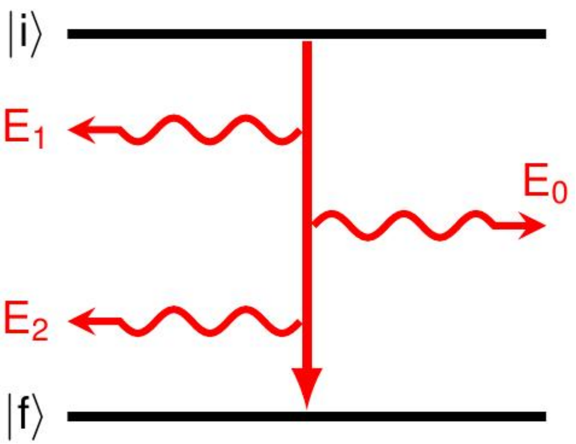
Experiments on the ‘Competitive Double-Gamma’ ($\gamma\gamma/\gamma$) Decay

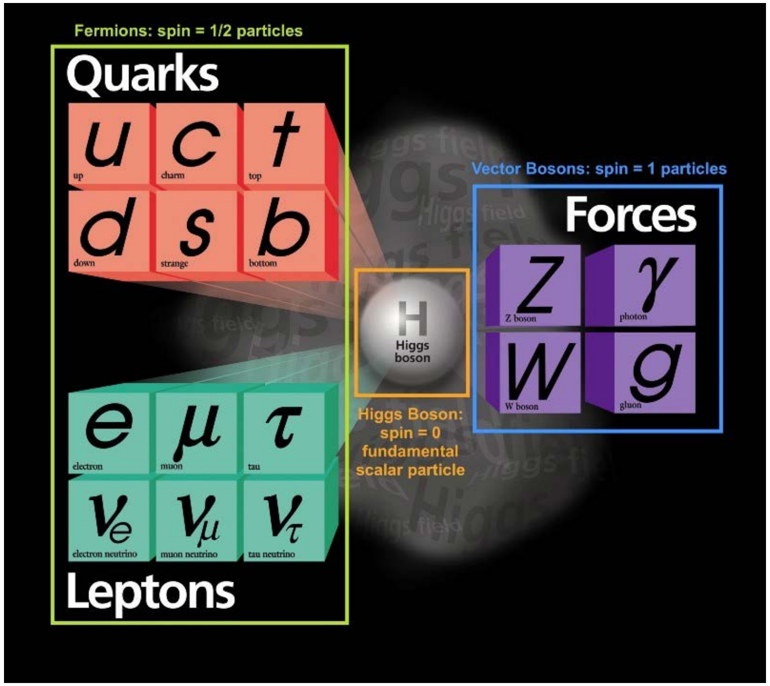
Norbert Pietralla, TU Darmstadt



- **Motivation and historical remarks**
- **Recent discovery of the $\gamma\gamma/\gamma$ decay**
- **Experimental opportunities and Outlook**

in collaboration with
T. Aumann, P. John, P. Napiralla, V
.Yu. Ponomarev, **H. Scheit** (TU Darmstadt),
J.J. Valiente Dobon, G. De Angelis (INFN)

Motivation



- Search for the neutrino mass
- If Majorana neutrino: $0\nu\beta\beta$
- $\lambda_{0\nu\beta\beta} = G\,|M|^2 \langle m_\nu \rangle^2$
- Need NME from theory
- Any constraint is welcome.
- Electroweak process of 2^{nd} order

Motivation

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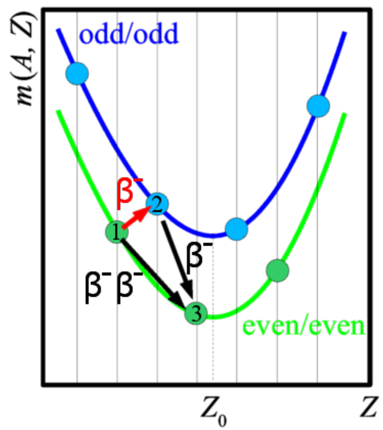
double β-decay
2νββ (0νββ)



first evidence in the laboratory:
*S. Elliot, A. Hahn, and M. Moe, PRL **59**, 2020 (1987)*

PHYSICAL REVIEW

Double Beta-Disintegration

M. Goeppert-Mayer, *The Johns Hopkins University*
(Received May 20, 1935)

Max Born (Göttingen, 1927):
"Study 2nd order processes!"

M. Göppert, Dissertation, 1929
M.Göppert-Mayer, Ann. Wiss. (1931)

Über Elementarakte mit zwei Quantensprüngen
Von Maria Göppert-Mayer
(Göttinger Dissertation)
(Mit 5 Figuren)

Einleitung

Der erste Teil dieser Arbeit beschäftigt sich mit dem Zusammenwirken zweier Lichtquanten in einem Elementarakt.

The double-gamma decay

First discussed by Maria Göppert-Mayer in her doctoral thesis in 1929

M. Göppert-Mayer, Über Elementarakte mit zwei Quantensprüngen

Second order process (10^{-6} weaker)

- $E_0 = E_1 + E_2$
- E_1, E_2 are continuous

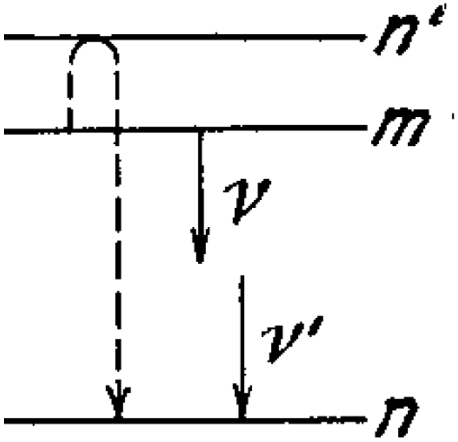


Fig.4
M. Göppert-Mayer, Ann.Wiss. (1931)

studied inverse in atomic physics

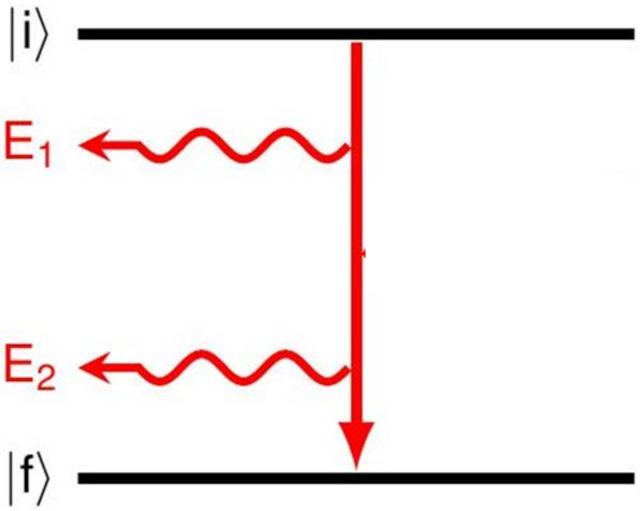
- *M. Lipes et al., PRL 15, 690 (1965)*
- *P.H. Mokler et al., Phys. Scr. 69, C1 (2004)*
- *K. Ilakovac et al., Rad. Phys. Chem. 75, 1451 (2006)*

The double-gamma decay in nuclear physics

$\gamma\gamma$-decay only known in a special case:

$0^+ \rightarrow 0^+$ (^{90}Zr, ^{40}Ca, ^{16}O)

- *J. Schirmer et al., PRL 53, 1897 (1984)*
- *J. Kramp et al., NPA 474, 412 (1987)*



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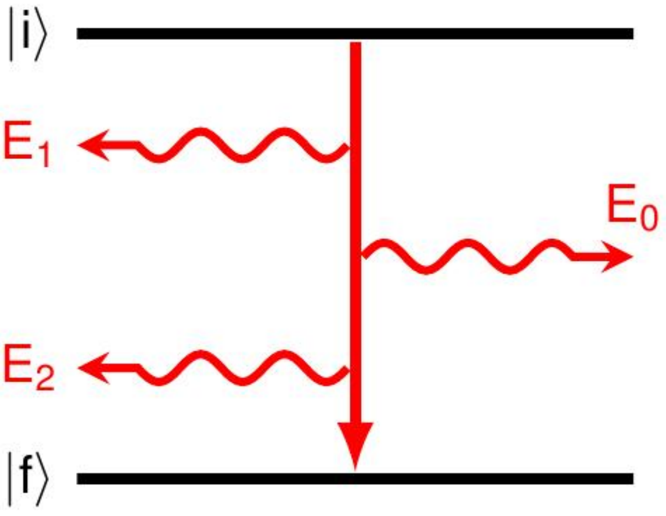
- *V.K. Basenko et al., Bull. Russ. Acad. 56, 94 (1992)*
- *C.J. Lister et al., Bull. Am. Phys. Soc. 58(13), DNP.CE.3 (2013)*



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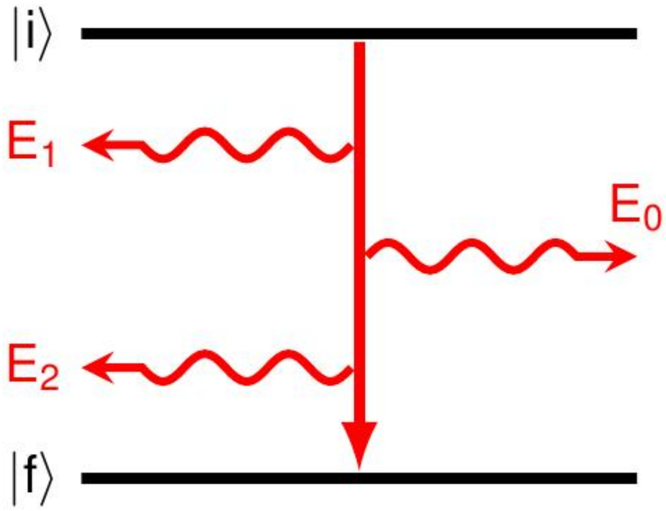
Dr. Christopher Walz
The two-photon decay of the 11/2⁻ isomer of ^{137}Ba and mixed-symmetry states of ^{92,94}Zr and ^{94}Mo
(Dissertation, TU Darmstadt, 2014)

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]

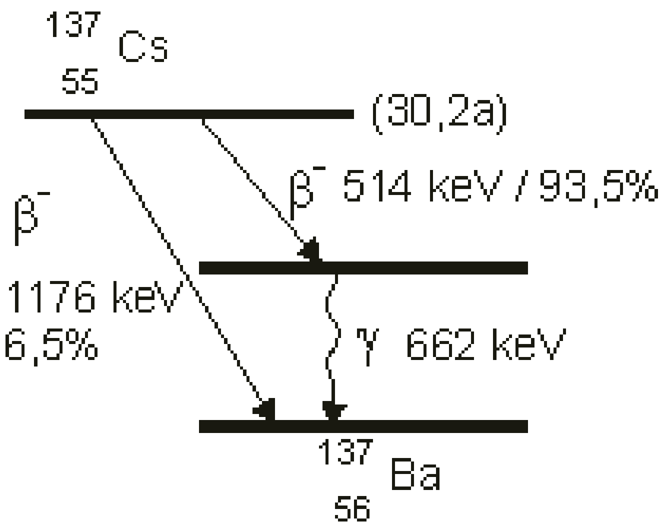


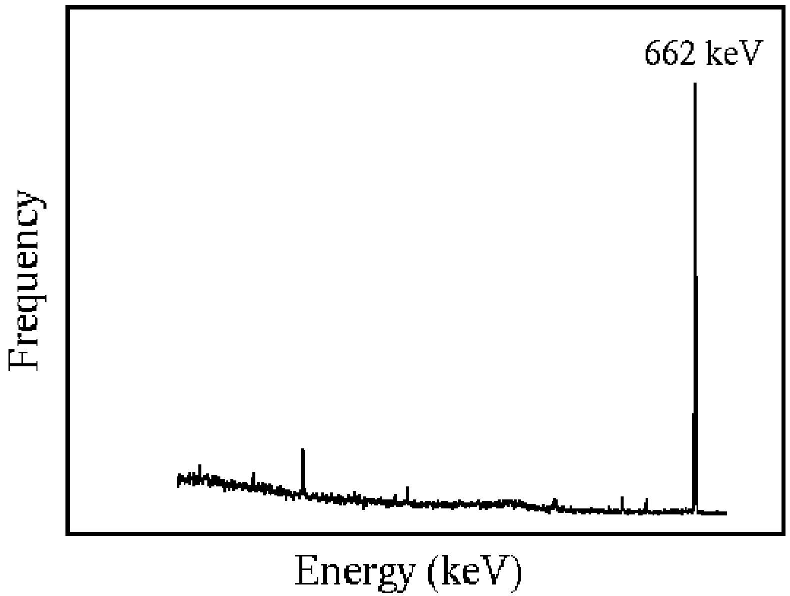
Dissertation Award 2014, TU Darmstadt
Dissertation Award 2014, EPS – NPD

and

C.Walz et al., Nature 526, 406 (2015)

Search for $\gamma\gamma/\gamma$ - decay in ^{137}Cs γ - standard

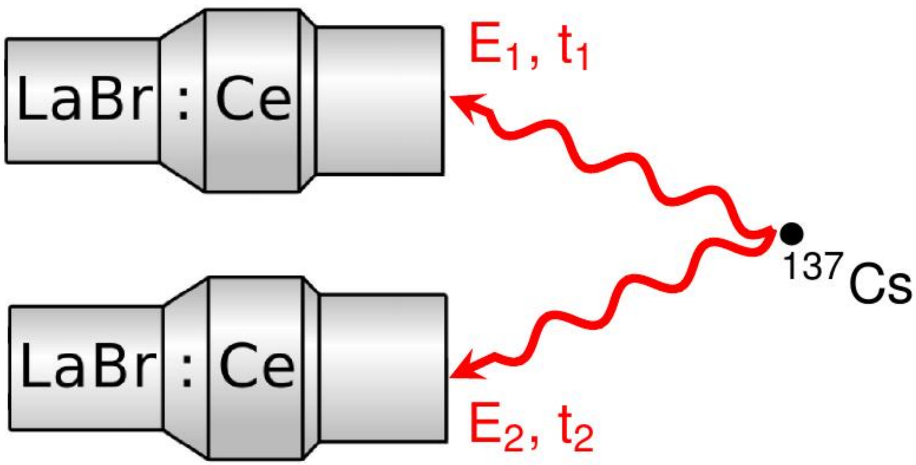


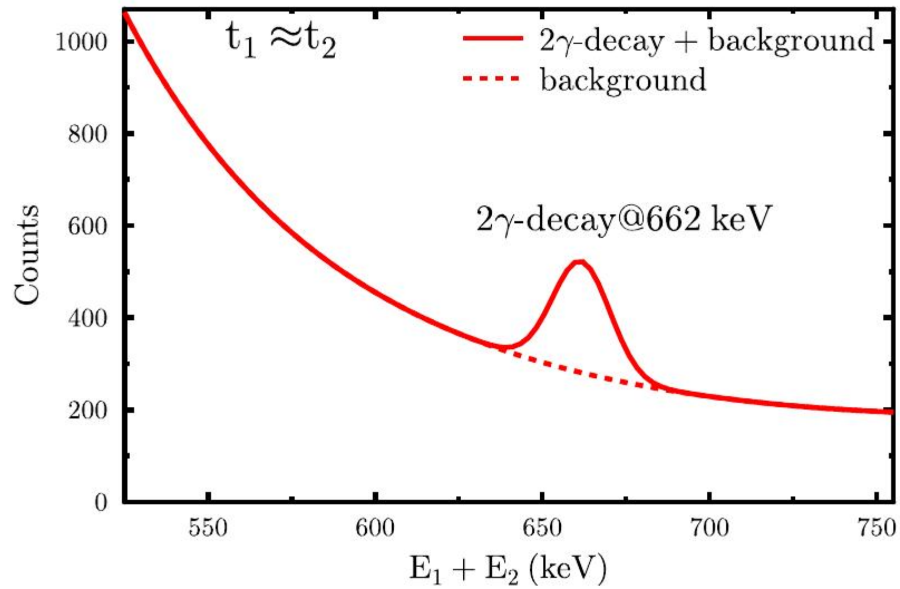


- Study 662-keV transition in ^{137}Ba
- use radioactive ^{137}Cs -source

Basic principle of the experiment

•use radioative ^{137}Cs -source: 16.3(5)µCi

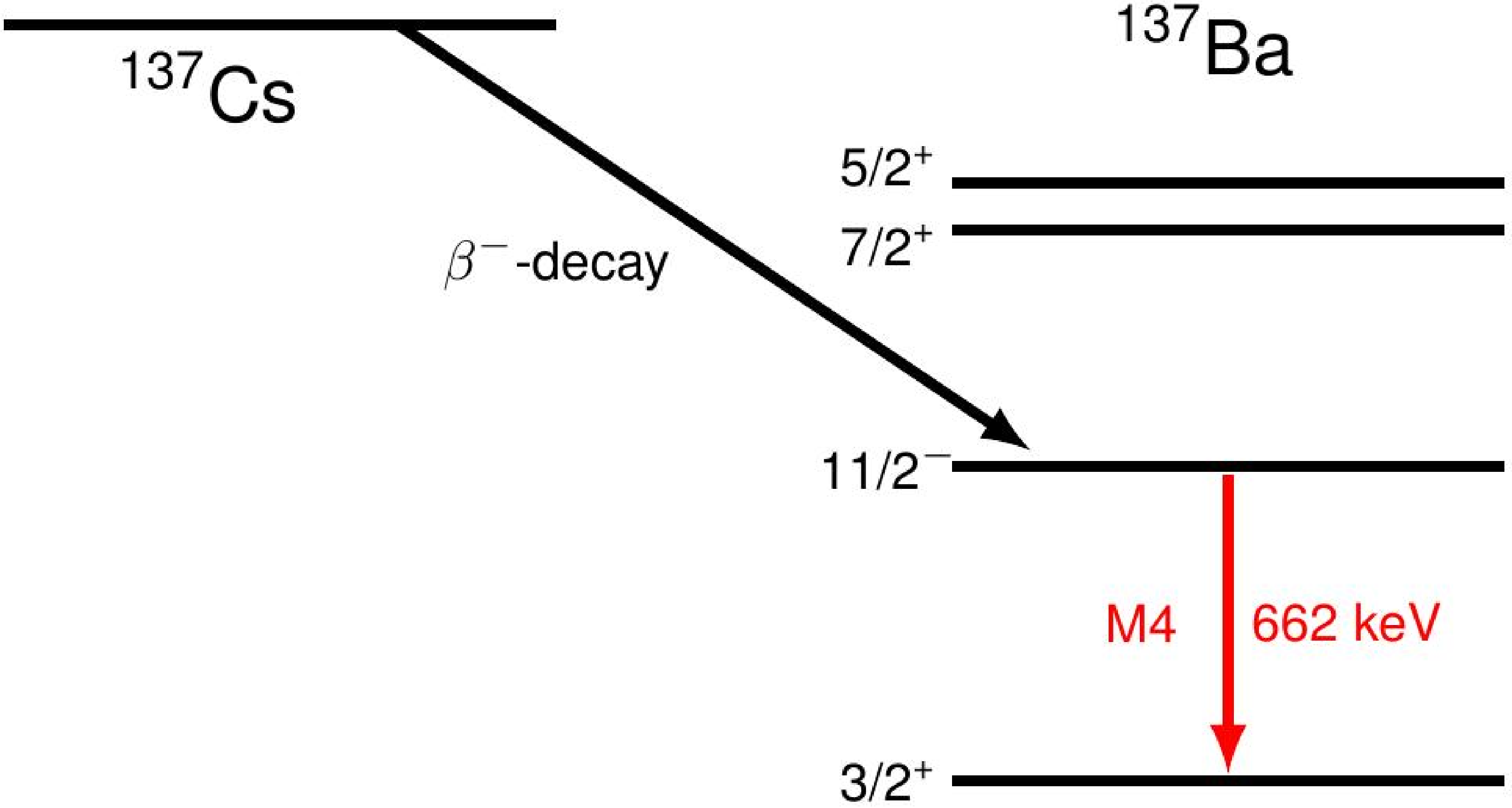




- background ↔ small decay probability (~1 event per day)
  - direct Compton scattering
  - random coincidences
  - cosmic rays, sequential Compton scattering, internal radioactivity

Decay scheme of ^{137}Cs

- Activity of ^{137}Cs -source: 16.3(5)µCi



Matrix element of the double-gamma decay

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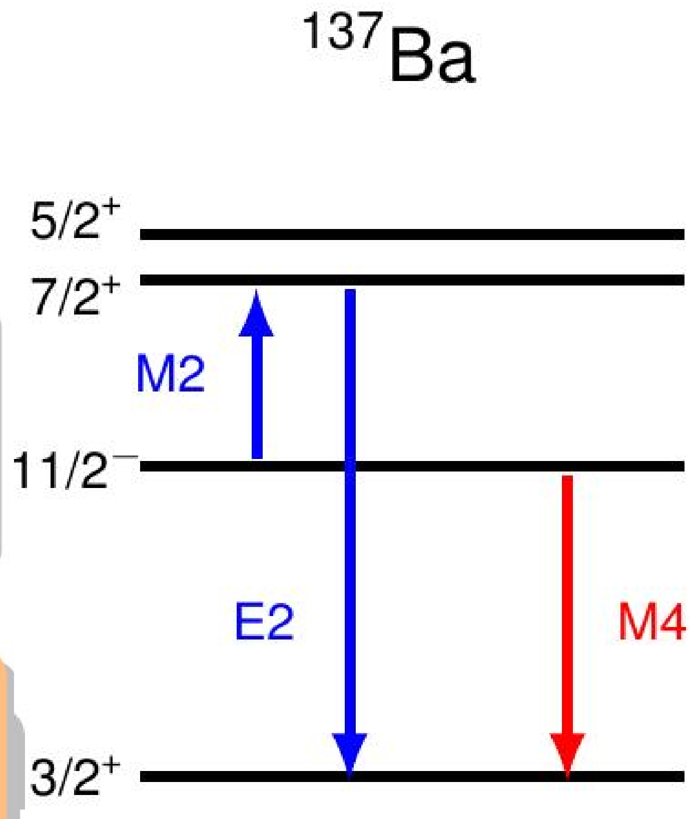
$$\frac{\mathrm{d}\Gamma^2_{\gamma\gamma}}{\mathrm{d}\omega\mathrm{d}\cos\theta}(\alpha_{OO'}, \ldots)$$

$$\alpha_{OO'} = \sum_n \frac{\langle f||\mathbf{O}||n\rangle \cdot \langle n||\mathbf{O}'||i\rangle}{E_n}$$

$$\alpha_{M2E2} = \frac{\langle 3/2^+||\mathbf{E2}||7/2^+\rangle \cdot \langle 7/2^+||\mathbf{M2}||11/2^-\rangle}{E_{7/2^+}} + \ldots$$



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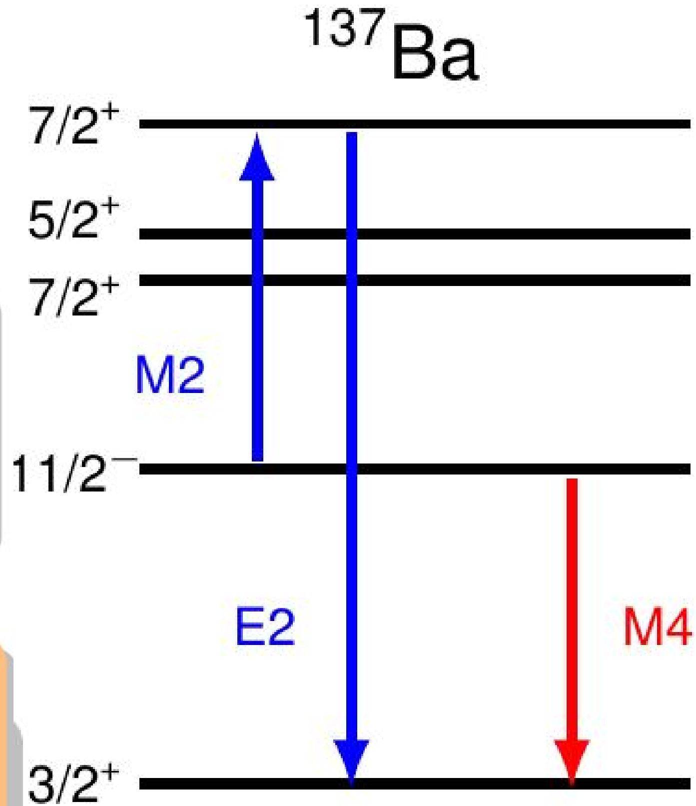

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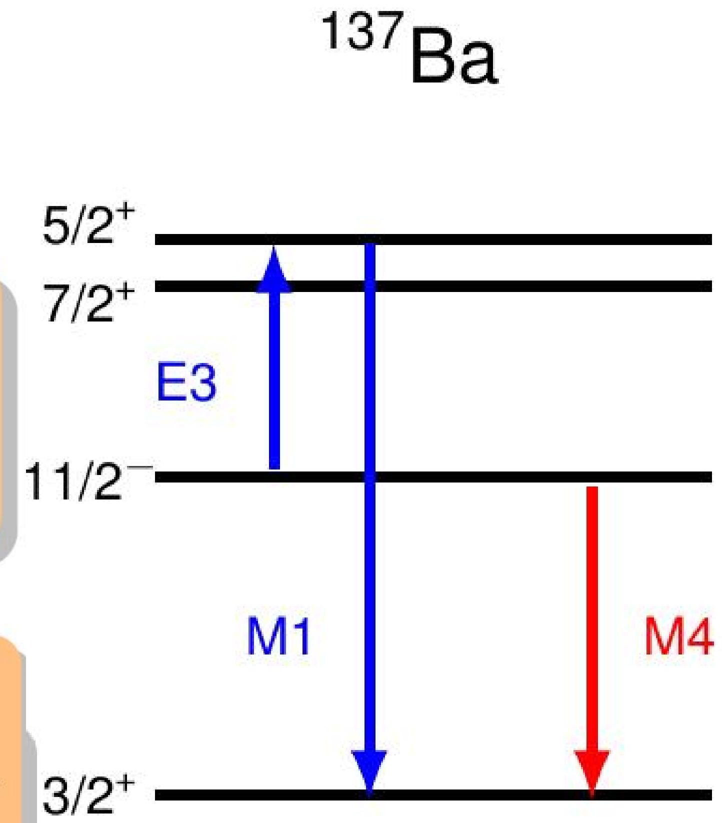
$$\alpha_{E3M1} = \frac{\langle 3/2^+||\mathbf{M1}||5/2^+\rangle \cdot \langle 5/2^+||\mathbf{E3}||11/2^-\rangle}{E_{5/2^+}} + \ldots$$

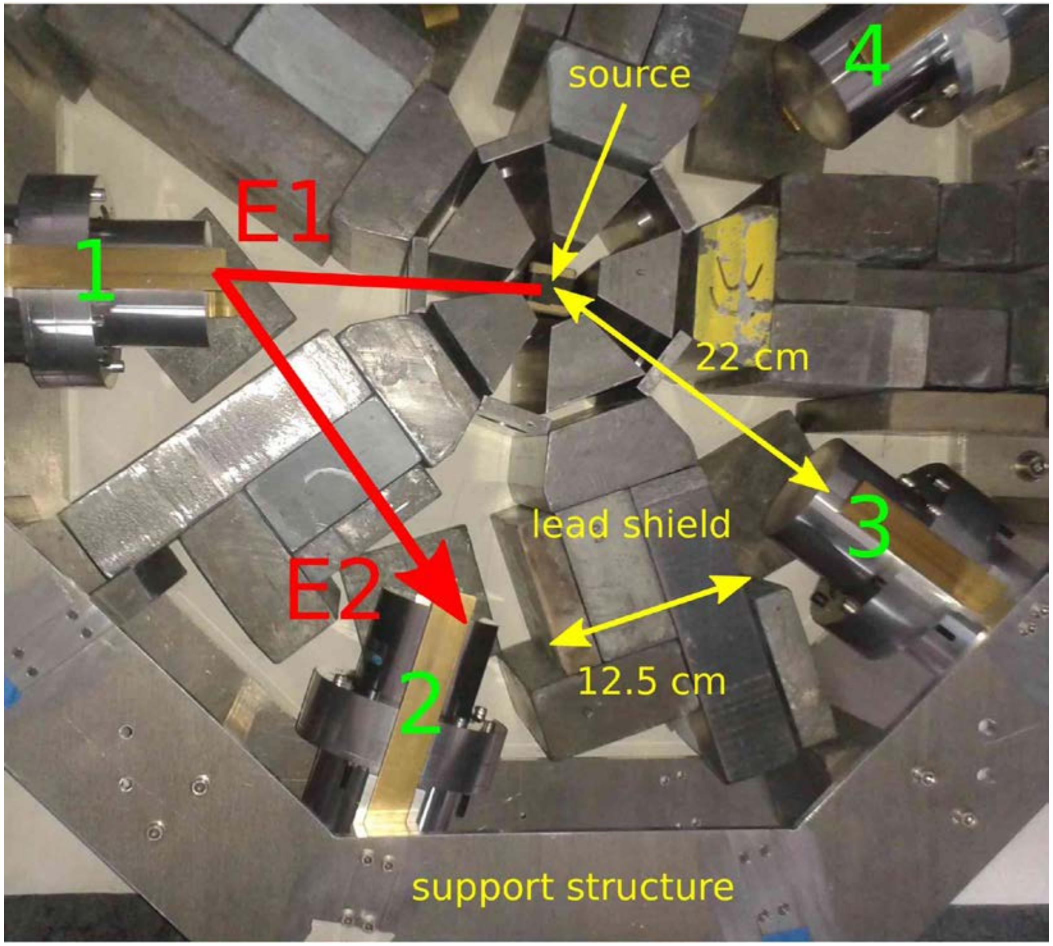


Experiment
(C. Walz, H. Scheit)

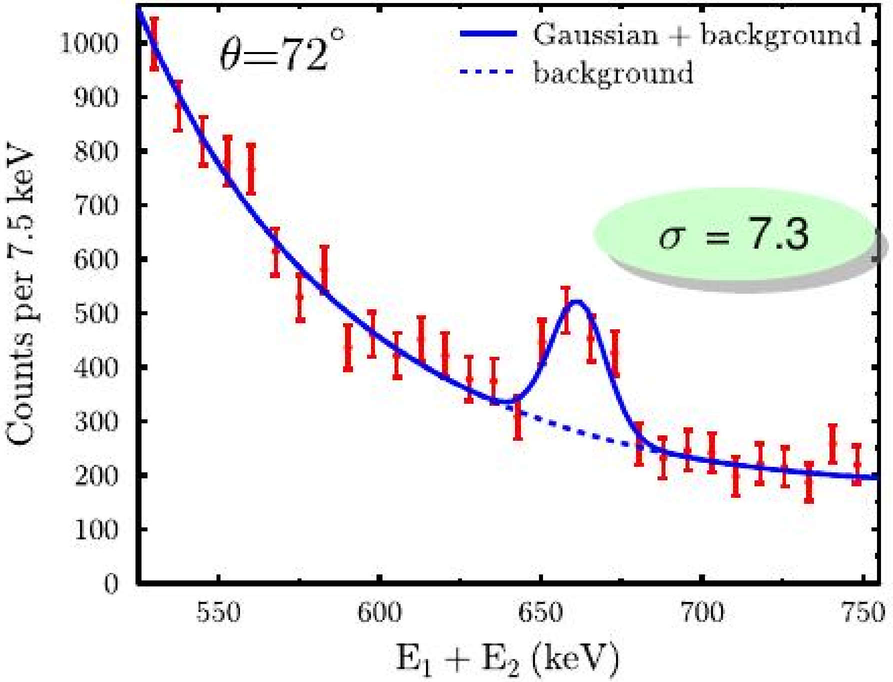
- 72°: 5 detector pairs
- 144°: 5 detector pairs

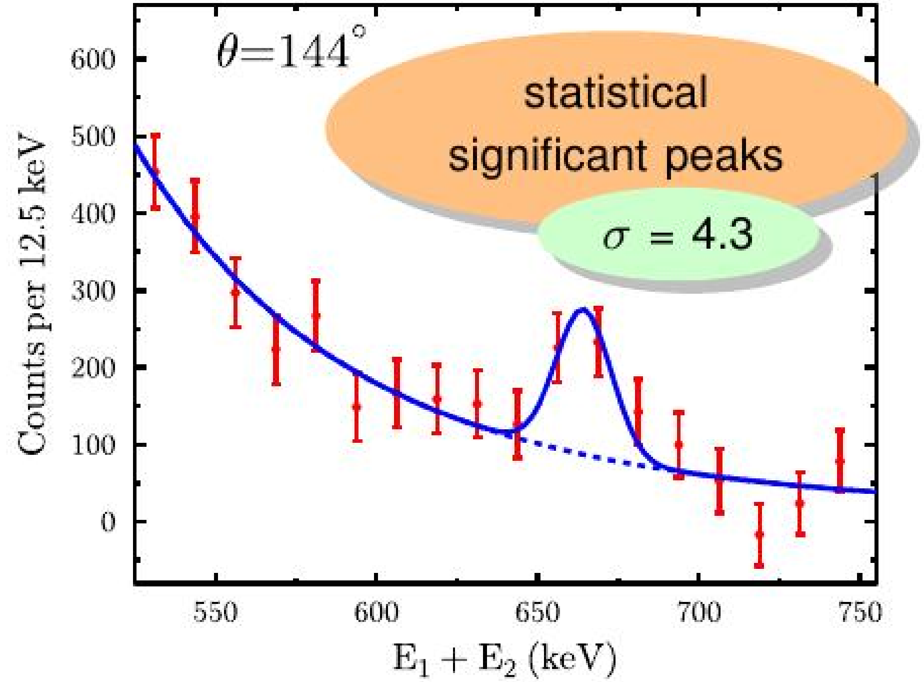
- $E_1 + E_2 = 662$ keV
- Compton scattering
  $\Longleftrightarrow$
  double-gamma decay

- $\epsilon_{abs} = 1.50(5)\%$
- measurement time: 1273 h



Signal



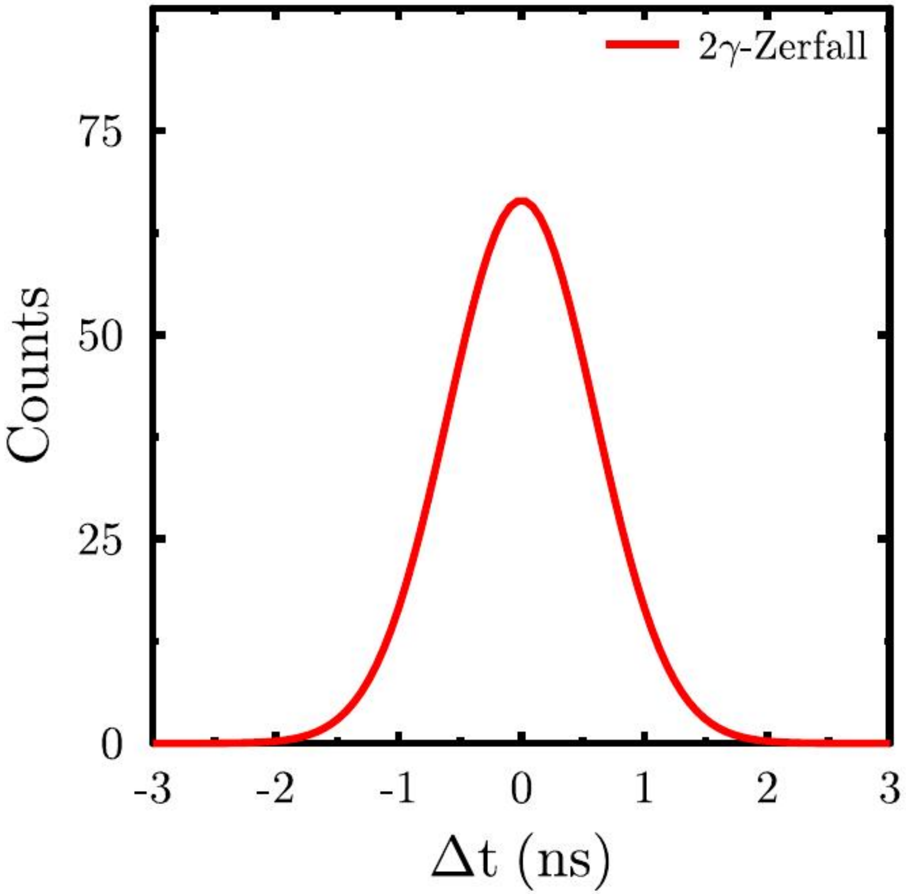


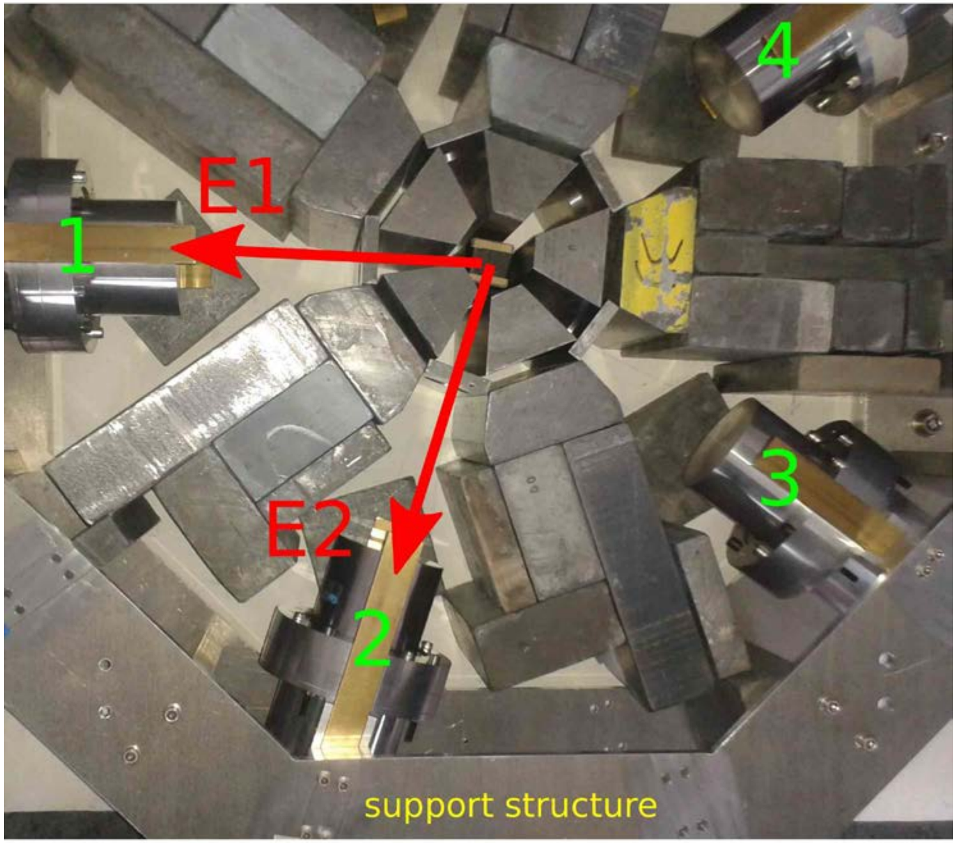
$A_{2\gamma}(72^\circ)$ = 693(95) counts
$\Gamma_{\gamma\gamma}/\Gamma_\gamma(72^\circ) = 1.56(23)\cdot 10^{-6}$

$A_{2\gamma}(144^\circ)$ = 325(76) counts
$\Gamma_{\gamma\gamma}/\Gamma_\gamma(144^\circ) = 0.70(18)\cdot 10^{-6}$

- Result: Successful observation of the competitive double-gamma decay

Timing Analysis





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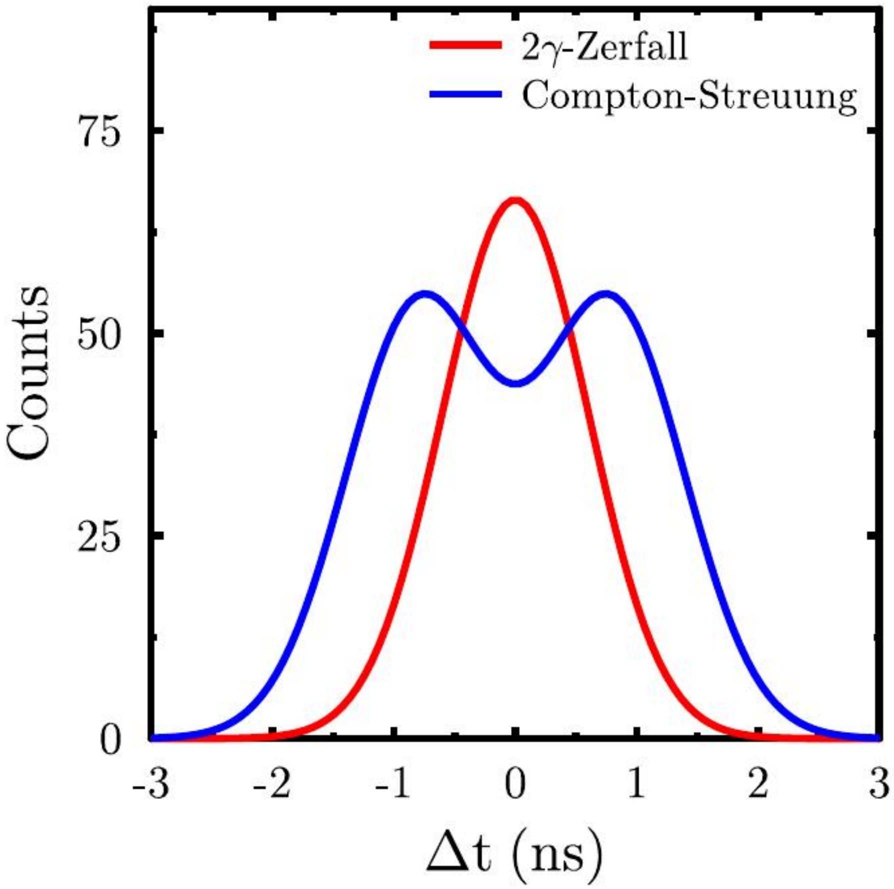

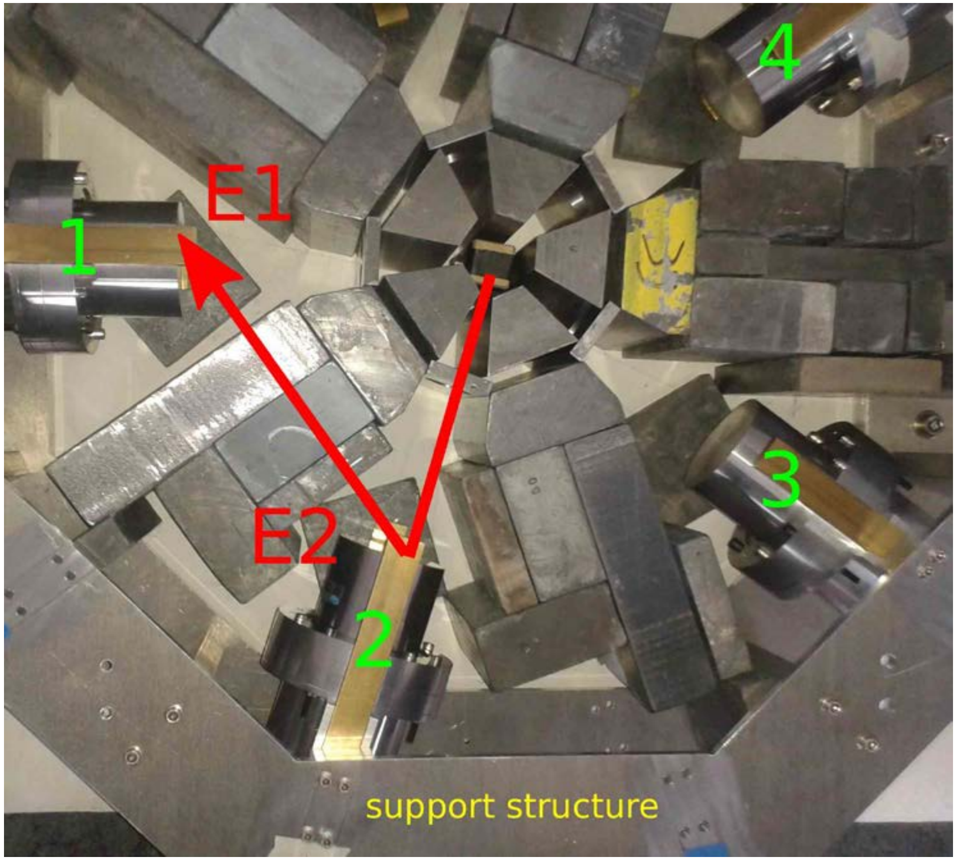

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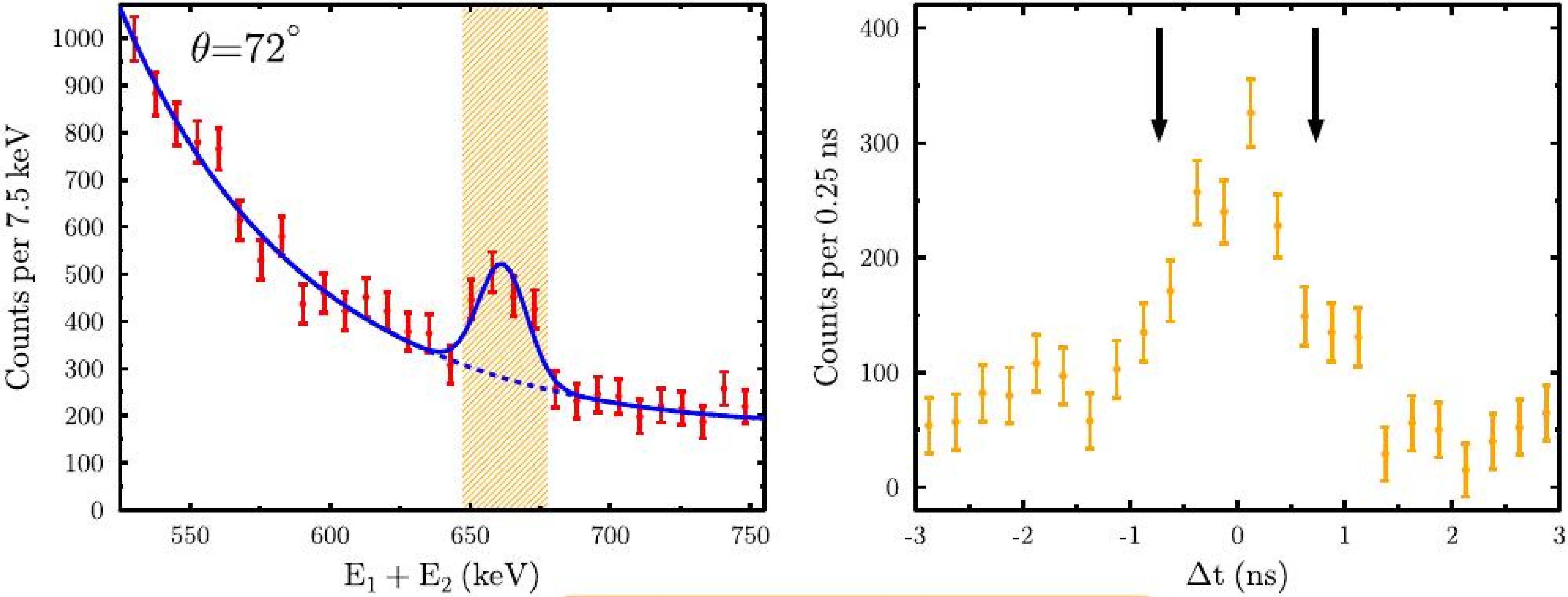

Shape of the time spec-
trum proofs that Compton
scattering is not the origin
of the peak at 662 keV

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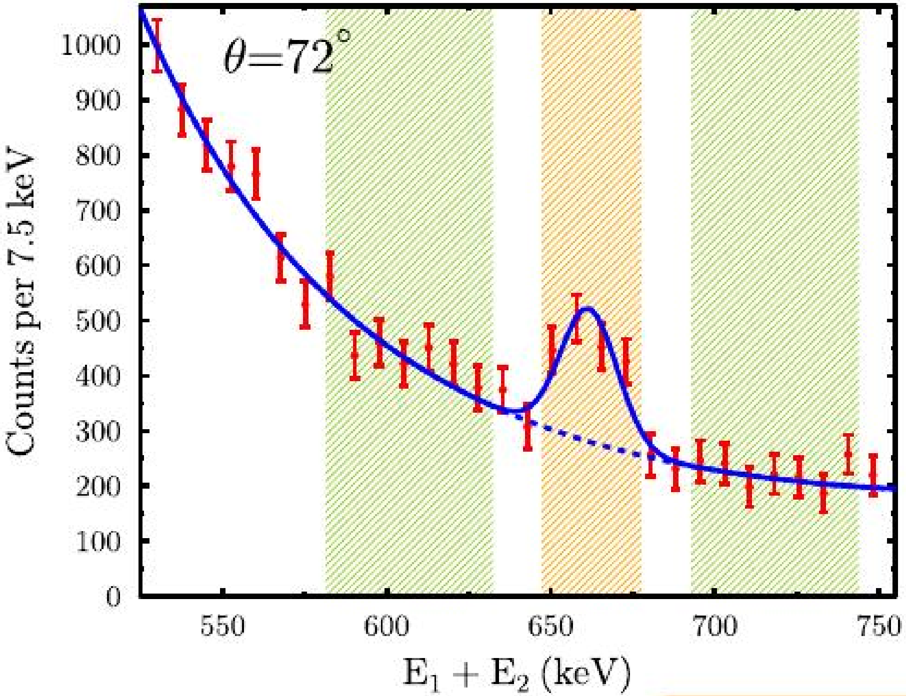
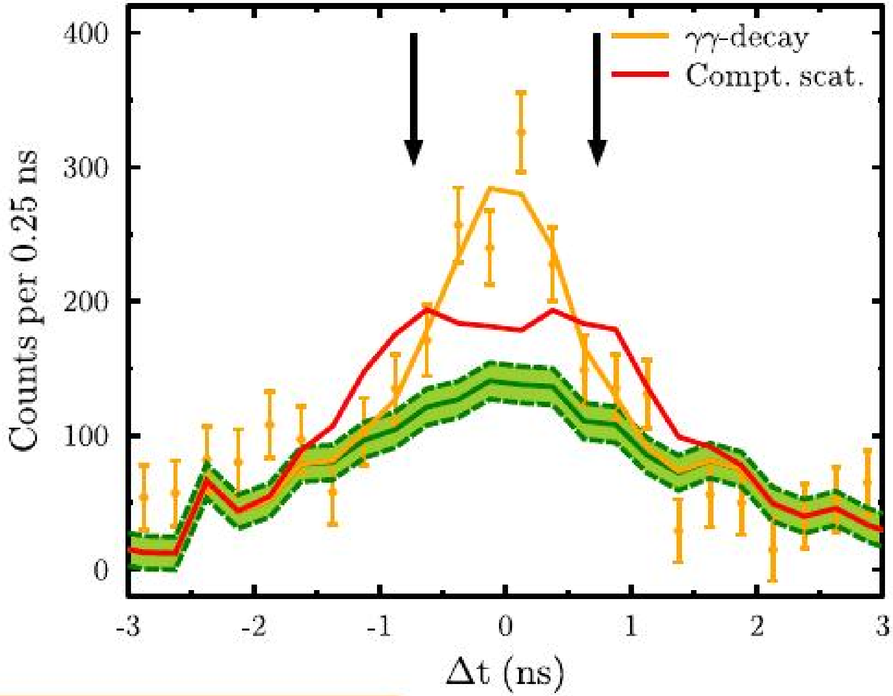
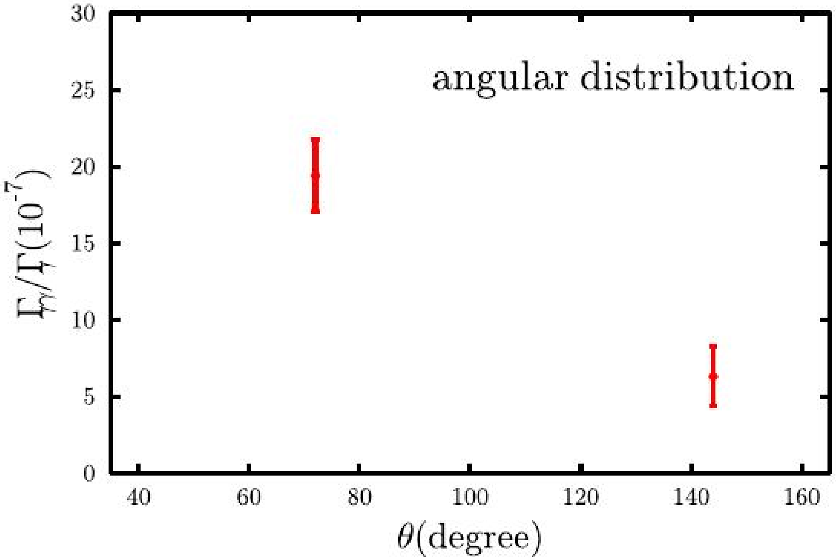
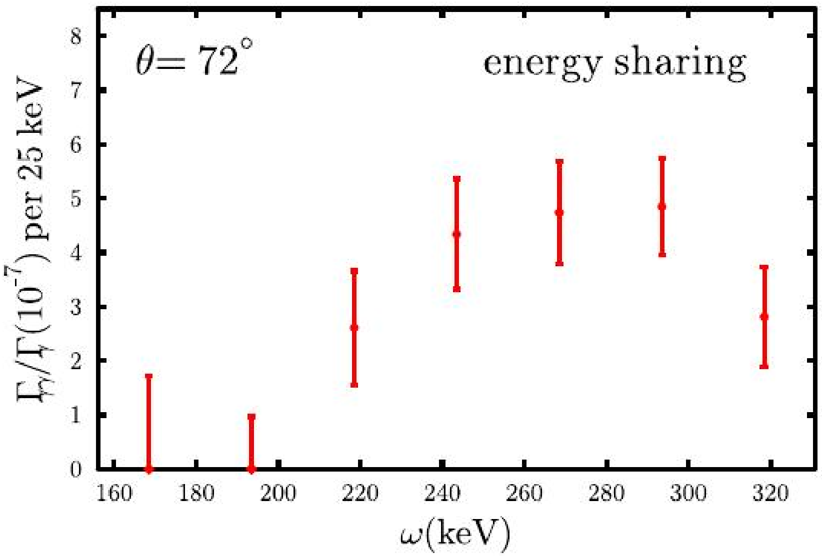




Shape of the time spectrum proofs that Compton scattering is not the origin of the peak at 662 keV

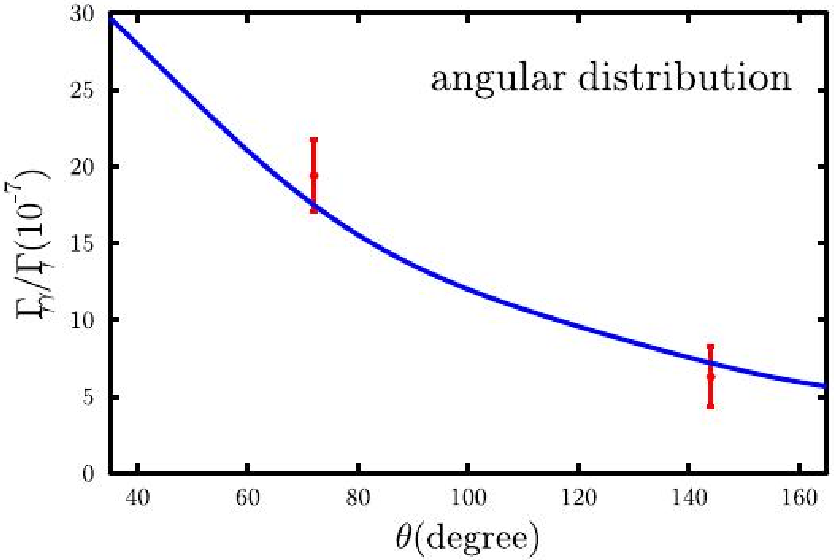
Results

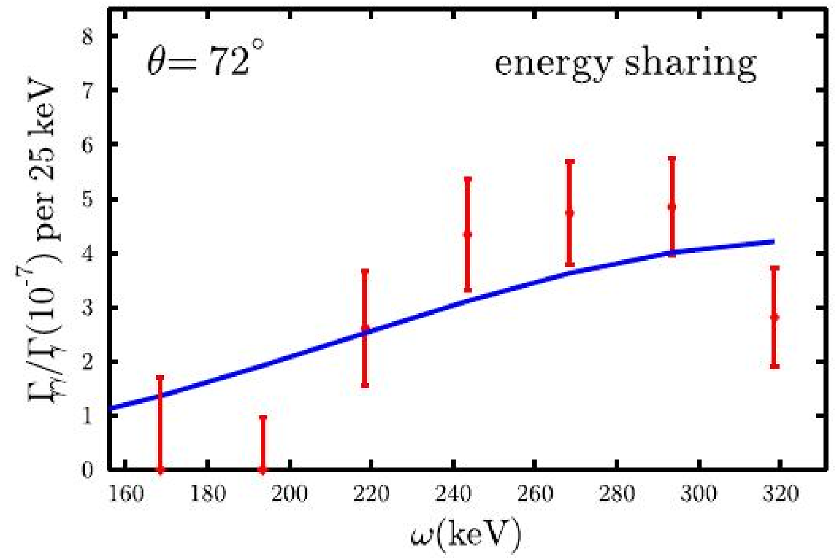




$$\frac{d\Gamma^2_{\gamma\gamma}}{d\omega\, d\cos\theta} = A_{qq}(\alpha^2_{M2E2}) + A_{od}(\alpha^2_{E3M1}) + A_x(\alpha_{M2E2} \cdot \alpha_{E3M1})$$

Results

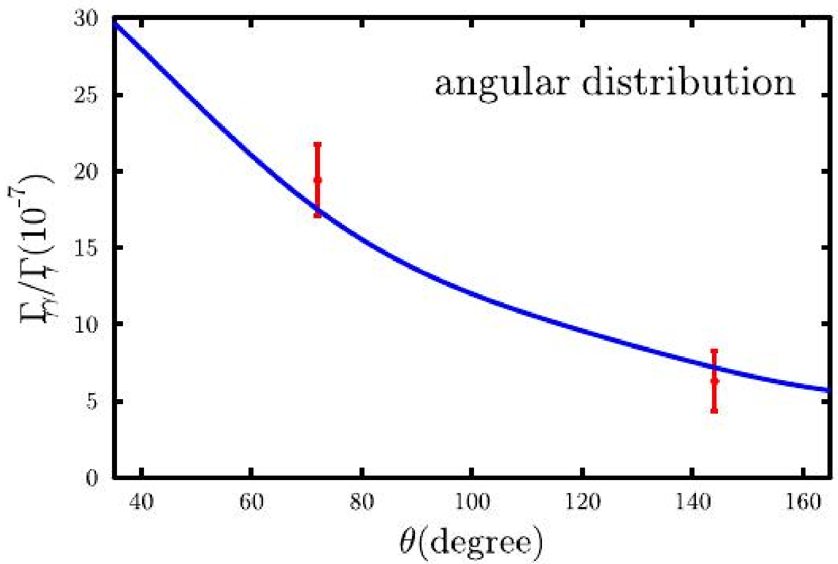


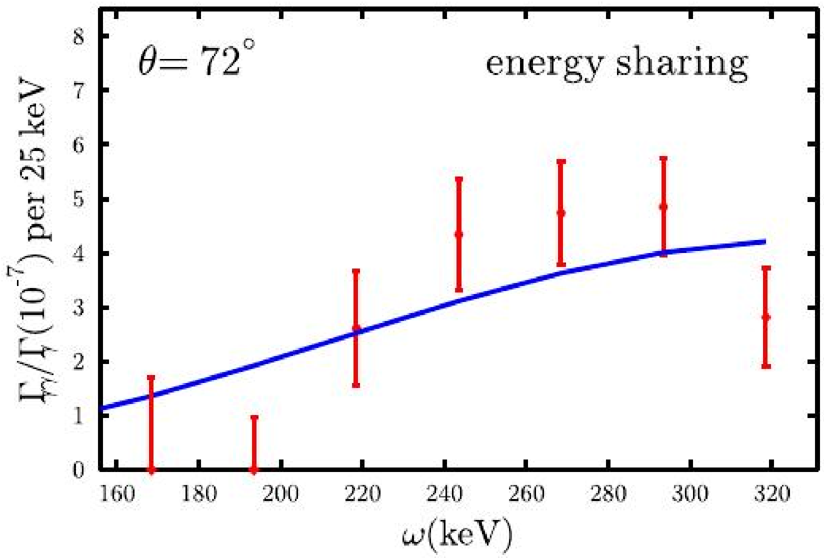


$$\frac{d\Gamma^2_{\gamma\gamma}}{d\omega d\cos\theta} = A_{qq}(\alpha^2_{M2E2}) + A_{od}(\alpha^2_{E3M1}) + A_x(\alpha_{M2E2} \cdot \alpha_{E3M1})$$

- Assumption: Only α_{M2E2} and α_{E3M1} contribute
- A_{qq}, A_{od} and A_x exhibit characteristic dependence on ω and θ
- fit both distributions simultaneously to determine α_{M2E2} and α_{E3M1}

Results





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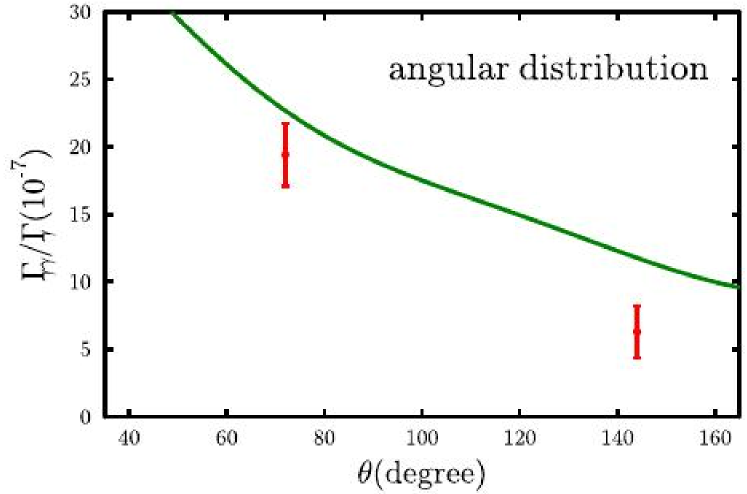
- A_{qq}, A_{od} and A_x exhibit characteristic...
- fit both distributions simultaneously to determine α_{M2E2} and α_{E3M1}

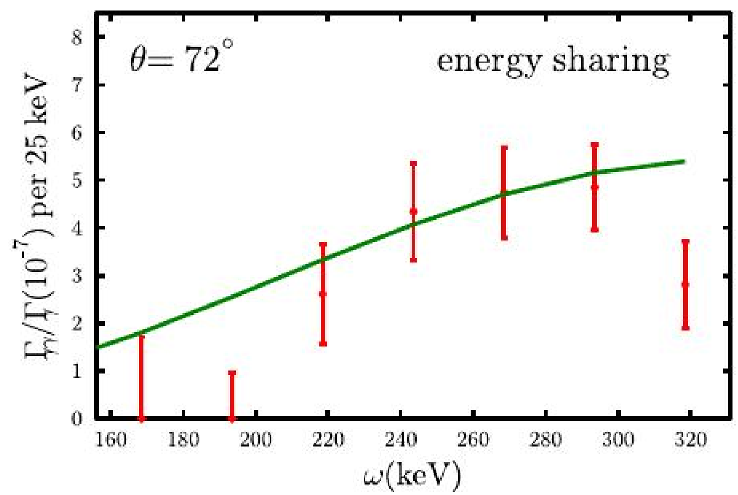
$$\alpha_{M2E2} = +38.2(36)\ e^2 fm^4 / MeV$$
$$\alpha_{E3M1} = +7.4(38)\ e^2 fm^4 / MeV$$

Results & Comparison to QPM

	exp	QPM
$\Gamma_{\gamma\gamma}/\Gamma_{\gamma}(10^{-6})$	2.1(3)	2.69
$\alpha_{\mathrm{M2E2}}(\frac{e^2 fm^4}{MeV})$	+38.2(36)	+42.6
$\alpha_{\mathrm{E3M1}}(\frac{e^2 fm^4}{MeV})$	+7.4(38)	+9.5

- α_{M2E2} dominates
- relative sign between α_{M2E2} and α_{E3M1} is positive
- good description in the framework of the QPM



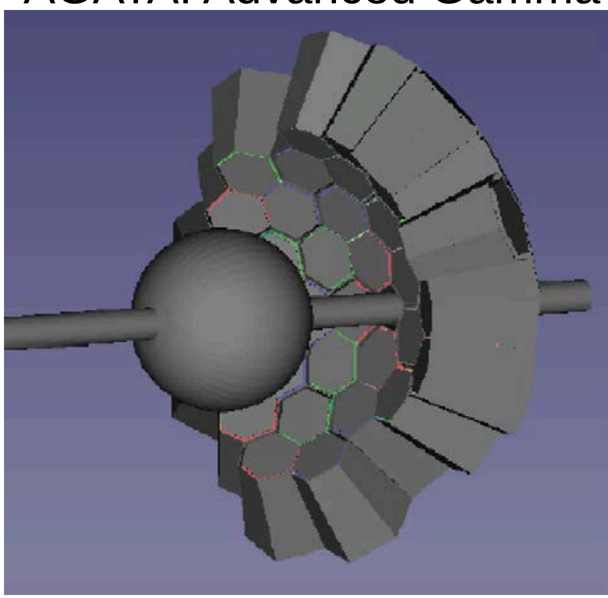


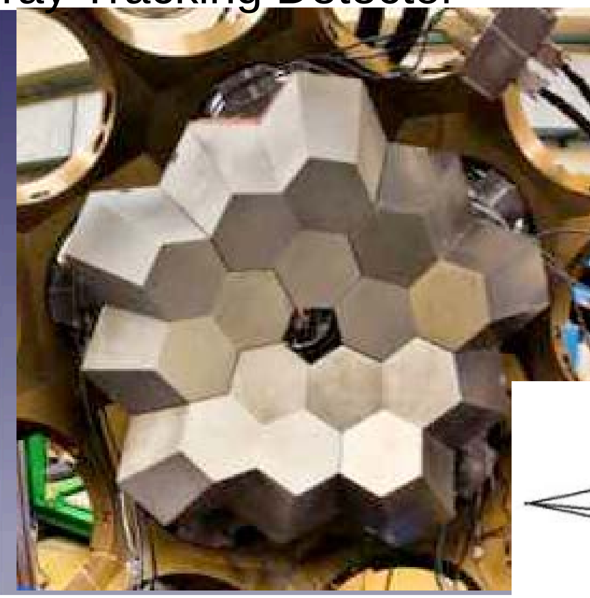
in collaboration with T. Aumann, V.Yu. Ponomarev, and **H. Scheit** (TU Darmstadt)

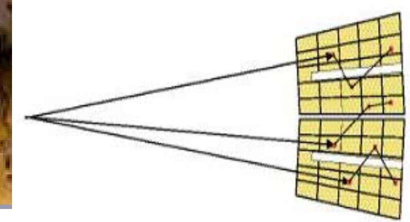
C. Walz, H. Scheit, NP et al., Nature **526**, 406 (2015).

Opportunities: γ-tracking detectors

AGATA: Advanced Gamma-ray Tracking Detector







Spatial resolution of γ-interaction points → Compton-background rejection
Continuous-angular coverage → complete angular distribution

in collaboration with G. De Angelis, J.J. Valiente Dobon + AGATA Collaboration

Opportunities: Other Multipolarities

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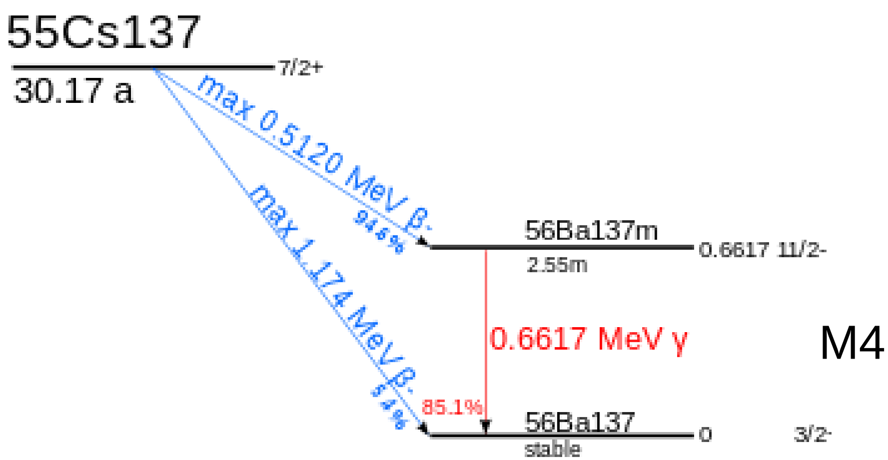
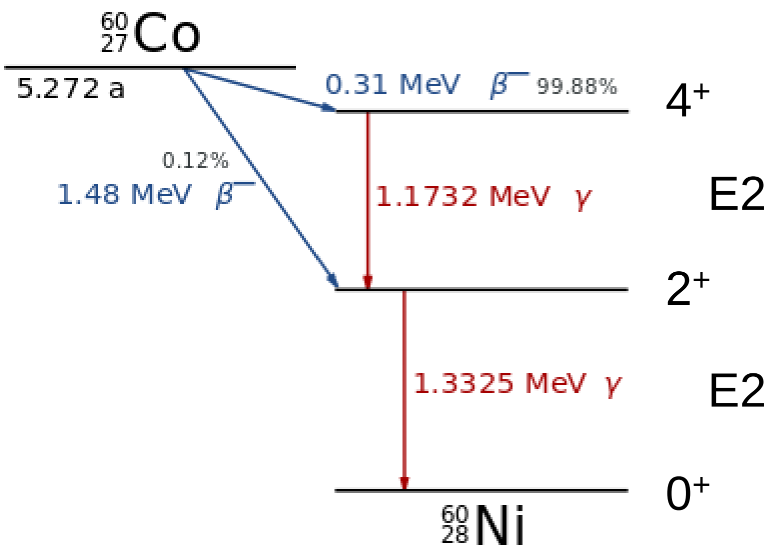
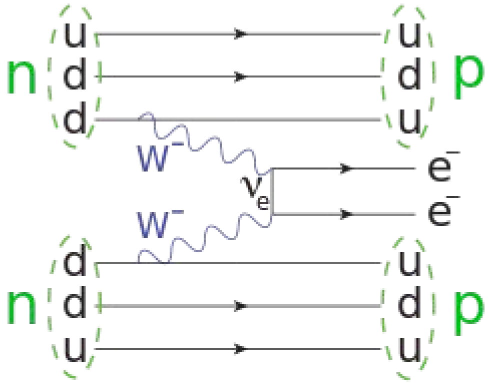




- E2 competitive to E1,E1 and M1,M1 double-gamma decay
- ^{60}Co allows for a high-statistics coincidence condition

Opportunities

- $\gamma\gamma/\gamma$-Decay can be measured for well-chosen transitions
- M1,M1 is related to Double-Gamow-Teller (DGT)
- Double-charge exchange (DCX) reactions conjectured to be related to $0\nu\beta\beta$ - NME *(Martinez Pinedo, Capuzzello and collaborators)*
- DGT related to $0\nu\beta\beta$ - NME (?) *(see J.Menendez, tomorrow 2:30 pm)*
- $\gamma\gamma$ - decay purely electromagnetic; no final-state interaction as in DCX *(see J.A. Lay Valera)*
- $\gamma\gamma$ - decay may provide opportunity for (partial) new constraint for NME predictions



Summary

- Observation of the competetive double-gamma decay
- Measurement of the energy sharing and angular distributions

- Branching ratio: $\Gamma_{\gamma\gamma}/\Gamma_{\gamma} = 2.1(3) \cdot 10^{-6}$ (in ^{137}Ba)
- Determination of the matrix elements a_{E2M2} and a_{E3M1}
- M2E2-decay paths through $7/2^{+}$ states dominate

- Formally similar to E1 polarizability / $0\nu\beta\beta$ - NME
- Related to Symmetry Parameter of Nuclear EoS ?
- Access to aspects of NME for $0\nu\beta\beta$ - decay ?

Summary

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- M2E2-decay…

Walz et al., *Nature* **526**, 406 (2015)

Thank you for attention!

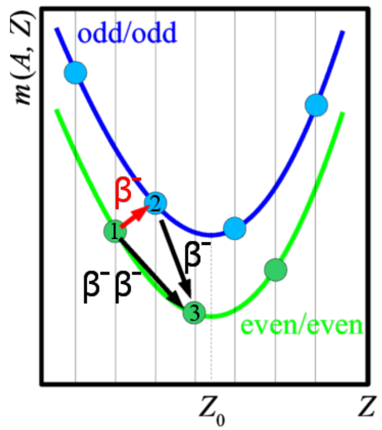
- Formally … NME
- Related t… arameter of Nuclear EoS ?
- Access to aspects of NME for 0νββ - decay ?


Keep EUROPE great again!

Radioactive decay: Second order

double β-decay

2νββ (0νββ)

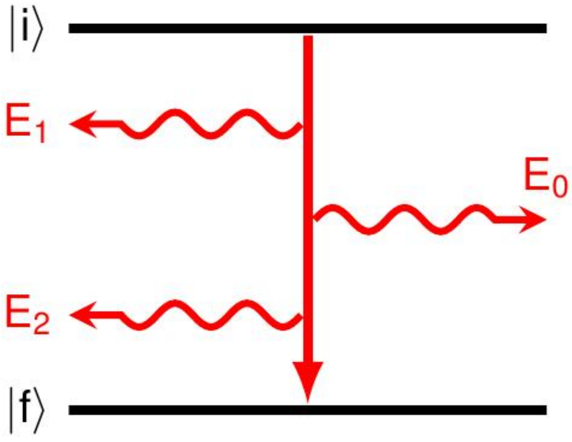


first evidence in the laboratory:

*S. Elliot, A. Hahn, and M. Moe, PRL **59**, 2020 (1987)*

(competitive) double γ-decay

γγ(/γ)



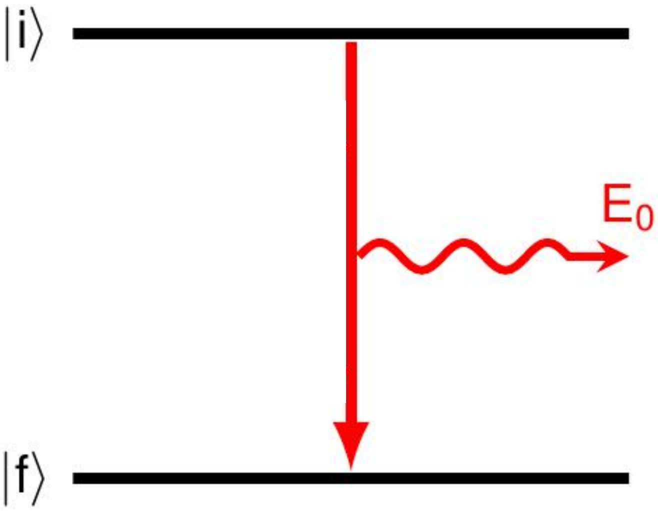
competitive double-gamma decay has not been observed before

$$\mathrm{M.E.} = \langle f|\hat{O}(2)\hat{O}(1)|i\rangle = \sum \langle f|\hat{O}(2)|n\rangle\langle n|\hat{O}(1)|i\rangle$$

The double-gamma decay

First discussed by Maria Göppert-Mayer in her doctoral thesis in 1929

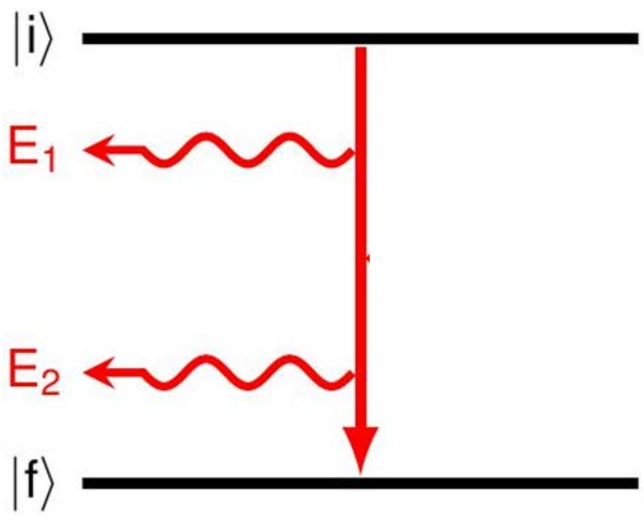
M. Göppert-Mayer, Über Elementarakte mit zwei Quantensprüngen



The double-gamma decay in nuclear physics

$\gamma\gamma$-decay only known in a special case:
$0^+ \rightarrow 0^+$ (^{90}Zr, ^{40}Ca, ^{16}O)

- *J. Schirmer et al., PRL 53, 1897 (1984)*
- *J. Kramp et al., NPA 474, 412 (1987)*



never observed in competition to allowed single γ-transition

- *W. Beusch et al., Helv Phys. Acta 33, 363 (1960)*
- *J. Kramp et al., NPA 474, 412 (1987)*
- *V.K. Basenko et al., Bull. Russ. Acad. 56, 94 (1992)*
- *C.J. Lister et al., Bull. Am. Phys. Soc. 58(13), DNP.CE.3 (2013)*

main experimental obstacle:

- presence of the one-photon decay

Objectives

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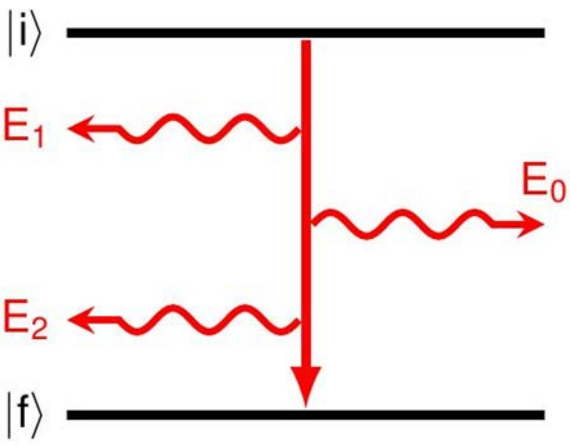
- Observation of the „competitive double-gamma decay" ($\gamma\gamma/\gamma$)

- Measurement of the energy distribution and $\gamma\gamma$-angular correlation

- Determination of the multipole order and radiation character



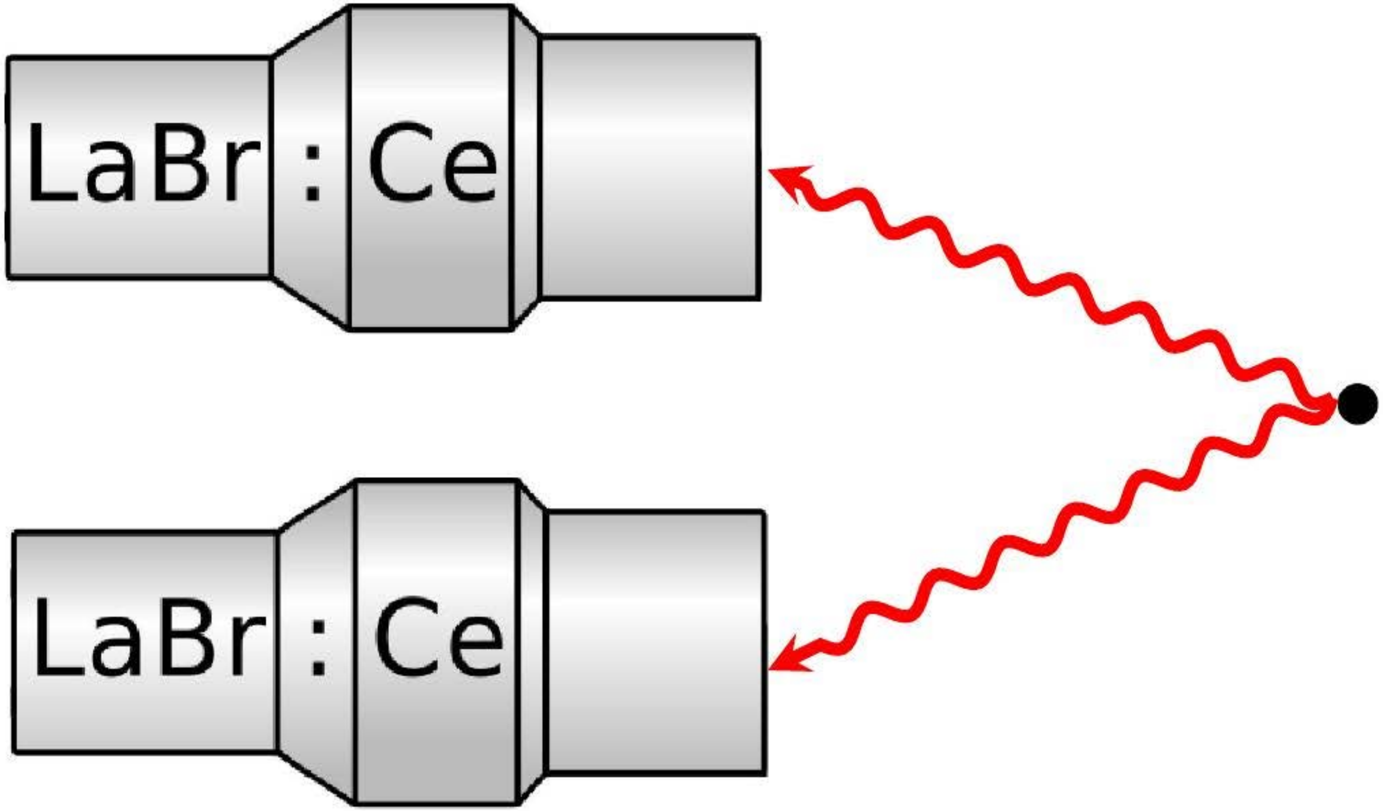
- Determination of $\gamma\gamma/\gamma$ - branching ratio $\Gamma_{\gamma\gamma}/\Gamma_{\gamma}$:

$$\Gamma_{\gamma\gamma}/\Gamma_{\gamma}(\theta) = \Gamma_{\gamma\gamma}/\Gamma_{\gamma} \cdot W(\theta)$$

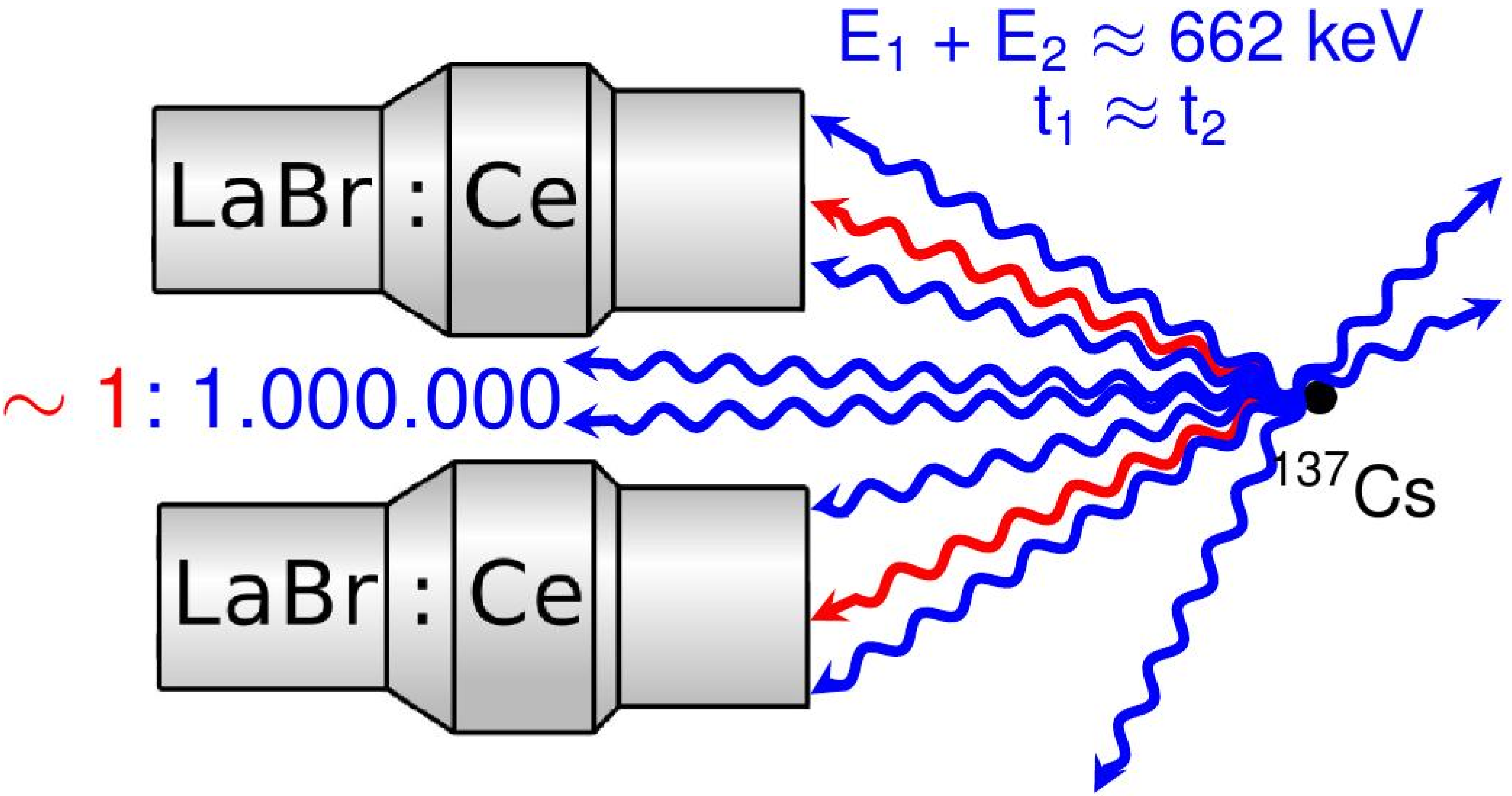
Outline

- Double-gamma - decay
- **Experiment**
- Data analysis & results
  - First $\gamma\gamma/\gamma$ - branching ratio
  - Multipole analysis
- Summary

Measurement Principle

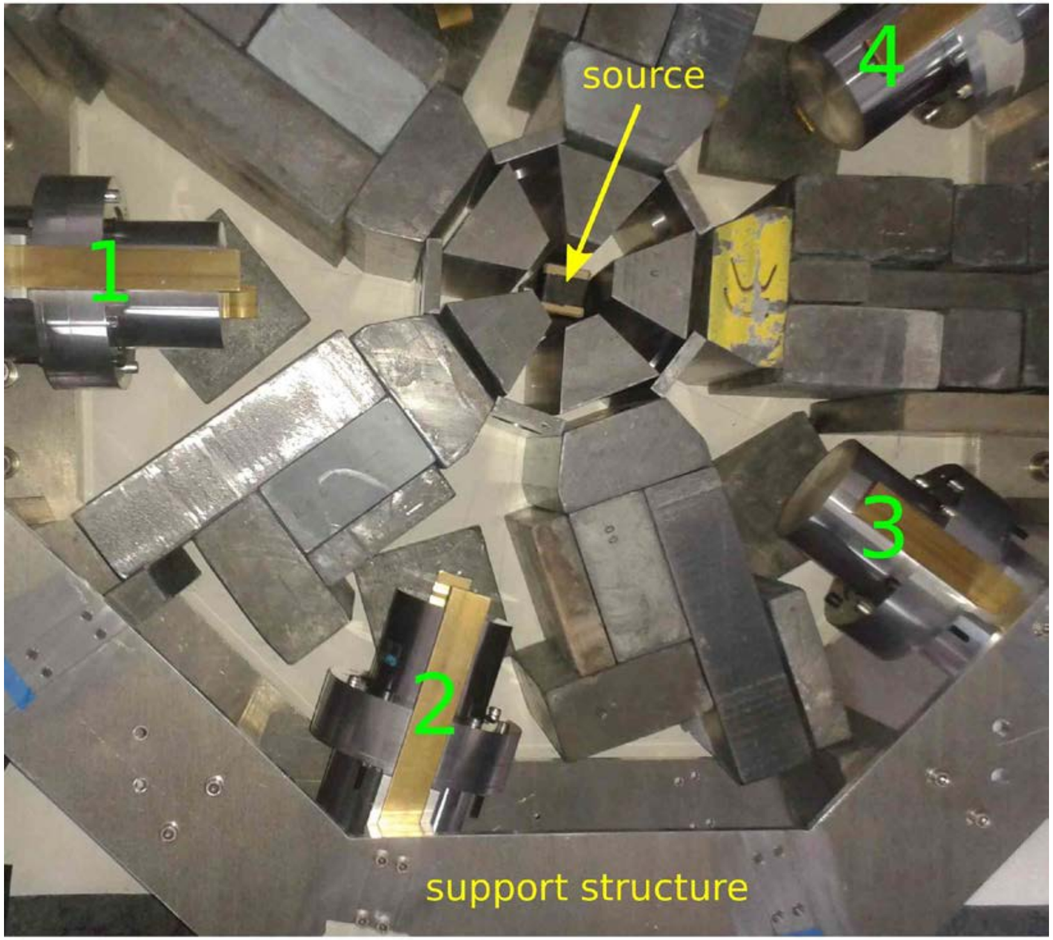


Challenge due to Background



The experimental setup & direct Compton scattering

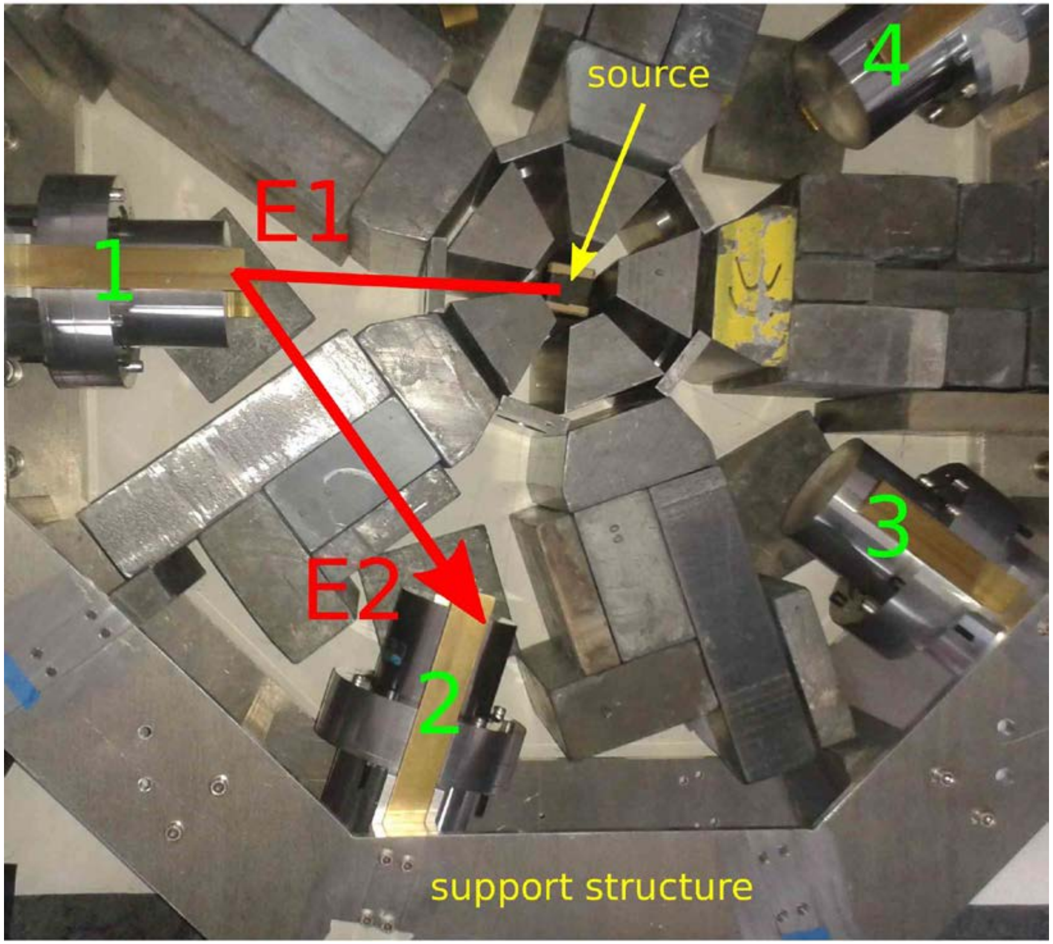
- 72°: 5 detector pairs
- 144°: 5 detector pairs



The experimental setup & direct Compton scattering

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

- $E_1 + E_2 = 662$ keV
- Compton scattering
  $\Longleftrightarrow$
  double-gamma decay



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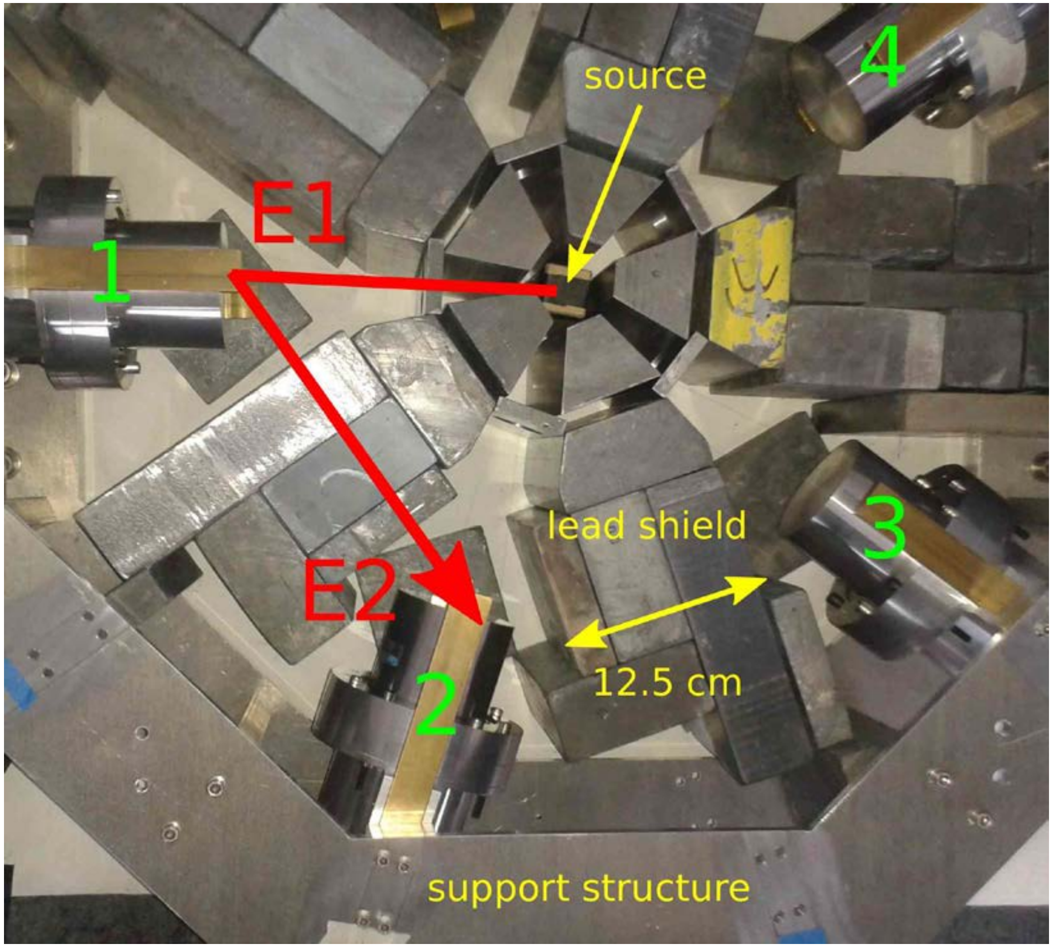
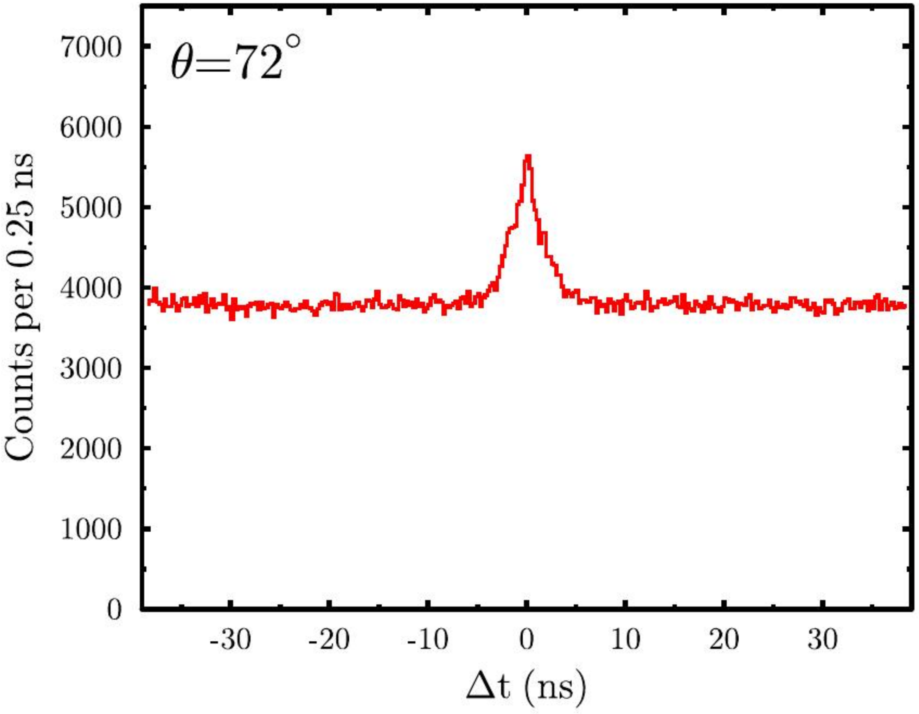


Time spectrum & random coincidences



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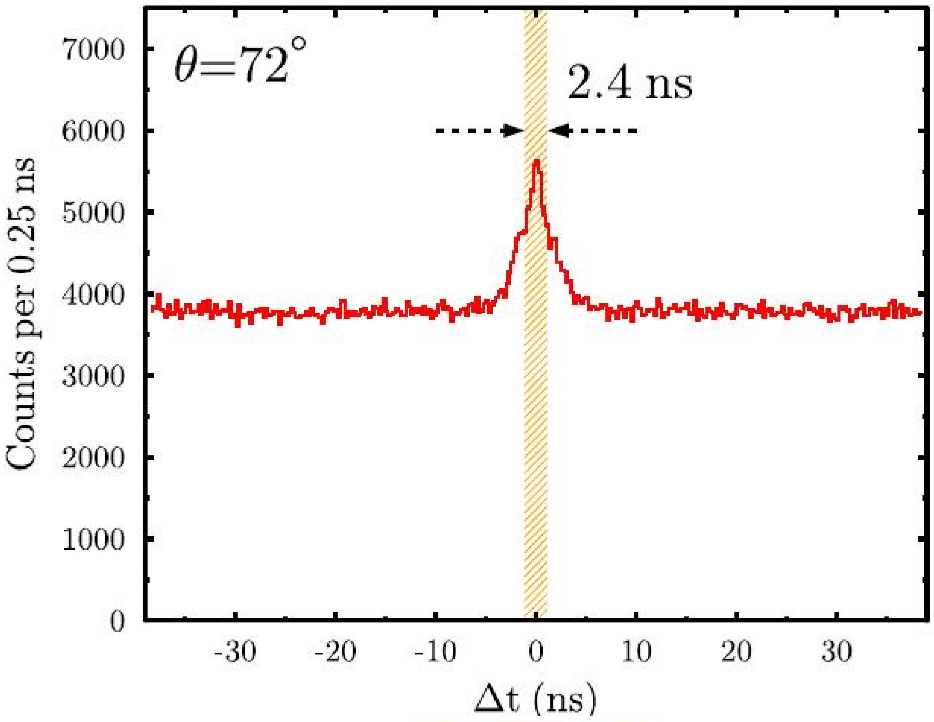
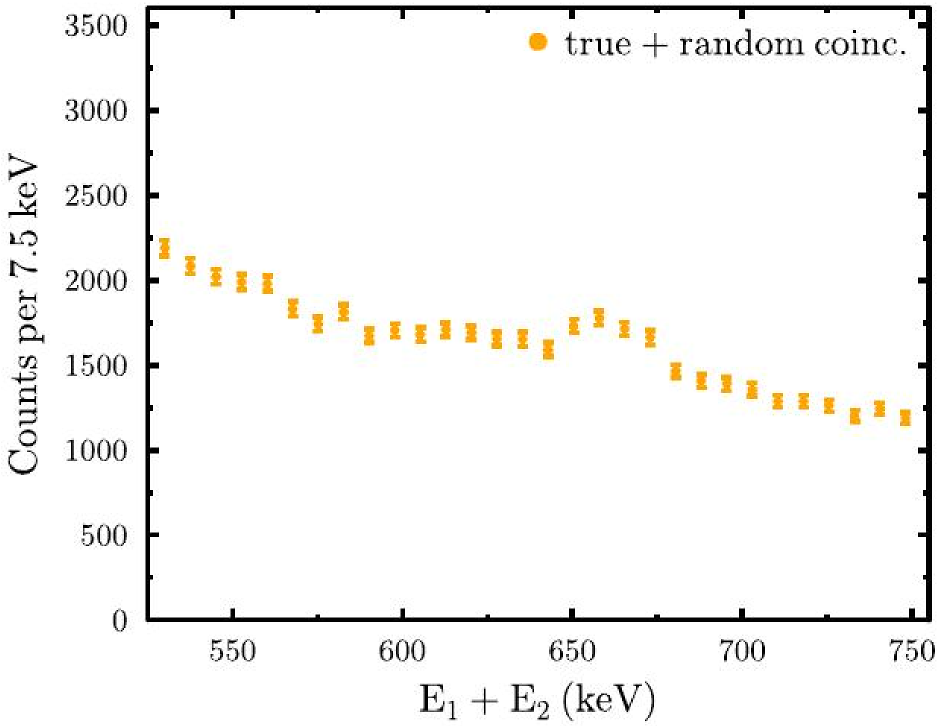
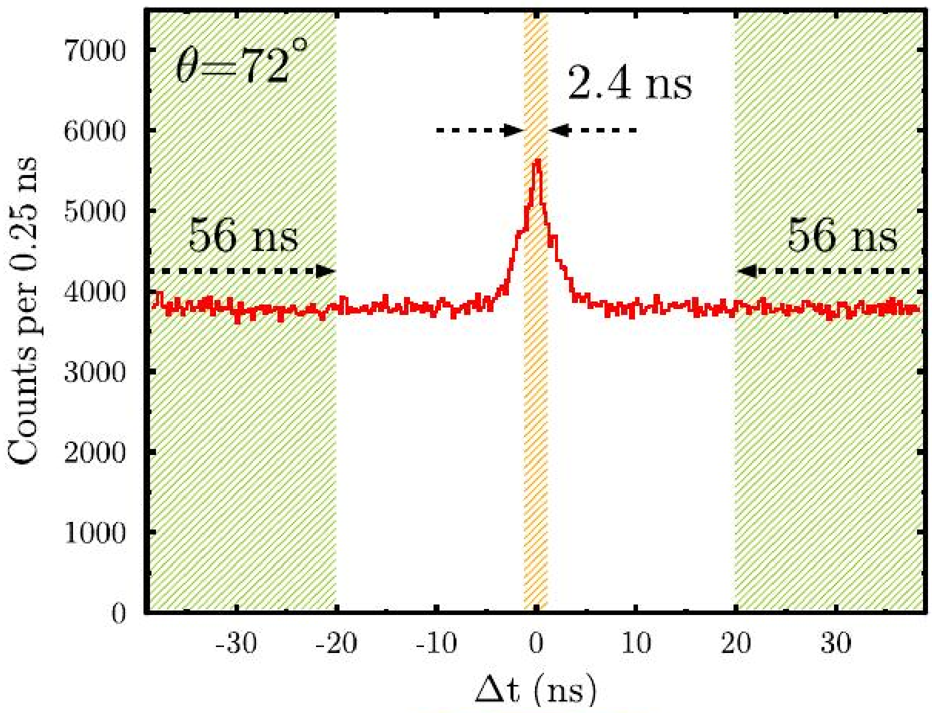
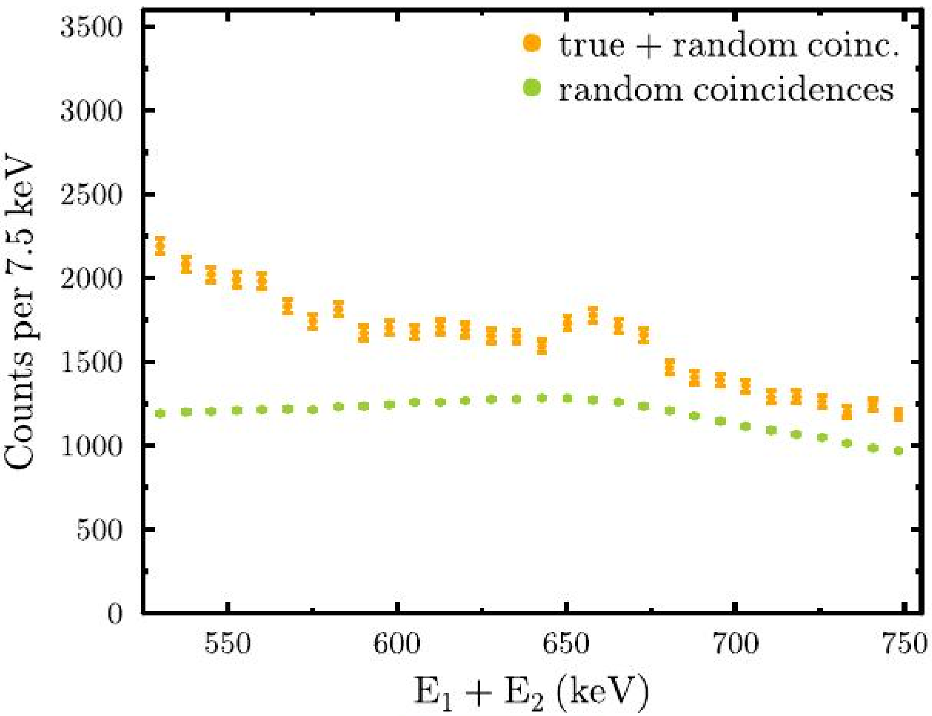




use excellent time resolution of the $LaBr_3$-detectors

Time spectrum & random coincidences

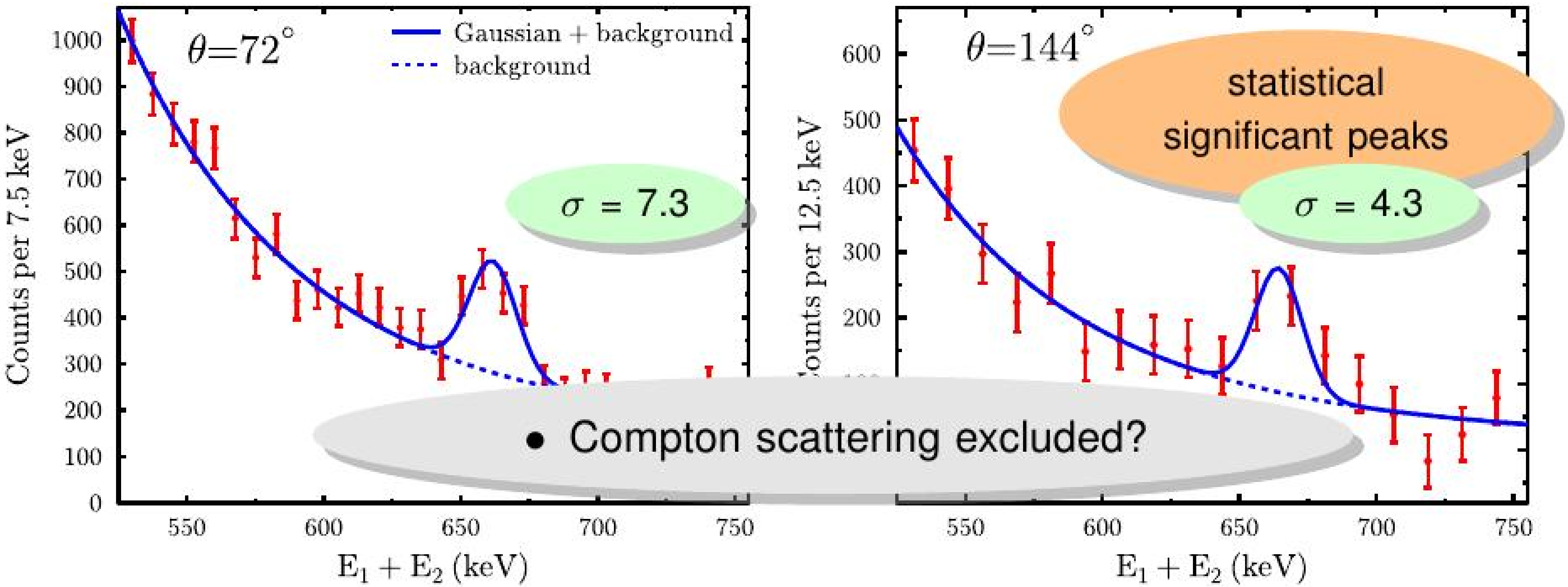




use excellent time resolution of the $LaBr_3$-detectors

random coincidences determine uncertainty

Results

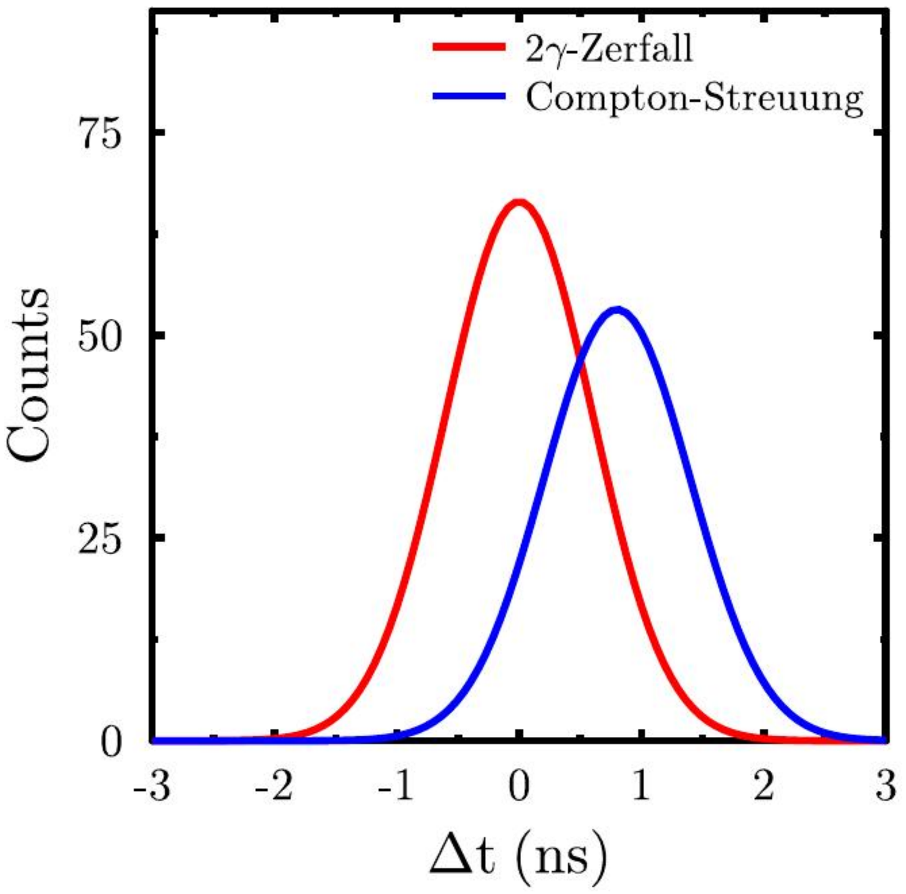


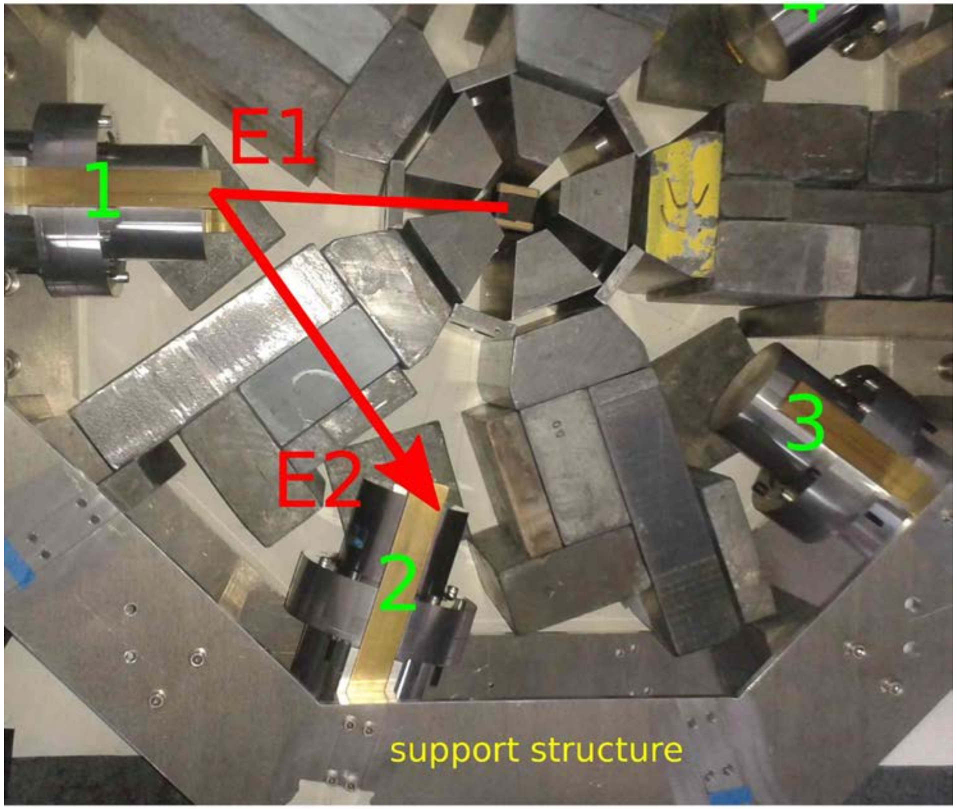
$A_{2\gamma}(72^{\circ})$ = 693(95) counts
$\Gamma_{\gamma\gamma}/\Gamma_{\gamma}(72^{\circ}) = 1.56(23)\cdot 10^{-6}$

$A_{2\gamma}(144^{\circ})$ = 325(76) counts
$\Gamma_{\gamma\gamma}/\Gamma_{\gamma}(144^{\circ}) = 0.70(18)\cdot 10^{-6}$

- Result: Successful observation of the competitive double-gamma decay

Critical analysis (1)





Outline

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- Double-gamma - decay
- Experiment
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Electric dipole polarizability $\leftrightarrow$ matrix element of the double-gamma decay

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Electric dipole polarizability:

$$a_D \propto \sum_n \frac{\langle 0^+_{\mathrm{gs}} || \mathbf{E1} || 1^-_{\mathrm{n}} \rangle \langle 1^-_{\mathrm{n}} || \mathbf{E1} || 0^+_{\mathrm{gs}} \rangle}{E_n}$$

Matrix element of the double-gamma decay ($\mathrm{J}^+_i = 0^+, 2^+$):

$$\alpha_{E1E1} \propto \sum_n \frac{\langle 0^+_{\mathrm{gs}} || \mathbf{E1} || 1^-_{\mathrm{n}} \rangle \langle 1^-_{\mathrm{n}} || \mathbf{E1} || J^+_i \rangle}{E_n}$$

- similar structure of a_D and α_{E1E1}
- α_{E1E1} alternative quantity?
- a_D requires measurement of $E1$-strengths over wide energy range (difficult)
  $\Longleftrightarrow$ α_{E1E1} accessible through one electromagnetic transition