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The AGATA Spectrometer: next generation gamma-ray spectroscopy

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On behalf of the AGATA collaboration

Abstract. The Advanced GAmma Tracking Array (AGATA) is a European project to develop and operate the next generation gamma-ray spectrometer. AGATA is based on the technique of gamma-ray energy tracking in electrically segmented high-purity germanium crystals. The spectrometer will have an unparalleled level of detection power for electromagnetic nuclear radiation. The tracking technique requires the accurate determination of the energy, time and position of every interaction as a gamma ray deposits its energy within the detector volume. Reconstruction of the full interaction path results in a detector with very high efficiency and excellent spectral response. The realisation of gamma-ray tracking and AGATA is a result of many technical advances and the spectrometer is now operational. AGATA has been operated in a series of scientific campaigns at Legnaro National Laboratory in Italy and GSI in Germany and is presently being assembled at GANIL in France. The status of the instrument will be reviewed.

1. Introduction

High precision gamma-ray spectroscopy is one of the powerful tools used to study the structure of excited nuclear states and it has contributed to the discovery of a wide range of new phenomena. Each major advance in gamma-ray detection has resulted in significant new insights into the structure of nuclei. These advances culminated in two state-of-the-art 4π arrays of escape-suppressed spectrometers, Euroball in Europe [1] and Gammasphere in the USA [2]. These arrays, of more than a 100 large volume germanium crystals each surrounded by a Compton-suppression shield, have pushed this particular detector technology to its limit, with an efficiency for a 1 MeV gamma ray of about 10% and a peak-to-total ratio of 0.5.

Over the last decade or so the consensus of opinion worldwide is that the next major step in gamma-ray spectroscopy involves abandoning the concept of a physical suppression shield and achieving the ultimate goal of a 4π Germanium detector ball through the technique of gamma-ray energy tracking in highly segmented Ge crystals. Such an instrument will have a huge increase in sensitivity for the detection of the weakest signal from the most exotic nuclei. It will have an unprecedented angular resolution, resulting in excellent energy resolution by minimizing Doppler broadening even at velocities of the emitting nuclei up to 50% of the velocity of light. It is superbly suited to be used in conjunction with the new generation of radioactive beam accelerators or existing stable beam facilities. It will be vital to realize the scientific potential of new facilities for example at

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FAIR, FRIB, HIE-ISOLDE, SPES, and SPIRAL2. Given the importance of this increase in sensitivity, collaborations have been established in Europe and the USA to construct 4π tracking spectrometers. In the USA the project is called GRETA (Gamma Ray Energy Tracking Array) [3] and in Europe AGATA (Advanced Gamma Tracking Array) [4]. Both these projects have taken the first step with the construction of GRETINA (Gamma Ray Energy Tracking In beam Nuclear Array) and first phases of AGATA. These projects represent major technological advances in radiation detection and each has taken a very similar overall approach. This article summarises very briefly the status of AGATA.

2. The elements of gamma-ray tracking

The improved sensitivity or resolving power is due to the new technique of tracking, which identifies the position and energy of gamma-ray interaction points in the detector segments. Since most gamma rays interact more than once within the crystal, the energy-angle relationship of the Compton scattering formula is used to track the path of a given gamma ray. The full gamma-ray energy is obtained by summing only the interactions belonging to that particular gamma ray. In this way there are no lost scatters into suppression shields and scattered gamma rays between crystals are recovered, thus a much higher overall efficiency can be achieved. A gain by a factor of 6 over Gammasphere/Euroball for a single 1 MeV gamma ray and about 20 times for 15 MeV gamma rays is expected. Other key benefits of a highly segmented Ge array include high energy resolution, high counting rate capability (a factor of ~5 over Gammasphere/Euroball), good angular position resolution (about 1° versus 6° for Gammasphere) critical for Doppler shift corrections since many experiments involve high recoil velocities, the ability to handle high multiplicities without summing (as interactions from different gamma rays can be resolved), and the ability to pick out low-multiplicity events hidden in a high background environment due to the possibility of rejecting background events using the directional information of the radiation. The segmentation plus tracking also makes high precision linear polarisation measurements possible. The modularity of the detector design makes it extremely versatile and flexible for use in many different configurations and in conjunction with many ancillary detectors.

The realisation of such a system has required 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.
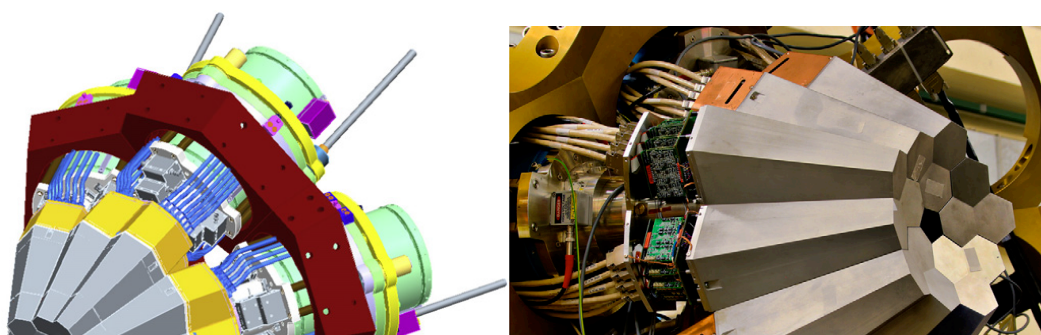
The detectors of AGATA (and GRETINA) are highly segmented n-type coaxial segmented germanium detectors supplied by the company Canberra, France. The crystals have a length of 9 cm and an initial diameter of 8 cm. Each crystal is shaped to form a hexagonal geometry and tapered at the front at an 8^0 angle. The tapering arises from the design of the full 4π detector ball being based on the geodesic arrangement of irregular 180 hexagons and 12 regular pentagons. The geometry and performance of AGATA is discussed in [5]. Each crystal is encapsulated into a thin Al can to protect the surface of the crystal. The crystals are segmented on their outer surface to provide the first level position of interaction information. The segmentation is 6 fold both longitudinally and azimuthally. This results in 37 signal outputs from the detectors, 36 segments and 1 signal from the core. The

performance of the individual detectors is excellent meeting the specifications, for example with the core energy resolution being less than 2.35 keV at 1.33MeV and the segments less than 2.3 keV. In the AGATA array there are three slightly different hexagonal shapes, which can be grouped easily in the geometry. Three detectors are therefore assembled together and housed in a so-called triple cryostat. This cryostat [6], which is provided by the company CTT Montabaur, cools the detectors and houses the 111 cold FETS and collaboration designed preamplifiers. Figure 1 shows a CAD design of the spectrometer and its realisation with 5 triple clusters (15 Germanium detectors) mounted for the experimental campaign at Legnaro National Laboratory (LNL).

The segmentation of the Ge crystal provides the initial position-of-interaction information. In order to perform gamma-ray tracking, the positions and energies of the gamma-ray interactions in the Ge must be even more accurately determined from the signal waveforms using pulse shape analysis. The position resolution is a key metric in the detector performance since it directly affects the efficiency and peak/total of the array, as well as the effective energy resolution of the array when the source of radiation is travelling with high recoil velocity. AGATA requires a state-of-the-art, purpose-built digital electronics and an associated data acquisition system to process the signals from the Ge crystals to enable accurate position information to be obtained. The system comprises an initial digitiser to sample each of the 37 signals to timestamp each signal (to 10ns), provide the energy of each segment and core and a digitised sample of the leading edge of each pulse. The latter is used later in the pulse shape analysis to determine the position of interaction. Following further processing the system collates and distributes the events to a computer cluster to perform pulse shape analysis, event reconstruction and tracking. A Global clock and trigger system has been developed to synchronise and time align the signals. The system needs to cope with a large numbers of channels, over 6000, and also with very high rates in each crystal, up to 50 kHz. Interfaces to enable coupling of ancillary detectors to the acquisition system have been developed. In the first phase of the AGATA project a full electronics and data acquisition system was provided for up to 30 detectors.

Crucial to the successful operation of a tracking array is the extraction of the position of each interaction within an event. The position and energy of a given interaction in the detector is found using a procedure called signal decomposition (pulse shape analysis). A computed signal basis is pre-calculated for each crystal using a simulation where a unit charge is placed at a given point in the crystal and the net and transient currents induced on each of the 36 segment contacts are calculated. Measured signals are then compared with linear combinations of these simulated signals, as there are typically multiple interaction points in a given crystal, with the best fit giving the location and charge (energy) of the interaction points. The calculation involves the geometry of the crystal, the bias voltage, and a model of the space charge distribution arising from crystal impurities. This idealised model of the crystal is not sufficient when applied to real signals, since corrections must be made for detector and electronic-response characteristics such as preamplifier shaping, relative time delays, and integral and differential cross-talk. These corrections are determined by comparing signal traces measured using gamma-ray sources to the signal basis, and fitting the required parameters. AGATA has a programme of scanning and characterising the crystals to provide a database of signals needed for validation of the simulations, for example see [7].

It has been shown experimentally that the pulse shape algorithms developed for AGATA can achieve an average position resolution of better than 5 mm (FWHM), which is sufficient for efficient gamma-ray tracking.

3. The deployment of AGATA

The AGATA collaboration of over 40 institutions in 13 countries in Europe was established to develop and construct a 4π tracking spectrometer. The AGATA collaboration defined that the full array would be realized in phases. In 2003 a Memorandum of Understanding (MoU) was signed by the partners for the research and development phase of the project. This first phase of the project involved constructing an array of 15 detector capsules, with all the electronics and data acquisition, pulse shape

and tracking algorithms and associated spectrometer infrastructure. This phase of the project is complete and AGATA has commenced a series of science campaigns.

AGATA is an instrument that moves between laboratories in order to take full advantage of the different beams and facilities available, and hence to maximise the breath of science that is addressed. In the first phase, AGATA was located at Legnaro National Laboratory up to the end of 2011[8]. AGATA was coupled to the PRISMA magnetic spectrometer and also used with a plunger for lifetime measurements and a suite of additional detectors, see [8]. A series of in-beam commissioning tests was performed followed by a successful science campaign of 23 experiments.

The spectrometer was then moved and operated at the GSI laboratory in Germany. At GSI AGATA was used to perform spectroscopy using the very high energy secondary beams from the UNILAC/SIS accelerator complex. At GSI the secondary beams of radioactive nuclei are produced by fragmentation of a range of stable primary beams and/or fission of a ^{238}U beam on a ^{9}Be or ^{208}Pb target placed at the entrance of the fragment recoil separator (FRS). The secondary beams were transported to the focal plane of the FRS where gamma-ray spectroscopy is performed using techniques such as relativistic Coulomb excitation and secondary fragmentation. The secondary beams are tracked through the FRS, and following reactions on a secondary target at the focal plane, are identified in terms of A and Z. For the GSI campaign AGATA consisted of up to 25 detectors. The reactions used at GSI result in high velocity recoils and a forward focusing of the gamma radiation emitted. Following extensive simulations and taking into account the mechanical design constraints the optimum efficiency was calculated to be achieved with only two detectors each cryostat in the most forward direction. A new double cryostat was therefore developed and the array was designed for 5 double and 5 triple cryostats, 25 detectors.

AGATA ceased operation at GSI in March 2014 and is currently being set-up and commissioned at the GANIL laboratory in France. The GANIL facility offers a large variety of radioactive and stable beams, ranging from ^{6,8}He to ^{238}U, over a wide range of energies from a few MeV/u up to 100 MeV/u. This wide spectrum of beams combined and the availability of several existing state-of-the-art spectrometers for gamma-ray and particle detection, such as VAMOS, has resulted in the collaboration deciding to host AGATA at GANIL until the end of 2018. At this time the instrument will have in excess of 45 detectors. Following this GANIL phase the instrument will return to LNL to take advantage of the radioactive beams from new facility, SPES.

4. Science advances, Summary and outlook

The advances made in Ge detector technology, digital data acquisition systems, signal decomposition and gamma-ray interaction reconstruction have proved that gamma-ray tracking spectrometers can be successfully deployed. AGATA and GRETINA (and GRETA) will have an enormous impact on the exploration of nuclear structure at the extremes of isospin, proton number, angular momentum, excitation energy, and temperature. It is encouraging that the first scientific results from AGATA are now regularly appearing in scientific journals that are advancing our knowledge of the nuclear landscape. An excellent example of the power of AGATA used in conjunction with PRISMA is the spectroscopy of the neutron rich nucleus ^{196}Os by John et al., [9]. The scientific papers are the result of time consuming hard work in analysing this new rather and complex data. AGATA is now proving to be able to make a major advance in gamma-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 in nuclei that are only produced with rates of the order of a few per second or less. The unprecedented angular resolution facilitates high-resolution spectroscopy with fast and ultrafast fragmentation beams giving access to the detailed structure of the most exotic nuclei that can be reached.

The instrumentation and technical advances driven by this work, and the knowledge gained by those involved, is important in a wide range of applications. These advances have potential impact in areas such as medical imaging in SPECT and PET systems, homeland security, and environmental monitoring.

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