The competitive double-gamma (“γγ/γ”) decay process with the AGATA spectrometer

J.J. Valiente-Dobón[1], N. Pietralla[2], A. Goasduff[3], P.-A. Söderström[2], O. Möller[2], P.R. John[2], P. Napiralla[2], G. De Angelis[1], D. Mengoni[3], …

1 Laboratori Nazionali di Legnaro, Istituto Nazionale di Fisica Nucleare, Padova, Italy.

2 Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany.

3 Dipartimento di Fisica e Astronomia, Università di Padova, Padova, Italy.

Overview

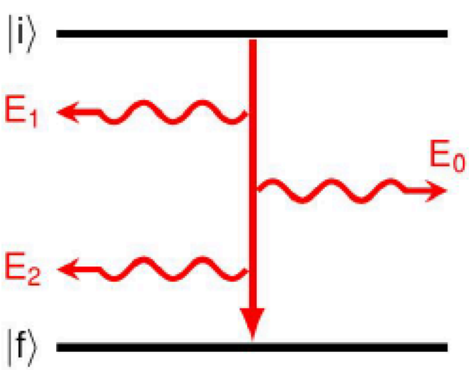
- Competitive double gamma decay process
- AGATA gamma-ray array
- Some starting simulations
- Summary

The genesis

First observation of the competitive double-gamma (“γγ/γ”) decay process

Norbert Pietralla, TU Darmstadt

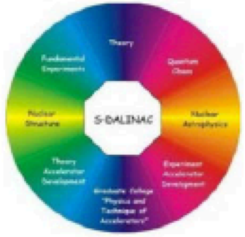
TECHNISCHE UNIVERSITÄT DARMSTADT



Dr. Christopher Walz
The two-photon decay of the 11/2⁻ isomer of ^{137}Ba and mixed-symmetry states of ^{92,94}Zr and ^{94}Mo
(Dissertation, TU Darmstadt, 2014)

Dissertation Award 2014, TU Darmstadt
Dissertation Award 2014, EPS - NPD

SFB634



Supported by DFG

in collaboration with
T. Aumann, V.Yu. Ponomarev, and **H. Scheit** (TU Darmstadt)
Nature **526**, 406 (2015).

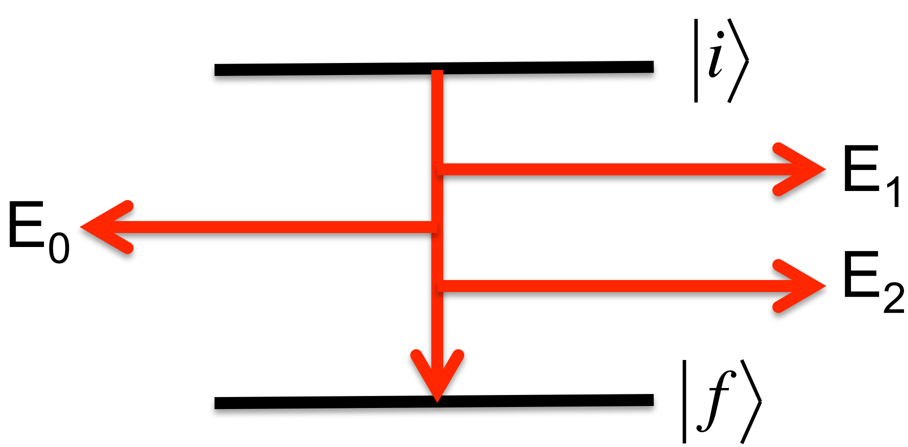
Competitive double gamma decay

- The two-photon decay process is a second order process in quantum electrodynamics (QED) → excited nuclear state emits two gamma-ray energy-quanta of continuous energy
- This double-gamma decay process is formally analogous to 0νββ
- Theoretically the γγ-decay process is treated as a second-order perturbation

First time observed competitive double-gamma ("γγ/γ") decay (Walz et al., nature **526**, 406 (2015))

- Energy sharing of the two gamma rays
- Angular distribution
- Branching ratio $\Gamma\gamma\gamma/\Gamma\gamma = 2.1\ 10^{-6}$ in ^{137}Ba
- Determination of the matrix elements involved in the γγ process → QP calculations

$$\langle f | \hat{\sigma} L | i \rangle$$



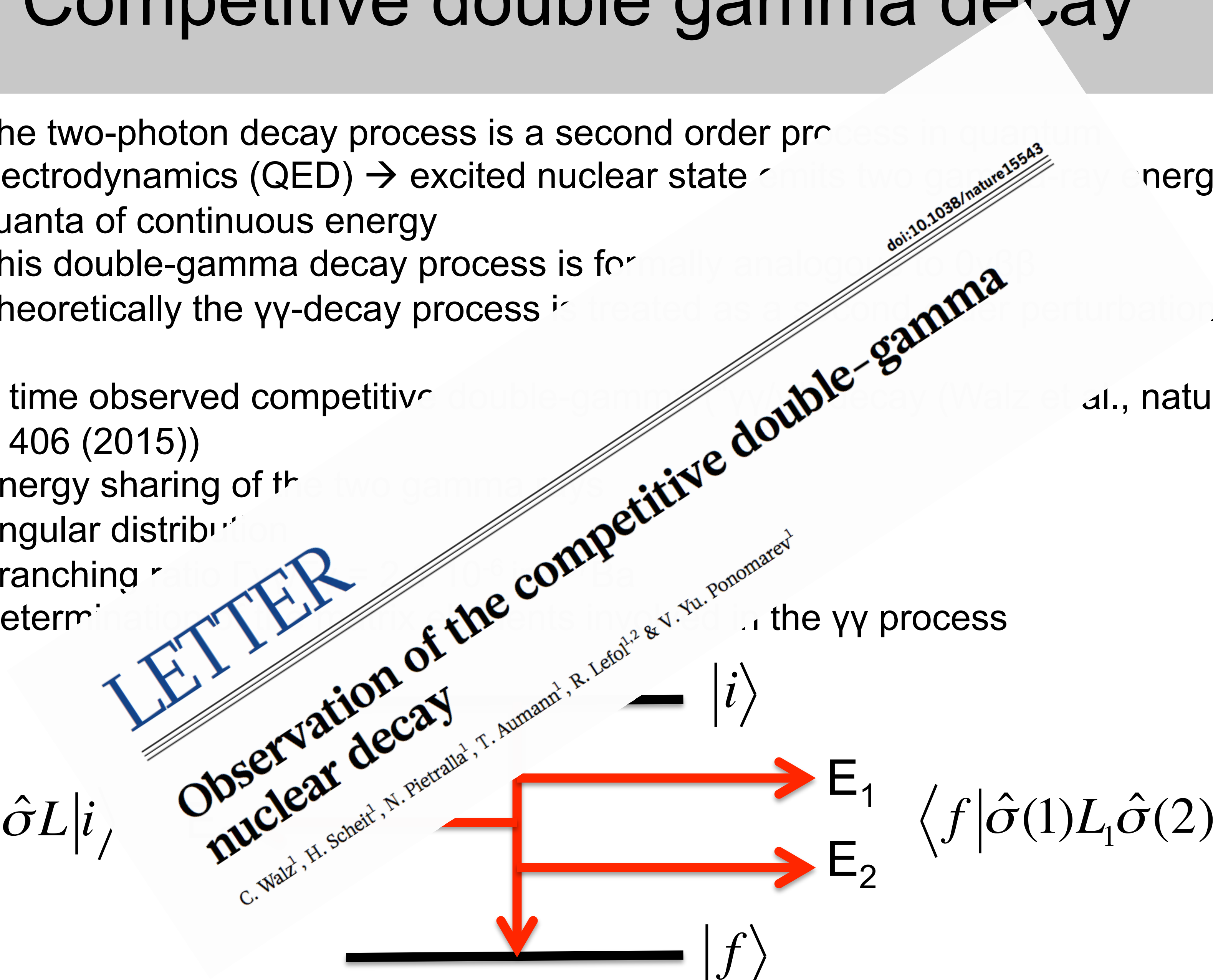
$$\langle f | \hat{\sigma}(1) L_1 \hat{\sigma}(2) L_2 | i \rangle$$

Competitive double gamma decay

- The two-photon decay process is a second order process in quantum electrodynamics (QED) → excited nuclear state emits two gamma-ray energy-quanta of continuous energy
- This double-gamma decay process is formally analogous to $0\nu\beta\beta$
- Theoretically the γγ-decay process is treated as a second-order perturbation.

First time observed competitive double-gamma (γγ/γ)-decay (Walz et al., nature **526**, 406 (2015))

- Energy sharing of the two gamma rays
- Angular distribution
- Branching ratio $\Gamma_{\gamma\gamma}/\Gamma_{\gamma} = 2 \times 10^{-6}$ in Ba
- Determination of the matrix elements involved in the γγ process


LETTER

doi:10.1038/nature15543

Observation of the competitive double-gamma nuclear decay

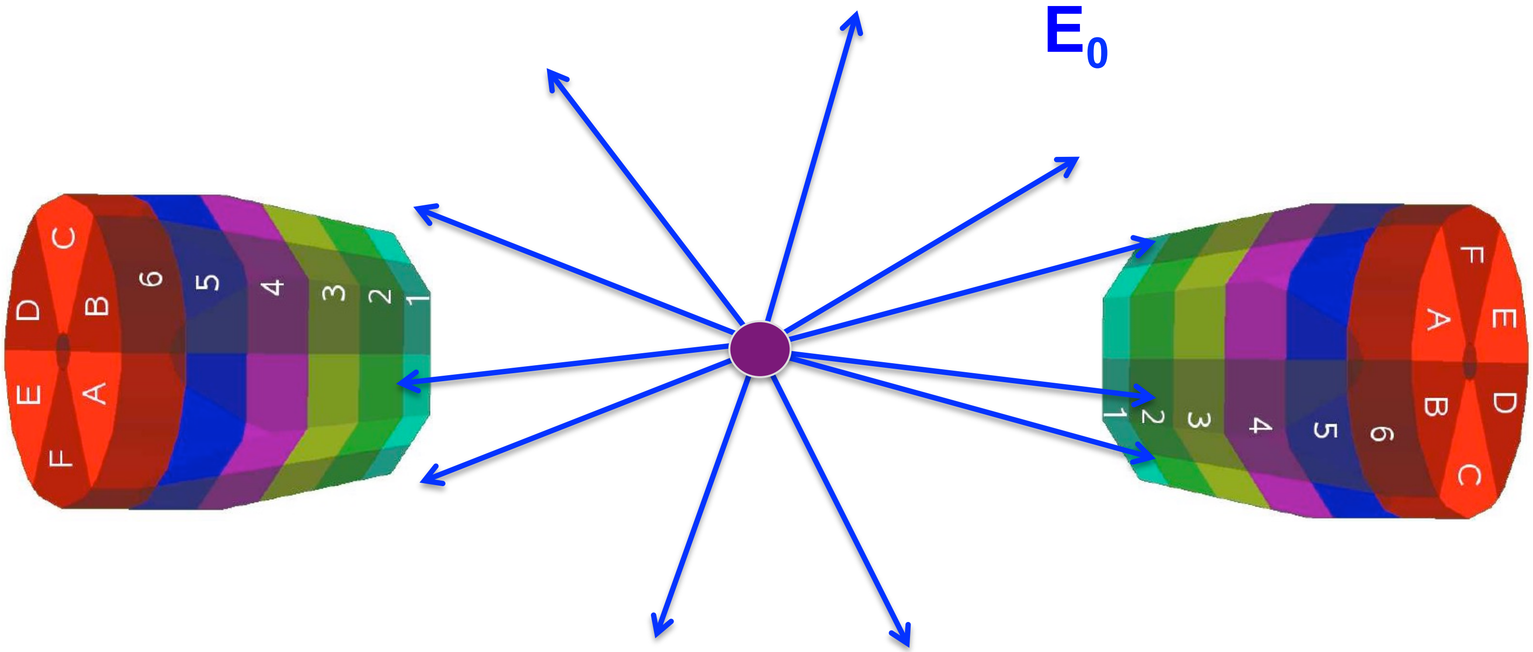
C. Walz[1], H. Scheit[1], N. Pietralla[1], T. Aumann[1], R. Lefol[1,2] & V. Yu. Ponomarev[1]

$$\langle f|\hat{\sigma}L|i\rangle$$

$$\langle f|\hat{\sigma}(1)L_1\hat{\sigma}(2)L_2|i\rangle$$

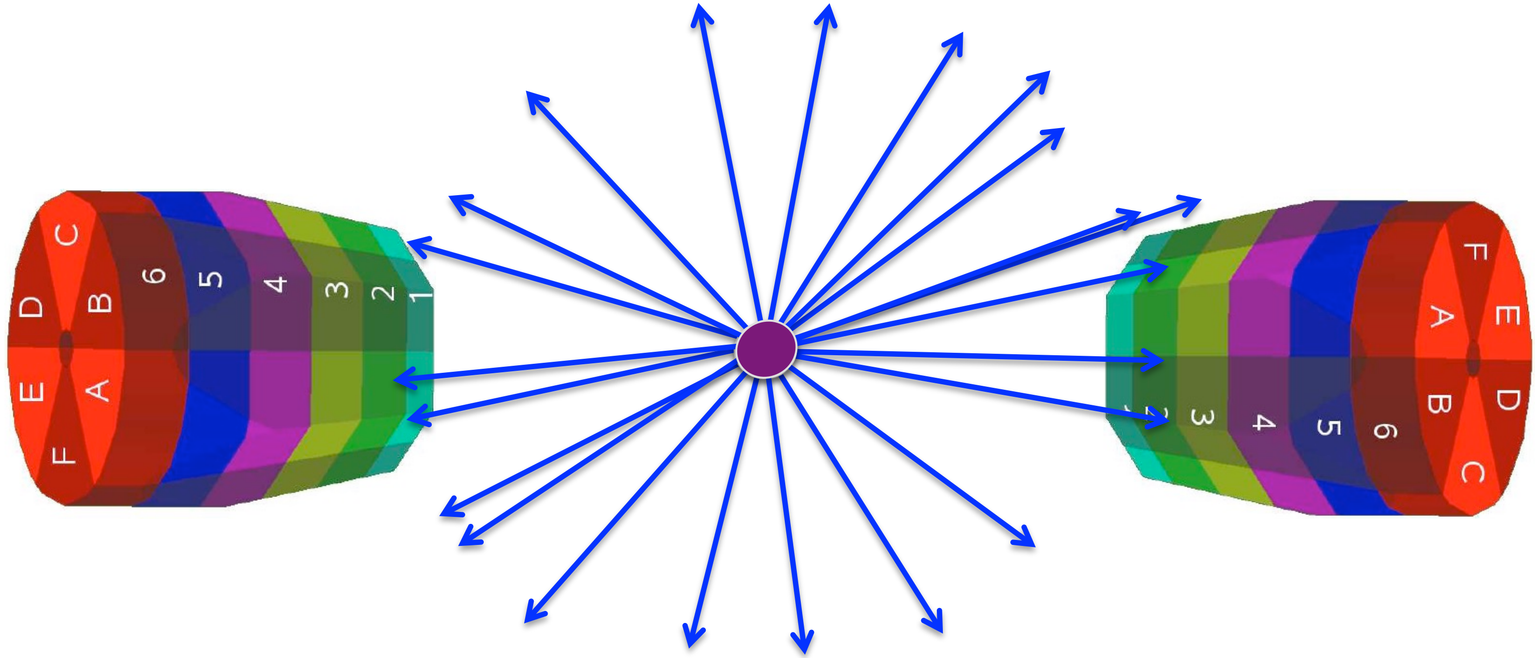
Experimental challenges

- The competitive γγ/γ decay process is at least five orders of magnitude smaller than the single gamma decay.
- Due to the nature of gamma radiation with matter, large probability to have a Compton effect that mimics the γγ/γ decay process $E_0 = E_1 + E_2$
- Two gamma rays with E_0 deposit partial energies → $\Sigma E_i = E_0$
- Gamma natural background



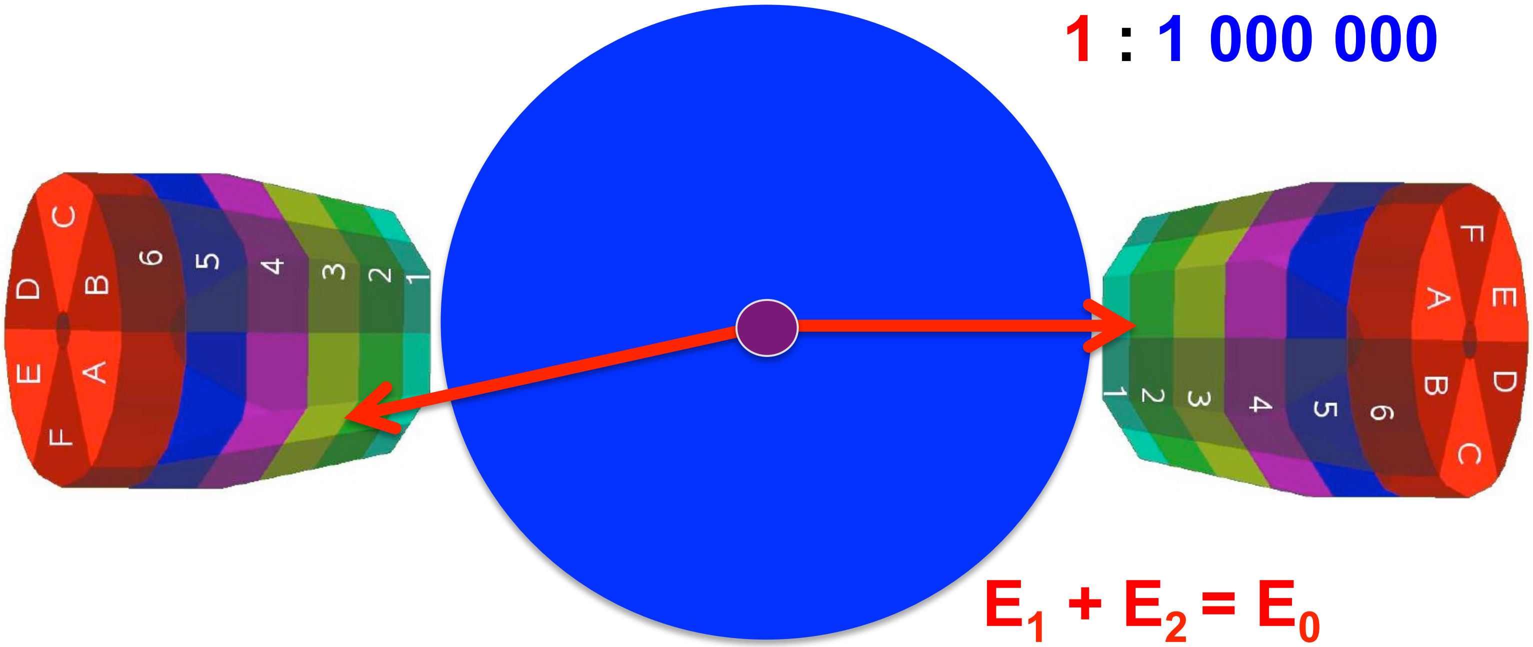
Experimental challenges

- The competitive γγ/γ decay process is at least five orders of magnitude smaller than the single gamma decay.
- Due to the nature of gamma radiation with matter, large probability to have a Compton effect that mimics the γγ/γ decay process $E_0 = E_1 + E_2$
- Two gamma rays with E_0 deposit partial energies → $\Sigma E_i = E_0$
- Gamma natural background



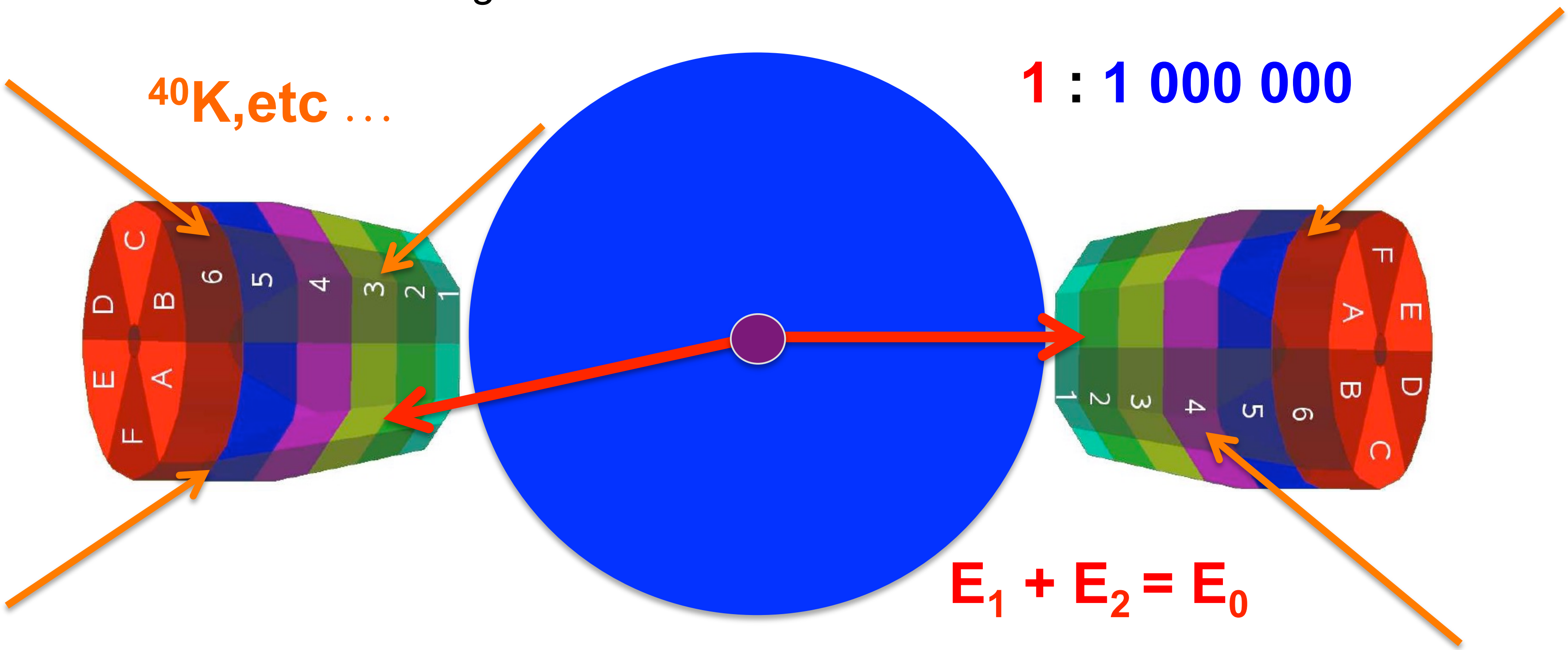
Experimental challenges

- The competitive γγ/γ decay process is at least five orders of magnitude smaller than the single gamma decay.
- Due to the nature of gamma radiation with matter, large probability to have a Compton effect that mimics the γγ/γ decay process $E_0 = E_1 + E_2$
- Two gamma rays with E_0 deposit partial energies → $\Sigma E_i = E_0$
- Gamma natural background

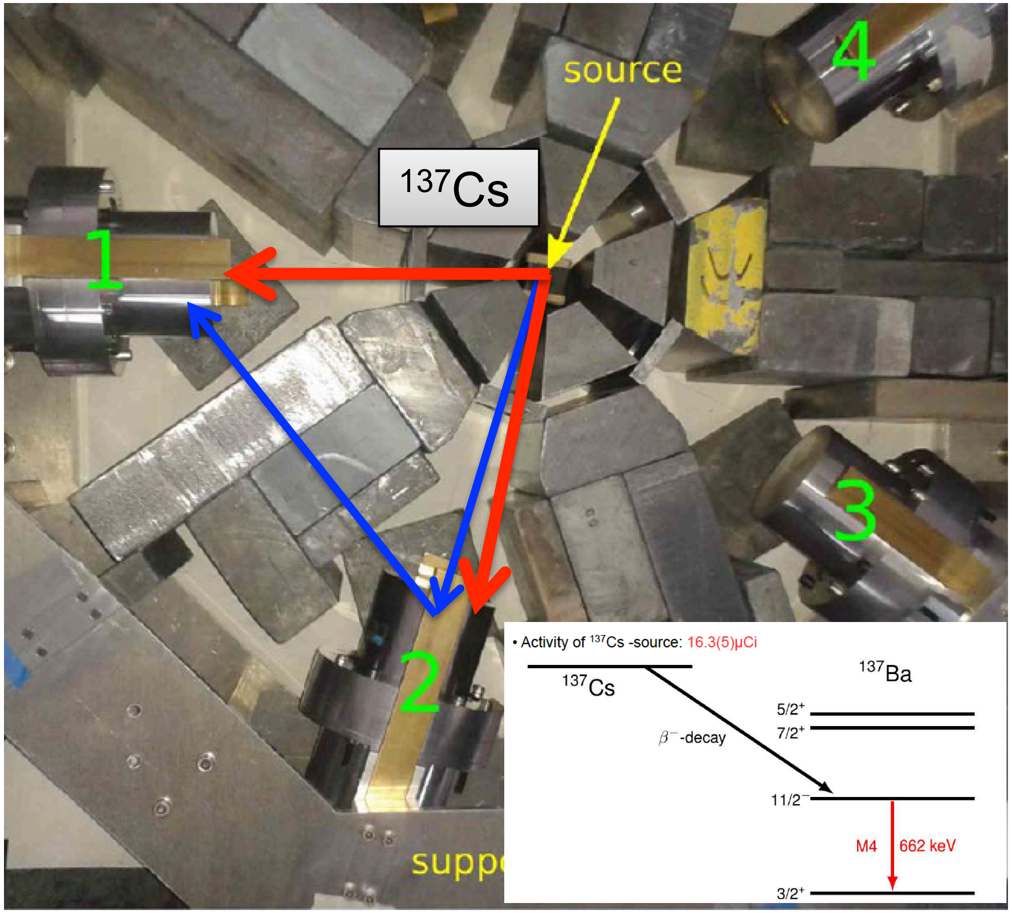


Experimental challenges

- The competitive γγ/γ decay process is at least five orders of magnitude smaller than the single gamma decay.
- Due to the nature of gamma radiation with matter, large probability to have a Compton effect that mimics the γγ/γ decay process $E_0 = E_1 + E_2$
- Two gamma rays with E_0 deposit partial energies → $\Sigma E_i = E_0$
- Gamma natural background

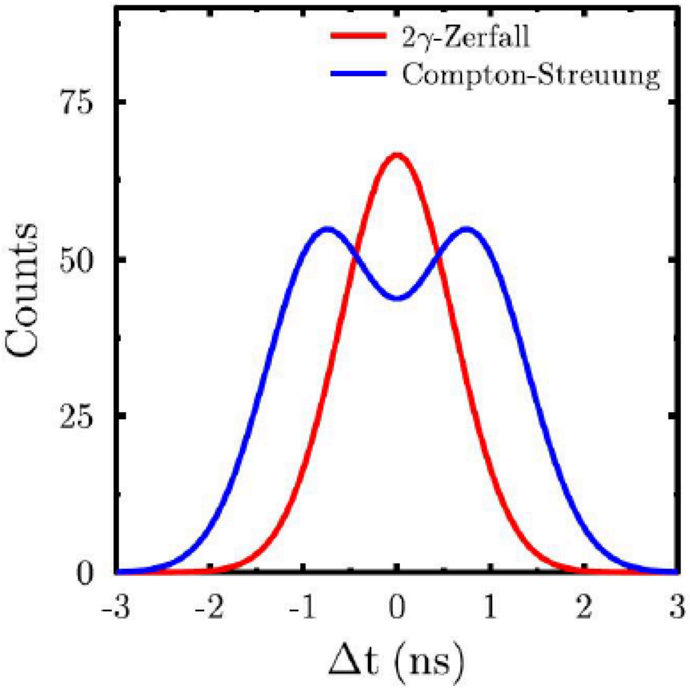


Overcoming experimental challenges



- 5 detector pairs 72°
- 5 detector pairs 144°

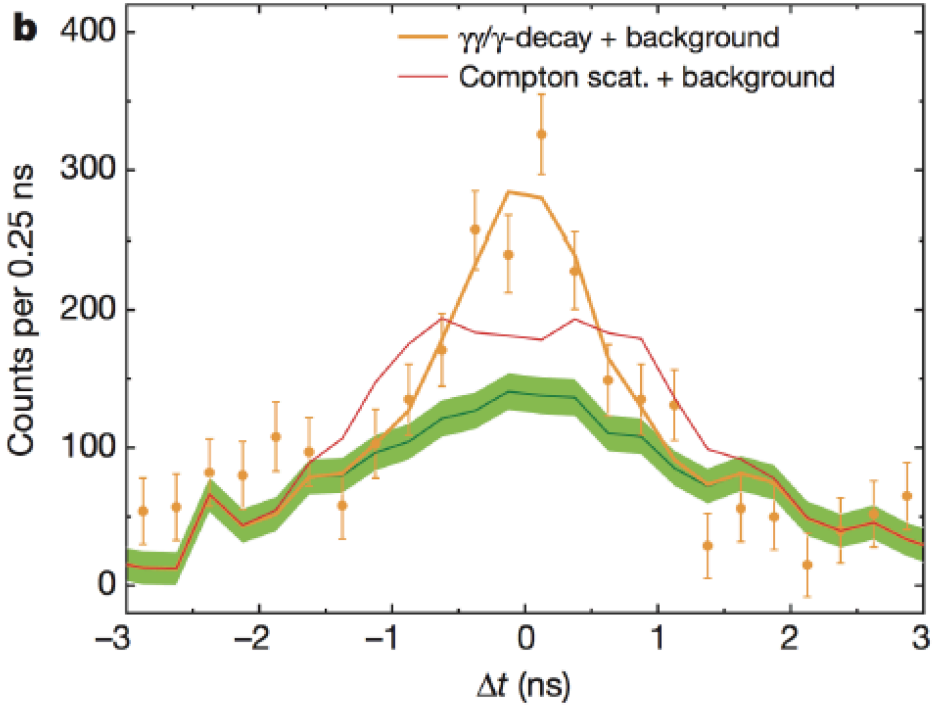
Use of fast $LaBr_3$:Ce scintillators



Courtesy of N. Pietralla

Timing reveals the competitive γγ/γ

The time spectrum originates from a real double gamma decay and not from Compton scattering



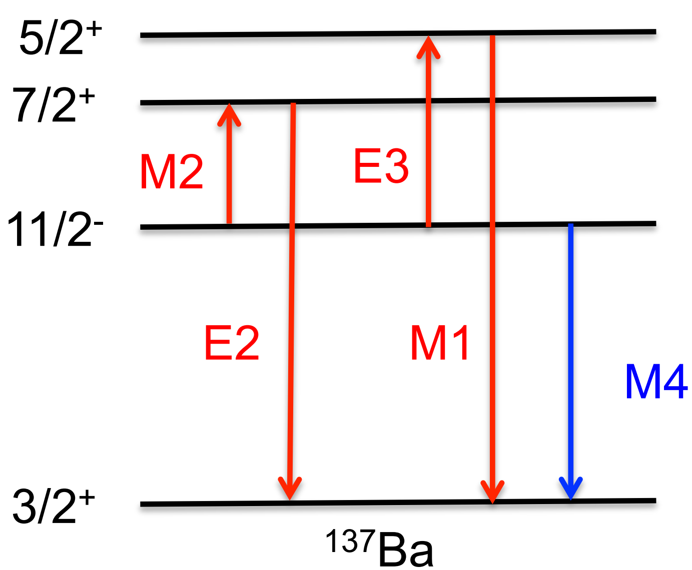
C. Waltz et al., Nature **526**, 406 (2015)

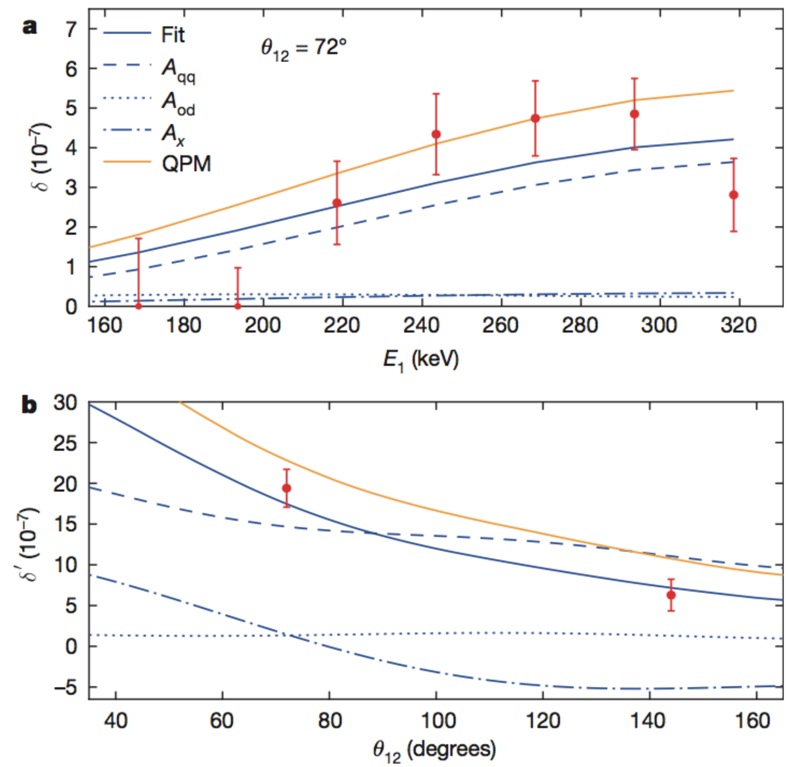
Fig. 1: Time difference spectra. The orange data points correspond to the event in coincidence with the energy-sum spectrum E_1+E_2 after the subtraction of the random coincidences. The green solid line corresponds to the background. The solid orange curve shows the expected time spectrum for γγ-decay, while the solid red curve shows the expected time spectrum, assuming the peak at 661.66 keV was caused by Compton-scattered γ-rays. Taken from Ref. [3], Fig. 2b.

Energy and angular distributions

Good agreement microscopic **quasiparticle–phonon calculations** (second-order perturbation) under the assumption that only α_{E2M2} α_{M1E3} contribute

$$\alpha_{SLSL\prime} = \sum_n \frac{\langle 3/2^+ || S\prime L\prime || I_n \rangle \langle I_n || SL || 11/2^- \rangle}{E_n - 0.5 E_0}$$





C. Waltz et al., Nature **526**, 406 (2015)

Differential branching ratio

$$\frac{d^5\Gamma_{\gamma\gamma}}{d\omega d\Omega d\Omega'} = A_{qq}(\alpha^2_{E2M2}, s) + A_{oq}(\alpha^2_{M1E3}, s) + A_x(\alpha_{E2M2}\alpha_{M1E3}, s)$$

Any chance with HPGe detectors?

Search of (“γγ/γ”) decay with Compton suppresed γ-ray arrays

- *W. Beuschet al., Helv. Phys. Acta33, 363 (1960)*
- *J. Krampet al., NPA 474, 412 (1987)*
- *V.K. Basenkoet al., Bull. Russ. Acad. 56, 94 (1992)*
- *C.J. Lister et al., Bull. Am. Phys. Soc. 58(13), DNP.CE.3 (2013)*

AGATA was built to be used in RIB facilities, which needs are beyond the capability of the best Compton-suppressed Detector Arrays:

- Low intensity for the nuclei of interest
- High background levels
- Large Doppler broadening
- High counting rates
- High γ-ray multiplicities

Any chance with HPGe detectors?

Search of (“γγ/γ”) decay with Compton suppresed γ-ray arrays

- *W. Beuschet al., Helv. Phys. Acta33, 363 (1960)*
- *J. Krampet al., NPA 474, 412 (1987)*
- *V.K. Basenkoet al., Bull. Russ. Acad. 56, 94 (1992)*
- *C.J. Lister et al., Bull. Am. Phys. Soc. 58(13), DNP.CE.3 (2013)*

AGATA in the double gamma decay:

- gamma tracking capabilities
- 10 times better in energy resolution
- higher efficiency
- continuus angular range
- larger gamma-gamma capabilities
- polarization measurements

Why AGATA for the ("γγ/γ") decay?

- Possibility to improve the timing from highly segmented HPGe detectors by using PSA techniques or maybe NN techniques?

NUCLEAR INSTRUMENTS AND METHODS 80 (1970) 233–238; © NORTH-HOLLAND PUBLISHING CO.

APPLICATION OF A PULSE SHAPE SELECTION METHOD TO A TRUE COAXIAL Ge(Li) DETECTOR FOR MEASUREMENTS OF NANOSECONDS HALF-LIVES

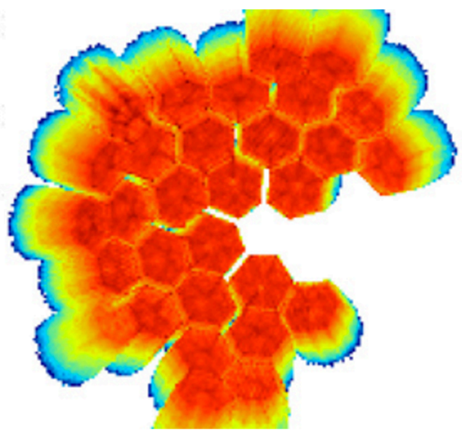
M. MOSZYŃSKI* and B. BENGTSON

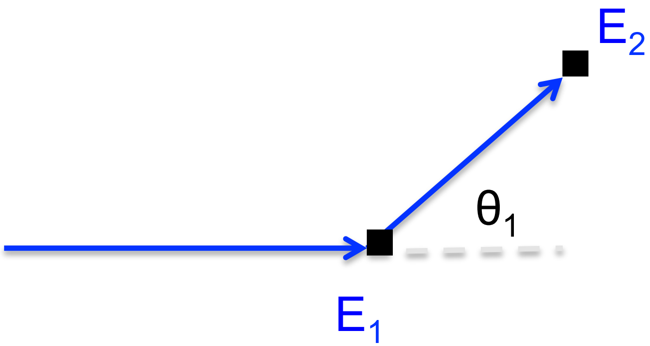
Institute of Physics, University of Aarhus, Aarhus, Denmark

Received 27 October 1969

A study of the pulse shape distribution from a 35 cm^3 true coaxial Ge(Li) detector has been performed for uniform γ-irradiation. Two well defined pulse-shape groups were found which could be separated completely by CR differentiation. The prompt time spectrum derived from the earlier group of pulses gave a fast and exponential slope over more than four decades. By this method it was possible to identify a very weak and delayed transition in the nanosecond range.

- Position sensitivity and PSA to get spatially a difference between Compton scattered events and real double gamma events.





Why AGATA for the (“γγ/γ”) decay?

- Possibility to improve the timing from highly segmented HPGe detectors by using PSA techniques or maybe NN techniques?

NUCLEAR INSTRUMENTS AND METHODS 80 (1970) 233–238; © NORTH-HOLLAND PUBLISHING CO.

APPLICATION OF A PULSE SHAPE SELECTION METHOD TO A TRUE COAXIAL Ge(Li) DETECTOR FOR MEASUREMENTS OF NANOSECONDS HALF-LIVES

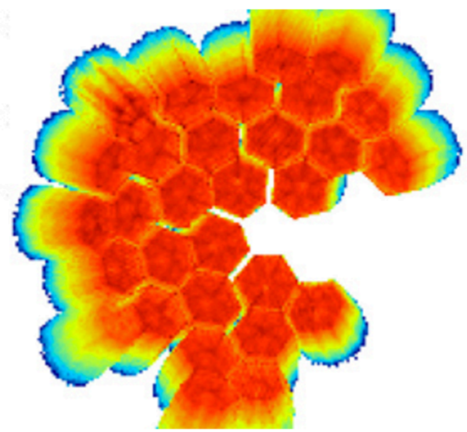
M. MOSZYŃSKI* and B. BENGTSON

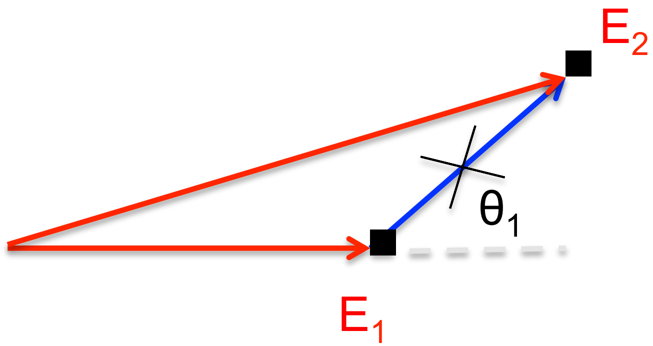
Institute of Physics, University of Aarhus, Aarhus, Denmark

Received 27 October 1969

A study of the pulse shape distribution from a 35 cm^3 true coaxial Ge(Li) detector has been performed for uniform γ-irradiation. Two well defined pulse-shape groups were found which could be separated completely by CR differentiation. The prompt time spectrum derived from the earlier group of pulses gave a fast and exponential slope over more than four decades. By this method it was possible to identify a very weak and delayed transition in the nanosecond range.

- Position sensitivity and PSA to get spatially a difference between Compton scattered events and real double gamma events.





Idea of γ-ray tracking

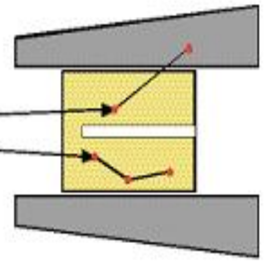
Compton Suppressed

$\varepsilon_{ph} \sim 10\%$

$N_{det} \sim 100$

$\Omega \sim 40\%$

$\theta \sim 8^o$



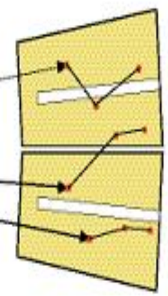
Ge Sphere

$\varepsilon_{ph} \sim 50\%$

$N_{det} \sim 1000$

$\Omega \sim 80\%$

$\theta \sim 3^o$



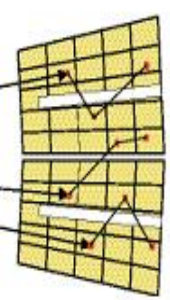
Tracking Array

$\varepsilon_{ph} \sim 50\%$

$N_{det} \sim 100$

$\Omega \sim 80\%$

$\theta \sim 1^o$



Pulse Shape Analysis
Gamma-ray Tracking

$\theta_{eff} \sim 1^o$

$N_{eff} \sim 10000$

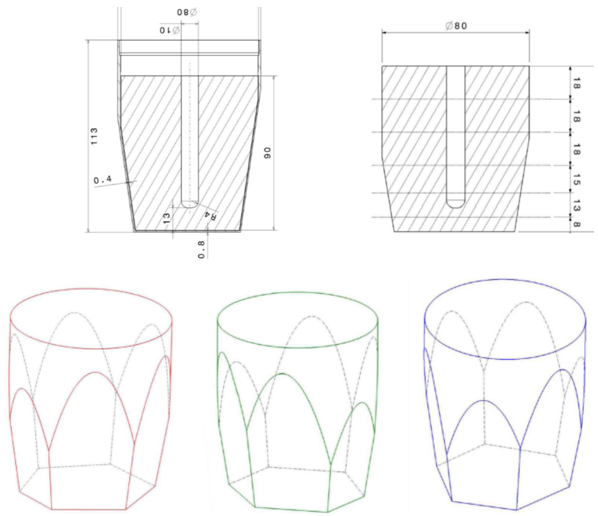
- 50% of solid angle taken by the AC shields
- large opening angle ➔ poor energy resolution at high recoil velocity

- too many detectors needed to avoid summing effects
- opening angle still too big for very high recoil velocity

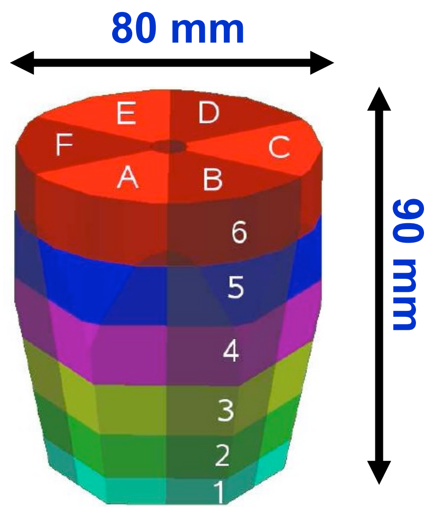
Smarter use of Ge detectors

- segmented detectors
- digital electronics
- time stamping of events
- analysis of pulse shapes
- tracking of γ-rays

AGATA detectors



Volume ~370 cc   Weight ~2 kg
(shapes are volume-equalized to 1%)

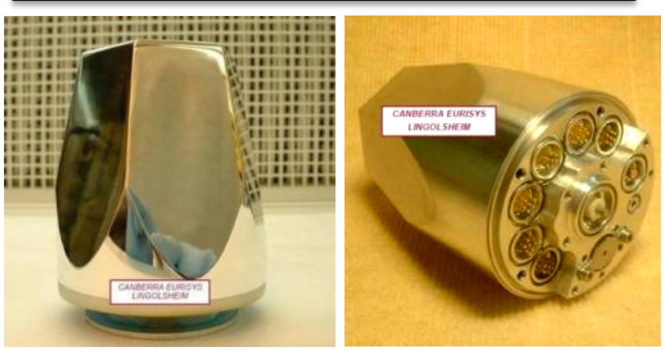


6x6 segmented cathode

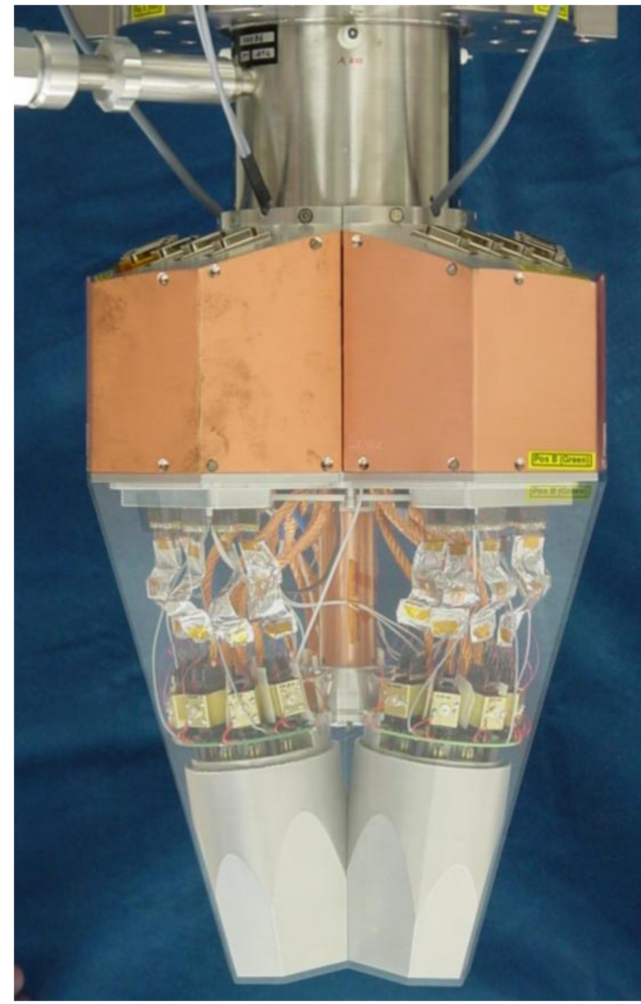
Cold FET for all signals

Energy resolution
Core: 2.35 keV
Segments: 2.10 keV
(FWHM @ 1332 keV)

A. Wiens et al. NIM A 618 (2010) 223
D. Lersch et al. NIM A 640(2011) 133



AGATA capsules
Manufactured by Canberra France



AGATA Asymmetric Triple Cryostat
Manufactured by CTT

AGATA reference

Nuclear Instruments and Methods in Physics Research A 668 (2012) 26–58

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

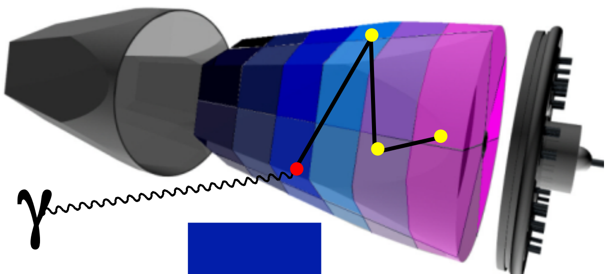
ELSEVIER

AGATA—Advanced GAmma Tracking Array

AGATA
ADVANCED GAMMA
TRACKING ARRAY

Flow chart for AGATA

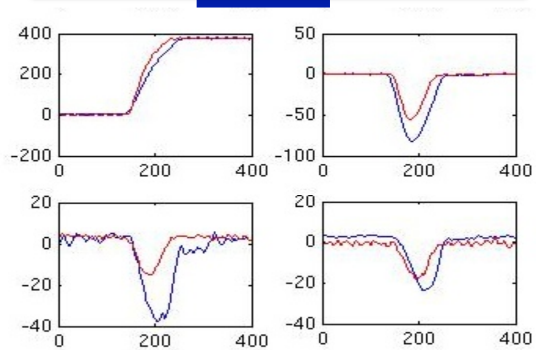
Highly segmented HPGe detectors



Synchronized digital electronics to digitize (14 bit, 100 MS/s) and process the 37 signals generated by crystals

HARDWARE

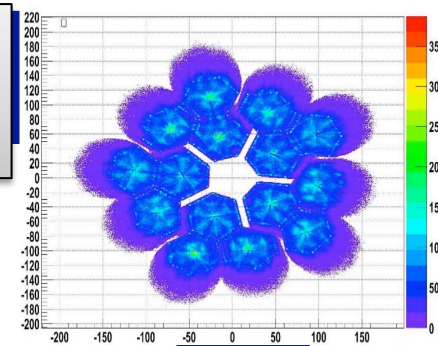
Pulse Shape Analysis of the recorded waves



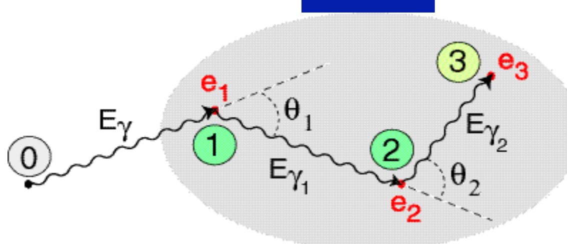
Identified interaction points

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

Event building of time-stamped hits and ancillaries



Reconstruction of γ-rays from the hits

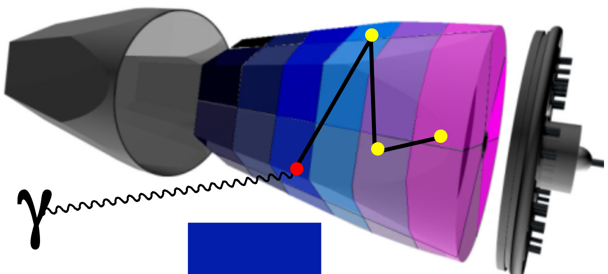


Analysis of gammas and correlation with other detectors

SOFTWARE

Flow chart for AGATA

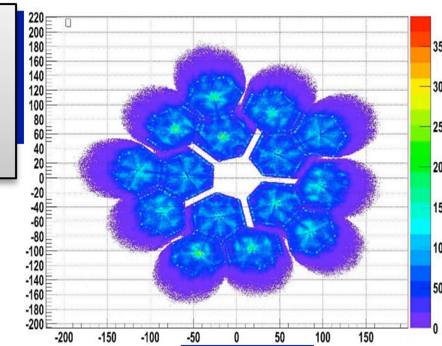
Highly segmented HPGe detectors



Synchronized digital electronics to digitize (14 bit, 100 MS/s) and process the 37 signals generated by crystals

HARDWARE

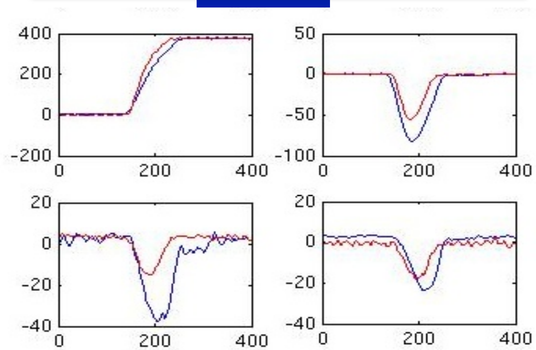
Event building of time-stamped hits and ancillaries



Identified interaction points

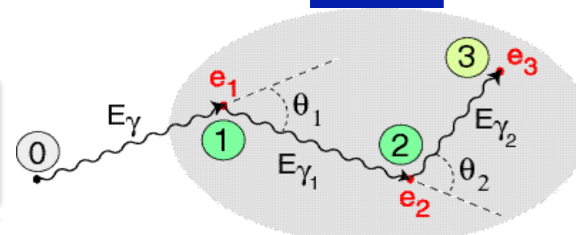
$(x,y,z,E,t)_i$

Pulse Shape Analysis of the recorded waves



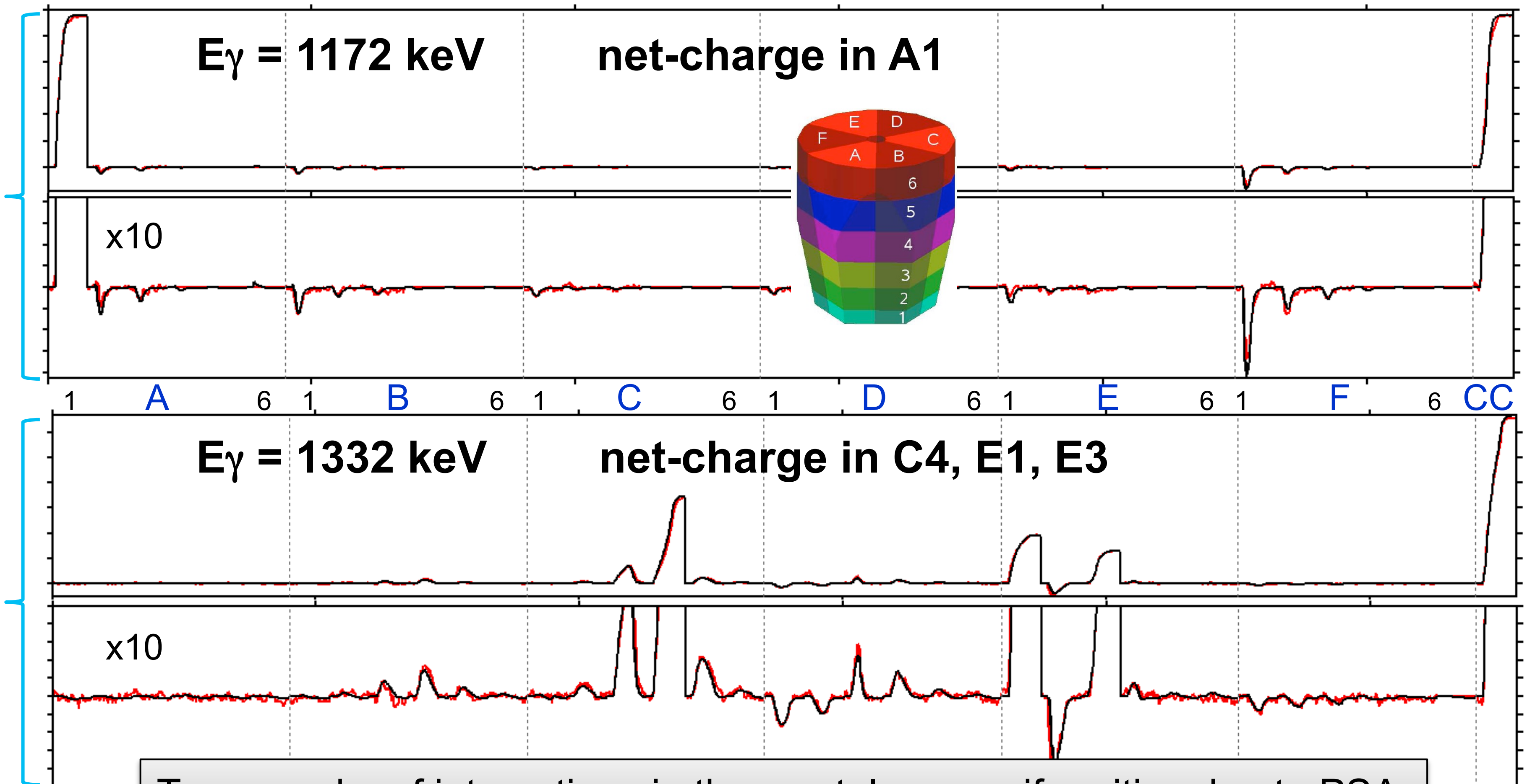
SOFTWARE

Reconstruction of γ-rays from the hits

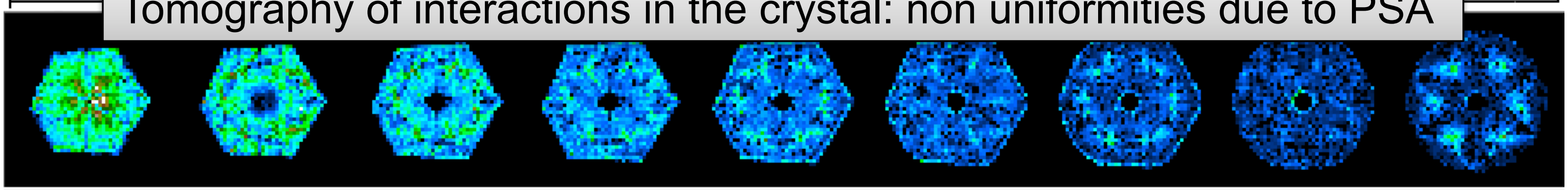


Analysis of gammas and correlation with other detectors

Examples of signals for 2 events



Tomography of interactions in the crystal: non uniformities due to PSA



Timing with HPGe detectors

- HPGe timing resolution 8 - 10ns → electric noise + signal changes shape depending on the gamma-ray interaction positions.
- Constant Fraction Discriminator (CFD) → perfectly rising time front

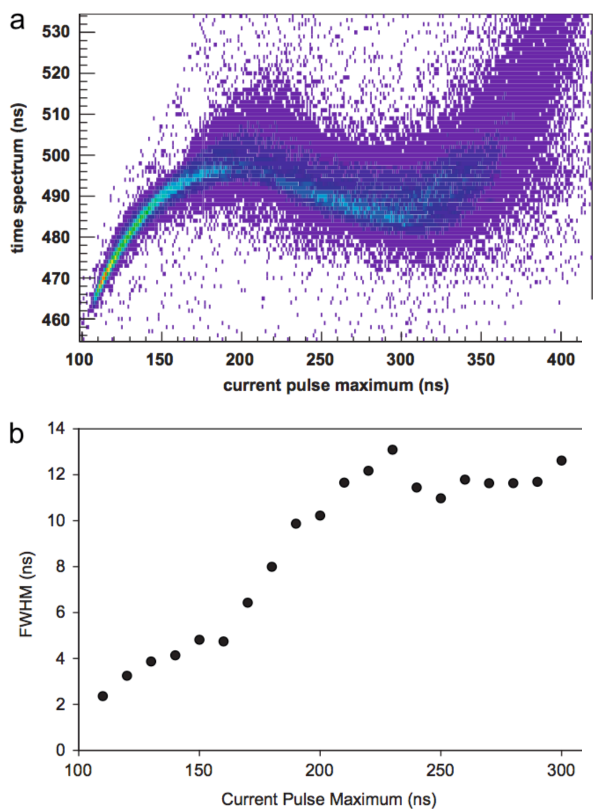


Fig. 3. (a) The 2-dimensional histogram displays the CFD output time distributi (y-axis) as a function of the current pulse maximum position (x-axis). (b) The C time resolution (i.e. FWHM of the vertical slices of the histogram in Fig. 3(a)) a function of the current pulse maximum position. In these plots reasonable l unoptimized CFD parameters are used. Error bars are smaller than the size of tne symbols.

Nuclear Instruments and Methods in Physics Research A 620 (2010) 299–304

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

HPGe detectors timing using pulse shape analysis techniques

F.C.L. Crespi [a], V. Vandone [a], S. Brambilla [b], F. Camera [a,*], B. Million [b], S. Riboldi [a], O. Wieland [b]

[a] Dipartimento di Fisica, Università di Milano, Italy
[b] INFN Sezione di Milano,Via Celoria 16, 20133 Milano, Italy

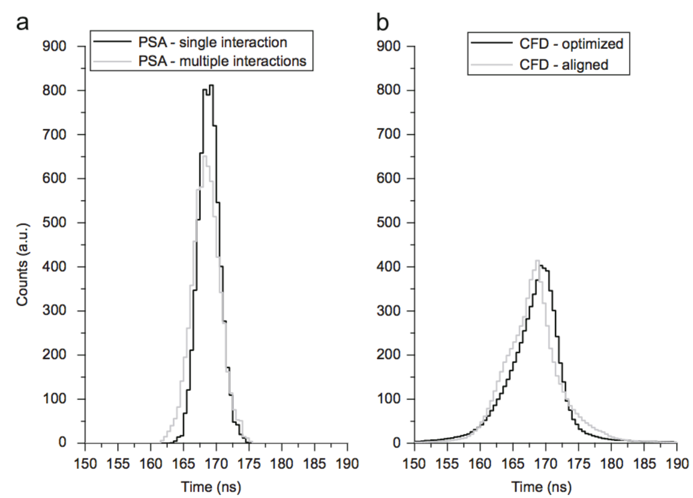


Fig. 6. Right panel: comparison between the time distributions obtained with a standard CFD with optimized coefficients (black line histogram, 7.6 ns FWHM) and the alignment of the centroid positions (grey line histogram, 8.2 ns FWHM; see Section 3 for details). Left Panel: time distributions obtained with the PSA algorithm. The black line histogram (3.2 ns FWHM) is the one related to the single interaction events, and the grey histogram refers to the multiple interaction events (4.2 ns FWHM).

NN algorithms for timing?

P.A. Söderström et al. an example for n/gamma discrimination

A feed-forward neural network was created based on the ROOT TMultiLayerPerceptron class. Designed with 75 input nodes (first 75 sampling points) - two hidden layers of 20 and 5 nodes → output one node 0 gamma ray and 1 neutron.

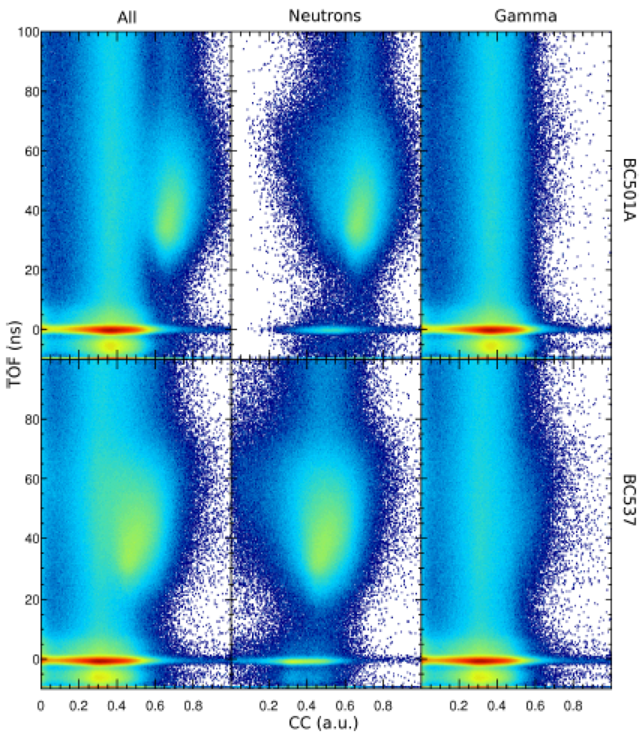


Figure 4: (Colour online.) Two-dimensional plots in logarithmic scale of time-of-flight versus digital charge comparison for the full data set (left), selected on neutrons (middle) and γ rays (right) for BC-501A (top) and BC-537 (bottom) using the artificial neural network.

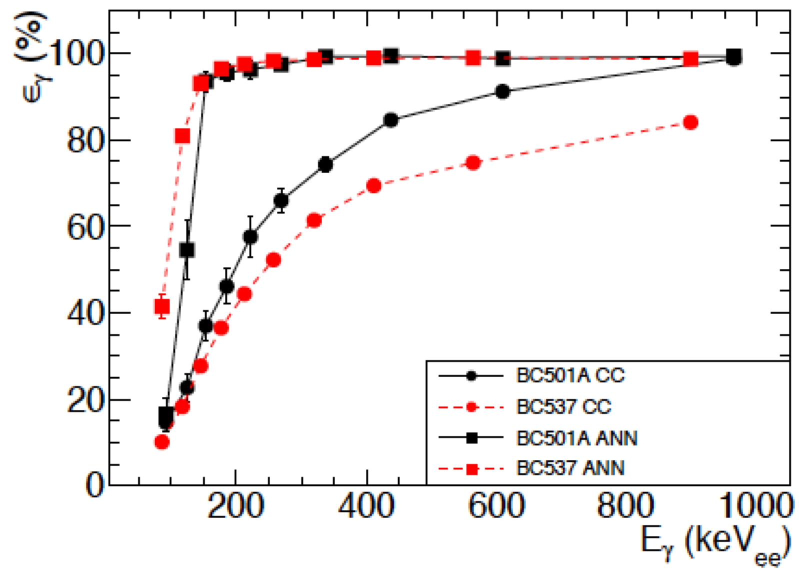
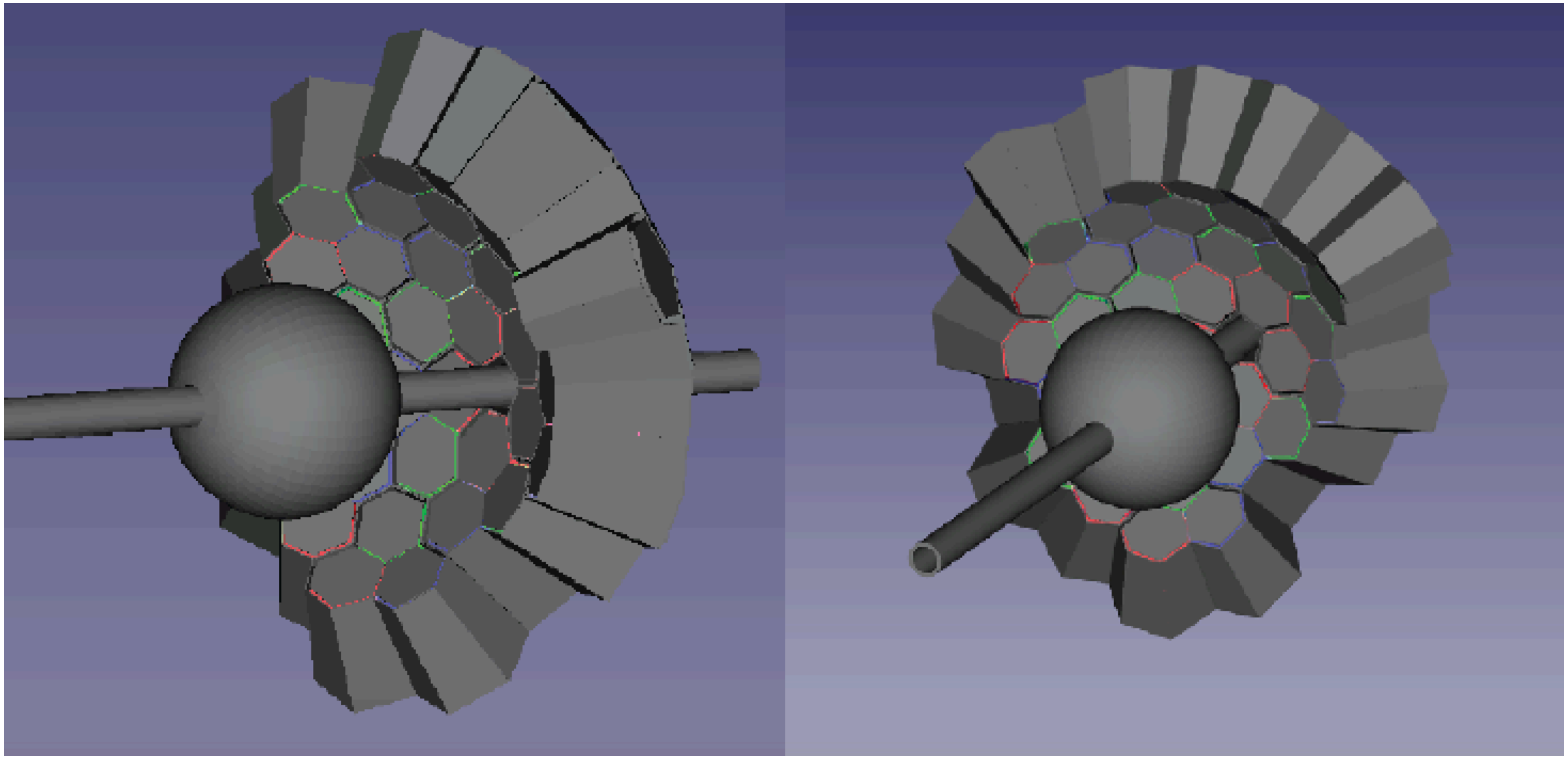


Figure 6: (Colour online.) Rejection efficiency of γ rays for a pulse-shape discrimination gate that contains 90 % of the neutrons. BC-501A is shown in black and BC-537 in red. The two discrimination algorithms are: artificial neural networks (squares) and charge comparison (circles).

AGATA simulations

To make some considerations we will consider the configuration at GANIL 2018 (by Alain Goasduff)

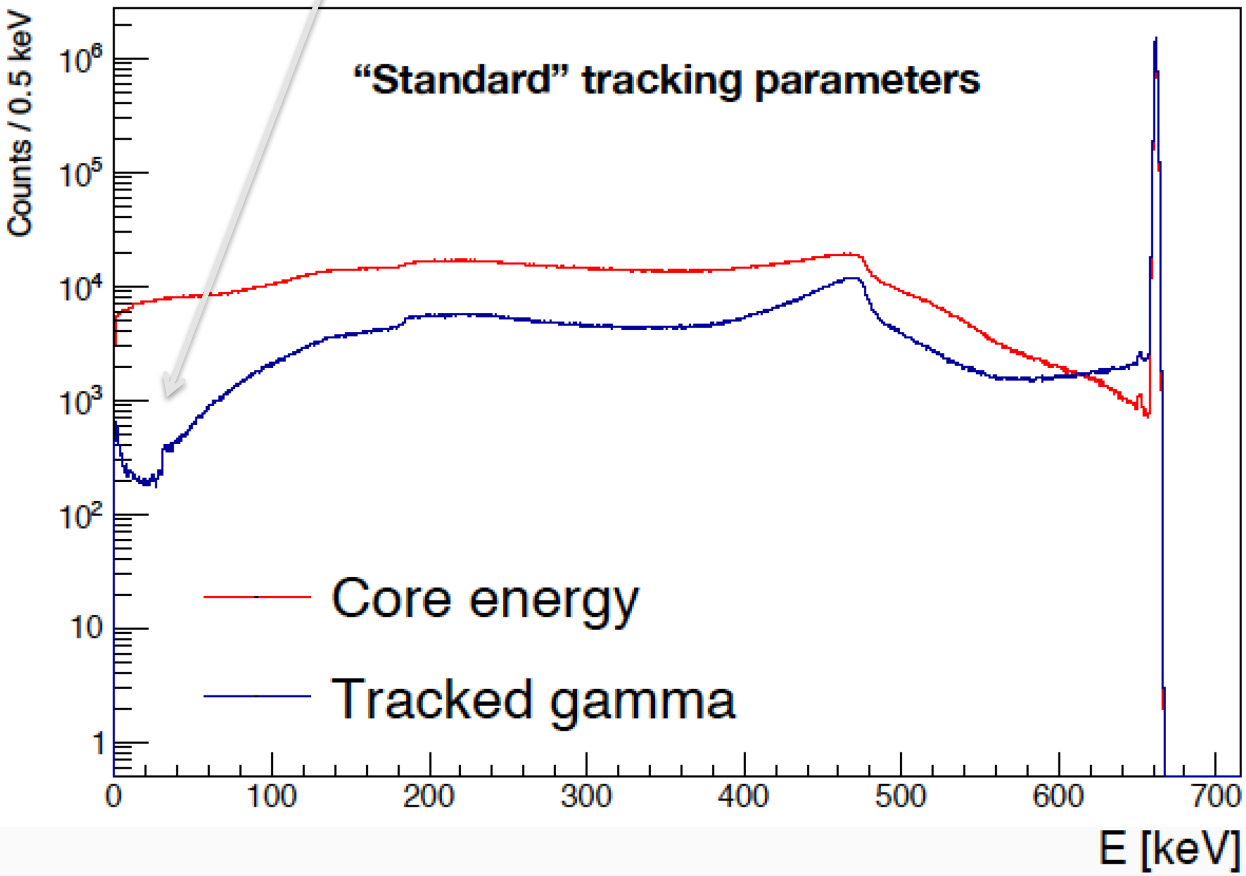
- 12 Agata Triple Cluster placed at backward angles
- AGATA at the nominal position, i.e. 23.5 cm from the target
- No anti-Compton shield between the HPGe.



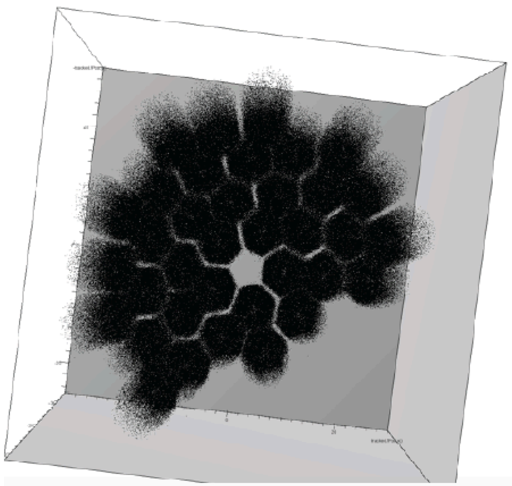
AGATA simulations

One unique gamma of 662 keV

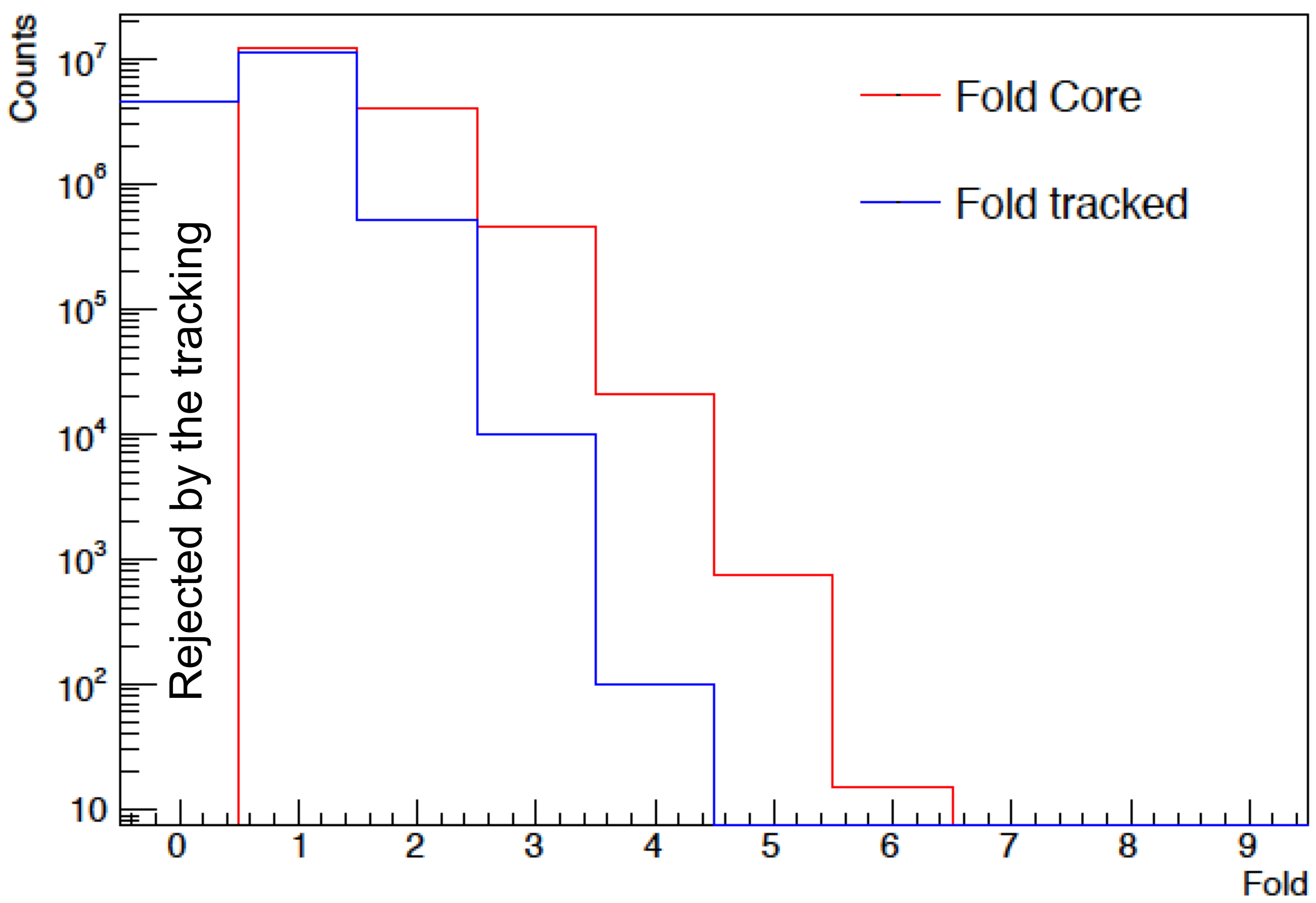
Threshold in the photo electric events



Tracking

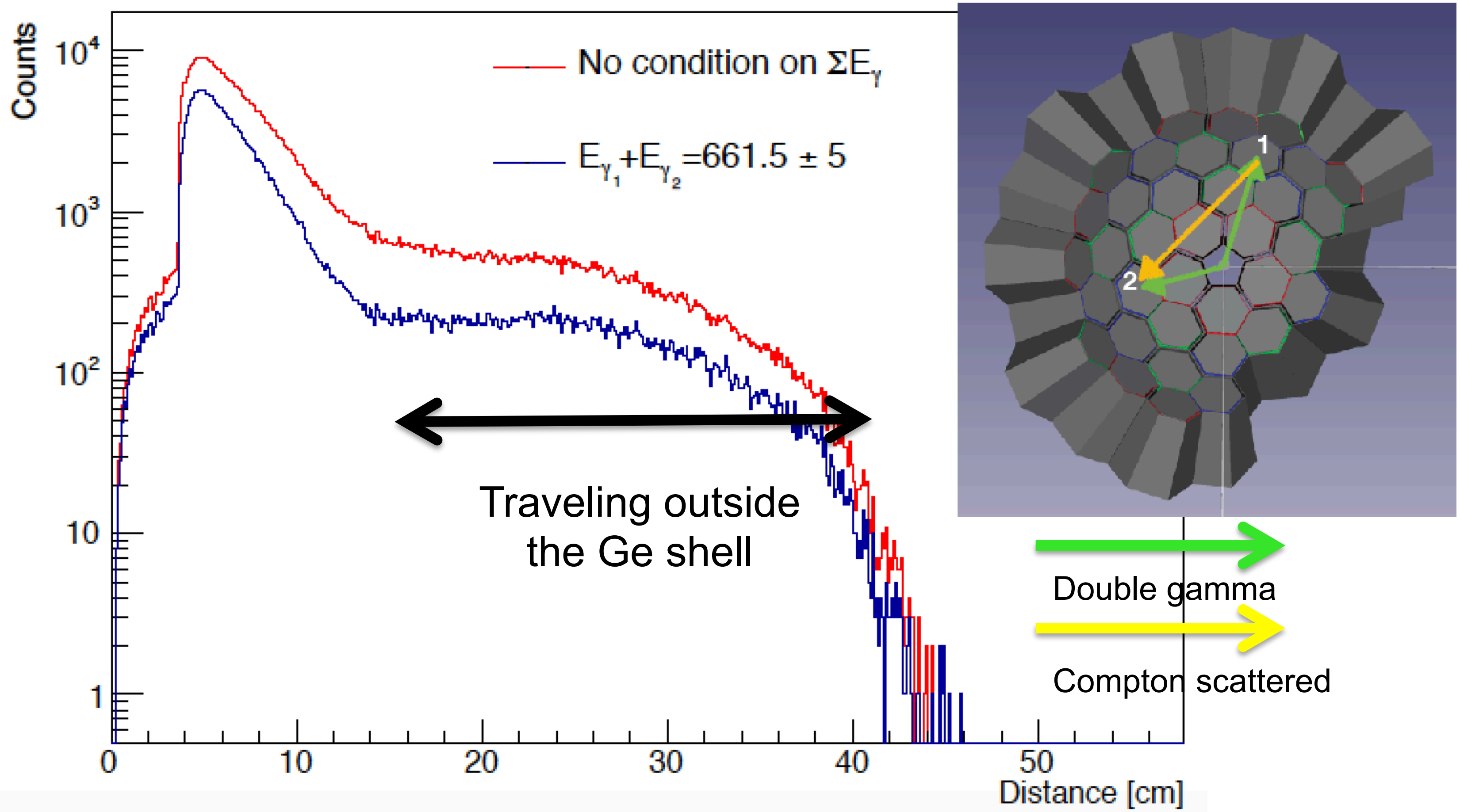


“Multiplicity” for 1 gamma 662 keV



AGATA

Distance between interactions: Tracking only fold 2 events



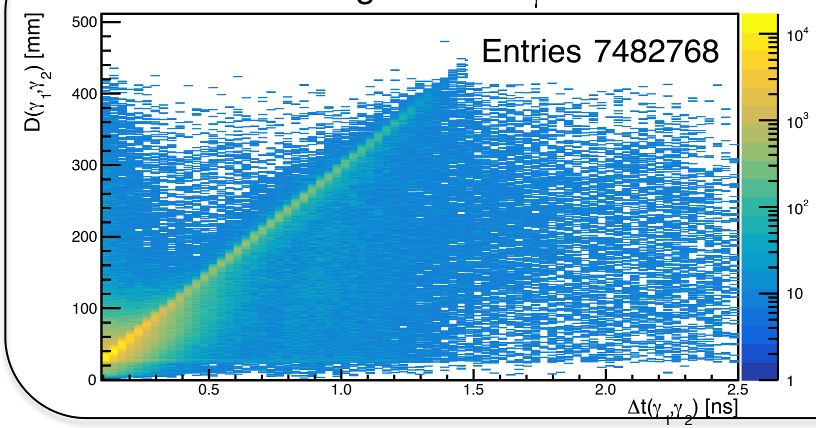
Tracking parameter d(γ1,γ2) ≤ 2.5cm → can not be a single event
Probability of being a single event is ~ 5%

AGATA distance vs. timing

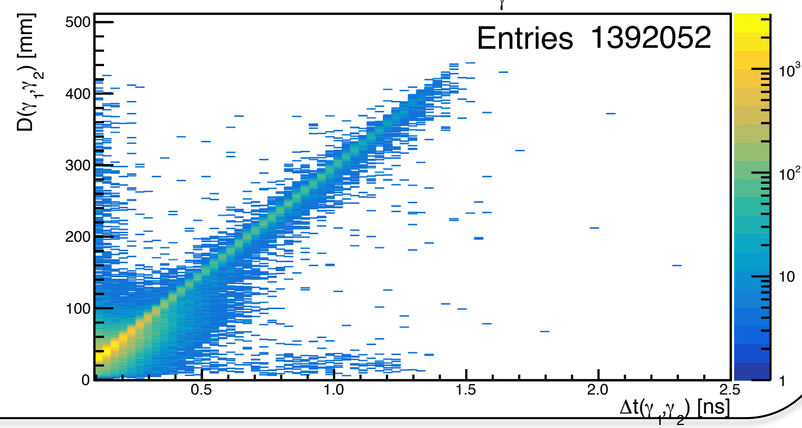
One gamma → Fold=2

Clusterization space 8 degrees

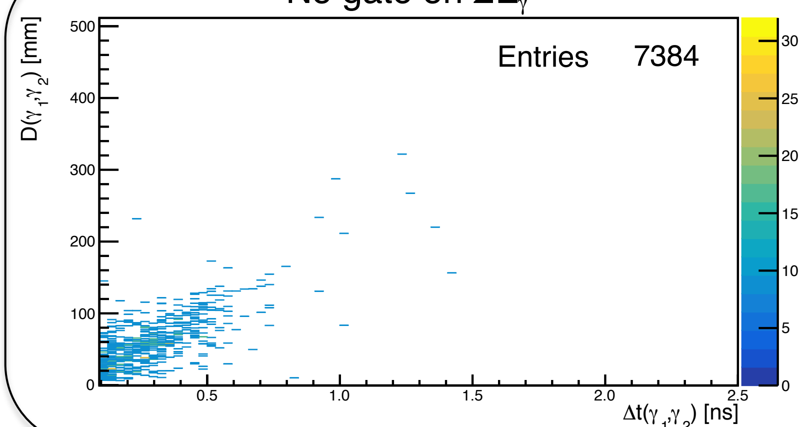
No gate on ΣE_γ



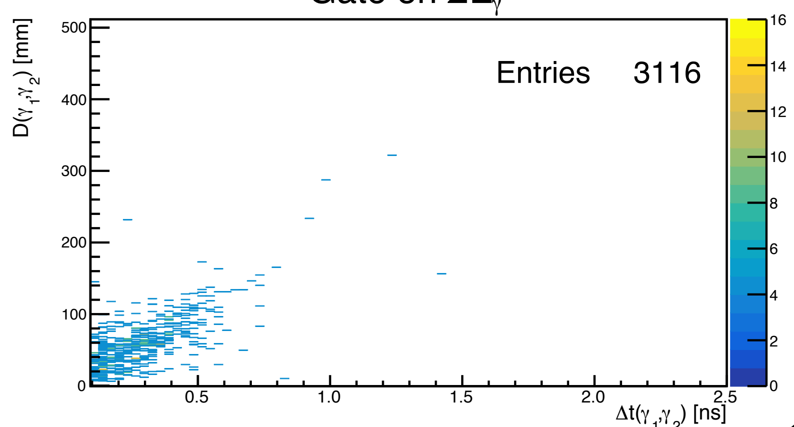
Gate on ΣE_γ



No gate on ΣE_γ

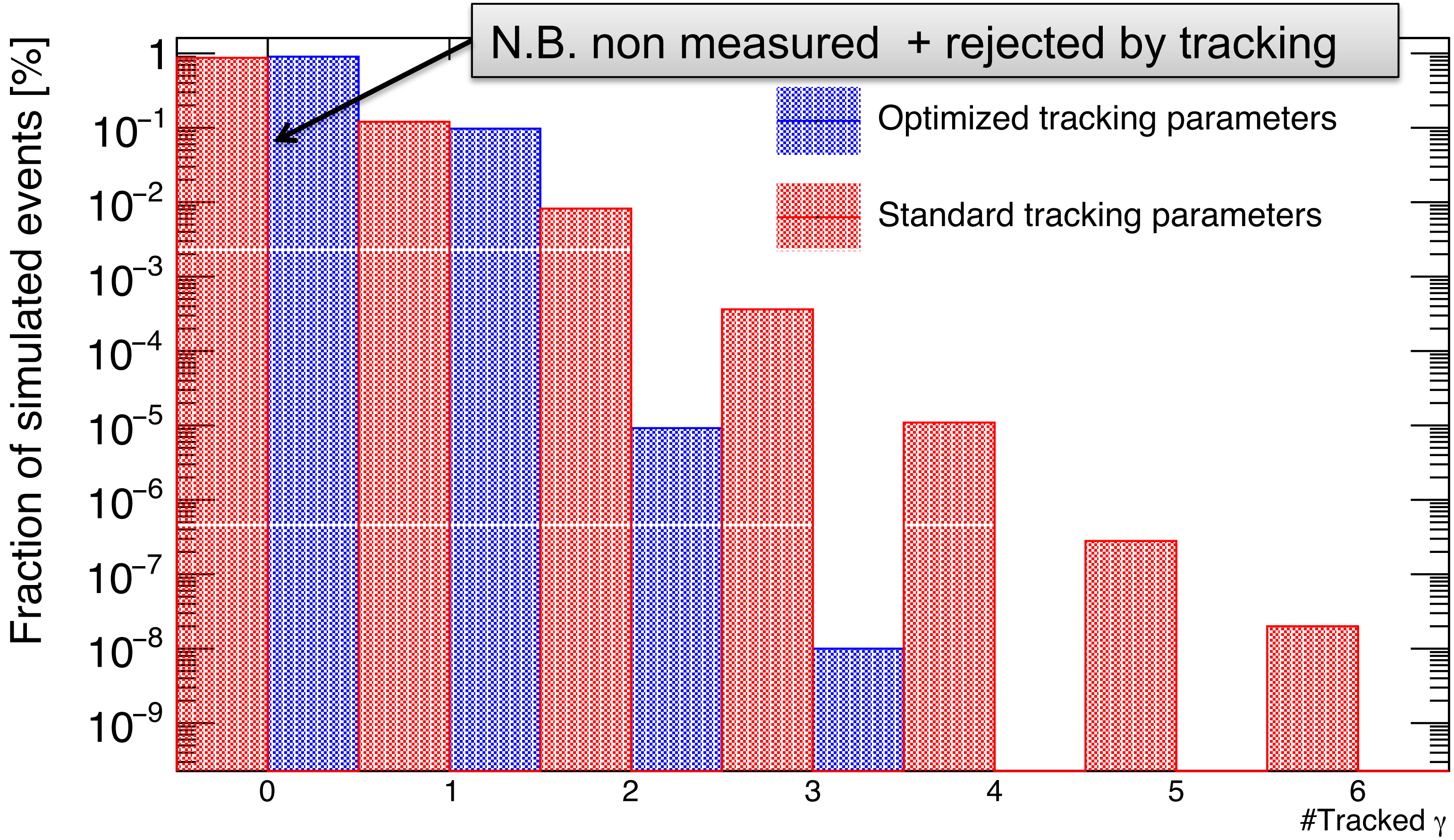


Gate on ΣE_γ



Clusterization space full AGATA

AGATA



Full systematic optimization of the tracking parameters → one unique gamma
Study of of tracking parameters with two gamma events
Realistic event generators (energy sharing & angular distribution)

Bayesian algorithms for tracking

Conditioned probability

Bayes-Tracking
A novel Approach to Gamma-Ray Tracking

P. Napiralla, H. Egger, P. John, N. Pietralla, M. Reese, C. Stahl

TECHNISCHE UNIVERSITÄT DARMSTADT

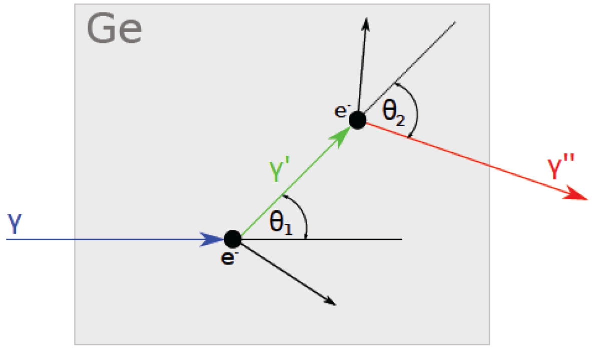


Figure: Compton-Escape Event in a Germanium detector

Tracking is a key ingredient in the search of γγ/γ → new tracking concepts Bayesian

Bayesian approach to $\gamma\gamma/\gamma$ experiments with AGATA

P. Napiralla

October 5, 2017

The probability of the double γ decay for a transition with energy E_γ:

$$P(\gamma\gamma, E_\gamma|\text{data}) = \frac{P(\text{data}|\gamma\gamma, E_\gamma) \cdot P(\gamma\gamma, E_\gamma)}{P(\text{data})}$$

Bayes-Tracking
Bayes' Theorem

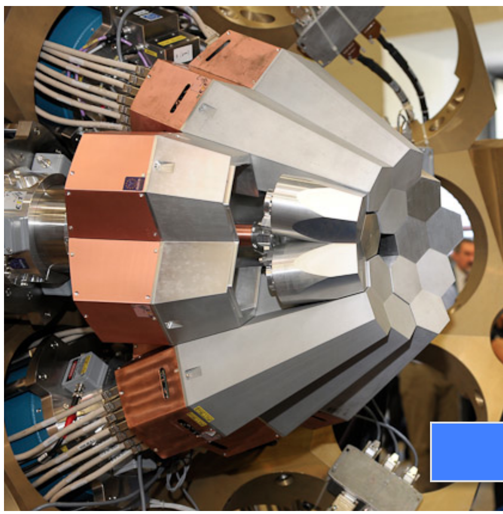
TECHNISCHE UNIVERSITÄT DARMSTADT

$$P(\textit{hypothesis}|\textit{data}) = \frac{P(\textit{data}|\textit{hypothesis}) \cdot P(\textit{hypothesis})}{P(\textit{data})}$$

	data	*hypothesis*
data	Evidence $P(\textit{data})$ Knowledge about *data*	**Likelihood Fct.** $P(\textit{data}|\textit{hypothesis})$ Plausibility of *data*, given *hypothesis* is true
hypo-thesis	Posterior $P(\textit{hypothesis}|\textit{data})$ Probability of *hypothesis*, given *data* is true	Prior $P(\textit{hypothesis})$ Knowledge about *hypothesis*

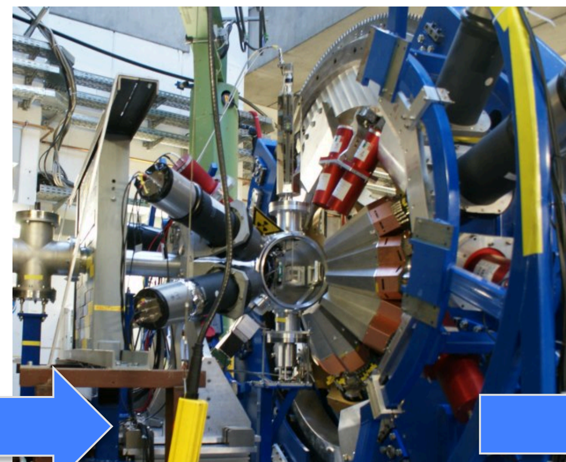
The AGATA time line

AGATA@LNL



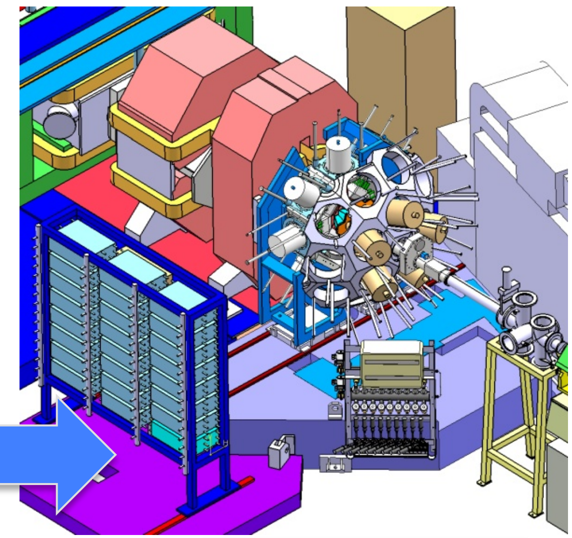
2009-2011

AGATA@GSI



2012-2014

AGATA@GANIL



2014- 2019…

AGATA is a last generation gamma spectrometer built to serve the most demanding needs of present and future Radiaoctive Ion Beam (RIB) facilities.

Program to study γγ/γ with AGATA

The plan is to first re-measure the energy and angular distributions from the Nature publication with a higher precision and as a proof of concept

- ^{137}Cs with a ~ 300 kBq activity 3-4 KHz singles (data ~ 1Tb hour)
- one-month source run, this would give us approximately 1.2 10^{11} full energy 662-keV events
- expected to have 10^5 double-gamma counts in the data set, can go down to 10^4 (N.B. 10^3 events were used over two months in order to measure the γγ/γ-decay branching ratio with an energy resolution of roughly 3%)
- Possibility to measure linear gamma-polarization (B. Alikhani et al., NIM A 675, 144 (2012) & P.G. Bizzeti et al., Eur. Phys. J. A. 51 (2015))
- Go for ^{60}Co)expected branching 10^{-8} → QPM predicts the dominance of E1-E1 over M1-M1 γγ/γ decay of the 2^+ state at 1332 keV of ^{60}Ni

Letter sent to ASC, ACC, project manager of AGATA, AGATA@GANIL (4/7/2017).

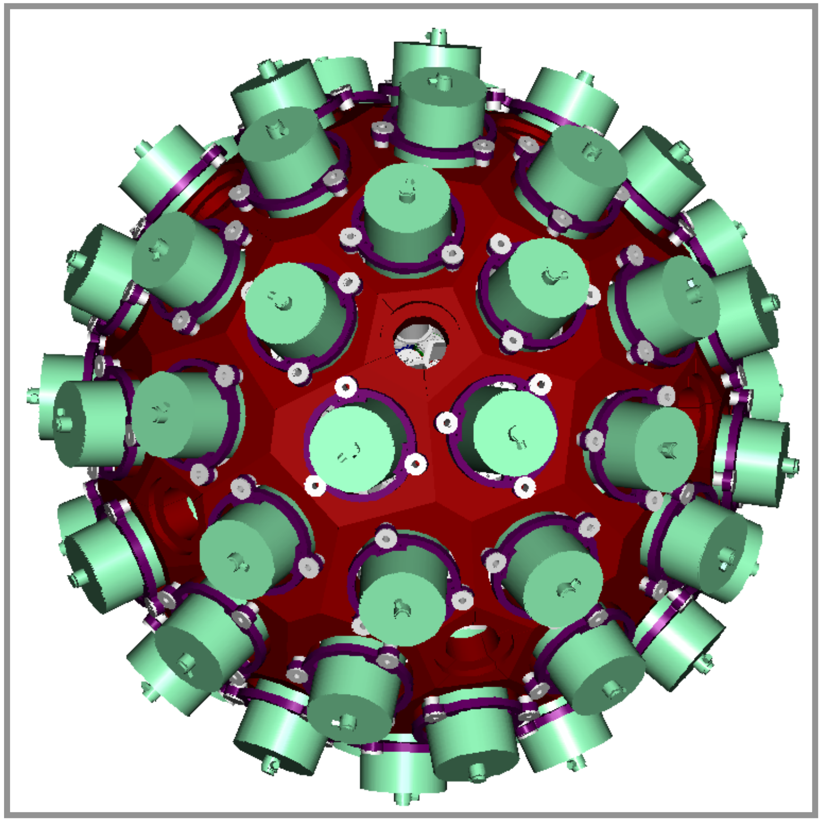
Summary

- Observation of the competitive double gamma decay using LaBr:Ce
- Measurement of the energy sharing, angular distributions between the two emitted gamma rays and branching ratio 2.1 (3) 10^{-6} for ^{137}Ba
- Comparison with QPM, determination of α_{E2M2} α_{M1E3} contribution
- Electric polarizability α_D related to equation of state – nuclear simmetry energy → This measurements can help on the
- Double-gamma decay process is formally analogous to 0vββ

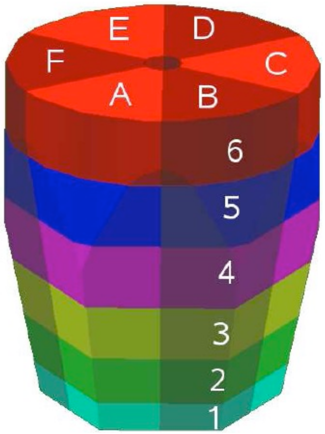
- For the future: proof of principle with AGATA with a ^{137}Cs source → later study ^{60}Co, other sources
- Detail study of **timing algorithms**
- Detail study of the **tracking algorithms**: forward tracking as well as new approaches as Bayesian tracking.

AGATA

(Advanced GAmma Tracking Array)



No anticompton – No collimators a pure ball of Ge.



The innovative use of detectors (pulse shape analysis, γ-ray tracking, digital DAQ) will result in high efficiency (~40%), excellent energy resolution and high counting rates 50 kHz.

Requirements of a γ-tracking array

efficiency, energy resolution, dynamic range, angular resolution, timing, counting rate, modularity, angular coverage, inner space

simulations

Quantity	**Target Value**	Specified for
Photo-peak efficiency (e_{ph})	**40 %** **20 %** **10 %**	E_γ = 1 MeV, M_γ = 1, $\beta < 0.5$ E_γ = 1 MeV, M_γ =30, $\beta < 0.5$ E_γ =10 MeV, M_γ = 1
Peak-to-total ratio (P/T)	**60 - 70 %** **40 - 50 %**	E_γ = 1 MeV, M_γ = 1 E_γ = 1 MeV, M_γ = 30
Angular resolution ($\Delta\theta_\gamma$)	**better than 1°**	for $\Delta E/E < 1\%$ at large β
Maximum event rates	**50 kHz**	Per crystal
Inner diameter	**23,5 cm**	for ancillary detectors