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The AGATA Spectrometer

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Abstract. The Advanced GAmma Tracking Array (AGATA) is a European project to develop and operate a high-resolution gamma-ray spectrometer. AGATA is based on the technique of gamma-ray energy tracking in electrically segmented high-purity germanium crystals. 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. AGATA can measure gamma rays from 10's of keV to 10 MeV with excellent efficiency and position resolution and has a very high count rate capability. The realisation of AGATA and gamma-ray tracking is a result of many technical advances. AGATA has operated in a series of successful scientific campaigns at Legnaro National Laboratory in Italy, GSI in Germany and GANIL in France. AGATA is now in its next phase of development as it evolves to the full 4π instrument. It is presently starting its next campaign at Legnaro.

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. Nuclear structure studies far from stability are entering into a high-precision era with the availability of increased intensities and purity of radioactive ion beams and new methods to produce exotic nuclei using stable beams. In order to perform such spectroscopy instruments with improved efficiency and sensitivity are required.

Over the years high resolution gamma-ray spectroscopy has evolved with the use of High-purity germanium detectors (HPGe) and the development of large spectrometer arrays [1]. The present major step in gamma-ray spectroscopy is the realisation of being able to track every interaction of a gamma ray as it scatters in the detector volume. This results in a system with vastly improved efficiency and spectral response. The technical advances required for tracking are driven by the need to identify ever weaker transitions in nuclei far from the line of stability, in the heaviest nuclei, in highly excited states or at the highest angular momentum. They coincide with the new radioactive beam facilities that are coming online and intense stable beam facilities presently operating. Two major tracking spectrometers [2], the Advanced GAmma Tracking Array (AGATA) [3] in Europe and the Gamma Ray Energy Tracking Array (GRETA) [4] in the USA have developed this tracking technique and are moving towards their full implementation. This paper summarises the status of AGATA that will operate at major accelerator facilities in Europe. It will operate in diverse environments such as using relativistic beams from the

FAIR/Super-FRS facility, high-intensity ISOL beams from the second-generation Radioactive Ion Beam (RIB) facilities (HIE-ISOLDE at CERN, SPES at Legnaro National Laboratory (LNL), SPIRAL2 at GANIL), and at the high-intensity stable beam facilities at GANIL, JYFL Jyväskylä, and LNL.

2. Technical developments

AGATA is a major collaborative European project to construct and operate a gamma-ray tracking spectrometer. The project started in 2003 with a research and development phase to realise the ingredients needed to perform tracking. The concept of gamma-ray tracking was first proposed by the Berkeley group [5]. It involves surrounding the target with $\sim$100 highly segmented germanium detectors and, using digital electronics and pulse shape analysis, be able to identify the position, energy and time of every interaction. The full interaction event for each gamma ray can then be reconstructed in software using the Klein-Nishina formula for Compton scattering to produce a system with very high efficiency. The design of AGATA is based on a 4π coverage using 180 [6], 36 fold segmented and encapsulated germanium detectors. Three of these detectors are mounted in a LN_2 cryostat, which also houses the cold FETs for preamplification, see Fig. 1. A bespoke digital electronics system was developed to accept the 37 signals from each detector (1 core signal and 36 segment signals), to record the signal pulse shape for subsequent analysis and to transport the digital data for tracking reconstruction. This research and development project phase was successful and a system of up to 15 detectors become operational in 2009 at LNL, Italy.

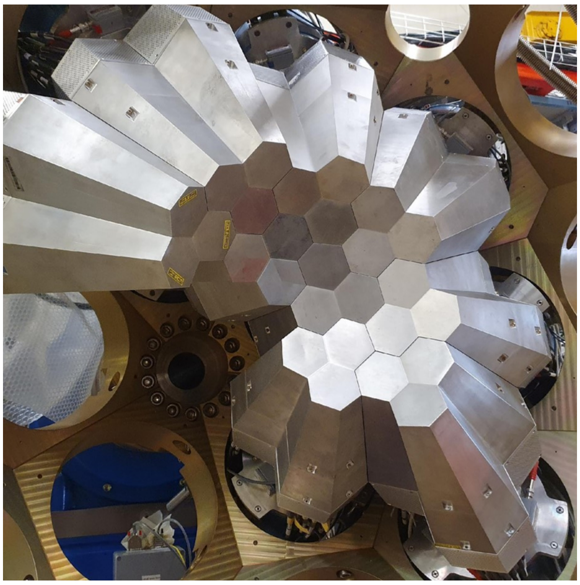

Figure 1. AGATA being installed at LNL in 2022. The triple detector cryostats and support frame are visible.

3. Deployment and exploitation

AGATA operated at LNL in a campaign from 2009-2011 where it was located at the target position of the PRISMA magnetic spectrometer [7]. Following this, the collaboration operated under a Memorandum of Understanding (MoU) that defined its scientific exploitation, operation and a continuing increase in the numbers of detectors, to 60 systems. Its next deployment, from 2012 to 2014, was at the GSI laboratory in Germany where it utilised the very high energy secondary beams from the UNILAC/SIS accelerator complex [8]. At GSI, 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 Separator

(FRS). The secondary beams were transported to the focal plane of the FRS where gamma-ray spectroscopy was performed using techniques such as relativistic Coulomb excitation. For the GSI campaign AGATA consisted of up to 25 detectors. The reactions used at GSI result in high recoil velocity and forward focusing of the emitted gamma radiation. The Doppler correction capabilities of AGATA using the position of interaction information was essential for this campaign to achieve good gamma-ray energy resolution. The spectrometer was then moved to GANIL, France in 2015 where it operated until 2021 [9]. AGATA was located at the target position of the VAMOS spectrometer and the number of available detectors gradually increased towards 60. The extensive range of stable beams from the cyclotron complex and ISOL radioactive beams from SPIRAL1 at GANIL were utilised in a very broad scientific programme.

In these campaigns AGATA was used with many complementary detector systems for channel selections and specific measurements. These included charged particle and neutron detectors, high-energy gamma detector arrays, fast-timing gamma systems and plungers for lifetime measurements [3, 7, 8, 9].

To date AGATA has produced 86 scientific publications (e.g. see [11]) and over 110 technical publications. This clearly demonstrates AGATA's impact but another very important outcome are the training aspects of the project, in particular for young scientists, engineers and technicians. A measure of this is that over 65 PhD's and 18 masters theses have been completed.

4. Towards 4π

The project has now entered its next phase to realise the 4π 180 detector array. This was driven by several factors including the scientific and technical impact and the need for a more sensitive instrument to answer the scientific questions that will be addressed with the new radioactive beam and high intensity stable beam facilities. A key step was the highlight recommendation in the 2017 NuPECC Long Range Plan [10] that supported the completion of the full geometry and endorsed by the statement ''The AGATA array is a unique and world-leading device for high-resolution gamma-ray spectroscopy for nuclear structure studies. Timely completion of the AGATA gamma-ray spectrometer is strongly needed." This stimulated the collaboration to produce a detailed science case, published in 2020 [12]. Figure 2 shows some examples of the science that AGATA will address.

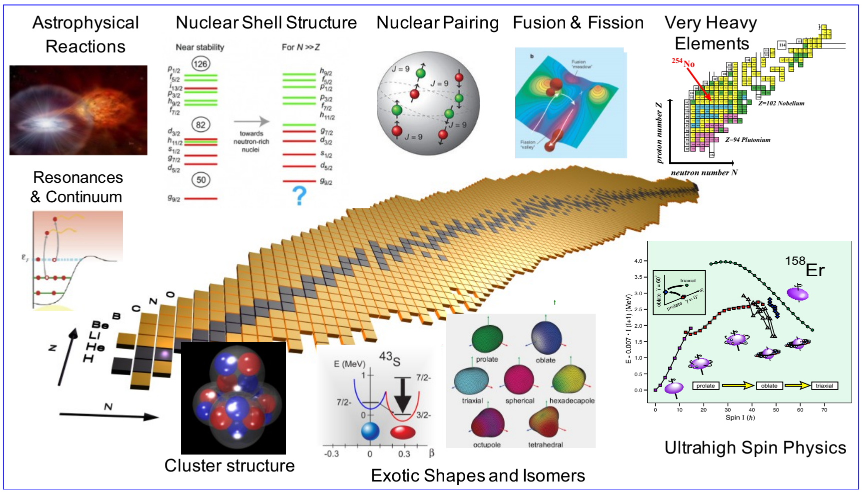

Figure 2. Illustration of some of the science that spans the nuclear landscape, which AGATA will investigate.

This science case covers the nuclear landscape to the extremes of isospin towards and beyond the drip lines, to the highest spins close to the fission limit and to the heaviest nuclei. The evolution of shell structure and magic numbers, the interplay between single-particle and collective degrees of freedom, shape co-existence, exotic shapes, nuclear pairing, reaction dynamics and key astrophysical reactions will be investigated.

An independent international review of the project was undertaken in 2020, which endorsed the NuPECC recommendation and noted the rich science case for a 3π system coupled to various ancillary detectors and spectrometers and the 4π array. This resulted in a new MoU that defines the realisation of a 3π system of 135 detectors in 10 years and subsequently 4π. The MoU has been signed by 11 countries and involves over 40 institutions.

Technical developments will continue to improve the performance of AGATA. As an example, the current UK AGATA project is not only responsible for the design and delivery of the mechanical structure (see Fig. 1), but also to make improvements in pulse shape analysis performance and detector characterisation. F. Holloway is leading developments of novel PSA using graph-accelerated algorithms to improve the overall processing rate [13]. S. D. Chen is developing a technique to create a self-calibrated pulse shape data base from source data so that the PSA technique does not need to rely on calculated waveforms for pulse shape comparison. These two developments when combined are aimed at improving key PSA features such as processing rates and position resolution.

The new phase to 4π is now operational and the next science campaign started in 2022 with AGATA back at LNL. Initially experiments will use the stable beams from the tandem and ALPI LINAC accelerators and subsequently radioactive ion beams from the SPES facility. Figure 1 shows AGATA during its commissioning in 2021 at the target position of the PRISMA spectrometer.

5. Summary

AGATA is now fully operational and has completed three science campaigns. The technical advances made to realise tracking are impressive and have an impact in applied areas of societal benefit. AGATA has entered its next phase to realise the full 4π spectrometer. It will gradually increase in sensitivity and efficiency whilst continuing to perform exciting science programmes at major European facilities.

6. Acknowledgments

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