Eur. Phys. J. A **15**, 265–269 (2002)
DOI 10.1140/epja/i2001-10265-1

THE EUROPEAN PHYSICAL JOURNAL A

Gamma-ray tracking: Utilizing new concepts in the detection of gamma-radiation

K. Vetter[a]

Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Received: 21 March 2002 /
Published online: 31 October 2002 –

Abstract. Gamma-ray tracking in a closed array of highly segmented HPGe detectors is a new concept for the detection of γ-radiation. Each of the interacting γ-rays is identified and separated by measuring the energies and positions of individual interactions and by applying tracking algorithms to reconstruct the scattering sequences, even if many γ-rays hit the array at the same time. The three-dimensional position and the energy of interactions are determined by using two-dimensionally segmented Ge detectors along with pulse-shape analysis of the signals. Such a detector will have new and much improved capabilities compared to current γ-ray spectrometer. One implementation of this concept, called GRETA (Gamma-Ray Energy Tracking Array), is currently being under development at LBNL.

PACS. 07.85.-m X- and gamma-ray instruments – 29.40.-n Radiation detectors – 29.40.Ka Cherenkov detectors – 29.40.Wk Solid-state detectors

1 Introduction

Many new facets of the nucleus have been discovered and explored over the last several years due to the construction and operation of large γ-ray arrays such as Gammasphere or Euroball. These arrays, consisting of approximately 100 modules of Compton-suppressed Ge detectors, have a total peak efficiency of about 0.1 (for a 1.3 MeV γ-ray) and a peak-to-total ratio (P/T) of about 0.6. These instruments provided a factor of about 100 improvement over previous detector systems in the ability to resolve weak features in a complex spectrum.

To improve the sensitivity in the detection of γ-radiation beyond the current systems, a closed shell of Ge detectors can be envisioned. This allows to almost completely cover the entire solid angle, and by adding the signal from neighboring detectors, the escaped energy is recovered and much higher efficiency can be achieved. However, for events with many coincident γ-rays, such as long cascades in the decay of nuclear high-spin states, the summing of two γ-rays hitting neighboring detectors reduces the efficiency and increases the background. In order to reduce this summing, a large number of detectors, of the order of 1000, is required. The cost of such a detector array will be prohibitive.

[a] e-mail: kvetter@lbl.gov

2 The γ-ray tracking concept

To circumvent the limitations associated with the previously mentioned detector systems we have developed a new concept which is based on the determination of the positions and energies for every interaction of each γ-ray. This novel technique of γ-ray tracking and its implementation called GRETA (Gamma-Ray Energy Tracking Array) aims at the identification and separation of individual γ-rays and is based on highly segmented Ge detector elements in combination with pulse-shape analysis to determine the location and energy of every interaction of each γ-ray. This information will be used to "track" all interactions of each γ-ray by using the energy-angle relation given by the Compton-scattering formula or particular pattern of the pair production process for higher γ-ray energies.

The tracking will not only enable to identify and separate multiple, coincident γ-rays, but in addition is able to distinguish full-energy events in the Ge crystal from partial-energy events, thereby improving considerably the response function (peak-to-total ratio). Furthermore, it allows the determination of the locations of the two first interactions of the scattering sequence. The localization of the first interaction point in a detector defines the angle of emission of that γ-ray from a source of known location relative to the detector and therefore allows to correct for the Doppler shift of γ-rays emitted in flight. With the identification and position of the first two interactions it is possible to determine the linear polarization of a γ-ray and thereby define its electric or magnetic character.

Due to the close packing of the Ge crystals and the use of the "add-back" feature of GRETA, the efficiency for detecting full-energy γ-rays will be much higher than previous detector systems, especially for high-energy γ-rays. The most impressive gain, however, to the currently existing arrays will be for experiments using fusion reactions to study high-spin states in the nucleus. These reactions are related to the emission of many simultaneous γ-rays (20–30) and a gain in sensitivity per γ-ray will result in a large sensitivity increase for the whole event.

To show the "proof of principles" of the proposed concept, we focussed on four key areas: 1) manufacture of segmented detectors which can provide signals for resolving and locating individual interaction points; 2) determination of the three-dimensional position sensitivity and resolution based on the dynamic and the noise of the measured signals; 3) electronics and signal processing methods for determining energy, time and position based on pulse-shape digitization and digital processing of signals; 4) tracking algorithms, using the energy and position information, to identify interaction points belonging to a particular γ-ray.

2.1 Highly segmented Ge detector

The ability to manufacture coaxial Ge detectors with a high degree of two-dimensional segmentation is an essential component of our approach towards γ-ray tracking. The combination of segmentation and pulse-shape processing of segment signals provides the energies and positions of interaction points which are used as input for tracking algorithms to identify and separate individual γ-rays and to determine the time sequence of the interactions.

Since GRETA focuses on the implementation of γ-ray tracking for a 4π γ-ray detector array, many of these Ge detectors have to be closely packed to maximize the solid-angle coverage [1]. The prototype detectors we obtained are designed to fit into a spherical shell of 110 tapered hexagonal and 10 pentagonal detectors, very similar to the Gammasphere geometry [2]. We obtained a 36 fold segmented prototype detector which was built by Eurisys Mesures three years ago. It consists of a closed-ended HP-Ge n-type crystal with a tapered hexagonal shape [3]. The geometry and dimensions are indicated in fig. 1. The outer electrode is divided into 36 parts by 6 longitudinal and 5 transverse segmentation lines. An average energy resolution of 1.14 keV and 1.94 keV was measured at a γ-ray energy of 60 keV and 1332 keV, respectively. A total integrated noise of about 4 keV was measured up to a frequency of 40 MHz. This low noise is not only important for energy, time or position resolution but also for trigger purposes [3].

2.2 Pulse processing

Pulse-shape analysis in a two-dimensional segmented detector allows to determine the position in three dimensions with an accuracy far better than the segmentation size. This is achieved by not only measuring the signal of the charge collecting electrode with the net charge signals but also by analyzing the transient signals of neighboring segments which display temporary image charges. Over the last year we focused on the determination of the achievable position resolution in our prototype detector. We were able to study the position resolution as a function of the location in the crystal, as a function of the direction, and as a function of the energy. This was accomplished by measurements as well as pulse-shape calculations. We were also able to determine the limiting factors for the position resolution [4].

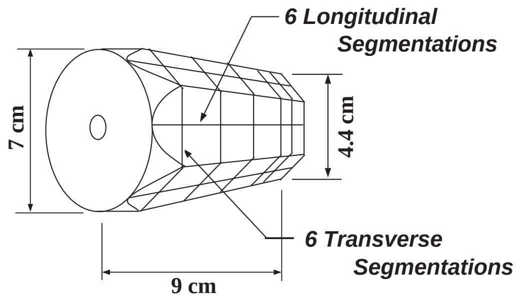

Fig. 1. The 36 fold segmented GRETA prototype detector with its tapered and hexagonal shape and the arrangement of its segments.

A coincidence setup as indicated on top of fig. 2 enabled us to measure signals based on single interactions throughout the detector volume. Considering the pulse shapes obtained in the segment with the net charge signal and the transient charge signals in the next neighbors allowed us to extract a three-dimensional position sensitivity of about 0.2 mm along the electrical-field lines, which is the very close to the drift direction of the charge carrier, and about 0.5 mm in the complementary directions, away from boundary lines. These values were obtained at a γ-ray energy of 374 keV. The position sensitivity described here reflects the relative change of the measured signals for the different positions in terms of the noise, which is main uncertainty in the signals. It measures the minimum distance between interactions that produce distinguishable signals. However, it neglects the absolute position of the detector relative to the source or effects, such as the range of the Compton electron or the intrinsic momentum of the Compton electron. The obtained sensitivity is remarkable considering the fact that the size of the segment is about $2 \times 2\,\mathrm{cm}^2$ implying an improvement of about a factor of 100.

To determine a real position resolution which is based on purely calculated signals on an event-by-event basis we collected about 5000 events in a three-day run on a fixed position in a front segment (see fig. 2). To determine the location of each interaction we used sets of calculated signals which were calculated on Cartesian grid with a spacing of 0.5 mm in all three dimensions. Each set of measured signals were fitted with the best calculated set of signals. As it can be seen by the set of signals in the middle of fig. 2 the calculated signals reproduce the

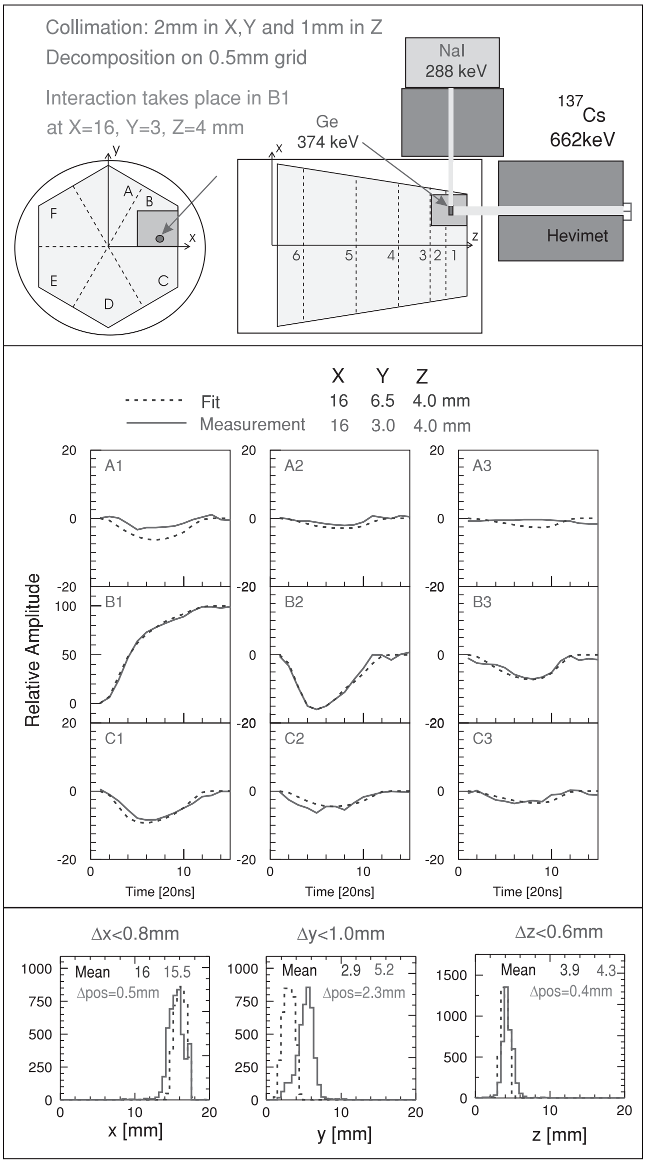

Fig. 2. Top: coincidence setup used to determine position resolution. Middle: example of fitted (*e.g.*, calculated) and measured signals. (full lines: measured, dashed lines: fitted) Bottom: measured (full lines) and simulated (dashed lines) x,y,z positions of interactions.

measured data exceptionally well. Based on the shape of purely calculated and fitted position spectra we are able to obtain a position resolution of 0.5 mm to 0.9 mm in all three dimensions. The position for the direction with the worst resolution was off by about 2 mm which can be explained by crystal orientation effects which were not taken into account in the calculations. While the dependence of the magnitude of the drift velocity from the crystal orientation have been taken into account, the change in the direction of the charge carrier as a function of electrical field and crystal orientation direction have not yet been taken into account. This is due to the missing analytical description of the hole mobility properties.

In order to determine locations and energies of multiple interactions in multiple segments, we developed algorithms to decompose signals into their individual components. For example, a 1.3 MeV γ-ray interacts on average 4 times (two interactions in two segments) before it is fully stopped in one crystal. However, the goal of these decomposition algorithms is not only to optimize the position resolution, but also to perform the decomposition in real time.

Several approaches we have pursued, so far, result in position resolution values between 2 mm and 5 mm, however, they differ significantly in computing time. Current χ^2-minimization algorithms suitable for real-time processing (*e.g.*, 5–10 GFlops) achieve in the order of 4-5 mm for a γ-ray energy of 1.3 MeV.

2.3 Tracking algorithm

We have developed tracking algorithms to associate the interactions we obtained in the above-described way with a certain γ-ray [5]. The goals of this algorithms are to identify interactions belonging to a given γ-ray and to resolve the tracks of multiple, coincident γ-rays, to distinguish between γ-rays which only left a partial energy and γ-rays which deposited their full energy in the detector system and to determine the first and second interactions. The first interaction is required for a proper Doppler correction, the second in connection with the first interaction is used for determining the linear polarization.

Most of our efforts have been focussed on the treatment of Compton scattering since this is the dominant interaction process for γ-ray energies between 150 keV and 5 MeV in germanium. Below 150 keV the photo-electrical effect and above 5 MeV the pair production process dominates. Recently, we developed also an algorithm to identify and recover γ-rays interacting by the pair production process by means of tracking.

The current Compton-tracking algorithm consists of three steps. Cluster identification is the first step of the algorithm. The interaction points within a given angular separation as viewed from the target are grouped into a cluster. In the second step, each cluster is evaluated by tracking to determine whether it contains all the interaction points belonging to a single γ-ray. The tracking algorithm uses the angle-energy relation of Compton scattering to determine the most likely scattering sequence from the position and energy of the interaction points. If the interaction points had infinite position and energy resolution, the tracking would be exact and the properly identified full-energy clusters will show no deviation from the scattering formula ($\chi^2 = 0$). Wrongly identified clusters or partial-energy clusters will deviate from the formula and the separation of the good and bad clusters would be easy. However, in reality, with finite position and energy resolution, the good clusters will also have a non-zero χ^2 and they cannot be separated cleanly from the bad clusters. This causes a lower efficiency and poorer P/T ratio. In the third step, we try to recover some of the wrongly identified γ-rays by either adding two bad clusters or by splitting a bad cluster into two. The clusters which do not satisfy any of the above criteria are rejected. This simulation was carried out for a number of different conditions such as the multiplicity and energies of the γ-rays as well as position resolution of the detector. Assuming a position resolution of 1.5 mm which appears to be feasible and reasonable assumptions concerning the geometry (*e.g.*, gaps and can thicknesses) an efficiency of about 30% and a peak to total of about 70% can be achieved. This has to be compared with Gammasphere which has an efficiency of about 8% and a peak to total of about 50% under the same conditions, which implies a gain of four in efficiency and 1.5 in peak to total for each of 25 emitted γ-rays.

While so far we have only discussed events of multiple, coincident γ-rays with the same γ-ray energies and "locally" optimized figure-of-merit cuts, we demonstrated that "globally" optimized cuts give not much worse results [5]. However, we want to point out that the mentioned values strongly depend on the details of the final geometry. In particular, the size of the gaps and the material between the crystals is crucial. In addition to the possible improvements discussed above another advantage of GRETA is the photo-peak efficiency for high-energy γ-rays (*e.g.*, $E_\gamma \geq 10$ MeV). Above the threshold of 1.022 MeV, the probability of pair production increases as energy increases. At 10 MeV, this probability is about 60% and therefore the pair production events need to be identified with a high efficiency. As for the Compton-tracking algorithm, we obtain a tracking efficiency of about 50% for the pair-tracking algorithm we developed.

3 Potential capabilities

The estimates of GRETAs final capabilities come from simulations using a spherical-shell geometry built out of 110 irregular hexagons and 10 regular pentagons. For one emitted γ-ray, we obtain a full-energy efficiency of 0.55 and 0.12 for γ-ray energies of 1.33 MeV and 15 MeV, respectively. A variety of physics can be addressed with the new capabilities of GRETA. Tracking can determine the scattering sequence and the linear polarization of a γ-ray and thereby define its electric or magnetic character, important information in most nuclear-structure studies. The localization of the first interaction point with GRETA can define the angle of emission of a γ-ray to better than one degree, and thus eliminate Doppler broadening for nuclei having v/c less than 20% and greatly reduce it for higher velocities. As an example consider the study of neutron-rich light nuclei, where the production of the interesting near-drip line nuclei is by fragmentation reactions resulting in product recoil velocities of $v/c = 30\%$, or higher. For a 1 MeV γ-ray emitted at 90° to the recoil direction, the contribution to the FWHM of the γ-ray peak due to the Doppler broadening would be 39 keV with a standard Gammasphere detector, but only 3.7 keV with GRETA. Clearly this improvement can have a large effect on the extracted physics, both in detecting weak γ-rays and in separating close-lying peaks. Localization is important for many experiments, especially those using inverse-reaction kinematics and heavy-ion Coulomb-excitation studies.

The very high efficiency for high-energy γ-rays, together with excellent energy resolution, will open up new studies of giant resonances in nuclei. For example, it will be possible to tag the giant-resonance γ-rays with known low-lying γ-rays to define the process being studied. The efficiency, response function and background suppression of GRETA will be important in many experiments where yields are low, *e.g.*, in experiments with ISOL- or fragmentation-type RIB facilities studying the most neutron- and proton-rich nuclei and in determining some important cross-sections and level schemes involved in astrophysical processes. The nucleus provides an excellent laboratory for many types of studies, and tests of the standard model, as well as of basic quantum mechanics can be made using GRETA. In many types of high-spin nuclear-structure studies, GRETA will improve the sensitivity by a factor of 1000 or more. This will be essential to discover the predicted very elongated hyperdeformed shapes and the expected pre-fission Jacobi shapes. It will also be necessary to elucidate the order-to-chaos transition in nuclei and to understand the superfluidity of this finite quantal system.

4 Summary and outlook

A γ-ray energy tracking array which is based on highly segmented Ge detector elements would provide far better efficiency, peak to background, counting rate and localization than any existing γ-ray array. These new capabilities will have a major impact in many areas of physics. Recent progress in detector segmentation, signal processing and γ-ray tracking has provided the proof of principle for the proposed concept.

For the next step in the development and construction of a full GRETA array we designed a module array of 3×3 segmented Ge detectors. The goal of such an instrument is to manufacture and arrange highly segmented Ge detectors in a close packing scheme, to study the tracking across crystal boundaries and to eventually start a physics program. The proposed instrument will consist of three modules of three 36 fold segmented Ge detectors in one cryostat. To allow easy handling and a close packing, each crystal will be encapsulated.

The expected performance of such a small device is impressive: At a distance of 10 cm from the source we expect an efficiency of about 3% and a P/T ratio of 0.7 by employing tracking. In particular the P/T ratio is remarkable considering the fact that no anti-Compton shield is used. Without employing tracking an efficiency of 3.5% and a P/T total of only 0.4 is expected. Even assuming two γ-rays in the module the efficiency is still about 2% and the P/T ratio is about 0.6. Two γ-rays in the module correspond roughly to a γ-ray multiplicity of 25 in the total solid angle.

The work on GRETA is embedded in the Nuclear Structure Group of the LBNL and therefore relies on many contributions from the group members. The Compton-tracking code was mainly developed by Greg Schmid; the pair-tracking algorithm was implemented by Takashi Teranishi. This work was supported by the US Department of Energy under contract No. DE-AC03-76SF0093.

References

1. M.A. Deleplanque *et al.*, Nucl. Instrum. Methods A **430**, 292 (1999).
2. I.Y. Lee, Nucl. Phys. A **520**, 641c (1990).
3. K. Vetter *et al.*, Nucl. Instrum. Methods A **452**, 105 (2000).
4. K. Vetter *et al.*, Nucl. Instrum. Methods A **452**, 223 (2000).
5. G.J. Schmid *et al.*, Nucl. Instrum. Methods A **430**, 69 (1999).