INVESTIGATION OF RARE NUCLEAR DECAYS — DOUBLE GAMMA DECAY IN ^{137}Ba NUCLEUS*

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Double gamma decay is a rare nuclear decay process first studied in 1930 by Maria Göppert-Mayer in her doctoral thesis. In this decay process, an excited nuclear state decays to a lower-lying state via a virtual intermediate state and emits two photons simultaneously. The sum of the energies of these two photons corresponds to the energy difference between the initial and final states. So far, this type of decay has been mainly observed in nuclei for which single-photon decay is forbidden ($0^+_2 \rightarrow 0^+$ transitions). The only case in which double gamma decay competes with a single gamma decay has been measured is ^{137}Ba. This paper contains information on the experimental setup developed at the Institute of Nuclear Physics Polish Academy of Sciences, Kraków (IFJ PAN) for the measurements of the double gamma decay. We present preliminary results for the study of the ^{137}Ba $11/2^-$ excited level double gamma decay, which was chosen as the reference case, before starting the systematic study of this rare process.

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1. Introduction

Double gamma decay is an electromagnetic process in which two photons are emitted simultaneously which was theoretically predicted in 1930s [1]. It can occur between states where a single-photon transition is forbidden due to spin conservation ($0^+_2 \rightarrow 0^+$ transitions) and has been measured in the ^{90}Zr [2, 3], ^{40}Ca [2, 3], and ^{16}O [3, 4]. In addition, double gamma decay can be observed when it competes with single gamma emission or other nuclear decay processes, as shown for the case of ^{137}Ba in Ref. [5]. This experiment was performed with two NaI detectors which measured the branching ratio

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of the transition probabilities for the first-order (single-gamma) and second-order (double-gamma) processes of $6.4 \pm 3.1 \times 10^{-6}$ [5]. Later, the theoretical description of this decay mode was developed in the work of Grechukhin [6], followed by Friar [7]. Since the 1990s, several attempts have been made to measure the ^{137}Ba $\gamma\gamma/\gamma$ branching ratio [8–10]. One of the experiments with the GAMMASPHERE setup led to the measurement of the E5 transition de-exciting the $11/2^-$ level in ^{137}Ba nuclei [11] (see the partial level scheme in figure 1). Finally, the use of modern scintillator-based detectors with very good time and energy resolution allows to measure the $\gamma\gamma/\gamma$ branching ratio at $2.05(37) \times 10^{-6}$ [12] and $2.62(30) \times 10^{-6}$ [13]. The investigation described here focused on reducing possible background sources and verifying the observation of the double gamma decay process for the excited state in the ^{137}Ba nucleus aiming to validate the setup developed at IFJ PAN.

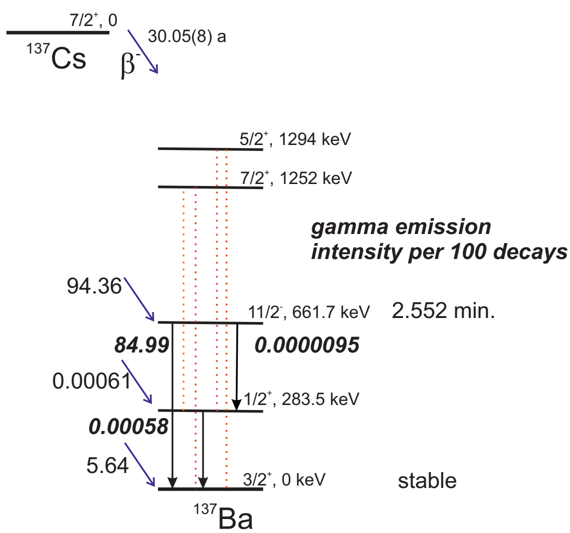

Fig. 1. (Colour on-line) Level scheme of the ^{137}Ba gamma de-excitation of states populated in the β decay of ^{137}Cs. Level energies and branching values taken from NNDC [14] and Ref. [11]. Black arrows mark gamma-ray transitions, while with dotted red lines double gamma-ray de-excitation process is marked.

2. Experimental setup

The experiment was performed in IFJ PAN using two PARIS [15] phoswiches, both of the $CeBr_3$:NaI type. These detectors have a good energy resolution of about $\frac{\Delta E}{E} \sim 4\%$ at 662 keV, as well as very good time resolution $\sigma \sim 0.3$ ns for ^{60}Co energies. In addition, the $CeBr_3$-type material does not contain strong internal radioactivity as observed in the $LaBr_3$-type scintillators [16]. A schematic view of the setup is shown in figure 2, where marked with blue colour (No. 1) there are the active volumes of $CeBr_3$ crystals (cubic size $2'' \times 2'' \times 2''$) coupled with NaI parts of phoswiches (red colour, No. 2) of $2'' \times 2'' \times 6''$ size. Both phoswiches were shielded with the 10 cm thick lead (light grey, No. 4), with additional tungsten bricks in between (dark grey, No. 3) to suppress the direct scattering of gamma rays between the detectors. The 860 kBq ^{137}Cs point source was placed at a distance of 17 cm from the detectors, which were arranged at an angle of 72° to each other. Data were collected using Caen ADC V785 coupled to the BaFPro module with gain amplification and constant fraction discriminator, and a TAC Ortec model 566.

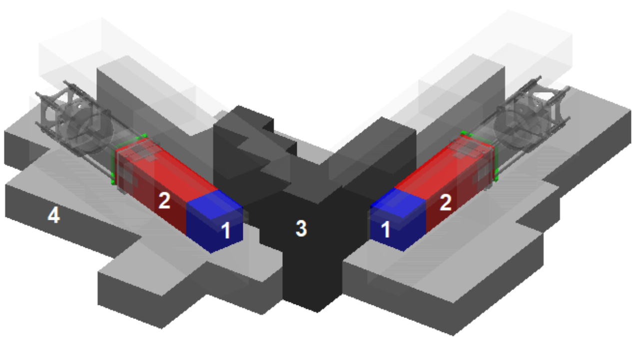

Fig. 2. (Colour on-line) Schematic view of the experimental setup with two $CeBr_3$:NaI phoswiches (blue, No. 1: $CeBr_3$ and red, No. 2: NaI parts) surrounded by 10 cm tungsten (dark grey, No. 3) and lead (light grey, No. 4) absorbers.

The series of Geant 4 [18] simulations were performed to find an optimal shielding aimed at suppressing the external background from cosmic rays as well as other sources of natural radioactivity. Another important requirement for the simulations was the avoidance of direct gamma-ray scattering between the $CeBr_3$ parts of the phoswiches. This was achieved by using the tungsten absorber, which consists of cubes with an edge length of 5.5 cm. The response function of the measured gamma-ray energy deposits was compared with simulations for a series of isotopic sources: ^{22}Na, ^{137}Cs, ^{152}Eu, ^{60}Co, and ^{88}Y.

Finally, the simulations of the full setup were compared with the measured spectrum for ^{137}Cs, which contains random coincidences that are one of the main origins of the background. For the experimental and simulated data, the energies measured with $CeBr_3$ parts were summed under the condition that their energy deposits E_1 and E_2 satisfy the condition $\|E_1 - E_2\| < 300$ keV, which prevents summation of the Compton backscattering of gamma rays on the target itself [19]. Energy deposits in the NaI part of the phoswiches were used as a veto, allowing for high-factor suppression of the cosmic ray background. The comparison between simulated and measured summed energy deposits for random coincidences of ^{137}Cs decays is shown in figure 3 and shows very good agreement, proving that the detector response is well described by the simulation software.

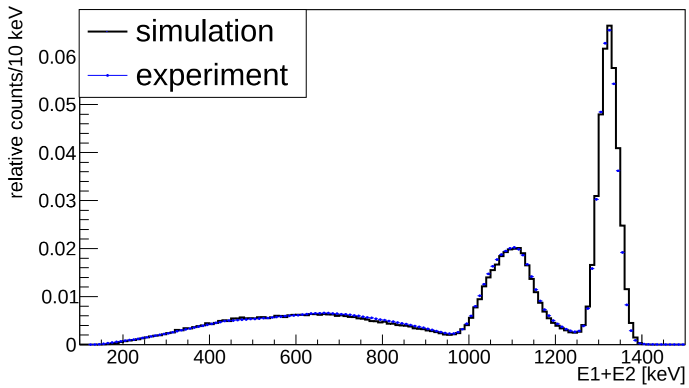

Fig. 3. Comparison between simulated (black line) and experimentally measured summed energy deposits of random coincidence (blue/gray dots) for ^{137}Cs source used in the measurements.

3. Results and outlook

Experimental data were collected for 49 days under good measurement conditions. The spectrum of summed energy deposits from two $CeBr_3$ parts of the phoswich detectors (with NaI deposits as a veto), registered in coincidence under the condition $\|E_1 - E_2\| < 300$ keV, is shown in figure 4. The

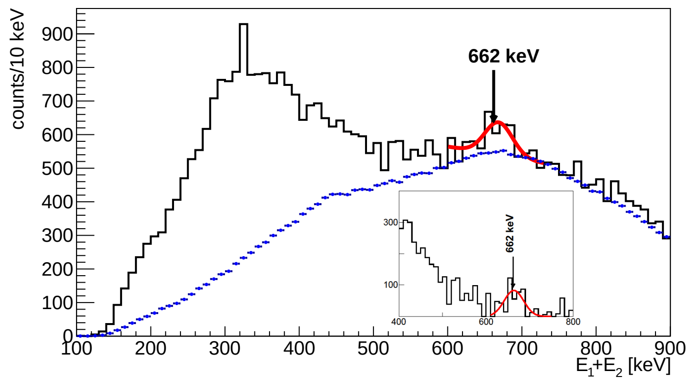

Fig. 4. (Colour on-line) Summed energy deposits in the $CeBr_3$ parts of the phoswiches gated by the prompt time (black line) together with random coincidence (blue/gray dots), with the red/dark gray line presented the fitted Gaussian shape with centroid corresponding to 662 keV.

prompt time gate was set to $\pm 2\sigma$, which corresponded to a time window of ± 0.8 ns, while random coincidences were obtained for the same measurement with the off-prompt 40 ns wide time gate (figure 4 blue/gray dots).

We observed 459(46) counts in the summed energy spectrum attributable to the double gamma decay of the 662 keV excited level in the ^{137}Ba nucleus (figure 4 red/dark gray line). The value of the branching ratio for the $\gamma\gamma/\gamma$ process from the presented experiment is currently being evaluated. Further investigation will be performed to understand the low-energy background between 100–500 keV of the summed energy spectrum. Our setup shows very good performance and proves that it is capable of measuring double gamma decay processes. In the future, after an extension, it can be used to measure the next candidate of the double gamma decay for the ^{207}Pb $13/2^{+}$ excitation level.

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