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# Gamma-Ray Tracking Arrays

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**Abstract**

The next generation of $4\pi$ arrays for high-precision $\gamma$-ray spectroscopy will involve $\gamma$-ray tracking detectors. They consist of high-fold segmented Ge detectors and a front-end electronics, based on digital signal processing techniques, which allows to extract energy, timing and spatial information on the interactions of a $\gamma$-ray in the Ge detector by pulse shape analysis of its signals. Utilizing the information on the positions of the interaction points and the energies released at each point the tracks of the $\gamma$-rays in a Ge shell can be reconstructed in three dimensions.

# 1 Concept of $4\pi$ $\gamma$-Ray Tracking Arrays

The investigation of new phenomena in atomic nuclei requires the study of their structure under extreme conditions at the boundary of stability, where the excitation energy, the spin or the ratio of protons and neutrons (isospin) take extreme values. The most powerful means for such studies is the high-precision $\gamma$-ray spectroscopy. Many interesting research topics, especially the investigation of the isospin degree of freedom requires the use of highly efficient and highly granulated $\gamma$-detector arrays.

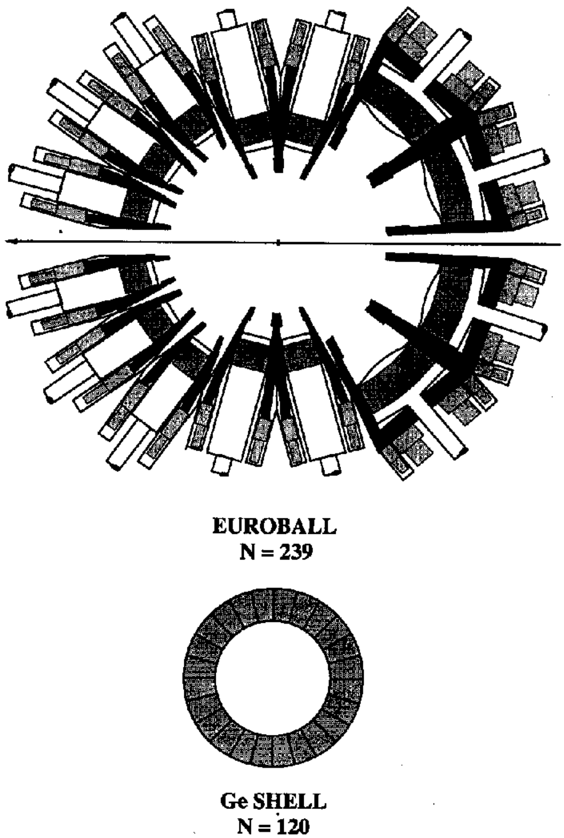


Figure 1: Cross-sections of the $\gamma$-ray array EUROBALL and a Ge shell. The two spectrometers are drawn approximately to scale. The Ge detectors are shown in grey and the BGO anti-Compton shields in black.

The state-of-the-art with respect to $4\pi$ $\gamma$-detector arrays is represented by EUROBALL in Europe and GAMMASPHERE in the USA consisting partly of composite and two-fold segmented Ge detectors, respectively. A new concept is required to increase the efficiency and granularity of $4\pi$ $\gamma$-detector arrays. In fig. 1 the $\gamma$-detector array EUROBALL and a Ge shell are shown in cross-section. EUROBALL consists of 15 CLUSTER detectors composed of seven Ge detectors, 26 CLOVER detectors composed of four Ge detectors, both types in compact geometries surrounded by common BGO (bismuth germanate) anti-Compton shields as well as 30 individually shielded Ge detectors [1]. The Ge shell is assumed to have an inner radius of 15 cm, a thickness of 9 cm and consists of 120 Ge detectors. In the present generation of $\gamma$-detector arrays about 50% of the total solid angle is covered by the BGO anti-Compton detectors. To significantly improve the efficiency, the coverage of the total solid angle with Ge detectors has to be maximized. The features of EUROBALL and the Ge shell are given in table 1 for a $\gamma$-ray multiplicity of $M_\gamma = 30$.

Table 1: Comparison of the features of EUROBALL and a Ge shell for a $\gamma$-ray energy of $E_\gamma = 1.3$ MeV and a $\gamma$-ray multiplicity of $M_\gamma = 30$.

| Features | EUROBALL | Ge shell | Ge shell with tracking |
|---|---|---|---|
| Number of detectors | 239 | 120 | 120 |
| Total photopeak efficiency | $\approx 6.5\%$ | $\approx 6.5\%$ | $\approx 18\%$ |
| Peak-to-total ratio | $\approx 37\%$ | $\approx 13\%$ | $\approx 58\%$ |

Although the Ge shell occupies the total solid angle it has only a total photopeak efficiency of $\epsilon \approx 6.5\%$ similarly to EUROBALL and a peak-to-total ratio of $P/T \approx 13\%$ which is approximately three times smaller than that of EUROBALL. The reason for such a poor performance is the large probability to detect several $\gamma$-rays in one detector and the scattering of $\gamma$-radiation between the Ge detectors due to the Compton effect. However, if one could follow the tracks of the $\gamma$-rays in the Ge shell and identify the interactions belonging to particular $\gamma$-quanta a dramatic improvement of its characteristics could be obtained resulting in $\epsilon \approx 18\%$ and $P/T \approx 58\%$. In addition, the Doppler shift correction can be significantly improved if the angles at which the $\gamma$-rays hit the Ge detectors can be determined with high precision. Such a Ge shell will have a sensitivity which is about two orders of magnitude larger than that of EUROBALL and GAMMASPHERE, respectively.

The prerequisite for the construction of such a $\gamma$-ray tracking array is the development of $\gamma$-ray tracking detectors. They consist of high-fold segmented Ge detectors and front-end electronics, based on digital signal processing techniques, which allows to extract energy, timing and spatial information on the interactions of a $\gamma$-ray in the Ge detector by pulse shape analysis of its signals. Utilizing the information on the positions of the interaction points and the energies released at each point the tracks of the $\gamma$-rays in a Ge shell can be reconstructed in three dimensions on the basis of the Compton scattering formula.

To design $\gamma$-ray tracking detectors for a $4\pi$ $\gamma$-detector array research and technical development is carried out in the following areas: (i) Development of segmented Ge detectors, (ii) Development of digital signal-processing electronics, (iii) Development of pulse shape analysis methods, (iv) Development of tracking algorithms and (v) Simulation of tracking arrays. Important results of the development work are discussed subsequently.

# 2 Development of Segmented Ge Detectors

A $4\pi$ $\gamma$-ray tracking array of large photopeak efficiency and resolving power will be composed of multi-segmented Ge detectors. They will allow to determine in three dimensions the positions at which each $\gamma$-ray interacts with the array. The interaction points of the $\gamma$-rays in the Ge detector are localized by means of the segmentation of one or both Ge detector contacts and pulse-shape analysis of the segment signals.

A six-fold segmented Ge detector has been successfully developed for the MINIBALL project on the basis of the encapsulated Ge detector of the EUROBALL project [2]. The Ge detector has a semi-hexagonal shape (hexagonal at the front face and circular at the rear side) and is subdivided into six triangular segments if viewed from the front face (azimuthal segmentation) by separation of the outer implanted contact. This detector is encapsulated, a technology which allows to cluster them in various configurations and to investigate and optimize the cabling, grounding and shielding to avoid microphony, cross-talk, shifts and oscillations.

A 25-fold segmented cylindrical Ge detector which has six azimuthal and four longitudinal segmentations plus one central circular segment at the front has been developed. It has 25 cold field-effect transistors, one for each segment all placed in the Ge crystal vacuum chamber. The energy resolutions of the seven front segments are $\approx 2.5$ keV and those of the eighteen rear segments are $\approx 2.0$ keV. The reason is that the Ge detector has a closed-end geometry leading to a radial electrical field in the coaxial rear part of the detector and to distortions from the radial field in its front part. No cross talk has been observed in the preamplifier signals.

Development work on a stack of segmented planar Ge detectors has been started. Technical improvements, like the reduction of the dead layer on the passivated surface or the use of an implanted phosphorous contact, would greatly increase the interest in such a detector.

# 3 Development of Digital Signal-Processing Electronics

The task of the pulse processing system is to digitize the preamplifier signal using an analog-to-digital converter (ADC) with sufficient resolution and sampling rate and to provide digital signal processing hardware powerful enough for on-line processing of the signals. The high dynamic range as well as the bandwidth of the preamplifiers of around 20 MHz implies the necessity to sample the preamplifier output signal with at least 12 bit and 40 Msps/s in order to allow for the desired digital signal processing and pulse shape analysis. A $\gamma$-ray tracking array consisting of about 120 Ge detectors, which are 24-36 fold segmented, will have up to 4000 processing channels producing each a primary data rate of 60 Mbyte/s. This requires a compact digital signal processing electronics with high computing power for on-line data reduction. In the ideal case the whole information should be reduced to only five values per interaction: $E_\gamma$, $t_\gamma$ and the three coordinates of the interaction point.

A new version of the Pulse-Processing ADC (PPADC) [3] in which up to eight digital processing channels can be integrated as daughter boards on one mother board has been built in cooperation with the company "target system electronics GmbH" Solingen, Germany. The mother board makes the communication with the host PC. Two daughter board versions exist, a 20 MHz version with a 12 bit 20 MHz ADC and two digital signal processors (DSP), and a 80 MHz version with two 12 bit 40 MHz ADCs, one programmable logic device (PLD) and one DSP, which has been specifically designed to allow for pulse-shape analysis. Software for control, testing, and readout of the PPADC has been written.

Depending on the information which has to be extracted from the Ge detector pulses, different optimized signal processing algorithms exist or have to be developed and applied. The time invariant Moving Window Deconvolution (MWD) for instance has been proven to be an optimal filter, if information about the released total energy $E_\gamma$ has to be extracted [4]. For triggering, timing and pulse shape analysis only the leading edge of the signals, i.e. a small part of the data stream is relevant. A trigger algorithm has been developed which allows to obtain a trigger efficiency of 100% down to 20 keV and 80% at 10 keV [3]. For lifetime measurements and the extraction of the position information, a timing with a resolution of sub sampling interval accuracy is needed. Therefore a new, digital timing discriminator has been designed, the algorithm of which is simple and compact enough to run on-line on the PPADC hardware. The concept is based on the idea, that the original detector signals are steplike in the very beginning. This means, that for a given preamplifier response function a very well defined relation exists between the starting point of the signal and the amplitudes of the first few samples measured. An algorithm based on this idea has been developed and implemented on the PPADC giving a time resolution of 8.5 ns for a large-volume Ge detector measured in coincidence with a plastic scintillator for a $^{60}$Co source taking the full dynamic range ($E_\gamma > 0$ keV) [3].

Furthermore, a digital energy channel, based on a 5 MHz 12 bit ADC has been developed. It employs a simple analog pre-filter, which avoids pulse pile up and cooperates with the digital filter to keep the quantization noise to a minimum. The hardware contains a small field programmable gate array (FPGA) and a low-price fixed-point DSP.

# 4 Development of Pulse Shape Analysis Methods

The pulse shapes produced by $\gamma$-rays interacting with a Ge detector contain the information about the three-dimensional position of each individual interaction within the detector volume and the energy released at each interaction. The tracking efficiency, and hence the final performance of a complete tracking array, depends on the precision of these data. The analysis should preferably be done on-line, to keep the data rate at a level, which can be handled by present data acquisition systems. That is, the algorithms have to be converted into efficient real-time code, which has to be implemented on dedicated, high performance digital signal processing electronics.

The charge collection process, i.e. the charge carrier drift in Ge crystals at high electric fields and low temperature has been experimentally and theoretically studied and an anisotropy of the drift velocity depending on the crystal orientation, as well as an orientation-dependent angular shift of the drift direction have been found [5]. For the first time it was demonstrated, that this anisotropic drift of the charge carriers must be taken into consideration in the analysis of pulse shapes of Ge detectors for position determination. Experimental investigations of this effect have been carried out with a semi-hexagonal Ge detector of the EUROBALL project. The detector was scanned with collimated $^{22}$Na and $^{241}$Am sources at fixed radii under variation of the azimuthal angle in a 360° range. It was found, that the charge collection time depends on the azimuthal angle showing a 90° symmetry with a maximum at the $< 110 >$ direction and a minimum at the $< 100 >$ direction of the face-centred cubic (FCC) Ge crystal [5]. The measurements were taken in the front and coaxial regions of the Ge detector. A variation of the charge collection time of up to 35% is obtained for different drift directions relative to the crystal orientation. The results are in good agreement with simulations and the charge collection process is considered to be well understood now [5].

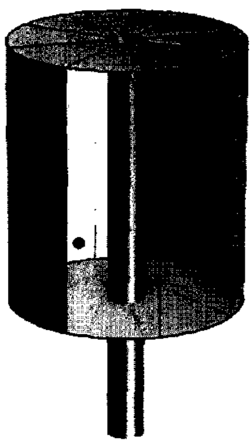

Figure 2: Eight-fold segmented true-coaxial Ge detector with four simulated interactions of $\gamma$-radiation with the detector shown as full circles.

Methods for a determination of the interaction positions of $\gamma$-rays in segmented Ge detectors have been developed. They take into account the shapes of the induced "real" and "mirror" signals. Real signals are measured at the electrodes of the segment, in which an interaction takes place. Mirror signals are measured on the electrodes of the neighbouring segments, where no interaction takes place and are due to a capacitative coupling between these segments and the moving charges. Simulated real and mirror signals of a 25-fold segmented detector were used as input to an artificial neural network and a genetic algorithm to study their ability to distinguish between single and multiple interactions and to extract the position and energy information. A correct identification of the number of interactions was obtained for the latter at a success rate of more than 90% with a position resolution of better than 2 mm and an energy resolution of better than 4% for two events.

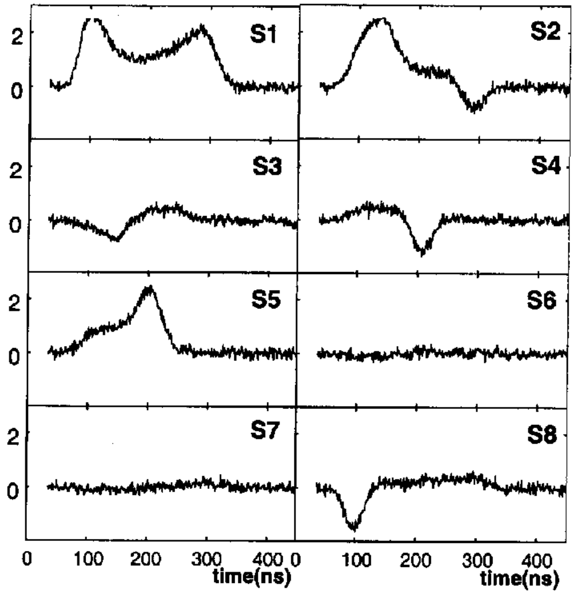


Figure 3: Simulated pulse shapes of preamplified signals derived from the eight segments corresponding to the simulated interaction points in the Ge detector shown in fig. 2.

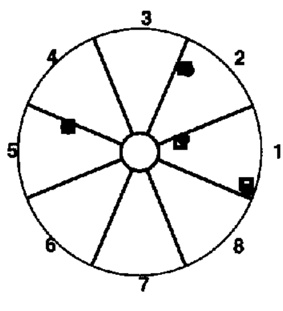


Figure 4: Cross section of the eight-fold segmented Ge detector shown in fig. 2. The simulated interaction points are indicated by full circles and the identified interaction points by open squares.

Furthermore, a pattern recognition system based on the wavelet transform of simulated preamplified signals was investigated [6]. To find an optimum wavelet transform, their properties were studied in view of the features of the current signals obtained by a differentiation of the Ge detector charge signals. A "wide-band" small support wavelet transform (WB4) has been selected for the processing of the pulse shapes of the detector signals. The wavelet coefficients of the signals were compared to data bases with wavelet coefficients of signal shape types (pattern classes) to identify the best fit via a first nearest neighbour algorithm and a calculation of the membership function of the identified class [6]. Results of a two-dimensional wavelet analysis are shown in figs. 2 to 4. In fig. 2 a three-dimensional picture of an eight-fold segmented, true-coaxial Ge detector is shown and the positions of four simulated interactions of $\gamma$-radiation with the detector are indicated by dots. In fig. 4 the interaction points can be seen in a two-dimensional projection. The pulse shapes corresponding to these interactions have been simulated by calculating the electric field in the Ge detector and taking into account the charge carrier transport. In fig. 3 the resulting simulated pulse shapes are shown. The segments 1, 2 and 5 show real signals and all other segments, except for segment 7, show mirror signals. In segments 1 and 2 the real signals are superimposed by mirror signals. These signals after digitization every 20 ns serve as input to the wavelet analysis. As result of this analysis the positions of the identified interaction points are indicated by open squares in fig. 4. The agreement with the original simulated interaction positions is excellent. It should be pointed out that two interactions were assumed in segment 1 and that both interactions have been identified with high precision (fig. 4). Hence, it is possible to decompose pulse shapes resulting from the superposition of several signals, here two real and one mirror signal, by wavelet analysis methods. The distance between the two interactions in segment 1 was large, however. If the interactions lie very close together a unique decomposition may not be possible.

The wavelet transform has also been applied to a determination of the interaction coordinates in three dimensions [6]. This requires that the Ge detector is also segmented in longitudianl direction. For a Ge detector with an eight-fold azimuthal and a four-fold longitudinal segmentation a similar precision for the localization of the interaction points in three dimensions as for the two-dimensional case has been obtained. It was found, that the interaction positions in a Ge detector can be determined with a resolution of the order of 1 mm$^3$ for single events. Multiple hits may be resolved if they lie more than 2 - 3 mm apart. The position resolution depends on the noise. The limit of the position resolution is the dimension of the charge carrier cloud produced in an interaction, being $\approx$ 1 mm.

# 5 Development of tracking algorithms

Extensive simulations of the interaction of $\gamma$-radiation with Ge detectors have been performed using the Monte Carlo code GEANT. The simulations have been carried out for a certain detector geometry and a standard set of $\gamma$-ray energies and $\gamma$-multiplicities. A result which is significant for the detector development and pulse shape analysis is that for a typical Ge detector of 80% relative efficiency with about 30 segments, the detection of a 1.33 MeV $\gamma$-ray produces in 50% of the cases more than one interaction point in the same segment. Concerning the energy distribution of the individual interactions of a $\gamma$-ray in a Ge detector it has been found that, rather independently of the initial $\gamma$-ray energy, most of the spectral intensity for photoelectric absorption lies somewhat above $E_\gamma \approx 100$ keV whereas the Compton scattering spectrum is peaked at a lower energy.

The successful development of two alternative algorithms for $\gamma$-ray tracking has shown that it is a viable solution for the development of a new generation of $4\pi$ $\gamma$-ray arrays. (i) In one method a two-step procedure is applied. At first clusters of interaction points are identified which likely represent the path of one $\gamma$-ray [7]. Subsequently for each cluster, a test of all permutations of the coordinates and energy depositions of the interaction points against the Compton scattering formula is carried out in order to distinguish the acceptable sequences from those that, because of incomplete absorption of the $\gamma$-ray, must be rejected. (ii) The other approach starts from points likely to be the last of the interaction sequence because they are associated with an energy deposition in the range of 100-300 keV and traces the tracks back, step by step using the Compton scattering formula and the cross sections for photo and Compton effects, to the origin of the $\gamma$-ray without assuming a preliminary clusterisation. This method is called "backtracking" [8] and allows, in principle, to disentangle the interaction points of two $\gamma$-rays which enter the detector at a very close distance. For cascades of 25 $\gamma$-rays and for an idealized spherical shell geometry, both tracking algorithms give presently a reconstruction efficiency of 30 to 70% for $E_\gamma = 1.33$ MeV, depending on the assumed accuracy to which the coordinates of the interaction points can be determined. The performance of the first tracking algorithm depends mainly on the correct identification of the clusters while the backtracking is limited by the position resolution of the interaction points. For the backtracking algorithm the peak-to-total ratio and reconstruction efficiency increase with decreasing resolving distance [8] emphasizing that the position resolution should be optimized.

# 6 Simulation of Tracking Arrays

Possible geometrical configurations for a realistic $4\pi$ $\gamma$-ray array have been studied. Three basically different geometries have been considered: (i) a compact spherical geometry built of 120 individual large volume tapered Ge detectors, (ii) barrel-type geometries with, respectively, 36 and 54 non-tapered cylindrical or hexagonal Ge detectors arranged in a honeycomb-like structure with the crystal axes oriented along the beam direction and (iii) a cubic geometry with stacks of highly segmented planar Ge detectors. The features of these arrays are summarized in table 2.

Table 2: Performance of simulated $4\pi$ $\gamma$-detector arrays of various geometries. The total photopeak efficiency $\epsilon$ and the peak-total ratio P/T is given for a $\gamma$-ray energy of $E_\gamma$ = 1.3 MeV and $\gamma$-ray multiplicities of $M_\gamma$ = 1 and 30, respectively.

| Array | Number of Ge detectors | Germanium (kg) | $M_\gamma = 1$ | | $M_\gamma = 30$ | |
|---|---|---|---|---|---|---|
| | | | $\epsilon$ (%) | P/T (%) | $\epsilon$ (%) | P/T (%) |
| Ideal Ge shell | | 233 | 65 | 85 | 36 | 60 |
| Realistic Ge shell | 120 | 140 | 39 | 85 | 18 | 58 |
| Barrel (hexagonal det.) | 54<br>36 | 135<br>90 | 30<br>25 | 55<br>52 | 15<br>12 | 46<br>44 |
| Barrel (cylindrical det.) | 54<br>36 | 168<br>112 | 29<br>26 | 58<br>56 | 16<br>14 | 48<br>50 |
| Cube array | 488 | 457 | 50 | 60 | 26 | 40 |
| EUROBALL | 239 | 210 | 9 | 56 | 6.5 | 37 |

In table 2 one can see that realistic arrays, taking into account gaps and inactive material between the detectors, show a significantly reduced performance in comparison to an ideal Ge shell. Furthermore, the total photopeak efficiencies and peak-to-total ratios are much smaller for a $\gamma$-ray multiplicity of $M_\gamma$ = 30 than for $M_\gamma$ = 1. The response of the arrays to high-multiplicity events depends on the performance of the tracking algorithm. In the simulation calculations conservative assumptions about the position resolution have been made. The cube array shows a larger total photopeak efficiency than the other arrays. It should be pointed out, however, that the amount of Ge assumed in this calculation is 3 - 4 times larger than that for the other arrays. For comparison also the features of EUROBALL are shown in table 2. For a realistic Ge shell the total photopeak efficiency is about three times larger than for EUROBALL and the peak-to-total ratio is significantly improved. Taking furthermore the improved energy resolution into account one can estimate that the sensitivity of such a tracking array is about two orders of magnitude larger than that of EUROBALL.

# 7 Conclusions

It can be concluded, that the basic principles of $\gamma$-ray tracking have been successfully developed and that a $\gamma$-ray tracking array with superior features can be built. Nevertheless, a large amount of detailed technical development is still required.

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