15th International Symposium on Capture Gamma-ray Spectroscopy and Related Topics (CGS15)

26.08.2014, Technische Universität Dresden

The Generalized Centroid Difference Method

for lifetime measurements via γ-γ coincidences using large fast-timing arrays

SPONSORED BY THE
Federal Ministry of Education and Research

Jean-Marc Régis

Institute of Nuclear Physics
Cologne, Germany

NuPNET
ERA-NET for Nuclear Physics Infrastructures

ikp

Content:

The Generalized Centroid Difference Method

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

γ-γ fast timing using **$LaBr_3(Ce)$** scintillator detectors

The **EXILL&FATIMA campaign 2013**

at the Institut Laue-Langevin

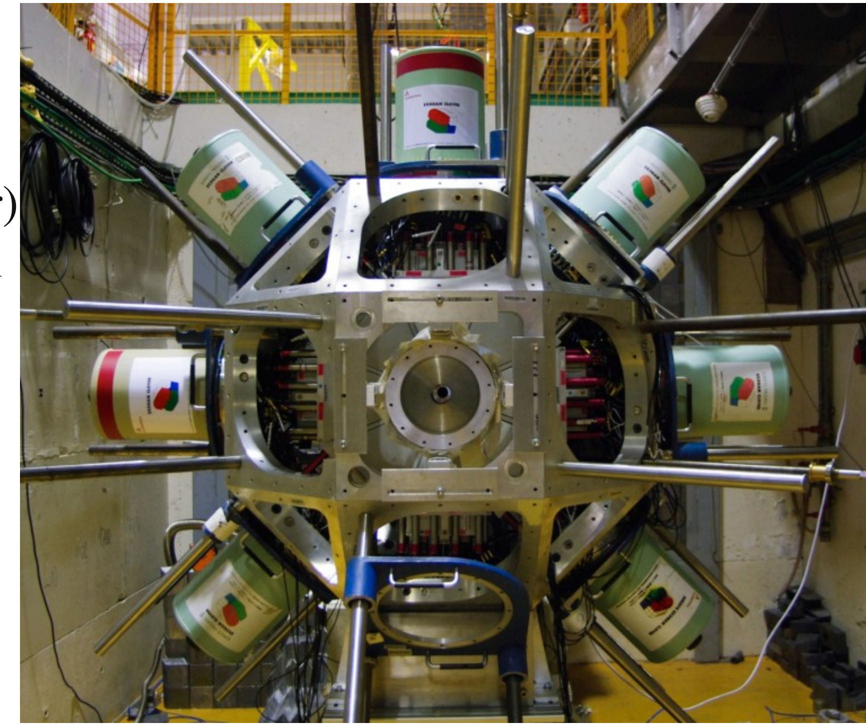
First results of **Germanium-gated γ-γ fast timing** of excited states in **fission products**

The EXILL and EXILL&FATIMA campaigns 2012 and 2013 at the

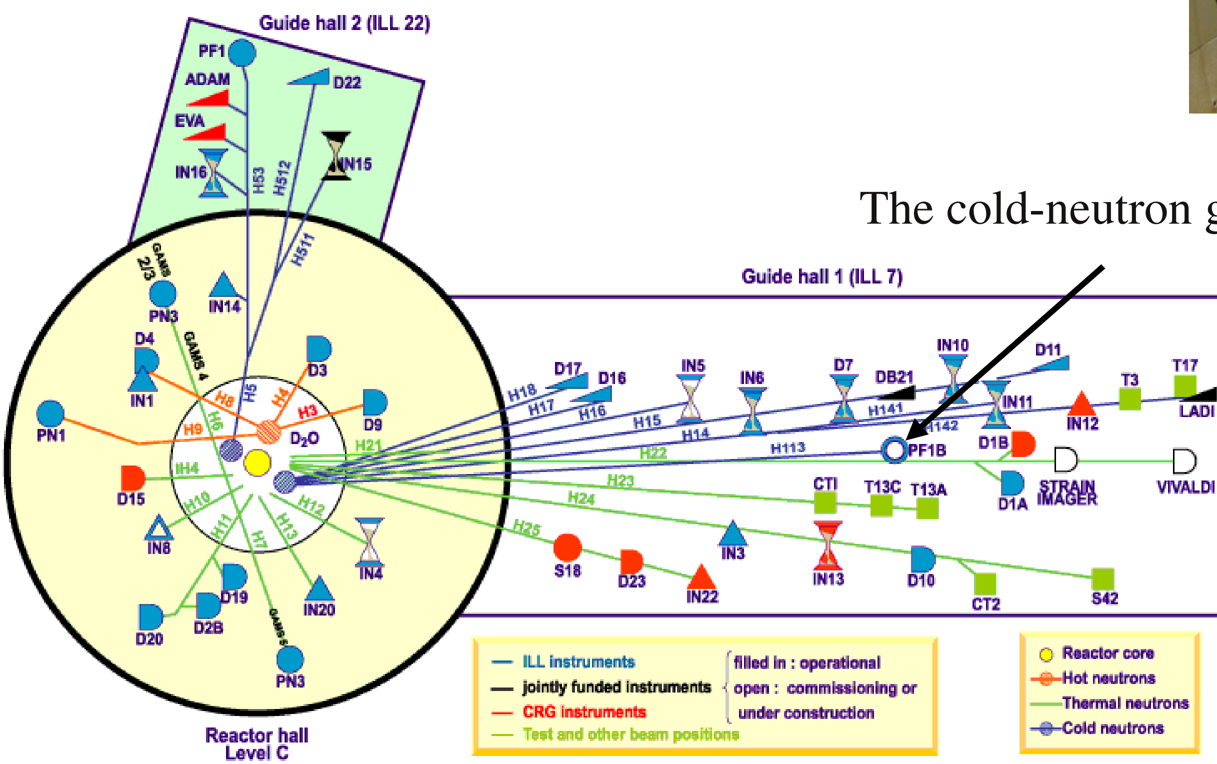
European research reactor of the
Institut Laue-Langevin
Grenoble, France

Collimated
(12 mm in diameter)
cold-neutron beam
with flux of about
10^8 n/(s cm²)

Part of the EXILL (EXOGAM@ILL) array



The cold-neutron guide PF1B



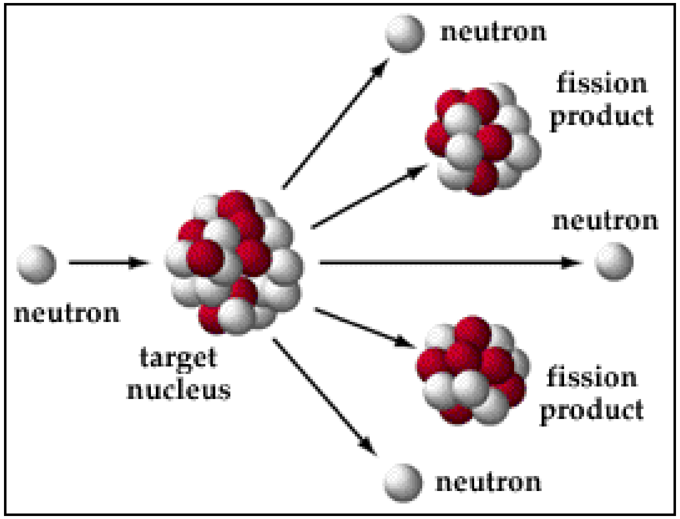
Aim: Prompt γ-ray spectroscopy for
nuclear structure studies using

neutron-capture (n,γ) experiments
(see talk of Jan Jolie)

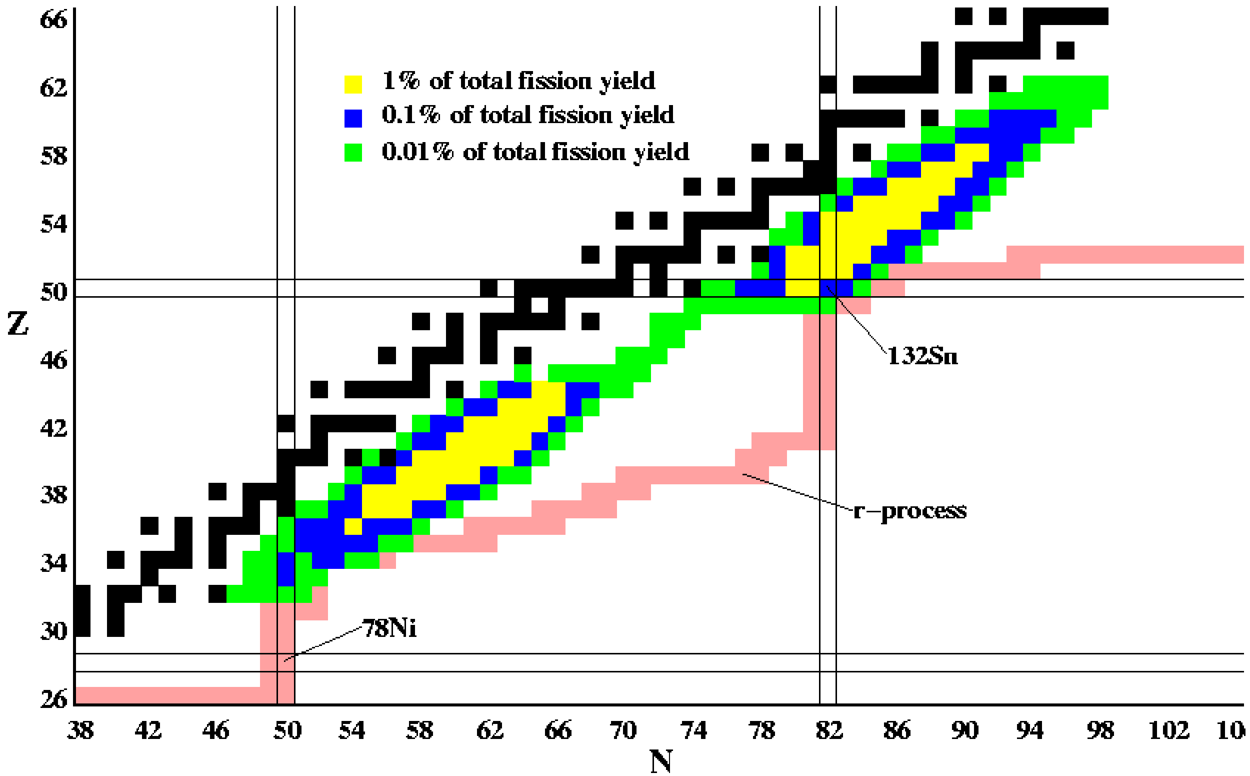
neutron-induced fission experiments

EXILL campaigns 2012/2013:

Prompt γ-ray spectroscopy of neutron-rich fission products



Thermal-neutron induced fission of ^{235}U:



Physics cases:

Region close to doubly magic

132Sn and 78Ni

Investigation of nucleon-nucleon interactions

The **A~100** mass region

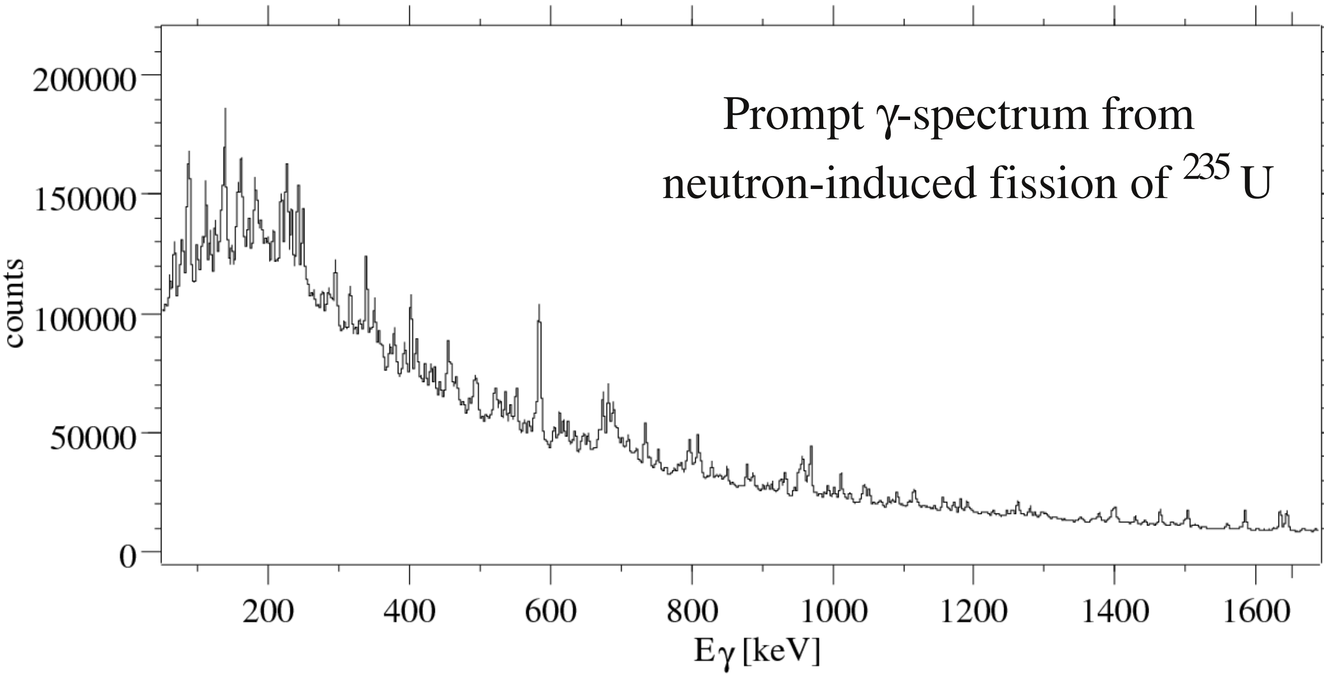
Evolution of collective excitations

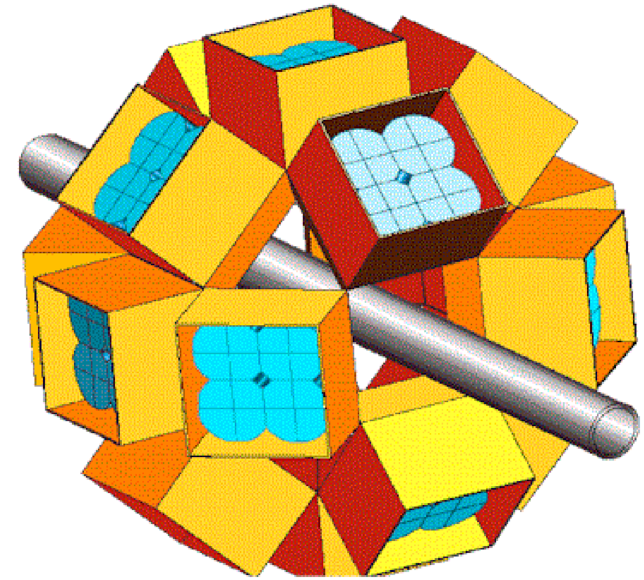
Shape transition or coexistence

Nuclear astrophysics on r-process nuclei

EXILL campaigns 2012/2013:

Prompt γ-ray spectroscopy of neutron induced fission products





Experiment:

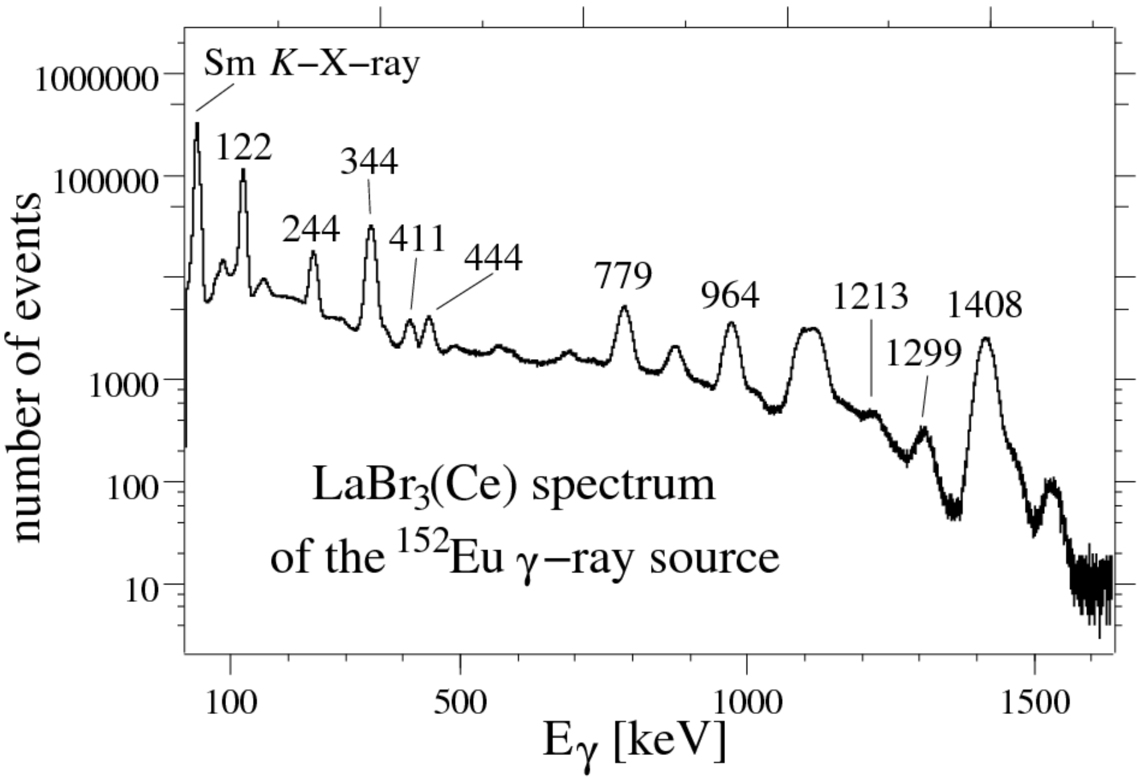
Some **200 nuclei** are produced with intermediate **high mean spin and high γ-ray multiplicity**.

At least, **triple γ-γ-γ coincidences are needed** to resolve the level scheme of a fission product.

Highly segmented γ-ray detector array is needed.

Ge-gated γ-γ fast timing possible using $LaBr_3$(Ce) scintillator detectors.

The $LaBr_3$(Ce) scintillator detectors for γ-ray spectroscopy

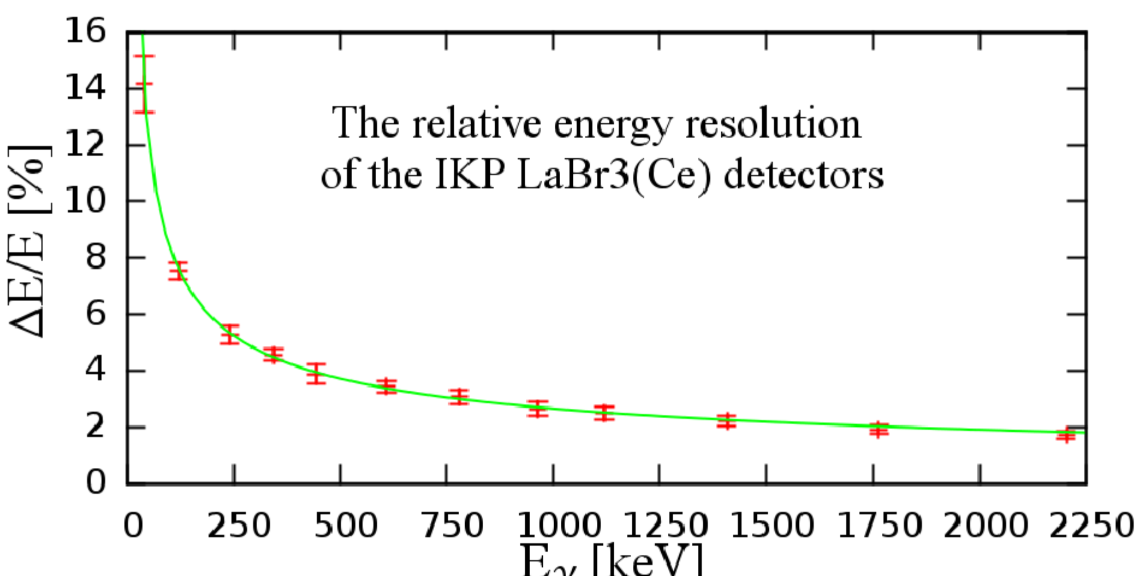


Amongst scintillators, the $LaBr_3$(Ce) provides
the **best energy resolution**
and corollary
the **best peak-to-background ratio.**

⇒ **$LaBr_3$(Ce) is the best choice for fast timing using γ rays.**

The **relative energy resolution** of 5% Ce-doped $LaBr_3$ scintillators:

3.3(2)% @ 662 keV.

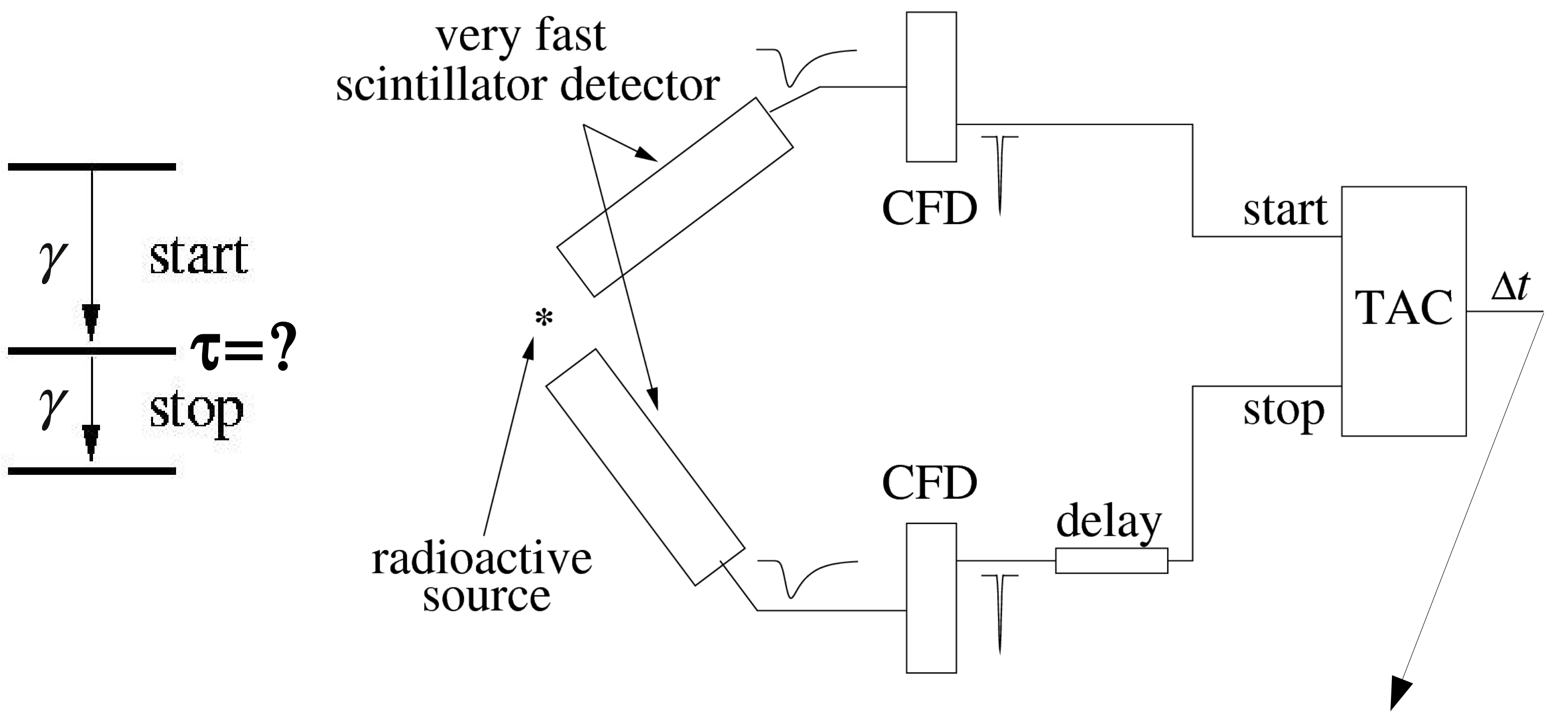


The γ-γ fast-timing technique

(CFD: constant fraction discriminator)

Setup:

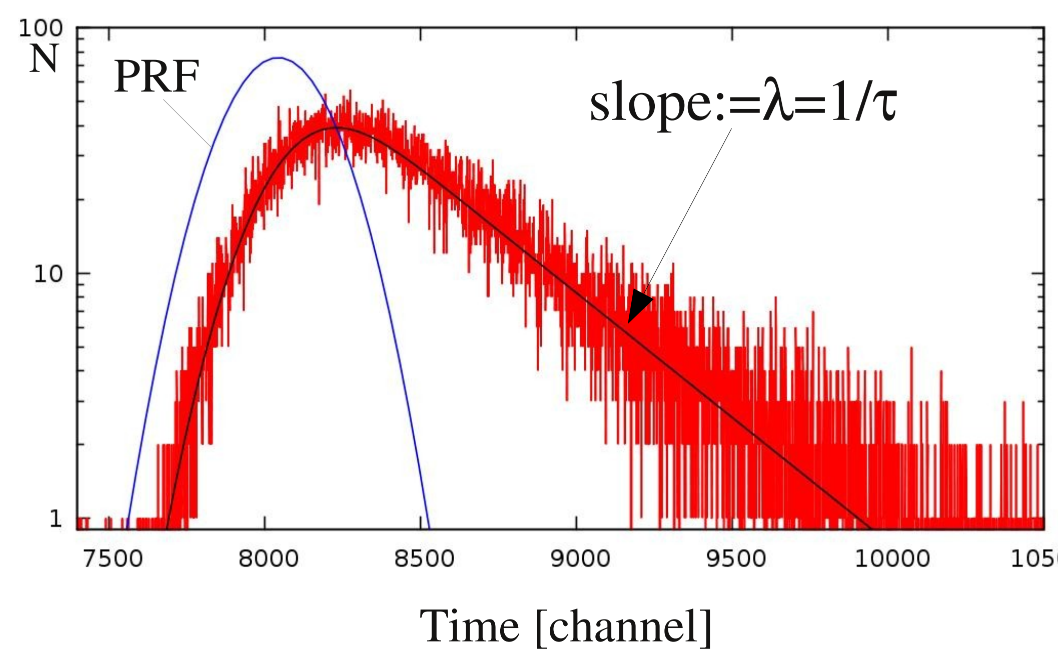
(TAC: time to amplitude converter)



The delayed time spectrum is a convolution of the **prompt response function** (PRF) *P(t)* with an exponential decay:

$$D(t) = \lambda N_0 \int_{-\infty}^{t} P(x) e^{-\lambda(t-x)} dx$$

Ideally, the PRF is a Gaussian distribution.



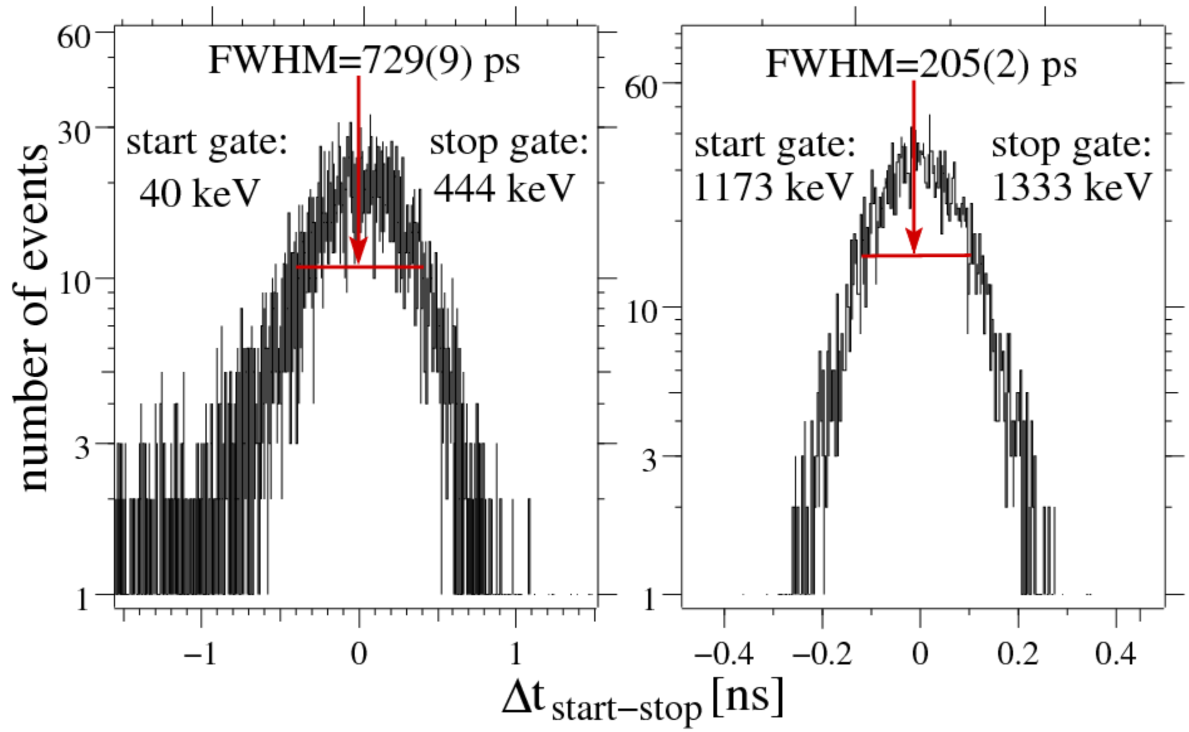
LaBr$_3$(Ce) γ-γ timing performance:

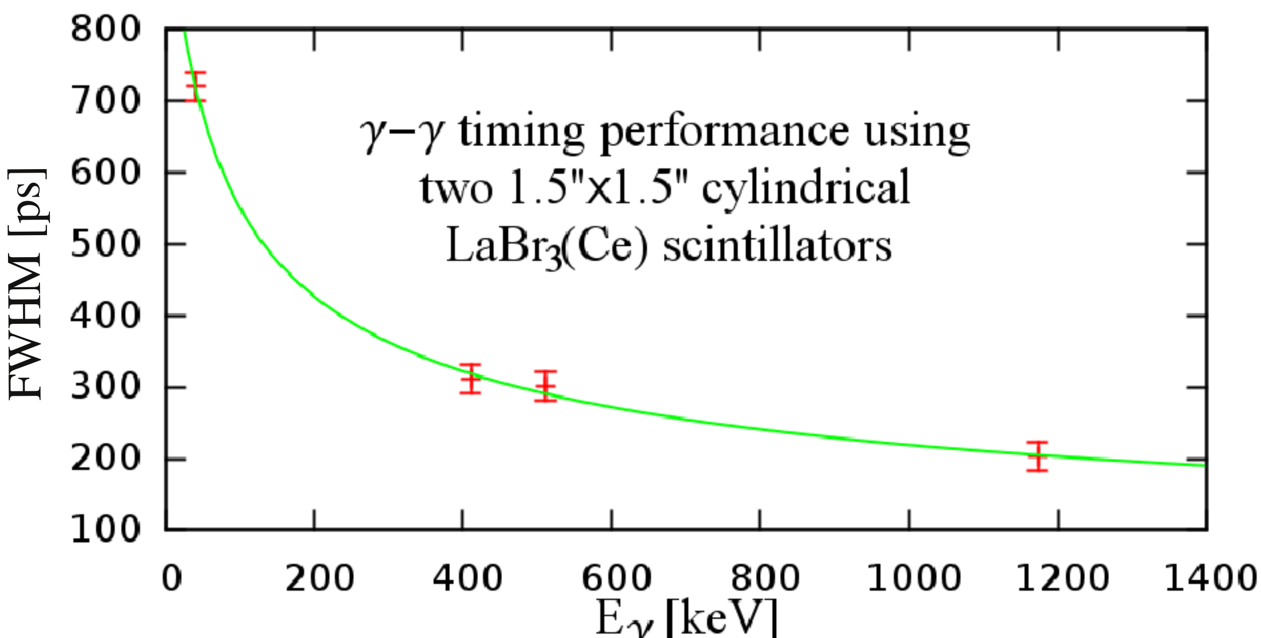
The FWHM of the PRF provides the limit of the slope method.

$\ln[D(t)] = -\lambda t$ for $t > t_0$+FWHM,

t_0 is the position (centroid) of the PRF.

Experimental PRFs (τ < 1 ps):





The non-linear "time-jitter" is due to the decrease of the relative amplitude variation with increasing amplitudes (energies).

Constant time spread related to the crystal size (light collection time) and the transit time spread of the PMT (~180 ps for two 1.5"x1.5" cylindrical LaBr$_3$ scintillators plus R9779 PMTs).

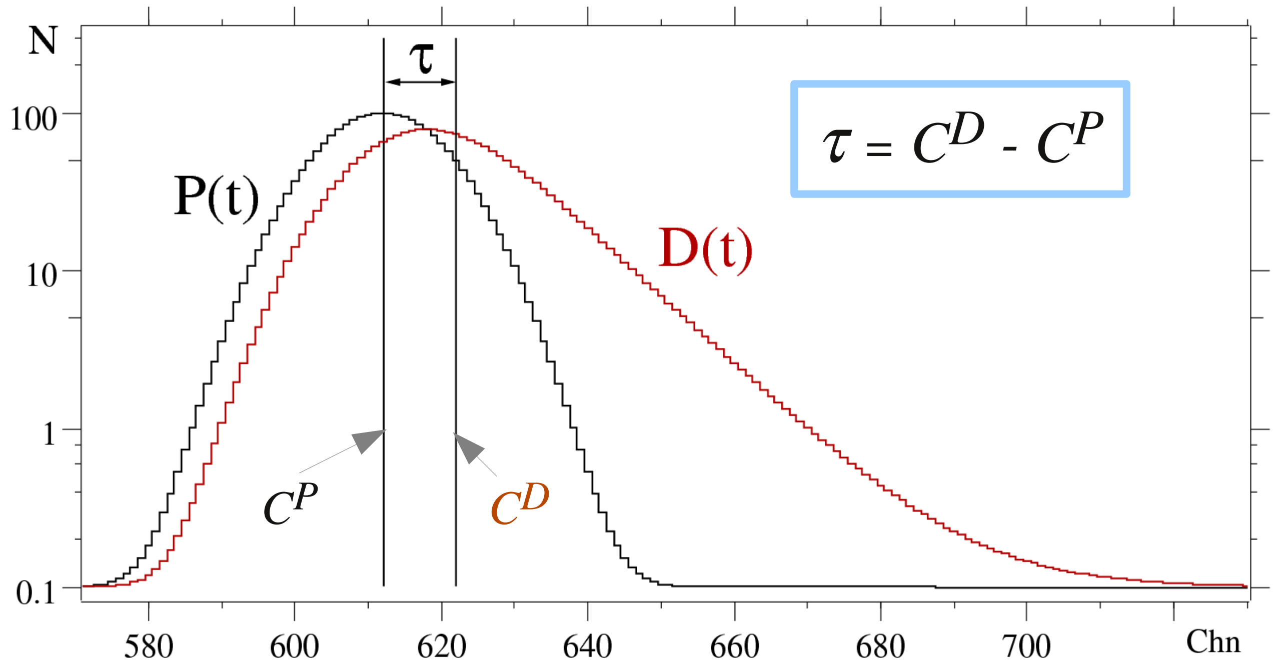
The Centroid Shift Method:

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

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

The statistical uncertainty is given by the standard deviation σ=FWHM/2.355 of the PRF:

$$\delta C = \delta t = \sigma / \sqrt{n}$$



Examples for extreme cases using two 1.5"x1.5" $LaBr_3$(Ce) scintillator detectors and assuming n=10000 events:

@ 1.2 MeV: FWHM=200 ps ⇒ $\delta t < 1$ ps

@ 40 keV: FWHM=730 ps ⇒ $\delta t = 3$ ps

The **centroid** of the "delayed" time spectrum is **shifted** from the "prompt centroid" of the convoluted PRF by the mean lifetime τ of the excited state:

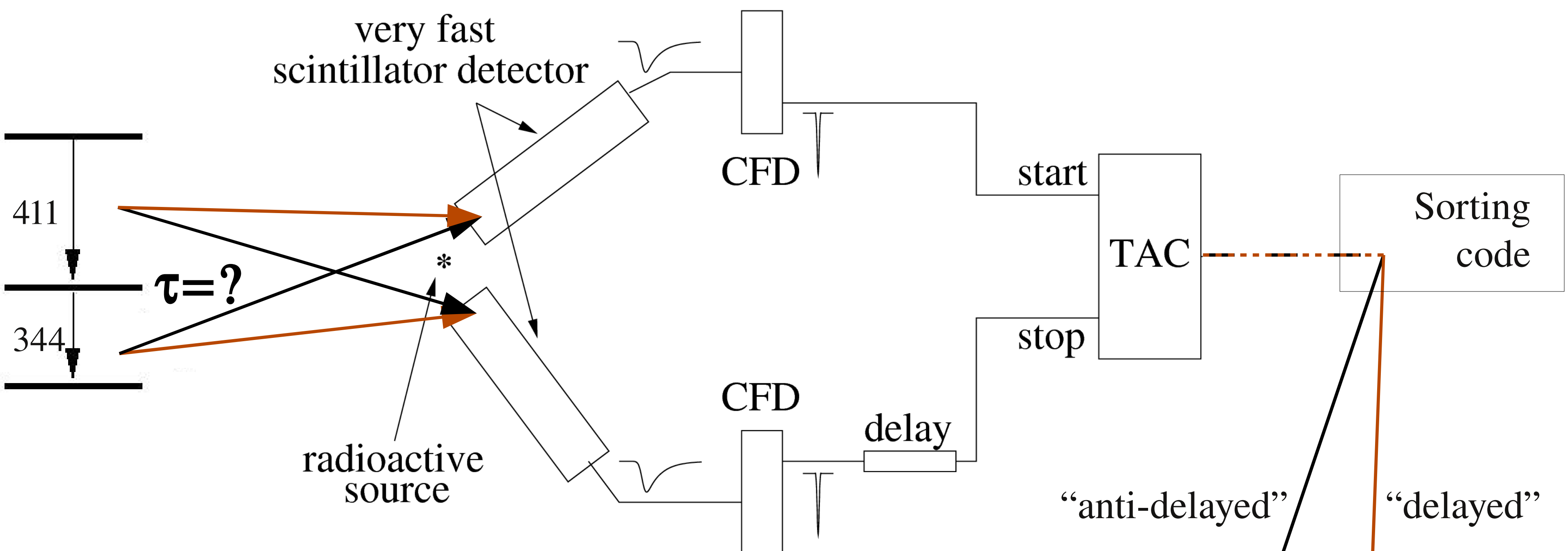
$$\tau = C^D(E_{start}, E_{stop}) \quad \underline{C^P(E_{start}, E_{stop})}$$

"the time-walk characteristics"

Note:

The PRF centroid C^P defines the physical zero-time independent of the shape of the PRF.

The γ-γ fast-timing technique

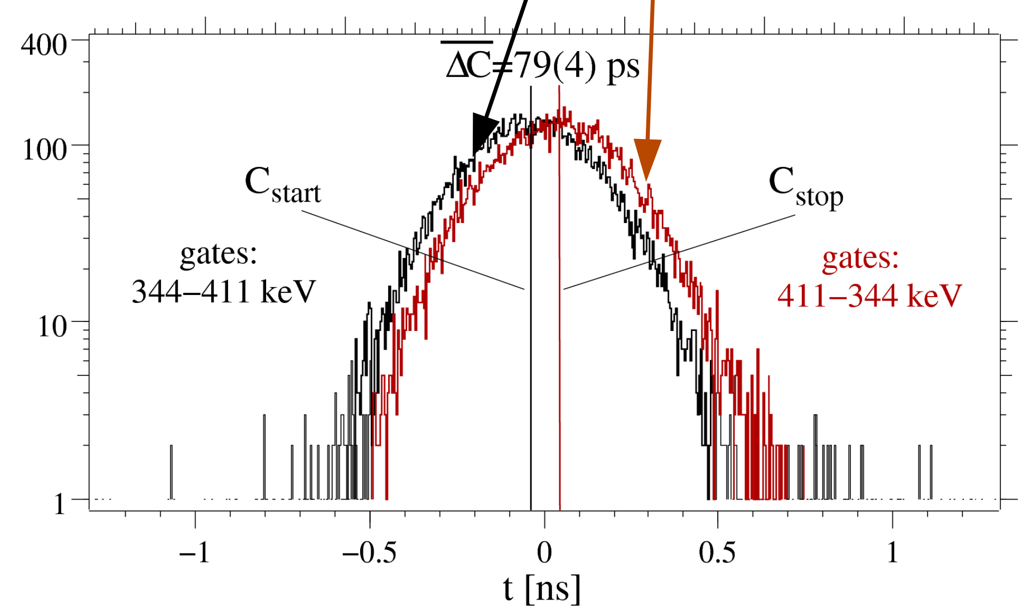


$$\Delta C_{decay} = C^{D}_{stop} - C^{D}_{start}$$

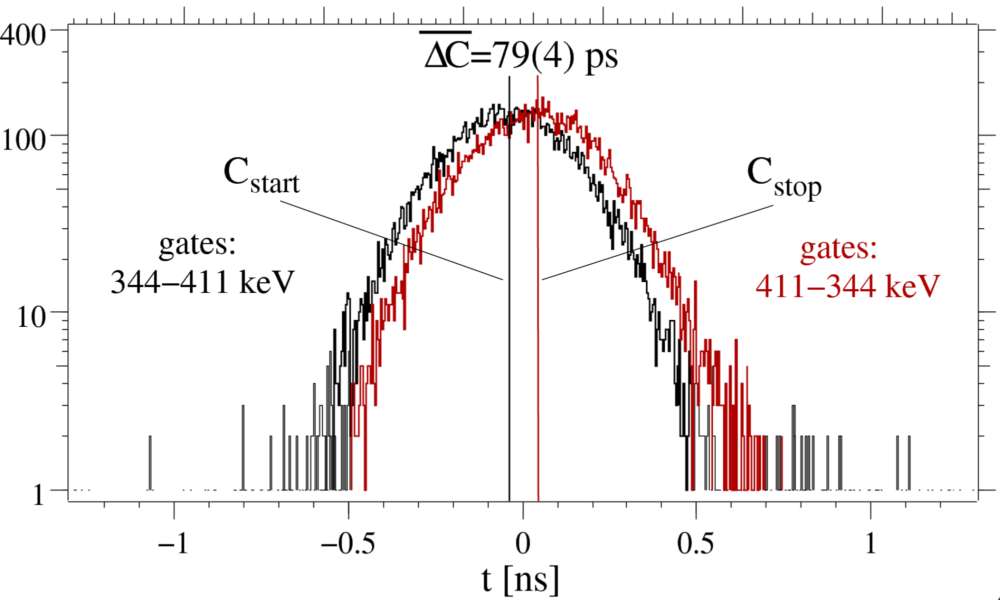
$$\Delta C_{decay} = C^{P}_{stop} - C^{P}_{start} + 2\tau$$

$$\boxed{\Delta C_{decay} = PRD_{decay} + 2\tau}$$

(PRD: prompt response difference)



The Mirror Symmetric Centroid Difference (MSCD) method



$$\Delta C(\Delta E)_{decay} = C^D_{stop} - C^D_{start} = \mathrm{PRD}(\Delta E) + 2\tau$$
$$\Delta E = E_{feeder} - E_{decay}$$

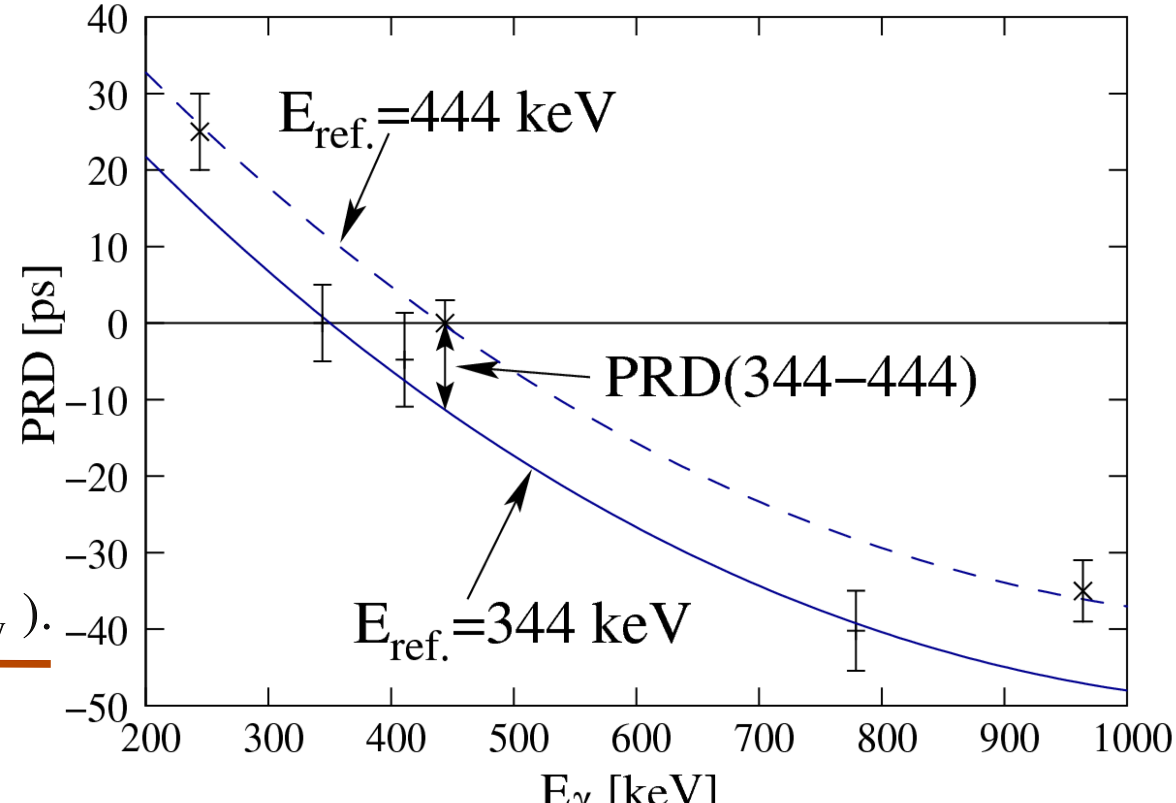
The **Prompt Response Difference**, $\mathrm{PRD} = C^P_{stop} - C^P_{start}$, describes the combined γ-γ time-walk characteristics of the setup.

The PRD is mirror symmetric:
$\mathrm{PRD}(\Delta E)_{decay} = -\mathrm{PRD}(-\Delta E)_{feeder.}$

The universal prompt calibration point:
$\mathrm{PRD}(\Delta E=0)=0.$

The PRD for any energy combination is given by:
$\mathrm{PRD}(\Delta E)_{decay} = \mathrm{PRD}(E_{feeder}) - \mathrm{PRD}(E_{decay})$.

The centroid difference diagram:



J.-M. Régis et al., NIM A **622** (2010)

The typical γ-γ time-walk characteristics of 2 $LaBr_3(Ce)$ detector assemblies

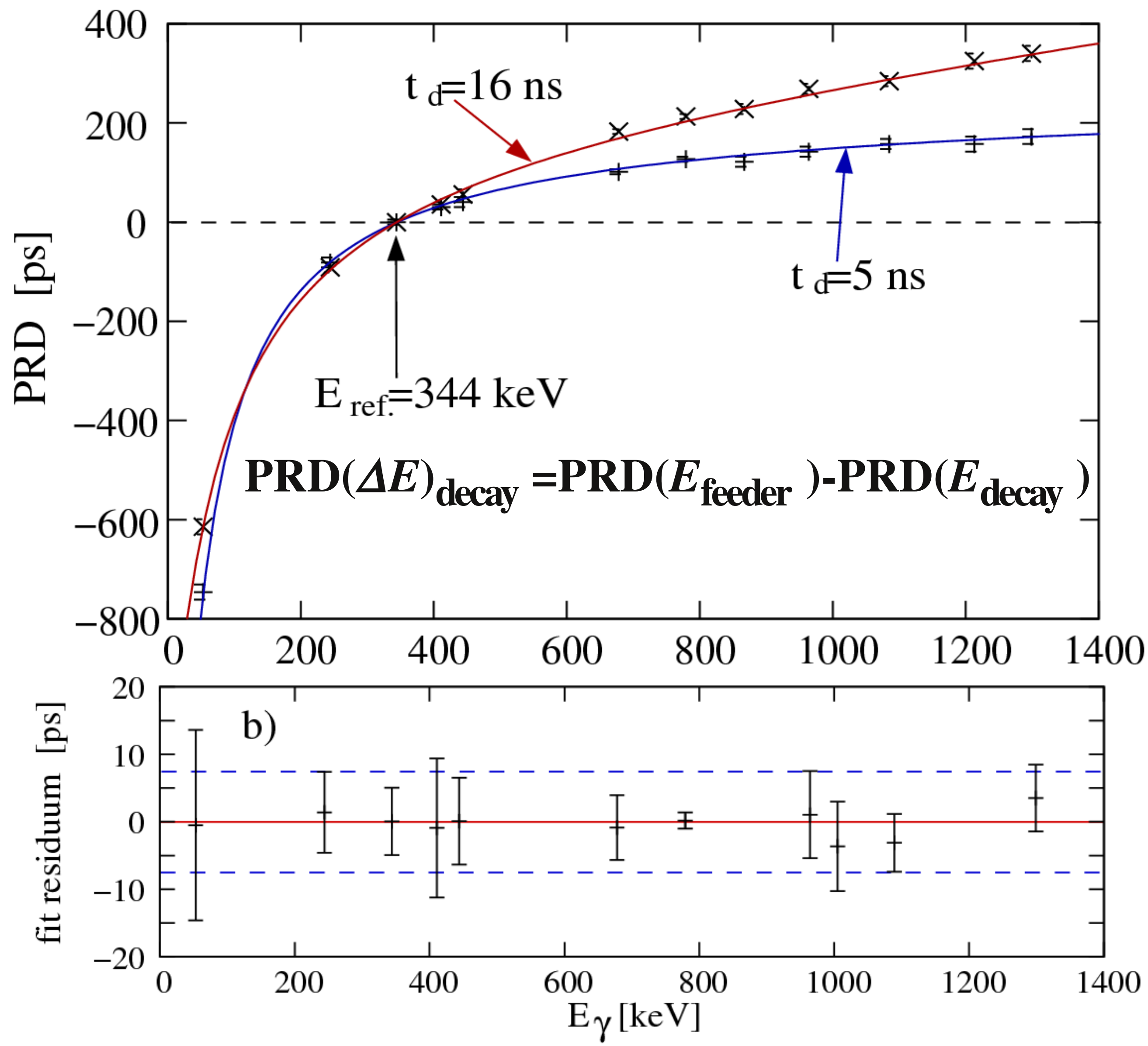
Calibration function:

$$\Delta C(E_\gamma) = \frac{a}{\sqrt{b + E_\gamma}} + cE_\gamma + d$$

Measured using a
^{152}Eu γ-ray source

Cancellation of time drifts
and timing asymmetries.

Precision of the PRD calibration:
~ 10 ps



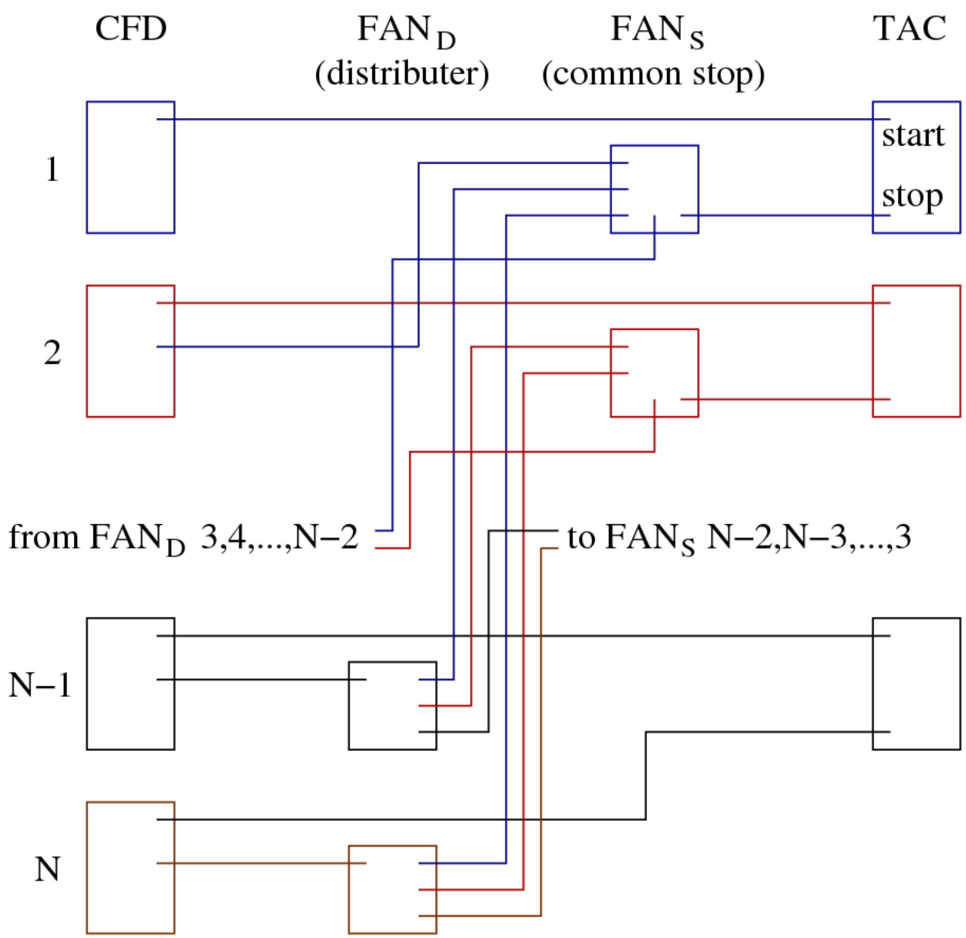
Limitation of the lifetime determination
for 40 keV < E_γ < 1408 keV:

δτ ~ 5 ps

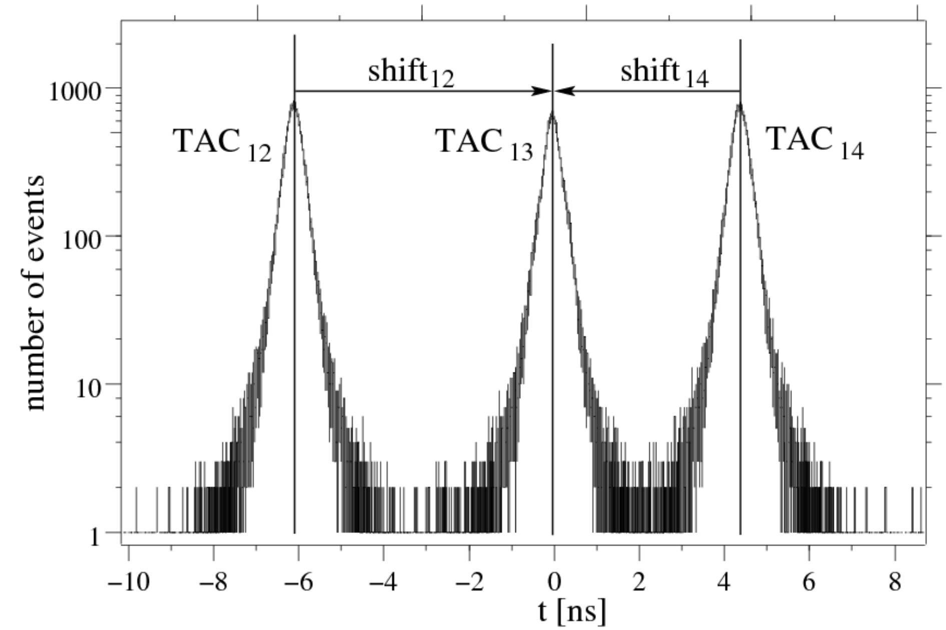
J.-M. Régis et al., NIM A **684** (2012)

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

An analog γ-γ fast-timing circuitry for an *N* detector fast-timing array:



Projection of TAC 1:



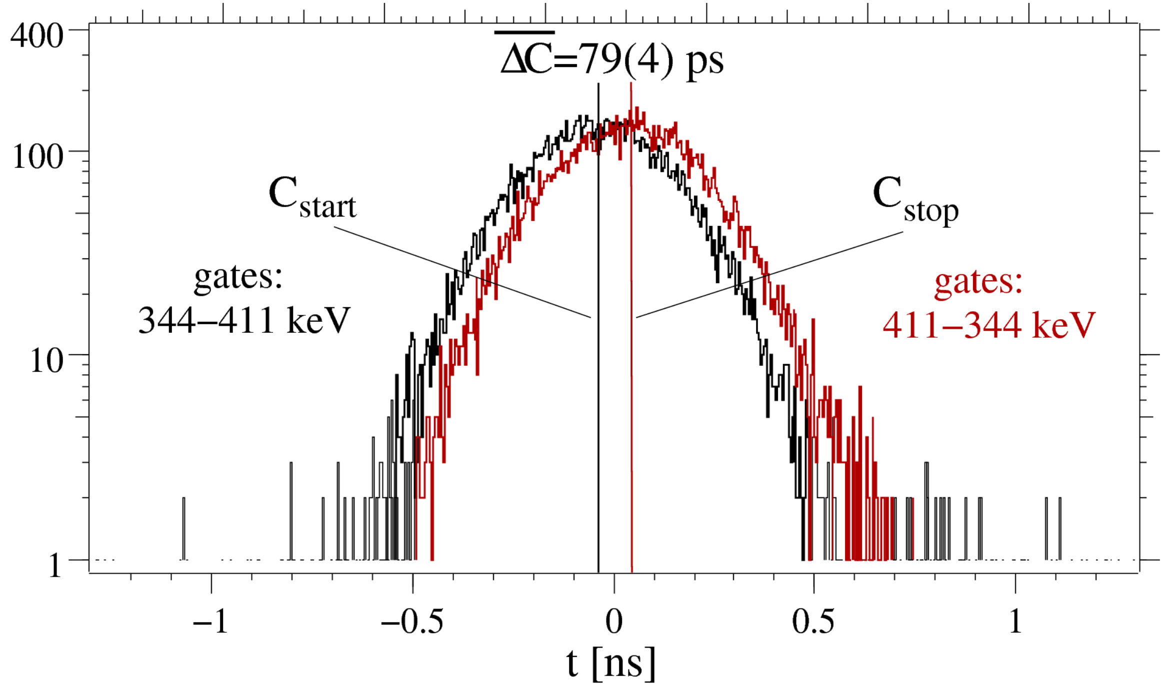
The TAC $shift_{ij}$ is defined by the cable length difference (time-shift) between the start and the different stop signals.

- Only minimum 2-fold coincidences are recorded ⇒ reduction of dead time effects.
- Coincidence resolving time of 5 ns achievable ⇒ reduction of random coincidences.
- Additional electronic time jitter < 10 ps.

J.-M. Régis et al., NIM A **721** (2013)

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

[J.-M. Régis et al., NIM A **721** (2013)]



The superposition of the N(N-1)/2 (aligned) time-difference spectra is mathematically equivalent to the definition of the mean:

$$\overline{\Delta C}_{decay}(\Delta E) = C_{stop} - C_{start} = \overline{PRD}(\Delta E) + 2\tau$$

$$\Delta E = E_{feeder} - E_{decay}$$

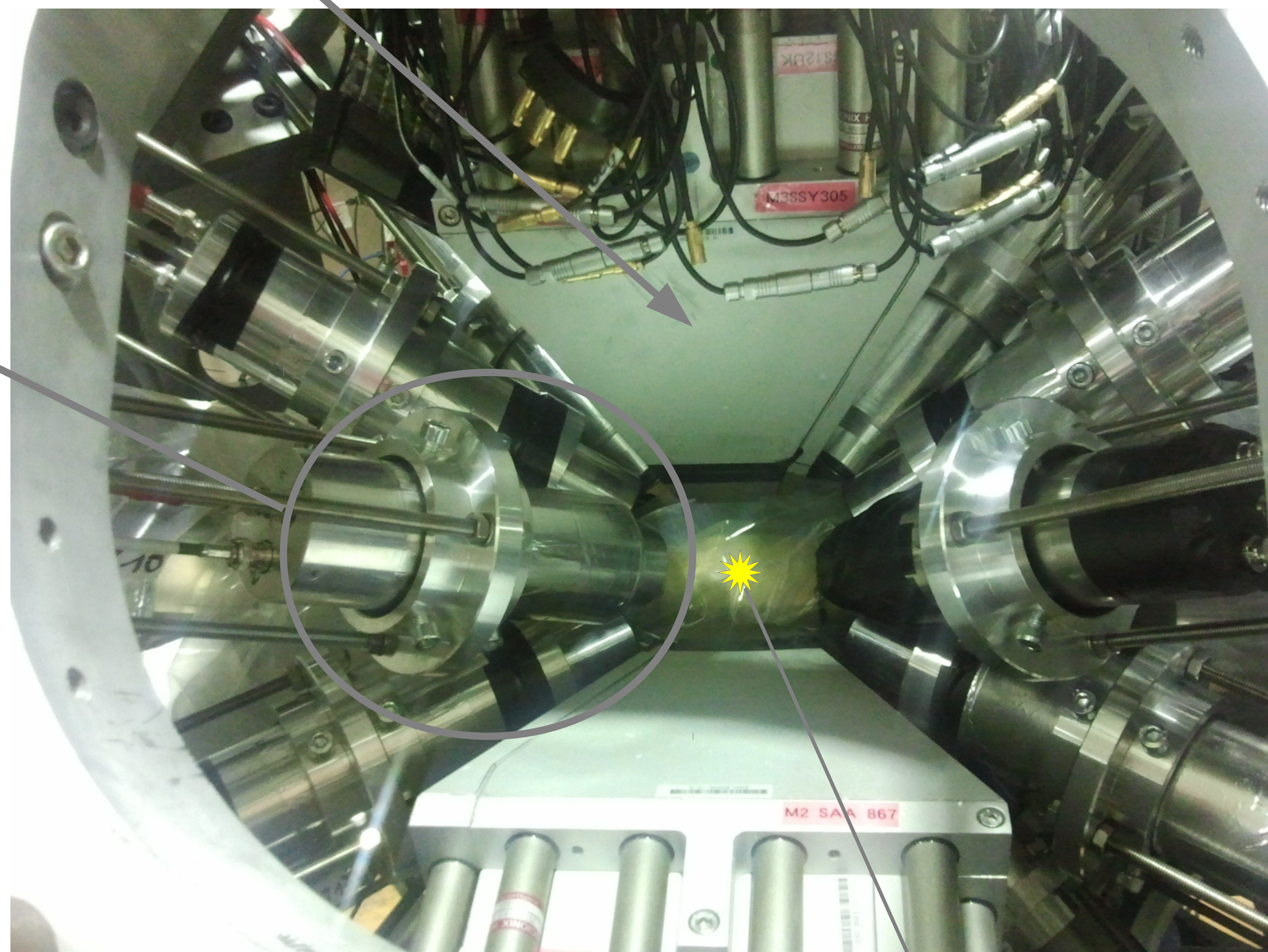
The mean prompt response difference $\overline{PRD}$ describes the combined zero-time vs. energy (time-walk) characteristics of the whole FATIMA spectrometer.

The fast-timing array FATIMA in combination with 8 EXOGAM clovers for Prompt γ-ray spectroscopy of 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



Digital trigger-less
data acquisition of
71 ADC channels

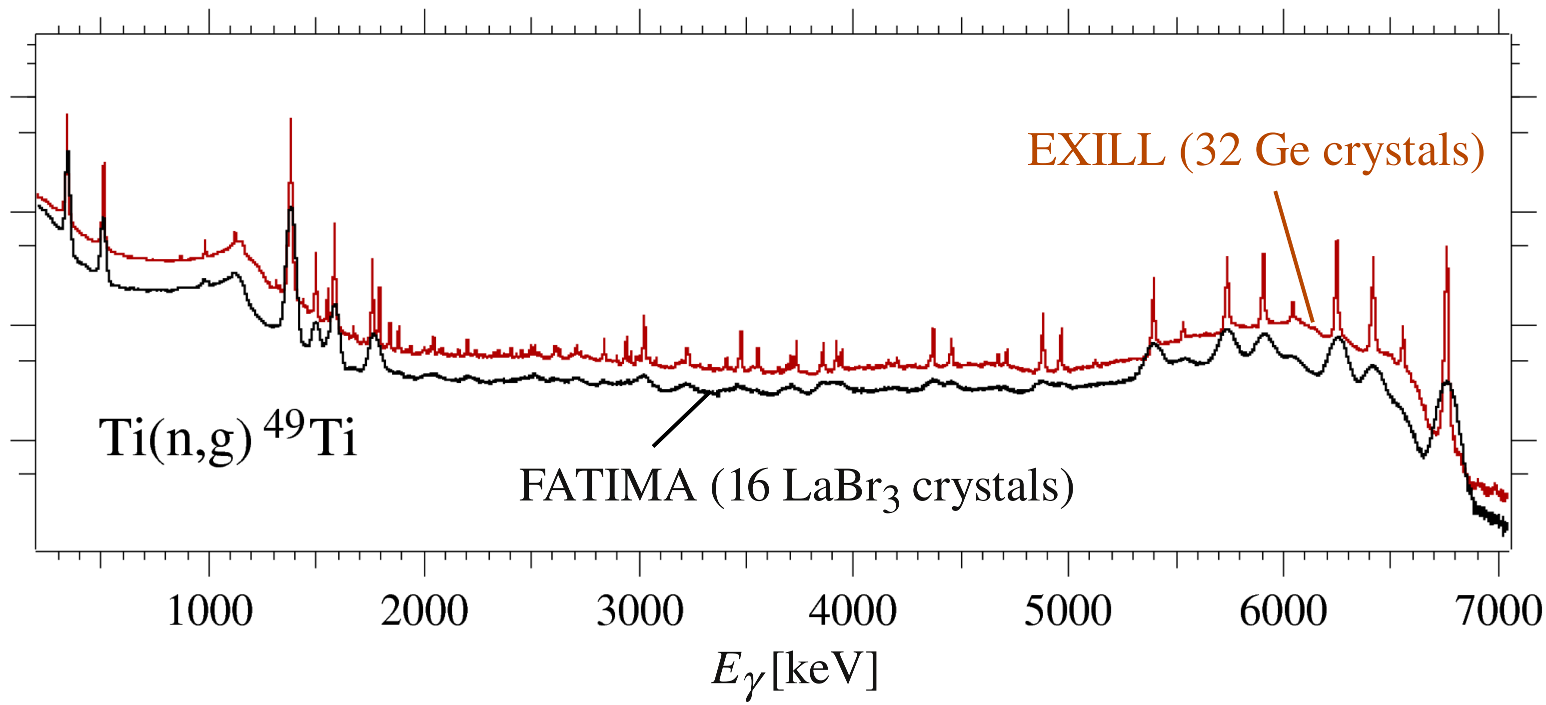
Data rate: up to 6.5 MB/s
Acquired data: ~ 40 TB

Target position

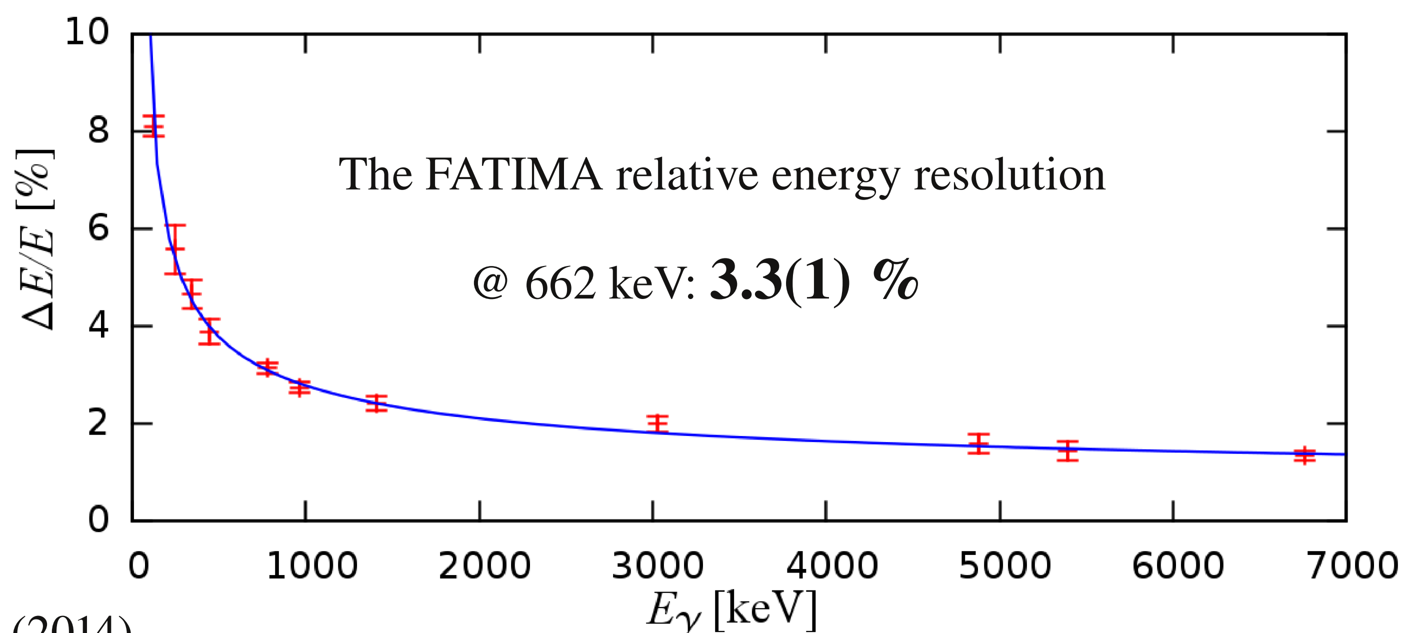
Energy performance of the EXILL & FATIMA spectrometer

Singles spectra

The $LaBr_3$ spectra need to be gain-matched in order to obtain the best energy resolution.



Fit function corresponds to the optimum resolution, as obtained for a linear energy response.

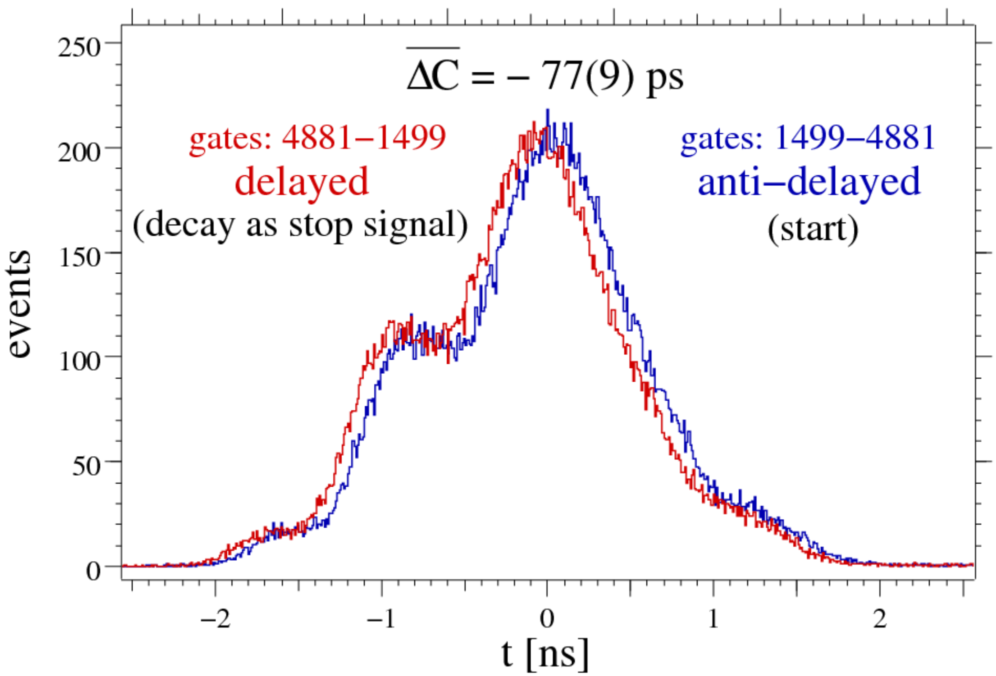


J.-M. Régis et al., NIM A **763** (2014)

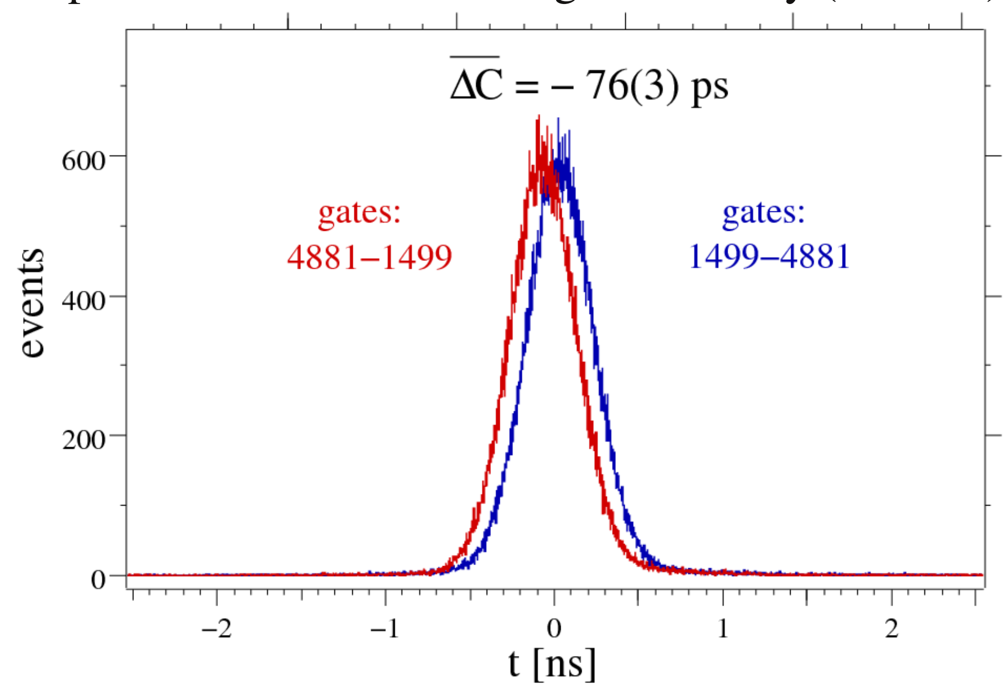
The generalized centroid difference method for EXILL&FATIMA 2013:

Superposition of fast-timing data independent of the detector-detector combination ij.

Raw data of a γ-γ cascade:



Aligned data using "$shift_{ij}$" constance in order to improve the statistical timing uncertainty (FWHM)



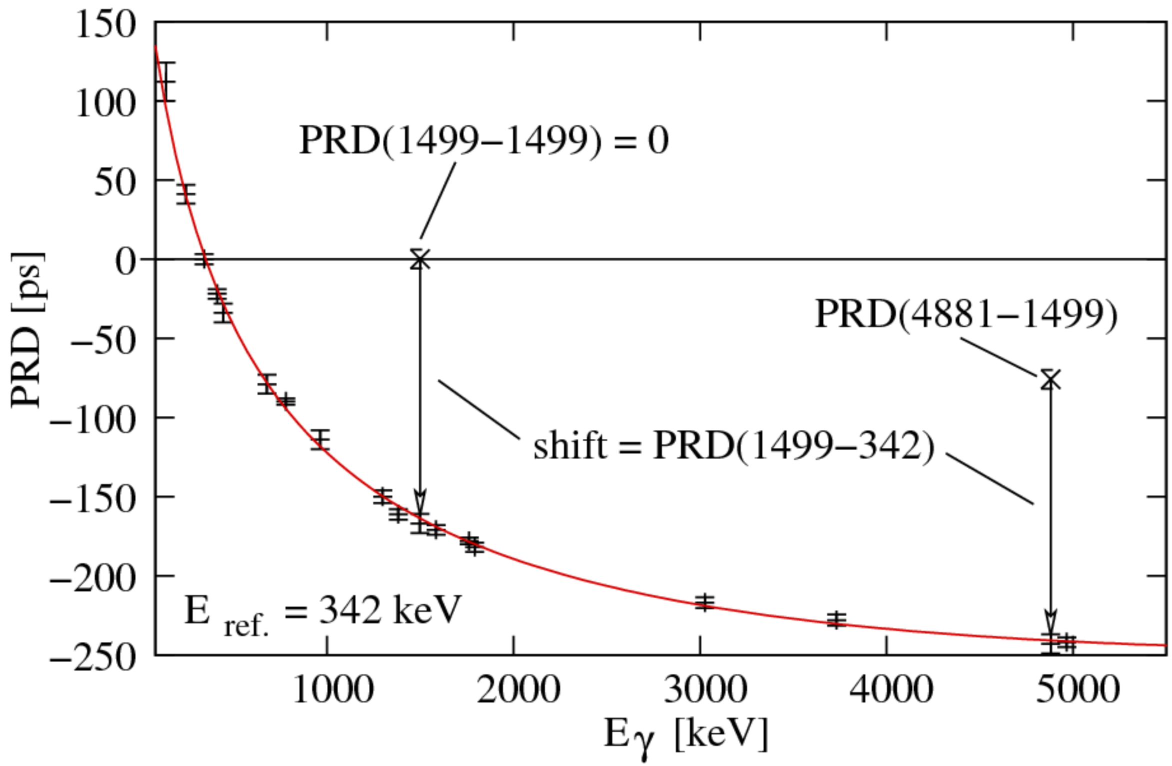
The centroid difference is independent of possible timing asymmetries.

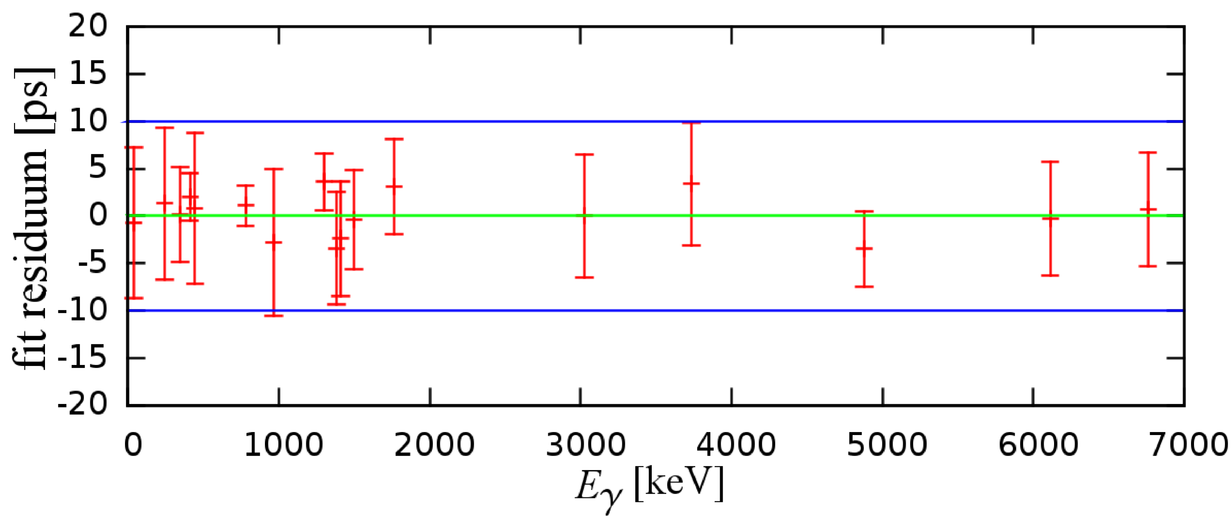
The centroid difference is independent of the $shift_{ij}$.

The electronic time drifts due to thermal fluctuations are canceled by the measurement of the centroid difference.

EXILL & FATIMA 2013: Ge-gated γ-γ fast timing

Picosecond sensitive lifetime determination using the GCD method.





Measured using
Ge-$LaBr_3$-$LaBr_3$ coincidences with
virtually no background contributions
from a ^{152}Eu source
for 40-1408 keV
and the reaction Ti(n,γ)^{49}Ti
for 137-6760 keV.

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

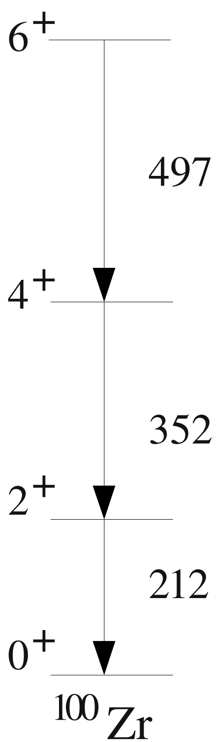
For 10000 events in the FATIMA time spectrum,
the **total uncertainty**
of the lifetime determination is
5 ps.

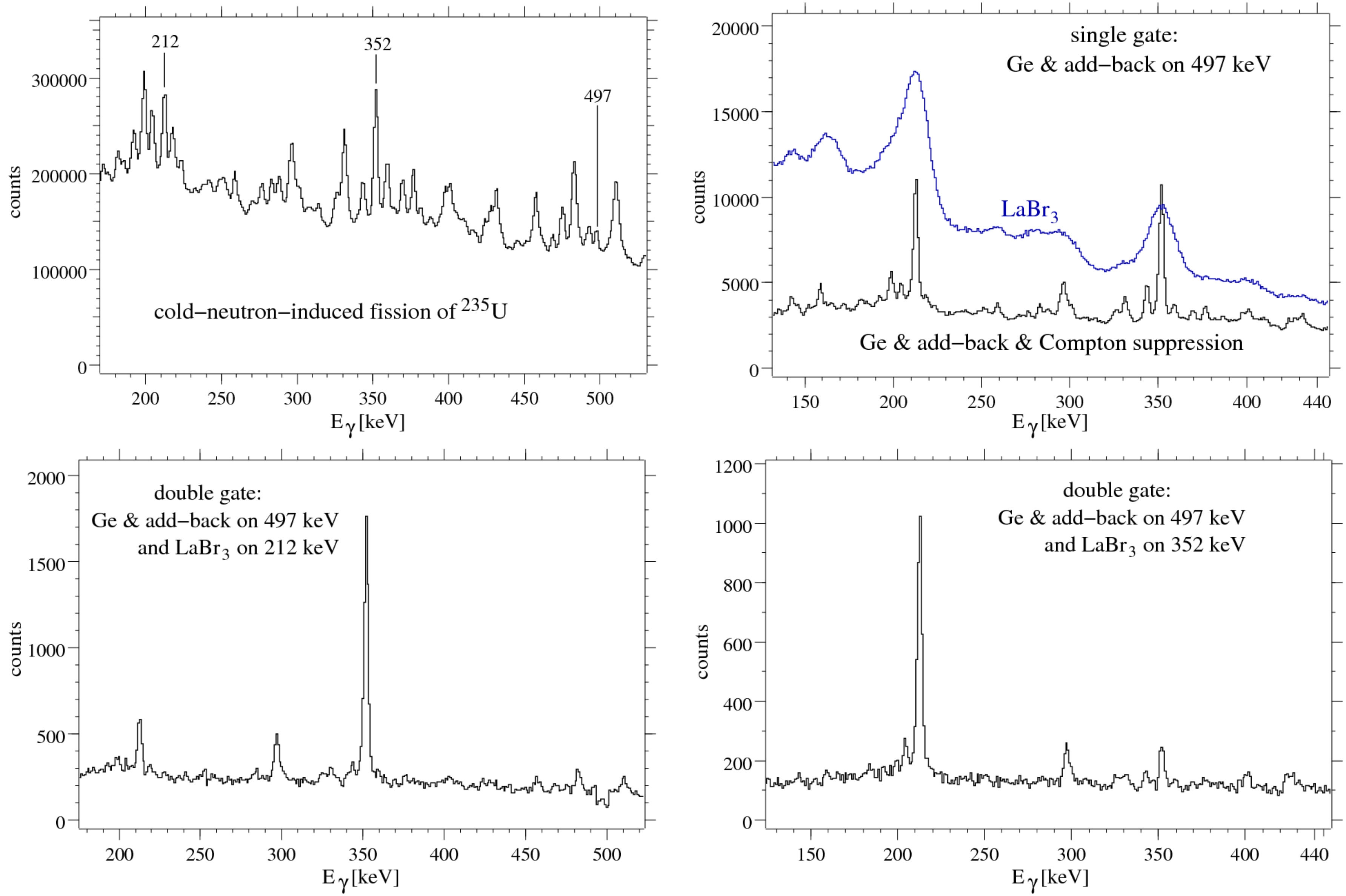
J.-M. Régis et al., NIM A **763** (2014)

EXILL & FATIMA 2013: Ge-gated γ-γ timing in about 100 fission fragments

Tests on ^{100}Zr (fission yield = 4.98% using ^{235}U target)

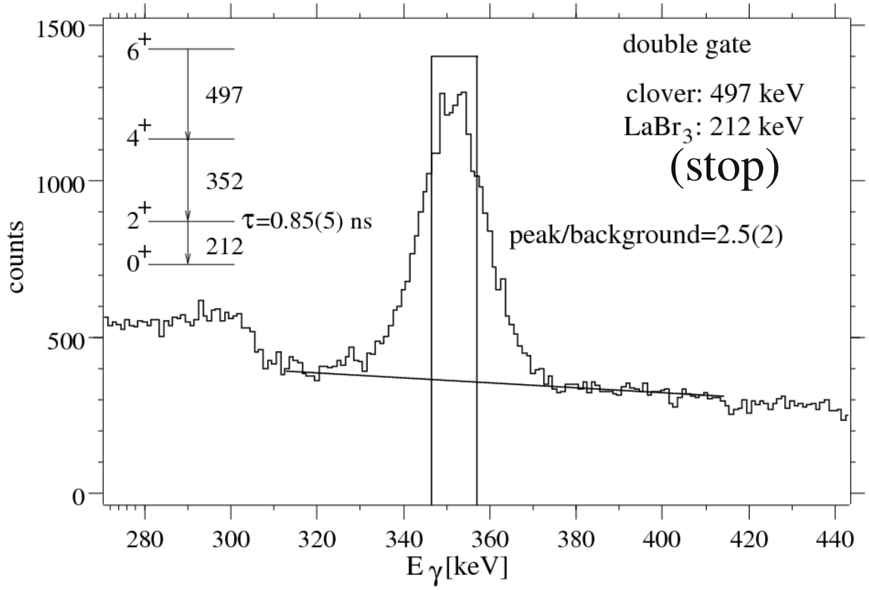
Used triple γ-γ-γ events out of 8 TB of data



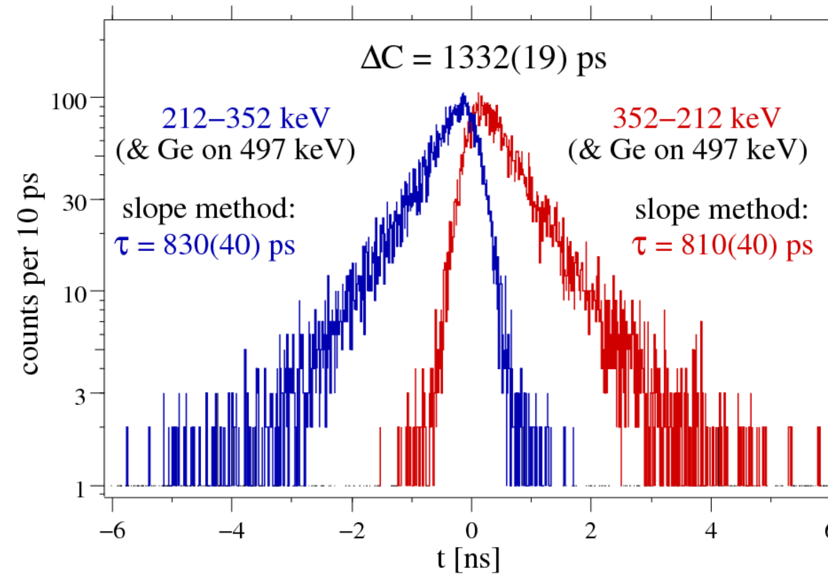


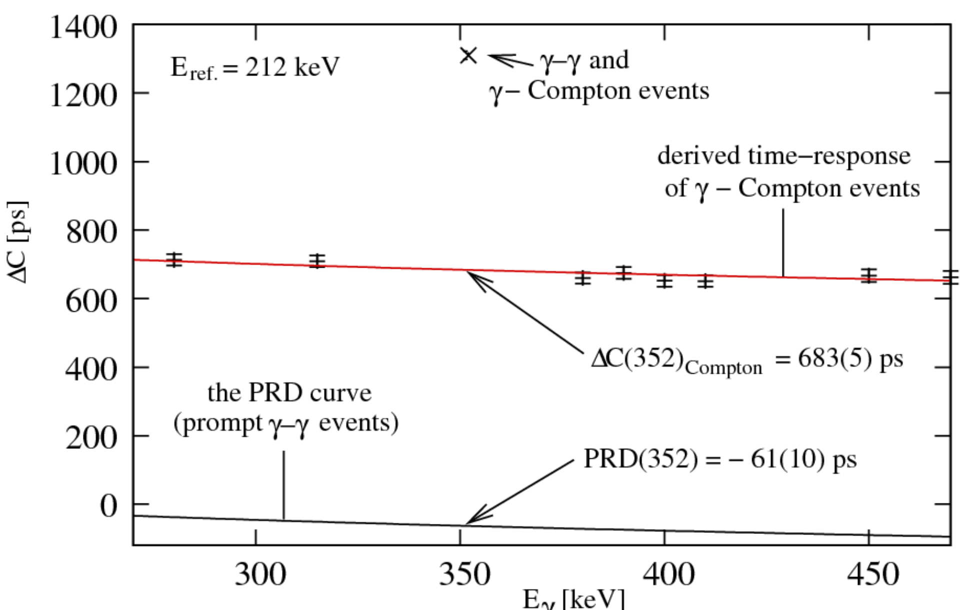
EXILL & FATIMA 2013: Ge-gated γ-γ fast timing

$LaBr_3$ projection of the doubly gated (E_γ,t)-start matrix



The two EXILL-gated FATIMA time spectra of the 352-212 keV cascade in ^{100}Zr





The GCD correction procedure for timing contributions of the Compton background:

$$\Delta C_{true} = \Delta C + \frac{\Delta C - \Delta C_{Compton}}{\Pi}$$

Π is the peak-to-background ratio.

Result: **τ = 820(20) ps**.

Inspired and sponsored by the FATIMA collaboration:
http://nuclear.fis.ucm.es/fasttiming/

L.M. Fraile, H. Mach, V. Paziy, G.S. Simpson, W. Korten, P.H. Regan, Zs. Podolyak, A.M. Bruce, C. Townsley, O.J. Roberts, J. Jolie, N. Saed-Samii, T. Kröll, S. Ilieva, S. Lalkovski, N. Marginean, D.G. Ghita, et al.

Many thanks to the EXILL core group for professional cooperation during the EXILL&FATIMA campaign 2013:

A. Blanc, G. de France, M. Jentschel, U. Köster, P. Mutti, G.S. Simpson, T. Soldner, C.A. Ur and W. Urban

THANK YOU FOR YOUR ATTENTION