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The Advanced Gamma Ray Tracking Array AGATA

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On behalf of the AGATA collaboration

New accelerator facilities for radioactive–ion beams will enter into operation in the next few years, providing the opportunity to explore unknown territories of the nuclear landscape. The foreseen harsh experimental conditions require the construction of a new generation of γ–ray detector arrays based on the emerging technique of γ–ray tracking. The "Advanced GAmma Tracking Array" (AGATA), proposed in Europe, will be built out of 120 or 180 highly segmented Ge crystals operated in position sensitive mode by means of digital data techniques and pulse shape analysis of the segment signals. AGATA will be capable of measuring γ radiation in a large energy range (from $\sim$ 10 keV to $\sim$ 10 MeV), with the largest possible photopeak efficiency (25% at $M_\gamma = 30$) and with good spectral response. The very good Doppler correction and background rejection capability of this γ–ray tracking array will allow to perform γ–ray spectroscopy experiments using fragmentation beams with sources moving at velocities up to $\beta \sim 0.5$.

1. INTRODUCTION

In the last decade, EUROBALL and GAMMASPHERE have been the highest efficiency 4π detector arrays available for in beam γ–ray spectroscopy. These arrays are built out of $\sim$ 100 Compton–suppressed high purity germanium (HPGe) spectrometers arranged in a spherical configuration around the reaction point and provide, for 1 MeV γ–rays, a total peak efficiency (ϵ_{ph}) of about 10% and a peak–to–total (P/T) ratio of about 60%. These figures combine to a good selectivity for identification of weak reaction branches and, in fact, the two detectors have played a major role in experimental nuclear structure studies. The γ–ray spectroscopy community has now the opportunity to extend the field of nuclear structure studies exploiting the radioactive ion beams provided by the next generation of accelerator facilities of ISOL and fragmentation type. It is well realized that, due to low beam intensities, large Doppler broadenings and high backgrounds, the experimental conditions at such facilities will be very challenging. To cope with them, both the total peak efficiency and the selectivity of our arrays must be improved and it is a matter of fact that this cannot be obtained by simply increasing the number of detectors. The reason is that, to obtain a good P/T ration the Ge crystals must be surrounded by the BGO suppression shields, which, however, take a consistent fraction of the solid angle and limit the total peak efficiency of the so–called 4π arrays to no more than 10%. The solution of the problem will come from recent advances in crystal segmentation technology and digital

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signal processing, which make it possible to operate large–volume germanium detectors in a position sensitive mode. With the knowledge of energy and position of the interaction points within the germanium crystal it is possible to reconstruct the interaction history of the absorbed gamma radiation, realizing the so–called gamma ray tracking concept [1]. According to realistic Monte Carlo simulations, an array consisting of a relatively small number (100–200) of such detectors will have an efficiency of up to 50% and a P/T–ratio of 70%. It should be remarked that an important aspect of γ–ray tracking is the possibility to determine with very good precision ($\sim 1^\circ$) the emission direction of the reconstructed transitions, allowing for an almost perfect correction of Doppler broadening effects for gammas emitted by nuclei recoiling at velocities as high as $\beta = 0.5$.

The unique capability of the γ–ray tracking arrays will allow the study rare reaction channels produced in experiments with weak beam intensities (e.g. radioactive beams), addressing many questions that are still open in nuclear structure, astrophysics and fundamental interactions. Finally, it is clear that, besides the perspective use for fundamental research, the principle of γ–ray tracking is also extremely interesting for its possible application in the field of γ–ray imaging.

2. GAMMA-RAY TRACKING

The feasibility of γ–ray tracking has been the subject of extensive R&D performed in the last seven years by GRETA [2] in the USA and the TMR network “Gamma Ray Tracking Detectors”[3] in Europe. The main lines of development are outlined in the following.

Tracking algorithms. The main task of γ–ray tracking is to identify the individual transitions of an event and to reconstruct their scattering sequence inside the detector using the energy and the spatial coordinates of the interaction sites. The characteristic features of γ–ray tracking can be best illustrated considering single gamma events (Fig. 1): **(i)** Low energy γ–rays end–up into isolated interaction points that are recognized as photoelectric absorption events upon checking the compatibility between γ–ray energy and interaction depth in the detector. **(ii)** Gamma rays with energy from a few hundred keV to some MeV are absorbed in the detector with a sequence of (a few) Compton scattering interactions and a final photoelectric effect. Such events are reconstructed using a figure of merit that quantifies how well the scattering angles determined form the position of the involved interaction points agree with the values obtained inserting the pertinent energies into the Compton scattering formula. The figure of merit is calculated for all permutations of the interaction points and the event is accepted if the merit of the best permutation is compatible with an empirically defined limit. **(iii)** Above a few MeV, pair production events become important. A strong signature of this mechanism is given by the fact that, at least for not too high γ–ray energies, the first point of interaction collects the total energy of the γ–ray minus the $2m_0c^2$ needed to create the e^+e^- pair, while the two annihilation photons generate their own clusters of interaction points in the vicinity of this site.

So far, the tracking algorithms have been developed and tested using data from Monte Carlo simulations where the finite resolution of actual detectors is taken into account by means of position and energy smearing procedures applied to the calculated interaction

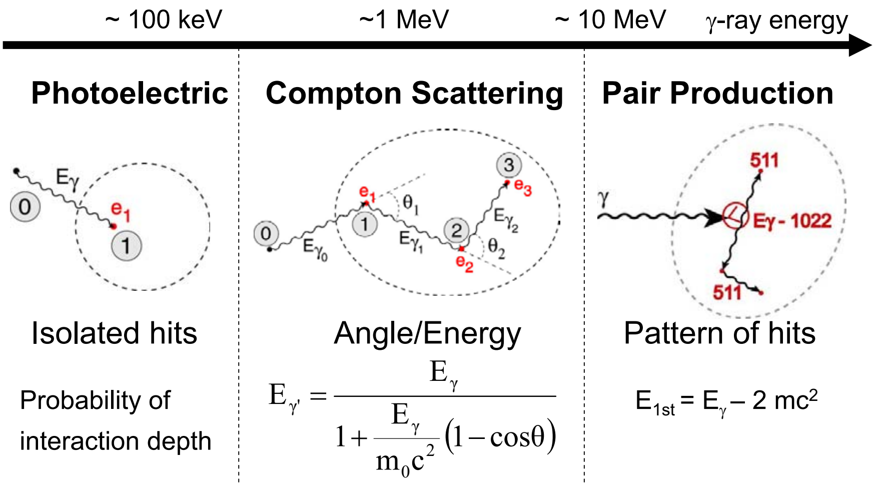

Figure 1. The relevant γ–ray interaction mechanisms and the features exploited by the tracking algorithms.

points. It is important to remark that, due to experimental uncertainties but also because of fundamental limits, every conceivable algorithm will always accept some background events (corresponding e.g. to partial energy release in the detector) and reject good ones. The amount of accepted background can normally be reduced at the cost of an increased rejection of good events: i.e. better P/T implies lower efficiency.

Real events involve in general several coincident γ–rays and are reconstructed following, essentially, two procedures. In the first one, we exploit the fact that the interaction points of transitions emitted into sufficiently separated directions tend to “cluster” into spatially isolated groups. We then search for cluster of interaction using different methods and validate them as individual transitions with the methods explained above. The reconstruction performance of our algorithms is often benchmarked using an ideal detector consisting of a shell of germanium with an inner radius of 15 cm and a thickness of 9 cm. Assuming a position resolution of 5 mm, the cluster–tracking yields $\epsilon_{ph} = 36\%$ and $P/T = 60\%$, for $M_\gamma = 30$. In the other approach, called “backtracking” [4], one starts from points with energy in the $\sim$ 100 keV range (likely to be the last, i.e. photoelectric, interaction of a transition) and then proceeds back, step by step, to the origin of the incident γ–ray looking for the correct Compton scattering vertices. Backtracking is more sensitive to position errors (and to the electron Compton profile) but is, possibly, better suited for gamma-ray imaging purposes.

Highly segmented germanium detectors. Several laboratories are pursuing the development of highly segmented germanium detectors, both of the cylindrical and the planar configuration. The following brief summary is limited to closed–end coaxial detectors, which are believed to be more suited for the construction of 4π tracking arrays. The

36-fold segmented "hexaconical" detector for GRETA at Berkeley, was the first prototype to be studied in details [5]. In Italy, we are using a 25 fold segmented detector (called MARS) that has 6 angular sectors, 4 transversal slices and a small segment on the front face [6]. To achieve the best performance in terms of energy and position resolution, these two detectors use cold FETs. There also cases (e.g. at Liverpool, Surrey and the array SeGA at NSCL) where room temperature FETs are preferred, but there are some worries for the effect of the reduced resolution (both in position and energy) of such detectors on the performance of γ–ray tracking.

Pulse shape analysis (PSA). The input for the tracking algorithms consists of energy and three–dimensional position and of each point of interaction. This information is obtained from an analysis of amplitude and shape of the signals induced at the detector electrodes by the charge collection process. An important feature of segmented detectors are the transient signals seen in the segments neighbours to the ones that collects the net charge released by the interaction. These signals have no charge at the end of the collection process and their amplitude and shape depend on the distance of the interaction point to the border of the segment. Signal shapes and amplitudes can be calculated rather accurately for almost arbitrary crystal geometries [7] using finite element analysis.

For the development and test of the algorithms for pulse shape analysis, simplified problems with just a few interactions within the segments are usually considered. The resulting composite signals from the segments are analyzed (decomposed) to extract the number, position, and energy of the original point(s) in various ways. Programs using e.g. genetic algorithms (GA) can determine the number of interactions correctly for 90% of the events with variances between reconstructed and true positions of typically ~ 2 mm. The performance of the PSA algorithms has been tested extensively with data from the GRETA and MARS prototypes using tightly collimated γ–sources. A more complete test of the GA algorithm has been done in the experiment described in the following.

Digital electronics and DAQ. To preserve the full signal–shape information that is needed to extract energy, timing and position of the interaction points, the electronics has to sample the preamplifier signals with fast ADCs (100 Ms/s, 14 bit) located as close as possible to the detectors. The energy content of the signals can be extracted using e.g. the so–called Moving Window Deconvolution (MWD) [8] and only a subset of samples relative to the leading edge of the signals has to be transferred to the data acquisition computers. This data can be easily reconstructed into events because the clock for all ADCs is generated centrally and each data–fragment is "time-stamped". The overall data flow into the DAQ of a 4π γ–ray tracking array can be in excess of 500 Mbytes/s.

In beam experiment. The performance of the algorithms developed for pulse shape decomposition has been verified with an in-beam experiment performed with the 25–fold segmented MARS [6] germanium detector. The idea was to check the achieved position resolution by looking at the improvement of energy resolution of a severely Doppler broadened peak when the detected energy is corrected using the position of the first interaction point. For this purpose, the Coulomb excitation experiment ^{56}Fe, at 240 MeV, on a thin ^{208}Pb target was selected. At this bombarding energy, the spectrum contains, practically, only the ^{56}Fe $2^+ \rightarrow 0^+$ transition at 846.7 keV. To get a large Doppler broadening, the germanium detector was placed close to the target position (Fig. 2, right panel). The direction of the scattered ^{56}Fe ions, which is needed to perform the Doppler correction, was

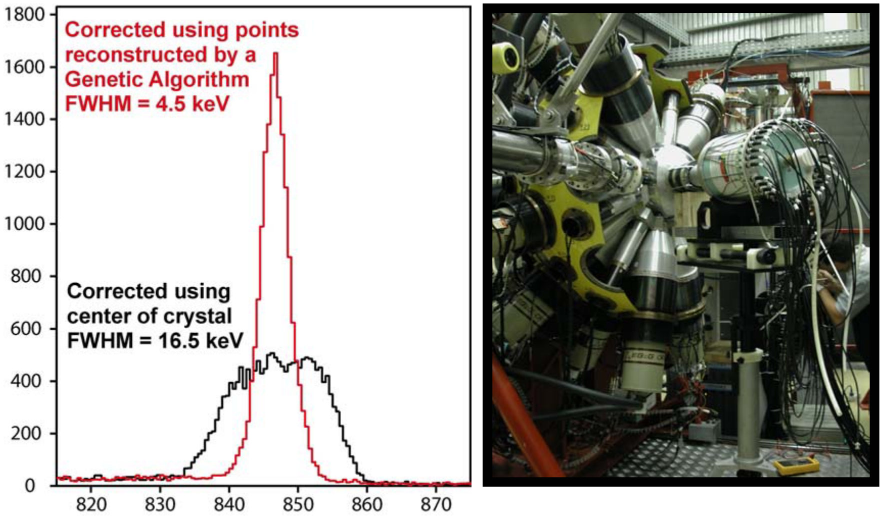

Figure 2. Coulex experiment with the MARS segmented detector. On the right panel the experimental setup at GASP with the detector mounted in the horizontal plane at 135° with respect to the beam axis. The left panel show the improvement of energy resolution of the 847 keV peak obtained with event–by–event Doppler shift correction using the position of the first interaction point as determined by Pulse Shape Analysis of the recorded wave forms

detected with a precision of $\sim 2°$ by 14 well collimated Si detectors. The $\sim 10^5$ collected events have been decomposed into interaction points using a Genetic Algorithm, and the final result of this analysis is shown in the left panel of Fig. 2. The improvement in energy resolution is reproduced by a detailed simulation of the experiment assuming a position resolution of 5 mm FWHM. In calculating the performance of a realistic γ–tracking array, it seems therefore safe to assume that pulse shape decomposition can be done with at least a 5 mm position resolution. Further R&D will most likely improve this value so that the figures given in the following should be taken as safe values.

3. AGATA

The Advanced GAmma Tracking Array (AGATA) [9] project is aimed at a full scale implementation of the γ–ray tracking concept in a European context. A similar project is pursued in the USA by the GRETA [2] collaboration.

The specific event that triggered the development of AGATA is the availability, in the near future, of radioactive beams from the upgraded GSI facility, from GANIL and from the SPES facility at LNL. However, the detector is being designed for a more general range of applications, e.g. also for experiments with high intensity stable beams. As already

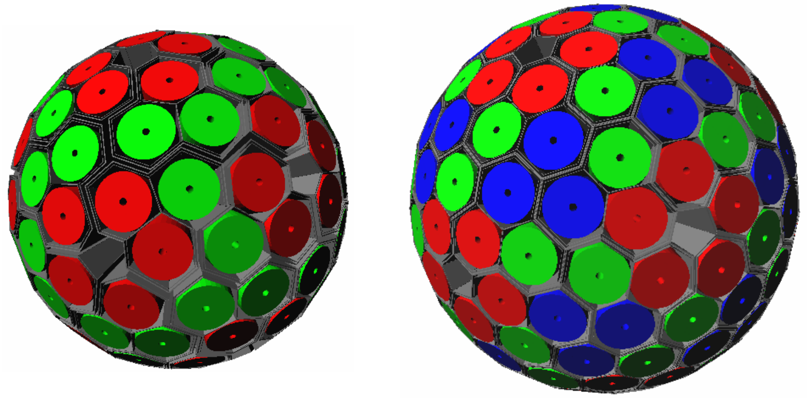

Figure 3. Schematic view of the two possible AGATA configurations. The smaller configuration has 120 hexagonal crystals of 2 different shapes (colour coded) that can be packed into 40 triple clusters of two different types. In the larger configuration 180 crystals of three different shapes are packed into 60 all–equal clusters.

mentioned, specific features of radioactive beams are: limited intensities, (particularly for the most exotic nuclei); wide range of recoil velocities (from stopped to $\beta = 50\%$); high gamma and particle backgrounds; large γ–ray multiplicities (up to $M_\gamma = 30$). To cope with these conditions, a 4π γ–array with the highest efficiency, selectivity, energy resolution and capability to handle high counting rates is required. These features can only be achieved with a close packed arrangement of germanium detectors, i.e. a 4π shell built from large, highly segmented large volume Ge crystals.

The geometric structure of AGATA is based on a geodesic tiling of the spherical surface with hexagons and 12 pentagons. Two possible configurations have been identified (see Fig. 3): a smaller one with 120 hexagons of two different shapes and a bigger one with 180 hexagons of three different shapes. The pentagons will, most likely, not be used and, to minimize inter–detector space losses, the hexagons will be packed into clusters of three crystals. The 120–configuration will therefore have 40 clusters (of two different types) while the 180–configuration will have 60 (all-equal) clusters. Using the largest available HPGe crystals (80 mm diameter, 90 mm length), the inner radius of the two arrays turns out to be 18 and 23 cm (large enough for ancillary detectors), while the total solid angle covered by germanium is $\sim 72\%$ and $\sim 80\%$ respectively.

The performance of the candidate arrays has been simulated within the GEANT4 [10] framework considering the actual hexa–conical shape of the crystals and the dead materials from the encapsulation and the canning into triple clusters [11]. In Tab. 1 the obtained total peak efficiency and peak to total ratio are compared with the performance of the "ideal shell" and of EUROBALL. Even if a realistic detector can achieve only about 50% of the performance of the ideal shell, the efficiency gain with respect to EUROBALL

Table 1
Performance of the possible AGATA configurations at $E_\gamma = 1$ MeV

Config.	Number of detectors (number of crystals)	Amount of germanium (kg)	ϵ_{ph} [P/T] % $M_\gamma = 1$	ϵ_{ph} [P/T] % $M_\gamma = 30$
Ideal 4π shell	1	233	65 [85]	36 [60]
AGATA 120	40 (120)	212	33 [54]	19 [44]
AGATA 180	60 (180)	320	38 [53]	24 [44]
EUROBALL	71 (239)	210	9 [56]	6 [37]

is really considerable. In particular for high γ–multiplicity experiments, this means an increase in selectivity of several orders of magnitude

The germanium crystals will be 36–fold segmented and the resulting 4440 or 6660 total segments will provide unprecedented position sensitivity. A key feature of AGATA is the capability to determine the emission direction of the detected γ–rays with a precision of $\sim 1^\circ$. This corresponds to an effective solid angle granularity of more than $5\,10^4$ (quite unachievable with individual germanium crystals) and ensures an energy resolution better than 0.5% for transitions emitted by nuclei recoiling at velocities as high as 50% of the speed of light. This value is only a factor of two worse than the intrinsic resolution of Ge detectors and corresponds to what the current arrays provide for ~ 10 times smaller recoil velocities.

The demonstrator. According to the MoU recently signed by the collaboration, the development of AGATA will proceed in stages, with the construction of the full array preceded by a final R&D phase aimed at building a subsystem (demonstrator) of 5 triple clusters. The demonstrator, complete with digital electronics, DAQ and full on line processing of the digitized data, should be ready in about 4 years and will be used for testing the γ–ray tracking concept in real experiments.

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