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Optimization of a coincidence system using plastic scintillators in 4π geometry

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Abstract

Improvements recently developed at the Nuclear Metrology Laboratory of IPEN-CNEN/SP in São Paulo were performed in order to increase the detector efficiency of a $4\pi\beta-\gamma$ coincidence primary system using plastic scintillators in 4π geometry. Measurements were undertaken and compared to the original system and Monte Carlo simulations of the extrapolation curves were calculated for this new system and compared to experimental results. For this purpose, the code Penelope was applied for calculating response functions for each detector and the code Esquema, developed at LMN, was used for simulating the decay scheme processes.

Keywords: Activity; Plastic scintillator; Cobalt 60; Monte Carlo; Coincidence system; Disintegration rate

1. Introduction

A 4π(PS)$\beta-\gamma$ coincidence primary system using plastic scintillators in 4π geometry has been recently developed at the Nuclear Metrology Laboratory (LMN) of IPEN-CNEN/SP in São Paulo (Baccarelli, 2003; Baccarelli et al., 2003) and the nuclides ^{241}Am, ^{60}Co and ^{133}Ba have been previously standardized with this system. Although good results have been obtained by comparison to conventional $4\pi\beta-\gamma$ coincidence using a proportional counter (PC) as the 4π detector, the beta efficiency was low (60% for ^{60}Co) and some remedial modifications were undertaken.

Modeling by Monte Carlo was introduced in order to predict the extrapolation curve. For this purpose, the code Esquema (Takeda et al., 2005; Dias et al., 2006) was modified to include response tables suitable for this new detector geometry. One factor that becomes important in the simulation is the beta-gamma efficiency, because of the solid nature of the beta detector. For PCs this effect is quite small (<1%) at low gas pressures. This factor was incorporated in the present simulation.

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2. Experimental

The 4π detector is a cylinder having a hole inside for introducing the radioactive source which is placed on a Collodion film held by a stainless steel or plastic ring, as shown in (Baccarelli, 2003). In this original coincidence system, the plastic scintillator is covered with Teflon on all sides except the surface coupled to the photocathode, in order to improve the light collection efficiency by diffuse reflection.

This system has only one photomultiplier tube and the light produced at the scintillator side opposite to the photocathode loses more than 50% of the original light yield before it reaches the photocathode. As a result, the pulse height spectrum consists of two parts: one stemming from the scintillator side close to the phototube and the other stemming from the opposite side of the scintillator, as shown in Fig. 1.

This asymmetry was removed by including an additional photomultiplier tube coupled to the plastic scintillator in a sandwich geometry. In this new geometry, the NaI crystal was placed orthogonally to the phototube axis, as close as possible to the source, as shown in Fig. 2. Two sets of electronics were tried. In the first set, the signals from both phototubes were summed with a sum-invert amplifier and then discriminated by a single-channel analyzer (SCA), as shown in Fig. 3. The output from this SCA fed two gates followed by a time to amplitude converter (TAC) and a multichannel analyzer (MCA).

In the second electronic set, additional discriminators were added to each photomultiplier line which fed a coincidence module, which in turn added signals to the discriminator connected to the single beta line. This procedure was applied in order to include coincidence beta counts, which were masked by noise, along with the single pulses.

The radioactive sources to be measured in the $4\pi(PS)\beta-\gamma$ system were prepared by dropping known aliquots of the solution on $10\,\mu g\,cm^{-2}$ Collodion films. The film holder was made of a stainless steel ring 0.1 mm thick, with 20 mm external diameter and a hole 10 mm in diameter. The best efficiency results were obtained using polyethylene rings 0.15 mm thick as source holders, due to the good light transparency of the polyethylene.

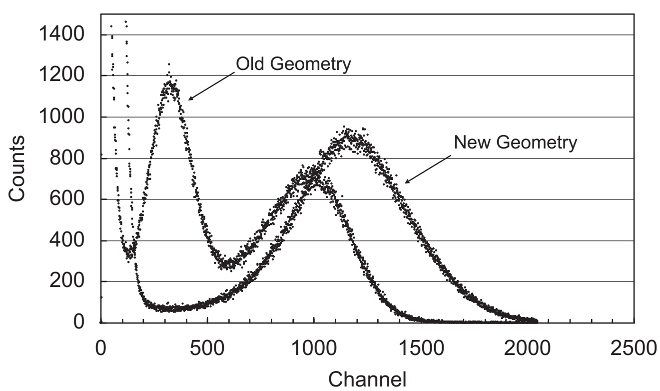

Fig. 1. Plastic scintillator pulse height spectrum for ^{241}Am. Two contributions can be seen: one stemming from the scintillator side close to the phototube and the other stemming from the opposite side of the scintillator.

3. Monte Carlo simulation

The code Esquema (Takeda et al., 2005; Dias et al., 2006), which simulates the extrapolation curve between the observed activity and the efficiency parameter, was applied. The detector response functions were obtained for this new detector geometry by applying the code Penelope (Salvat et al., 2001). Isotropic monoenergetic electron beams were simulated for the plastic detector in the energy range from 5 to 3400 keV in 1 or 3 keV energy intervals. The simulation for photons was performed for the plastic scintillator and NaI crystal in the range from 50 to 1500 keV in 4 keV energy intervals. All individual cases were simulated running Penelope for five million histories each.

4. Results and discussion

The resulting TAC spectrum using the first electronic set up with a ^{60}Co source is shown in Fig. 4. The peak to the left is due to beta singles. The peak to the right corresponds to gamma singles and the middle peak to coincidences. The coincidence peak width was 46 ns, which is much narrower than the case of a PC, as expected. This feature allows higher counting rates as compared to PC coincidence measurements. It was observed that the beta efficiency for ^{60}Co increased from 60% using the old coincidence system to 77% in this new system.

Using the second electronic setup and including delay modules, the TAC spectrum is modified, showing two coincidence peaks, as shown in Fig. 5. The left peak in the middle region is due to coincidences between beta singles and gamma singles. The right peak in the middle region corresponds to coincidences between beta–beta coincidences in the noise region and gamma singles.

Measurements with a ^{60}Co source showed that part of the beta–beta coincidences are transferred to the peak corresponding to coincidences between beta singles and gamma singles. This can be explained because a low amplitude beta pulse placed in the noise region is more

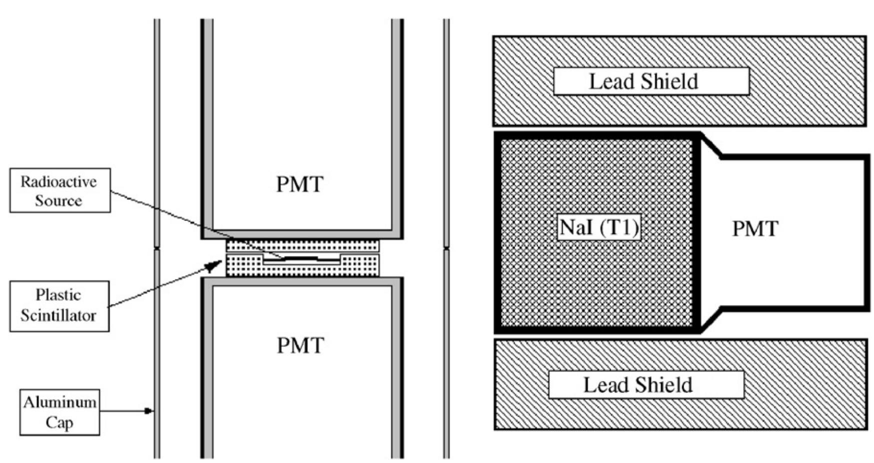

Fig. 2. . New geometry developed for the $4\pi(PS)\beta-\gamma$ coincidence system.

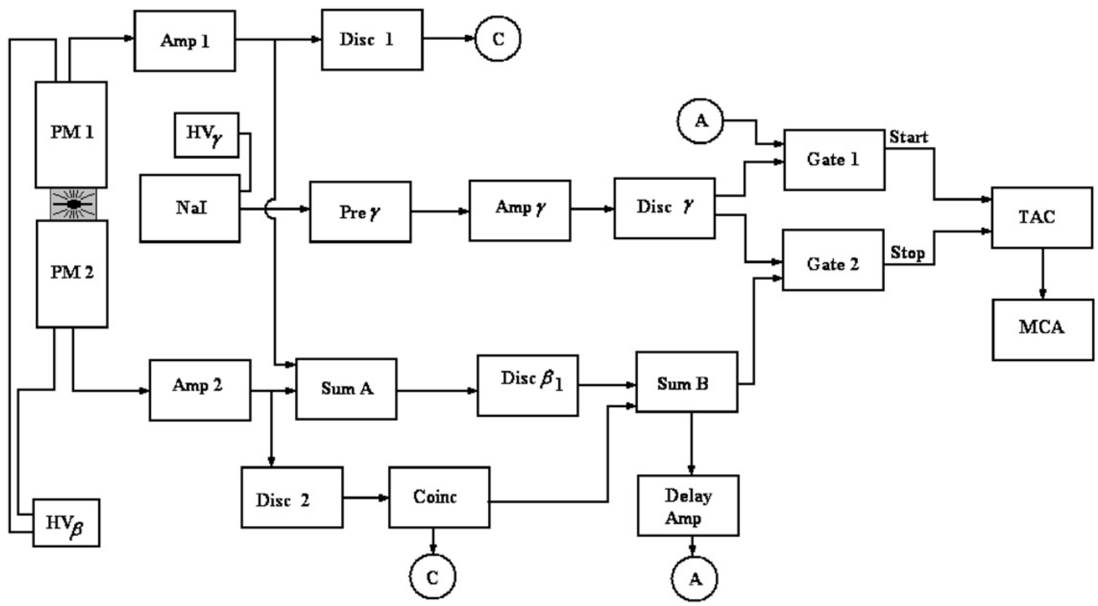

Fig. 3. Electronic diagram of the $4\pi(PS)\beta-\gamma$ coincidence system.

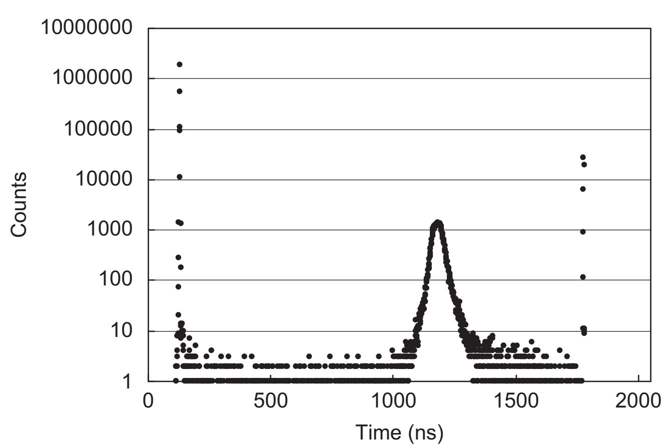

Fig. 4. . TAC spectrum using the first electronic set up with a ^{60}Co source. The peak to the left is due to beta singles. The peak to the right corresponds to gamma singles and the middle peak to coincidences.

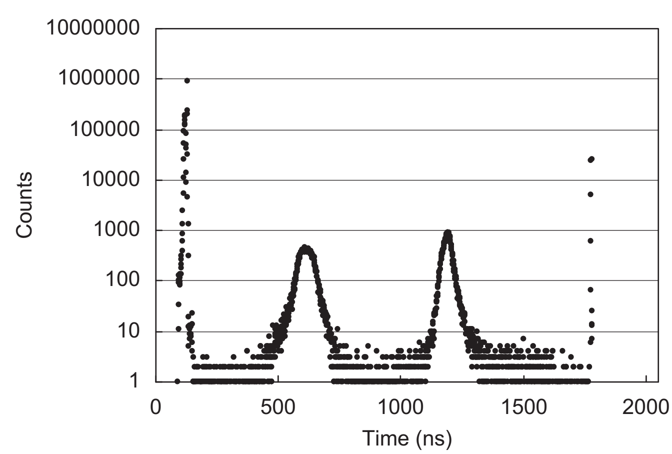

Fig. 5. TAC spectrum using the second electronic setup. The right peak in the middle region is due to coincidences between beta singles and gamma singles. The left peak in the middle region corresponds to coincidences between beta–beta coincidences in the noise region and gamma singles.

likely to be in coincidence with a larger beta pulse placed above noise, coming from the other side of the plastic scintillator. This latter pulse would be normally detected and placed in the peak due to beta singles and gamma singles. As a result the coincidences between beta pulses in the noise region do not add counts significantly to the beta–gamma coincidence peak.

Simulations with the code Penelope showed that most electrons below 1 keV do not reach the plastic scintillator because they are absorbed in the 3 mm high 20 mm wide air space located between the two sides of the plastic scintillator, necessary for introducing the radioactive source, which is held by a Collodion film placed on a stainless steel or plastic ring. Alternative means of placing the source are being examined in order to overcome this limitation.

The beta–gamma efficiency (the gamma efficiency of the 4π detector) becomes important in the present coincidence system because of the solid nature of the 4π detector. At zero discrimination level, this efficiency calculated by the code Penelope increases from 4.7% at 4.5 keV to a maximum of 12% at 50 keV then decreases to 4.0% at 1.4 MeV. This effect tends to increase the slope of the extrapolation curve between the observed activity ($N_\beta N_\gamma/N_c$) and the efficiency parameter $(1-N_c/N_\gamma)/(N_c/N_\gamma)$. However, in some cases part of this effect is compensated by gamma–gamma coincidences.

For instance, ^{60}Co has two gamma rays in cascade. One may be detected in the plastic scintillator and the other in the NaI, resulting in a coincidence, which decreases the slope of the coincidence curve. For complex decay schemes

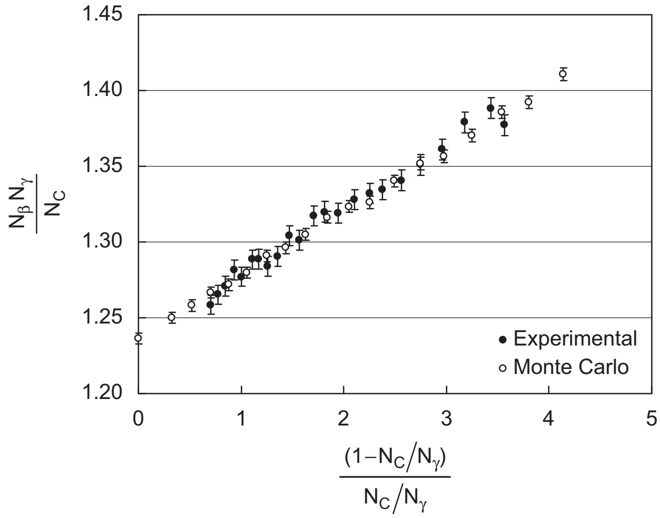

Fig. 6. Extrapolation curve for ^{60}Co obtained with 4π(PS)$\beta-\gamma$ coincidence system. The closed dots are experimental values and the open dots are Monte Carlo calculation.

this effect may be more pronounced. Fig. 6 shows the extrapolation curve for ^{60}Co obtained with this new system.

The observed slope is 3.5%, about half the value of the beta–gamma efficiency calculated by Monte Carlo, which is around 7.1%, after summing the two gamma ray contributions. This indicates that there are coincidences between one gamma ray detected in the plastic scintillator and the other gamma ray, detected in the NaI crystal. The experimental extrapolation curve was well reproduced by a new version of code Esquema, which takes into account gamma–gamma coincidences, as shown in Fig. 6.

5. Conclusion

The improvements incorporated in the new system increased the ^{60}Co beta efficiency from 60% to 77%. This value is not yet considered satisfactory. Further improvements are foreseen which includes reduction of the air space between the two parts of the plastic scintillator. This effect can be simulated by code Esquema, using new response functions calculated by Penelope.

The experimental results showed that the use of beta–beta coincidences did not contribute significantly to improve the beta efficiency. Therefore, the additional complexity in the electronic system may not be justified.

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