THE AGATA PROJECT*

J. Gerl

Gesellschaft für Schwerionenphysik GSI, 64291 Darmstadt, Germany
for the AGATA Collaboration

(Received January 21, 2003)

A novel 4π γ-detector array designed as a closed shell of Ge crystals is currently under development. It will consist of 180 large Ge crystals. For the first time pulse shape analysis and γ-ray tracking will be employed to distinguish γ-rays scattering inside the shell and to determine the point of impact. A full energy peak efficiency of 50% at multiplicity $M = 1$ and up to 24% at $M = 30$ are expected, resulting in a sensitivity increase of up to three orders of magnitude for subtle nuclear structure investigations.

PACS numbers: 29.30.–h, 29.30.Kv, 29.40.Gx, 29.40.Wk

1. Introduction

Understanding nuclear excitations is one of the principal goals of nuclear structure studies. The most powerful tool to investigate nuclear structure under extreme conditions is high precision γ-ray spectroscopy. The study of the γ-decay properties of the atomic nucleus has provided an enormous quantity of information on the behaviour of such a system, for example, under the influence of high temperatures, high spin or large deformations as well as for extreme isospin values (the proton-to-neutron ratio) and of the total nuclear mass. New challenges for nuclear spectroscopy are imminent at a time when high intensity radioactive ion beams are emerging in a wide energy range: from the Coulomb energy regime, typical for the European ISOL facilities (SPIRAL and the planned EURISOL), to the intermediate and relativistic energy regimes of fragmentation facilities, such as SIS/FRS and in particular the new GSI facility.

In the Coulomb energy regime the classical reaction types (transfer, deep-inelastic or compound reactions) become available with intensities comparable to that of today's stable beams. At intermediate energies, *i.e.* between

* Presented at the XXXVII Zakopane School of Physics "Trends in Nuclear Physics", Zakopane, Poland, September 3–10, 2002.

50 and 200 MeV/u, Coulomb excitation can be employed to populate low-spin states; depending on the available beam energy highly excited states up to the giant resonances can be reached. For even higher energies secondary fragmentation becomes a powerful tool to create very exotic fragments that are excited to relatively high spins, *i.e.* in violent collisions spins of more than $30\hbar$ can be reached. Finally, the rarest species, *i.e.* close to the drip lines, can be studied using decay spectroscopy after implantation. Exotic beams allow approaching and mapping the drip-line regions in order to answer the open questions in nuclear structure physics and to explore nuclear stability at the very limits. Nuclei far from stability allow amplifying and isolating particular aspects of the nuclear interaction and dynamics and may favour the occurrence of new symmetries.

First and foremost, high-resolution γ-spectroscopic studies will open up unique possibilities allowing a very rich physics program to be addressed, that covers the full range of topics in which the nuclear physics community is currently interested: the investigation of exotic nuclei will be aiming at essentially all nucleonic degrees of freedom, such as *(i)* proton-rich nuclei at and beyond the proton drip line and the extension of the $N = Z$ line, *(ii)* neutron-rich nuclei towards the drip line in medium heavy elements and *(iii)* the heaviest elements and towards new super-heavy elements. The internal degrees of freedom of nuclei will be exploited by investigating *(i)* ultra-high spin states produced in extremely cold reactions, *(ii)* metastable states at high spins and at very large deformation, *(iii)* Multi-Phonon Giant resonances as well as other high-temperature phenomena, such as quantum chaos.

An instrument of major importance for these studies is a high performance γ-ray spectrometer capable of disentangling the structure of exotic nuclei produced with extremely small cross section in an overwhelming background of less exotic nuclei and possibly under the constraint of severe Doppler effects.

Over the last decade Compton suppressed Ge arrays have been steadily optimised [1,2] and further leaps are improbable with this technology. A totally new concept is required in order to further increase the efficiency and granularity of 4π γ-detector arrays, namely a shell built purely from Ge detectors shown in Fig. 1 to scale besides the EUROBALL spectrometer. The Ge shell presented here is assumed to have an inner radius of 15 cm, a thickness of 9 cm and consists of 100–200 closely packed, individually encapsulated Ge detectors. In the present generation of γ-detector arrays, typically 30 % of the total solid angle is covered with germanium material, the rest being used by the BGO shields. On the contrary, the germanium coverage of the shell can be as high as 80 % so that the probability for a γ-ray to end up in the active, high-resolution part of the array is max-

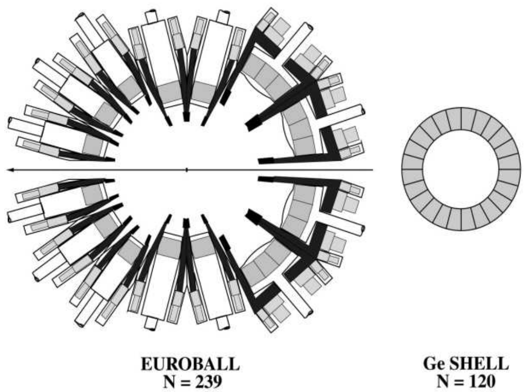

Fig. 1. Cross sectional view of EUROBALL IV compared to a pure shell of the same volume of Ge.

imised. Despite the larger solid-angle coverage, the total photo-peak efficiency of this shell is a priori not better than for EUROBALL, while the peak-to-total ratio is actually three times smaller. The reason for such a poor performance is the large probability to detect more than one γ-ray in the same detector and the scattering of γ-radiation between the germanium detectors. However, if the tracks of the γ-rays in the Ge shell are followed and all their individual interaction points are identified, a dramatic performance improvement will be obtained. In addition, for transitions emitted by fast moving nuclei, the Doppler-shift correction and therefore the final spectral resolution could be done in an optimal way, as the angles at which the γ-rays hit the Ge detectors can be determined with high precision from the knowledge of the first interaction point.

This new concept is called γ-ray tracking [3–5]. The position sensitivity of the detectors is achieved by a segmentation of the outer contact and by analysing the charge drift times within a segment and the mirror charges induced in the neighbouring segments. Thus, one will be able to detect the individual interaction points of a γ-ray being Compton-scattered and finally absorbed in the Ge detectors. Several recently developed γ-arrays are already employing segmented detectors and have strongly contributed to the technological progress [6–8]. Reconstructing the γ-ray's track and comparing it with the Compton-scattering formula makes it possible to decide whether the γ-ray was emitted from the target and fully absorbed in the Ge shell. From Monte Carlo simulations one expects that a Ge tracking array will have highest efficiency (maximum coverage of the solid angle with Ge detectors), excellent performance for the correction of Doppler effects (emission angle of the γ-ray determined from the first interaction point in the Ge detector) and a very good peak-to-total ratio (by distinguishing between fully and partially absorbed events).

2. Requirements for AGATA

Even though radioactive beams from next generation facilities will often approach today's intensity of stable beams, the most exotic nuclei under investigation will always be produced with extremely low rates. A γ-ray spectrometer to study these nuclei must be a universal instrument capable of measuring γ-radiation in a large energy range (from a few tenths keV up to 10 MeV and more), with the largest possible efficiency and with a very good spectral response. The nuclei of interest are often rarely produced, but can be accompanied by much more abundant, less exotic species. The radiation can be emitted by fast moving sources and in a hostile environment of high background radioactivity (Bremsstrahlung, neutrons and charged particles, *etc.*). This requires the simultaneous optimisation of several and sometimes conflicting properties:

- The full energy or photo-peak efficiency ($P_{\rm fe}$), *i.e.* the probability to detect the total energy of any emitted photon individually, must be maximised (for both low and high γ-ray multiplicity) in order to identify the weakest reaction channels.

- A very good spectral response measured by the peak-to-total ratio (P/T), *i.e.* the ratio of full energy efficiency to the total interaction efficiency, must be obtained in order to preserve good spectrum quality also for high-fold coincidences.

- A very good angular resolution for the emission direction of the detected γ-quanta must be achieved in order to sufficiently reduce the strong Doppler effects of radiation sources moving with velocities up to $v/c = 0.5$.

- The system must be capable of high event rates, either because the background radioactivity might dominate for very low intensity radioactive beams or because a very high luminosity is needed in order to populate the weakest reaction channels.

- A suitable free inner space must be available in order to allow for additional detection systems inside the Ge ball that allow to better select the nuclei of interest, *i.e.* ancillary detectors to measure light charged particles, heavy ions, *etc.*

In the following the basic properties of such a system, called the Advanced GAmma Tracking Array (AGATA)[9], are discussed. With the properties anticipated for AGATA several orders of magnitude improvement in resolving power will be obtained (see Fig. 2) making it extremely more

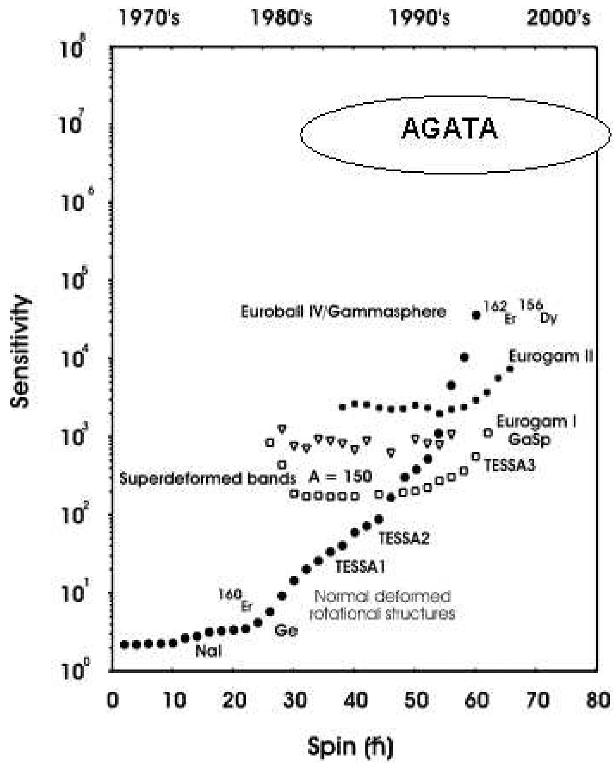

Fig. 2. Sensitivity of γ-detection arrays.

powerful than all current or near future arrays. The total full energy efficiency (P_{fe}) for a single γ-ray is essentially determined by the amount of Ge material that can be placed around the radiation source since it depends on the probability that the total energy is absorbed by the detector. Using the best techniques available today for constructing closely packed arrays of Ge detectors, *i.e.* composite detectors of encapsulated Ge crystals close to 80% of the total solid angle can be covered with active Ge material. In that way a maximum total full energy efficiency above 70% can be obtained for low-energy γ-rays (around 100 keV) that have a much smaller interaction length compared to the length of the detectors. For higher energy γ-rays the thickness of the Ge shell becomes very important. With Ge crystals of 10 cm length a total full energy efficiency close to 50% should be possible at an energy of 1 MeV as shown in Fig. 3, compared to the best high-spin spectrometers for stable beams ($P_{\mathrm{fe}} \approx 10\%$) and current high-efficiency spectrometers for radioactive beams ($P_{\mathrm{fe}} \approx 20\%$). With this choice of crystals it will be possible to achieve $\approx 10\%$ efficiency even for 10 MeV γ-rays, while using even longer crystals would increase the costs dramatically.

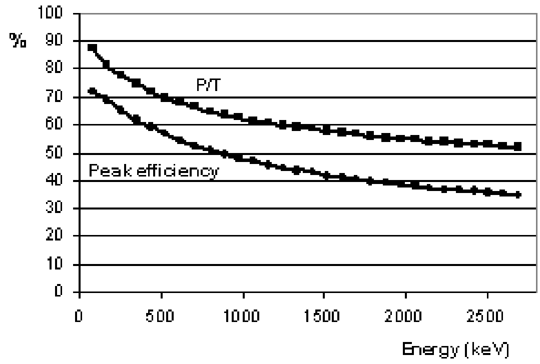

Fig. 3. Response of AGATA as a function of γ-ray energy (for multiplicity $M = 1$).

For higher γ-ray multiplicity it must be ensured that different γ-rays do not deposit energy in the same detection element. To optimise this "single-hit probability" the number of detection elements must be very large compared to the total number of interactions in the detector. Simulations have shown that each detection element should not cover a solid angle larger than 10^{-3} of 4π which together with a suitable segmentation in depth leads to a total number of detection elements of the order of 6000–8000. In this situation the full energy efficiency will be essentially determined by the effectiveness of the tracking algorithms in reconstructing the tracks of the γ-rays. Realistic simulations of the tracking performance indicate that an efficiency of 20% for an energy of 1 MeV and at $M_\gamma \leq 30$ can be reached (see Fig. 4). The superiority of AGATA in every domain of γ-ray spectroscopy is clearly demonstrated by a comparison with the best high-spin spectrometers for stable beams ($P_{\rm fe} \approx 6$ % at $M_\gamma \leq 30$).

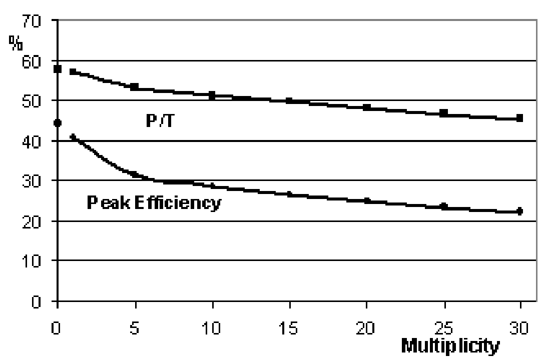

Fig. 4. Efficiency and P/T of AGATA as a function of multiplicity for cascades of 1 MeV γ-transitions. The values are based on a tracking efficiency of about 50% which is likely to be improved in the near future.

The peak-to-total ratio describes the spectral response of the detector. In a tracking spectrometer the P/T ratio can be optimised by the tracking algorithms. In this way a P/T ratio up to 70% can be reached for individual 1 MeV γ-rays. Even at multiplicity $M_\gamma = 30$ a very good P/T ratio of 50% can be achieved. When the tracking is optimised to obtain highest efficiency a P/T ratio of 60% can still be realised at low multiplicity, which compares favourably with conventional γ-ray spectrometers using escape-suppressed detectors. An optimal position resolution is also assured by the high granularity of AGATA, since the segments are sufficiently small in order to determine the interaction position(s) within one segment with very high precision.

This key feature of AGATA allows to determine the emission direction of all detected γ-quanta within an opening angle smaller than 1°, corresponding to an array with an "effective granularity" of $\approx 10^5$ elements. In this way an energy resolution better than 0.5 % is ensured for transitions emitted by nuclei at velocities up to $v/c \leq 50$ %. This value is comparable to current spectrometers used at 10 times smaller recoil velocities and is only a factor of 2 larger than the intrinsic resolution of Ge detectors at 1 MeV. Fig. 5 shows the simulated energy spectrum for EUROBALL and for AGATA if the γ-emitting nucleus moves at $v/c = 50$ %.

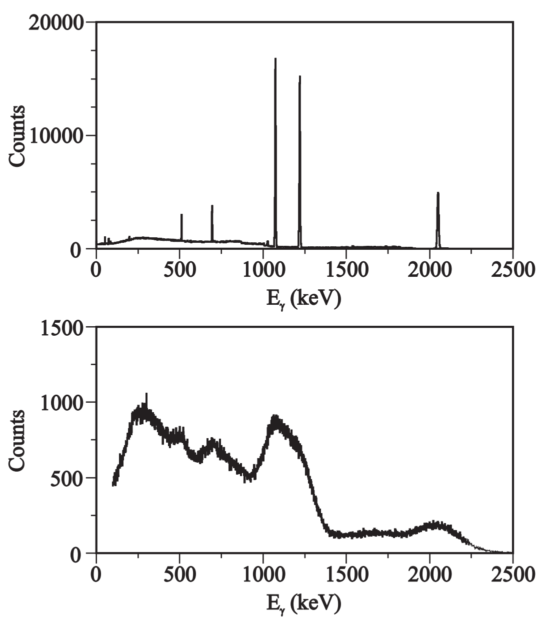

Fig. 5. Simulated energy spectrum for EUROBALL (bottom) and for AGATA (top) if the γ-emitting nucleus moves at $v/c = 50$ %.

3. Design of AGATA

Following the above discussion the geometrical structure of AGATA is a spherical shell composed of 12 regular pentagons and 180 hexagons. Owing to the symmetries of this specific bucky-ball construction three slightly different irregular hexagons are needed. To minimise inter-detector space while preserving modularity, three hexagonal crystals (one of each type) are arranged in one cryostat. Each Ge crystal is encapsulated in a very thin Aluminium can — a new technology developed in the framework of the EUROBALL and MINIBALL projects. The crystals are electronically divided into 6×6 azimuthal and longitudinal segments. Thus the total number of segments in the array is 6780. The inner radius of the array is about 19 cm.

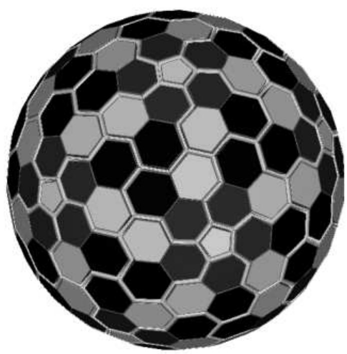

Fig. 6. Artistic view of the AGATA array.

The AGATA electronics will be based on digital signal processing, by which the pre-amplifier output is sampled and digitised with fast ADCs to record the time evolution ("shape") of the signals. From the signal detected in a segment and the mirror charges observed in its neighbours the interaction position of a γ-ray can be determined with an accuracy of 1–2 mm. Digital processing electronics, placed directly adjacent to the detectors, will extract energy, timing and interaction positions from the sampled signals. Each data item will be time stamped, allowing later event reconstruction as well as the construction of delayed coincidences without dead-time problems. In addition, software triggering will be implemented, providing an easily configurable and flexible event "filter", especially important for rare events.

From the front–end detector electronics, the preprocessed data packets will be transferred in parallel by high band width fiber links to a central event builder. This will perform all necessary functions of time-ordering, data-merging and gain-matching in order to fully re-construct the γ-ray interaction sequence by using tracking algorithms.

The tracking algorithms use the results of the pulse-shape analysis to reconstruct completely the path of the γ-ray in the detector. The starting point is a list of the positions and deposited energies of all the interaction points of the incident γ. By use of the Compton scattering formula and of statistical criteria for the photoelectric and pair production mechanisms a figure of merit for each sequence of interaction points is produced and by cycling on the possible permutations a best sequence of interaction points is selected. Several different tracking algorithms have been developed, two of which are the clusterisation [10] and backtracking [11] methods.

The clusterisation method relies on the fact that the interaction points of a γ-ray scattering in the detector tend to be found in a small volume. This is connected with the forward peaking of the scattering cross section and the decreasing mean free path with energy. Clusters of points are identified through use of Artificial Intelligence or Pattern Recognition methods. The backtracking method attempts to reconstruct the path of the γ-ray back from its final interaction point to the emission point. The method is based on the observation that the energy of the final photoelectric interaction is located in a narrow energy band, typically between 100 and 300 keV for a wide range of incident γ-ray energies. This method has the advantage that long-range scattering (*e.g.* across the array) can be recovered.

4. Outlook

To build the AGATA array substantial development work needs first to be performed. This will include the development of a 36-fold segmented, encapsulated Ge detector, the construction of cryostats for composite detector systems, the miniaturisation of the front–end electronics, the implementation of pulse-shape analysis and tracking algorithms in real time as well as the realisation of a data acquisition system capable of handling the extremely high data streams. The knowledge needed to construct a γ-ray tracking array is distributed over various European laboratories which have joined the common project. Therefore, excellent presuppositions exist in Europe to realise a first γ-ray tracking array and, thereby, to introduce a new quality in γ-ray spectroscopy for the application in fundamental research. Finally, it should be noted that the development of position-sensitive Ge detectors will lead to important "spin-offs", as has been proven by previous technologies developed by the nuclear structure community. The γ-ray tracking techniques developed for AGATA will have a strong impact on high resolution and high sensitivity γ-imaging, being of prime importance for medical and industrial applications.

REFERENCES

[1] J. Simpson, *Z. Phys.* **A358**, 139 (1997).

[2] I.Y. Lee, *Nucl. Phys.* **A520**, 641c (1990).

[3] R. Lieder *et al.*, *Nucl. Phys.* **A682**, 279c (2001); R. Lieder *et al.*, *Prog. Part. Nucl. Phys.* **46**, 399 (2001).

[4] M.A. Deleplanque, *Nucl. Instrum. Methods Phys. Res.* **A430**, 292 (1999).

[5] Th. Kröll, D. Bazzacco, *Nucl. Instrum. Methods Phys. Res.* **A463**, 249 (2001).

[6] J. Eberth *et al.*, *Prog. Part. Nucl. Phys.* **46**, 389 (2001).

[7] F. Azaiez, *Nucl. Phys.* **A654**, 1003c (1999).

[8] J. Gerl *et al.*, VEGA-proposal, GSI Report, 1998.

[9] AGATA technical proposal, ed. J. Gerl and W. Korten, 2001.

[10] G.J. Schmid *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A430**, 69 (1999).

[11] J. van der Marel, B. Cederwall, *Nucl. Instrum. Methods Phys. Res.* **A437**, 538 (1999).