AGATA PHASE 2

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AGATA-FRANCE coll.

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Nuclear physics is one of the most challenging fields of subatomic physics. This is because the properties of the nucleus arise from the combined action of the strong and electromagnetic forces acting between many elementary particles. Establishing how nuclear behaviours emerge from the basic properties of Quantum Chromo Dynamics (QCD) is one the goals of modern nuclear physics. To reach this goal, the experimental approach is to probe this emergence in nuclei with a different ratio of number of neutrons to protons (isospin=N/Z), or with different masses (A) or in a given nucleus at different temperatures (E*) and angular momentum (I) or in nuclear matter with varying densities… This de facto implies studying different regions of the Segré chart in

different experimental conditions, which requires in turn to take data at different accelerator facilities using the best adapted reaction mechanism and observables.
One of the most sensitive probes of the state of a nucleus is its electromagnetic radiation, especially when the emitted photons are detected in High Purity Germanium (HPGe) detectors, which so far, hold the record in terms of energy resolution. Tracking arrays based on HPGe crystals mark a major advance in the development of gamma-ray detector devices, as they can withstand large counting rates, provide unprecedented Doppler correction capabilities, enhanced polarization sensitivity and gains of up to 3 orders of magnitude in sensitivity compared to arrays based on Compton-suppressed HPGe detectors.

Strengthened by 2 decades of a successful collaboration around the EUROBALL gamma-ray multi-detector array and successful R&D within the auspices of the 5th framework of the European Union, several European countries established in 2003 a new collaboration called AGATA (Advanced GAmma Tracking Array). The aim was to demonstrate the feasibility of gamma-ray tracking and subsequently, to construct the European 4π gamma-ray tracking spectrometer. AGATA has gone through a demonstration phase (2003-2008) and a 1st phase of construction (2009-2020). AGATA is currently hosted at the GANIL facility and taking data. It has been constantly growing and comprises now 41 working crystals, corresponding to ~1500 channels of high resolution & high throughput electronics.

The AGATA collaboration is now preparing the next phase of the project (phase 2), which consists in the upgrade of the infrastructure, hardware and software required to instrument 180 detectors in order to cover a near 4π solid angle and attain the optimal performances of the array. According to the recommendations in the 2017 long-range plan from NUPECC, "AGATA represents the state-of-the-art in gamma-ray spectroscopy and is an essential tool underpinning a broad program of studies in nuclear structure, astrophysics and nuclear reactions". Moreover, "AGATA will be exploited at all the large-scale radioactive and stable beam facilities and in the long term must be fully completed in full (..) geometry in order to realize the envisaged scientific program".

France (and in particular IN2P3) has been one of the 4 major partners of the AGATA collaboration with Germany, Italy and UK since the beginning of the R&D phase and has a strong visibility in terms of technical developments (hardware & software) and also physics output from the device.

This document is organized as follows: First, the physics that motivates the construction of a 4π tracking array will be briefly presented. The technical ingredients of AGATA will then be given. This will be followed by an outline of the organization of the AGATA collaboration and a quick review of the milestones and achievements of the AGATA project. Finally, the 2nd phase of the project will be detailed, highlighting the foreseen IN2P3 involvement and investment in terms of capital, running costs and manpower. Attached to this document, the reader may find a draft of the AGATA White Book as well as the Project Definition for phase 2, as it stands today.

Summary

Science Case

The main motivation for the construction of a 4π tracking array such as AGATA is to be able to probe the manifestations of the underlying forces at play in the nucleus in extreme conditions of N, Z, A, E*, I, … In this sense, AGATA is a high-precision frontier tool.
One can mention a few topics of interest, which are detailed in the AGATA white book: the study of shell evolution, understanding the microscopic origin of nuclear deformation and the interplay between single-particle and collective degrees of freedom, the search for exotic and extreme shapes in particular nuclear hyperdeformation, establishing shape coexistence and shape transitions and understanding the underlying mechanisms, testing theoretical predictions for neutron and proton skins, probing the nature of pair correlations and investigating how angular momentum is generated, measuring the degree of isospin-symmetry breaking, find fingerprints of chaos in nuclei, …
AGATA is also the ideal tool to measure fundamental nuclear properties such as gamma-ray strengths, fission barriers as well as the excitation energy and lifetime of bound and unbound nuclear states relevant for astrophysical processes such as for e.g. the r process, which has recently played out in real time following the cataclysmic gravitational-wave source GW170817.
Finally, AGATA has the potential resolving power to study rare decay modes, such as second-order electromagnetic processes involving the simultaneous emission of 2 photons. It can also contribute to other areas of research, such as the search for permanent atomic electric dipole moments (EDMs) which would violate P, T hence CP symmetries.

Technical Description

The concept of a tracking array was introduced in the 90s to increase the efficiency of multi-detector arrays. The idea was to remove the anti-Compton shields used in the previous generations of gamma-ray multi-detectors and replace them with active Ge, thereby covering most of 4π solid angle with high-resolution material.

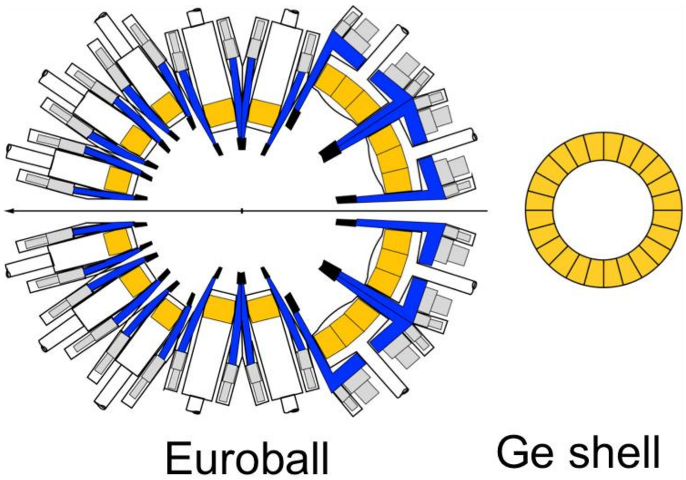

Figure 1: Schematic illustration of the transition from a standard 4π Ge detector array, such as Euroball with 239 Ge Compton-suppressed Ge detectors (yellow detectors surrounded by blue anti-Compton shields covering more than 2π), to a 4π tracking array composed solely of Ge crystals.

In order to recover a good signal-to-noise ratio, i.e. in order to distinguish the photons which deposit all their energy in the Ge crystals from those who just scatter out of them, the trajectories of the gamma rays have to be reconstructed by an algorithm which "tracks" the photons as they interact in the Ge crystals.
The necessary ingredients of a tracking array are:

- highly-segmented encapsulated HPGe crystals,
- high-resolution fast preamplifiers,
- digital electronics to record and process the signals from all the segments and central contact of a crystal,
- triggering and synchronization system
- high-throughput DAQ to process the high flow of data
- pulse shape analysis (PSA) algorithms to decompose the signals from each crystal and identify the interaction points in each segment
- tracking algorithms to reconstruct the photon trajectories from the energies and positions of the interaction points
- complex data analysis to merge and analyse data from AGATA and any ancillary device
- large storage capacities

AGATA in its complete 4π geometry would be composed of 180 36-fold segmented hexagonal shaped tapered HPGe crystals, each one situated at 23.5 cm from the source of the photons of interest.

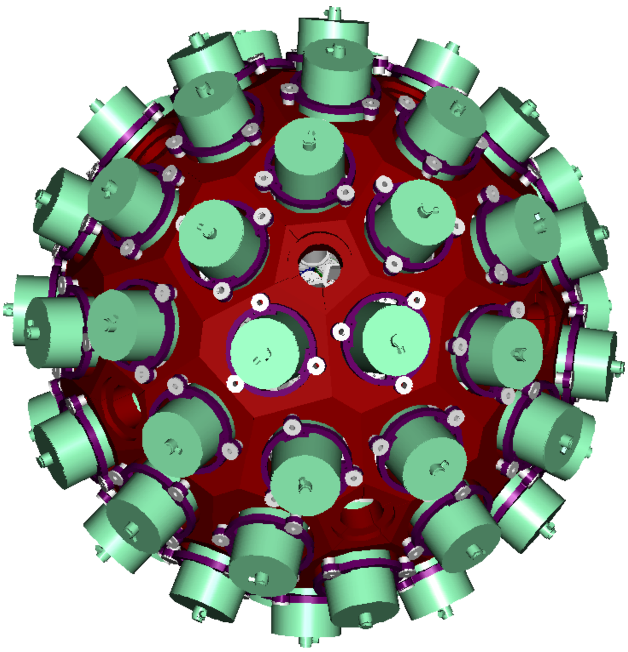

Figure 2: Artist's view of AGATA 4π. Only the mechanical holding frame (red) and cryostat dewars (green) are visible.

The crystals are especially encapsulated in order to facilitate manipulation and repair. There are 3 different shapes of crystal, referred to as crystal A, B and C. They are operated together in one vacuum "triple-cryostat" and cooled by LN2. These AGATA Triple Clusters (ATC) form the AGATA detector unit. Each unit produces 111 signals, which are pre-amplified and then digitized at a rate of 100 Msps with 14 bit precision.

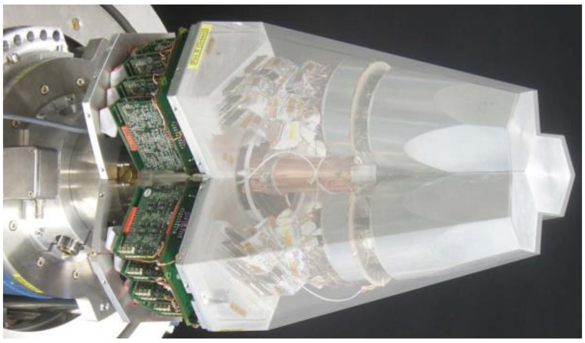

Figure 3: Photo-montage showing the inside of an ATC, in particular the 3 capsules, together with the cold and warm pre-amplification stages.

The corresponding signal energies, sample traces and timing information are extracted by the pre-processing electronics and then sent to the DAQ computers for further processing (PSA, tracking and data replay and analysis…).
The key parameters of AGATA are its efficiency ε, peak-to-total (P/T), energy resolution (ΔE), angular resolution, polarization sensitivity and counting rate capabilities. In particular, when analysing N-fold coincidences between gamma rays, the sensitivity scales with $S= (\varepsilon \cdot (P/T) / \Delta E)^N$. AGATA is also a versatile instrument that can be coupled to many different kinds of ancillary detectors in order to enhance its sensitivity to the particular physical signal of interest. When designing such ancillaries, the free space available inside the array plays an important role

Organization

At the European level, 3 bodies govern the AGATA collaboration: the AGATA Steering Committee (ASC) is the decision making body, representing the funding agencies. 11 countries are represented today. The representatives for France are G. Duchêne (IN2P3) and Ch. Theisen (CEA).
The AGATA Management Board (AMB) is responsible for the execution of the project along the lines defined by the ASC. France has been, and continues to be well represented with many AMB group and team leaders (5 teams are currently led by IN2P3 physicists/engineers and the Data Flow group is coordinated by A. Korichi, an IN2P3 physicist).
Finally the AGATA Collaboration Council (ACC) represents the ~40 institutions collaborating in the AGATA project and advises the ASC on scientific matters. Its chair, W. Korten, is a French representative (CEA).
The collaboration meets regularly during the annual AGATA weeks, where the groups and teams present the status of affairs and the foreseen developments, and the physics and future plans are discussed on an annual basis also during the EGAN/NUSPIN (and in the future NUSREB) workshops. The AGATA collaboration has also regular meetings with its American counterpart, the GRETINA/GRETA collaboration. Collaborative ventures on PSA, tracking and detector simulation and characterization have been initiated.
Two dedicated websites exist; one for the AGATA project (www.agata.org) and the other for the ACC (npg.dl.ac.uk/agata_acc/).
In France, the AGATA project also has its own organization, with a scientific (A. Lopez-Martens) and technical (E. Legay) coordinator and representatives from the 6 laboratories involved in AGATA (A. Korichi for CSNSM, G. de France for GANIL, G. Duchêne for IPHC, D. Verney for IPNO, N. Redon for IPNL, M. Zielinska for CEA) as well as

the GANIL campaign manager (E. Clément), the French ASC representatives and the current chair of the ACC (W. Korten). The collaboration has set up a web site that can be found here: http://agata.IN2P3.fr.

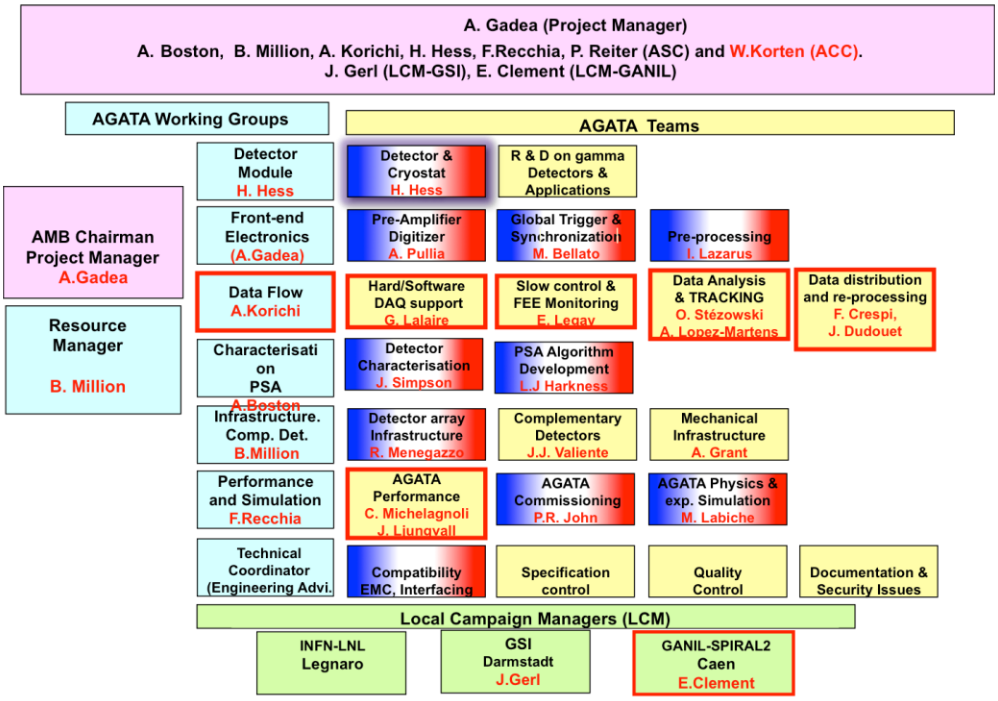

Figure 4: Organigram of the AGATA Management Board, where the red boxes show which groups are led by French scientists or engineers and the French flags indicate which teams have active French members.

Several meetings are organized during the year to discuss budget, HR, R&D and physics related issues. One to two meetings a year are organized with the funding agencies, generally before or after the scheduled ASC meetings. Technical and scientific members of AGATA-France meet every year for the so-called AGATA France days. In total, an average of ~20 full time equivalent researchers, students and engineers contribute to AGATA-France (this includes the construction, the maintenance, the R&D, the exploitation and the physics-related work). The detail of the IN2P3 fraction of this effort over the years is given in the figure below.

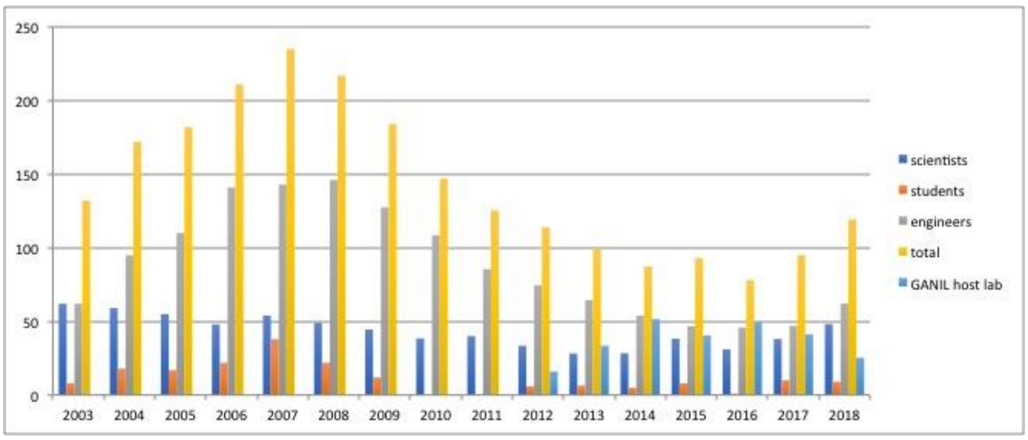

Figure 5: IN2P3 manpower (man.months) effort for the AGATA construction, maintenance and R&D since 2003. Also reported the GANIL host lab effort. From 2016 onwards (years for which the data is available), the effort related to the physics research with AGATA (exploitation and data analysis) is ~42-48 man.month/year.

Milestones

Demonstrator phase (2003-2008)

Following extensive R&D work within the TMR program of Europe, a MoU was signed in 2002 by 12 countries in order to construct the prototype of a tracking array. IN2P3 signed this MoU after positive evaluation of the demonstrator project by the Scientific Council of IN2P3 on 09/11/2001.
The prototype consisted of 5 AGATA units and associated electronics, data acquisition system and infrastructure and was installed at LNL, Italy.
The associated technical design report can be found here: http://npg.dl.ac.uk/agata_acc/publications_documentation/TDR_EUJRA.pdf .
IN2P3 laboratories were especially involved in the design of the detector infrastructure (IPHC), preamplifiers (GANIL), digitizers (IPHC), ATCA back-end electronics (CSNSM, IPNO), data acquisition architecture and analysis tools (CSNSM, IPNL, IPNO), detector simulation, scanning and signal database generation (CSNSM, IPHC), development of pulse shape decomposition and tracking algorithms (CSNSM, IPHC, IPNO). A review of the R&D was carried out and financial adjustments were requested at the scientific Council of IN2P3 on 20/06/2005.
Successful commissioning and demonstration of online PSA and tracking in 2009 resulted in the AGATA founding paper[1].
For this phase, the French investment in terms of manpower and money is resumed in the following table (the 3 numbers correspond to the IN2P3/GANIL/CEA contributions).

Country	Funds contributed in k€ (2003-2008)	Personnel in person months (2003-2008)
Bulgaria	0	45
Finland	2	8
France	1,408 744/322/342	1,442 1087/62/293
Germany	1,241	509
Italy	1,391	907
Poland	0	85
Romania	57	40
Sweden	819	199
Turkey	750	70
UK	950	559
Total	**6,618**	**3,864**

Figure 6: Total contribution (funds and manpower) to the AGATA demonstrator phase.

Construction phase (2009-2015, 2016-2020)

Following the encouraging recommendations of the 29/06/2009 Scientific Council of IN2P3, the institute signed a new MoU in 2009. It was renewed in 2015 (signed in 2018). This MoU determined the conditions of construction of AGATA up to 20 detector units (1/3 of 4π) and its operation in campaigns in terms negotiated by the ASC and the envisaged host laboratories (LNL, GSI and GANIL). In particular the document establishes the operational costs of the array as it grows from 5 to 20 units and the

[1] *AGATA – Advanced GAmma Tracking Array: S. Akkoyun and the AGATA collaboration, Nucl. Instr. Meth. A 668 (2012) 26*

required capital investments. It is to be noted that the AGATA collaboration has built close to a 1/3 of the 4π array within this predefined budget.
Following a signed agreement between IN2P3, GANIL and CEA, the French capital investment was split into contributions of 61% (IN2P3), 10% (GANIL) and 29% (CEA),. It had been 50%, 25% and 25% in the demonstration phase of the project, but due to foreseen investments for SPIRAL2 and for hosting AGATA, the GANIL share was reduced and the other contributions increased. They are summarized here:

Country	**Capital investment k€ (2009-2019)**
Bulgaria	0
Finland	145
France	2390 (1469,261,660)
Germany	2846
Italy	2304
Poland	0
Romania	0
Spain	638
Sweden	0
Turkey	0
UK	894
Total	**9244**

Figure 7: Total investment per country for AGATA during the fist phase of construction.

France is the owner of 11 AGATA crystals (6/1/4) and 3 triple cryostats (2/1/0). The details of the French expenditure are shown in the following table.

	IN2P3	**GANIL**	**IRFU**		**Total**
Detectors	1135,14	112,6	557,25		**1804,99**
FEE	130,2	99,01	0		**229,21**
DAQ	164,83	15	9,87		**189,7**
Infra	39,2	34,11	92,88		**166,19**
Ancillary	0	0	0		**0**
Data ana	0	0	0		**0**
TOTAL	1469,37	260,72	660		**2390,09**

Figure 8: Details of the French capital investment during the 1st phase of construction (2009-2019)

Compared to the planned investment, IN2P3 still owes 30 kEuros and CEA ~50 kEuros. The GANIL also invested ~380 kEuros from 2012-2014 to be able to host AGATA (with a contribution of 39 kEuros from IN2P3 for the mechanical structure) and has an annual running cost budget of ~ 10 kEuros.

Regarding the operational costs, these have been growing with the size of the array and are shared between the French partners (2/3 for IN2P3, 1/6 for GANIL and 1/6 for CEA):

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
/	17,5	15,0	25,0	33,4	34,7	43,1	46,6	52,0	60,4	62,0

Figure 9: Operation costs (kEuros) paid by IN2P3.

In terms of implication in the construction phase, the activities of IN2P3 laboratories have grown to include the design and maintenance of the AGATA database (IPNL), which is an essential tool when moving the array from one place to the next, customer acceptance tests (CAT) of AGATA detectors and triple cluster maintenance (IPHC).

Achievements

The AGATA collaboration has demonstrated that it could, at the same time, successfully exploit and construct a complex detector array. To our knowledge, this is a unique case of constant detector upgrade and infrastructure growth. Moreover, continuous R&D has improved the detector quality (neutron damage correction) & failure rate (new encapsulation). Smart techniques have been developed to considerably reduce detector-scanning times and new analysis tools and methods have simplified data taking, monitoring and analysis. Tracking algorithms have been constantly improved. Simulation packages have been developed to calculate waveforms (Agata Detector Library simulation software) and estimate performances (AGATA GEANT4 simulation package). AGATA electronics has proven to be linear and very stable over long periods of time, with gain changes < 10^{-4}. The collaboration has demonstrated that it could reach the specification average position resolution of 5 mm. This has made it possible to attain close to sub-fs lifetime measurements. Finally, a record maximal loss-free rate of 5000 Hz PSA decompositions per crystal has been reached on line by the AGATA collaboration.

On the physics front, AGATA was inaugurated in April 2010 at LNL. Since then it has smoothly and successfully moved to GSI (2012-2014) and then GANIL (2015-2021). In LNL from 2009-2011, AGATA benefited from 146 days of beam time on target with 21 approved experiments, at GSI the number of experiments was 8, and at GANIL, there have so far been 209 days of beam time dedicated to AGATA for a total of 22 experiments.

The physics campaigns at these 3 European facilities have yielded close to 40 peer-reviewed articles (excluding conference proceedings or review articles) of which 6 have been published in Phys. Rev. Lett (2 with an IN2P3 first author). The complete list of scientific publications related to AGATA can be found on the collaboration website:

http://npg.dl.ac.uk/agata_acc/publications_documentation/Agata_scientific_publications.pdf

A few examples of detailed spectroscopic results obtained with AGATA are given below. They illustrate different properties of the array at work.

Angular resolution (consequence of the position resolution of PSA):

The first example is taken from the GANIL campaign where a heavy ^{238}U beam impinged on a Be target and the VAMOS spectrometer was used to identify the fission fragments. An unprecedented set of 205 well-identified nuclei, some quite exotic, and their corresponding prompt γ-ray emission spectra could be obtained. The figure below shows the Doppler-corrected photon spectra for isotopes of Zr. The gain of almost a factor 2 in energy resolution with respect to the EXOGAM array is evident. This property together with the (A,Z) identification have allowed to revisit, correct and amend many decay schemes and obtain information on the interplay between single-particle and collective degrees of freedom in the region north-east of ^{78}Ni[2].

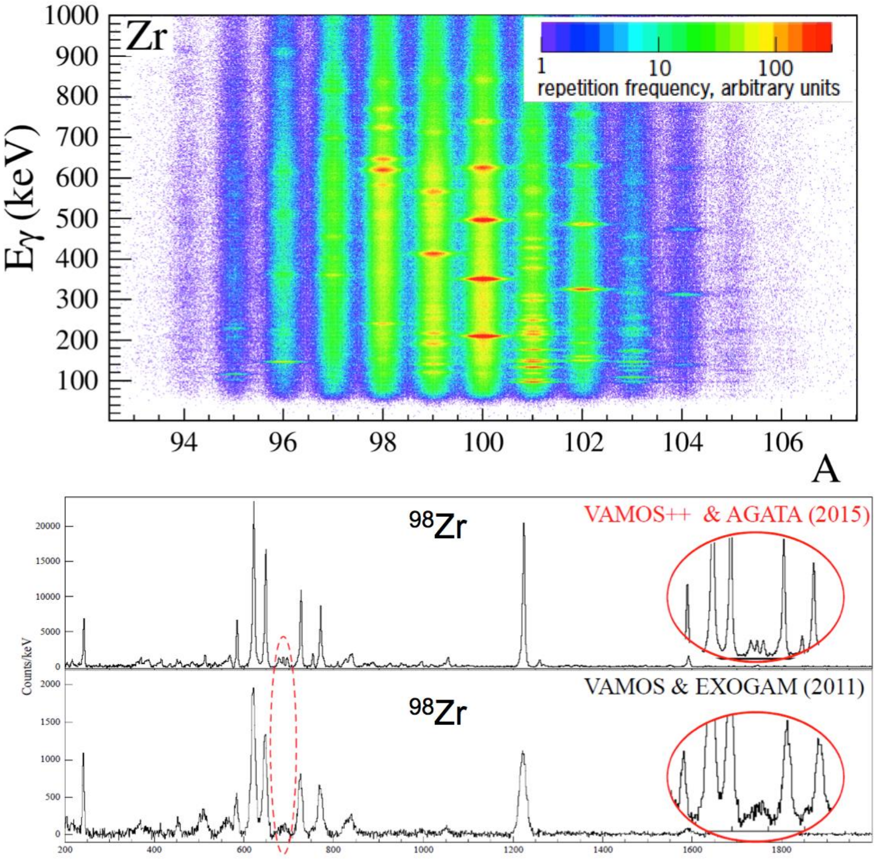

Figure 10: prompt γ-ray spectrum measured in EXOGAM or AGATA in coincidence with Zr isotopes identified in VAMOS.

The second example is taken from the LNL campaign. The figure below shows the photon energies measured in the reactions ^{14}N(^{2}H,n)^{15}O and ^{14}N(^{2}H,p)^{15}N at 32 MeV as a function of the angle of detection of the photon with respect to the beam axis. The slant and the shape of the line corresponding to the decay of the 6.79 MeV state in ^{15}O give a new upper limit of 0.5 fs for the lifetime of the state. This in turn constrains the astrophysical S-factor of the ^{14}N(p,γ)^{15}O reaction, which is important in the solar composition problem. This is the first time sub-fs lifetimes are measured with a Ge array[3].

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[2] ^{96}Kr – Low-Z boundary of the island of deformation at N=60, J. Dudouet et al., Phys. Rev. Lett. 118, 162501 (2017) and J. Dudouet submitted to Phys. Rev. Lett.

[3] *The lifetime of the 6.79 MeV state in ^{15}O as a challenge for nuclear astrophysics and gamma-ray spectroscopy: a new DSAM measurement with the AGATA Demonstrator array, C. Michelagnoli, PhD thesis (2013), University of Padua*

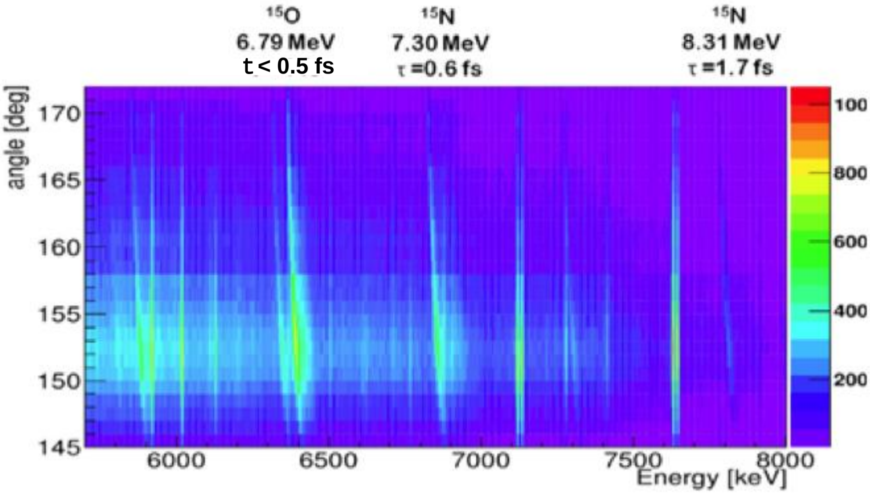

Figure 11: Angle of detection vs measured photon energy for various high-energy transitions in ^{15}O and ^{15}N.

The last example is taken from the GSI campaign where lifetimes of isobaric multiplets have been studied in order to test the theoretical prediction of the linearity of the quadrupole transition matrix elements with isospin projection Tz=(N-Z)/2. For the A=46 T=1 multiplet, relativistic ^{46}V, ^{46}Cr and ^{46}Ti ions (v/c~50%) produced in the fragmentation of a ^{58}Ni beam were Coulomb excited on gold targets. In the ^{46}Ti and ^{46}V cases, a novel stretched target system composed of 3 gold foils was used. The spectrum shown below reveals 3 peaks for the decay of the 2^+ state in ^{46}V. This is only made possible by the resolving power of AGATA, whose position resolution can resolve the emissions occurring at slightly different velocities after passage through each foil. The intensity ratios of the 3 lines give access to the lifetime of the 2^+ state. No non-linear dependence of the measured E2 matrix elements for the 2^+ to 0^+ as a function of isospin was found for the A=46 multiplet, indicating no isospin mixing[4].

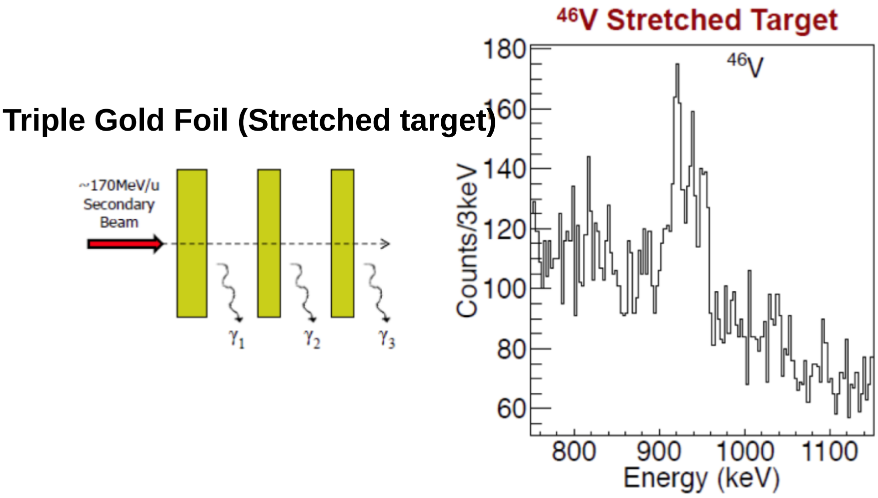

Figure 12: Schematic drawing of the triple-gold foil target system used at GSI to determine the lifetime of the 2+ state in ^{46}V and measured energy of the 2^+-0^+ transition in ^{46}V following Coulomb excitation on the stretched target.

[4] *A. Boso et al., in preparation*

Polarization sensitivity

The capability of AGATA detectors as Compton polarimeters was investigated during the LNL campaign using the Coulomb excitation of the first excited state in ^{104,108}Pd isotopes with a ^{12}C beam and two AGATA clusters, positioned as close as possible to 90 degrees with respect to the beam direction. The expected polarization of γ rays was calculated with accuracy and the ratio of the measured asymmetry coefficient to the calculated polarization gives the corresponding analysing power of AGATA. It was found to be larger than the one of a standard clover detection system[5]. This allows AGATA to measure the linear polarization of photons in cases of weaker nuclear alignments or for rare phenomena in general.

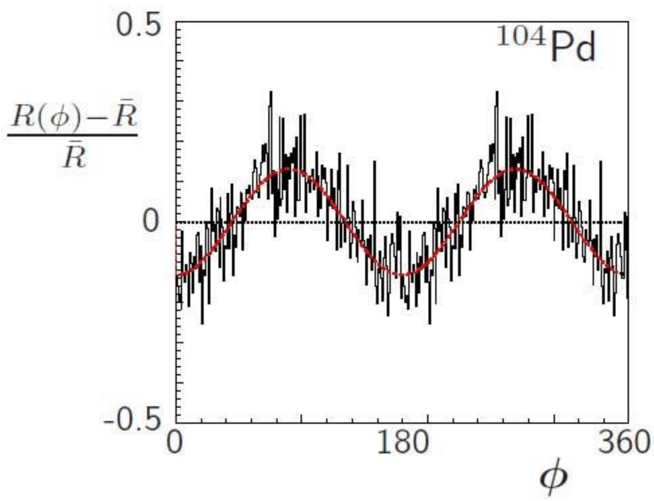

Figure 13: Experimental asymmetry as a function of the azimuthal angle ϕ of Compton scattering measured for the deexcitation of the first 2^+ state in ^{104}Pd populated by Coulomb excitation.

It is to be noted that many experiments are still under analysis. The publication policy of the AGATA collaboration is that the physicists and engineers who have contributed to the construction of AGATA are members of a core list and are systematically given the opportunity to be an author of all the AGATA physics papers. Regarding technical publications, these represent more than 50 publications since 2009 and cover aspects of imaging, tracking, PSA, cross-talk and neutron-damage corrections, detector characterization and performance studies. The complete list of technical publications can be found at:
http://npg.dl.ac.uk/agata_acc/publications_documentation/Agata_publications.pdf).
Finally, more than 50 PhD students have dealt with AGATA-related issues or analysed AGATA data. AGATA has also been the perfect subject for engineering summer students.

GRETINA/GRETA project

Only 2 tracking arrays are currently being built around the world: AGATA in Europe and GRETINA/GRETA in the USA. Just like AGATA, GRETINA is a mobile array, which spends time at Argonne National Laboratory and the National Superconducting Cyclotron Laboratory/Michigan State University in alternating campaigns taking advantage of the different beams and ancillary devices available at each site. GRETINA has gone through

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[5] *Analyzing power of AGATA triple clusters for gamma-ray linear polarization,P.G. Bizzeti, Eur. Phys. J. A51 (2015) 49*

the various stages of project approvals by DOE and the American γ-ray spectroscopy community has recently received approval of the project's final design and release of funds for the construction of the 4π array GRETA. The construction schedule aims to complete the 4π configuration in 2025.
There are some technical differences between the 2 projects: The GRETA 4π array will be composed of 120 36-fold-segmented crystals instead of 180. This leaves a larger inner radius for the target chamber of AGATA – and therefore more space for ancillary devices. The expected performance for high-multiplicity events is also slightly better. The cryostats of GRETINA hold 4 crystals while the detector unit of AGATA is the triple cluster. The GRETINA detector segments are instrumented with warm FETs while the 1st stage of all the AGATA preamplifiers are close to LN2 temperature. The AGATA collaboration takes care of mounting the capsules into the cryostats and all the inner cabling, while MIRION (ex-CANBERRA) performs that task for the GRETINA collaboration. All these factors make for slightly different signal properties, most notably the cross talk between segments in a crystal is more important at GRETINA than at AGATA. The PSA capabilities are similar at both arrays, with a slight advantage to AGATA, which manages a higher on-line signal decomposition rate per crystal. The PSA algorithm used at GRETINA allows for the reconstruction of more than one photon interaction per segment and this leads to slightly different hit patterns. Consequently, the tracking algorithms developed for both arrays are also a little bit different but despite these differences, the final performances of the arrays are very similar.
Since 2016, regular AGATA-GRETINA workshops are held in Europe and in the USA. The 3rd edition of the workshop will be held in Argonne in October 2019. Collaborative work on common challenges such as detector characterization, PSA and tracking have begun.

Phase 2 of the AGATA project

The collaboration is preparing to upgrade the subsystems of AGATA to be able to instrument and operate 60 ATCs at different facilities in Europe. The upgrade is planned in such a way as to sustain the growth from 20 to 60 units (180 individual crystals), to improve the performance of the subsystems, to enhance the mobility of the array and the compatibility with the hosting laboratories and to achieve full tracking performance:

	Goal (180 detectors)	29 crystals (2016)
Energy Resolution 121 keV 1332 keV 1382 keV (v/c=6%)	 ≤1.3 keV ≤2.3 keV 4.3 keV	 Achieved Achieved Achieved
Efficiency (+tracking) 1332 keV	 34%	 3.8%
P/T 1173 keV (no threshold on Eγ)	 49%	 37%
Crystal rate PSA rate	50 kHz 20 kHz	Achieved 4-5 kHz

While the P/T increases slightly as fewer photons scatter out of the edges of the detector and the efficiency of AGATA grows as a function of the number of detector units present in the array, the power to extract weak and rare signals from a large background of other photons will grow as a **power law** of the efficiency. This is illustrated in the well-known plot of the resolving power as a function of time and shows that the full power of AGATA, in terms of P/T and efficiency, is only achieved with a full 4π array.

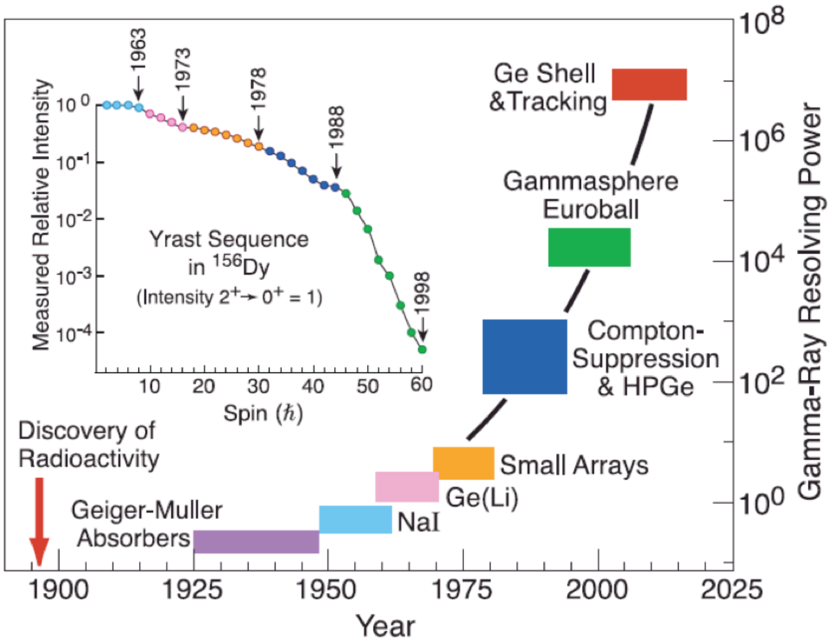

Figure 14: Resolving power of photon detectors as a function of time and detector-technology. In the left top corner is shown the smallest measured yrast intensity in 152Dy, with respect to the 2+ → 0+ transition, as measured with successive generations of γ–ray spectrometers.

AGATA will be the working horse for high-resolution gamma-ray spectroscopy in Europe for the next 2 decades. It has been identified in the recent NUPECC long-range plan as a key instrument for the next generation facilities such as SPES-Italy or FAIR in Germany (see contribution to this SC). Thanks to its gain in sensitivity and efficiency as a function of it completeness, AGATA will be involved in all high-impact subjects of modern nuclear science. The AGATA collaboration has prepared a detailed scientific project from 2020 to 2030 and beyond, described in great details in the "White-Book" attached to the present document. The scientific objectives can be summarized as follows:

- Nuclear structure at the extreme of isospin in Radioactive beams facilities such as FAIR, ISOLDE, SPES or SPIRAL1 in the field of shell evolution far from stability around the doubly magic ^{132}Sn, ^{100}Sn and east of ^{208}Pb to benchmark realistic nucleon-nucleon interaction.
- Search for the role of the 3-body interaction and continuum effects at the drip lines in light system at FAIR, ISOLDE and SPIRAL1
- Search for evidence of clustering effect in the nuclear matter all along the nuclear chart from light to very heavy elements
- In-beam High resolution gamma-ray spectroscopy of Super Heavy Elements as close as possible of the Island of Stability at the University of Jyvaskyla in complementarity with the low energy facilities (SPIRAL2, FLNR, UNILAC-GSI)

- Search for evidence of isospin symmetry breaking and proton-neutron pairing in nuclear matter in N=Z nuclei as close as possible of ^{100}Sn using stable beams (GANIL, LNL) or radioactive beams (FAIR, ISOLDE, SPIRAL1).
- Nuclear structure at the extreme of spin in stable beam facilities such as GANIL or LNL
- High resolution gamma-ray spectroscopy of nuclear astrophysics reaction in Radioactive Ions Beams facility (ISOLDE, SPIRAL1, SPES)

The required gain in sensitivity to achieve these ambitious goals is related to a series of upgrades of the current detectors as listed in the next section.

In addition, AGATA as gamma-ray spectrometer, will be involved in large scale experimental setups using complementary detectors for charged-particle spectroscopy (GRIT- see contribution to this SC), NEDA for neutron detection, PARIS for high energy photons (see contribution to this SC) and magnetic spectrometers. These complex setups are part of the AGATA roadmap and are fully included in the AGATA integration work (mechanics, DAQ, electronics and analysis software) to optimize the physics output at the different Europeans facilities.

Details of the upgrade

Detectors: The collaboration plans to order 12 capsules and 4 triple cryostats per year (the cryostats include the GANIL/Milano preamplifiers). MIRION (ex-CANBERRA) is for now the sole manufacturer of AGATA-type detectors – though discussions are underway with ORTEC (this might make prices go down a little). Detectors represent the main cost of the phase 2 of AGATA: ~32.1 MEuros between 2021 and 2030 (this includes spare ATCs and spare capsules). To cope with orders, the collaboration must train new experts in the field of highly segmented detector integration, maintenance and repair and the workload must be divided between the host laboratories and the CAT sites. This has implications for GANIL, IPHC and CEA detector laboratories.

Electronics: The electronics of AGATA is currently of 2 types: phase 0 electronics, which was designed in 2004 and first produced in 2006-2009, and phase 1 electronics, which was designed in 2012 and first produced in 2014. In both cases, the frontend electronics (preamplifier and digitizers) is not in the same location as the pre-processing electronics. Both phases also face a common issue of component obsolescence for construction, repairing and maintenance.
Phase 2 electronics is therefore planned to be produced in collaboration with an industrial partner who will maintain, produce and buy in advance specific components, which have a short shelf time. The electronics will be more integrated (the digitizer and pre-processing boards will be integrated), consume less power, be faster, and cost less. It will also have new features, especially in terms of monitoring and readout. A proof of concept, based on evaluations boards, should be ready mid-2019. The IN2P3 laboratories involved in the design of this subsystem are CSNSM for the 10GB Ethernet readout module and IPHC for the pre-processing firmware. GANIL is also involved in the clock distribution and triggering system and interface.
The present budget implies a total 3.3 MEuros cost from 2021-2030.

DAQ: The future AGATA DAQ will continue to use the architecture NARVAL/DCOD developed by IPNO and CSNSM. In terms of performance, it will benefit from future faster processors. The DAQ architecture will evolve in 2 stages according to the

electronics present in the system. Until phase 0 and phase 1 electronics are replaced by phase 2 electronics, the DAQ must host the electronics PCIx cards, which sets a requirement of one server/crystal. In this case, improvements to the processing time can be made by early filtering and/or splitting of crystal events. Once the new electronics based on Ethernet is ready, the CPU can be distributed over high performance farms and use GPU optimization.
The inclusion of upgraded and/or new and tracking algorithms is also foreseen. The improvement of the overall performance of AGATA is one of the main goals of the ANR OASIS launched in 2018 involving CSNSM, GANIL, IPHC and CEA. Moreover, the AGATA Data Flow group is currently investigating to what extent machine learning could benefit signal decomposition and Compton cluster recognition.
The upgrade of the DAQ (servers, storage, analysis machines) requires a budget of 1.5 MEuros**.**

Infrastructure: The upgrade of AGATA requires a new low-voltage power supply (LVPS), a new High voltage (HV) system and an upgrade of the LN2 filling system, which should satisfy the space constraints of the growing array. The effort and maintenance is mainly under the responsibility of CEA. The IPHC is also involved with the production of new patch boxes.
Concerning the mechanical infrastructure upgrade, it includes enlarging the honeycomb to accommodate 60 ATCs, the main support of the array based on a shaft able to sustain and rotate half of the array, which can be doubled to 4π and a new detector mounting system for precise and safe triple cluster loading/unloading.
The overall infrastructure budget is estimated to 1.4 MEuros**.**

Envisaged Host sites and timeline

At the last ASC meeting in March 2019, the siting for the next years was fixed: AGATA will stay at GANIL until 2021 and then move to Legnaro National Laboratories. Other facilities, which have expressed interest in hosting AGATA are FAIR, JYFL and ISOLDE.

HR, capital investment and OC

The collaboration is in the process of writing a new MoU for phase 2. The envisaged involvement of French scientists and engineers in the development and maintenance of AGATA in its phase 2 is given in the figure below.

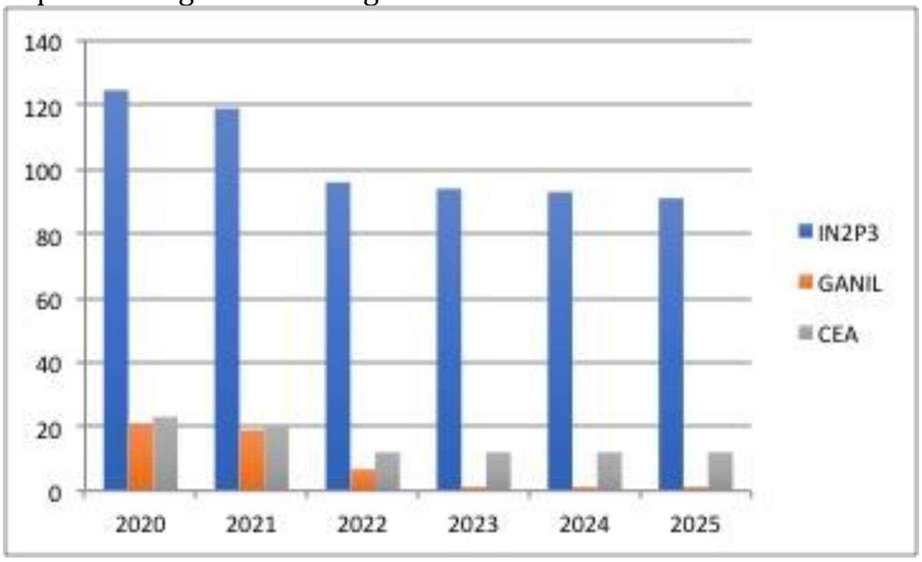

Figure 15: Estimated number of man months that will be implicated during the first years of the upgrade of AGATA. The numbers for IN2P3 include postdocs (hired in 2018 and 2019) and potential engineering students.

It is difficult to estimate the number of scientists that will be involved in data taking and analysis with AGATA, since many AGATA users come from outside of the AGATA collaboration (i.e. AGATA-building community). One can nevertheless say that many groups have shown interest in campaigns at LNL, JYFL, GANIL, FAIR and ISOLDE in the process of writing the AGATA white book. As an example, 9 LoIs were submitted by French spokespersons in preparation for the workshop recently held in Legnaro to discuss the physics opportunities of using AGATA with stable beams at LNL (63 LoI were submitted in total, many of them involving French researchers).
Regarding the capital investment and operational costs estimated for the upgrade and exploitation of AGATA, they are resumed in the following 2 tables.

Item	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Total
Capsules/Clusters	72/24	84/28	96/32	108/36	120/40	132/44	144/48	156/52	168/56	180/60	
Detector	2528,5	2566,4	2604,9	2643,9	2683,6	2723,9	2764,7	2806,2	2848,3	2891	27061,4
Cryostat	468,5	475,5	483,6	489,9	497,2	504,7	512,2	519,9	527,7	535,6	5014,8
Electroics	488,5	0	503,3	0	518,5	0	534,1	0	550,3	558,5	3153,2
GTS/SMART	0	120									120,0
PSA/DAQ	0	483				343				357	1183,0
Storage		112,5				112,5				112,5	337,5
Analysis		10				10				10	30,0
Infrastructure	415,1			440,6							855,7
Mechanics	230,3			330							560,3
Total	**4130,9**	**3767,4**	**3591,8**	**3904,4**	**3699,3**	**3694,1**	**3811**	**3326,1**	**3926,3**	**4464,6**	**38315,9**
France	**826,2**	**753,5**	**718,4**	**780,9**	**739,9**	**738,8**	**762,2**	**665,2**	**785,3**	**892,9**	**7663,2**
IN2P3	**504,0**	**459,6**	**438,2**	**476,3**	**451,3**	**450,7**	**464,9**	**405,8**	**479,0**	**544,7**	**4674,5**

Figure 16: Required capital investment as a function of year to upgrade AGATA to acquire and instrument 180 capsule/60 cluster array. The French contribution is calculated assuming a 20% share of the total cost. The IN2P3 contribution is computed using the current 61%/10%/29% sharing between IN2P3, GANIL and CEA partners, but this sharing has still not been decided.

Item	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
Capsules in setup	60	60	72	84	96	108	120	132	144	156	162	180
Expected Capsule failures	5	5	6	7	8	9	9	10	11	12	13	14
failures Under Warranty	0	0	1	2	2	2	2	2	2	2	2	2
Detectors in setup	20	20	24	28	32	36	40	44	48	52	54	60
Detectors												
LN2	73,5	73,5	85,5	97,5	109,5	121,5	133,5	145,5	157,5	169,5	175,5	193,5
Capsule maintenance/repair	257,6	261,4	265,3	269,3	328,0	388,4	394,3	457,4	522,2	589,0	657,6	728,1
Detector&Cryostat maintenance /repair	77,6	78,7	95,9	113,5	131,7	150,4	169,6	189,4	209,7	230,5	243,0	274,0
Including Preamplifer exchange…												
and Other repairs (feedthrough, cabling,…)												
Detector laboratories	60	60	60	60	60	60	60	60	60	60	60	60
Infrastructure												
HV/LV, Autofill, infrastructure	21,8	21,8	26,1	30,5	34,8	39,2	43,5	47,9	52,2	56,6	58,7	65,3
Electronics and DAQ												
Elect. maintenance/replacement	72,0	73,1	89,0	105,4	122,3	139,6	157,5	175,8	194,7	214,0	225,6	254,4
DAQ maintenance/replacement	63	63	75,6	88,2	100,8	113,4	126	138,6	151,2	163,8	170,1	189
Other costs												
Grid costs	24	24	24	24	24	24	24	24	24	24	24	24
Shipping costs	25	25	27	29	31	33	33	35	37	39	41	43
Mechanics	8	8	8	8	8	8	8	8	8	8	8	8
Total operation & maintenance costs	**682,4**	**688,5**	**756,4**	**825,4**	**950,1**	**1077,5**	**1149,3**	**1281,5**	**1416,5**	**1554,4**	**1663,5**	**1839,4**

Figure 17: Operational costs (for exploitation, repair & maintenance) related to the upgrade of AGATA as a function of capsules in the setup.

The contribution of France to the running costs will be of the order of ~17% of the total cost, as it has been the case until now. This means ~110 kEuros in 2021 and 310 kEuros in 2032. The sharing between French partners has yet to be determined.

Project of AGATA “Infrastructure de Recherche”

In order to gain visibility in the national scientific roadmap and secure the substantial pluriannual funding required, it would be beneficial that AGATA become an Infrastructure de Recherche. The document required for the first stage of the process has been prepared and is now in the hands of our DAS.

SWOT analysis

Strengths	**Weaknesses**
-Develop, build and exploit a state-of-the-art photon spectrometer -Technical expertise in HPGe detectors, electronics and DAQ -European effort -Precision spectroscopy of exotic nuclei -Discovery potential	-European effort -Few experts
Opportunities	**Threats**
-Involvement of a new Ge detector provider (ORTEC) and possible CTT-MIRION collaboration for cryostat production	-Lack of funding and HR -Little beam time in some of the hosts sites -One detector and one cryostat provider

Conclusion

To conclude, the AGATA collaboration has proven that it is a successful collaboration. The pursuit of the construction of AGATA towards 4π array is essential to the entire low-energy nuclear physics community as AGATA is foreseen to be the precision tool at all the major stable and radioactive beam facilities in Europe. In conjunction with other state-of-the-art equipment, currently available or being developed, AGATA will push the frontiers of the nuclear chart accessible to the high-resolution gamma-ray spectroscopy probe, providing a better understanding of the complex and multi-faceted behaviour of the nucleus.

Members of the AGATA-France collaboration in 2018

(NSIP data for IN2P3. Permanent staff is marked in blue, technical staff in black, PhD students in green, Postdocs in red)

CSNSM : A. Astier, N. Dosme, J. Dudouet, E. Dupont, L. Gibelin, J. Jacob, N. Karkour, A. Korichi, X. Lafay, E. Legay, D. Linget, J. Ljungvall, A. Lopez-Martens, X. Grave
GANIL : C. Belkhiria, M.Blaizot, A. Boujrad, P. Bourgault , N. Charly, E. Clément, S. Coudert, G. DeFrance, B. Duclos, G. Lalaire, S. Leblond, A. Lemasson, C. Maugeais, L. Ménager, D. Ralet, , J. Ropert, F. Saillant, C. Wittwer
IPHC : Ch. Bonin, L. Charles, B. De Canditiis ,F. Didierjean, G. Duchêne, M. Filliger, G. Heitz, N. Ollivier-Henry, K. Rezynkina, M. Richer, C. Schwab, M.H. Sigward, D. Thomas
IPNL : C. Aufranc, G. Beaulieu, L. Ducroux , T. Dupasquier , N. Redon, O. Stezowski, X. Fabian
IPNO : C. Delafosse, P. Le Jeannic , D. Verney,

CEA :,S. Ansari ,T. Joannem , M. Karolak, M. Kebbiri A. Lotodé ,M. Siciliano, Ch. Theisen, R. Touzery, W. Korten, M. Zielinska

Other (past and future) AGATA users (either participants to AGATA experiments or spokerspersons of AGATA-related proposals or Letters of Intent) include physicists from the VAMOS, PARIS, MUGAST/GRIT collaborations as well as nuclear astrophysicists, more than doubling the number of physicists in the list above :
CSNSM : I. Deloncle, G. Georgiev, R. Lozeva, C. Petrache, S. Roccia
GANIL : N. Alahari, B. Bastin, F. De Oliveira, M. Rejmund
IPHC : D. Curien, O. Dorvaux, C. Schmitt, L. Stuttgé
IPNO : M. Assié, D. Beaumel, Y. Blumenfeld, N. Desereville, F. Flavigny, F. Leblanc, M. MacCormick, S. Franchoo, F. Hammache, F. Ibrahim, I. Matea, J.Stefan
LPC : A. Matta
CEA : M. Vandebrouck