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DARMSTADT

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

Heiko Scheit

TECHNISCHE UNIVERSITÄT DARMSTADT

September 27, 2016

# Introduction

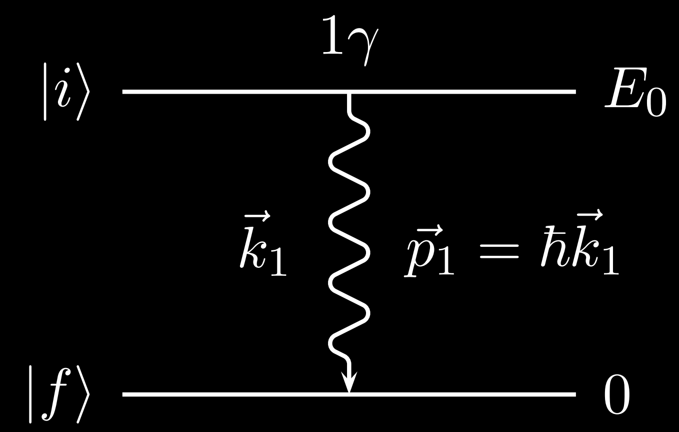
# Emission of Electromagnetic Radiation One and Two Photon(s)





- **single** photon emission

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



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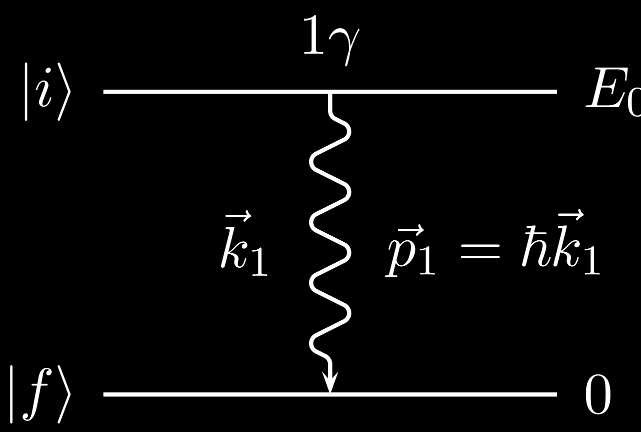
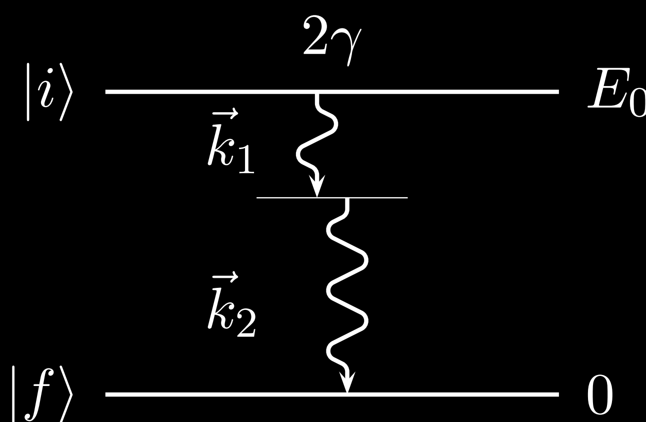



- **double-gamma** decay: two photons emitted **simultaneously**

$$E_0 = E_1 + E_2$$



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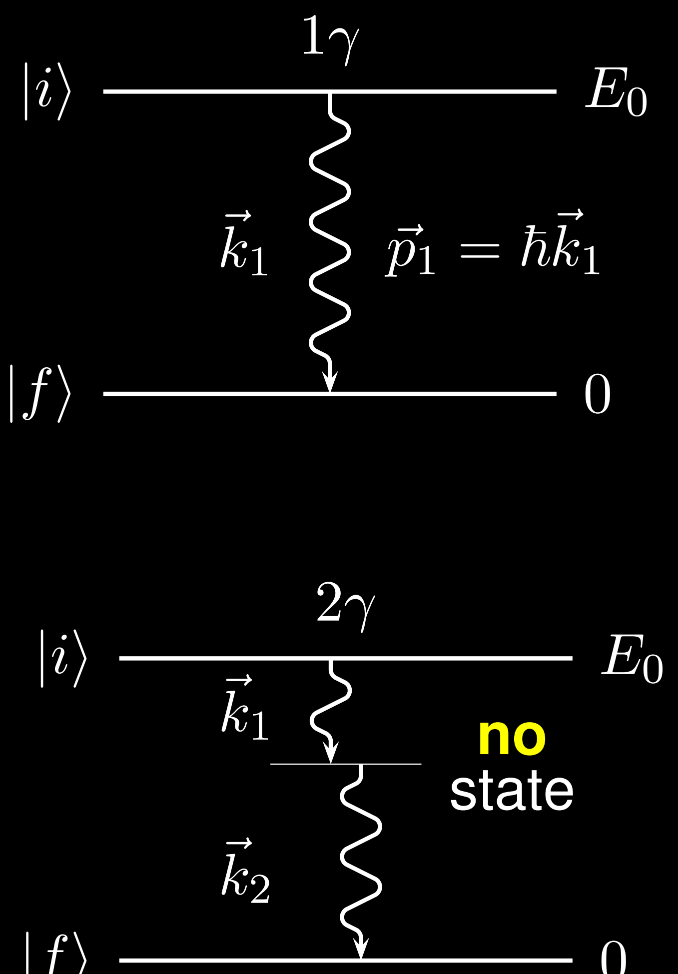

# Similar: Positronium
# Decay into 2,3,4... Photons

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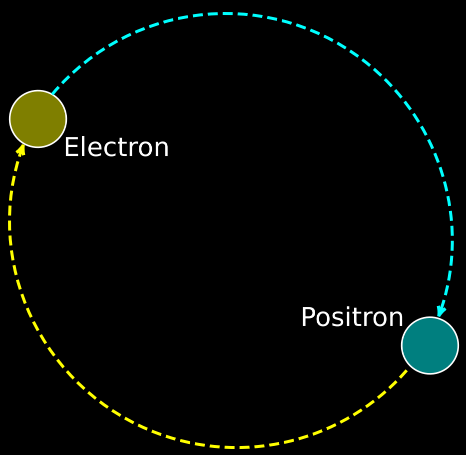

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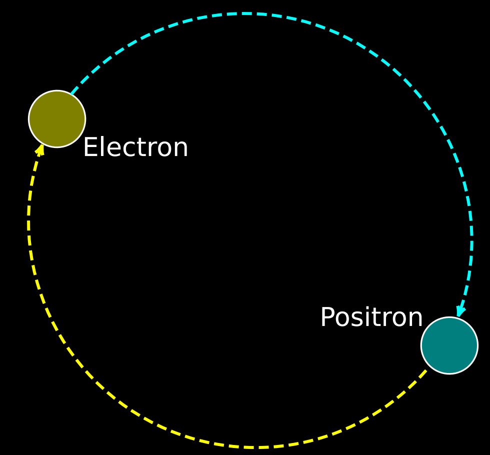


- decay into $N_\gamma$ photons
  - due to momentum conservation: $N_\gamma \geqslant 2$
  - due to charge conjugation parity
    - para-Ps ($S = 0$): $N_\gamma = 2, 4, \ldots$
      (for $N_\gamma = 1$: well known back-to-back **511 keV** $\gamma$ rays)
    - ortho-Ps ($S = 1$): $N_\gamma = 3, 5, \ldots$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

# Decay Width
# First Order Perturbation Theory



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

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

- **Fermi's Golden Rule**

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

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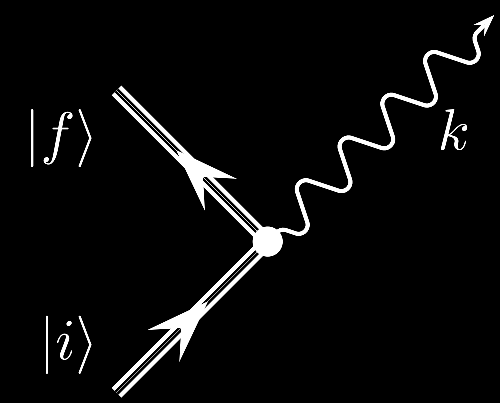
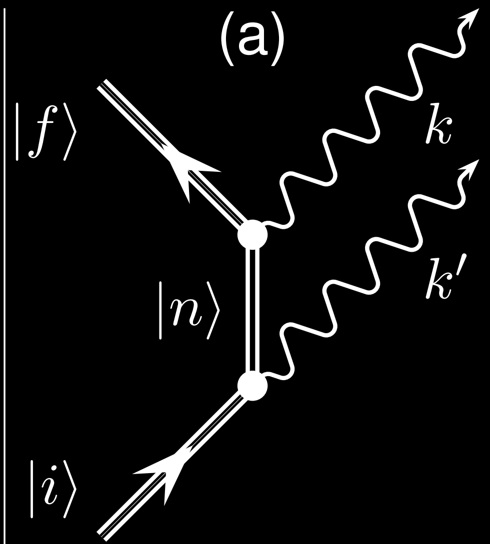



$\rho_f$: density of final states; $H_{\rm int}$: interaction Hamiltonian
$\vec{j}_{\rm N}(\vec{r},t)$: nucl. current density; $\vec{A}(\vec{r},t)$: EM vector potential

# Second Order



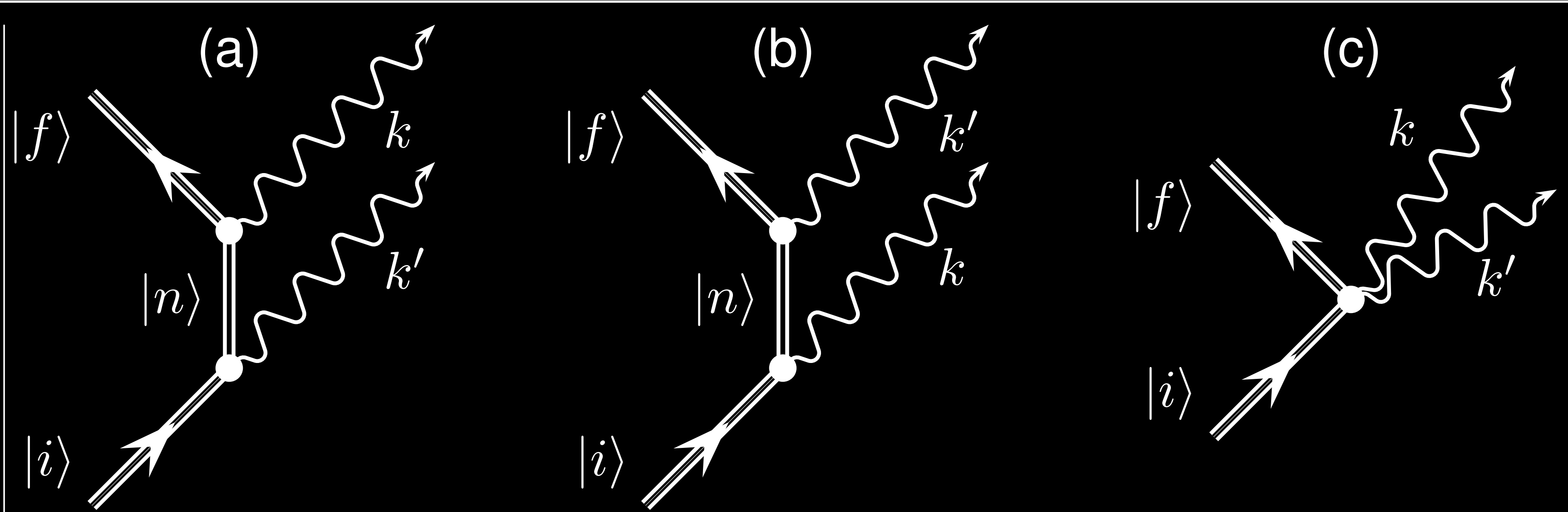




# Second Order








- 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)

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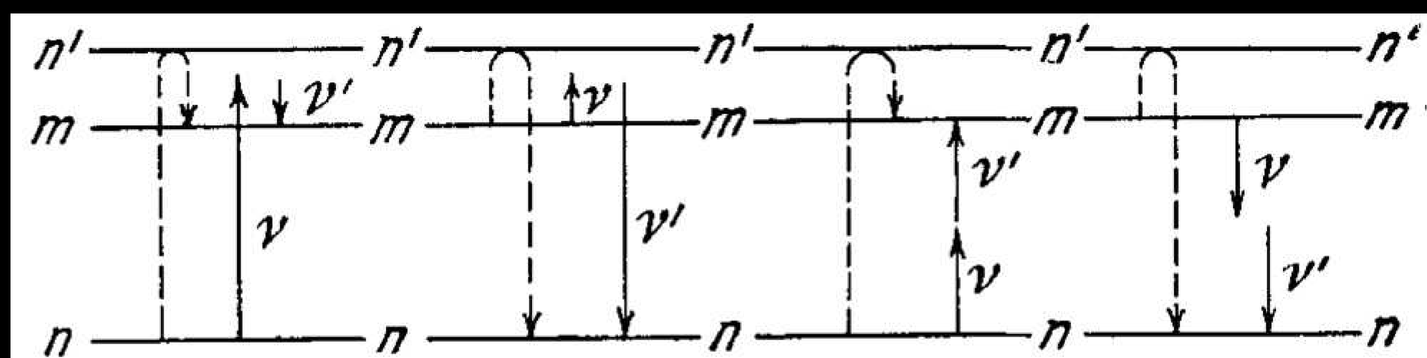
- not only two-photon **emission**, but also **absoption** and Raman scattering




- used routinely in atomic physics
- (later MGM also predicted double $\beta$-decay)

# Double-Gamma Decay in Nuclei

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- 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
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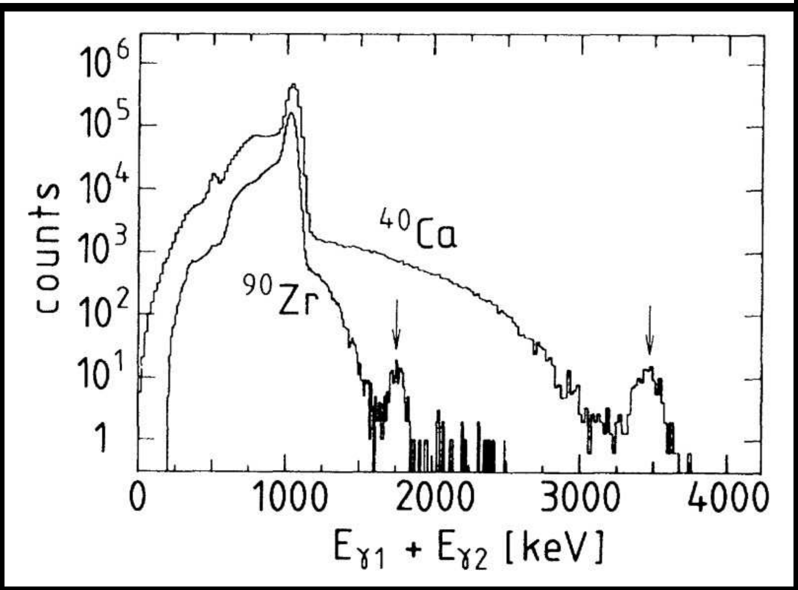
- HD-DA Crystal ball ($4\pi$; 162 NaI(Tl))



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Introduction
EM radiation
Positronium
Decay rate
Second Order
Historical Detour
$\gamma\gamma$-decay
$\gamma\gamma/\gamma$-Decay
Experiment
Results
Summary
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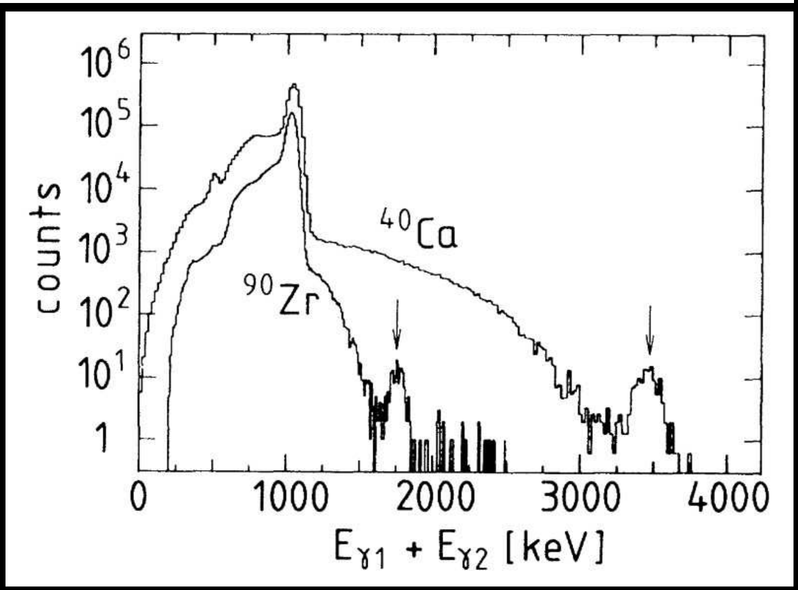


- same group: **$^{16}$O**
- common to all: $0^+ \to 0^+_{\mathrm{gs}}$ transitions

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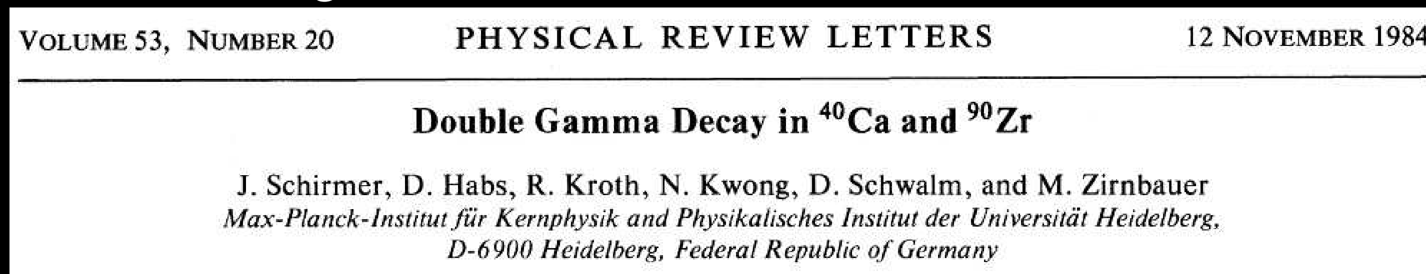

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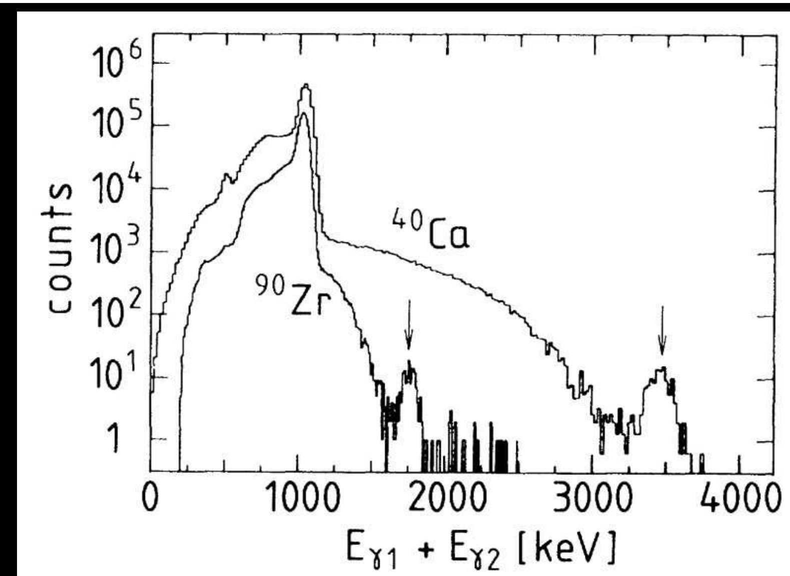


- same group: **$^{16}$O**
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**single** photon decay **strictly forbidden**

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

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





- two photons emitted **simultaneously**

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- two photons emitted **simultaneously** with **continuous** energy spectrum

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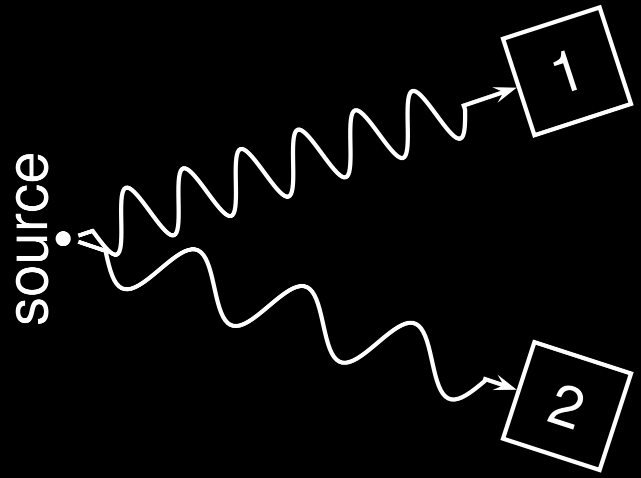
- but **energy** is **conserved**:

$$E_0 = E_1 + E_2$$



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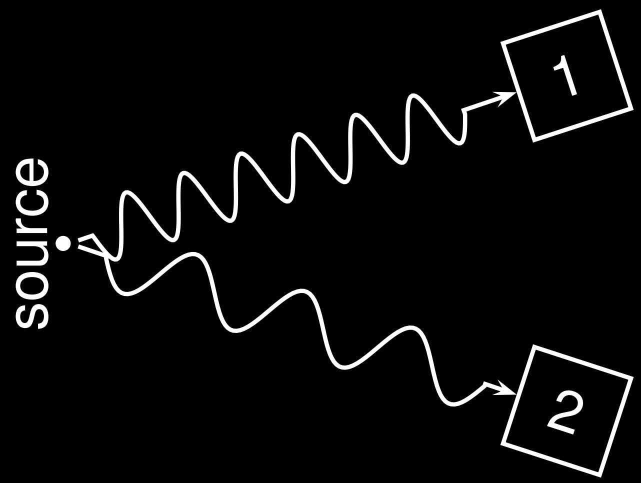


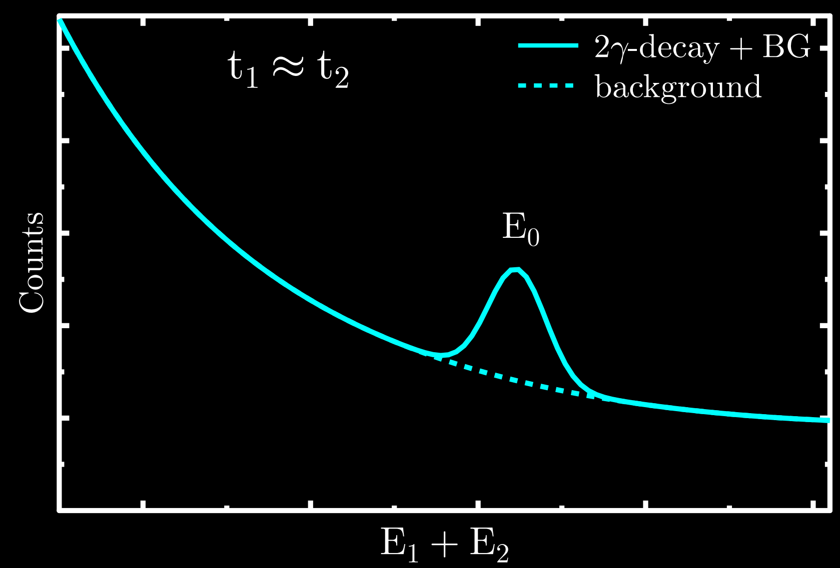


$E_0$: transition energy; $E_{1/2}$: energies of two photons

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

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- very small branching ratio $\Gamma_{\gamma\gamma}/\Gamma_{\gamma} \ll 10^{-4}$

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- **Compton scattering**
  energy of **single** $\gamma$ ray deposited in two detectors
  - exact same signature for **energy sum**

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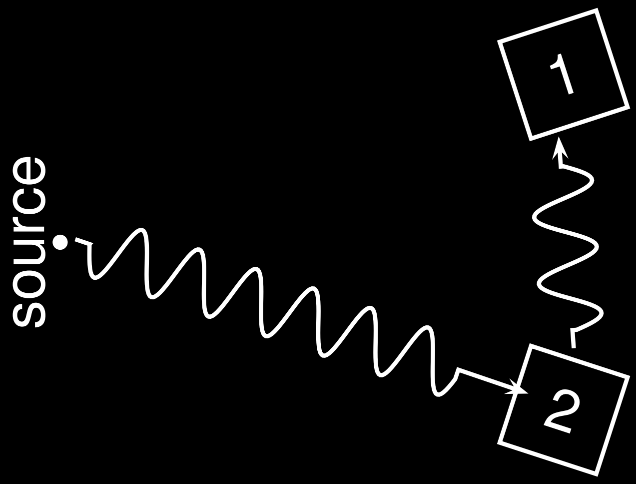
  but:
  - different energy distribution
  - different path of photons: shielding



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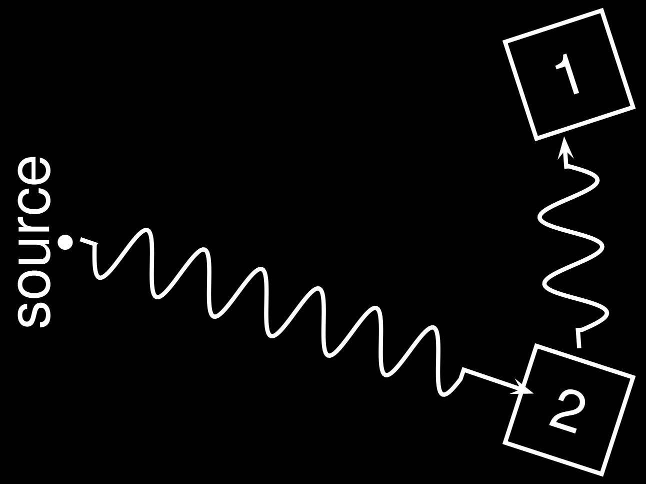
  energy of **single** $\gamma$ ray deposited in two detectors
  - exact same signature for **energy sum**

    $$E_0 = E_1 + E_2$$

    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

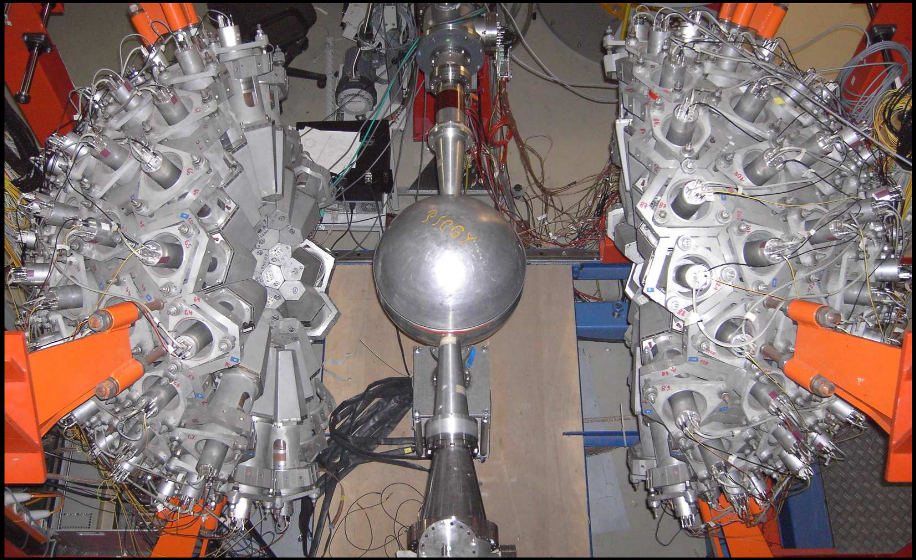




- so far: NaI(TI) detectors
  - standard detector, if **high efficiency** is crucial
  - but: poor **time** and **energy resolution**

Heidelberg-Darmstadt
Crystal- ball
full solid angle $4\pi$

162 NaI(TI) detectors



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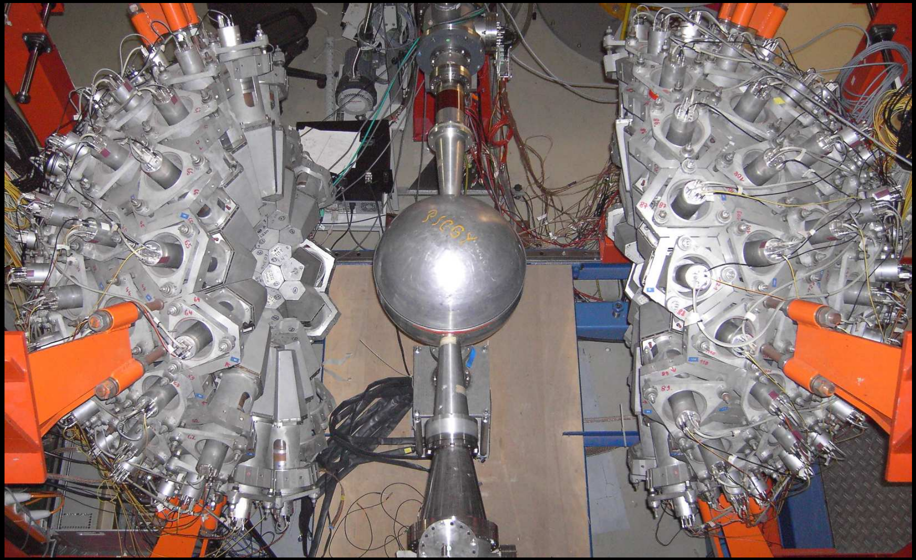
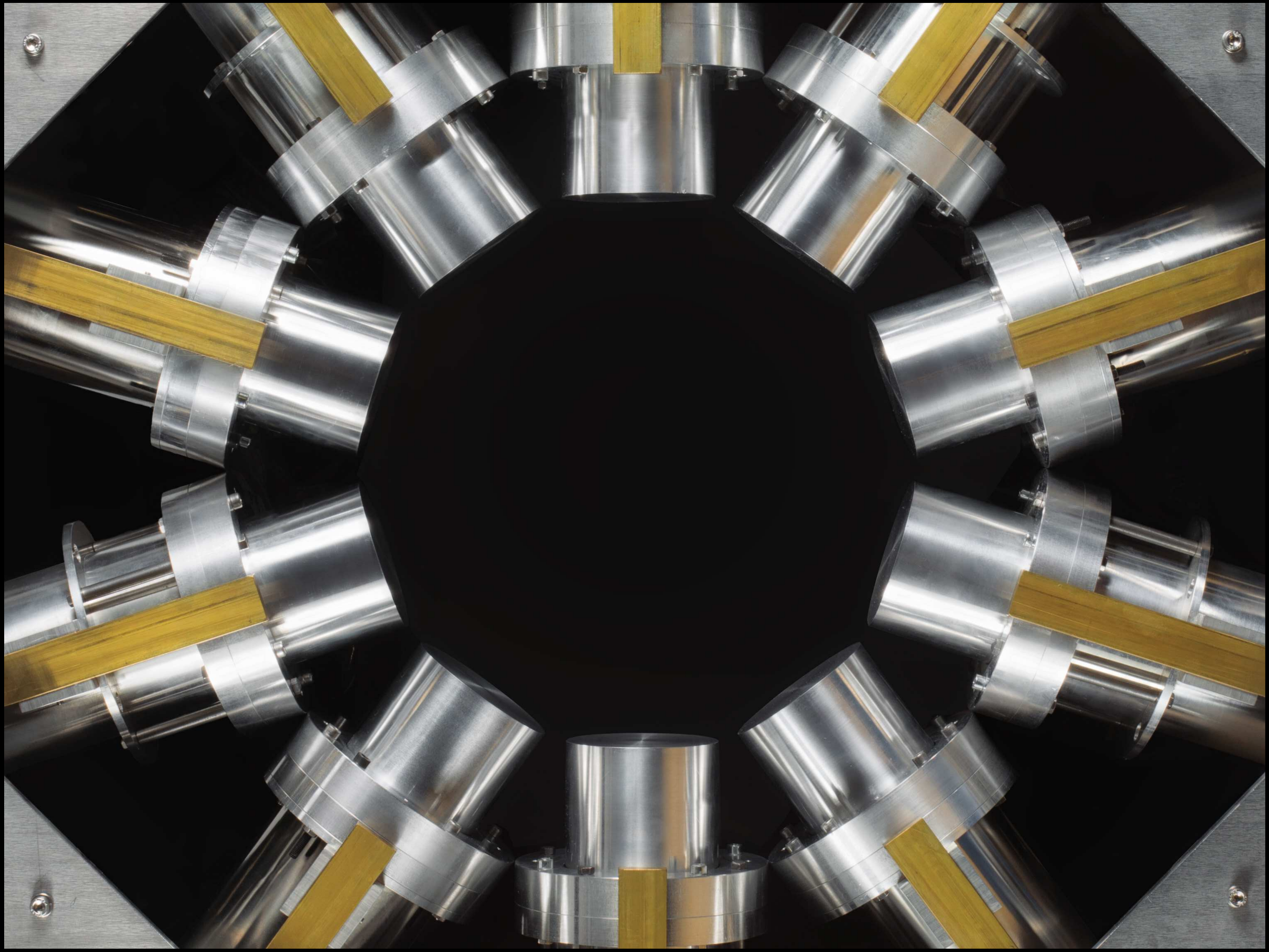


- **large volume $LaBr_3(Ce)$** detectors available:
  - better energy resolution by a factor 2–3
  - better time resolution by a factor 5–10
  - very fast $\rightarrow$ high rate measurements

# GALATEA array
# 18 $LaBr_3$(Ce) detectors (3" × 3")







# Experimental Setup

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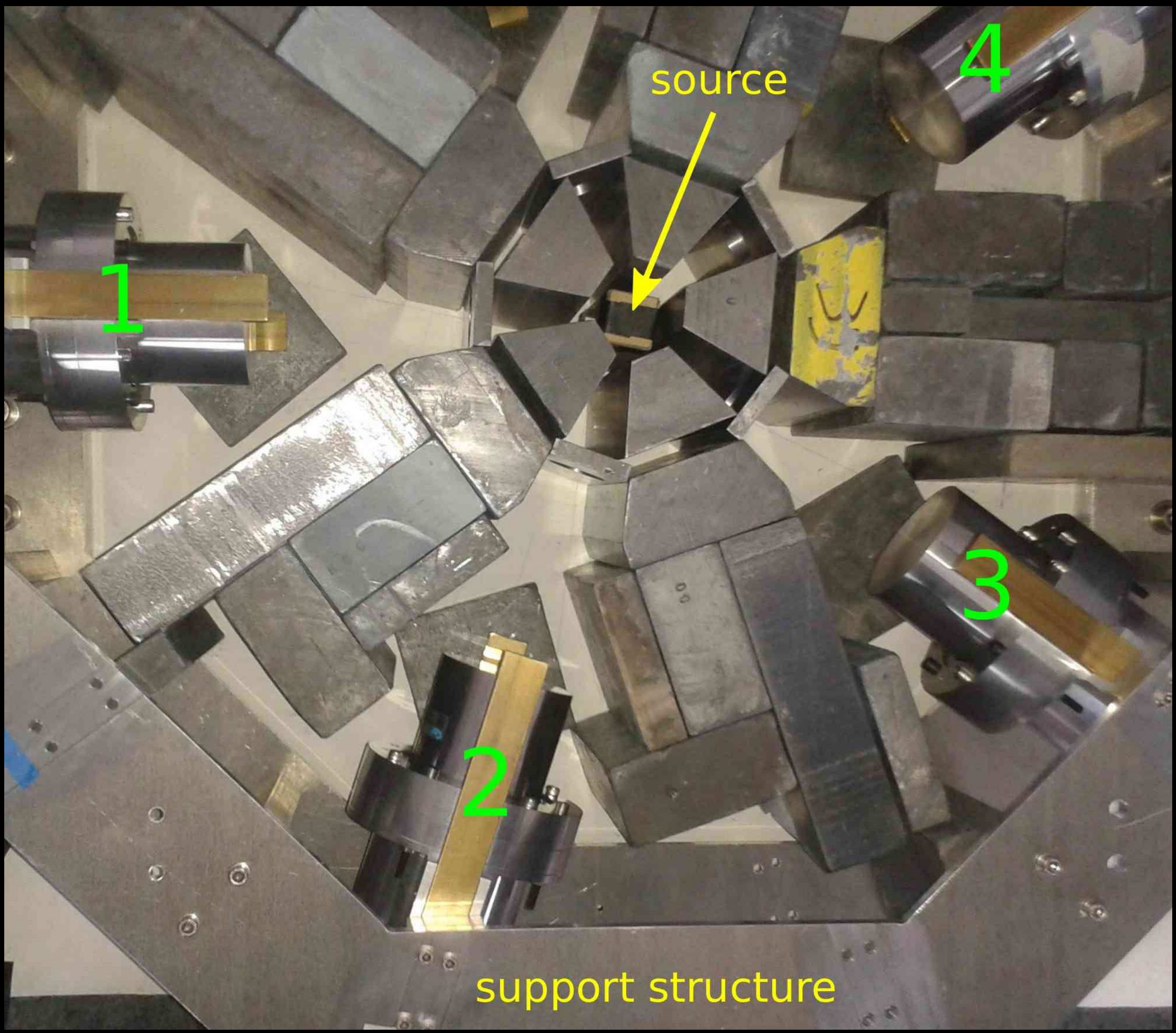


- 5 $LaBr_3(Ce)$ detectors
- 72°: 5 detector pairs
- 144°: 5 detector pairs
- $\epsilon_{FE}(662$ keV$) = 1.5\%$
- $\epsilon_{\gamma\gamma} \approx 4 \cdot 10^{-4}$
- $\Delta E = 3\%$ (FWHM)
- $\Delta t = 1$ ns (FWHM)
- on disk: **53 days**
- source: $^{137}Cs$ (600 kBq)
- thick **Pb blocks** between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

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

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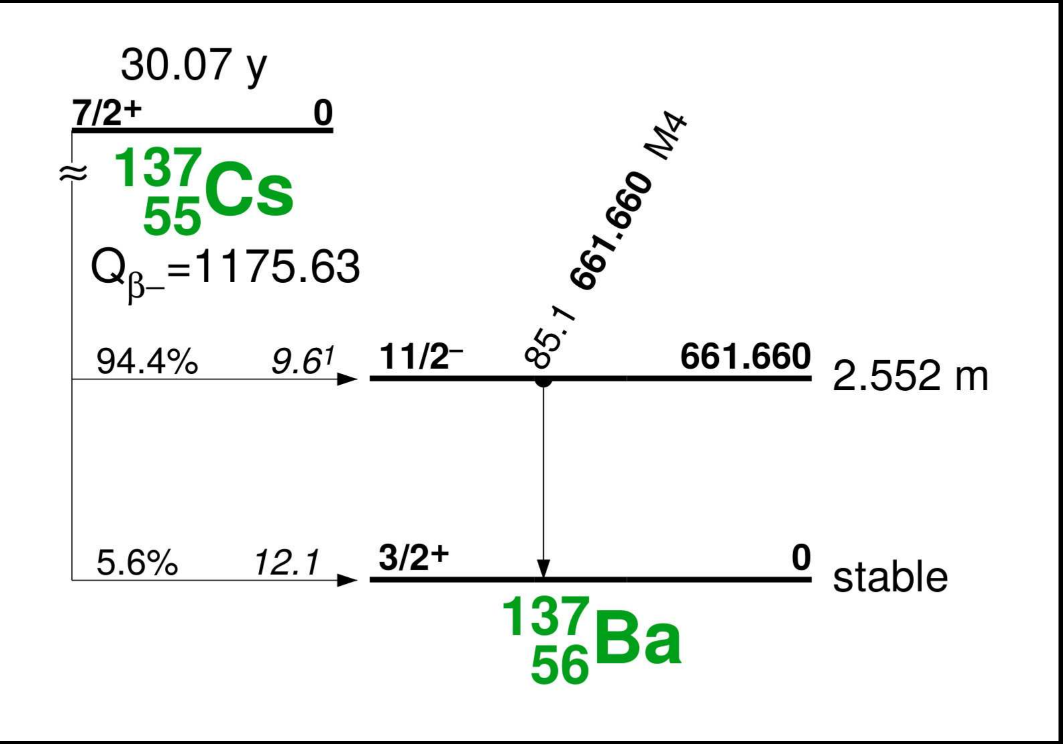
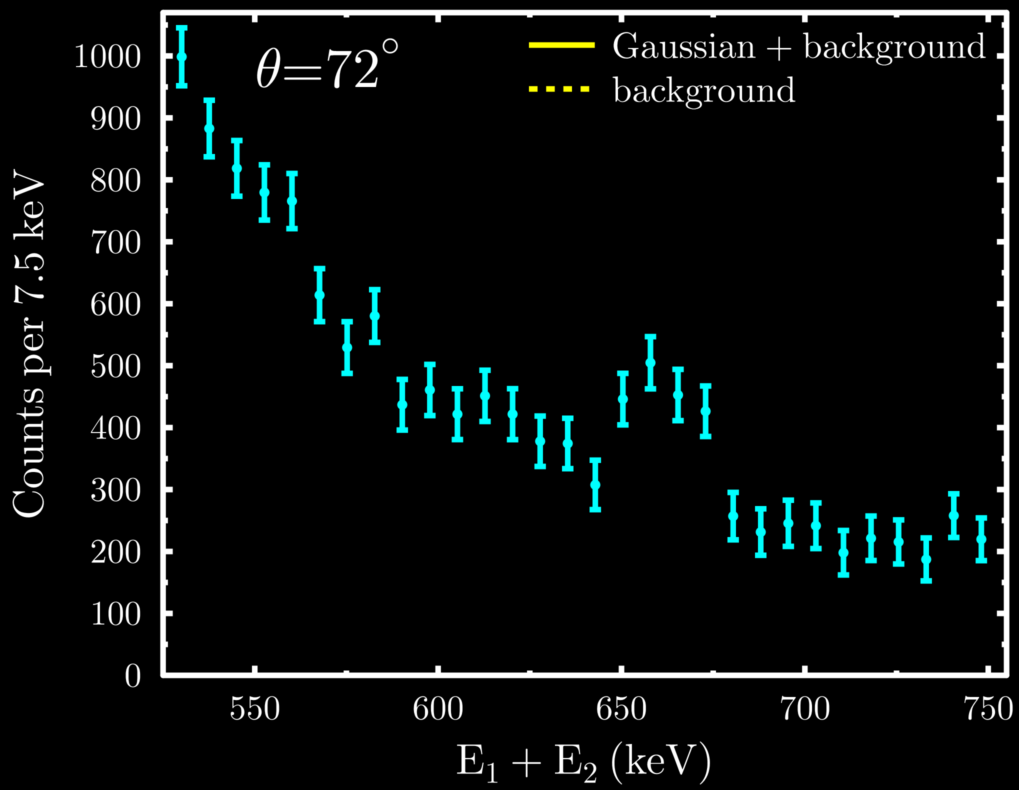



- $11/2^- \rightarrow 3/2^+$ transition of $^{137}$Ba (M4)

# Results

# Results
# Random subtracted energy spectra



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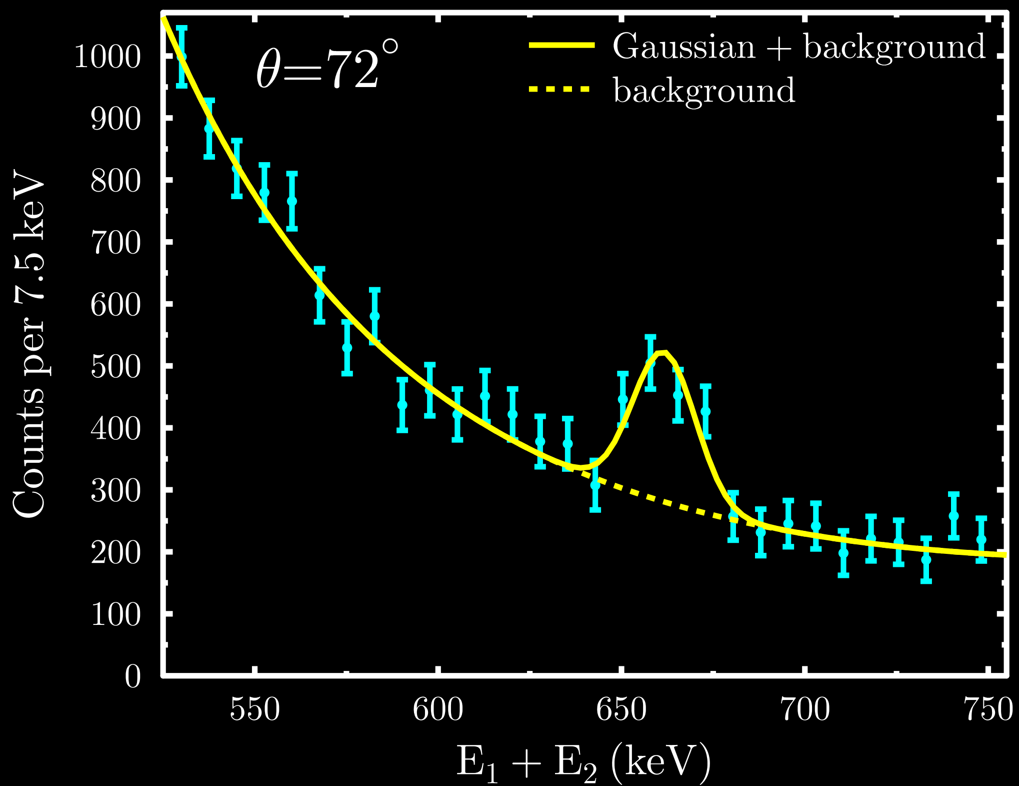


$693(95)$ counts $\quad (\sigma = 7.3)$

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

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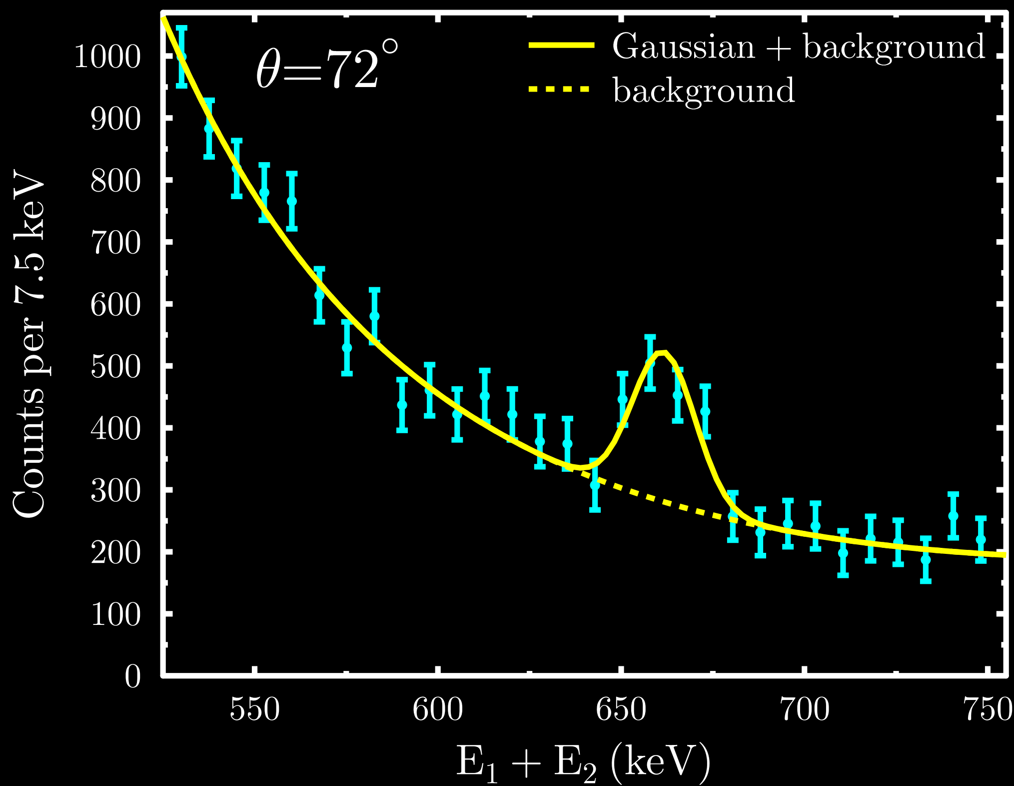
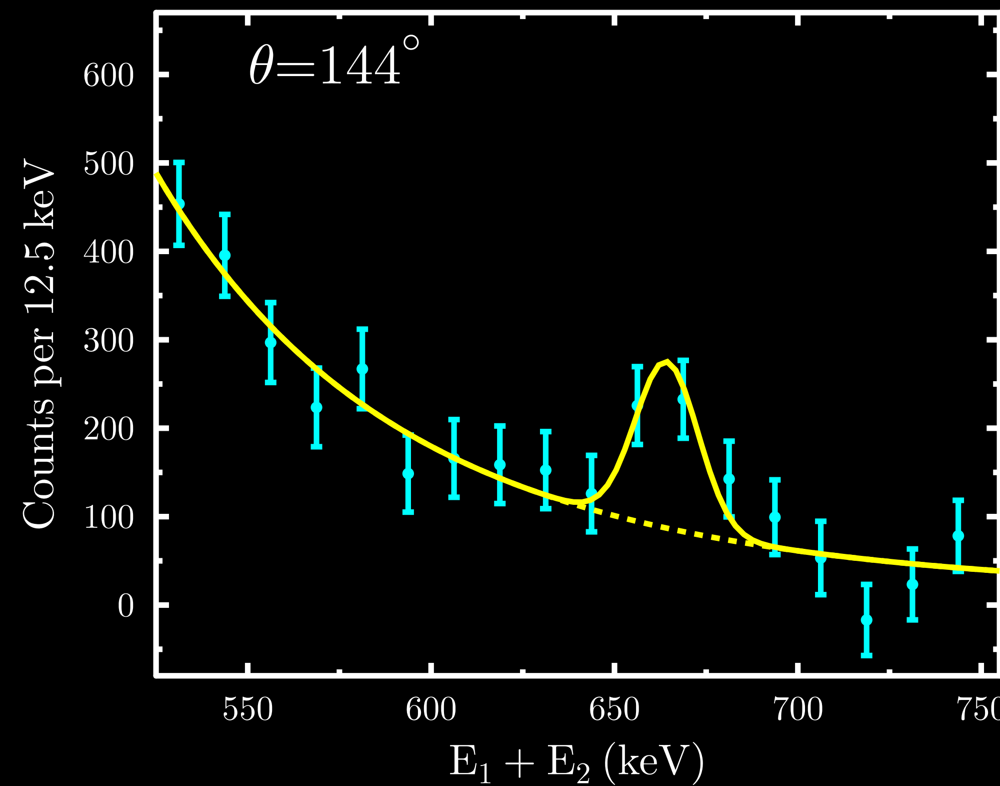



$693(95)$ counts $\quad (\sigma = 7.3)$

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

$325(76)$ counts $\quad (\sigma = 4.3)$

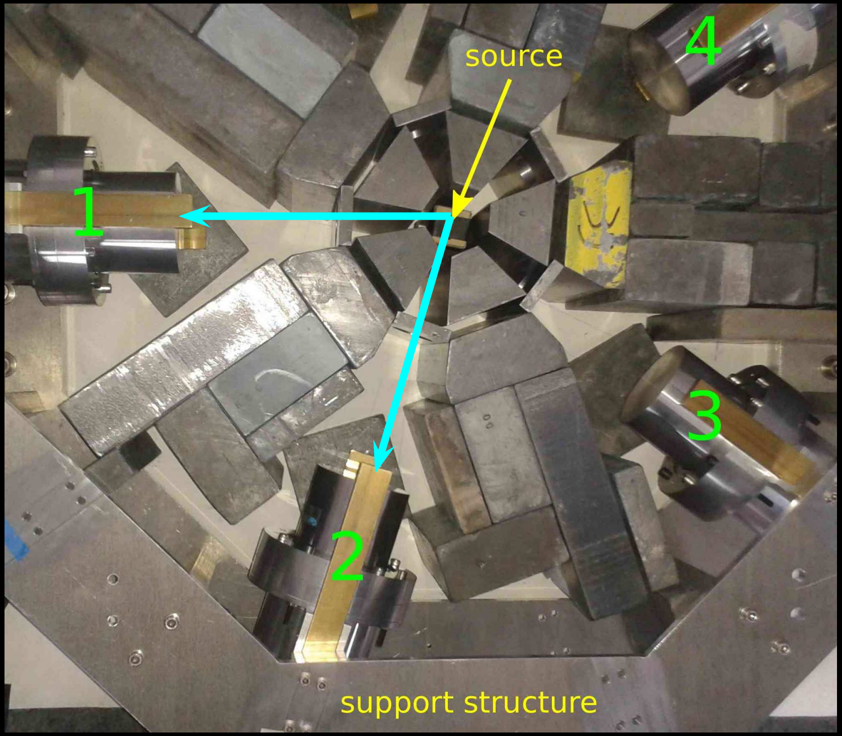
$\Gamma_{\gamma\gamma}/\Gamma_{\gamma} = 0.70(18) \cdot 10^{-6}$

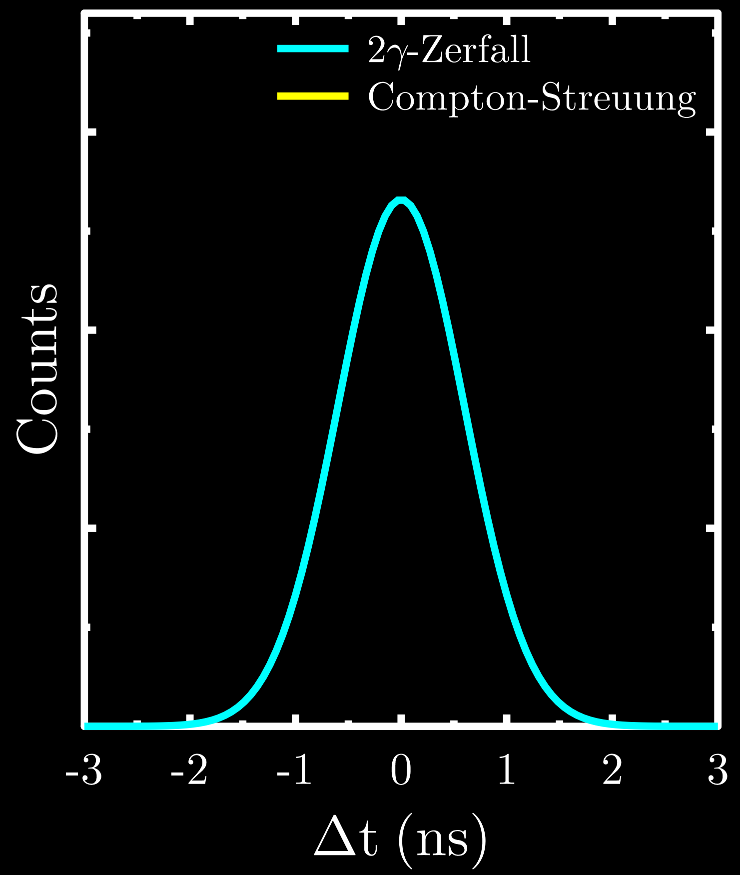
**observation** of the competitive double-gamma decay

very pronounced **angular correlation**

# Compton Scattering excluded?





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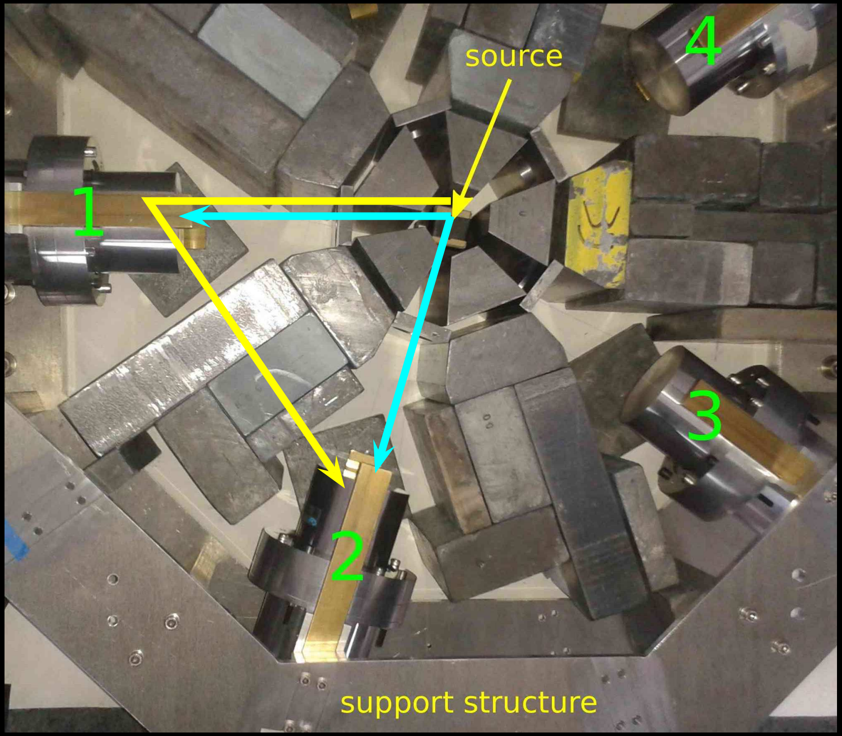


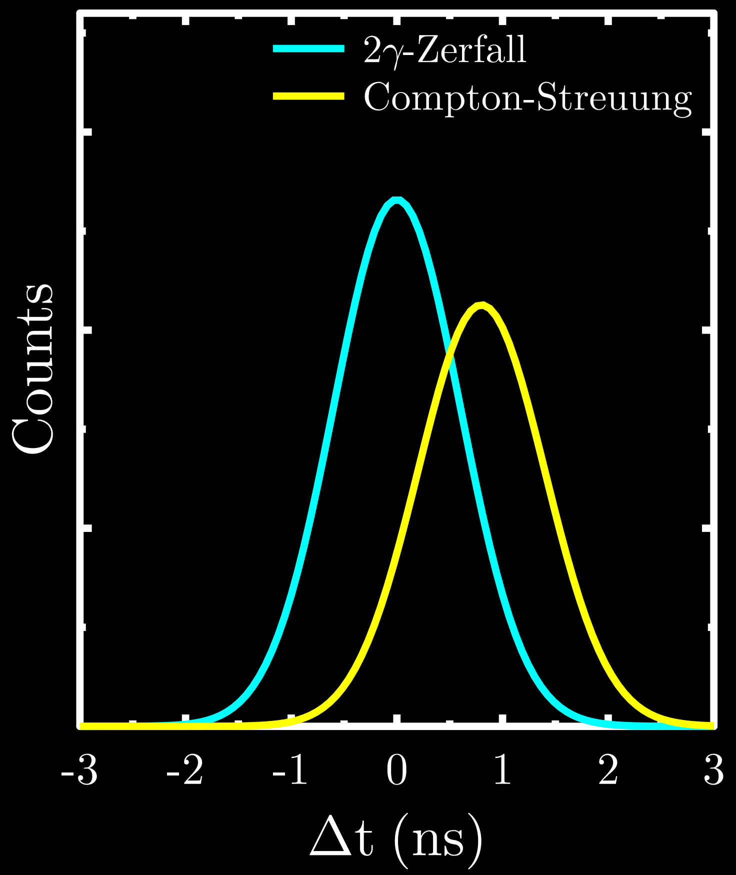

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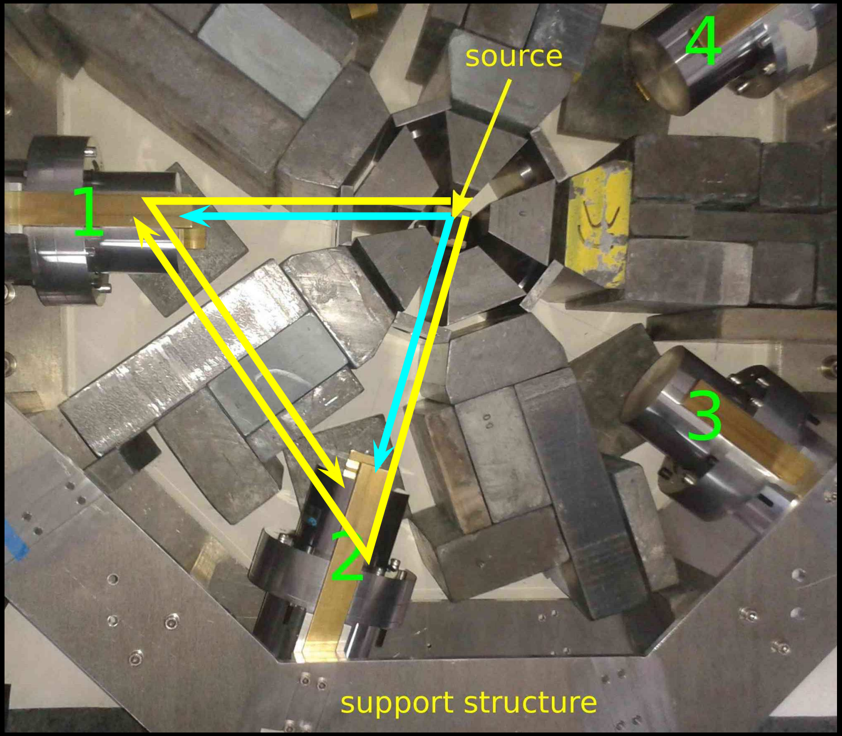


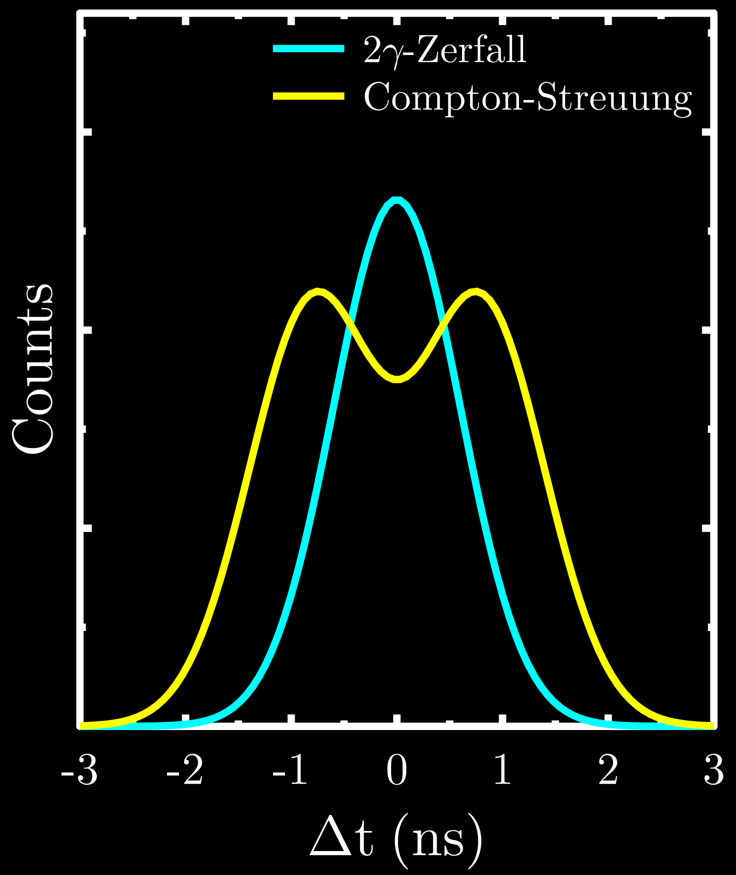


- **Compton scattering** should be visible in **time spectrum**

# Compton Scattering excluded? (2)

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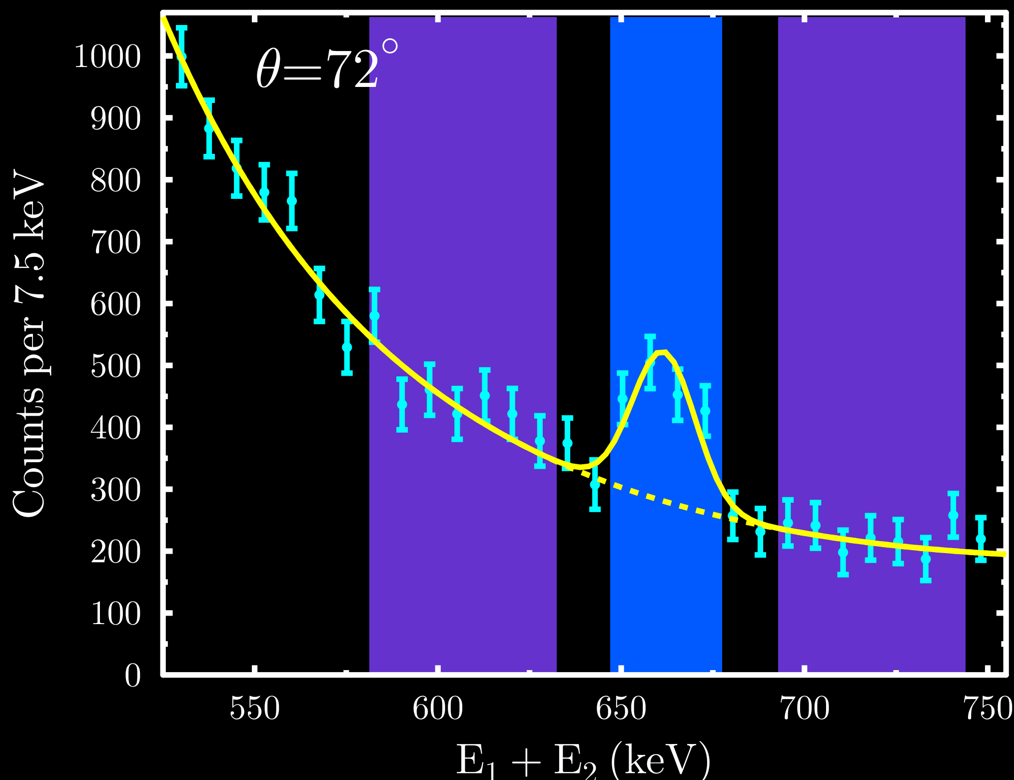
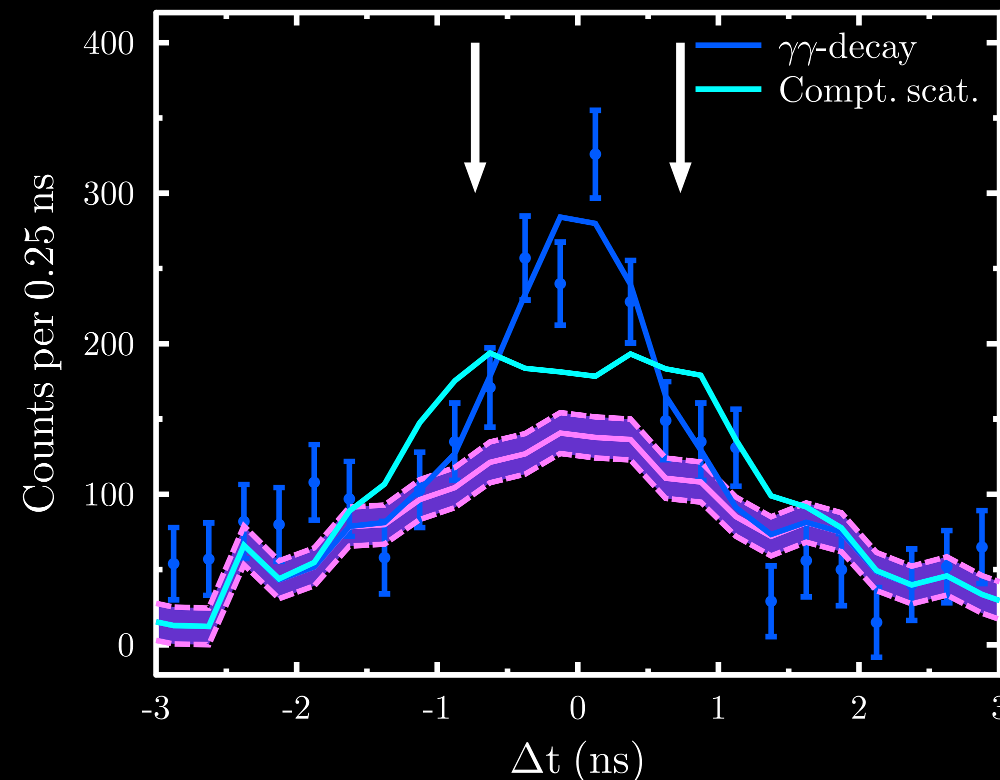
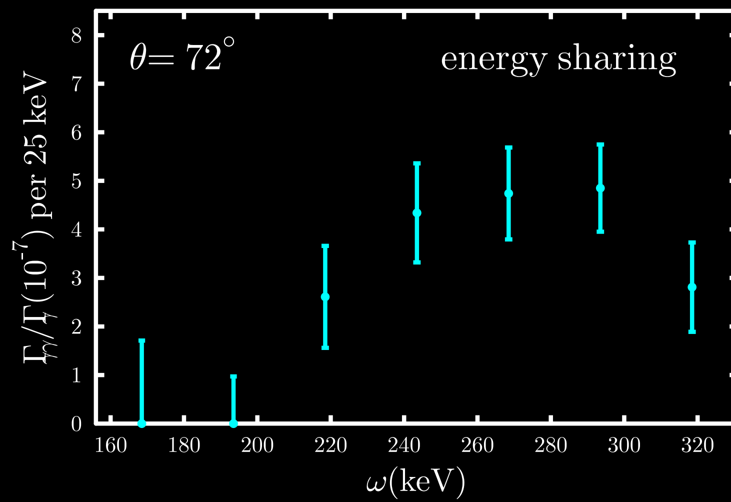


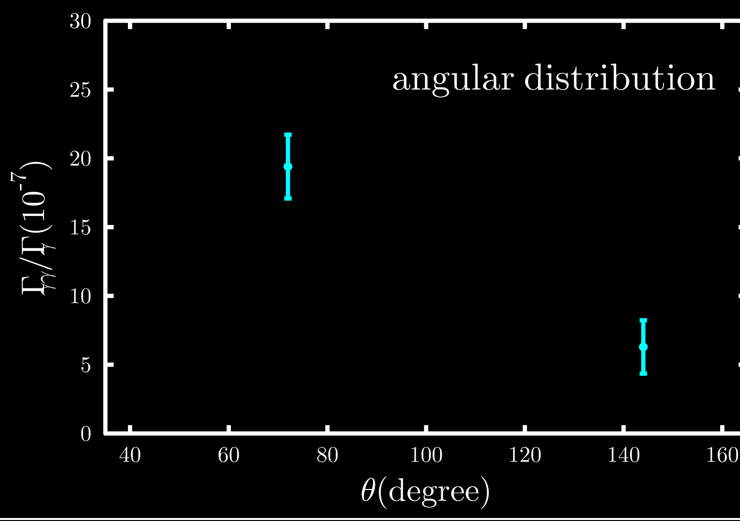




data are **not** compatible with **Compton scattering**

- energy spectra of individual gamma rays



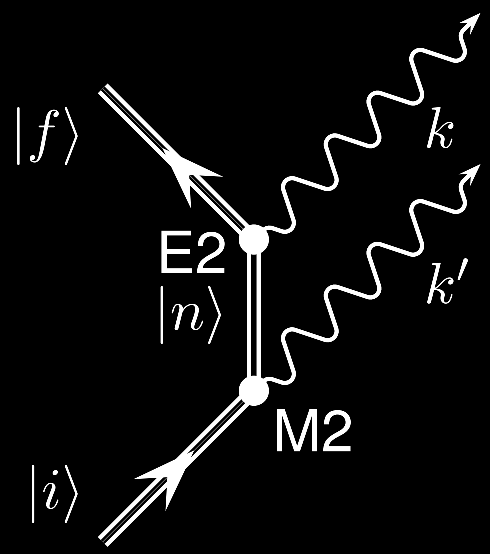

- angular correlation

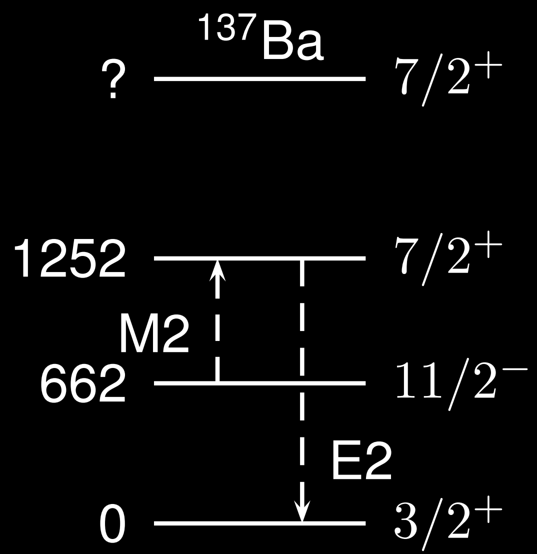


# Transition Matrix Elements
# Transition Polarizabilities $\alpha$







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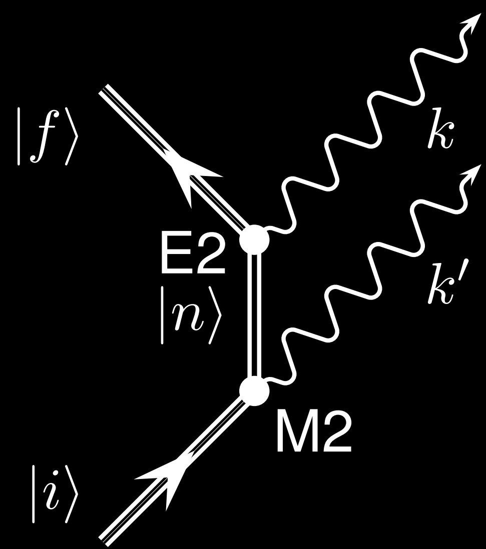
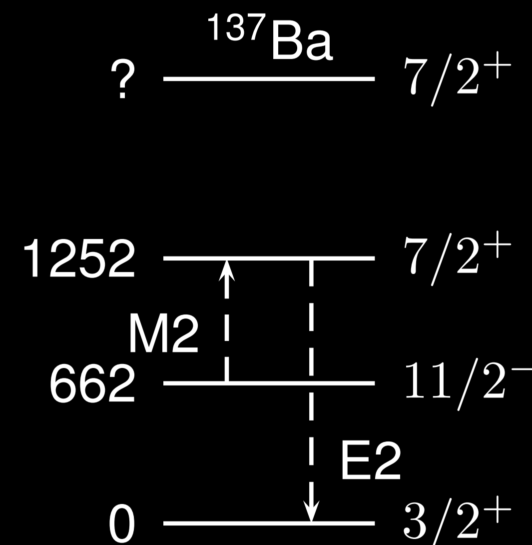


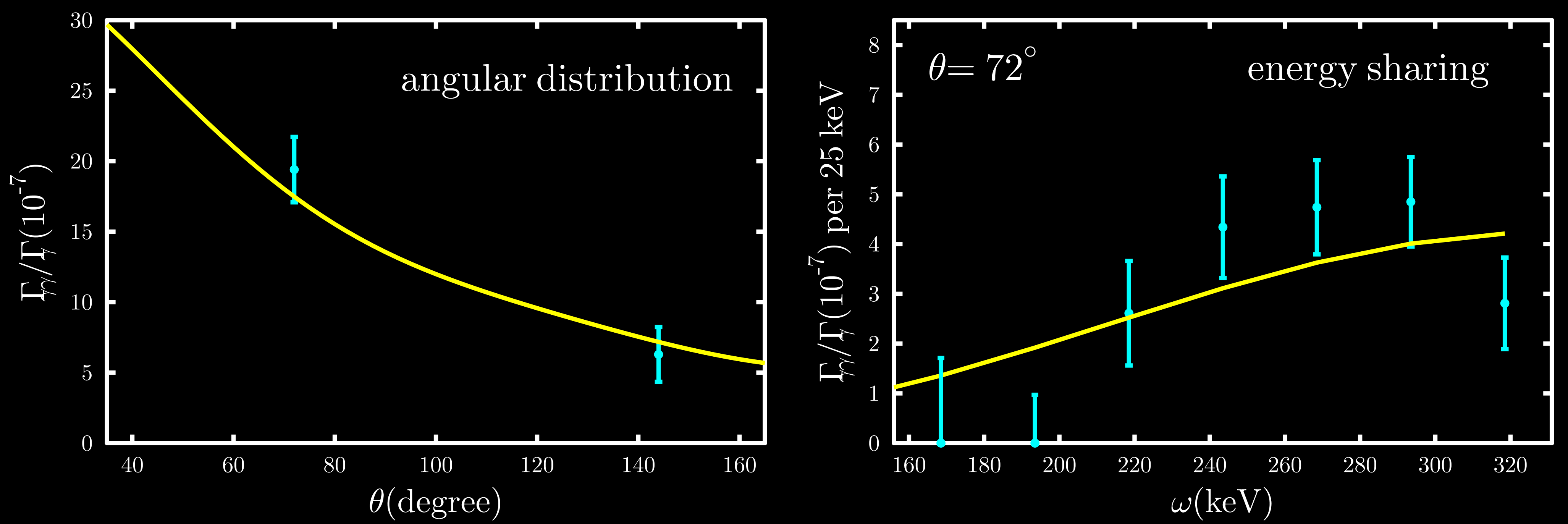

$$\alpha_{E2M2} \propto \sum_n \frac{\langle \tfrac{3}{2}^+_{\rm gs} \| \mathbf{E2} \| \tfrac{7}{2}^+_n \rangle \langle \tfrac{7}{2}^+_n \| \mathbf{M2} \| \tfrac{11}{2}^- \rangle}{E_n}$$

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

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

# 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 $\alpha_{E2M2}$ and $\alpha_{M1E3}$ considered in **simultaneous fit**
- $A_{qq}$, $A_{od}$ and $A_x$ exhibit characteristic dependence on $\omega$ and $\theta$

# Quasi-particle phonon model

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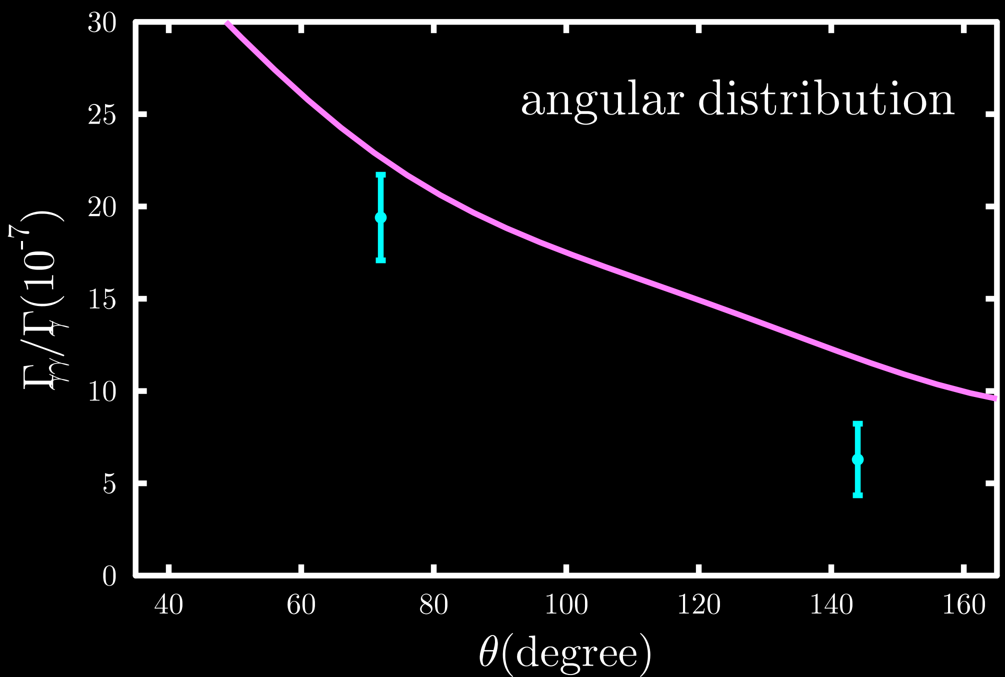


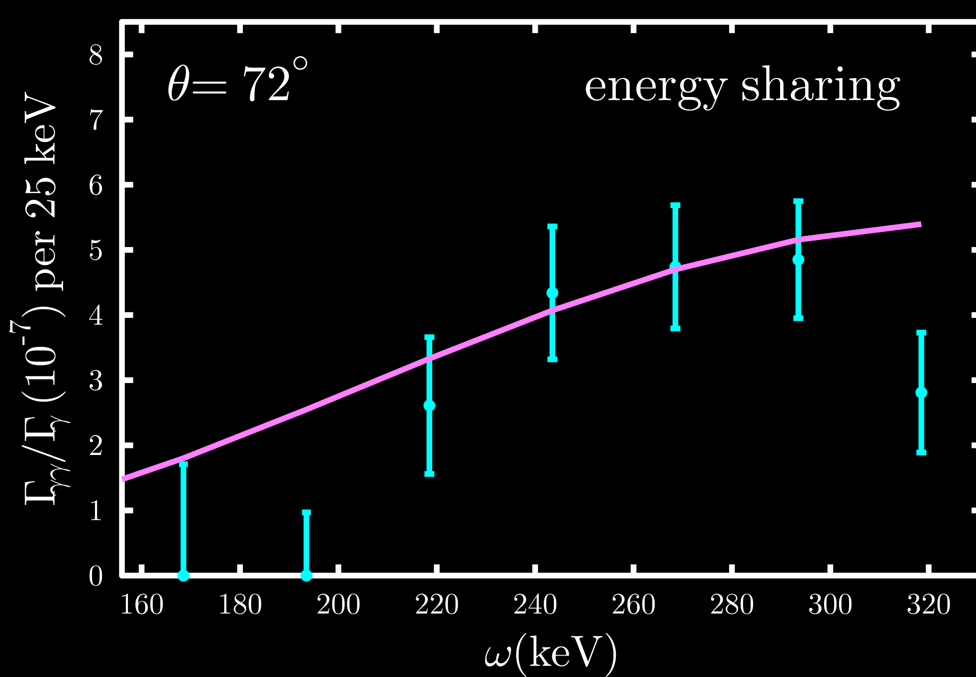


| | Exp. | QPM |
|---|---|---|
| $\Gamma_{\gamma\gamma}/\Gamma_\gamma(10^{-6})$ | 2.05(31) | 2.69 |
| $\alpha_{\mathrm{M2E2}}(\frac{e^2\mathrm{fm}^4}{\mathrm{MeV}})$ | +33.9(28) | +42.60 |
| $\alpha_{\mathrm{E3M1}}(\frac{e^2\mathrm{fm}^4}{\mathrm{MeV}})$ | +10.1(42) | +9.50 |

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

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

# 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**
- search for cases dominated by $E1E1$ transitions with **improved** experimental setup
- **competition**: D.J. Millener, R.J. Sutter (NaI(Tl))
  C.J. Lister (Gammasphere)
- Collaborators
  - **Christopher Walz** (setup, data taking, data analysis)
  - N. Pietralla, T. Aumann, R. Lefol, V. Yu. Ponomarev (QPM)

# The End

# QPM running sum

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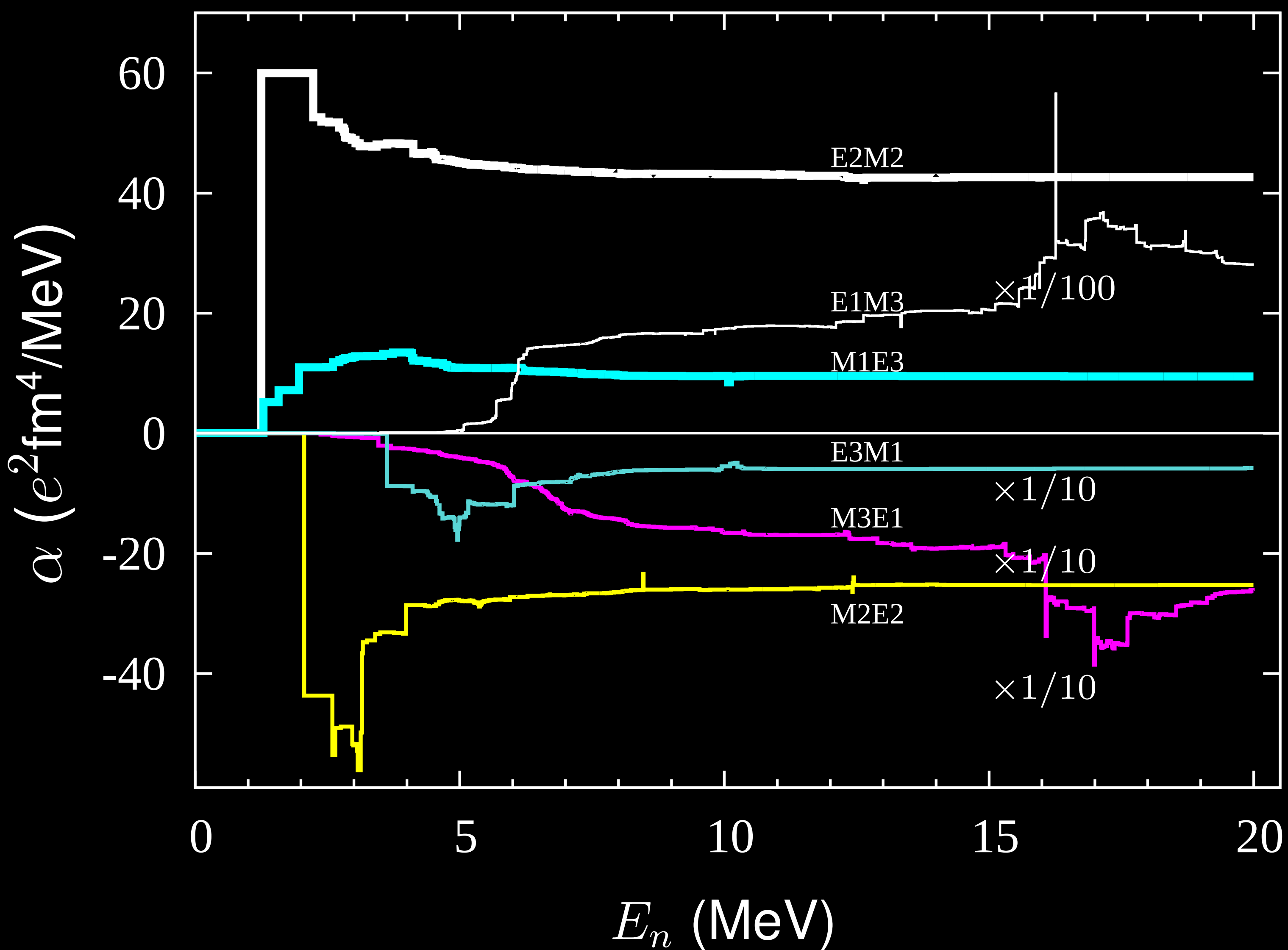
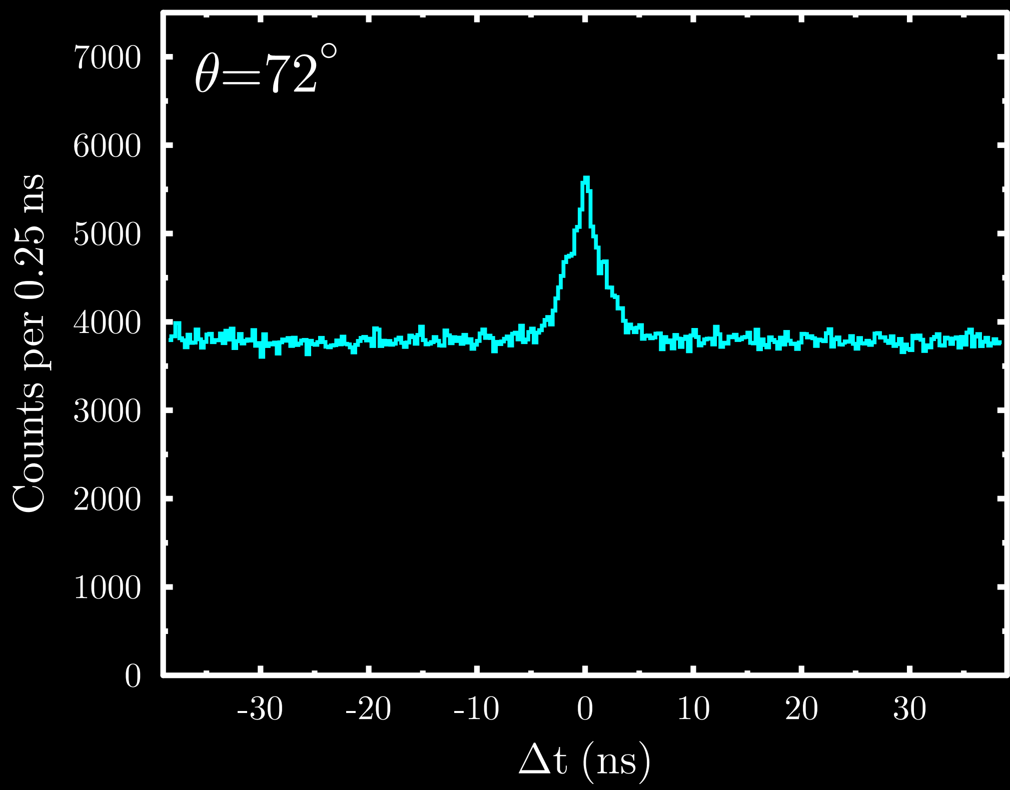
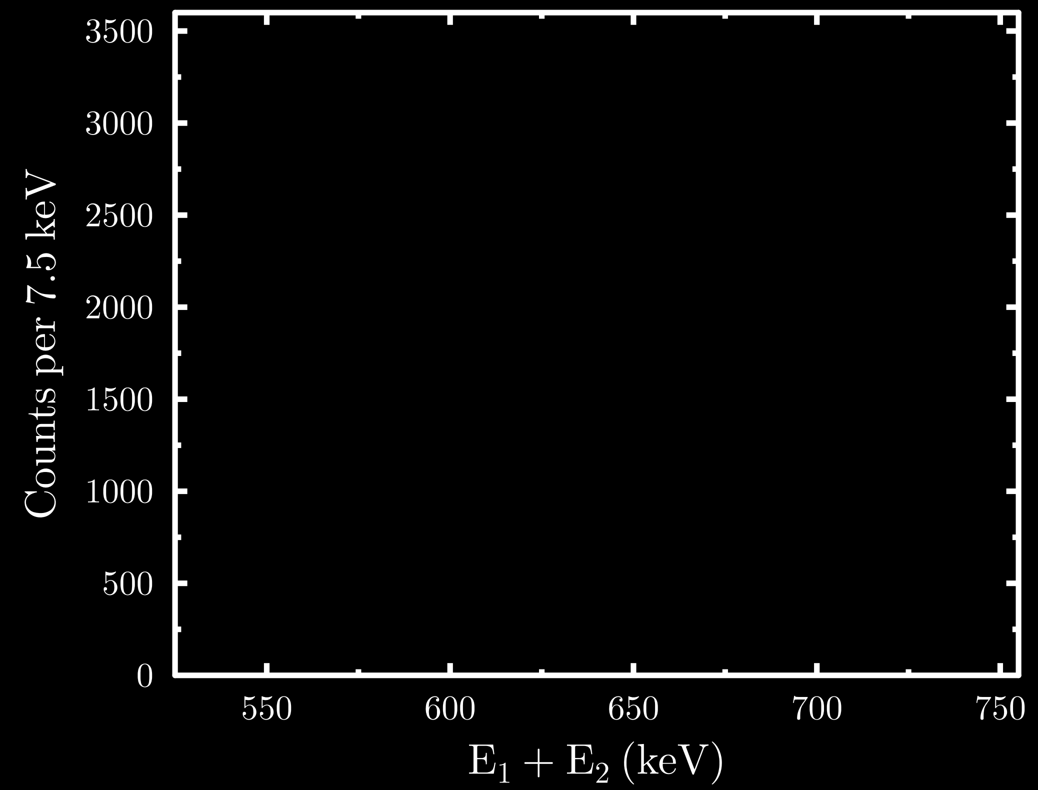


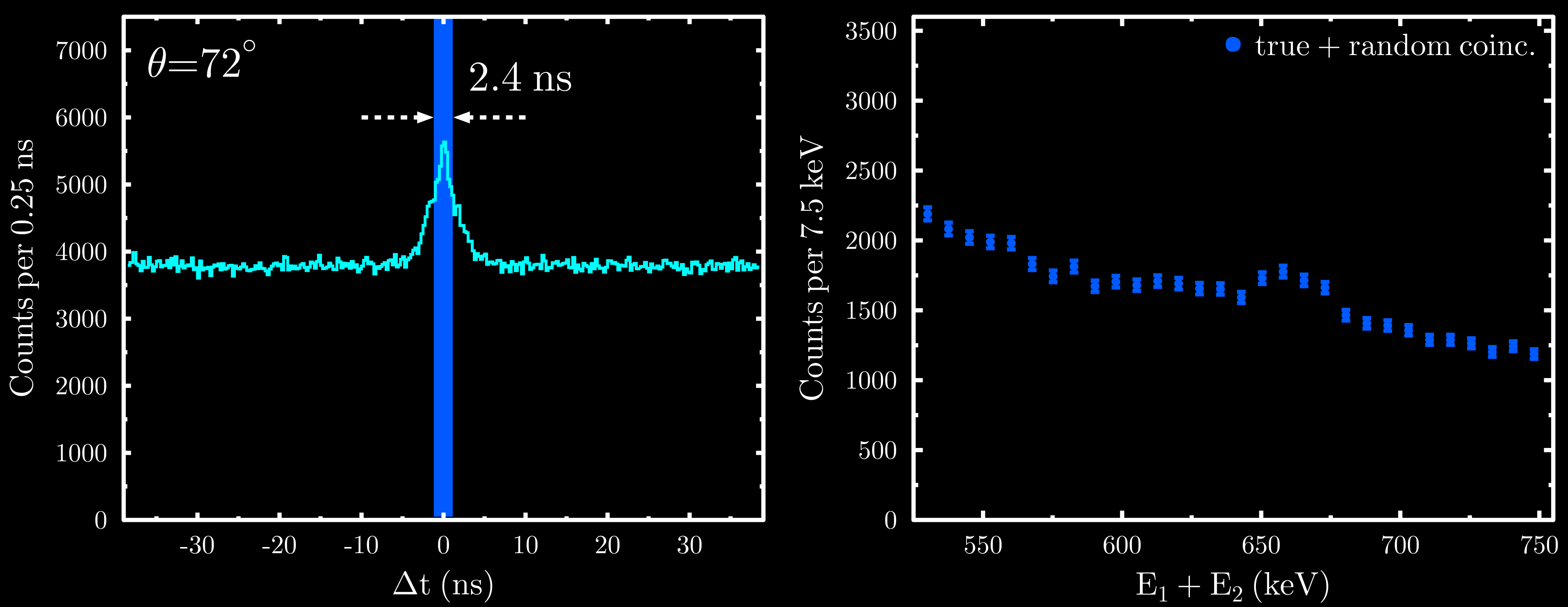
# Time and Energy Spectra



# Time and Energy Spectra





# Time and Energy Spectra

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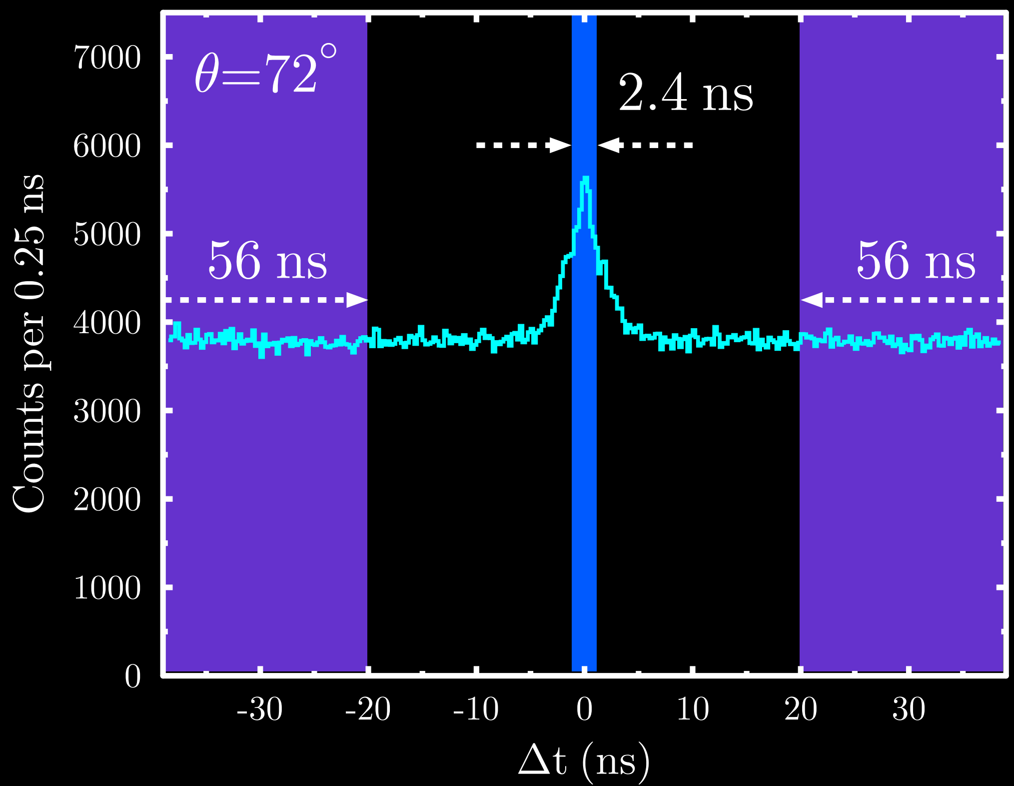
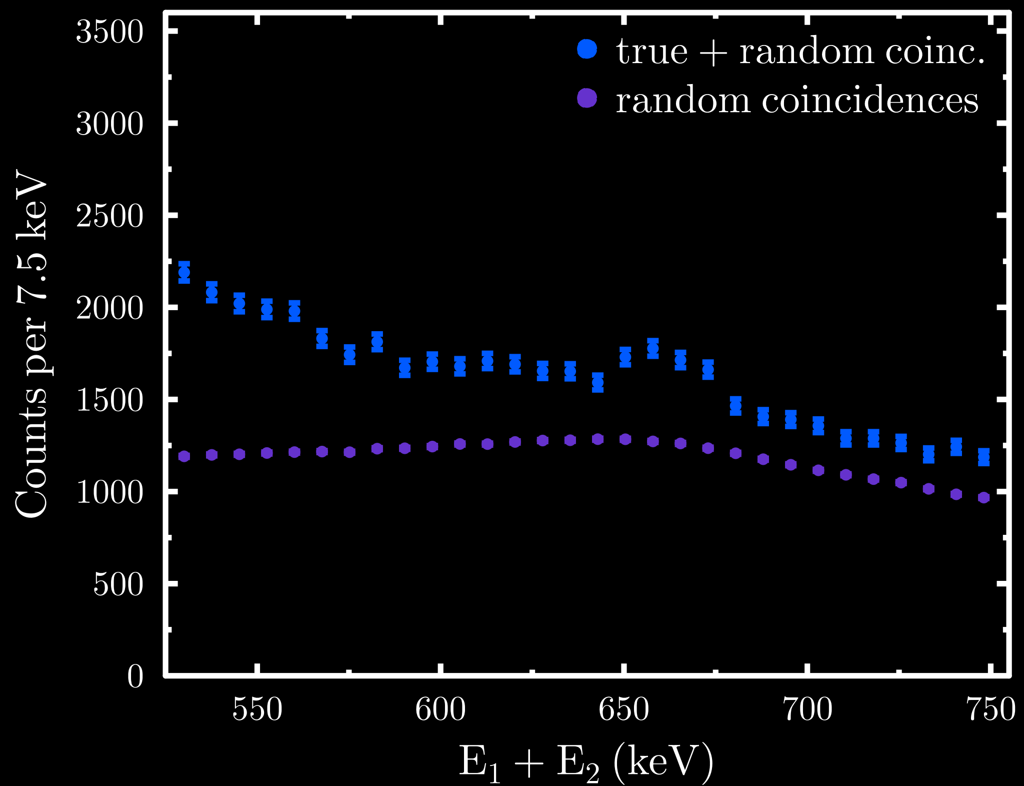


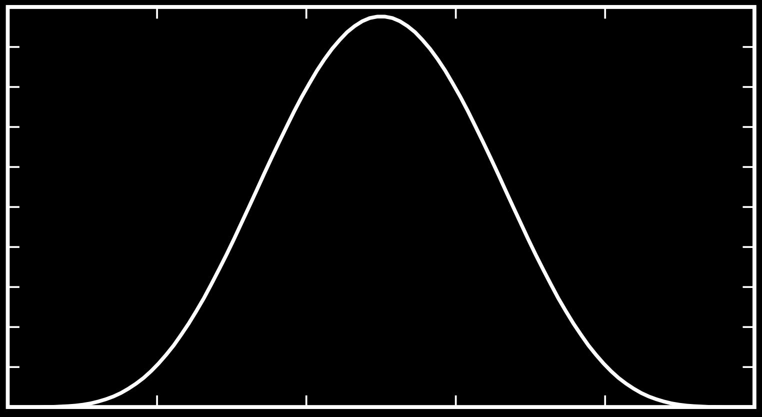




- random coincidences dominant

# Other Observables
# Indvidual Energies



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




- E2M2: $E_1^5 E_2^5$

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# Indvidual Energies



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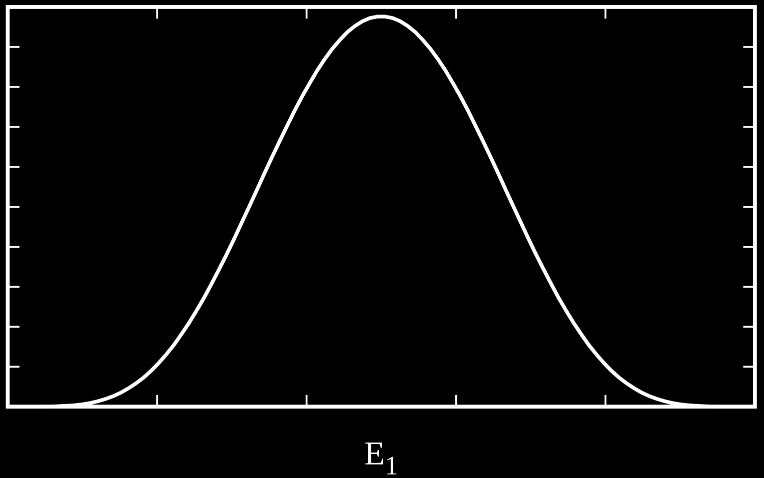
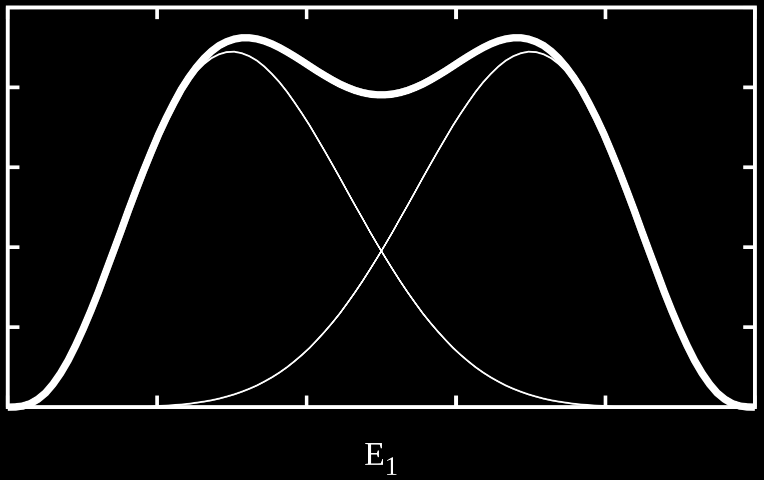



- E3M1: $E_1^7 E_2^3 + E_1^3 E_2^7$



# Non-symmetric Angular Correlation (about 90°)

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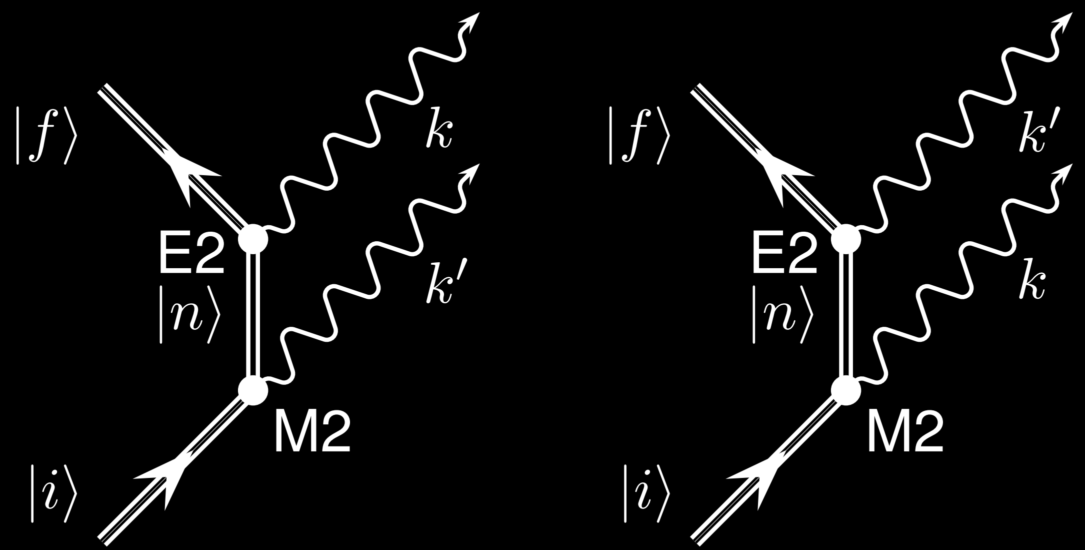
- **single gamma** decay: symmetric about 90°
  (e.g. 2 $\gamma$ rays of $\gamma$-cascade)
- $\gamma\gamma$ decay: **non-symmetric** angular correlation

# Non-symmetric Angular Correlation (about 90°)





- **single gamma** decay: symmetric about 90° (e.g. 2 $\gamma$ rays of $\gamma$-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

# Polarizability



- $\alpha_D$: diagonal **polarizability**

$$\alpha_D \quad \propto \quad \sum_n \frac{B(E1; 0^+ \rightarrow 1_n^-)}{E_n}$$

# Polarizability

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

# Polarizability

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

$$\alpha_{fi} \propto \sum_n \frac{\langle 0^+_{\mathrm{gs}} \| E1 \| 1^-_n \rangle \langle 1^-_n \| E1 \| 2^+_1 \rangle}{E_n}$$

- $\alpha_{fi}$: **off-diagonal** or transition **polarizability**
  - determined from single number: $\Gamma_{\gamma\gamma}/\Gamma_\gamma$
- $\alpha_D$: full E1-strength must be measured (difficult)
- relation between $\alpha_D$ and $\alpha_{fi}$ not established