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The response of the Euroball Cluster detector to γ-radiation up to 10 MeV

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Abstract

The Euroball Cluster detector consists of seven closely packed hexagonal encapsulated germanium detectors which are mounted in a common cryostat and surrounded by a BGO suppression shield. By adding back the Compton scattered events between the seven germanium detectors the detector system behaves similar as a single germanium detector with a volume of 2000 cm^3. The response of this very large germanium detector to γ-rays up to 10 MeV has been measured using a short lived ^{24}Al source produced at the Cologne FN Tandem accelerator. At 10 MeV the efficiency of the Cluster detector is nearly one order of magnitude larger than that of a 30% germanium detector.

1. Introduction

The Euroball project and the development of Cluster detectors are described in detail in previous publications [1-7]. The Cluster detector is so far the most advanced germanium detector concerning total absorption efficiency for γ-rays and possible coverage of the solid angle with germanium in a 4π spectrometer.

The Euroball Cluster detector consists of seven individually encapsulated germanium detectors. These single detectors on average have an efficiency of 60% [1] [1,2]. The composite Cluster detector is surrounded by a common BGO [2] anti-Compton shield. Fig. 1 shows the arrangement of the detectors schematically. This set-up allows adding up the signals of neighbouring detectors arising from Compton scattered γ-rays and to recover total absorption events [1-7]. By this technique a germanium volume of $\approx$2000 cm^3 is obtained. Thus, the Compton background is reduced, the peak to total ratio enhanced, and the photopeak efficiency increased simultaneously.

The first experiments using the Cluster detector were done with the reactions (p,p$'\gamma$) and (d,pγ) in Cologne [8] and with the resonant (γ,γ') reaction in Darmstadt [9]. In these experiments the very high efficiency was vital to the success of the measurements, because these low-spin and low-multiplicity experiments produce particularly high energy γ-ray transitions. A precise determination of the performance of the Cluster detector at high γ-ray energies which will be discussed in this paper was therefore clearly needed. The first successful tests of the Cluster detector were done with radioactive sources.

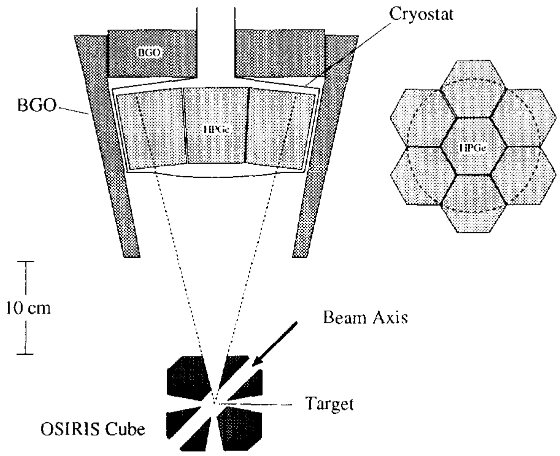

Fig. 1. Schematic picture of the experimental set-up of the first in beam measurement using the Cluster detector. The distance between the detector and the target position was 25.7 cm. On the right hand side a bottom view of the germanium part of the Cluster detector is shown. The dotted lines indicate the solid angle of the Cluster detector in the experiment.

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[1] Relative to a 3×3 in. NaI(Tl) detector for 1.33 MeV γ-rays.
[2] $Bi_4Ge_3O_{12}$.

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2. Experimental procedure

The experimental procedure to determine the efficiency of a γ-ray detector at high energies is well described in the literature [10-13]. Usually the response of the detectors is calibrated by using radioactive sources at lower energies and capture reactions like $^{27}Al(p,\gamma)^{28}Si$ at higher energies. To cover the entire energy range it is necessary to use different capture reactions and different resonance energies.

In the present work a more convenient method for the high-energy γ-ray calibration of the Cluster detector was used which also avoids difficulties caused by the non-isotropic angular distribution of the emitted γ-rays following the proton capture. We determined the properties of the detector by producing a short-lived radioactive source which emits γ-rays with energies up to 10 MeV. For this purpose we have chosen the reaction [14-16]

$$^{24}\mathrm{Mg(p,n)}^{24}\mathrm{Al} \xrightarrow{\beta^+} {}^{24}\mathrm{Mg}^* \xrightarrow{\gamma} {}^{24}\mathrm{Mg}.$$

Its β^+-decay is characterized by a very high Q-value and the excited ^{24}Mg nuclei emit several high energy γ-rays. The relative intensities of the γ-rays are well known from measurements by Warburton et al. [14] and Honkanen et al. [15]. This knowledge allowed us to determine the efficiency of the Cluster detector. The present data were obtained by bombarding a 5 mg/cm^2 ^{24}Mg target with protons from the Cologne FN tandem accelerator. The beam energy was E_p = 18 MeV which is 2.7 MeV above the threshold energy for this reaction [17,18]. Data were taken for 40 h and recorded with the Cologne FERA-analyzer [19-21]. In particular fast 14 bit ADCs were used to ensure an optimum performance in the add-back mode of the Cluster detector and to keep the good energy resolution over the large energy range of 10 MeV.

The Cluster detector was mounted at the Osiris cube spectrometer [22]. Its tungsten shield has two holes each at 45°, at 135°, and at 90° with respect to the beam axis. The Cluster detector was placed at 135°. This backward angle was selected to minimize the neutron damage of the germanium cluster. For comparison five common germanium detectors were placed at the free places of the Osiris cube spectrometer. To get a large solid angle the nearest distance between the Cluster detector and the target position that is possible (25.7 cm) was chosen. This distance is smaller than the distance of 43 cm which will be used in the Euroball III set-up [1-7]. Therefore, an additional collimator was necessary to avoid direct irradiation of the anti-Compton shield. The compromise of a large solid angle and a good shielding of the BGO against the target can be seen in Fig. 1. This set-up leads to a solid angle of 1.6% of 4π for the Cluster detector. In comparison, the solid angle of one of the other detectors was 0.75% of 4π.

The decay scheme of ^{24}Al shows two isomeric β^+-decay modes. States in ^{24}Mg are populated on the one hand via the decay from the ground state of ^{24}Al with spin and parity

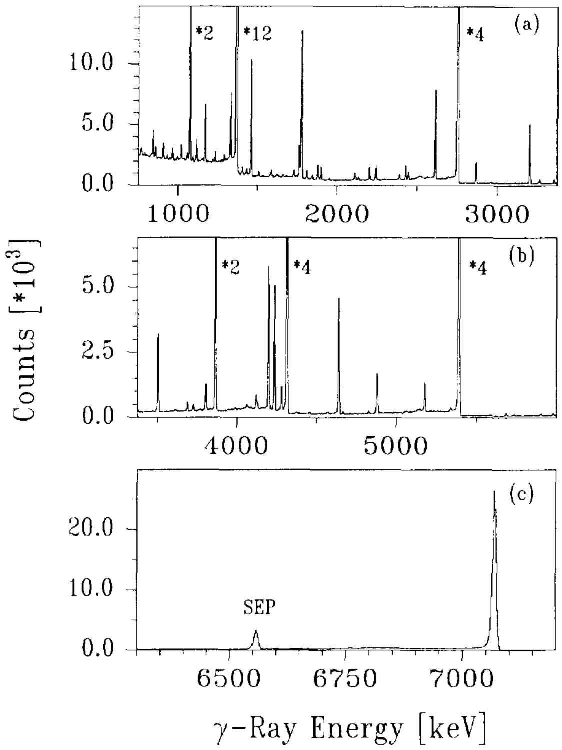

Fig. 2. γ-ray spectrum obtained with the Cluster detector by measuring the γ-rays following the β^+-decay of ^{24}Al. In parts (a) and (b) the energy range up to 6 MeV is shown. The intensities of the marked (*) lines must be multiplied with the numbers behind the asterisks. The lower part (c) shows one peak at 7069 keV and its single escape peak. The good peak to background ratio in the three spectra highlight the good performance of the Cluster detector at high γ-ray energies.

$J^\pi = 4^+$ and a lifetime of 2.053 s and on the other hand through the first excited state with $J^\pi = 1^+$ and a lifetime of 131 ms [23]. For the chosen reaction the strength of the population of the first excited state in ^{24}Al and therefore the ratio of the decay modes is unknown. Nevertheless the efficiency of the Cluster detector could be determined by using a special pulsing of the proton beam and timing of the data acquisition system. Thus, ^{24}Al was produced by bombarding the target with protons for a time interval of 4 s. After this interval the beam was switched off and the data acquisition started after a delay of 1 s for an interval of 3 s. This procedure and the short lifetime (131 ms) of the first excited state in ^{24}Al guaranteed that the γ-rays recorded mainly resulted from the β^+-decay of the ground state. To increase the number of low energy γ-ray transitions, data from a ^{226}Ra source were additionally collected. In this way and by using the relative intensities of the γ-rays following the β^+-decay of the ground state, we were able to calibrate the efficiency of the Cluster detector for γ-ray energies up to 10 MeV. The spectrum measured with the Cluster detector is shown in Fig. 2. The good peak to background ratio in this spectrum is striking. The good efficiency of the Cluster

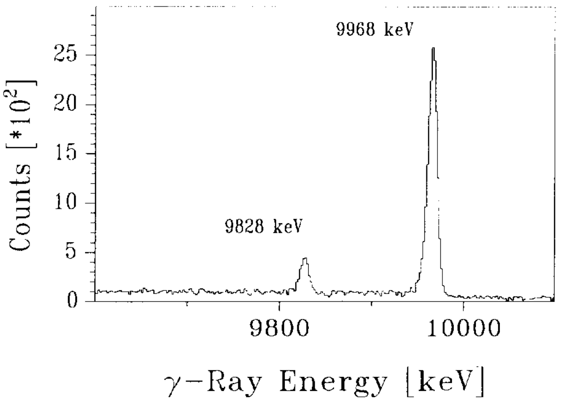

Fig. 3. Ground state transitions at 9828 and 9968 keV measured after the β^+-decay of the first excited state in ^{24}Al (131 ms lifetime). To clean this spectrum the spectrum measured after the β^+-decay of the ground state is subtracted.

detector for high energy γ-rays is demonstrated in Fig. 2c. At this picture the 7069 keV γ-ray transition from the 4_3^+ state to the first excited 2^+ state in ^{24}Mg is presented in an enlarged energy scale. The low intensity of the single escape peak provides evidence for the excellent performance of the Cluster detector including the anti-Compton shield at higher energies.

For a more detailed investigation of the behaviour at higher energies, especially the add-back factor, a second measurement was carried out. The β^+-decay of the first excited state in ^{24}Al strongly populates the 1^+-levels at 9828 and 9968 keV. The ground state transitions from these levels could be measured by changing the time interval between the switching off of the beam and the start of the data collection as well as the data acquisition interval itself. We collected the data for an interval of 4 s directly after having switched off the beam. Fig. 3 presents these ground state transitions.

3. The relative efficiency

The relative efficiency of the Cluster detector is shown in Fig. 4. In comparison the relative efficiency of a standard germanium detector with 30%[3] efficiency is shown. The efficiency for high energy γ-rays of the Cluster detector is one order of magnitude higher. The total γ-ray efficiency of the Cluster detector depends not only on the individual efficiency of the encapsulated germanium detectors but also on the capability to operate the detector in the add-back mode. In this mode the energies deposited in several detectors because of Compton scattering can be added up and the full energy of a γ-ray can be determined in many cases. The number of individual germanium detectors that participate to one Compton scattering event is called "fold". Fig. 5 shows the fold distribution of the Cluster detector in the energy range from 186 keV to 10 MeV. The importance of the add-back technique is obvious. For very low γ-ray energies (< 200 keV) the photo effect in one germanium detector is the most likely process for the interaction between the incident γ-ray and the Cluster detector, i.e. 1 fold events are dominant. The number of multiple events – in particular 2 fold events – increases very fast with increasing γ-ray energy. Below about 2.5 MeV the amount of 3 and higher fold events is still small so that the 2 fold coincidences are most important for the add-back mode. It can also be seen that for energies greater than 5 MeV the contribution of the multiple events due to Compton scattering and pair creation becomes greater than the number of single events. This interesting fold distribution yields additional information about the detector properties and the measured data. Thus, it is possible to identify sum lines in the γ-ray spectra of the Cluster detector by analyzing the fold distribution. This is presented elsewhere [24].

[3] Relative to a 3×3 in. NaI(Tl) detector for 1.33 MeV γ-rays.

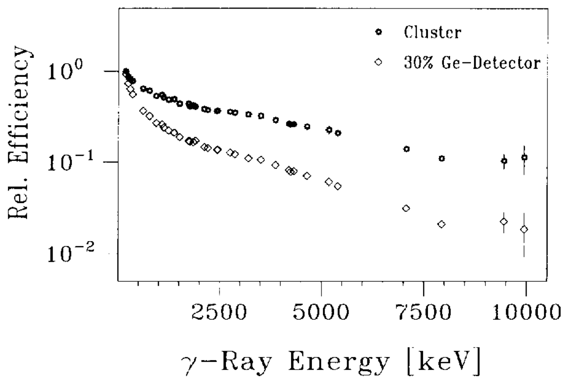

Fig. 4. Relative efficiency of the Cluster detector in comparison to a common germanium detector. The efficiency for high energy γ-rays of the Cluster detector is about one order of magnitude higher. The different solid angles covered by the detectors are already considered.

From the fold distribution the energy dependent add-back factor of the Cluster detector could be extracted (see Fig. 6). The add-back factor is defined as the total number of photo

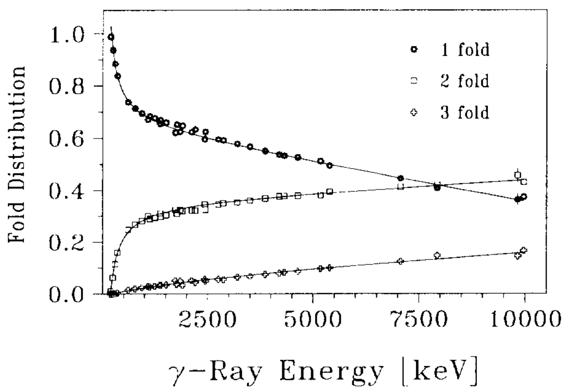

Fig. 5. Fold distribution in the Cluster detector up to 10 MeV. The curves are drawn to guide the eye.

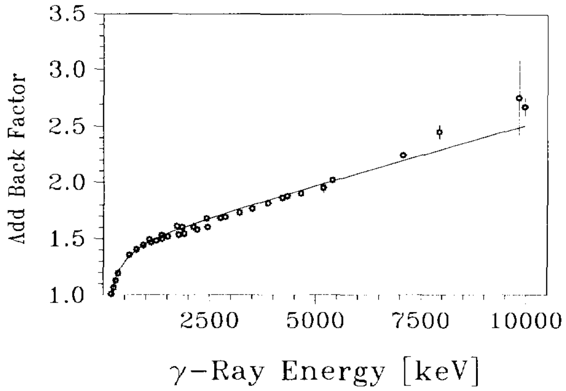

Fig. 6. The add-back factor of the Cluster detector is shown. It increases from 1.0 at very low γ-ray energies up to 2.7 around 10 MeV. The curve is drawn to guide the eye.

events[4] divided by the number of single photo events for a given energy. It increases very fast from 1.0 for low energies ($\leq$ 250 keV) to 1.5 for 1500 keV. An add-back factor of 1.0 means that no multiple events occur, whereas a factor of 1.5 means that one-third of all events are multiple events. The characteristic above 2.5 MeV is nearly linear in energy for the range shown in figure 6. We could determine an add-back factor of 2.7 at the highest γ-ray energy of 9968 keV.

4. Conclusion

Results obtained from the first in beam measurement using the Euroball Cluster detector are presented in this work. The γ-rays following the β^+-decay of ^{24}Al were used to investigate the high energy performance of the Cluster detector. In particular the relative efficiency of the Cluster detector, a comparison with a standard germanium detector, the fold distribution in the Cluster detector, and the energy dependent add-back factor could be extracted from the collected data. The total-absorption efficiency of a Cluster detector at 10 MeV is similar to the efficiency of a standard germanium detector at 1 MeV.

High resolution γ-ray spectroscopy with germanium detectors in the energy range of a few MeV was the main source of nuclear structure information during the last 30 years. With the Cluster detector the energy range for high resolution γ-ray spectroscopy is extended to $\geq$ 10 MeV thus providing access to new research fields for nuclear structure studies. Nuclear resonance fluorescence experiments with (γ,γ') reactions at S-Dalinac in Darmstadt using a Cluster detector [9] e.g. yielded exciting new results on collective dipole excitations in a series of nuclei which could not successfully be investigated with standard germanium detectors.

[4] The total number of photo events includes all single and all multiple fold photo events recorded in all germanium capsules of the Cluster detector.

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