• Next “big” European $4\pi \gamma$-array for NS studies at
  – Radioactive beam facilities: GSI, GANIL, SPES, … EURISOL
  – High intensity stable beam facilities: LNL, Jyväskylä, ...
• Based on years of worldwide R&D on $\gamma$-ray tracking
• Collaboration of 10 EU countries
  – Funded by national agencies and by EU
• Constructed in phases
  – Demonstrator 2003 · · · 2007
  – Phases of Full Array · · ·
The AGATA Collaboration

- **Bulgaria:** Univ. Sofia
- **Denmark:** NBI Copenhagen
- **Finland:** Univ. Jyväskylä
- **France:** GANIL Caen, IPN Lyon, CSNSM Orsay, IPN Orsay, CEA-DSM-DAPNIA Saclay, IReS Strasbourg
- **Germany:** HMI Berlin, Univ. Bonn, GSI Darmstadt, TU Darmstadt, FZ Jülich, Univ. Köln, LMU München, TU München
- **Italy:** INFN/Univ. Padova, Milano, LNL, Firenze, Camerino, Napoli, Genova
- **Poland:** NINP & IFJ Krakow, SINS Swierk, HIL & IEP Warsaw
- **Romania:** NIPNE & PU Bucharest
- **Sweden:** Univ. Lund, KTU Stockholm, Univ. Uppsala
- **UK:** CLRC Daresbury, Univ. Brighton, Keele, Liverpool, Manchester, Paisley, Surrey, York
AGATA Organisation

Steering Committee  ASC
Chair: Marcello Pignanelli, Milan
14 representatives of 10 EU countries

Management Board  AMB
PM: John Simpson, Daresbury
7 Working Groups

Detector Module  J.Eberth
Local Level Processing  R.Krücken
Conceptual Design and Global Level Processing  D.Bazzacco
Design and Infrastructure  G.Duchêne
Ancillary Detectors and their Integration  A.Gadea
Data Analysis  J.Nyberg
EU Contact  W.Korten

~20 Working Teams
R&D on $\gamma$-ray tracking

- MC simulations
  - EGS4, MCNP, GEANT3 $\rightarrow$ GEANT4
- gamma-ray tracking algorithms
  - Clusterization*, Backtracking,
  - Forward Fuzzy Tracking, Probabilistic Tracking, …
- Pulse Shape Analysis
- Segmented Ge detectors
- Electronics ( $\rightarrow$ in Electronics-III )

*For consistency, all quoted figures are from the Clusterization algorithm
The “Standard” Germanium Shell

Idealized configuration to determine maximum attainable performance

$$R_i = 15 \text{ cm}$$
$$R_o = 24 \text{ cm}$$
$$230 \text{ kg of } Ge$$

$$E_\gamma = 1.33 \text{ MeV}$$
$$M_\gamma = 30$$

$$\varepsilon_{ph} = 65\%$$
$$P/T = 85\%$$

$$M_\gamma = 30 \rightarrow \varepsilon_{ph} = 36\%$$
$$P/T = 60\%$$

Assuming 5 mm Position Resolution

A high multiplicity event

27 gammas detected -- 23 in photopeak
16 reconstructed -- 14 in photopeak
Efficiency of Standard Ge Shell vs. Position Resolution and $\gamma$ Multiplicity

The biggest losses are due to multiplicity (mixing of points), not to bad position resolution. Improve tracking algorithms!!

$E_\gamma = 1.33$ MeV
Packing = Smearing

Shell with $\sim 6000$ segments

Position resolution (mm)
5 mm

Peak Efficiency (%) vs. Position resolution (mm)

- $M = 2$
- $M = 5$
- $M = 10$
- $M = 20$
- $M = 30$

Efficiency (%) vs. Multiplicity

- Position resolution 5 mm
- Packing in segment
- Centering in segment
Segmented Ge detectors & PSA

• Medium-fold segmentation
  – VEGA ➟ 4-fold clover, large crystals
  – EXOGAM ➟ 4-fold clovers
  – MINIBALL ➟ 6-fold and 12-fold, hexaconical encapsulated
  – Liverpool ➟ 6 x 2 -fold, cylindrical, inner segmentation

• High-fold segmentation
  – MARS ➟ 25 fold cylindrical
  – TIGRE ➟ 24 fold, 36 fold cylindrical

• Characterisation of detectors ➟ A. Boston

• Pulse Shape Analysis Algorithms
  – GA ➟ works fairly well but very slow
  – ANN ➟ fast but rather impossible to train for complete detector
  – Wavelets based Pattern Recognition ➟ being developed for realistic crystals
MARS 25-fold segmented prototype

Length: 90 mm
Diameter: 72 mm
Efficiency ~ 80%
6 x 4 + 1 segments

cold FETs for all segments; warm FET for core

A “complex” event
Pulse Shape Calculations and Analysis by a Genetic Algorithm

Thorsten Kröll, LNL-TUM
In-beam test of PSA performance

Beam $^{56}\text{Fe} @ 240 \text{ MeV}$

Target: $^{208}\text{Pb}$ 3.7 mg/cm$^2$

MARS Ge detector

$\theta_{\text{MARS}}$ 135° to beam

$\Delta \theta_{\text{MARS}} \approx 22°$

PHOBOS: 15 particle detectors

$\theta_{\text{p.d.}} \sim 60°$ to beam

$\Delta \theta_{\text{p.d.}} \approx 2.6°$

$\approx 90°$ to Ge detector

Coulex of $^{56}\text{Fe}$ on $^{208}\text{Pb}$ @ 60°

$E(2^+) = 846.8 \text{ keV}$

$\sigma(0^+ \rightarrow 2^+) \approx 250 \text{ mb/sr}$

recoil velocity $\sim 0.08 \text{ c}$

Event Rate $\approx 2 \text{ Hz}$

Energy resolution of Doppler corrected spectrum reflects accuracy of interaction points position as determined by PSA.
MARS at GASP

DAQ of MARS
MC Simulation of Experiment

MARS: \( \theta = 134.6^\circ \) \( \varphi = 270.4^\circ \) \( d = 17 \) cm
PHOBOS: \( \theta = 53.1^\circ \) \( \varphi = 216.5^\circ \)
Beam: \( ^{56}\text{Fe} \) \( 240 \) MeV
Target: \( ^{208}\text{Pb} \approx 3.7 \text{ mg/cm}^2 \)
\( \rightarrow \) Average \( \beta \approx 7.4\% \)

Effects considered in the simulation:
- Opening angle of PHOBOS \( \pm 1.3^\circ \)
- Target thickness
  - \( dE/dx \) before and after scattering
  - \( \sigma_{\text{CLX}} \) as function of energy
- Beam spot \( \pm 2 \) mm

"perfect" position resolution
FWHM = 2.6 keV

interaction points with "simulated"
\( \langle d \rangle \approx 5 \) mm error
FWHM = 3.5 keV

non-corrected spectrum

"simulated" error obtained from reconstruction of simulated interactions points using a GA

Simulated resolutions have to be folded with intrinsic energy resolution of detector 2.2 keV @ 846.8 keV
Correction of Doppler Broadening
reconstruction of interaction points by a Genetic Algorithm

24 individual detectors
with $\Delta \theta \approx 9^\circ$

single detector
with $\Delta \theta \approx 22^\circ$

Doppler Corrected
using reconstructed interaction points
FWHM = 4.5 - 5 keV

corrected using the segments
FWHM = 6 - 6.5 keV

Expected final results:
perfect tracking
$\Rightarrow$ 3.4 keV
positional error<br>$<d> \approx 5$ mm
$\Rightarrow$ 4.2 keV

Tapered detectors will perform better as most of the difficult front part is cut away

Analysis by Thorsten Kröll, LNL-TUM
Only 10% of data analyzed so far
## AGATA SPECS

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Specified for</th>
<th>Target Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photo-peak efficiency ($\varepsilon_{ph}$)</td>
<td>$E_\gamma = 1$ MeV, $M_\gamma = 1$, $\beta &lt; 0.5$</td>
<td>50 %</td>
</tr>
<tr>
<td></td>
<td>$E_\gamma = 1$ MeV, $M_\gamma = 30$, $\beta &lt; 0.5$</td>
<td>25 %</td>
</tr>
<tr>
<td></td>
<td>$E_\gamma = 10$ MeV, $M_\gamma = 1$</td>
<td>10 %</td>
</tr>
<tr>
<td>Peak-to-total ratio (P/T)</td>
<td>$E_\gamma = 1$ MeV, $M_\gamma = 1$</td>
<td>60 - 70 %</td>
</tr>
<tr>
<td></td>
<td>$E_\gamma = 1$ MeV, $M_\gamma = 30$</td>
<td>40 - 50 %</td>
</tr>
<tr>
<td>Angular resolution ($\Delta\theta_\gamma$)</td>
<td>$\Delta E/E &lt; 1%$</td>
<td>better than 1°</td>
</tr>
<tr>
<td>Maximum event rates</td>
<td>$M_\gamma = 1$</td>
<td>3 MHz</td>
</tr>
<tr>
<td></td>
<td>$M_\gamma = 30$</td>
<td>300 kHz</td>
</tr>
<tr>
<td>Inner free space ($R_i$)</td>
<td></td>
<td>170 mm</td>
</tr>
</tbody>
</table>

**Detector requirements:**

- efficiency, energy resolution, dynamic range, angular resolution, timing, counting rate, modularity, angular coverage, inner space
Geodesic Tiling of Sphere using 60–240 hexagons and 12 pentagons
Two candidate configurations

Ge crystals size:
- length 90 mm
- diameter 80 mm

120 hexagonal crystals, 2 shapes
- 40 triple-clusters, 2 shapes
- Inner radius (Ge) 17 cm
- Amount of germanium 220 kg
- Solid angle coverage 74%
- Singles rate ~70 kHz
- 4320 segments
- Efficiency: 38% ($M_\gamma=1$), 21% ($M_\gamma=30$)
- Peak/Total: 63% ($M_\gamma=1$), 47% ($M_\gamma=30$)

180 hexagonal crystals, 3 shapes
- 60 triple-clusters, all equal
- Inner radius (Ge) 22 cm
- Amount of germanium 310 kg
- Solid angle coverage 80%
- Singles rate ~50 kHz
- 6480 segments
- Efficiency: 40% ($M_\gamma=1$), 25% ($M_\gamma=30$)
- Peak/Total: 65% ($M_\gamma=1$), 50% ($M_\gamma=30$)
## Comparison of the 2 configurations

<table>
<thead>
<tr>
<th></th>
<th>Configuration 1</th>
<th>Configuration 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of crystals</td>
<td>120</td>
<td>180</td>
</tr>
<tr>
<td>Solid Angle (%)</td>
<td>74</td>
<td>80</td>
</tr>
<tr>
<td>$\varepsilon_{ph}$ / PT at $M = 1$ (%)</td>
<td>38 / 63</td>
<td>40 / 65</td>
</tr>
<tr>
<td>$\varepsilon_{ph}$ / PT at $M = 1$ (%)</td>
<td>21 / 47</td>
<td>25 / 50</td>
</tr>
<tr>
<td>Inner free space (cm)</td>
<td>16</td>
<td>21*</td>
</tr>
<tr>
<td>Angular resolution</td>
<td></td>
<td>better</td>
</tr>
<tr>
<td>Counting rate (kHz)</td>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td>Number of clusters / types</td>
<td>40 / 2</td>
<td>60 / 1</td>
</tr>
<tr>
<td>Rings of clusters</td>
<td>3-7-10-10-7-3</td>
<td>5-10-15-15-10-5</td>
</tr>
<tr>
<td>Angular coverage of rings</td>
<td>irregular</td>
<td>very regular</td>
</tr>
<tr>
<td>Electronics channels</td>
<td>4440</td>
<td>6660</td>
</tr>
<tr>
<td>Cost</td>
<td>nn M €</td>
<td>30 % higher ?</td>
</tr>
</tbody>
</table>

To reduce cost of germanium, A-180 could be squeezed to similar size as A-120. Efficiency reduces also but all nice symmetries remain; smaller crystals simplify PSA.
The Phases of AGATA-180

4π Array
AGATA Detectors

Hexagonal Ge crystals
- 90-100 mm long
- 80 mm max diameter
- 36 segments
- Al encapsulation
  - 0.6 mm spacing
  - 0.8 mm thickness
- 37 vacuum feedthroughs

- 3 encapsulated crystals
- 111 preamplifiers with cold FET
- ~230 vacuum feedthroughs
- LN$_2$ dewar, 3 liter, cooling power ~6 watts

Italy&Germany ordering 3 symmetric encapsulated crystals.
Cryostat will be built by CTT in collaboration with IKP-Köln
Cluster ready by mid 2004
Dead Materials and Inner Detectors

- **Thickness of**
  - Capsule side: 0.8 mm
  - Cryostat side:
    - front: 1.5 mm
    - back: 3.0 mm
  - Inner “ball”: 10 mm

- **Efficiency (%)**

- **Legend**
  - no dead materials
  - with capsules and cryostats
  - + inner Al shell, 1 cm thick
Starting to build AGATA

The Forward Quadrant with 45 crystals in 15 triple-clusters

Graph showing efficiency and solid angle for different values of β.
The First Step: The AGATA Demonstrator
Objective of the final R&D phase 2003-2007

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 €