γ-ray spectroscopy and the measurement of excited-state lifetimes

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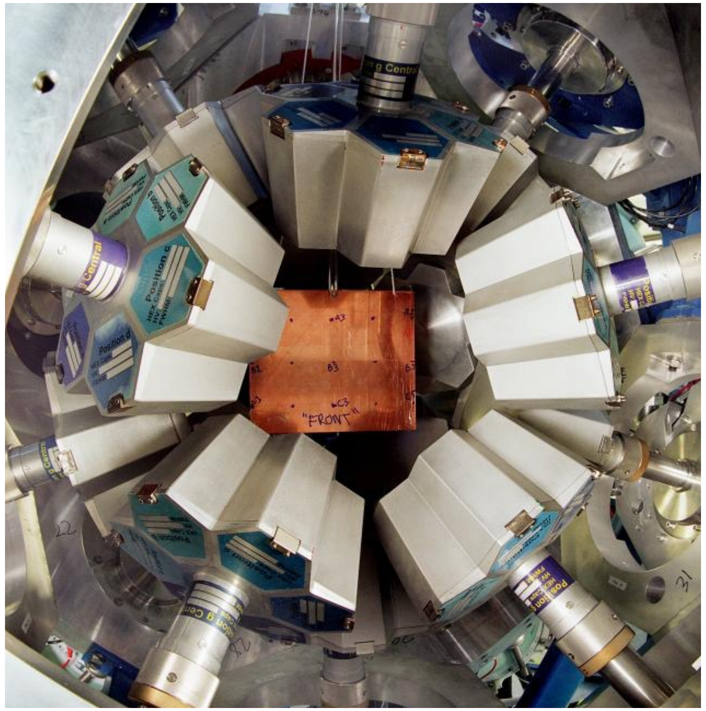
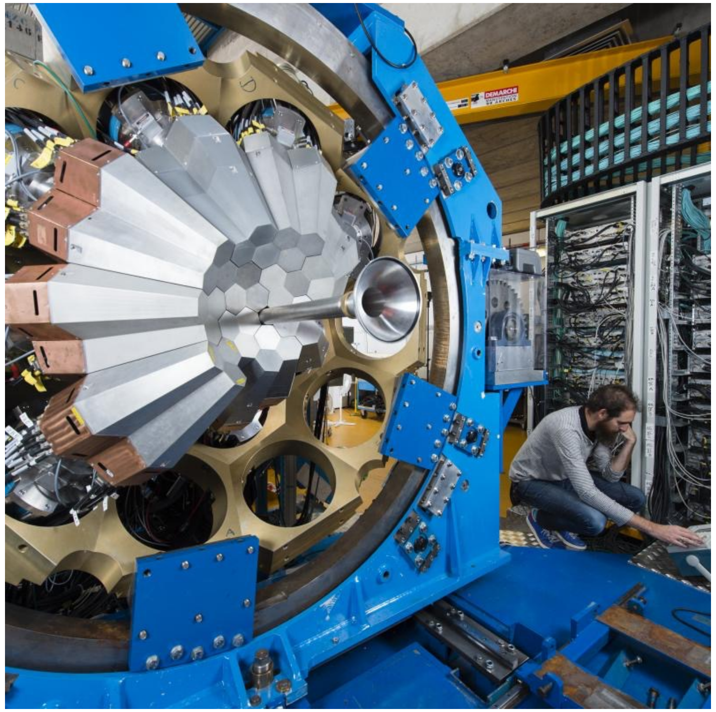
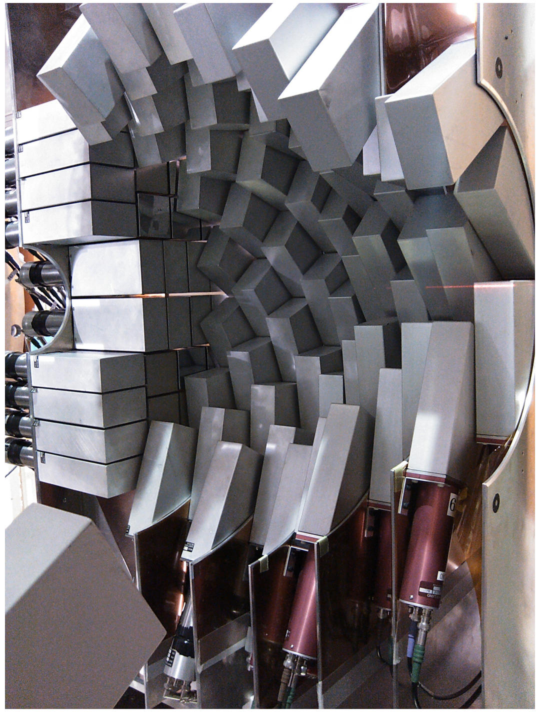






Thanks to Caterina Michelagnoli (ILL) for some material !

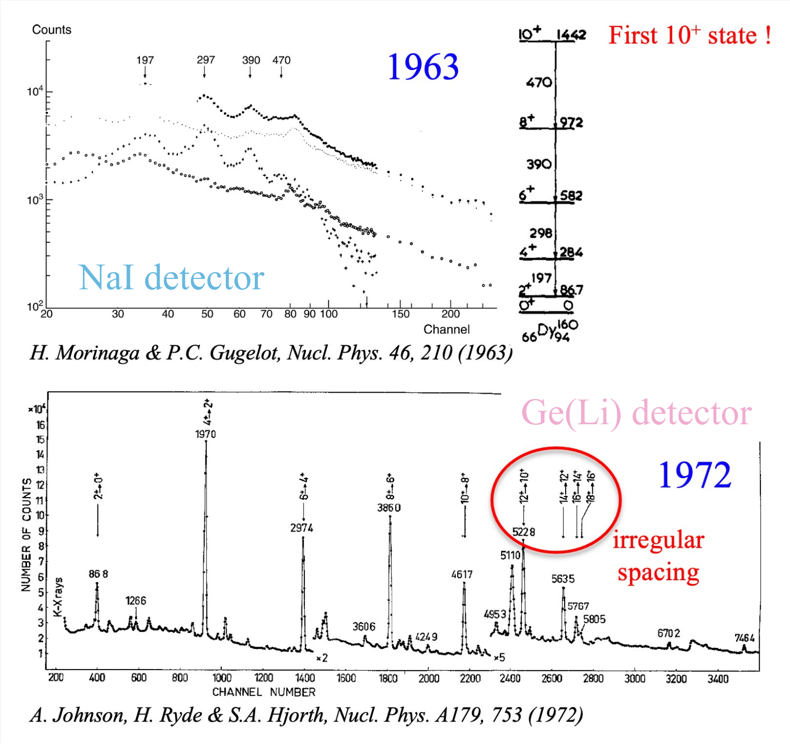
Some of the γ-ray spectrometer in use today

We have many different since which is the "best" depends on the experiment we would like to do (and the money we have) !

- energy resolution
- time resolution
- photopeak efficiency
- peak-to-total P/T

Energy resolution: From NaI to Ge detectors

One of the first rotational bands observed following α-induced reactions:

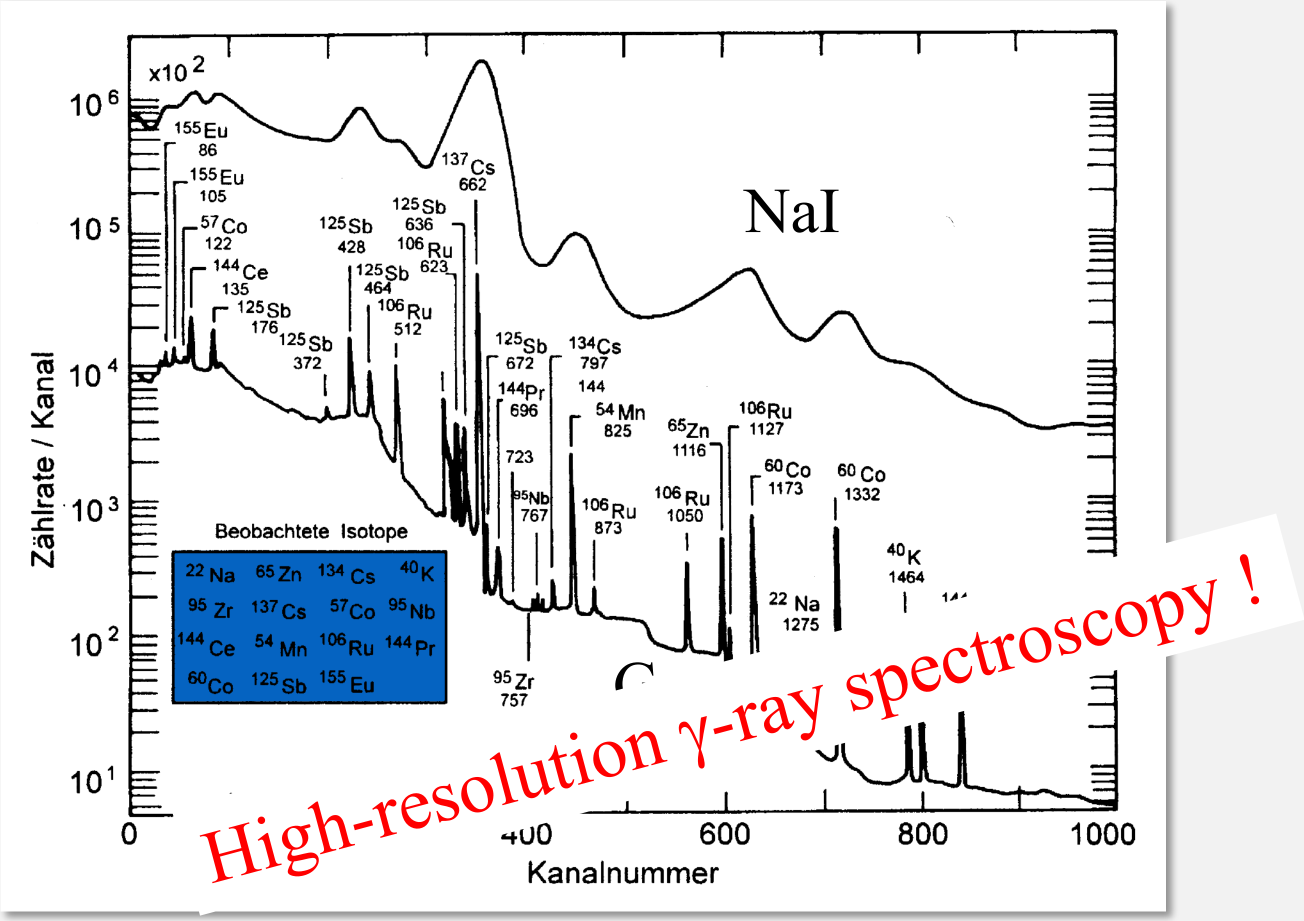


H. Morinaga & P.C. Gugelot, Nucl. Phys. 46, 210 (1963)

A. Johnson, H. Ryde & S.A. Hjorth, Nucl. Phys. A179, 753 (1972)

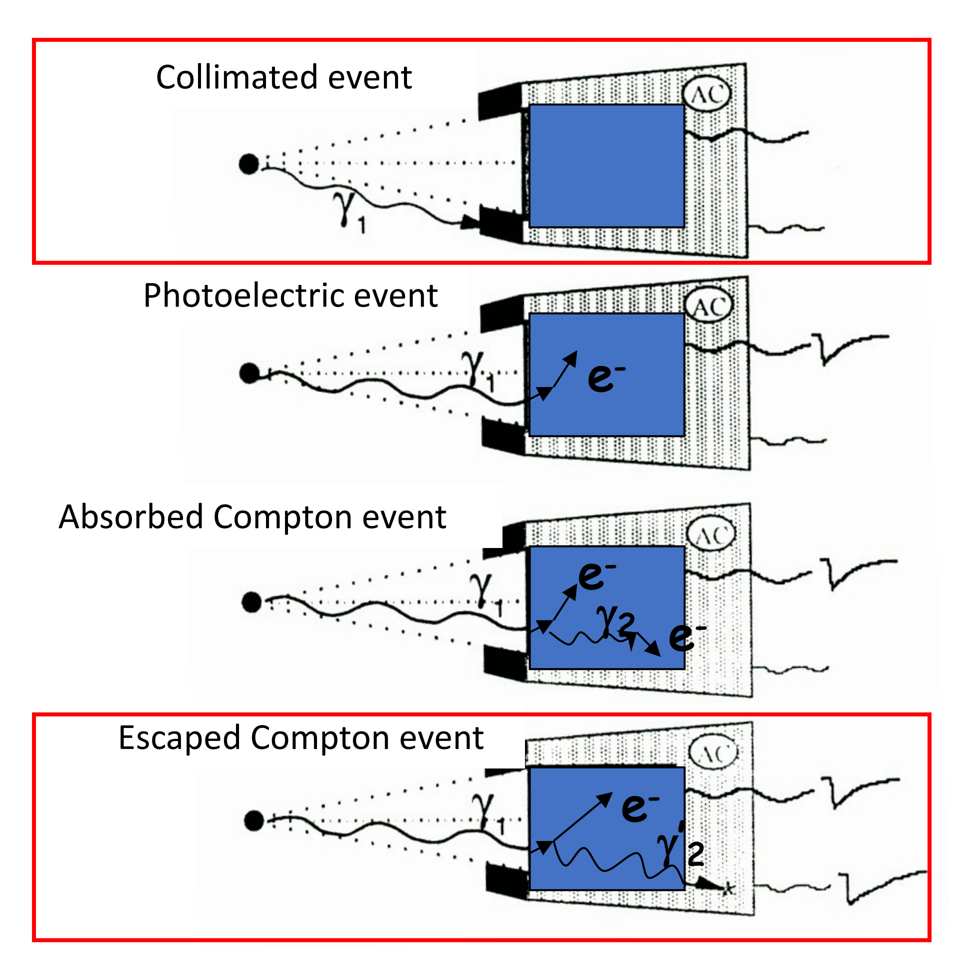
Use of Ge detectors:
Breakthrough in nuclear structure physics

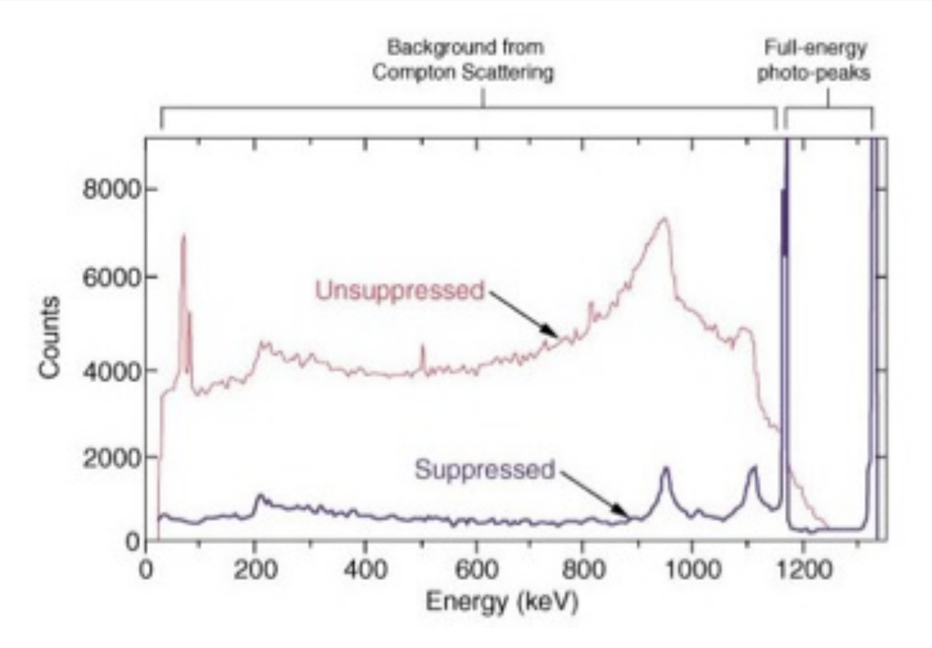
FWHM ~2 keV at 1.3 MeV



γ-ray spectrum of an air filter with radioactive aerosols, whose activity stems from the atmospheric nuclear wapon experiments between 1958 und 1963.

Compton-suppressed Ge detectors





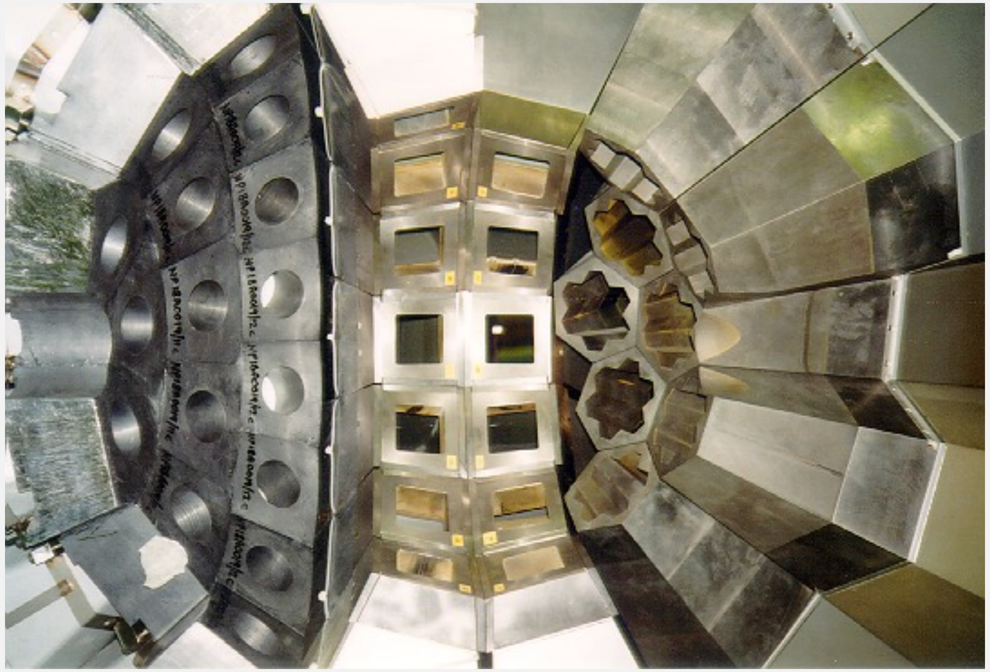
peak-to-total ratio P/T:
area of photopeak relative to total area

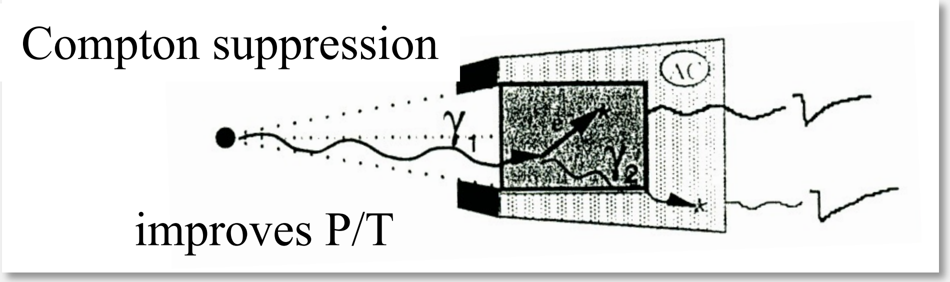
$$P/T = 0.2\text{-}0.3 \Rightarrow 0.5\text{-}0.6$$

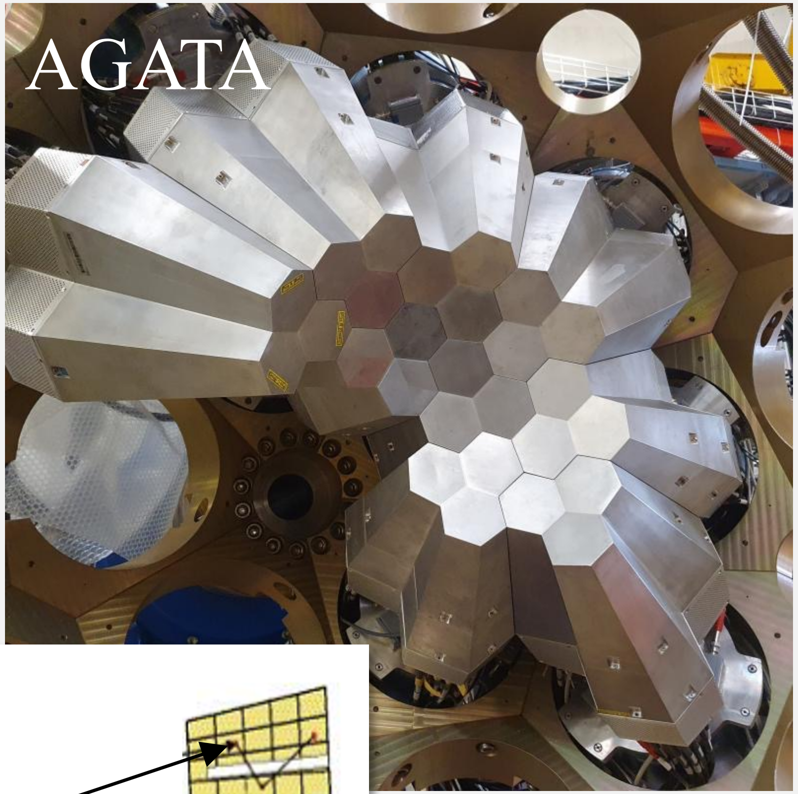
Passive shielding – throws away “bad” events !

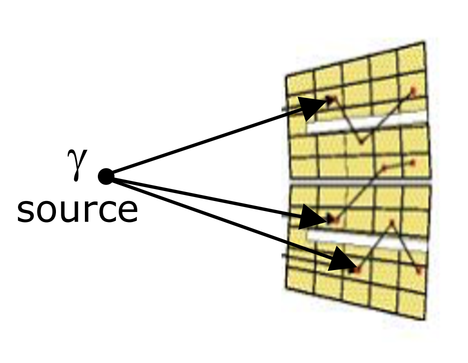
Compton-suppressed versus tracking array

View into the collimators of EUROBALL:



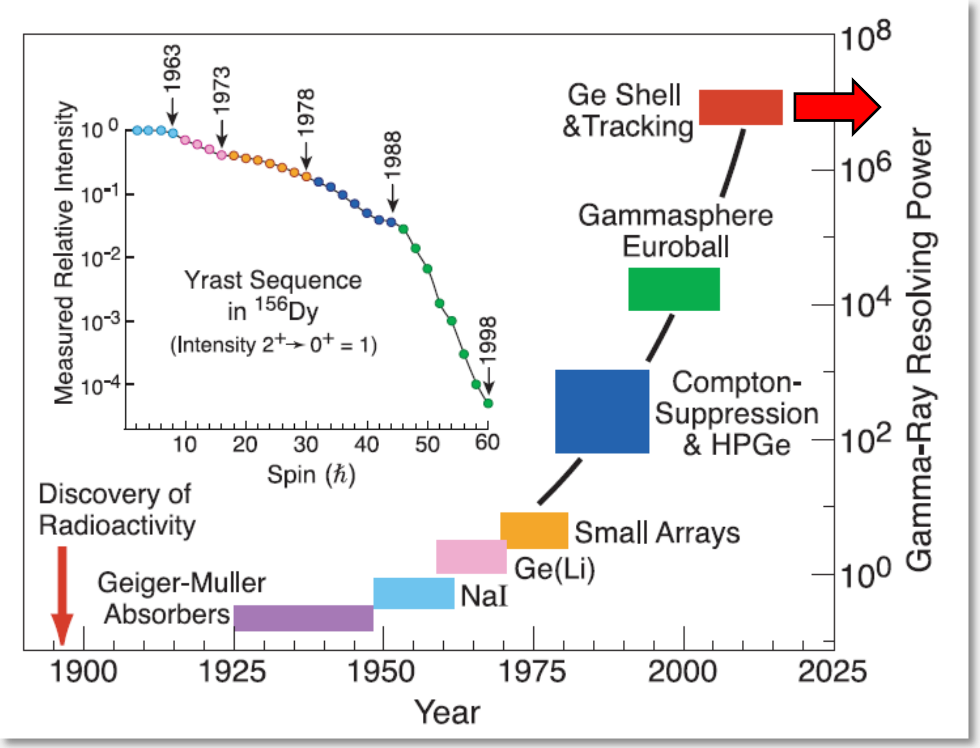


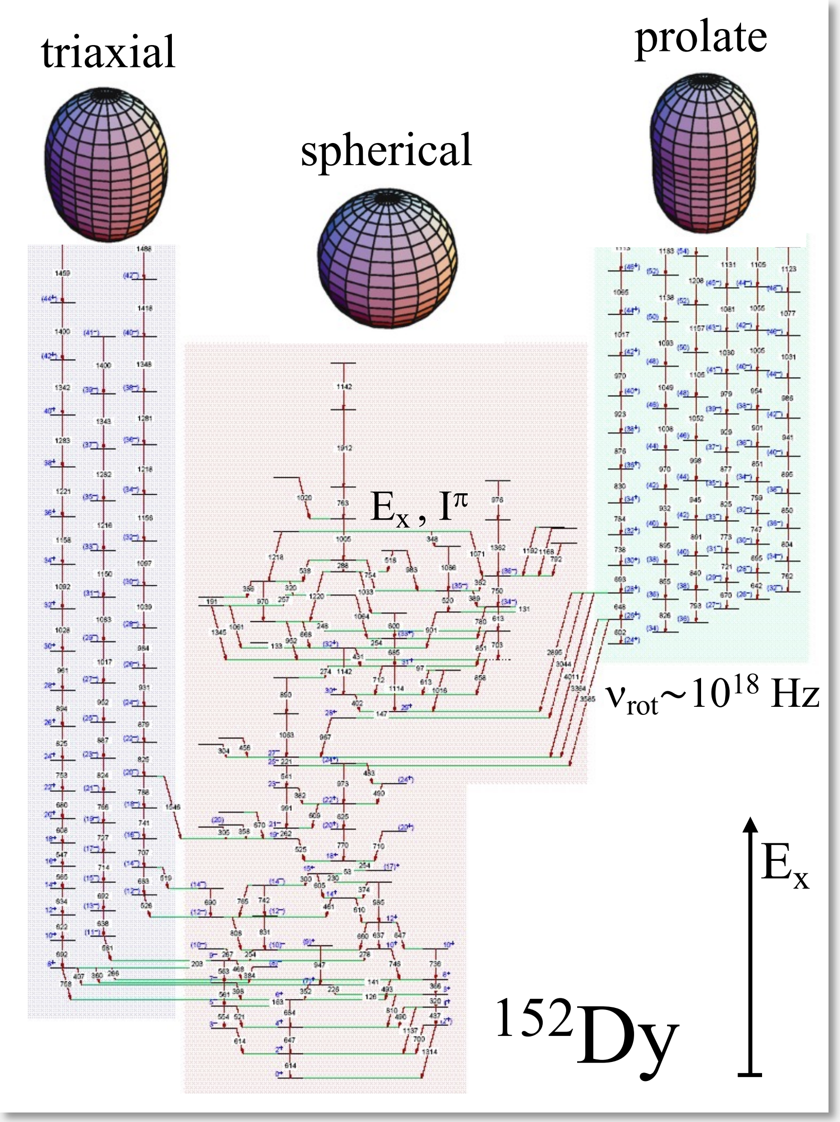




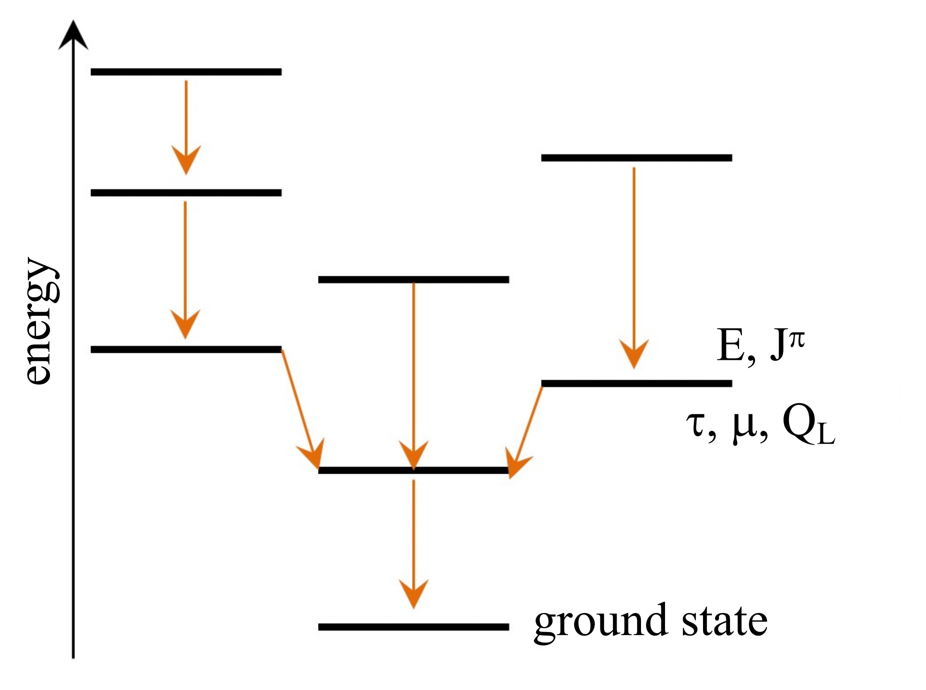
even better P/T
higher efficiency
smaller Δθ ➡ reduced Doppler broadening

Evolution of γ-ray spectroscopy





Angular distributions and correlations



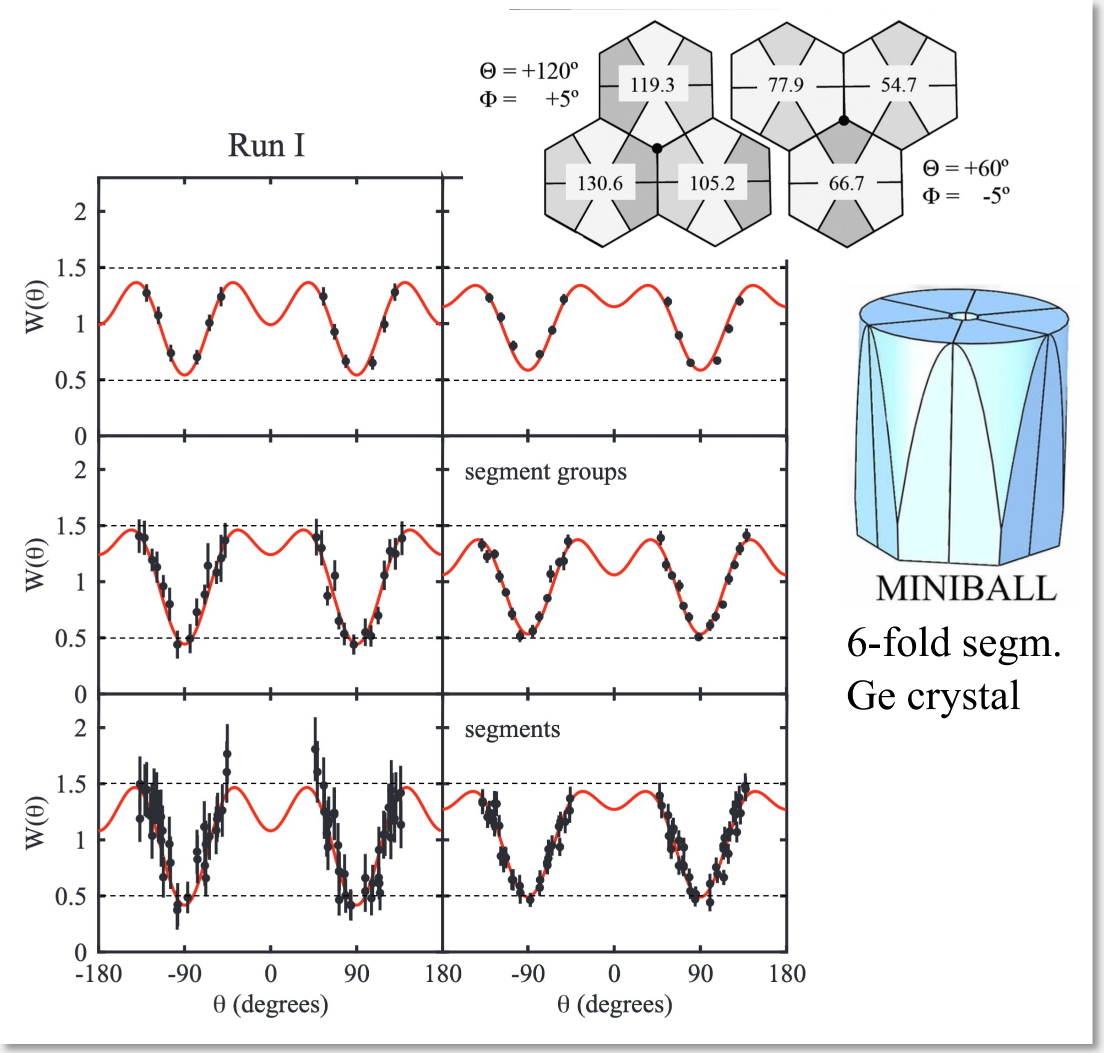
Relevant quantities for the comparison with theoretical predictions:

- excitation energy E
- spin J
- parity π
- lifetime τ
  (transition probability)
- magnetic dipole moment μ
- electric multipole moment Q_L

Measuring γ-ray

energy
angular distribution/corr.
linear polarization

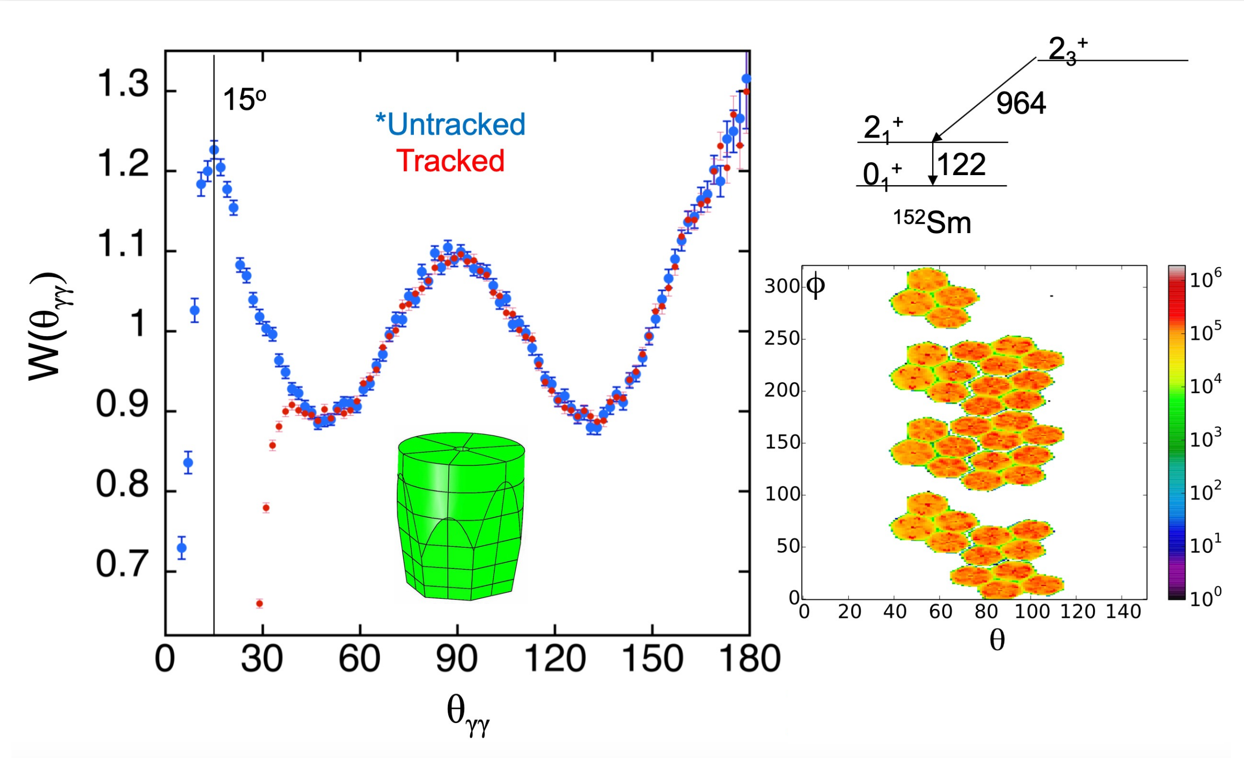
Angular distributions and correlations



6-fold segm. Ge crystal

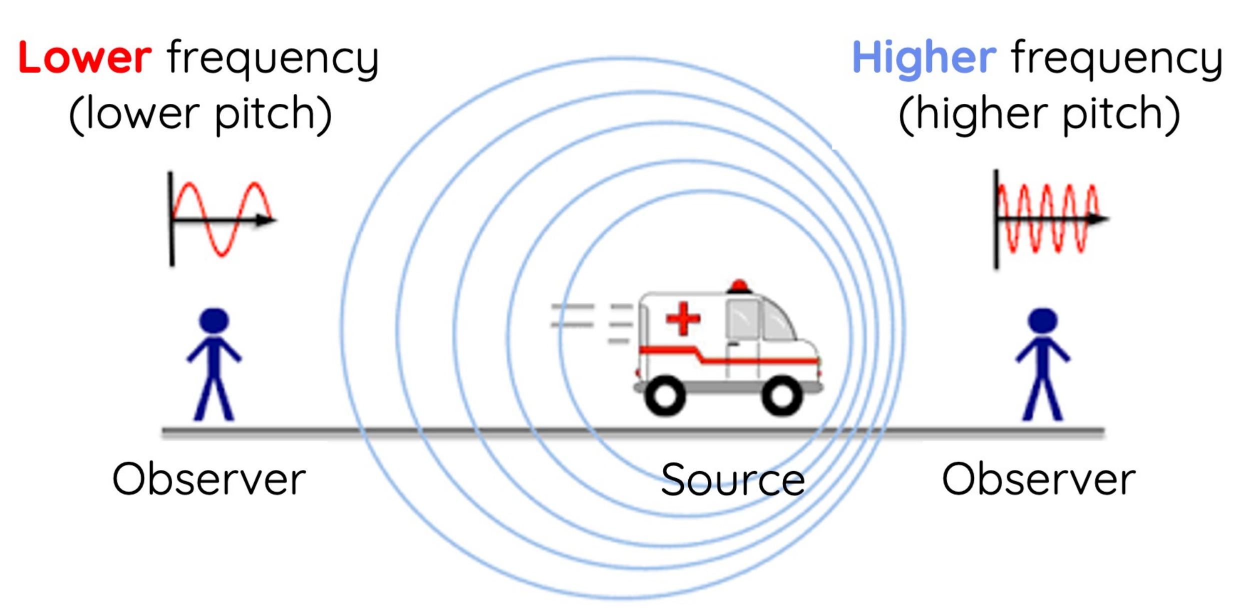
A. Illana et al., Physics Review C 89, 054316 (2014)

tracking array

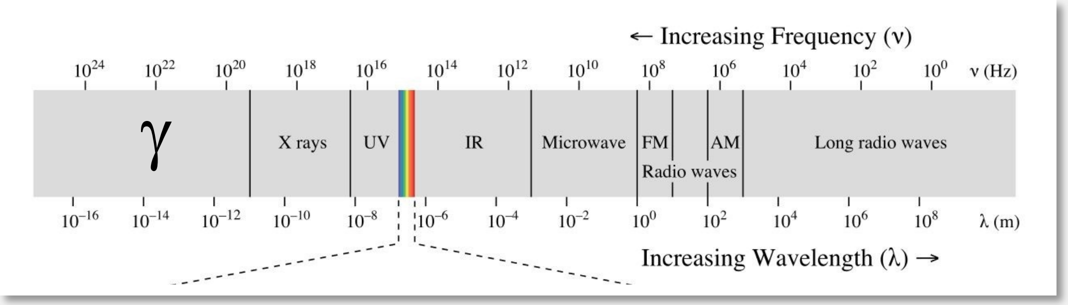


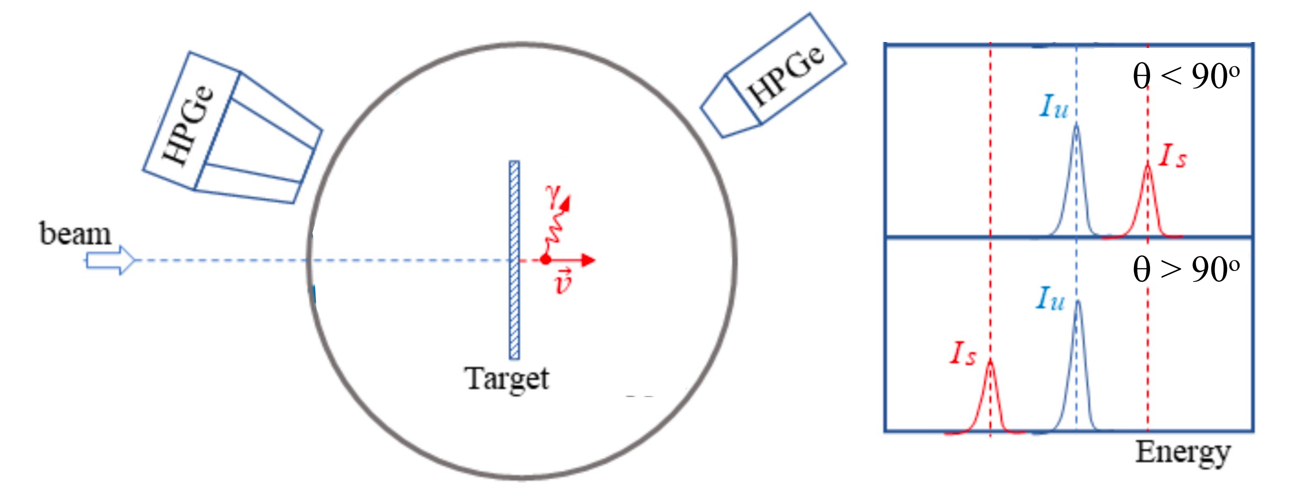
The higher the segmentation, the higher is the sensitivity to angular distributions/correlations – and therefore also magnetic and quadrupole moments !

γ-ray emission from moving ions: The Doppler effect



Higher frequency in our experiments means higher γ-ray energy !

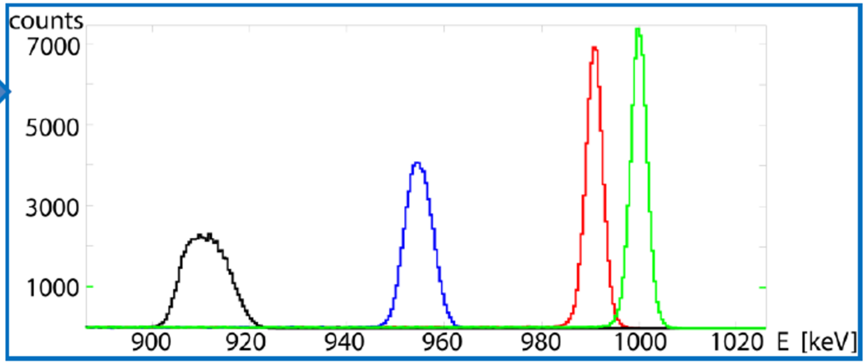




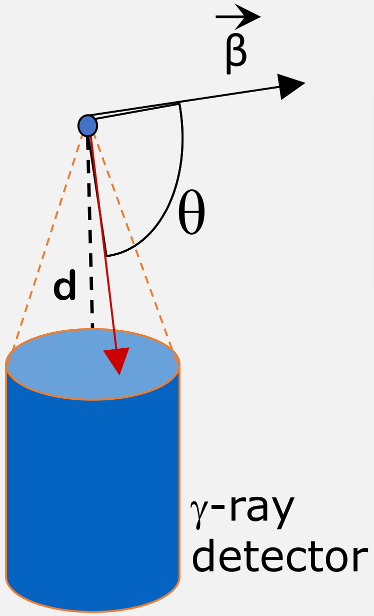
γ-ray emission from moving ions

$$E_\gamma^{Lab}(\theta) = E_\gamma^{CM} \frac{\sqrt{1-\beta^2}}{1-\beta\cdot\cos\theta}$$

E_0=1MeV
β=0, 0.01, 0.05, 0.10
(fixed direction)
$\theta = 158\, deg$



$\vec{\beta}$ is a key info.

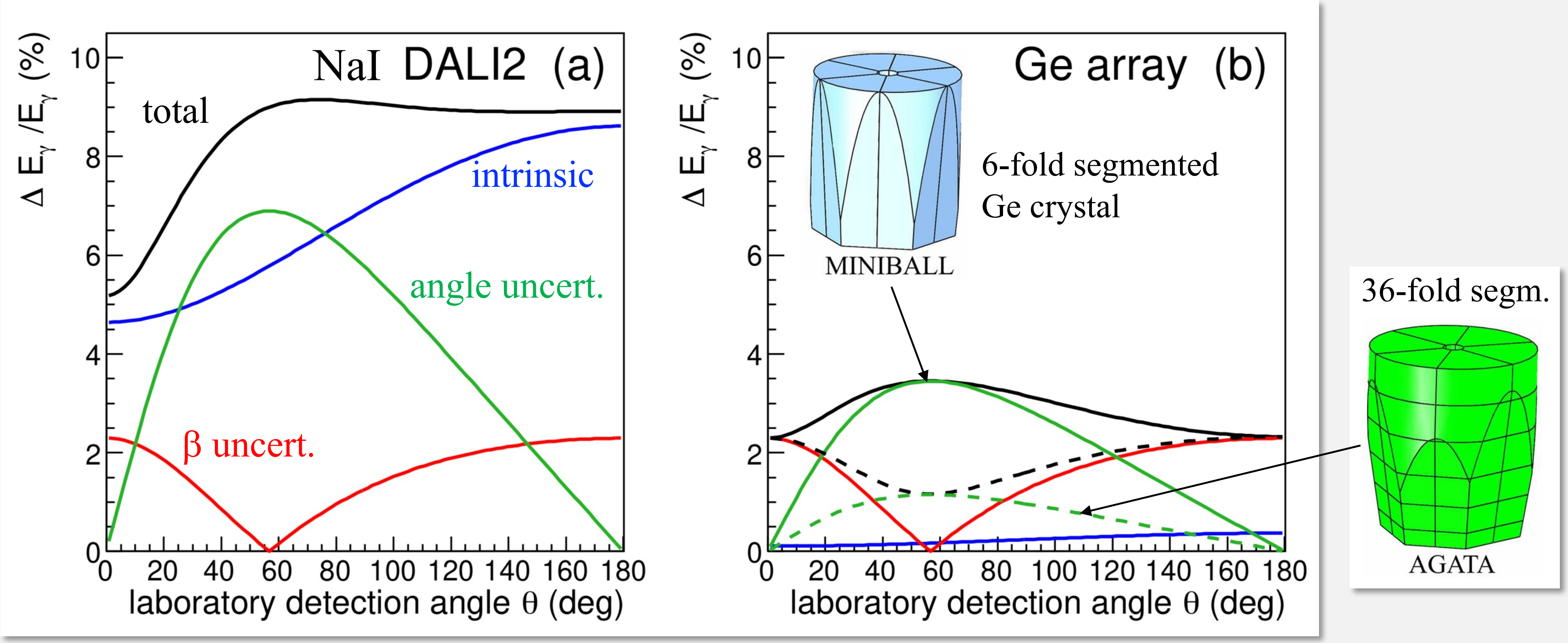


$$\left(\frac{\Delta E_{CM}}{E_{CM}}\right)^2 = \left(\frac{\Delta E_{lab}}{E_{lab}}\right)^2 + \left(\frac{\beta - \cos\theta_{lab}}{(1-\beta^2)(1-\beta\cos\theta_{lab})}\right)^2 (\Delta\beta)^2 + \left(\frac{\beta\sin\theta_{lab}}{1-\beta\cos\theta_{lab}}\right)^2 (\Delta\theta_{lab})^2$$

intrinsic — velocity spread — angular spread

energy loss in target — detector opening angle

In-beam energy resolution at relativistic energies



200 MeV/u beam on a 4 mm Be secondary target, $\langle\beta\rangle = 0.55$, $\Delta\beta = 0.016$, $E_\gamma = 1$ MeV

Content

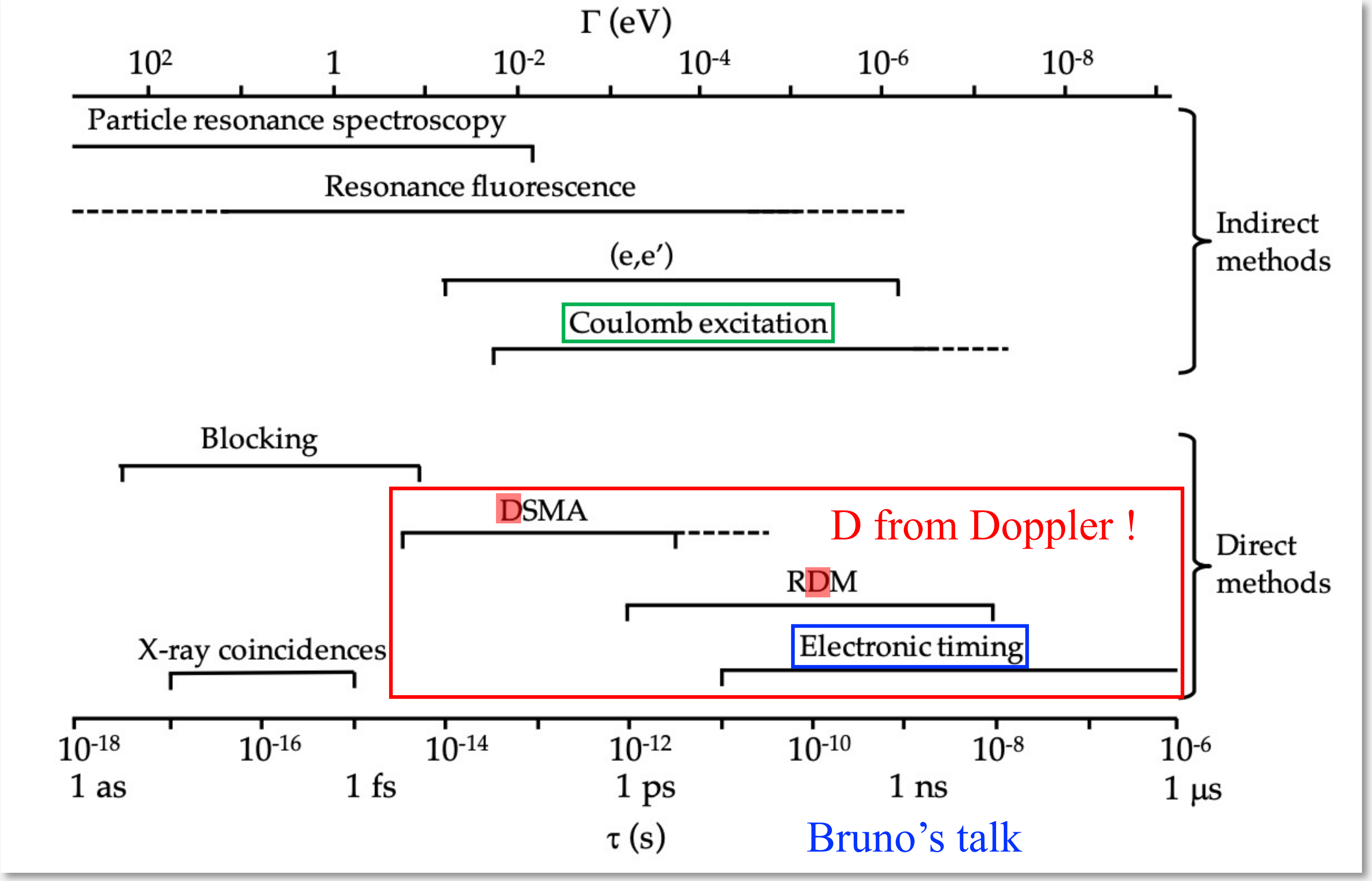
- Why do we perform γ-ray spectroscopy ?
- Characteristic parameters of γ-ray spectrometer:

  What do we need for which type of experiment ?
- Short history of instrumental developments
- Why do we need γ-ray tracking arrays ?

  In-beam energy resolution

- Measurement of excited-state lifetimes: Doppler-shift techniques

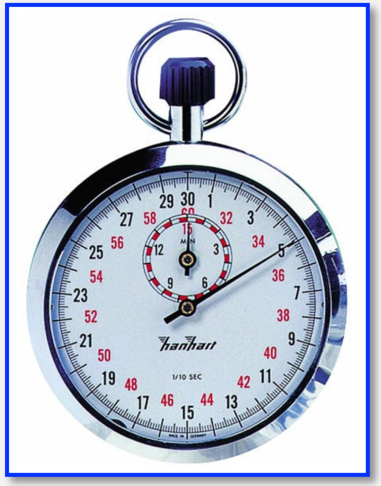
Lifetimes of excited states in atomic nuclei



cross sections

transition strengths

lifetimes

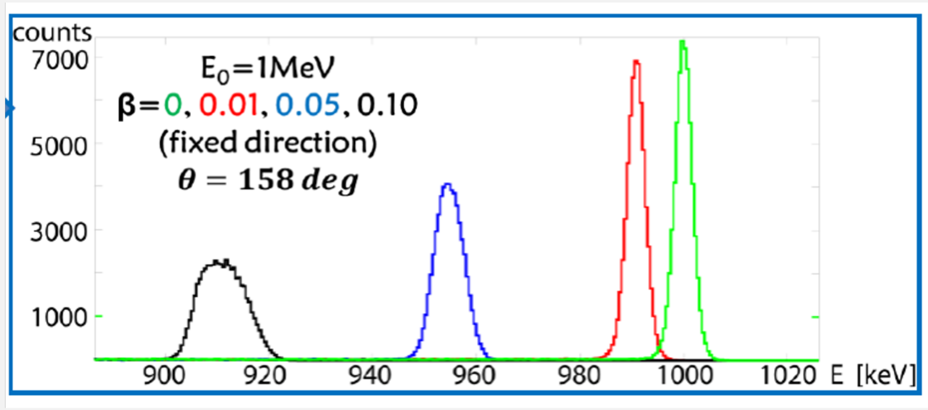


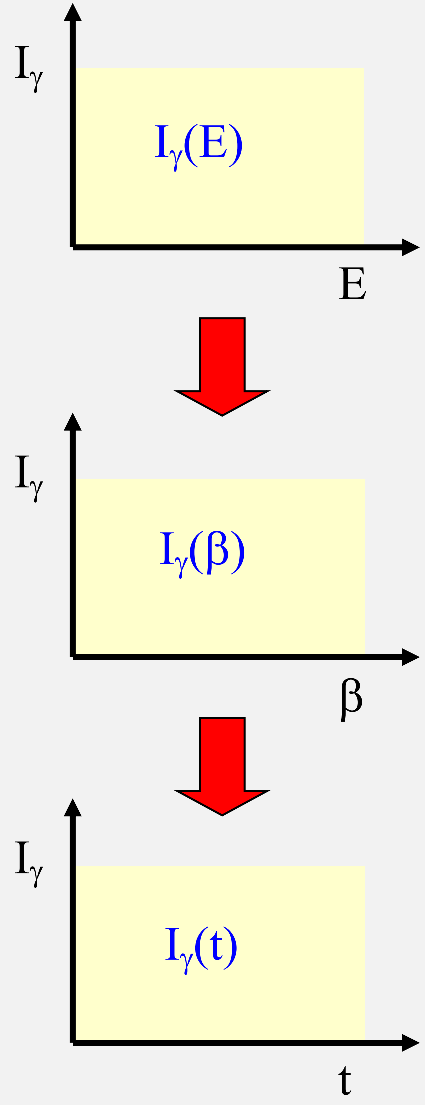
$$E_{\gamma}^{Lab}(\theta) = E_{\gamma}^{CM} \frac{\sqrt{1-\beta^2}}{1-\beta \cdot \cos\theta}$$

Doppler-shift as a clock if β or θ depend on t !

Basic principle of all Doppler techniques

$$E_\gamma^{Lab}(\theta) = E_\gamma^{CM} \frac{\sqrt{1-\beta^2}}{1-\beta\cdot\cos\theta}$$





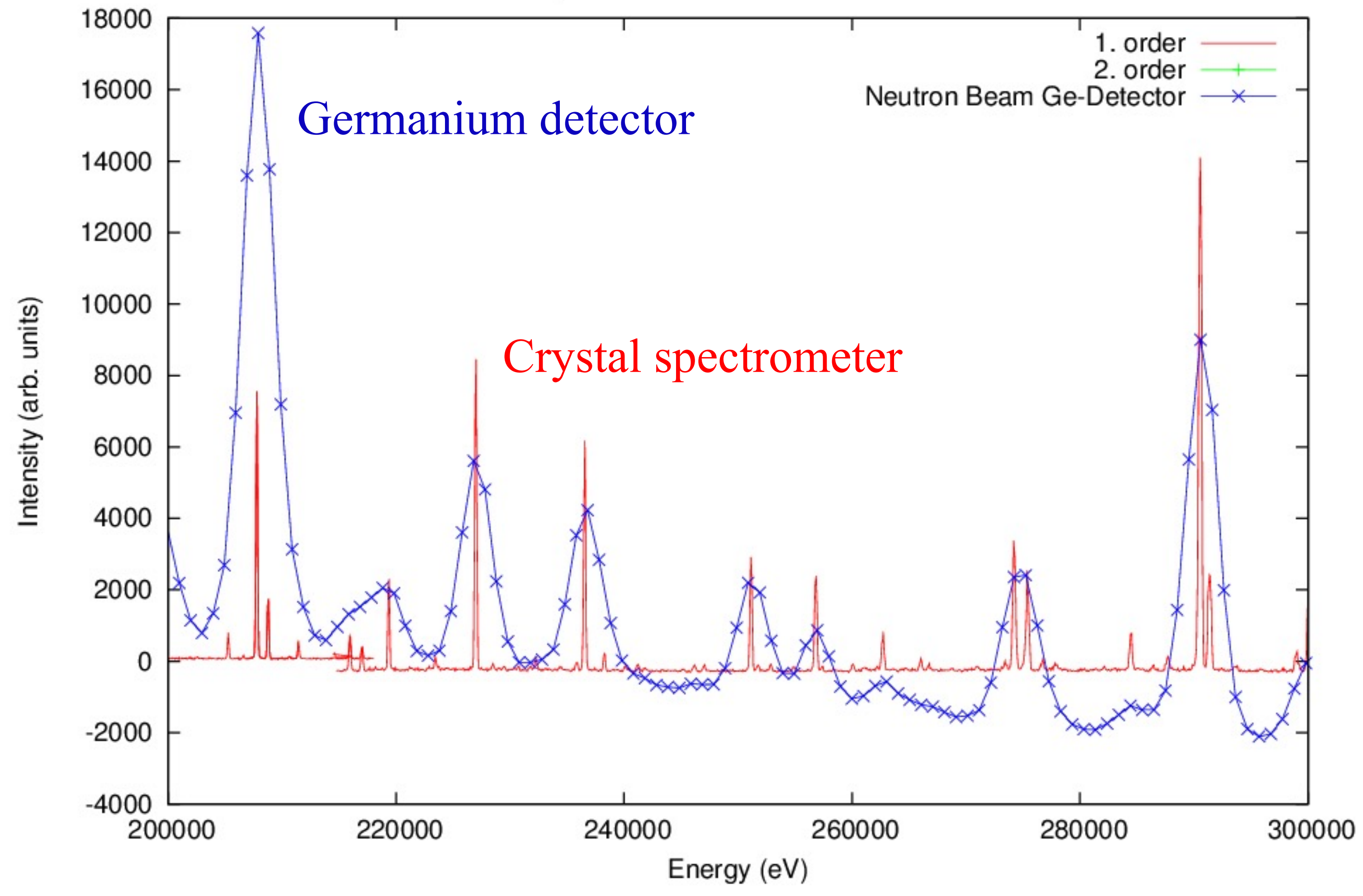
Measurement:
Energy distribution of the emitted γ radiation

with $E_\gamma^{Lab}(\beta)$ known

if the velocity distribution $\beta(t)$ is known

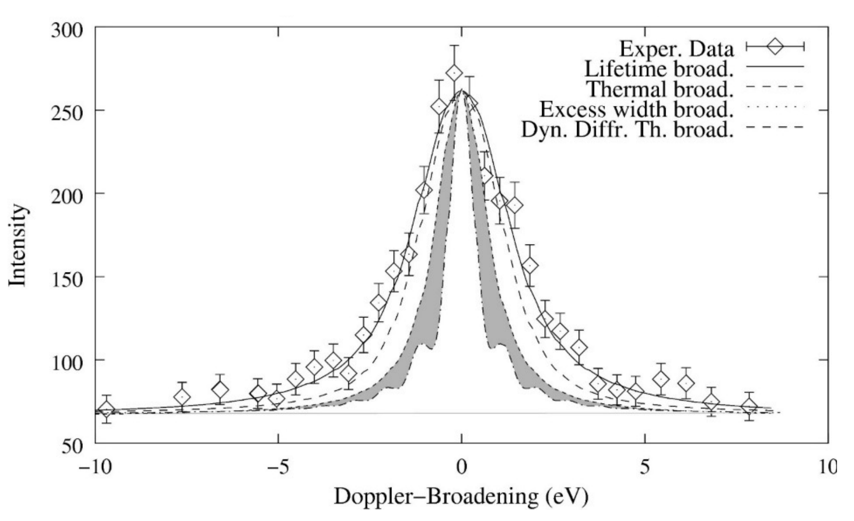
$$I_\gamma(t) = A(t) = A_0\cdot e^{-\lambda t} = A_0\cdot e^{-t/\tau}$$

GAMS4 energy resolution and lifetime sensitivity

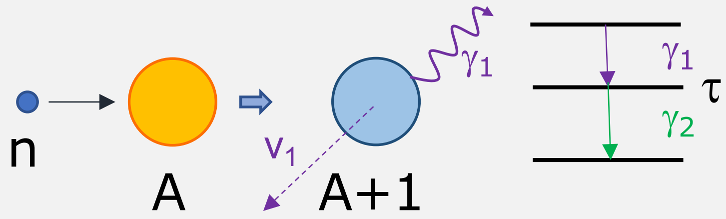


"High resolution" is very relative !

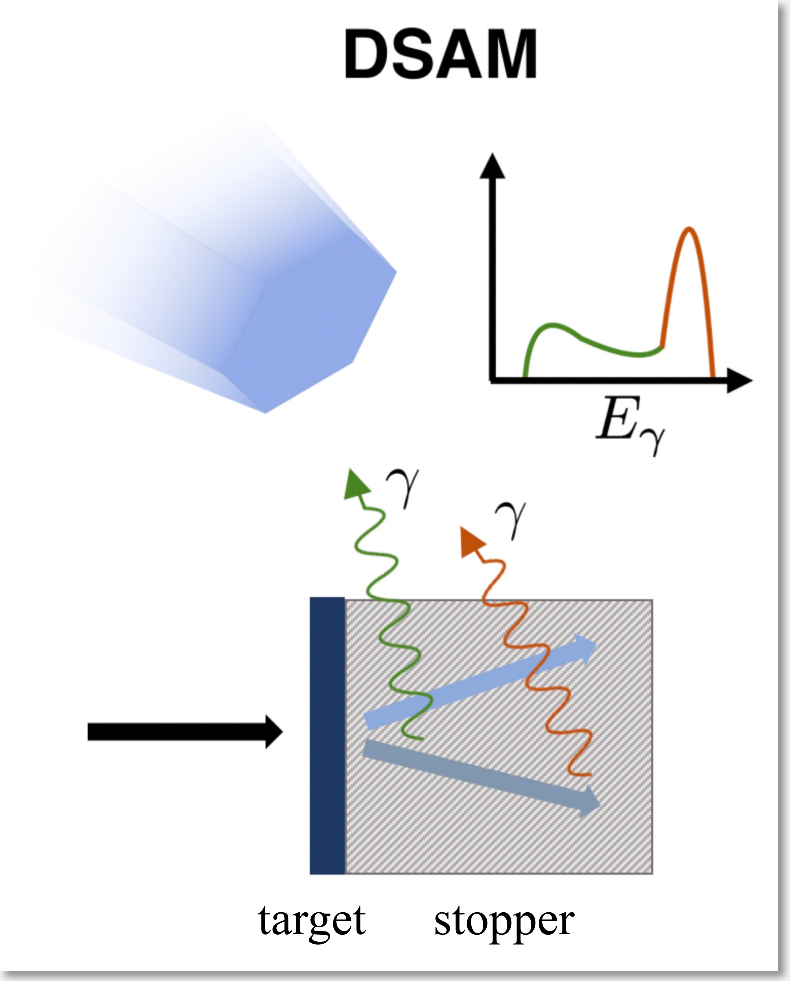
GRID
(Gamma-Ray Induced Doppler broadening)



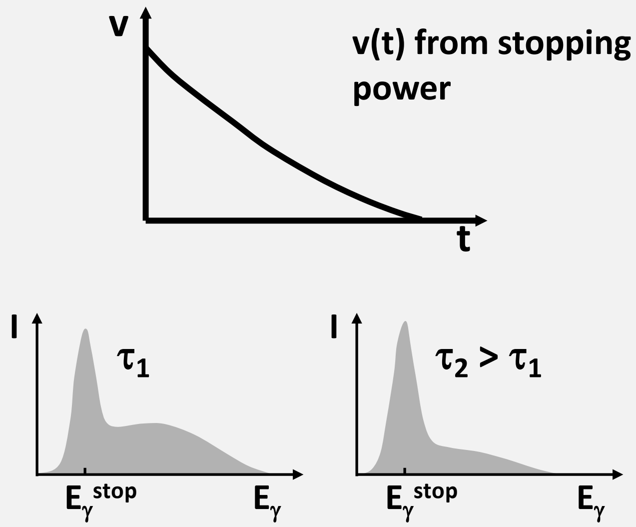
$1\,fs < \tau < 5\,ps$



Doppler-shift attenuation method (DSA)



The lifetime of the excited state is compared with the slowing-down time of the emitting nucleus in the stopper



Typical lifetime range: $\tau = 0.1\text{-}1.5$ ps

DSA example from real life

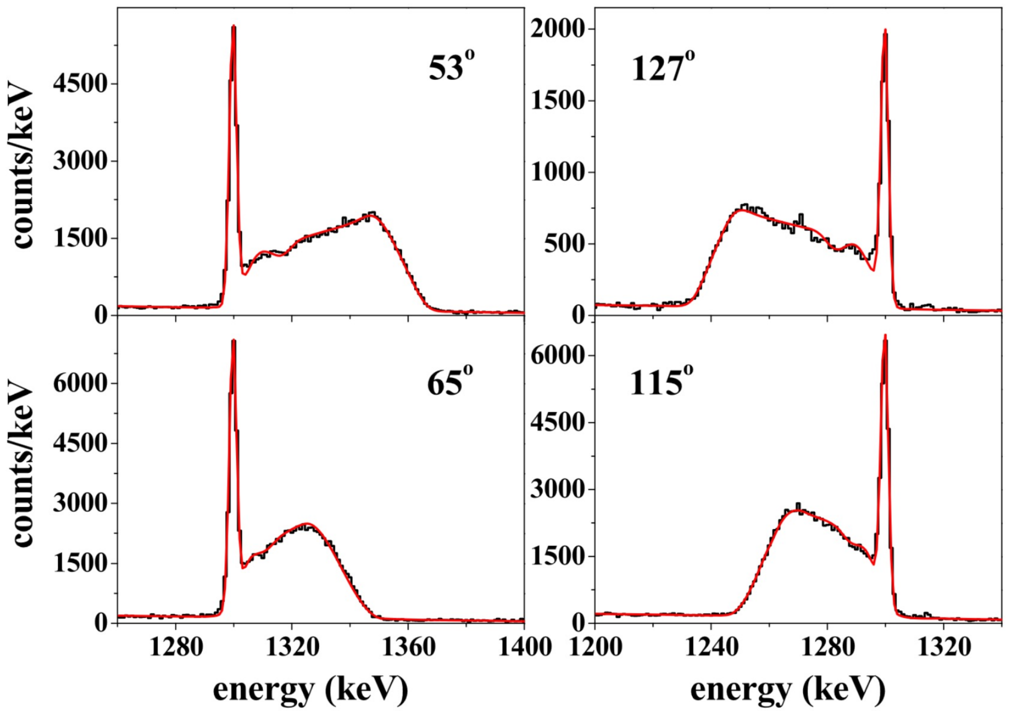


Fig. 1. Lineshape fits for the $2_1^+ \rightarrow 0^+$ transition in ^{114}Sn observed in the Ge crystals at the designated polar angles with respect to the beam axis, in coincidence with C ions.

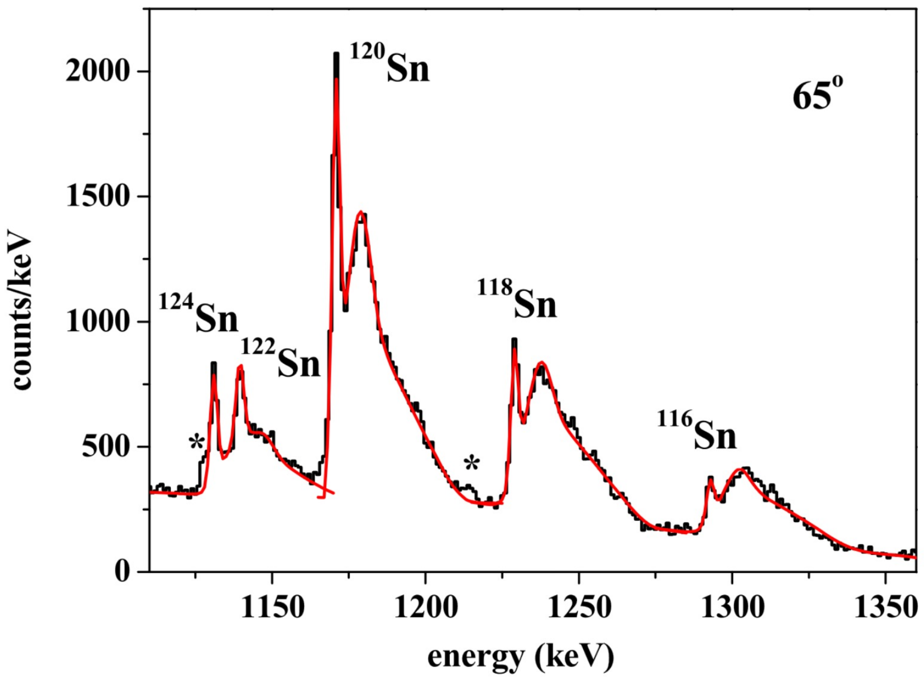
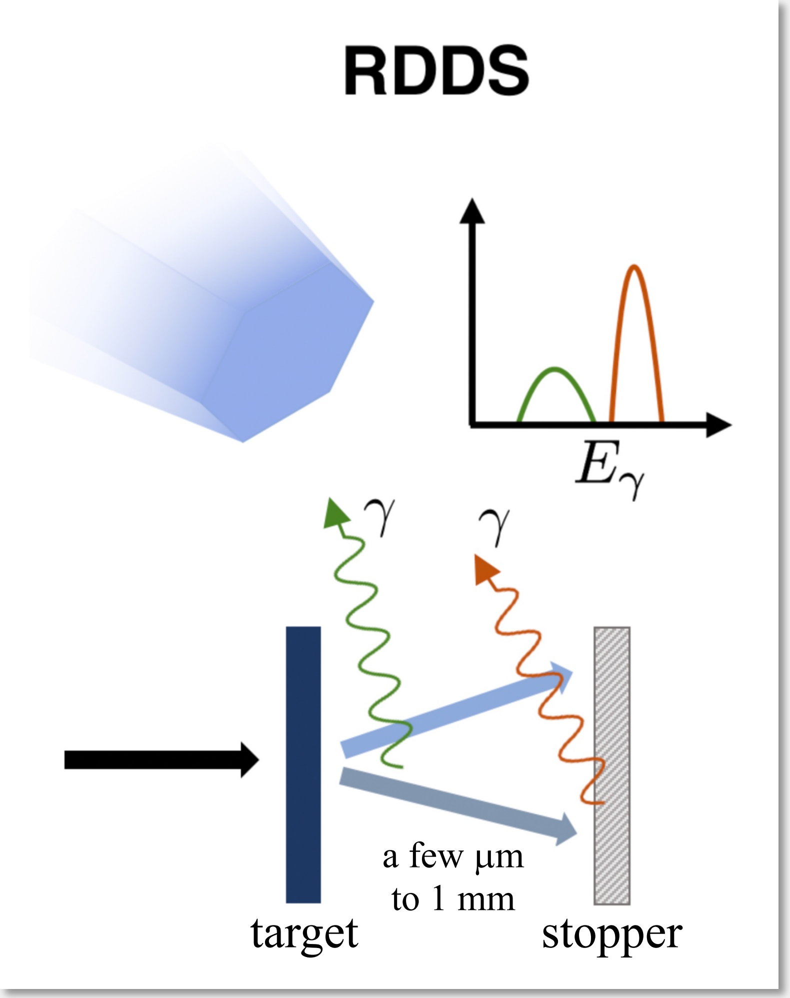


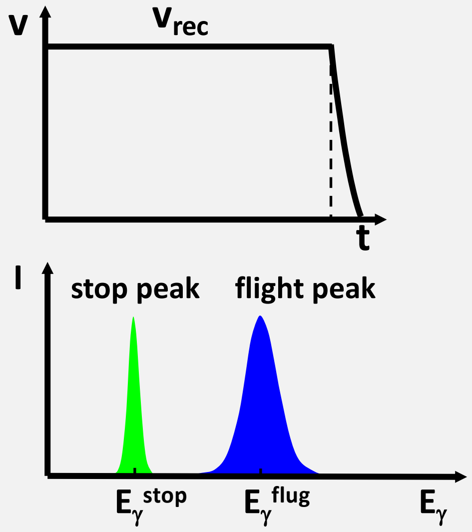
Fig. 2. Lineshape fits of the $2_1^+ \rightarrow 0^+$ transitions in ^{116,118,120,124}Sn in the spectrum observed in the Ge detectors positioned at ±65° from the experiment performed at the Australian National University [14]. Stars label two contaminating transitions in ^{106}Pd and ^{110}Pd.

A. Jungclaus et al., Physics Letters B 695, 110 (2011)

Recoil Distance Doppler-shift technique (RDDS)

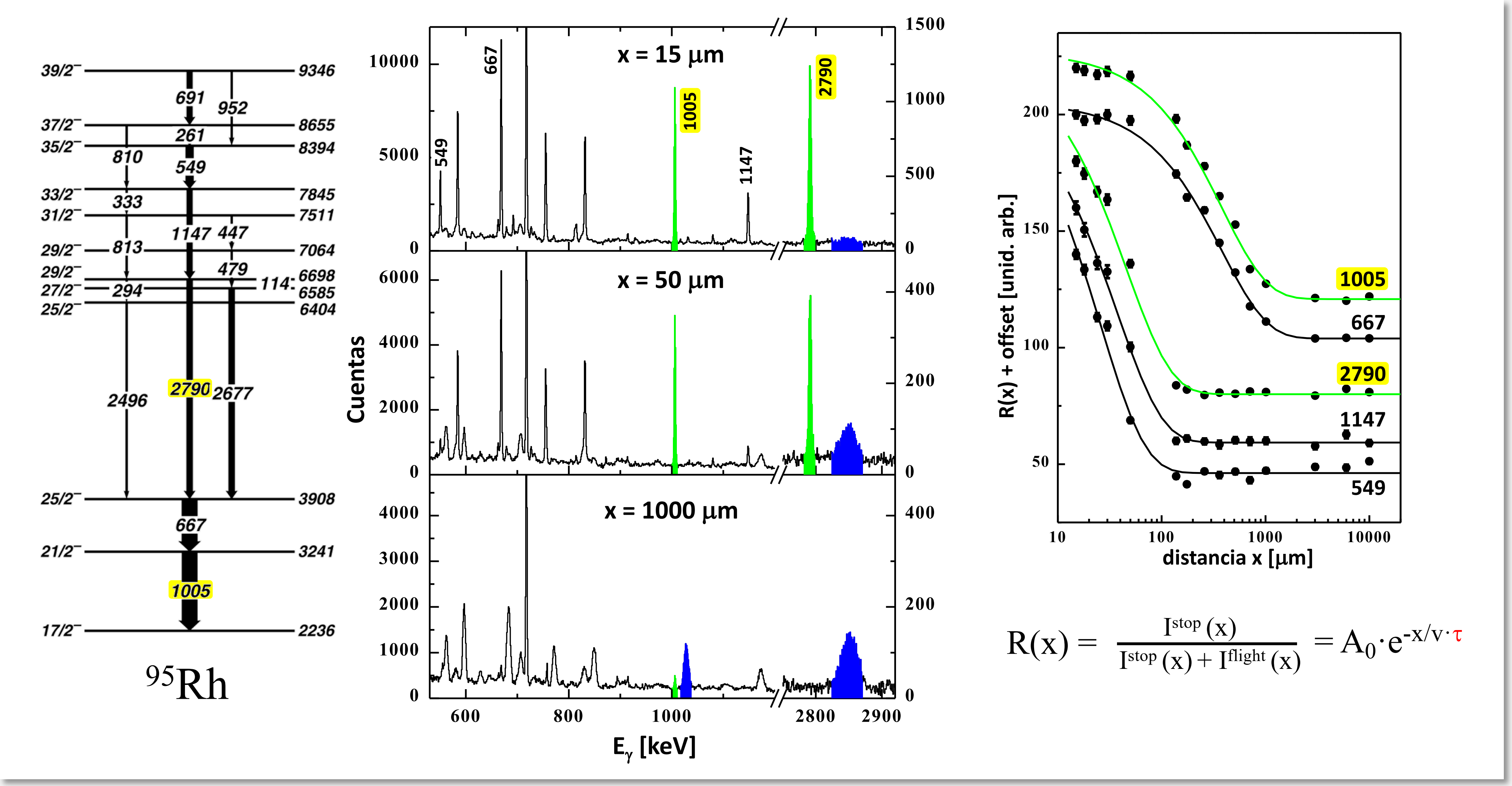


The intensities of the two peaks in the γ-ray spectrum vary as a function of the target-to-stopper distance.



Typical lifetime range: τ = 1 ps -3 ns
Typical velocity range: $\beta < 0.1$

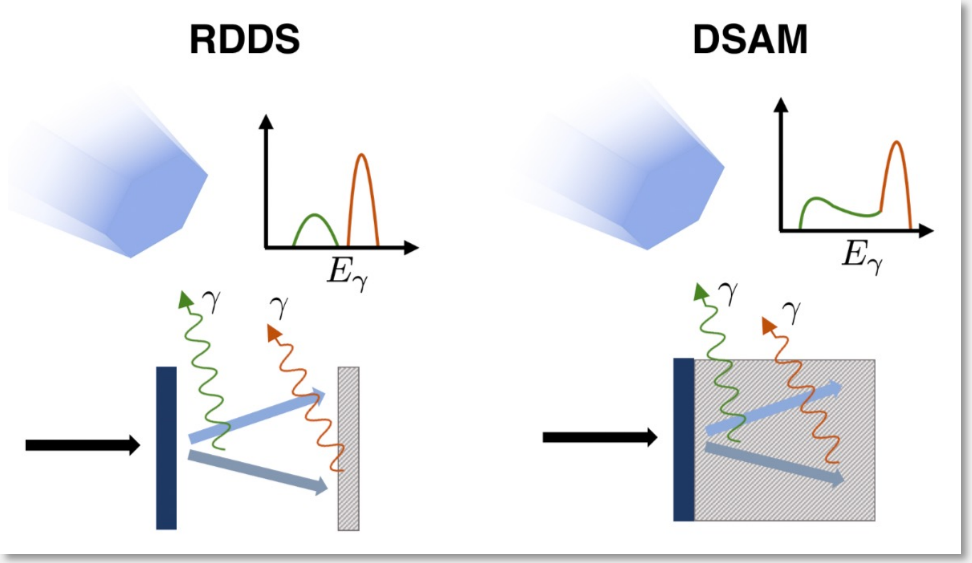
RDDS example from real life

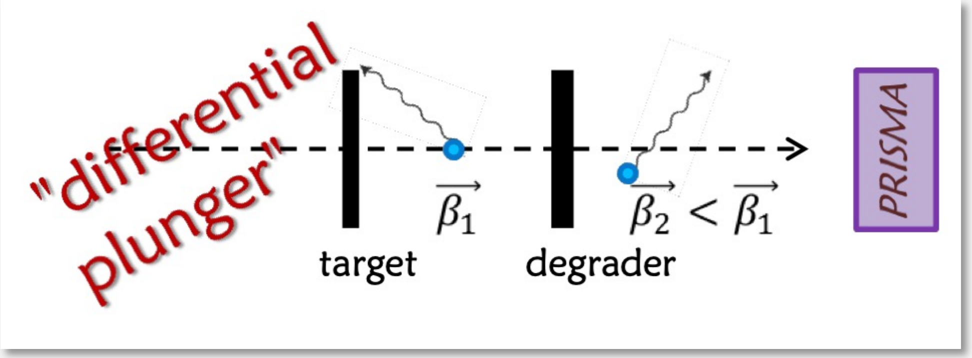


$$R(x) = \frac{I^{stop}(x)}{I^{stop}(x) + I^{flight}(x)} = A_0 \cdot e^{-x/v \cdot \tau}$$

A. Jungclaus et al., Physics Review C 60, 014309 (1999)

Doppler-shift techniques: Some comments





Observed and non-observed indirect population of the excited state of interest ➡ effective lifetime measured

With radioactive ion beams, we need to be careful not to stop the beam in the focus of the γ-ray spectrometer.

One may need to identify the reaction product behind the target ➡ differential plunger

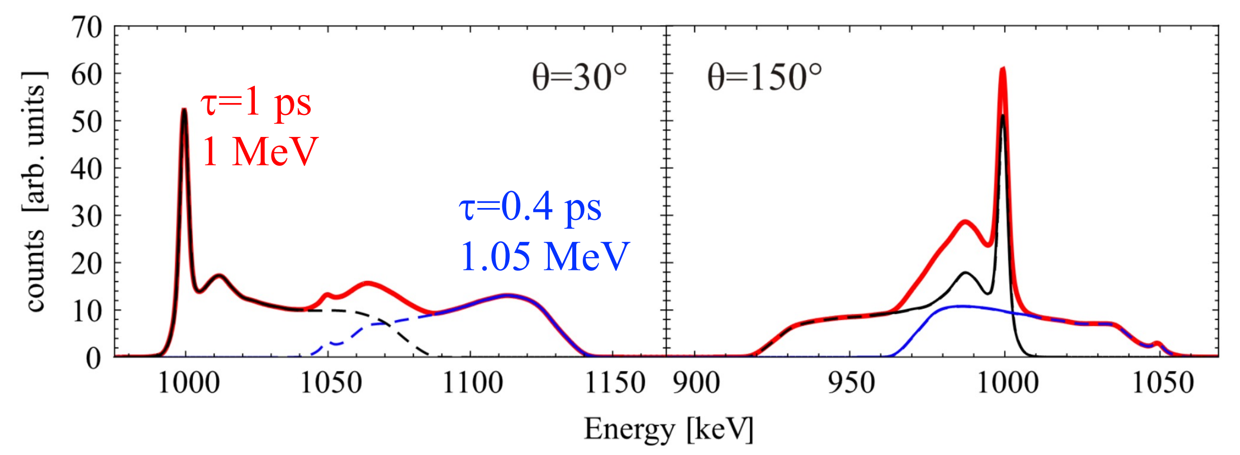
Uncertainties in the description of the slowing-down process (i.e., in the stopping powers)

Variety of different techniques available, many of them based on γγ coincidence information.

From individual detectors to γ-ray tracking arrays ….

Doppler-shift attenuation (DSA) with tracking arrays

Two overlapping γ-ray transitions:



Difficult to disentangle !

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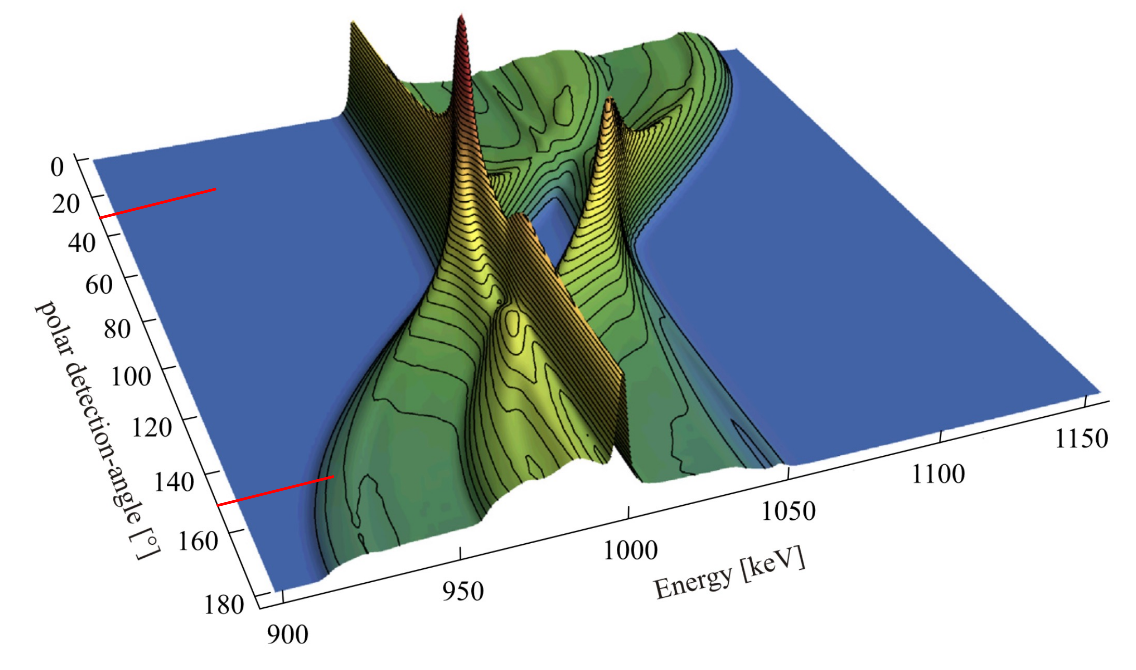
ELSEVIER

APCAD—Analysis program for the continuous-angle DSAM☆

Christian Stahl *, Jörg Leske, Marc Lettmann, Norbert Pietralla

Institut für Kernphysik, Technische Universität Darmstadt, Germany

Two-dimensional spectrum, continuous angle:

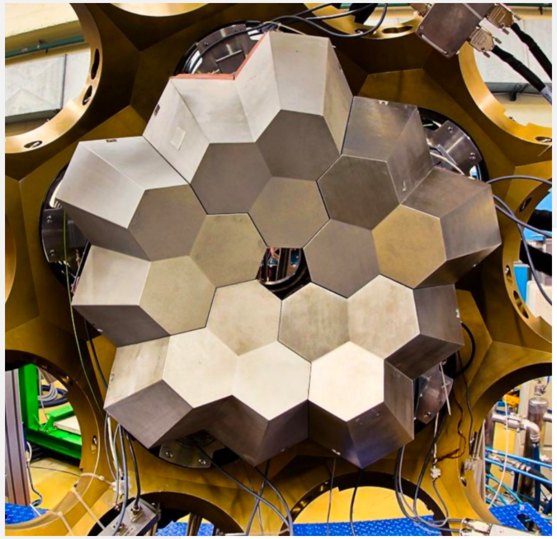


Overlapping lineshapes measured over a broad range of detection angles allows for a sensitive extraction of the individual level lifetimes.

This is a simulation, but …

DSA with the AGATA demonstrator

AGATA demonstrator



beam energy	2_1^+ level lifetime $\tau_{2_1^+}$ [fs]
546 MeV	$524.3^{+2.2}_{-1.4}(stat)\ ^{+26.6}_{-24.8}(sys)$
500 MeV	$(523.7 \pm 2.1\,(stat)\ ^{+17.2}_{-19.9}(sys))$

Christian Stahl, PhD thesis TU Darmstadt, 2015

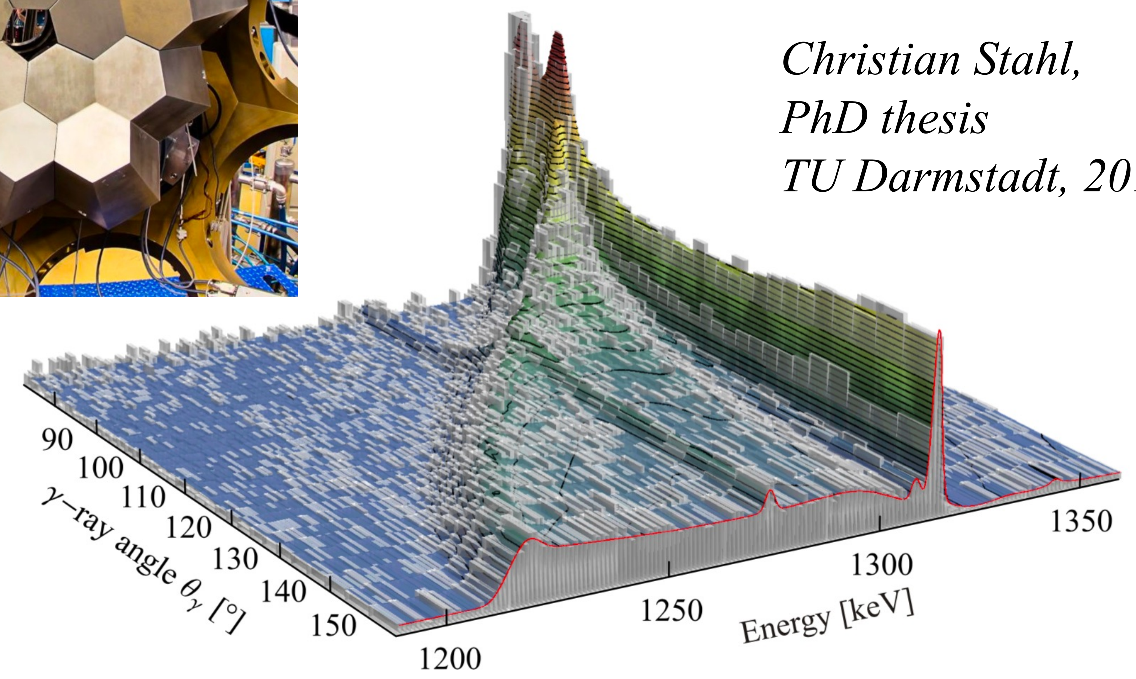


Figure 6.29.: Doppler-broadened lineshape of the $2_1^+ \to 0_1^+$ transition of ^{136}Xe observed with the composite target at 546 MeV beam energy (gray bars). The smooth, colored surface represents the best fit to the data obtained with APCAD. See text for details.

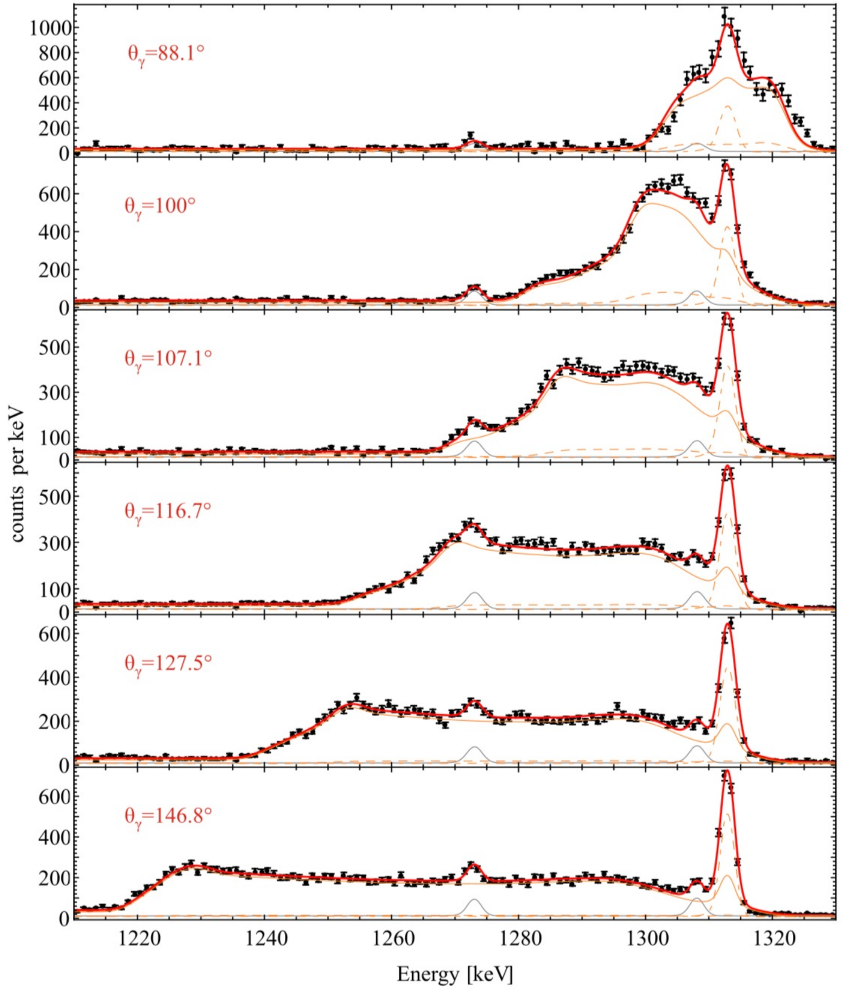
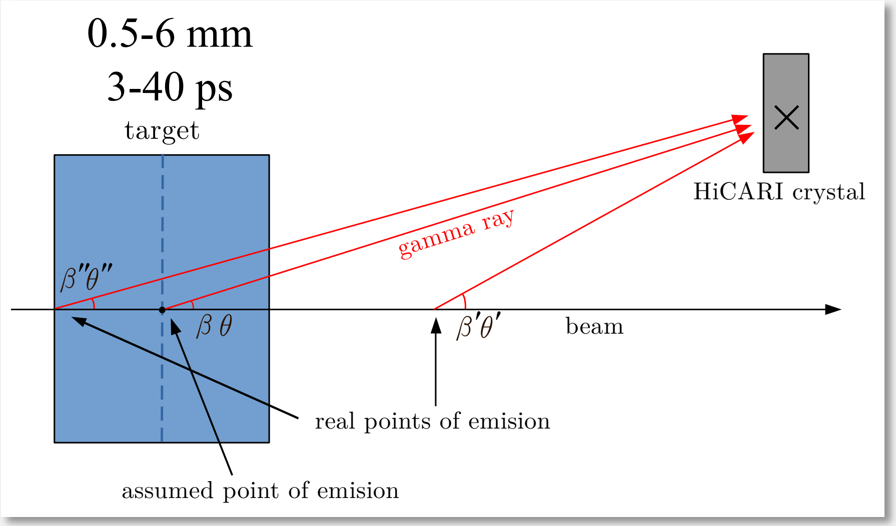


Figure 6.30.: Doppler-broadened lineshape of the $2_1^+ \to 0_1^+$ transition of ^{136}Xe observed with the composite target at 546 MeV beam energy. The thick, red line shows the full fit. The fraction of decays that stem from direct population of the 2_1^+-state are drawn as solid, orange line. The fraction of events stemming from population of the 2_1^+-state via the decay of the short-lived 3_1^- state are drawn as orange, dashed lines. Events connected to feeding from long-lived states are drawn as orange, dashed-dotted line. Contaminants are drawn in gray. See text for details.

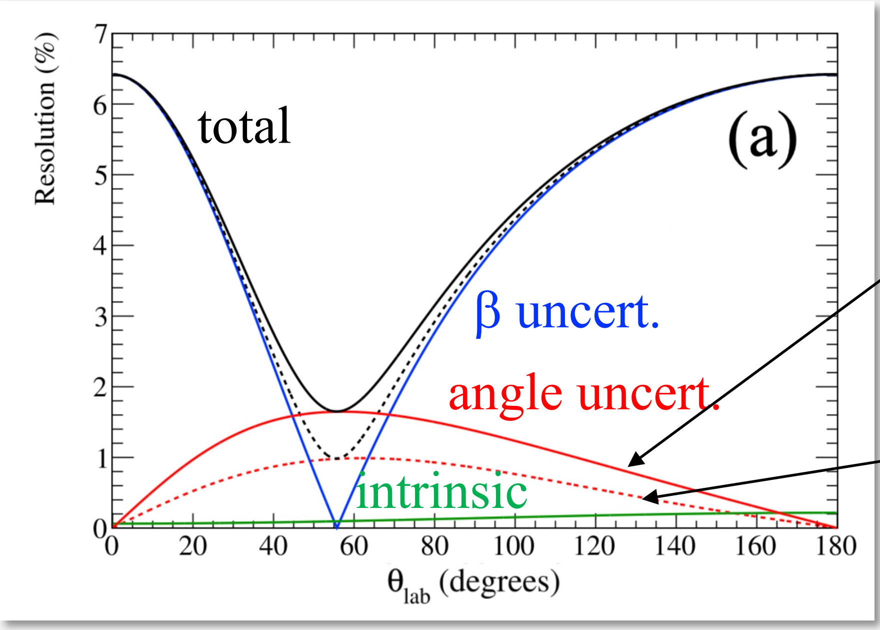
Doppler-shift techniques at relativistic energies

Experiments with radioactive beams at fragmentation facilities (RIBF, GSI/FAIR, FRIB …)

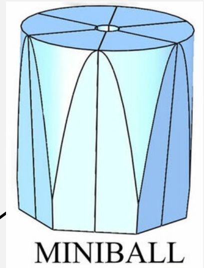
$\beta = 0.5 \Rightarrow v \sim 0.15$ mm/ps



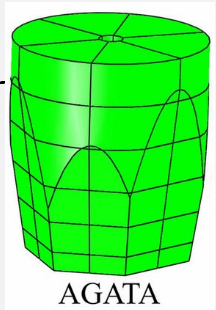
$$E_\gamma^{Lab}(\theta) = E_\gamma^{CM} \frac{\sqrt{1-\beta^2}}{1-\beta \cdot \cos\theta}$$



6-fold segmented



36-fold segmented

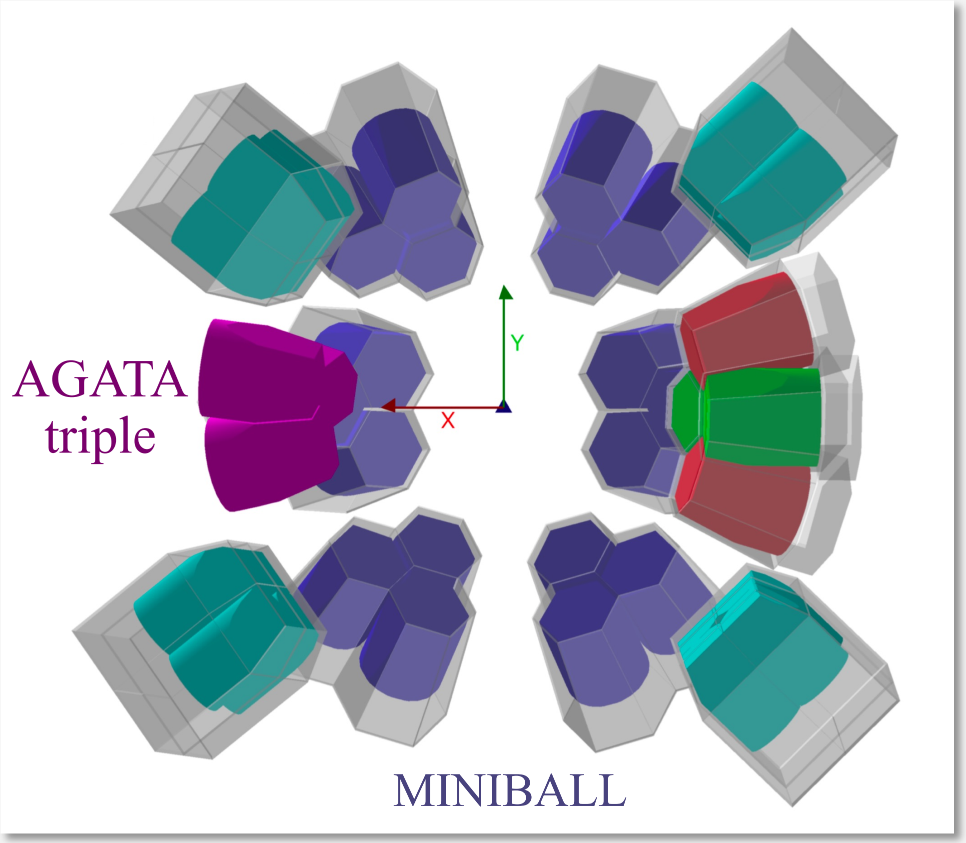


<u>Two effects:</u>

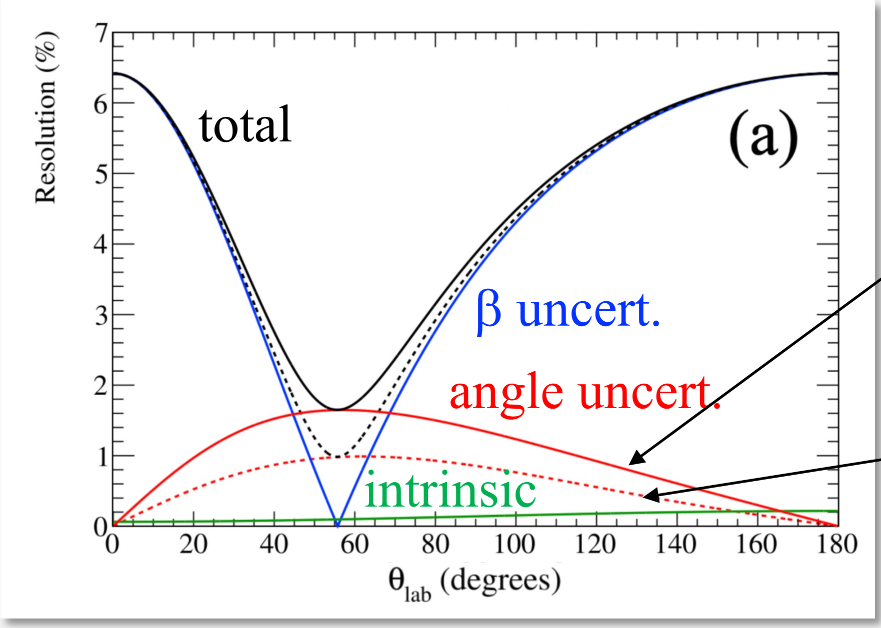
- changing β during flight though the target
- changing θ behind the target

Doppler-shift techniques at relativistic energies

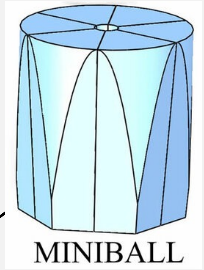
HiCARI@RIBF 2020



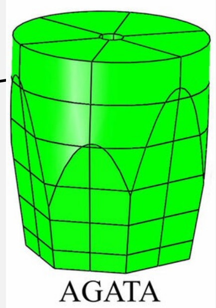
$$E_\gamma^{Lab}(\theta) = E_\gamma^{CM} \frac{\sqrt{1-\beta^2}}{1-\beta\cdot\cos\theta}$$



6-fold segmented



36-fold segmented



Doppler-shift techniques at relativistic energies

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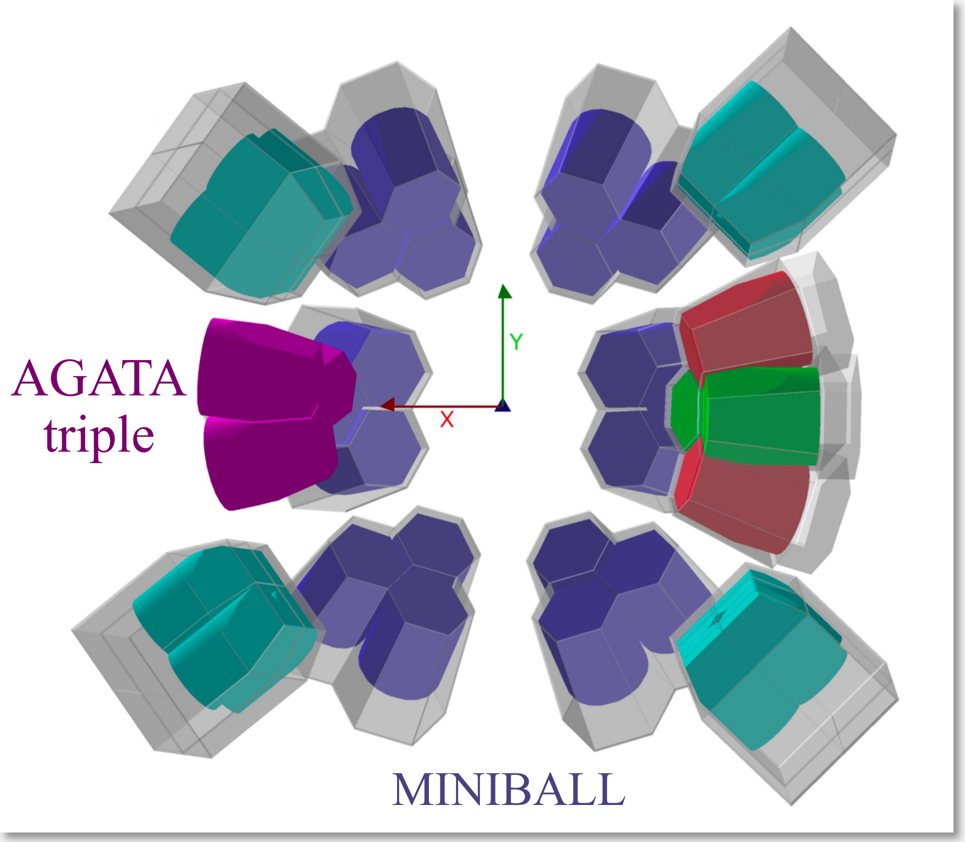

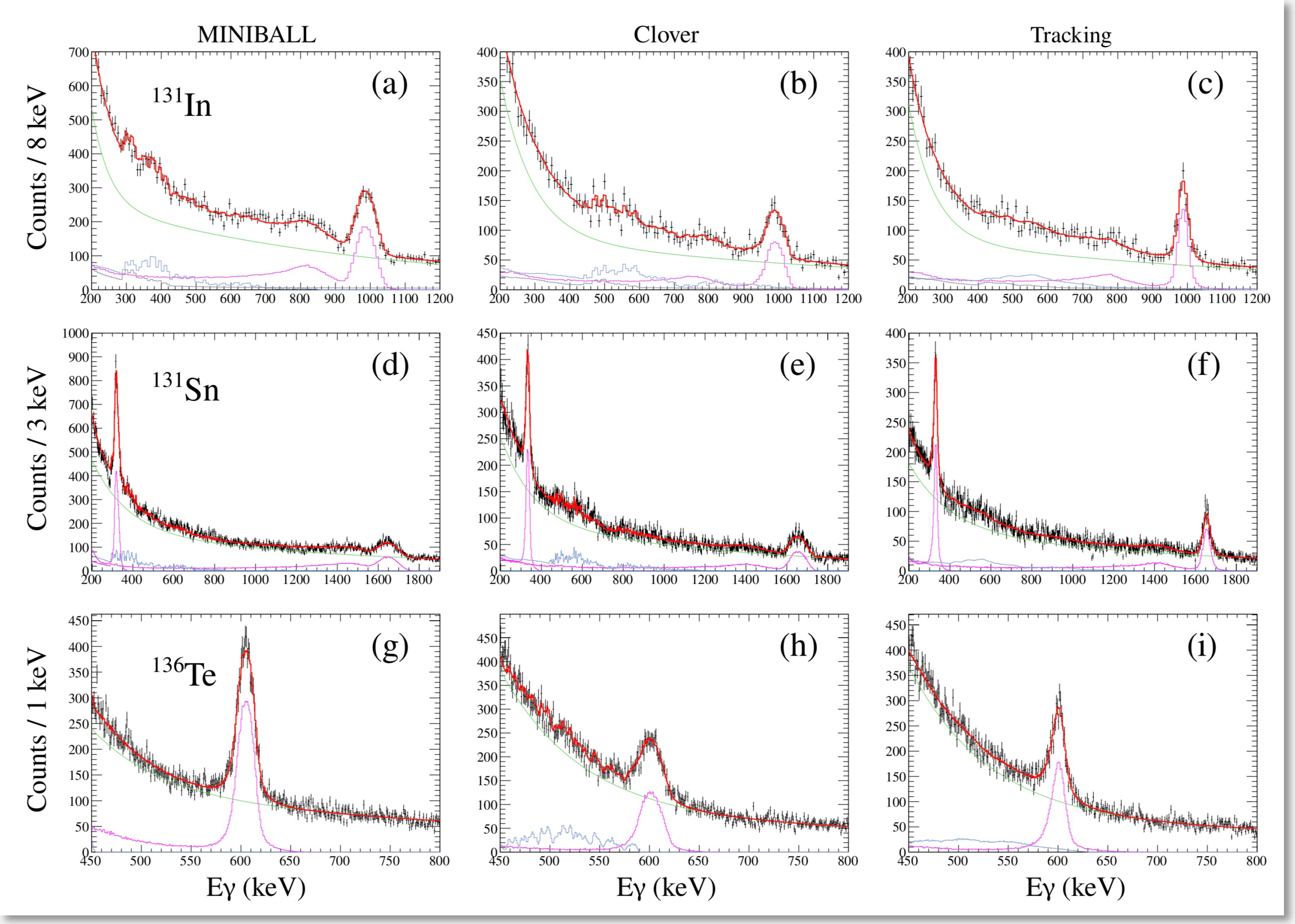

Jaime Acosta et al., in preparation

Doppler-shift techniques at relativistic energies

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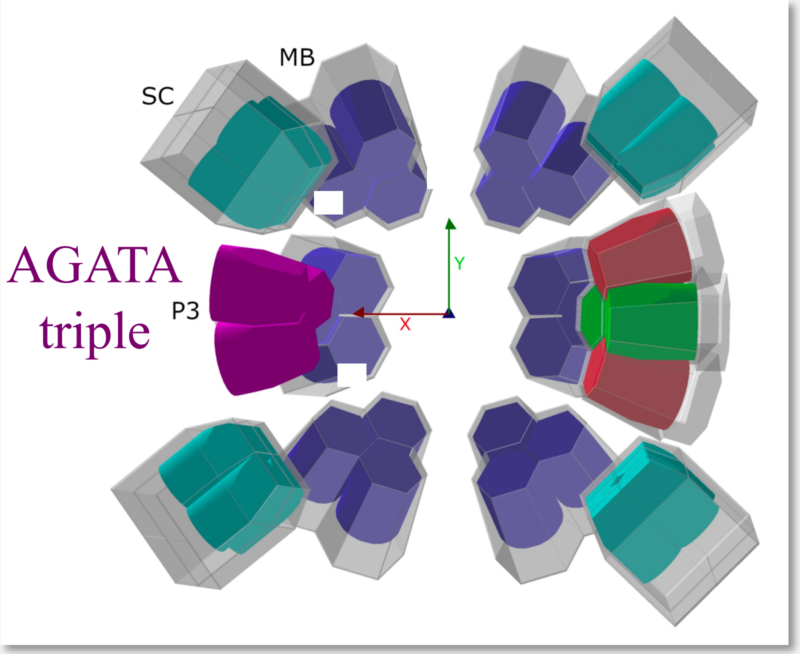
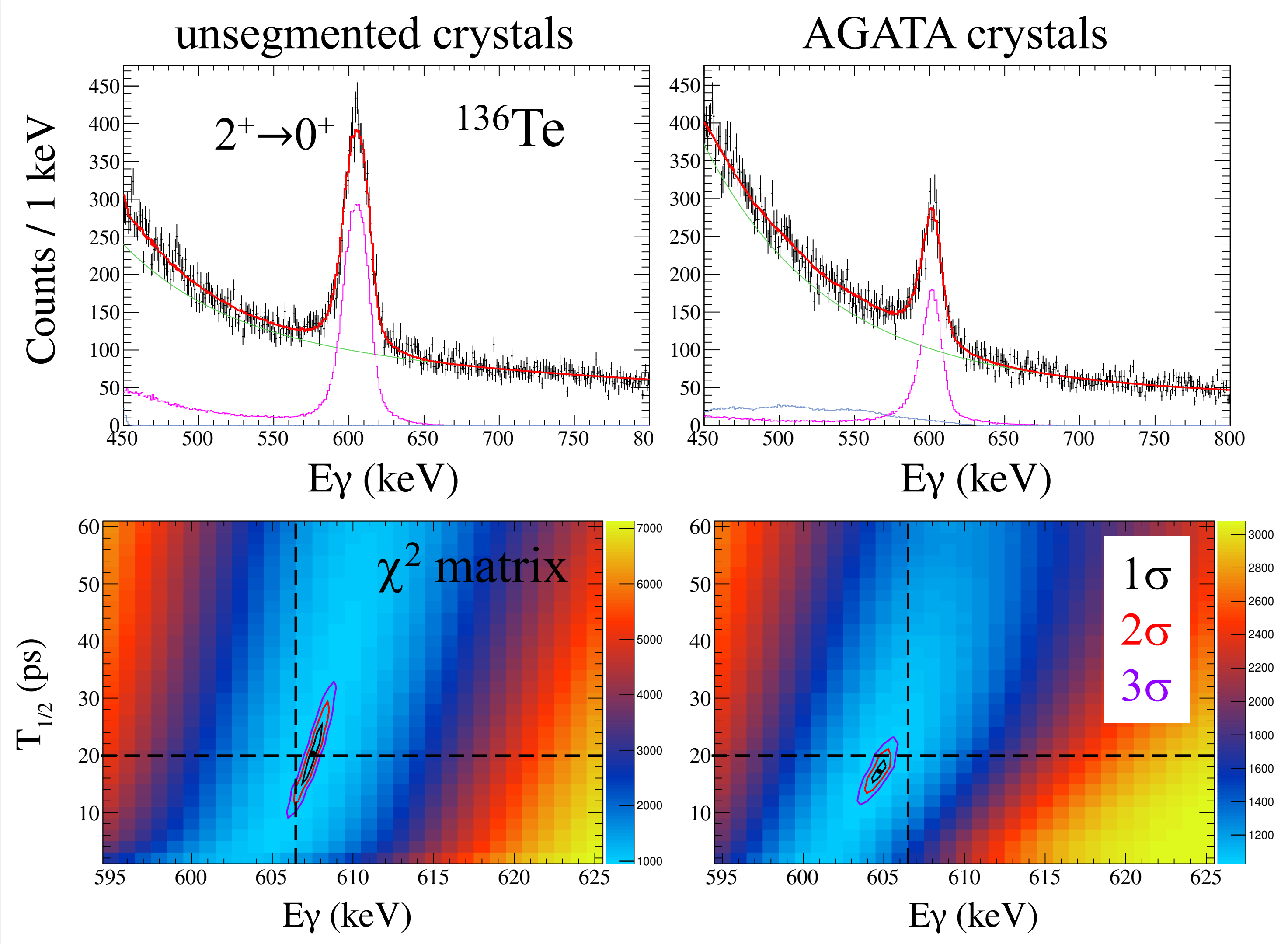
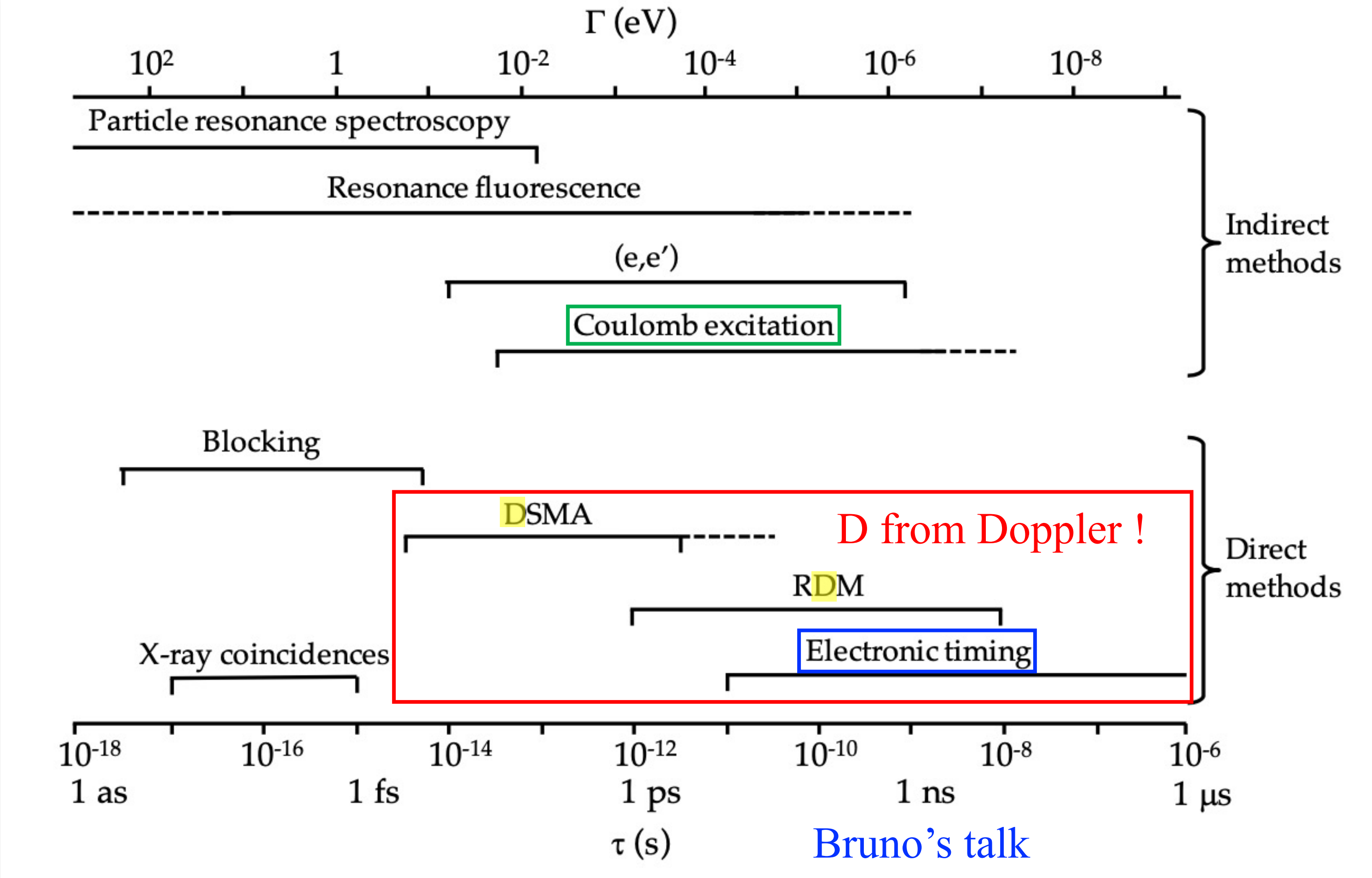




Position resolution of AGATA provides unprecedented sensitivity to excited-state lifetimes !

Jaime Acosta et al., in preparation

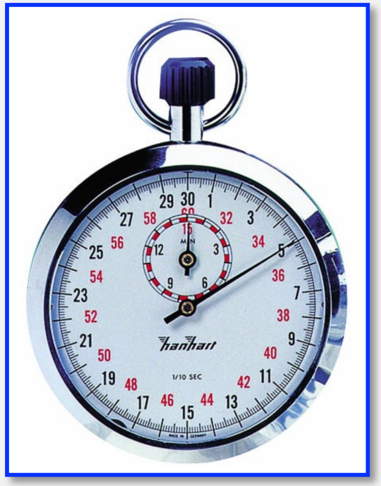
Lifetimes of excited states in atomic nuclei



cross sections

transition strengths

lifetimes

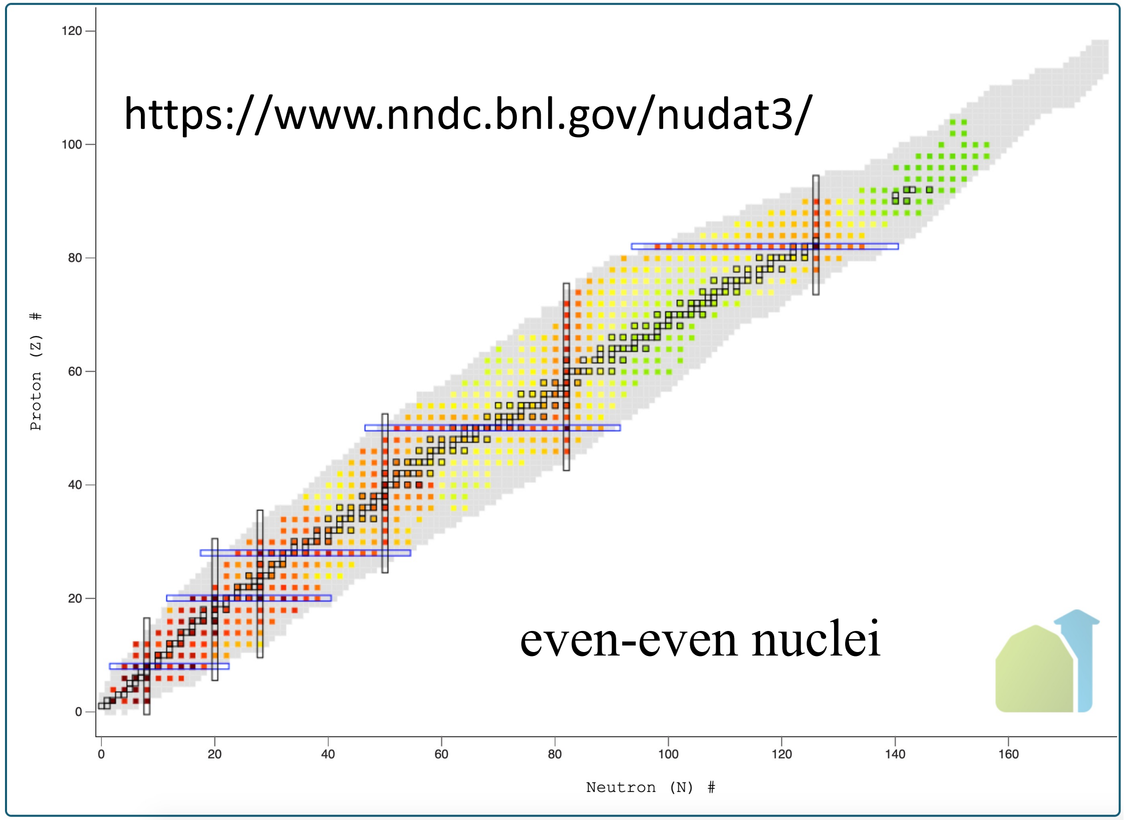


$$E_\gamma^{Lab}(\theta) = E_\gamma^{CM} \frac{\sqrt{1-\beta^2}}{1-\beta\cdot\cos\theta}$$

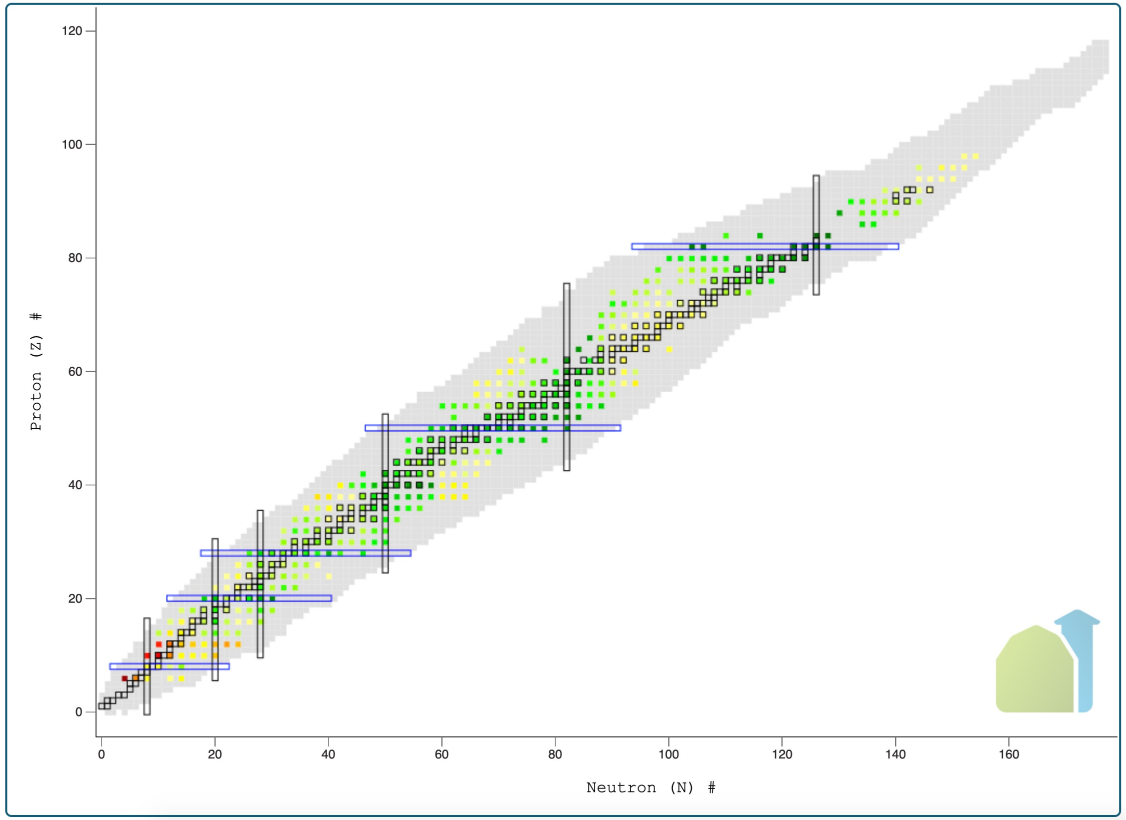
Doppler-shift as a clock if β or θ depend on t !

Current status of measured 2_1^+ energies and lifetimes

$E(2_1^+)$ systematics

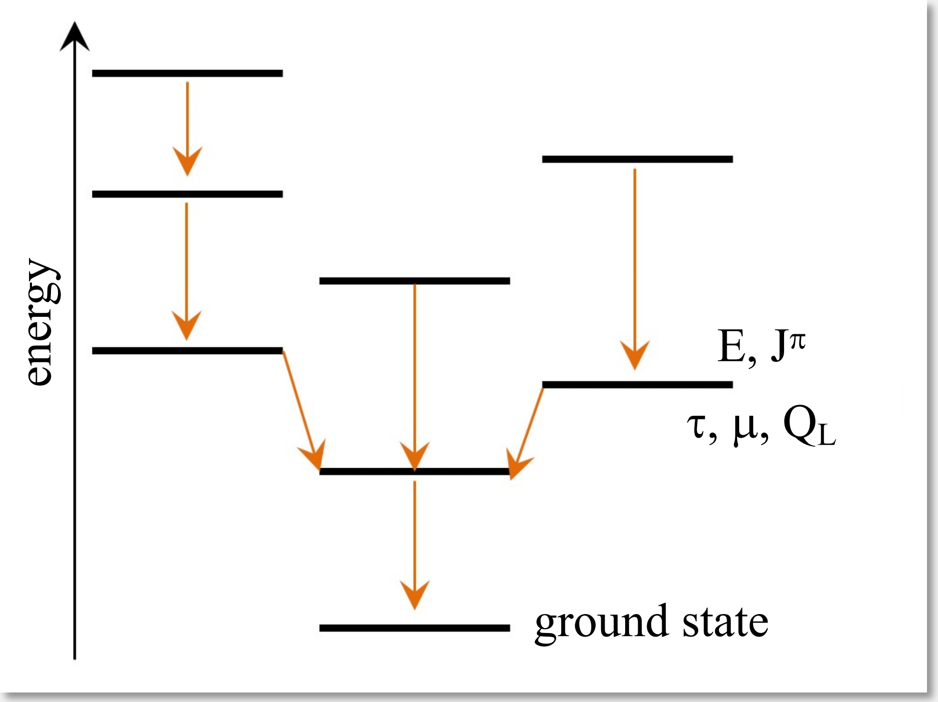


β extracted from $B(E2;2^+\text{-}0^+)$



Still a lot of work to be done. And these are only the first excited 2^+ states !

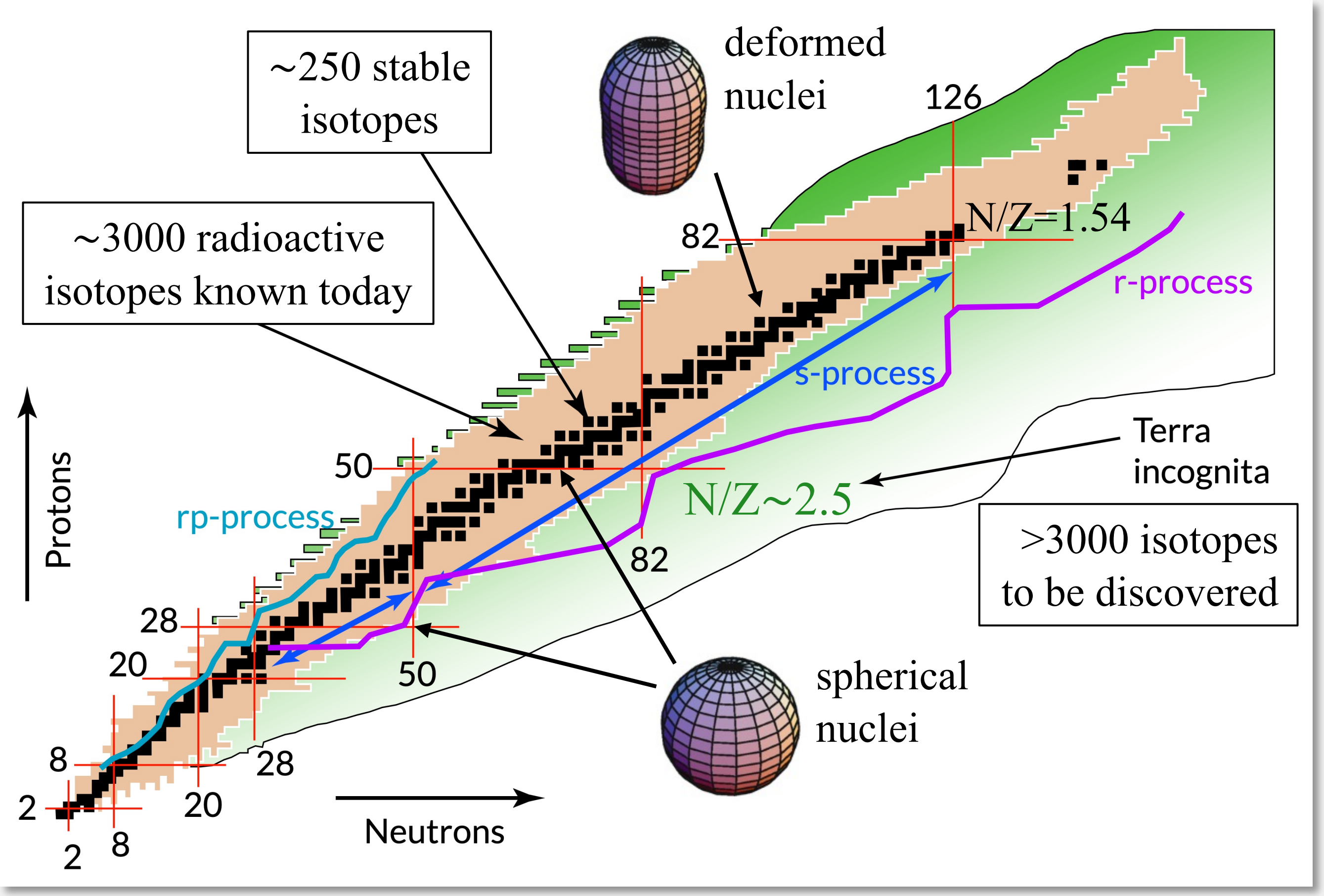
Quantities determined using γ-ray spectroscopy

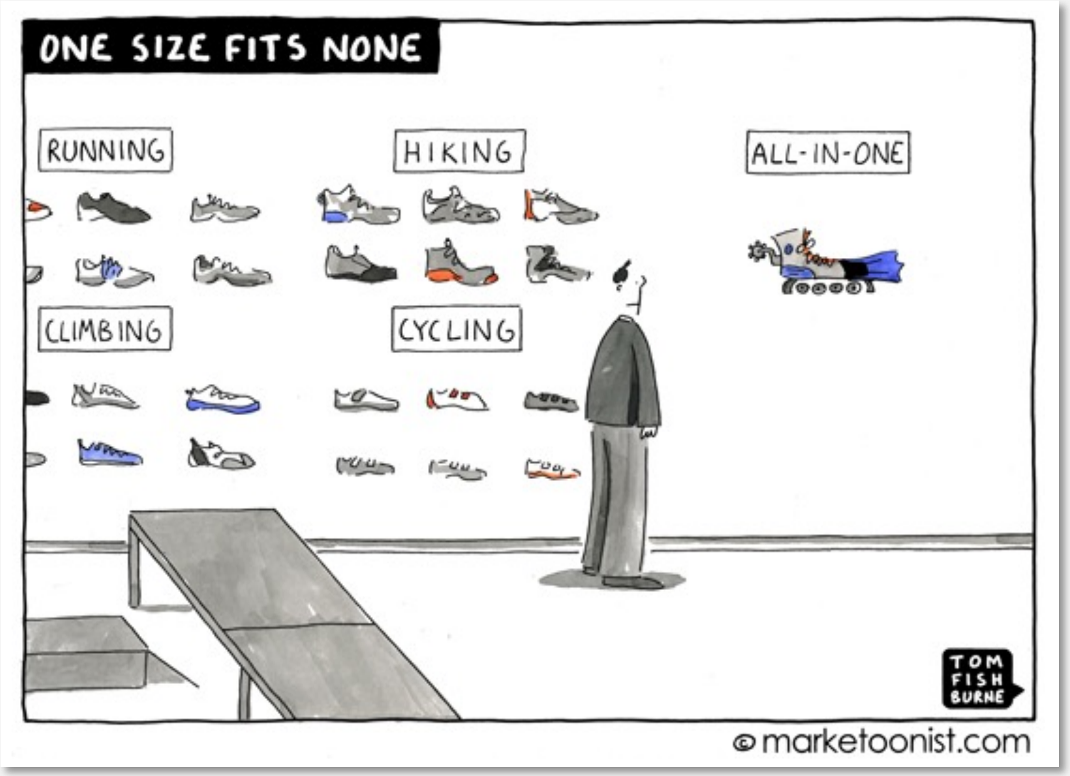


Relevant quantities for the comparison with theoretical predictions:

	<u>Measuring γ-ray</u>
• excitation energy E	energy
• spin J	angular distribution/corr.
• parity π	linear polarization
• lifetime τ (transition probability) • magnetic dipole moment μ • electric multipole moment Q_L	large variety of experimental techniques

Our playground: The chart of nuclides





A lot of recent progress on the theory side …

New generation of radioactive beam facilities (FAIR, FRIB, RIBF Upgrade …), new tracking γ-ray spectrometer: We will have a lot of fun in the coming years !