Response function to low energy β particles in a thin plastic scintillator

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Our β-decay measurements require extremely accurate half-life and branching-ratio measurements in order to be competitive in testing the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. While the measurements themselves are simple in principle, the required precision makes them very demanding.

The measurement of a branching ratio requires the simultaneous measurement of β-γ coincidences and β singles. The set-up we use in these measurements includes a 70% HPGe detector 15 cm from the source, and a 1 mm thick plastic scintillator 4 mm from the source on the opposite side. The measuring cycle has been described, for example, in ref. [2]. If the efficiency of the β-detector, ε_β, did not depend on the energy of the incoming particle, then the branching ratio could be extracted directly from the β-γ coincidences and β singles: denoting the total number of observed β-γ coincidences and β-singles by $N_{\beta\text{-}\gamma}$ and N_β we can write

$$\left.\begin{aligned} N_\beta &= N_{decays} \times \varepsilon_\beta \\ N_{\beta-\gamma} &= N_{decays} \times \varepsilon_\beta \times BR_\gamma \times \varepsilon_\gamma \end{aligned}\right\} \Rightarrow \qquad BR_\gamma = \frac{N_{\beta-\gamma}}{N_\beta \times \varepsilon_\gamma} \qquad (1)$$

where ε_γ is the efficiency of the γ-ray detector and BR_γ is the branching ratio for the γ ray of interest. This equation demonstrates the critical role played by the absolute efficiency of the HPGe detector and puts tough demands on its precision, since it is this precision that ultimately limits what can be achieved for the branching ratio. We already know the absolute efficiency of our detector to very high precision [2] having performed a complex series of source measurements along with corresponding Monte Carlo (MC) simulations, the later allowing us to make a reliable interpolation between measured values.

However, there is another factor that affects the result. Equation (1) must be corrected to account for the energy dependence of the response function of the β-detector. In general, any β decay includes several branches, each populating a different state in the daughter nucleus. Each branch has a different end-point energy and consequently has a slightly different probability for detection in the β detector. As a result, the ε_β in the equation for N_β does not exactly cancel with the ε_β in the equation for $N_{\beta\text{-}\gamma}$. This situation becomes even more important in our measurements because of two important factors: (1) as with any detection system, noise must be rejected by a low-energy threshold, which also rejects some low-energy betas; and (2) the nuclei we study have quite high Q-values and decay via branches with a wide range of different end-point energies. To account for these factors, it is important that the numerator in eq. (1) should contain the β-detection efficiency specific to the branch of interest, while the denominator should include the overall β-detection efficiency for all branches. In the case of ^{34}Ar, where Q_{EC} = 6063 keV, the decay populates excited levels in ^{34}Cl ranging from 461 keV to 3129 keV. Thus the end-point energies span a range of more than 2.6 MeV, enough to make variation in the β efficiency quite significant.

As there is no easy experimental access to mono-energetic electrons and even less to mono-energetic positrons, we have opted to examine the experimental efficiency of our detector based on measurements of total spectra, compared with MC calculations that mimic the experimental geometries

and materials. While for the calibration of the HPGe detector we used the CYLTRAN code from the "Integrated Tiger Series" [3], in our study of the β-detector we used the EGSnrc code [4], since CYLTRAN does not distinguish positron from electron interactions, and ignores higher-order effects such as in-flight annihilation. Our initial source measurements and MC calculations revealed the importance of the correct description of the composition and geometry of the source [5]. This prompted us to use in the present measurements only those sources for which we knew the exact geometry and material used in the source, its backing and supporting frame.

In a first series of experiments, we used a home-made ^{60}Co source. It had been prepared from a 10-mm-diameter, 3- μm-thick foil of 99.9% pure ^{59}Co, activated at the Texas A&M TRIGA reactor. After activation, the foil was sandwiched between two 4-μm-thick mylar foils, the whole system being held by a frame whose inner diameter was 15.5 mm with inner edges tapered to minimize electron scattering. Measurements were then made with the source located at distances ranging from 3 mm to 15 mm from the plastic scintillator. Fig. 1 presents an inter-comparison of the experimental and MC-simulated spectra for a source-scintillator distance of 3 mm. The MC simulation was performed with the EGSnrc package [4]. The numerical effort to simulate electron and positron spectra is significantly higher – and more time consuming – than that required to model a gamma spectrum because the slowing down process in the case of the β particles involves thousands of elementary interactions. Thus, when generating a MC spectrum, we used enough computer time to obtain the statistics necessary to define the energy range below about 500 keV and then scaled the spectrum up to match the experimental number of counts. As can be seen from Fig. 1, the MC and experimental spectra are almost identical although for higher energies the MC data show more statistical scatter than the experimental data.

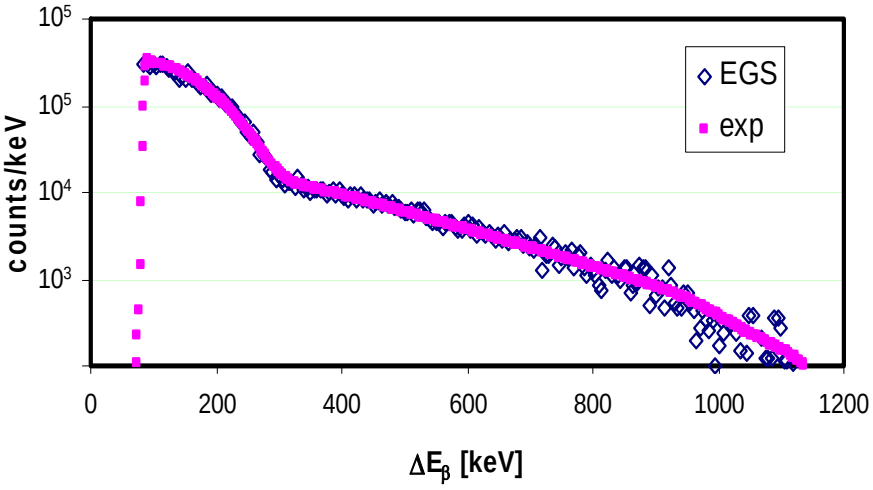

Figure 1. Experimental (solid squares) versus Monte-Carlo [4] (open diamonds) data for the β- spectrum from a ^{60}Co source as recorded by a 1-mm-thick ΔE plastic scintillator.

Since Eq. 1 includes the β-efficiency in both numerator and denominator, only the relative changes in β efficiency are required for a full analysis. However, as a further validation of our MC simulation, we compared the experimental and MC-predicted absolute efficiencies. In the case of ^{60}Co, with a threshold energy of 80 keV we found the experimental efficiency to be 14.5% vs. 14.7% for the MC calculation, which is very satisfactory agreement.

Since ^{60}Co emits electrons and the superallowed decays of interest to us are actually positron emitters, we undertook a second series of experiments, in which we measured a ^{22}Na source, commercially available from Amersham. As with the ^{60}Co source, we measured total spectra at various source-detector distances and compared them with the corresponding MC simulations. Fig. 2 compares the experimental and MC spectra obtained for the ^{22}Na source located 4 mm from the scintillator.

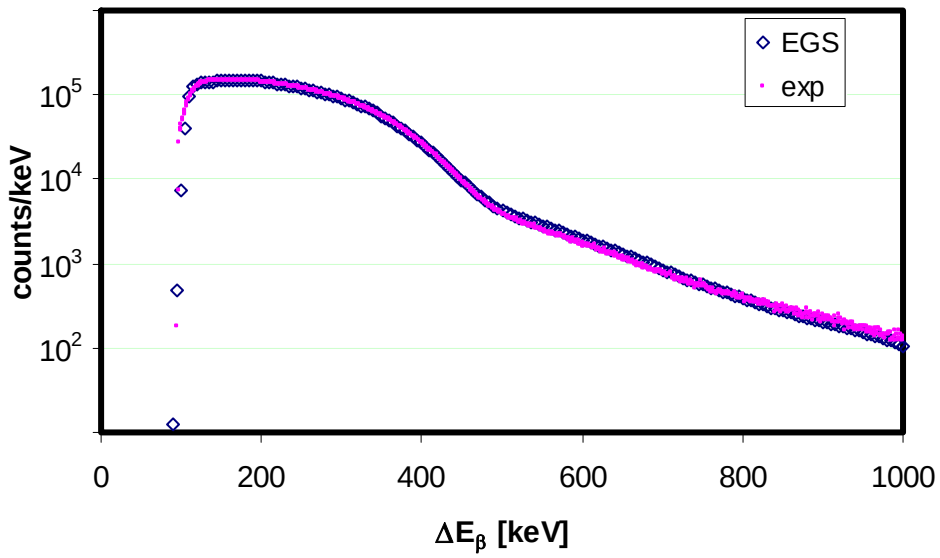

Figure 2. Experimental (solid squares) versus Monte-Carlo [4] (open diamonds). β^+ spectra in the 1mm thick ΔE plastic scintillator as generated by a ^{22}Na source

As this case is closer to our experimental conditions, the MC spectrum was calculated with significantly higher statistics than in the ^{60}Co case. Obviously the MC simulation gives a very good description of the experimental spectrum. We would like to have compared the absolute efficiencies as we had done for ^{60}Co but unfortunately the supplier's information regarding the source dimensions and strength was inadequate. This prompted us to order a new source, specifically designed to suit our purposes with a very thin cover and backing. Measurements on the new source are expected to improve even further our characterization of the response function of our β detector to positrons.

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