γ-ray spectrocopy techniques with AGATA

Damian Ralet

Centre de Sciences Nucléaires et de Sciences de la Matière

- γ-ray spectroscopy: problematic
- What is AGATA?
- AGATA: some numbers
- γ-ray studies with AGATA
- Lifetime measurements with AGATA
- Conclusion

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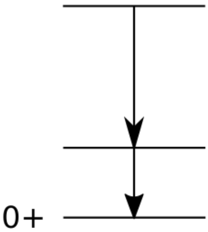
Why do we detect γ rays

γ rays are powerful probe of the nuclear structure:



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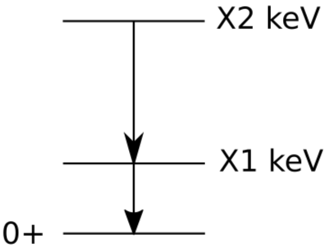
Energies of the level and relative intensities



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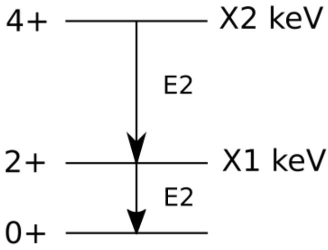
Determination of the multipolarity and spin/parity assignment



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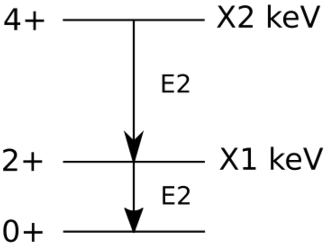
Lifetime of the state (τ): related to the transition probability



$$\tau = \frac{1}{1.22 \cdot E_\gamma^5 \cdot B(E2;2^+ \rightarrow 0^+)}$$

Cf. A Orbertelli lectures

Requirement for a γ-ray detector

What is needed for a good γ-ray detector:

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4. High-fold capacities for γ-γ coincidences
5. Low background/good background rejection (room background and Compton background)

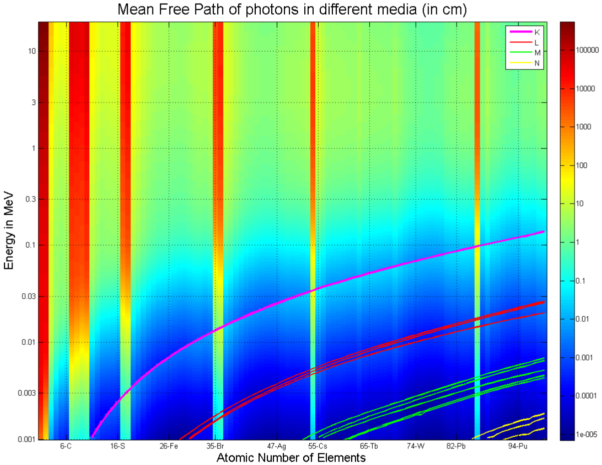
γ-ray interaction with matter

No easy to detect a γ ray:

γ-ray interaction with matter

From: https://en.wikipedia.org/wiki/Mean_free_path

No easy to detect a γ ray:



(Nobel gas with low density: high mean free path)

Type of γ ray detectors

Scintillator usually: good timing properties, with energy resolution that is acceptable:

1. NaI: at 1 MeV $\Delta E \sim$ 50 keV, $\Delta T \sim$ 10 ns)
2. BaF_2(Ce) at 1 MeV ($\Delta E \sim$ 200 keV, $\Delta T \sim$1 ns)
3. $LaBr_3$ at 1 MeV ($\Delta E \sim$ 30, $\Delta T \sim$800 ps)

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Semi-conductor: excellent energy resolution, poorer time resolution compared to scintillator detectors (due to the drift time of the charges:

1. Silicon ($Z = 14$): Cannot be large volume: not easy to detect γ-ray
2. Germanium ($Z = 32$) detector ($\Delta E \sim 2$, $\Delta T \sim$20 ns): $\rightarrow$ It is possible to have large volume

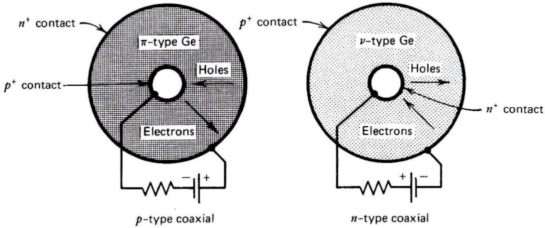
High purity germanium detector

Germanium detectors are the optimum detector for γ spectroscopy studies.

But it need to be cooled down at liquid nitrogen temperature (77 K) to reduce noise coming from thermal excitation (small band gap: 0.72 eV).

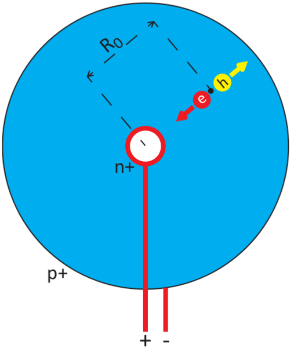
The co-axial germanium detector

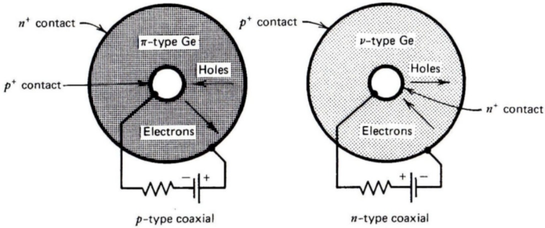
Two types of coaxial high purity geranium detector:
P-type and N-type.
Usually: n+ contact by lithium diffusion
and p+ contact by boron implantation



The co-axial germanium detector

γ-ray interact in the depleted area
Creation of a charge cloud inducing signals on the electrodes





γ-ray interaction in germanium

Mainly three type of interaction in Germanium:

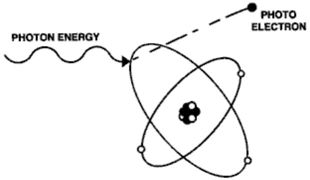


Figure 2-XIV. Gamma Interaction by Photoelectric Effect

γ-ray interaction in germanium

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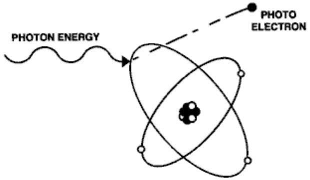
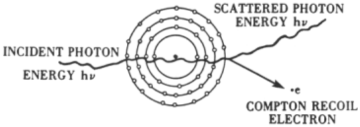


Figure 2-XIV. Gamma Interaction by Photoelectric Effect



Compton Scattering
(Courtesy of Dresser Atlas)

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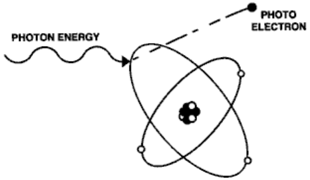

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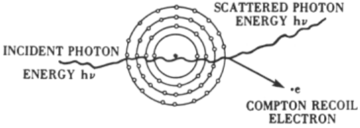

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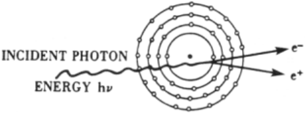
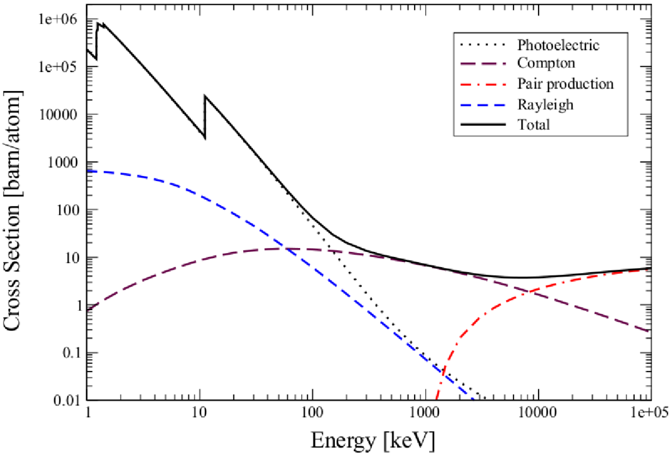


Pair Production

γ-ray interaction in germanium

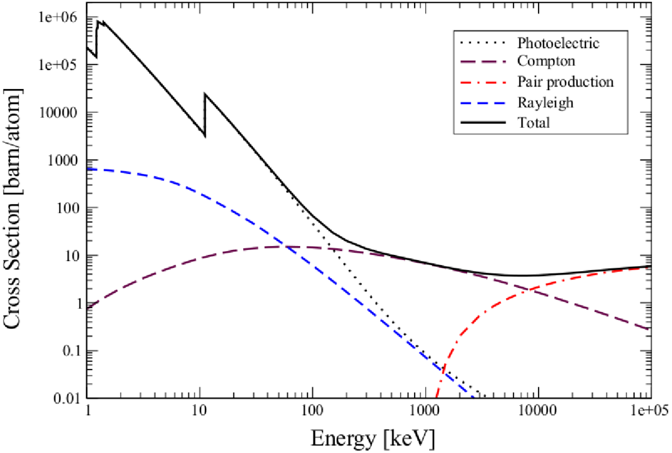
Cross section of γ-ray in Germanium



γ-ray interaction in germanium

Cross section of γ-ray in Germanium

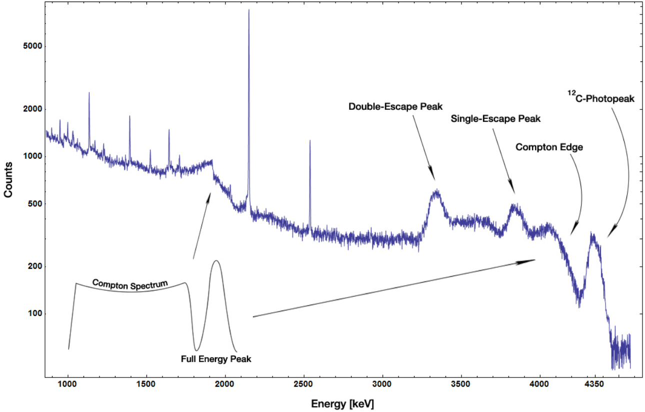
Typical nuclear structure γ-ray energy: 10 keV to 20 MeV



Compton scattering

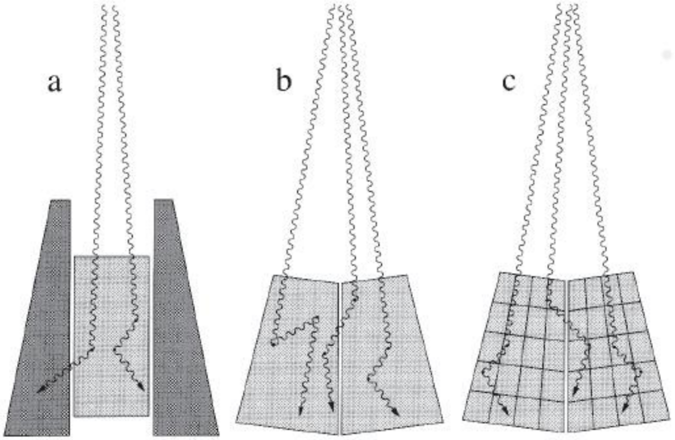
Compton scattered γ-ray can escape the active volume

γ-ray from an americium-beryllium source



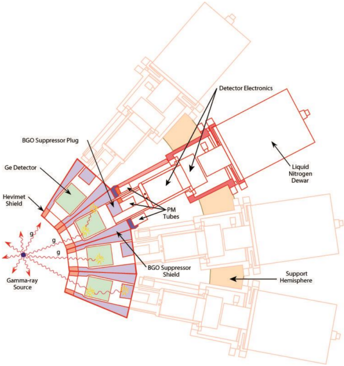
Compton scattering

(a) Compton shield
(b) Compacting and add-back
(c) Compton tracking array



Compton suppression array

GammaSphere (USA)



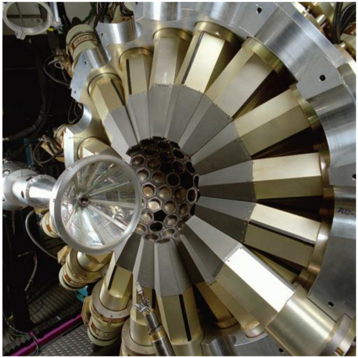
110 escape suppressed Ge detectors of
(70 detectors segmented into two halves)
70% efficiency

M.A. Deleplanque, R.M. Diamond eds.
Gammasphere Proposal (1987)

GAMMASPHERE

Berkeley, Argonne
1993 – 1996

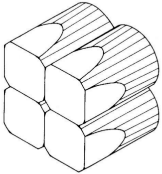
abs. efficiency ≈ 10 %



Compacted germanium array

Clover detectors

24 Clover Detector



improved eff. by add-back
better Doppler correction
linear polarization

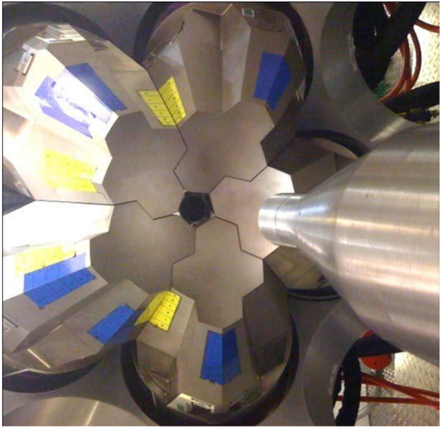
F.A. Beck, G. Duchene

EUROGAM II
french-british collaboration

abs. eff. 8.1%

Tracking array

Two in the world: GRETINA (USA) and AGATA (Eu)



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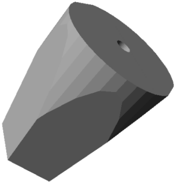
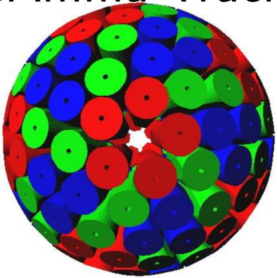
S. Akkoyun, NIM A 668 (2012) 26

AGATA: Advance GAmma Tracking Array

Ge crystals size:
Length 90 mm
Diameter 80 mm

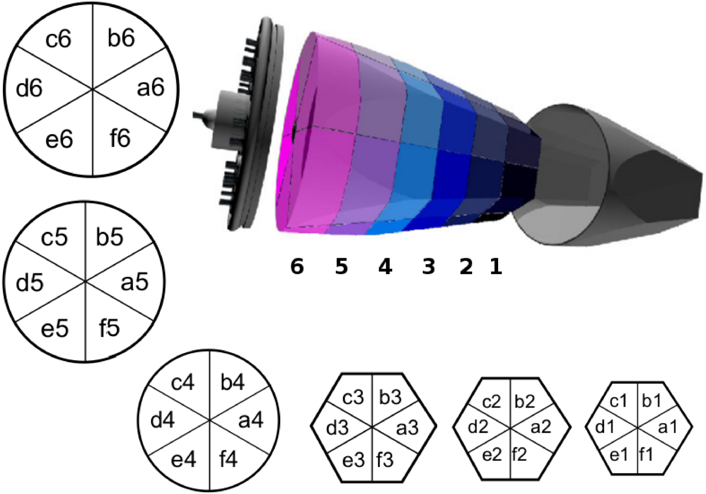




180 hexagonal crystals		3 shapes
60 triple-clusters		all equal
Inner radius (Ge)		23.5 cm
Amount of germanium		362 kg
Solid angle coverage		82 %
6480 segments		
Efficiency:	43% (M_γ=1)	28% (M_γ=30)
Peak/Total:	58% (M_γ=1)	49% (M_γ=30)

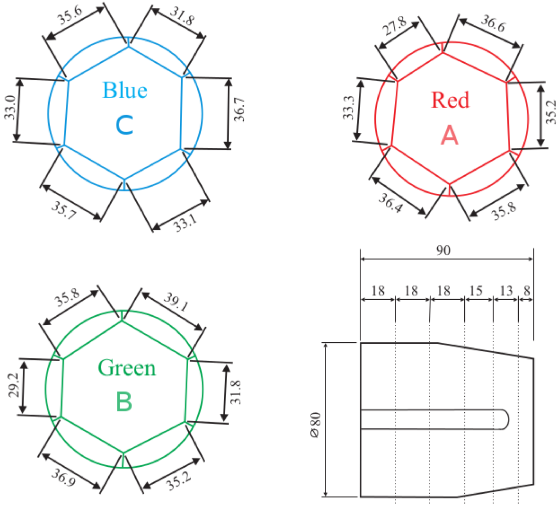
High purity segmented detector

Detector segmentation: 36 segments



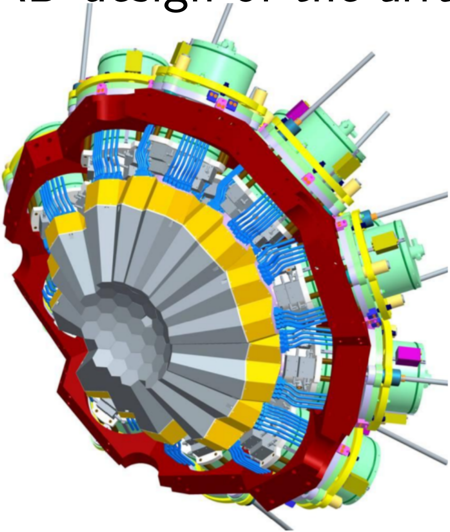
High purity segmented detector

Dimensions of the detectors



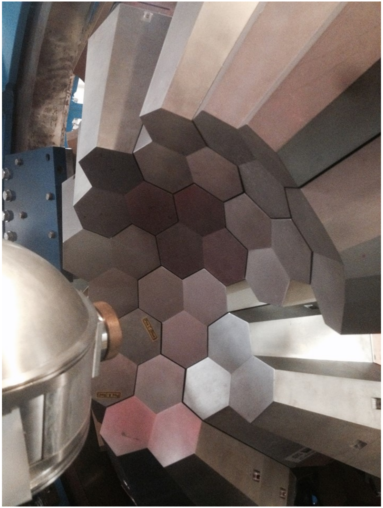
High purity segmented detector

CAD design of the array



High purity segmented detector

In reality 32 detectors in GANIL



Detector characteristics

High-purity Germanium detector
divided in 36 segments

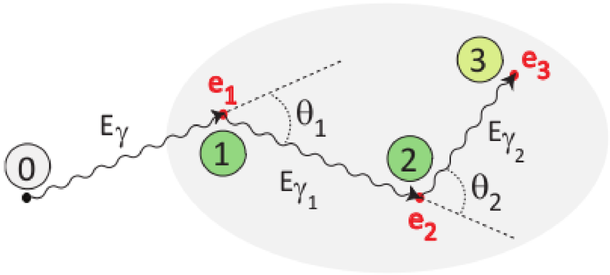
Central-contact with two energy gain

Dedicated digital electronics: 38 channels
that have to be coupled with "ancillary" detectors

4π consist of 180 detectors financed by 12
European countries

Tracking in AGATA

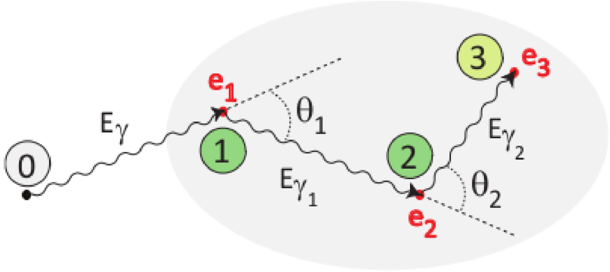
The basic idea is the Compton scattering formula:



Tracking in AGATA

The basic idea is the Compton scattering formula:

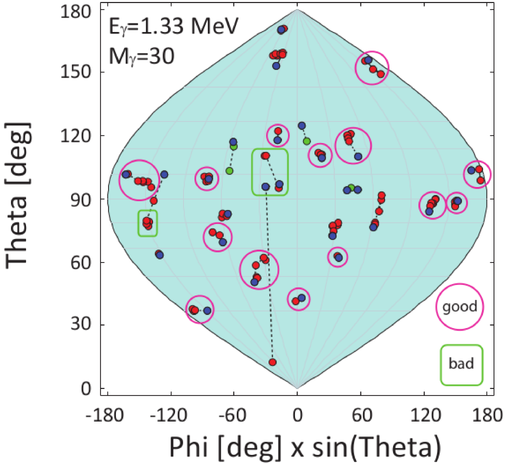
$$E_{\gamma_i} = \frac{E_{\gamma_{i-1}}}{1+\frac{E_{\gamma_{i-1}}}{m_0 c^2}(1-\cos(\theta_i))}$$



Tracking in AGATA

A. Lopez-Martens et al., NIM A 533 (2004) 454-466

Clustering and Figure of Merit assign for each cluster



Tracking in AGATA

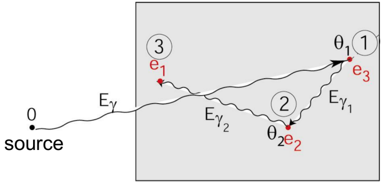
A. Lopez-Martens et al., NIM A 533 (2004) 454-466

Clustering and Figure of Merit assign for each cluster

What tracking does

Questions :

1) Is the event complete : $\sum e_i = E_\gamma$
2) What is the right sequence



1) from source + interaction positions :

$$\cos(\theta_1) = \frac{\vec{01} \cdot \vec{12}}{|\vec{01}|.|\vec{12}|} \Rightarrow E_{\gamma 1,pos} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1-\cos(\theta_1))}$$

from energy deposition + incident energy:

$$E_{\gamma 1} = E_\gamma - e_1$$

2) $\Rightarrow$

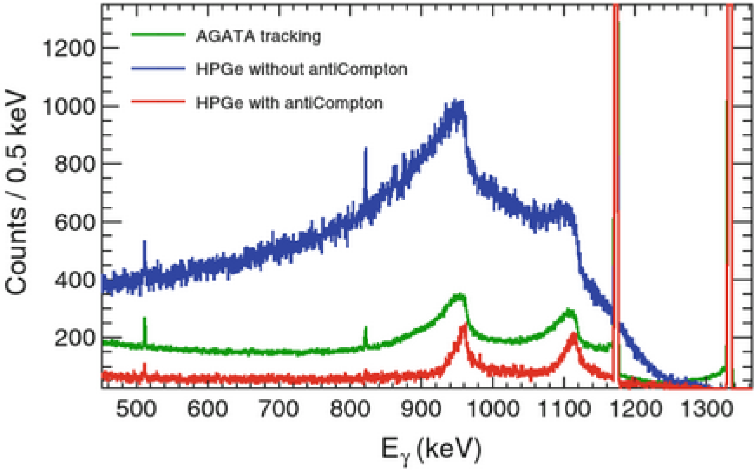
$$E_{\gamma 2,pos} = \frac{E_{\gamma 1}}{1 + \frac{E_{\gamma 1}}{m_e c^2}(1-\cos(\theta_2))}$$

$$E_{\gamma 2} = E_{\gamma 1} - e_2$$

Track order = Permutation with best $\chi^2 = \sum_{n=1}^{2} \left[\frac{E_{\gamma n} - E_{\gamma n,pos}}{\sigma} \right]^2$ (or other figure of merit)

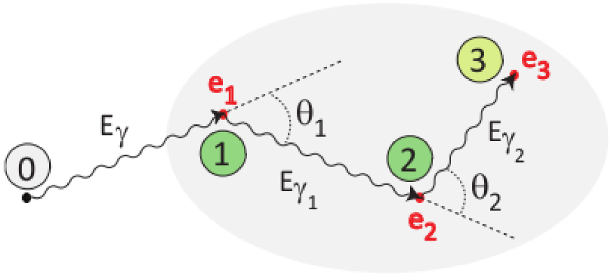
Tracking in AGATA

Simulations of ^{60}Co



What is needed to track a γ-ray?

(1) Energy of each interaction (hit) inside the detectors: obtained with dedicated electronics



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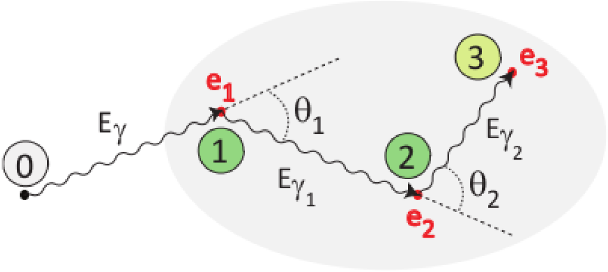
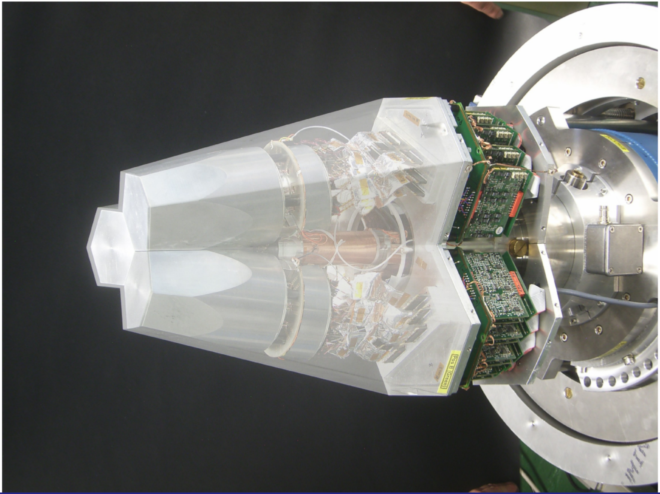
(2) Positions of each hit : Pulse Shape Analysis



(1) Energy of each segment

We need the energy of 36 segments

2 central contact signal (same signal with two energy gains)



(1) Energy of each segment

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2 central contact signal (same signal with two energy gains)

(a) Fully digital electronics

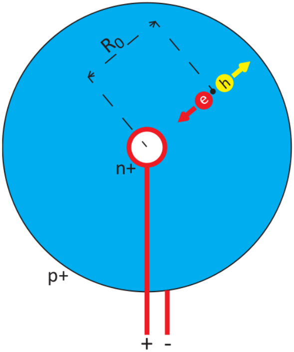
(b) Digitizer: 100 MHz, 14 bit with two energy range

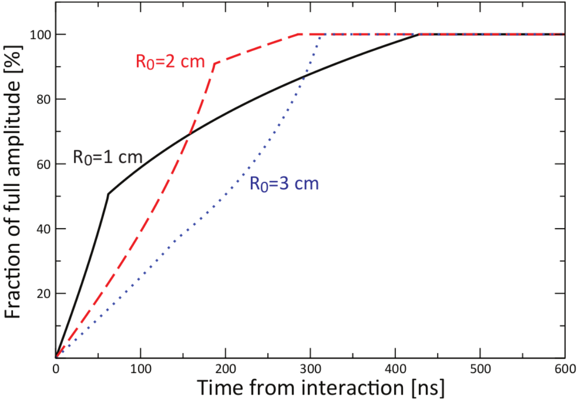
(c) Energy extracted from a Moving Windows deconvolution filter (MWDF or Jordanov Filter)

to determine the pulse high thus the energy of the hit

(2) Pulse Shape Analysis

Basic idea: dependence of the pulse as a function of the position of the hit inside the detector





(2) Pulse Shape Analysis

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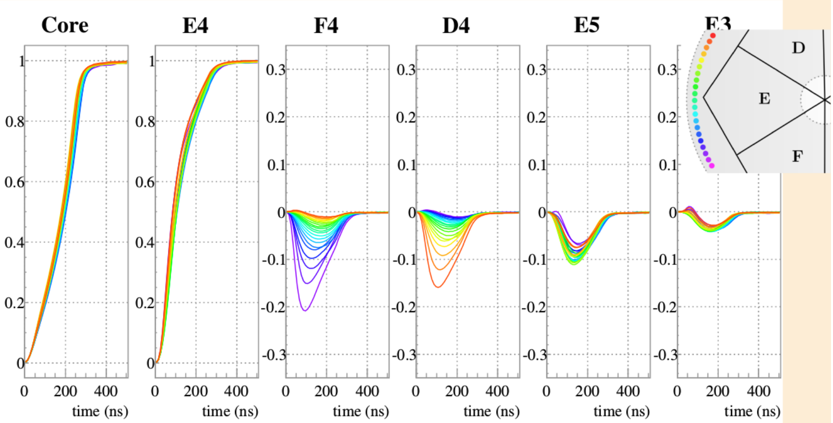
as a function of the position of the hit inside the detector

Example along azimuth



(2) Pulse Shape Analysis

Basic idea: dependence of the pulse
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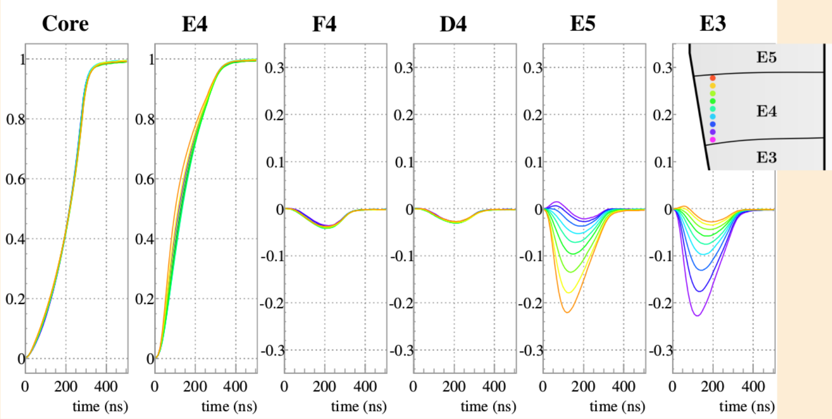
Example along depth



Signal basis: simulated

B. Bruyneel et al. Eur. Phys. J. A. 52, (2016)

Generation of a signal basis on a grid of 2 mm pitch

Known positions are associated to the signal response of the detector

Signal basis: simulated

B. Bruyneel et al. Eur. Phys. J. A. 52, (2016)

Generation of a signal basis on a grid of 2 mm pitch
Known positions are associated to the signal response of the detector
Based on the AGATA Data Library (ADL) program simulations

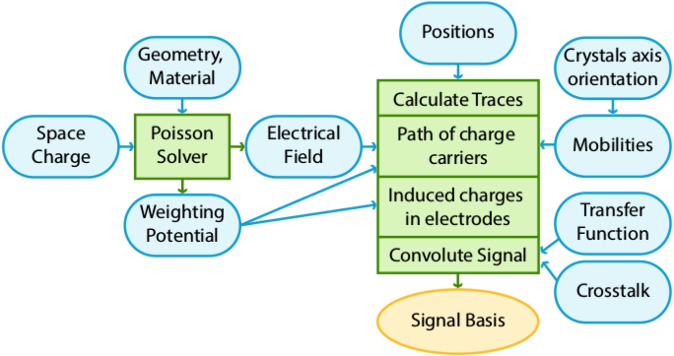
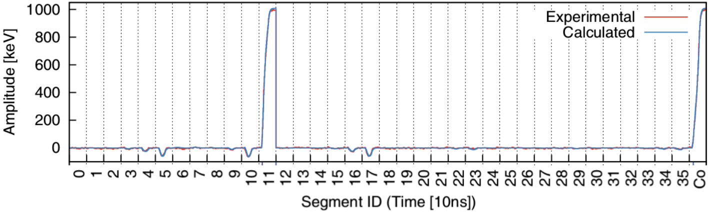


Fig. 2. Block diagram of the routines (green) and the input (blue) for an ADL simulation.

Comparison of signals

Figure from: *B. Bruyneel et al. Eur. Phys. J. A. 52, (2016)*

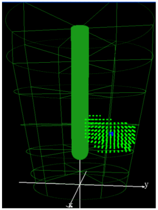


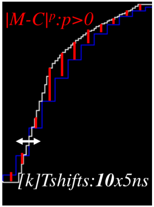
Comparison of signals

R. Venturelli, LNL annual report 2004

Grid-search algorithm used online

$$\chi^2_{\bar{l},\bar{k}} = \min_{\substack{l \in \{SEG\_GRID\_PTS\} \\ -Tshifts<k<Tshifts}} \left\{ \sum_{\substack{i \\ j}}^{\substack{Tsamples \\ Signals}} \left| M_i(j) - C_i^l(j+k) \right|^p \right\}$$





[i] Signals: TRANSIENTS, NET CHARGE, CORE (up to 37)

[j] Time samples of the traces

[k] Time shift of the traces

[l] Segment grid points

$p = 0.3$: Distance metric optimized. Can be modified.

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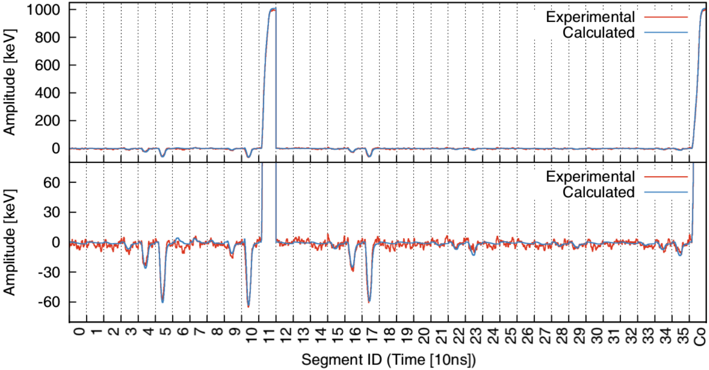
Figure from: *B. Bruyneel et al. Eur. Phys. J. A. 52, (2016)*



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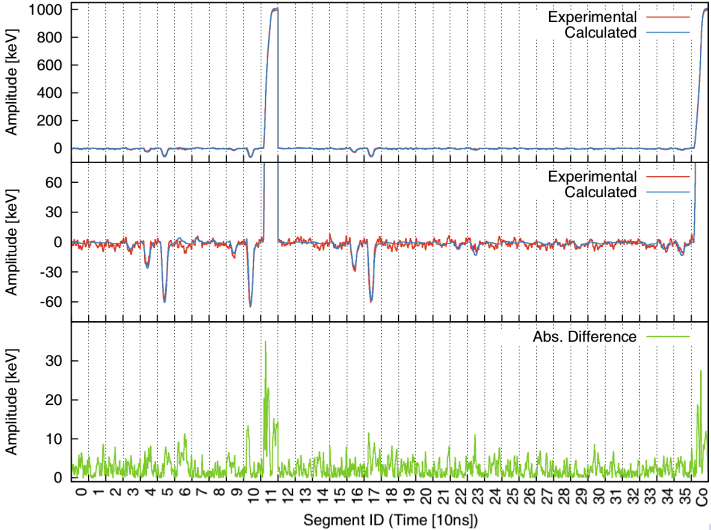

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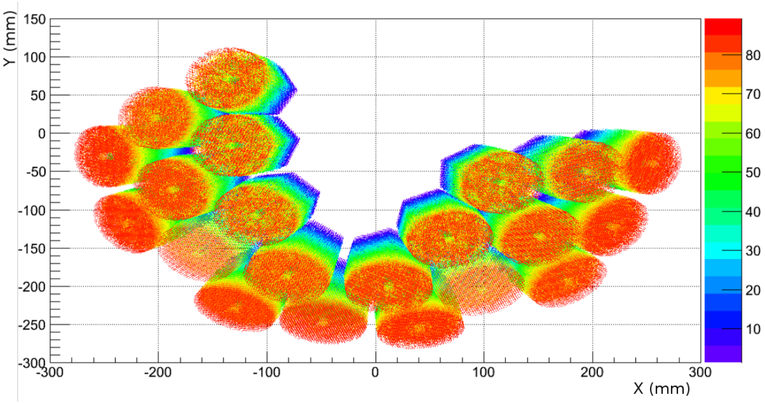
Measured efficiencies

Up to 21 AGATA crystals (2014)

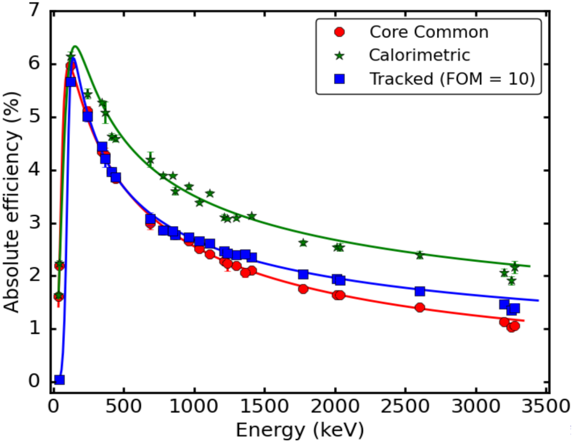


Measured efficiencies

N. Lalović, NIMA 806, 258-266 (2016)

For 21 AGATA detectors at 1172 keV:

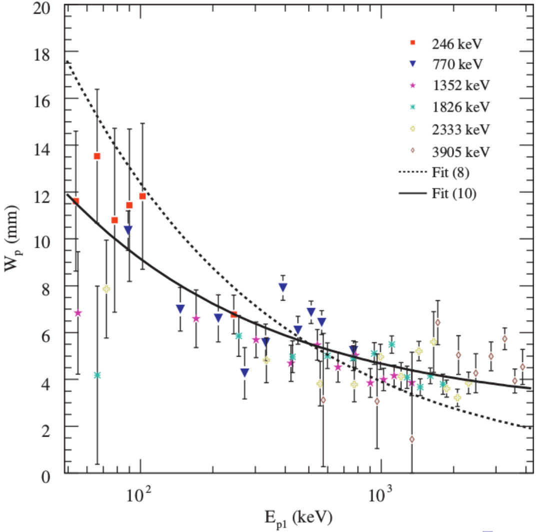
2.38% core common, 2.55% tracked, 3.3% calorimetric



Position resolution

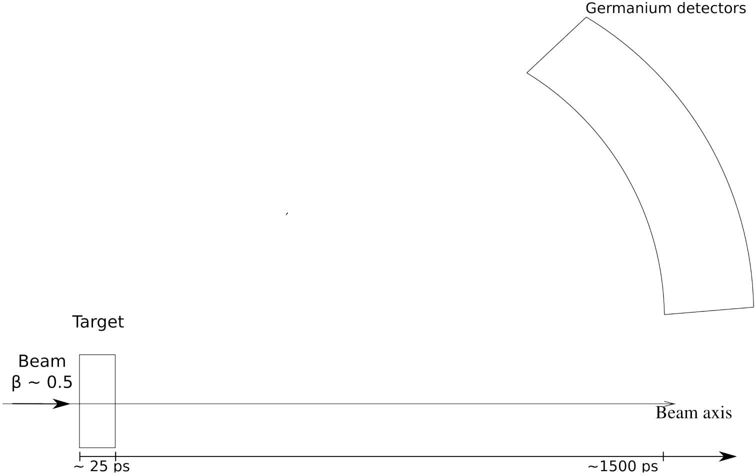
P.A. Söderström et al. NIMA 638, 96-109 (2011)

5 mm FWHM position resolution at 1 MeV



Gain in Doppler-correction

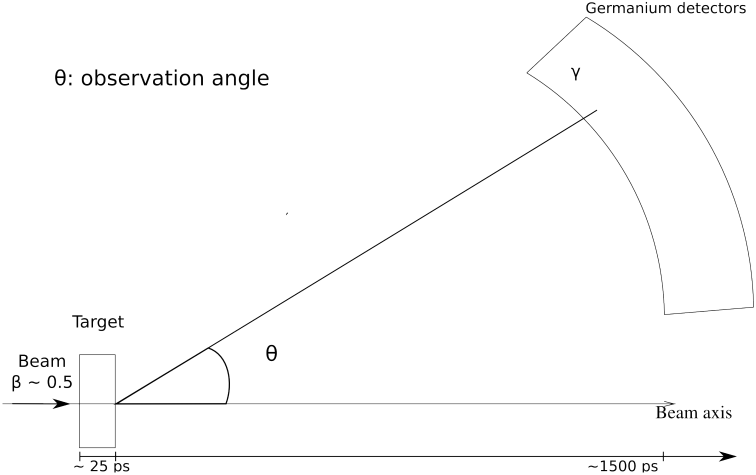
Doppler-shifted energies: $E_{lab} = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}$



Gain in Doppler-correction

Doppler-shifted energies: $E_{lab} = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}$

θ: observation angle

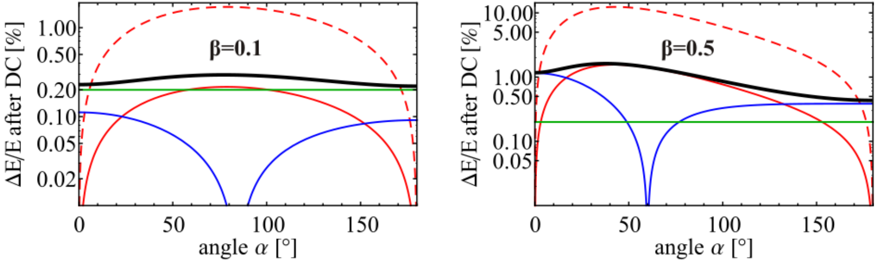


PSA impact on resolution

C. Stahl, PhD Thesis at TUD 2015

Resolution after Doppler correction

$$\Delta E^2 = \left(\frac{\partial E'}{\partial \beta}\Delta\beta\right)^2 + \left(\frac{\partial E'}{\partial \alpha}\Delta\alpha\right)^2 + \Delta E^2_{intr}$$

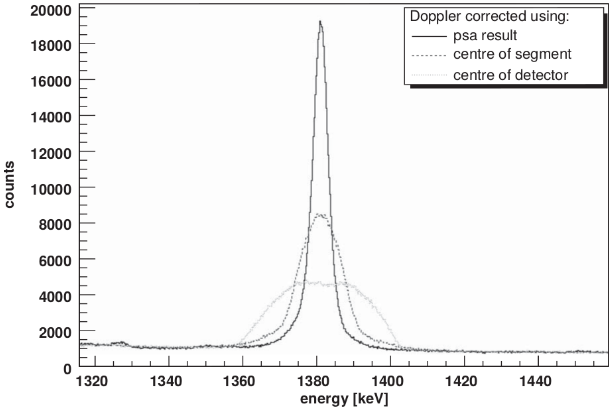


PSA impact on resolution

F. Recchia et al. NIMA 604, 555-562 (2009)

Effect of the PSA on the energy resolution after Doppler correction ($\beta \approx 5\%$)

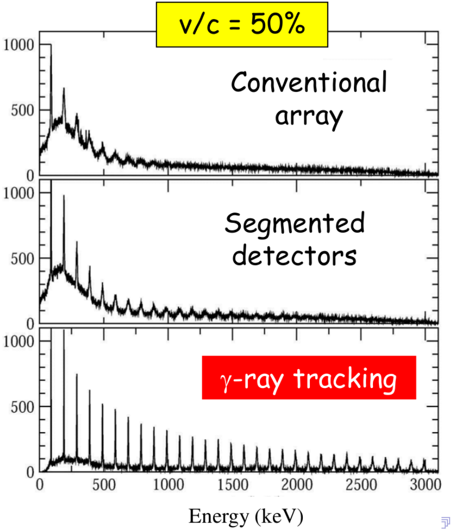
1382 keV first excited $3/2^-$ state of ^{49}Ti



PSA impact on resolution

F. Recchia, PhD Thesis, 2008

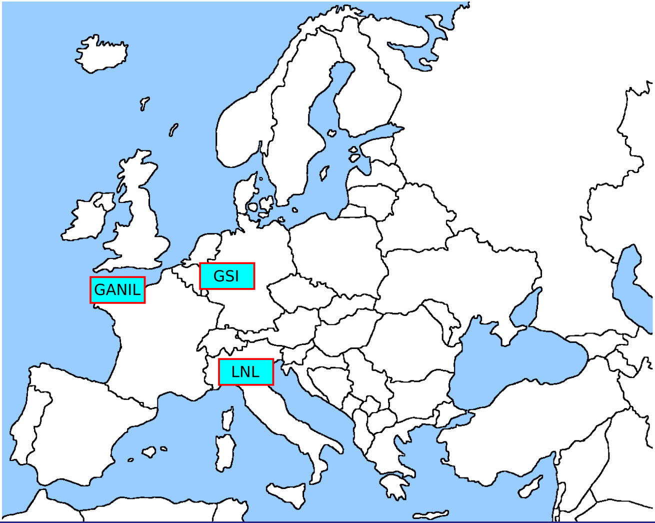
AGATA: simulated spectra



- γ-ray spectroscopy: problematic
- What is AGATA?
- AGATA: some numbers
- γ-ray studies with AGATA
- Lifetime measurements with AGATA
- Conclusion

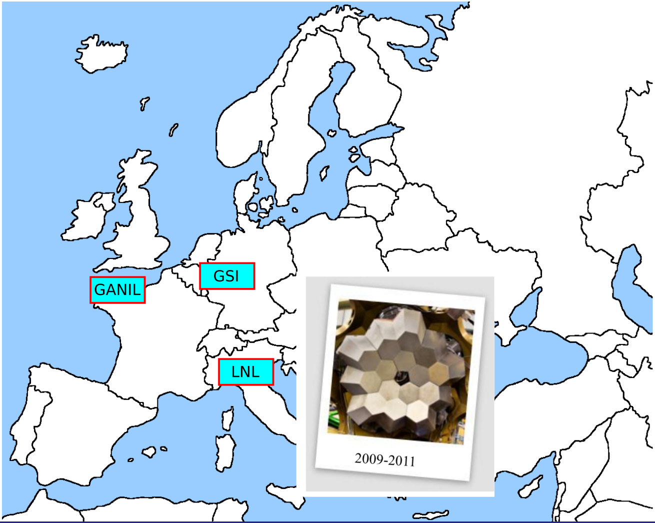
Some facilities in Europe

AGATA: a moving detector



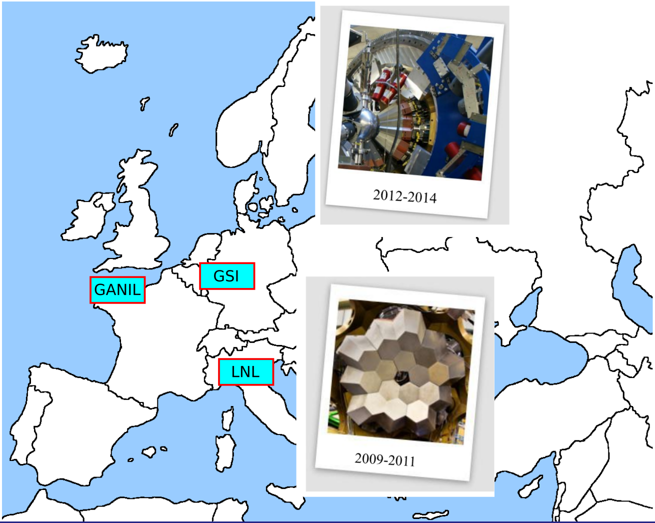
Some facilities in Europe

AGATA: a moving detector
LNL (Italy): up to 15 crystals



Some facilities in Europe

AGATA: a moving detector
GSI (Germany): up to 22 crystals



Some facilities in Europe

AGATA: a moving detector
GANIL (France): up to 32 crystals

Not fully build

AGATA array is not yet at 4π

Not fully build

AGATA array is not yet at 4π

32 detectors installed in GANIL: close to 1π

Not fully build

AGATA array is not yet at 4π

32 detectors installed in GANIL: close to 1π

AGATA has not sufficient efficiency and granularity for pure γ-γ studies

Not fully build

AGATA array is not yet at 4π

32 detectors installed in GANIL: close to 1π

AGATA has not sufficient efficiency and granularity for pure γ-γ studies

Large variety of beams and ancillary detectors are needed to identified the reaction products and access the nuclear structure observables

Complementary detectors

Charged particles detectors:

1. FRS (FRagment Separator) + LYCCA (calorimeter) at GSI, beam velocity $\beta \approx 0.5$
2. VAMOS++ (magnetic spectrometer) at GANIL, beam velocity $\beta \approx 8\%$
3. PRISMA at LNL $\rightarrow$ similar to VAMOS
4. Silicon detectors for light charge particles detection

FRS: H. Geissel *et al.* NIMB 70 (1992) 286-297

LYCCA: P. Golubev *et al.* NIMA 723 (2013) 55-66

VAMOS++: M. Rejmund *et al.* NIMA 646 (2011) 184

PRISMA: A.M. Stefanini *et al.* NPA 701 (2002) 217-221

Complementary detectors

Additional γ-ray detectors:

1. BaF2 and LaBr3 scintillators from HECTOR at GSI/LNL
2. FATIMA LaBr3 scintillators at GANIL for this year campaign
3. PARIS phoswitch at GANIL for this year campaign

Neutrons detectors:

1. NEDA detectors for the 2018 campaign in GANIL

HECTOR: A. Giaz *et al.* NIMA 729 (2013) 910

PARIS: A. Ghosh. *et al.* J. of. Instrum. 11 (2011) 05023

FATIMA: http://nuclear.fis.ucm.es/fasttiming/

NEDA: T. Hüyük *et al.* EPJA 52 (2016) 55

Observables and AGATA

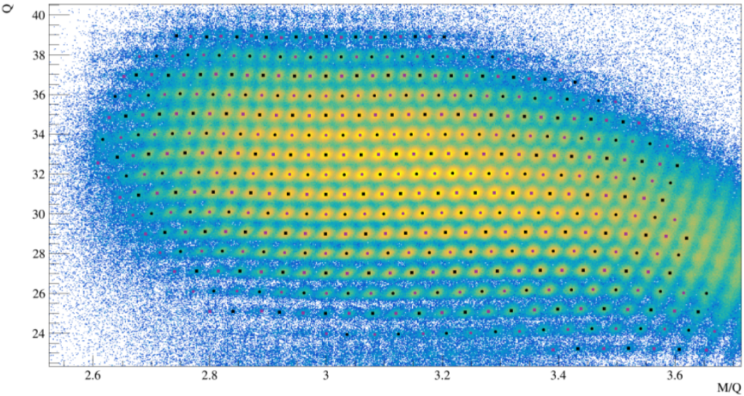
1. γ-ray energies: hard to compete with 4π arrays (lack of efficiency)
2. Lifetime of excited state that is related to the reduced transition strength:

- Doppler Shift Attenuation Method (DSAM) with continuous angle
- Relativistic version of DSAM
- Recoil Distance Doppler Shift (RDDS) methods and plunger measurements
- Utilisation of fix targets to determine the lifetime (similar to a plunger measurement)

AGATA@GANIL: energies

J. Dudouet, IPN Lyon

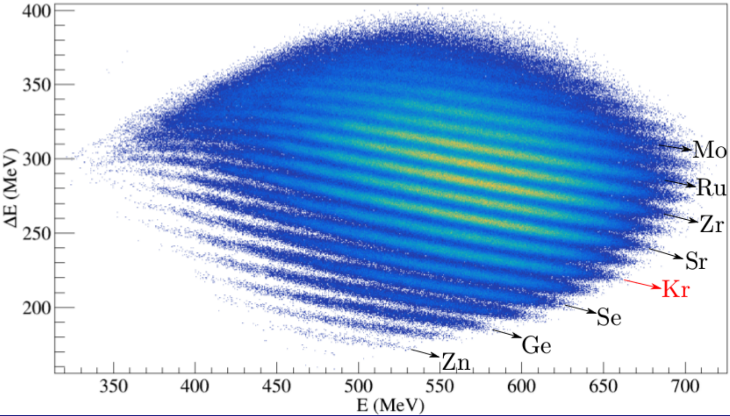
Only spectroscopy of neutron rich isotopes
(fission products of ^{238}U)
Identified in charge state (Q) and mass (M)



AGATA@GANIL: energies

J. Dudouet, IPN Lyon

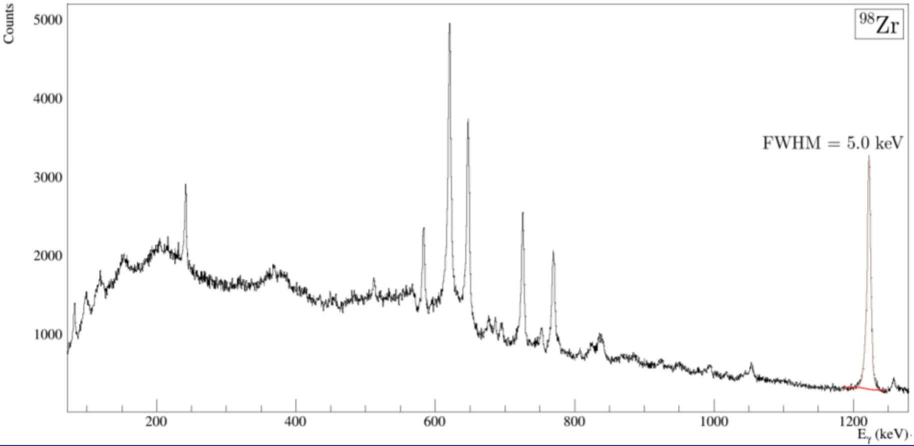
Only spectroscopy of neutron rich isotopes
(fission products of ^{238}U)
Identified the proton number (Z)
$\rightarrow$ total of 205 nuclei uniquely identified



AGATA@GANIL: energies

J. Dudouet, IPN Lyon

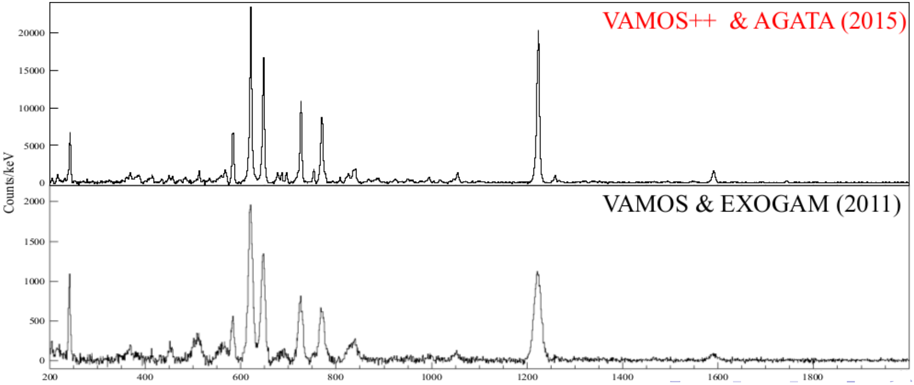
Only spectroscopy of neutron rich isotopes
(fission products of ^{238}U)
γ-ray spectrum for ^{98}Zr



AGATA@GANIL: energies

J. Dudouet, IPN Lyon

Comparison to the previous array (EXOGAM) that was in GANIL with very similar setup



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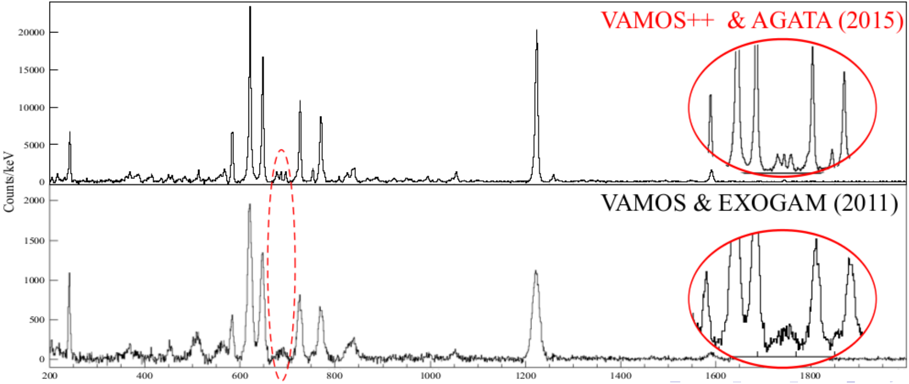

- γ-ray spectroscopy: problematic
- What is AGATA?
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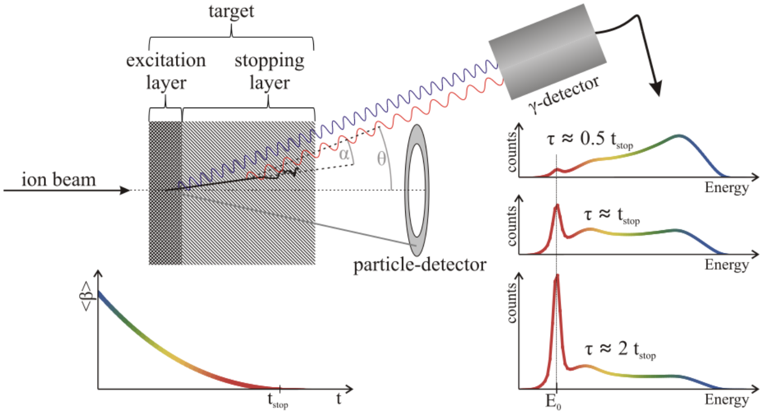
- γ-ray studies with AGATA
- **Lifetime measurements with AGATA**
- Conclusion

Continuous angle DSAM

C. Stahl, PhD Thesis at TU-Darmstadt 2015

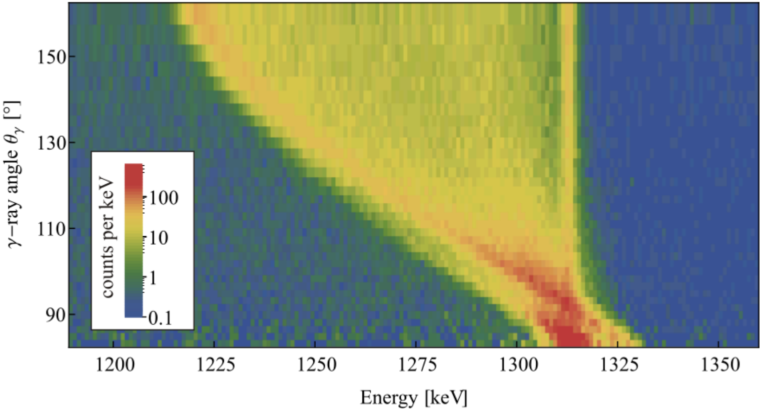
Principle of stopped beam Doppler Shift Attenuation Method (DSAM)



AGATA@LNL: ^{136}Xe

C. Stahl, PhD Thesis at TU-Darmstadt 2015

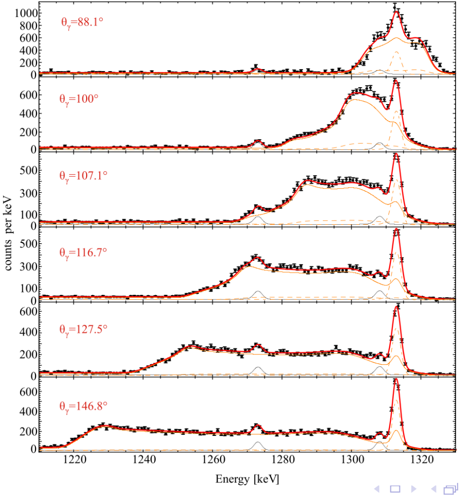
1313 keV $2^+ \rightarrow 0^+$ transition of ^{136}Xe



AGATA@LNL: ^{136}Xe

C. Stahl, PhD Thesis at TU-Darmstadt 2015

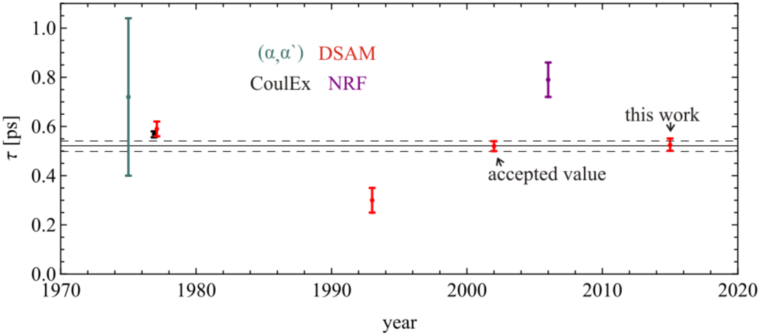
Complex Monte-Carlo simulations for a fit of the spectra at different angles



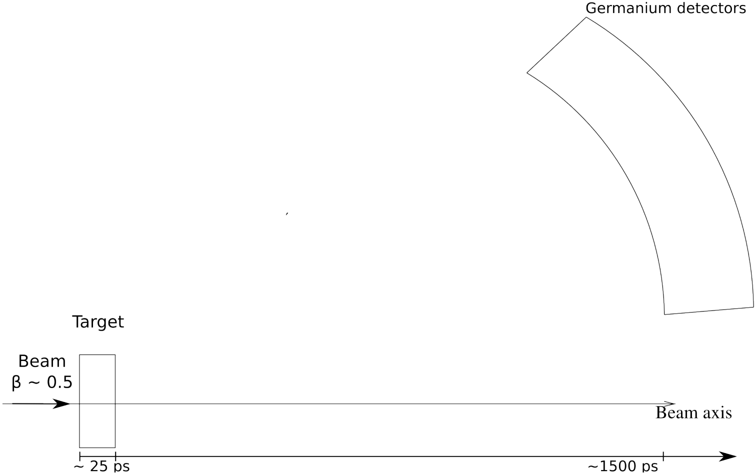
AGATA@LNL: ^{136}Xe

C. Stahl, PhD Thesis at TU-Darmstadt 2015

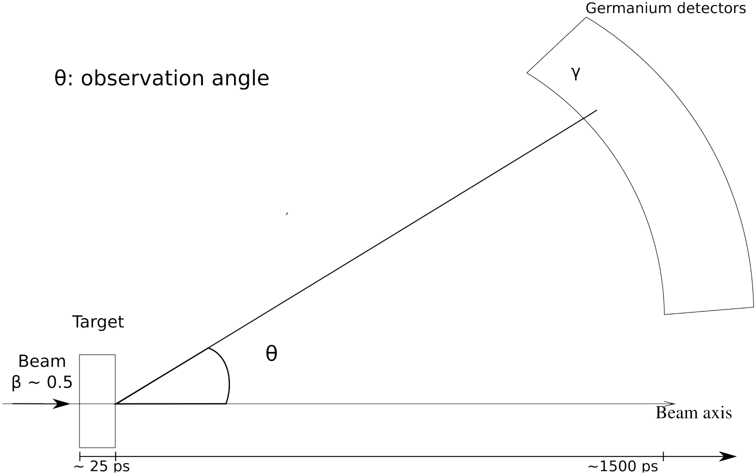
Perfect agreement with adopted value obtained



Relativistic version of DSAM



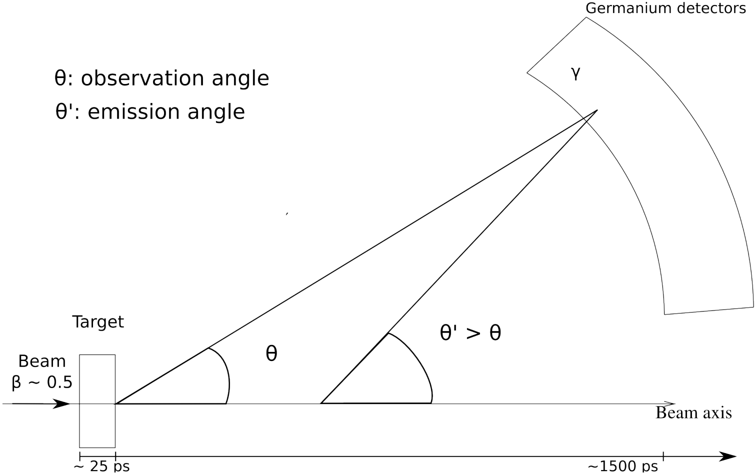
Relativistic version of DSAM



Relativistic version of DSAM

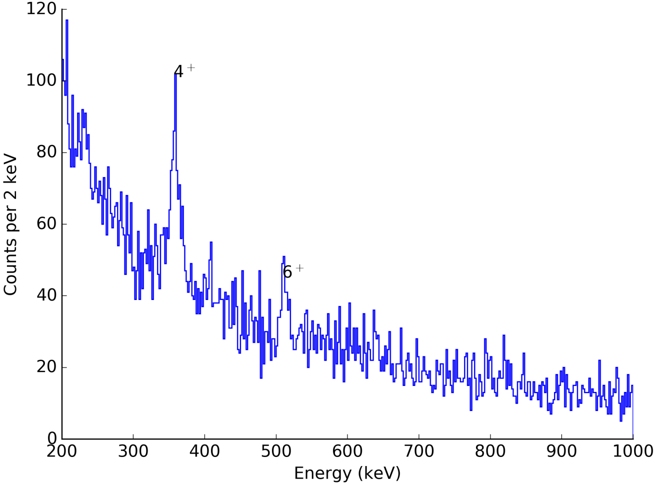
θ: observation angle

θ': emission angle



AGATA@GSI: n-rich Mo isotopes

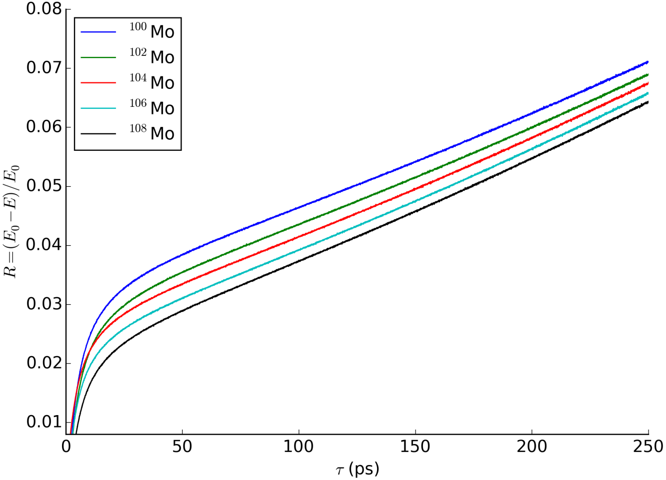
γ-ray spectrum: ^{104}Mo: energy shift of 3% for the $4^+ \rightarrow 2^+$ transition



AGATA@GSI: n-rich Mo isotopes

D. Ralet, Phys. Rev. C, submitted

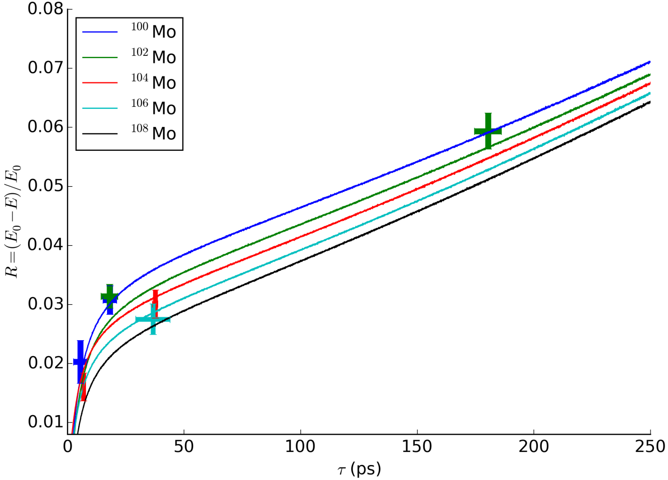
Monte-Carlo simulations of the centroid shift (R) as a function of the half-life



AGATA@GSI: n-rich Mo isotopes

D. Ralet, Phys. Rev. C, submitted

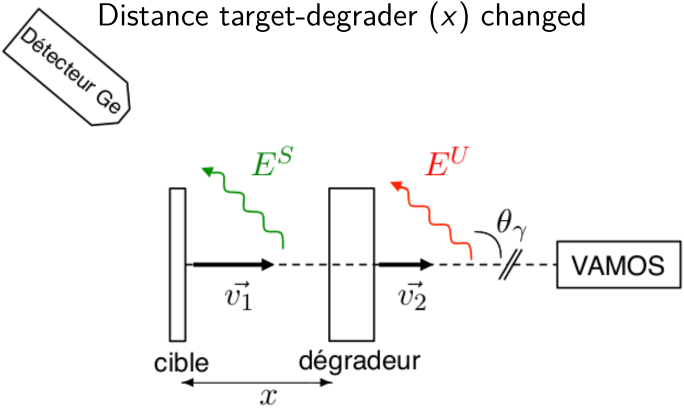
Agreement between measured centroid and known lifetime of the excited levels



Lifetime with a plunger

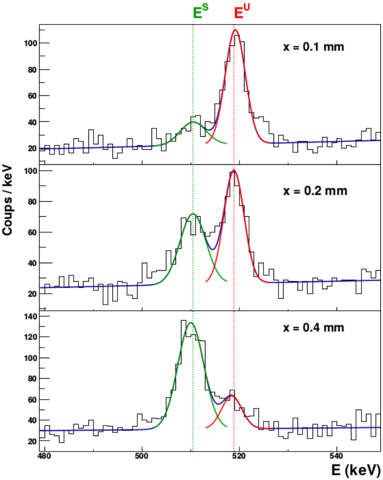
In flight spectroscopy with a plunger

Target produced nuclei in an excited level
Decay with two velocity
Distance target-degrader (x) changed



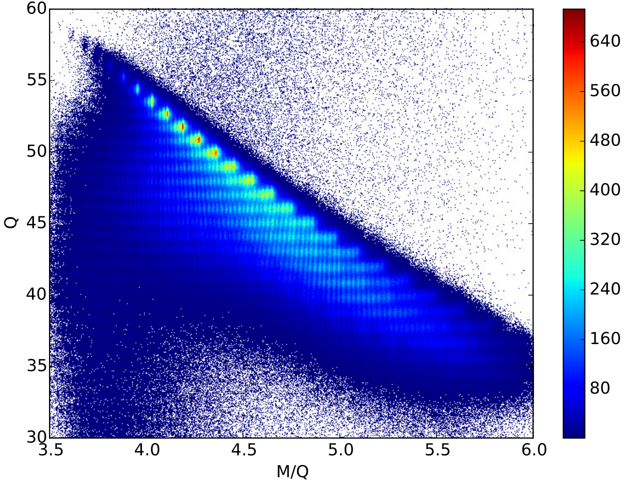
Lifetime with a plunger

Doppler correction (with velocity after the degrader) produced two component for each transitions



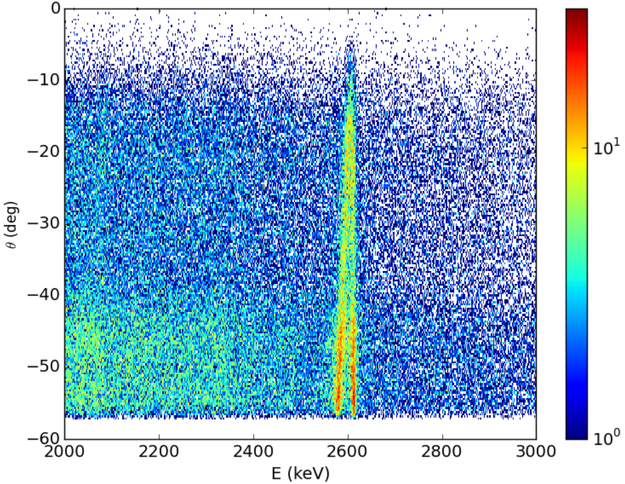
AGATA@GANIL: ^{208}Pb region

GANIL experiment to study the ^{208}Pb region
with mutli-nucleon transfer reactions (identified in VAMOS)



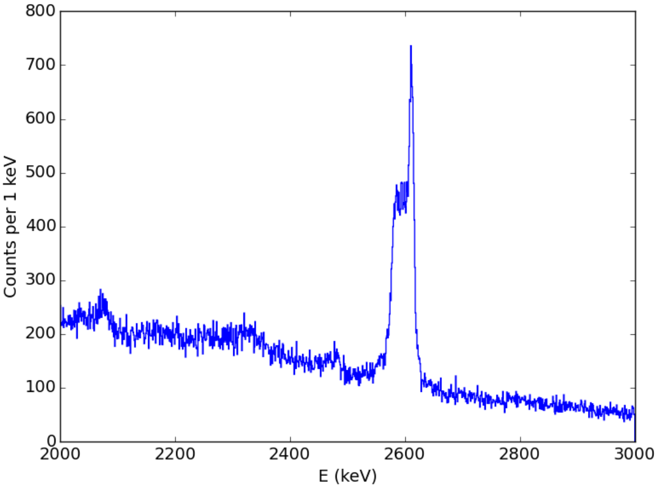
AGATA@GANIL: ^{208}Pb region

First excited state in ^{208}Pb, d=1 mm, with a know lifetime of 16.7(3) ps



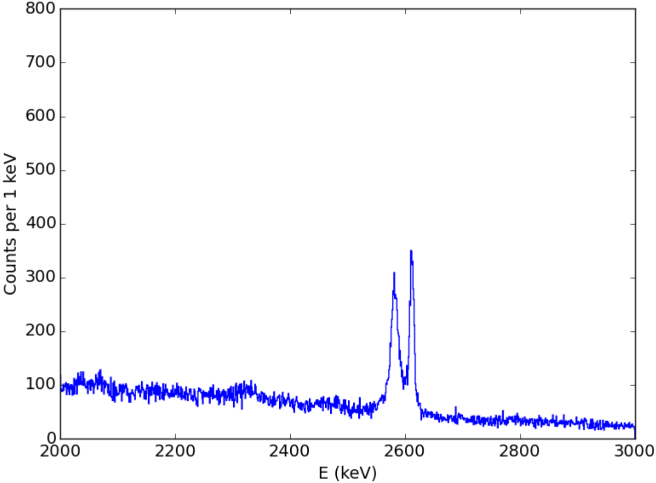
AGATA@GANIL: ^{208}Pb region

Without angle cut



AGATA@GANIL: ^{208}Pb region

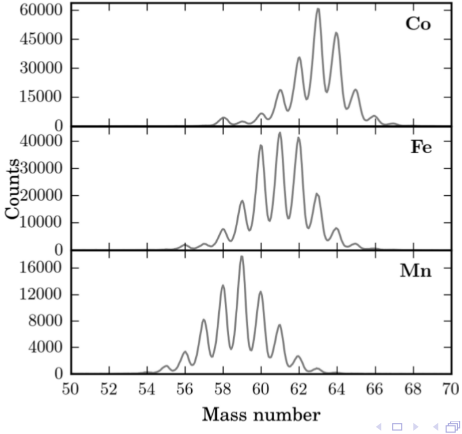
With and optimized angle selection of $\theta < -30$



AGATA@GANIL: $^{62-64}$Fe region

M. Klinterfjord, Phys. Rev. C 95 (2017) 024312

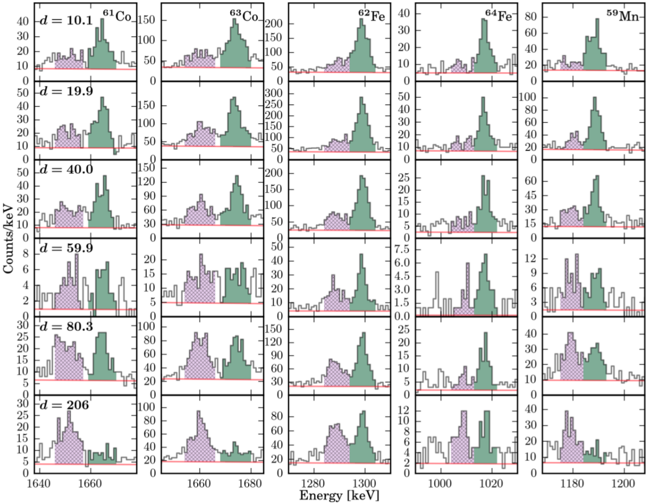
GANIL experiment to study the ^{64}Fe region
VAMOS provided clean identifications
of the transfer reaction products



AGATA@GANIL: $^{62-64}$Fe region

M. Klinterfjord, Phys. Rev. C 95 (2017) 024312

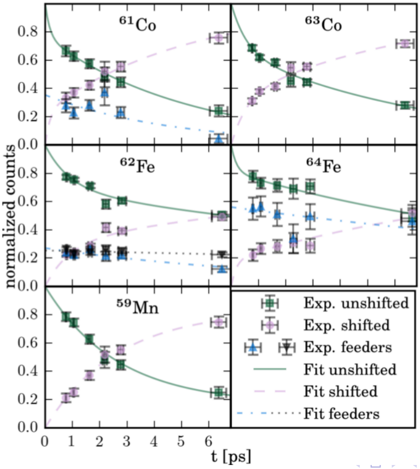
Several distances to get lifetime of all the nuclei



AGATA@GANIL: $^{62-64}$Fe region

M. Klinterfjord, Phys. Rev. C 95 (2017) 024312

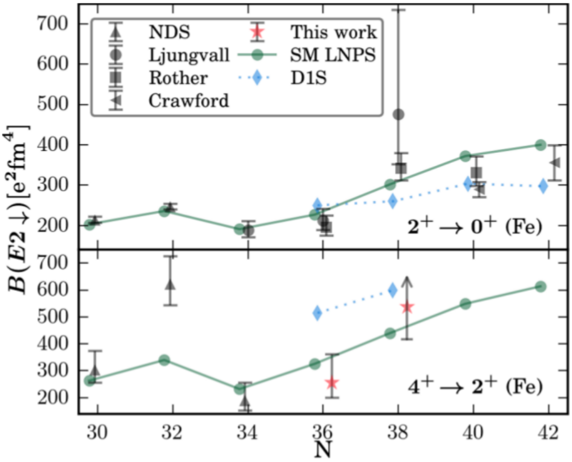
Fitting the shifted and unshifted transitions and potential feeding



AGATA@GANIL: $^{62-64}$Fe region

M. Klinterfjord, Phys. Rev. C 95 (2017) 024312

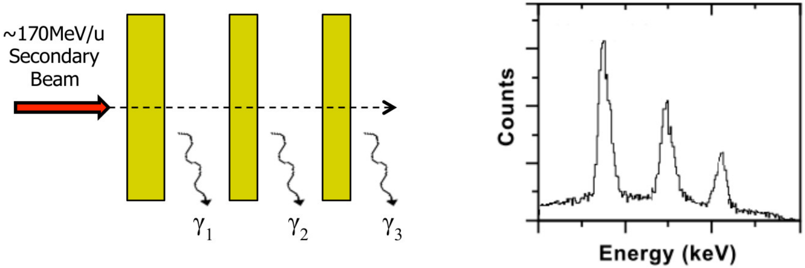
Lifetime results converted in reduce transition strength



Plunger with fixed target

Courtesy: A. Boso, S. Milne, M. Bentley

Fix target lifetime measurement
High beam velocity Fix target lifetime measurement

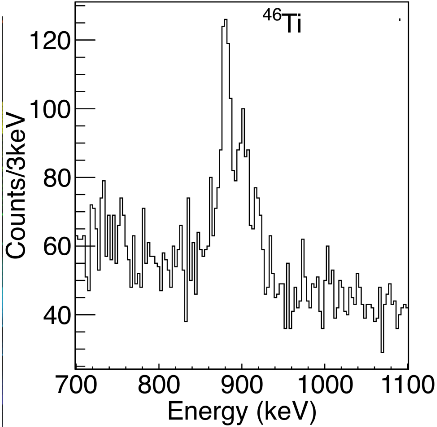


AGATA@GSI: ^{46}Ti and ^{46}V

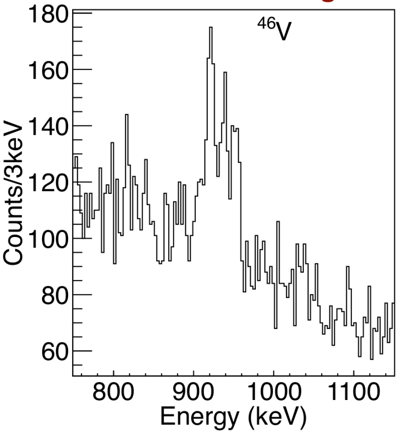
Courtesy: A. Boso, S. Milne, M. Bentley

With the triple target stack
nice separation between the components

^{46}Ti Stretched Target



^{46}V Stretched Target



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Summary

A tracking array such as AGATA is a real gain for γ-ray spectroscopy studies

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Summary

A tracking array such as AGATA is a real gain for γ-ray spectroscopy studies

Provide a considerable gain in resolution after Doppler correction

Allowed low statistic studies and precise measurement of the γ-ray energies

Considerable gain for precise lifetime measurement with a plunger or using DSAM methods

In the future, AGATA will be coupled to new facilities in Europe: SPES (Italy), FAIR (Germany) and SPIRAL (France)