Characterization of \( \gamma \)-ray tracking arrays: performance of the first phase of AGATA and GRETA using \(^{60}\text{Co}\) source

Introduction

Performance of Tracking arrays

AGATA and GRETINA comparison

Conclusion
Event by event
Number of $\gamma$ rays,
For each $\gamma$ ray:
1$^{st}$ and 2$^{nd}$ interaction points, path

For the best performances:
Energy resolution, absolute photo-peak efficiency, peak-to-total ratio
Energy Resolution of AGATA & GRETINA

$^{12}C(^{84}Kr[394 MeV], 4n)^{92}Mo$

Doppler Broadening:
Towards intrinsic resolution!

V/C 10% → FWHM 0.4%

Best and Beautiful arrays for
Fast beams
Efficiency and P/T of tracking arrays

Observed areas for $^{60}\text{Co}$ source

$$A_{obs}^{1173} = S \epsilon_p(1173)(1 - C_k(1333)) \times (1 - C_R)(1 - C_s(1173)),$$

$$A_{obs}^{1333} = S \epsilon_p(1333)(1 - C_k(1173)) \times (1 - C_R)(1 - C_s(1333)),$$

$$A_{obs}^{2506} = \frac{1}{N} S \epsilon_p(1173)\epsilon_p(1333)C_f(1 - C_R) \times (1 - C_s(1173))(1 - C_s(1333)),$$

$C_f$ is the angular correlation factor

Correct for the fact that the 1173 can knock out counts in the 1333 line and vice versa.

CR is the correction for random $\gamma$ rays hitting the detector

$$C_R = \frac{\epsilon_R \Delta t}{N} \frac{dR}{dt},$$

$$S = A_{st}L_F.$$

$S$ is the Number of $\gamma$ rays emitted

LF is the Life Fraction (dead time or other loss)

$$C_s = \frac{F - 1}{F}$$

The probability for a $\gamma$ ray to scatter out of a crystal, to be detected by other crystals in the array and successfully sum up to the photo-peak.

$$\frac{P}{T} \equiv \frac{\epsilon_p}{\epsilon_T},$$

$$C_k(e) = \frac{C_f \epsilon_T(e)(1 + C_s(e))}{N},$$
Summed Peak Method: SPM
\[ \frac{A_{obs}(2506)}{A_{obs}(1173)} \]
\[
\varepsilon_p(1333) = N \left\{ \frac{A_{obs}(2506)}{A_{obs}(1173)C_f} \right\} / \left\{ 1 - C_s(1333) + \frac{A_{obs}(2506)}{A_{obs}(1173)} \frac{1 + C_s(1173))}{N(P/T)(1333)} \right\} 
\]

Calibrated Source Method: CSM
[S and \( L_f \) must be known]
\[
\varepsilon_p(1333) = \frac{A_{obs}(1333)}{S(1 - C_R)(1 - C_s(1333))} + \frac{(1 + C_s(1173))A_{obs}(2506)}{NS(P/T)(1173)(1 - C_R)(1 - C_s(1173))(1 - C_s(1333))} 
\]

External Trigger Method
\[
A_{obs}(1333) = A_{ext}(1173) \times \varepsilon_p(1333)C_f(1 - C_R) 
\]

With CCcal and CCsum: six measurements of the array efficiency
We saw how the observed peak areas relate to the actual array efficiencies.

Once the peak areas have been correctly determined, efficiencies, true peak areas and peak–to–total ratios can be extracted.

\[
A_{true}^{true}(1173) \equiv S \epsilon_p(1173) \\
A_{true}(1333) \equiv S \epsilon_p(1333) \\
A_{true}(2506) \equiv S \epsilon_p(1173) \epsilon_p(1333) C_f \\
A_{true}^{true}(1173) \equiv \frac{A_{obs}(1173)}{(1 - C_k(1333))(1 - C_R)(1 - C_s(1173))}, \\
A_{true}(1333) \equiv \frac{A_{obs}(1333)}{(1 - C_k(1173))(1 - C_R)(1 - C_s(1333))}, \\
A_{true}(2506) \equiv \frac{A_{obs}(2506)}{(1 - C_R)(1 - C_s(1173))(1 - C_s(1333))}.
\]

\[
(P/T)_{true} = \frac{A_{true}(1173) + A_{true}(1333) + A_{true}(2506)}{A_{tot}}.
\]

\[
A_{obs} = (1 + C_s) A_{true}
\]

\[
(P/T)_{tracked} = \frac{A_T(1173) + A_T(1333)}{A_{tot}},
\]

\[
\epsilon_{track} = \frac{A_T(1333)}{S \epsilon_p(1333)} \\
\epsilon_{track} = \frac{A_T(1333)}{A_{obs}(1333) \frac{(1-C_k(1173))(1-C_R)(1-C_s)}{}} \equiv \frac{A_T(1333)}{A_{true}(1333)}
\]

Include for CCcal and CCsum but not for tracked spectra.
More details can be found in:

Characterization of gamma–ray tracking arrays: a comparison of GRETINA and Gammasphere using a $^{60}$Co source

T. Lauritsen$^a$, A. Korichi$^b$, S. Zhu$^a$, A.N. Wilson$^c$, D. Weisshaar$^d$, J. Dudouet$^e$, A.D. Ayangeakaa$^a$, M.P. Carpenter$^a$, C.M. Campbell$^f$, E. Clement$^b$, H.L. Crawford$^f$, M. Cromaz$^f$, P. Fallon$^f$, J.P. Greene$^a$, R.V.F. Janssens$^a$, T.L. Khoo$^a$, N. Lalović$^{k,i}$, I.Y. Lee$^f$, A.O Macchiavelli$^f$, R.M. Perez-Vidal$^g$, S. Pietri$^i$, D.C. Radford$^i$, D. Raitel$^b$, L. Riley$^d$, D. Seweryniak$^a$, O. Stezowski$^e$


This method has been applied to AGATA

AGATA data translated into GRETINA format

All Data could be sorted with the same software and same tracking code for the comparison of AGATA and GRETINA
Performance of AGATA@GSI with $^{60}$Co source

A. Korichi to be published
**FOM spectrum**, a measure of how well the interaction angles and interaction energies follow the Compton scattering formula inside a gamma ray. Typical spectrum of FOM values (in log):

\[
E'_\gamma = \frac{0.511}{1 + \frac{0.511}{E_\gamma} \cdot \cos(\theta)}
\]

\[
FOM = \sum_i \frac{\sqrt{\left(\theta_i^{theo} - \theta_i^{obs}\right)^2}}{n_i - 1}; n_i > 1
\]

- Single hits, FOM==0
- Single interaction located beyond their range
- Overflow

**Typical FOM cut**

'**mostly good guys**'

'**mostly bad guys**'

<table>
<thead>
<tr>
<th>fm</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6277593</td>
<td>0.5427</td>
<td>0.6638</td>
</tr>
</tbody>
</table>
Performance of AGATA@GANIL with $^{60}$Co source

<table>
<thead>
<tr>
<th></th>
<th>SPM cal source1</th>
<th>CSM cal source2</th>
<th>SPM sum source1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_p(\text{pure})$</td>
<td>4.26(12)%</td>
<td>4.48(13)%</td>
<td>4.00(16)%</td>
</tr>
<tr>
<td>($P/T$)$_{obs}$</td>
<td>0.328(5)</td>
<td>0.224(5)</td>
<td>0.184(5)</td>
</tr>
<tr>
<td>($P/T$)$_{true}$</td>
<td>0.371(5)</td>
<td>0.270(5)</td>
<td>0.363(5)</td>
</tr>
<tr>
<td>$\epsilon_{\text{track,nsi}}$</td>
<td>82(1)%</td>
<td>81(1)%</td>
<td>82(1)%</td>
</tr>
<tr>
<td>$\epsilon_{\text{track,hsi}}$</td>
<td>95(1)%</td>
<td>94(1)%</td>
<td>95(1)%</td>
</tr>
<tr>
<td>$C_f$</td>
<td>1.0275</td>
<td>1.0275</td>
<td>1.109</td>
</tr>
<tr>
<td>$C_s$</td>
<td>0</td>
<td>0</td>
<td>0.307(5)</td>
</tr>
</tbody>
</table>

Abs$\_Eff$$_{tracked}$=3.80% $P/T$=41% FOM cut=1.0  
Abs$\_eff$$_{tracked}$=3.25% $P/T$= 49  no_singles  
(29 crystals )

A Better $P/T$ compared to GSI
But the array Is more compact :  
72% versus 68%

But also more passive material :  
3 crystals not active at GSI

Cluster angle = 20 degrees

A Better $P/T$ compared to GSI
But the array Is more compact :
72% versus 68%

But also more passive material :
3 crystals not active at GSI
Comparison AGATA@GANIL and GRETINA@ANL

Cluster angle = 20 degrees

AGATA and GRETINA

28 crystals positioned at 23.5 cm

\[ 4.25\% = \left(\frac{18.5+3.5}{23.5+3.5}\right)^2 \times 6.4\% \]

28 crystals positioned at 18.5 cm

4\pi\text{ array scaling using GEANT4 simulations with 10\% uncertainty}

AGATA 180 crystals yields : 37(4)\%

GRETA 120 crystals : 34(4)\%

As expected!
Comparing the spectra: P/T

FOM cut: 0.8 for AG and 0.64 for GT
70% of gamma-rays in both arrays

PSA/Decomposition:

- GRETINA: more than one interaction/segment
- AGATA: only one interaction/segment

TBD: process the AGATA (or GRETINA) data through the same Decomposition PSA to conclude
Tracking codes comparison

OFT- AGATA tracking code

ANL- GRETINA tracking code

They are doing a very good job!!!

Tracking performance can even be improved by other means

Linear Polarization : fantastic


Partha Chowdhury contribution
For single hits: We can improve the tracking by other means:

Looks like a low energy 'single interaction'

Reject

Single hits fom=0

Single interaction over range

Absorption Probability

\[ p(z) = 1 - e^{-(\mu/\rho)z} \]
Comparing the P/T:

**Compactness:** number of crystal sides that have close neighbors to total number of crystal sides.

AGATA@GSI

GANIL

The packing of the array matters!

More compact
More crystals
Yields a better PT

GRETINA@ANL

MSU compact

Best setup compactness of 71% and yields a better P/T
Conclusion

Doppler correction capabilities: beautiful for fast beams
Specification met
AG & GT similar

Tracking efficiency:
Specification met
AG & GT similar

Some issues still remain

But ...

Combine our efforts
To make it!
This work has been performed ANL – CSNSM collaboration

And the AGATA-GRETINA collaboration

Thank you!
First AGATA-GRETINA tracking arrays collaboration meeting
December 5-7, 2016

First Circular

We are pleased to announce the first AGATA-GRETINA collaboration meeting to be held at ANL on 5-7 of December 2016.

The workshop will be devoted to discussions about common challenges related to tracking arrays, including the physics, technical details and analysis of data from these arrays. We intend to organize these workshops on a yearly or bi-yearly basis, alternating between meeting places in the US and EU.

We are hoping these workshops will foster collaborations between the AGATA and GRETINA communities and help define and accomplish our common challenges.

Organizing and Advisory committee:

B. Birkenbach, IKP-Koeln, Germany.
A. Boston, Liverpool University, UK.
M.P. Carpenter, ANL, USA.
A. Gadea, IFIC-Valencia, Spain.
A. Korichi (co-chair) CSNSM-CNRS, France.
T. Laurissen (co-chair) ANL, USA.
A.O. Macchiaveli, LBNL, USA.
D. Radford, ORNL, USA.
O. Stezowski, IPNL-CNRS, France.
D. Weisshaar, NSCL, USA.
Extra slides
For single hits: We can improve the tracking by other means:

Looks like a low energy 'single interaction'

Single hits fom=0

Single interaction over range

Absorption Probability

\[ p(z) = 1 - e^{-\left(\frac{\mu}{\rho}\right)pz} \]
Tracking efficiency and P/T for GRETINA

\[ \epsilon_{\text{track}} = \frac{A_T(1333)}{A_{\text{obs}}(1333) (1-C_k(1173))(1-C_R)(1-C_s)} \equiv \frac{A_T(1333)}{A_{\text{true}}(1333)} \]

\[ (P/T)_{\text{tracked}} = \frac{A_T(1173) + A_T(1333)}{A_{\text{tot}}} \]

Analysis of data from GRETINA at ANL:

Compactness was 63%. Best setup had compactness of 71% and yielded a better P/T

<table>
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<th>SPM sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \epsilon_p(\text{mixed}) )</td>
<td>6.11(9)%</td>
<td>6.05(9)%</td>
<td>-</td>
</tr>
<tr>
<td>( \epsilon_p(\text{pure}) )</td>
<td>6.42(6)%</td>
<td>6.0(6)%</td>
<td>6.5(6)%</td>
</tr>
<tr>
<td>( (P/T)_{\text{obs}} )</td>
<td>0.321(5)</td>
<td>0.321(5)</td>
<td>0.192(5)</td>
</tr>
<tr>
<td>( (P/T)_{\text{true}} )</td>
<td>0.385(5)</td>
<td>0.381(5)</td>
<td>0.363(11)</td>
</tr>
<tr>
<td>( \epsilon_{\text{track,nsi}} )</td>
<td>92(1)%</td>
<td>93(1)%</td>
<td>92(1)%</td>
</tr>
<tr>
<td>( \epsilon_{\text{track,nsi}} )</td>
<td>93(1)%</td>
<td>94(1)%</td>
<td>93(1)%</td>
</tr>
<tr>
<td>( C_s )</td>
<td>0</td>
<td>0</td>
<td>0.293(5)</td>
</tr>
</tbody>
</table>

Weighted mean: 6.27(4)% for 28 crystals (included external/internal measurements too)
Regarding the P/T: GEANT4 says we should be doing better than we are.

Simulation needs to be improved too.
Quasi-online data analysis

Buffer size not adapted to the counting rates and actors spectra enabled

Buffer size adapted to the counting rates and actors spectra enabled

Buffer size not adapted to the counting rates and actors spectra disabled

Jérémie Dudouet: dudouet@ipnl.in2p3.fr

AGATA collaboration meeting 2015: 6-7 July 2015
Tracking 101: determining the interaction sequence and how 'good' a gamma ray is

Cluster, find interaction sequence
Evaluate scattering angle
<-- energy consistency with the Compton scattering formula:

\[ E'_\gamma = \frac{0.511}{1 + \frac{0.511}{E_\gamma} - \cos(\theta)} \]

\[ FOM = \sum \sqrt{\left(\frac{\theta_i^{\text{theo}} - \theta_i^{\text{obs}}}{n_i - 1}\right)^2}; n_i > 1 \]

FOM < ~0.6-0.8 considered GOOD
FOM > ~0.8 considered BAD (Compton events)

Note: Single interactions cannot be tracked
OFT- tracking code

ANL- tracking code fom cut=0.6

Tracking codes are doing the job

jeremie_nsi.spe ;P/T= 0.468 ;p1/p2/sum= 1146917/ 1084651/ 4764551 :: photoeff = 0.045 ;
totaleff = 0.095 ; p2eff = 0.043 ; *= 0.9791

fom_nsi06.spe ;P/T= 0.488 ;p1/p2/sum= 1247299/ 1184123/ 4984402 :: photoeff = 0.049 ;
totaleff = 0.100 ; p2eff = 0.047 ; *= 1.1571

fom_nsi08.spe ;P/T= 0.462 ;p1/p2/sum= 1353925/ 1289846/ 5722022 :: photoeff = 0.053 ;
totaleff = 0.114 ; p2eff = 0.052 ; *= 1.1288
It Helps!

$^{122}\text{Sn}(^{40}\text{Ar}[170\text{MeV}],4n)^{158}\text{Er}$

June 5-6, 2015-

$P/T = 0.27$  $P/T = 0.34$