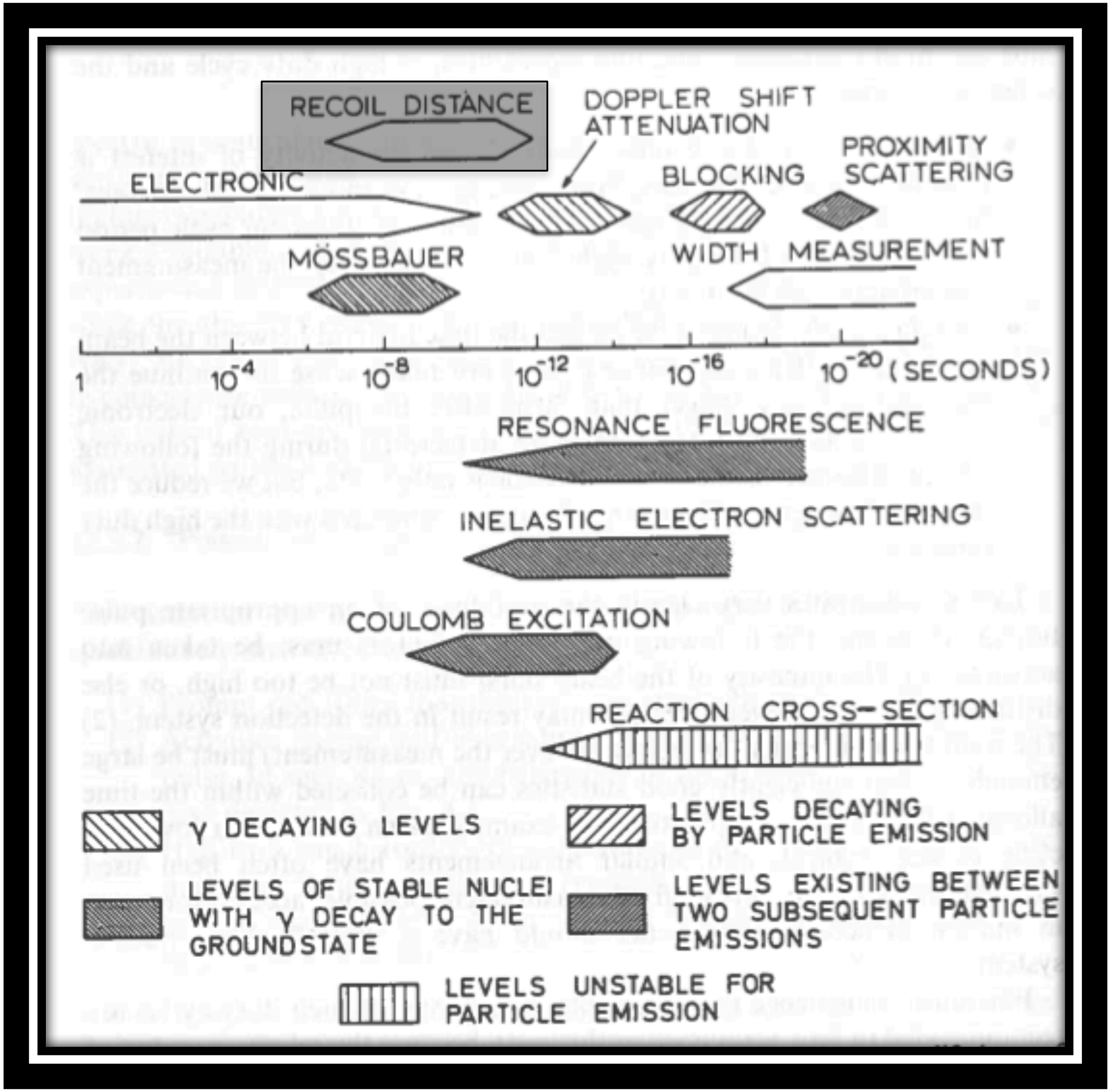
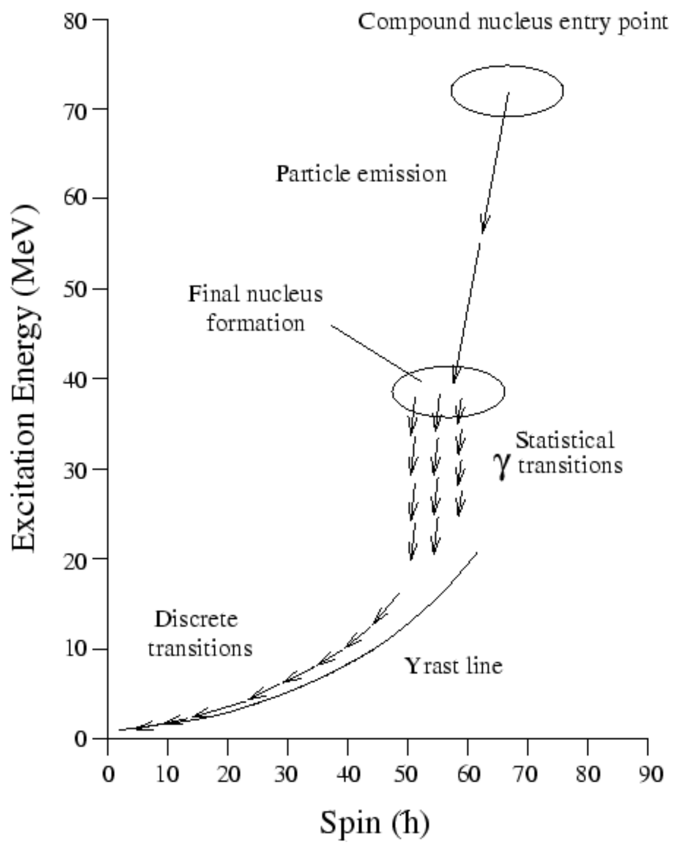
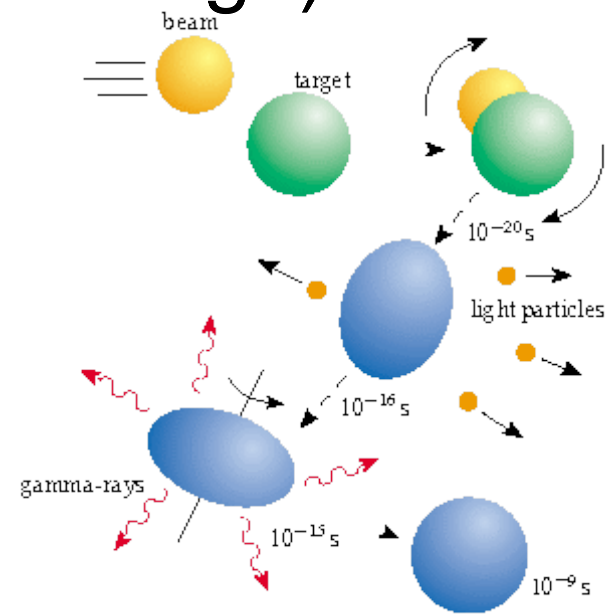
PH3: LECTURE 2

Tuomas Grahn
Jyväskylä Summer School 2017
University of Jyväskylä


RECOIL DISTANCE
DOPPLER SHIFT ATTENUATION
PROXIMITY SCATTERING
ELECTRONIC
BLOCKING
MÖSSBAUER
WIDTH MEASUREMENT
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20} (SECONDS)
RESONANCE FLUORESCENCE
INELASTIC ELECTRON SCATTERING
COULOMB EXCITATION
REACTION CROSS-SECTION
γ DECAYING LEVELS
LEVELS DECAYING BY PARTICLE EMISSION
LEVELS OF STABLE NUCLEI WITH γ DECAY TO THE GROUNDSTATE
LEVELS EXISTING BETWEEN TWO SUBSEQUENT PARTICLE EMISSIONS
LEVELS UNSTABLE FOR PARTICLE EMISSION

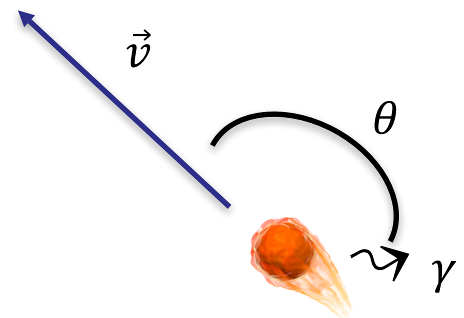
How to measure lifetimes in prompt spectroscopy (in ps range)?





2. Doppler-shift methods–Recoil distance Doppler-shift (RDDS)

Direct, fast-timing method is applicable (in certain cases) down to the ~10 ps level We now concentrate on a method based on the *Doppler-shift* of observed energies of γ rays.



When a moving nucleus (*v*/c=β) emits γ rays, the observed energy can be expressed as

$$E_s = E_0\left(1 + \beta\cos\theta_\gamma\right)$$

where θ is an angle of detection with respect to the velocity vector and E_0 is the energy at rest.

Note the dependence on the velocity of the emitter. We will come back to this.

Principle of lifetime determination

Now, according to the radioactive decay law, the intensity of radiation emitted at rest is

$$I_0 = N_0 e^{\frac{-d}{v\tau}}$$

Similarly, for the radiation emitted in flight

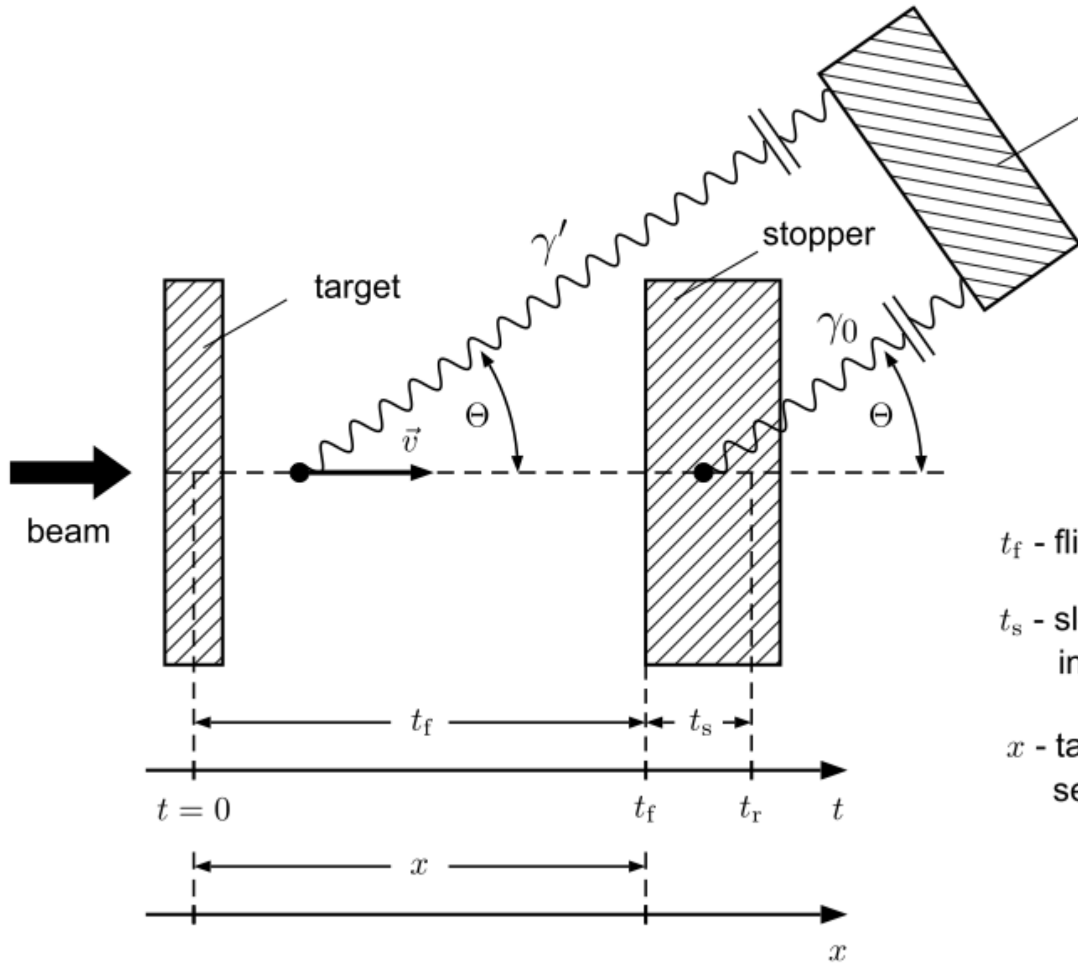
$$I_s = N_0\left(1 - e^{\frac{-d}{v\tau}}\right)$$

Here *d* is the flight distance of the γ-ray emitter.
This gives an idea of lifetime determination:
Measure the intensity of the γ rays as a function of *d*.
The lifetime is normally determined from the ratio *R* (normalisation):

$$R = \frac{I_0}{I_s + I_0} = e^{\frac{-d}{v\tau}}$$

Conclusion: we need an apparatus which can be used to measure γ-ray intensity as a function of distance

The plunger device



t_f - flight time

t_s - slowing-down time in the stopper

x - target-stopper separation

Review: [A Dewald et al., Progress in Part. Nucl. Phys. 67,786 (2013)]

The plunger device

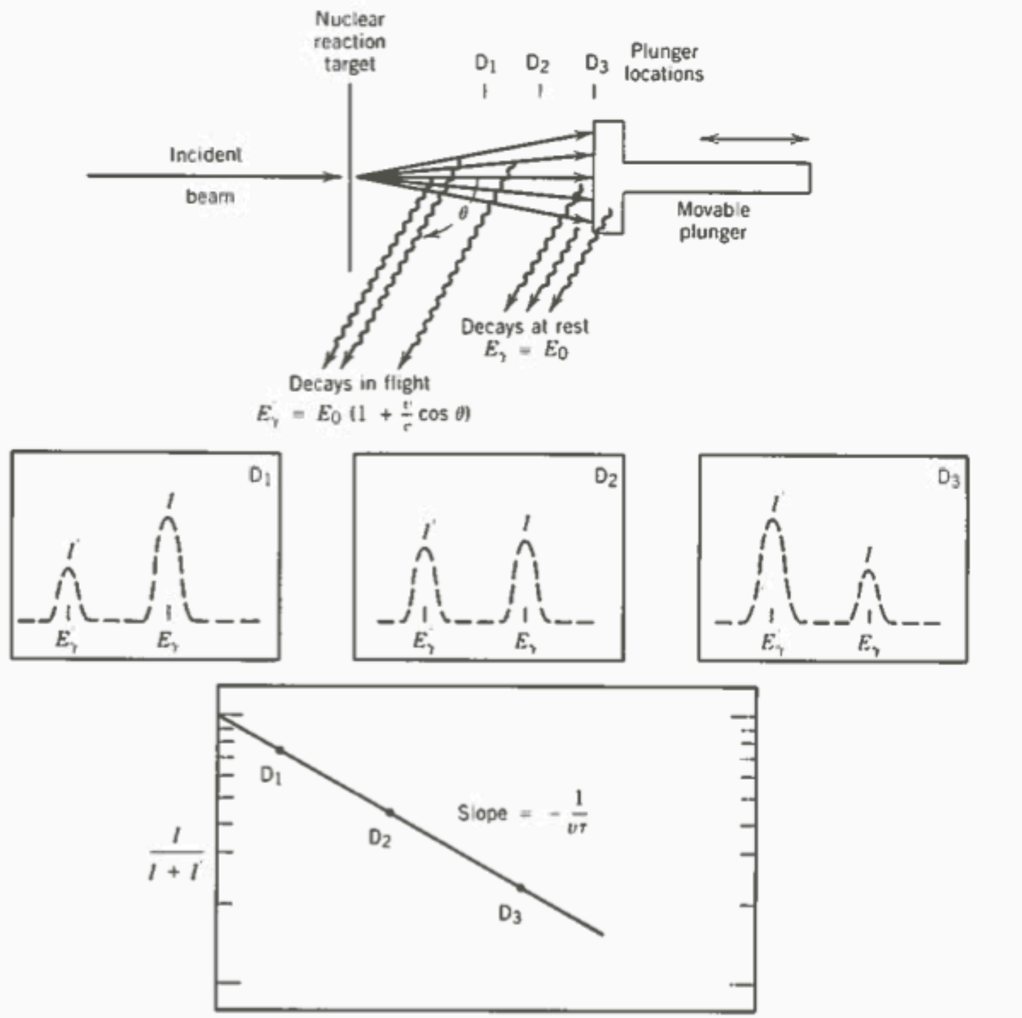
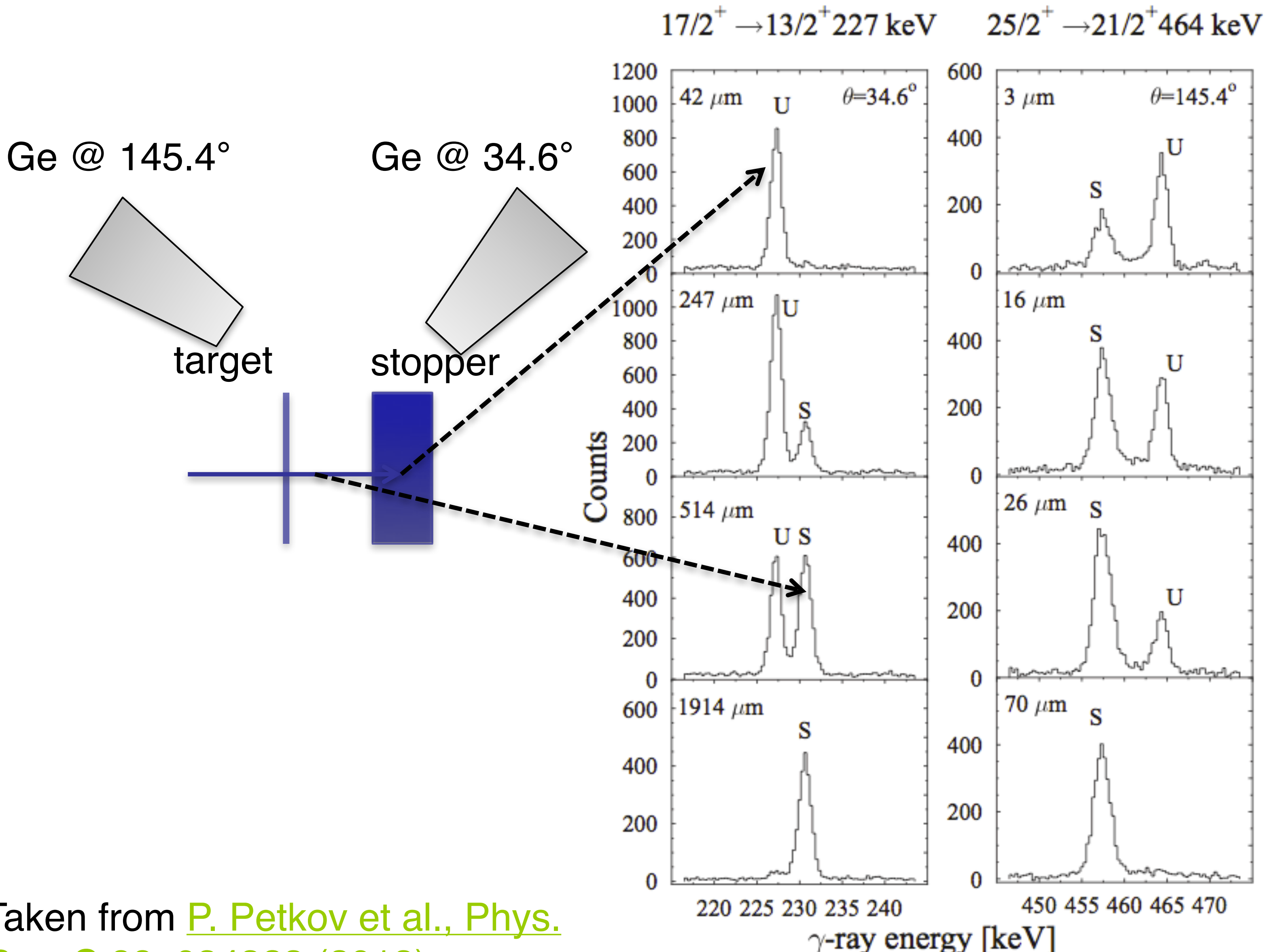


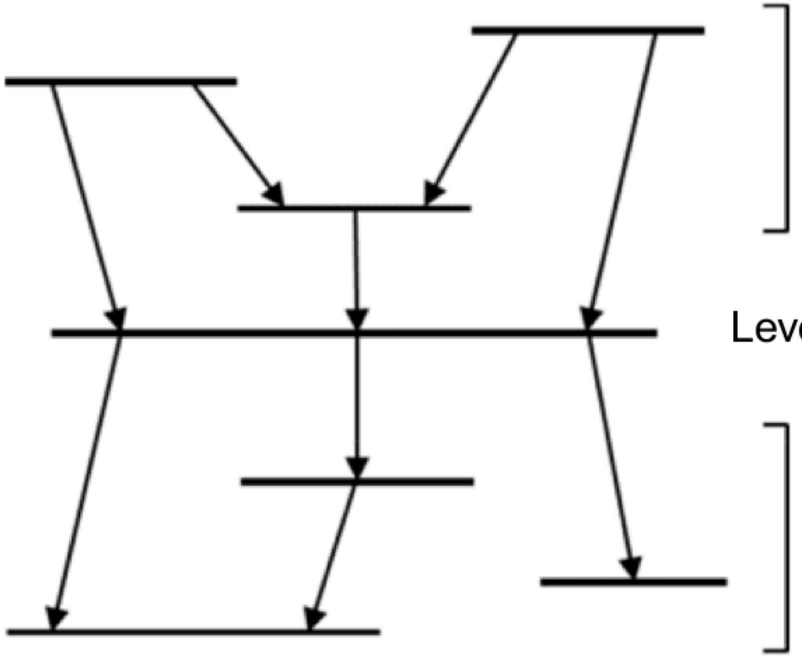
Figure 7.34 Schematic views of the Doppler-recoil method of lifetime measurement. Decaying nuclei are observed by a detector whose axis makes an angle θ with the recoil direction. Moving the plunger changes the relative numbers of decays in flight and at rest, which can be used to determine the mean life of the decay.

Spectra of ^{155}Dy with the plunger device



Taken from P. Petkov et al., Phys. Rev. C 88, 034323 (2013)

- Usually in real cases more levels are involved.
- Level of interest (L_i) is fed by a complicated pattern of transitions.



In general case, the differential equation for the level *i* reads:

$$\frac{d}{dt}n_i(t) = -\lambda_i \cdot n_i(t) + \sum_{k=i+1}^{N} \lambda_k \cdot n_k(t) \cdot b_{ki}.$$

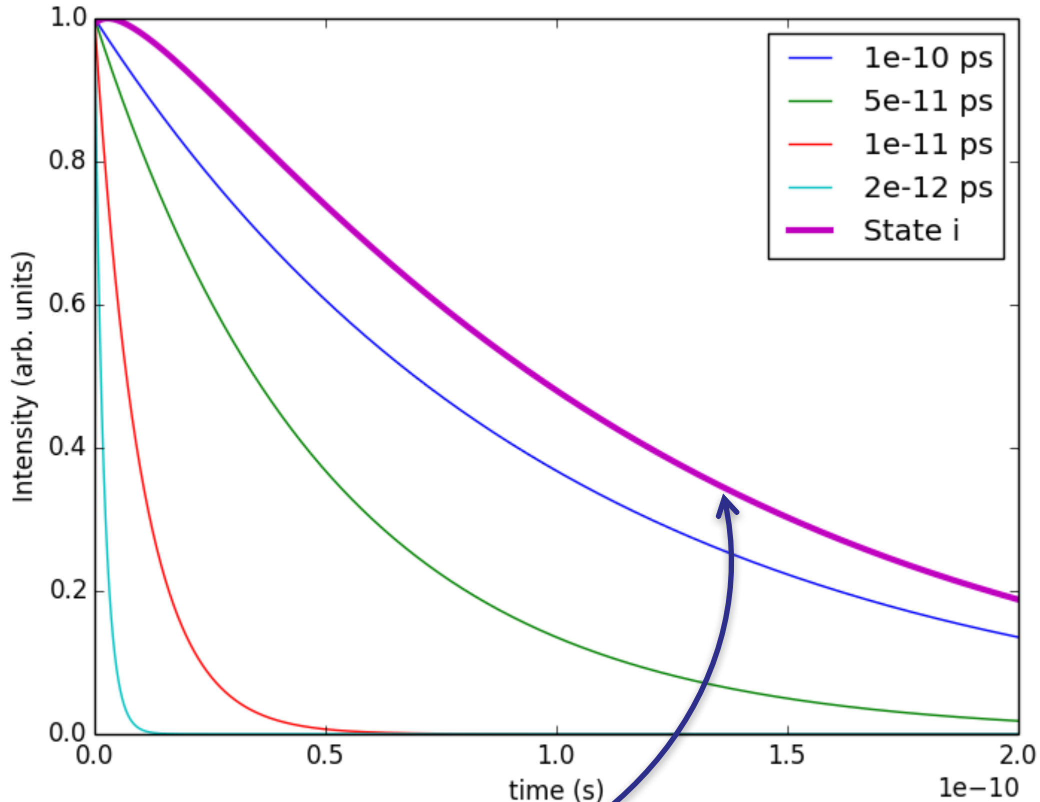
A solution:

This is fitted to the experimental data$\Rightarrow \lambda_i$

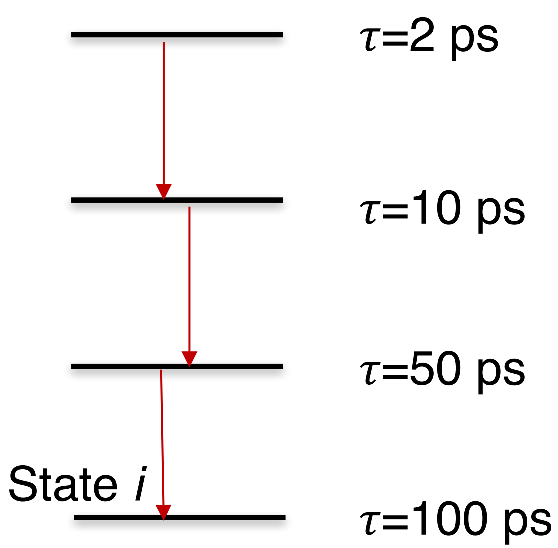
$$R_i(t) = P_i e^{-t\lambda_i} + \sum_{k=i+1}^{N} M_{ki}\left[(\lambda_i/\lambda_k)e^{-t\lambda_k} - e^{-t\lambda_i}\right]$$

$$\text{where } M_{ki}(\lambda_i/\lambda_k - 1) = b_{ki}P_k - b_{ki}\sum_{m=k+1}^{N} M_{mk} + \sum_{m=i+1}^{k-1} M_{km}b_{mi}(\lambda_m/\lambda_k).$$

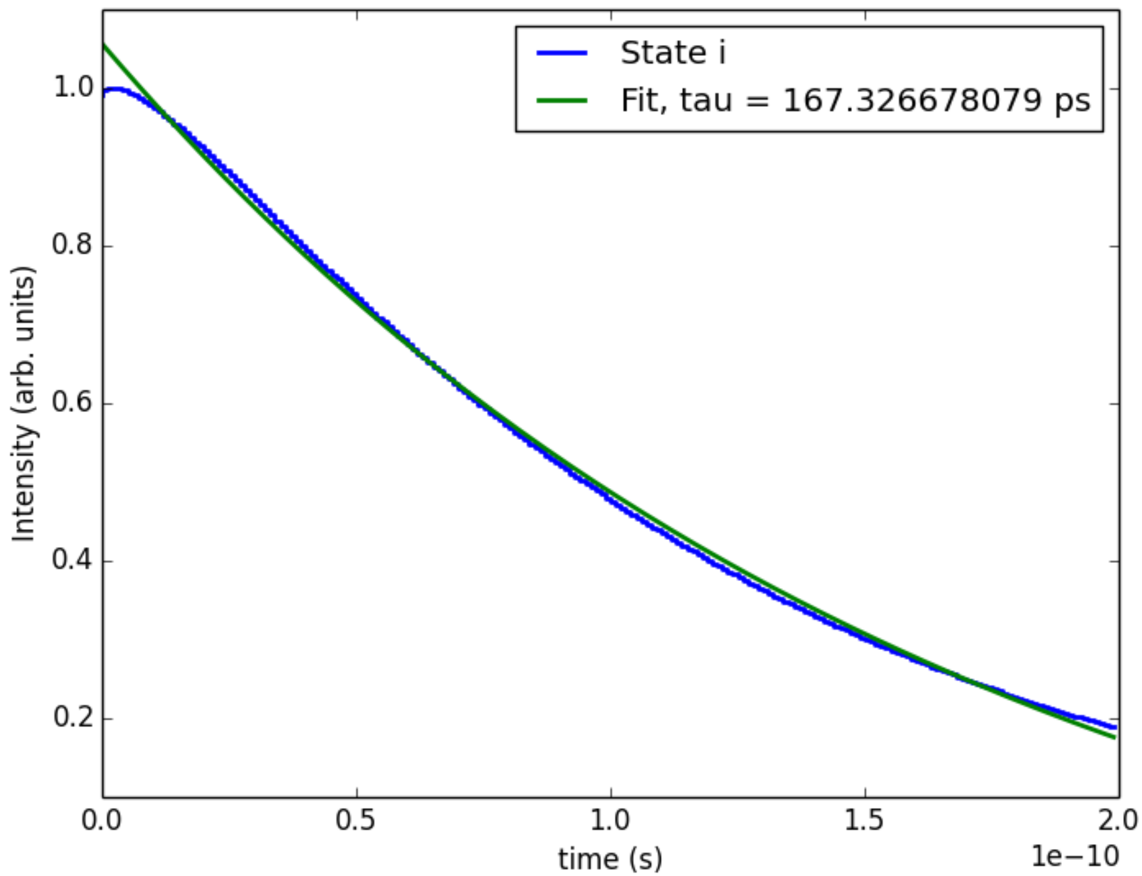
What decay curve is observed?



Effective lifetime, i.e. what is observed, includes the time behaviour of all preceding transitions.



What if $ae^{-\lambda t}$ would be fitted to the observed data?



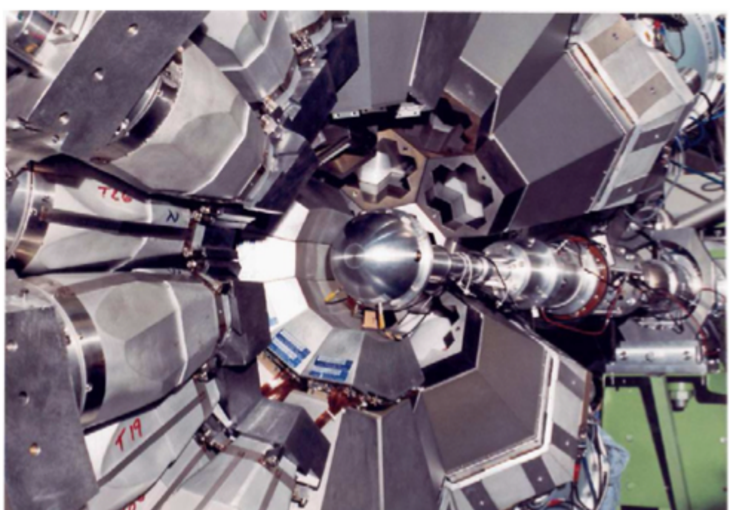
Wrong lifetime, 167 ps instead of 100 ps. Why is that?
Because of the lifetime history. So this is not enough. One need to simulate the feeding or do something else.

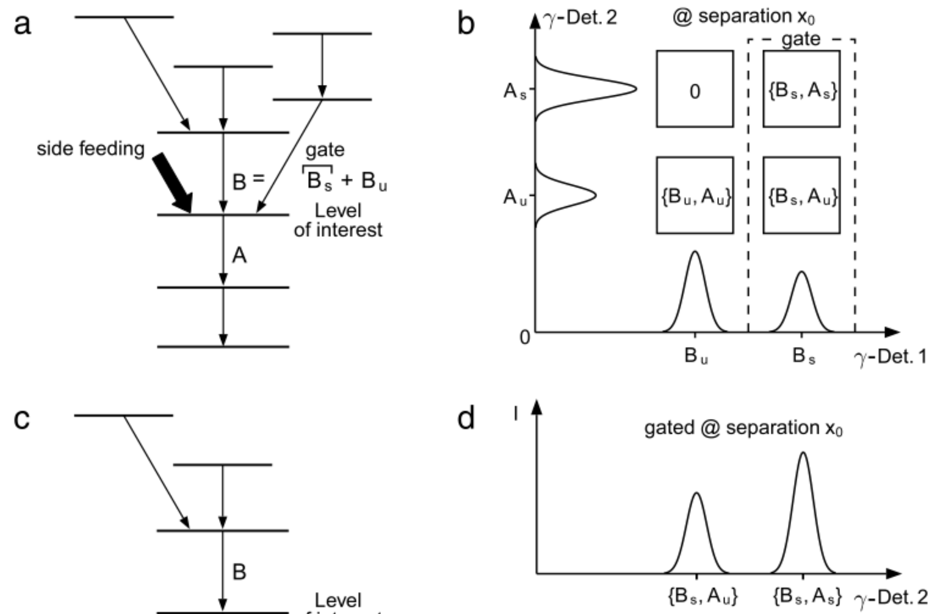
The fit of $R_i(t)$ involves significant number of free parameters that can not be controlled. In addition, *unobserved side feeding to the level L_i* is a problem. Several corrections have to be taken into account:

- Relativistic effects (lifetimes, observations angles)
- Slowing down in the stopper
- Solid angle effects (finite size of a detector)
- Detector efficiencies
- Recoil deorientation in vacuum

Many complex problems $\Rightarrow$ better method needed.

Coincidence plunger with large Ge-detectors arrays (Gammasphere, GASP, EUROBALL)





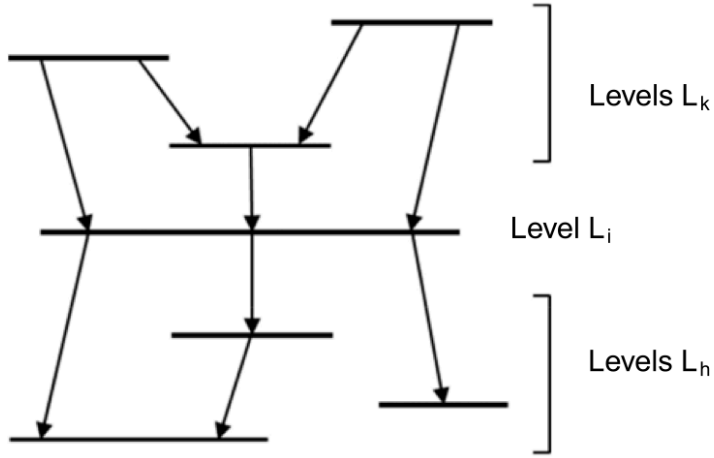
$$\Longrightarrow \quad \tau = \frac{\{B_s, A_u\}(x_0)}{\Delta\{B_s, A_s\}(x_0)} \cdot \frac{\Delta x}{v},$$

where $\Delta\{B_s, A_s\}(x_0) =$
$\{B_s, A_s\}(x_0) - \{B_s, A_s\}(x_0 + \Delta x)$.

The Differential Decay Curve Method (DDCM)

The difficulties in `conventional´ lifetime analysis triggered the introduction of DDCM A. Dewald et al., Nuc. Instrum. Meth. A 329, 248 (1989)

$$\tau_i(t) = 1/\lambda_i = \frac{-R_i(t) + \sum_k b_{ki}\alpha_{ki}R_k(t)}{\frac{d}{dt}R_i(t)}$$



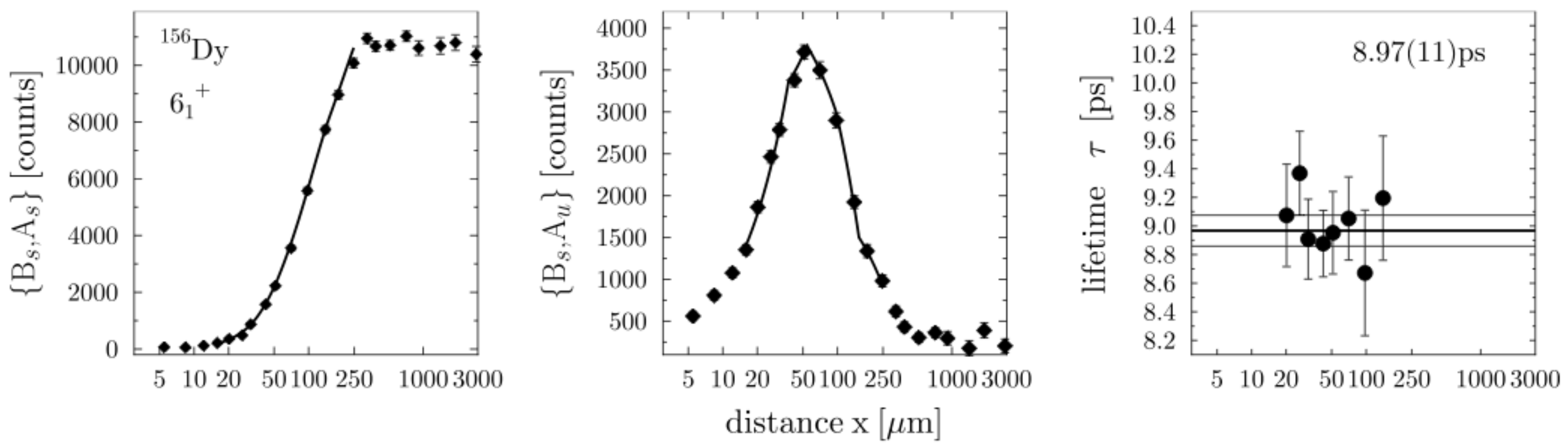
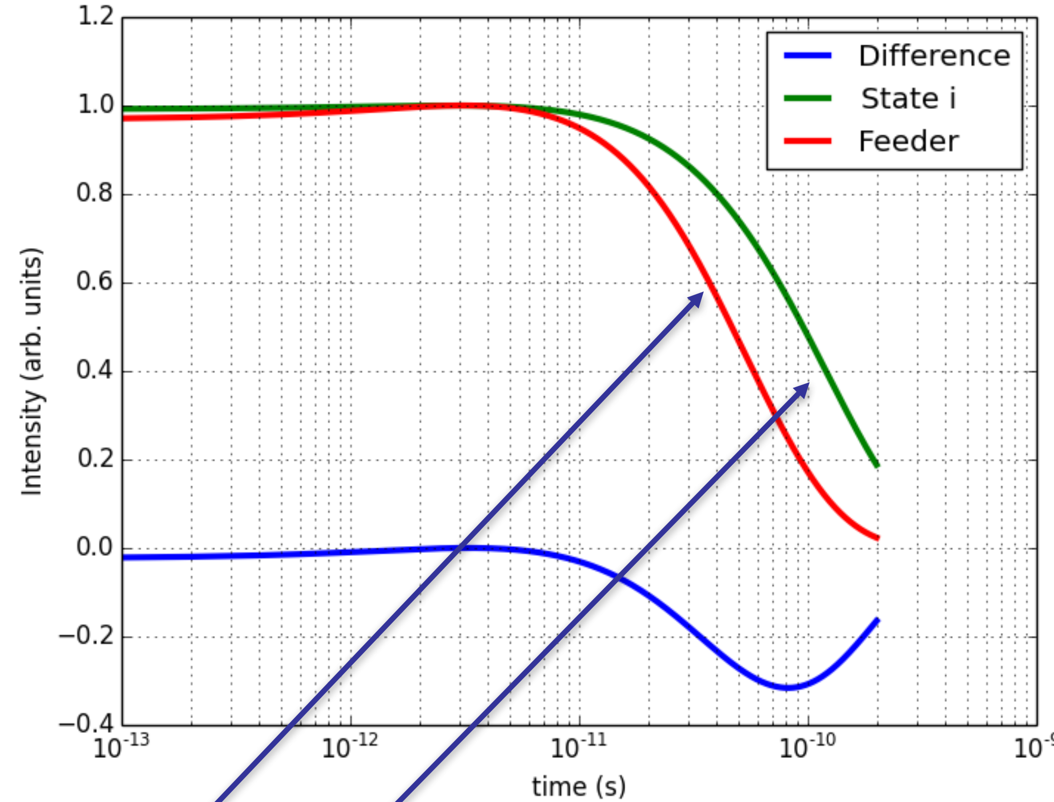
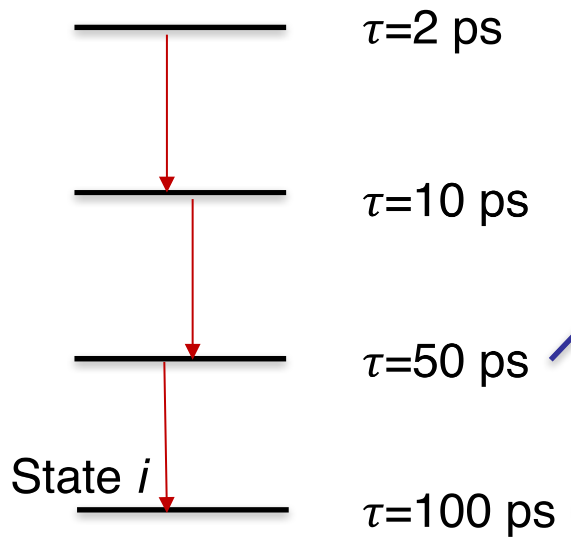
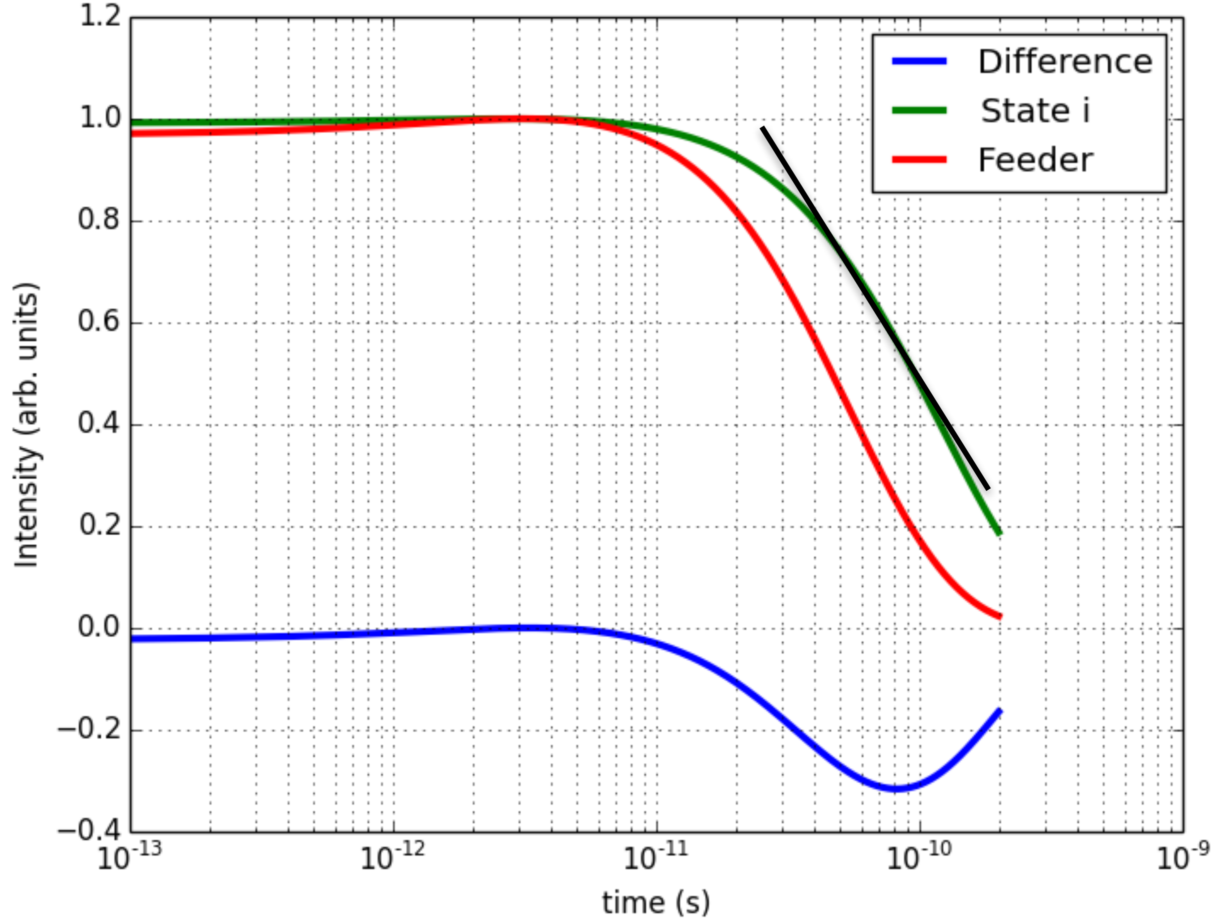


Fig. 42. DDCM coincidence analysis of the 6_1^+ state in ^{156}Dy [31]. The solid line in the left panel is a fit with second order polynomials to the data. The solid line in the middle panel is the derivative of this function multiplied by the lifetime τ. In the right panel the τ-curve is shown calculated according to Eq. (34). See also text.





$$\tau_i(t) = 1/\lambda_i = \frac{-R_i(t) + \sum_k b_{ki}\alpha_{ki}R_k(t)}{\frac{d}{dt}R_i(t)}$$



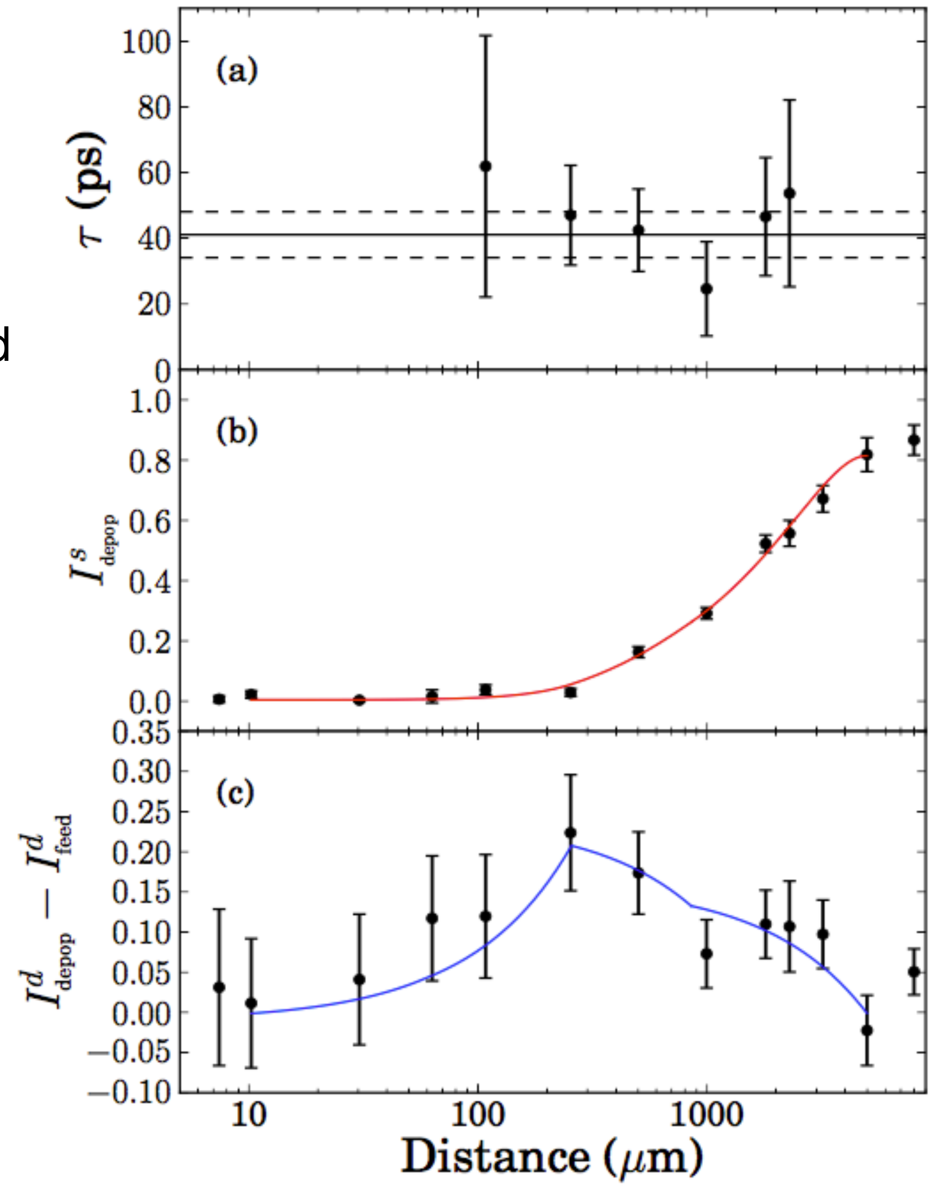
Approximation: straight line, derivative=0.4/6.5 $\cdot$ 10^{-11},
difference=0.3 $\Rightarrow$ $\tau \approx 50$ ps

Still not good enough, but note our very rough approximation

$$\tau_i(t) = 1/\lambda_i = \frac{-R_i(t) + \sum_k b_{ki}\alpha_{ki}R_k(t)}{\frac{d}{dt}R_i(t)}$$

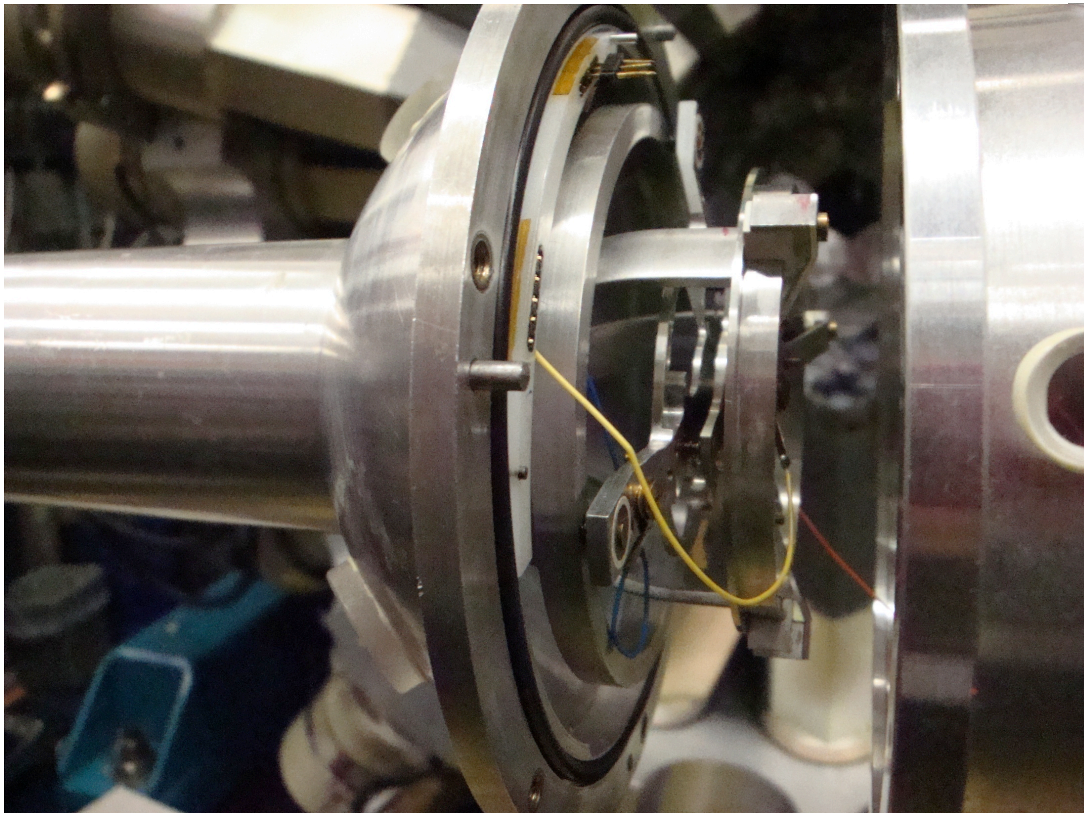
In reality, smoothly connected second-order polynomials are fitted to the data in order to get the derivative.

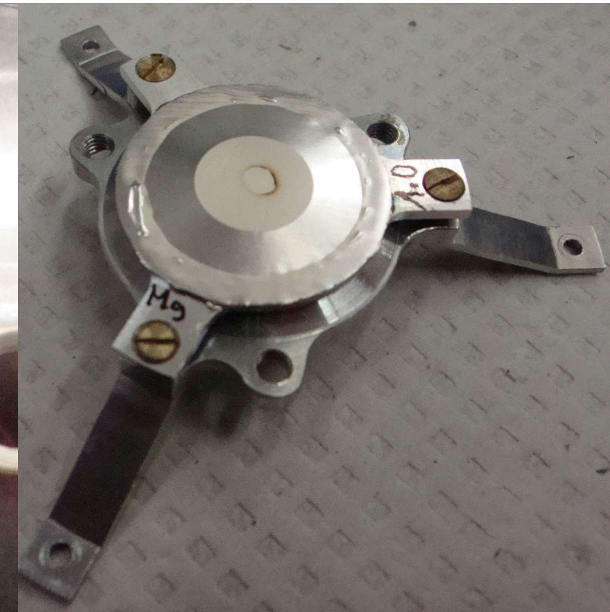
Note that the fit is only required for the derivative. The rest can be extracted from the data.

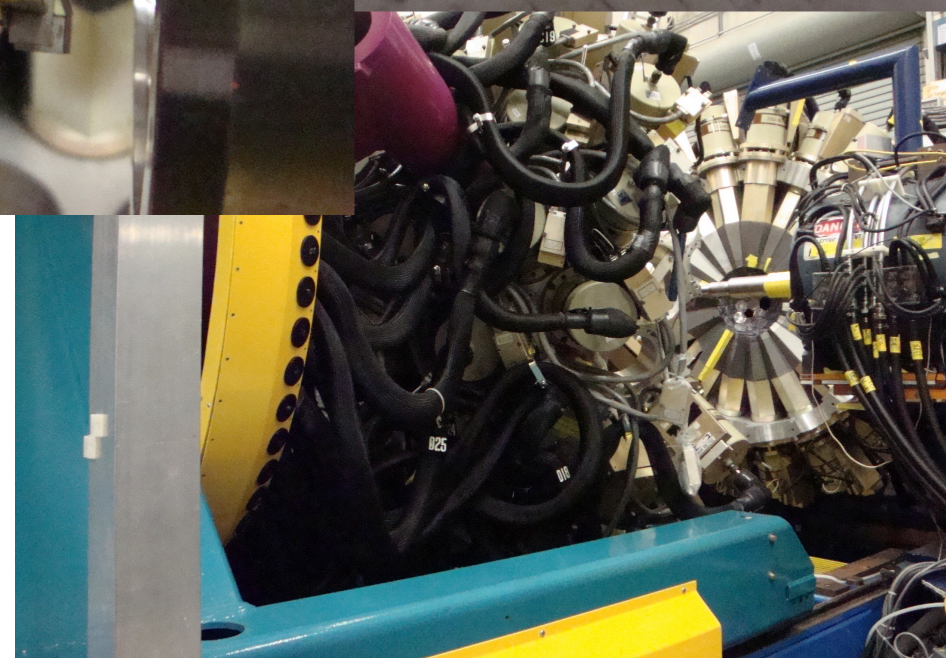


$$\tau_i(t) = 1/\lambda_i = \frac{-R_i(t) + \sum_k b_{ki}\alpha_{ki}R_k(t)}{\frac{d}{dt}R_i(t)}$$

Plunger at Gammasphere at Argonne National Lab.







Gammasphere: an array of
110 Ge detectors
at the ATLAS accelerator
lab. at ANL near Chicago.

Plunger at Gammasphere at Argonne National Lab.

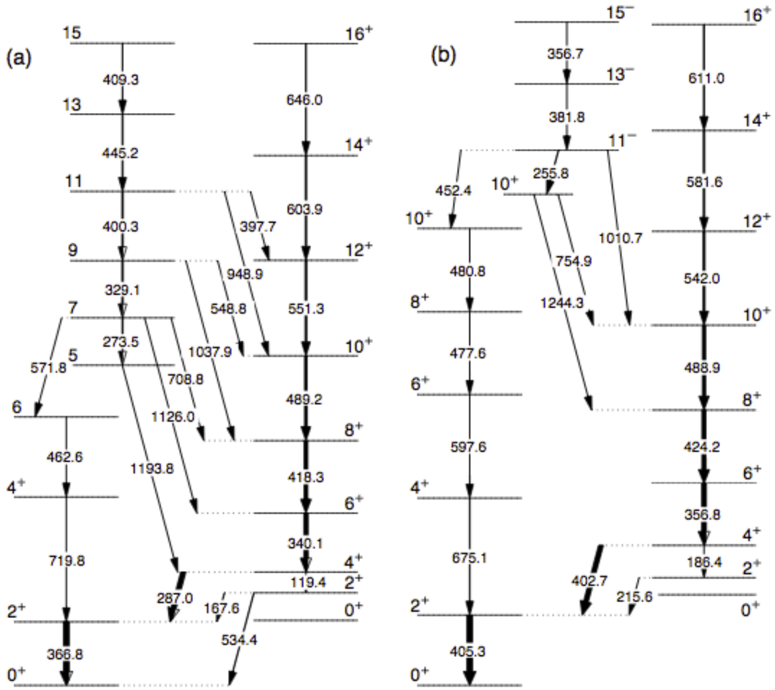


FIG. 2. Partial level schemes of (a) ^{184}Hg and (b) ^{186}Hg showing states of interest. Data are taken from Refs. [20, 21].

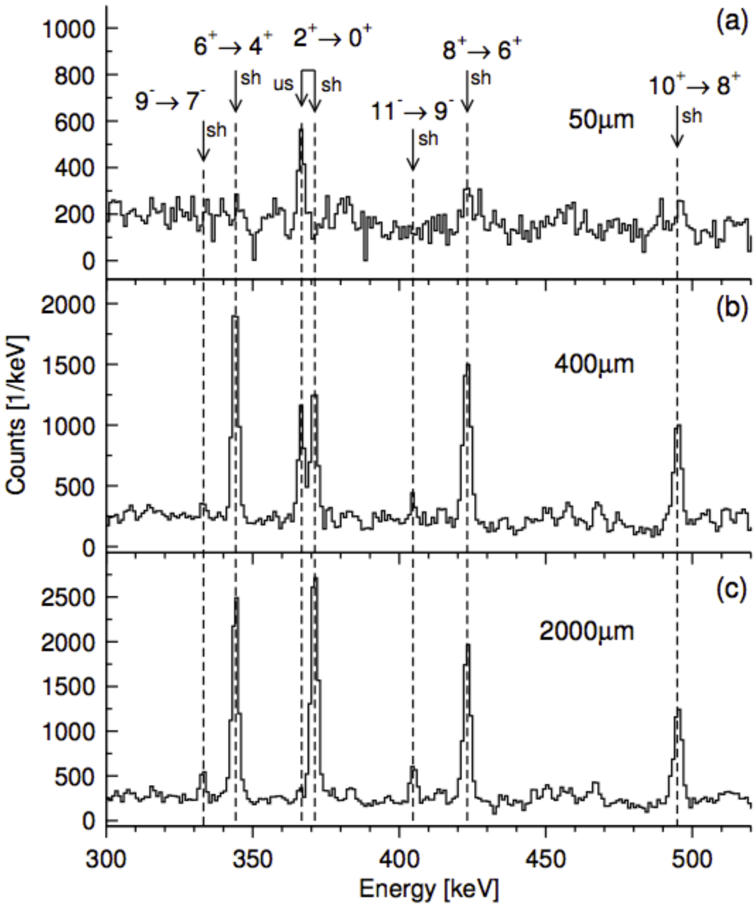
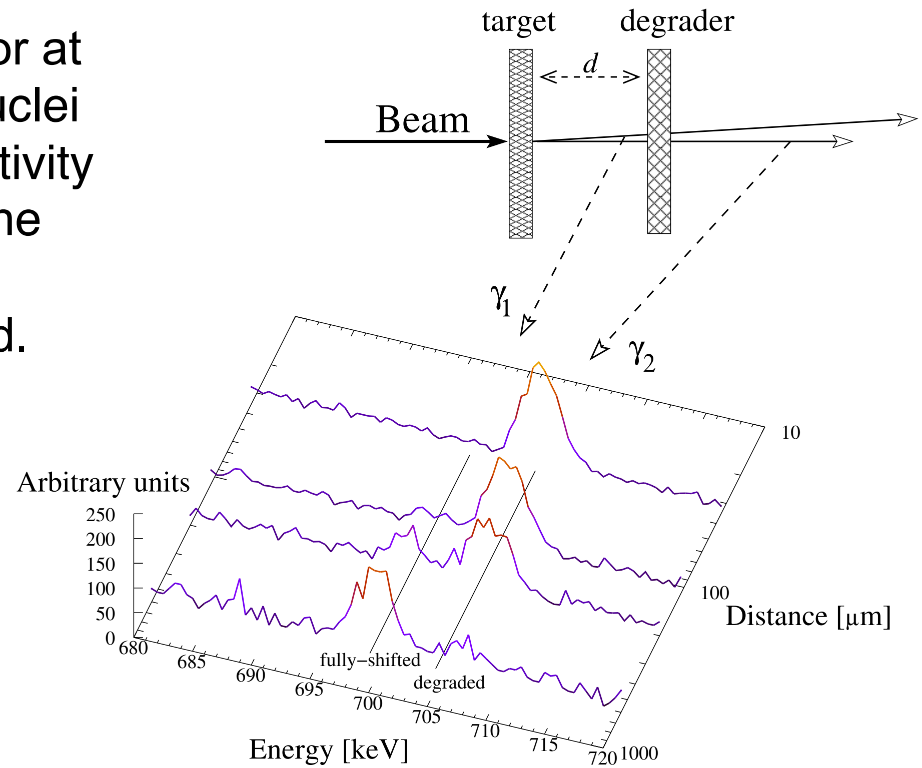


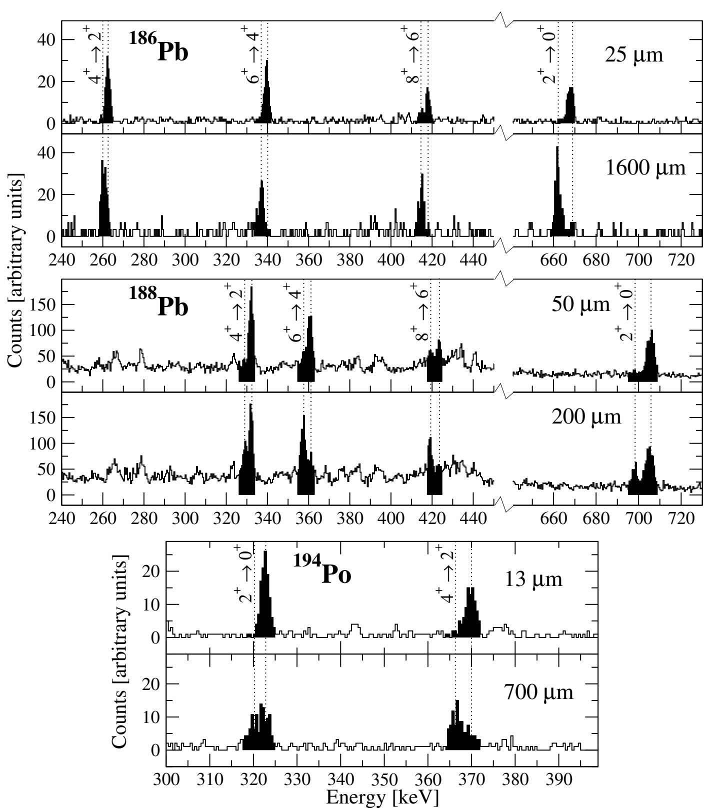
FIG. 3. Gamma-ray spectra from the Gammasphere detectors at $\theta \approx 53°$, gated on the shifted (sh) component of the $4_1^+ \rightarrow 2_1^+$ transition in ^{184}Hg at a target-to-stopper distance of (a) 50 μm, (b) 400 μm, and (c) 2000 μm. Transitions which feed the 4_1^+ state only have their shifted (sh) component in coincidence, while one also observes the unshifted (us) component of the $2_1^+ \rightarrow 0_1^+$ depopulating transition.

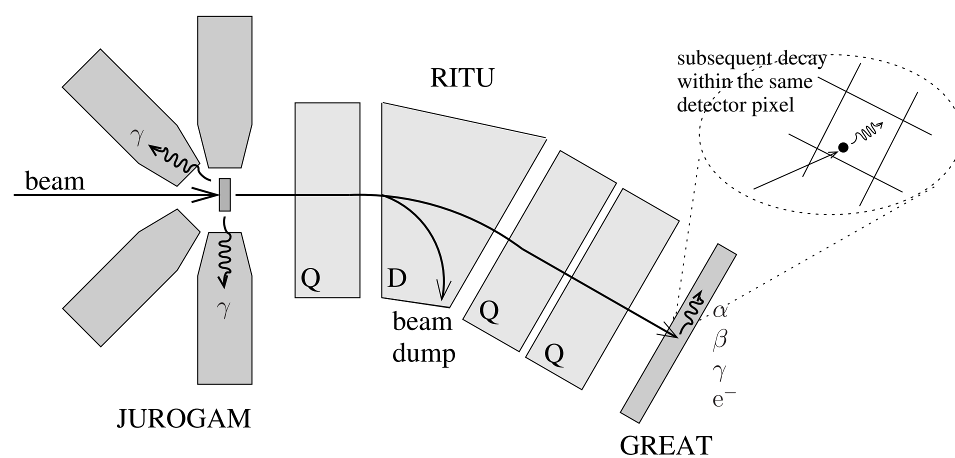
L. P. Gaffney et al. arXiv:1402.5030 [nucl-ex]

Modern developments: RDDS with recoil identification

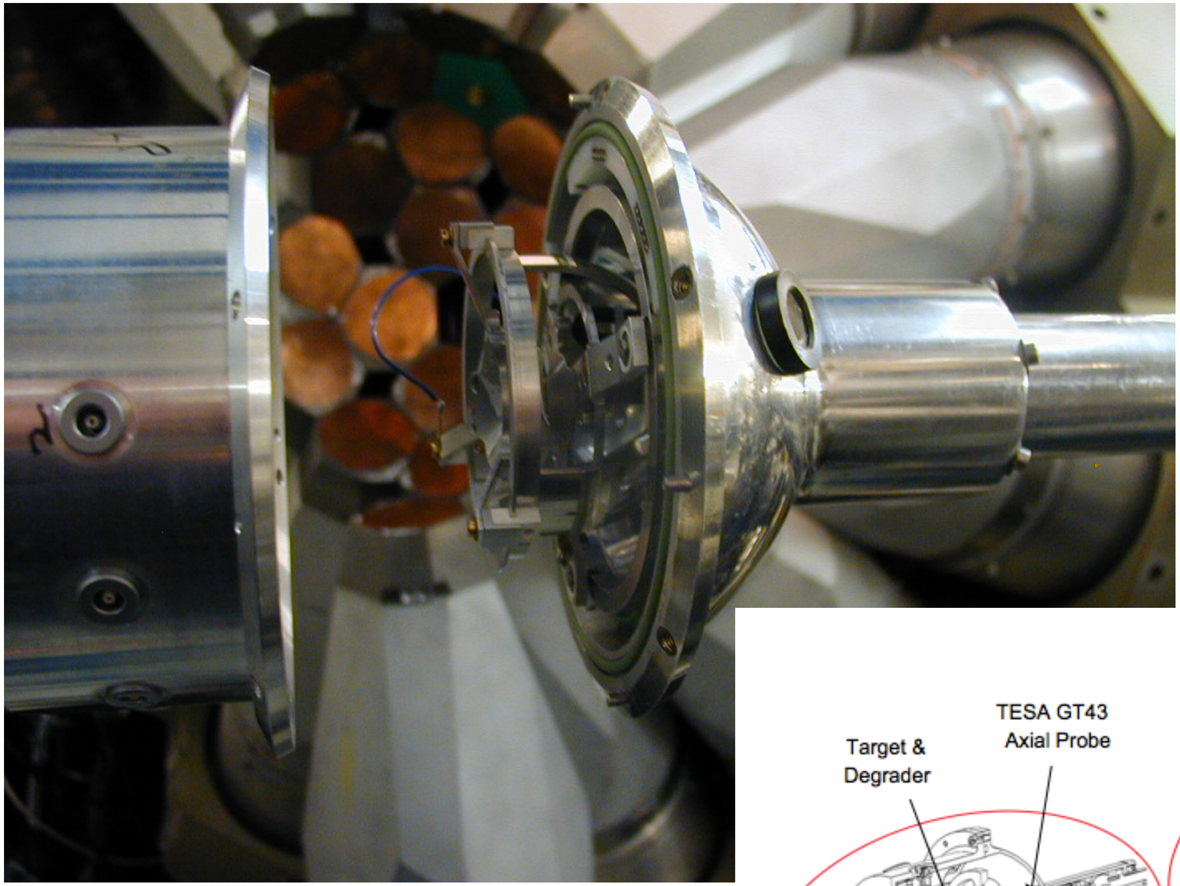
Plunger at the RITU recoil separator at JYFL : Production of investigated nuclei is so rare ($1/10^9$) that extreme sensitivity is required. *The RITU separator* is the solution, however the stopper foil of the plunger has to be replaced.

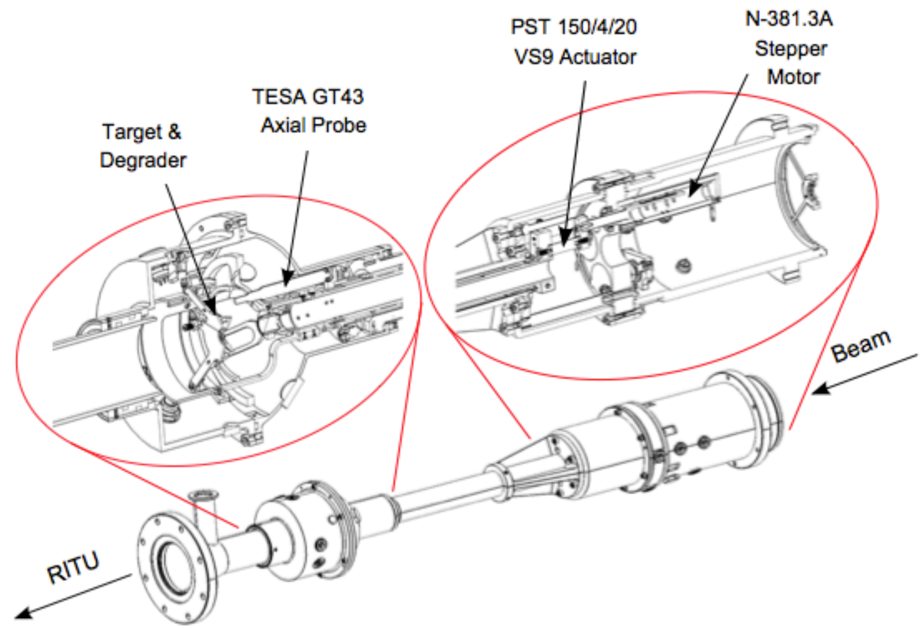






Plunger at RITU



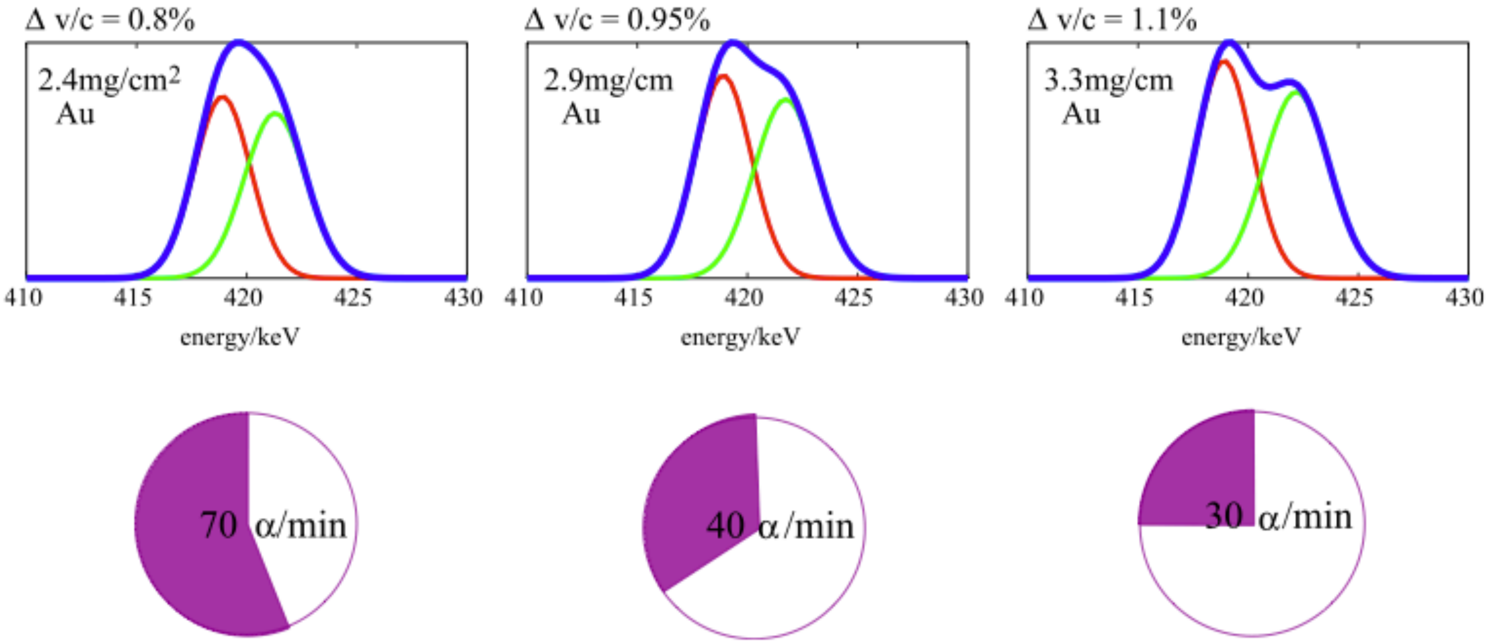


DPUNS plunger at JYFL:
[M. Taylor et al., Nucl. Instrum. Meth. Phys. Res. A 707, 143 (2013)]

Challenges with RDDS measurements at RITU

- Recoils travel through extra material. This increases small angle scattering after production
- Interactions also increase counting rates of the Ge detectors (need to keep below certain limits)
- RITU transmission efficiency is also reduced
- Peak components are not well separated

State-of-the-art measurements at the limits!



Other variants of the RDDS measurements

The advantage of the RDDS method is that is not relying on any model in lifetime extraction (c.f. DSAM, CoulEx).
(Better) suitable for in-beam studies (than fast-timing, since)

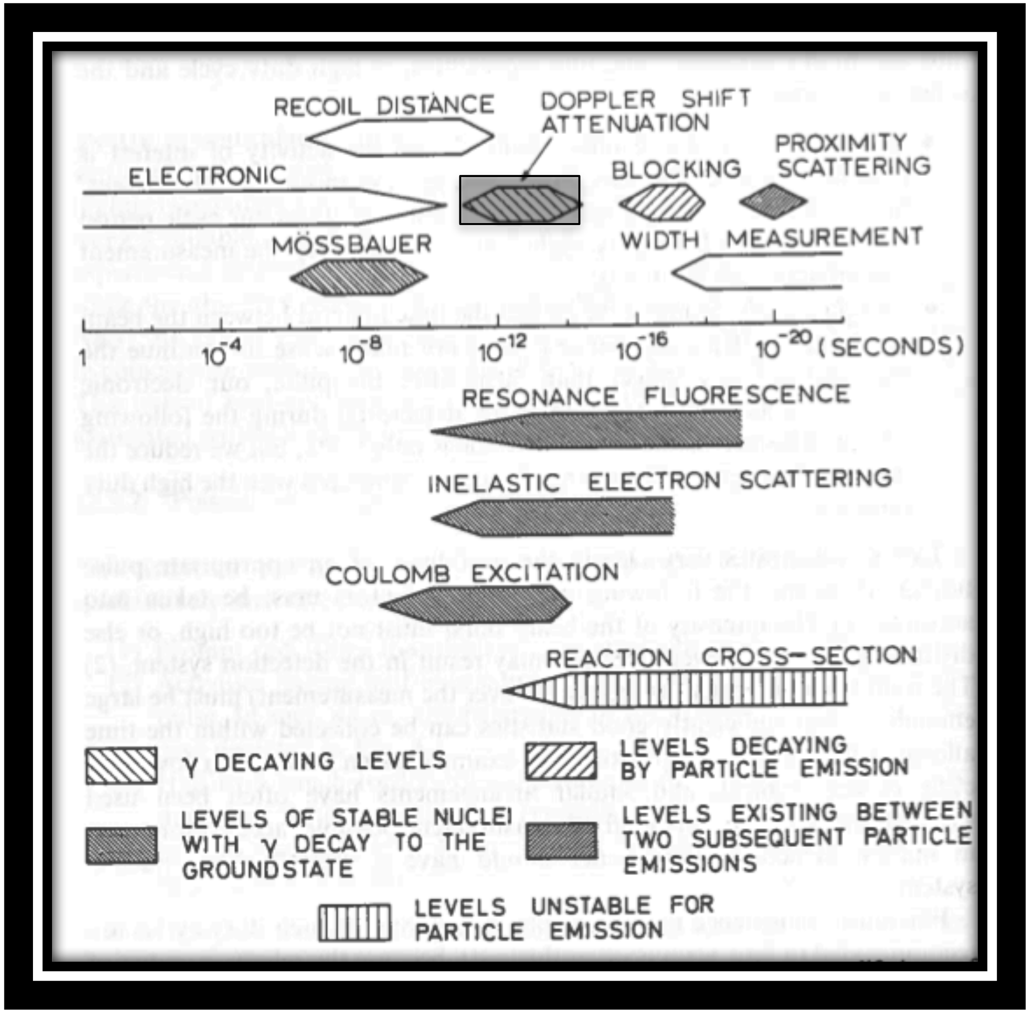
- Can nowadays easily fitted at many major instruments/detector arrays
- Well suitable for the lifetime range of collective transitions
- Efficient Ge arrays already existing

Extensions to:

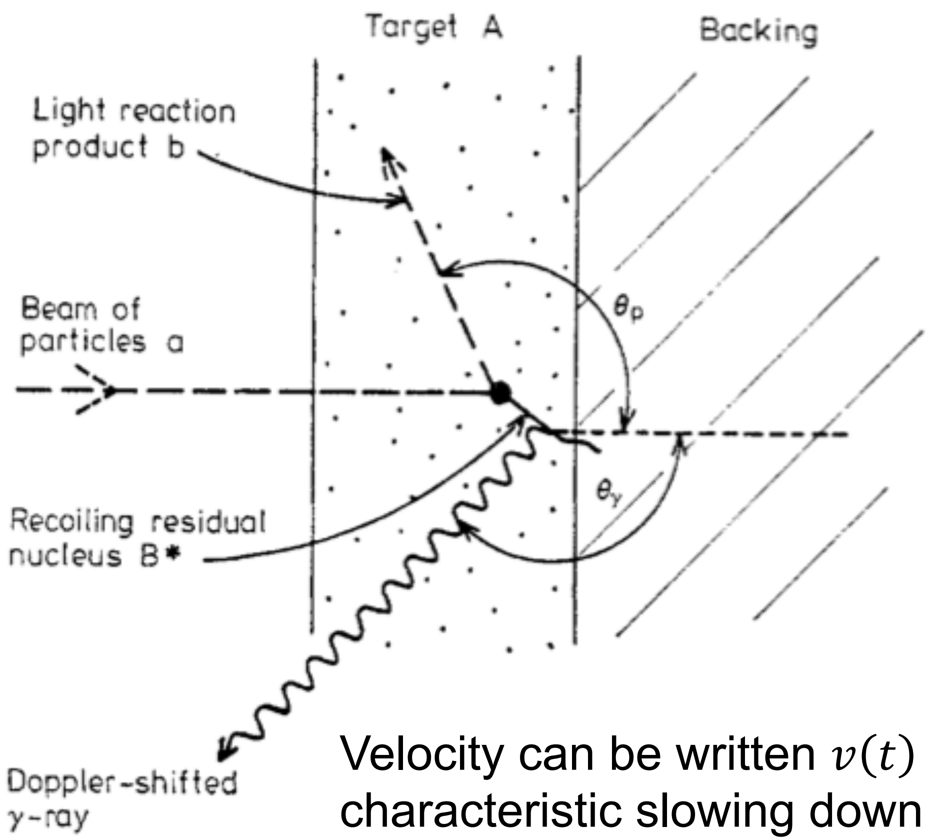
- RDDS measurements following Coulomb excitation at JYFL
- Deep-inelastic reactions at CLARA + PRISMA at Legnaro National Laboratory
- Fast radioactive beams (NSCL, GSI)
- Re-accelerated radioactive beams (HIE-ISOLDE, TRIUMF)

3. Doppler-shift attenuation method (DSAM)

Principle: When a lifetime is comparable with the slowing-down time of the ion moving in material, a certain line shape of γ rays is observed.



3. Doppler-shift attenuation method (DSAM)



Nucleus (ion) slows down in material. After a time $\boldsymbol{\tau}$ the initial velocity v_0 has dropped to v.

$E_s = E_0(1 + \beta\cos\theta_\gamma)$, where

$\beta = \frac{v}{c}$

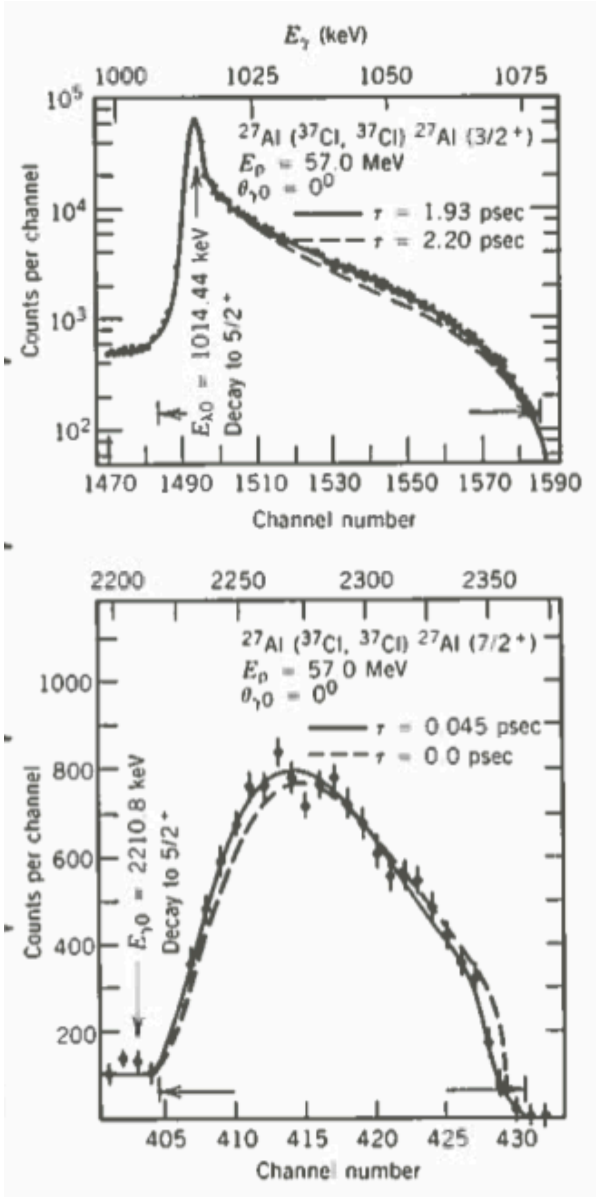
DSA factor $F = \frac{v}{v_0}$

Velocity can be written $v(t) = v_0 e^{\frac{-t}{\alpha}}$, where α is the characteristic slowing down time of the material

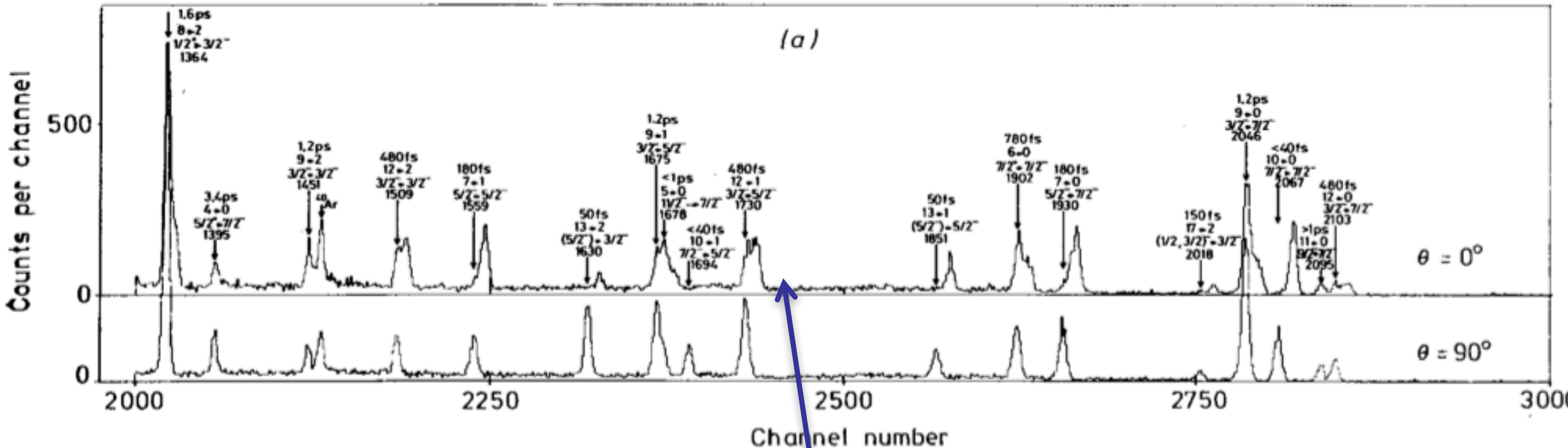
Now lineshape can be approximated as $\mathrm{d}N(v) = \frac{\alpha}{v\tau}\left(\frac{v}{v_0}\right)^{\alpha/\tau}\mathrm{d}v$

- DSAM is based on the mechanism of charged particles interacting with matter. Once we understand (?) this interaction, lifetime can be deduced.
- DSAM is used in the γ-ray spectroscopy to measure sub-ps to few ps lifetimes.
- The method relies heavily on the stopping theory, which is not necessarily well known.

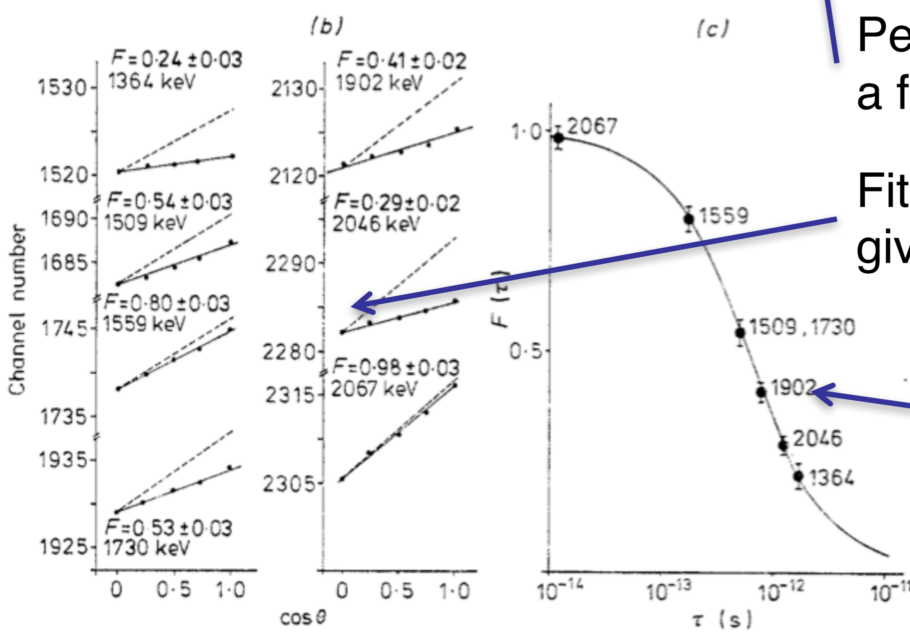
There are basically two ways to extract the lifetime:



^{43}Ca DSAM experiment



Peak centroids extracted from data as a function of the detection angle

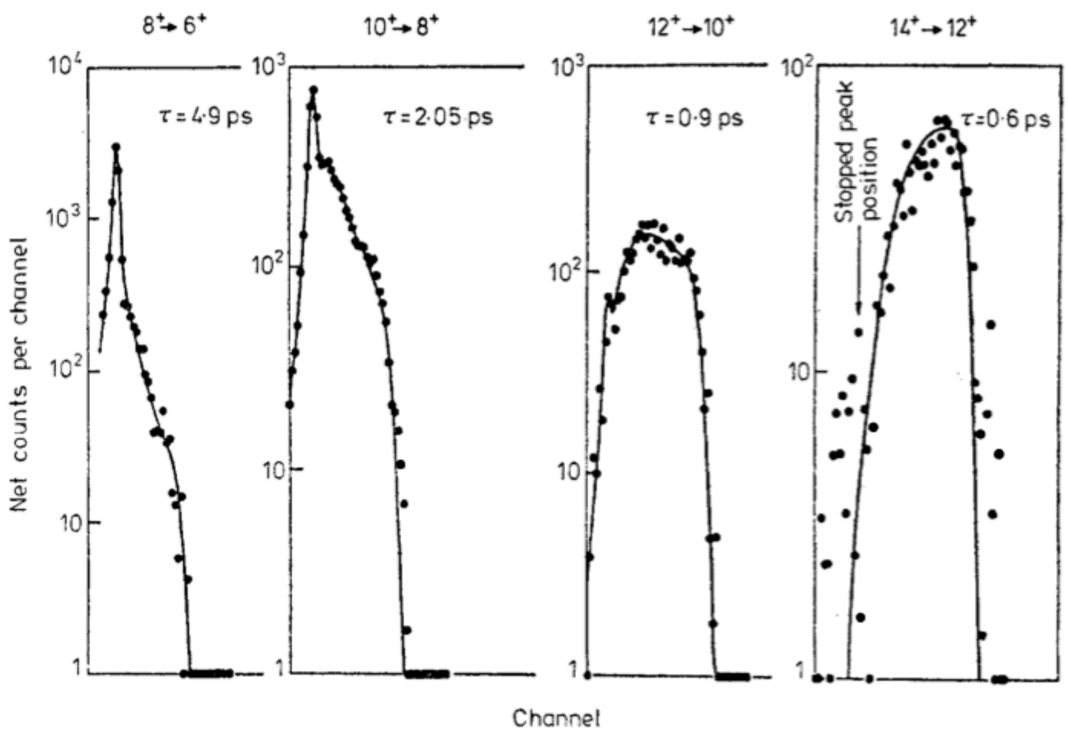


Fits of the speed of the recoils give $F(\tau)$ values

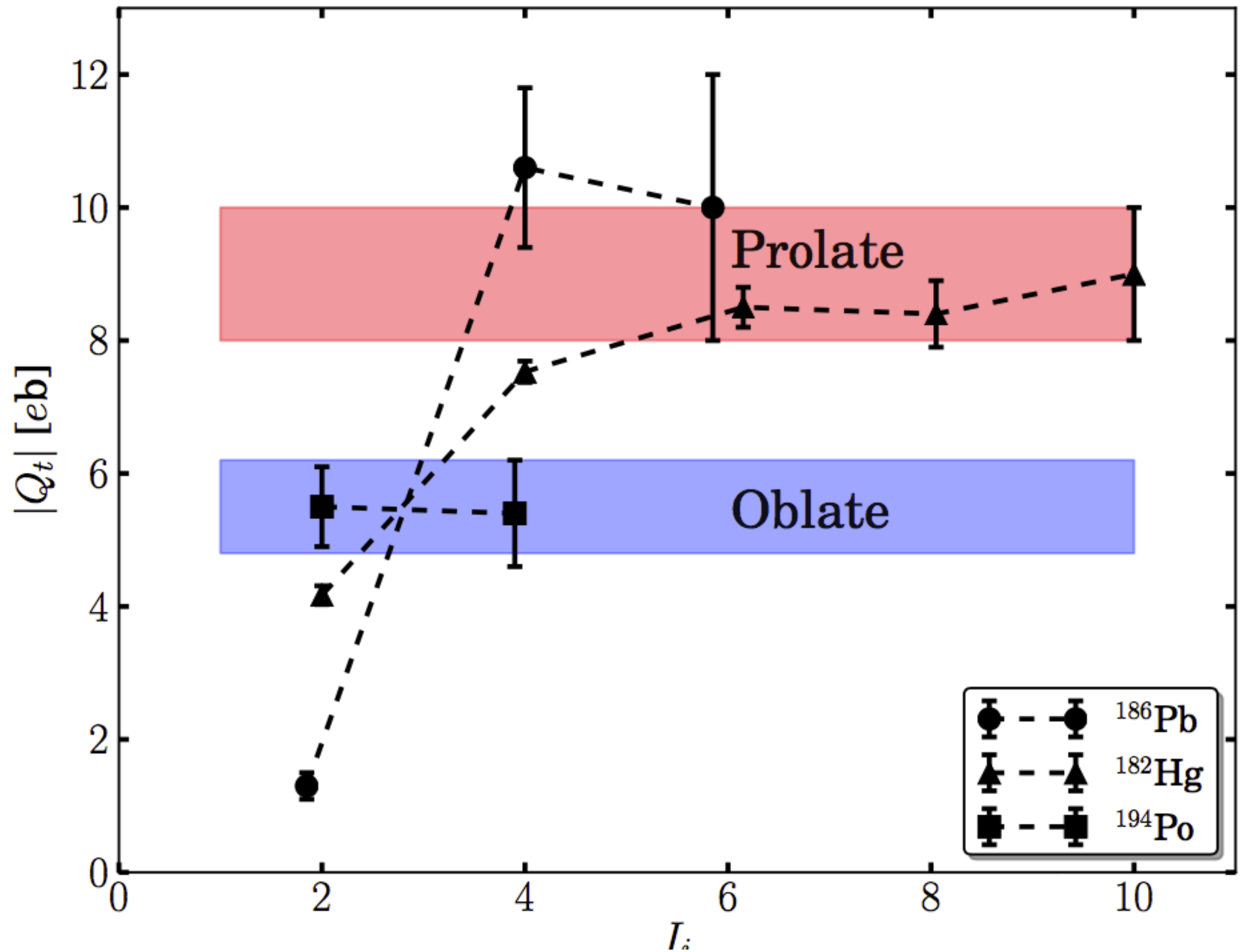
$F(\tau)$ can be calculated using stopping theory ⇒ comparison with data (fit) gives the lifetime

^{174}Yb DSAM measurement

Another method is to compare γ-ray lineshape at θ=0° and 90° to that calculated theoretically $\Rightarrow$ lifetime.



- DDCM has also been applied to the DSAM data analysis to gain a better control of the feeding.
- DSAM measurements have been carried out with fast radioactive beams (AGATA at GSI)



From: R. Julin et al. J. Phys. G: Nucl. Part. Physi. 43, 024004 (2016)

Contact information

- www.jyu.fi
- tuomas.grahn@jyu.fi