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ANGULAR CORRELATION MEASUREMENT WITH THE iThemba LABS SEGMENTED CLOVER DETECTOR*

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Measurements of the angular correlation function $W(\theta)$ were performed with the iThemba LABS segmented clover detector. A set of measurements with radioactive sources and irradiated targets was carried out to check the performance of the detector. At short detector-to-source distance, the detector covers the whole range of angles needed for precise angular correlation measurements. Preliminary results show that our detector can measure precisely angular correlation functions, including for transitions with large multipole order such as E3, M4, E4, *etc.*, and deliver mixing ratios δ of mixed magnetic and electric nature.

1. Introduction

The iThemba LABS segmented clover detector is of the TIGRESS [1] type. It comprises four Ge crystals, each of them segmented eight-fold on the outer contact, see Fig. 1. Thus, the detector has 32 signals from the segments and 4 from the inner cores. Segmented detectors are new generation Ge detectors. They are able to measure the position of a γ-ray interaction

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inside the detector's volume. Therefore, these detectors can be used as a standard Ge detector or one can extract additional information using their segments.

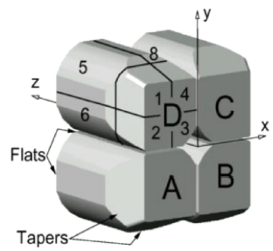

Fig. 1. A sketch showing the segmented clover, comprising four eight-fold segmented crystals.

For instance, if one utilises the 32 segments as individual detectors, the segmented clover can be used for direction-sensitive measurements, such as Doppler correction, angular distributions and correlations, g-factor measurements based on recoil in vacuum technique, linear polarization, lifetime measurements based on Doppler effects, *etc.* A set of measurements was carried out to check the performance of the detector for angular correlations measurements. For this task, data were collected with several γ-ray sources (*e.g.* ^{60}Co, ^{133}Ba, ^{207}Bi, *etc.*) to evaluate the performance of the detector in close geometry. A few natural targets (*e.g.* Cd, Au, Pd, Mo, *etc.*) were also irradiated with neutrons in the neutron therapy vault at iThemba LABS to test the activity that can be produced and the performance of the segmented clover detector.

2. Angular correlation $W(\theta)$

When two γ rays that are emitted successively in nuclear de-excitation are detected in coincidence, the coincidence counting rate, $W(\theta)$, depends on the angle θ between their directions of propagation. The measured intensity is fitted with

$$W(\theta) = A_0[1 + a_2P_2(\cos\theta) + a_4P_4(\cos\theta)]\,, \tag{1}$$

where A_0 is the true intensity of the γ ray and $P_2(\cos\,\theta)$, $P_4(\cos\,\theta)$ are Legendre polynomials. Values of a_2 and a_4 determine the multipole order and mixing ratio δ (for mixed transitions). Values of a_2 and a_4 can be calculated theoretically if the multipolarities of the transitions are known, or can be free parameters in a fit of experimental data.

The mixing ratio helps to extract information about the shape and magnetic properties of the nucleus. Thus, measuring $W(\theta)$, one can deduce the multipole order of the γ rays, their mixing ratios δ, *etc.* This can be done for oriented nuclear states (*e.g.* produced in fusion–evaporation or other nuclear reactions, or at low temperature, *etc.*) or for non-oriented states (*e.g.* β-decaying nuclei).

Majority of experimental data on mixing ratios δ was obtained in the 1970s, with few measuring angles and very old detectors, (*e.g.* Ge(Li), NaI), thus, the mixing ratios δ could be uncertain in many cases. Since then, new generation of detectors have been built. Therefore, this opens an opportunity to produce new data for tens (or hundreds) of nuclei. Before one can revisit the measurements of angular correlations of some nuclei, it is desirable to check the reliability and performance of the segmented clover detector. The angular correlations of the cascades from some of the irradiated targets and standard sources were measured and compared with the theoretical angular correlation functions.

3. Experiments and data analysis

In order to measure the angular correlation of γ-rays, radioactive sources (*e.g.* ^{60}Co, ^{133}Ba, ^{207}Bi, *etc.*) and activated targets (*e.g.* Cd, Au, Pd, Mo, *etc.*), were placed at 4 cm in front of the Ge crystals. Data were collected using XIA Pixie-16 modules digital electronics [2] and MIDAS digital data acquisition system. Data were recorded for each of the 36 channels of the detector if there was a signal larger than a set energy threshold. The data were analysed using CERN ROOT environment [3]. Data analysis was carried out as follows:

(i) The Ge detector was calibrated by collecting singles spectra from ^{152}Eu source.

(ii) It was established that temperature variations following LN_2 fills have an effect on the amplifiers of the segments causing drifts in the output signals. Therefore, gain drift corrections were done.

(iii) When a γ ray deposits its energy in a segment of the Ge crystal, the other segments register proportional crosstalk. It has the appearance of a charge collecting signal with small amplitude often with opposite polarity and generates an energy reading on the non-hit segments of the crystal. It affects all measurements that collect data on segments. Therefore, proportional crosstalk correction was performed for each combinations of segments, details are given in Refs. [4, 5].

(iv) The data from all four crystals were merged. Direct histograms for segments and cores, angular correlation matrices for seg_i *vs.* seg_j, and summed angular correlation matrices were created.

Any unknown or unexplained contribution to the coincidence peak affects the coincidence intensity, thus a thorough analysis of the spectra and appropriate background corrections should be done. Experimental backgrounds due to Compton scattering, coincidence summing effects, random coincidences and also the background generated from the background under the gate were removed.

The iThemba LABS segmented clover detector has 32 individual segments, which results in 992 segments pairs. Considering that the angle between two γ rays registered in segments 1 and 2, $\theta(s_1, s_2)$, where γ_1 is registered in s_1 and γ_2 in s_2, is different from $\theta(s_2, s_1)$ due to a different depth of the γ-ray absorption, there are in principle 992 different angles. However, the segmented clover consists of 4 crystals with the same geometry and the same segmentation. For instance, the angle $\theta(s_1, s_2)$ for crystal A is the same as $\theta(s_1, s_2)$ for crystal B. Thus, the angular correlation matrices for pairs of equivalent segments were summed together, producing 122 different matrices corresponding to angles ranging from 6° to 85°. The angles between two γ rays absorbed in the segments were estimated by taking the geometrical center of the segments in the (x, y) plane and estimating the average depth z of absorption depending on the γ-ray energy.

After the relative intensity of the coincident γ rays was measured for each angle bin, the a_2 and a_4 parameters were found by fitting the experimental data distribution with the angular correlation function given by Eq. (1).

In addition to measuring angular correlations for γ-ray sources, targets of natural materials were irradiated with neutrons. The neutron beam was produced when a ^{9}Be target was bombarded with 66 MeV proton beam in the neutron therapy vault at iThemba LABS, *i.e.* $^{9}\mathrm{Be}(p,n)^{9}\mathrm{B}$. The energy range of the neutrons produced was from 0 to 66 MeV. The neutron beam was then used to irradiated natural targets such as Cd, Au, Pd, Mo, *etc.* that were placed at the entrance of the neutron therapy gantry. The mass of the targets was around 0.5–1 g. The targets were irradiated for 2 hours and the dose rate of the targets after irradiation ranged from 5 to 23 μSv/h. After the irradiation, targets were taken to the measurement area, where counting began. Targets were placed 4 cm away from the center of the segmented clover detector for counting. The count rate per crystal ranged from 0.4 to 6 kHz from the targets, while the count rate for the room background was around 100 Hz.

In this paper, we will discuss results obtained from the neutron activation of the natural Cd target. Measurements from activated Cd target took 14 minutes. The initial count rate was around 2.5 kHz per crystal. We were able to identify γ rays from ^{111}Cd following the decay of the 48.54 minutes isomer, see Figs. 2 and 3. To measure the angular correlation for the 151–245 keV cascade, the double coincidence data were sorted into 992 two-

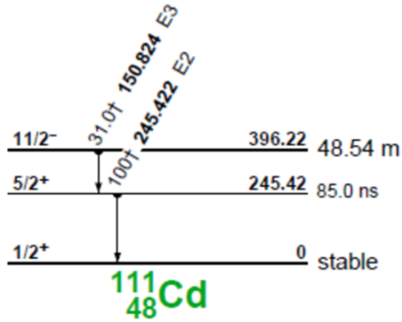

Fig. 2. Partial level scheme of ^{111}Cd [6].

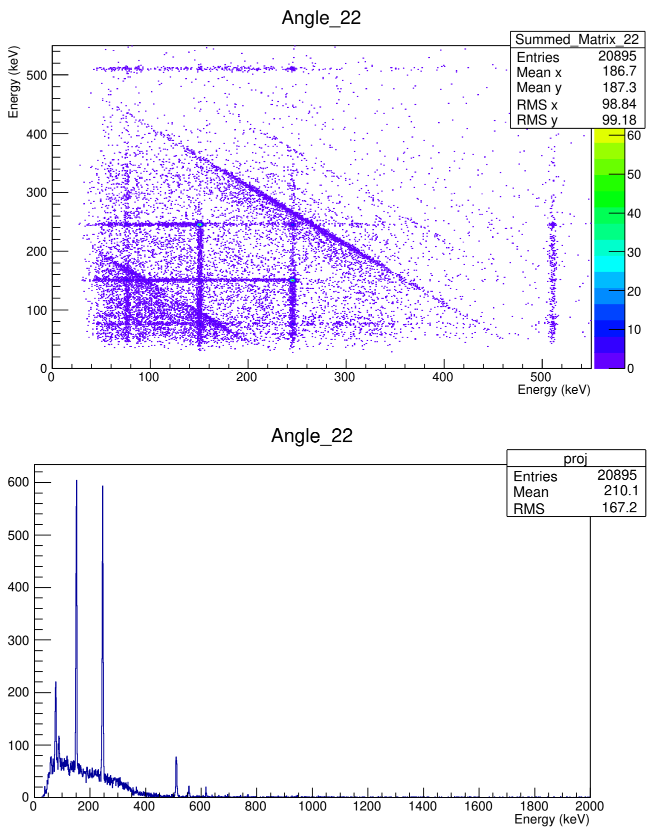

Fig. 3. The γ–γ angular correlation matrix (top) and its total projection for bin 22 that corresponds to $\theta = 47.4°$ (bottom).

dimensional matrices, after which the matrices corresponding to the same angles were summed together, producing 122 summed angular correlation matrices. The time window for each coincidence event was 1000 ns. As an example, an angular correlation matrix, corresponding to the $\theta = 47.4°$ is shown in Fig. 3 (top), while its projection is presented in Fig. 3 (bottom). The two strong γ-ray peaks correspond to the isomeric decay of ^{111}Cd.

Spectra gated on the 151 keV γ-ray were produced from each matrix, for example, the spectra shown as dotted red line in Fig. 4. Background spectra were generated by gating on a region next to the 151 γ-ray peak, (see Fig. 4, spectra shown as dashed green line), and subtracted from the former ones to produce the background-subtracted spectra (see Fig. 4, spectra shown as solid blue line). These background-sub-tracted spectra were used to measure

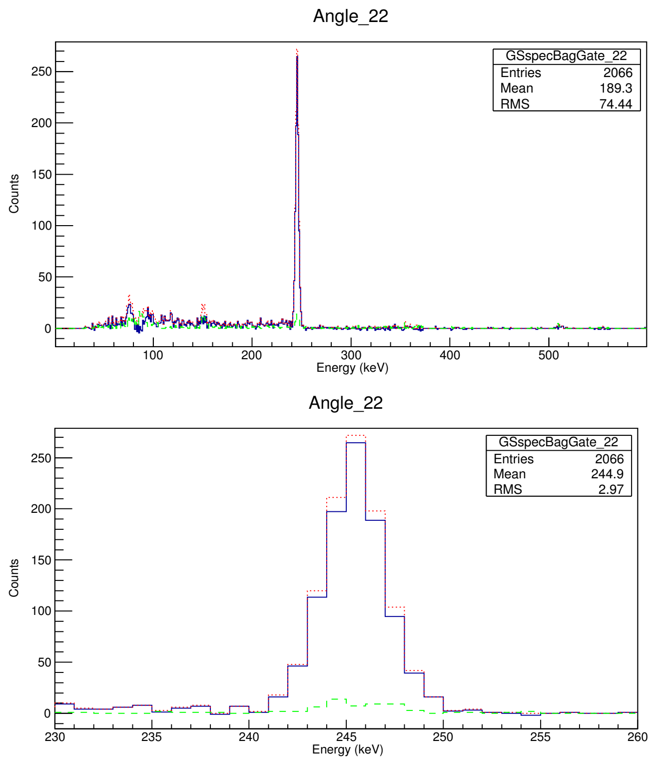

Fig. 4. (Colour on-line) Gated spectra from the bin 22 angular correlation matrix that corresponds to $\theta = 47.4°$. (top) A spectrum gated on the 151 keV γ ray (dotted red line); a background spectrum gated on a region next to the 151 keV peak (dashed green line); and a background-subtracted spectrum, made as a difference between the two former spectra (solid blue line). (bottom) The same as upper figure but zoomed around the 245 keV peak.

the areas N_n of the 245 keV peak for each angle θ_n. The areas were then corrected for detector efficiency ε_n, which was calculated using the efficiency for each segment pair i, j that contributed to the angular correlation matrix for angle θ_n. The efficiency ε_n is given by

$$\varepsilon_n(\gamma_1, \gamma_2) = \sum_{i,j} \varepsilon_i(\gamma_1)\varepsilon_j(\gamma_2)\,, \tag{2}$$

where γ_1 stand for 151 keV and γ_2 for 245 keV transitions, respectively. To calculate $\varepsilon_i(\gamma)$, direct γ-ray spectra were constructed for each segment. The intensity I_n of the coincident 245 keV and 151 keV γ rays for each angle θ_n, is given by

$$I_n = \frac{N_n}{\varepsilon_n}\,. \tag{3}$$

4. Results and discussion

At 4 cm source-to-crystals distance, the face of the detector covers large opening angle of around 90°. Therefore, it covers the whole range of angles needed for precise angular correlation measurements. Figure 5 shows results for $W(\theta)$ measured for 151–245 keV cascade from an irradiated target of

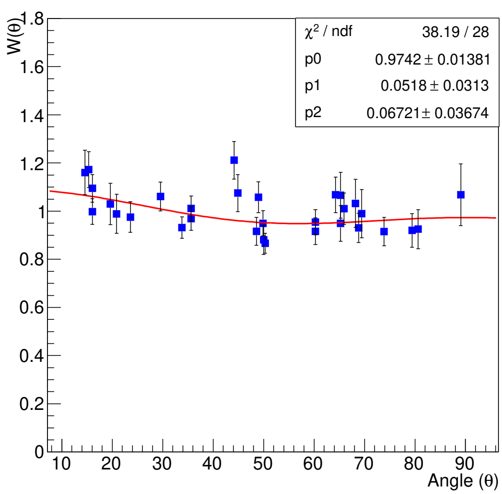

Fig. 5. Preliminary results of the measured angular correlation intensities $W(\theta)$ of the 151–245 keV cascade in ^{111}Cd, for a quarter of all possible angles of the iThemba LABS segmented clover detector, because for low-energy γ rays, only the front segments are sensitive. The uncertainties on the data points represent the statistical errors on the measured areas. The coefficients $p0$, $p1$ and $p2$ represent the measured values of the parameters A_0, a_2 and a_4, respectively.

natural Cd with a neutron beam. The E3 multipolarity of the 151 keV transition was previously measured through the K and total internal conversion coefficients [7]. This is the first time that it is measured through angular correlations. Preliminary results on the measured angular correlations for the 151–245 keV cascade are shown in Fig. 5. A fit with the angular correlation function of Eq. (1) yields $a_2 = 0.052(31)$ and $a_4 = 0.067(37)$. Assuming a pure E2 multipolarity for the 245 keV transition, and using the measured values of a_2 and a_4 and the code DELTA [8] a value of $\delta = -0.259(56)$ was extracted. This suggests that the 151 keV E3 transition may have a M4 component.

These results are preliminary, as some improvements of the analysis are in progress. For instance, Geant4 simulations are being setup in order to determine the average angle and its variance for each segment pair depending on the γ-ray energy. In addition, a small correction due to the finite opening angle of each segment will be carried out. This will further improve the accuracy and precision of the measured δ.

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