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Observation of the competitive double-gamma nuclear decay

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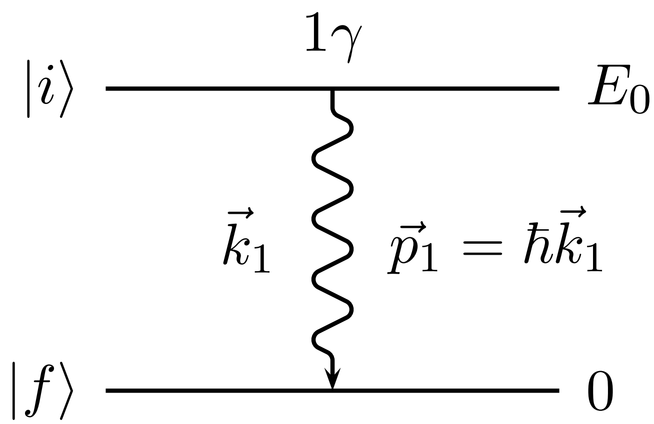
Introduction

Emission of Electromagnetic Radiation
One and Two Photon(s)

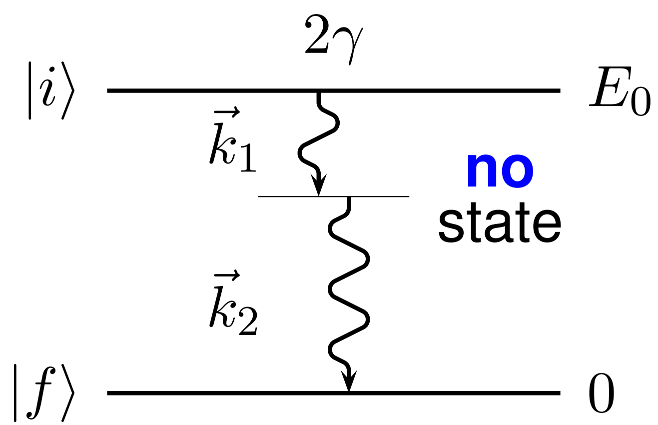
- **single** photon emission

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



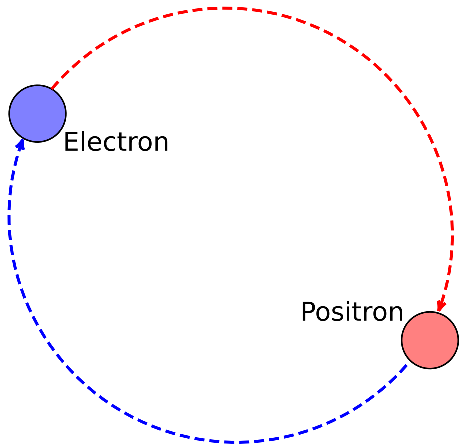
- **double-gamma** decay: two photons emitted **simultaneously**

$$E_0 = E_1 + E_2$$



Similar: Positronium Decay into 2,3,4... Photons

- bound system of an electron and a positron



- decay into N_γ photons
  - due to momentum conservation: $N_\gamma \geqslant 2$
  - due to charge conjugation parity
    - para-Ps ($S = 0$): $N_\gamma = 2, 4, \ldots$
      (for $N_\gamma = 1$: well known back-to-back **511 keV** γ rays)
    - ortho-Ps ($S = 1$): $N_\gamma = 3, 5, \ldots$
      (**three photons** in lowest order)

Decay Width
First Order Perturbation Theory

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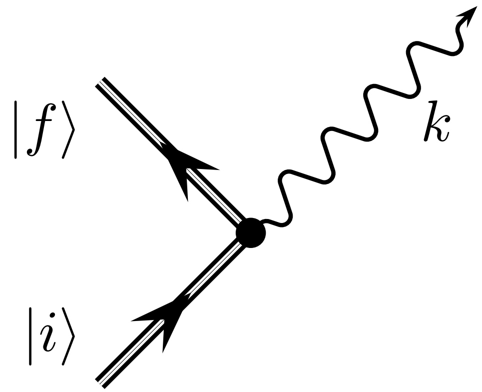
- interaction of a nucleus with the free EM radiation field:

$$H_{\text{int}} = -\frac{1}{c}\int \vec{j}_{\text{N}}(\vec{r},t)\vec{A}(\vec{r},t)d^3r$$

- **Fermi's Golden Rule**

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



ρ_f: density of final states; H_{int}: interaction Hamiltonian
$\vec{j}_{\text{N}}(\vec{r},t)$: nucl. current density; $\vec{A}(\vec{r},t)$: EM vector potential

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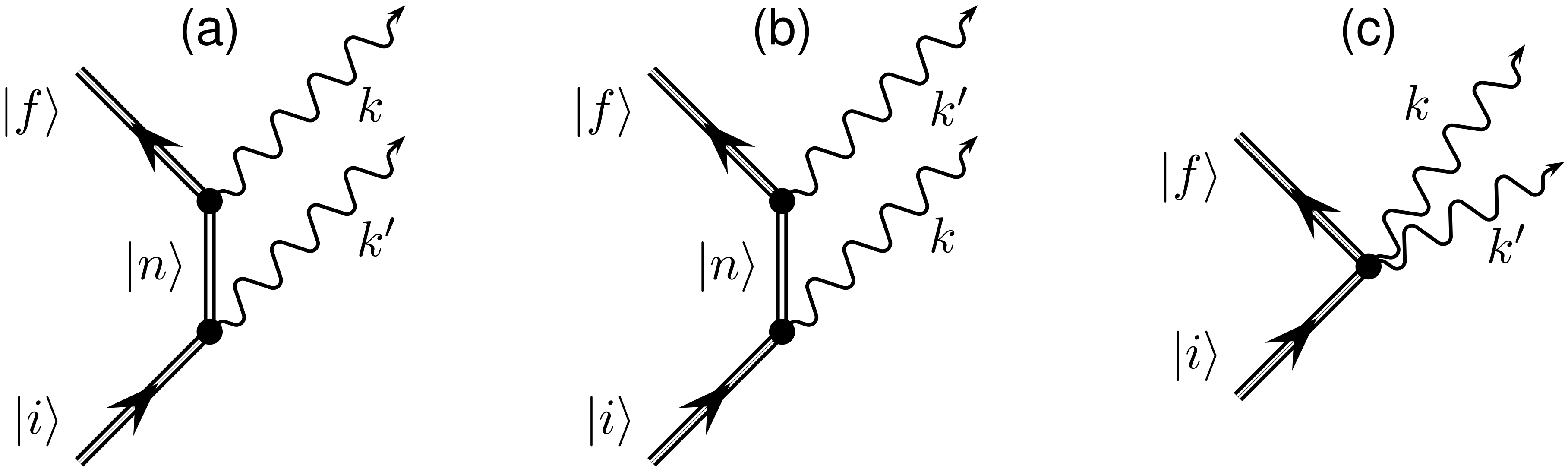
Second Order



- 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:
  first order, but quadratic in the radiation field A^2
- theory is fully developed

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

Historical Detour

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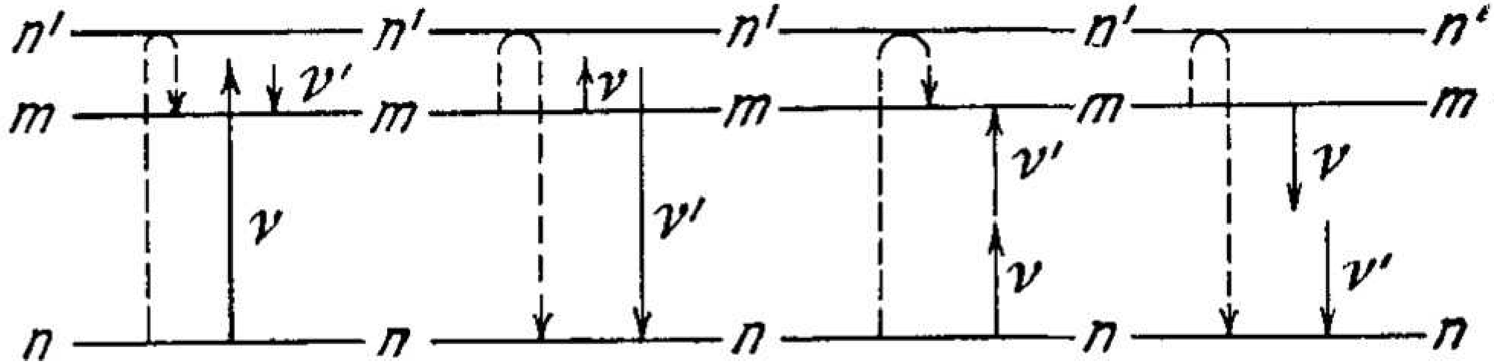
- first discussed in doctoral thesis (1930) of
  Maria Göppert-Mayer

  Über Elementarakte mit zwei Quantensprüngen

  Von Maria Göppert-Mayer

  (Göttinger Dissertation)

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



- used routinely in atomic physics
- (later MGM also predicted double β-decay)

Double-Gamma Decay in Nuclei

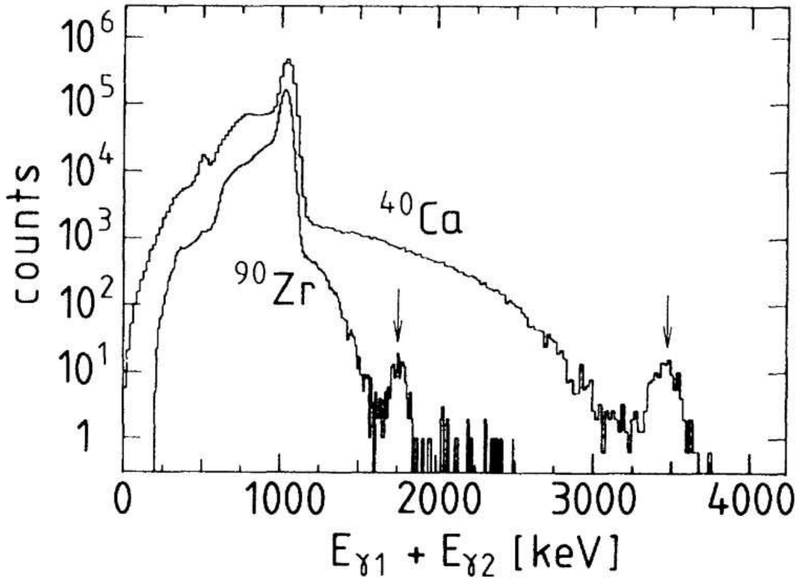
- first **unambiguous** observation in **^{40}Ca and ^{90}Zr**

VOLUME 53, NUMBER 20 PHYSICAL REVIEW LETTERS 12 NOVEMBER 1984

Double Gamma Decay in ^{40}Ca and ^{90}Zr

J. Schirmer, D. Habs, R. Kroth, N. Kwong, D. Schwalm, and M. Zirnbauer
Max-Planck-Institut für Kernphysik and Physikalisches Institut der Universität Heidelberg, D-6900 Heidelberg, Federal Republic of Germany

- HD-DA Crystal ball (4π; 162 NaI(Tl))



- same group: **^{16}O**
- common to all: $0^+ \to 0^+_{\rm gs}$ transitions

single photon decay **strictly forbidden**

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

Double-gamma decay: $0^+ \rightarrow 0^+$ transitions

Experiment

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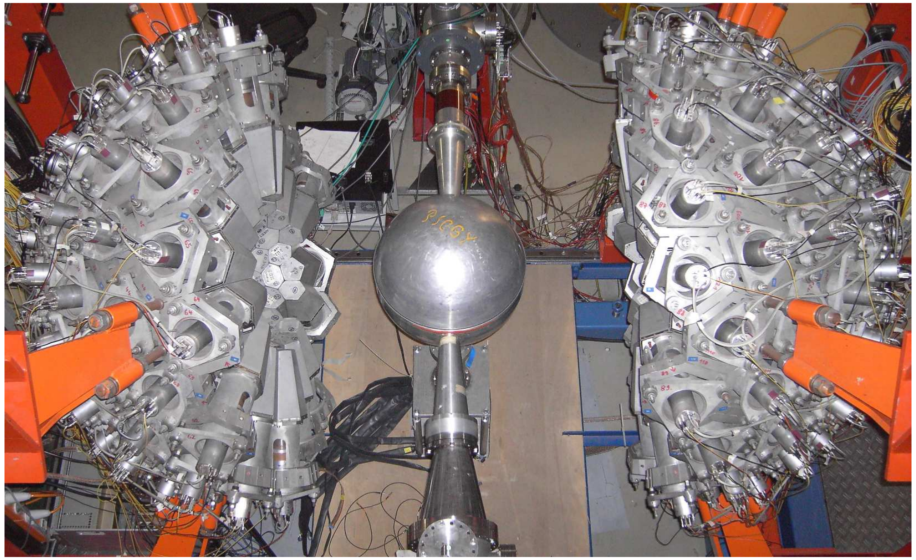
- γ detection using the **Heidelberg-Darmstadt Crystalball**

Heidelberg-Darmstadt Crystalball

full solid angle 4π

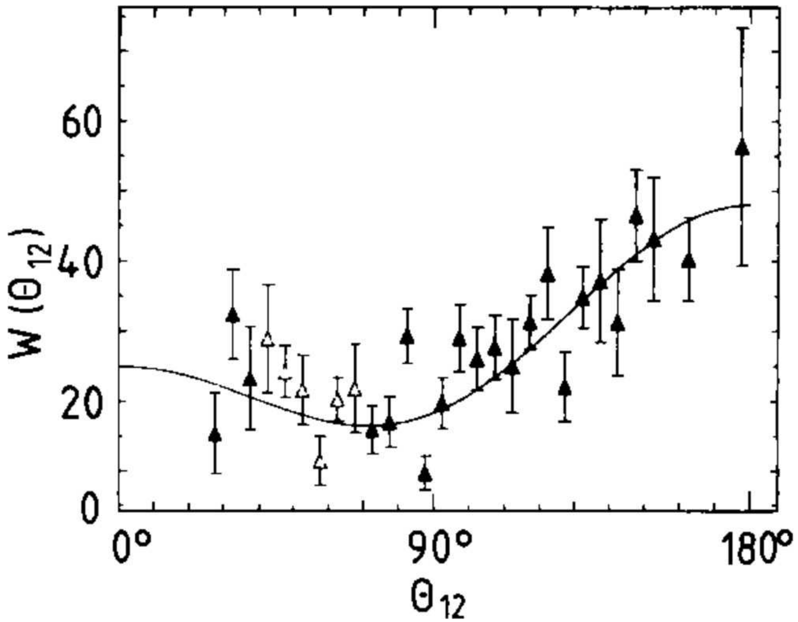
162 NaI(Tl) detectors



- **selective** population of 0_2^+ state by **proton** in-elastic **scattering** (p, p')
- coincidence: proton, 2 γ-rays
- ^{16}O, ^{40}Ca, ^{90}Zr

Main Findings

- $\gamma\gamma$-decay can proceed via E1E1, M1M1, E2E2
- E2E2 is very small, as expected
- surprisingly **E1E1** is **strongly suppressed** $(30 \ldots 300)$
- E1E1 and M1M1 transitions are comparable in strength
  - signature: E1, M1 interference
  - angular correlations not symmetric about 90°



E1E1 Suppression

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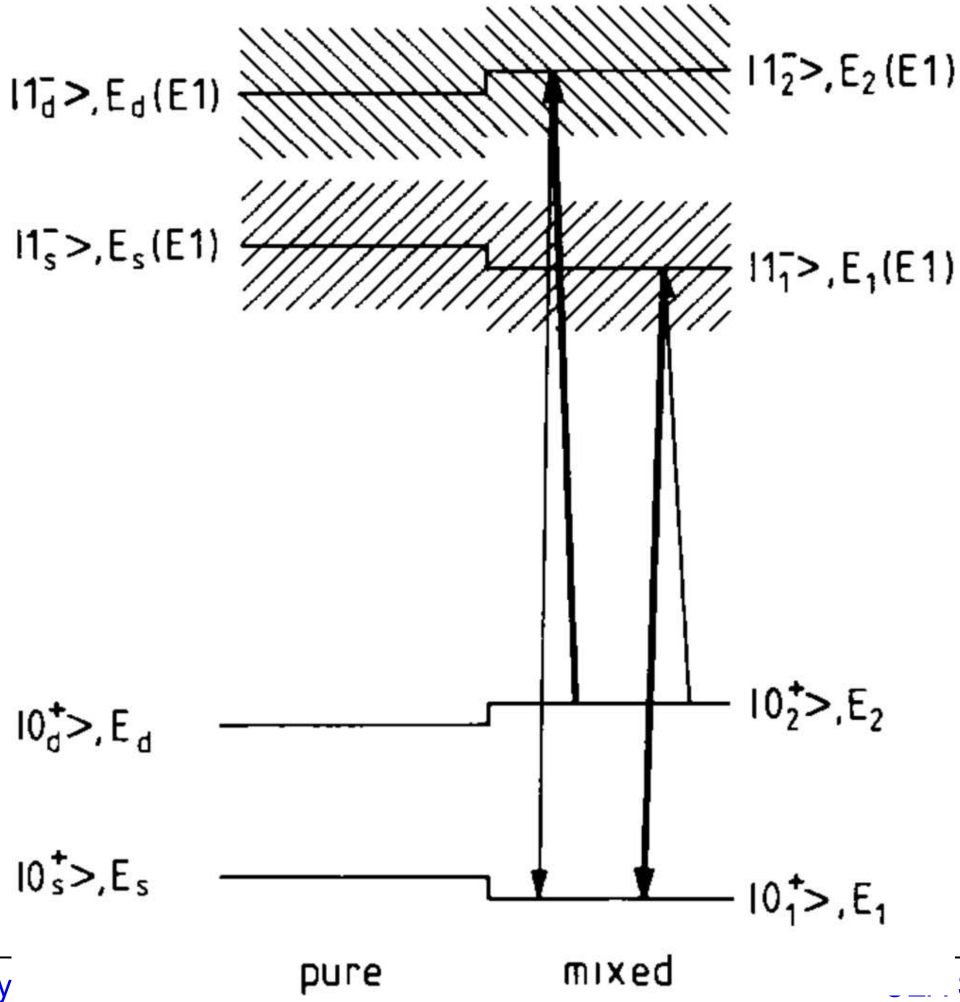
To explain the E1E1 suppression:

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



Results ^{16}O, ^{40}Ca, ^{90}Zr

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Nucleus	^{16}O	^{40}Ca	^{90}Zr
$\Delta E_{12} = E_2 - E_1$[MeV]	6.049	3.352	1.761
$T_{1/2}$[ns]	0.067	2.1	61
$(\Gamma_{\gamma\gamma}/\Gamma_{tot}) \cdot 10^{-4}$	6.6 ± 0.5	4.5 ± 1.0 [a])	1.8 ± 0.3 [a])
$\alpha^{12}_{E1}[10^{-3}\ fm^3]$	$16\ 9 \pm 4.3$ (2.7 ± 0.7)	7.8 ± 1.9	20.1 ± 10.9
$\chi^{12}[10^{-3}\ fm^3]$	-2.7 ± 0.7 (-16.9 ± 4.3)	-18.3 ± 4.5	-10.4 ± 5.7
$\alpha^{12}_{E2}[fm^5]$	$\leqslant 120$	$\leqslant 670$	$\leqslant 4000$
$\lvert\langle 0^+_1 \lvert \bar{r}^2 \rvert 0^+_2 \rangle\rvert$ [fm^2]	3.55 ± 0.21 [b])	2.6 ± 0.1 [c])	1.71 ± 0.06 [d])
$\alpha^{11}_{E1}[10^{-3}\ fm^3]$	585 [e])	2230 [e])	6330 [e])
$\chi^{11}_{P}[10^{-3}\ fm^3]$	1.78 [f])	5.65 [f])	14.5 [f])
$\bar{E}_{E1} - E_1$[MeV]	24 [e])	20.2 [e])	16.7 [g])
$\bar{E}_{M1} - E_1$[MeV]	17 [h])	10 [i])	9 [j])

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

Competitive Double-Photon Decay: $\gamma\gamma/\gamma$

Competitive Double-Photon Decay: $\gamma\gamma/\gamma$

- for $0^+ \rightarrow 0^+$ transitions:
  - **single** photon decay **strictly forbidden**
  - $\Gamma_{\gamma\gamma}/\Gamma \sim 10^{-4}$
  - $\Gamma \approx \Gamma_{\text{IP}}$ (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

Experiment

Experimental Signatures

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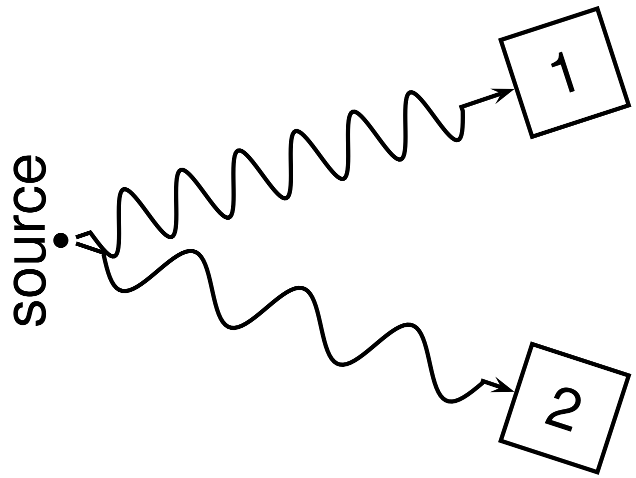
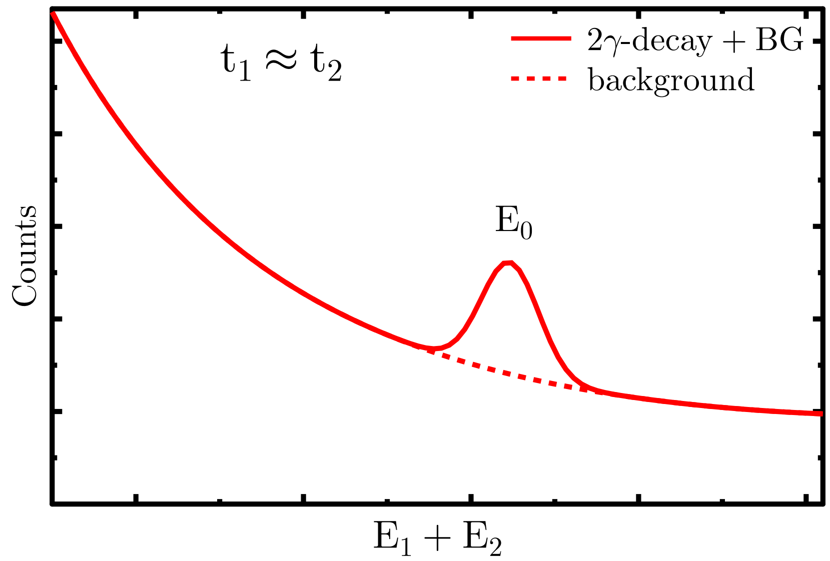
- two photons emitted **simultaneously** with **continuous** energy spectrum
- but **energy** is **conserved**:

$$E_0 = E_1 + E_2$$





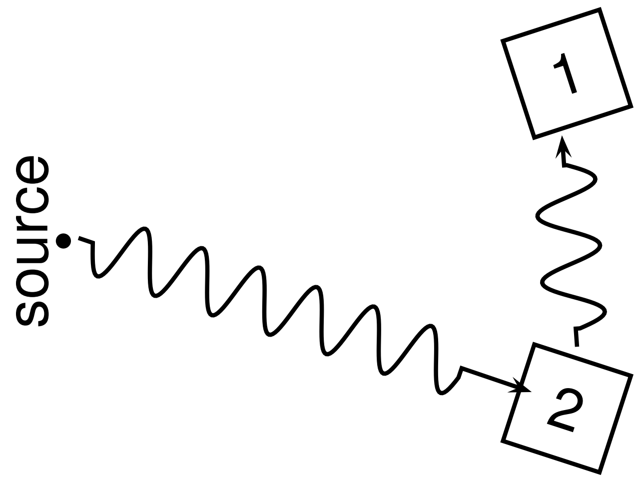
E_0: transition energy; $E_{1/2}$: energies of two photons

Experimental Obstacle(s) for the Competitive Double-Gamma Decay

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



Recent Experimental Advance: $LaBr_3(Ce)$ Detectors

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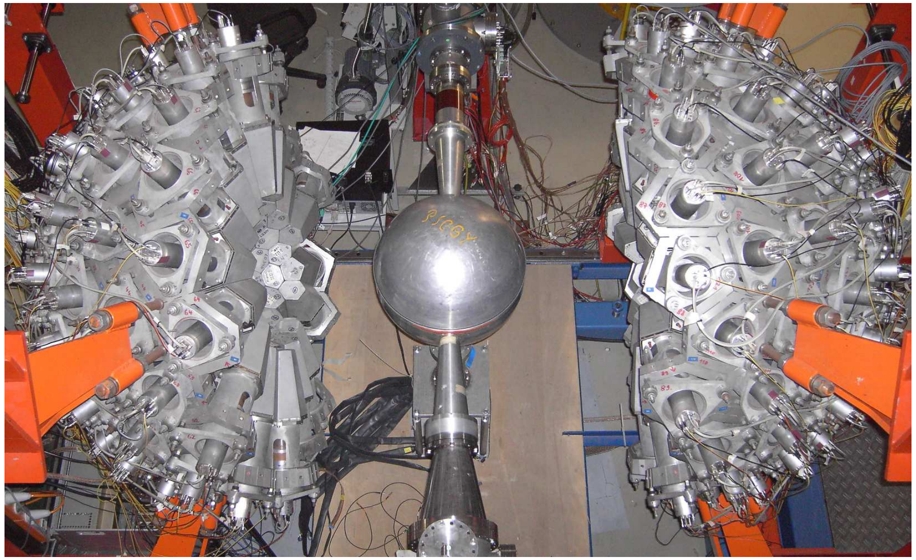
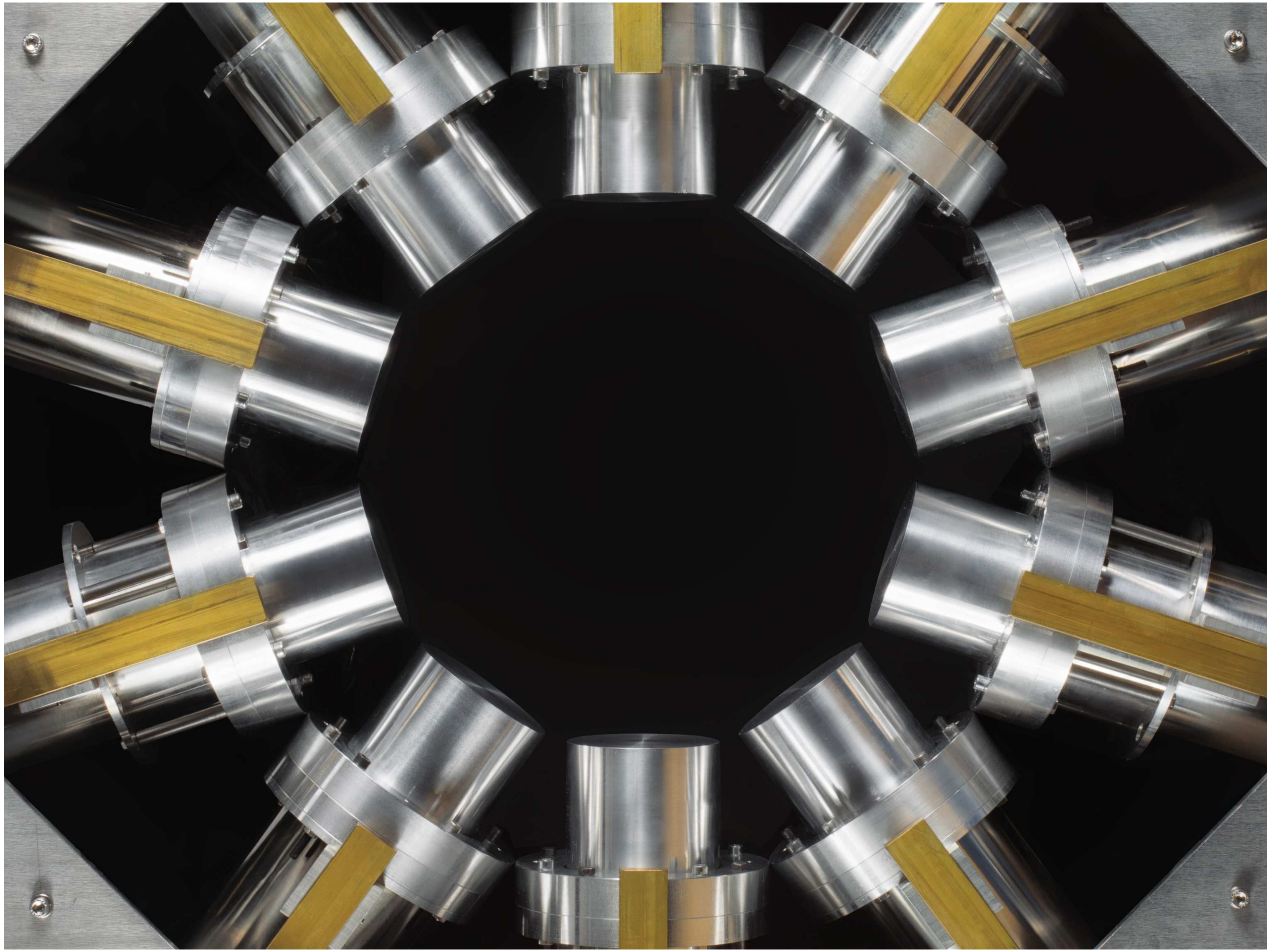
- so far: NaI(Tl) detectors
  - standard detector, if **high efficiency** is crucial
  - but: poor **time** and **energy resolution**

Heidelberg-Darmstadt Crystalball
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 $\to$ high rate measurements

GALATEA array
18 $LaBr_3$(Ce) detectors ($3" \times 3"$)



Experimental Setup

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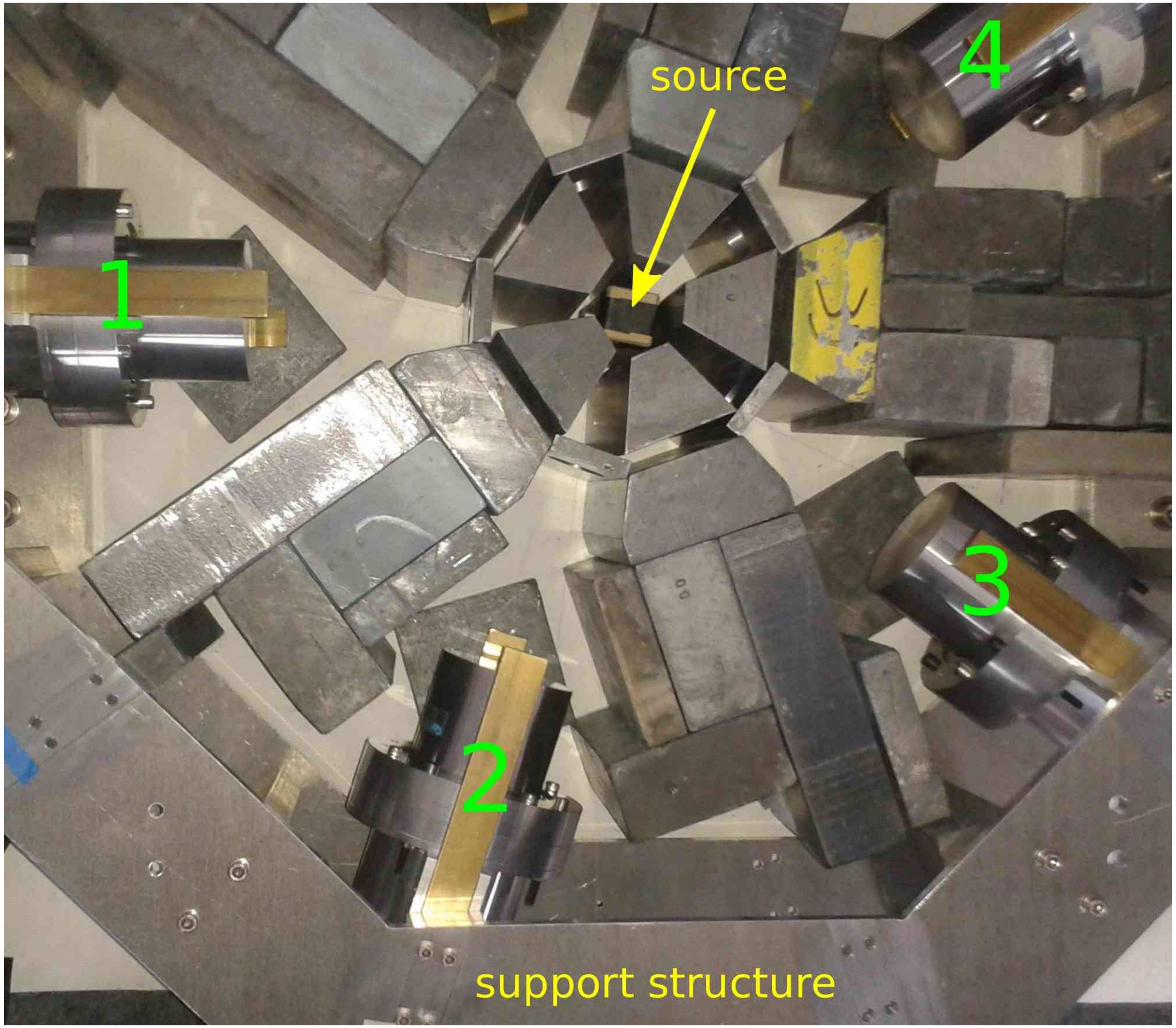

- 5 $LaBr_3(Ce)$ detectors
- 72°: 5 detector pairs
- 144°: 5 detector pairs
- $\epsilon_{FE}(662$ keV$) = 1.5\%$
- $\epsilon_{\gamma\gamma} \approx 4 \cdot 10^{-4}$
- $\Delta E = 3\%$ (FWHM)
- $\Delta t = 1$ ns (FWHM)
- on disk: **53 days**
- source: ^{137}Cs (600 kBq)
- thick **Pb blocks** between detectors

Source of (two-)photons: ^{137}Cs (gamma calibration standard)

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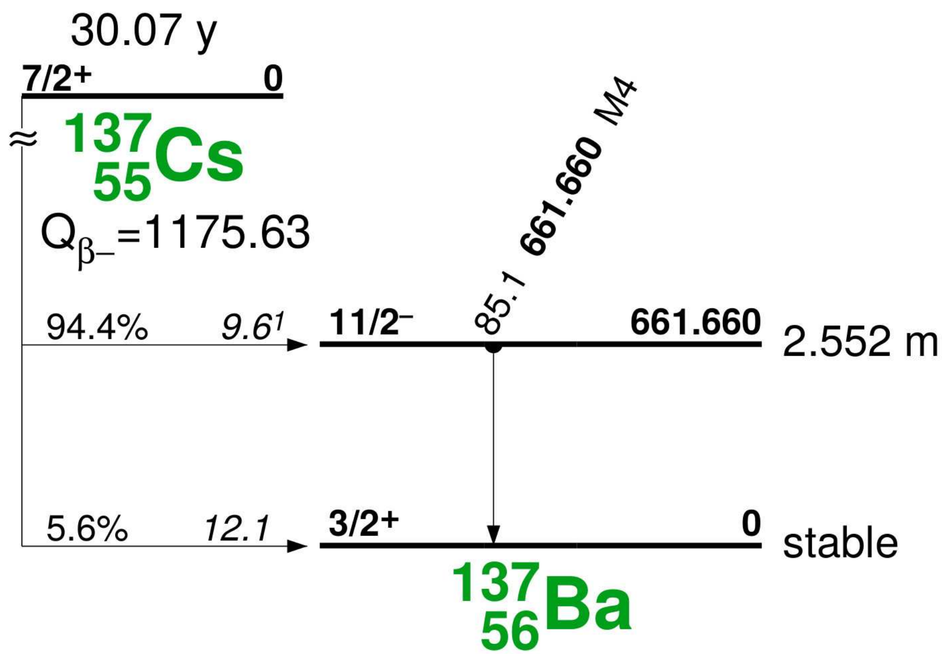
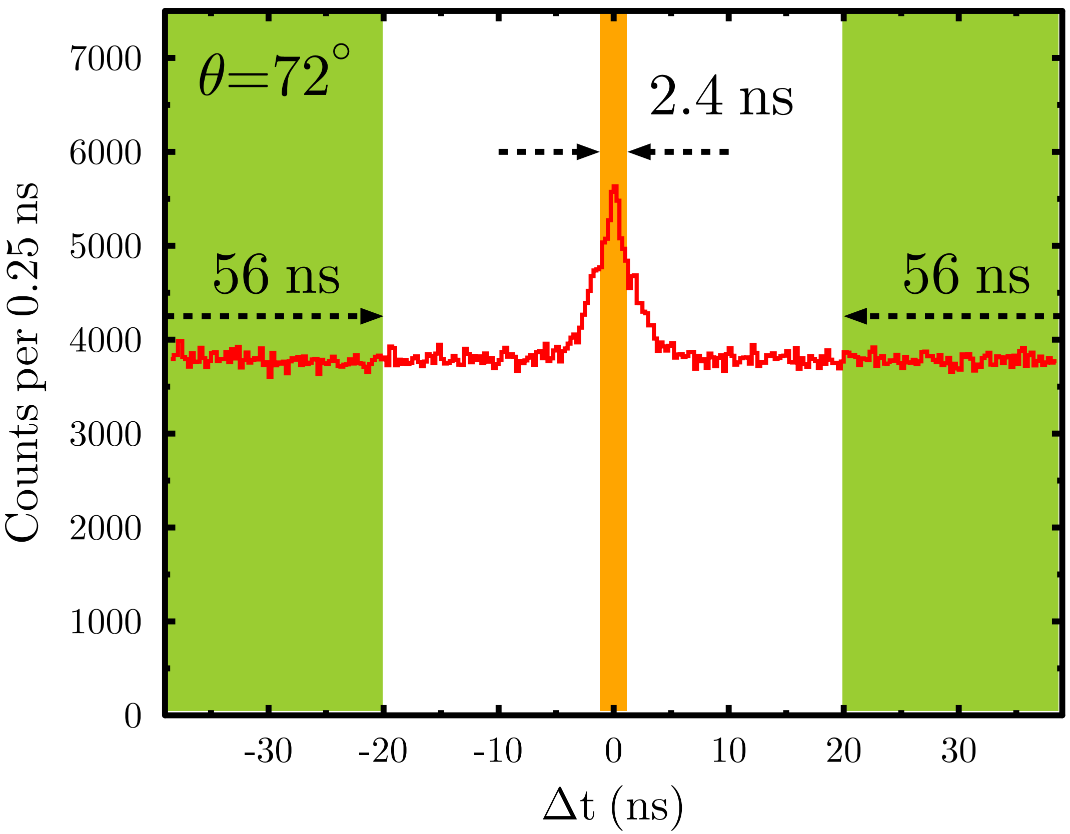
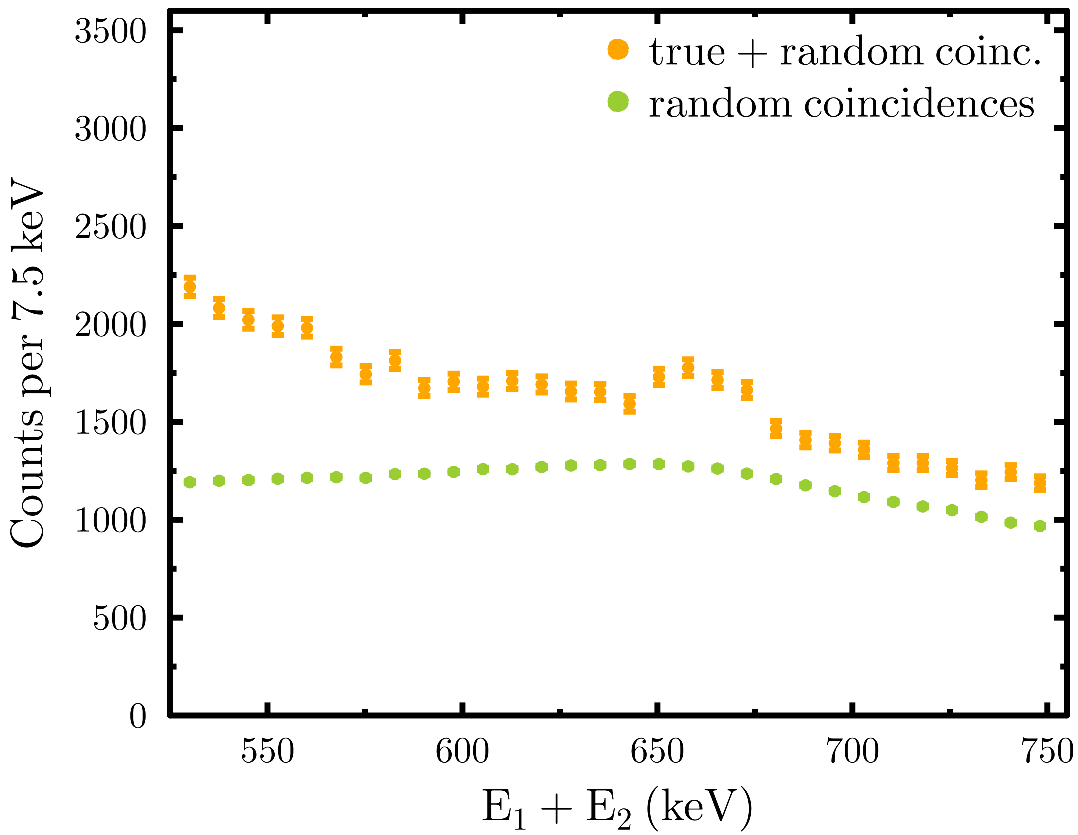


- $11/2^- \rightarrow 3/2^+$ transition of ^{137}Ba (M4)

Results

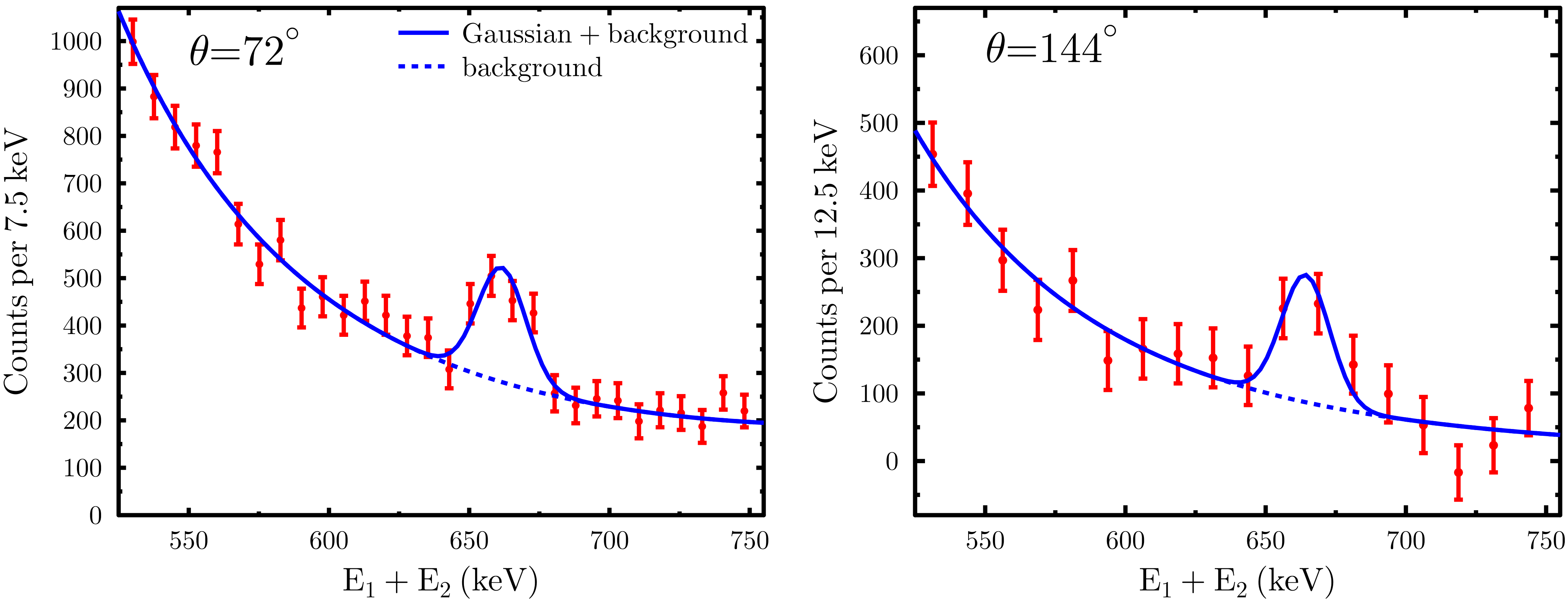
Time and Energy Spectra





- random coincidences dominant

Results
Random subtracted energy spectra



$693(95)$ counts $\quad (\sigma = 7.3)$ | $325(76)$ counts $\quad (\sigma = 4.3)$

$\Gamma_{\gamma\gamma}/\Gamma_\gamma = 1.56(23) \cdot 10^{-6}$ | $\Gamma_{\gamma\gamma}/\Gamma_\gamma = 0.70(18) \cdot 10^{-6}$

observation of the competitive double-gamma decay

very pronounced **angular correlation**

Compton Scattering excluded?

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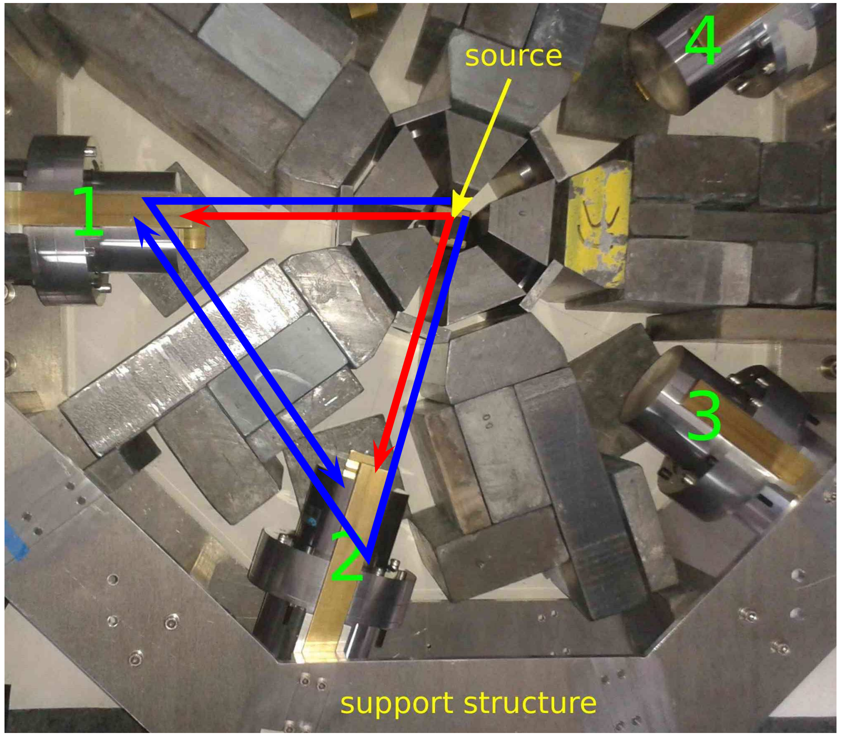
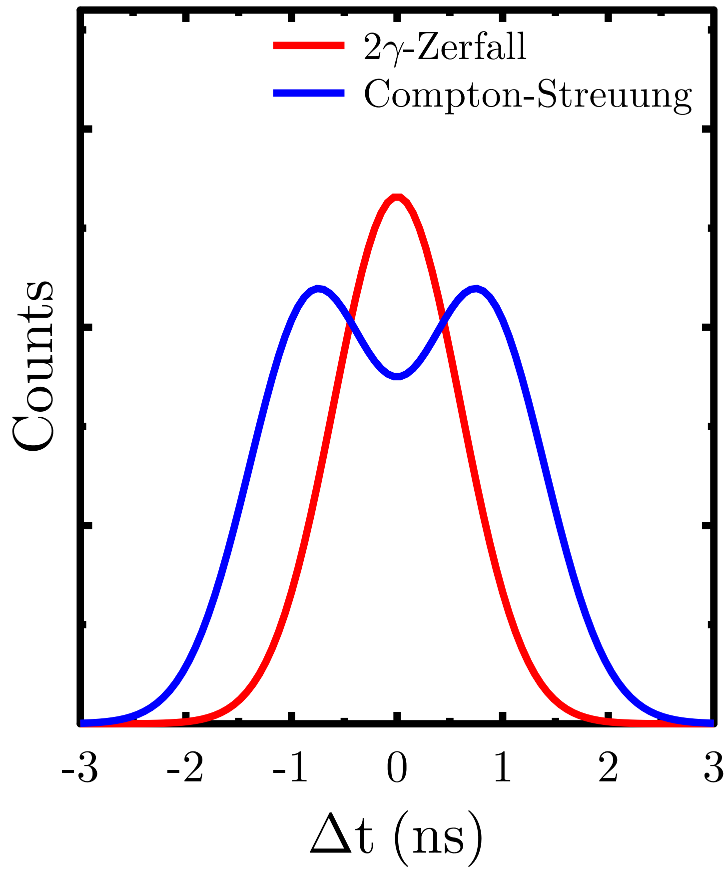
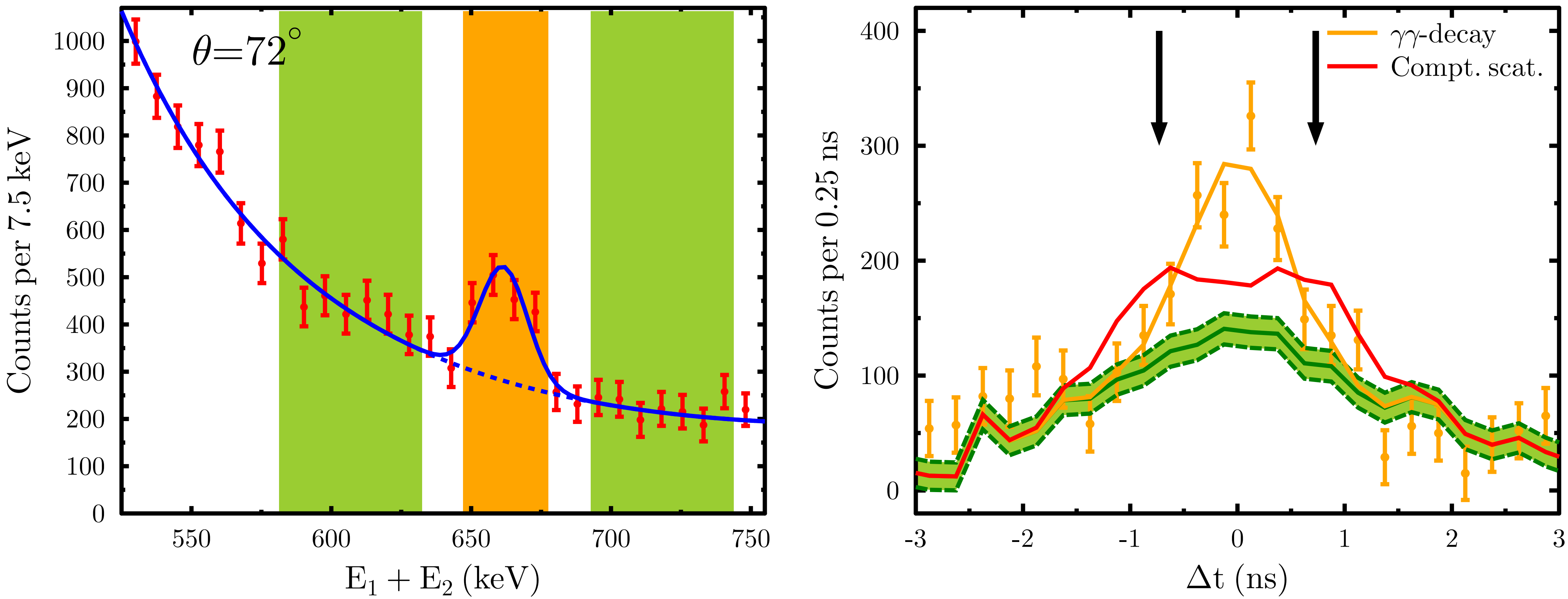




- **Compton scattering** should be visible in **time spectrum**

Compton Scattering excluded? (2)



data is **not** compatible with **Compton scattering**

Other Observables

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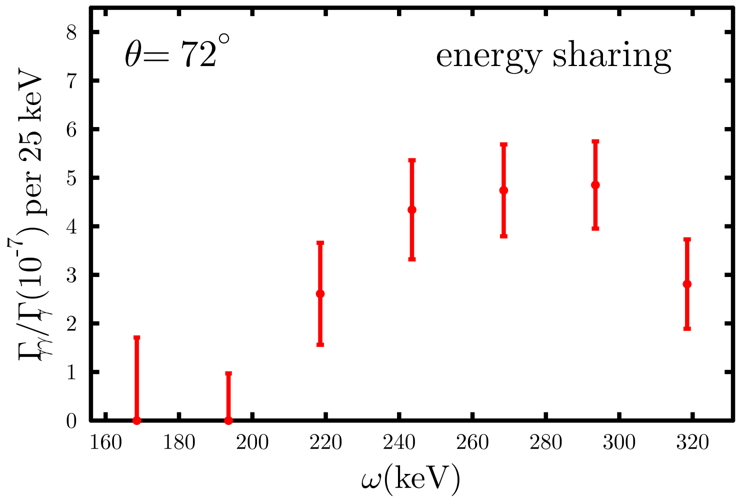
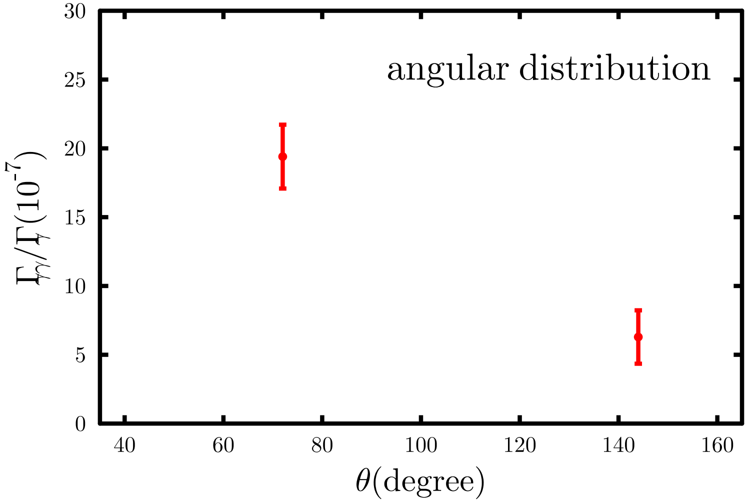
- energy spectra of individual gamma rays



- angular correlation



Other Observables
Individual Energies

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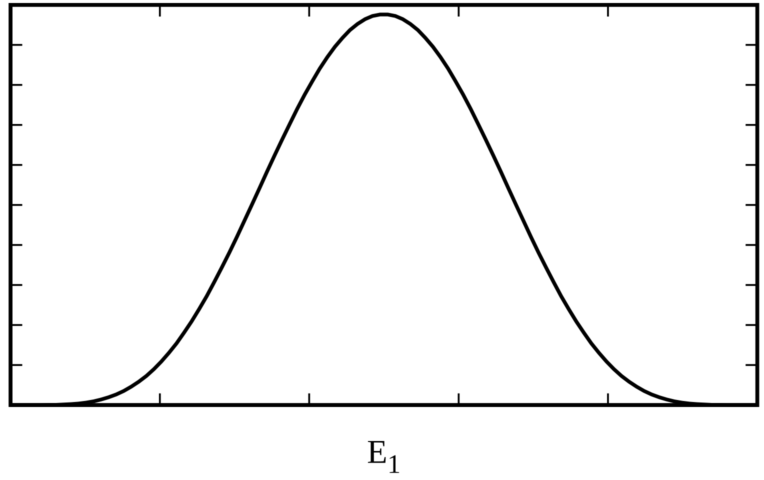
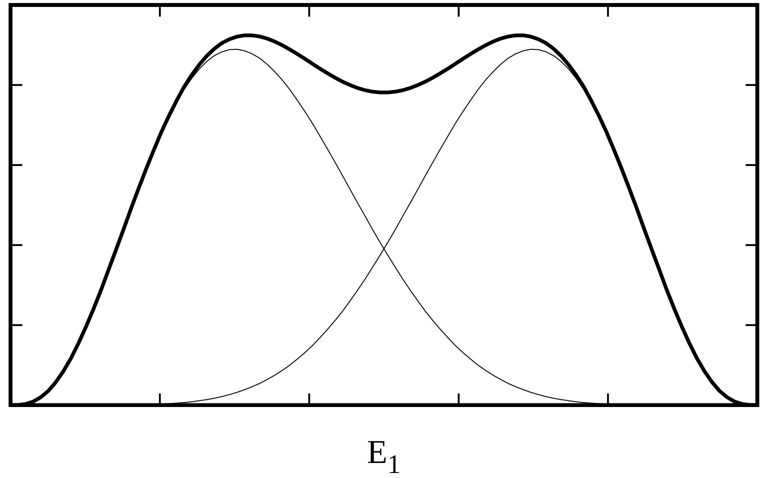
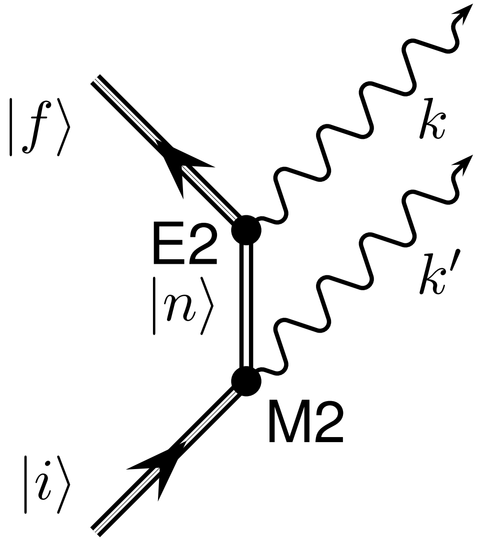
- transitions of multipolarities λ_1 and λ_2
- like two individual γ transitions: $\Gamma_{\gamma\gamma} \propto E_1^{2\lambda_1+1} E_2^{2\lambda_2+1}$
- E2M2: $E_1^5 E_2^5$

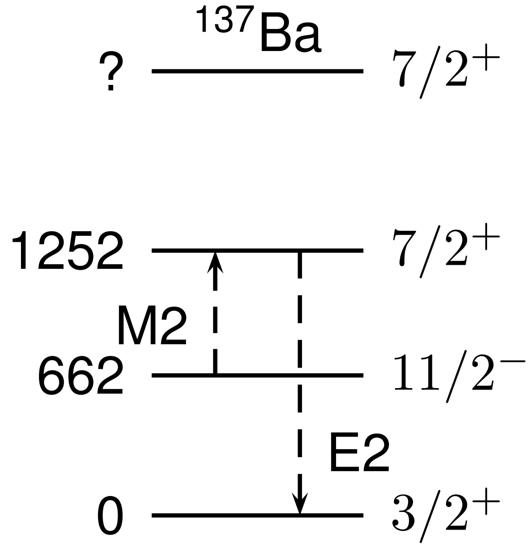


- E3M1: $E_1^7 E_2^3 + E_1^3 E_2^7$



Transition Matrix Elements
Transition Polarizabilities α





$$\alpha_{E2M2} \propto \sum_n \frac{\langle \frac{3}{2}^+_{gs} \| \mathbf{E2} \| \frac{7}{2}^+_n \rangle \langle \frac{7}{2}^+_n \| \mathbf{M2} \| \frac{11}{2}^- \rangle}{E_n}$$

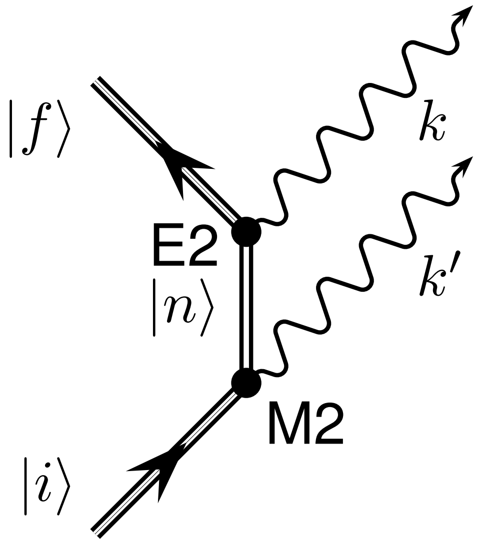
$\alpha_{S'L'SL}$ can be

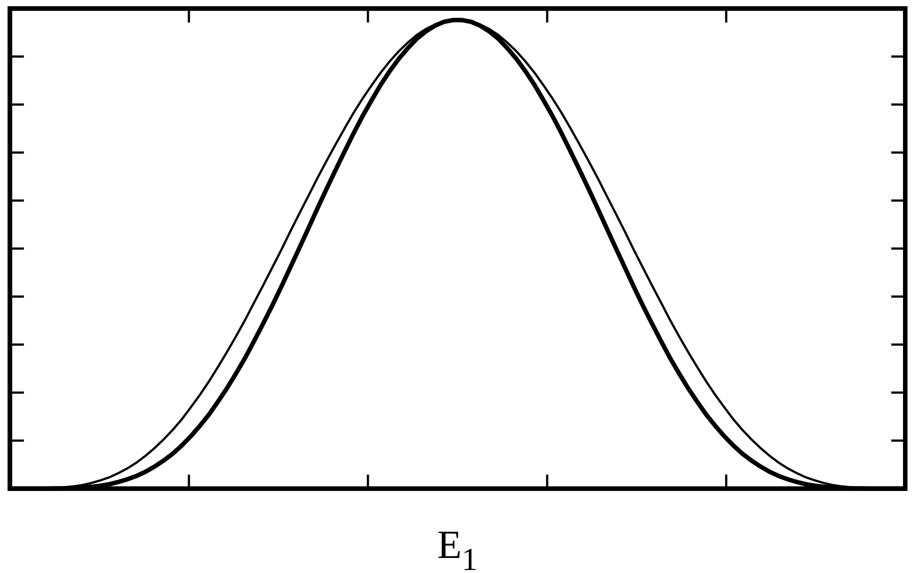
- obtained from theory (e.g. shell model, QPM)
- fit parameter

Other Observables
Individual Energies (2)

- influence of the matrix elements (propagator)

$$\alpha_{E2M2} \propto \sum_n \frac{\langle \frac{3}{2}^+_{\mathrm{gs}} \| \mathbf{E2} \| \frac{7}{2}^+_n \rangle \langle \frac{7}{2}^+_n \| \mathbf{M2} \| \frac{11}{2}^- \rangle}{E_n + \omega'}$$

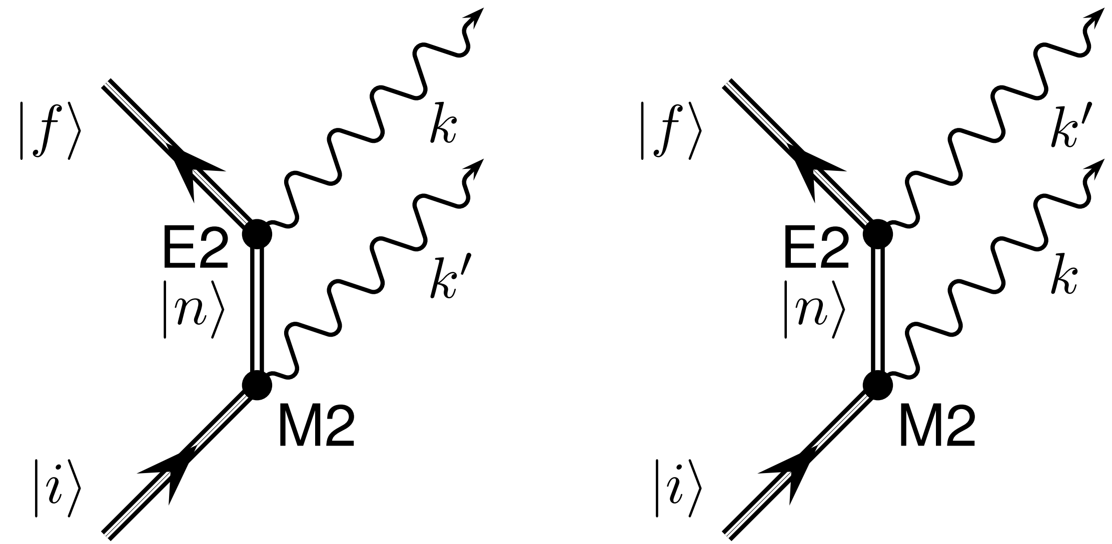




- not observed yet

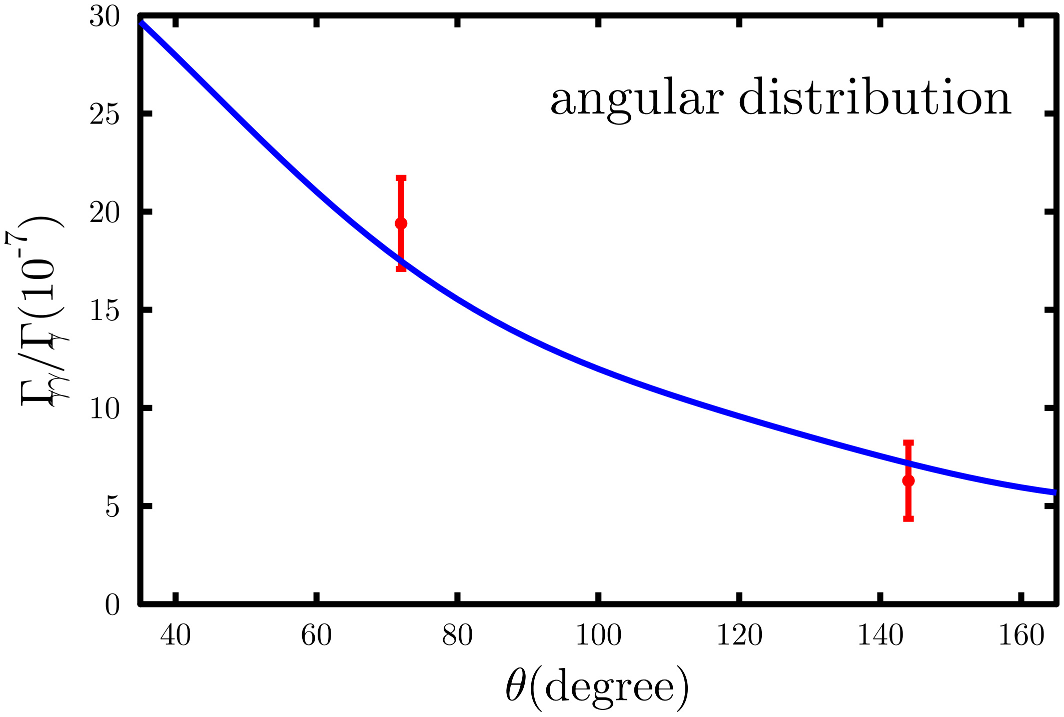
Non-symmetric Angular Correlation (about 90°)

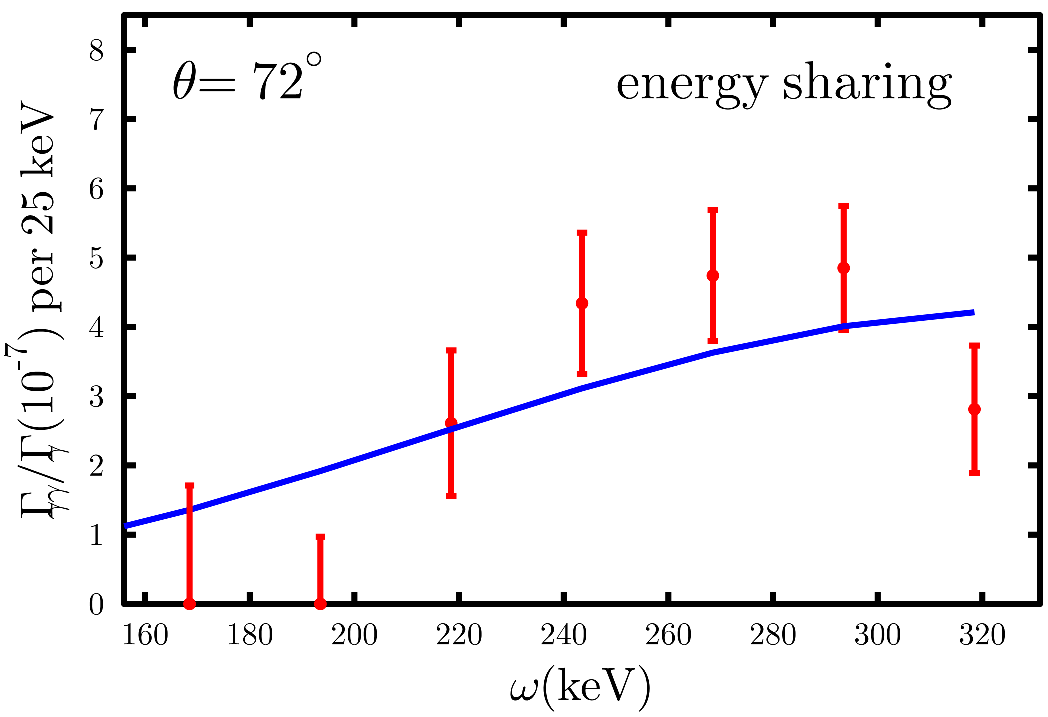
- **single gamma** decay: symmetric about 90° (e.g. 2 γ rays of γ-cascade)
- $\gamma\gamma$ decay: **non-symmetric** angular correlation
- ^{137}Ba: $11/2^- \to 3/2+$: change of parity: one interaction must be **M** and one must be **E**



- **interference** of M2 and E2

Fit result

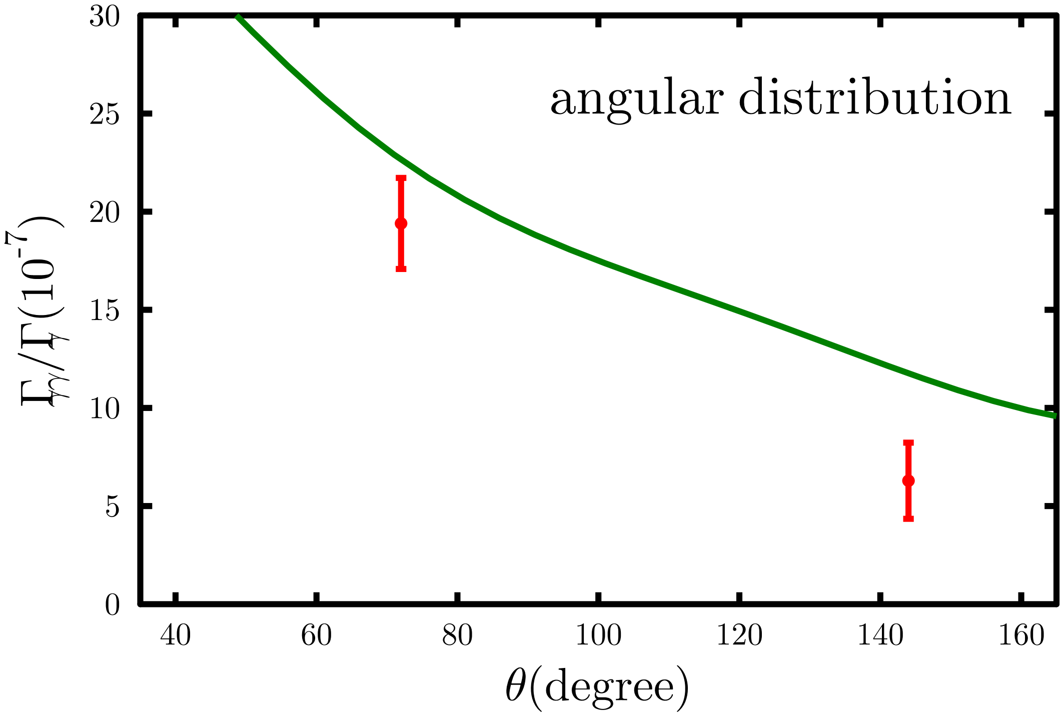


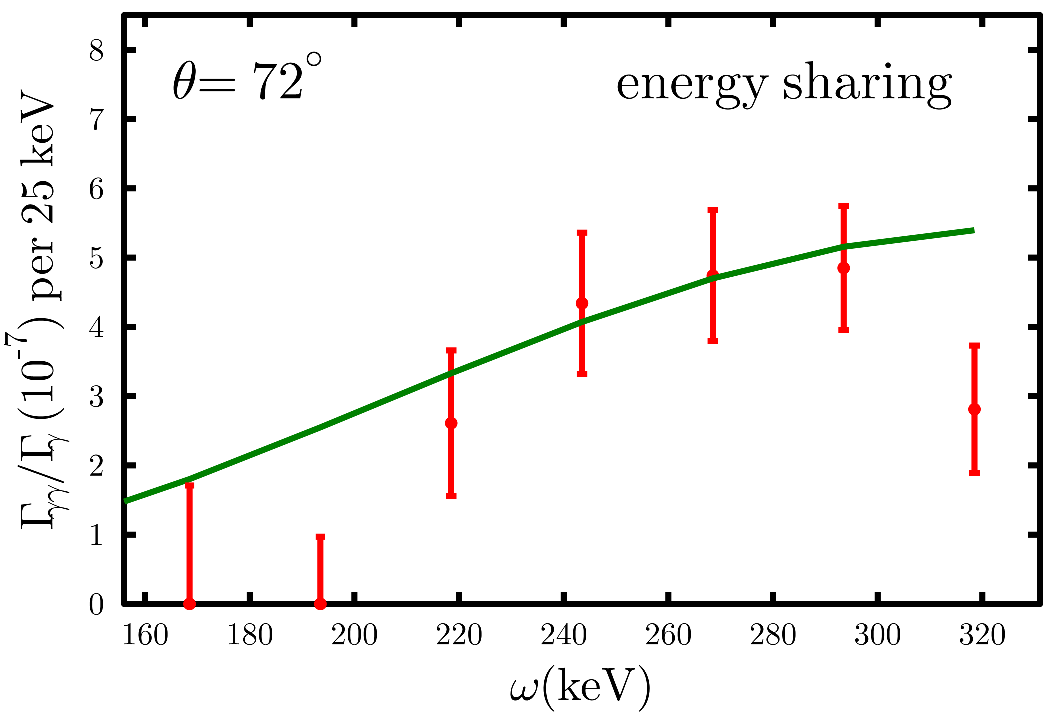


$$\frac{d\Gamma^2_{\gamma\gamma}}{d\omega d\theta} = A_{qq}(\alpha^2_{E2M2}) + A_{od}(\alpha^2_{M1E3}) + A_x(\alpha_{E2M2} \cdot \alpha_{M1E3})$$

- only the dominant α_{E2M2} and α_{M1E3} considered in **simultaneous fit**
- A_{qq}, A_{od} and A_x exhibit characteristic dependence on ω and θ

Quasi-particle phonon model





	Exp.	QPM
$\Gamma_{\gamma\gamma}/\Gamma_\gamma(10^{-6})$	2.05(31)	2.69
$\alpha_{\mathrm{M2E2}}(\frac{e^2\mathrm{fm}^4}{\mathrm{MeV}})$	+33.9(28)	+42.60
$\alpha_{\mathrm{E3M1}}(\frac{e^2\mathrm{fm}^4}{\mathrm{MeV}})$	+10.1(42)	+9.50

- α_{M2E2} dominates
- relative sign between α_{E2M2} and α_{M1E3} is positive
- good description by the **QPM** (V. Yu. Ponomarev)

C. Walz, HS et al., **Nature 526**, 406 (2015) + supplement

QPM running sum

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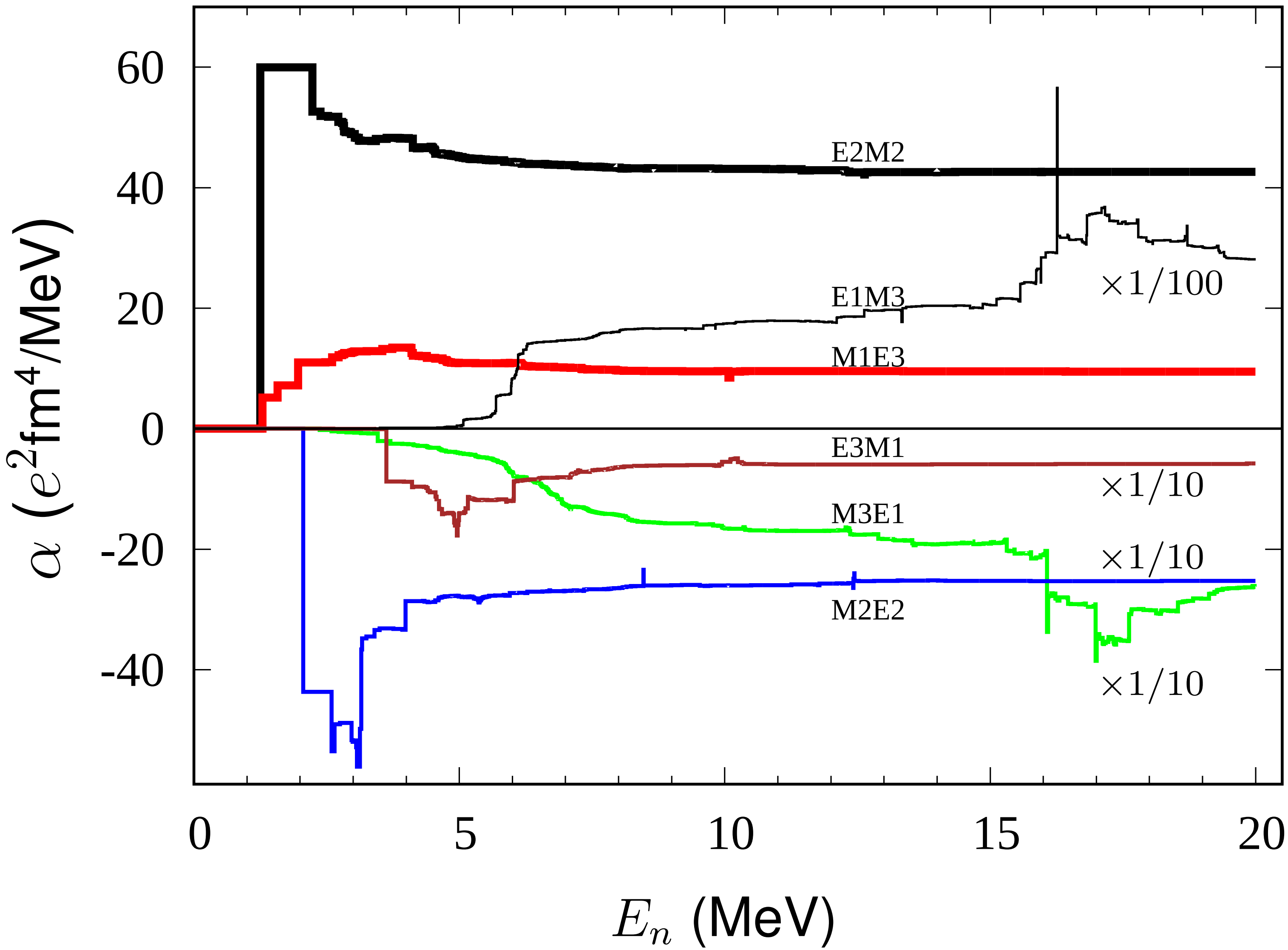

Summary

Summary and Outlook

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- **Observation** of the competitive double-gamma decay

$$\Gamma_{\gamma\gamma}/\Gamma_{\gamma} = 2.05(31) \cdot 10^{-6}$$

- well described by QPM
- first step to a systematic study of **transition polarizabilites**
- with **improved** experimental setup
  - search for cases dominated by $E1E1$ transitions with
  - revisit ^{137}Ba, ^{90}Zr

- Collaborators
  - **Christopher Walz** (experimental setup, data taking, data analysis)
  - Norbert Pietralla, Tom Aumann, Ronan Lefol, **Vladimir Yu. Ponomarev** (QPM)

Main Reference

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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]

406 | NATURE | VOL 526 | 15 OCTOBER 2015

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- plus extended supplement

The End