Overview Lecture 1:

- Short Intro – Structural Evolution and the Role of Lifetimes
- The nano-second regime – Fast Electronics Scintillation Timing
  - Basic Principle; Examples from recent experiments
  - Future Applications
- The pico-second regime – Recoil Distance Doppler Shift Method
  - Plunger Device
  - Coincidence Analysis Technique
  - Example Application: Centrifugal Stretching

„Köln West”

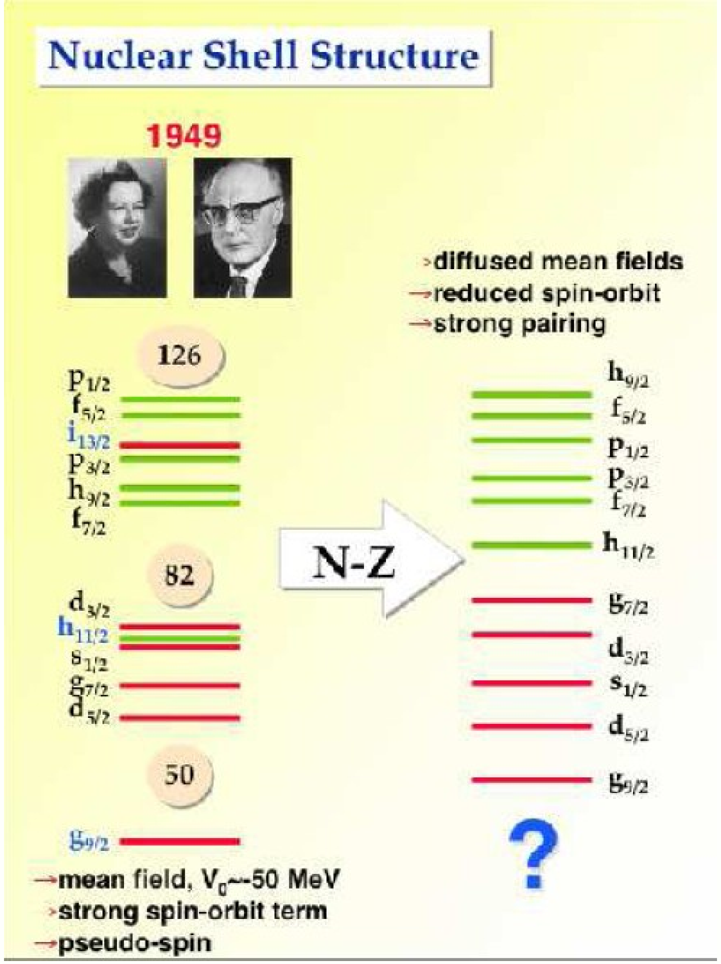
„Yale East”

Some Questions in Nuclear Structure Physics

(non-complete!)

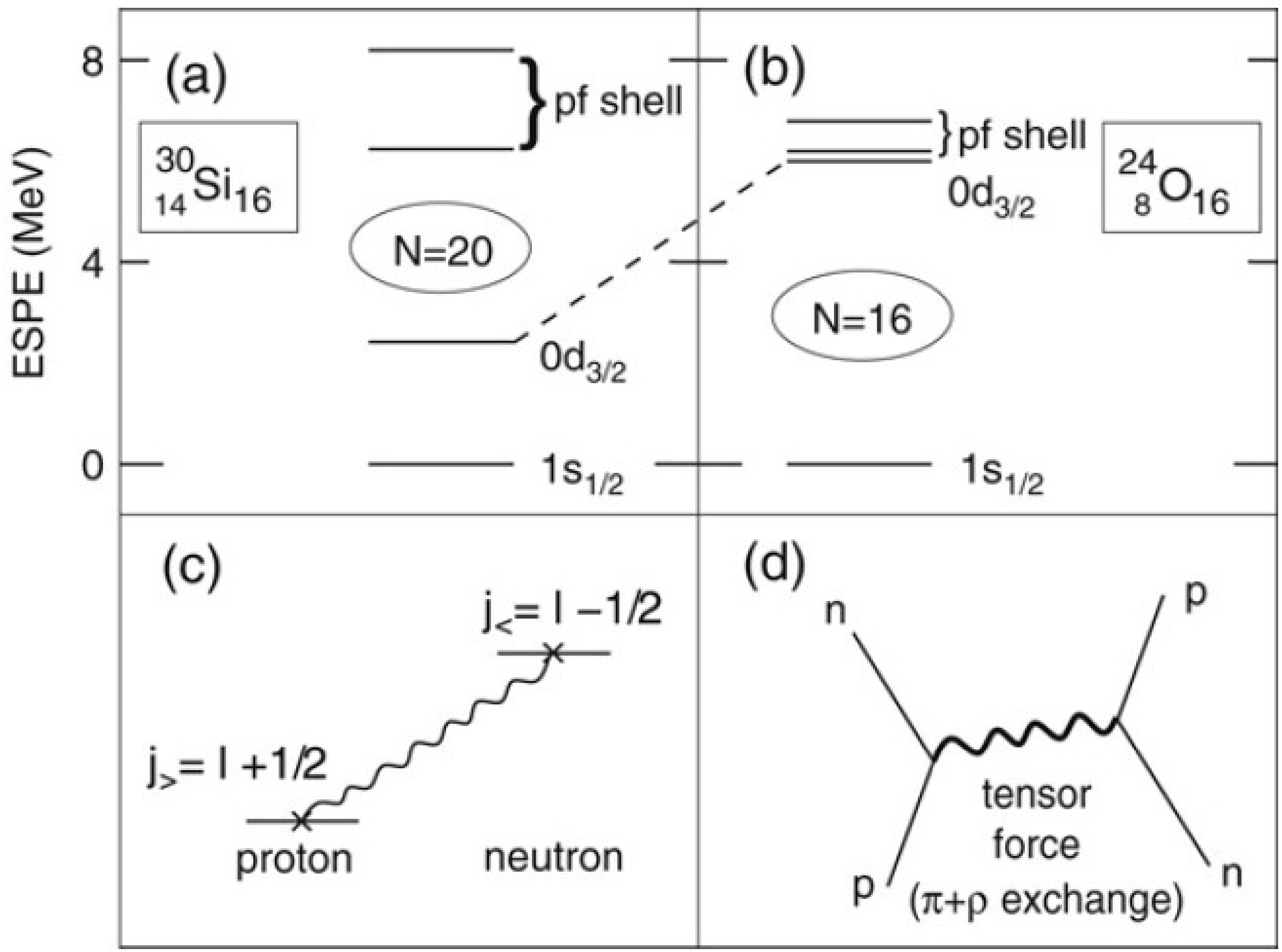
Understanding multi-nucleon interactions !

- Proton-Neutron interaction responsible for shifts of single-particle energies
- Disappearance and Appearance of shell closures
- Limits or nuclear existence
- Emergence and evolution of collectivity: mixing of many single-particle wave functions
- Phase transitions (of deformation)
- Generation of Elements (-> Nucl. Astro.)

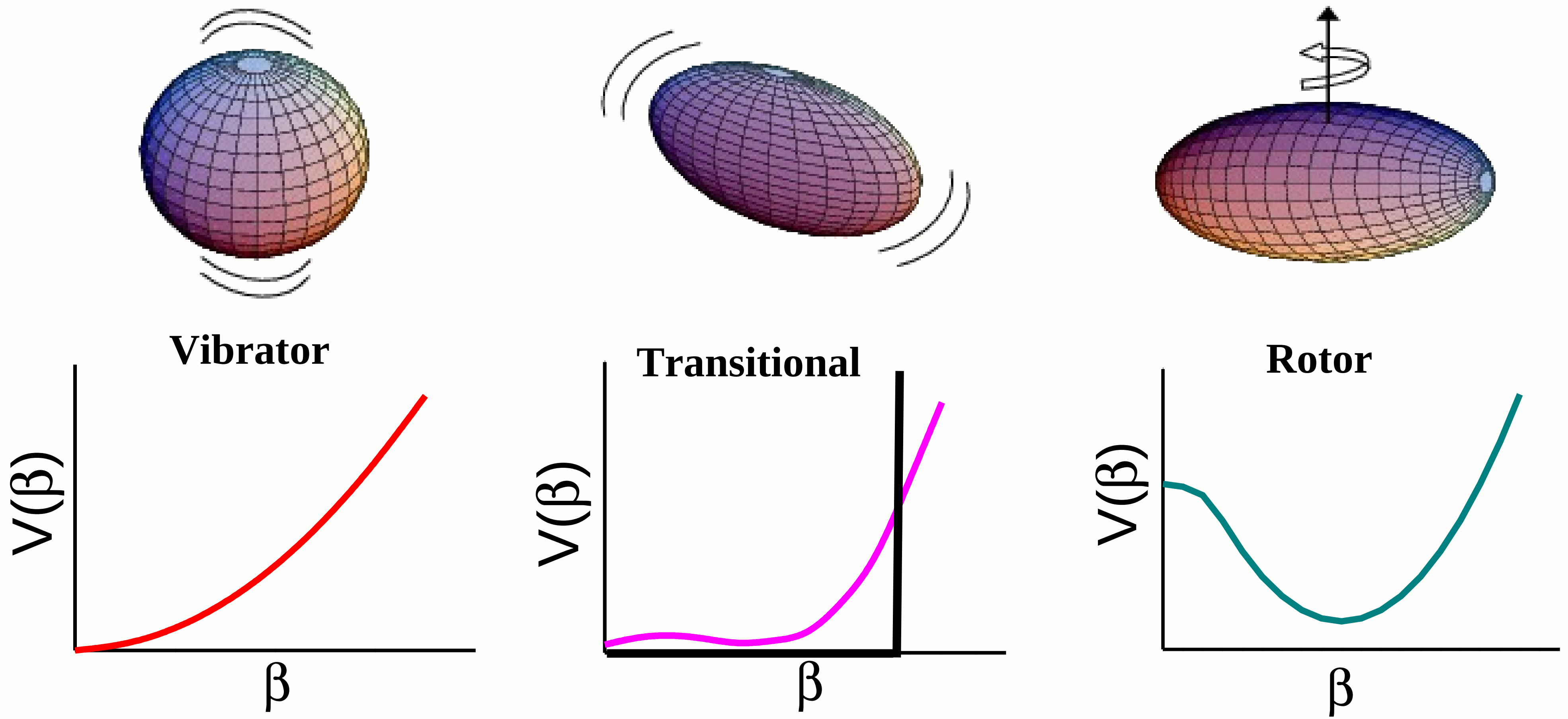


Classic Example: Shell Changes

T. Otsuka, D. Abe / Progress in Particle and Nuclear Physics 59 (2007) 425–431



(Collective) Nuclear Phases



F. Iachello, Phys. Rev. Lett. 85, 3580 (2000); 87, 052502 (2001).

Shape Invariants

$$q_2 = \langle 0_1^+ | (Q \cdot Q) | 0_1^+ \rangle = \sum_j B(E2; 0_1^+ \rightarrow 2_j^+)$$

$$q_3 = \sqrt{\frac{35}{2}} \; |\langle 0_1^+ | [QQQ]^{(0)} | 0_1^+ \rangle|$$

$$q_4 = \langle 0_1^+ | (Q \cdot Q) \; (Q \cdot Q) | 0_1^+ \rangle$$

$$q_5 = \sqrt{\frac{35}{2}} \; |\langle 0_1^+ | (Q \cdot Q) \; [QQQ]^{(0)} | 0_1^+ \rangle|$$

$$q_6 = \frac{35}{2} \; \langle 0_1^+ | [QQQ]^{(0)} \; [QQQ]^{(0)} | 0_1^+ \rangle$$

Needs lifetimes!

Model independent !!!

$$K_n = \frac{q_n}{q_2^{n/2}} \qquad \text{for} \quad n \in \{3, 4, 5, 6\}$$

Dimension-less

Invariant = invariant under symm. Trafos (e.g. rotation)

q_2 gives Quadrupole Deformation β

$$\mathbf{q_2} = \left(\frac{\mathbf{3ZeR^2}}{\mathbf{4}\pi}\right)^{\mathbf{2}} \langle\beta^{\mathbf{2}}\rangle \equiv \left(\frac{\mathbf{3ZeR^2}}{\mathbf{4}\pi}\right)^{\mathbf{2}} {\beta_{\mathrm{eff}}}^{\mathbf{2}}$$

$$\mathbf{K_3} = \frac{\langle\beta^{\mathbf{3}}\cos\mathbf{3}\gamma\rangle}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{3/2}}} \equiv \cos\mathbf{3}\gamma_{\mathrm{eff}}$$

$$\mathbf{K_4} = \frac{\langle\beta^{\mathbf{4}}\rangle}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{2}}}$$

$$\mathbf{K_5} = \frac{\langle\beta^{\mathbf{5}}\cos\mathbf{3}\gamma\rangle}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{5/2}}}$$

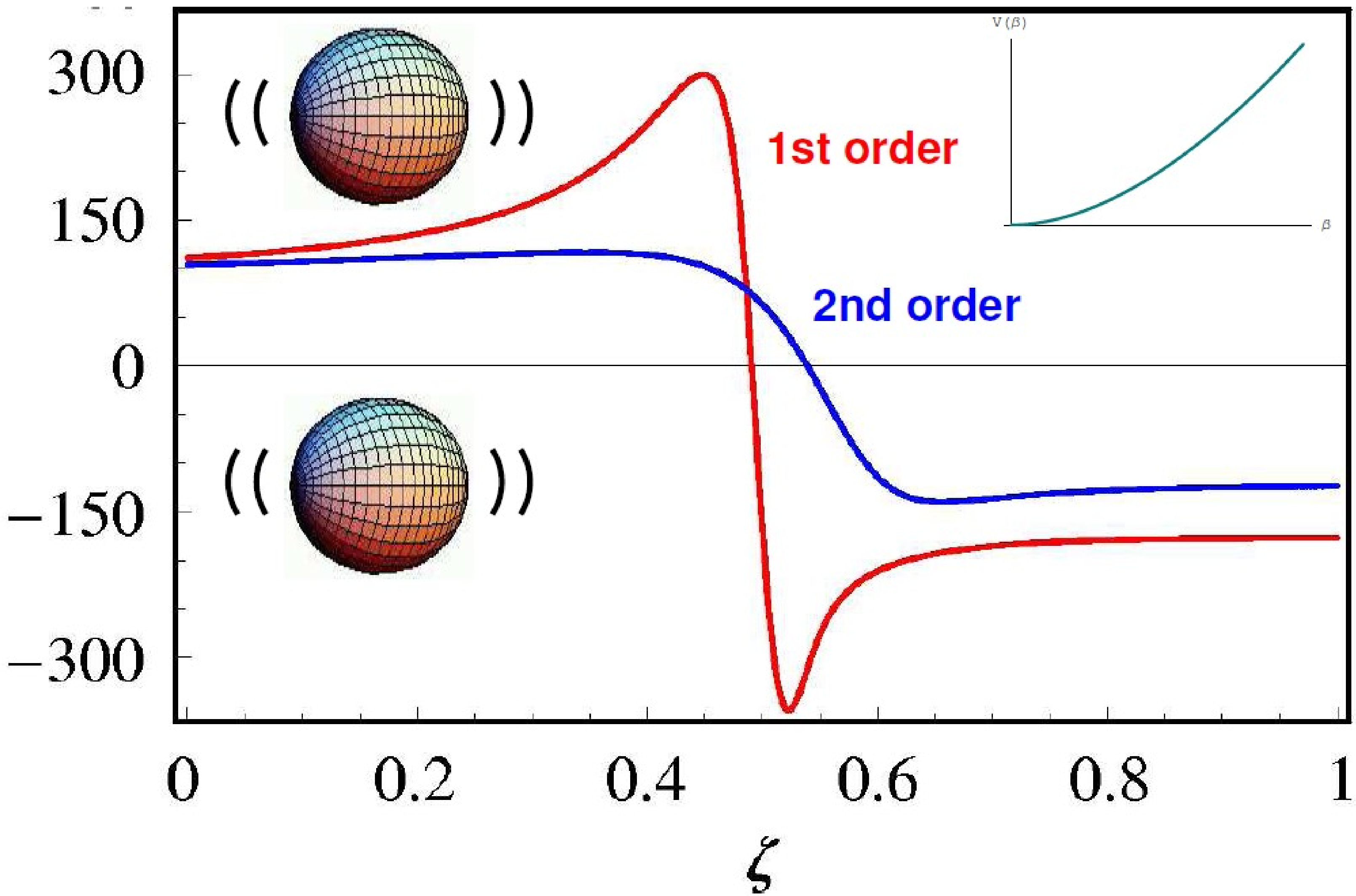
$$\mathbf{K_6} = \frac{\langle\beta^{\mathbf{6}}\cos^{\mathbf{2}}\mathbf{3}\gamma\rangle}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{3}}}$$

Fluctuations:

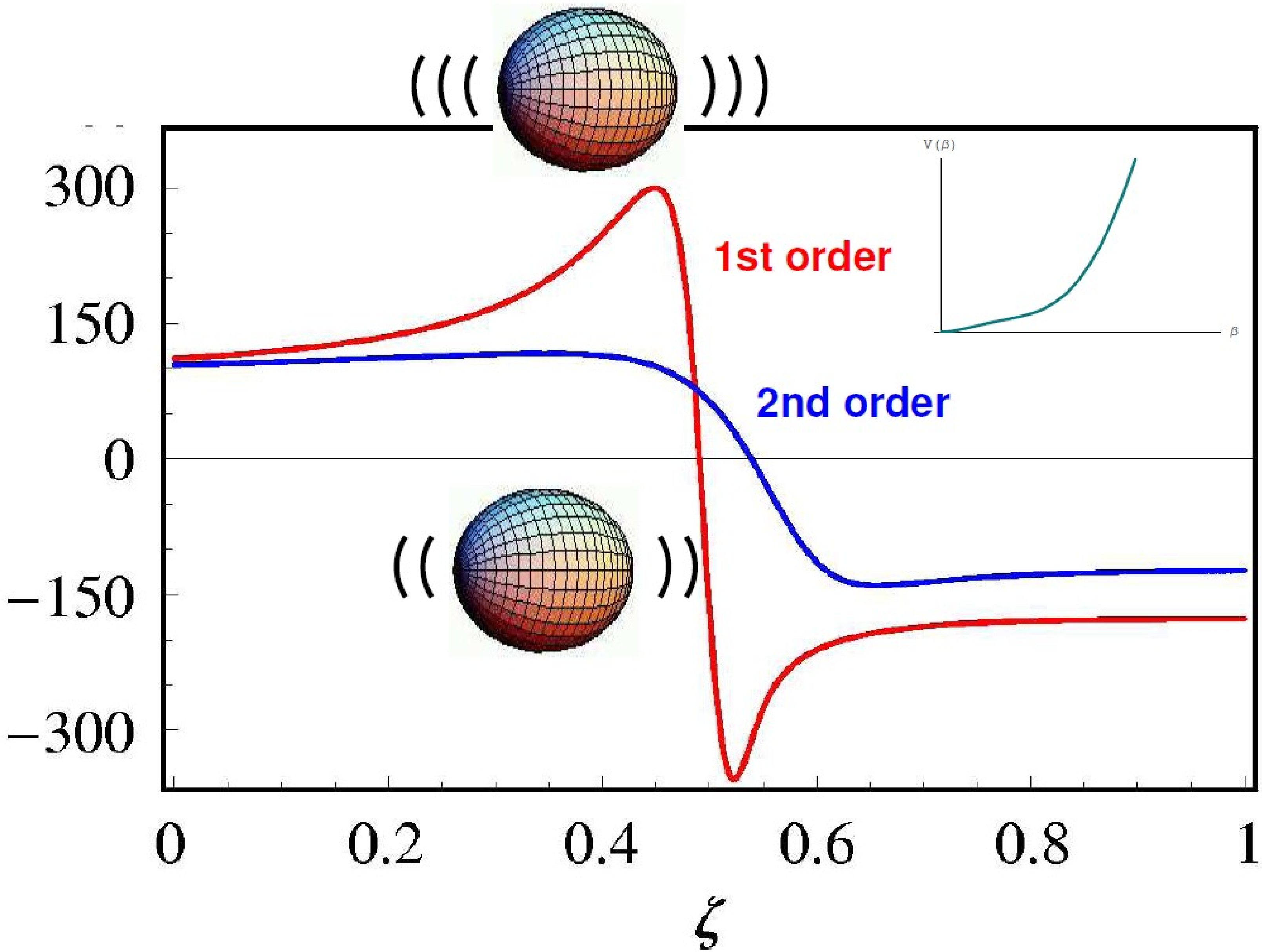
$$\sigma_\beta = \frac{\langle\beta^{\mathbf{4}}\rangle - \langle\beta^{\mathbf{2}}\rangle^{\mathbf{2}}}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{2}}} = \mathbf{K_4 - 1}$$

$$\sigma_\gamma = \frac{\langle\beta^{\mathbf{6}}\cos^{\mathbf{2}}\mathbf{3}\gamma\rangle - \langle\beta^{\mathbf{3}}\cos\mathbf{3}\gamma\rangle^{\mathbf{2}}}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{3}}} = \mathbf{K_6} - {\mathbf{K_3}}^{\mathbf{2}}$$

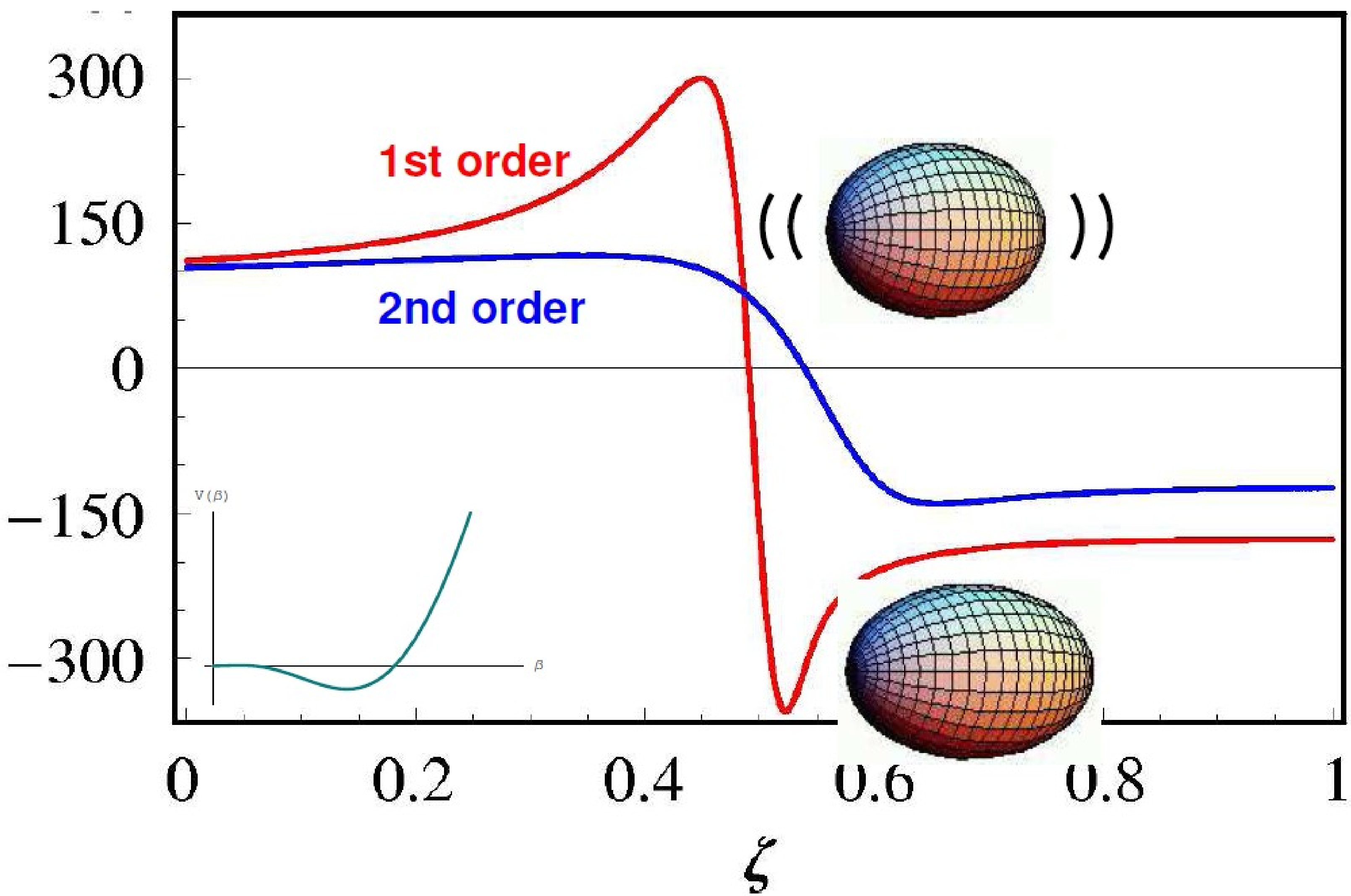
$$\mathbf{q_2(0_2^+) - q_2(0_1^+)\ ,\ \ N = 30}$$



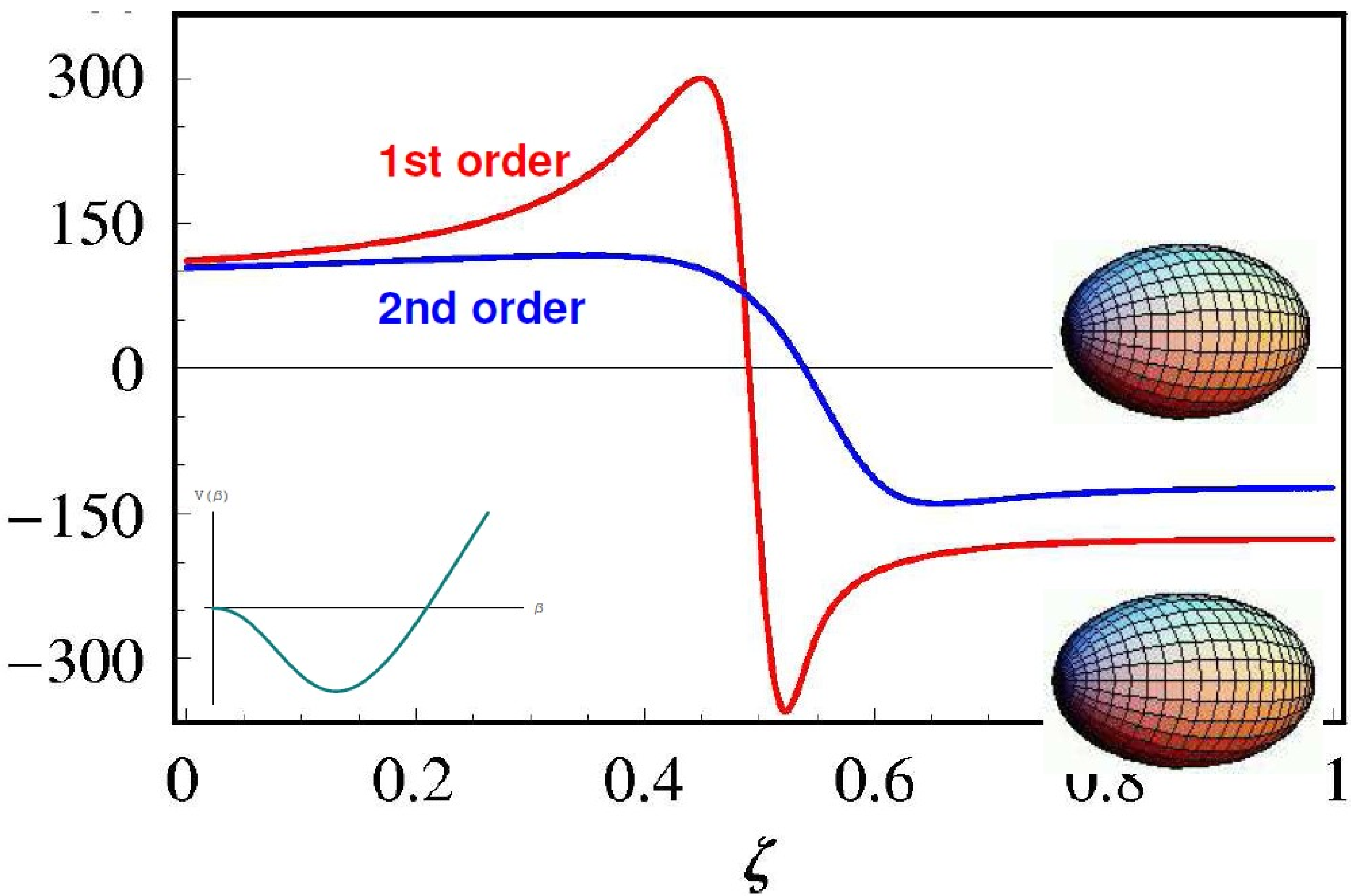
$$q_2(0_2^+) - q_2(0_1^+)\ ,\ N = 30$$



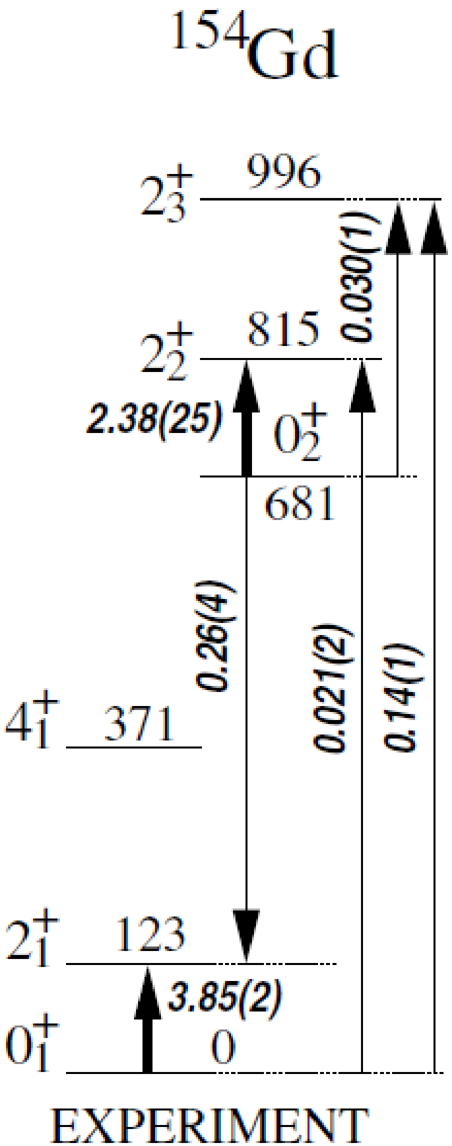
$$q_2(0_2^+) - q_2(0_1^+)\ ,\ N = 30$$



$$\mathbf{q_2(0_2^+) - q_2(0_1^+)\ ,\ \ N = 30}$$



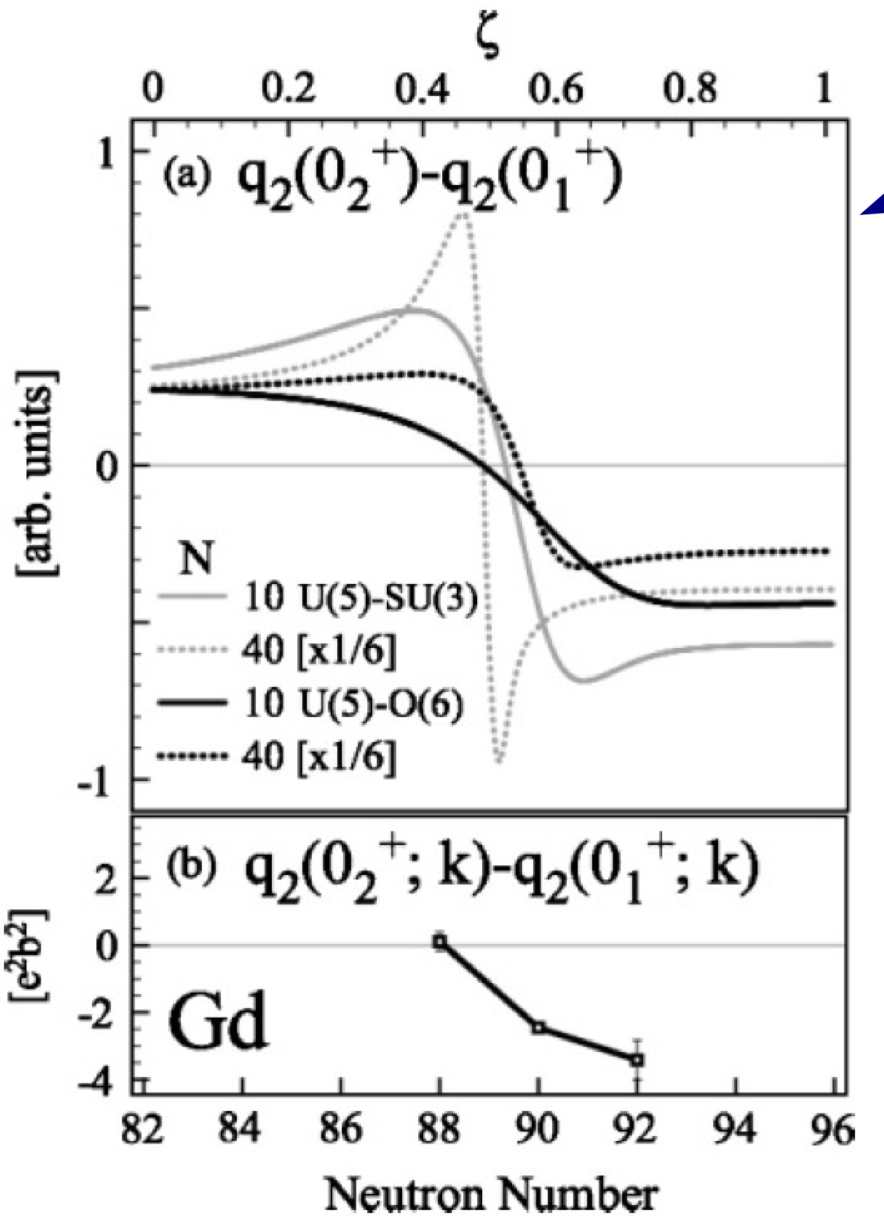
B(E2)'s needed for q_2



Typically, only few B(E2) transitions are sizeable -> truncate sum at 2_3^+

$$q_2 = \langle 0_1^+ | (Q \cdot Q) | 0_1^+ \rangle = \sum_j B(E2; 0_1^+ \to 2_j^+)$$

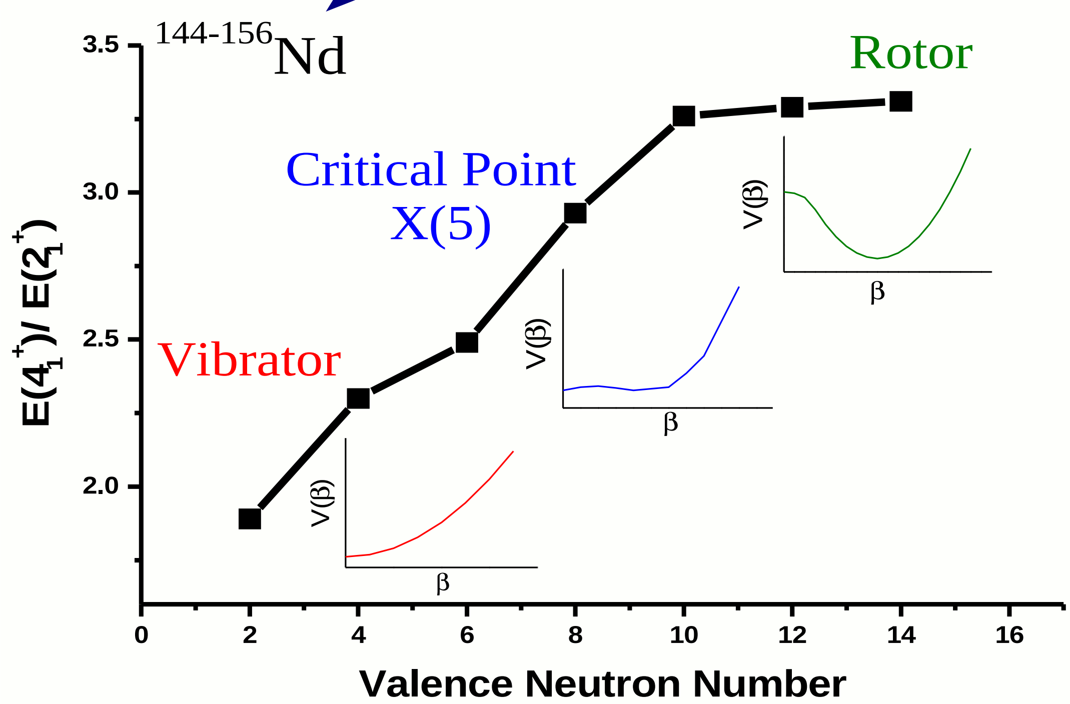
Lifetimes => Evolution of Structure, i.e. Evolution of Mean-Field Potential

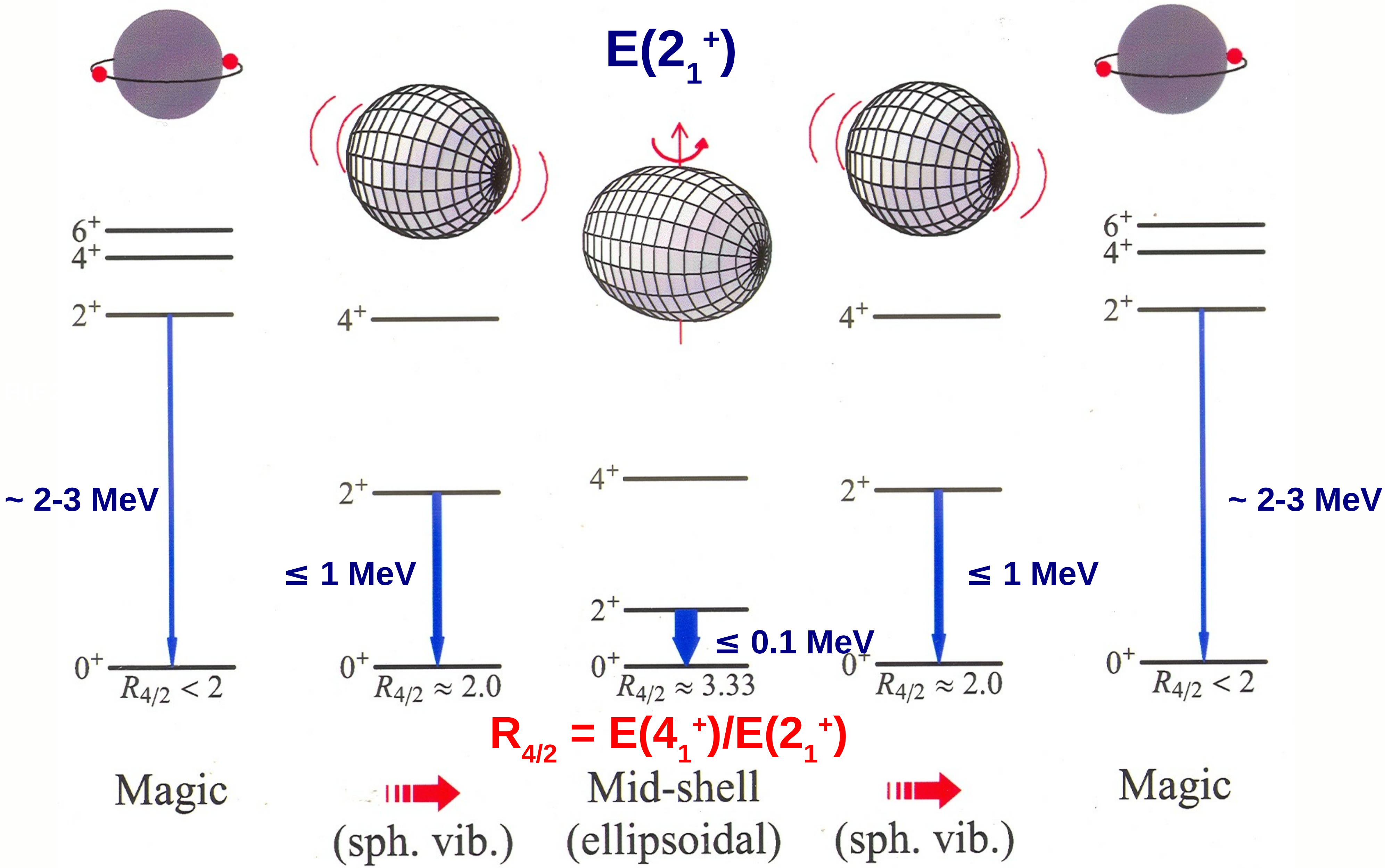


Gd

The „famous" N~90 region

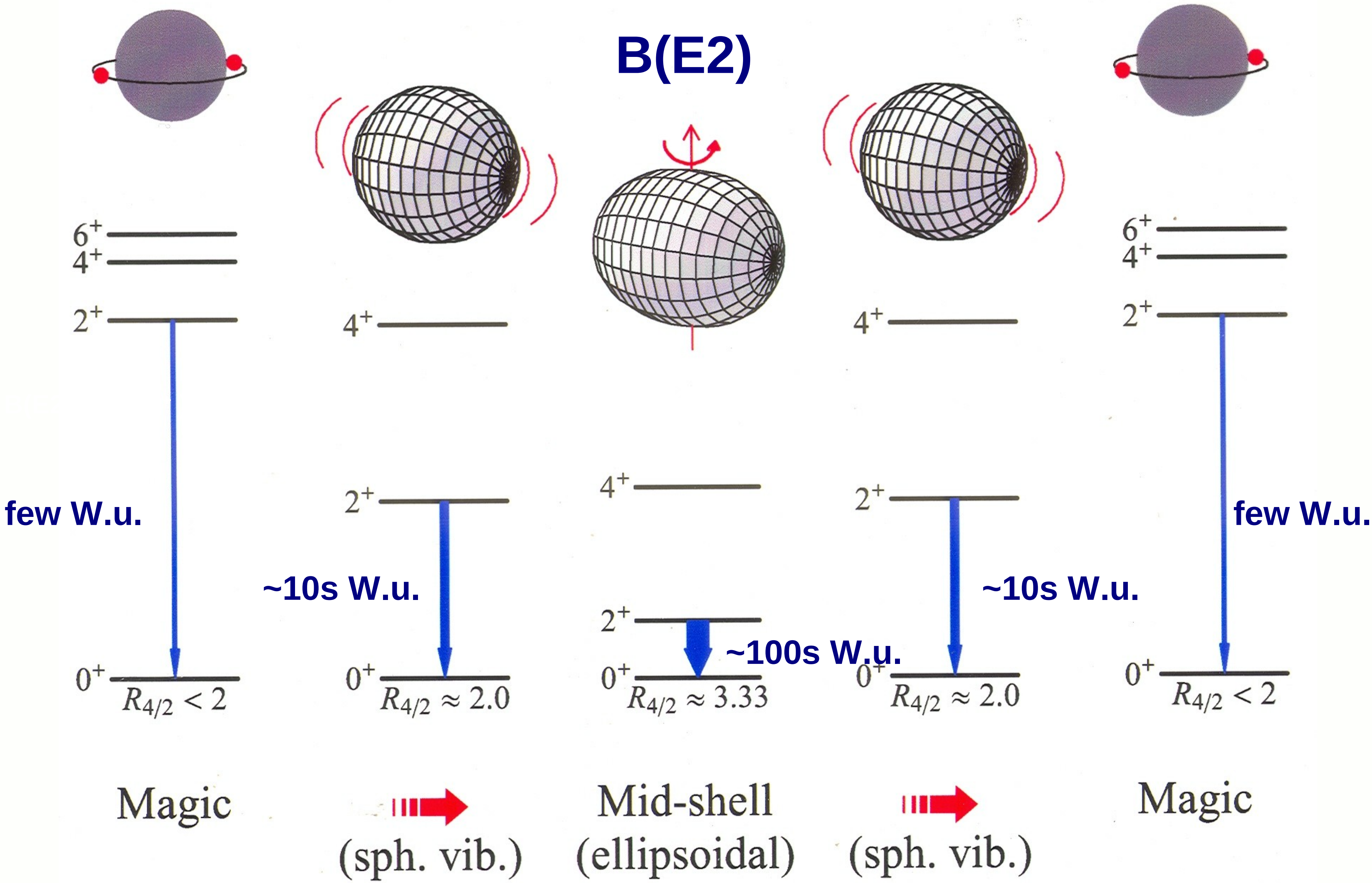
Nd





E(2_1^+)
6+
4+
2+
~ 2-3 MeV
0+
$R_{4/2} < 2$
4+
2+
≤ 1 MeV
0+
$R_{4/2} \approx 2.0$
4+
2+
≤ 0.1 MeV
0+
$R_{4/2} \approx 3.33$
4+
2+
≤ 1 MeV
0+
$R_{4/2} \approx 2.0$
6+
4+
2+
~ 2-3 MeV
0+
$R_{4/2} < 2$
$R_{4/2} = E(4_1^+)/E(2_1^+)$
Magic
(sph. vib.)
Mid-shell
(ellipsoidal)
(sph. vib.)
Magic

Evolution of Nuclear Structure



Orders of Magnitude

$$B(E2;2_1^+ \rightarrow 0_1^+) \propto I/(E_\gamma^5 \tau)$$

$$\tau \propto I/(E_\gamma^5 B(E2;2_1^+ \rightarrow 0_1^+))$$

Eγ ~ 100 – 1000s keV => min. 5 orders of magnitude
B(E2) ~ few – 100s W.u. => another 2 orders of magnitude

2_1^+ lifetimes alone vary over ~7 orders of magnitude!

(Isomers, p-n non-symmetric states etc. add even more)

We need appropriate experimental methods for every ~2-3 orders of magnitude.
(That is, different methods for different regions or/and physics cases!)

So, there is a lot of different lifetimes to measure,
now a few examples how to do it:

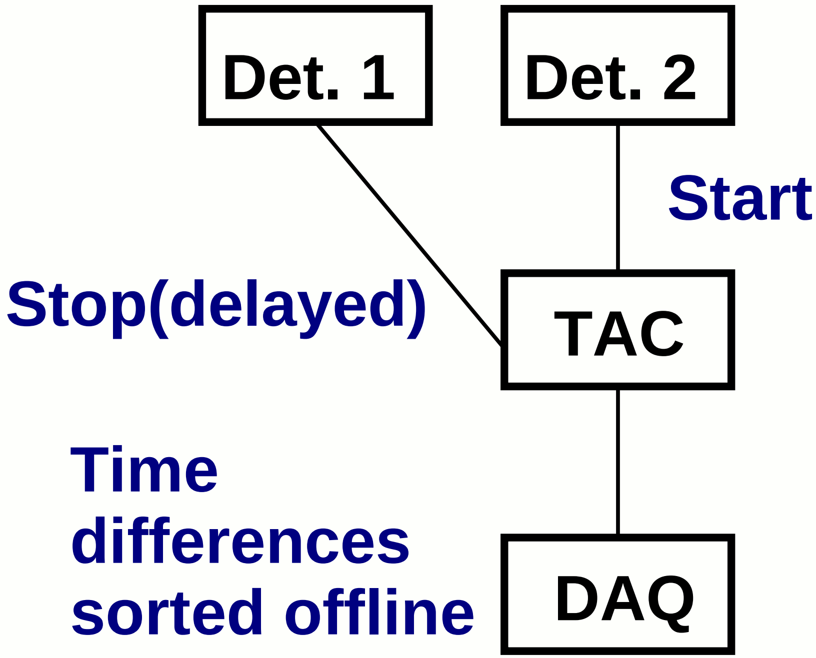
ns - regime

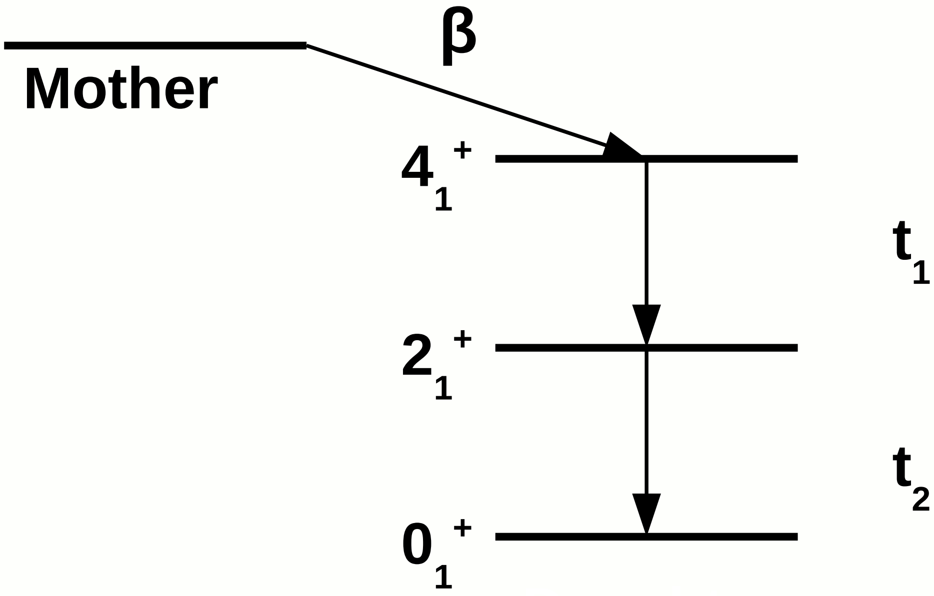
(the „easiest" one)

Fast Electronics Scintillation Timing (FEST)

Straight forward, with or without β-gate,

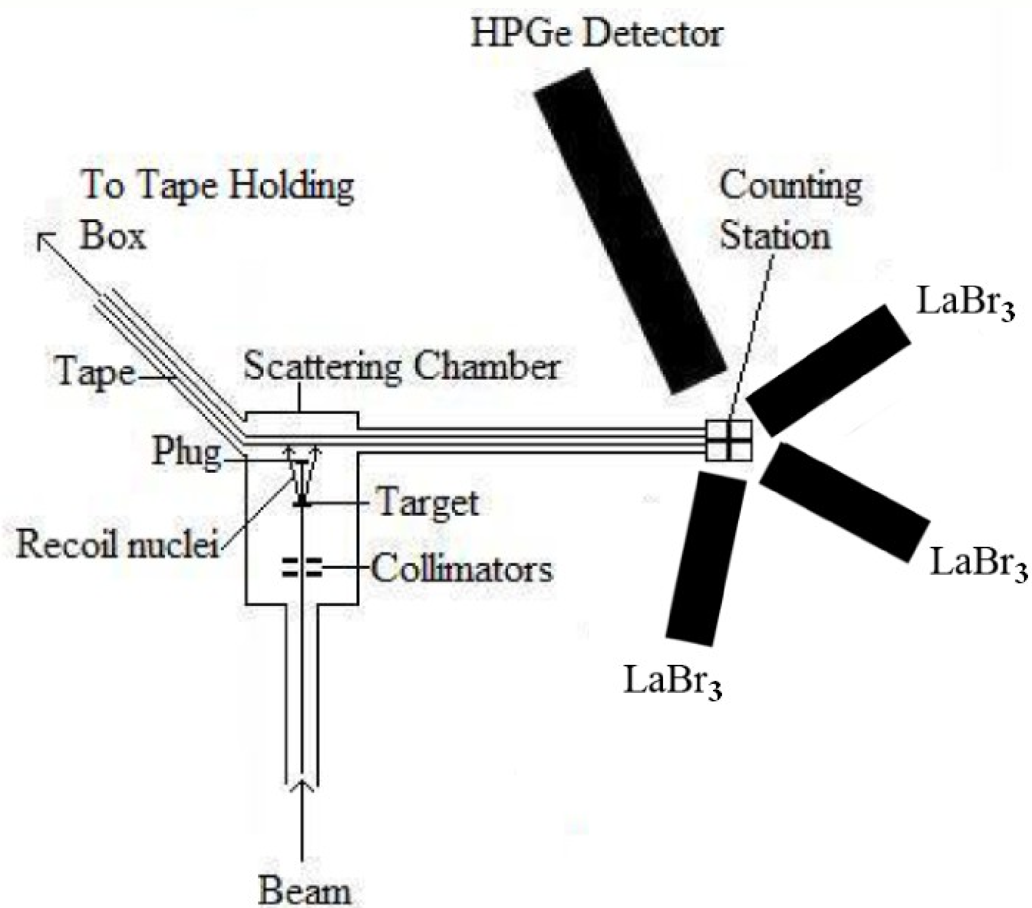
$$B(E2) \propto \frac{1}{\tau}$$





t_2-t_1 ~ exp(λ=1/τ)

Moving Tape Collector



Array of $LaBr_3$ Scintillators:

Here: 3 x 1.5“x1.5“ cylindrical

Supplied by University of Cologne

Time resolution comparable to BaF_2

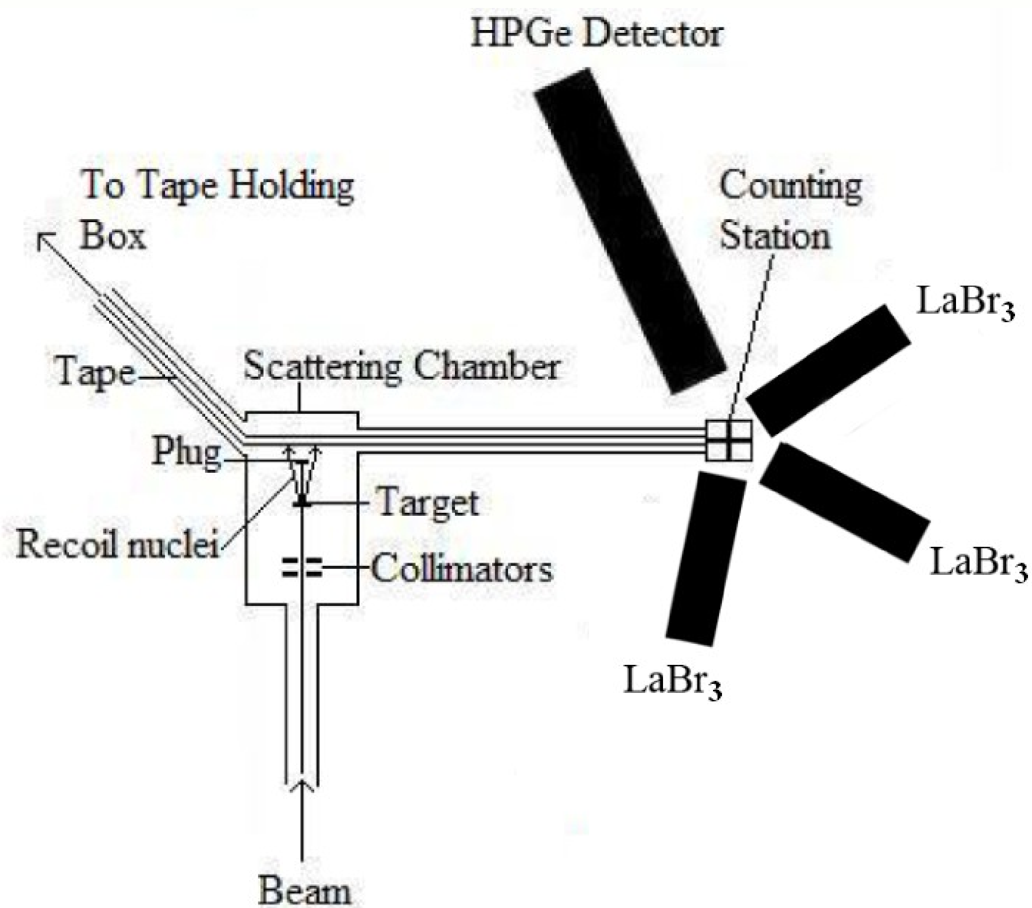
...but superior (min. 3%) energy resolution

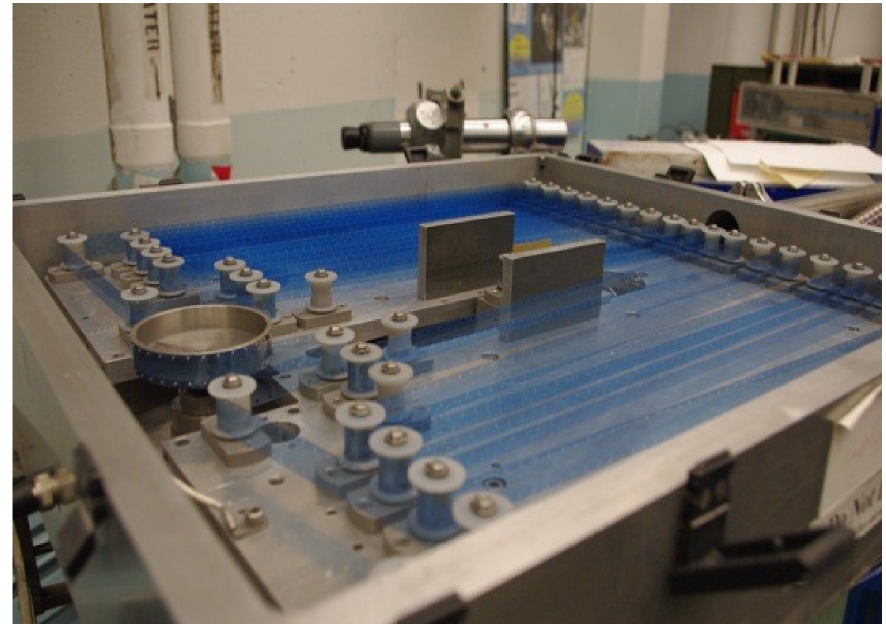
3 detectors allow for 6 permutations

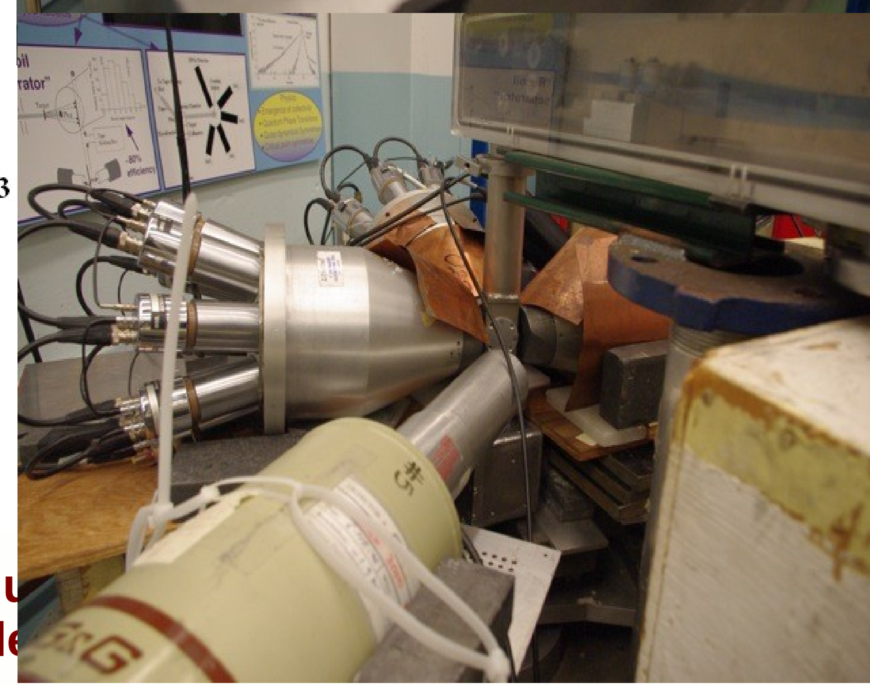
In this scheme (taken from WNSL) we create the nuclei in-beam.
Alternative: direct implantation of radioactive nuclei on the tape (e.g., CARIBU + X-array)

MTC at Yale (retired)

Moving Tape Collector

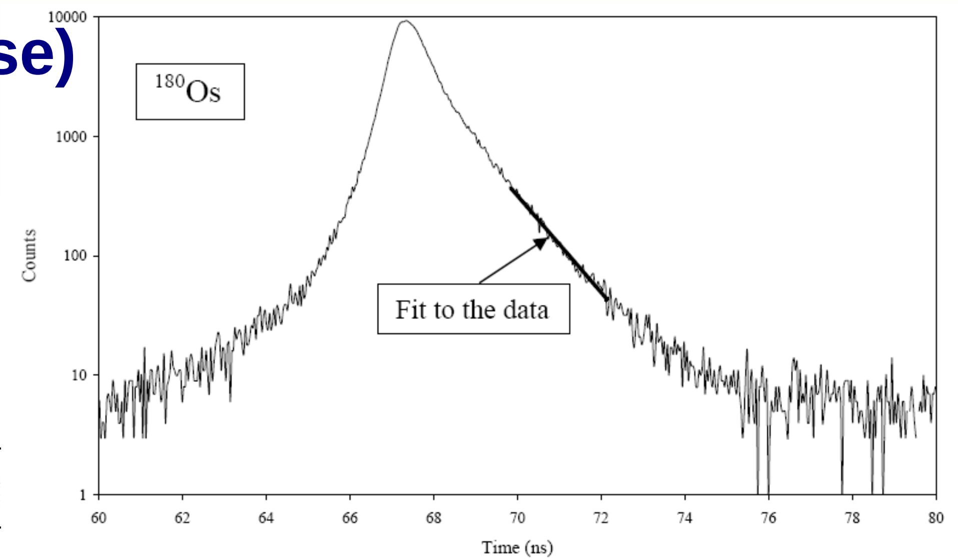




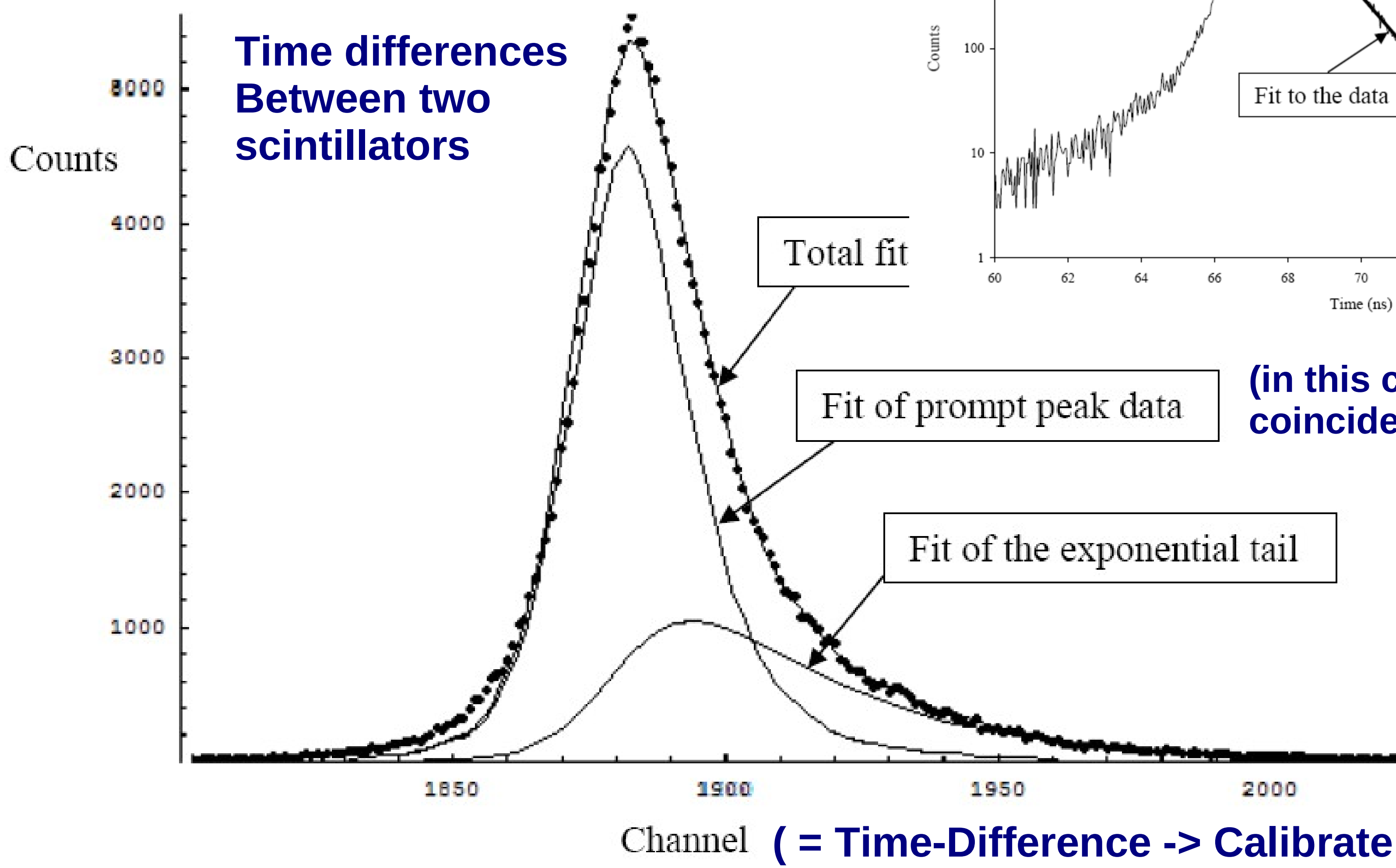


In this scheme (taken from WNSL) we create the nu
Alternative: direct implantation of radioactive nucle

Prompt Peak (Instrument Response)
Exponential Tail (Decay Curve)



Time differences Between two scintillators



(in this case from ^{60}Co coincidences)

(= Time-Difference -> Calibrate with delays!)

Background Correction

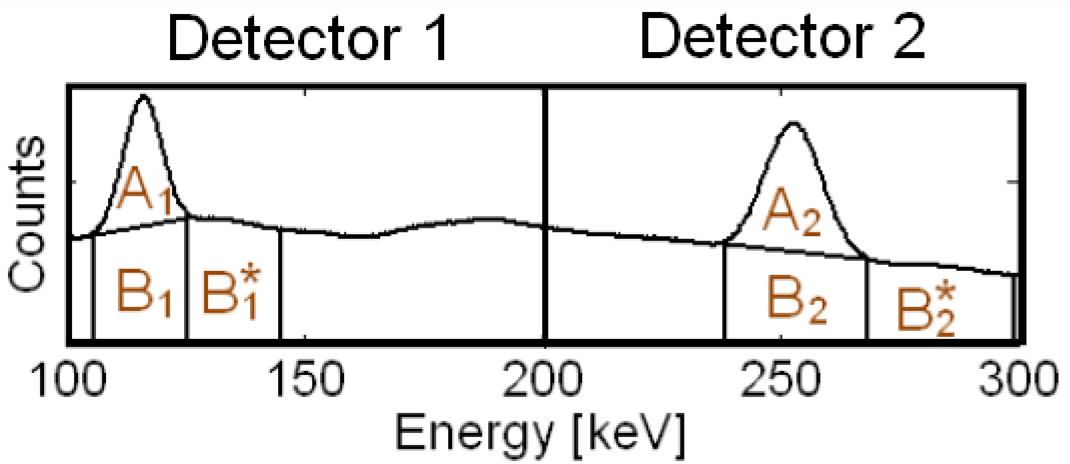
Why? Background has a "lifetime" - for example it can be from Compton-Background from higher-lying transitions.

Divide energy gates into peak and background (A+B)

$B_1 \approx B_2^*$

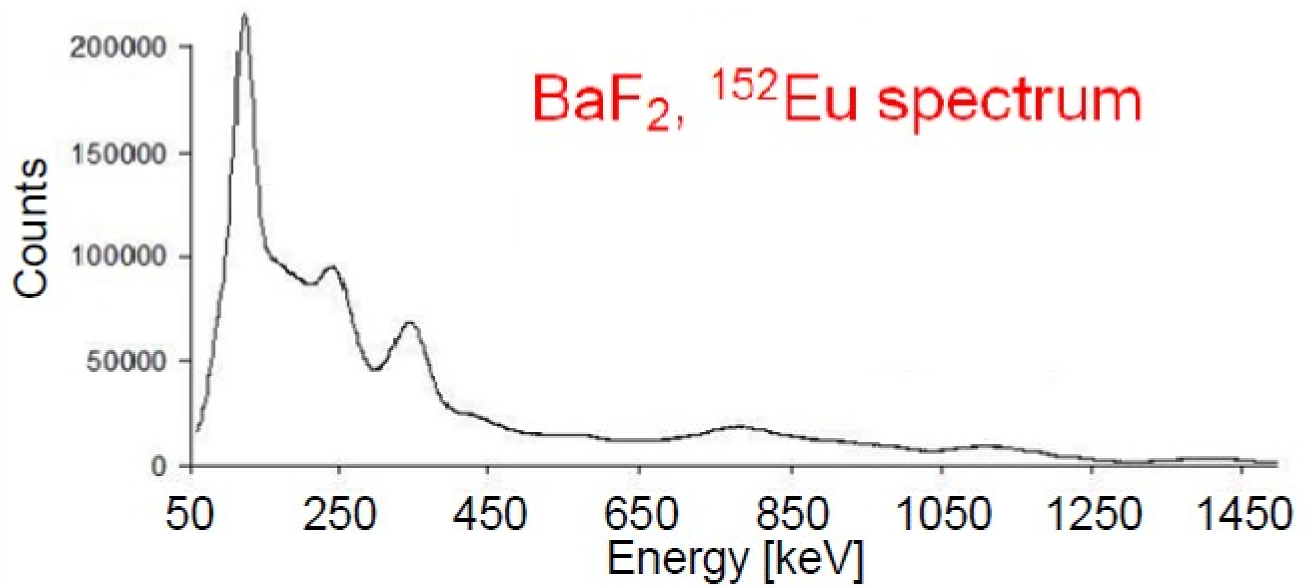
do not Bg gate on Compton's!

-> only gate on the right!



$$A_1A_2 = (A_1+B_1)(A_2+B_2) - B_1(A_1+B_2) - (A_1+B_1)B_2 + B_1B_2$$

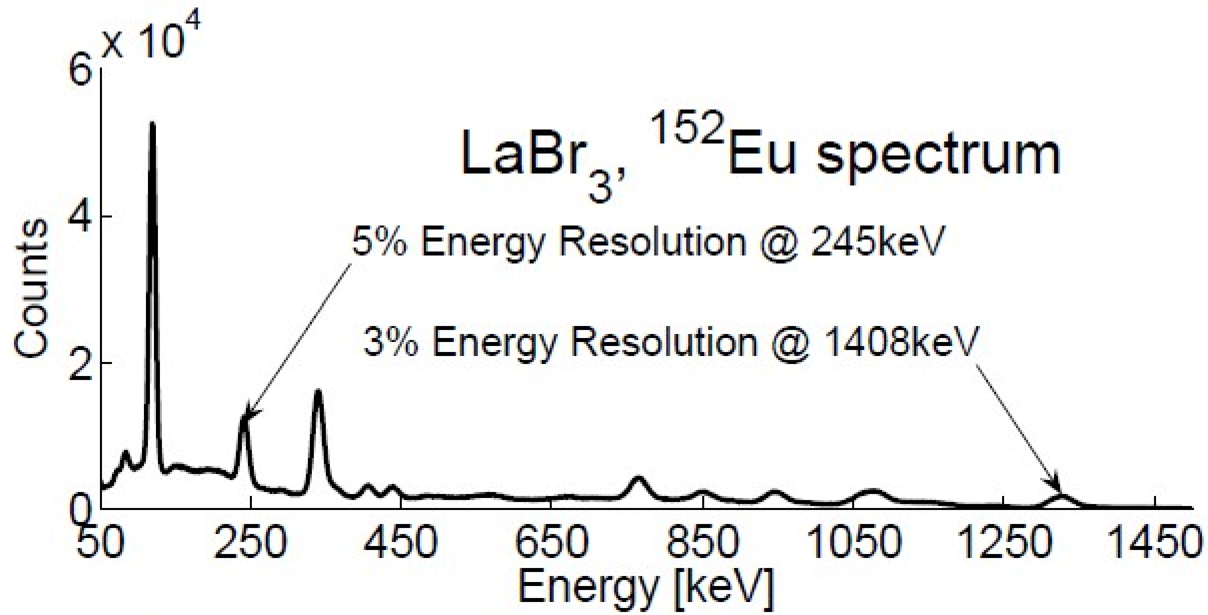
Old (BaF_2) Scintillator Resolution



peaks overlap,

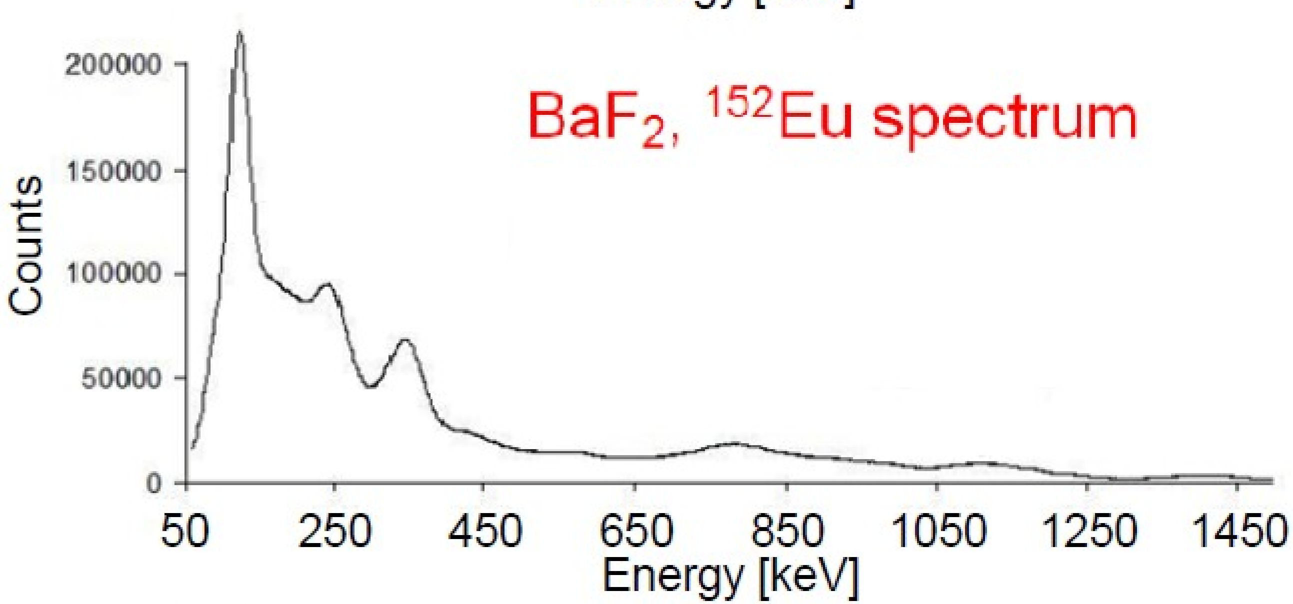
background ?

vs. New ($LaBr_3$) Resolution



separable peaks,

background visible



peaks overlap,

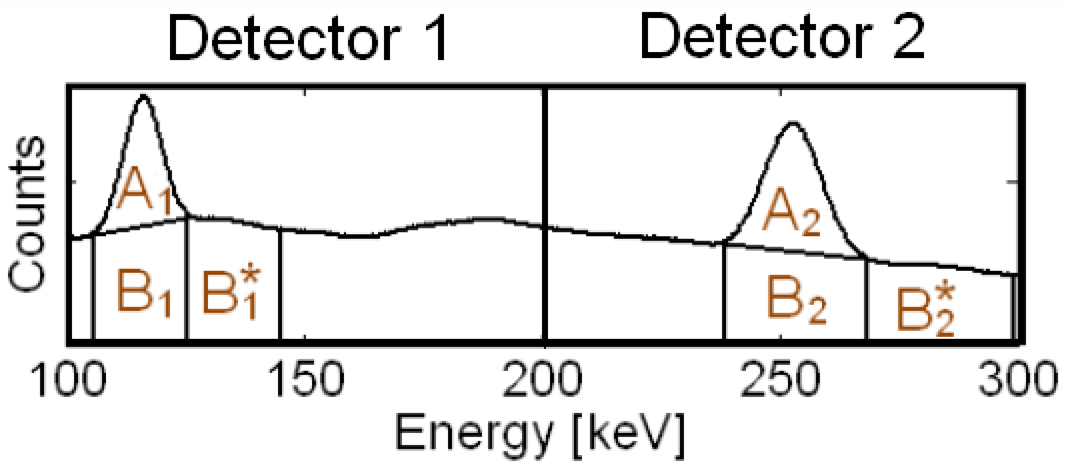
background ?

Background Correction

Why? Background has a "lifetime" - for example it can be from Compton-Background from higher-lying transitions.

Divide energy gates into peak and background (A+B)

$B_1 \approx B_2{}^*$
do not Bg gate on Compton's!
-> only gate on the right!



$$A_1A_2 = (A_1+B_1)(A_2+B_2)$$
$$- B_1(A_1+B_2) - (A_1+B_1)B_2$$
$$+ B_1B_2$$

Background Correction

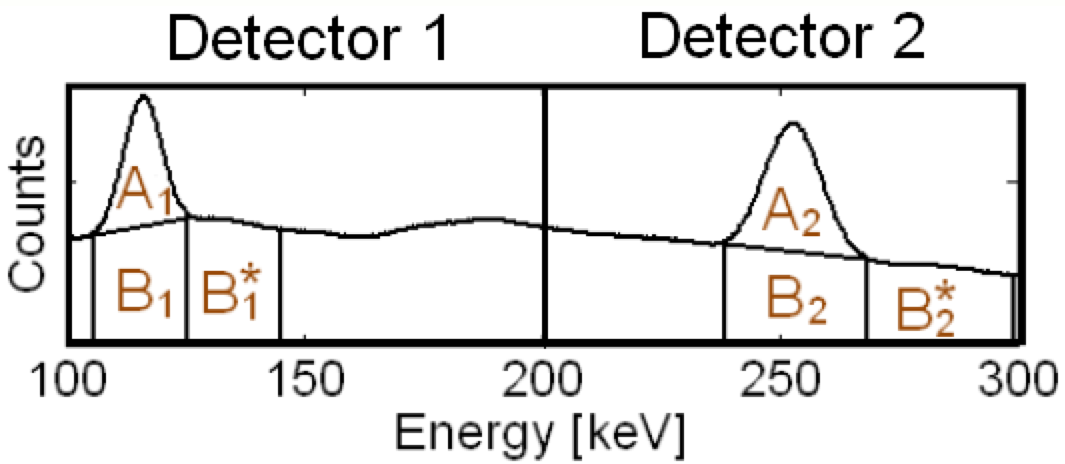
Why? Background has a "lifetime" - for example it can be from Compton-Background from higher-lying transitions.

Divide energy gates into peak and background (A+B)

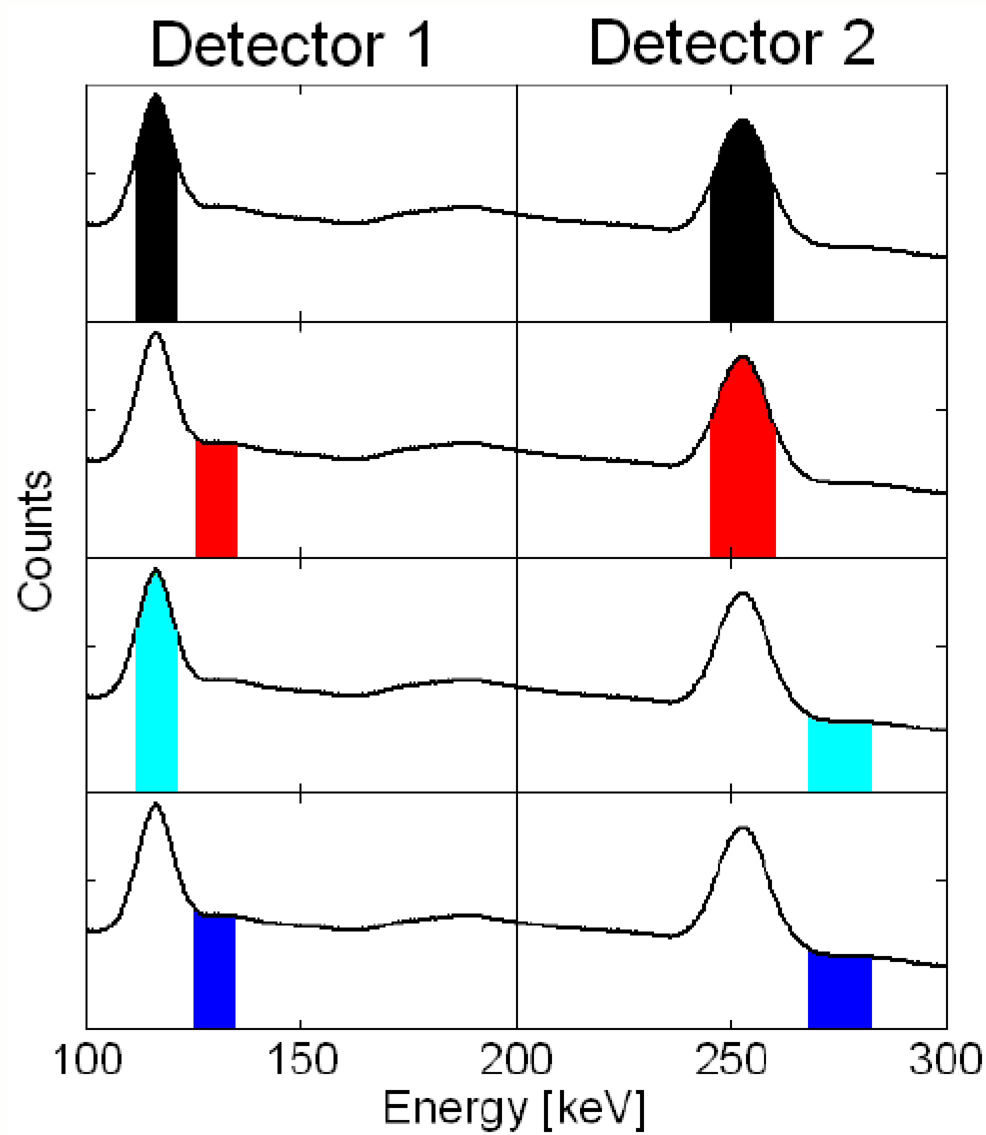
$B_1 \approx B_2^*$

do not Bg gate on Compton's!

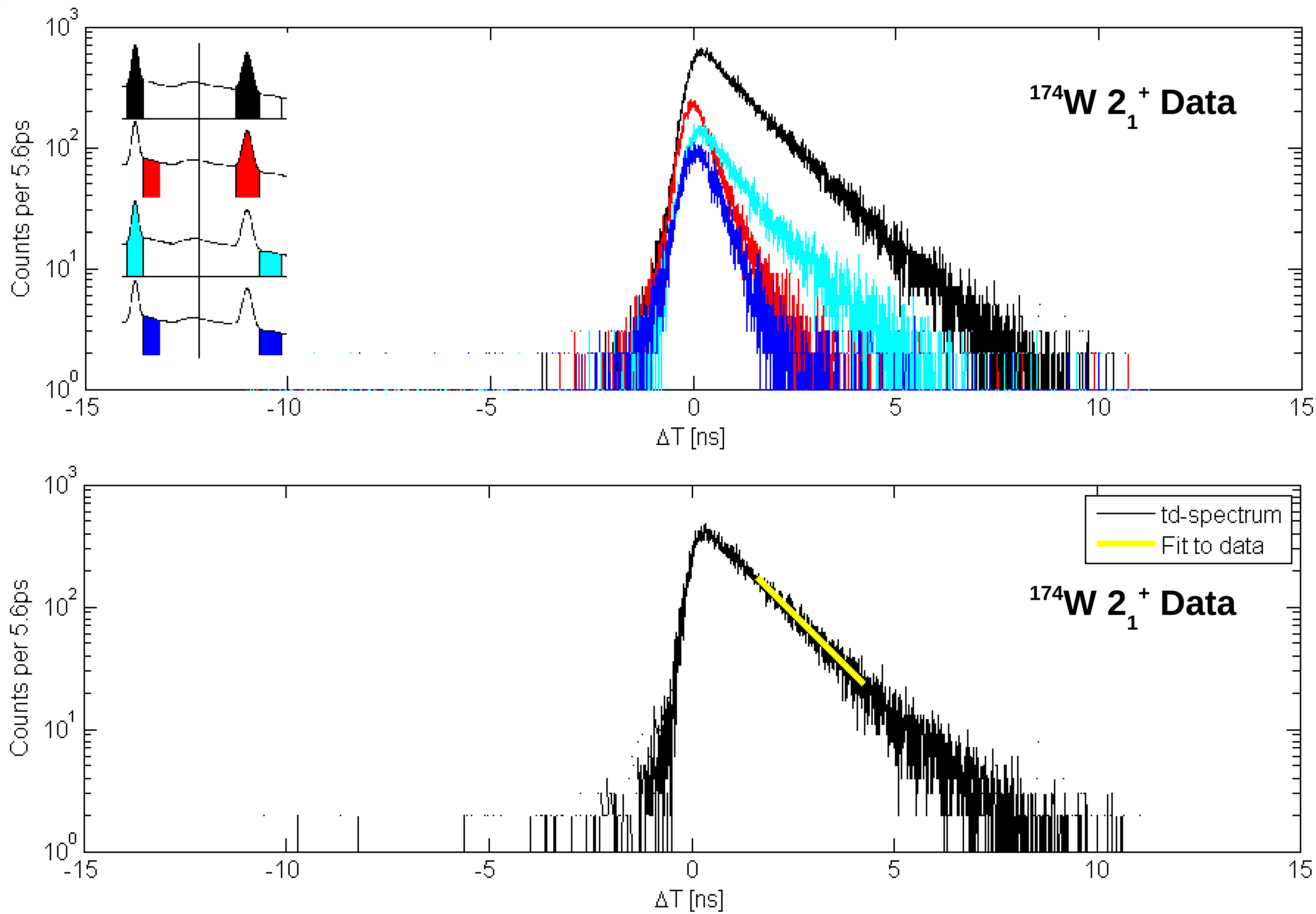
-> only gate on the right!



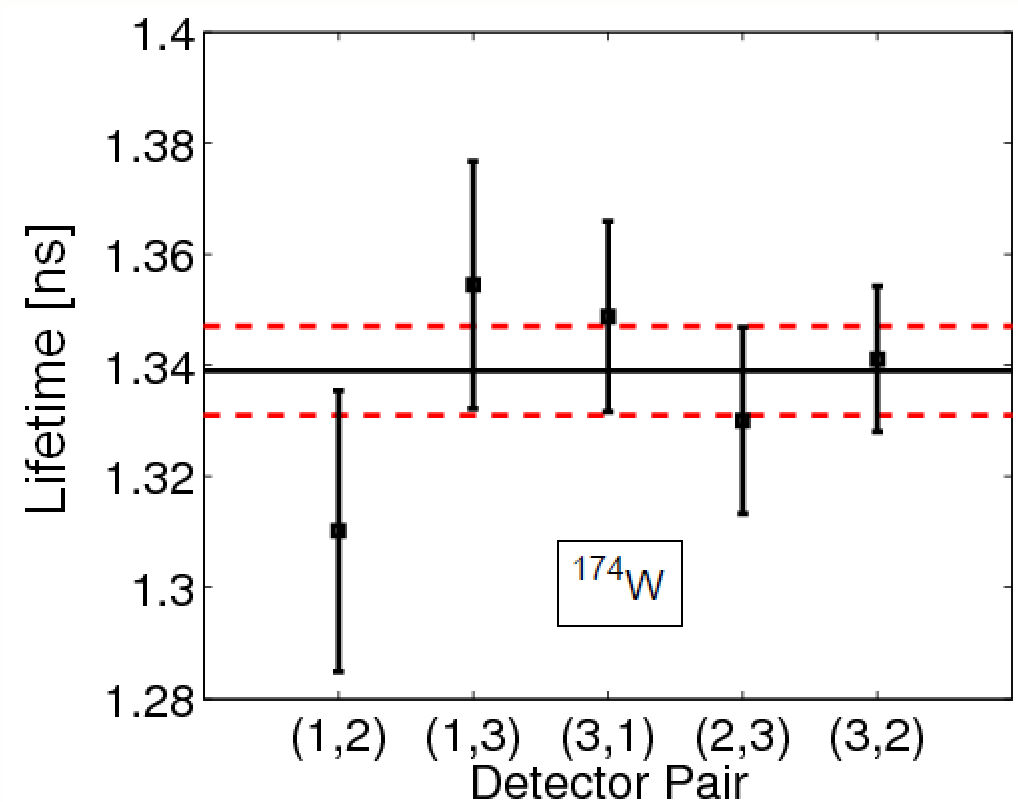
$$A_1A_2 = (A_1+B_1)(A_2+B_2) - B_1(A_1+B_2) - (A_1+B_1)B_2 + B_1B_2$$

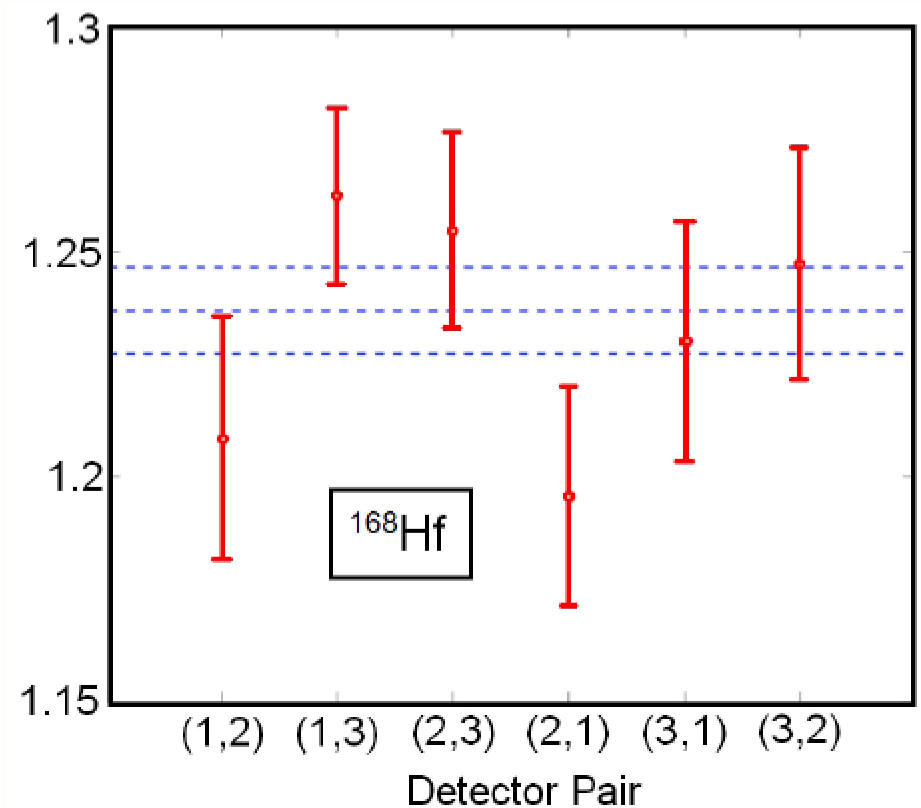


Deconvolution T-Diff. Spectra



Examples: ^{174}W, ^{168}Hf





^{174}W 2_1^+ (Nathan Cooper et. al.)

τ = 1.339(8)ns

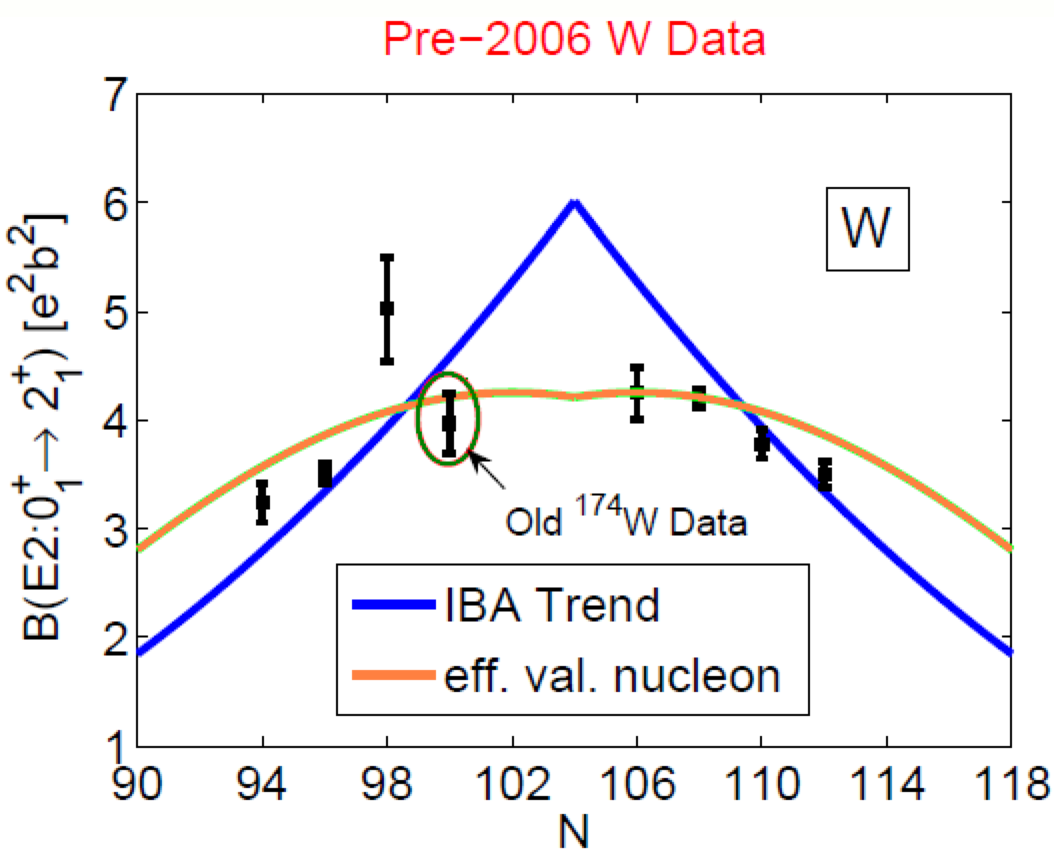
τ_{lit} = 1.64(10)ns

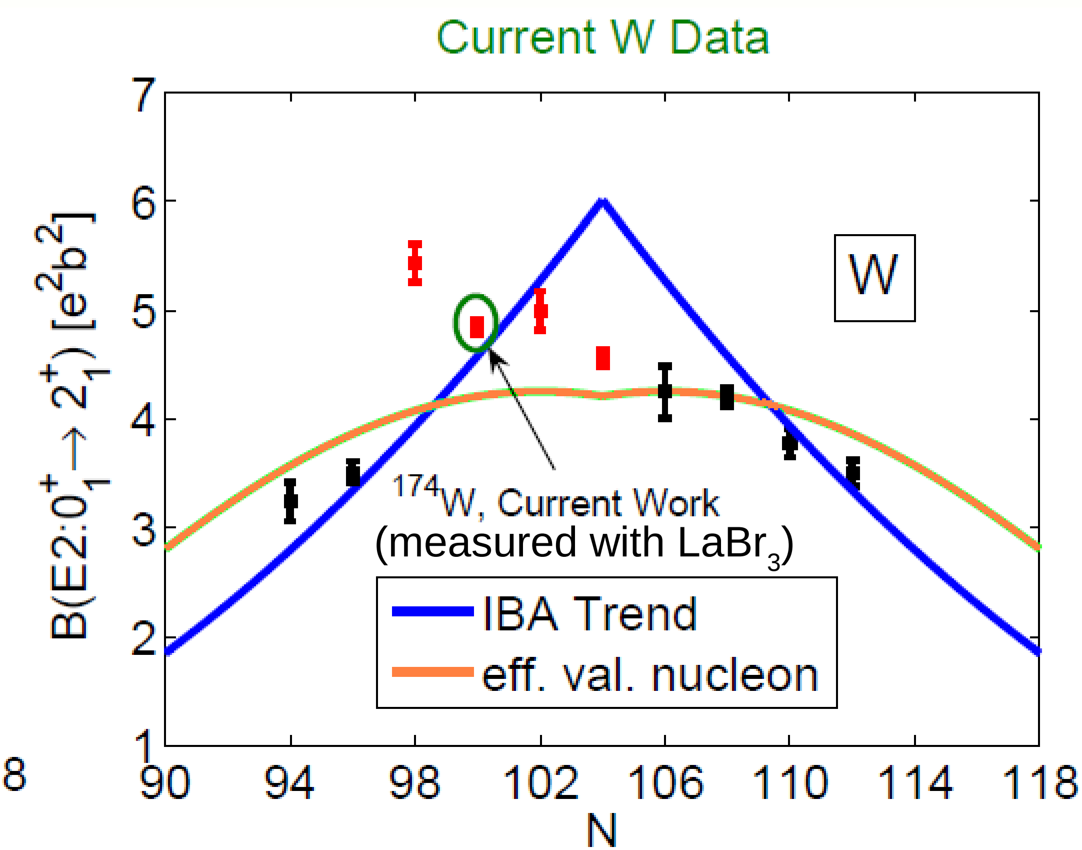
^{168}Hf 2_1^+ (Marco Bonett-Matiz et. al.)

τ = 1.237(10)ns

τ_{lit} = 1.28(6)ns

Learn sth. new from Systematics





=> Things seem a bit more complicated than anyone expected

^{176}W : J.-M. Regis et al. NIM A 606 (2009)
^{172}W, ^{178}W : M. Rudigier et al. Nucl. Phys. A 847 (2010)

More Details on Fast Timing

I only showed the basic principles, and the simplest possible measurements. Everything else is derived from this, for example centroid shift method:

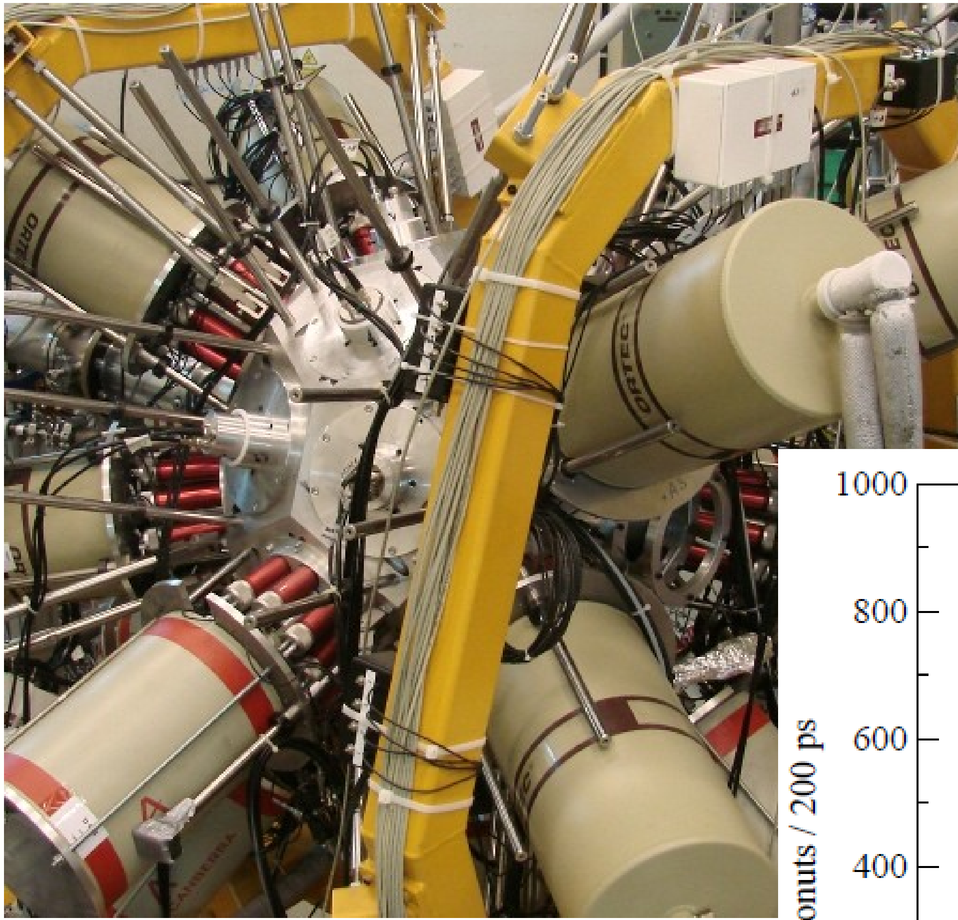
If the exp. slope is too small, only measure shift of TD-centroid. Suggested literature:

J.-M. Regis, Nucl. Instr. Meth. A 622, 83 (2010)

Beta-decay is very clean – if this is not the case, e.g. for high-lying isomers, beam cocktails, etc.:

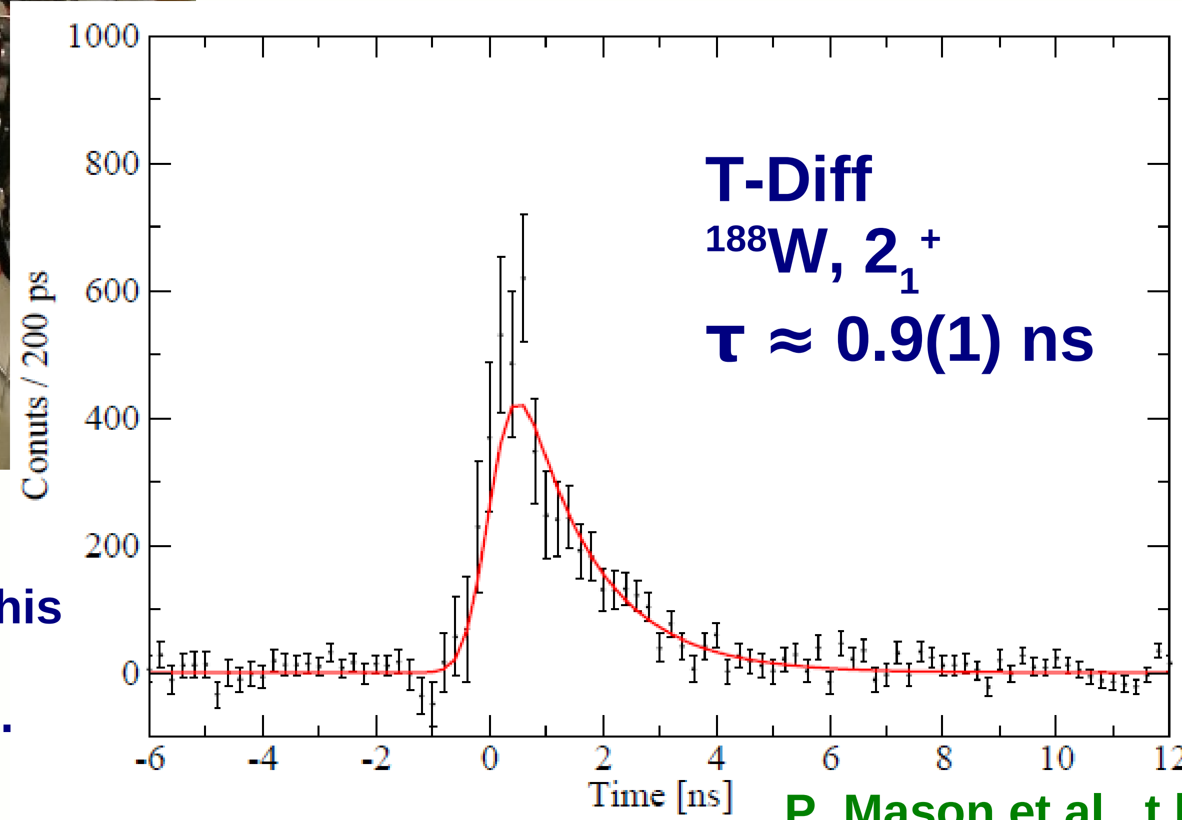
Add high-resolution HPGe's for a clean gate, and/or use additional triggers: (particle-ID, beta-/alpha-decay, ...)

Example for HPGe – cleaned Data



For example, at NIPNE (Bucharest)
8 HPGe + 11 $LaBr_3$ setup

^{186}W (^{7}Li,αp) ^{188}W

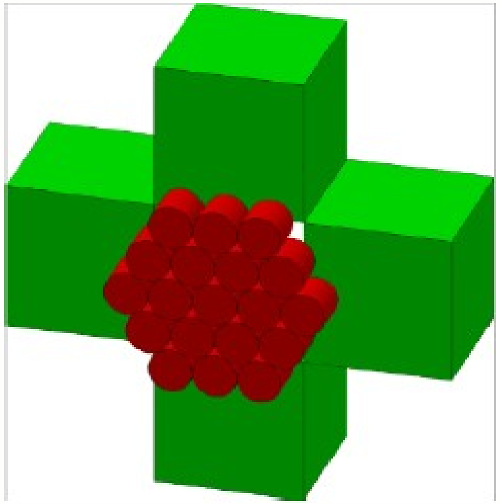


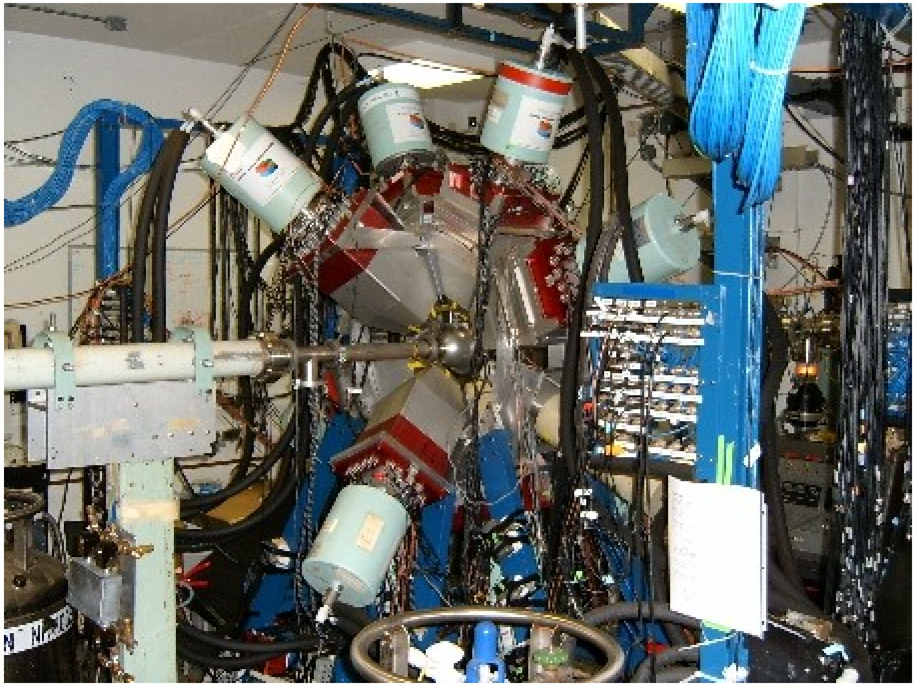
P. Mason et al., t.b.p.

HPGe requirement set on (any)
Γ-rays from ^{188}W to seperate out this
weak reaction channel;
then look at $LaBr_3$ time-difference.

Large Clover Ge detector array (YRAST-Ball?) at the NSCL / FRIB decay station, combined with $LaBr_3$ array

Compact configuration





Fast timing on CARIBU isotopes with X-array (Clovers) + $LaBr_3$'s

Fast timing at ILL (Grenoble) after n-capture (Exogam + $LaBr_3$'s)

Fast timing at RIKEN-RIBF (EURICA + $LaBr_3$'s)

... idea always the same: high-efficiency HPGe + $LaBr_3$

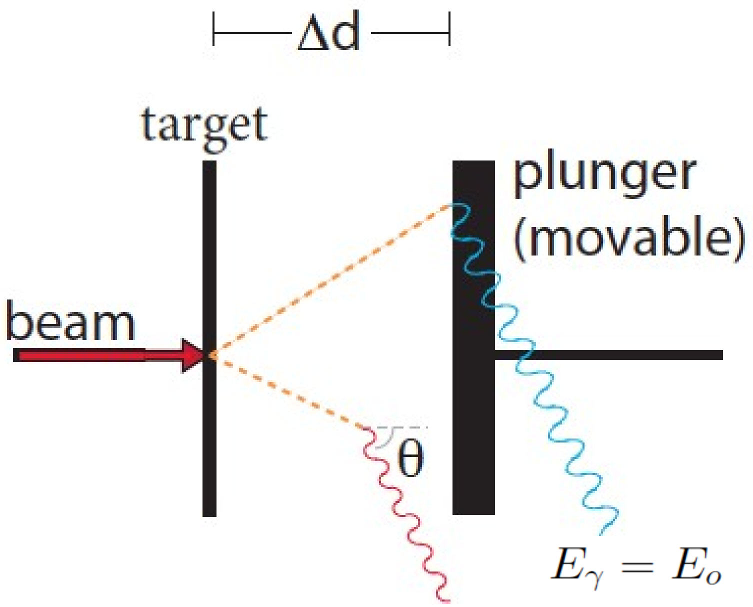
Region 2

At some point, clocks are not fast enough !

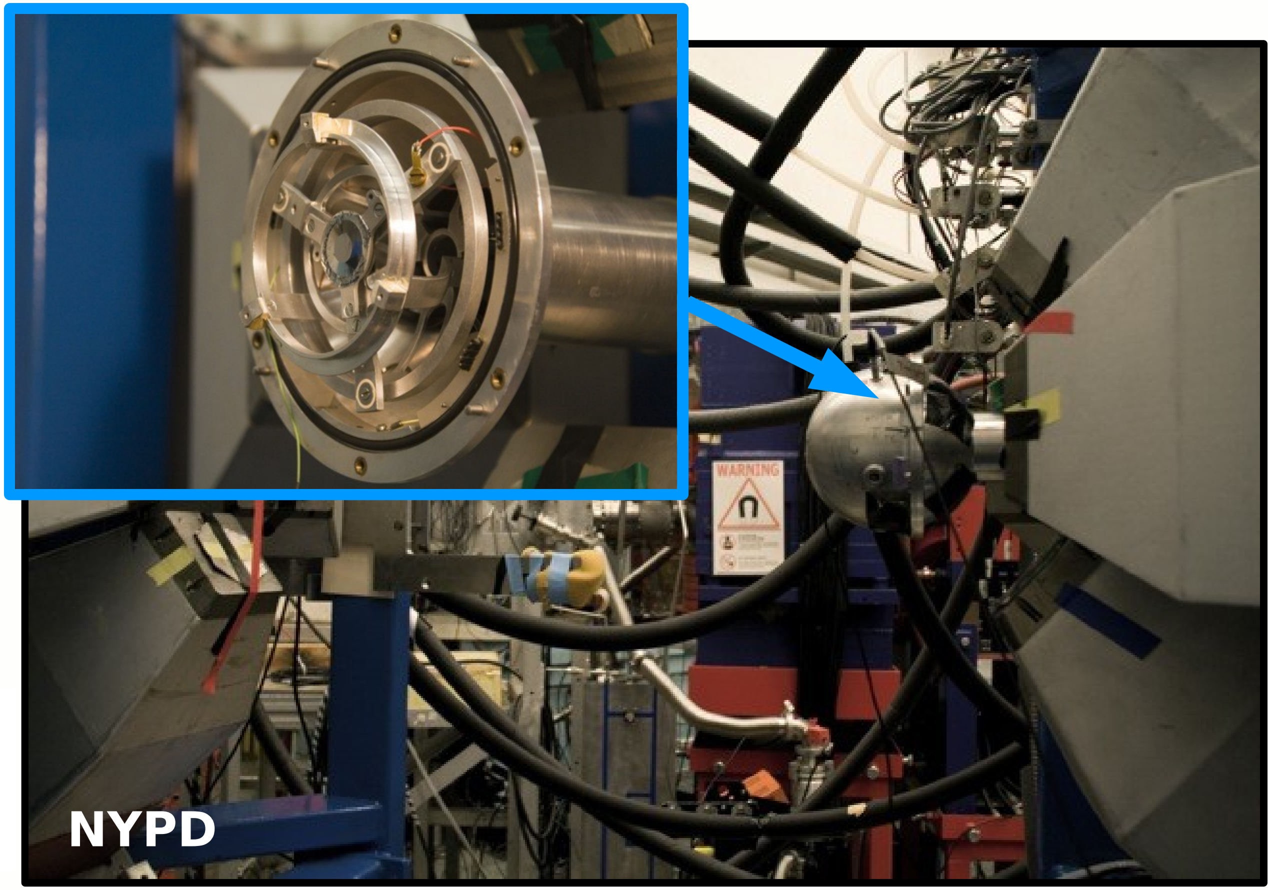
ps - regime

(Doppler Shifts for direct Lifetime Measurements)

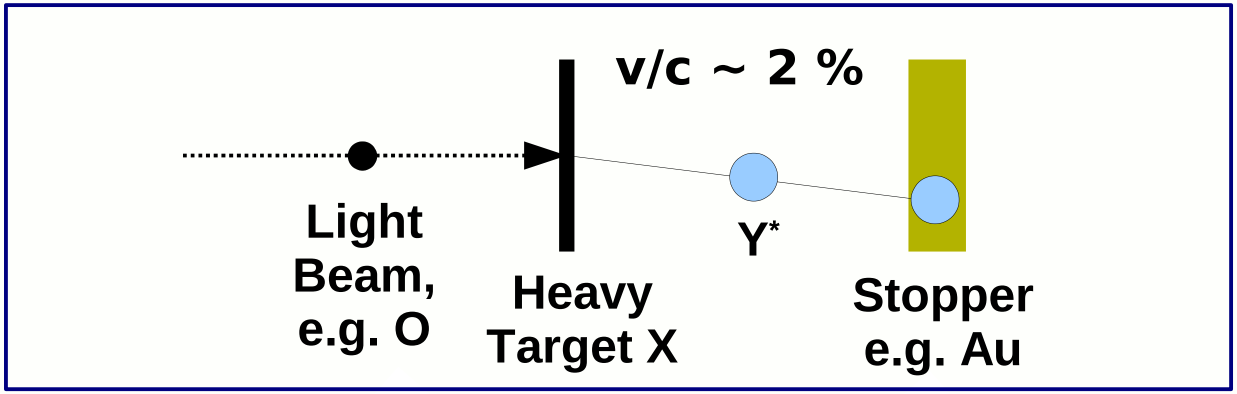
Recoil Distance Doppler Shift (RDDS) method
-> pico-second regime

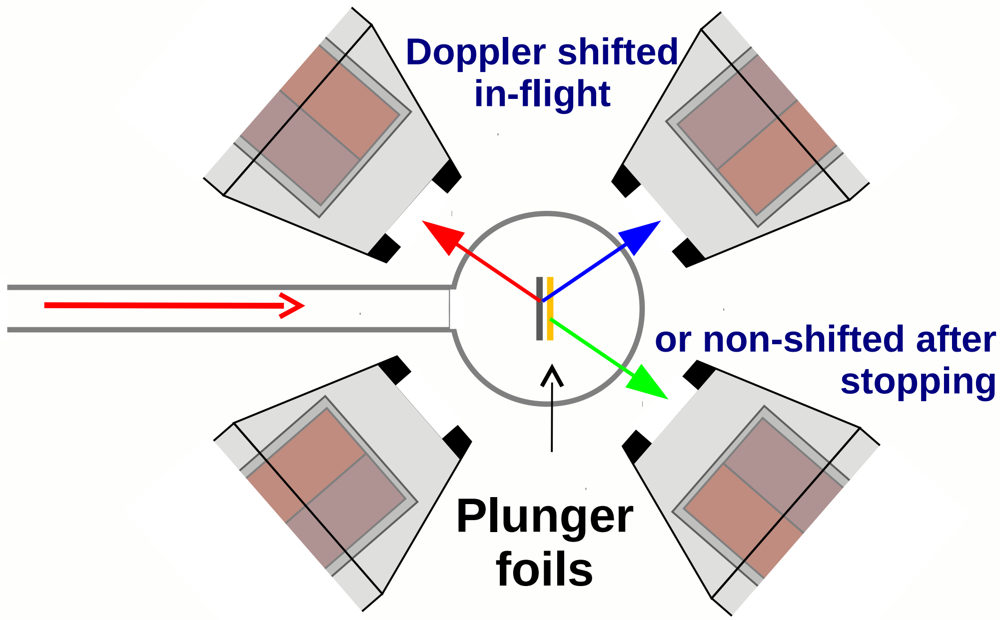


$$E'_\gamma = E_o(1 + \frac{v}{c}cos(\theta))$$

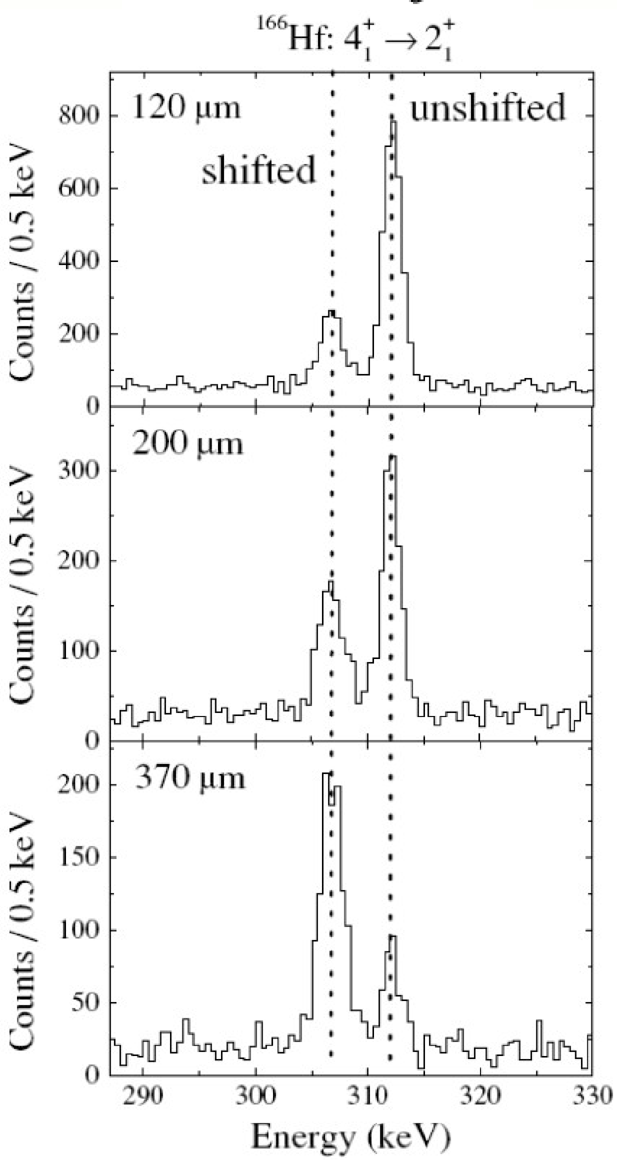


Yale Plunger





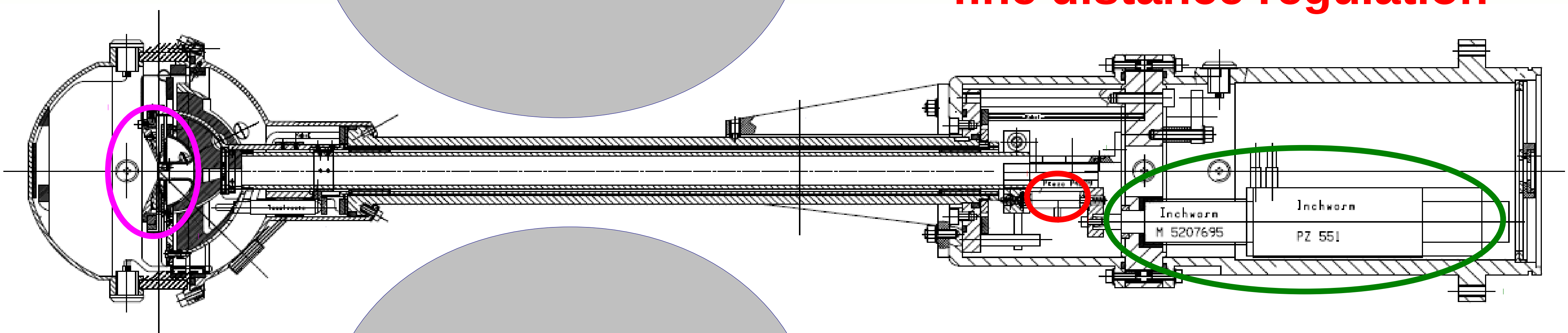
$$E_{sh} = E_o(1 + \frac{v}{c}\cos\theta)$$



Cologne-Type Plunger Device

Detector arrays

Piezo: fine distance regulation



Target/ Stopper

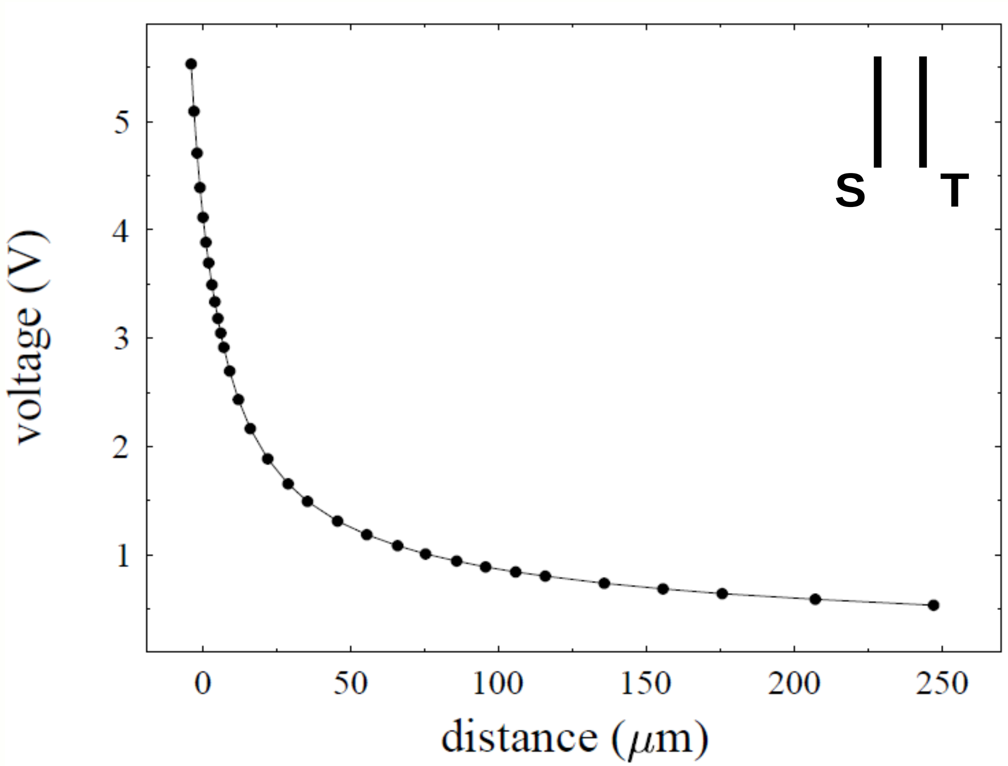
Detector arrays

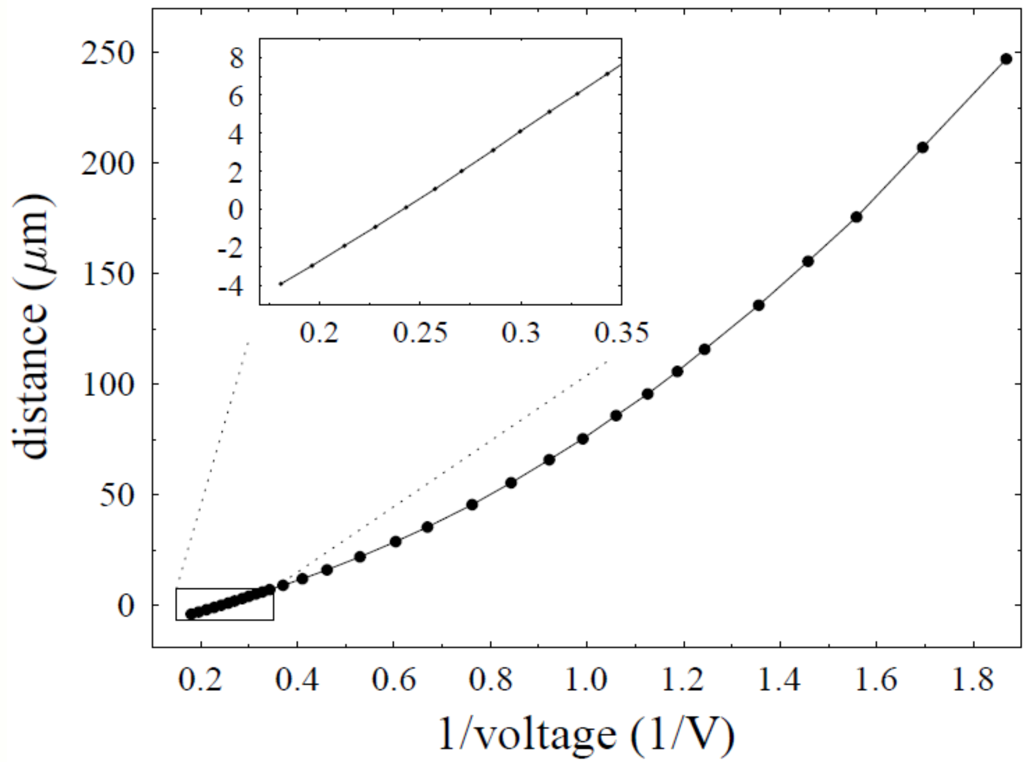
Inchworm Motor: coarse distance setting

Calibrate the Foil Distance

(against a built in micrometer)

Put voltage (pulse) on one foil, read pulse height from the other -> Capacitance measurement !

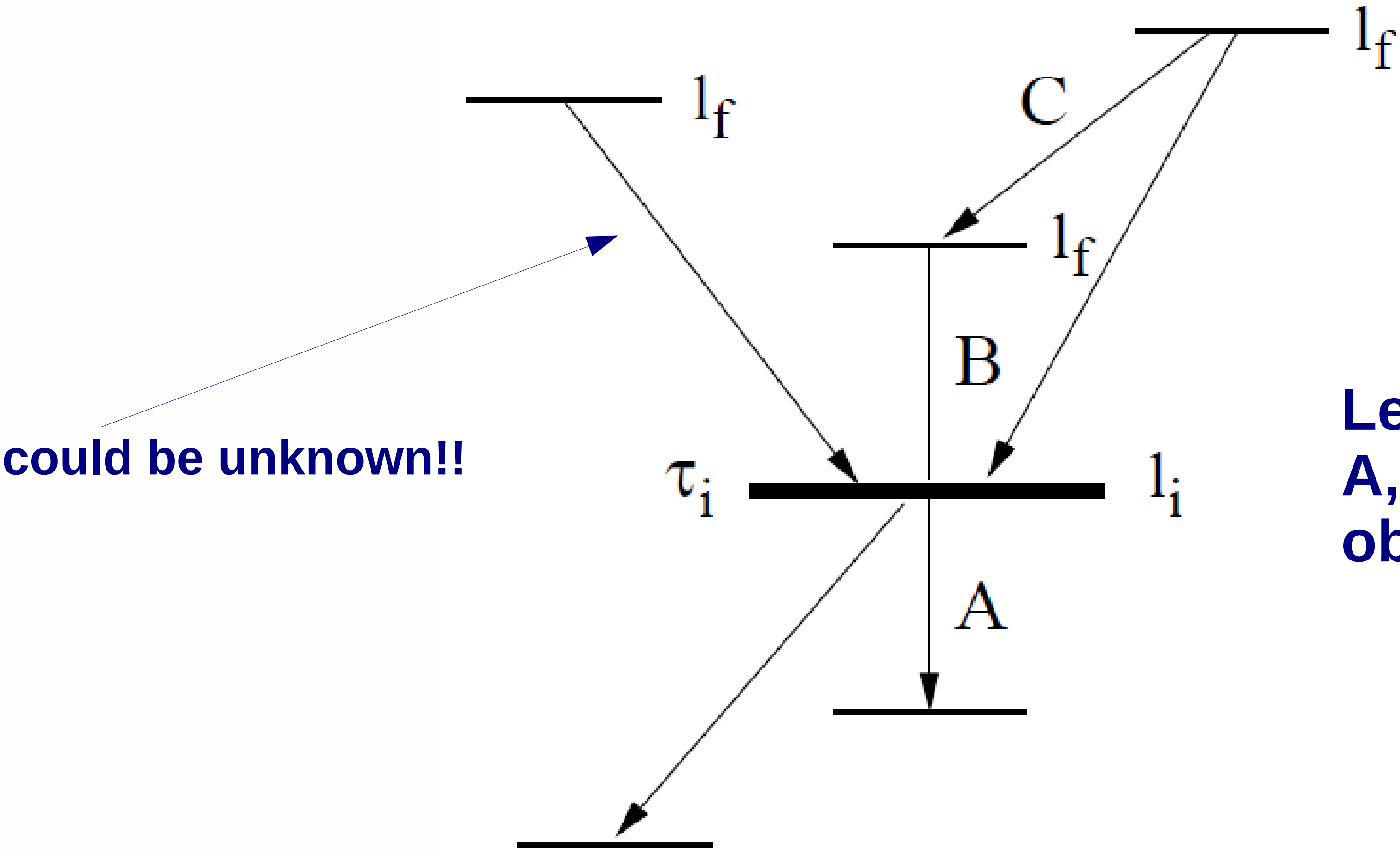




Gives a good idea of offset (minimum foil distance), more important: ***relative distances can easily be measured!***

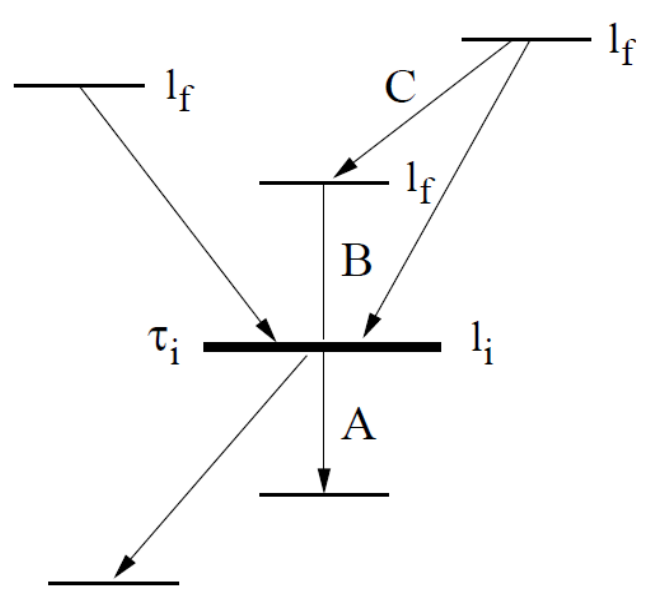
Differential Decay Curve Method
(typically used for most plunger experiments)

In general, the decay scheme is complicated:



Let's say, A, B, C are observed !

Differential Decay Curve Method



general decay law: $\dot{n}_i = -\lambda_i n_i(t)$

$n_i(t)$ **number of nuclei in state i at time t**

λ_i **decay constant for state i**

b_{fi} **decay branching from state f to i**

$$\frac{d}{dt}n_i(t) = -\lambda_i(t)n_i + \sum_f \lambda_f n_f(t) b_{fi}$$

decay **feeding**

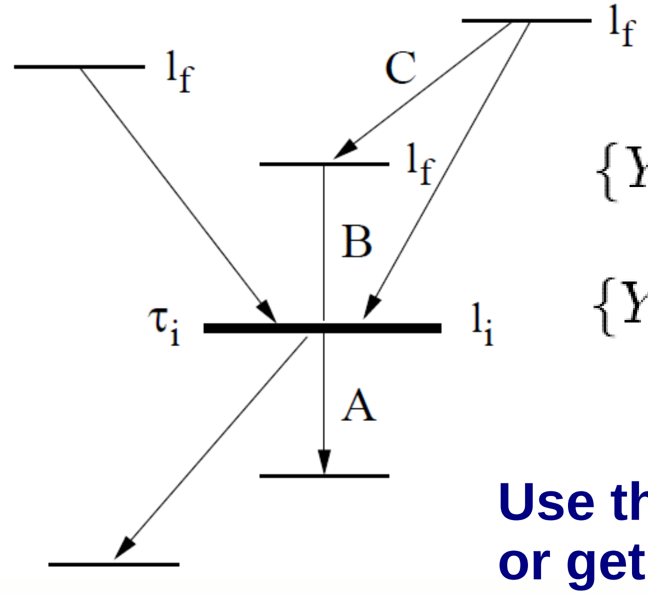
$N_i(t)$ **number of nuclei that decayed out of state i unitl time t**
that is proportional to the γ-ray intensity !

$$\tau_i(t) = \frac{-N_i(t) + \sum_f b_{fi} N_f(t)}{\frac{d}{dt}N_i(t)}$$

Problem: feeders are in general not completely observed => false measurement

General Principle: DDCM

Differential Decay Curve Method in Coincidence Experimens



For any coincidence between gammas X and Y:

$$\{Y, X\} = \{Y_S, X_S\} + \{Y_S, X_U\} + \{Y_U, X_S\} + \{Y_U, X_U\}$$

$\{Y_U, X_S\} = 0$ **if transition X is preceding transition Y (for example X=B, Y=A)**

Use this with previous equation gives (check as homework, or get the papers by Petkov, Dewald, von Brentano, ...) gives:

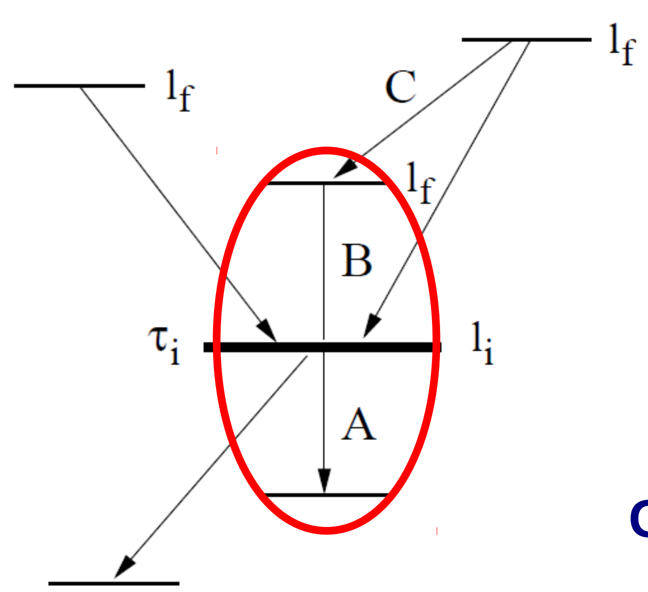
$$\tau(t_k) = \frac{\{C_S, A_U\}(t_k) - \alpha\{C_S, B_U\}(t_k)}{\frac{d}{dt}\{C_S, A_S\}(t_k)}$$

$$\alpha = \frac{\{C, A\}}{\{C, B\}} = \frac{\{C_S, A\}}{\{C_S, B\}} = \frac{\{C_S, A_U\} + \{C_S, A_S\}}{\{C_S, B_U\} + \{C_S, B_S\}}$$

This is a bit complicated, and is for the *general* case.
Simplify further: Gate only and directly on the shifted component of B !!

General Principle: DDCM

Differential Decay Curve Method in Coincidence Experimens



$$\tau(t_k) = \frac{\{C_S, A_U\}(t_k) - \alpha\{C_S, B_U\}(t_k)}{\frac{d}{dt}\{C_S, A_S\}(t_k)}$$

$$\alpha = \frac{\{C, A\}}{\{C, B\}} = \frac{\{C_S, A\}}{\{C_S, B\}} = \frac{\{C_S, A_U\} + \{C_S, A_S\}}{\{C_S, B_U\} + \{C_S, B_S\}}$$

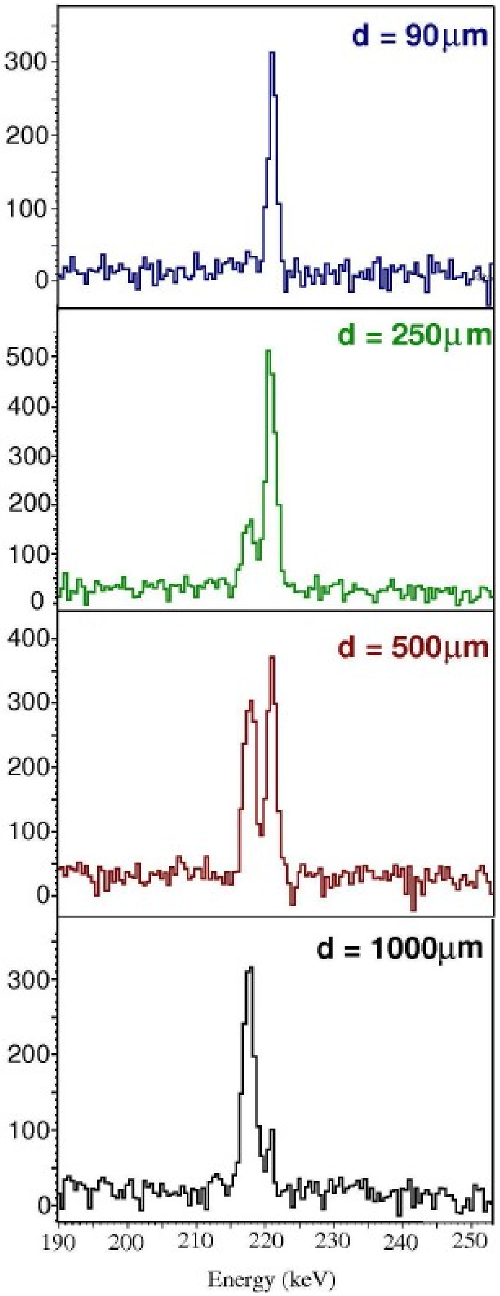
Gate on B_s only: no side-feeding included!

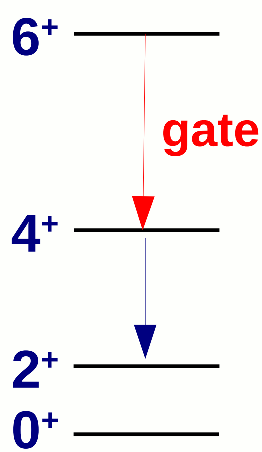
$$\tau(t_k) = \frac{\{B_S, A_U\}(t_k)}{\frac{d}{dt}\{B_S, A_S\}(t_k)}$$

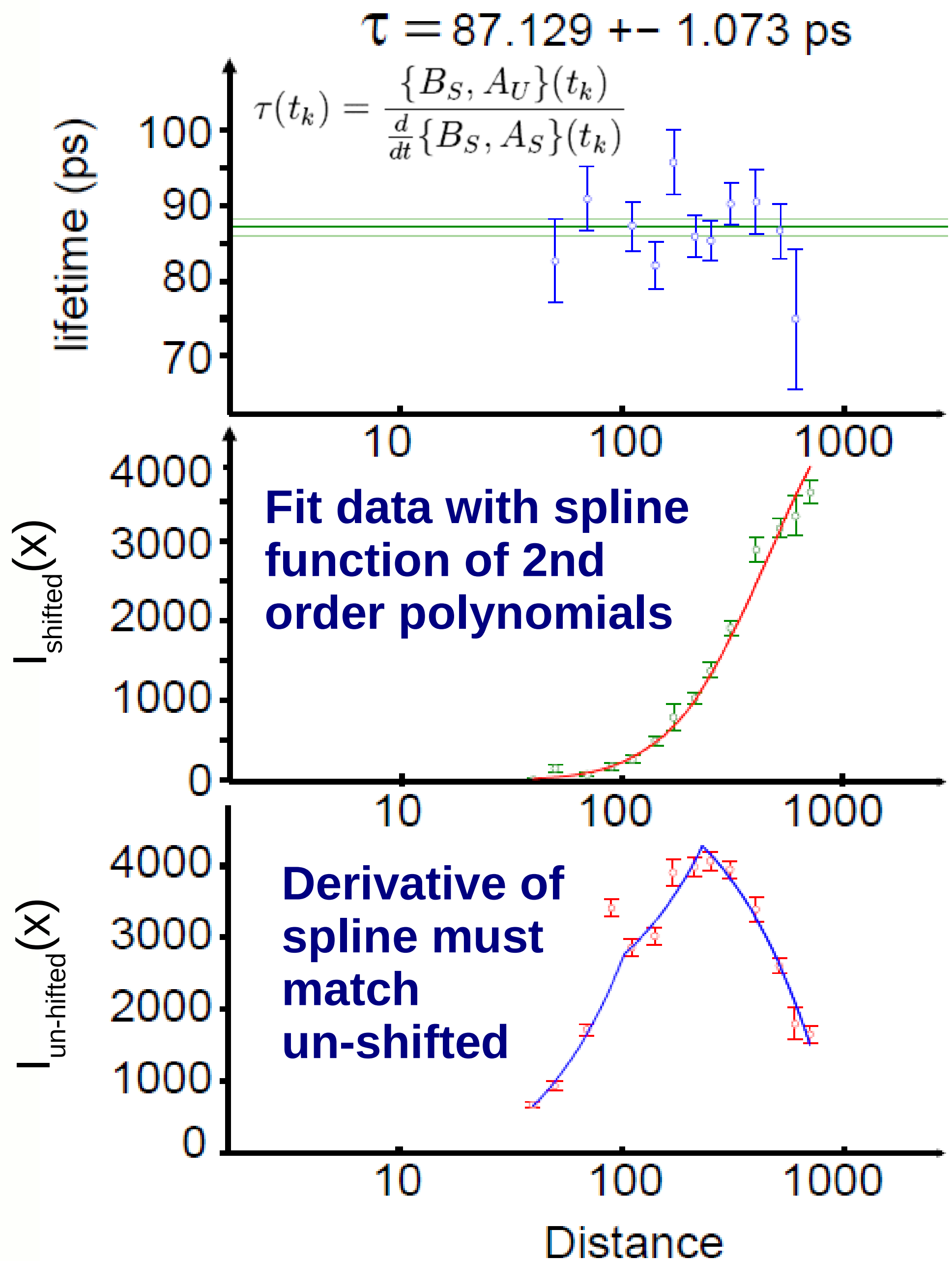
Gate on Doppler-shifted direct feeder;
-> measure unshifted and shifted components of transition of interest (A)

Even better: it is a differential !!
(in the end absolute distance does not count, but changes in distance, which we can measure)

Example: ^{170}Hf, $\tau(4_1^+)$, gate on 6->4



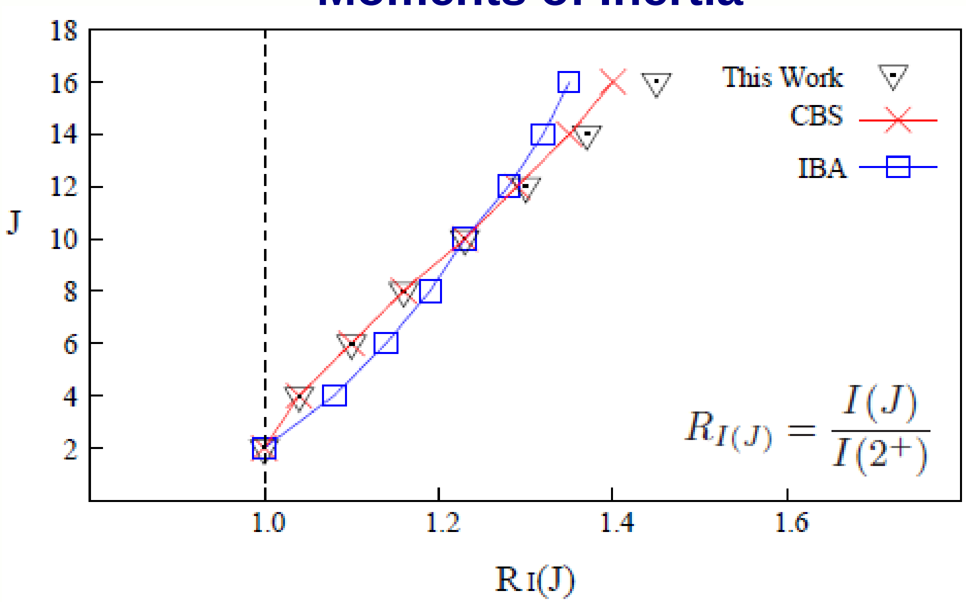




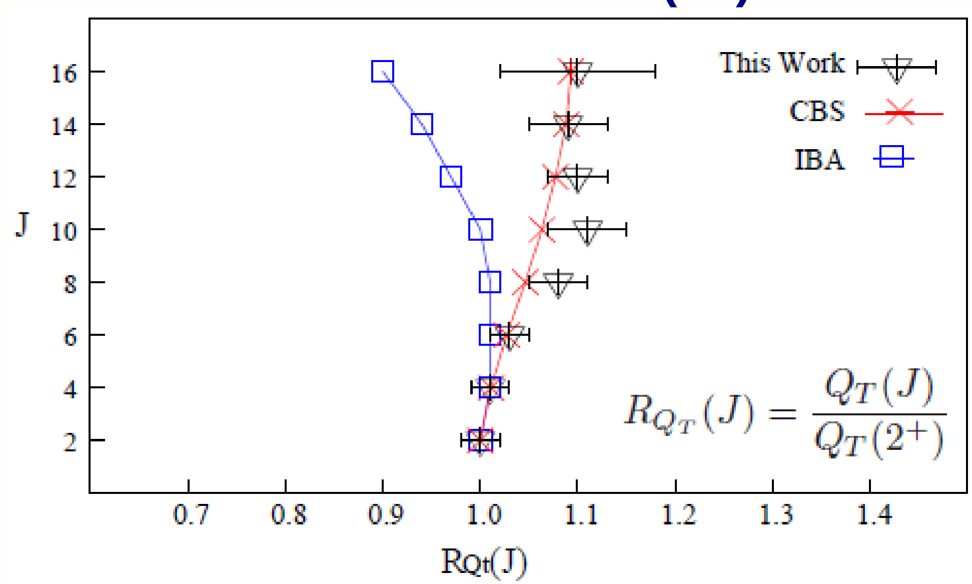
Centrifugal Stretching in ^{170}Hf

Deformation of the nucleus does not remain constant when it spins up !

Moments of Inertia

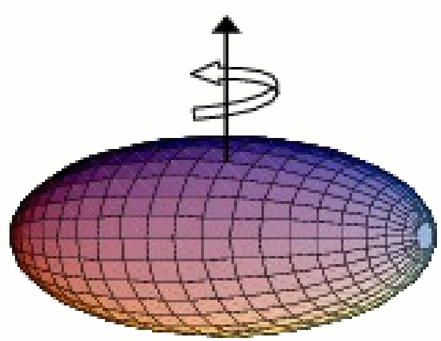


Deformation from B(E2)'s



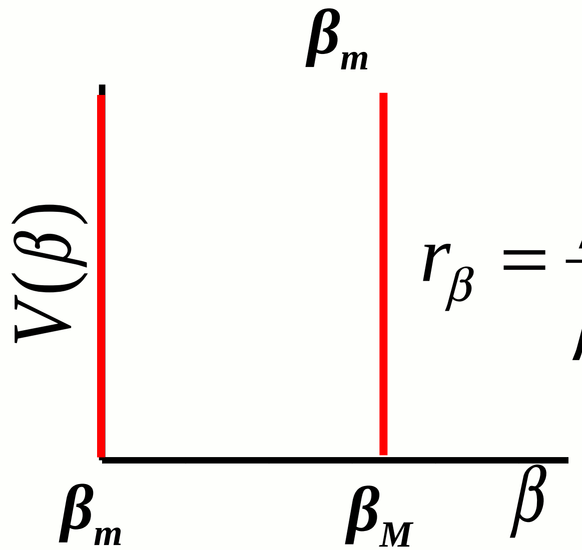
with transition quadrupole moments:

$$Q_T(I) = \sqrt{\frac{16\pi}{5}} \frac{B(E2)}{< I,0,2,0|I-2,0 >}$$

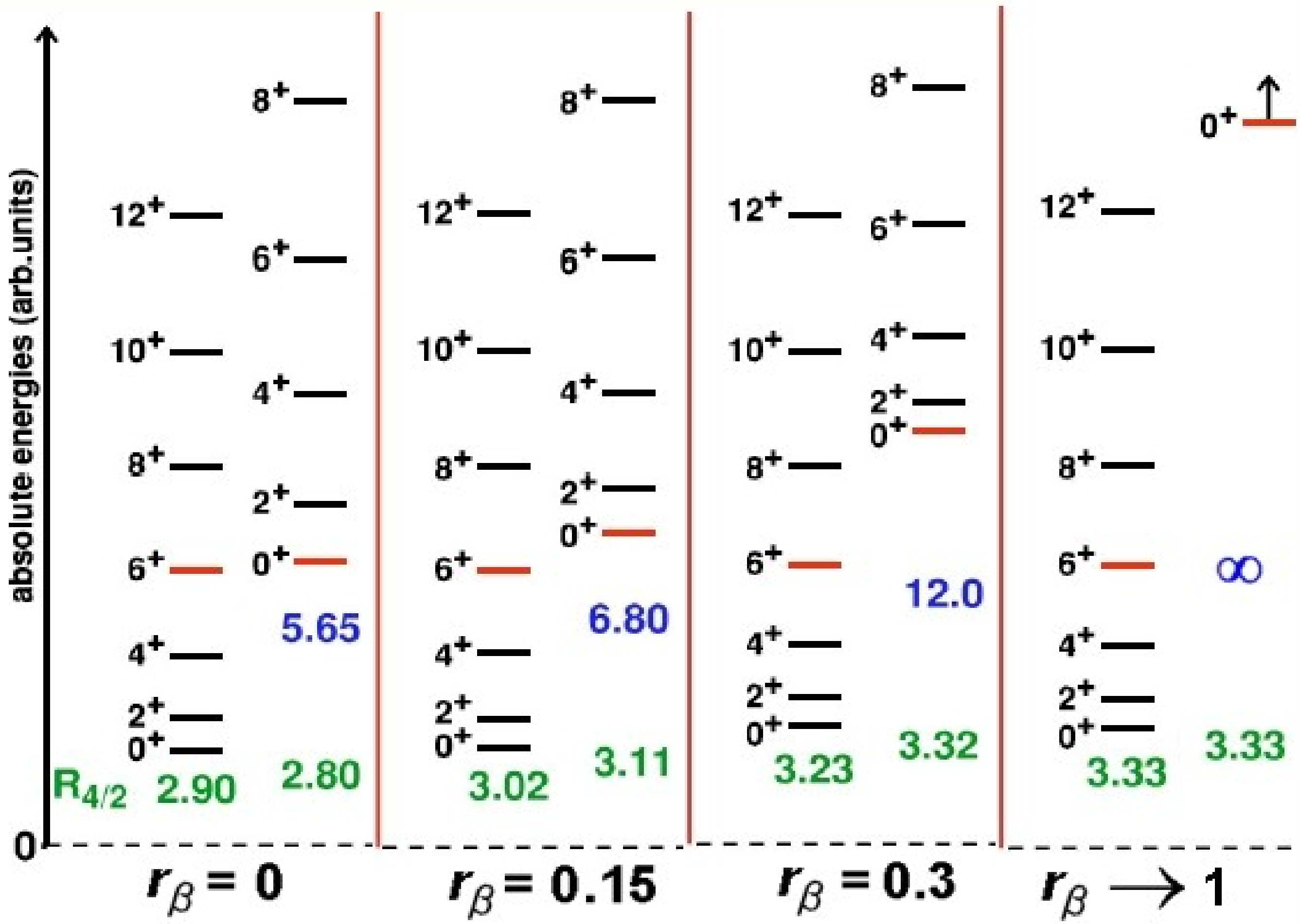


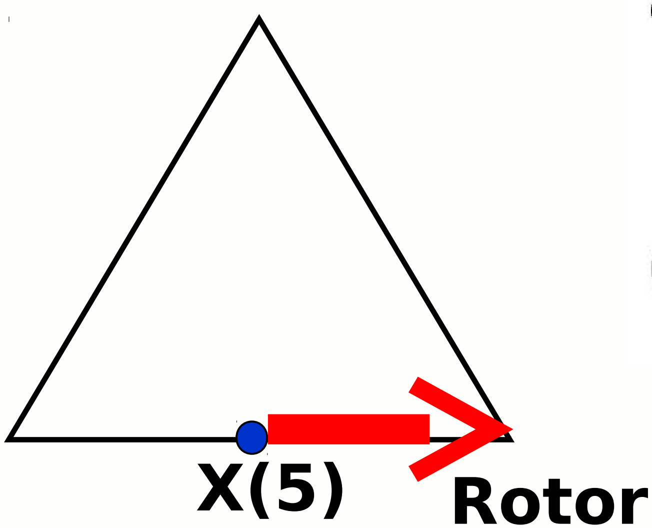
Nucleus elongates, like a drop – not rigid!

Confined Beta-Soft Model



$$r_\beta = \frac{\beta_m}{\beta_M}$$





N. Pietralla and O.M. Gorbachenko, Phys. Rev. C 70, 011304(R) (2004).