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Perspectives on the measurement of competitive double gamma decay with the AGATA tracking array

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Summary. — The double-gamma decay is a second order electromagnetic process where two photons are emitted simultaneously. It is characterized by low branching ratios, making its measurement interesting both theoretically and also experimentally. Although this process has been already observed in the past, a recent publication claimed its observation in competition with the single gamma decay. A measurement of this process with the AGATA spectrometer (Advanced GAmma Tracking Array) will deliver more detailed results. A test of feasibility of this challenging measurement has been performed through GEANT4 simulations of the decay of the ^{137}Ba isotope. Particular emphasis is placed on the tracking algorithm which allows to reconstruct a scattering gamma-ray event based on the position and energy of every interaction point within the AGATA germanium detector.

1. – Introduction

The double-γ decay, consisting in the prompt emission of two photons, can occur between states where a single photon transition is prohibited (*i.e.* $0^+ \rightarrow 0^+$ transition) as well as in competition with the single γ-emission or other decay processes. In the first case this decay mode was first observed in 1959 and following decades [1, 2], however a recent article [3] was published in Nature regarding the first measurement of this process in competition with the single-γ decay. The authors studied the ^{137}Ba $\frac{11}{2}^-$ state, that decays via the emission of two photons with a branching ratio of $\approx \Gamma_{\gamma\gamma}/\Gamma_\gamma = (2.05 \pm 0.37)\,10^{-6}$. The first observation made use of an array of $LaBr_3$ scintillators, taking advantage of the good timing properties of these detectors to distinguish real events from a background composed by natural radiation and Compton scattering (CS) between detectors. While some attempts of measuring this decay with High Purity Germanium (HPGe) detectors have been carried out [4], none of them delivered a positive outcome. A measurement of the process with AGATA could not only provide a higher energy resolution, but also allow for precise angular distribution measurements and thus investigations about transition multipolarity.

The intent of this contribution is to present a preliminary study of the capabilities of AGATA to measure the competitive double-γ decay making use of the GEANT4 simulation tool.

1˙1. *The AGATA array.* – The AGATA array [5] represents a state-of-the-art γ-ray spectrometer, combining the high energy resolution of HPGe detectors with a highly efficient array featuring an unprecedented angular resolution.

The principle behind a γ-tracking array such as AGATA is to exploit multiple segmented crystals in order to detect not only the energies of the γ interactions within the array, but also their positions; this allows for the reconstruction of the path followed by the photon.

The position of the interaction is extracted by means of the Pulse Shape Analysis (PSA) algorithm. The data is later fed to the tracking algorithm [5, 6], which employs statistical considerations based on the interaction cross-section as well as the Compton formula (eq. 1) to reconstruct the original event, *i.e.* the direction of emission of the γ rays and their energy.

$$E' = \frac{E_0}{1 + \frac{E_0}{m_e c^2}(1 - \cos\Theta)} \tag{1}$$

Here E' and E_0 are the energies of the Compton-scattered and the incident photon respectively while Θ represents the scattering angle. Various algorithms exist to perform the tracking of a photon, however this contribution focuses on OFT [6] (Orsay Forward Tracking), which is characterized by three parameters that can be tweaked to better adapt the response of the code to the physics of interest.

1˙2. *Challenges.* – One of the main challenges to face, aside from the background radiation unavoidably present, consists to keep under control a particular class of events: a γ ray emitted in the single-photon decay that interacts in one part of detector via CS and later deposits the remaining energy in the array. OFT reconstructs scattered events up to a certain precision and it is possible for a single photon to be reconstructed with multiplicity two or higher. Since the deposited total energy is the same and the interaction time difference is indistinguishable for a HPGe detector, the signatures of a real double-γ event and a secondary scattered photon are the same.

2. – The simulation and the tracking performance

The simulation of the response function of the array is carried out in various steps: single or double photons are generated randomly with the correct angular and energy distributions [3], the interaction of radiation with matter is simulated with GEANT4 and the returned interaction points are later analyzed by OFT. In order to optimize the tracking parameters, the same number of double- and single-γ events have been tracked with several sets of parameters. A total of 3×10^6 events for both single and double γ were used. It is necessary to select parameters that not only minimize the yield of

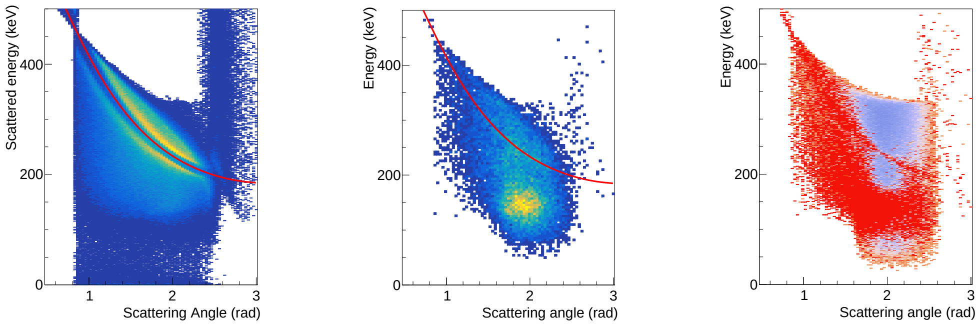

Fig. 1. – Comparison of the correlation between scattering angle and energy of mis-tracked single-photon, for the typical OFT parameter values (left) and optimized parameters (center) together with CS equation (eq. 1) in red. (right) In red are shown regions of prevalence of the mis-tracked single events and in blue of correctly tracked double-γ.

mis-tracked γ, but also maximize the number of correctly reconstructed double-γ events. A reconstructed event was accepted as either a wrongly tracked single γ or a correctly tracked double-γ if the energy sum was within 2 keV from the transition energy and the distance between the first interaction points of the two reconstructed photons was larger than 125 mm, since a large fraction of incorrectly tracked single γ populates this region. The optimal combination of the tracking parameters was found by grid search as the ratio was not showing rapid variations. With respect to their typical values, the resulting parameters were able to decrease the number of incorrectly reconstructed single γ by about 1.5 orders of magnitude.

Correlations between observables can be used to estimate the performance of OFT. Figure 1 (left), for instance, shows the correlation between scattering angle and energy of events reconstructed as double γ with the typical parameters. A strong correlation is observed close to the CS formula (eq. 1, red line). This feature is no longer present with the optimized values (central panel) resulting in a more uniform distribution. Simulating double-γ events, it is possible to identify areas, in red (right panel), with prevalence of mis-tracked γ and areas, in blue, where events of interest (double-γ) are dominant.

Table I shows the calorimetric efficiency ϵ, the ratio $R_i\epsilon$ between multiplicity two and total simulated events, the similar ratio $R_i'\epsilon$ excluding regions in red (Fig. 1) and the same quantity R_i', taking into account the efficiency of single- (γ) and double-γ ($\gamma\gamma$) decays. The ratio between these values needs to be compared with the branching ratio of the competitive double-γ decay. These results impressive but still below the needed level of sensitivity.

Table I. – *Simulation results for single- and double-γ decay for optimized OFT parameters.*

Event Type	ϵ	$R_i\epsilon$	$R_i'\epsilon$	R_i'
γ	8.97×10^{-2}	7.04×10^{-5}	3.81×10^{-6}	4.24×10^{-5}
$\gamma\gamma$	1.78×10^{-2}	3.27×10^{-3}	1.15×10^{-3}	6.47×10^{-2}
Ratio $\gamma/\gamma\gamma$	5.04	2.15×10^{-2}	3.31×10^{-3}	6.55×10^{-4}

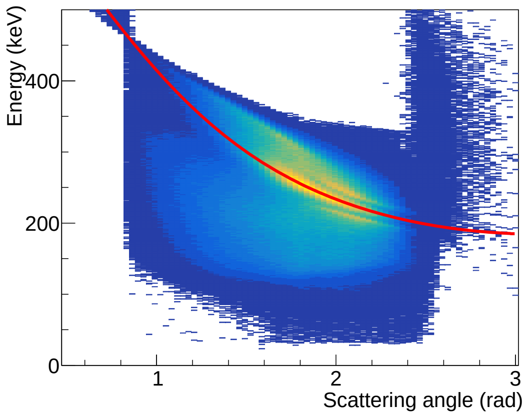

Fig. 2. – Correlation plot between scattering angle and energy for the experimental data.

3. – Preliminary experimental considerations

A preliminary data set of approximately 50 h of ^{137}Cs source has been analyzed which allowed to estimate that for a total of 10000 double-γ events, 260 TB f disk space are needed. From this data set it was observed, for instance, the tendency of the PSA to cluster interaction points, thus biasing the hit position determination. A complete study of the clusterization effect on the OFT outcome will further improve the knowledge of the performances of AGATA. The stability in time of the system has been tested with single segments not showing fluctuations (> 1 keV) in the time lapse of approximately of 50 hrs. Figure 2 shows the experimental correlation between scattering angle and energy of events reconstructed as double γ with the optimal OFT parameters. The picture shows a strong correlation in correspondence with the CS, a feature not observed in the simulation (Fig. 1 (center)).

4. – Conclusions

While this measurement constitutes an experimental challenge, improvements are expected in the near future, such as a more precise position determination and uncertainty estimation. Moreover, a more refined statistical analysis in the event tracking algorithm could improve its performance [7]. The planned increase of the solid angle coverage of the AGATA array will increase the sensitivity to the double-γ detection, opening new possibilities for the measurement of double-γ decays in other nuclei.

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