

THE AGATA SPECTROMETER*

J. SIMPSON

on behalf of the AGATA Collaboration

CCLRC Daresbury Laboratory
Daresbury, Warrington WA4 4AD, UK*(Received November 30, 2004)*

The global consensus of opinion is that the next major step in γ -ray spectroscopy involves abandoning the concept of a physical suppression shield and achieving the ultimate goal of a 4π Ge ball through the technique of γ -ray energy tracking in electrically segmented Ge crystals. The resulting spectrometer will have an unparalleled level of detection power to nuclear electromagnetic radiation. Its sensitivity for selecting the weakest signals from exotic nuclear events will be enhanced by a factor of up to 1000 relative to its predecessors. It will have an unprecedented angular resolution making it ideally suited for high-energy resolution even at recoil velocities of up to 50% of the velocity of light. Therefore, it is ideally suited to be used in conjunction with the new generation of radioactive beam accelerators or existing stable beam facilities. In Europe, a collaboration has been established to construct a 4π tracking spectrometer called AGATA (Advanced Gamma Tracking Array). This collaboration has signed a Memorandum of Understanding for the first phase of the project to perform the research and development necessary to finalise the technology for γ -ray tracking and hence fully specify the full 4π spectrometer. The status of this first phase of the AGATA project is described.

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1. Introduction

The study of the gamma-ray decay between quantal states of the atomic nucleus plays a pivotal role in discovering and elucidating the wide range of nuclear structure phenomena. Each major technical advance in gamma-ray detection devices has resulted in significant new insights into nuclear

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science. This is illustrated schematically in Fig. 1 which shows the sensitivity achieved in terms of the weakest states that can be observed with each advance in γ -ray array technology.

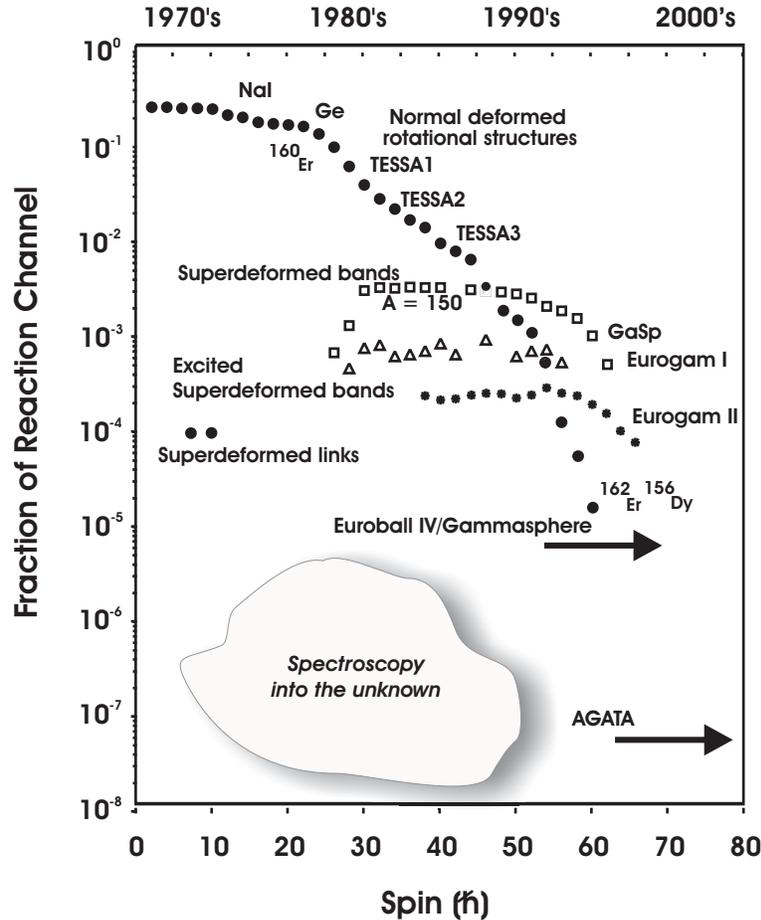


Fig. 1. The sensitivity of γ -ray arrays measured by the fraction of the reaction channel that can be observed as a function of spin for some selected nuclear structure phenomena. The associated timeline and arrays are indicated.

For example, over the last 20 years I have studied the evolution the structure of the yrast states of nuclei near ^{158}Er with increasing angular momentum. The first major technical advance for these experiments was the construction of the first TESSA array of escape suppressed spectrometers. This array enabled the systematics of non-yrast normal-deformed states to spin 20–30 to be investigated [1]. The next advance was the use of heavy ion beams that enabled much higher angular momentum states

to be populated and in ^{158}Er a shape change from prolate to oblate near spin 40 was observed [2]. Array technology continued to develop with increasingly bigger spectrometers and with the Eurogam spectrometer many favoured band terminating states were established in $^{157-159}\text{Er}$ in the spin 40–50 region (*e.g.* [3]). Very recently the Gammasphere array (currently the world's biggest array) has identified how these special favoured band termination states are populated [4]. In order to observe even weaker states at ultra-high spin and discover even more exotic shape changes a much more powerful spectrometer is required.

The worldwide consensus of opinion is that the next generation of gamma-ray spectroscopy instruments should be based on a tracking spectrometer. This involves abandoning the concept of physical suppression shields and achieving the ultimate goal of a 4π Ge ball through the technique of γ -ray energy tracking in electrically segmented Ge crystals [5–7]. The resulting spectrometer will have an unparalleled level of detection sensitivity to nuclear electromagnetic radiation. Its sensitivity for selecting the weakest signals from exotic nuclear events will be 1000 times greater than current instruments and will ensure a wide impact on science in a variety of fields. In the recent discussions about the future of Nuclear Physics in Europe within NuPECC and FINUPHY, the AGATA project is regarded as one of the key instruments for nuclear structure research.

Given the importance of this development and its far-reaching implications, it is not surprising that a European collaboration has already been established to construct a 4π tracking spectrometer called AGATA (Advanced GAMMA Tracking Array) [8, 9]. A memorandum of understanding was signed in 2003 by 10 countries (recently more countries have joined) to establish the AGATA collaboration and the framework within which the project is organised.

The new challenges for nuclear spectroscopy which provide the impetus for AGATA are emerging principally from the new generation of high intensity radioactive ion beam facilities currently being developed worldwide. These provide beams with energies spanning the Coulomb energy regime, typical of the European ISOL facilities (SPIRAL, REX-ISOLDE), to the intermediate and relativistic energy regimes of fragmentation facilities, such as SIS/FRS at GSI. AGATA is vital for these laboratories and for the planned major new facilities at GSI (FAIR), GANIL (SPIRAL II), Legnaro (SPES) and EURISOL. The science case for the full array is, to a major extent, the science case for the future of nuclear structure research itself. With its massive increases in resolving power and efficiency, it is the promised impact of this device, coupled to the new generation of radioactive beam facilities, which will permit access to the furthest reaches of the nuclear chart. The study of structure at the very limits of nuclear stability is crucial in order to

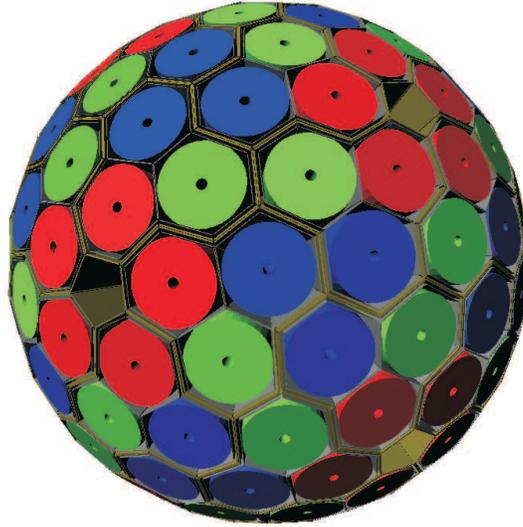


Fig. 2. The 180 geometry of AGATA.

answer some of the most pressing questions in the field. These include the isospin dependence of the effective nuclear interaction, the ability to explain collective phenomena from the properties of the individual nucleons and the limits of nuclear existence and indeed Mendeleev's table of the elements. In the last decade, it has become clear that many of our preconceptions of nuclear structure have to be revised. Nuclear radii are not always proportional to $A^{1/3}$; instead, neutron-rich nuclei develop a diffuse region of neutron "skin" or "halo" which can extend much further. The values of the magic numbers of the nuclear shell model for neutrons and protons are no longer sacrosanct: the strength of the $T = 0$ part of the nucleon-nucleon interaction means that the position of the neutron (proton) shell closure varies with the proton (neutron) number. The number of neutron-rich nuclei which can exist is far greater than anticipated: improvements in the treatment of the self-consistent nuclear problem, including more realistic estimates of correlations and clustering, predict a neutron drip line which seems to be constantly receding. AGATA will focus on all these aspects through studies of *(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 neutron drip line in medium heavy elements and *(iii)* the heaviest elements towards new superheavy elements. The response of nuclei to angular momentum and temperature will be investigated by probing ultra-high spin states produced in extremely cold reactions, metastable states at high spins and large deformations and multi-phonon giant resonances. Other high-temperature phenomena, such as quantum chaos, may also be investigated.

AGATA will represent a dramatic advance in γ -ray detection that will have wide ranging applications in medical imaging, astrophysics, nuclear safeguards and radioactive waste monitoring, as well as introducing a new plateau of detection capability for nuclear structure studies.

In recent years several pilot projects in Europe [10] and the USA [6,7] have shown that the principle of γ -ray tracking is feasible by establishing experimentally that it is possible to determine the position of an interaction with sufficient accuracy over a range of energies from tens of keV to several MeV. Modelling, using GEANT has also been carried out over an extended energy range to develop methods to track gamma-ray events once the interaction points are known. The first phase of AGATA is to prove that a tracking array can be realised by designing and building a sub-array of detector modules (called the demonstrator) and measuring the tracking performance in actual experiments. This demonstrator will represent a first generation tracking detector in its own right, while also acting as the crucial first step towards the full 4π array.

2. The elements of AGATA

The new technique of gamma-ray tracking involves measuring accurately the position and energy of all the γ -ray interaction points in the detector segments. The position of the first interaction defines the angle of emission of the γ ray from the source, relative to the detector and is particularly important when detecting radiation emitted by a nucleus recoiling after a reaction since it determines the extent of the energy spread arising from the Doppler shift. The angular definition in AGATA compared with Gammasphere or Euroball will result in an order of magnitude improvement in spectral response. Since most of the γ rays interact more than once within the crystal, the energy and angle relationship of the Compton scattering formula is used to track the path of a given γ ray. The full energy can then be retrieved by summing all the individual deposited energies for this γ ray. Very high efficiency can then be obtained in such a 4π spectrometer since there are minimal dead areas.

The realisation of such a system will require the development of highly segmented germanium detectors, digital electronics, pulse shape analysis to extract energy, time and position information and tracking algorithms to reconstruct the full interaction. The milestones in the research and development phase of AGATA are:

- development of a highly-segmented encapsulated Ge detector,
- development of a cryostat to hold a cluster of segmented detectors,
- design and development of digital electronics,

- development of algorithms for energy, time and position,
- development of tracking algorithms,
- design and manufacture of associated infrastructure,
- construction of a demonstrator of detectors and test with sources and in-beam.

3. The performance of AGATA

The optimum performance or sensitivity of a γ -ray spectrometer is obtained by maximising the full energy or photopeak efficiency whilst maintaining the best spectral quality. For AGATA these quantities have to be maximised for both low and high multiplicity and low and high velocities (up to $\beta \approx 0.7$). In addition AGATA must have very good angular resolution to determine the emission direction of the detected γ ray, be able to run at very high rates, either because of high radioactivity or high beam intensities, and have sufficient inner space to allow additional detectors to be installed.

The AGATA collaboration has investigated several options for the design of the spectrometer. Several geometries with different numbers of detectors for the arrangement of coaxial detectors have been considered for the tiling of a sphere with various numbers of hexagons and 12 pentagons. The performance of AGATA has been simulated using a Monte Carlo code based on GEANT4 which simulates the interaction of γ rays in the detectors and allows inclusion of realistic shapes and passive materials [11, 12].

The chosen geometry is based on tiling the sphere with 180 hexagons and 12 pentagons. This is shown schematically in Fig. 2. In this geometry the 180 hexagons can be grouped into 60 identical triple modules or clusters. It was decided early on in the project that the fraction of efficiency brought by using the pentagons was not worth the cost of developing and handling this crystal shape. Besides, the remaining gaps will be useful for supporting the array.

Table I summarises the characteristics of the 180 detector geometry and Table II gives the calculated photopeak efficiency and peak to total at 1 MeV for various multiplicities. It should be noted that the performance of a γ -ray tracking array depends strongly on the pulse shape analysis and γ -ray tracking algorithms. The development and optimisation of these is a major part of the AGATA project and it is expected that these performance figures will improve. Nevertheless, Table II shows that the 180 detector spectrometer will have a very high efficiency and excellent spectral response even at high multiplicities. The geometry has a high granularity with an angular resolution of 1.25° which will be very important for Doppler corrections at high recoil velocity experiments.

TABLE I

The characteristics of the geometry of the 180 detector AGATA.

| | |
|--------------------------------------|------|
| Number of crystal shapes | 3 |
| Number of cluster shapes | 1 |
| Number of clusters | 60 |
| Solid angle coverage (%) | 82 |
| Amount of Ge (kg) | 362 |
| Crystal face to centre distance (cm) | 23.5 |
| Number of electronics channels | 6660 |

TABLE II

The predicted performance of the 180 detector AGATA at 1 MeV.

| Multiplicity | 1 | 10 | 20 | 30 |
|-------------------|------|------|------|------|
| Efficiency (%) | 43.3 | 33.9 | 30.5 | 28.1 |
| Peak to total (%) | 58.2 | 52.9 | 50.9 | 49.1 |

The detectors of AGATA are highly segmented coaxial germanium crystals. The crystals have a length of 9 cm and an initial diameter before shaping of 8 cm. In order to fit into the 4π ball, the cylindrical crystals are tapered to form a hexagonal geometry at the front of the crystal with an $\approx 8^\circ$ tapering angle. A schematic of the capsule is shown in Fig. 3. In the 180 configuration three slightly different shapes are required to maximise the solid angle coverage. Each crystal is encapsulated into a thin Al can using the same technology that is used for the Euroball Cluster [13, 14] and Miniball [15] detectors. The outer contact of each crystal is divided into 6×6 azimuthal and longitudinal segments to give 36 electronically independent outputs.

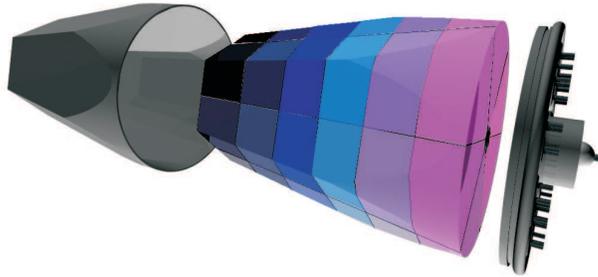


Fig. 3. The AGATA capsule.

The AGATA collaboration has ordered three capsules from the company Canberra Eurisys and to date two have been delivered and tested by the collaboration. These first three capsules have a symmetric hexagon geometry with a 10° tapering angle and are the same as have been purchased by the Gretina/Greta project in the USA. The longitudinal segmentation scheme has segments in steps at 8, then 13, 15, 18, 18 and 18 mm from the front of the crystal. The first two capsules have been tested in a test cryostat at the University of Cologne and excellent results have been obtained. Using preamplifiers developed by the collaboration in the GANIL laboratory and Cologne the measured energy resolutions are 0.9–1.1 keV at 122 keV and 1.9–2.1 keV at 1.3 MeV for the segment signals. For the core signals the energy resolution is 1.2 keV at 122 keV and 2.1 keV at 1.3 MeV. The overall cross talk of the whole system of 37 signals was measured to be below 10^{-3} . These measurements and the quality of the signals are very encouraging. In beam tests are planned to measure the performance of these detectors, in particular the position sensitivity that can be achieved. The position will be measured from the digitised outer segment signal, the radial position coming from the risetime and shape of the pulse and the azimuthal position from the relative magnitude of the transient charge signals that are induced in neighbouring segments. This simplified method was used for the Miniball detectors where a position resolution of 5mm was achieved [15]. This is just sufficient for successful tracking [5] and preliminary indications are that the new AGATA detectors will have even better position resolution. It is also expected that the refined pulse shape decomposition algorithms that are presently being developed will improve further the position resolution.

4. Data processing

AGATA requires a state-of-the-art and purpose built digital electronics and associated data acquisition system to process the signals from the Ge detectors. The full system has to cope with over 6000 channels with the rate of each detector possibly up to 50 kHz. A schematic diagram of the system architecture is shown in Fig. 4.

The segmented detectors provide 37 signals (36 outer contacts, 1 inner core) from the FET/preamplifiers. The electronics principle of AGATA is to sample these outputs with fast ADCs to preserve the full signal information in a clean environment so that accurate energy, time and position can be extracted. The first stage of the electronics will be a digitiser card, located close to the detector. The digitiser contains 100 MHz 14 bit ADCs to digitise the signal and then the information is transmitted via an optical link to a “remote” pre-processing card. This card performs digital signal processing that is local to a particular detector such as energy determination and time.

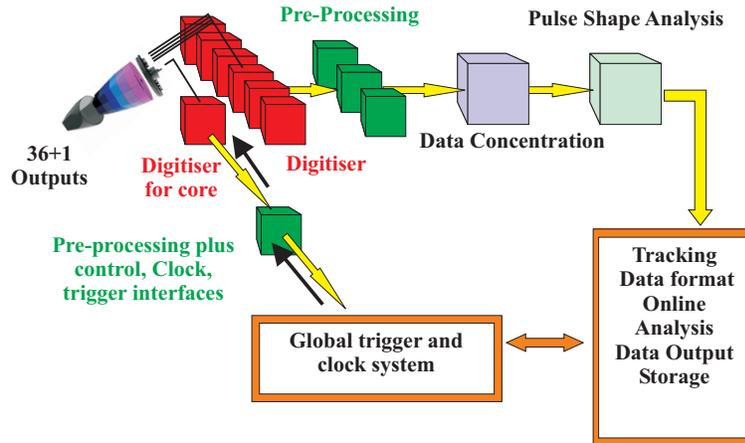


Fig. 4. Schematic diagram of the AGATA electronics system.

These cards transmit their outputs to the pulse processing part of the system which is envisaged to be farm of computers. This farm assembles the full data from all elements of the array, uses PSA algorithms to determine the position of the interactions, performs tracking to reconstruct the events and assembles the resulting data for storage. The whole system shares a global time reference (clock) which is supplied by a global trigger and synchronisation control system which is distributed by a network of optical fibres to the front-end electronics of each crystal.

5. The demonstrator

This research and development phase of AGATA will construct the demonstrator, which will comprise the detectors, the electronics and acquisition system and all associated infrastructure. A view of a CAD image of a sub-array of 5 triple cluster modules (15 capsules) is shown in Fig. 5. This sub-array is very powerful in its own right and even at the AGATA detector to target distance of 23.5 cm it has an efficiency of $\approx 3.5\%$ at 1.3 MeV. In addition to the detector and electronics developments there is an active programme on the optimisation of pulse shape algorithms (mostly for position) and on the development and optimisation of tracking algorithms. The effect of ancillary detectors on the performance of the instrument is also being considered [16]. The demonstrator will be tested with sources in the first instance and then in-beam either in stand-alone mode or coupled to existing ancillary detectors at various European laboratories. In parallel there is much activity in the design of the associated infrastructure needed to operate

such a complex instrument (*e.g.* high and low voltage supply and control, grounding, liquid nitrogen supply). The final aim of the collaboration in the research and development phase is to produce a full technical proposal including all aspects of the projects and a science case for the construction of the full 4π spectrometer.

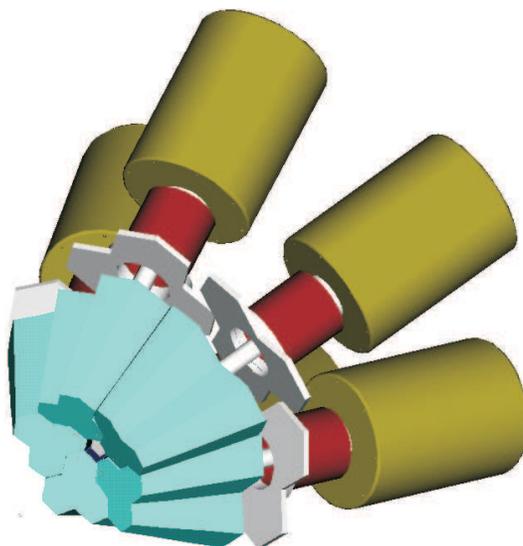


Fig. 5. The AGATA demonstrator with 5 triple clusters.

6. Summary and outlook

AGATA will have an enormous impact on the exploration of nuclear structure at the extremes of temperature, spin and isospin, the title of this conference. This radically new device will constitute a dramatic advance in γ -ray detection sensitivity that will enable the discovery of new phenomena, which are only populated in a tiny fraction of the total reaction cross section or of nuclei that are only produced with rates of the order of a few per second or less. Its unprecedented angular resolution will facilitate high-resolution spectroscopy with fast fragmentation beams giving access to the detailed structure of the most exotic nuclei that can be reached. Finally, the capability to operate at much higher event rates will allow the array to be operated for reactions with intense γ -ray backgrounds, which will be essential for the study of, for example, transuranic nuclei.

I thank all the many people who are working hard to realise this exciting new project.

REFERENCES

- [1] J. Simpson *et al.*, *J. Phys. G. Nucl. Phys.* **10**, 383 (1984).
- [2] J. Simpson *et al.*, *Phys. Rev. Lett.* **53**, 648 (1984).
- [3] J. Simpson *et al.*, *Phys. Lett.* **B327**, 187 (1994).
- [4] A.O. Evans *et al.*, *Phys. Rev. Lett.* **92**, 252502 (1985).
- [5] AGATA Technical Proposal, eds J. Gerl, W. Korten (Sept 2001).
- [6] K. Vetter, *Nucl. Phys. News Int.* **12**, 15 (2002).
- [7] M.A. Deleplanque, *Nucl. Instrum. Methods Phys. Res.* **A430**, 292 (1999).
- [8] J. Gerl, *Acta Phys. Pol. B* **34**, 2481 (2003).
- [9] J. Simpson, R. Krücken, *Nucl. Phys. News Int.* **13**, 15 (2003).
- [10] R.M. Lieder, *Nucl. Phys.* **A682**, 279c (2001).
- [11] E. Farnea, D. Bazzacco, LNL Annual Report 2003, LNL-INFN(REP)-202/2004 158 (2003).
- [12] E. Farnea, <http://agata.pd.infn.it/documents/simulations/comparison.html>
- [13] J. Simpson *Z. Phys.* **A358**, 139 (1997).
- [14] J. Eberth *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A369**, 135 (1996).
- [15] J. Eberth *et al.*, *Prog. Part. Nucl. Phys.* **46**, 389 (2001).
- [16] F. Recchia, E. Farnea, D. Bazzacco LNL Annual Report 2003, LNL-INFN(REP)-202/2004 160 (2003).