Double-γ decay process with the γ–tracking array AGATA: possible links with $2\beta0\nu$

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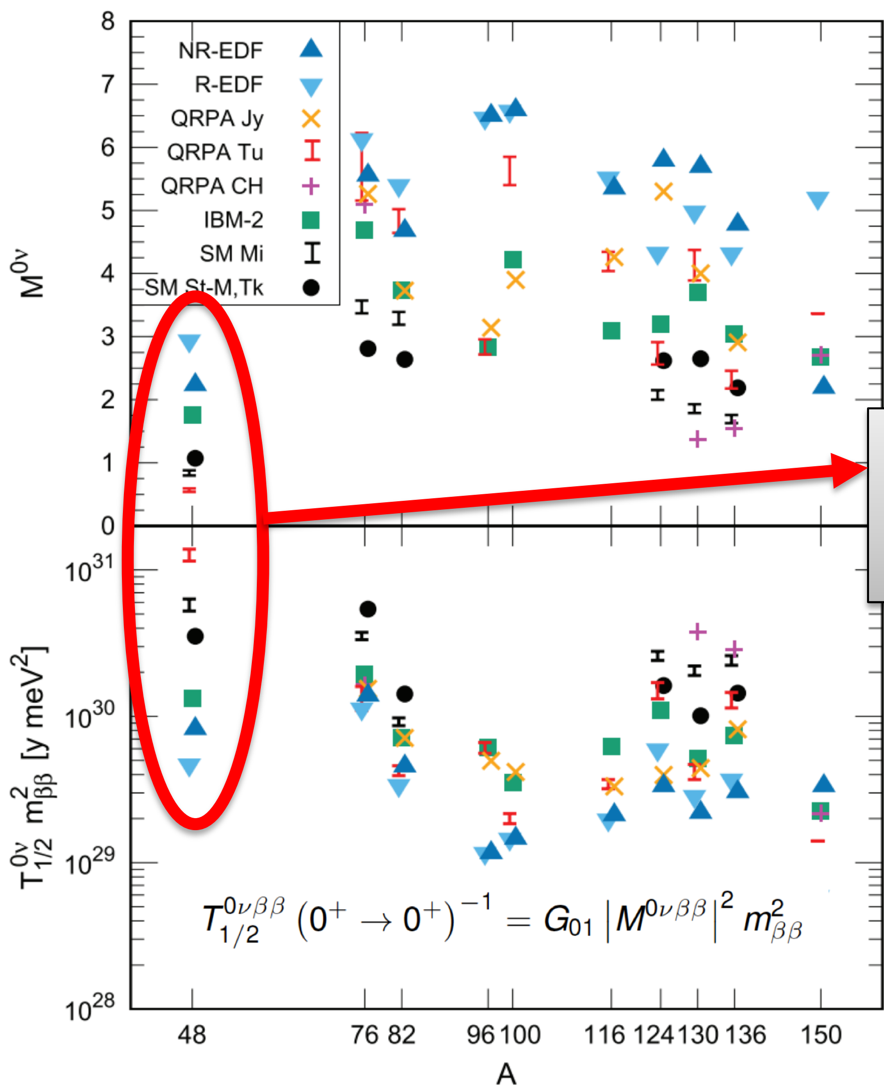
Collaborators:
TU-Darmstadt → **N. Pietralla**, T. Aumann, H. Scheit, **P. Napiralla**, P.R. John, V .Yu. Ponomarev.
INFN/Padova Uni. → A. Goasduff, G. De Angelis, **D. Brugnara**, D. Mengoni

Overview

- How to approach the NME?
  - DCX reactions
  - DGT transitions
  - Double-gamma decay
- Competitive double gamma decay process
- AGATA gamma-ray tracking array can efficiently measure the double gamma decay process → experimental difficulties.
- Summary

Theoretical NME



Theoretical Nuclear Matrix Elements (NME) disagree by more than a factor of 2. Maybe also quenching is needed.

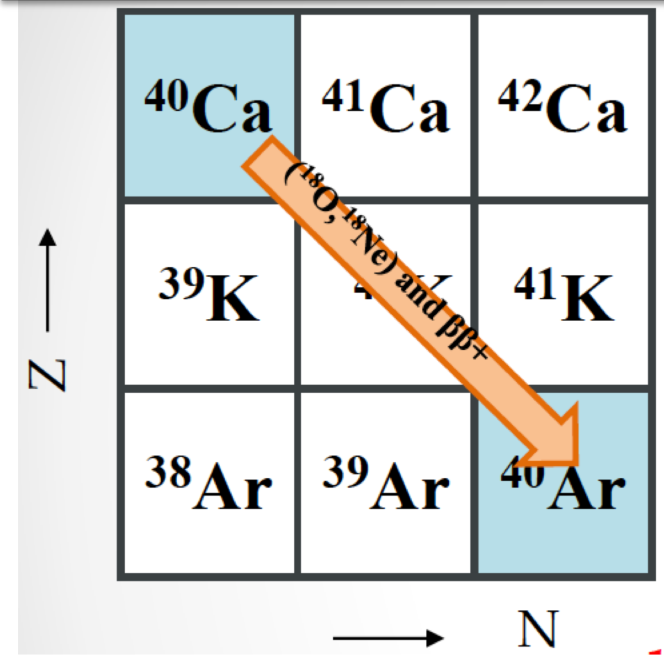
In the case of ^{48}Ca the uncertainty in the M^{0v} → more than an order of magnitude in the $T_{1/2}$

J. Engel and J. Menendez Rep. Prog. Phys. 80 (2017) 046301.

DCX reactions and 2β0ν

Feasibility

$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ 270 MeV



Measured: dσ(DCE)/dΩ= 11μb/sr

Competing processes are at the 1% level

- DCE mediated by strong interaction, ββ0v by weak interaction
- DCE includes sequential multinucleon transfer mechanism

BUT

- Same initial and final wave functions
- Similar operator …

The idea of NUMEN is to go to more relevant cases such as: ^{76}Ge, ^{116}Cd, ^{130}Te, ^{136}Xe

There are experimental challenges:

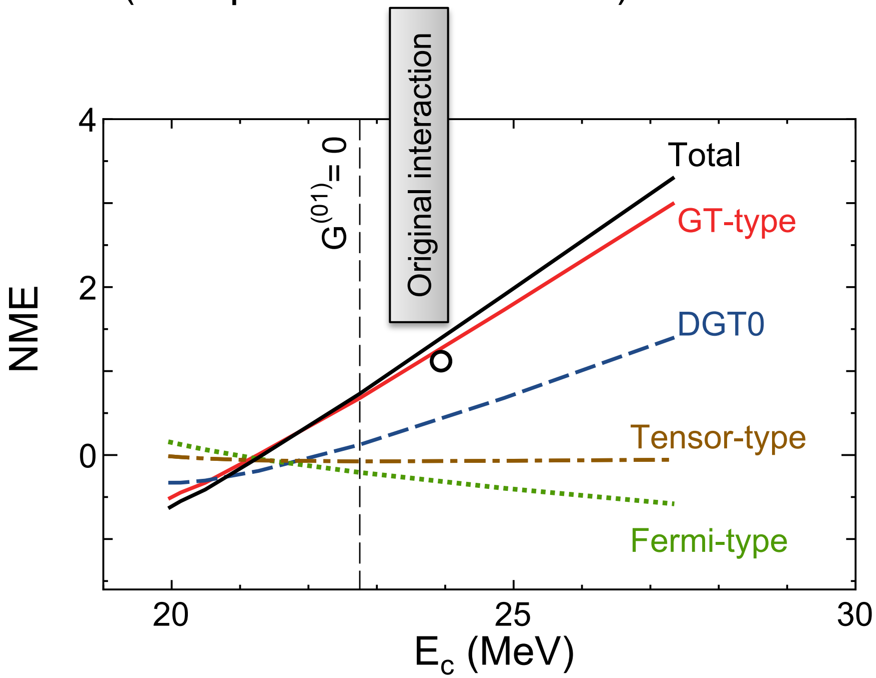
- Large beam intensities
- $\beta^-\beta^-$ requires a radioactive beam (^{18}Ne,^{18}O)
- Some cases, not enough energy resolution → γ detectors

F. Cappuzzello, et al. Eur. Phys. J. A (2015) 51: 145

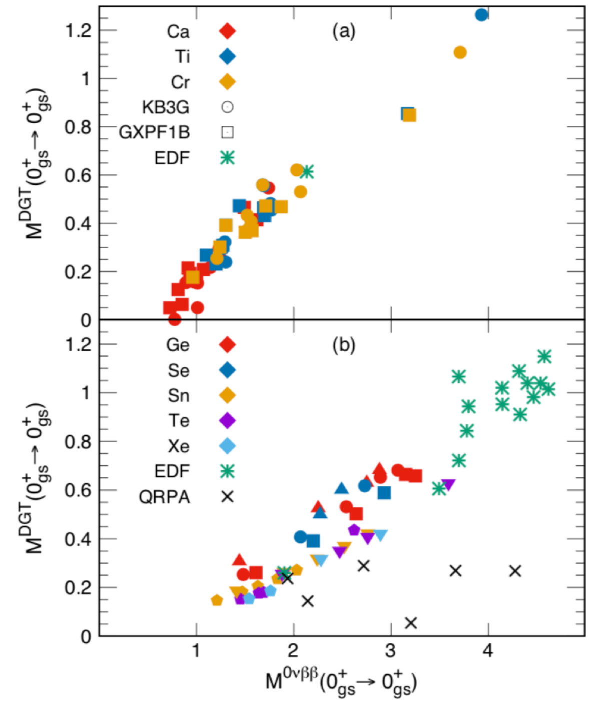
DGT and 2β0ν

Presentation on 7th March (2017) INT: Double Gamow-Teller transitions and its relation to neutrinoless 2β decay (N. Shimizu, J. Menendez, and K. Yako) → PRL (Accepted 2nd March 2018).

arXiv:1709.01088 [nucl-th]



^{48}Ca → NME, dominated by $M_{0\nu}$, is well correlated with the average energy of the DGT GR (so far never measured experimentally)

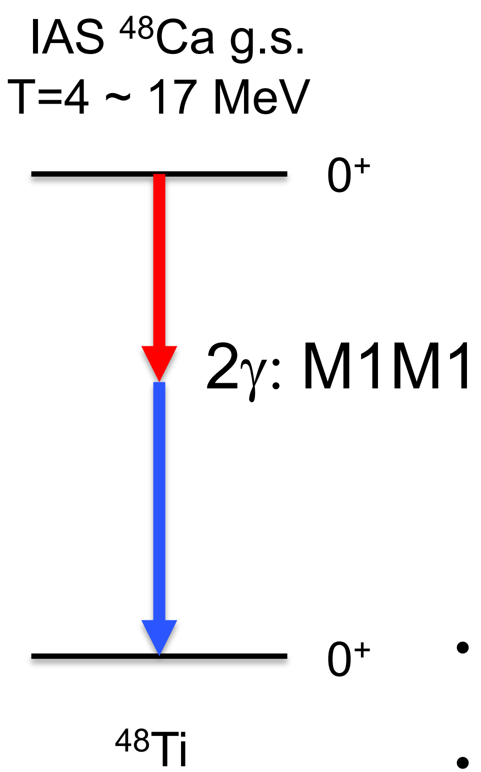


Linear correlation DGT transition to the final g.s. and the 0νββ decay NME. The correlation origins in the dominant short-range character of both transitions.

Exp. Challenge: $0^+ \to 0^+$ 0.03 per mil of total DGT

Any possible relation 2γ – 2β0ν ?

J. Menendez and N. Shimizu working on theoretical relations 2γ – 2β0ν



- 2γ has the same initial and final states as in 2β0ν
- The magnetic dipole operator (M1) and the Gamow-Teller (GT) operator are similar. They have the same major components of the isovector (IV) spin στ term.
- Electromagnetic interaction vs. weak interaction
- The matrix elements in both cases have an energy denominator → in the 2β0ν the dependece is mainly dominated by the neutrino momentum transfer

- (T=4) 0^+ IAS of ^{48}Ca particle decay is isospin forbidden and also the direct decay to the ^{48}Ti g.s.
- Need to know the width of the T=4 state in ^{48}Ti
- How to populate efficiently the 0^+ (T=4)?
- How to be sensitive to the 2γ?

Experimental approach IAS - 2γ

$^{50}Ti(p,t)^{48}Ti$ Q = -10.6 MeV
$^{46}Ca(^{4}He,2n)^{48}Ti$ Q = -8.36 MeV
$^{48}Ca(^{3}He,3n)^{48}Ti$ Q = -5.01 MeV
$^{48}Ca(^{20}Ne,^{20}O)^{48}Ti$ Q = -6.50 MeV
…..

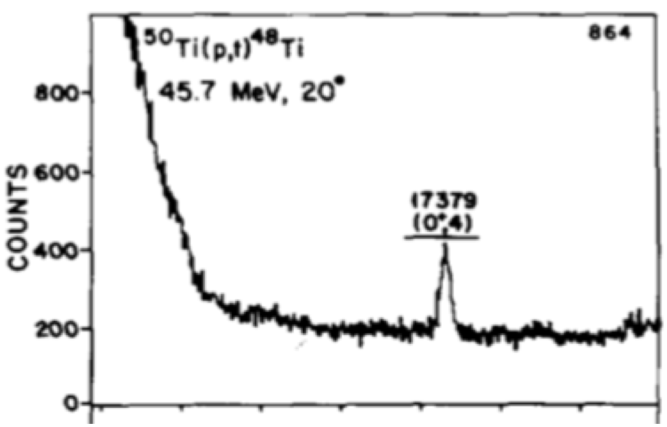
1.E.2: 1.E.7

Nuclear Physics **A309** (1978) 329 – 343; © *North-Holland Publishing Co., Amsterdam*

EXPERIMENTAL DISPLACEMENT ENERGIES OF ISOBARIC ANALOG STATES IN THE $1f_{\frac{7}{2}}$ SHELL †

R. T. KOUZES, P. KUTT, D. MUELLER and R. SHERR
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

Received 27 June 1978



DCX $^{48}Ca(\pi+,\pi-)^{48}Ti$

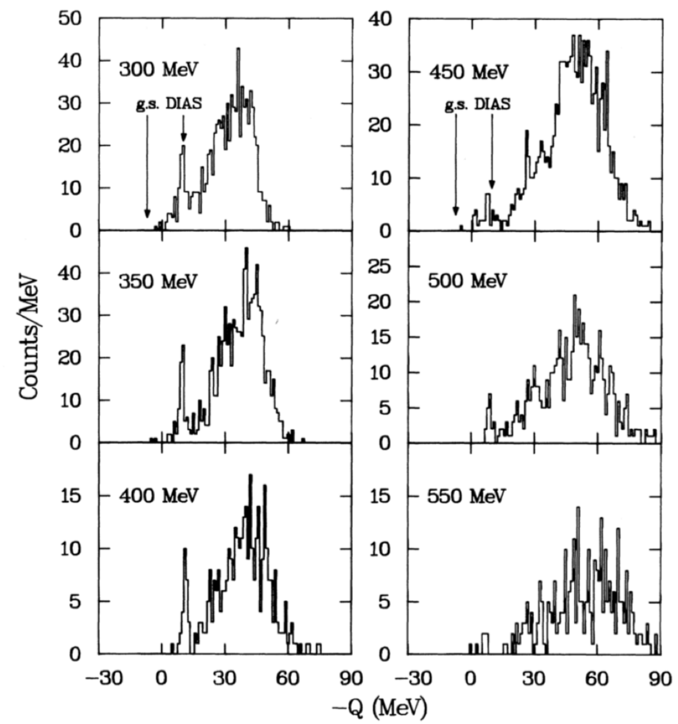


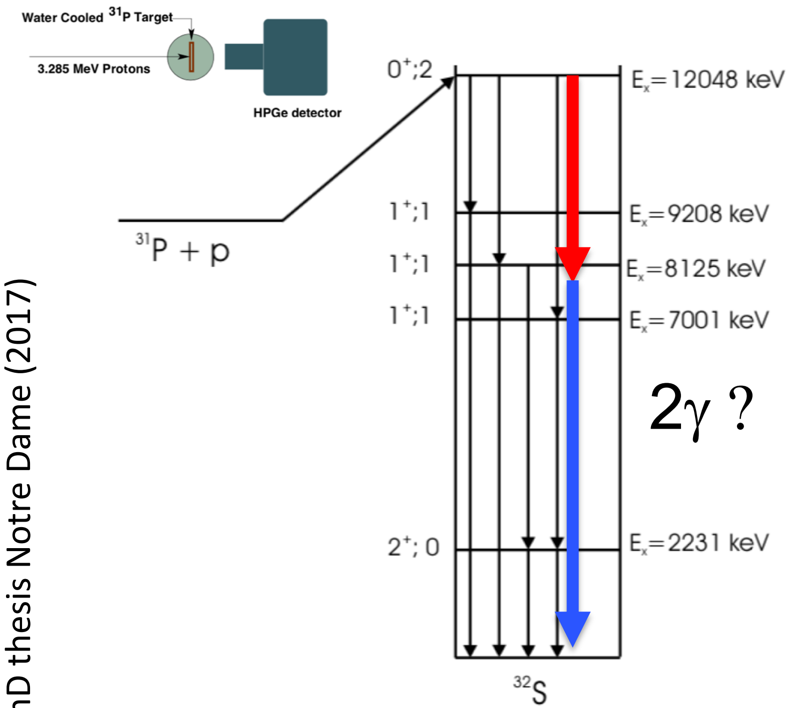
TABLE V. Results of using Eqs. (1) and (2) to calculate cross sections for ^{42,44,48}Ca averaged over 400–500 MeV.[a]

Transition	$d\sigma/d\Omega_{exp}$ (μb/sr)	DIAS only[b] $d\sigma/d\Omega_{calc}$ (μb/sr)	Fit DIAS + g.s.[c] $d\sigma/d\Omega_{calc}$ (μb/sr)	χ^2
^{42}Ca → ^{42}Ti (DIAS)	0.747±0.109	0.747	0.498	5.24
~~^{44}Ca → ^{44}Ti (DIAS)~~	~~0.855±0.125~~	~~0.855~~	~~0.987~~	~~1.12~~
^{48}Ca → ^{48}Ti (DIAS)	2.49±0.284	2.49	2.43	0.04
^{44}Ca → ^{44}Ti (g.s.)	0.094±0.047	0.418	0.0901	0.01
^{48}Ca → ^{48}Ti (g.s.)	0.026±0.026	0.308	0.0663	2.37

A.L. Williams PRC43 766 (1991)

Gamma decay from IAS

S. Triambak, PhD thesis Notre Dame (2017)



Total width Γ = 40(15) eV. Although the state is mainly unbound to isospin-forbidden proton and α emission, it also de-excites to the ground state via γ transitions, with $\Gamma_\gamma \approx 2$ eV

LEVEL ENERGIES AND DOPPLER-CORRECTED GAMMA RAY ENERGIES FROM ^{32}S.

J^π, T	E_x (keV)		E_γ (keV)
	Previous work	This work	
2^+, 0	2230.57(15)[a]	...	...
1^+, 1	7002.5(10)[b]	7001.44(36)	4770.49(33)
1^+, 1	8125.40(20)[a]	8125.32(24)	5894.32(28)
			8124.12(24)
1^+, 1	9207.5(7)[b]	9207.55(71)	9206.13(71)
0^+, 2	12045.0(4)[c]	12047.96(28)	2840.32(14)
			3922.37(15)
			5046.09(39)

The isospin selection rules follow as a direct consequence ΔT = 0, ±1 for allowed γ transitions → otherwise isotensor components besides the isoscalar-isovector components.

^{31}P target with an ≈ 6 μA, 3.285 MeV proton beam

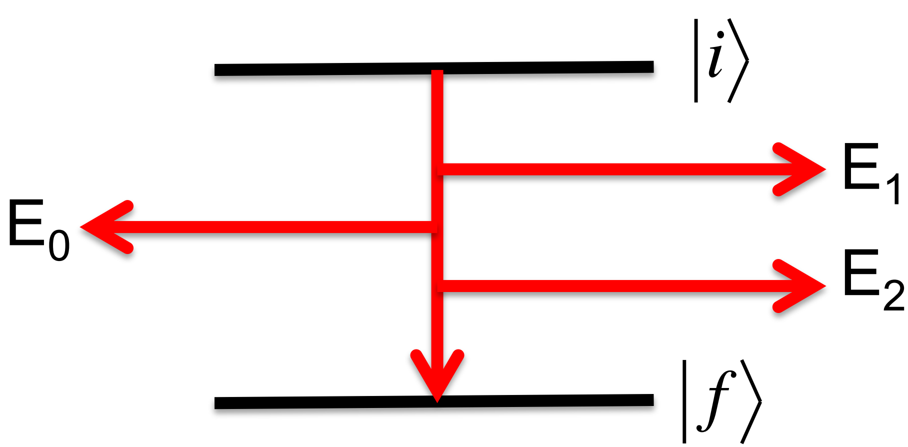
Competitive double gamma decay

- 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
- 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

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



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

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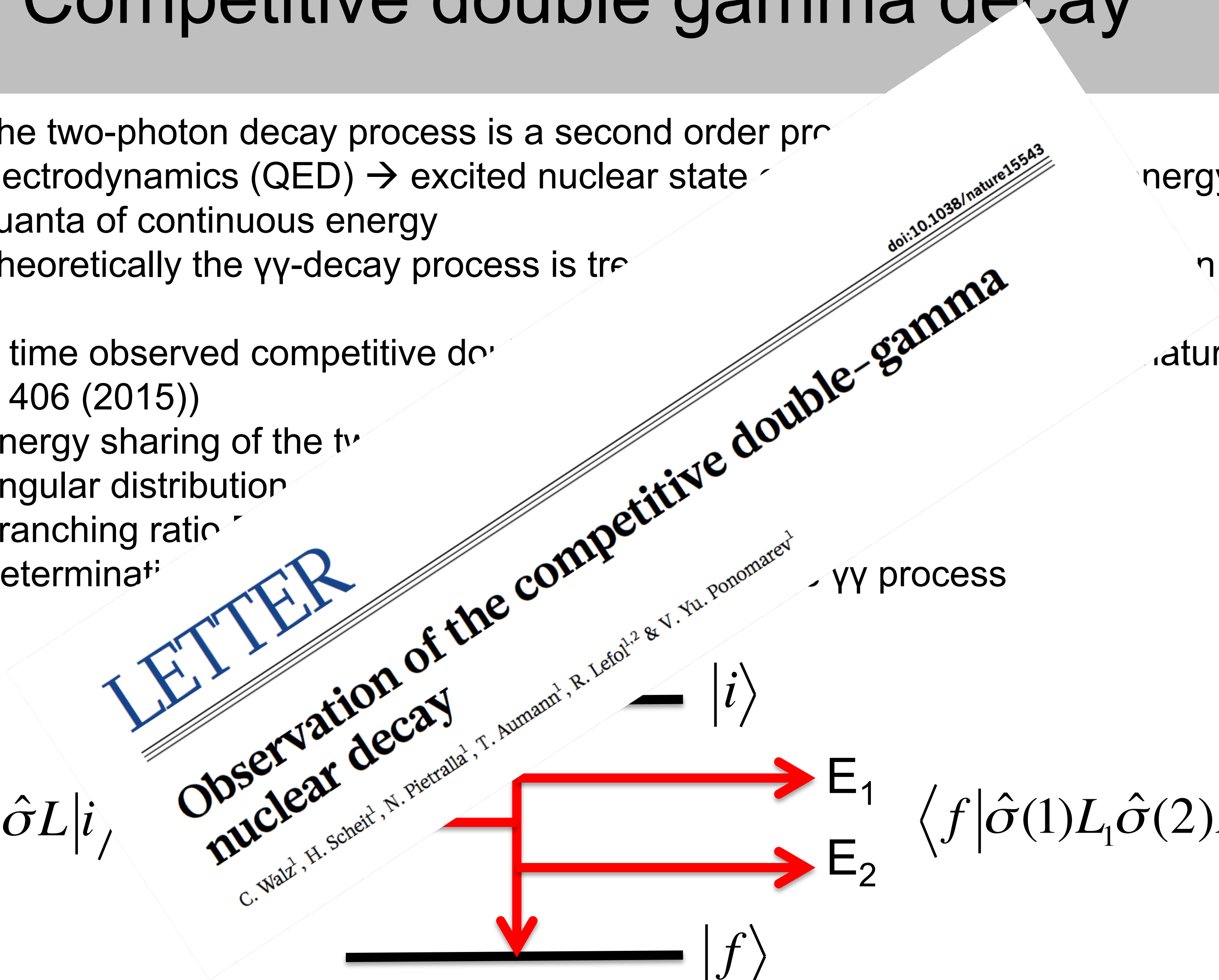
- Energy sharing of the tv…
- Angular distributior…
- Branching ratic…
- Determinat… … γγ process


doi:10.1038/nature15543

LETTER

Observation of the competitive double-gamma nuclear decay

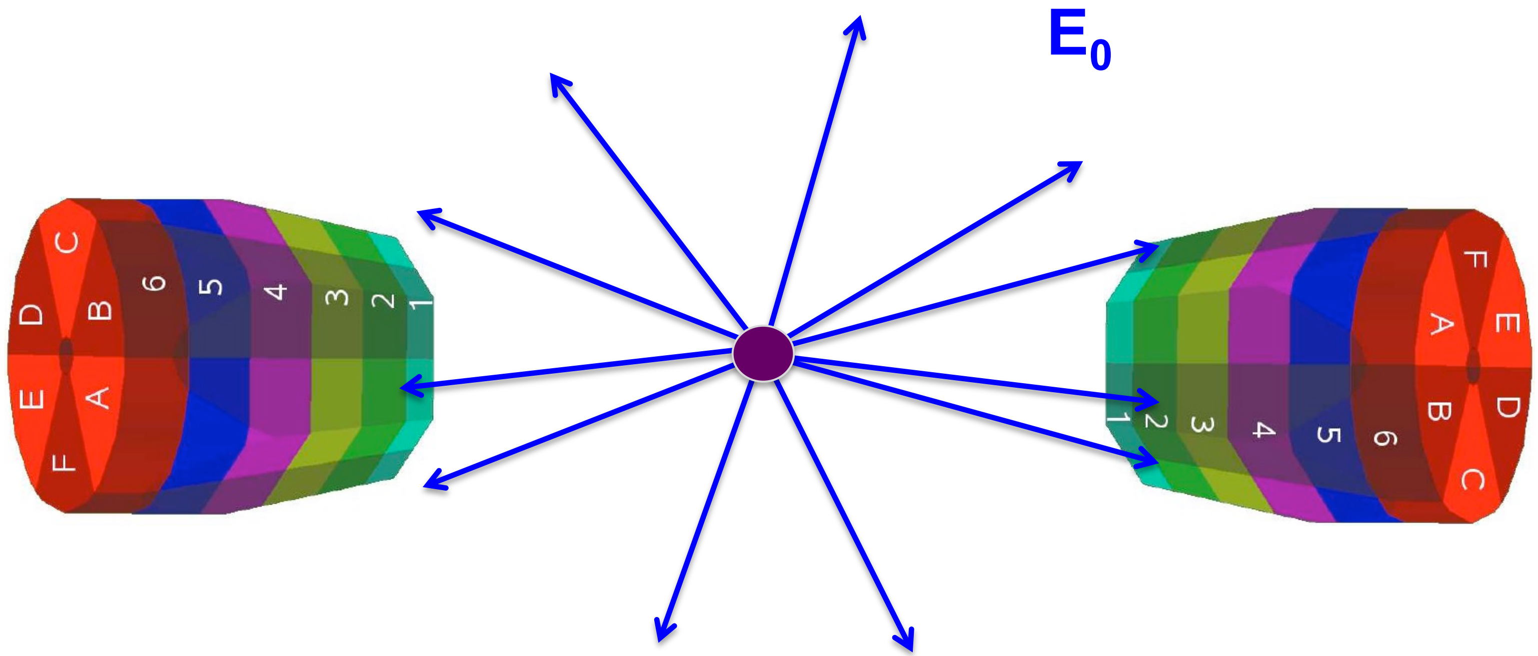
C. Walz[1], H. Scheit[1], N. Pietralla[1], T. Aumann[1], R. Lefol[1,2] & V. Yu. Ponomarev[1]

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

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

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



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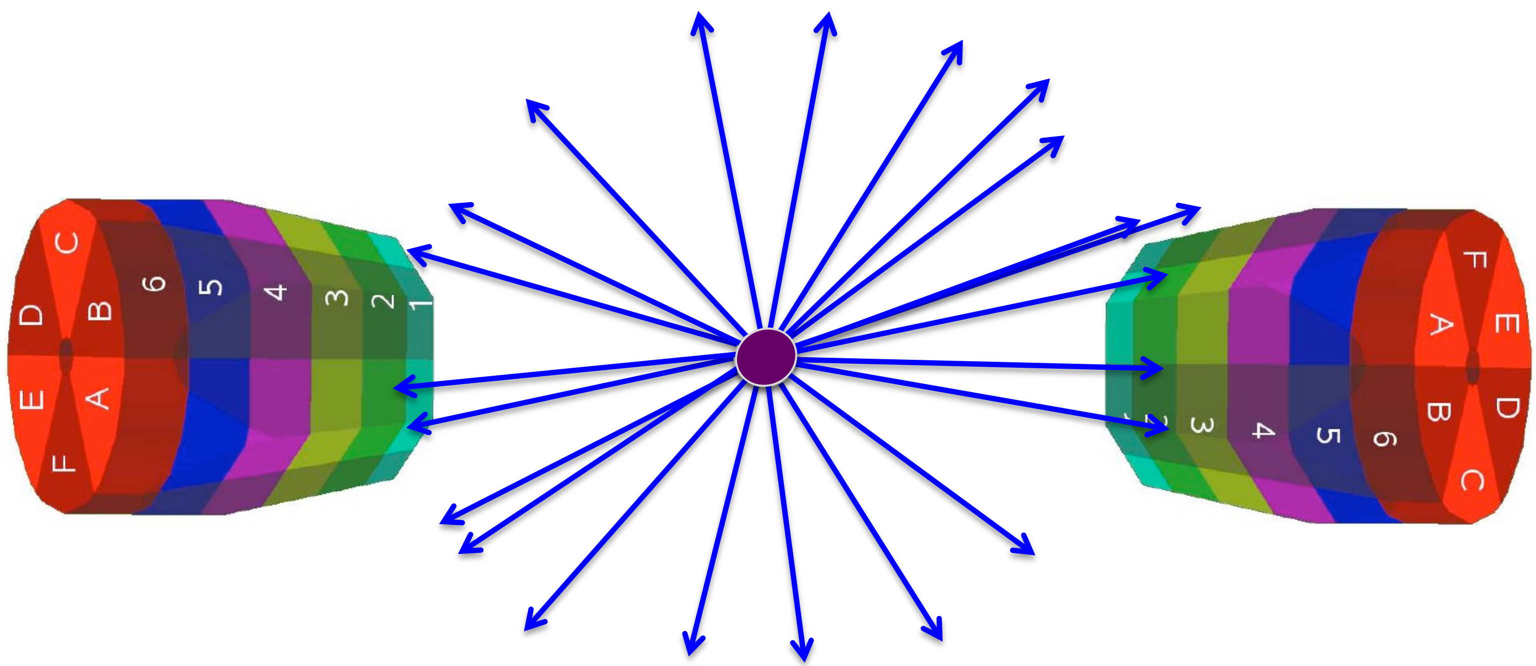

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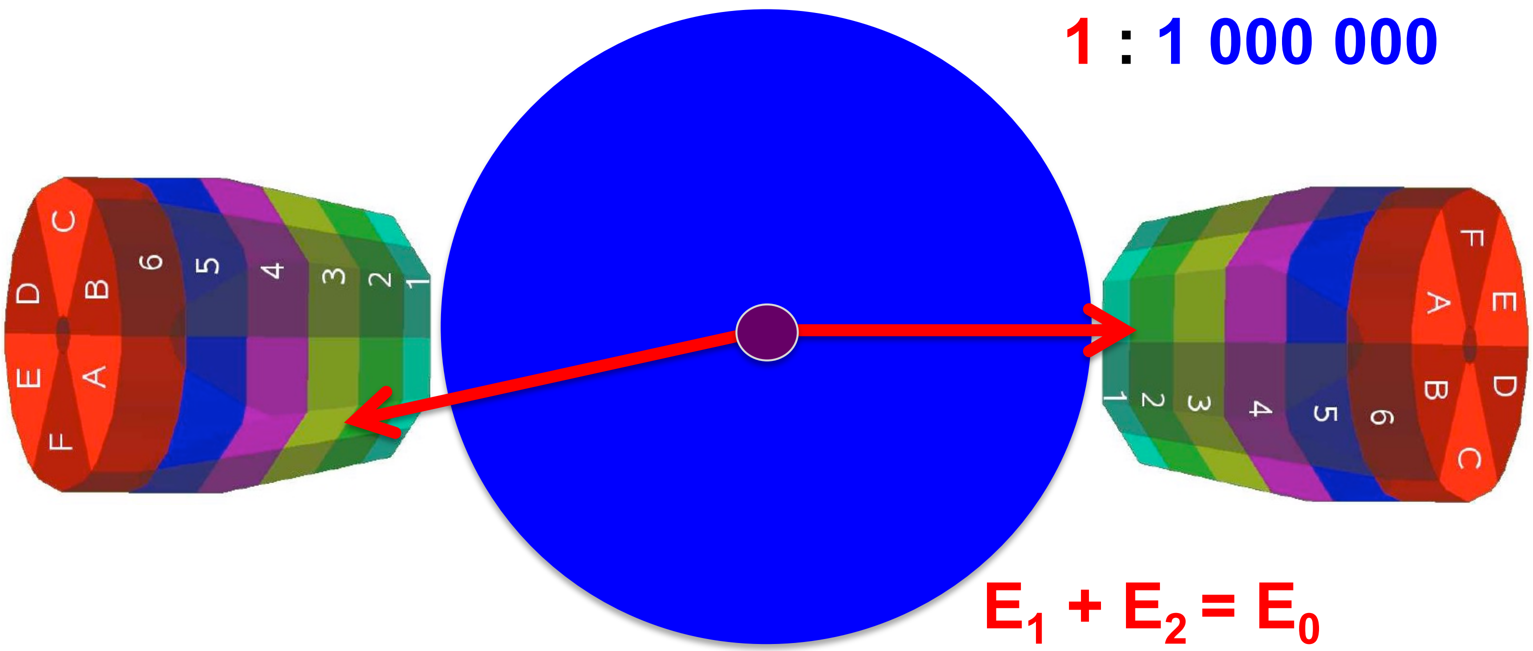

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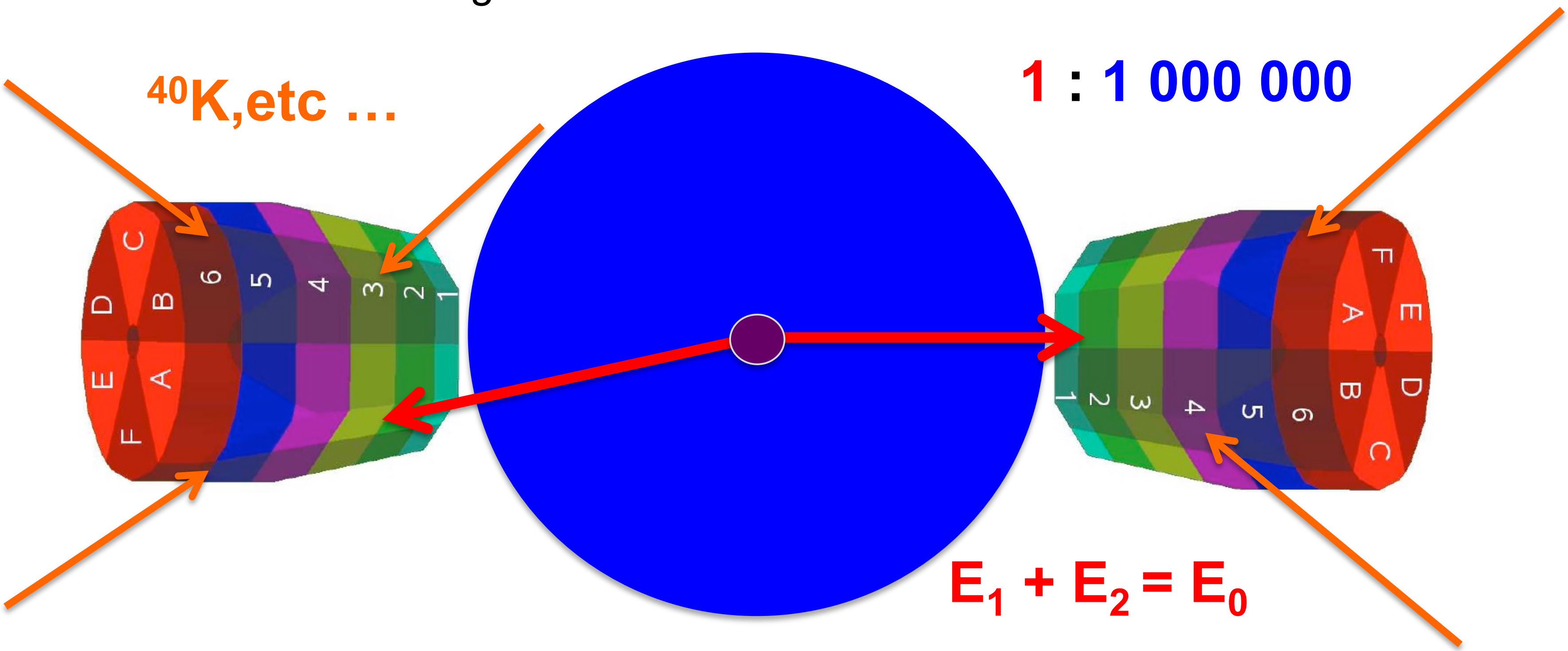
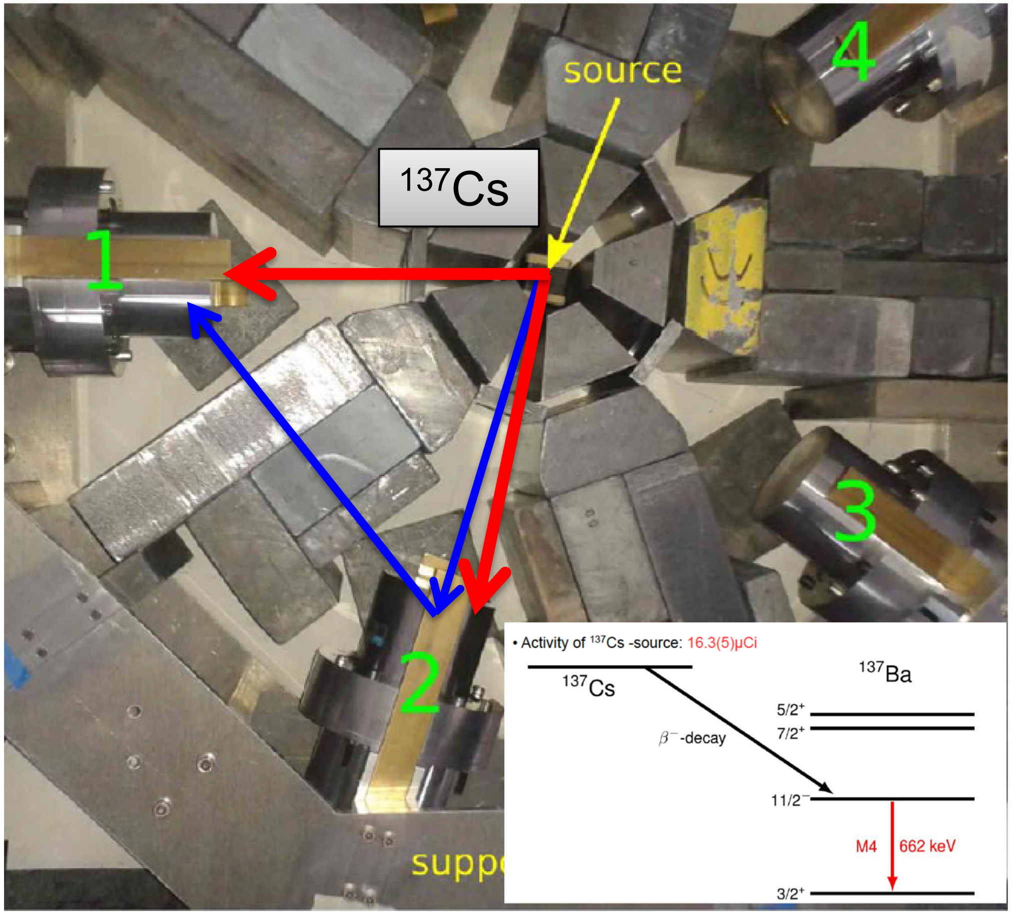
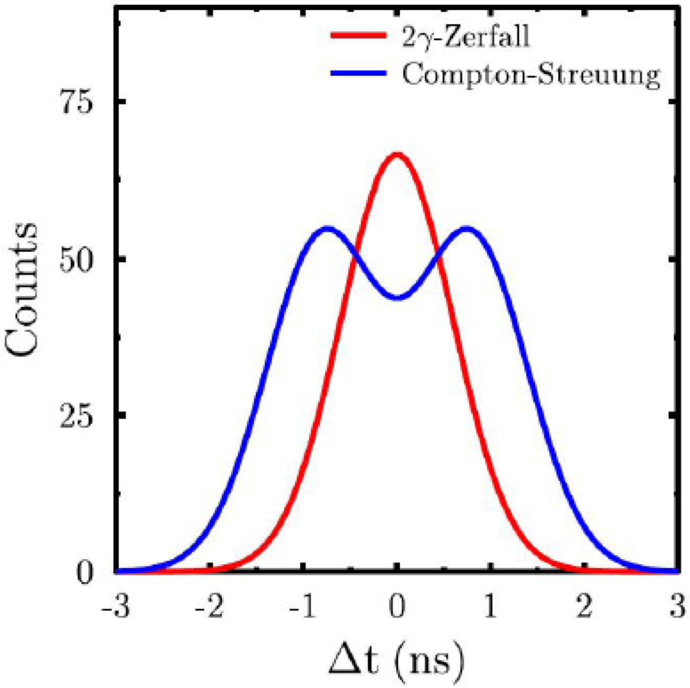


Overcoming experimental challenges



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

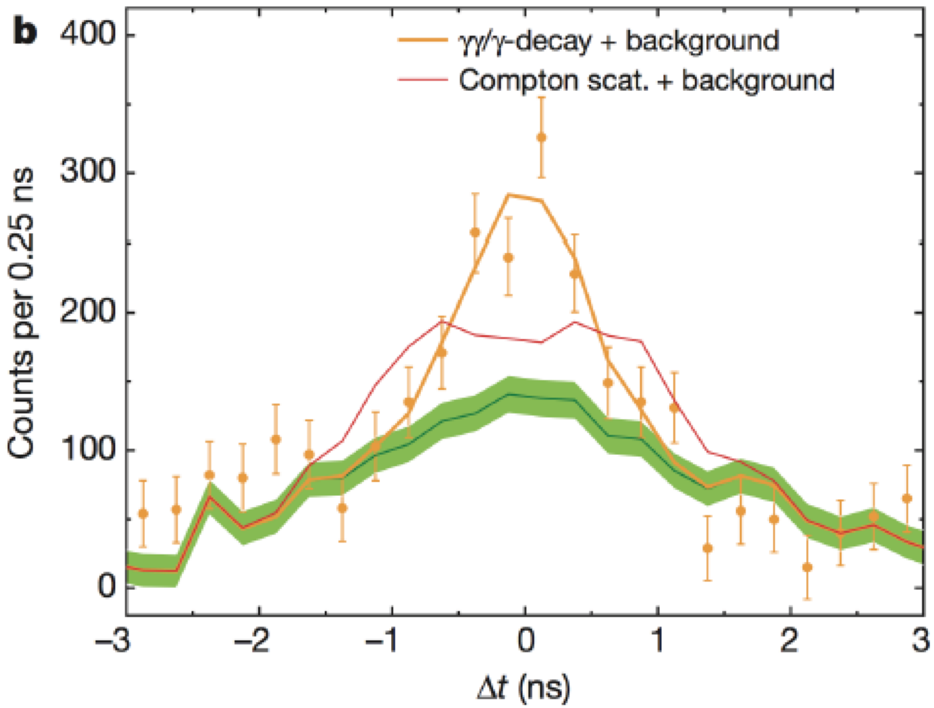
Use of fast $LaBr_3$:Ce scintillators



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



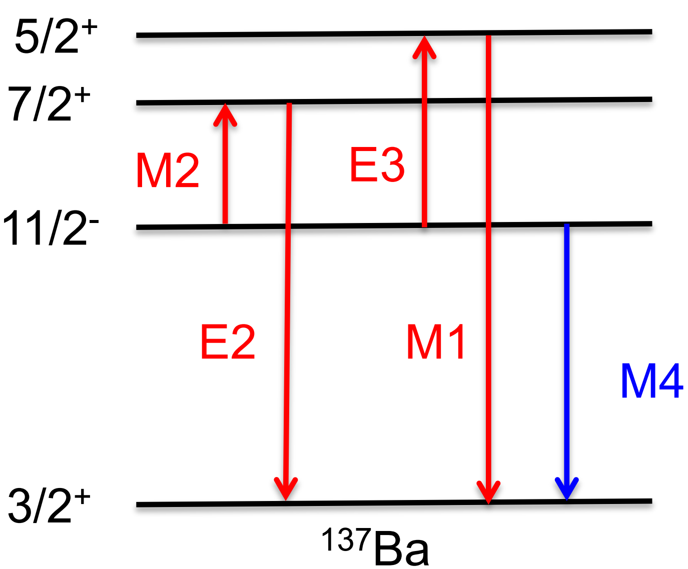
C. Waltz et al., Nature **526**, 406 (2015)

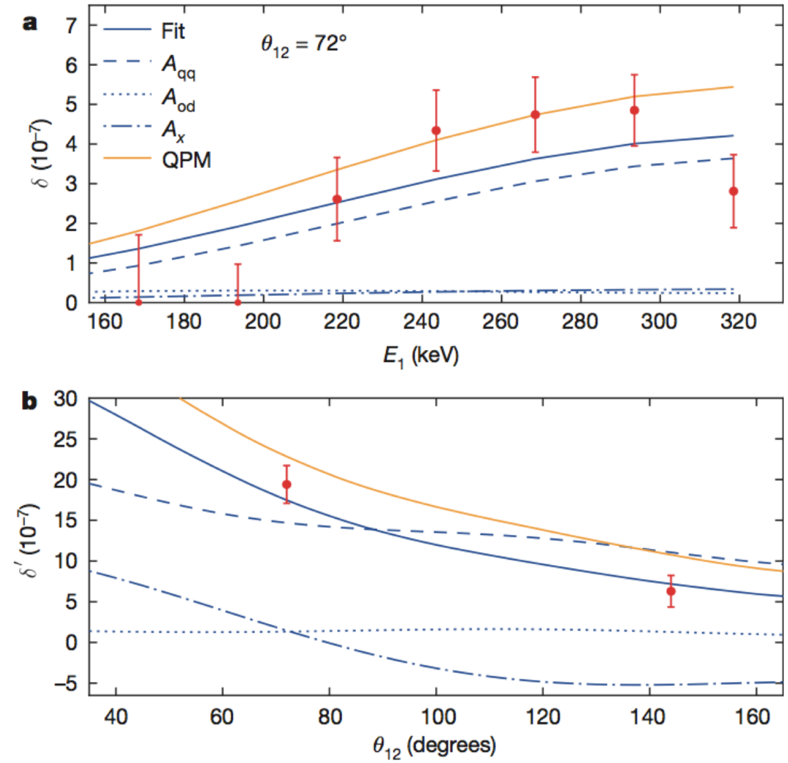
Fig. 1: Time difference spectra. The orange data points correspond to the event in coincidence with the energy-sum spectrum E_1+E_2 after the subtraction of the random coincidences. The green solid line corresponds to the background. The solid orange curve shows the expected time spectrum for γγ-decay, 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

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





Differential branching ratio

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

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

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

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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

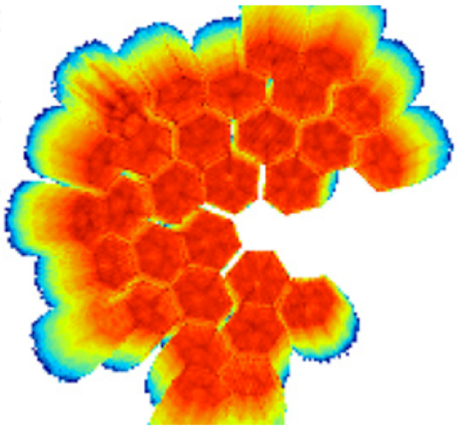
M. MOSZYŃSKI* and B. BENGTSON

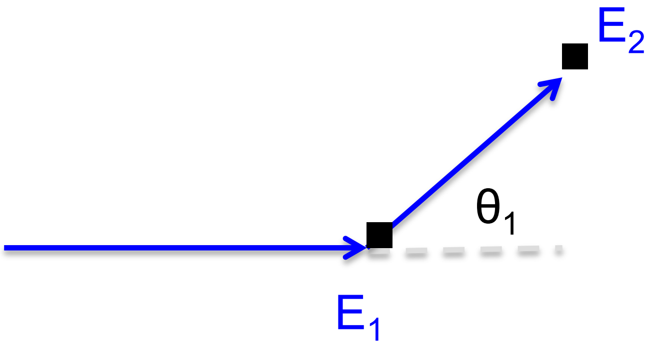
Institute of Physics, University of Aarhus, Aarhus, Denmark

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.





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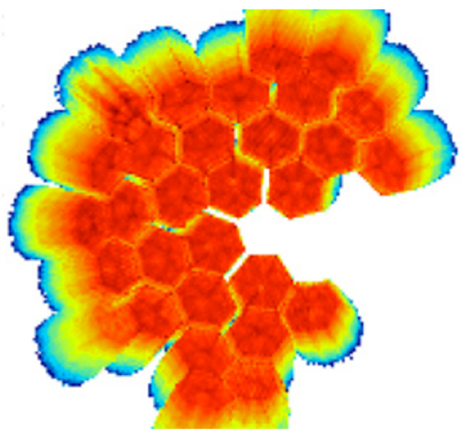
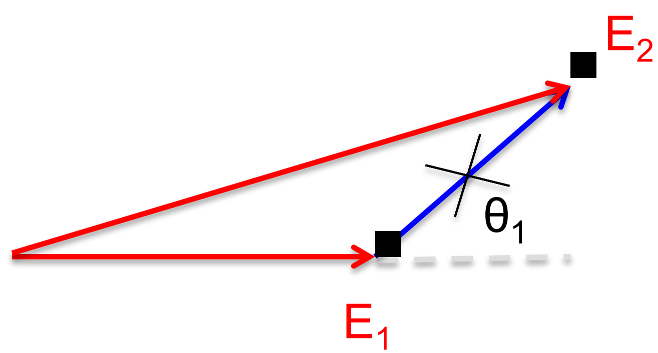




Idea of γ-ray tracking

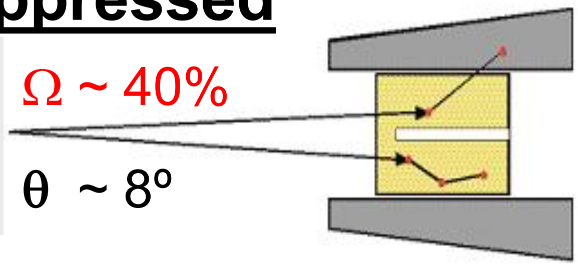
Compton Suppressed

ε_{ph} ~ 10%

N_{det} ~ 100

Ω ~ 40%

θ ~ 8°



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

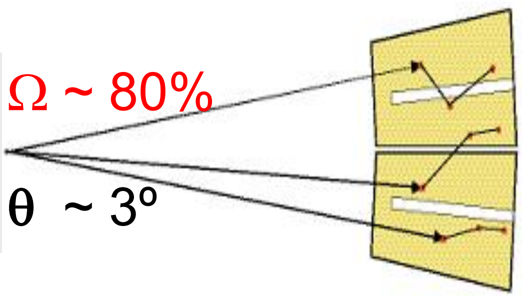
Ge Sphere

ε_{ph} ~ 50%

N_{det} ~ 1000

Ω ~ 80%

θ ~ 3°



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

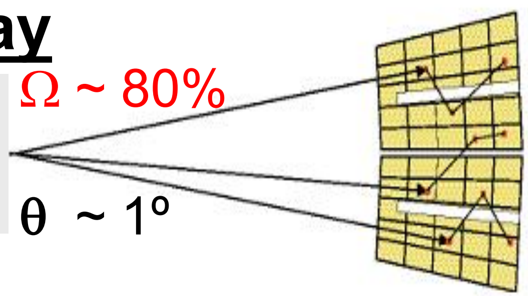
Tracking Array

ε_{ph} ~ 50%

N_{det} ~ 100

Ω ~ 80%

θ ~ 1°

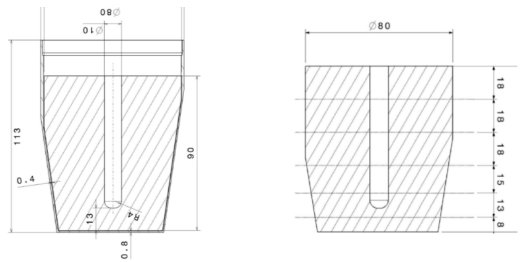


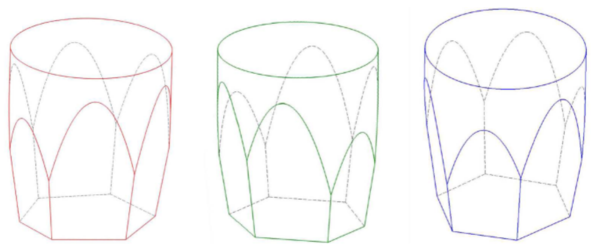
Pulse Shape Analysis
Gamma-ray Tracking
➔ θ_{eff} ~ 1°
N_{eff} ~ 10000

Smarter use of Ge detectors

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

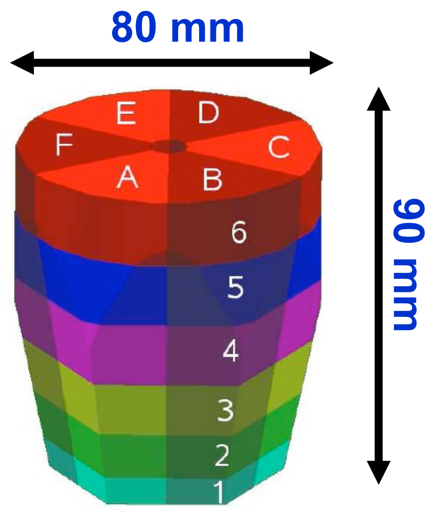
AGATA detectors





(d) A - red (e) B - green (f) C - blue

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

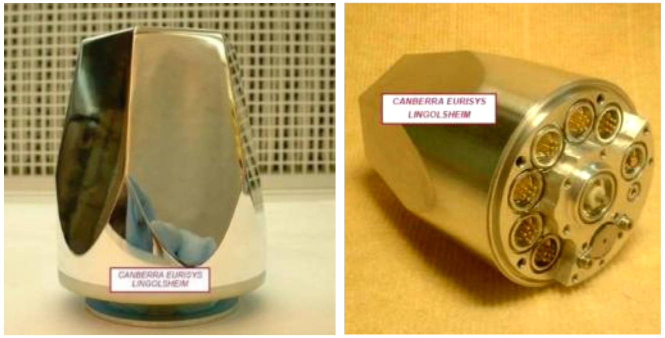


6x6 segmented cathode

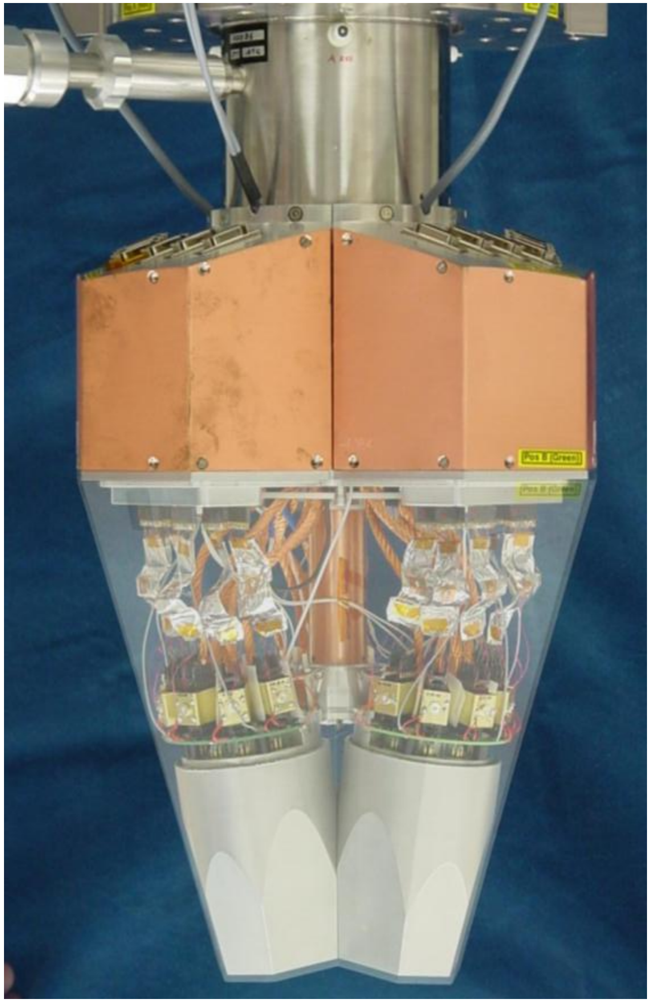
Cold FET for all signals

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

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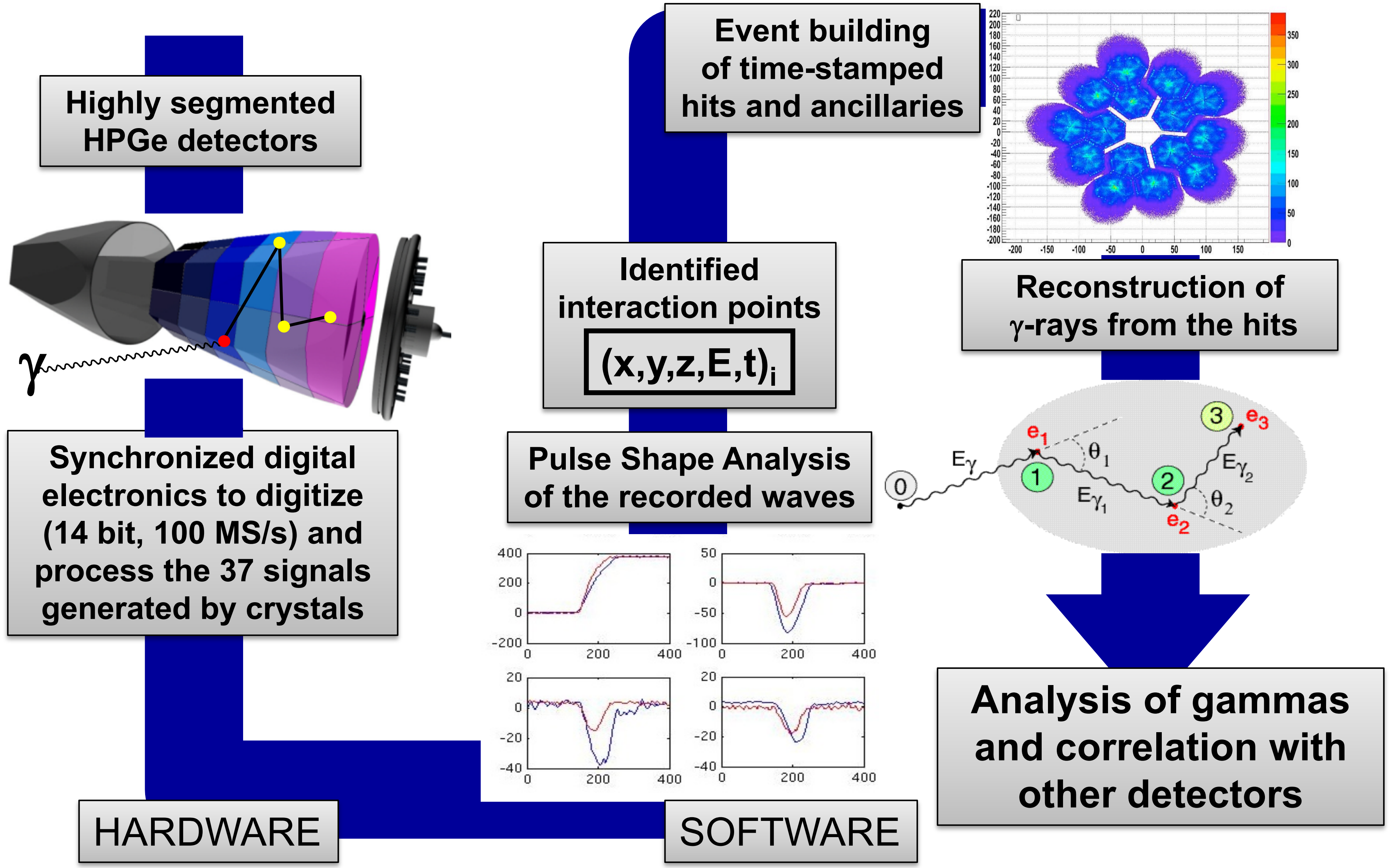
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

AGATA—Advanced GAmma Tracking Array

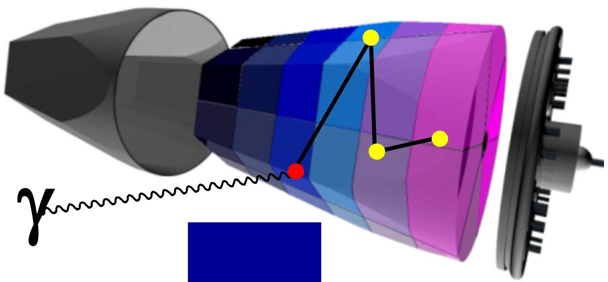
AGATA
ADVANCED GAMMA TRACKING ARRAY

Flow chart for AGATA



Flow chart for AGATA

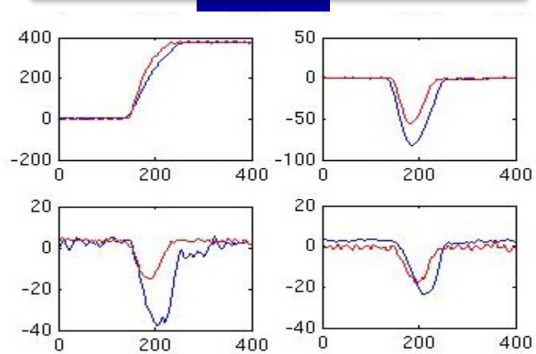
Highly segmented HPGe detectors



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

HARDWARE

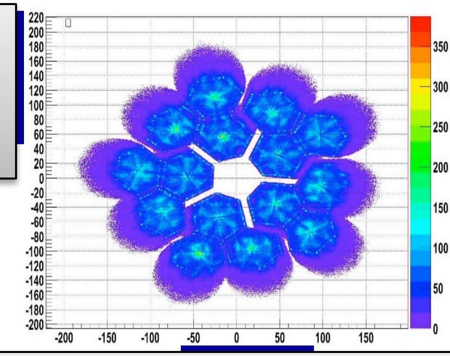
Pulse Shape Analysis of the recorded waves



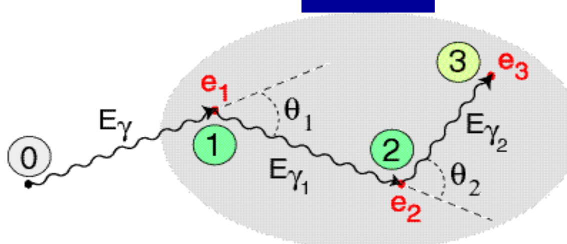
Identified interaction points

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

Event building of time-stamped hits and ancillaries



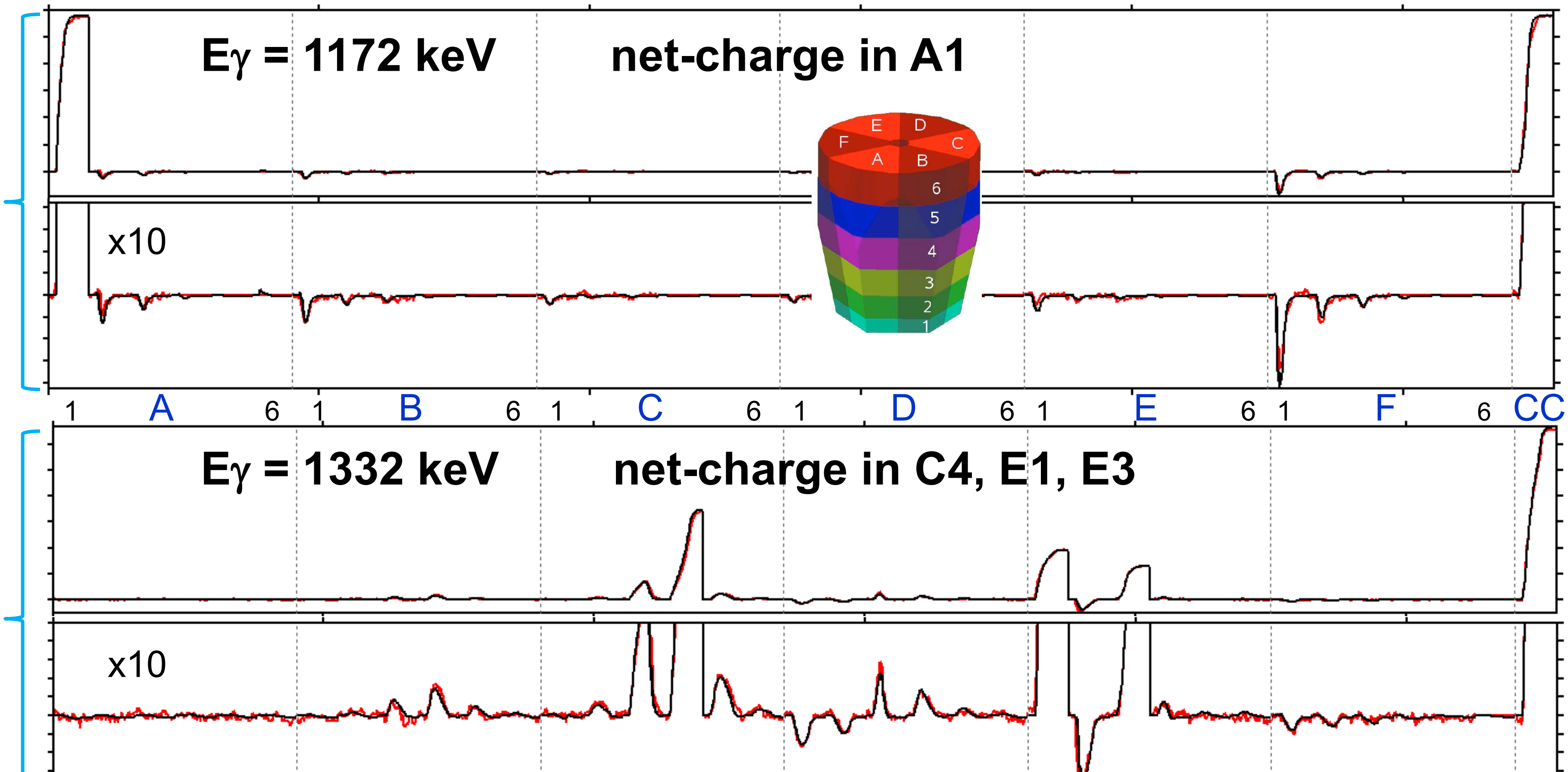
Reconstruction of γ-rays from the hits



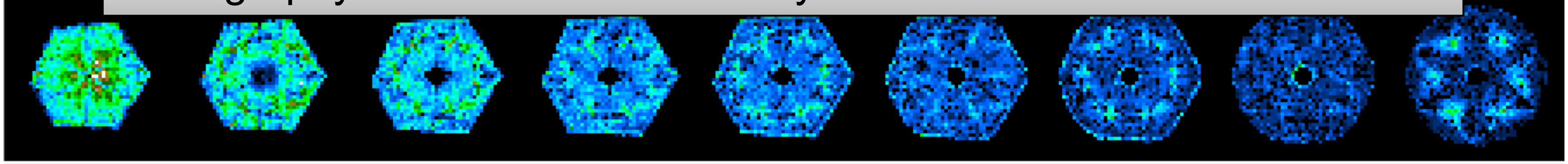
Analysis of gammas and correlation with other detectors

SOFTWARE

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

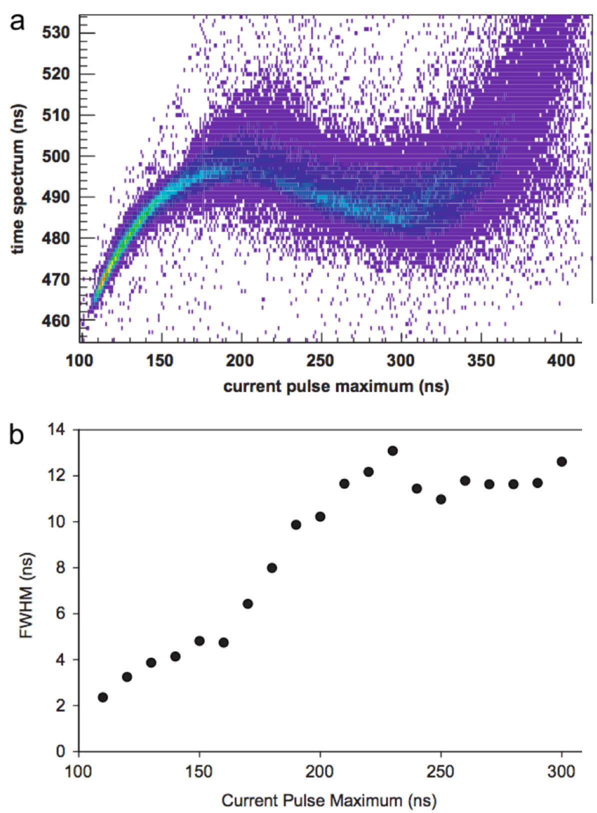


Fig. 3. (a) The 2-dimensional histogram displays the CFD output time distributi (y-axis) as a function of the current pulse maximum position (x-axis). (b) The C time resolution (i.e. FWHM of the vertical slices of the histogram in Fig. 3(a)) a function of the current pulse maximum position. In these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

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HPGe detectors timing using pulse shape analysis techniques

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[a] Dipartimento di Fisica, Università di Milano, Italy
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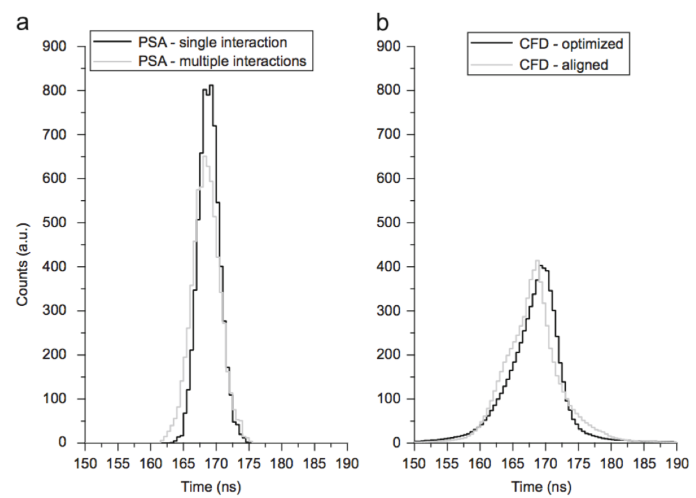


Fig. 6. Right panel: comparison between the time distributions obtained with a standard CFD with optimized coefficients (black line histogram, 7.6 ns FWHM) and the alignment of the centroid positions (grey line histogram, 8.2 ns FWHM; see Section 3 for details). Left Panel: time distributions obtained 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.

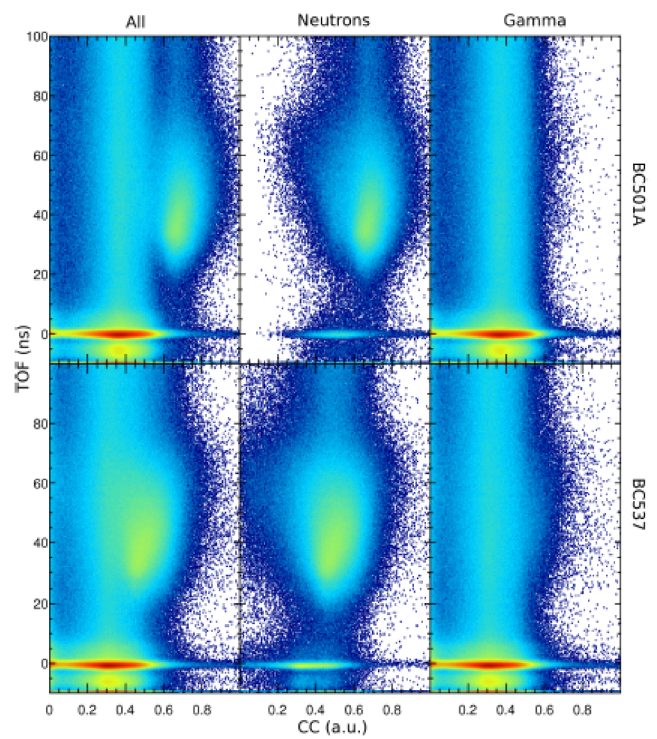


Figure 4: (Colour online.) Two-dimensional plots in logarithmic scale of time-of-flight versus digital charge comparison for the full data set (left), selected on neutrons (middle) and γ rays (right) for BC-501A (top) and BC-537 (bottom) using the artificial neural network.

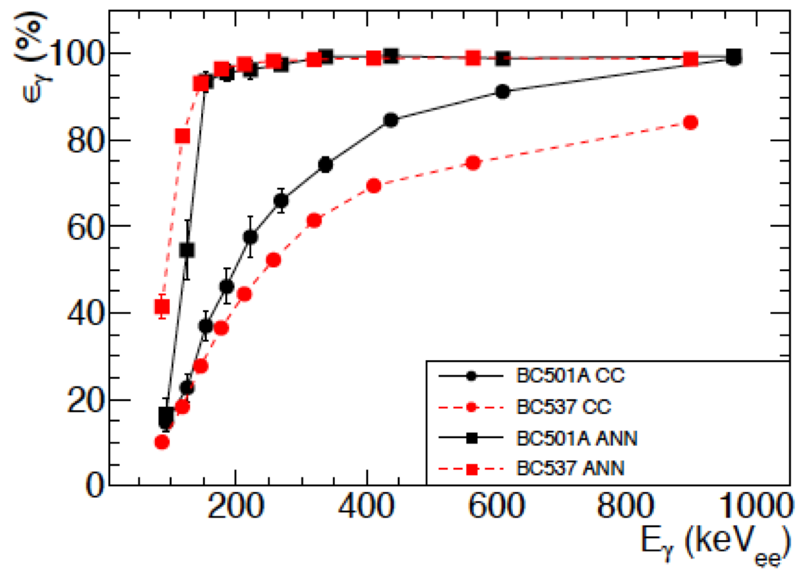
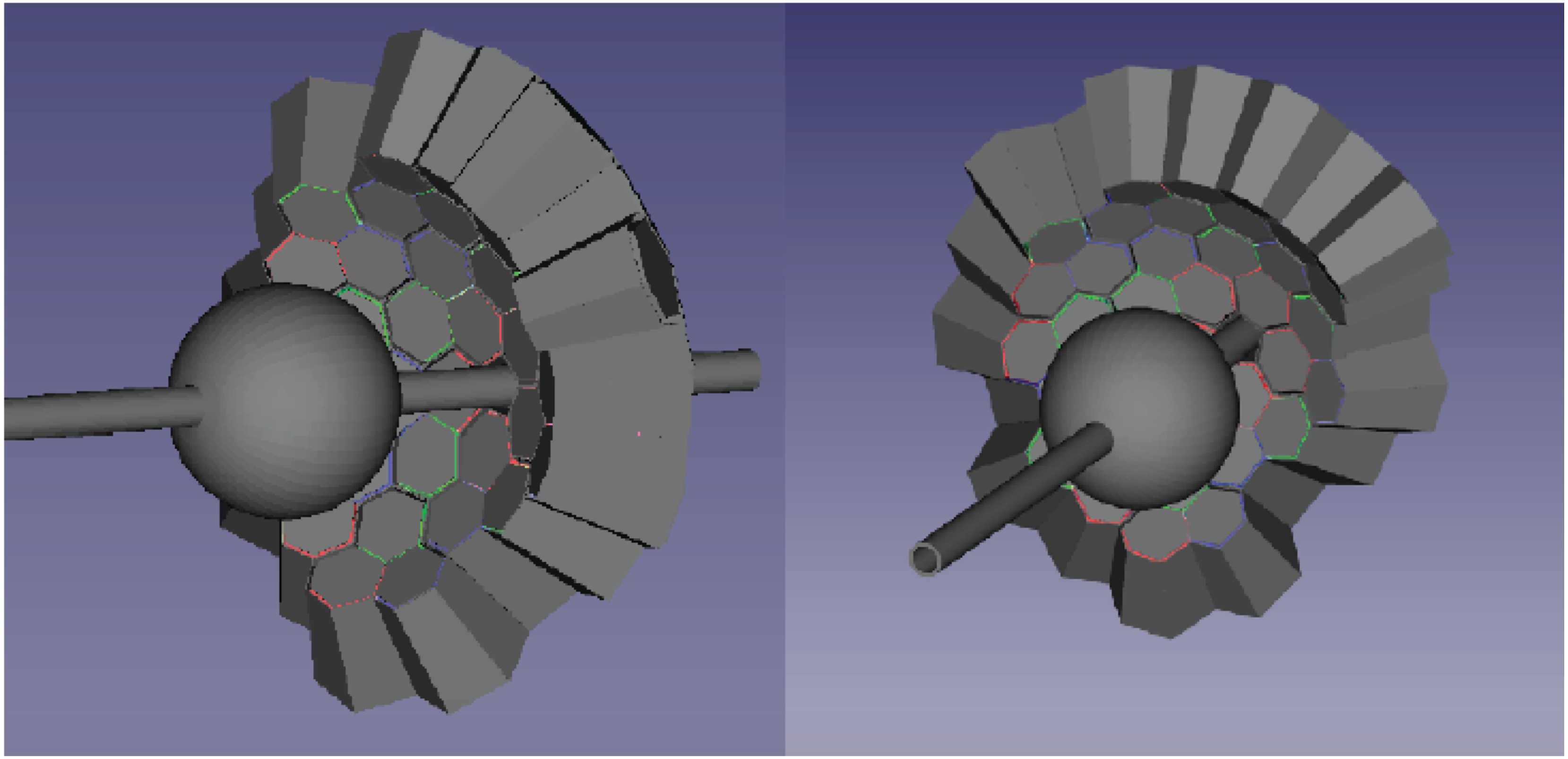


Figure 6: (Colour online.) Rejection efficiency of γ rays for a pulse-shape discrimination gate that contains 90 % of the neutrons. BC-501A is shown in black and BC-537 in red. The two discrimination algorithms are: artificial neural networks (squares) and charge comparison (circles).

AGATA simulations

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

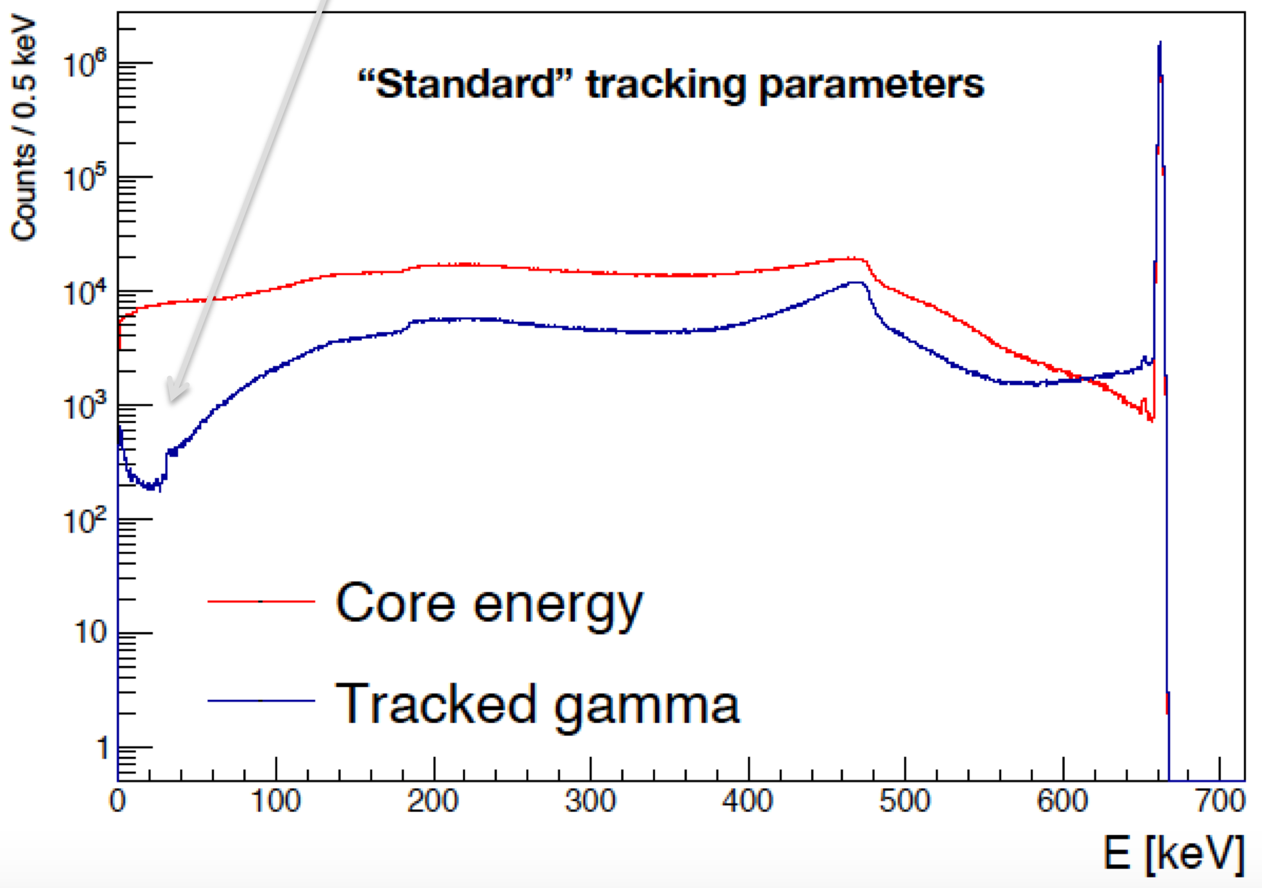
- 12 Agata Triple Cluster placed at backward angles
- AGATA at the nominal position, i.e. 23.5 cm from the target
- No anti-Compton shield between the HPGe.



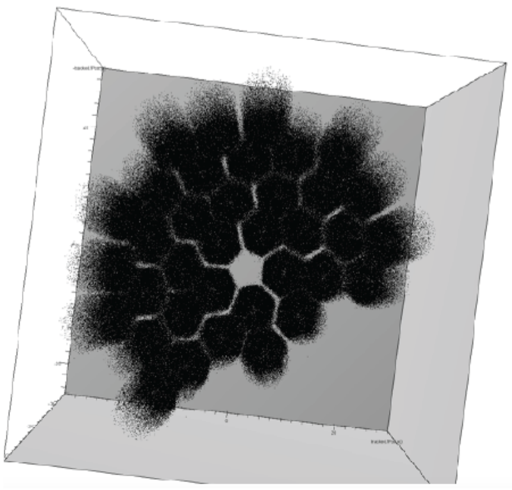
AGATA simulations

One unique gamma of 662 keV

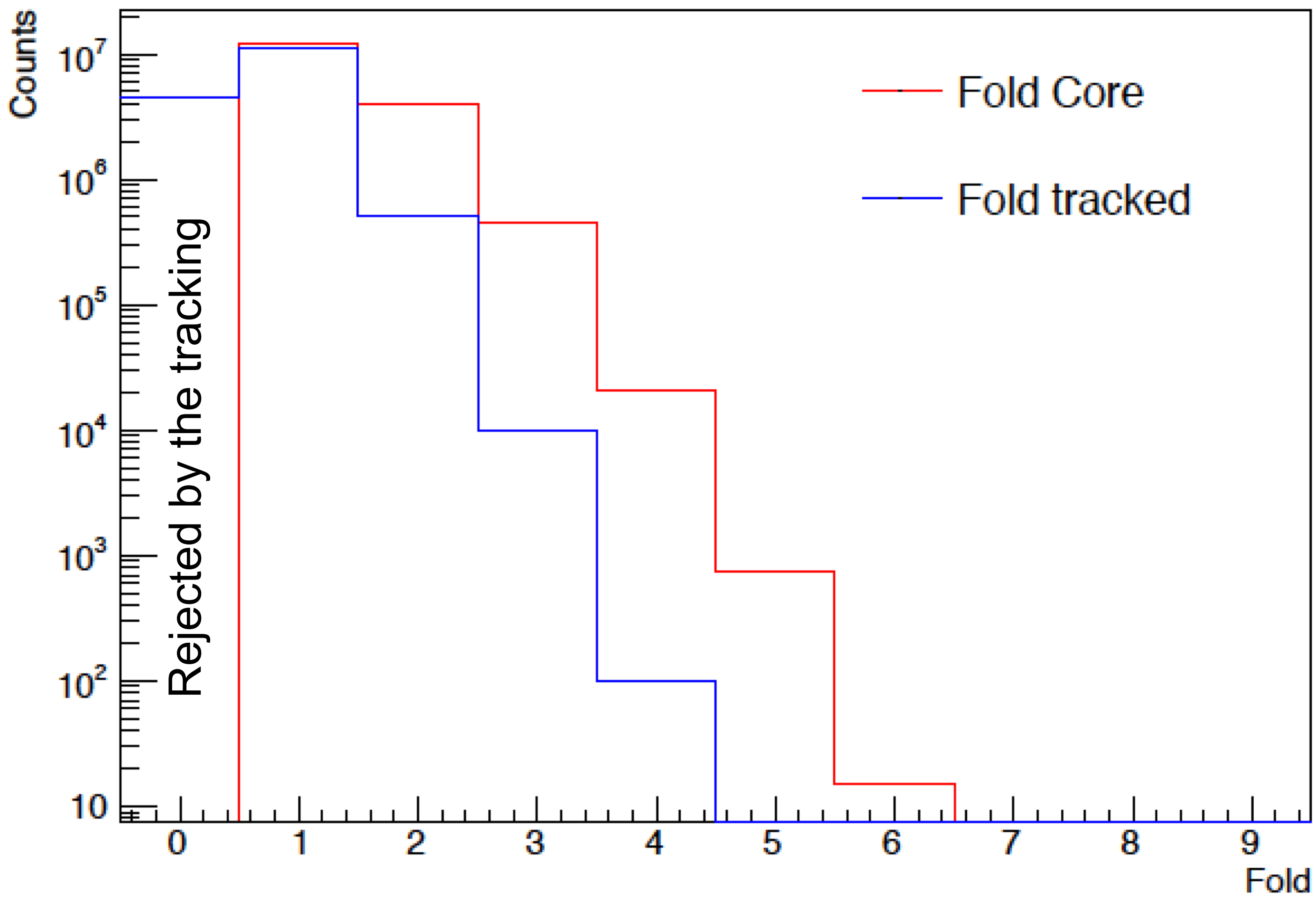
Threshold in the photo electric events



Tracking

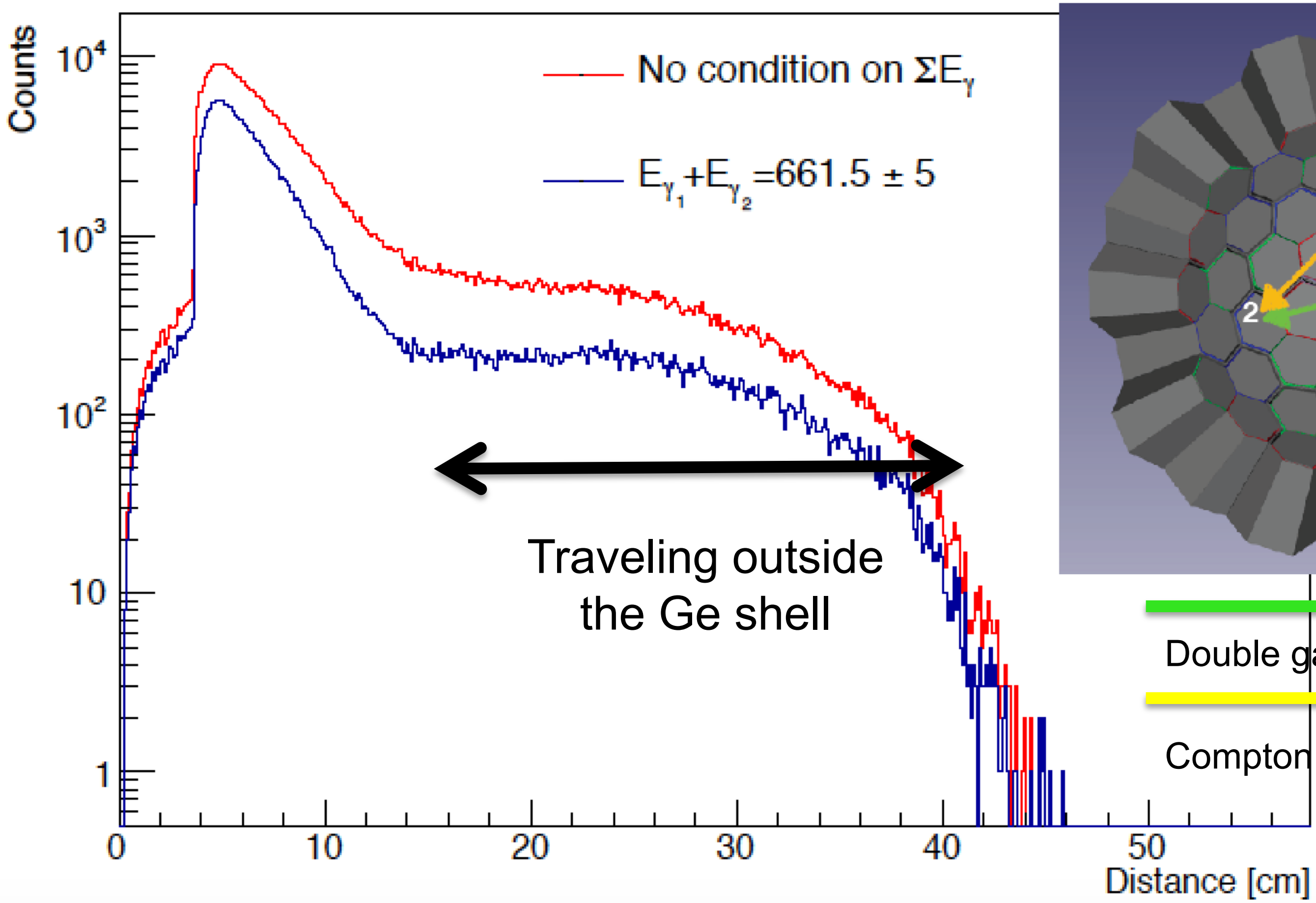


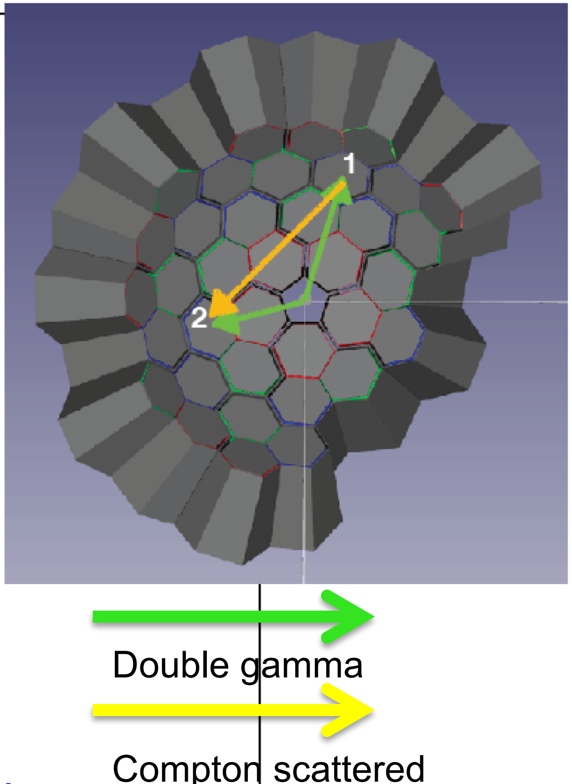
“Multiplicity” for 1 gamma 662 keV



AGATA

Distance between interactions: Tracking only fold 2 events



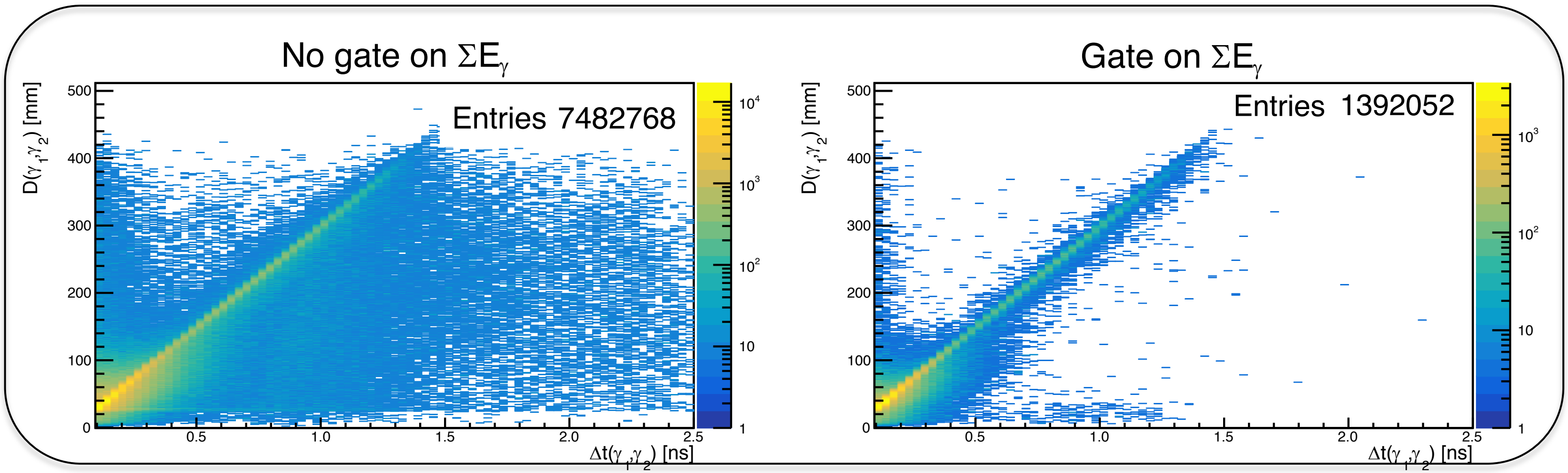


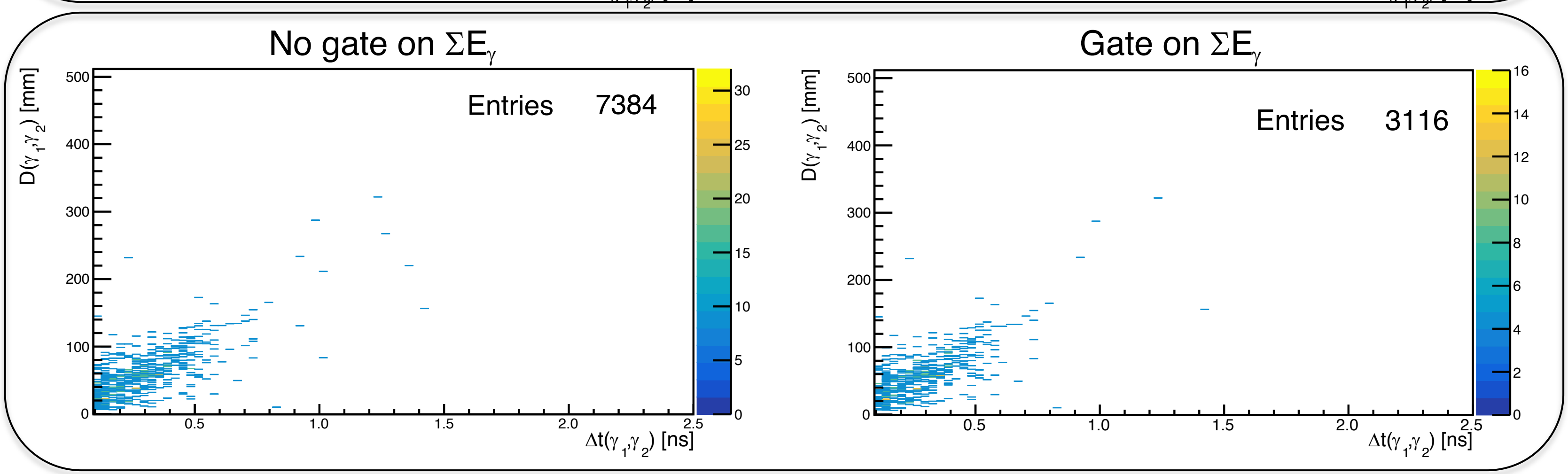
Tracking parameter d(γ1,γ2) ≤ 2.5cm → can not be a single event
Probability of being a single event is ~ 5%

AGATA distance vs. timing

One gamma → Fold=2

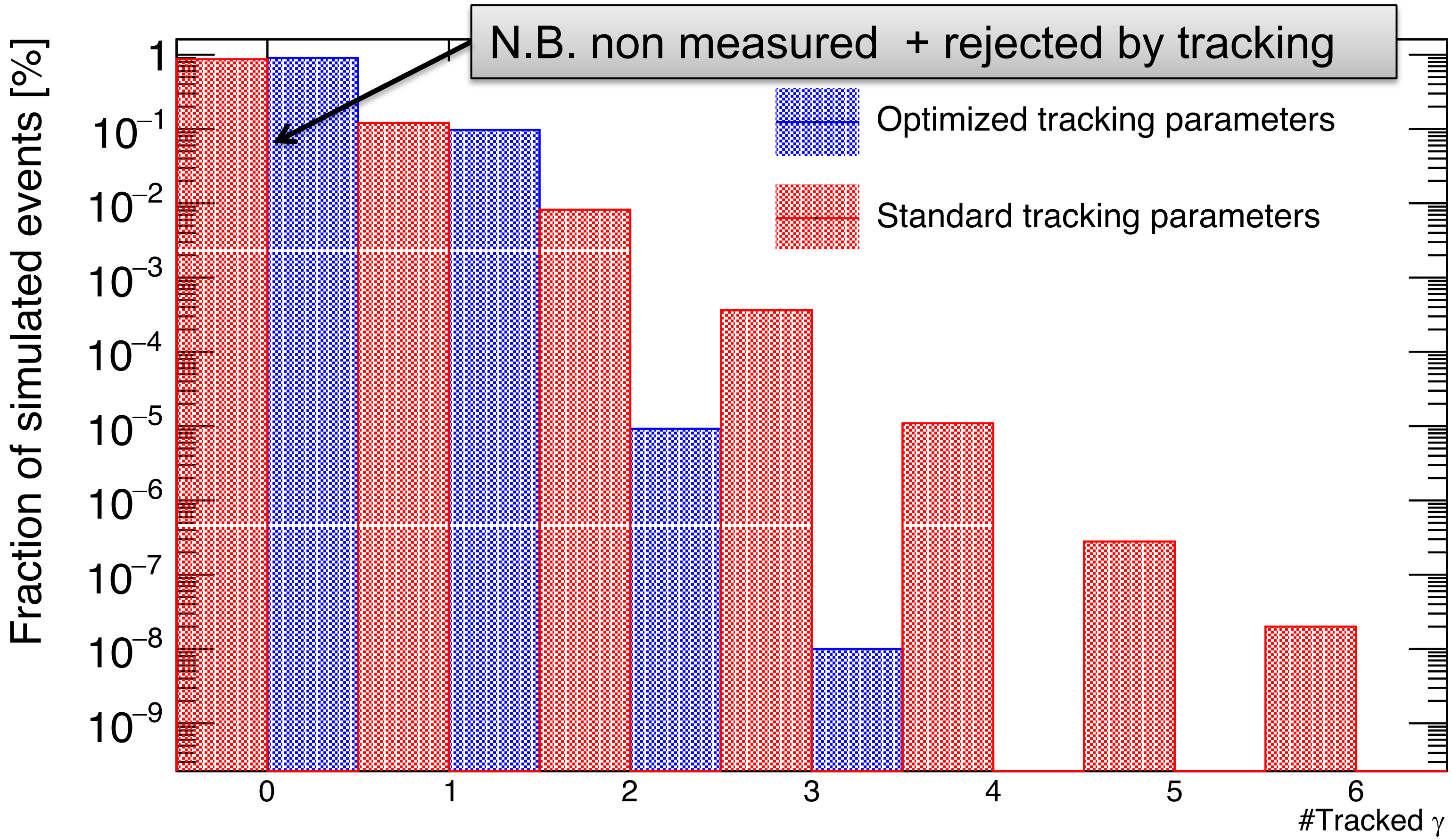
Clusterization space 8 degrees





Clusterization space full AGATA

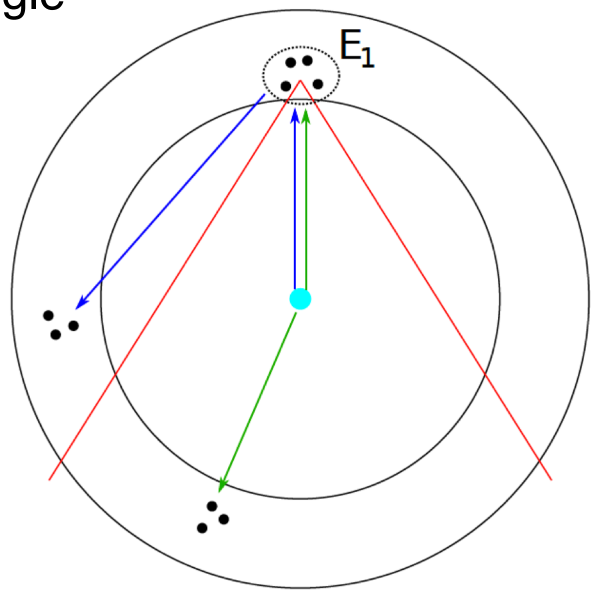
AGATA

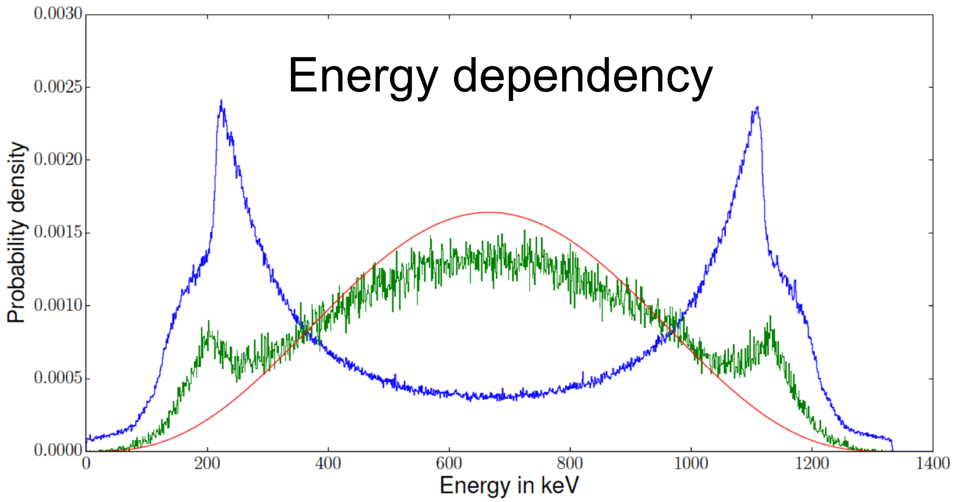


Full systematic optimization of the tracking parameters → one unique gamma
Study of of tracking parameters with two gamma events
Realistic event generators (energy sharing & angular distribution)

Energy and geometry of γ vs. $\gamma\gamma$

Due to the dynamics of the Compton-scattering, a single photon (blue arrows) depositing the energy E1 can only interact outside of the cone. If the next measured interactions are inside the cone, it is very likely that they stem from an additional photon (green arrows). The opening angle of the cone strongly varies with the amount of interactions in the cluster of E1 , the incident photon energy E0 and the allowed interval width .





1 gamma

2 gamma

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

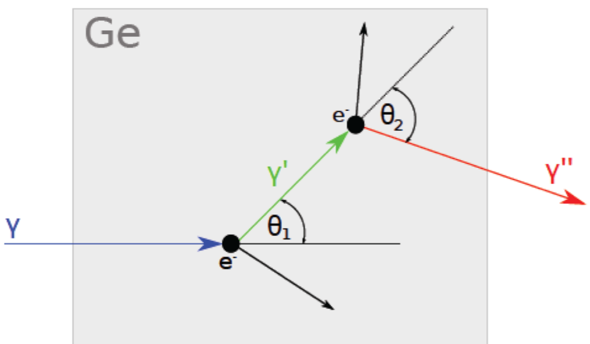


Figure: Compton-Escape Event in a Germanium detector

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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

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

	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*

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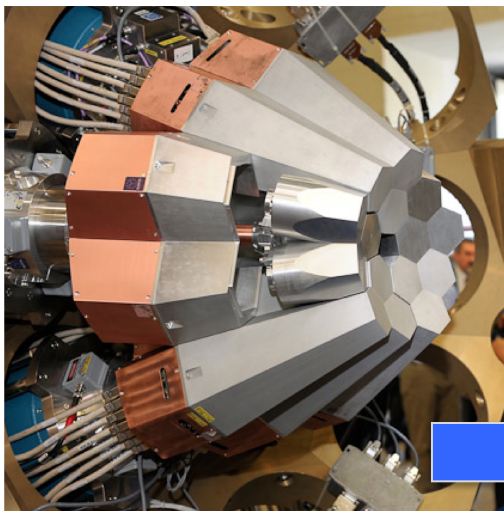
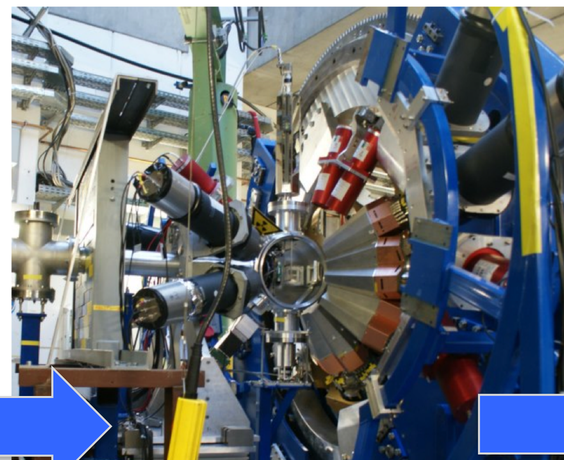
The AGATA time line

AGATA@LNL



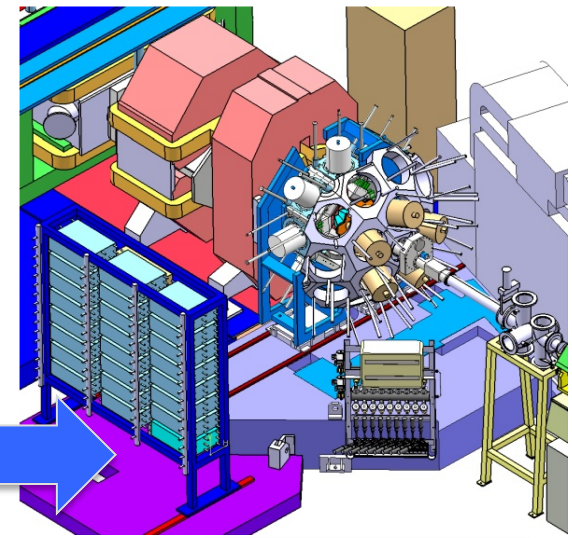
2009-2011

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.

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
- **Double-gamma decay process can help on the NME of 0vββ**?
  - **Experimental study of IAS double gamma decay**
  - **Theoretical description → correlation γγ and 0vββ**
- Electric polarizability α_D related to equation of state – nuclear simmetry energy? Possible theoretical link?

- 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.