC results to the experimental data. For all three cases the low-energy cut-off threshold was also chosen as a free parameter in the fit, and from all three fits we obtained the same low-energy threshold, 80±3 keV. The resulting comparisons for our three sources as well as the normalized residuals, for ^{137}Cs, ^{133}Ba, and ^{207}Bi, appear in Figures 2, 3 and 4 respectively.

The agreement between the Geant4 simulations and experiment is good for all three sources, although for ^{207}Bi the normalized χ^2 of 8.9 is less impressive than for the other two (0.4 for ^{133}Ba and 4.0 for ^{137}Cs). In this case, the discrepancy comes partly from the fact that the energy range of the fit, 80 – 1143 keV, was much wider than for the others. It is also possible that the higher χ^2 is caused by our simple linear extrapolation of the results in [8] to describe the peak width in our simulated response function. If the resolution were in fact somewhat worse than this extrapolation indicates - a not unreasonable possibility - then the agreement with experiment could be considerably improved. It is also worth noting that the slight discrepancies in the peak positions evident in all three spectra could be explained by small non-linearities in the experimental energy calibration.

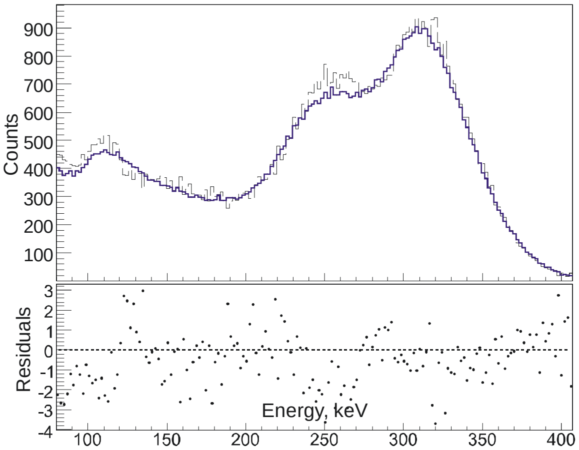

Figure 3. Measured spectrum for the decay of ^{133}Ba, compared to the Geant4 result simulated with the low-energy EM package (thin dashed line – Geant4; thick solid line - experiment).

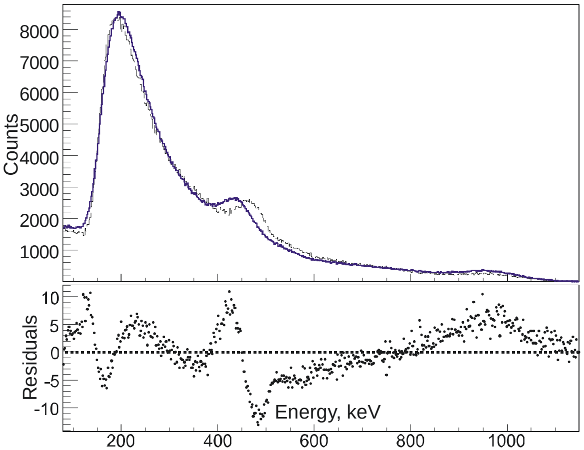

Figure 4. Measured spectrum for the decay of ^{207}Bi, compared to the Geant4 result simulated with the low-energy EM package (thin dashed line – Geant4; thick solid line - experiment).

Although the activities of the radioactive sources that we used for this work are nominally 1 μCi (37 kBq), the accuracy of this value was quoted to an approximate ±15% by the supplier, Isotope Products Laboratory. So that we could get a more precise value for our β-detector efficiency, we made our own measurement of the ^{207}Bi source activity using our well-calibrated HPGe γ-detector [9] to detect the known γ rays from the decay. In this way we established the source activity to be of 1.31(1) μCi as of 16 January, 2008. Now, knowing the activity of the source as well as the low-energy threshold already obtained from our fit, we could deduce from our experimental data the absolute efficiency of the β-detector to be 3.48(2)% at the distance of 13.2(1) mm (as determined with an AccuRange 600^{TM} Laser Displacement Sensor, which has an absolute precision better than 0.1 mm). With exactly this geometry, the Geant4 simulation yielded an absolute efficiency of 3.50(1)%, in excellent agreement with experiment.

We now consider that the quality of the simulations for our plastic β detector is quite sufficient to provide the precision we require for our superallowed β-decay studies.

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