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GRETA: utilizing new concepts in γ-ray detection☆

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Abstract

We present a new concept for γ-ray detector arrays. An example, called GRETA (Gamma-Ray Energy Tracking Array), consists of highly segmented HPGe detectors covering 4π solid angle. The new feature is the ability to track the scattering sequence of incident γ-rays and in every event, this potentially allows one to measure with high resolution the energy deposited, the location (incident angle) and the time of each γ-ray that hits the array. GRETA will be of order of 1000 times more powerful than the best present arrays, such as Gammasphere or Euroball, and will provide access to new physics.

1. Introduction

Much of what we known about nuclear energy levels has come from studying the electromagnetic radiation emitted when the system makes a transition from one state to another. For a nucleus, the order of magnitude of the transition energy is 1 MeV. For about 30 years, high-purity germanium (Ge) crystals have been the detectors of choice for such studies. Improvement in detector properties (size, energy resolution) and in detector number (large arrays) has recently culminated in the construction of Gammasphere [1], Eurogam [2,3] and Euroball [2–4]. These arrays all use the concept of Compton suppression to improve the peak-to-background ratio in the γ-ray spectra. In this paper, we present a new concept for a γ-ray detector array, illustrated in the detector system called GRETA (Gamma-Ray Energy Tracking Array), that will have a resolving power[2] 100–1000 times greater than Gammasphere. GRETA consists of a "solid" shell of about 100 highly segmented Ge detectors. The solid angle subtended by the Ge detectors will be 4π (instead of approximately 2π as in a Compton-suppressed array), and the Compton-scattered γ-rays will be recovered (instead of rejected) by tracking the γ-ray interactions from one detector to the next.

These γ-ray detector arrays are primarily used to study nuclear structure and reactions. However, they can also play an important role in other fields

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[2] As will be discussed later (Section 2.2.4), the resolving power of such arrays depends to some extent on the experiment considered.

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in which the nucleus is used as a laboratory; for example, in studying fundamental interactions or astrophysics; or in searches for exotic forms of matter such as strange matter. The unique characteristics of GRETA will enable us to address new kinds of physics.

The next section will review the development of γ-ray detectors, leading to the need for a new concept. Section 3 will present the GRETA concept. Section 4 will outline the methods used to design such a detector array and the present status of the research and development. Section 5 will briefly review the new physics that can be done with such an array.

2. Development of γ-ray detectors

We will first present the characteristics of a good γ-ray detector array and then review the development of the Ge detectors. Some of the new physics discoveries made using such arrays will be mentioned at the end of each section.

2.1. Characteristics of a γ-ray detector array

An ultimate goal of a γ-ray detector array is to resolve all possible γ-ray decay sequences. Usually, detectors, such as microscopes or telescopes, are characterized by their resolving power. In nuclear structure physics, there are many weakly populated sequences embedded in large and complex backgrounds and the ability of the instrument to resolve such sequences depends on the detailed nature of both the sequence and the background, so that there is no unique definition of the "resolving power" of the detector. However, the concept of resolving power has proved useful and will be discussed in more detail in Section 2.2.4 when evaluating the performance of detector arrays. Even without an explicit definition, it is clear that the important properties of a γ-ray detector are: (1) high efficiency in detecting incident γ-rays; (2) high energy resolution; (3) high ratio of full-energy events to total (full energy and partial energy) events (called the peak-to-total ratio or P/T ratio); (4) high granularity to localize individual γ-rays; and (5) stable operation and long life. The basic element of such a detector system is (and has been for more than 30 years) a semiconductor detector made of germanium, and the main reason for this has been their high γ-ray energy resolution. Progress has been made in both the size of these detectors and their arrangement into efficient arrays.

2.2. Development of Ge detector systems

2.2.1. The first Ge detectors

In 1962, the first Li-drifted Ge detectors were made [5]. The new feature was their excellent γ-ray energy resolution (6 keV at 1 MeV) – about a factor of 10 better than that of their predecessor, the NaI scintillator. The first detectors had a small volume ($\sim$ 1 ml) and a very small full-energy efficiency, $\sim$ 1% of that of the standard NaI scintillator (7.5 cm diameter $\times$ 7.5 cm long at 25 cm from the source). But soon thereafter, Ge detectors with efficiencies around 10% were used. By 1970, γ–γ coincidence measurements using two Ge detectors were routinely used to construct complicated nuclear level schemes. A major discovery in nuclear structure using these detectors was the so-called "backbending" in ground-state rotational bands of moderately deformed nuclei in 1971 [6]. Because of the high energy resolution of these Ge detectors, weak γ-ray transitions could be seen for the first time up to and above spin 14. Around that spin, irregularities (backbendings) in the rotational bands revealed Coriolis effects [7] aligning single-particle angular momentum along the rotation axis. This "alignment" concept led to the study of single-particle motion in a rotating potential and the development of the cranking models. Such models have formed the basis for understanding the properties of nuclei at high spins and have been used ever since in both theoretical and experimental developments in nuclear structure.

2.2.2. High-purity Ge detectors

A milestone in the development of Ge detectors came in 1971 [8] with the development of high-purity Ge detectors. This meant that there was no longer a need for Li drift and bigger detectors could be made, providing much greater efficiency, particularly important in coincidence experiments.

2.2.3. Compton suppression and detector arrays

In 1980, a big step was made with the development of arrays of Compton-suppressed Ge detectors. One way to decrease the background of partial-energy γ-ray events is to veto these events whenever possible. The large majority of these occurs when a γ-ray Compton scatters in the Ge detector and the scattered γ-ray escapes the detector, leaving only a partial energy signal that is of no interest. It is then advantageous to suppress this event. This is done by surrounding each Ge detector with another efficient γ-ray detector which catches the escaped Compton-scattered γ-ray and vetoes the recording of the signal from the Ge detector. This is the Compton-suppression technique. Typically, it increases the peak-to-total ratio of a 1.3 MeV γ-ray from 20%, for a bare Ge detector (of size 7 cm diameter by 8 cm long), to 50%, for a Compton suppressed detector. This well-known technique was "revived" around 1980 in the construction in Copenhagen of the first "array" of five elements, each composed of a Ge detector which is Compton-suppressed by a large NaI scintillator [9,10]. At that time, a more efficient scintillator, bismuth germanate (BGO), was being developed. Due to its high density and Z, this material is about three times more efficient per unit length than NaI in interacting with gamma rays. The Berkeley Nuclear Structure group pioneered the BGO Compton suppressors and assembled the first large array of 21 Compton-suppressed Ge detectors called HERA [11,12]. Such arrays were developed in parallel in Europe, particularly in Daresbury, UK where various configurations of arrays called TESSA were set up. It was with one of these arrays that "superdeformed nuclei at high spins" were discovered in 1986 [13]. Superdeformed nuclei are loosely referred to as nuclei which are more deformed than "usual", i.e. typically they have the shape of an axially symmetric ellipsoid with a ratio of the long to short axis around 2. They are interesting because the forces that the nucleons feel in such nuclei differ in systematic ways from those felt in "normal" nuclei. For example, the Coriolis and centrifugal forces due to rotation are weaker relative to the coupling to deformation than in normal nuclei and this gives us a chance to study nuclei under new conditions. An important resulting property of superdeformed nuclei is that they are the best (nuclear) rotors known, giving deexcitation spectra of equally spaced gamma rays which are relatively easy to search for in two- or three-dimensional γ-ray spectra. Except for the heaviest (the fission isomers), the superdeformed nuclei are populated in nuclear reactions only at very high spins (40–60 $\hbar$), and the reaction mechanism is such that their population is very small, typically only about 1% of the total reaction cross section. The key to finding and studying these nuclei was to make use of the regular spectra and of the increased efficiency of multidetector arrays, which provide higher-order coincidence spectra and thus higher resolving power.

2.2.4. Resolving power and 4 π arrays

To quantify the performance of 4π arrays and plan new ones, the concept of resolving power – the ability to isolate a given sequence of gamma rays from a complex spectrum – was introduced [1]. Our precise definition of the resolving power [14] is dependent on assumptions related to the type of spectra. (Other formulations have been given by Radford [15]).

We consider the γ-ray spectra typically produced in nuclear fusion reactions, which consist of a number of γ-rays per cascade extending over a certain energy range. This determines an average energy spacing per transition (SE). We further assume that the background is essentially unrelated to the peaks (which means that the cascade of interest has a small intensity and is not in coincidence with the bulk of the background). To be "resolved", a peak must stand out above the background and also be statistically significant. We take as criteria for a peak to be "resolved" from the background that the peak-to-background ratio is one and that there must be N counts in the peak.

The peaks are measured with an energy resolution δE, so that every time we set a gate on such a peak (i.e., a coincidence gate of width δE), we improve the peak-to-background ratio for that sequence by a factor around SE/δE. We also take into account that a γ-ray peak represents only a fraction P/T of the γ-ray total intensity (see Section 2.1), and further that a typical gate includes only a fraction of the full-energy peak (a realistic number for a FWHM gate on a Gaussian peak is 76%). The improvement in peak-to-background is then given by $R = 0.76(\mathrm{SE}/\delta E)P/T$. In this derivation of the resolving power, we assume that for any fold considered, the peaks to resolve are much smaller than the background. Thus, the peak-to-background ratio in the one-fold spectrum for a branch of intensity α is αR, and for an f-fold coincidence spectrum (i.e. one where f γ-rays are detected) this ratio is αR^f. Thus, for a peak-to-background ratio of one, $\alpha R^f = 1$.

The number of counts n in the peaks of an f-fold coincidence spectrum for a branch of intensity α is $n = \alpha N_0 \varepsilon^f$, where N_0 is the total number of events, and ε is the total full-energy peak efficiency of the array for a typical energy.

We now apply the criteria given above to define the resolving power. The conditions for a cascade of minimum intensity (α_0) to be "resolved" (N counts in a peak with peak-to-background ratio one) define an "optimum-fold" (F) that will just satisfy the criteria given above. Thus we have $N = \alpha_0 N_0 \varepsilon^F$ and $\alpha_0 R^F = 1$. The intensity of that cascade $\alpha_0 = 1/R^F$ defines the resolving power RP as $1/\alpha_0 = R^F$. At this optimum fold, F, α_0 represents the smallest sequence intensity that can be "resolved" in that spectrum. By eliminating F using the equations for α_0 and N, one obtains the expression for the resolving power as a function of ε and R:

$$\mathrm{RP} = \exp[\ln(N_0/N)/(1 - \ln \varepsilon/\ln R)]. \quad (1)$$

This formula shows that the important parameters which determine the performance of this type of γ-ray array are the energy resolution, δE, of the detectors, their characteristic peak-to-total ratio, P/T, and the full-energy peak efficiency, ε. What the first generation arrays such as HERA have done over previous systems of three or four Ge detectors is to improve (1) the P/T through Compton suppression and (2) the full-energy peak efficiency through the number of detectors used. If we take $N = 100$ and a typical value of $N_0 = 2.88 \times 10^{10}$, corresponding to a reaction rate of 10^5/s for a duration of 80 h, then $\ln(N_0/N) = 19.5$. We can evaluate the resolving power of the HERA array mentioned in the previous paragraph. In the evaluation one takes into account realistic experimental conditions and defines δE_{eff} as an "effective" energy resolution, which includes not only the intrinsic resolution of Ge detectors (approximately 2 keV for a 1 MeV gamma ray), but also other effects that might affect the peak width, such as the Doppler broadening due to the recoil velocity of the product nuclei that emit the γ-rays and the finite size of the Ge detector. For HERA, $\varepsilon = 0.012$, $\delta E_{\mathrm{eff}} = 6.1$ keV, $\mathrm{P/T} = 0.40$. We take $\mathrm{SE} = 60$ keV for all our evaluations. The resolving power of HERA is then 50 for γ-rays of approximately 1 MeV.

In 1987, another big step was accomplished when the Berkeley Nuclear Structure group proposed an array design that was optimized to maximize the solid angle covered by the Ge detectors, and that took advantage of the fact that bigger Ge detectors could then be manufactured (efficiency of 75% of that of the standard NaI detector (cf. Section 2.2.1) as compared to 25% for the HERA Ge detectors), which improved the P/T as well as the efficiency. Each Ge detector was still surrounded by a BGO Compton suppressor, and altogether, almost the entire 4π solid angle was covered by 110 Ge detectors and their BGO Compton suppressors. The array is called Gammasphere and it was built at the Lawrence Berkeley National Laboratory with the participation of other US National Laboratories and Universities. Dedicated in December 1995, Gammasphere is a National Facility and was operated at LBNL until September 1997. It was then moved for some period of time to the Argonne National Laboratory. Detector arrays of similar resolving power were constructed in parallel in Europe (Eurogam, succeeded now by the Euroball array).

The Gammasphere detailed design will not be discussed here, but there is one property that should be mentioned because it affects the resolving power: approximately 70 of a total of 110 Ge detectors are segmented into two D-shaped halves through the electrical segmentation of the outer electrode. This feature, which will be discussed in a following paragraph, increases the effective energy resolution of the Ge detectors (δE_{eff} decreases) by reducing the Doppler broadening due to the finite size of the angle subtended by each detector. For Gammasphere, $\delta E_{\mathrm{eff}} = 3.95$ keV, $\mathrm{P/T} = 0.46$, which gives $R = 5.3$ and $\varepsilon = 0.09$, so that the resolving power is now approximately 3000, about 60 times that of HERA. An example of the increased power of these new arrays is the discovery of the "linking transitions" between superdeformed states and normally deformed states in some nuclei around mass 190 [16]. These transitions are indeed very weak, around 1% of the intensity of the superdeformed bands (which themselves have an intensity around 1% of the total cross section) and their observation corresponds to the gain made possible by the increase in resolving power. Observing these "superdeformed decay" transitions helps understand how the nucleus makes such a dramatic transition between two states where its shape is very different. These links have been observed in very few cases (5–10 out of about 300 bands known) and the full decay mechanism is still not clear. Many failed searches in other nuclei indicate that higher resolving power is needed to elucidate completely the decay mechanism of superdeformed bands.

2.2.5. Clustering of Ge detectors – towards 4π Ge shell

In parallel with Gammasphere design and construction, new types of Ge detectors were developed as a means of maximizing the efficiency and P/T of big arrays. The two most important ones are the clover detector [17,18] and the cluster detectors [19,20] which are both components of the Euroball array mentioned earlier. In present arrays, each of these is surrounded by a Compton suppressor. The clover detector is a composite of four coaxial Ge detector elements whose side surfaces have been cut so that they fit together much like the leaves of a clover (see Fig. 1). The main advantage of such detectors is their large efficiency (140%) while the localization remains similar to that of a single detector since one can usually determine which of the four elements is first hit by an incoming gamma ray. Thus the Doppler broadening is reduced to that of one of the elements. Such composite detectors utilize a new concept that considerably increases the efficiency of an array: the concept of "adding back". By adding the energy of signals that scatter between crystals, the efficiency of a clover detector is increased by a factor 1.5 over the sum of the contributions from the individual crystals. The cluster detector is an assembly of seven Ge detectors closely packed in a single cryostat (see Fig. 2). The novelty of this cluster is that each element of this assembly of seven is an encapsulated

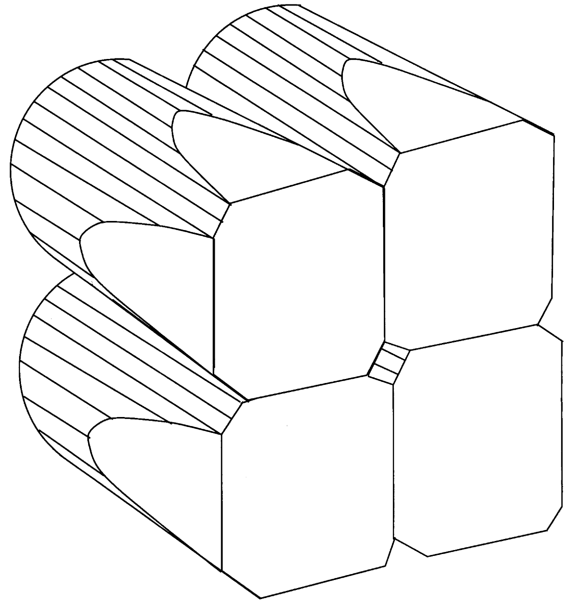

Fig. 1. Schematic drawing of a clover detector (from Ref. [17]).

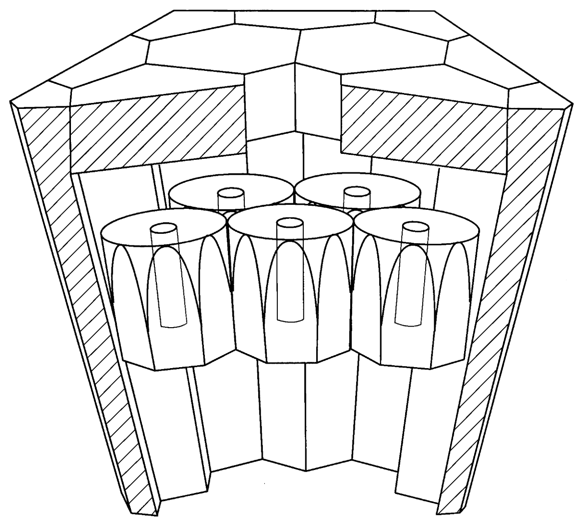

Fig. 2. Schematic diagram (side view cross section) of a cluster of 7 HPGe detectors (5 visible) surrounded by their BGO Compton suppressor (from Ref. [19]).

Ge detector [19,20]. An encapsulated detector is hermetically encased (in vacuum) in an aluminum can which is very close (1 mm) to the Ge crystal and provides electrical shielding. The seven detectors are packed very close together (crystal-to-crystal distance of 2.7 mm) in a cryostat with a ~ 5 mm spacing to the outer can which provides heat shielding. In this way the space between each detector in the group is minimized while retaining flexibility to retrieve individual detectors for repair. Clover and cluster detectors can increase the resolving power of an array, compared with arrays containing only conventional detectors, due to higher efficiency and P/T. However, they suffer to some extent the same limitations as Gammasphere-type detectors: (1) part of the useful solid angle is lost for Compton suppression and (2) the gain in efficiency and P/T is partly offset by summing effects where two γ-rays interacting in the same detector are counted as one, due to the large solid angle of such detectors. The summing effects can be remedied by using many such composite detectors far enough away from the γ-ray source, but the cost of such arrays would be prohibitive. This is where the new concept of GRETA comes in and qualitatively changes what can be achieved in γ-ray detection.

3. GRETA concept

3.1. GRETA principle

GRETA consists of a "solid" shell of (about 100) highly segmented large (e.g., 8 cm diameter by 9 cm long) HPGe detectors. The outer contact (surface of the coaxial detector) is segmented into many "rectangular-like" areas. The full energy and angle with respect to the beam direction of each incident γ-ray are determined by measuring, with high resolution, the energy and position of each of its interactions in the Ge crystals (see Fig. 3). The incident γ-ray is reconstructed by identifying these interactions using a tracking algorithm based on the Compton-scattering formula which describes the interactions. The γ-ray energy is obtained by adding the energy deposited at each interaction, and the emission angle of the incident γ-ray is deduced from the position of the first interaction. Using fast transient digitizers, an additional gain in efficiency comes from the reduced dead time. In addition, it is expected that, using parallel processing, this analysis can be done in real time. The improvement over previous arrays comes from three areas: (1) the efficiency is increased because nearly 100% of the solid angle is occupied by the Ge detectors which provide a useful high-resolution energy signal (instead of 46% in Gammasphere, for example) and, in addition, most gamma rays Compton-scattered to another crystal can be recovered; (2) because of the high segmentation, each γ-ray interaction can now, in principle, be resolved and attributed (by tracking) to a particular incident gamma ray, thus eliminating the summing problem and improving the peak-to-total ratio; and (3) since the interaction-position resolution is high (of order 2 mm), the position of the first interaction of a γ-ray will give its direction from a target or source with that precision and the Doppler broadening effects due to finite detector size will be greatly reduced.

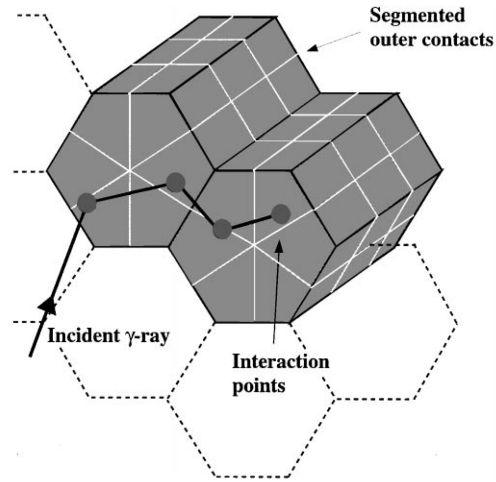

Fig. 3. Schematic view of interactions (dots) of an incident γ-ray in highly segmented HPGe detectors. The positions and energies of the interactions are used to reconstruct the energy and angle of the incident γ-ray.

3.2. Determination of the γ-ray-interaction position

3.2.1. The radial position

It is known [21] that an average radial position of interactions from one γ-ray in a coaxial detector can be determined by the drift time of the charge toward the electrodes. However, this property has not been used in typical nuclear physics experiments although a hardware circuit to determine the drift time of the main signal has been implemented in Gammasphere [22]. In GRETA, the radial position of an interaction is related to the drift time in the segment that receives the net charge from the interaction as well as to the shape of the transient signals (see Section 3.2.3). It will be deduced from the full decomposition of all the signals in the detector.

3.2.2. *Azimuthal and depth position*

In the Gammasphere two-fold segmented detector (Section 2.2.4, Fig. 4), the incident γ-ray may be completely absorbed in one half of the crystal, and it is then observed as a net charge signal in the corresponding electrode. If the γ-ray scatters into the other half of the crystal, there is a net charge in each electrode and in that case, its localization is based on the proportion of the energy deposited in each half. This gives a position resolution that is less than the size of the segment and is about a third of the solid angle subtended by the detector. Based on simulations and measurements, an often used procedure of position determination is that if more than 90% of the total γ-ray energy is deposited in one segment, the incident γ-ray is assumed to hit the center (of the front surface) of that segment, and if the energy deposited in one segment is between 10% and 90% of the total γ-ray energy, the incident γ-ray is assumed to hit the center (of the front face)

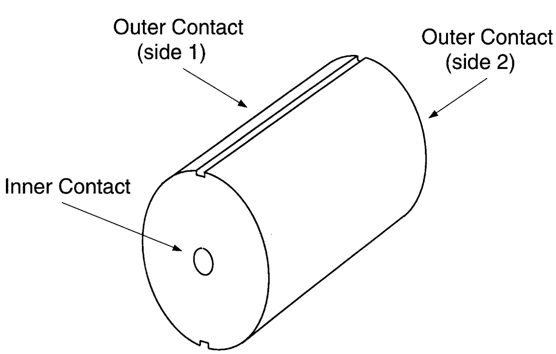

Fig. 4. Schematic view (from the back) of a Gammasphere segmented HPGe detector.

of the detector. Of course, when there is a net charge in both halves, one cannot distinguish between a scattering of one γ-ray from one side to the other and a double hit, but the latter are small (typically $< 10\%$ in Gammasphere). In GRETA, one would like to segment the outer electrode of the Ge detector such that only one γ-ray interaction occurs in each segment. A crude evaluation using the interaction length of γ-rays (of a typical energy of 1 MeV) indicates this requires "rectangular-like" segments 2–3 cm on a side etched onto the outer surface of the detector (i.e., in the length (z) direction, and in the azimuthal ($r\phi$) direction). By just collecting the net charge signals on each segment that fires, the azimuthal- and z-position resolution would correspond to roughly the size of the segment. However, one can do better than this by making use of the transient signals induced in neighboring electrodes.

3.2.3. *The transient signal*

In the two-fold segmented detectors of Gammasphere, one could analyze the energy distribution of the net charges in adjacent segments to obtain a position resolution better than the size of the segments, but one can do much better by analyzing the transient "induced charges" in neighboring segments. It was realized [23] that the charge drifting towards one electrode induces a signal in the neighboring electrodes and that the characteristics of this transient signal depend on the position of the interaction relative to the boundaries of the electrodes. Fig. 5 shows schematically the current signals produced when the charge from an interaction drifts toward its destination electrode as indicated in the Ge cross-section diagram on the left. The solid line shows the current signal in the segment where the interaction takes place. The signal increases continuously until the charge is neutralized when it reaches the electrode. The dashed lines are the transient currents as a function of time in the two neighboring segments. Their general behavior can be understood simply by considering the field lines that intersect each electrode and generate the image charges. Thus, in the segment where the interaction took place, the image charge always increases until the charge reaches the electrode, while in the neighboring segments, the transient image charge will

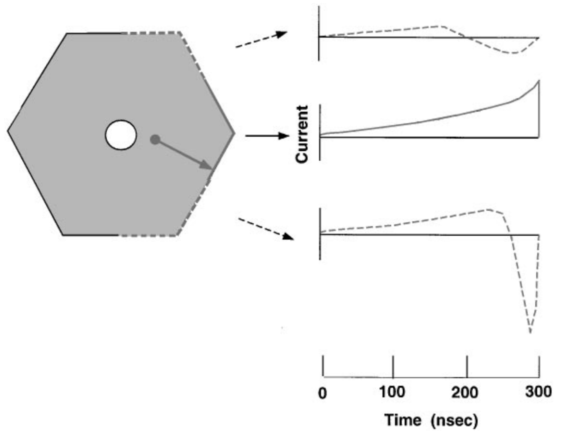

Fig. 5. Current signals on three electrodes (right) from a charge drifting toward the outside electrodes. The position of the interaction is shown as a dot on the detector cross section (left). The current from the destination electrode is the solid line and its integral is the net charge which gives the energy. The current from each neighboring electrode (dashed lines) integrates to zero.

decrease (and therefore the current will change sign) when the charge gets close enough to the destination electrode, and they will decrease more or less rapidly depending on the initial position of the charge. The net charge will be zero in these neighboring segments. Both the amplitude and the time of the maximum of the transient current signals can be used as parameters that define the position of the interaction with greater precision than the size of the segments. Using a prototype 12-segment Ge detector, tests are presently being performed to determine the attainable position resolution (see Section 4.2). A position resolution of a few mm in three dimensions is expected.

3.3. *Reconstruction of the incident γ-rays and of their energy*

Once the position and energy of each γ-ray interaction in the Ge detectors have been determined (with a known resolution) the next step is to deduce which interactions belong to a given γ-ray, sum up their energies to obtain the incident γ-ray energy and find the first interaction to obtain the γ-ray direction. So far, an algorithm involving a three-step process has been implemented [24,25], which constitutes a preliminary evaluation of this aspect of GRETA. The first step is to group the interactions into "initial clusters", which are assumed to result from the interactions of one incident γ-ray in the Ge detector array (at present considered to be a solid Ge shell). In a second step, the interactions within each cluster are evaluated (tracked) using the Compton formula to determine whether it is a "good" cluster. If not, one tries to maximize the number of good clusters in a third step by rearranging (adding or splitting) the original clusters and then testing the rearranged clusters once more with the Compton formula. This algorithm has been tested using simulated data from GEANT [26] which provides a set of interaction points generated by a number of input γ-rays. The following subsections give a more detailed description of this reconstruction process.

3.3.1. *Cluster creation*

We define clusters by the angle ν from the center of the array subtended by a pair of interactions. In this step we ignore the depth (z) of the interaction points. If the angle defined by any two interaction points is smaller than ν, these interactions are defined as initially belonging to the same cluster. The cluster is expanded if any additional points are found to be within the angle ν from any cluster point. The set of clusters defined in this way is then tested using the Compton formula.

3.3.2. *Tracking*

Tracking has been extensively used before in particle detection. It generally uses a trajectory or time sequence of the particle position. This is not possible with γ-rays where all the signals from a series of γ-rays from one event appear simultaneous. In our case, tracking uses the energy deposited and the 3-dimensional position of each interaction point. The energy deposited (E_d) is the energy difference between the incident γ-ray and the scattered γ-ray. It is related to the scattering angle θ by:

$$E_{\rm d} = E_\gamma - E'_\gamma$$

$$= E - \frac{0.511}{(0.511/E\gamma) + 1 - \cos\theta}, \qquad (2)$$

where E_γ is the sum of the energies of the interaction points in the cluster. From the measured value of E_d, the scattering angle can be determined. However, the scattering angle can also be obtained from the position of the consecutive interaction points. The consistency of these two values is a test of the scattering sequence assumed. This is a very complicated problem since in a typical event, there are of order 20 γ-rays, each having on the average 4 interactions in the Ge shell. Such tracking techniques have not been used before, except perhaps in astronomy in so-called Compton γ-ray observatories to determine the direction of a γ-ray source in the sky. However, tracking is much simpler in this case because the source emits a single γ-ray at a time and only the first Compton interaction is used.

To evaluate a sequence in GRETA we use a figure of merit, which is basically the total χ^2 resulting from the difference of the two scattering angle values for all interaction points in the cluster. For a cluster of n interaction points, there are $n!$ possible scattering sequences. These sequences are tested to find the one with the minimum χ^2. If it is below a predetermined threshold for χ^2, the cluster is defined to represent a "good" γ-ray. If it is above, the clusters are split or added in some prescribed way and then tested again in the same way using the Compton formula. This process produces a set of reconstructed γ-rays which is compared to the known set of input γ-rays to give the peak-to-total ratio and an efficiency curve as a function of υ. Such a study of the dependence of the performance on the angle parameter υ (see Section 4.3) will determine which value(s) of υ to use in the analysis of experimental data.

The above cluster recognition algorithm is one possible approach and shows the "principle" of reconstruction of the incident γ-rays. Other algorithms need to be explored, as well as different techniques such as neural networks.

3.4. Preliminary description of GRETA

The goal of this section is to give the reader a realistic idea of what such an array would look like. Since the design studies are not finished, we will only describe a possible detector configuration, as well as general components of the electronics and acquisition systems.

3.4.1. Detectors

A geometry that keeps the spherical symmetry and in which the Ge material covers the 4π solid angle is similar to that of Gammasphere [1]. It consists of 120 elements, 110 (almost) regular hexagons and 12 pentagons, two of which are used for the entrance and exit beam pipes in nuclear physics experiments at accelerators. Taking into account the present production limitations on the diameter of the Ge detectors (approximately 8 cm), tapered hexagonal detectors with the back part cylindrical, as shown in Fig. 6, optimize the amount of Ge material used without losing too much efficiency: only the last 1.4 cm at the back of the detector will not cover the full space. Using the Gammasphere geometry, this gives an inner radius (to the front face of the crystal) of approximately 12 cm, enough space to accommodate auxiliary detectors. A segmentation into 36 elements corresponds roughly to one interaction length and thus there are approximately 4000 segments in GRETA. Other packing geometries are being considered, for example, using cubic or regular hexagonal shape detectors that will make better use of the Ge material but will no longer have spherical symmetry.

3.4.2. Electronics

The present view is that cold FETs in the same vacuum as the crystal will give the best energy resolution. There is some uncertainty as to whether

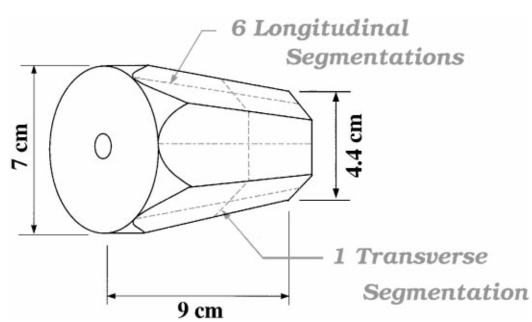

Fig. 6. Schematic perspective view (from the back) of the 12-segmented HPGe first GRETA prototype. The segmentation of the outer electrode is indicated as dashed lines.

connection with GRETA by the X-ray Instrumentation Associates company [29] and will be ready for tests soon. Finally, as computer technology keeps improving, we expect that it will be feasible to acquire a set of parallel computers well suited to perform the γ-ray reconstruction analysis. We believe an electronics and acquisition system which can analyze the signals "in flight" is achievable.

4.5. Future developments

We are presently developing algorithms to deduce the γ-ray interaction positions from a composite signal due to multiple hits in one segment. This is the last step needed to prove that the GRETA concept is valid and can be used in an actual detector array. Much remains to be done before finalizing a design for GRETA. Prototypes will be used to compare measurements with calculations, optimize algorithms, and determine characteristics of detectors and electronics. A 36-segment detector has been ordered, and later, a 7- or 9-detector prototype should help finalize the design of the array.

5. GRETA capabilities for new physics

Although the GRETA detector is, in some sense, the next step in the recent development of γ-ray detector systems, it is a very large step. The improvement in performance in some areas is so large that it seems entirely new capabilities are provided. For purposes of discussing the new physics GRETA will enable, we will (somewhat arbitrarily) focus on four areas where such "new" capabilities will be realized.

One area that is entirely new is the *characterization* of an incident γ-ray through tracking; that is, measuring each interaction point and requiring consistency between the total energy and the energy and scattering angle at each point. A major advantage is that close-lying γ-rays can be separated, including ones that hit the same crystal. This also allows one to distinguish full-energy events in the crystal (those that track with low χ^2) from partial-energy events (those that do not track with low χ^2), thereby improving considerably the response function (peak-to-total ratio). This reduction of background is important for almost all experiments involving γ-rays. Measuring the scattering angle between the first and second interaction point gives information on the linear polarization of a γ-ray which defines its electric or magnetic character; essential information in many nuclear structure studies, e.g. the determination of the parity of nuclear levels. From simulations the polarization sensitivity, $Q(E_\gamma)$, is estimated to be 0.35, which is higher than any polarimeter ever built (even those with extremely small efficiencies). A figure of merit for polarimeters is generally taken [31] to be: $\varepsilon[Q(E_\gamma)]^2$, where ε is the efficiency of the detector, and on this basis GRETA is at least 100 times better than any previous system, including Gammasphere and Euroball. In addition, tracking can distinguish γ-rays emitted by the source from those originating outside the detector, important for reducing the background in some types of experiment with low counting rates. The tracking information will become more important when one must be more certain about the nature of an event.

The *localization* of the first interaction point in a detector defines the angle of emission of that γ-ray from a source (target) of known location relative to the detector. Through tracking, GRETA will be able to locate that first interaction point to within 2 mm (FWHM), or at a distance from the source (to the average depth of the first interaction around 1 MeV) of 15 cm, to within a FWHM angle of 0.8°. For a standard Gammasphere-size detector ($\sim$ 7 cm dia.) at a typical distance of 25 cm from the source, this FWHM angle is about 8°, an order of magnitude worse. This angular resolution is especially important when detecting γ-rays emitted by a fast-moving source because such γ-rays have a Doppler energy shift that depends on the angle of emission, and this creates an energy spread in a detector that depends on the uncertainty in the angle of emission defined by the localization. As an example consider the study of neutron-rich light nuclei, where the production of near-drip-line nuclei is by fragmentation reactions resulting in product velocities v/c of 30%, or higher. For a 1 MeV γ-ray emitted at 90° to the beam direction, the contribution to the FWHM of the energy spread due to the Doppler broadening would be

39 keV with a standard Gammasphere detector, while it would be 3.7 keV with GRETA. This improvement can have a large effect on the physics, both in detecting weak γ-rays and in separating nearby peaks. An example of this type of experiment was the Coulomb excitation of a secondary beam of ^{44}S produced in the primary fragmentation reaction ^{48}Ca + ^{9}Be [32]. The ^{44}S beam was subsequently Coulomb excited in a thin gold foil at the center of an array of position-sensitive NaI detectors. Due to its better intrinsic resolution, localization and efficiency, GRETA would have ~ 100 times more sensitivity for detecting the resulting 1.3-MeV γ rays than the NaI array. Localization is important for other experiments involving large recoil velocities, e.g. those using inverse-reaction kinematics and many Coulomb-excitation studies.

GRETA has a much higher *efficiency* for detecting full-energy γ-rays than previous detector systems, especially for high-energy γ-rays; e.g. at 10 MeV the efficiency is more than an order of magnitude larger than in previous arrays. This high efficiency is due to: (1) the 4π germanium coverage, whereas detectors like Gammasphere and Euroball have closer to 2π germanium coverage; and (2) the "add-back" feature of GRETA, where γ-rays can be tracked out of one germanium crystal and into an adjacent one, and by adding the appropriate interaction points, the full energy can be recovered. The gain of GRETA efficiency over Gammasphere efficiency is roughly a factor of 3, 6 and 20, respectively, for the energies of 0.1, 1, and 10 MeV. While the gain is large everywhere, it increases with increasing γ-ray energy due to GRETA's improved ability to collect larger showers. This efficiency will be especially important in ISOL experiments where the beam intensities are likely to be low, and in giant resonance experiments where the combination of high efficiency and high-energy resolution is unprecedented. An interesting example outside the nuclear-structure area is the accurate measurement of the decay probability of positronium into four γ-rays. This experiment requires detection of five γ-rays, the four just mentioned plus one for identification (through the 1.275 MeV γ-ray associated with the decay of ^{22}Na), and GRETA will have about 500 times the probability of detecting such a decay compared with detectors such as Gammasphere or Euroball. The present limit for the decay of triplet positronium into four gamma rays is, $4\gamma/3\gamma < 10^{-5}$, and the estimated five γ-ray detection rate with GRETA is about 10 per second, indicating that the limit could probably be reduced by a factor of 100 or more. This is an enormous improvement in such an experiment.

One of the principal driving forces for the development of detector systems such as Gammasphere and GRETA has been the high-spin studies following fusion reactions. These are cases where there are high multiplicity (20–30) γ-ray cascades and the interesting physics is often in very rare cascades (e.g. superdeformed bands). As discussed earlier, a measure of the *sensitivity* in these kinds of studies is the "resolving power", which combines energy resolution, efficiency, response function, granularity and rate in an appropriate way. An important property of GRETA, due to newly designed electronics, is that it will be able to sustain counting rates more than 20 times higher than Gammasphere (about 4×10^4 per second per sector or more than 2×10^5 per second for each detector) and this large gain in rate is important for many types of experiments. Consider a typical fusion reaction experiment where the average angular momentum left in the product nucleus is around $40\hbar$, resulting in the emission of ~ 20 γ-rays per event with average energy 1 MeV. Gammasphere would catch an average of 2 full-energy γ-rays per event, whereas, GRETA will catch between 5 and 10, and these 5 or 10 could be accumulated at more than 20 times the rate. It is clear that this will bring a qualitative improvement in the experiments. For example, the linking transitions between superdeformed and normally deformed states are very difficult to detect now – only a few cases known with several linking transitions in those cases – but GRETA's much greater sensitivity may be able to resolve completely this decay (perhaps hundreds of pathways), providing unprecedented information on the energy levels between the superdeformed band and the ground state. There are many other examples where the large gain in sensitivity with GRETA will be crucial.

GRETA has a variety of new capabilities which will be used in various combinations to accomplish the goals of many types of physics. The objective of this section has been to give some hint of this variety.

6. Conclusion

GRETA, the next generation γ-ray detector array, successor of Gammasphere and Euroball, goes beyond the limit reached by these arrays which were based on Compton suppression. GRETA uses the new concept of γ-ray tracking, made possible largely by technical advances in Ge detector segmentation. This leads to large gains in resolving power and also to new kinds of measurements, such as the event-by-event characterization of γ-rays, and the detection of high-energy, high-resolution γ-rays. Gamma-ray detector evolution is important for many types of physics.

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