Nuclear Structure studies using Advanced-GAMMA-Tracking techniques

Caterina Michelagnoli

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World-wide projects for $\gamma$-ray spectroscopy

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

Use highly segmented Ge detectors + digital electronics to reconstruct the path of $\gamma$ rays in the detector medium

**GRETA**
(Gamma-Ray Energy Tracking Array)
World-wide projects for $\gamma$-ray spectroscopy

Use highly segmented Ge detectors + digital electronics to reconstruct the path of $\gamma$ rays in the detector medium

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

**GRETA** (Gamma-Ray Energy Tracking Array)

- **Grand Accelerateur National d’Ions Lourdes (GANIL)**, France (2014 – at present)
- **GSI**, Germany (2012-2014) @ fragment separator
- **Legnaro National Lab.** (2009-2012) **Demonstrator phase**
PART 1 (September 28\textsuperscript{th} 2015)

General Introduction: Physics Motivation
1. Nuclear structure and $\gamma$-ray spectroscopy
2. Structure of neutron-rich fission fragments

$\gamma$-ray tracking: Motivation and Concept
1. In-beam $\gamma$-ray detection: requirements
2. From conventional germanium detector arrays to $\gamma$-ray tracking
3. $\gamma$-ray tracking (”philosophy”, approximations, open questions)

Pulse Shape Analysis (PSA)
1. Principle
2. Position resolution and Compton imaging

(be aware ... personal selection of topics!)
Outline

PART 2 (September 29th 2015)

Pulse Shape Analysis (PSA)
1. Signal bases calculation
2. Signal decomposition

Some results from Ge position sensitive mode operation and γ-ray tracking

The AGATA array of segmented HPGe detectors
1. Implementation of Pulse Shape Analysis and Tracking concepts
2. The AGATA detectors and preamplifiers
3. The structure of electronics and data acquisition
4. Digital signal processing (at high counting rate)
5. (AGATA data processing)

AGATA+VAMOS (magnetic spectrometer) at GANIL

(be aware ... personal ⊔ selection of topics!)
The Atomic Nucleus

Z

N

number of protons, Z

number of neutrons, N

The Nuclear Shell Model

The Nuclear Shell Model

Maria Goeppert Mayer
1906 - 1972
PR75, 1969 (1949)

J. Hans D. Jensen
(1907 – 1973)
PR75, 1766 (1949)

NOBEL PRIZE 1963

PR75, 1766 (1949)
Nuclear Excitations

Shell Model

Cooper Pairs

Collective Excitations

Need to tune model parameters collecting nuclear experimental information
Nuclear Excitations

Shell Model

Cooper Pairs

Collective Excitations

Test of nucleon-nucleon interaction
by comparing the experimental results to model prediction

Need to tune model parameters collecting nuclear experimental information

What is the effective nucleon-nucleon interaction?
What are the limits of existence for bound nuclei (driplines)?
The Structure of the Nucleus

Observables:

- energy levels ($E_i$)
- spin ($J_i$)
- parity ($\pi_i$)
- lifetime (transition probabilities) ($\tau_i$)
- nuclear moments (g-factors)

- systematics (e.g. shape transitions)
- benchmarks for nuclear models (e.g. Nuclear Shell Model)
The Structure of the Nucleus

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Systematics (e.g. shape transitions)
Benchmarks for nuclear models (e.g. Nuclear Shell Model)

Measuring γ-ray:

- Energy
- Angular distribution
- Linear polarization
- Energy Doppler shift (for example)
- Angular distribution vs t

γ-ray spectroscopy is an approach for the study of nuclear structure.

Population in excited state(s) and observe γ-ray de-excitation radiation.

observables include:

- Energy levels
- Spin
- Parity
- Lifetime
- Nuclear moments

γ-ray spectroscopy is a method for studying nuclear structure.
Level schemes vs Energy spectra

What we want ...

${}^{152}\text{Dy}$
Level schemes vs Energy spectra

What we want ...

152\text{Dy}

What we get ...

Analysis of complex spectra with many lines close in energy
Nuclear deformation in the A~100 region

γ-ray spectroscopy of neutron-rich isotopically-identified fission fragments

\[ ^{238}\text{U} + ^{9}\text{Be} \]

**Collision**

\[ M_P, V_P \rightarrow M_T \]

**Fusion**

\[ M_{CN} = M_P + M_T \]

\[ V_{CN} = \frac{M_P V_P}{(M_{CN})} \]

**Fission in motion**

\[ M_1, V_1, \Theta_1 \]

\[ M_2, V_2, \Theta_2 \]

Gamma ray detector + mass spectrometer
Intense $^{238}\text{U}$ beam to induce fission in inverse kinematics.
$^{238}\text{U}$ beam (@ 6.2 MeV/A) on $^9\text{Be}$ target

Id. of the element

Id. of the isotope

Isotopic identification event-by-event in the magnetic spectrometer


Courtesy of M. Rejmund
Collectivity in neutron-rich Zr nuclei

A. Navin et al.,
Collectivity in neutron-rich Zr nuclei

How we can do better?
- Low energy gamma rays
- Resolution (EXOGAM: 8 keV at 1.2 MeV)
- Gamma linear polarization measurements
- ...

**A. Navin et al.,**
In-beam $\gamma$-ray spectroscopy: requirements

**Energy resolution** ($E_\gamma \sim 10$ keV - 10 MeV), in order to disentangle complex spectra
  $\rightarrow$ germanium detectors

**Peak to Total ratio** (large continuous Compton background), in order to maximize “good events”
  $\rightarrow$ Compton background suppression
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**Doppler correction capability,** energy resolution dominated by Doppler broadening if the velocity vector and the emission angle of the $\gamma$-ray are not well known ($\beta \sim 5\text{-}10\%$, up to 50%)

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**Good solid angle coverage** (ideally $4\pi$), in order to maximize efficiency

**Good granularity,** in order to reduce multiple hits on the detectors for high $\gamma$-ray multiplicity events

**Avoid dead materials** that could absorb radiation (→ preserve low energies)
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**Avoid dead materials** that could absorb radiation ($\rightarrow$ preserve low energies)

**High counting rate capability** (frequently background much stronger than channel of interest)

**Time resolution** (prompt events selection, lifetimes)
Energy resolution

From **Sodium Iodide** to **Germanium detectors**

Response function = differential spectrum obtained with a detector when hit by monochromatic radiation

60’s → Use of Ge(Li) detectors marks the beginning of high-resolution in-beam $\gamma$-ray spectroscopy

70’s → Only few detectors, operated in $\gamma-\gamma$ coincidence. Development of the HP-Ge detector.

**Use of Germanium detectors = breakthrough in nuclear structure**

$^{104}$Ag and $^{106}$Ag

FWHM = 2 keV at 1.3 MeV
Doppler broadening: effective energy resolution

\[ E_{\gamma}^{\text{Lab}} (\theta) = E_{\gamma}^{\text{CM}} \frac{\sqrt{1 - \beta^2}}{1 - \beta \cdot \cos \theta} \]

\[ \beta = \frac{v}{c} \]

Source at rest → intrinsic energy resolution

Efficiency vs Resolution:

- Small \( d \) → Large \( \Omega \) → High eff → Poor FWHM
- Large \( d \) → Small \( \Omega \) → Low eff → Good FWHM

\( E_0 = 1 \text{MeV} \)

\( \beta = 0, 0.01, 0.05, 0.10 \) (fixed direction)

\( \theta = 158 \text{ deg} \)
Doppler broadening: effective energy resolution

\[
E_{\text{Lab}} = E_{\gamma} \frac{\sqrt{1 - \beta^2}}{1 - \beta \cdot \cos \theta_{\text{Lab}}}
\]

Opening

Recoil

Intrinsic
# Photon interaction with matter

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Interaction Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>~100 keV</td>
<td>Photoelectric</td>
</tr>
<tr>
<td>~1 MeV</td>
<td>Compton Scattering</td>
</tr>
<tr>
<td>~10 MeV</td>
<td>Pair Production</td>
</tr>
</tbody>
</table>

### Photoelectric

- Energy transfer from photon to electron
- Equation: 
  \[ E_{e1} = E_{\gamma} - E_b \]
- Cross section: 
  \[ \sigma \propto \frac{Z^n}{E_{\gamma}^{3.5}}, \quad n \approx 4 \div 5 \]

### Compton Scattering

- Photon散射
- Equation: 
  \[ E_{\gamma} = \frac{E_{\gamma} \gamma}{1 + \frac{E_{\gamma}}{m_0 c^2} (1 - \cos \theta)} \]
- Cross section: 
  \[ \sigma \propto Z^2 \]

### Pair Production

- Photon interacts with matter to produce electron-positron pair
- Equations: 
  \[ (E_{\gamma} > 2m_e c^2) \]
  \[ \sigma \propto Z^2 \]
Cross Sections in Germanium

Mean free path: \( \lambda(E) = \frac{M_A}{(N_{AV} \cdot \rho)} \cdot \frac{1}{\Sigma \sigma_E} \)

\( \lambda(10 \text{ keV}) \sim 55 \mu\text{m} \quad \lambda(100 \text{ keV}) \sim 0.3 \text{ cm} \quad \lambda(200 \text{ keV}) \sim 1.1 \text{ cm} \)

\( \lambda(500 \text{ keV}) \sim 2.3 \text{ cm} \quad \lambda(1 \text{ MeV}) \sim 3.3 \text{ cm} \)
Compton Scattering (1)

assuming that the e\(^{-}\) is at rest, from conservation of energy and momentum:

\[
E_{\gamma i} = \frac{E_{\gamma i-1}}{1 + \frac{E_{\gamma i-1}}{m_0 c^2}(1 - \cos \theta_i)}
\]

\[
e_i = E_{\gamma i-1} - E_{\gamma i}
\]

Energy of scattered \(\gamma\)

Energy of scattered e\(^{-}\)

Arthur Holly Compton
Nobel prize 1927
Compton Scattering (2)

The angular distribution of the scattered photon is described by the Klein-Nishina formula:

\[
\frac{d\sigma}{d\Omega} = z r_e^2 \left( \frac{1}{1 + \alpha (1 - \cos \theta)} \right)^2 \left( \frac{1 + \cos^2 \theta}{2} \right) \left( 1 + \frac{\alpha^2 (1 - \cos \theta)^2}{(1 + \cos^2 \theta)[1 + \alpha (1 - \cos \theta)]} \right)
\]

\[\alpha = E/Me^2\]

and \(r_e\) is the classical electron radius.

For \(E_\gamma > \) few 100 keVs the angular distribution is highly anisotropical and peaked to small forward angles. It strongly “focuses” with the increasing photon energy.
Continuum Compton

The spectrum of the scattered electrons can be deduced from the Klein-Nishina formula:

\[
\frac{dN}{dE_e} \propto \left( 1 + \frac{f^2(E_e)}{2} \right)^{1 + \frac{1}{f^2(E_e)}} \left[ 1 + \frac{E_e^2}{E_\gamma(E_\gamma - E_e)} \right]
\]

\[
f(E_e) = 1 - \frac{m_ec^2}{E_\gamma} \frac{E_e}{E_\gamma - E_e}
\]

Since the actual energy deposition is performed by the electrons, photons interacting via Compton scattering will produce a continuum.

Corrections are needed since electrons are not free, rather bound in materials, producing a smoothening of the actual spectrum (Compton profile)
Shape of the $\gamma$ spectrum for a typical size Ge detector

- **Compton continuum**
- **Full-energy peak**
- **Single-escape peak**
- **Double-escape peak**

High probability that the incoming photons are only partially absorbed. Response function: full-energy peak, continuum generated by photons which underwent Compton scattering and, if the photon energy is larger than 1.022 MeV, peaks due to the missed detection of one or both the annihilation photons (single and double escape peaks).
Escape-suppressed Ge detectors (Compton suppression)

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

For large-volume Ge crystals the Anticompton shield (AC) improves the PeakToTotal ratio (P/T) from ~20% to ~60%.

In a $\gamma-\gamma$ measurement, the fraction of useful peak-peak coincidence events grows from 4% to 36%.

For high fold (F) coincidences the fraction of useful coincidences is $P/T^F$.
GASP @ Legnaro Nat. Lab.

*Lifetime measurements with Doppler Shift Techniques*

7 rings @ 35°, 60°, 72°, 90°, 108°, 120°, 145°

- 40 HPGe + AC (config. II)
  - $d_{\text{target-det.}} = 22$ cm
  - $\varepsilon_{\text{ph}} \sim 5.8\% @ 1332.5$ keV
- Pb collimator (6 cm thick)
  - inner space $R_{\text{int}} = 15$ cm


GAMMASPHERE

up to 110 Compton-Suppressed Ge detectors

I.Y. Lee, NPA 520 (1990) 641

EUROBALL

15 Clusters (7-Ge); 26 Clovers (4-Ge); 30 single Ge
71 CS-systems
239 Ge crystals

Efficiency \( \varepsilon_p \) ~ 10 — 5 %
Peak/Total \( PT \) ~ 55 — 40 %
\(( M_\gamma=1 \rightarrow M_\gamma=30)\)

Solid angle covered by Ge \( \rightarrow 40-50 \% \)
The “spectroscopic history” of $^{156}$Dy is a notable example of how the progress with the acceleration and detection techniques leads to better insight on the nuclear structure.
The nucleus is always full of surprises

Instrumentation advances $\iff$ New Science
Advances in γ-ray spectroscopy: sensitivity vs year

new eyes for new phenomena:

*super-deformation in* $^{156}$Dy

major/minor axis = 2:1

Sensitivity = inverse of the weakest channel reaction cross-section that can be measured over total cross section
Advances in γ-ray spectroscopy: sensitivity vs year

Ge detector system sensitivity vs year

new eyes for new phenomena:

super-deformation in $^{156}\text{Dy}$

major/minor axis = 2:1

AGATA (EU) and GRETA (US) will allow unprecedented gamma detection sensitivity, by using the germanium detectors in position sensitive mode (Pulse Shape Analysis and Tracking)

Sensitivity = inverse of the weakest channel reaction cross-section that can be measured over total cross section
The $\gamma$-ray spectroscopy dream

Cover the whole detection solid angle by germanium and track the path of the $\gamma$-rays inside the detector medium

- segmented detectors
- digital electronics
- timestamping of events
- analysis of pulse shapes
- tracking of $\gamma$-rays

4 time more efficient than standard arrays, also for high $\gamma$ multiplicity (28 % $M_\gamma$=30)

High count rate capabilities (100s KHz)

“continuous” angular distributions of the $\gamma$ interaction points ($\theta \sim 1^\circ$)

Study of nuclei in extreme conditions of angular momentum and neutron/proton asymmetry

“perfect” Doppler correction (6 keV @ 1 MeV, $\beta$=50%)

New accuracy and sensitivity for nuclear level lifetimes $\gamma$ linear polarization
Position resolution used to limit Doppler broadening of gammas emitted in flight -- Benefits of the $\gamma$-ray tracking

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

v/c = 20 %

Detector → Segment → Pulse shape analysis + tracking $\gamma$
Tracking of radiation

in High Energy Physics

“continuous tracks” from very energetic particles

huge detectors for “one” experiment

Physics ← the study of “complete” events

in Nuclear Spectroscopy

“many” low energy (0.01 -- 10 MeV) neutral transitions with low density of energy deposition

“general-purpose” detectors for a large variety of experiments

Physics ← large number of incomplete events
Position-sensitive operation mode and $\gamma$-ray tracking

highly segmented HPGe detectors

Event by event:
how many gammas, for each gamma: energy, first interaction point, path
Position-sensitive operation mode and $\gamma$-ray tracking

- Highly segmented HPGe detectors
- Digital electronics to record sampled waveforms
- Event by event: how many gammas, for each gamma: energy, first interaction point, path
Position-sensitive operation mode and $\gamma$-ray tracking

- Highly segmented HPGe detectors
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- Event by event: how many gammas, for each gamma: energy, first interaction point, path
- Pulse Shape Analysis of the recorded waves
Position-sensitive operation mode and $\gamma$-ray tracking

- Highly segmented HPGe detectors
- Digital electronics to record sampled waveforms
- Identified interaction points (hits) $(x, y, z, E, t)_i$
- Pulse Shape Analysis of the recorded waves
- Event by event: how many gammas, for each gamma: energy, first interaction point, path
Position-sensitive operation mode and $\gamma$-ray tracking

highly segmented HPGe detectors

digital electronics to record sampled waveforms

Identified interaction points (hits)

$(x, y, z, E, t)_i$

Pulse Shape Analysis of the recorded waves

reconstruction of $\gamma$-rays from the hits (tracking)

Event by event: how many gammas, for each gamma: energy, first interaction point, path
Aim of gamma-ray tracking

deposited energies and the positions of all the interactions points of an event in the detector

\[ e_1, x_1, y_1, z_1 \]
\[ e_2, x_2, y_2, z_2 \]
\[ \ldots \]
\[ e_n, x_n, y_n, z_n \]

reconstruct individual photon trajectories and write out photon energies, incident and scattering directions

\[ E_1, (\theta, \phi)_{inc,1}, (\theta, \phi)_{sc,1} \ldots \]
\[ E_2, (\theta, \phi)_{inc,2}, (\theta, \phi)_{sc,2} \ldots \]
\[ \ldots \]
\[ E_i, (\theta, \phi)_{inc,i}, (\theta, \phi)_{sc,i} \]

discard events corresponding to incomplete energy release
Aim of gamma-ray tracking

deposited energies and the positions of all the interactions points of an event in the detector

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\[ E_i, (\theta, \phi)_{inc,i}, (\theta, \phi)_{sc,i} \]

discard events corresponding to incomplete energy release

Doppler correction

Linear Polarization
Questions:
1) Is the event complete?
2) What is the right sequence?
Tracking of Compton Scattered Events

Source position is known

Questions:
1) Is the event complete?
2) What is the right sequence?
Tracking of Compton Scattered Events

Questions:
1) Is the event complete?
2) What is the right sequence?

From energy deposition + incident energy

$$E_y^E = \sum_{i=n}^{N-1} e_i$$

$$\cos \theta^p = \frac{01 \cdot 12}{|01| \cdot |12|}$$

$$E_y^P = \sum_{i=n+1}^{N-1} e_i$$

$$E_y^E$$

$$1 + \frac{E_y^E}{m_0 c^2 (1 - \cos \theta^p)}$$

Track order = permutation with best $\chi^2$

$$\chi_n^2 = \left( \frac{E_y^E - E_y^P}{\sigma} \right)^2$$

$$\Rightarrow \chi^2 \approx \sum_{n=1}^{N-1} \chi_n^2$$
Find $\chi^2$ for the $N!$ permutations of the interaction points.

Fit parameter is the permutation number.

Accept the best permutation if its $\chi^2$ is below a predefined value.
Identification is not 100% sure

→ spectra will always contain background

The acceptance value determines the quality (P/T ratio) of the spectrum

Often we use the \( R = \text{Efficiency} \cdot PT \) to qualify the reconstructed spectra
Reconstruction of multi-gamma events

• **Analysis of all partitions of measured hits is not feasible:**
  Huge computational problem
  (~$10^{23}$ partitions for 30 points)
  Figure of merit is ambiguous $\rightarrow$ the total figure of merit of the “true” partition not necessarily the minimum

• **Forward peaking of Compton scattering cross-section implies**
  that the hits of one gamma tend to be localized along the emission direction

\[
\frac{d\sigma_{KN}}{d\Omega} = Z \frac{r_0^2}{2} \left( \frac{E'}{E} \right)^2 \left[ \frac{E'}{E} + \frac{E}{E} - \sin^2 \theta \right]
\]

• **The most used algorithm (G.Schmid et al. NIMA 430 1999, GRETA)** starts by identifying clusters of points which are then analyzed as individual candidates gammas
Forward tracking implemented for AGATA

1. Create cluster pool => for each cluster, $E_{\gamma_0} = \sum$ depositions in the cluster
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2. Find most probable sequence of interaction points, test the 3 mechanisms
   1. do the interaction points satisfy the **Compton** scattering rules ?
      \[
      \chi^2 \approx \sum_{n=1}^{N-1} W_n \left( \frac{E_{\gamma'} - E_{\gamma'}^{\text{Pos}}}{E_{\gamma'}} \right)_n^2
      \]
   2. does the interaction satisfy **photoelectric** conditions (e_{\gamma}, depth, distance to other points) ?
   3. do the interaction points correspond to a **pair production** event ?
      \[
      E_{1st} = E_{\gamma} - 2 m_e c^2
      \]
Forward tracking implemented for AGATA

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\]

2. does the interaction satisfy **photoelectric** conditions (\( e_1, \text{depth, distance to other points} \))?

3. do the interaction points correspond to a **pair production** event?
   \[ E_{1st} = E_{\gamma} - 2 \, m_e c^2 \]

3. Select clusters based on \( \chi^2 \)
Examples of tracked source spectra

~40 keV X-rays

$^{152}$Eu

12 AGATA detectors
Performance of the Germanium Shell

Idealized configuration to determine maximum attainable performance.

1.33 MeV $M_\gamma = 1$ $M_\gamma = 30$

$\epsilon_{ph} (%)$ 65 36

P/T(%) 85 60

Reconstruction by Cluster-Tracking
Packing Distance: 5 mm
Position Resolution: 5 mm (at 100 keV)

A high multiplicity event

$E_g = 1.33$ MeV
$M_g = 30$

27 gammas detected
16 reconstructed
23 in photopeak
14 in photopeak
The biggest losses are due to multiplicity (mixing of points) not to bad position resolution.

5 mm is the standard "realistic" packing and smearing assumption.

If positions inside segments are not known, performance is a factor 2 worse.

Standard shell; $E_\gamma = 1.33$ MeV; Packing=Smearing; Energy independent smearing.
The biggest losses are due to multiplicity (mixing of points) not to bad position resolution.

5 mm is the standard "realistic" packing and smearing assumption.

If positions inside segments are not known, performance is a factor 2 worse.

Sub-segment position resolution is needed.
Pulse Shape Analysis (PSA)

8 AGATA Triple Clusters (24 detectors) @ GANIL “captured” during an experiment

Reconstruction of the interaction points (hits)
Pulse shapes in a coaxial Ge detector

Reverse bias (-HV on p\(^+\) contact) depletes bulk and generates high electric field

Radiation $\rightarrow$ carriers in the bulk, swept out by electric field $\rightarrow$ signal

On “true” coaxial detectors, the shape depends on initial radius
**Segmented detectors**

- When one of the electrodes is (electrically) segmented, the motion of charges within one segment induces a *transient* signal also in the neighboring electrodes.
- Contrary to the segment where the interaction takes place (the charge is released), the total collected charge in the neighboring electrodes is null.
- The amplitude of the induced transient signals provides a convenient way to locate the interaction with sub-segment precision.

**Segmentation of an AGATA detector**
Pulse Shape Analysis concept

Interaction occurred in segment 4
(net charge signal)

Interaction is closer to segment 3 (larger amplitude than segment 5)
Pulse Shape Analysis concept

Interaction occurred in segment 4 (net charge signal)

Interaction is closer to segment 3 (larger amplitude than segment 5)

Sub-segment precision ... but not enough to efficiently perform tracking!

→ Pulse Shape Analysis
Pulse Shape Analysis concept

791 keV deposited in segment B4
Pulse Shape Analysis concept

791 keV deposited in segment B4

(10, 10, 46)
Pulse Shape Analysis concept

791 keV deposited in segment B4
Pulse Shape Analysis concept

791 keV deposited in segment B4

(10,20,46)
Pulse Shape Analysis concept

791 keV deposited in segment B4
Pulse Shape Analysis concept

791 keV deposited in segment B4

z = 46 mm
Pulse Shape Analysis concept

791 keV deposited in segment B4

Result of Grid Search Algorithm

(10, 25, 46)
Method = Doppler correction capability in an in-beam experiment

**REACTION CHANNEL:** $^{48}\text{Ti}(d,p)^{49}\text{Ti}$

<table>
<thead>
<tr>
<th>beam</th>
<th>$^{48}\text{Ti}$</th>
<th>100 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>target</td>
<td>$^{48}\text{Ti} + ^2\text{H}$</td>
<td>220 $\mu$g/cm$^2$</td>
</tr>
<tr>
<td>Si detector</td>
<td>thickness</td>
<td>300 $\mu$m</td>
</tr>
<tr>
<td>Si detector</td>
<td>segmentation</td>
<td>32 rings, 64 sectors</td>
</tr>
</tbody>
</table>

**AGATA triple symmetric cluster**

Simulation of reaction + detector response

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**Position resolution of AGATA**

F. Recchia et al., NIMA 604 (2009) 555
P-A. Soederstroem et al., NIMA 638 (2011) 96

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**Fig. 10.** Width of the simulated 1382 keV peak as a function of the position smearing for the full triple cluster. Individual crystal energy resolution have been considered. All of the segment multiplicities are taken into account. The horizontal arrow indicates the experimental width.
Imaging of $E_\gamma = 1332$ keV gamma rays

AGATA used as a big and expensive Compton Camera

$$\cos \theta = 1 + \left( \frac{1}{E_\gamma} - \frac{1}{E'_\gamma} \right) m_0 c^2$$

Source at 51 cm ➔ $D_x \sim D_y \sim 2$ mm $D_z \sim 2$ cm

F. Recchia et al., NIMA 604 (2009) 60
Doppler correction capabilities

AGATA Demonstrator at LNL

Inelastic scattering

\( ^{17}\text{O} \) @ 20 MeV/u on \(^{208}\text{Pb}\)

F. Crespi, Milano
Outline

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AGATA+VAMOS (magnetic spectrometer) at GANIL

(be aware ... personal selection of topics!)