AGATA: Status and Perspectives

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on behalf of the AGATA Collaboration
Outline

• Basic concepts: pulse shape analysis and gamma-ray tracking
• Gamma-ray tracking arrays: AGATA and GRETA (in strict alphabetical order)
• Status of AGATA
Composite & encapsulated detectors

CLOVER

EB-CLUSTER
Why do we need AGATA?

Our goal is to extract new valuable information on the nuclear structure through the γ-rays emitted following nuclear reactions.

Problems: complex spectra!
Many lines lie close in energy and the “interesting” channels are typically the weak ones ...
Challenges in Nuclear Structure

Shell structure in nuclei
- Structure of doubly magic nuclei
- Changes in the (effective) interactions

Proton drip line and N=Z nuclei
- Spectroscopy beyond the drip line
- Proton-neutron pairing
- Isospin symmetry

Transfermium nuclei
- Exotic shapes and isomers
- Coexistence and transitions

Neutron rich heavy nuclei (N/Z → 2)
- Large neutron skins \((r_\nu - r_\pi \rightarrow 1\text{fm})\)
- New coherent excitation modes
- Shell quenching

Nuclei at the neutron drip line (Z→25)
- Very large proton-neutron asymmetries
- Resonant excitation modes
- Neutron Decay
Why do we need AGATA?

- Low intensity
- High background
- Large Doppler broadening
- High counting rates
- High $\gamma$-ray multiplicities

Conventional arrays will not suffice!

High efficiency
High sensitivity
High throughput
Ancillary detectors

Harsh conditions!
Need instrumentation with
Efficiency vs. Resolution

With a source at rest, the intrinsic resolution of the detector can be reached; efficiency decreases with the increasing detector-source distance.

With a moving source, due to the Doppler effect, also the effective energy resolution depends on the detector-source distance.

Small $d$ $\iff$ Large $\Omega$ $\iff$ High $\varepsilon$ $\iff$ Poor FWHM
Large $d$ $\iff$ Small $\Omega$ $\iff$ Low $\varepsilon$ $\iff$ Good FWHM
Compton scattering

The cross section for Compton scattering in germanium implies quite a large continuous background in the resulting spectra.

Concept of anti-Compton shield to reduce such background and increase the P/T ratio.
From conventional Ge to $\gamma$-ray tracking

**Compton Shielded Ge**
- $\varepsilon_{\text{ph}} \sim 10\%$
- $N_{\text{det}} \sim 100$
- $\Omega \sim 40\%$

**Ge Sphere**
- $\varepsilon_{\text{ph}} \sim 50\%$
- $N_{\text{det}} \sim 1000$
- $\theta \sim 8^\circ$

**Ge Tracking Array**
- $\varepsilon_{\text{ph}} \sim 50\%$
- $N_{\text{det}} \sim 100$
- $\Omega \sim 80\%$
- $\theta \sim 1^\circ$

Efficiency is lost due to the solid angle covered by the shield; poor energy resolution at high recoil velocity because of the large opening angle.

Using only conventional Ge detectors, too many detectors are needed to avoid summing effects and keep the resolution to good values.

The proposed solution: Use the detectors in a non-conventional way!

AGATA and GRETA
Ingredients of Gamma Tracking

1. Highly segmented HPGe detectors

2. Digital electronics to record and process segment signals

3. Pulse Shape Analysis to decompose recorded waves

4. Reconstruction of tracks evaluating permutations of interaction points

Identified interaction points \((x, y, z, E, t)_i\)

Reconstructed gamma-rays
Arrays of segmented Ge detectors
(for Doppler correction)

- **EXOGAM segmented clovers** with 4x4 fold segmentation

- **MINIBALL triple-clusters** with 6 and 12 fold segmentation

- **Segmented Germanium Array (SeGA)** with 32-fold segmentation
Pulse Shape Calculations and Analysis by a Genetic Algorithm

\[ i_{e/h} = -q_{e/h} \cdot \frac{\rho}{E_w} \cdot \rho_{\text{drift}} (\rho/E) \]

In-beam test of PSA: MARS detector

Coulx. of $^{56}$Fe at 240 MeV on $^{208}$Pb, $v = 0.08c$

Corrected using points determined with a Genetic Algorithm

Corrected using center of segments → 24 detectors with $\Delta \theta \approx 9^\circ$

Corrected using center of crystal → one detector with $\Delta \theta \approx 22^\circ$

Position resolution → 5 mm FWHM

Similar result from an experiment done with the GRETA detector
An alternative approach: Grid search

- Search the best $\chi^2$ for pulse shapes in the reference base
- The pulse shapes associated to one point in the reference base are chosen as sample
- The $\chi^2$ of the sample is calculated for all the points in the reference base
- The results obtained for the in-beam experiment are quite similar to those obtained with a genetic algorithm

Other approaches (neural networks, wavelets, etc.) are currently attempted within the collaboration
**γ-ray tracking**

Photons do not deposit their energy in a continuous track, rather they lose it in discrete steps.

One should identify the sequence of interaction points belonging to each individual photon.

Tough problem! Especially in case of high-multiplicity events.

A high multiplicity event:

\[ E_\gamma = 1.33 \text{MeV}, \ M_\gamma = 30 \]
Interaction of photons in germanium

Mean free path determines size of detectors:

\[ \lambda(10 \text{ keV}) \sim 55 \mu\text{m} \]
\[ \lambda(100 \text{ keV}) \sim 0.3 \text{ cm} \]
\[ \lambda(200 \text{ keV}) \sim 1.1 \text{ cm} \]
\[ \lambda(500 \text{ keV}) \sim 2.3 \text{ cm} \]
\[ \lambda(1 \text{ MeV}) \sim 3.3 \text{ cm} \]
\[ \lambda(2 \text{ MeV}) \sim 4.5 \text{ cm} \]
\[ \lambda(5 \text{ MeV}) \sim 5.9 \text{ cm} \]
\[ \lambda(10 \text{ MeV}) \sim 5.9 \text{ cm} \]
Tracking algorithms

Basic ingredient: Compton scattering formula

\[ E_E^\gamma = \sum_{i=n}^{N-1} e_i \]
\[ \cos \theta^P = \frac{01 \cdot 12}{|01| \cdot |12|} \]
\[ \Rightarrow \quad E_P^\gamma = \frac{E_E^\gamma}{1 + \frac{E_E^\gamma}{m_0 c^2} (1 - \cos \theta^P)} \]
\[ \chi^2_n = \left( \frac{E_E^\gamma - E_P^\gamma}{\sigma} \right)^2 \]
\[ \Rightarrow \quad \chi^2 \approx \sum_{n=1}^{N-1} \chi^2_n \]
Reconstruction of multi-gamma events

Analysis of all partitions of measured points is not feasible:
Huge computational problem
(\(\sim10^{23}\) partitions for 30 points)
Figure of merit is ambiguous \(\rightarrow\) the total figure of merit of the “true” partition not necessarily the minimum

1 - **Cluster (forward) tracking**
2 - **Backtracking**
3 - **Other approaches**
   (fuzzy tracking, etc.)
Forward tracking

(G. Schmid, 1999; mgt implementation by D. Bazzacco, Padova)

1. Create cluster pool => for each cluster, $E_{\gamma 0} = \sum \text{cluster depositions}$

2. Test the 3 mechanisms
   1. do the interaction points satisfy the Compton scattering rules ?

   $\chi^2 \approx \sum_{n=1}^{N-1} W_n \left( \frac{E_{\gamma} - E_{\gamma}^{\text{Pos}}}{E_{\gamma}} \right)^2$

   2. does the interaction satisfy photoelectric conditions ($e_1$, depth, distance to other points) ?

   3. do the interaction points correspond to a pair production event ?

   $E_{1\text{st}} = E_\gamma - 2m_e c^2$

3. Select clusters based on $\chi^2$
Backtracking
(J. Van der Marel et al., 1999)

Photoelectric energy deposition is approximately independent of incident energy and is peaked around 100-250 keV.

=> interaction points within a given deposited energy interval \((e_{\text{min}} < e_i < e_{\text{max}})\) will be considered as the last interaction of a fully absorbed gamma.
1. Create photoelectric interaction pool: $e_{\text{min}} < e_i < e_{\text{max}}$

2. Find closest interaction $j$ to photoelectric interaction $i$
   - prob. for photoelectric interaction $> P_{\text{phot,min}}$
   - distance between interaction points $< \text{limit}$
   
   $E_{\text{inc}} = e_i + e_j, E_{\text{sc}} = e_i$

3. Find incident direction from incident + scattered energies
   
   $\cos \theta = 1 - m_e c^2 (1/E_{\text{sc}} - 1/E_{\text{inc}})$

4. Find previous interaction $k$ or source along direction
   - $\cos \theta(\text{energy}) - \cos \theta(\text{position}) < \text{limit}$
   - prob. for Compton interaction $> P_{\text{comp,min}}$
   - distance between interaction points $< \text{limit}$
   
   $E_{\text{inc}} = e_i + e_j + e_k, E_{\text{sc}} = e_i + e_j$

The last points of the sequence are low energy and close to each other $\rightarrow$ bad position resolution and easily packed together
Benefits of the $\gamma$-ray tracking

- scarce
- good
- Definition of the photon direction
- Doppler correction capability

$v/c = 20\%$

Detector
Segment
Pulse shape analysis + tracking $\gamma$
AGATA

- High efficiency and P/T ratio.
- Good position resolution on the individual $\gamma$ interactions in order to perform a good Doppler correction.
- Capability to stand a high counting rate.

Pulse shape analysis + $\gamma$-ray tracking
Building a Geodesic Ball (1)

Start with a platonic solid e.g. an icosahedron

On its faces, draw a regular pattern of triangles grouped as hexagons and pentagons. E.g. with 110 hexagons and (always) 12 pentagons

Project the faces on the enclosing sphere; flatten the hexagons.
Building a Geodesic Ball (2)

A radial projection of the spherical tiling generates the shapes of the detectors. Ball with 180 hexagons.

Space for encapsulation and canning obtained cutting the crystals. In the example 3 crystals form a triple cluster.

Add encapsulation and part of the cryostats for realistic MC simulations

Al capsules
- 0.4 mm spacing
- 0.8 mm thick

Al canning
- 2 mm spacing
- 2 mm thick
Geodesic Tiling of Sphere
using 60–240 hexagons and 12 pentagons
The Monte Carlo code for AGATA

- Based on Geant4 C++ classes
- Geodesic tiling polyhedra handled via a specially written C++ class
- Relevant geometry parameters read from file (generated with an external program)
- Possibility to choose the treatment of the interactions for $\gamma$-rays (including Rayleigh scattering, Compton profile and linear polarization)
- Event generation suited for in-beam experiments
Class structure of the program

* Possibility to change parameters via a messenger class

* Messenger classes are not shown!
## GRETA vs. AGATA

<table>
<thead>
<tr>
<th>Ge crystals size:</th>
<th>Length 90 mm</th>
<th>Diameter 80 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 hexagonal crystals</td>
<td>2 shapes</td>
<td>30 quadruple-clusters</td>
</tr>
<tr>
<td>Inner radius (Ge)</td>
<td>18.5 cm</td>
<td>Amount of germanium</td>
</tr>
<tr>
<td>Solid angle coverage</td>
<td>81 %</td>
<td>4320 segments</td>
</tr>
<tr>
<td>Efficiency:</td>
<td>41% ($M_γ=1$)</td>
<td>25% ($M_γ=30$)</td>
</tr>
<tr>
<td>Peak/Total:</td>
<td>57% ($M_γ=1$)</td>
<td>47% ($M_γ=30$)</td>
</tr>
<tr>
<td>180 hexagonal crystals</td>
<td>3 shapes</td>
<td>60 triple-clusters</td>
</tr>
<tr>
<td>Inner radius (Ge)</td>
<td>23.5 cm</td>
<td>Amount of germanium</td>
</tr>
<tr>
<td>Solid angle coverage</td>
<td>82 %</td>
<td>6480 segments</td>
</tr>
<tr>
<td>Efficiency:</td>
<td>43% ($M_γ=1$)</td>
<td>28% ($M_γ=30$)</td>
</tr>
<tr>
<td>Peak/Total:</td>
<td>58% ($M_γ=1$)</td>
<td>49% ($M_γ=30$)</td>
</tr>
</tbody>
</table>
Absolute efficiency value includes the effects of the tracking algorithms! Values calculated for a source at rest.
Effect of the recoil velocity

The comparison between spectra obtained knowing or not knowing the event-by-event velocity vector shows that additional information will be essential to fully exploit the concept of tracking.

<table>
<thead>
<tr>
<th>$\beta$ (%)</th>
<th>5</th>
<th>20</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_s$(cm)</td>
<td>1.5</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>$\sigma_{\text{dir}}$(degrees)</td>
<td>2</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>$\Delta_\beta$ (%)</td>
<td>2.4</td>
<td>0.7</td>
<td>0.3</td>
</tr>
</tbody>
</table>

![Graph showing FWHM vs. Uncertainty on the recoil direction (degrees) with different $\beta$ values: $\beta = 50\%$, $\beta = 20\%$, and $\beta = 5\%$.](image)
AGATA/GRETA Prototypes

MINIBALL-style cryostat used for acceptance tests

“standard” preamplifiers

Encapsulation
0.8 mm Al walls
0.4 mm spacing

36-fold segmented, encapsulated detector
Segmentation of AGATA crystals

The impact of effective segmentation

tapering angle $\sim 8^\circ$

geometrical segmentation
Energy Resolution
(measured with analogue electronics)

The 36 segments Core

Guaranteed FWHM
at 1.33 MeV : < 2.30 keV, mean < 2.1 keV
at 60 keV : < 1.35 keV, mean < 1.15 keV

Measured FWHM
at 1.33 MeV : 2.13 keV
at 122 keV : 1.10 keV

Guaranteed FWHM
at 1.33 MeV : 2.35 keV
at 122 keV : 1.35 keV

The 3 detectors are very similar in performance
AGATA Cryostats

Individual, for tests  Triple, for experiments

differential-output preamplifiers with fast reset of saturated signals  (Milano/Ganil, Köln)
AGATA detector scanning

Liverpool coincidence setup with multileaf collimator

Other system being developed at CSNSM Orsay and GSI

Full scan in 1 mm³ grid almost impossible → define characteristic points to calibrate calculations
AGATA
(Advanced GAmma Tracking Array)

4π γ-array for Nuclear Physics Experiments
at European accelerators
providing radioactive and high-intensity stable beams

Main features of AGATA

- **Efficiency:** 43% ($M_{\gamma}=1$) 28% ($M_{\gamma}=30$)
  
  today’s arrays ~10% (gain ~4) 5% (gain ~1000)

- **Peak/Total:** 58% ($M_{\gamma}=1$) 49% ($M_{\gamma}=30$)
  
  today ~55% 40%

- **Angular Resolution:** ~1° →
  
  FWHM (1 MeV, v/c=50%) ~ 6 keV !!!
  
  today ~40 keV

- **Rates:** 3 MHz ($M_{\gamma}=1$) 300 kHz ($M_{\gamma}=30$)
  
  today 1 MHz 20 kHz

- 180 large volume 36-fold segmented Ge crystals packed in 60 triple-clusters
- Digital electronics and sophisticated Pulse Shape Analysis algorithms allow
- Operation of Ge detectors in position sensitive mode → γ-ray tracking
- Demonstrator ready by 2007; Construction of full array from 2008
AGATA Steering Committee

Chairperson J.Gerl, Vice Chairperson, N.Alamanos
G.deAngelis, A.Atac, D.Balabanski, D.Bucurescu, B.Cederwall,

AGATA Managing Board

J.Simpson (Project Manager)
D.Bazzacco, G.Duchêne, J.Eberth, A.Gadea, W.Korten, R.Krücken, J.Nyberg

AGATA Working Groups

Detector Module
J.Eberth
Detector Performance
R.Krücken
Data Processing
D.Bazzacco
Design and Infrastructure
G.Duchêne
Ancillary detectors and Integration
A.Gadea
Simulation and Data Analysis
J.Nyberg
EURONS
W.Korten

AGATA Teams

Preamplifiers
A.Pullia
Detector and Cryostat
D.Weisshaar
PSA
R.Gernhäuser/ P.Desesquelles
Detector characterisation
A.Boston
Digitisation
P.Medina
Pre-processing
I.Lazarus
Global clock and Trigger
M.Bellato
Data acquisition
X.Grace
Run Control & GUI
G.Maron
Mechanical design
K.Fayz/J.Simpson
Infrastructure
P.Jones
R&D on gamma detectors
D.Curien
Electr. and data acq.
Ch. Theisen
Impact on performance
M.Palacz
Mechanical integration
Devices for key Experiments
N.Redon
Gamma-ray Tracking
W.Lopez-Martens
Experiment simulation
E.Farnea
Detector data base
K.Hauschild
Data analysis
O.Stezowski

AGATA organisation April 2005
Illegal Alien sneaked into the Management!!!

The Management
The First Step:  
The AGATA Demonstrator  
Objective of the final R&D phase 2003-2008

1 symmetric triple-cluster  
5 asymmetric triple-clusters  
36-fold segmented crystals  
540 segments  
555 digital-channels  
Eff. 3 - 8 % @ $M_\gamma = 1$  
Eff. 2 - 4 % @ $M_\gamma = 30$ 

Full ACQ  
with on line PSA and $\gamma$-ray tracking 

Test Sites:  
GANIL, GSI, Jyväskylä, Köln, LNL  
Cost ~ 7 M €
Status of development

• Funding
  - a 4 triple-clusters system (12 crystals) secured (almost)
  - Sweden and Turkey bidding for a triple cluster each

• Detectors
  - 11 of the 12 detectors ordered
  - 3 of them (symmetric) delivered and tested
  - partial coincidence scan for one detector done at Liverpool
  - first triple cluster being assembled now at Köln
  - in beam experiment planned end of August at the Köln Tandem with Miniball (XIA) electronics
  - delivery of first asymmetric detector by November 2005

• Electronics and DAQ
  - design frozen at the last AGATA week (Feb. 2005)
  - development of modules ongoing (hardware and FPGA software)
  - first full chain for one detector to be tested in spring 2006

• Tracking methods
  - full MC simulation of the system well advanced
  - pulse shape decomposition proceeding but still a kind of bottleneck
  - $\gamma$-ray tracking well advanced
  - simulation of experiments, including ancillary detectors, progressing well
Status and Evolution

- Configuration chosen in 2004
- Development of Demonstrator ready in 2007
- Next phases discussed in 2005-2006
- New MoU and bids for funds in 2006-2007
- Start construction in 2008

- $1\pi$ ready in 2010 (10 M€) ~ 4 clusters/year
- $3\pi$ ready in 2015 (20 M€)
- $4\pi$ ready in 2018 (10 M€)

Keeping the schedule depends on availability of funds and production capability of detector manufacturer
The Phases of AGATA

5 Clusters

Demonstrator

Main issue is Doppler correction capability → coupling to beam and recoil tracking devices

Replace/Complement

Peak efficiency
3 - 8 % @ $M_\gamma = 1$
2 - 4 % @ $M_\gamma = 30$

Improve resolution at higher recoil velocity
Extend spectroscopy to more exotic nuclei
The Phases of AGATA

15 Clusters

The first “real” tracking array
Used at FAIR-HISPEC, SPIRAL2, SPES, HI-SIB
Coupled to spectrometer, beam tracker, LCP arrays ...
Spectroscopy at the N=Z (^{100}Sn), n-drip line nuclei, ...
The Phases of AGATA

45 Clusters

Ideal instrument for FAIR / EURISOL
Also used as partial arrays in different labs
Higher performance by coupling with ancillaries
The Phases of AGATA

60 Clusters

Full ball, ideal to study extreme deformations and the most exotic nuclear species
Most of the time used as partial arrays
Maximum performance by coupling to ancillaries
Summary

- Gamma-ray tracking arrays will be very powerful tools to extract valuable information for nuclear structure and reaction studies.
- Work continues ...