Outline: Two-photon decay

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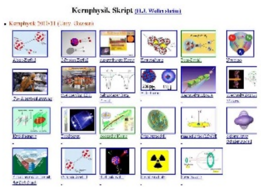
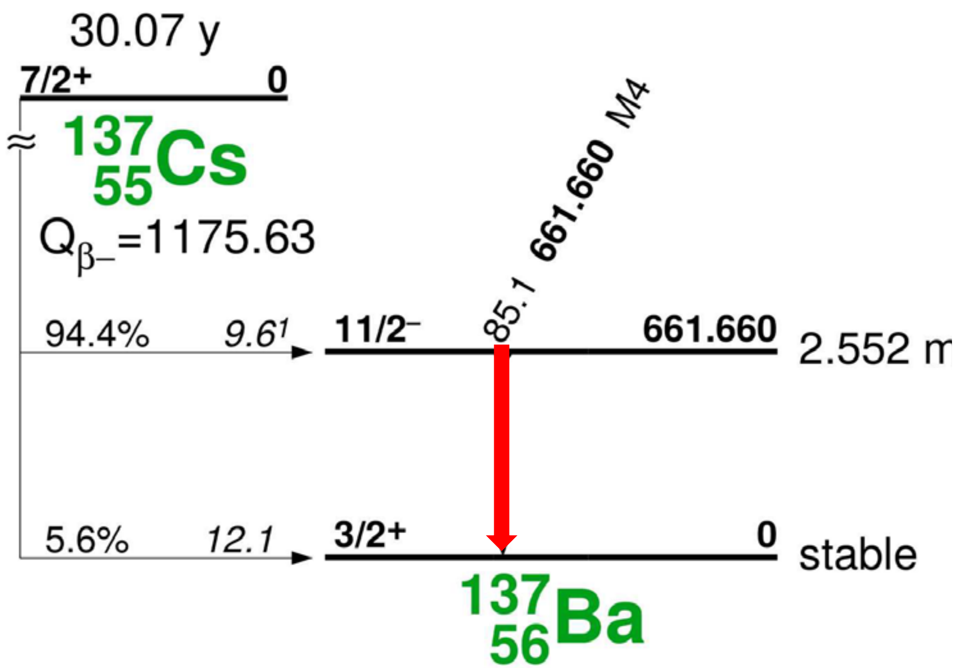
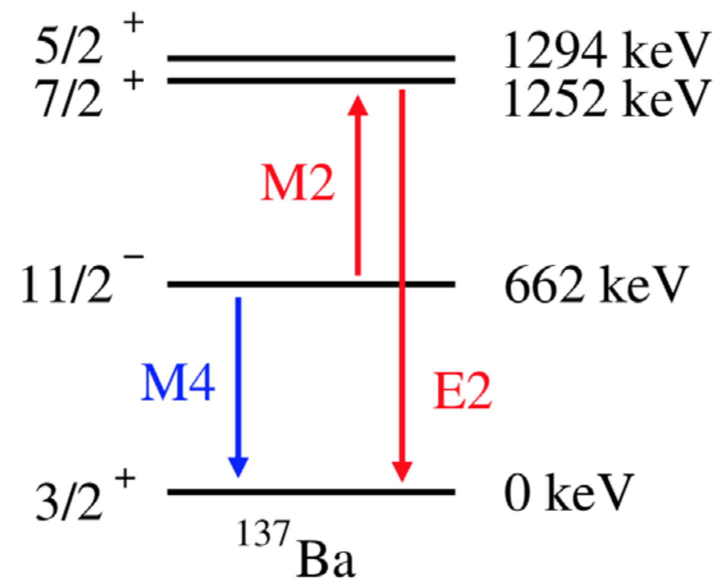
web-page: https://web-docs.gsi.de/~wolle/ and click on



1. 2-photon atomic transitions
2. double-γ decay in nuclear physics
3. positronium decay

Second order photon emission in nuclei



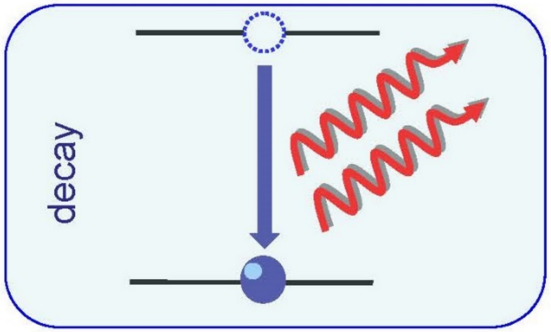


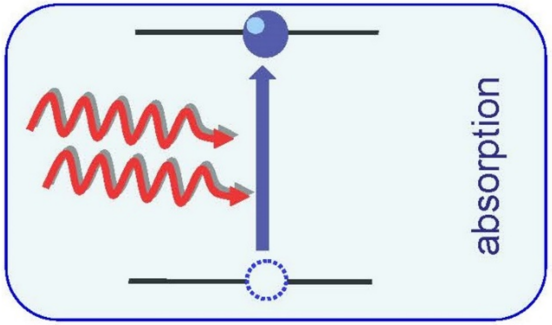
$$\tau(11/2) = \left[T(ME4; 11/2 \rightarrow 3/2) \cdot \left(1 + \alpha_T(M4)\right)\right]^{-1}$$

$$T(M4; 11/2 \rightarrow 3/2) = 1.877 \cdot 10^{-6} \cdot E_\gamma^9 \cdot B(M4; 11/2 \rightarrow 3/2)$$

Two-photon atomic transitions

- In 1929 in her PhD thesis Maria Göppert-Mayer suggested that bound-bound transitions can undergo under simultaneous absorption/emission of two correlated photons.





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. Mit Hilfe der Diracschen Dispersionstheorie[1]) wird die Wahrscheinlichkeit eines dem Ramaneffekt analogen Prozesses, nämlich der Simultanemission zweier Lichtquanten, berechnet. Es zeigt sich, daß eine Wahrscheinlichkeit dafür besteht, daß ein angeregtes Atom seine Anregungsenergie in zwei Licht-

- For many years two-photon decay/excitation of atoms and ions has attracted much of experimental and theoretical interest.

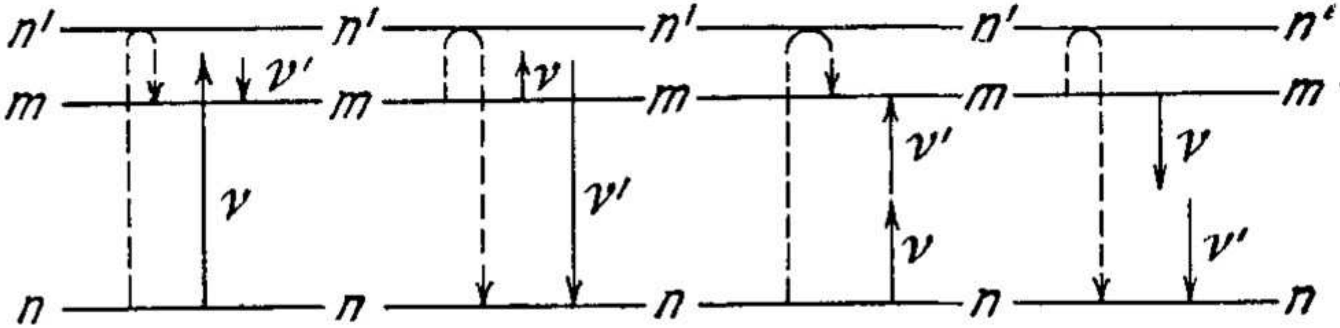
Two-photon atomic transitions

- In 1929 in her PhD thesis Maria Göppert-Mayer suggested that bound-bound transitions can undergo under <u>simultaneous</u> absorption/emission of two correlated photons.

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

> ➢ $E_0 = E_1 + E_2$
> ➢ E_1, E_2 are continuous

- not only two-photon emission, but also absorption and Raman scattering

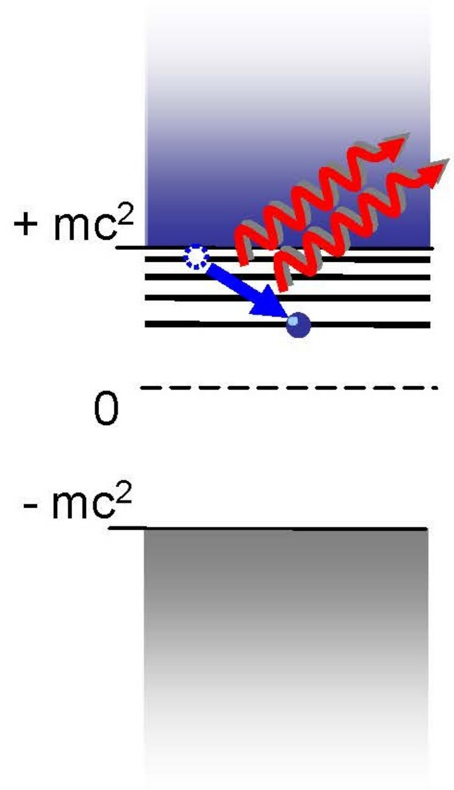


M. Göppert-Mayer, Ann. Wiss. (1931)

Two-photon atomic transitions

- Analysis of the two-photon decay requires knowledge about complete spectrum of the

$$\tilde{M}_{fi} \propto \sum\!\!\!\!\!\!\!\int_{\nu} \frac{\langle \psi_f | \boldsymbol{\alpha}\, \boldsymbol{\varepsilon}_2\, e^{-i\mathbf{k}\mathbf{r}_2} | \psi_\nu \rangle \langle \psi_\nu | \boldsymbol{\alpha}\, \boldsymbol{\varepsilon}_1\, e^{-i\mathbf{k}\mathbf{r}_1} | \psi_i \rangle}{E_\nu - E_i + \hbar\omega_1}$$



- The summation in the second-order transition amplitude includes a summation over the discrete part of the spectrum as well as an integration over the positive and negative-energy continuum.

- A large number of studies have been performed over the last decades to investigate
  - ➢ Total decay rates
  - ➢ Energy (spectral) distributions

PRL **104,** 033001 (2010) PHYSICAL REVIEW LETTERS week ending 22 JANUARY 2010

Spectral Shape of the Two-Photon Decay of the $2\,^1S_0$ State in He-Like Tin

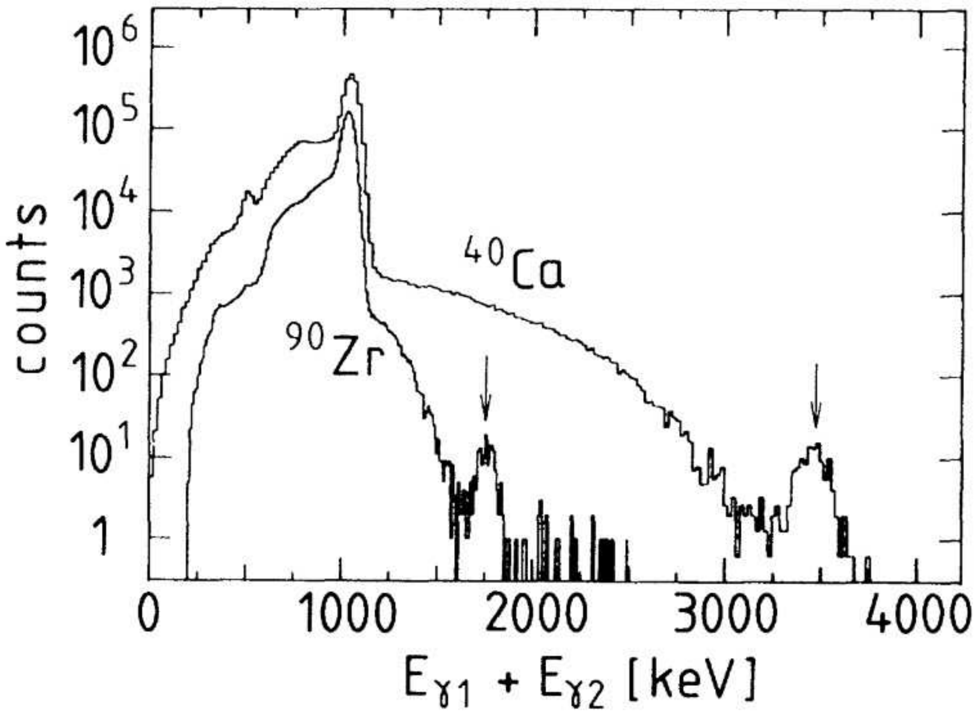
S. Trotsenko,[1,2,3] A. Kumar,[2] A. V. Volotka,[4] D. Banaś,[5] H. F. Beyer,[2] H. Bräuning,[2] S. Fritzsche,[2] A. Gumberidze,[6] S. Hagmann,[1,2] S. Hess,[1,2] P. Jagodziński,[5] C. Kozhuharov,[2] R. Reuschl,[7] S. Salem,[1,2] A. Simon,[8] U. Spillmann,[2] M. Trassinelli,[7] L.C. Tribedi,[9] G. Weber,[2,10] D. Winters,[2] and Th. Stöhlker[2,3,10,*]

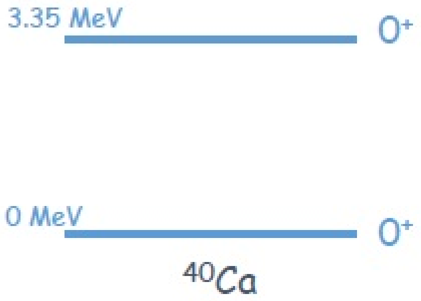
Double-gamma decay in nuclear physics

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

Heidelberg – Darmstadt Crystal ball (4π, 162 NaI)

single photon decay strictly forbidden

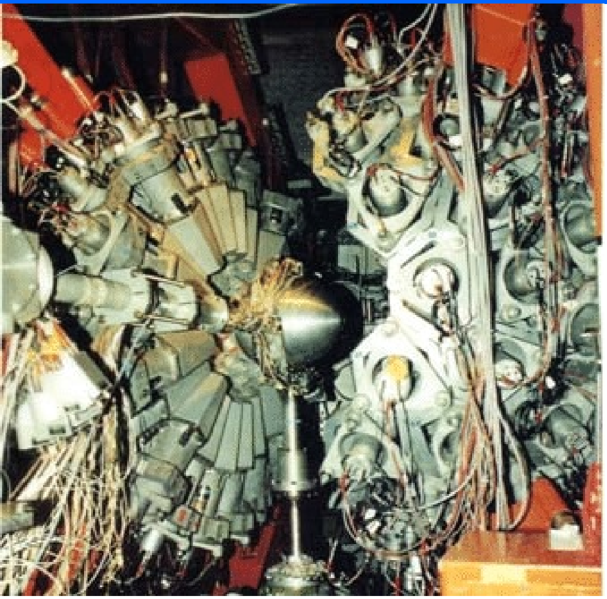


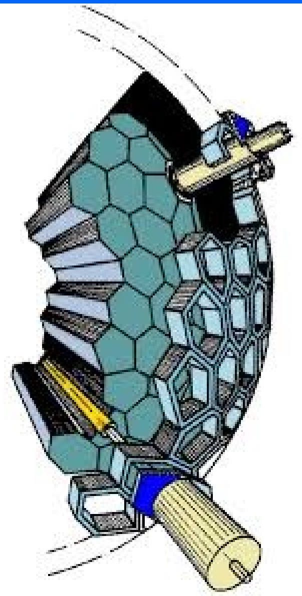


Sum-energy spectrum in coincidence with protons populating the states of interest

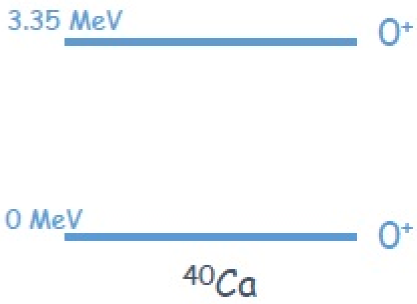
J. Schirmer et al., PRL 53, 1897 (1984), J. Kramp et al., NPA 474, 412 (1987)

Double-gamma decay in nuclear physics





Heidelberg – Darmstadt Crystal ball (4π, 162 NaI)
angular resolution $\pm 9^0$

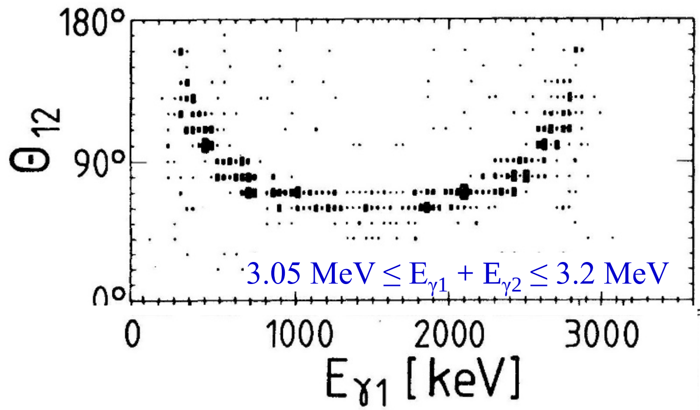


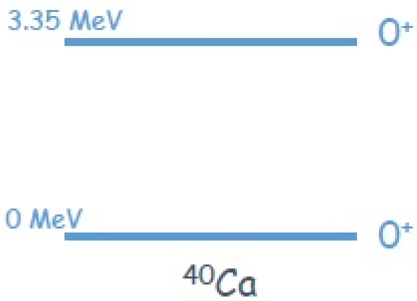
γ-background: internal pair conversion and subsequent positron annihilation in flight

$$\frac{1}{E_{\gamma 1}} + \frac{1}{E_{\gamma 2}} = \frac{(1 - cos\theta_{12})}{m_e c^2}$$

$$E_{\gamma 1} + E_{\gamma 2} = E_{e+} + 2m_e c^2 \cong E_0$$

Double-gamma decay in nuclear physics





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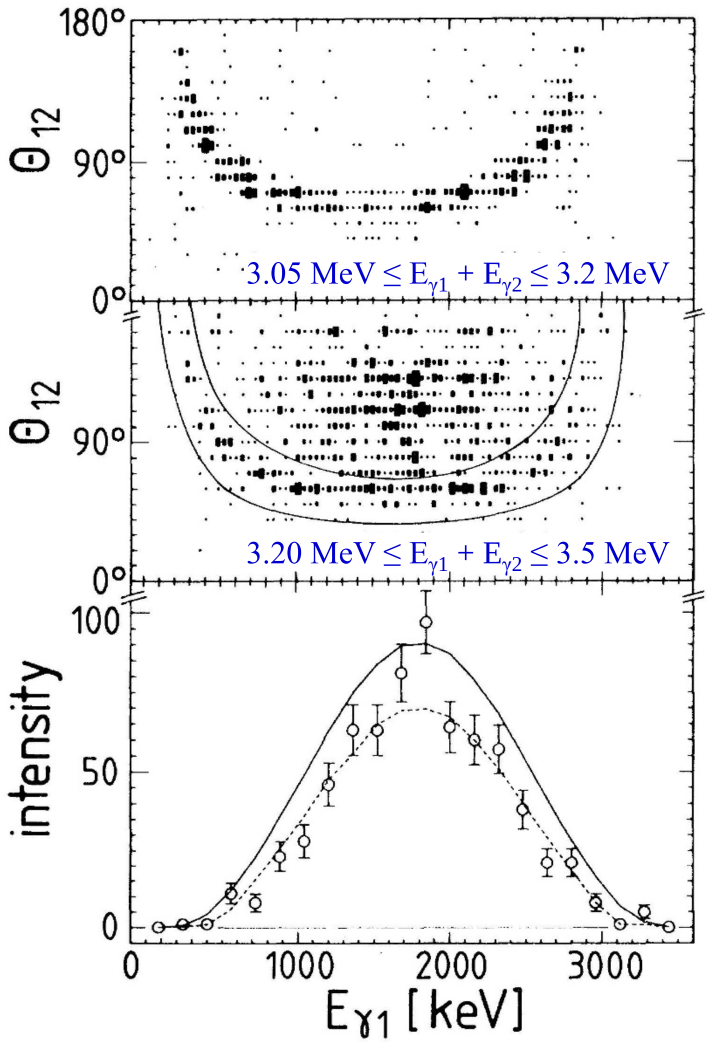
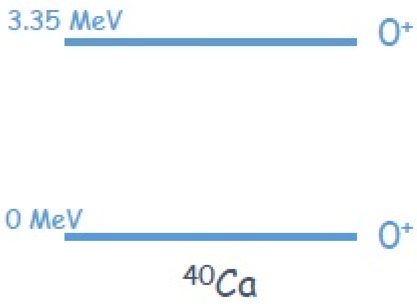
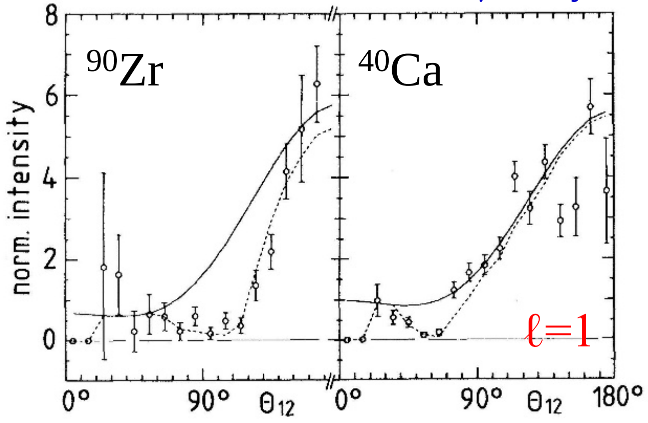
Double-gamma decay in nuclear physics



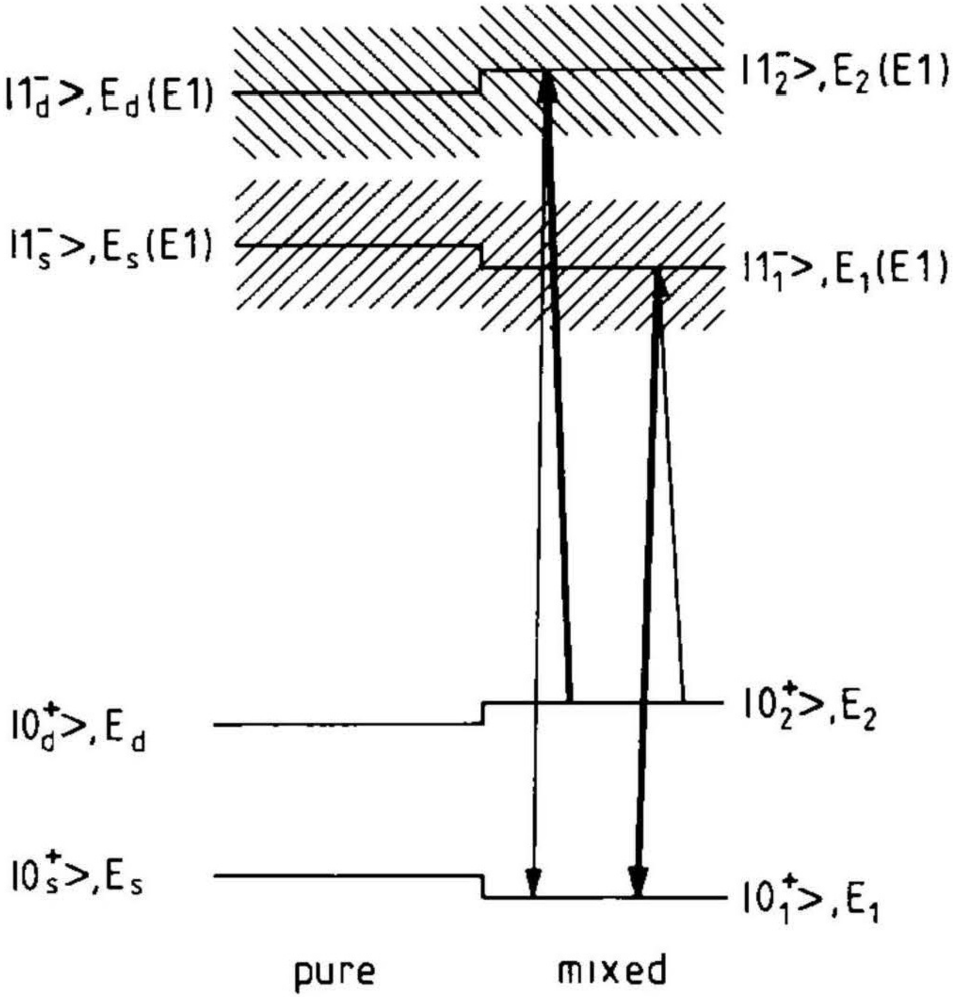


directional correlation of 2γ-decay



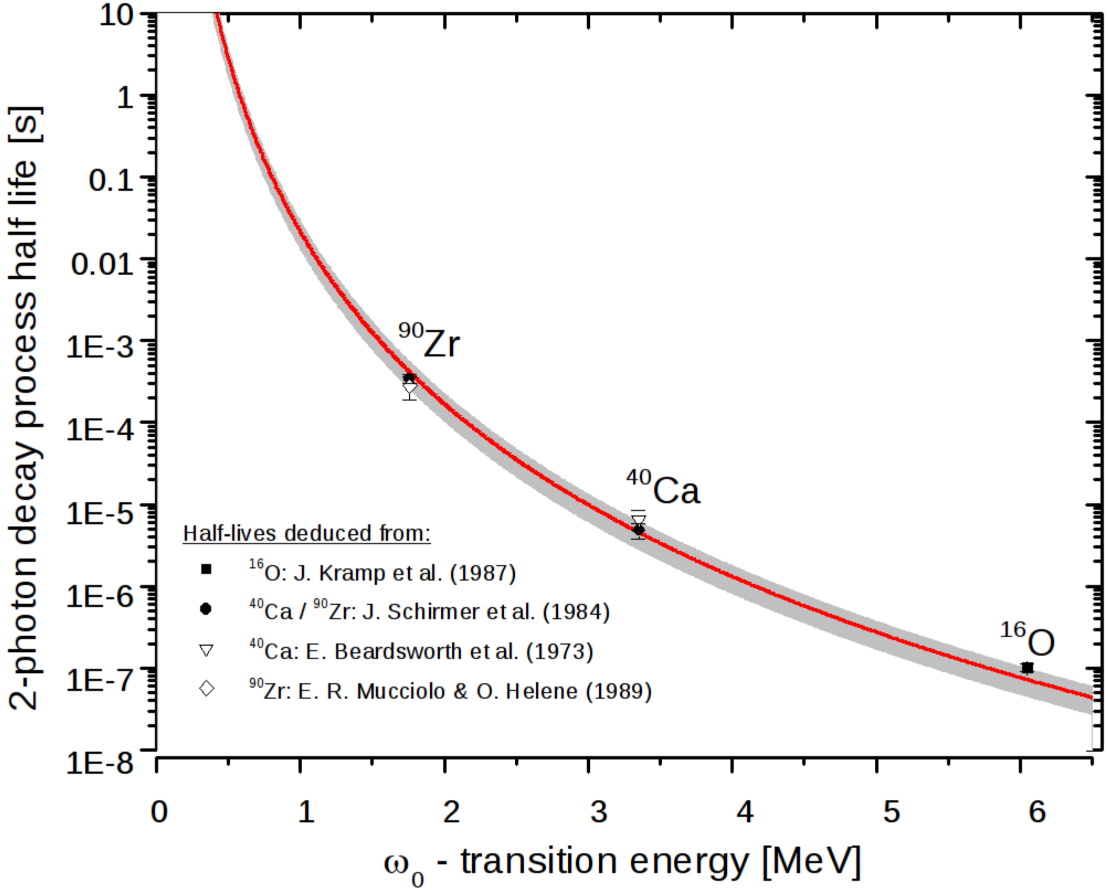
angular correlation not symmetric around 90^0

Double-gamma decay in nuclear physics



2-state mixing model for 0^+ state and 1^- GDR states
states couple only via GDR states

Double-gamma decay in nuclear physics



2γ nucleus	$\Gamma_{\gamma\gamma}/\Gamma_{total}$
^{16}O	$6.6(5)\cdot 10^{-4}$
^{40}Ca	$4.5(10)\cdot 10^{-4}$
^{90}Zr	$1.8(1)\cdot 10^{-4}$

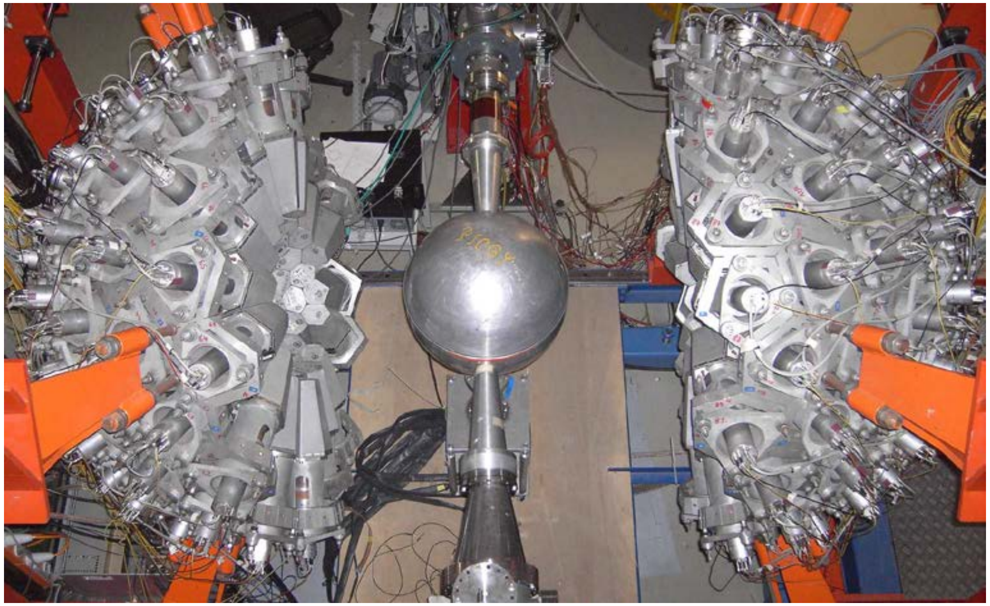
$0^+ \rightarrow 0^+$ (^{68}Ni, ^{72}Ge, ^{80}Ge,^{96}Zr,^{98}Zr,^{98}Mo)

Recent experimental advance: $LaBr_3(Ce)$ detectors

- so far: NaI(Tl) detectors
  - standard detectors, if high efficiency is crucial
  - but: poor time and energy resolution

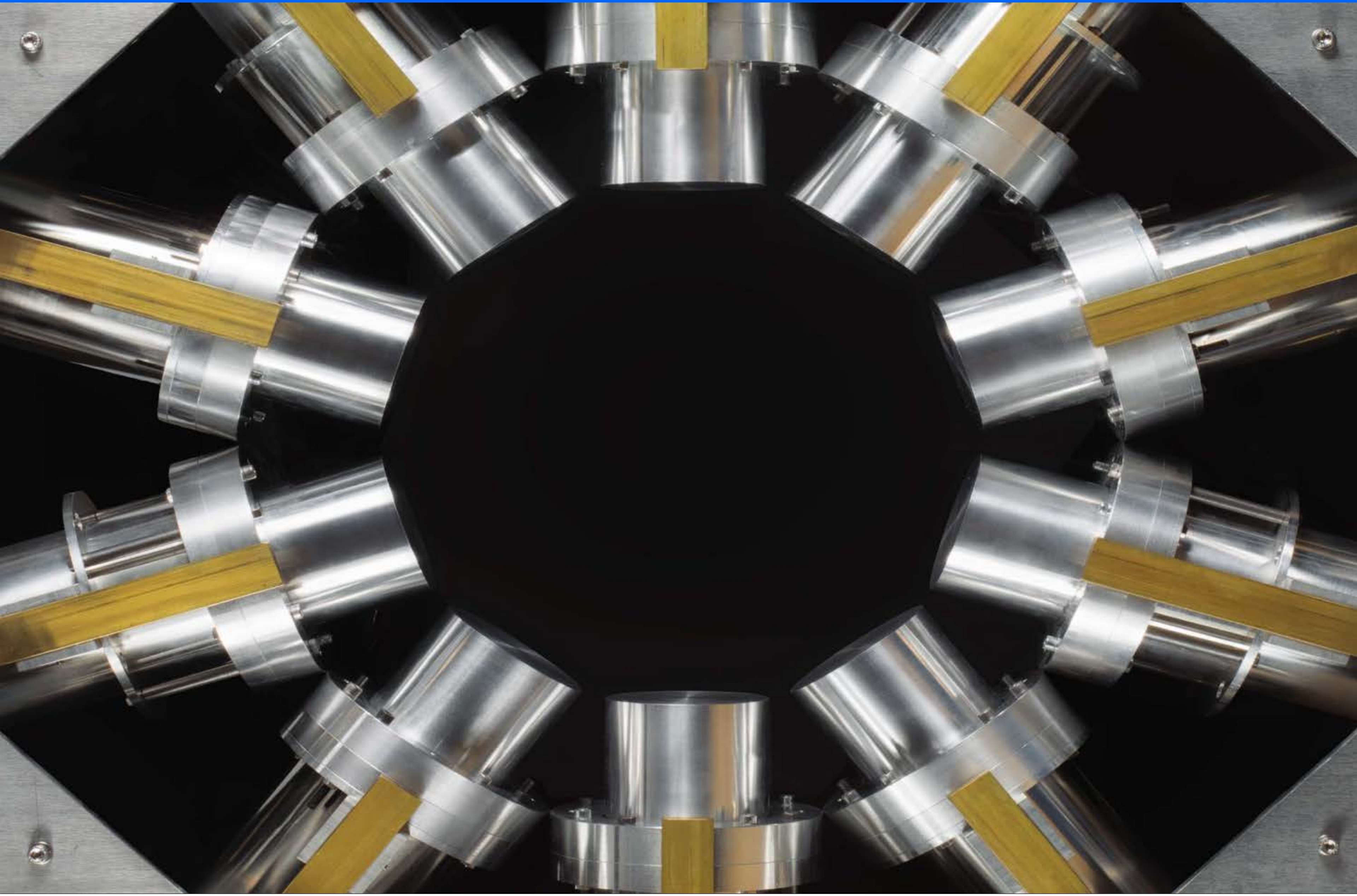
Heidelberg-Darmstadt Crystal-ball

full solid angle 4π 162 NaI(Tl) detectors



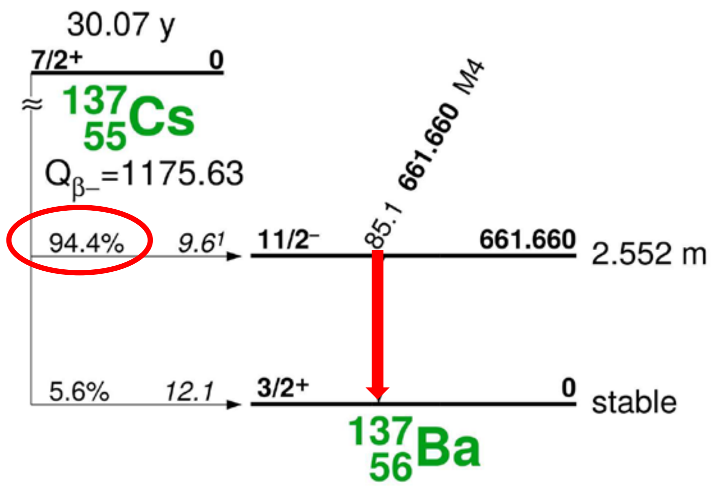
- large volume $LaBr_3(Ce)$ detectors available:
  - better energy resolution by a factor 2-3
  - better time resolution by a factor 5-10
  - very fast → high rate measurement

GALATEA array: 18 $LaBr_3(Ce)$ detectors (3"x3")



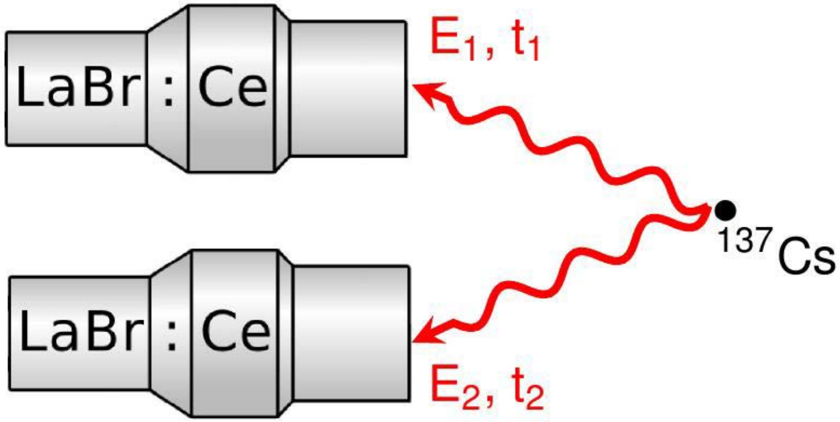
Competitive double-photon decay: $\gamma\gamma/\gamma$

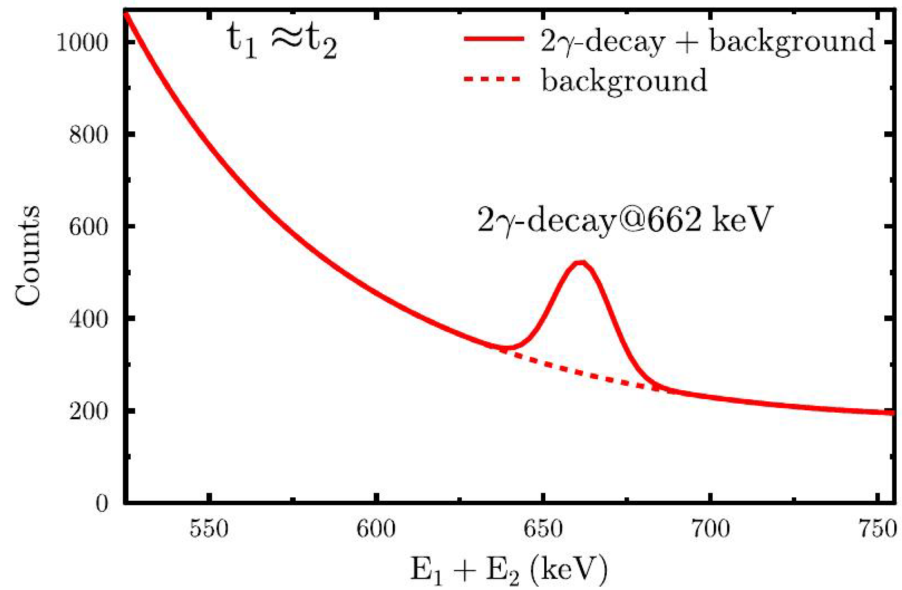
- for $0^+ \rightarrow 0^+$ transitions:
  - single photon decay strictly forbidden
  - $\Gamma_{\gamma\gamma}/\Gamma \sim 10^{-4}$
  - Γ/Γ_{IP} (internal pair production)
- Competitive double-gamma decay ($\gamma\gamma/\gamma$)
  - $\gamma\gamma$ decay competing with allowed single gamma decay
  - $\Gamma \approx \Gamma_\gamma$
  - $\Gamma_{\gamma\gamma}/\Gamma_\gamma \ll 10^{-4}$
  - has never been observed, despite a few searches in last 30 years



Basic principle of the experiment

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



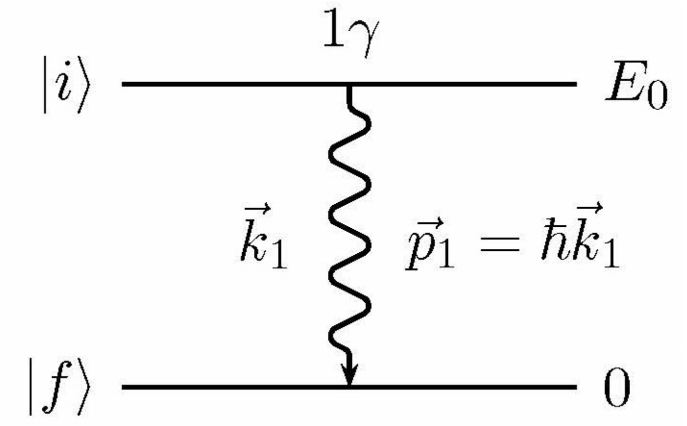


- background ↔ small decay probability (~ 1 event per day)
  - direct Compton scattering
  - random coincidences
  - cosmic rays, sequential Compton scattering, internal radioactivity

Emission of electromagnetic one and two photon(s)

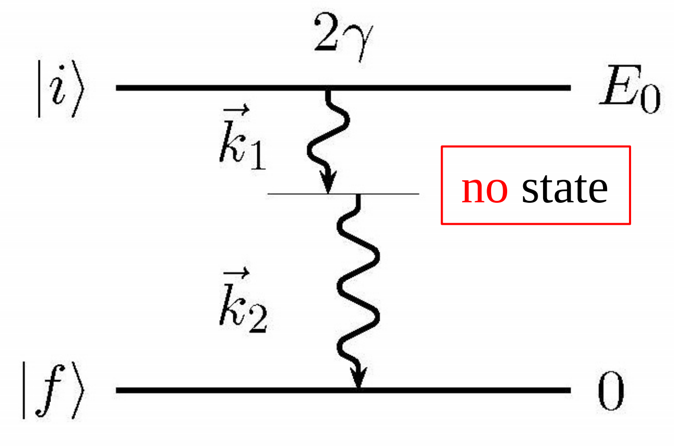
- single photon emission

$$E_0 = E_1 = \hbar\omega_1$$



- double-gamma decay
two photons emitted
simultaneously

$$E_0 = E_1 + E_2$$



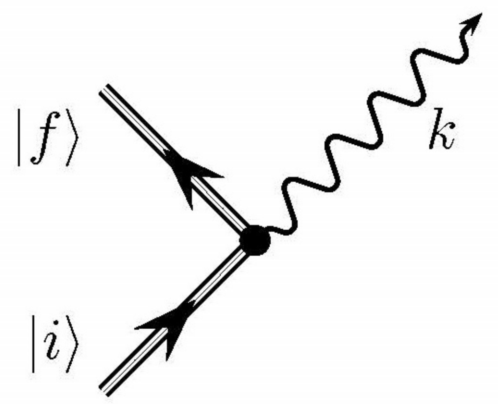
Decay width: first order perturbation theory

- Interaction of a nucleus with free EM radiation field:

$$H_{int} = -\frac{1}{c}\int \overrightarrow{j_N}(\vec{r},t)\vec{A}(\vec{r},t)d^3r$$

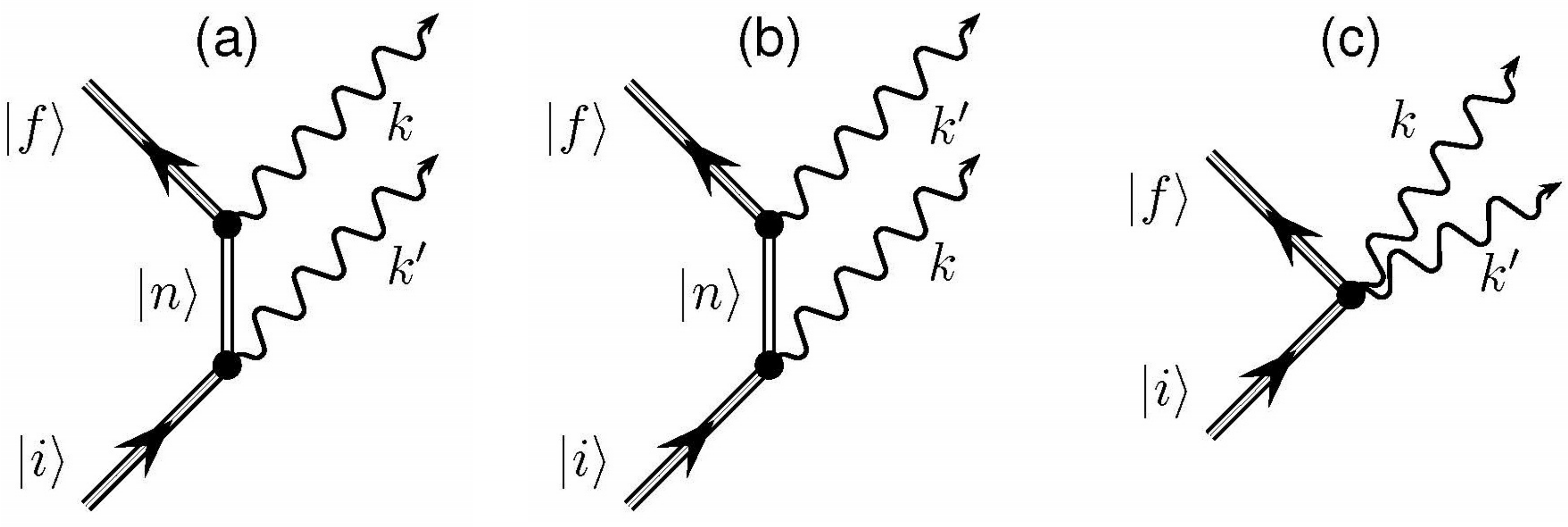
- Fermi's Golden Rule

$$\Gamma_\gamma = 2\pi|\langle f|H_{int}|i\rangle|^2\rho_f$$



ρ_f: density of final states; H_{int}: interaction Hamiltonian; $\vec{j}_N(\vec{r},t)$: nuclear current density; $\vec{A}(\vec{r},t)$: EM vector potential

Second order



- a,b) resonance amplitudes (second order in $\vec{j} \cdot \vec{A}$ interaction)
  - sum over all intermediate states $|n\rangle$
  - usual selection rules apply at each vertex

- c) Seagull amplitude (introduced as a correction to the non relativistic treatment of the nuclear Hamiltonian): first order, but quadratic in the radiation field A^2

- theory is fully developed

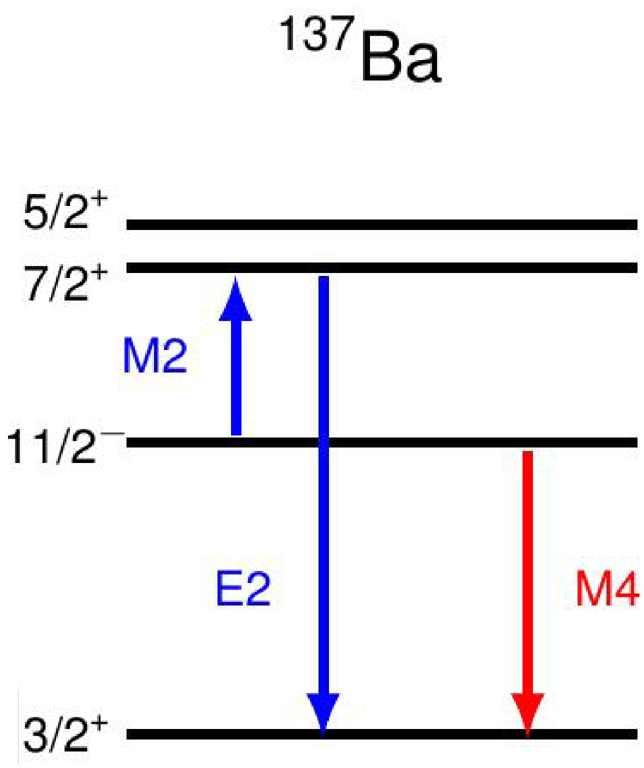
J. Kramp, …, D. Schwalm et al., NPA 474, 412 (1987)

Matrix element of the double-gamma decay

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

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

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



Matrix element of the double-gamma decay

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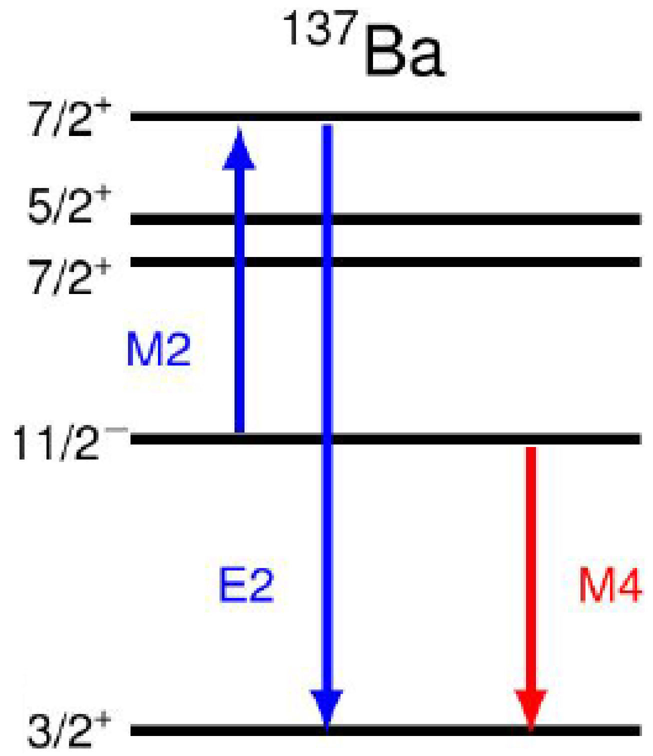

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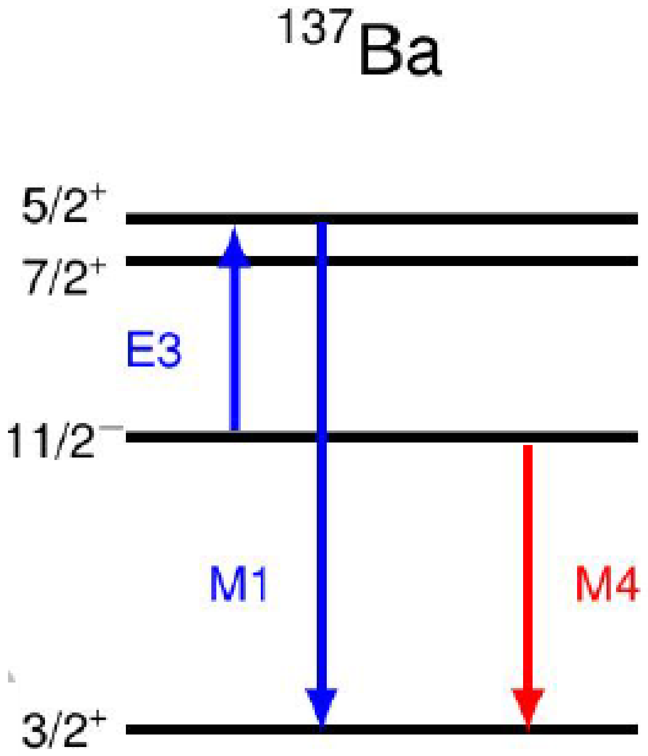
$$\alpha_{E3M1} = \frac{\langle 3/2^+||\mathbf{M1}||5/2^+\rangle \cdot \langle 5/2^+||\mathbf{E3}||11/2^-\rangle}{E_{5/2^+}} + \ldots$$



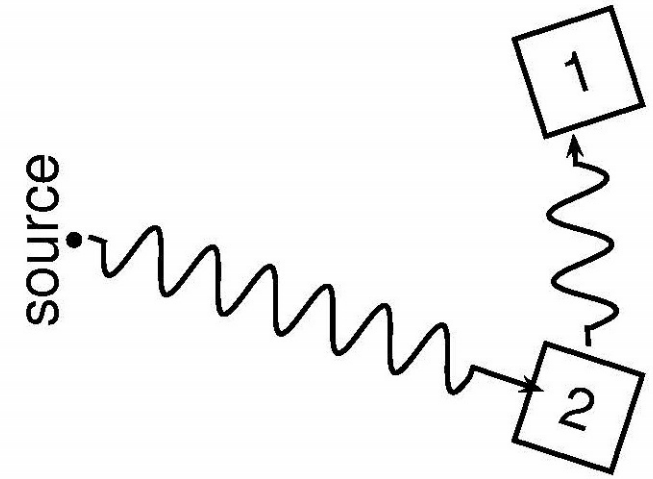
Experimental Obstacle

- very small branching ratio $\Gamma_{\gamma\gamma}/\Gamma_{\gamma} \ll 10^{-4}$
- Compton scattering
  energy of single γ-ray deposited in two detectors
  - exact same signature for energy sum

$$E_0 = E_1 + E_2$$

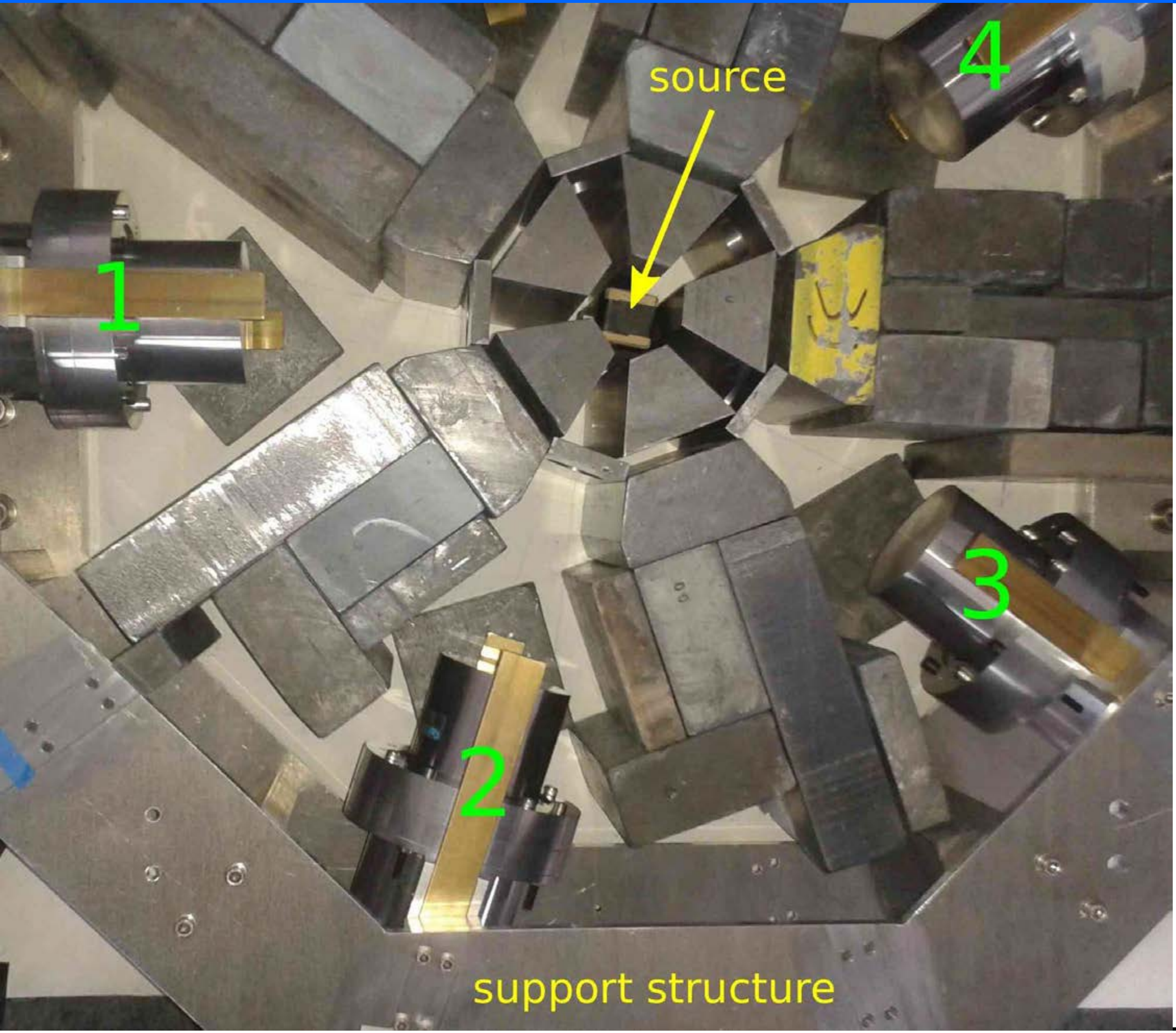
  but
  - different energy distribution
  - different path of photons: shielding

  - almost same timing $(\Delta t \sim 1ns)$
    but:
    - $\Delta t \neq 0$
- *no problem for* $0^+ \rightarrow 0^+$



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

Experimental setup



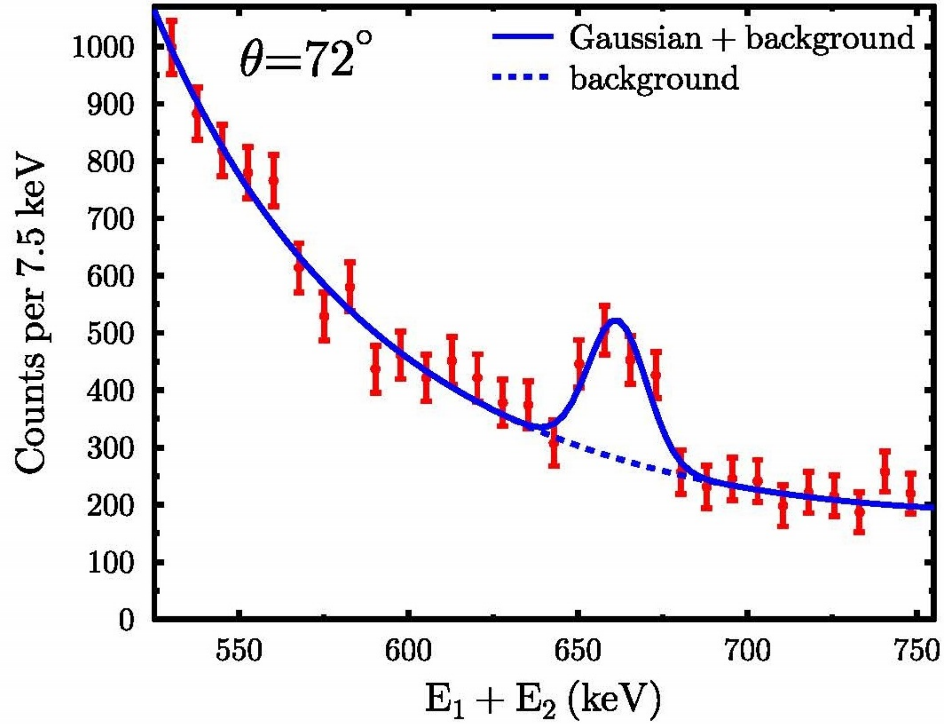
- 72^0: 5 detector pairs
- 144^0: 5 detector pairs

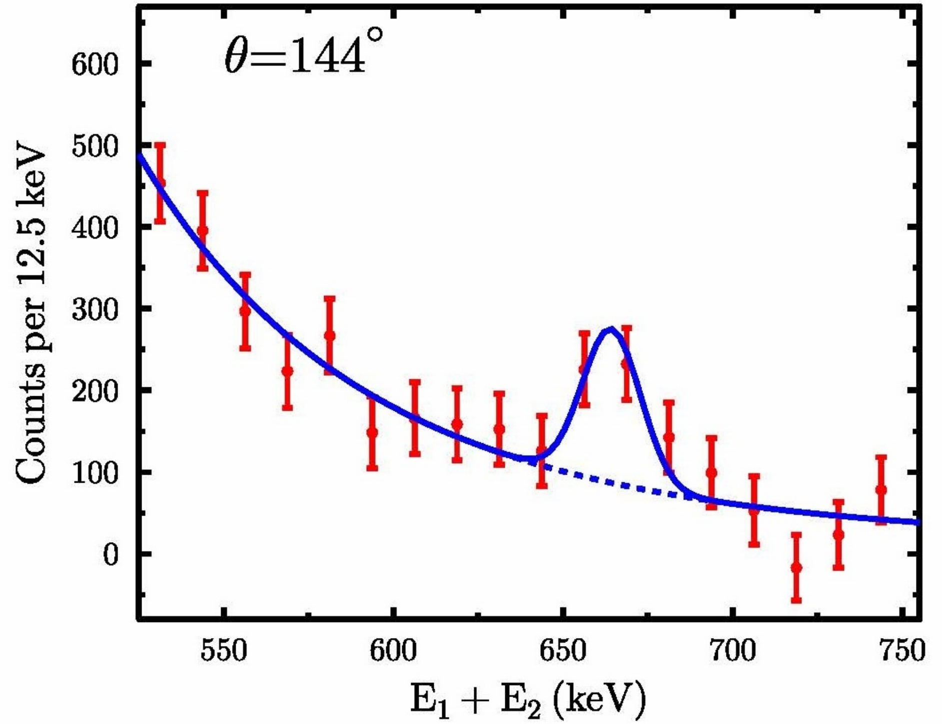
- thick Pb blocks between detectors

- ε_{FE}(662 keV) = 1.5 %
- $\varepsilon_{\gamma\gamma} \approx 4 \cdot 10^{-4}$
- ΔE = 3% (FWHM)
- Δt = 1 ns (FWHM)

- on disk: 53 days
- source: ^{137}Cs (600 kBq)

Results – random subtracted energy spectra



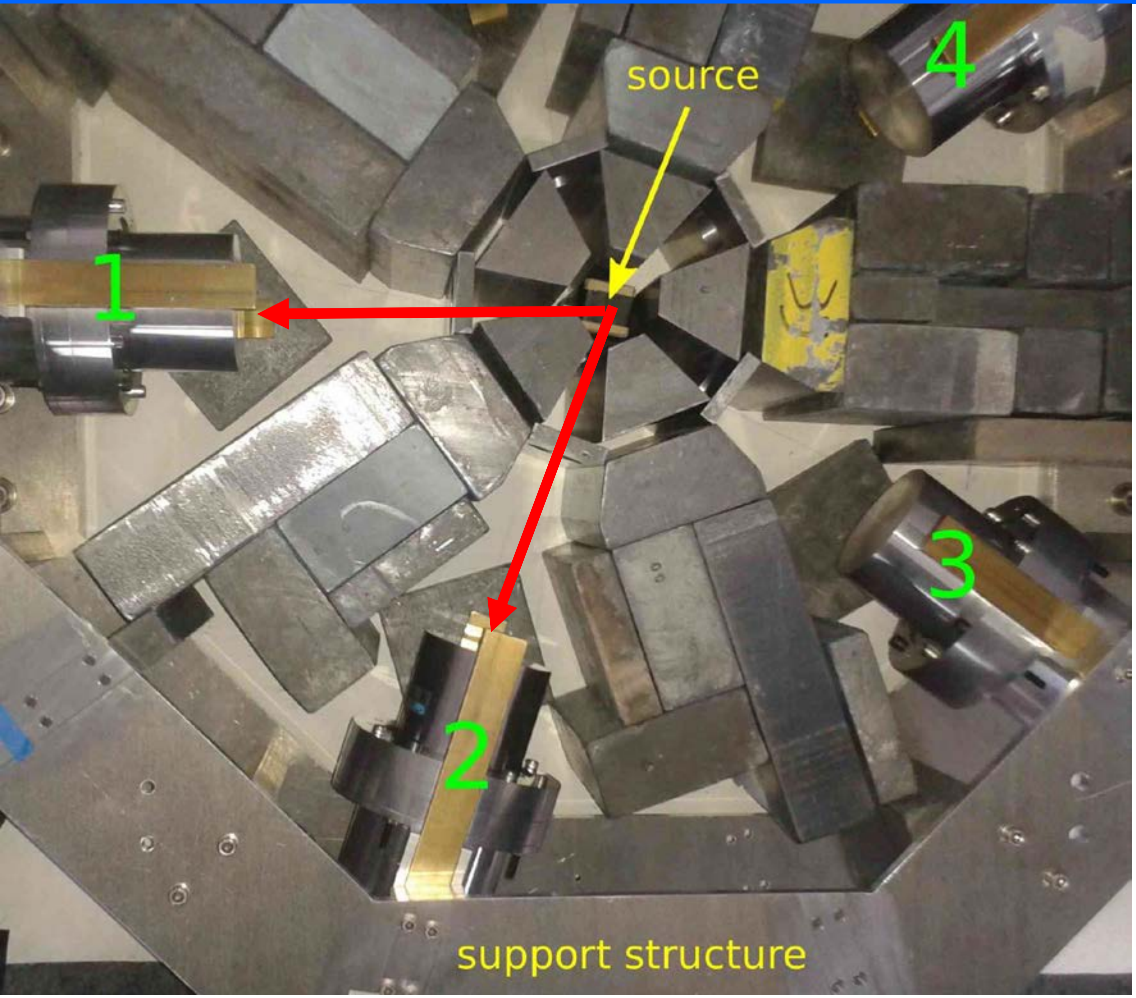


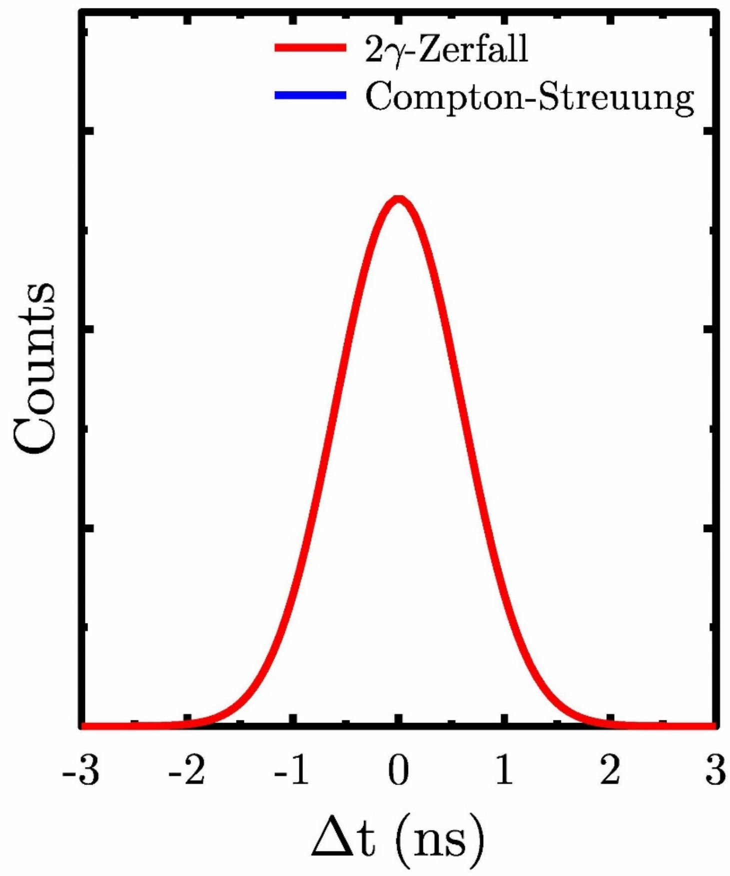
693(95) counts (σ = 7.3)
$\Gamma_{\gamma\gamma}/\Gamma_{\gamma} = 1.56(23)\cdot10^{-6}$

325(76) counts (σ = 4.3)
$\Gamma_{\gamma\gamma}/\Gamma_{\gamma} = 0.70(18)\cdot10^{-6}$

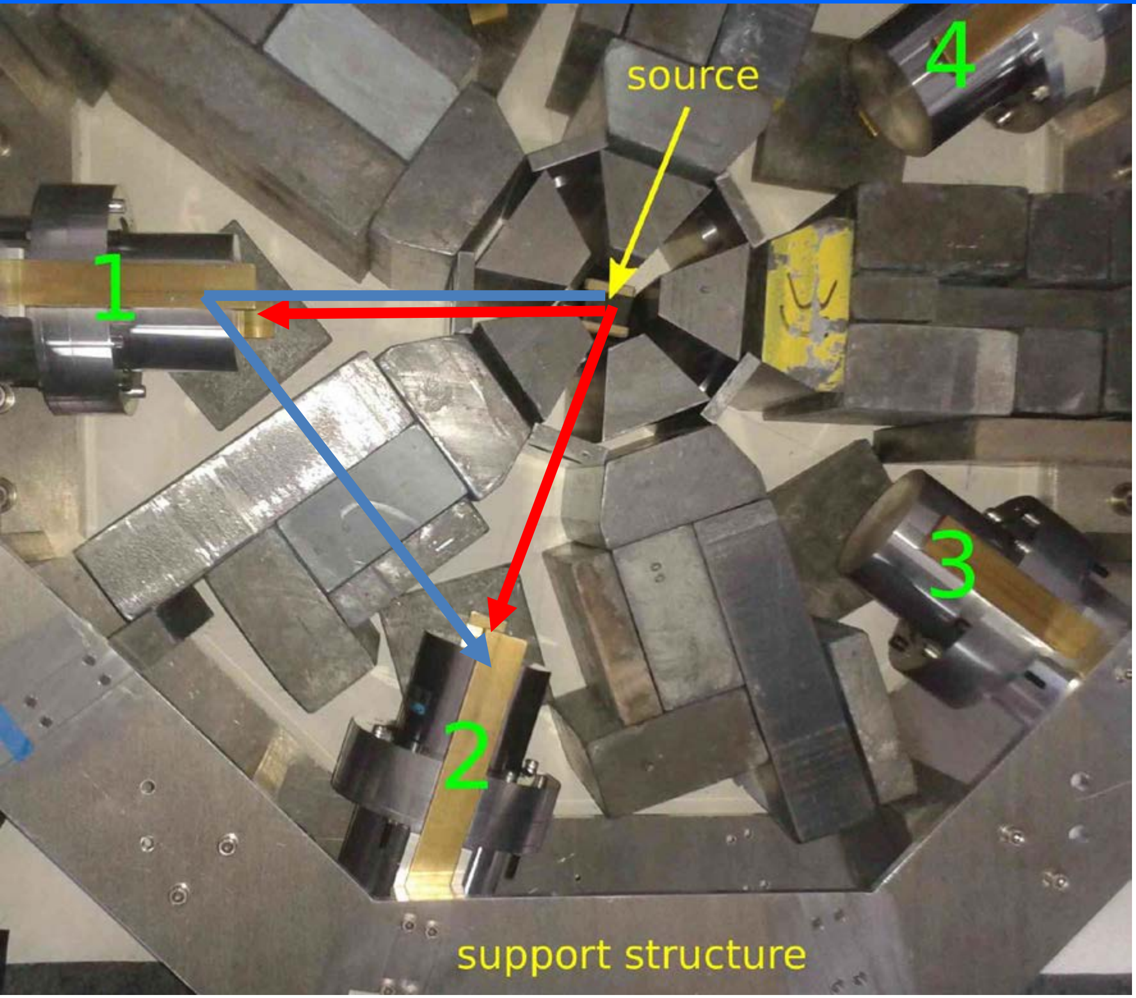
observation of the competitive double-gamma decay
very pronounced angular correlation

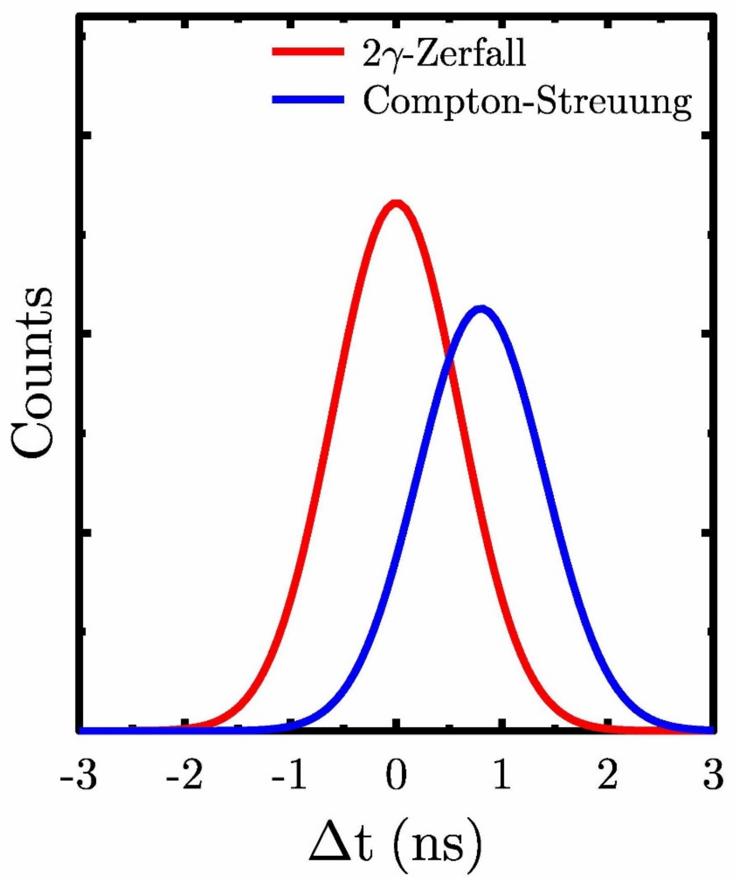
Time analysis





Time analysis





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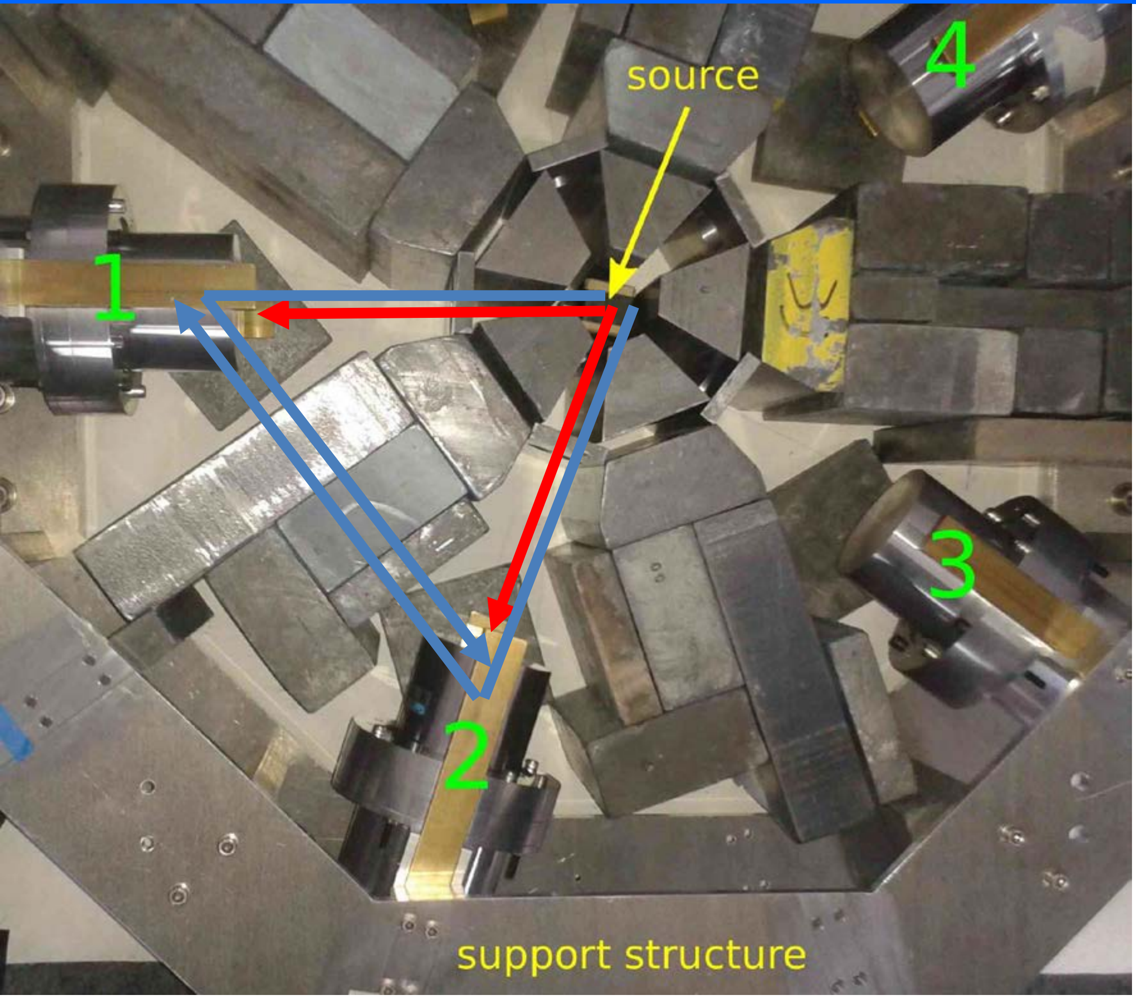
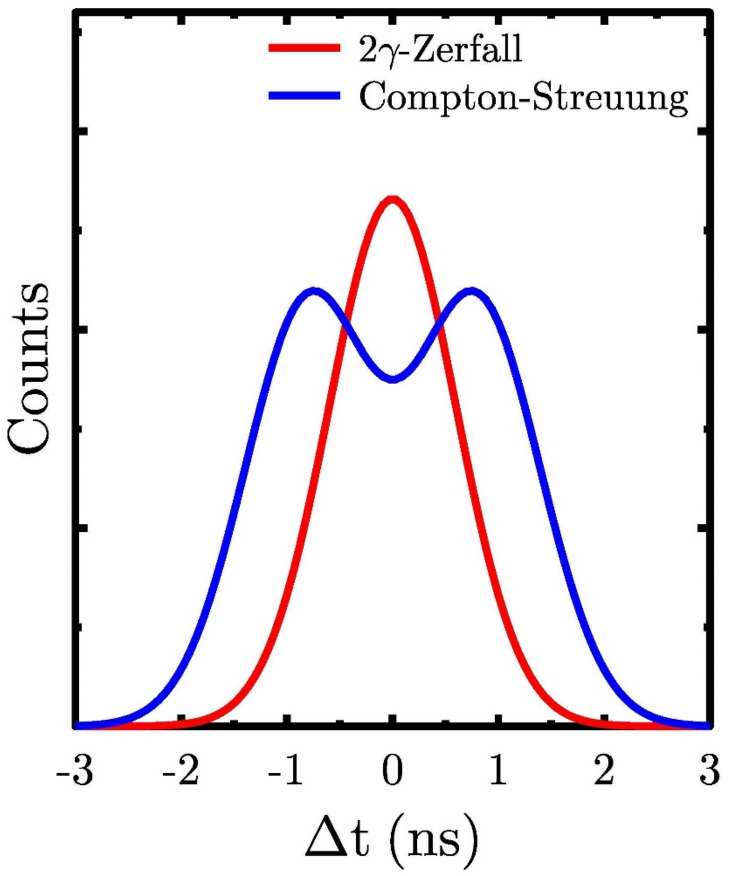
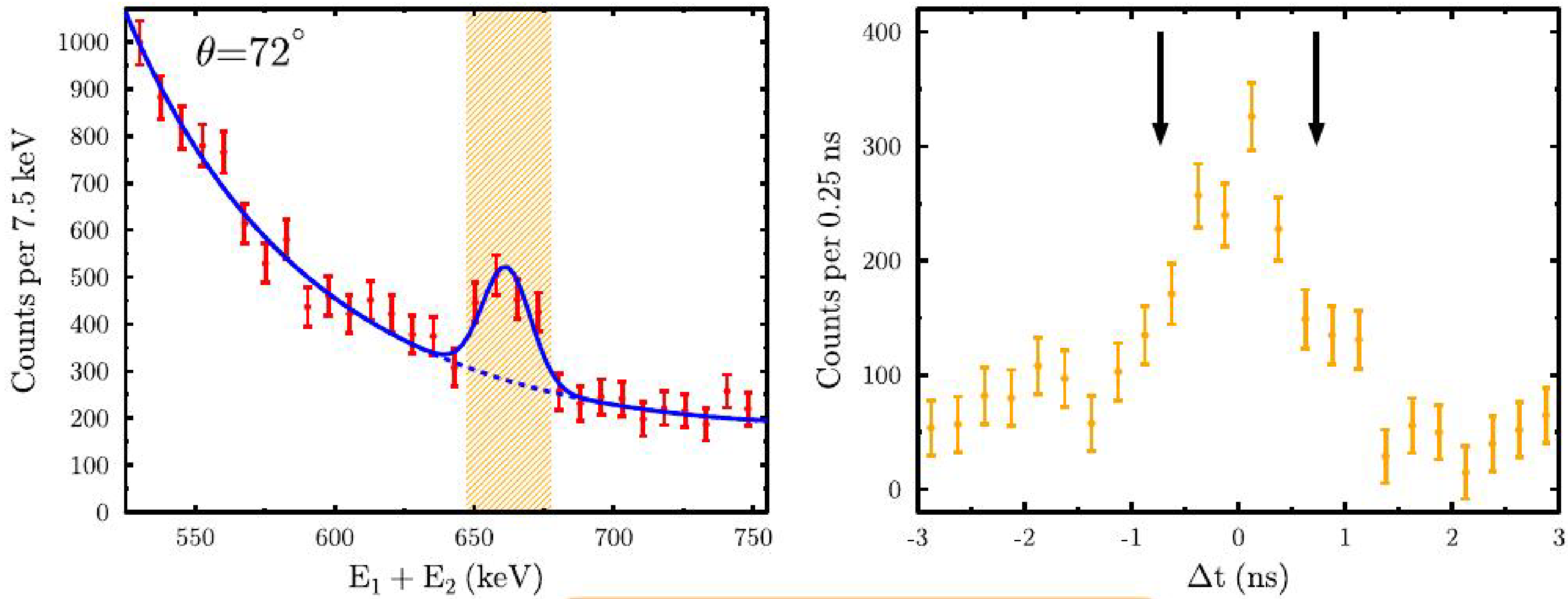




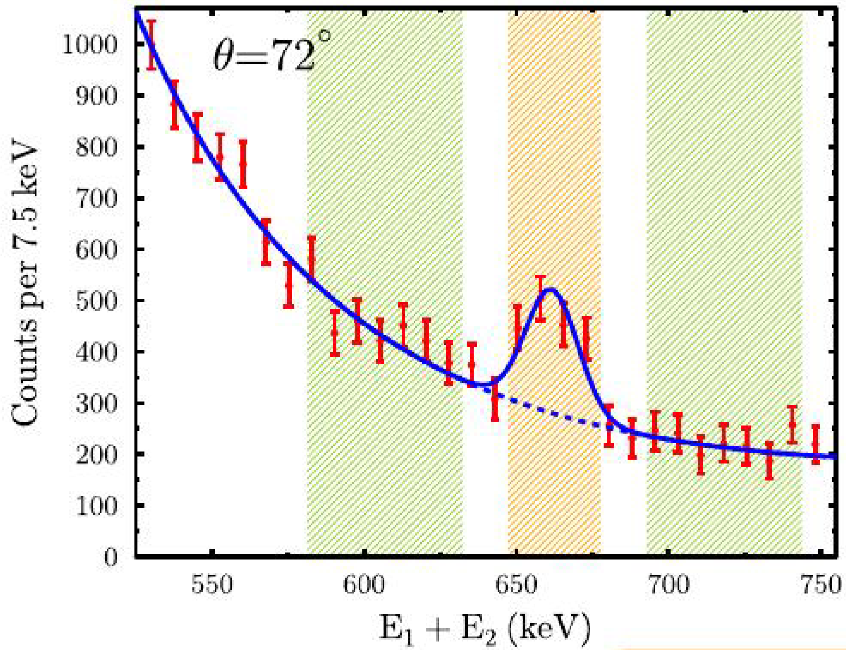
- Compton scattering should be visible in time spectrum

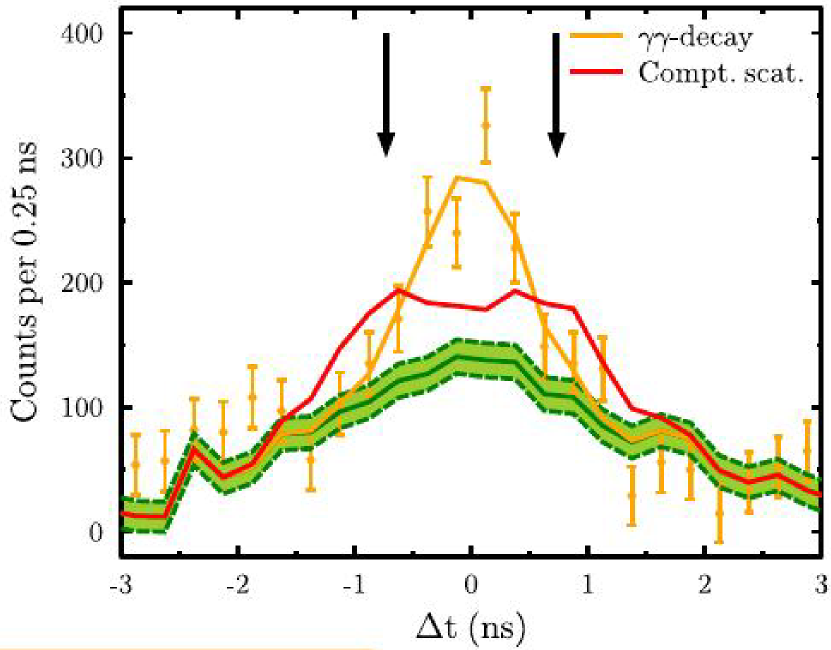
Time analysis



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

Time analysis





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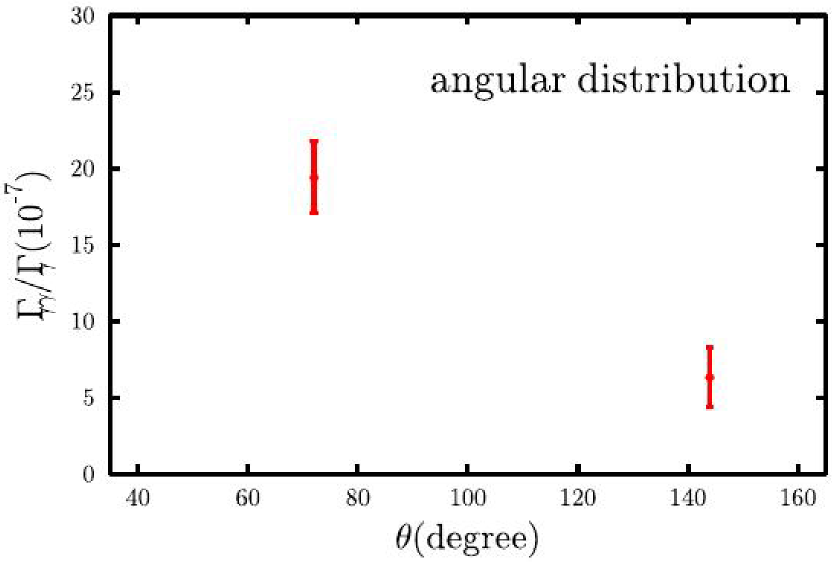
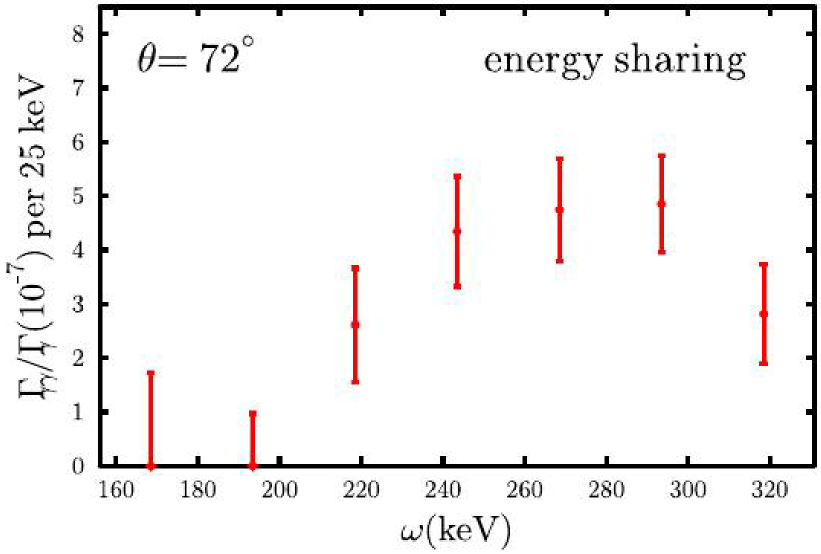
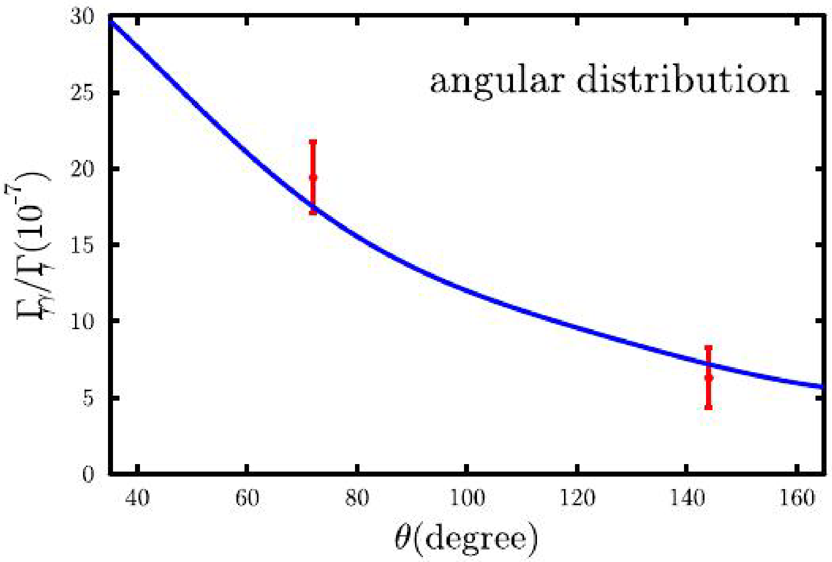
Results

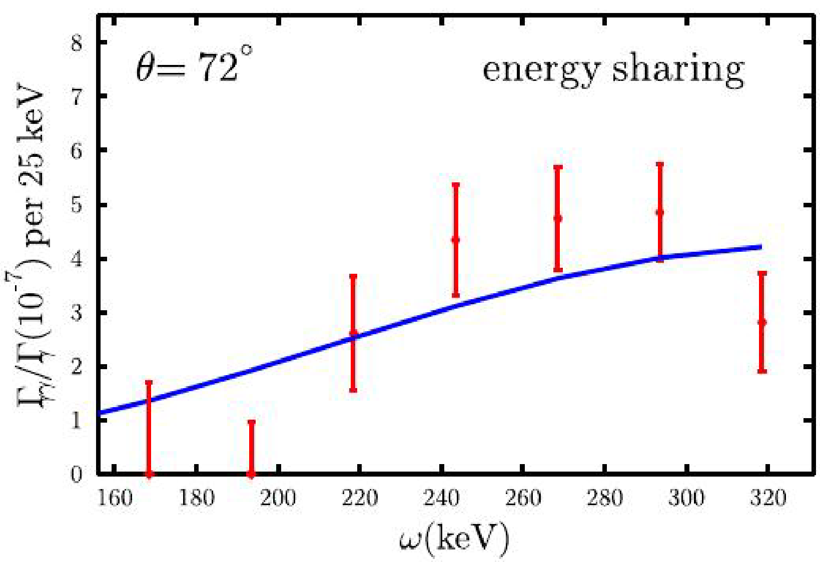




$$\frac{d\Gamma^2_{\gamma\gamma}}{d\omega\, d\cos\theta} = A_{qq}(\alpha^2_{M2E2}) + A_{od}(\alpha^2_{E3M1}) + A_x(\alpha_{M2E2} \cdot \alpha_{E3M1})$$

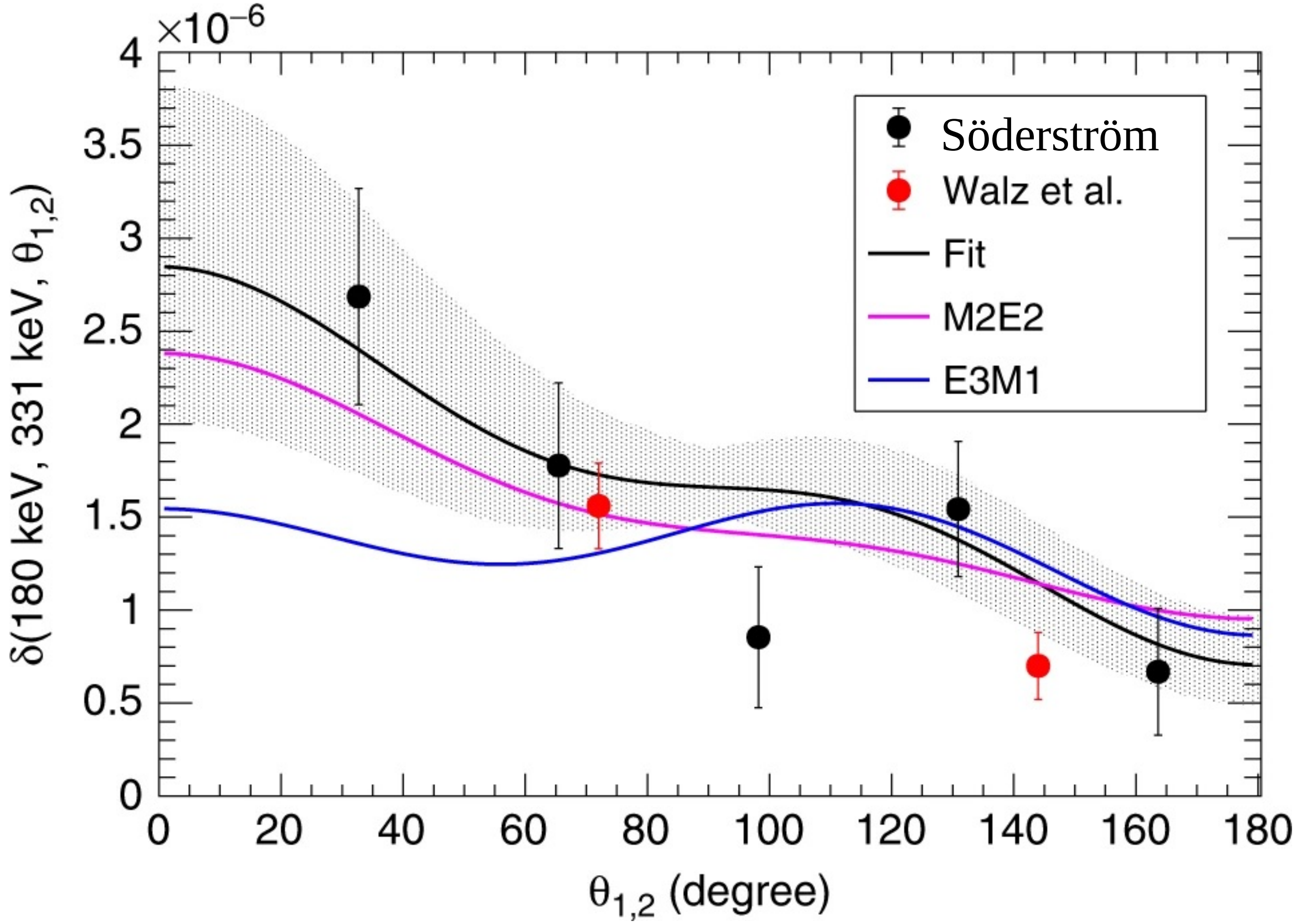
Results





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

Angular distribution



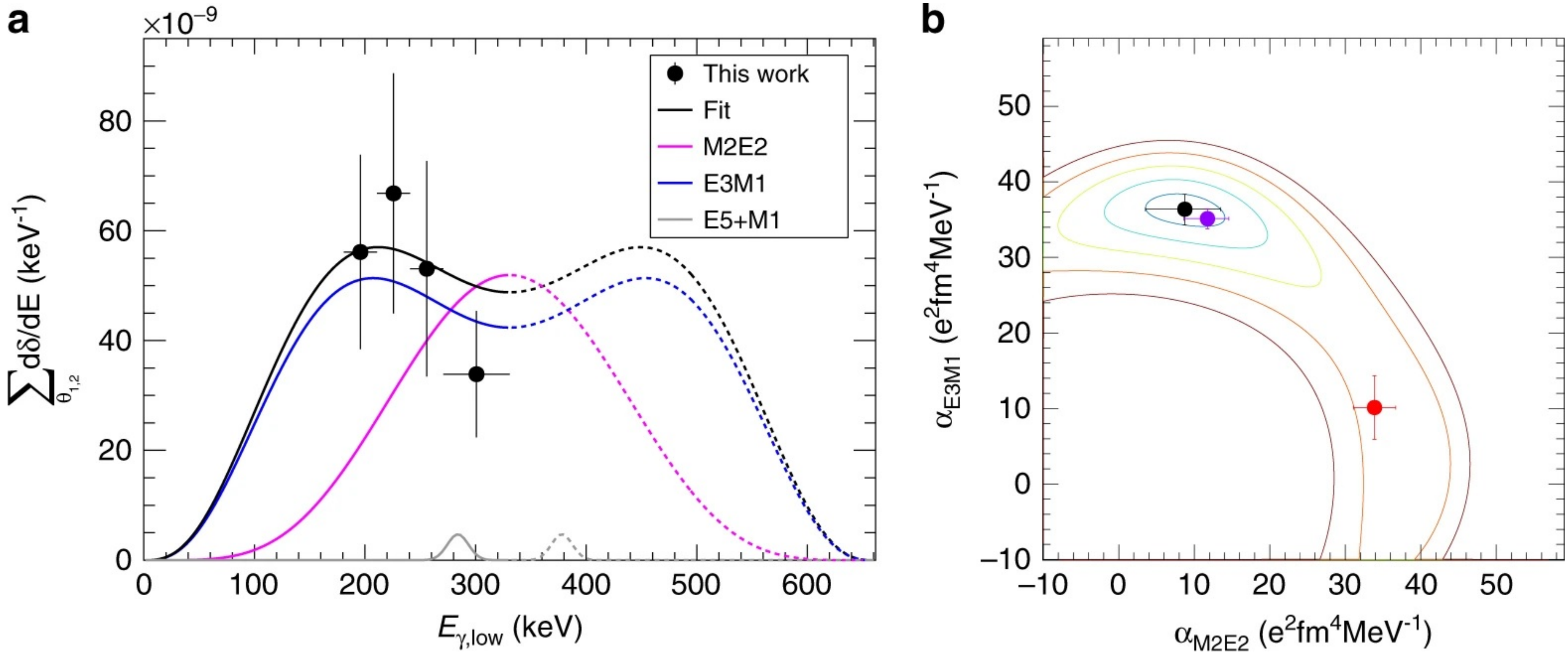
$$W_{\ell=2,\ell=2}(\theta) = 1 + \frac{1}{3}P_1(cos\theta) + \frac{5}{49}P_2(cos\theta) + \frac{1}{7}P_3(cos\theta) + \frac{40}{441}P_4(cos\theta)$$

$$W_{\ell=1,\ell=3}(\theta) = 1 - \frac{1}{8}P_1(cos\theta) + \frac{5}{49}P_2(cos\theta) + \frac{3}{8}P_3(cos\theta)$$

no symmetry axis:
odd Legendre polynomials

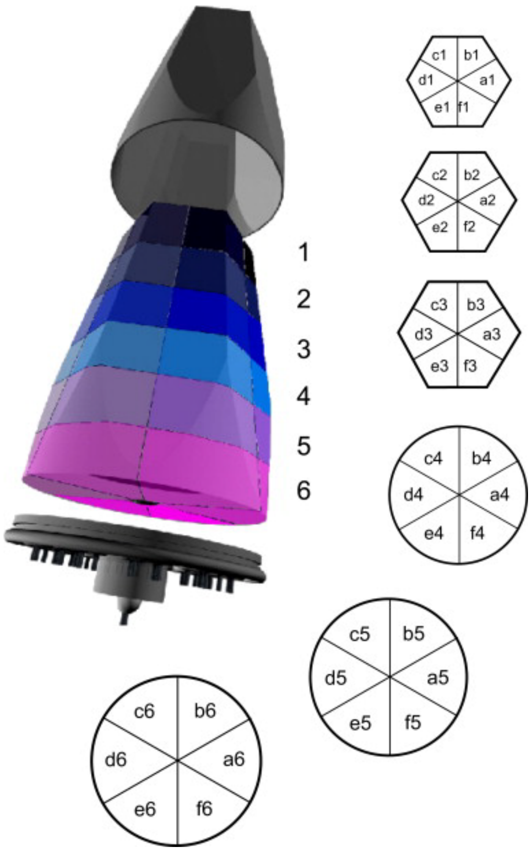
C. Walz et al.; Nature 406 526 (2015); P.-A. Söderström et al.; Nature Commun. 11, 3242 (2020)

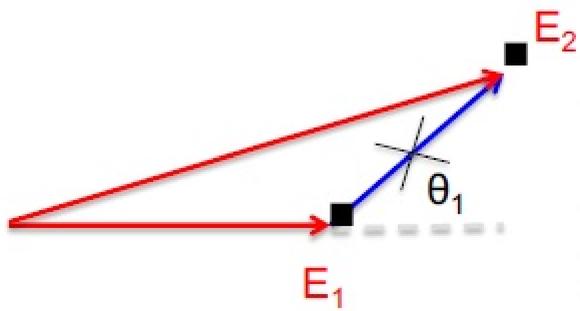
Multipole nature of the γγ/γ decay

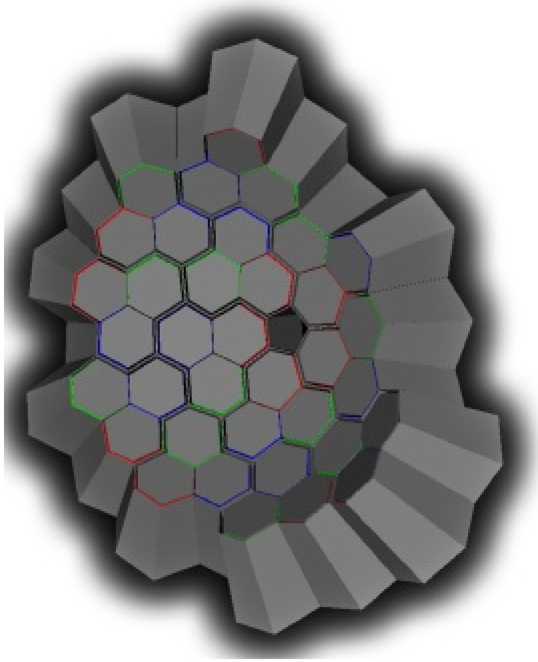


	$\Gamma_{\gamma\gamma}^{exp}/\Gamma_{\gamma}^{exp}$ (10^{-6})	α_{M2E2} (e^2fm^4/MeV)	α_{E3M1} (e^2fm^4/MeV)
Walz	2.05(30)	33.9(28)	10.1(42)
Söderström	2.62(37)	±8.8(50)	±36.4(20)

Future: AGATA for the $\gamma\gamma$-decay







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

Appendix: Legendre polynomials

$$P_0(cos\theta) = 1$$

$$P_1(cos\theta) = cos\theta$$

$$P_2(cos\theta) = \frac{1}{2}(3cos^2\theta - 1)$$

$$P_3(cos\theta) = \frac{1}{2}(5cos^3\theta - 3cos\theta)$$

$$P_4(cos\theta) = \frac{1}{8}(35cos^4\theta - 30cos^2\theta + 3)$$

$$P_5(cos\theta) = \frac{1}{8}(63cos^5\theta - 70cos^3\theta + 15cos\theta)$$

$$P_6(cos\theta) = \frac{1}{16}(231cos^6\theta - 315cos^4\theta + 105cos^2\theta - 5)$$