Monte Carlo Simulations for Modern gamma-tracking Arrays

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Outline

• From conventional to gamma-ray tracking arrays
• Results from Monte Carlo simulations for AGATA
• Polarization studies with Geant4
Why do we need AGATA?

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

Problems: complex spectra! Many lines lie close in energy and the "interesting" channels are typically the weak ones...
European $\gamma$-ray detection systems
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

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

Nuclei at the neutron drip line (Z→25)
- Very large proton-neutron asymmetries
- Resonant excitation modes
- Neutron Decay

Transfermium nuclei
- Exotic shapes and isomers
- Coexistence and transitions

Shape coexistence

Nuclear shapes
Why do we need AGATA?

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

Harsh conditions! Need instrumentation with:

- High efficiency
- High sensitivity
- High throughput
- Ancillary detectors

Conventional arrays will not suffice!
From conventional Ge to $\gamma$-ray tracking

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

### Ge Sphere
- $\varepsilon_{ph} \sim 50\%$
- $N_{det} \sim 1000$

### Ge Tracking Array
- $\varepsilon_{ph} \sim 50\%$
- $N_{det} \sim 100$
- $\Omega \sim 80\%$

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!

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.

AGATA and GRETA
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
Ingredients of Gamma Tracking

1. Highly segmented HPGe detectors
2. Digital electronics to record and process segment signals
3. Identified interaction points \((x, y, z, E, t)_i\)
4. Reconstruction of tracks evaluating permutations of interaction points

Pulse Shape Analysis to decompose recorded waves

Reconstructed gamma-rays
Benefits of the $\gamma$-ray tracking

- Definition of the photon direction
- Doppler correction capability
- Detector
- Segment
- Pulse shape analysis + tracking $\gamma$

scarce

good

$v/c = 20\%$
Why Monte Carlo Simulations?

- Careful optimization of the geometry of the array
- Evaluation of the expected performance of the array in a consistent way
- Production of controlled datasets to develop and train the required algorithms
The Monte Carlo code for AGATA

- Based on Geant4 C++ classes
- Event generation suited for in-beam experiments
- Gamma-ray tracking is not included directly in the code (complicated process in itself!)
- “Raw” data produced by the Geant4 program are processed with a tracking code (in this work, mgt) and analyzed with other programs
**Class structure of the program**

- **Agata**
  - **Agata RunAction**
  - **Agata EventAction**
  - **Agata PhysicsList**
  - **Agata VisManager**
  - **Agata GeneratorAction**
  - **Agata GeneratorOmega**
  - **Agata SteppingAction**
  - **Agata SteppingOmega**
  - **Agata Detector Construction**
    - **Agata Detector Ancillary**
    - **Agata Detector Array**
    - **Agata SensitiveDetector**
    - **Agata HitDetector**

- **CSpec1D**
- **CSpec2D**

- ***Agata Analysis**
- ***Agata Emitted**
- ***Agata Emitter**
- ***Agata InternalEmission**
- ***Agata ExternalEmission**

- **Camera**
  - ***Camera**
  - ***Camera**
  - ***Camera**
  - ***Camera**

- **CConvex Polyhedron**

* Possibility to change parameters via a messenger class

**Messenger classes are not shown!**
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.
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
Building a Geodesic Ball (3)
Geodesic Tiling of Sphere using 60–240 hexagons and 12 pentagons
The code: geometry

1. Candidate configurations for AGATA which have been investigated have 120 or 180 hexagonal crystals; they have been chosen because of the possibility to form clusters of detectors with few elementary shapes.

2. The solid angle coverage is maximized only using irregular hexagons; with regular hexagons the performance of the array is lower because of the spaces between the crystals.

3. Geodesic tiling polyhedra handled via a specially written C++ class (D.Bazzacco)

4. Relevant geometry parameters read from file (generated with an external program)
## GRETA vs. AGATA

<table>
<thead>
<tr>
<th>GRETA</th>
<th>AGATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge crystals size:</td>
<td>Ge crystals size:</td>
</tr>
<tr>
<td>Length 90 mm</td>
<td>Length 90 mm</td>
</tr>
<tr>
<td>Diameter 80 mm</td>
<td>Diameter 80 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GRETA</th>
<th>AGATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 hexagonal crystals</td>
<td>180 hexagonal crystals</td>
</tr>
<tr>
<td>30 quadruple-clusters</td>
<td>60 triple-clusters</td>
</tr>
<tr>
<td>Inner radius (Ge) 18.5 cm</td>
<td>Inner radius (Ge) 23.5 cm</td>
</tr>
<tr>
<td>Amount of germanium 237 kg</td>
<td>Amount of germanium 362 kg</td>
</tr>
<tr>
<td>Solid angle coverage 81 %</td>
<td>Solid angle coverage 82 %</td>
</tr>
<tr>
<td>4320 segments</td>
<td>6480 segments</td>
</tr>
<tr>
<td>Efficiency: 41% ($M_γ=1$) 25% ($M_γ=30$)</td>
<td>Efficiency: 43% ($M_γ=1$) 28% ($M_γ=30$)</td>
</tr>
<tr>
<td>Peak/Total: 57% ($M_γ=1$) 47% ($M_γ=30$)</td>
<td>Peak/Total: 58% ($M_γ=1$) 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 ancillary devices

Absolute photopeak efficiency (tracking included)

Peak-to-total ratio (response function)

Ancillary devices have an impact comparable to the case of conventional arrays (tracking is “robust”!)
The code: physics

1. Schematic built-in event generator
2. Possibility to decode “realistic” event structure and sequence from a formatted text file
3. Possibility to couple the code to generic Geant4 event generators
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>
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 €

Main issue is Doppler correction capability → coupling to beam and recoil tracking devices
AGATA Demonstrator + PRISMA

First installation site for the Demonstrator: the PRISMA spectrometer at LNL

- 195 MeV \( ^{36}\text{S} + ^{208}\text{Pb}, \theta_s = 80^\circ \)
- \( E/E \) < 2%
- \( Z/Z \) ~ 60 for \( Z=20 \)
- \( \Delta t \approx 350 \text{ ps}, \Delta X = 1 \text{ mm} \)
- \( \Delta Y = 2 \text{ mm} \)
- \( \Delta t < 500 \text{ ps} \)
- \( \Delta X = 1 \text{ mm} \)
- \( \Delta Y = 2 \text{ mm} \)
Effect of the recoil velocity

\[ ^{90}\text{Zr} \text{ recoils with } E \sim 350 \text{ MeV (with 10\% dispersion) assumed.} \]

\[ \beta \text{ from reconstructed trajectory length and TOF.} \]

\[ \text{Direction from start detector.} \]
Performance

~14 cm: Possible target-detector distance for the Demonstrator on PRISMA

1 MeV photons, point source at rest. Tracking is performed.
Effect of the recoil velocity

Typical values for reaction products at PRISMA

1 MeV photons, $M_\gamma = 1$. Tracking is performed.
AGATA vs. Conventional arrays

**AGATA 1π**

45 HPGe detectors
(15 triple clusters)

**GASP Conf. II**

40 HPGe detectors
with anti Compton
“Realistic” Simulations

$^{28}\text{Si} + ^{28}\text{Si}@125$ MeV. Particle detection with EUCLIDES. Kinematical recalibration.

E. Farnea, F. Recchia
RIISING vs. AGATA

$^{54}\text{Cr} \ "\text{coulex}\" @ 135 \text{ AMeV}$

FWHM @ 835 keV

RISING exp. 6.9
RISING sim. 8.4
AGATA full 4.9
AGATA demo 3.1
The code: physics

1. Possibility to choose set of Geant4 interactions for photons (standard treatment or low-energy treatment)
2. Compton profile optionally considered
3. Linear polarization of the photons optionally considered

Starting considerations: in principle, linear polarization of photons is included into the Geant4 standard libraries. A non-standard approach is used, defining a “polarization vector” specifying the direction of the electric field vector. Does this produce the correct results?
Unpolarized Compton scattering

The angular distribution of the scattered photon is a function of the photon energy and of the scattering angle:

\[
W(E_0, \theta) = \frac{r_0^2}{2} \left( \frac{E_1}{E_0} \right)^2 \left[ \frac{E_1}{E_0} + \frac{E_0}{E_1} - \sin^2 \theta \right] \rightarrow W(\theta) = \frac{\alpha^2}{2} \left( \gamma - \sin^2 \theta \right)
\]

\[
E_1 = \frac{E_0}{1 + \frac{E_0}{m_0c^2} (1 - \cos \theta)}
\]
Polarized Compton scattering

In this case the angular distribution depends also on the direction of the polarization (in the pictures the direction $e_0$ is along the $x$ axis). In case of a fully polarized photon beam:

$$W(\theta, \varphi) = \frac{r_0^2}{2} \left( \frac{E_1}{E_0} \right)^2 \left[ \frac{E_1}{E_0} + \frac{E_1}{E_0} - 2 \sin^2 \theta \cos^2 \varphi \right] = \frac{\alpha^2}{2} \left( \gamma - 2 \sin^2 \theta \cos^2 \varphi \right)$$

$$\sin \theta \cos \varphi = \cos \delta = \vec{e}_0 \cdot \vec{d}_1$$
A convenient formalism to treat polarization (linear and circular) is that of the Stokes parameters and of the scattering matrix developed by Fano et al.

Order zero approximation: define polarization through the Stokes parameters and convert internally to the native Geant4 formalism. Check with simple ideal cases that the results are consistent with theory.
Our test bench was an "ideal" 8-elements polarimeter (plus a central scatterer and an additional external scatterer to study double scattering).

The "red" detector lies in the scattering plane.
Asymmetry

- The asymmetry ratio is used to benchmark symmetric polarimeters:

\[ A(\theta, \varphi) = \frac{W(\theta, \varphi) - W(\theta, \varphi + 90)}{W(\theta, \varphi) + W(\theta, \varphi + 90)} \]

- Using a beam of known polarization one can determine the polarization sensitivity:

\[ Q = \frac{A}{A_{th}} \begin{cases} A_{th}(90,90) = \frac{1}{\gamma - 1} & \text{for fully polarized beams} \end{cases} \]

- The experimental asymmetry (to be compared to the theoretical value) should be corrected by the polarization sensitivity:

\[ A_{exp} = \frac{A}{Q} \]
Non-symmetrical polarimeter, or polarization non-orthogonal to the scattering plane

Data are fitted with the following expression:

\[ I(\varphi) = I_0 \left( \gamma - \sin^2 \theta \left( 1 + P \cos 2(\varphi - \psi) \right) \right) \]

From \( P \) and \( \psi \) the maximum asymmetry is found, \( A_{\text{max}} = A(\theta, \psi) \), which should be compared to the theoretical value:

\[ A_{\text{max}}(\theta, P) = \frac{P \sin^2 \theta}{\gamma - \sin^2 \theta} \]

\[ E_0 = 450.6 \text{ keV} \]
\[ \theta = 90^\circ \]
\[ \chi^2 = 1.13 \]
\[ I_0 = 504.8(3) \]
\[ P = 0.76(1) \]
\[ \psi = -64.4^\circ(4) \]
\[ A_{\text{max}} = 0.54(2) \]
Check with G4LowEnergy interaction

511 keV at 90° \((E_1 = 255.5\text{ keV})\)

<table>
<thead>
<tr>
<th>Stokes Angle</th>
<th>[1 1 0] Cal. 255</th>
<th>[1 0 0] (90,90)</th>
<th>[1 1 0] (90,90)</th>
<th>[1 1 0] (90,30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>559640</td>
<td>413</td>
<td>739</td>
<td>297</td>
</tr>
<tr>
<td>45</td>
<td>348833</td>
<td>355</td>
<td>581</td>
<td>251</td>
</tr>
<tr>
<td>90</td>
<td>138782</td>
<td>316</td>
<td>444</td>
<td>239</td>
</tr>
<tr>
<td>135</td>
<td>348493</td>
<td>358</td>
<td>566</td>
<td>281</td>
</tr>
<tr>
<td>180</td>
<td>560222</td>
<td>412</td>
<td>744</td>
<td>328</td>
</tr>
<tr>
<td>225</td>
<td>348954</td>
<td>333</td>
<td>588</td>
<td>249</td>
</tr>
<tr>
<td>270</td>
<td>139925</td>
<td>311</td>
<td>454</td>
<td>227</td>
</tr>
<tr>
<td>315</td>
<td>348392</td>
<td>349</td>
<td>562</td>
<td>267</td>
</tr>
</tbody>
</table>

\[A_{exp} = \frac{1}{Q} \frac{I_{max} - I_{min}}{I_{max} + I_{min}}\]

\[Q = \frac{A_{exp}}{A_{th}} = 0.702(1)\]

- \[\psi_{exp} (\text{deg}) = 0, 90, 90, 81(4)\]
- \[A_{exp} = \frac{A_{exp}}{Q} = 0.19(4), 0.35(3), 0.22(4)\]
- \[\psi_{th} (\text{deg}) = 0, 90, 90\]
- \[A_{th} = 0.8571, 0.5714, 0.6857, 0.4296\]

Given the symmetry, opposite detectors can be summed. Individual analysis can put in evidence anomalies.

\(\psi = \text{angle where the minimum of the angular distribution lies}\)

\[A = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}\]
Problems with G4 interactions

- Careful inspection of the code show that the low energy interaction sets provided with the Geant4 package treats polarization in a conceptually wrong way, resulting in a factor 2 attenuation of the anisotropy.
- The “standard” interaction set treats polarization properly from the conceptual point of view, but the implementation fails.
- Both of them were rewritten in a more satisfactory way (D. Bazzacco).
General comparison

[Diagram showing bar charts comparing different materials and orientations for various standards and new standards.]
The performance of AGATA (and GRETA) under a wide range of conditions has been evaluated in a realistic way using a specially written, Geant4-based C++ code.

The treatment of linear polarization provided by Geant4 has been revised in order to obtain results compatible with the theoretical expectations.