γ-ray tracking with AGATA

New perspectives for spectroscopy

• Introduction to AGATA
• Pulse shape analysis and γ-ray tracking
• Capabilities and opportunities

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Final Symposium of the Sino-German GDT Cooperation

Ringberg Castle 18.10. – 24.10.2015
Experimental Conditions and Challenges at future Radioactive Beam Facilities

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

Need for $\gamma$-spectrometer based on $\gamma$-ray tracking

High efficiency
High sensitivity
High throughput
Ancillary detectors
Ingredients of Gamma-Ray 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
Advanced GAmma Tracking Array

- 180 hexagonal crystals
- 60 triple-clusters
- Inner radius (Ge) 23.5 cm
- Amount of germanium 362 kg
- Solid angle coverage 82%
- 36-fold segmentation 6480 segments
- Singles rate ~50 kHz

Efficiency: 43% ($M_γ=1$) 28% ($M_γ=30$)
Peak/Total: 58% ($M_γ=1$) 49% ($M_γ=30$)

- 6660 high-resolution digital electronics channels
- needs proof of principle → demonstrator at Legnaro
Two international collaborations

**AGATA**
(Advanced-GAMMA-Tracking-Array)

- @ GANIL, AGATA+VAMOS
  ongoing first experimental campaign
  2014 → 2018

- @ GSI, AGATA+FRS, PreSpec
  2012 → 2014

- @ LNL, AGATA Demonstrator
  (+PRISMA, TRACE, DANTE, HELENA)
  2009 → 2012

**GRETA**
(Gamma-Ray Energy Tracking Array)
From the Demonstrator to AGATA $1\pi$

LNL: 2009-2011
15 crystals (5TC)
Total Eff. ~6%

GSI: 2012-2014
24 crystals (3DC+6TC)
Total Eff. ~9%

GANIL: 2014-2018
45 crystals (15 TC)
Total Eff. ~15%

Demonstrator + PRISMA
AGATA + FRS
AGATA+VAMOS

Status autumn 2015
delivered & ordered
detectors: 42 crystals
AGATA Triple Cryostat

- integration of 111 high resolution spectroscopy channels
- cold FET technology for all signals

Challenges:
- mechanical precision
- LN2 consumption
- microphonics
- noise, high frequencies

- D. Lersch et al. NIM A 640(2011) 133-138
Performance: Energy resolution

Averages of the segment resolutions @ 60 keV:
- A001: 1011 +/- 53 eV
- B002: 1039 +/- 70 eV
- C002: 965 +/- 63 eV

Averages of the segment resolutions @ 1333 keV:
- IKP / Legnaro:
  - A001: 2.19 keV / 2.00 keV
  - B002: 2.09 keV / 1.98 keV
  - C002: 2.1 keV / 1.94 keV
Energy resolution & Cross talk

Details: 1.3MeV line

Corrected

Uncorrected

<table>
<thead>
<tr>
<th>fold</th>
<th>Segsum</th>
<th>corrected</th>
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<tbody>
<tr>
<td>1</td>
<td>1.99</td>
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<td>2</td>
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<td>2.06</td>
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<td>4.07</td>
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<td>6</td>
<td>4.38</td>
<td>2.23</td>
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<td>7</td>
<td>4.69</td>
<td>2.34</td>
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</tbody>
</table>

FWHM 60keV: 1.20 → 1.02!

Digital signal processing at high count rate

“nominal” count rate of 30 kHz

core long traces

amplitudes from MWD:
risetime 5us
risetime 2.5us

time [10 ns]

Digital signal processing \(\Rightarrow\) work in conditions that would be impossible with conventional electronics
Pulse Shape Analysis concept

Result of Grid Search Algorithm

(10, 25, 46)

791 keV deposited in segment B4
Pulse shape analysis two examples

$E_\gamma = 1172$ keV  net-charge in A1

$E_\gamma = 1332$ keV  net-charge in C4, E1, E3

Tomography of interactions in the crystal: non uniformities due to PSA
Result of AGATA tracking
Reconstructed initial gamma rays with: - gamma ray energy - 1st interaction position $\rightarrow$ Doppler correction - 2nd interaction position $\rightarrow$ Polarization

1st interaction positions after PSA and Tracking

- $< 4$ mm FWHM resolution obtained
- PSA online at rates $> 15$ kHz per crystal
$^{42}\text{Ca}@170\text{MeV} + ^{208}\text{Pb}$

Kinematical coincidences

Position sensitive MCP

- Line shape without BGO
- energy resolution $\Delta E = 4.9$ KeV corresponds to $\Delta x < 4$ mm

$^{1524,7}\text{keV}$

$^2 - 0^+\text{keV}$

Uncorrected
Doppler-corrected (Ca)
Doppler-corrected (Pb)

AGATA position resolution

<table>
<thead>
<tr>
<th>$\Delta x$ FWHM</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2 mm</td>
<td>Doppler corr. meas.</td>
<td>F. Recchia et al. NIM A (2009)</td>
</tr>
<tr>
<td>4.0 mm</td>
<td>Doppler corr. meas</td>
<td>P.-A. Söderström et al. NIM A (2011)</td>
</tr>
<tr>
<td>3.5 mm</td>
<td>511keV source meas.</td>
<td>S. Klupp, M.Schlarb, R. Gernhäuser</td>
</tr>
</tbody>
</table>
Line shape higher multiplicity events

Doppler corrected $^{238}\text{U}$ γ-ray spectra

Counts per 1 keV

$^{238}\text{U}$

$6^+ \rightarrow 4^+$

$8^+ \rightarrow 6^+$

$10^+ \rightarrow 8^+$

$12^+ \rightarrow 10^+$

$14^+ \rightarrow 12^+$

$16^+ \rightarrow 14^+$

$18^+ \rightarrow 16^+$

Fission

Particle coincidence time spectrum

$\text{Counts}$

$E_\gamma [\text{keV}]$

Resolving power high multiplicity events

\[ ^{40}\text{Ar} + ^{122}\text{Sn} \rightarrow ^{158}\text{Er} \]

(24 capsules) Fold5  GANIL-June 2015

A. Korichi, C. Michelagnoli, E. Clement
Line shape high $\gamma$-ray energy

Escape lines are identified and discriminated by $\gamma$-ray tracking

First interaction points yield angular distributions:
- E1 transition from the $1^{-}$ state at 5.512 MeV
- E2 transition from the $2^{+}$ state at 6.194 MeV

Position resolution & Doppler effects

Doppler correction needed for beam and target like nuclei

Example: $^{136}\text{Xe}: 2^+ \rightarrow 0^+$ 1313 keV

No Doppler correction

Doppler correction for beam like Xe
Lifetime of the 6.792 MeV state in $^{15}\text{O}$

$^{14}\text{N}(^{2}\text{H},n)^{15}\text{O}$ and $^{14}\text{N}(^{2}\text{H},p)^{15}\text{N}$ reactions, inverse kinematics

$^{17}\text{O}$

$^{16}\text{O}$

$^{15}\text{O}$

$^{15}\text{N}$

$^{14}\text{N}(^{2}\text{H},n)$

$^{14}\text{N}(^{2}\text{H},p)$

$^{15}\text{N}$

Source

AGATA DSAM line shape

nucleon-transfer

fusion-evaporation
Lifetime of the 6.79 MeV state in $^{15}\text{O}$

$^{14}\text{N}^{(2\text{H},n)^{15}\text{O}}$ and $^{14}\text{N}^{(2\text{H},p)^{15}\text{N}}$ reactions

inverse kinematics

Continuous DSAM lifetime measurement

New upper limit of $< 0.5$ fs on the lifetime of the 6.79 MeV state in $^{15}\text{O}$

Lower limit of the width of the state

$\Gamma > 1.07$ eV

C. Michelagnoli et al., Phys. Rev. Lett. accepted
PreSPEC-AGATA Setup @ GSI

**FRS**
- Particle selection: $B_p$-$\Delta E$-$B_p$
- Particle identification: TPC tracking detectors
  - ToF measurement
  - Energy-loss measurement

**AGATA**
- Triple & double cluster pulse shape analysis and $\gamma$-ray tracking

**HECTOR+**
- BaF&LaBr scintillators

**LYCCA**
- Outgoing particle tracking and identification: $Z$ identification via $E$-$\Delta E$
  - Mass identification via $E$-ToF

C. Domingo-Pardo et al., NIM A 694 297-312 (2012)
Reminder: Doppler effect

\[ E_{\text{laboratory}} = E_{\text{rest}} \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos(\theta_{\text{lab}})} \]

**80Kr**

\[ ^{2+}_{1} \] 616.6 keV

\[ ^{0+}_{1} \] 550 mb

- large Coulex cross section
- no decay inside the target
Location of Gamma Emission

Michael Reese, TU Darmstadt
Partially-polarized 555.8-keV and 433.9-keV lines in $^{104}\text{Pd}$ and $^{108}\text{Pd}$ after Coulomb excitation.

Analyzing power for $\gamma$-ray linear polarization

Analyzing power: $A = 0.48$

Summary

• Status AGATA:
  ✓ highly segmented HPGe detectors
  ✓ digitizer & front-end electronics
  ✓ pulse shape analysis & γ-ray tracking
  ✓ position sensitive γ-ray detection: Δx~3-4 mm

• Improved conditions for in-beam γ-ray spectroscopy
  - energy resolution (reduced Doppler effects)
  - detection efficiency at higher energies
  - line shape (escape line suppression)
  - angular distributions from 1st interaction point
  - polarization sensitivity from 2nd interaction point
  - lifetime measurements
  - back ground suppression
Acknowledgements