

DEVELOPMENT OF γ -RAY TRACKING DETECTORS*

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The next generation of 4π arrays for high-precision γ -ray spectroscopy AGATA will consist of γ -ray tracking detectors. They represent 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 γ -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 γ -rays in a Ge shell can be reconstructed in three dimensions on the basis of the Compton-scattering formula.

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1. Concept of 4π γ -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, the ratio of protons and neutrons (isospin) or the total mass take extreme values. The most powerful means for such studies is the high-precision γ -ray spectroscopy.

The opportunities offered by beams of exotic nuclei for research in the areas of nuclear structure physics and nuclear astrophysics are exciting and world-wide activity in the construction of different types of radioactive beam facilities bears witness to the strong scientific interest in the physics that can be probed with such beams. Exotic beams allow to approach and map the drip line regions so that the very limits of nuclear stability can be explored. Nuclei far from stability allow us to amplify and isolate particular aspects of the nuclear interaction and dynamics. Future work will involve, *e.g.*, mapping the neutron drip line, exploring the evolution of shell structure and neutron skins, developing a deeper understanding of proton-neutron pairing, creating further superheavy nuclei and investigating the astrophysical r -process path.

Radioactive beams can be produced with the ISOL or fragmentation techniques. Especially in the latter case the final nuclei to be studied can have very high recoil velocities (up to $v/c = 0.5$). Even though radioactive ion beams from the next generation facilities will be much more intense, the exotic nuclei of interest will be produced with low rates. A γ -ray spectrometer to study the produced nuclei must, therefore, have the largest possible detection efficiency, a very good spectral response, a high count rate capability and must allow for an optimal Doppler shift correction. These features can only be provided by a new generation of spectrometers built from γ -ray tracking detectors.

The γ -ray tracking detectors have been developed in the framework of the TMR Network Project "Development of Gamma-Ray Tracking Detectors for 4π Gamma-Ray Arrays". 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 γ -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 γ -rays in a Ge shell can be reconstructed in three dimensions on the basis of the Compton scattering formula. Similar developments are carried out in the framework of the GRETA project [1].

Presently, the state-of-the-art with respect to 4π γ -detector arrays is represented by Euroball in Europe and Gammasphere in the USA consisting of individual as well as composite and two-fold segmented Ge detectors, respectively, surrounded by Compton-suppression detectors [2]. The γ -ray tracking detectors allow to build a Ge detector shell without any Compton-suppression detector. Therefore, the coverage of the total solid angle with Ge is increased by more than a factor of two with respect to Euroball and the capability to add back Compton-scattered γ -rays is optimised by the use of γ -ray tracking. The elements of a γ -ray tracking array are: (i) high-fold segmented Ge detectors, (ii) digital signal processing electronics, (iii) pulse-shape analysis algorithms and (iv) tracking algorithms.

2. Elements of a γ -ray tracking array

2.1. High-fold segmented Ge detectors

In order to achieve a large tracking efficiency the positions at which the γ -rays interact inside the detector volume, should be determined with an accuracy of 1–2 mm. This corresponds to an effective granularity of approximately 30000 voxels per Ge detector. It is impossible to achieve such a granularity by a physical segmentation of the detector. However, pulse shape analysis methods have been developed, which can provide this position accuracy together with high resolution energy and time information. These methods require a medium level segmentation of the outer detector contact into 36 segments.

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 front segments are ≈ 2.5 keV, except for the central one for which it is 1.8 keV, and those of the eighteen rear segments are ≈ 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.

2.2. Digital signal-processing electronics

The interaction points of the γ -rays in the Ge detector can be localized with a much higher accuracy than defined by the geometry of the segments if a pulse-shape analysis of the segment signals is carried out. This can be achieved by digital means only. The preamplified detector signal has to be digitized with at least 12 bit resolution and at a speed of at least 40 MSPS (million samples per second) in order to preserve all relevant features of

the signal in its digital representation. It is the task of the digital processing electronics to digitize the preamplifier signal using an Analog-to-Digital Converter (ADC) and to provide digital signal processing hardware powerful enough for on-line processing of the signals. A γ -ray tracking array consisting of about 190 Ge detectors, which are 36-fold segmented, will have almost 7000 digital signal processing channels producing each a primary data rate of 88 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_γ , t_γ and the three coordinates of the interaction point.

Digital signal processing electronics has been pioneered by the Jülich group in cooperation with the company "target system electronics GmbH" Solingen, Germany through the development of the Pulse-Processing ADC (PPADC) [3–5]. The most advanced version of the PPADC has two 12 bit 40 MSPS ADC's, one Programmable Logic Device (PLD) and one Digital Signal Processor (DSP) on board providing enough computing power to allow for pulse-shape analysis.

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_γ has to be extracted [4]. For triggering, timing and pulse shape analysis only the leading edge of the signal, *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 [5]. For lifetime measurements and the extraction of the position information, a timing with a resolution of sub sampling interval accuracy is needed. Therefore, a 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) [5].

2.3. Pulse-shape analysis algorithms

The shapes of the current pulses, obtained from the charge pulses of the Ge detector preamplifier by differentiation, 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 with which this information can be extracted.

Methods for a determination of the interaction positions of γ -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 capacitive coupling between these segments and the moving charges.

A pattern recognition system based on the wavelet transform of preamplified signals was investigated [6]. To find an optimum wavelet transform, their properties were studied in view of the features of the current signals of Ge detectors. A “wide-band” small support wavelet transform (WB4) has been selected for the processing of the pulse shapes of the real and mirror signals from the detector segments. 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].

The wavelet transform has been applied to simulated signals from a Ge detector segmented in azimuthal and longitudinal directions to determine the interaction coordinates in three dimensions [6]. For a Ge detector with an eight-fold azimuthal and a four-fold longitudinal segmentation it was found, that the interaction positions can be determined with a resolution of the order of 1 mm³ 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 ≈ 1 mm.

2.4. Development of tracking algorithms

Extensive simulations of the interaction of γ -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 γ -ray energies and γ -ray multiplicities. For the energy distribution of the individual interactions of a γ -ray in a Ge detector it has been found that, rather independently of the initial γ -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 γ -ray tracking has shown that it is a viable solution for the development of a new generation of 4π γ -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 γ -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 γ -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 γ -ray without assuming a preliminary clusterisation. This method is called “backtracking” [8] and allows, in principle, to disentangle the interaction points of two γ -rays which enter the detector at a very close distance. For cascades of 30 γ -rays and for an idealized spherical shell geometry, both tracking algorithms give presently a reconstruction efficiency of up to 60 % for $E_\gamma = 1$ 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.

3. Design of the Advanced GAMMA-Tracking Array

A European γ -ray tracking array called AGATA (Advanced GAMMA-Tracking Array) has been proposed. The geometrical structure of AGATA is based on the geodesic tiling of a sphere with 180 hexagons and 12 pentagons. Owing to the symmetries of this specific geometry three slightly different irregular hexagons are needed. To minimise the space between the detectors the hexagonal Ge detectors are contained in 60 γ -ray tracking modules. Each cryostat of the γ -ray tracking module contains three 36-fold segmented Ge detectors of hexagonal, tapered shape (8 cm diameter at the rear side, 10 cm length). The pentagonal Ge detectors have individual cryostats. The inner radius of AGATA is 17 cm and the total solid angle covered by the Ge material is close to 80 %.

The total number of segments in the γ -detector array AGATA is 6780. Together with pulse-shape analysis, this provides unprecedented position resolution. Realistic simulations of the tracking performance indicate an

efficiency of $\varepsilon_{ph} = 40\%$ and a peak-to-total ratio of $P/T = 65\%$ for a γ -ray energy of $E_\gamma = 1$ MeV and a γ -ray multiplicity of $M_\gamma = 1$. For a cascade of 30 γ -rays the corresponding values are $\varepsilon_{ph} = 25\%$ and $P/T = 50\%$. For comparison, the features of Euroball are $\varepsilon_{ph} \approx 9\%$ and $P/T \approx 56\%$ for $M_\gamma = 1$ and $\varepsilon_{ph} \approx 6\%$ and $P/T \approx 37\%$ for $M_\gamma = 30$. A key feature of AGATA is the high precision for determining the emission direction of the detected γ -quanta of $< 1^\circ$. This ensures an energy resolution better than 0.5% for transitions emitted from nuclei recoiling at velocities as high as 50% of the speed of light. This value is only a factor of two bigger than the intrinsic resolution of Ge detectors and is comparable with values currently observed with Euroball at 10 times smaller recoil velocities. AGATA will be, depending on the experimental conditions, orders of magnitude more powerful than all current and near-future arrays.

4. Conclusions

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

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