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New expertise in γ-γ fast timing using arrays of $LaBr_3(Ce)$ detectors

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ikp

Content:

The Generalized Centroid Difference Method

to analyze **γ–γ time-difference spectra** from a large **fast-timing array**

The **EXILL&FATIMA campaign 2013**

at the Institut Laue-Langevin

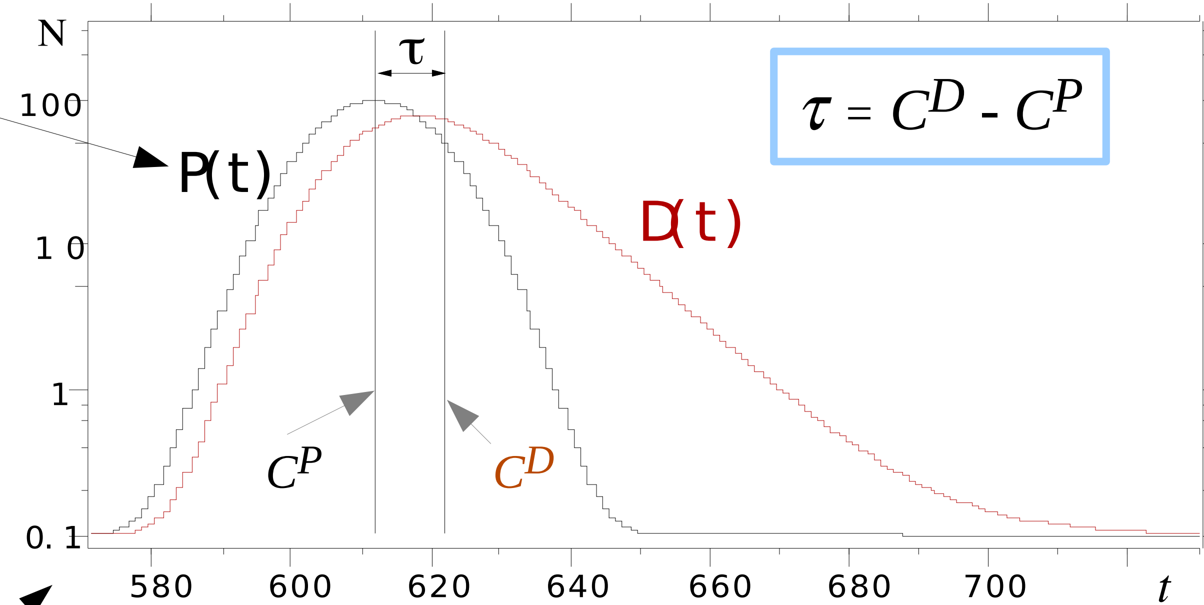
NEUTRONS FOR SCIENCE®

Results of **Germanium-gated γ–γ fast timing** of excited states in **fission fragments**

How to correct for background contributions to the time spectra?

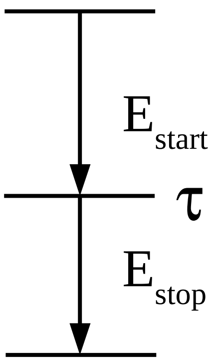
Basis: The picosecond sensitive Centroid Shift Method

The prompt response function (PRF) obtained for $\tau < 1$ ps.



The centroid or center of gravity is the first moment of a time distribution *D(t)*:

$$C^D = \langle t \rangle = \frac{\int t\, D(t)\, dt}{\int D(t)\, dt}$$



Asuuming no background contributions, the **centroid** of the "delayed" time spectrum D(t) is **shifted** from the centroid of the convoluted PRF P(t)

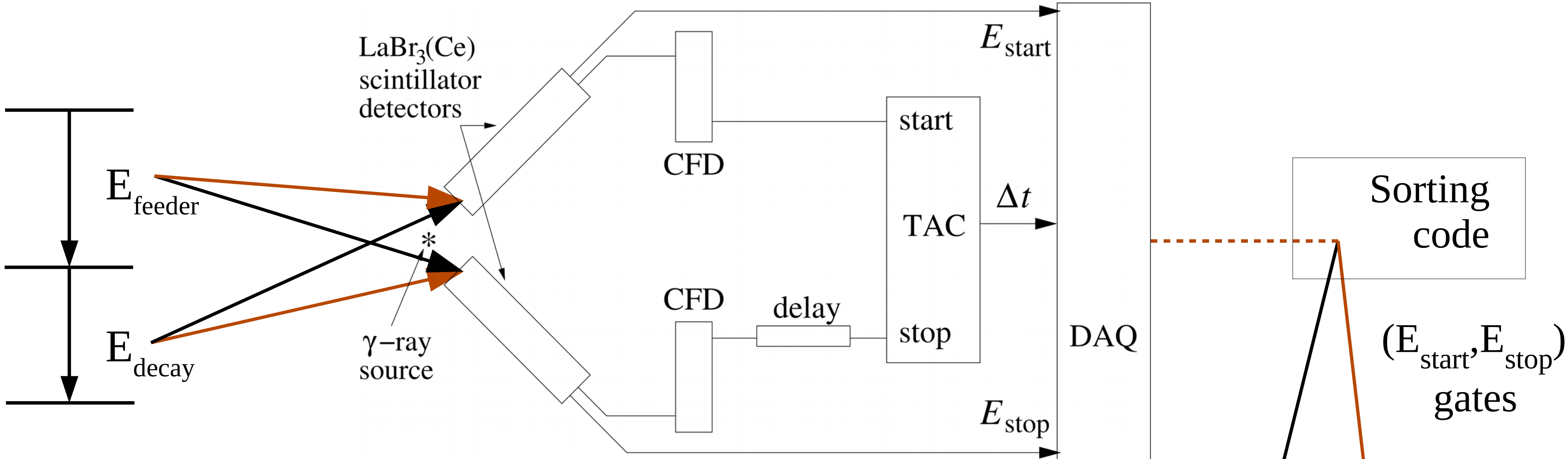
by the mean lifetime τ of the excited state:

$$\tau = C^D(E_{start}, E_{stop}) - \underline{C^P(E_{start}, E_{stop})}$$

"the time-walk characteristics"

In general: $C^P(E_{start}, E_{stop}) = T_0 + T(E_{start}) + T(E_{stop})$, where $T(E)$ is the detector time response.

The γ–γ fast-timing technique and the Generalized Centroid Difference method



Experimental centroid difference:

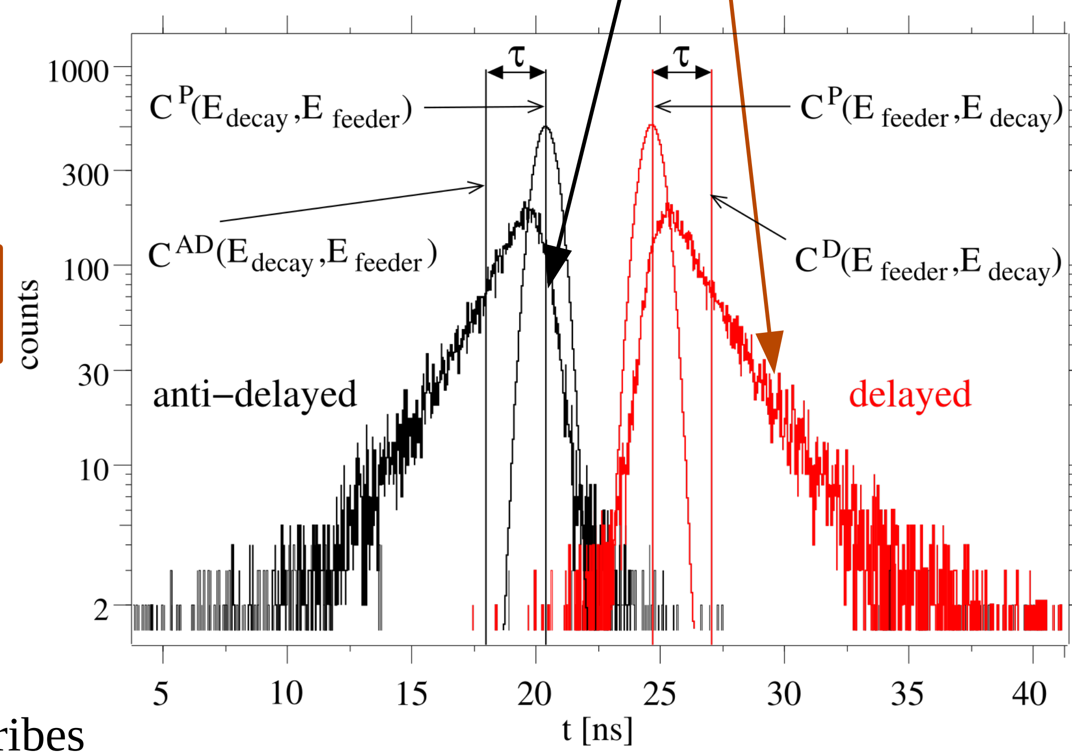
$$\Delta C(E_{feeder},E_{decay})=C^{Delayed} - C^{Anti\ Delayed}$$

Physics:

$$\Delta C(E_{feeder},E_{decay}) = PRD(E_{feeder},E_{decay}) + 2\tau$$

N detectors: Superposition of the data only by distinguishing between the start and stop signals.

$$\overline{\Delta C}_{FEP} = \overline{PRD} + 2\tau$$

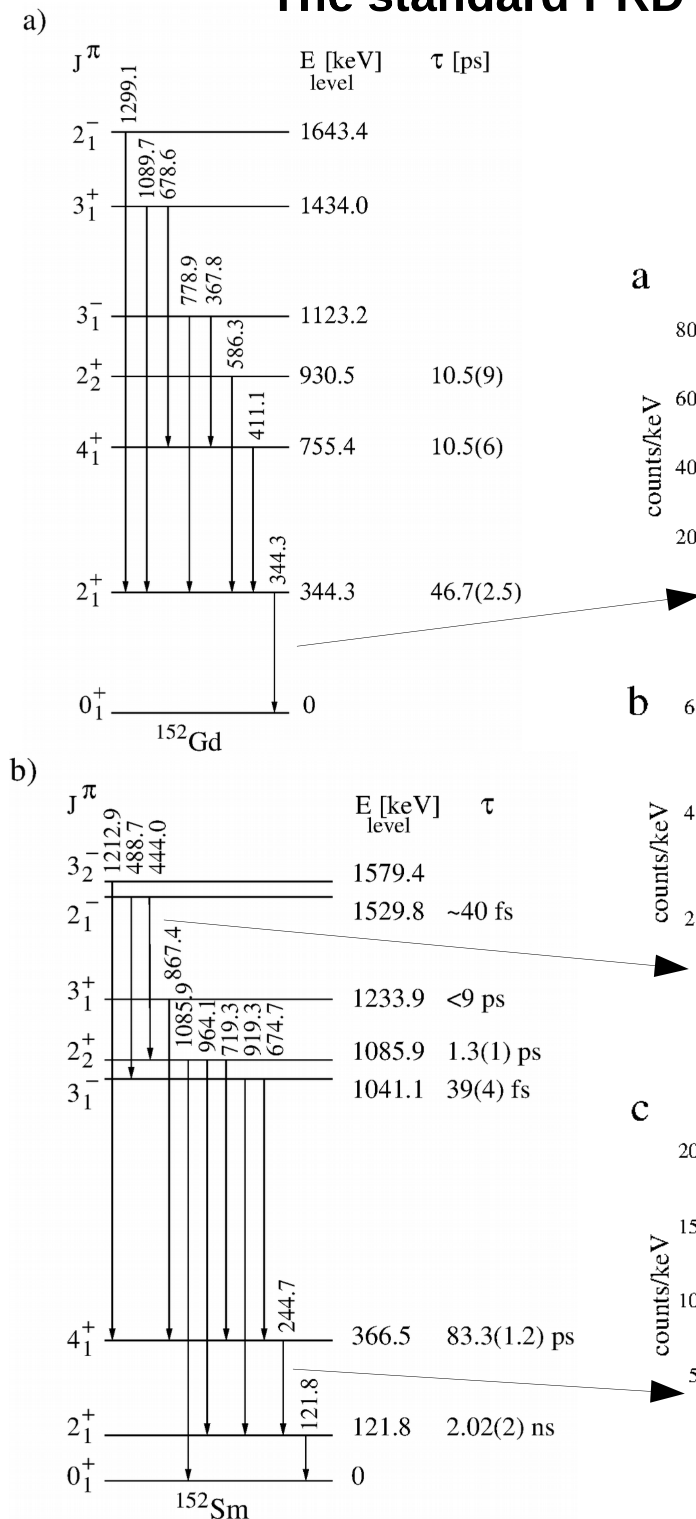


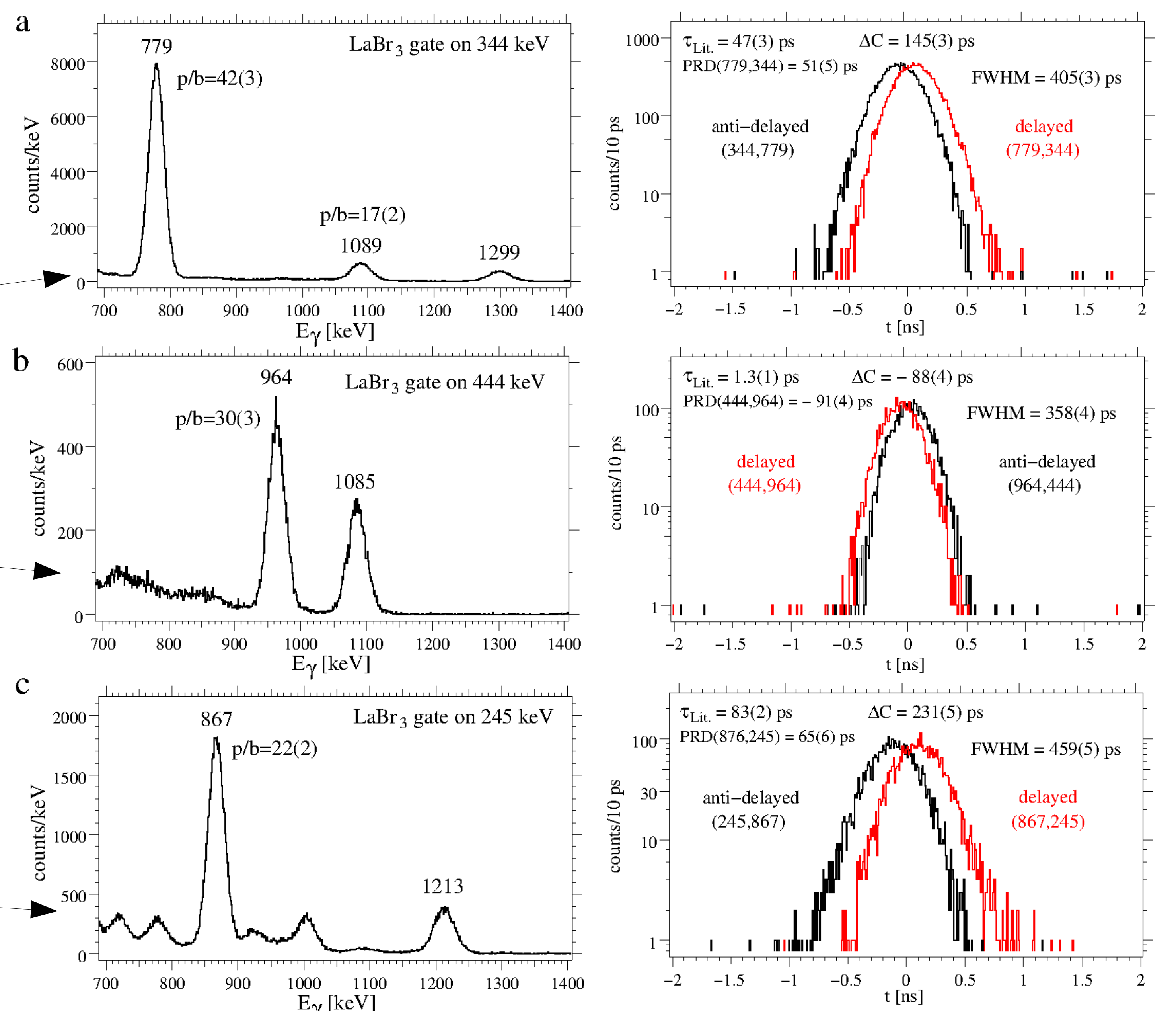
The **Prompt Response Difference** (PRD) describes the linearly combined **γ–γ time walk** of the fast-timing array.

J.-M. Régis et al., NIM A **726** (2013)

The standard PRD calibration procedure using the ^{152}Eu γ-ray source

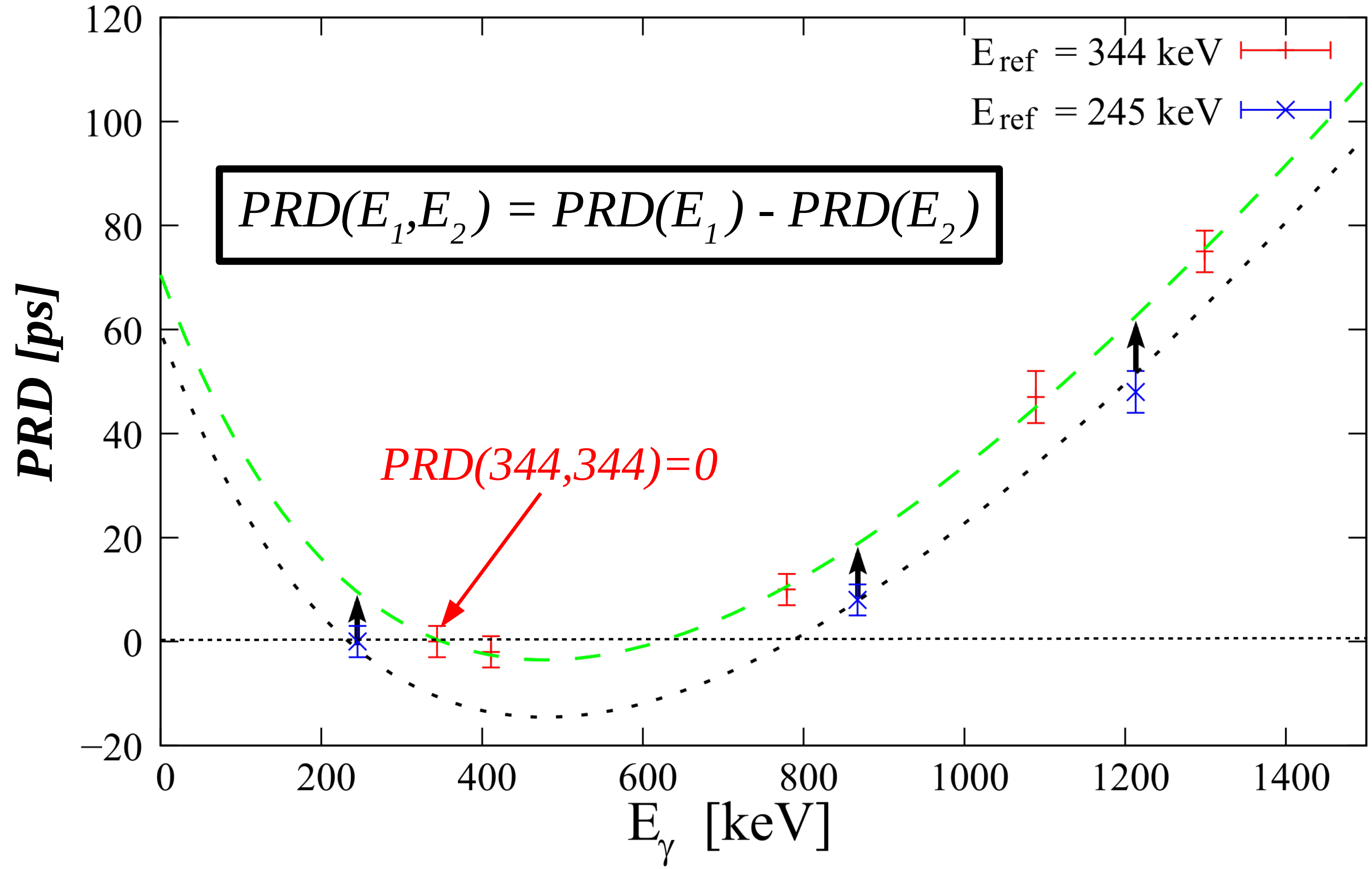
- nearly no background (no correction needed)
- precisely known picosecond lifetimes
- several γ rays connecting one state for different states





Picosecond sensitive lifetime determination using the mirror-symmetric GCD method.

The PRD calibration procedure using ^{152}Eu:



Measured using
$LaBr_3$-$LaBr_3$ coincidences with
virtually no background contributions.

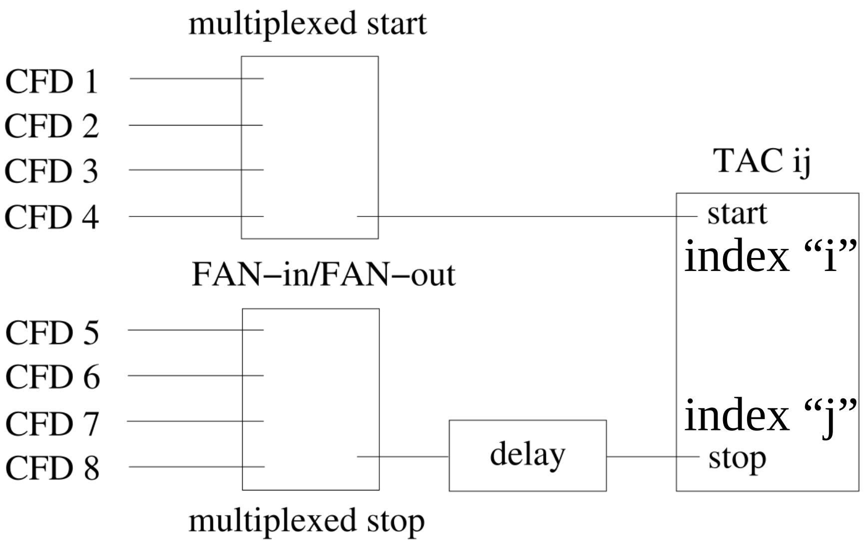
PRD uncertainty within 3σ: typically 5-10 ps

Advantage of the GCD method: no correction and therefore, no systematic error is introduced.

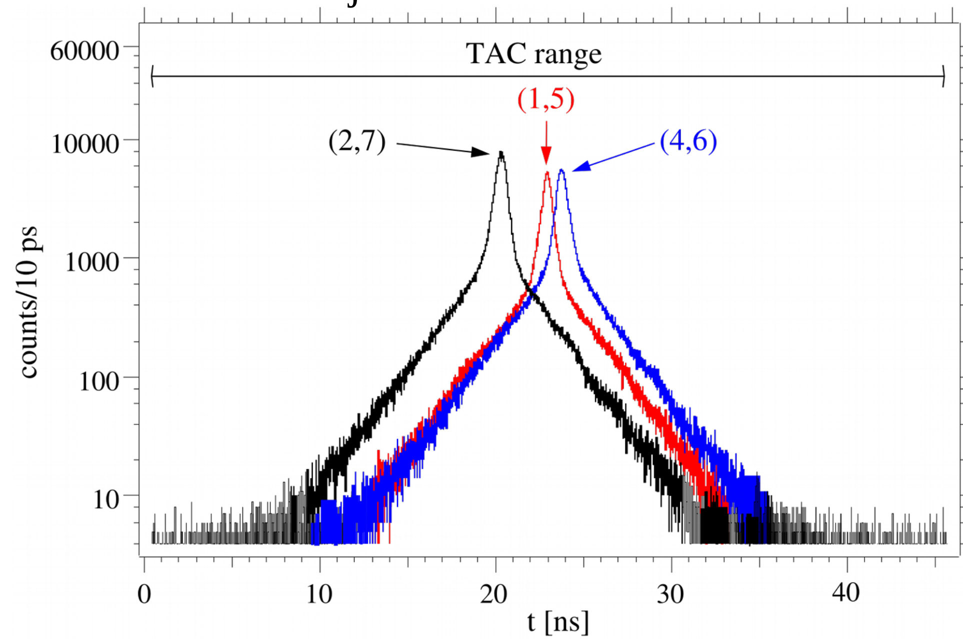
J.-M. Régis, N. Saed Samii et al., NIM A **823** (2016)

The Generalized Centroid Difference (GCD) Method for γ–γ fast-timing arrays

An analog γ–γ fast-timing array circuitry for trigger-less data acquisition:



The TAC_{ij} projections:



Off-line alignment of the TAC_{ij} projections using $shift_{ij}$ constants and superposition of the data to perform the GCD method.

{1,2,3,4} x {5,6,7,8} ∈ TAC A

{1,2,5,6} x {3,4,7,8} ∈ TAC B

{1,3,5,7} x {2,4,6,8} ∈ TAC C

Only combinations with $i < j$ are accepted (simplified sorting algorithm).
Invalid or multiple combinations are excluded off-line.
=> 3 TAC and 2 FAN modules for 8 detectors (28 combinations).

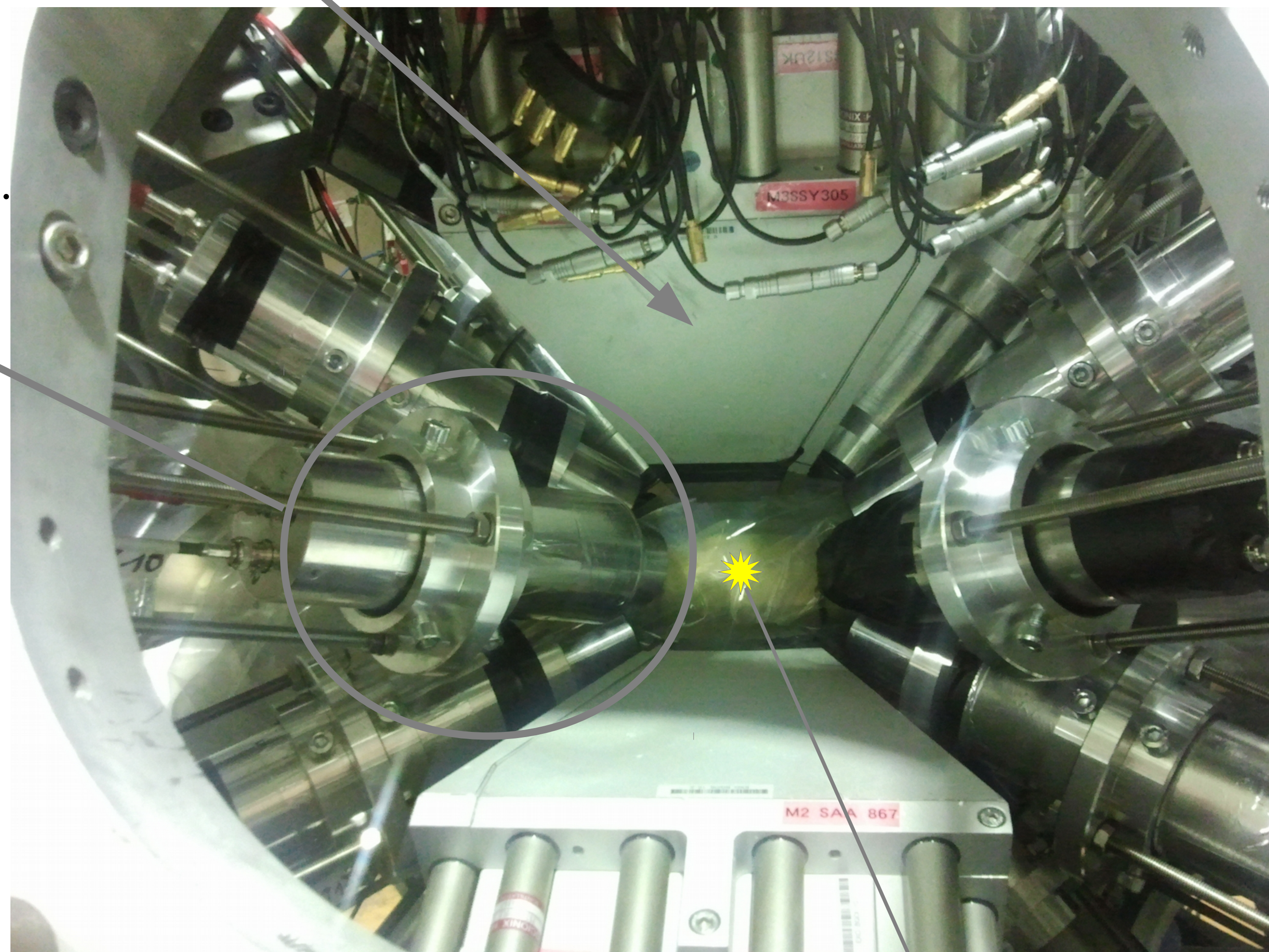
Main advantages: **no dead-time effects for detector rates of up to 30 kHz and almost no degradation of time resolution (<10 ps).**

J.-M. Régis, N. Saed Samii et al., NIM A **823** (2016)

The EXILL&FATIMA mixed array for prompt γ-ray spectroscopy of cold-neutron induced capture/fission experiments at ILL 2013

Ring of 8 BGO shielded EXOGAM clovers used to provide one or two selective γ-triggers.

16 almost equal $LaBr_3(Ce)$ detectors for γ–γ lifetime measurements.



Collimated cold-neutron beam

Ø1.2 cm

Target position

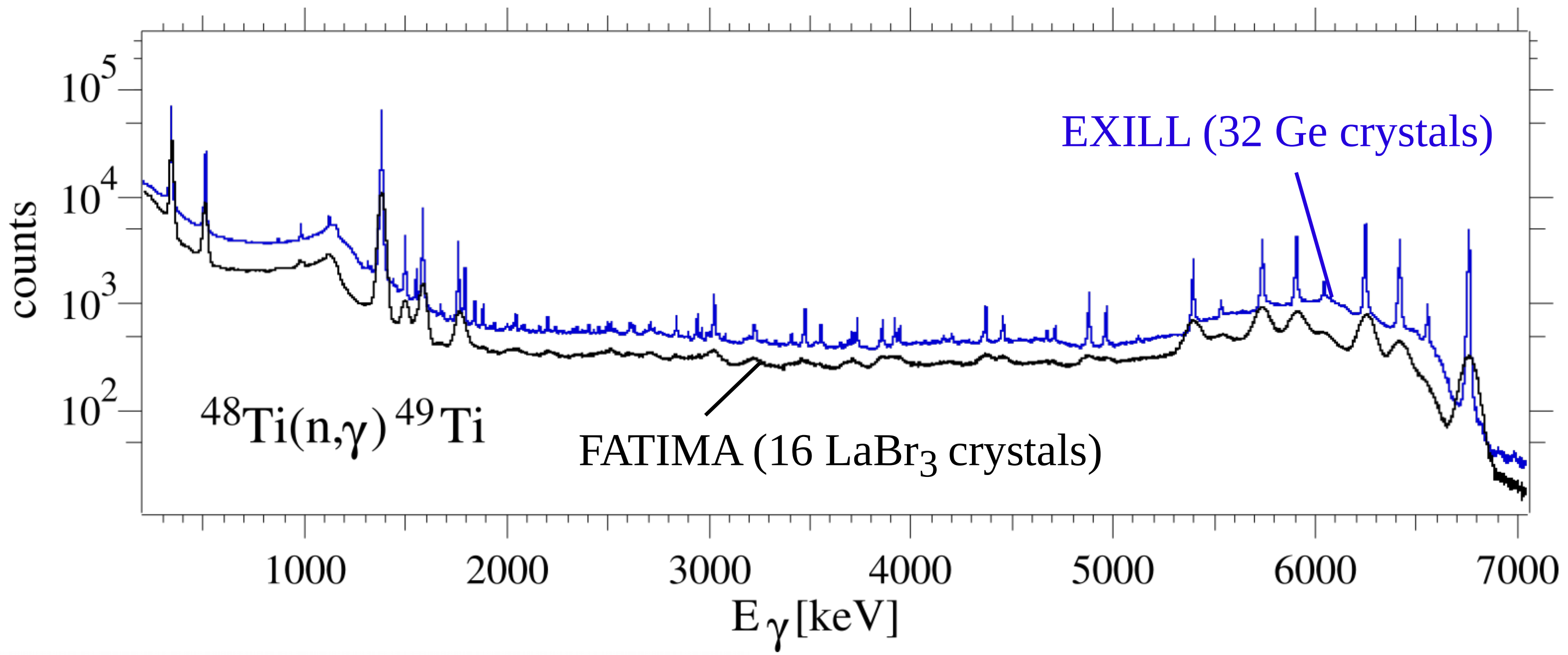
Trigger-less digital data acquisition of 71 digitiser channels

Detector rate: up to 25 kHz
Data rate: up to 6.5 MB/s
Acquired data: ~ 40 TB

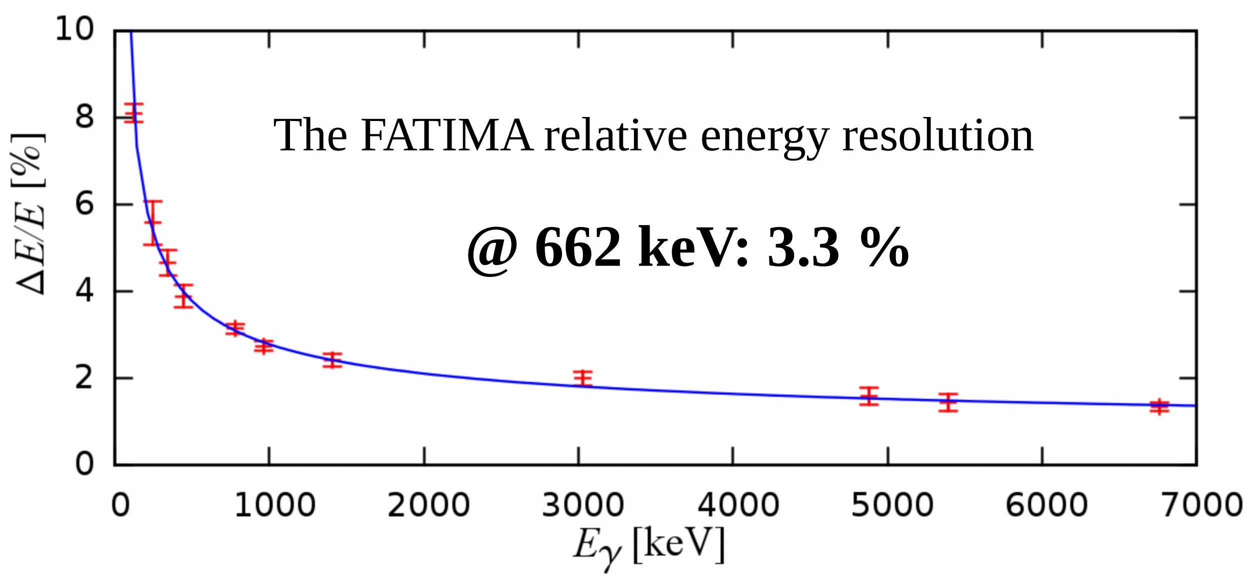
FATIMA: Inter-detector Compton scattering (cross talk) detected in neighbouring $LaBr_3(Ce)$detectors. Off-line elimination (loss of statistics: about 15%). Small Compton suppression of about 10% achieved.

Energy performance of the EXILL & FATIMA spectrometer @ ILL 2013

Singles spectra



The $LaBr_3$ spectra are gain-matched to obtain the best energy resolution.



Absolute full-energy peak efficiencies:

	@ 662 keV	@ 1.3 MeV
EXILL	**4.9%**	**3.0%**
FATIMA	**3.7%**	**2.1%**

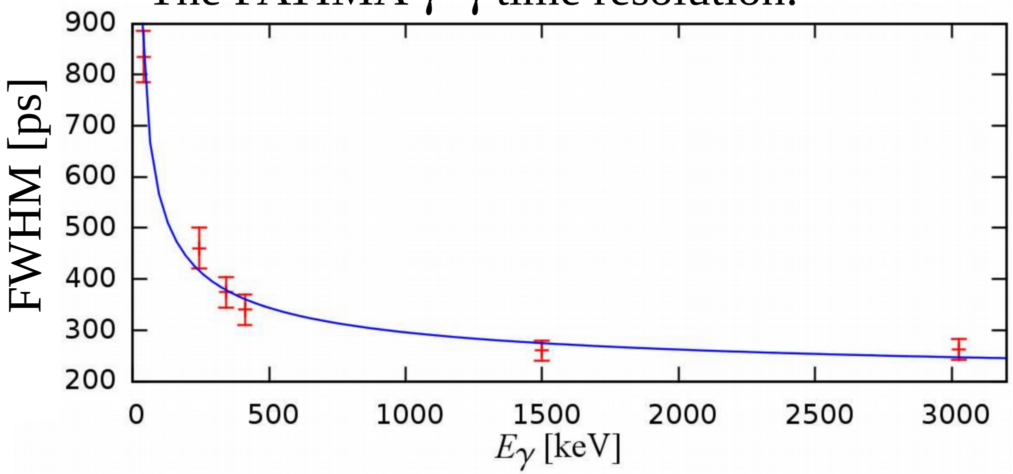
J.-M. Régis, G.S. Simpson et al., NIM A **763** (2014)

Timing performance of FATIMA @ ILL 2013

Consited of: 8 cylindrical Ø1.5”x1.5”

and 8 cylindrical Ø1.5”x 2” LaBr3(Ce) scintillators

The FATIMA γ–γ time resolution:



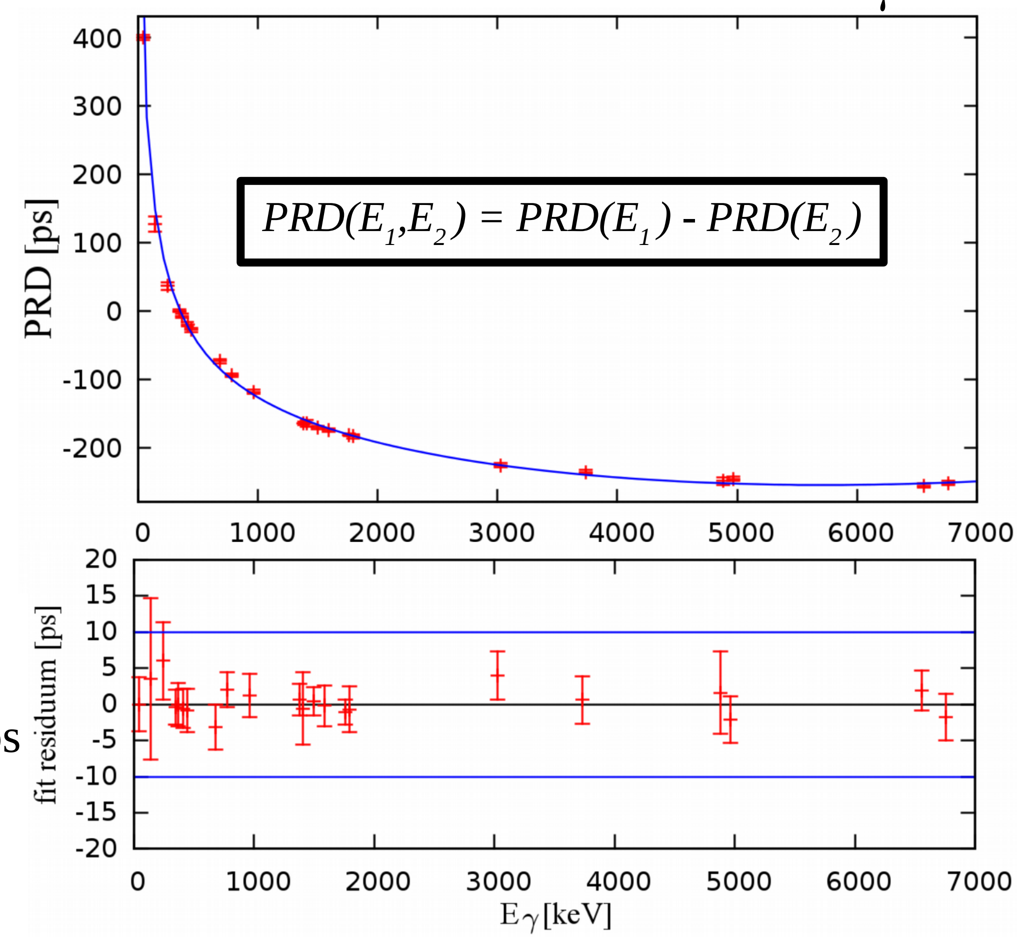
For τ < FWHM:

The statistical centroid uncertainty: $\delta C \sim \frac{FWHM}{2.355\sqrt{n}}$

e.g. FWHM=500 ps and n=1000 counts: δC ~ 7 ps

Uncertainty of the PRD determination corresponding to a 3σ standard deviation: δPRD = 10 ps

The FATIMA γ–γ time walk PRD(E_γ):

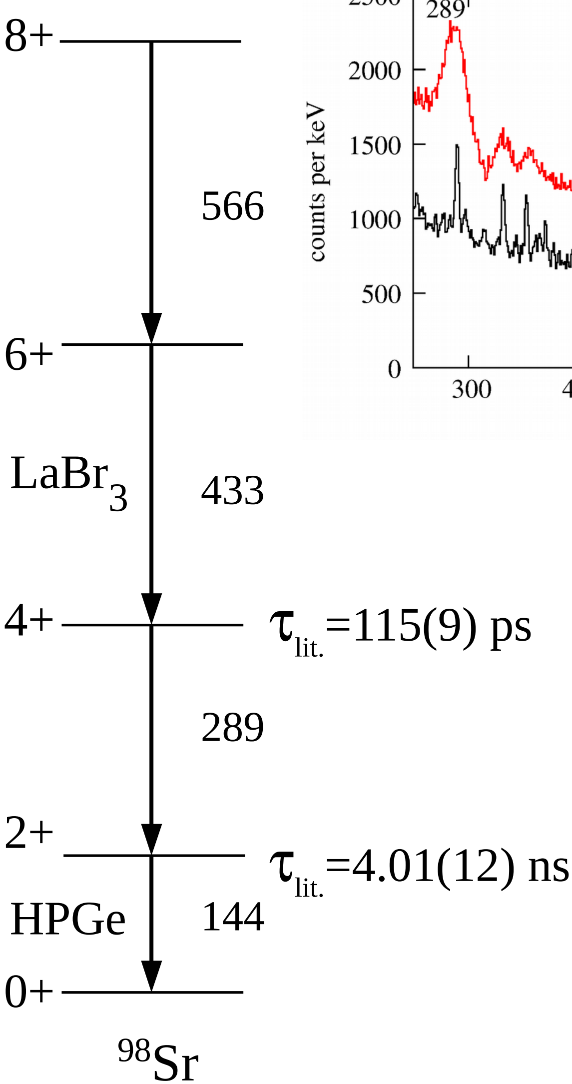


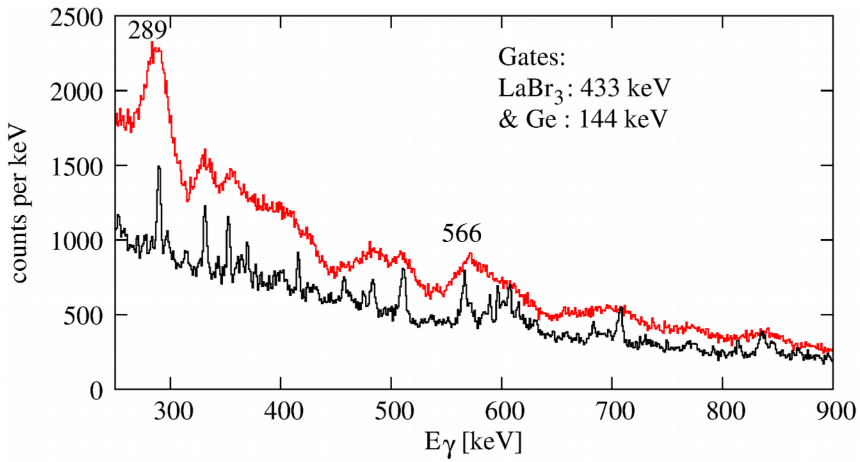
EXILL&FATIMA 2013:

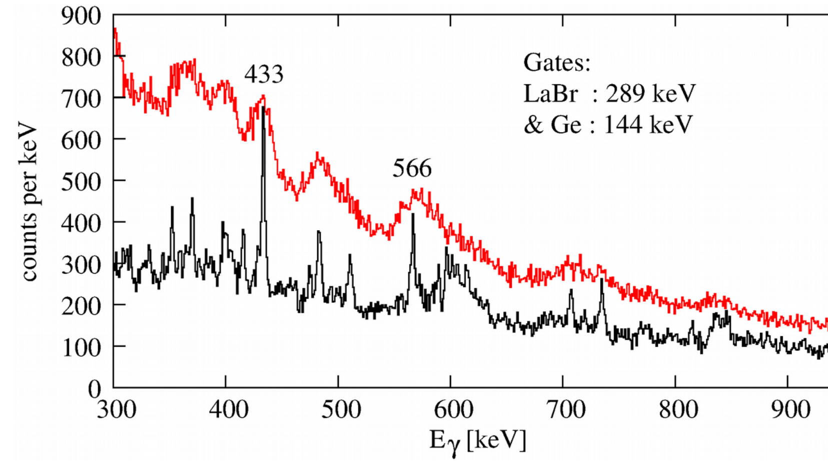
Identification of fission fragments & investigation on background and contamination

10 days cold-neutron-induced fission of ^{235}U

fisson yield of ^{98}Sr: 0.81%



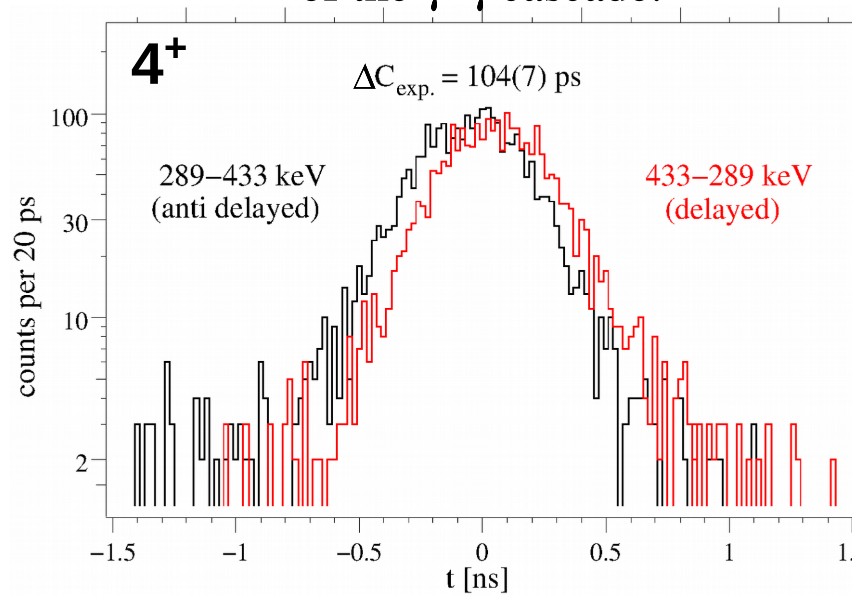




The LaBr3 peak-to-background ratio in this case is smaller than 0.5.

About 65% of the events are related to the background underneath the two FEPs of the γ–γ cascade.

HPGe-gated γ–γ timing:



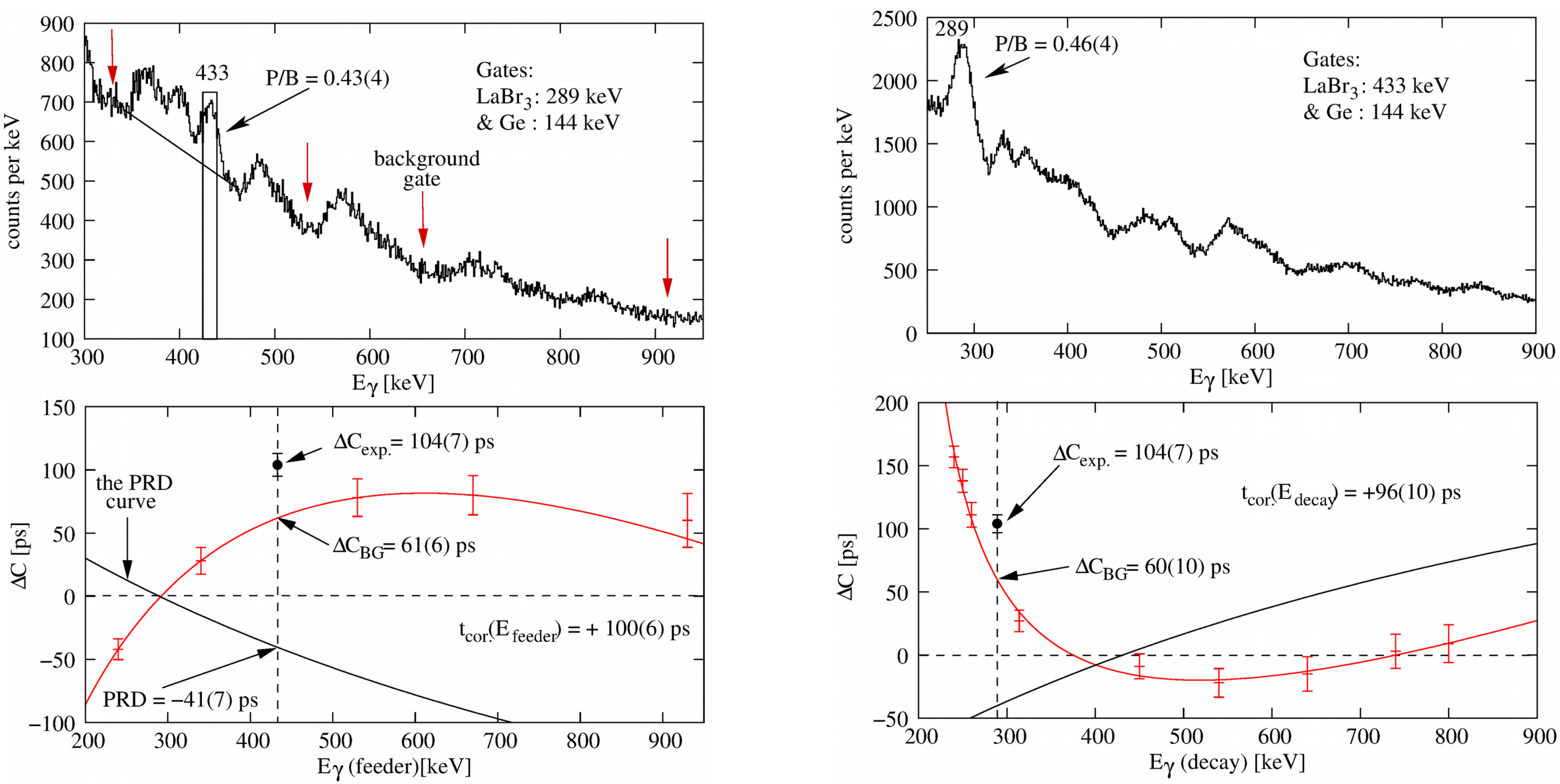
About 2600 counts per time distribution

The first 4+ state in ^{98}Sr: $\tau_{lit.}$ = 115(9) ps (β–γ timing, H. Mach et al., Phys. Lett. B 230, 1989)

Assuming only one background contribution, this correction is exact: $t_{cor.} = \dfrac{\Delta C_{exp.} - \Delta C_{BG}}{P/B}$

Using γ–γ timing: The time responses ΔC_{BG} of the two background components are needed.

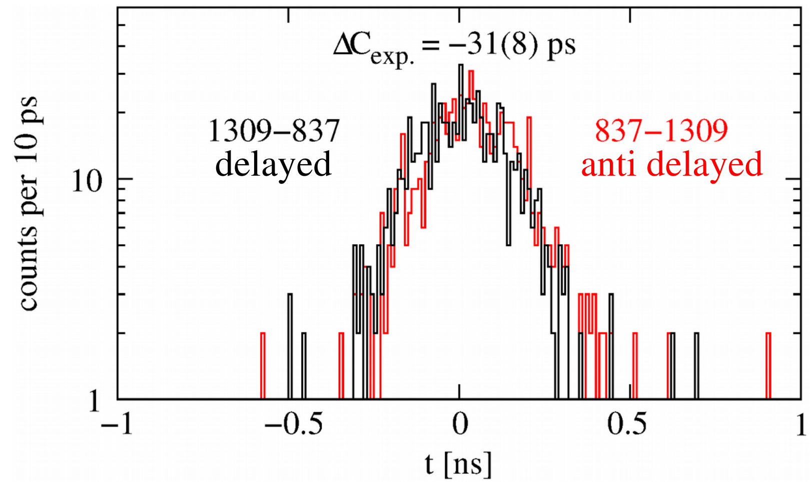
As a good approximation: $\Delta C_{FEP} = \Delta C_{exp.} + [t_{cor.}(E_{feeder}) + t_{cor.}(E_{decay})]/2$



=> ΔC_{FEP} = 202(12) ps, PRD = - 41(7) ps => $\tau = (\Delta C_{FEP} - PRD)/2$ = 121(11) ps

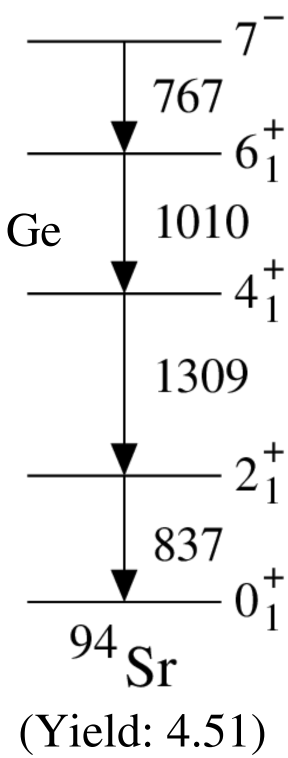
The first 2+ state in ^{94}Sr: $\tau_{lit.}$ = 10(4) ps

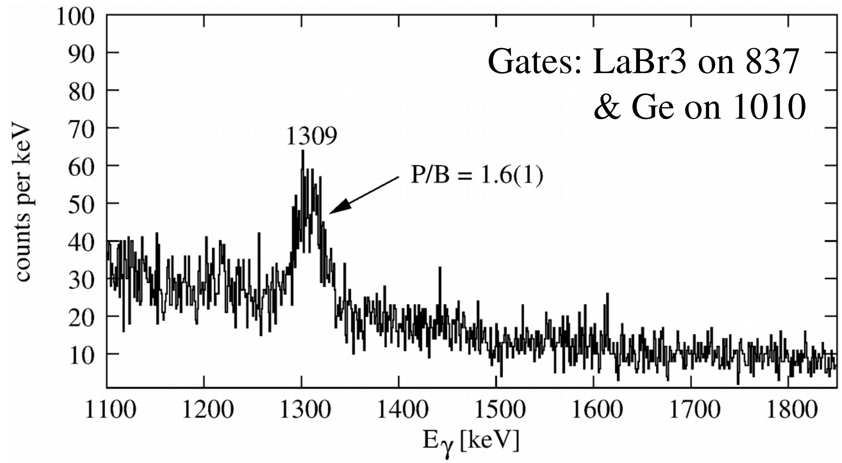
(β–γ timing, H. Mach et al., NPA 523, 1991)

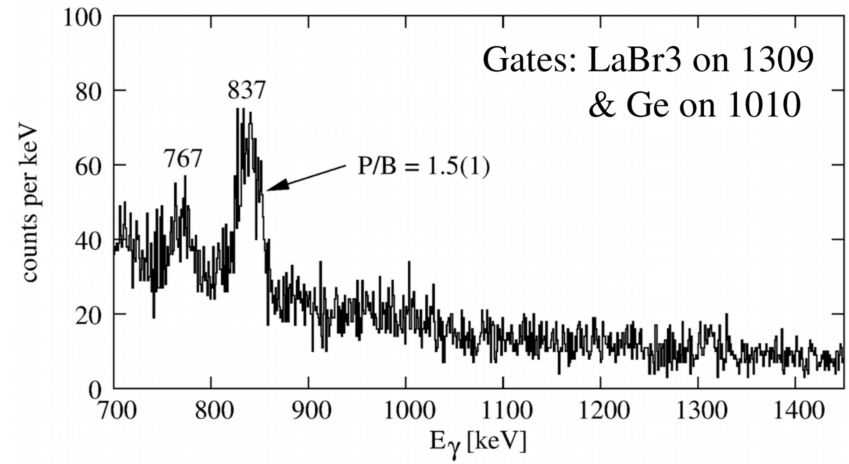


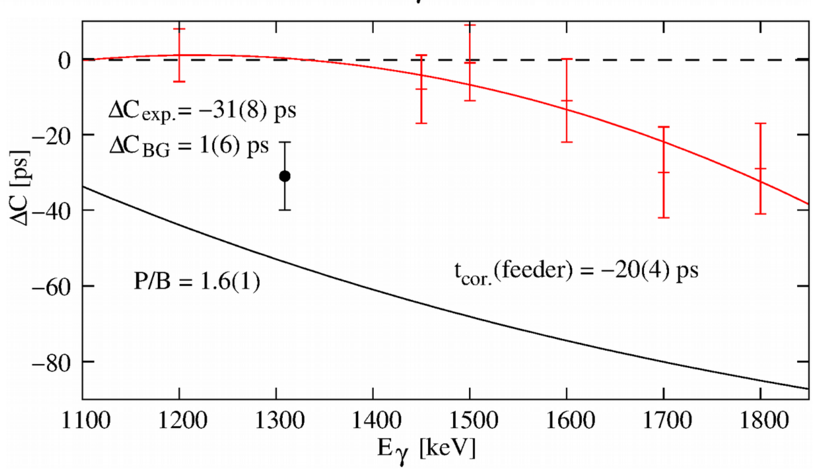
Experimental observations:

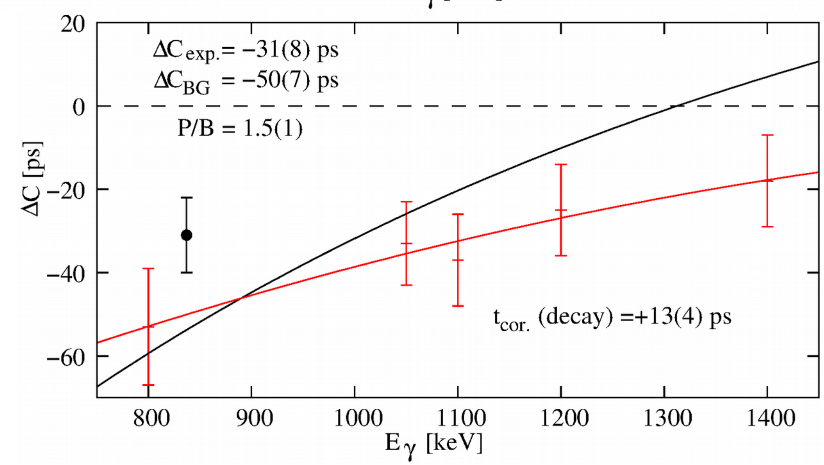
Generally, the shifts of the two background components relative to the total time spectrum are different, sometimes with opposite sign.









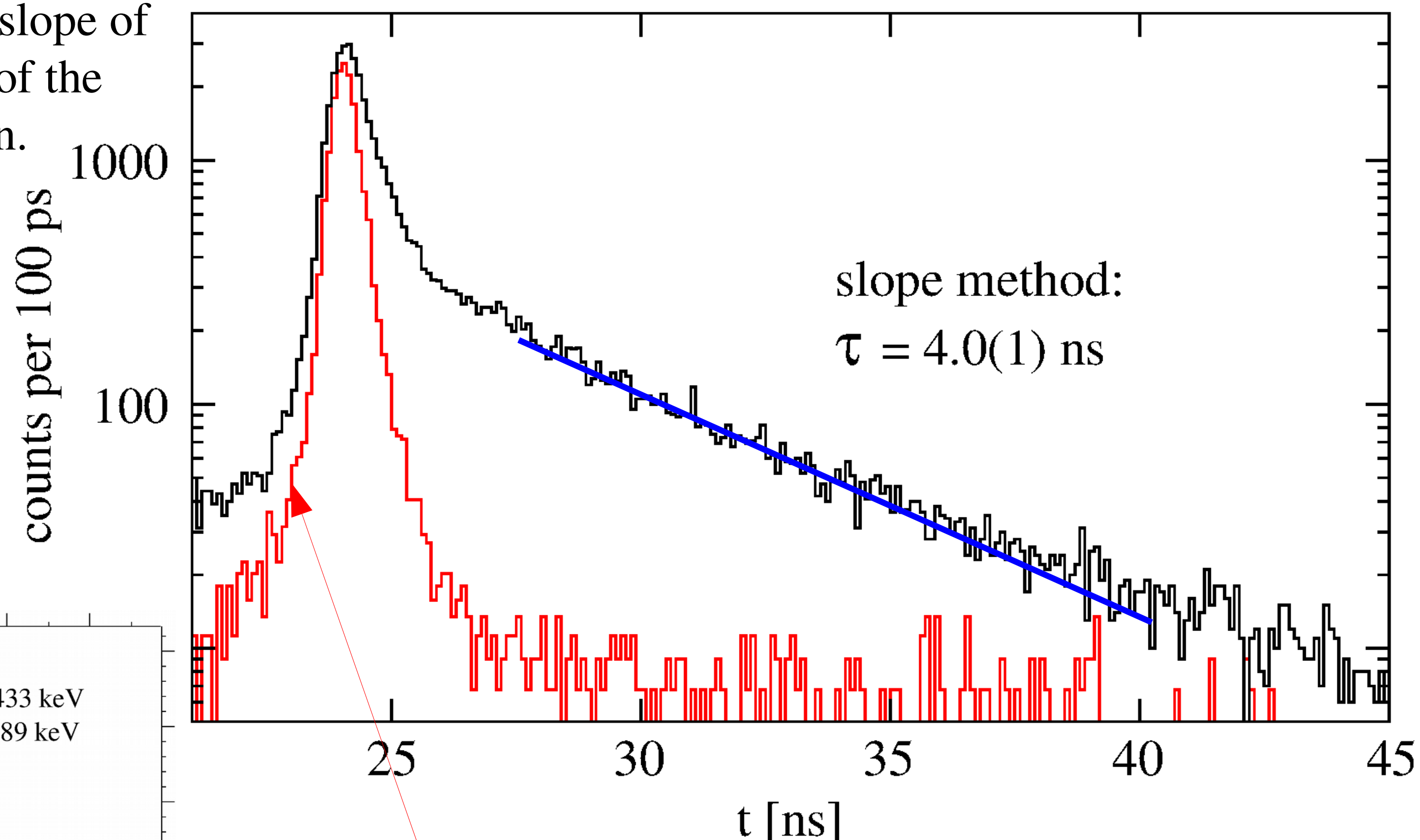


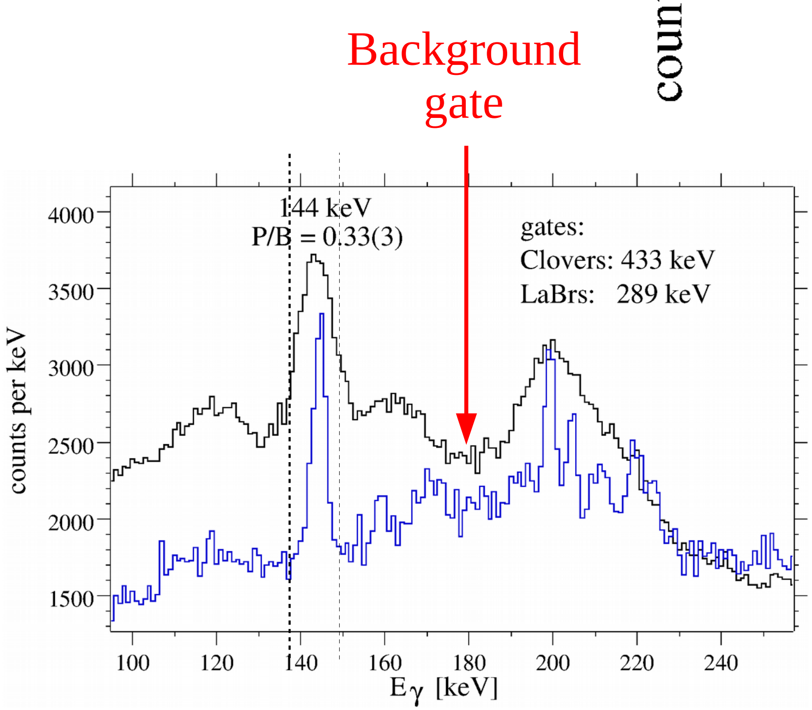
=> ΔC_{FEP} = - 35(9) ps, PRD = - 53(7) ps => $\tau = (\Delta C_{FEP} - \text{PRD})/2$ = 9(6) ps

Considering the Slope Method for long lifetimes τ >1 ns

The first 2^+ state in ^{98}Sr: $\tau_{lit.} = 4.01(12)$ ns (β–γ timing, H. Mach et al., Phys. Lett. B 230, 1989)

In case of a two component time distribution, the most precise result for the longer decay is obtained from the slope of the long component of the total time distribution.





The distribution of the time-correlated background at 180 keV.

The position, FWHM and the artificial slope of the relatively fast background time distribution are dependent on the energy.

Conclusions

The **EXILL&FATIMA** campaign was a ground-breaking facility for future γ-γ timing experiments using **large fast-timing arrays** such as: **DESPEC for FAIR@GSI**.

So far: More than 30 lifetimes in more than 12 nuclei have been measured in the range of 10 ps to 4 ns.
8 scientific articles on nuclear structure physics have been published.

Precise and consistent values could be determined for cases with peak-to-background ratio of 0.3 to 2.5.

New GCD method to generate and analyze γ-γ time distributions.
Good background-time correction by precise determination of peak-to-background ratios and centroids of background-time distributions.

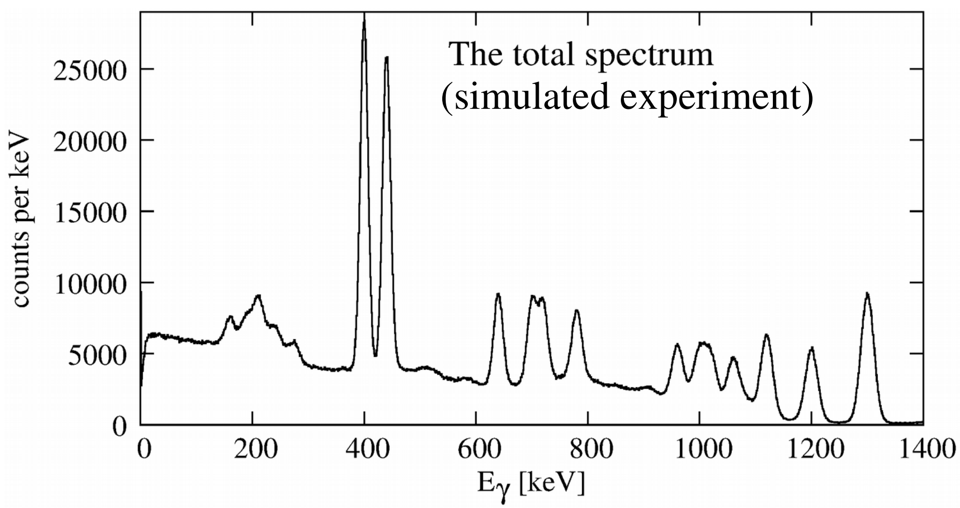
Experimental observations on the timing behavior of the background are confirmed by recent GEANT4 Monte Carlo simulations.

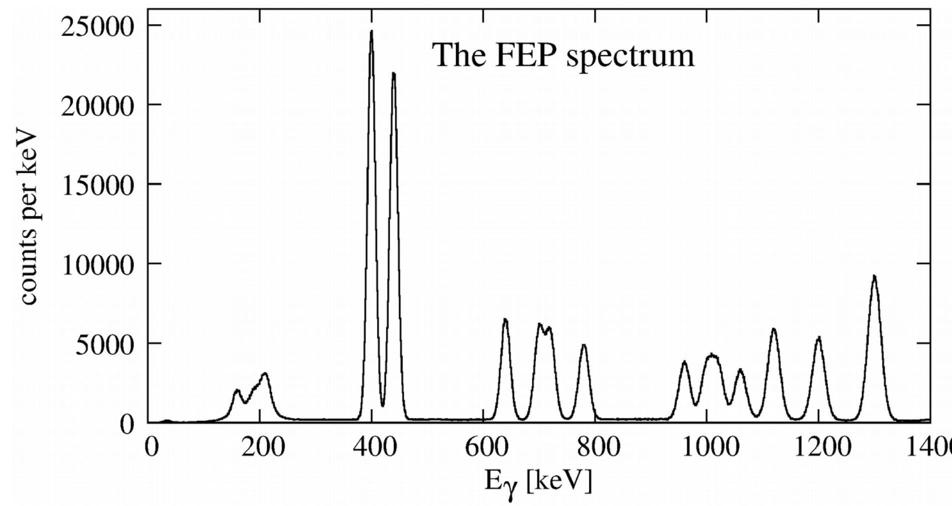
Thank you very much for your attention

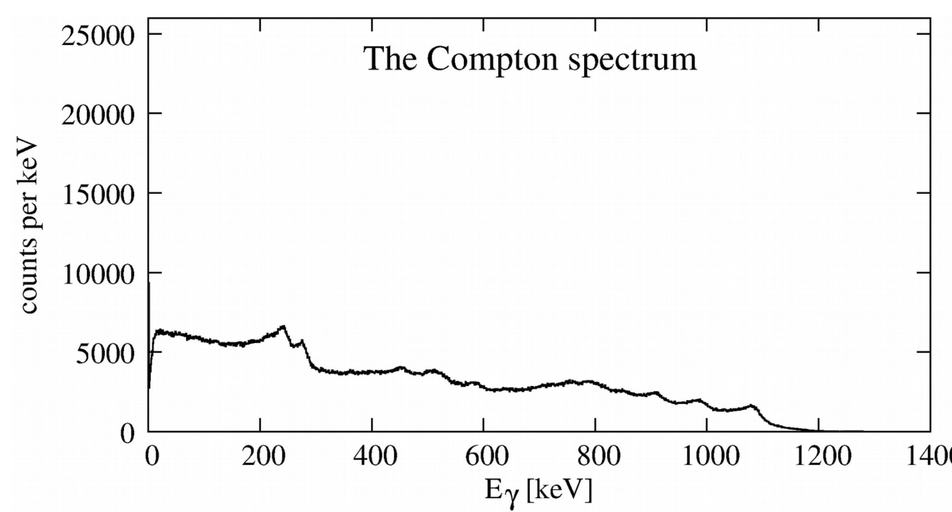
Monte Carlo Simulation of a γ–γ fast-timing experiment using GEANT4

- 2 LaBr3(Ce) detectors face-to-face with distance of 10 cm
- 3 different γ-ray interactions according to their cross sections
- location of each interaction and the corresponding energy release recorded
- intrinsic zero-time response related to full-energy peak (FEP) events
- **TEST**: non-linear time difference between FEP and Compton events (^{60}Co); simulation vs. experiment: **exact agreement!**

Simulation:



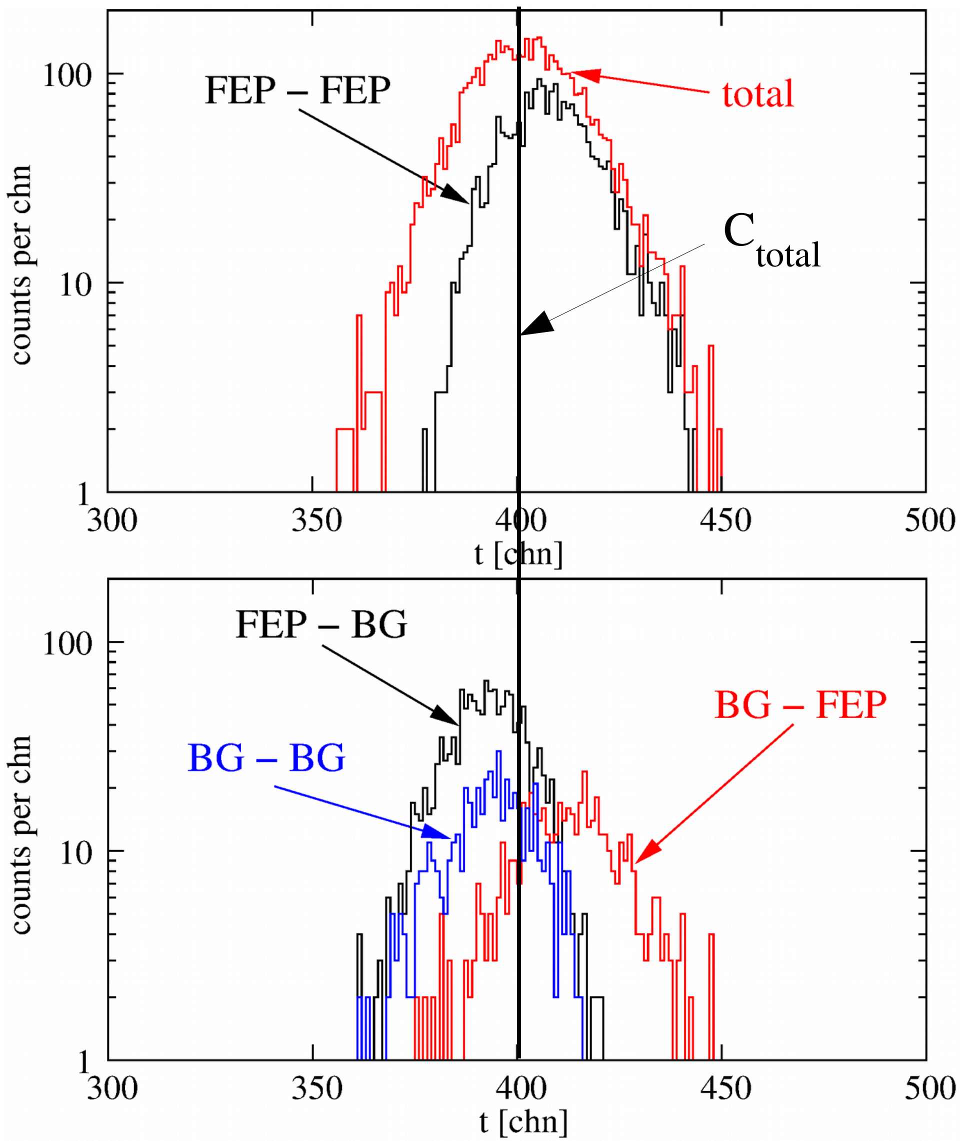




M. Dannhoff, IKP Köln, PhD Thesis in work

Monte Carlo Simulation of a γ–γ fast-timing experiment using GEANT4

One example:



Generated using a constant E_{feeder} - E_{decay} condition.

Component	centroid	relative intensity
Total (Exp.)	402	100%
FEP – FEP	408	47%
FEP – BG	392	30%
BG – FEP	412	12%
BG – BG	393	11%

First observation using different energies, lifetimes and P/B ratios:

No significant systematical error could be measured using the proposed time correction given on slide 12.

to be continued ...

M. Dannhoff, IKP Köln, PhD Thesis in work