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^{137}Ba Double Gamma Decay Measurement with GAMMASPHERE

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Abstract. The study of the electromagnetic moments (EM), and decay probability, provides detailed information about nuclear wave functions. The well-know properties of EM interactions are good for extracting information about the motion of nucleons. Higher order EM processes always occur, but are usually too weak to be measured. In the case of a $0^+ \rightarrow 0^+$ transitions [1, 2], where a single gamma transition is forbidden, the simultaneous emission of two γ-rays has been studied. An interesting opportunity to further investigate 2-photon emission phenomena is by using a standard ^{137}Cs source populating, via β-decay, the $J^\pi = 11/2^-$ isomeric state at 662 keV in ^{137}Ba. In this case, two photon process can have contributions from quadrupole-quadrupole or dipole-octupole multipolarities in direct competition with the high multipolarity M4 decay. Since the yield of the double gamma decay is around six orders of magnitude less than the first order transition, very good statistics are needed in order to observe the phenomena and great care must be taken to suppress the first-order decay. The Gammasphere array is ideal since its configuration allows a good coverage of the angular distribution and the Compton events can be suppressed. Nevertheless the process to understand and eliminate the Compton background is a challenge. Geant4 simulations were carried out to help understand and correct for those factors.

1 Introduction

An interesting phenomena that has been studied since the beginning of quantum electrodynamics is the second-order EM process involving the decay of states by the simultaneous emission of two photons. This process was first mention by M. Goppert [3] and has been extensively studied in atomic transitions. For nuclear decays this type of emission has been studied for cases where the first order process is forbidden, such as the decay of excited $J^\pi = 0^+$ states in ^{16}O and ^{40}Ca. In the case where the direct transition is not forbidden the two photon decay as a secondary EM process becomes very shadowed and difficult to observe.

The ^{137}Cs source is frequently assumed to have a single 662 keV γ-ray and is one of the best cases for seeking competition between first and second order decays. In fact, there is another low-lying γ-emitting state and the 2.55 min $J^\pi = 11/2^-$ isomer has two branches, the decays from this state are shown in Figure 1 including the new branch [4].

It is necessary to take this two-step decay into account and consider how this will affect a measurement of simultaneous 2-photon emission. Part of the difficulty is that the true second order decay is only phase-space constrained, so the 2-photon just have to add up to 662 keV but are continuous distributions.

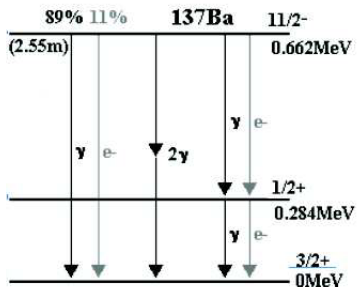

Figure 1. Decay of the isomer level $11/2^-$ of ^{137}Ba.

2 Experimental Setup and Analysis

In principle, one just needs a single γ-ray detector and a source in order to observe both the cascade γ-rays and the 2-photon decay. We take advantage of the Gammasphere array which is a well known device for nuclear spectroscopy and nuclear structure research [5]. The array has more than 100 HpGe detectors each surrounded by a BGO Compton suppressor. For this experiment only a selection

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of 68 detectors were used avoid the scattering from the back of the array.

The excellent energy resolution of the HpGe, ~1 keV at 300 keV, is ideal for the measurement of the discrete gamma lines, and allows great sensitivity for the low intensity branches. The high segmentation of the array allows a reduction of the rate measured in each detector and permits a selection of the pair of detectors where the probability for Compton scattering is low.

The aim is to measure the decay in ^{137}Ba after β-decay from a ^{137}Cs standard calibration source. The source used has an activity of 19.27(58) μCi, and was measured during two weeks, collecting a total of $\sim 5 \times 10^9$ events. Details of the experiment and data sorting procedure are described in Ref. [4].

A first selection of the desired events is made by using a double trigger, where only events where two different detectors are activated are recorded. This helps in reducing the huge number of events coming from the single photon 662 keV branch from the $11/2^-$ state directly to the $3/2^+$ ground state ($\sim 7 \times 10^5 \gamma/s$). Even with Compton suppression, there are a large number of triggers (~7000/sec) coming from the 662 keV scattering between two counters and creating a false trigger.

3 Sort and Analysis

For true 2-photon events, the distribution is peaked at near equal energies. A useful analysis approach is to select data with only two detectors firing and with a total (calorimetric) energy of 662 keV. The "energy-difference" spectrum should then reveal the 2-photon distribution. For Gammasphere this distribution is still Compton dominated and a further sort criteria is needed. A useful parameter is the opening angle between counters, θ_{12}.

To observe the distribution of events a matrix of energy difference vs. opening angle between pairs of detectors is shown in Figure 2. The stripes observed for the opening angle (θ_{12}) are due to the angular separations of each detector pair and is calculated for the value at the center of the detectors. Since BGO detectors fill the area between the Ge counters it is not a continuous distribution of θ_{12}. For near 180° scattering, the γ-rays can freely backscatter across the array and result in well defined "horns" in the distribution with energy differences around ±293 keV.

The region of opening angles near 90° has the least Compton scattering, so this is where the opportunity to find the true 2-photon emission is highest.

To observe the 2-photon events a projection of opening angles from 85° to 95° in Figure 2 has been plotted in Figure 3. The two step cascade peaks show up as two well defined small peaks at ±94 keV. The two broad peaks from the Compton scattering are superimposed on to a distribution of events that we consider to come mainly from the two photon events. It has been measured in Ref [4] that the 378-keV gamma decay from the well-known 662-keV isomer in ^{137}Ba is a small branch, only 1.12(9)×10^{-7}. This cascade branch is ~30 times weaker than the theoretical estimate for the two photon decay and will not have any practical effect in the observation of the two photon decays. However, the challenge is to verify that those events that build the "bump" are genuinely two photon events and quantify the true 2-photon branch. The concern is that some of the bell shaped distribution still comes from some complicated manifestation of Compton scattering which artificially augments the true 2-photon signal.

4 Simulation

Lately there has been widely used and developed Monte-Carlo simulations that include accurate description of the physical phenomenologies that undergo, in this case, the radiation matter interactions. Together with the geometrical description of the detectors array it is possible to simulate the complete detection process. We have used the CERN toolkit Geant4 [6] to simulate the Gammasphere array, the base of the detector geometry has been provided by the GFNUN [7], the geometry includes each HpGe crystal and a close approximation of the six BGO wedges surrounding each germanium crystal, as well as one BGO cube in the back of each crystal. Neither the heavy metal cover of the Ge crystal generally used to shield the low

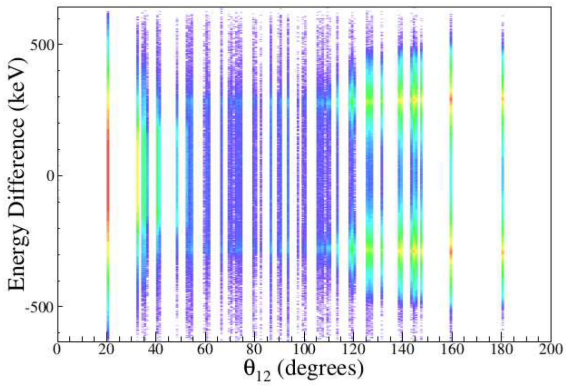

Figure 2. Energy difference for Compton scattered gamma rays as function of the separation angle θ_{12}, the intensity is represented in color code with the maximum being red and the minimum purple.

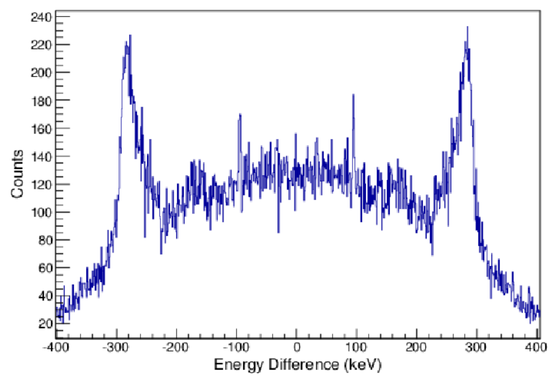

Figure 3. Projection of the measured energy difference for events with opening angles from 85° to 95°

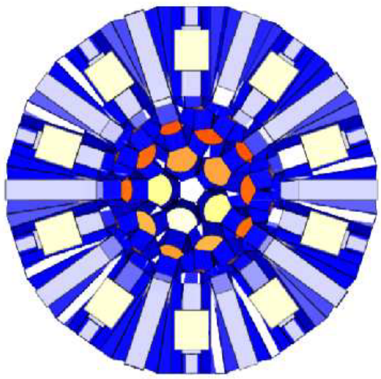

Figure 4. Geant4 simulation of Gammasphere including the Ge crystals (white) and the BGO detectors (blue).

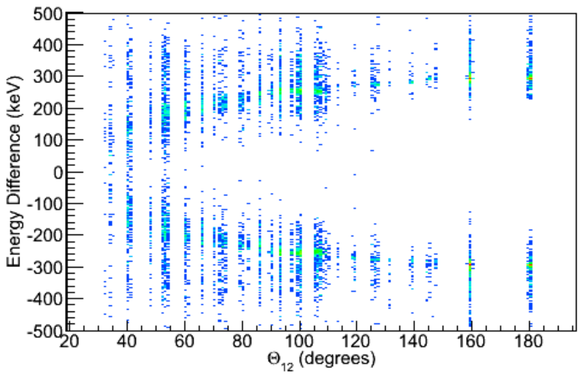

Figure 5. Simulated energy difference between a detector pair vs. opening angle.

energy radiation, nor the aluminum capsules or the liquid nitrogen containers have been included.

Figure 4 shows one of the spheres of the full Gammasphere array simulated, the white cubes represent the Ge crystals and the blue wedges the BGO scintillators. With this geometry we can construct a similar plot for the energy difference deposited in a pair of detectors as a function of the opening angle as it was done for the experiment. Since this simulation does not include background or the double gamma cascade all the events that activate two detectors are always due to Compton scattering.

As shown in Figure 5, there are very specific discrepancies between the experimental and simulated data. The main issue is that there are no events detected around 20°. In the simulation due to the high efficiency of the BGO detectors it is very unlikely that a gamma ray will be scattered into two adjacent Ge detectors without being absorbed by the BGO suppressor. Clearly, the functionality of the suppressors is not just geometric. We find there are almost no events around zero energy difference for angles greater than 60°, which implies there is an excellent chance to observe the 2-photon decay in that region without being affected by the Compton events.

5 Perspectives

To corroborate the results of the simulated events another well tested simulation of the GRETINA array has been used in the same way to observe in more detail the effects of the Compton scattered events. These latest results, shown in Figure 6, prove that we can emulate the distribution of events that form the two "horns" for different angles, but the value of opening angle selected in the simulation to reproduce the 90° distribution is 120° ± 5°, the implications of this have to be discussed. Even though there is a good possibility for the reproduction and subtraction of the Compton events, there has to be a good understanding of all the characteristics of the Compton scattering profile to proceed.

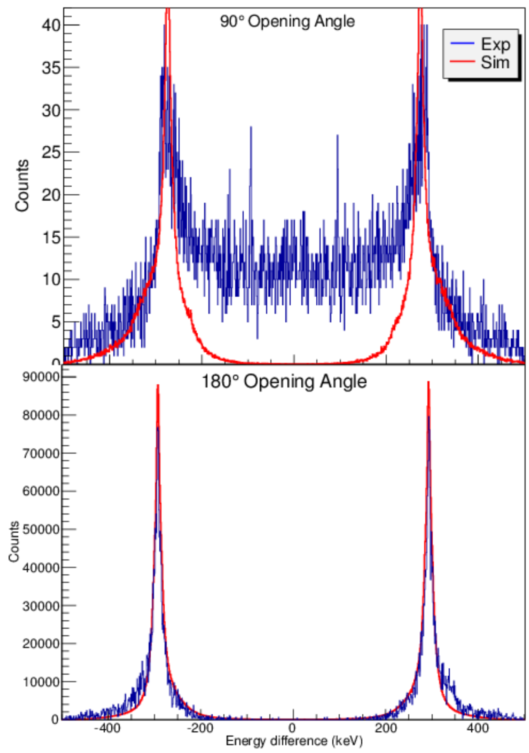

Figure 6. Comparison of the experimental and simulated (GRETINA) projections for the opening angles at 90° and 180° (±5°) on the energy difference.

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