LISA: Lifetime measurements with Solid Active targets

Kathrin Wimmer

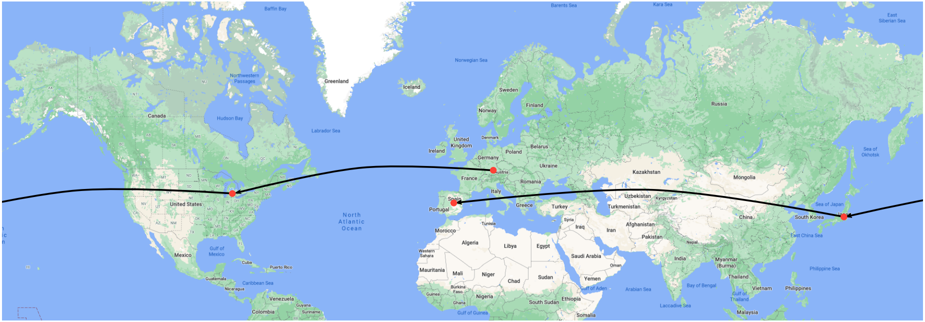
Instituto de Estructura de la Materia - CSIC Madrid

10. May 2021

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

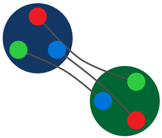
A bit about me

- studied at Ludwigs-Maximilians Universität (Munich) and Università di Pisa (Italy)
- PhD at TU Munich (2010), work done at REX-ISOLDE, CERN (Switzerland)
- moved to the National Superconducting Cyclotron Laboratory (USA) as postdoc (2010 - 2012)
- Assistant Professor at Central Michigan University (2012 - 2014)
- Faculty (Kōshi) at The University of Tokyo (2014 - 2019)
- since June 2019 at CSIC
- main research theme: structure and reactions with exotic nuclei



Outline

Symmetry breaking and collectivity



- nuclei govern the Universe at many length (fm to km) and time scales (μs to Gy)
- dual quantum liquid consisting of protons and neutrons which are interacting
- leads to the well-known shell structure of atomic nuclei
- strong nuclear interaction and its isospin dependence leads to changes along isotopic and isotonic chains
- shell evolution can change the spacing and ordering of the single-particle orbitals
  $\rightarrow$ degenerate levels in a nuclear Jahn-Teller effect
  $\rightarrow$ spontaneous symmetry breaking and quantum phase transitions
- excitations associated with collective quantum mechanical rotations or vibrations

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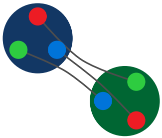

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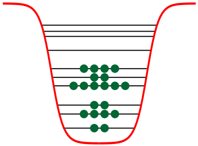

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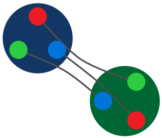

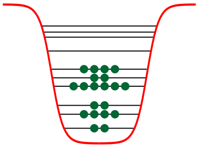

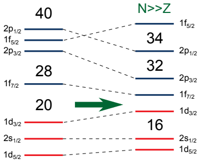

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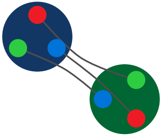

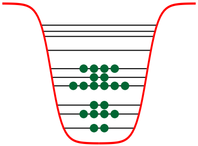

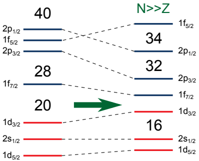

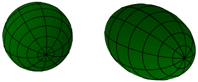

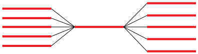

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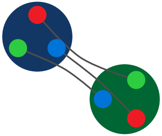
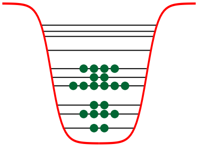
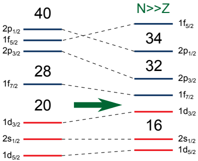
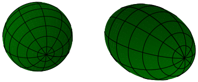
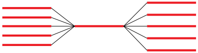




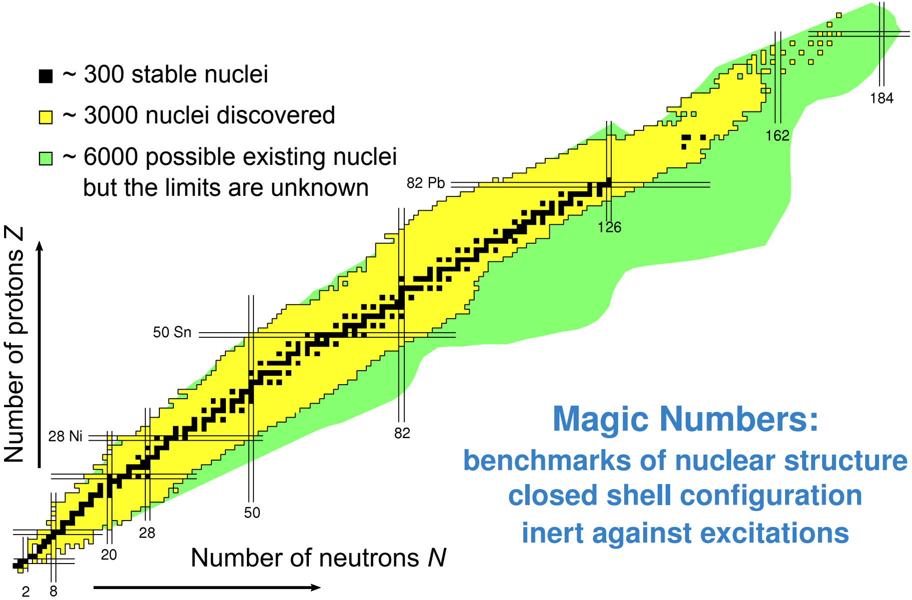






where and how does collective motion and deformation of nuclei emerge from the single-particle degrees of freedom of the protons and neutrons?

The nuclear chart: our playground



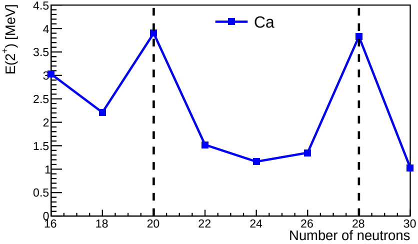
Magic Numbers:

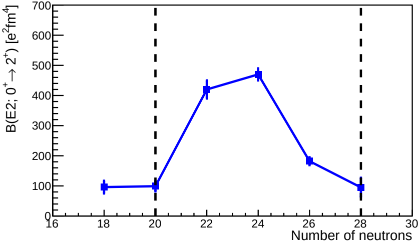
benchmarks of nuclear structure

closed shell configuration

inert against excitations

Example: disappearance of shell closures





http://www.nndc.bnl.gov/ensdf/, K. Wimmer and P. Doornenbal, Prog. Part. Nucl. Phys. (2021)

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^{30}Si	^{32}Si	^{34}Si	^{36}Si	^{38}Si	^{40}Si	^{42}Si	^{44}Si
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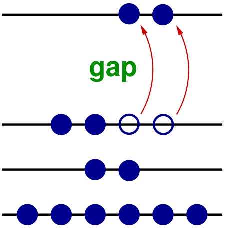
- high energy of the first excited state
- small B(E2) value, difficult to excite



- many exotic nuclei do not show these signatures

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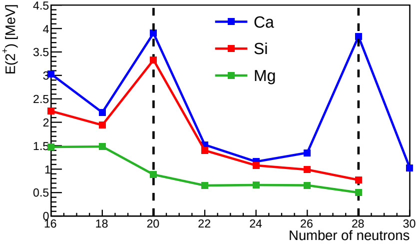

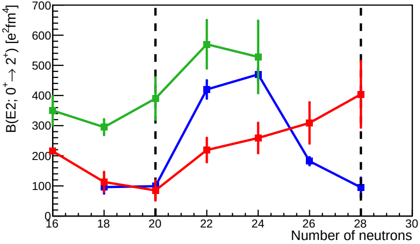

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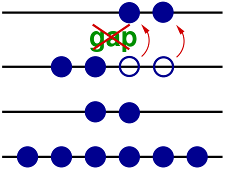

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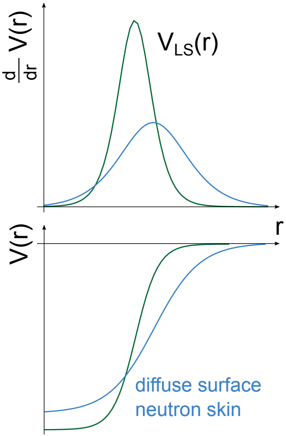
Nuclear forces can change level ordering



Figures adapted from T. Otsuka et al., Phys. Rev. Lett. 105, 032501 (2010), Phys. Rev. Lett. 87, 082502 (2001), Phys. Rev. Lett. 95, 232502 (2005).

- spin-orbit interaction, excess neutron distribution leads to weaker spin-orbit effect
- three-body interactions, needed to explain binding of light nuclei
- tensor interaction between protons and neutrons
- all affect the level spacing and ordering

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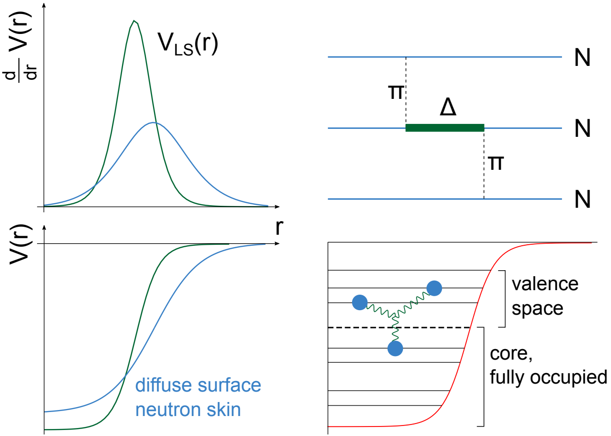

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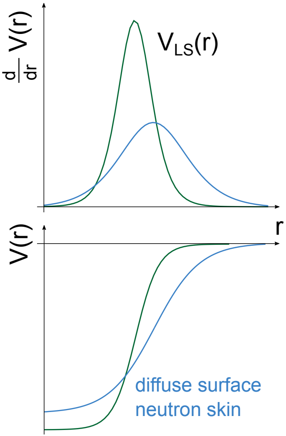

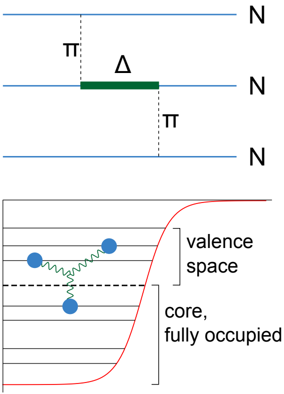

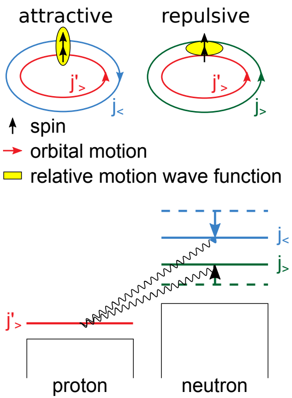

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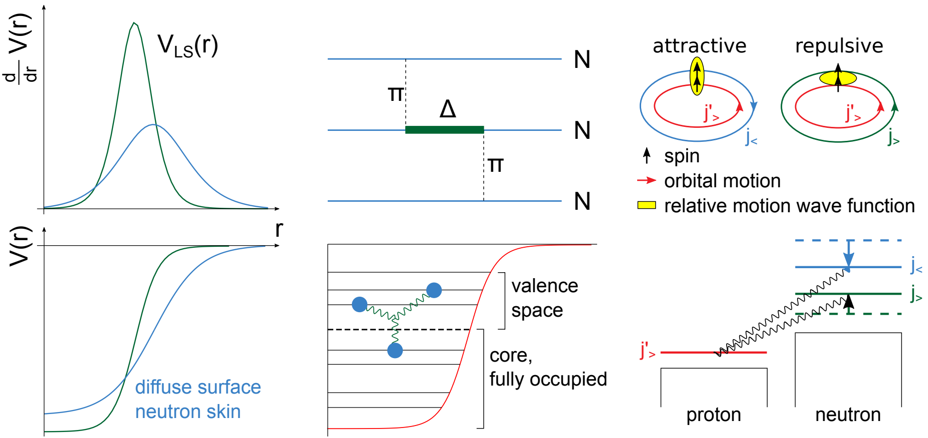

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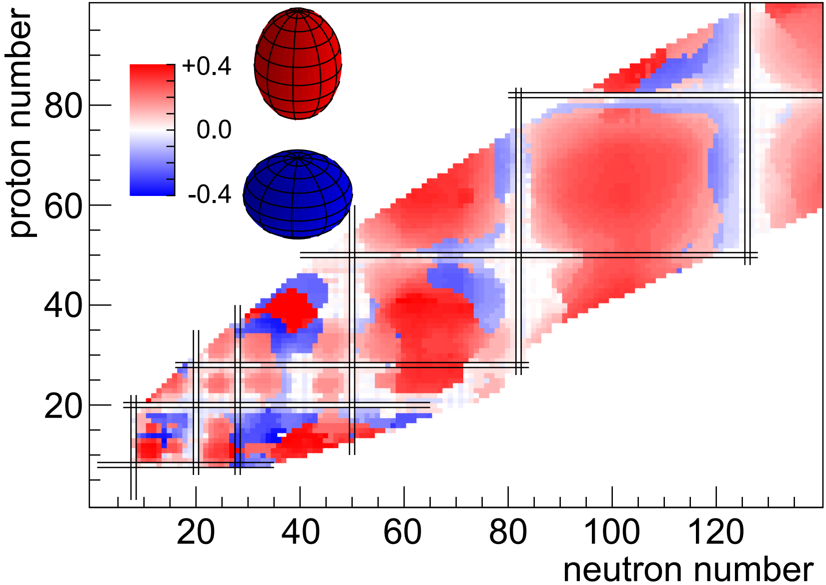
Predicted shapes of nuclei

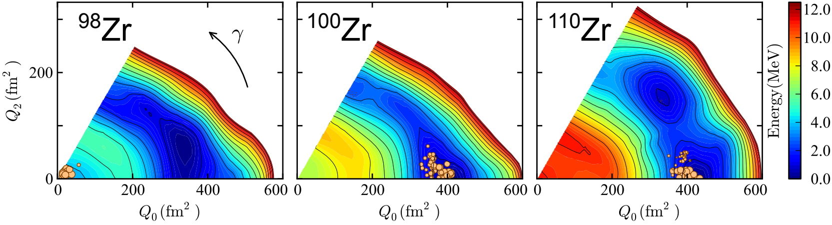
- predicted deformation parameters using finite-range droplet macroscopic model



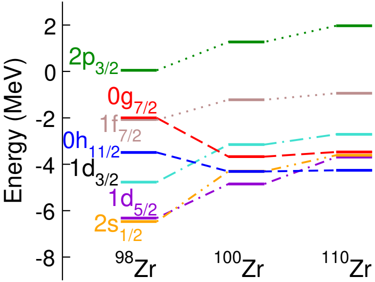
P. Möller et al., At. Data Nucl. Data Tables **109** (2016) 1.

Collective excitations

- a deformed nucleus is characterized by collective and coherent quantum mechanical rotations or vibrations



- shapes change as a function of proton or neutron number
- proton-neutron interaction changes the ordering and spacing of levels
- (near-) degeneracy triggers symmetry breaking and deformation
- calculations predict deformation and triaxiality for ^{110}Zr



T. Togashi et al., Phys. Rev. Lett. **117** (2016) 172502.

Experimental observables of collectivity

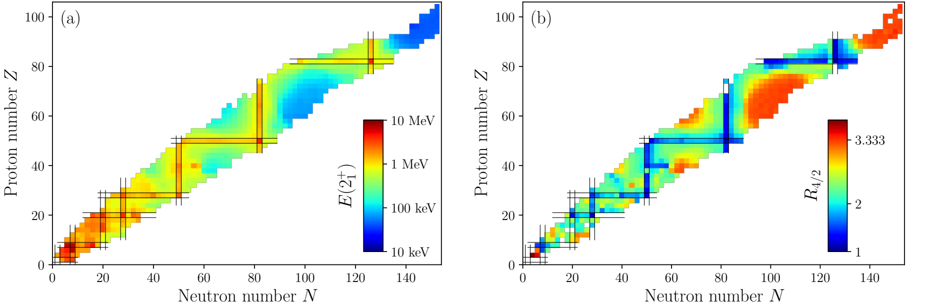


Figure from K. Wimmer and P. Doornenbal, Prog. Part. Nucl. Phys. (2021).

- excitation energy of the first 2^+ state
- ratio $R_{4/2} = E(4_1^+)/E(2_1^+)$ mirrors the $E(2_1^+)$ behavior
- magic nuclei: pair breaking $\rightarrow$ similar energies of 2_1^+ and 4_1^+ $\rightarrow$ $R_{4/2} \sim 1$
- vibrational nuclei: 2_1^+ state one phonon, 4_1^+ two phonon excitation $\rightarrow R_{4/2} = 2$
- rotational nuclei: $E(J) \propto J(J+1) \rightarrow R_{4/2} = 3.33$

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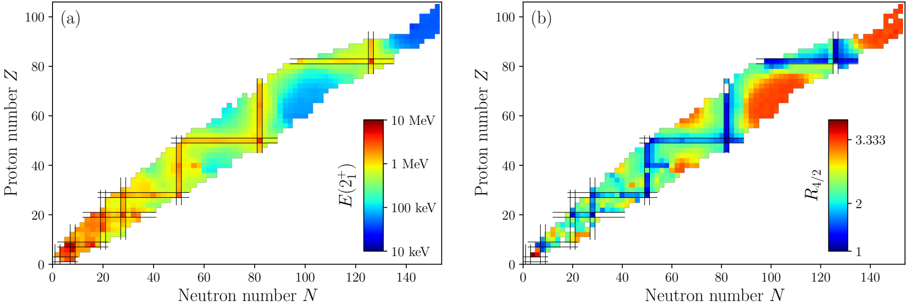

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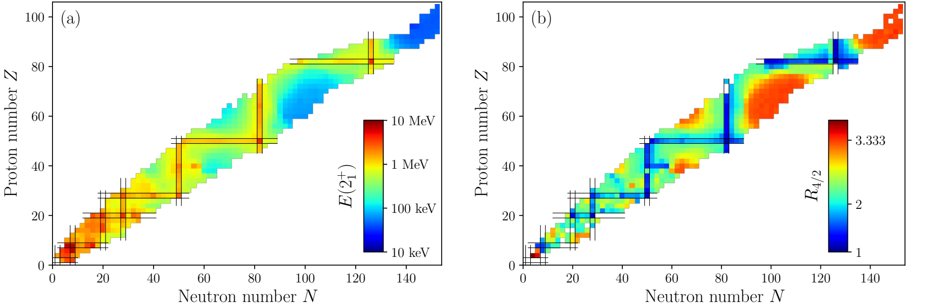

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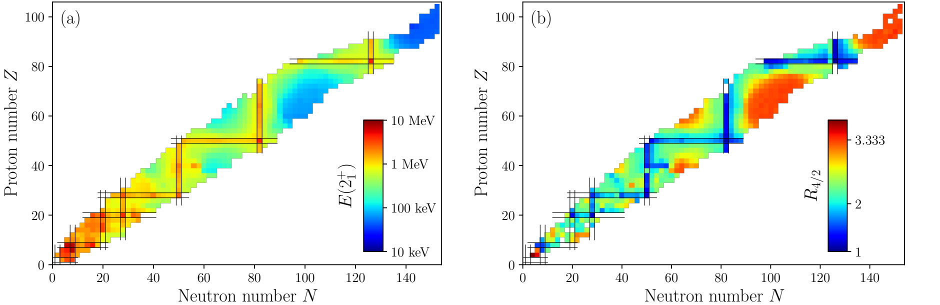

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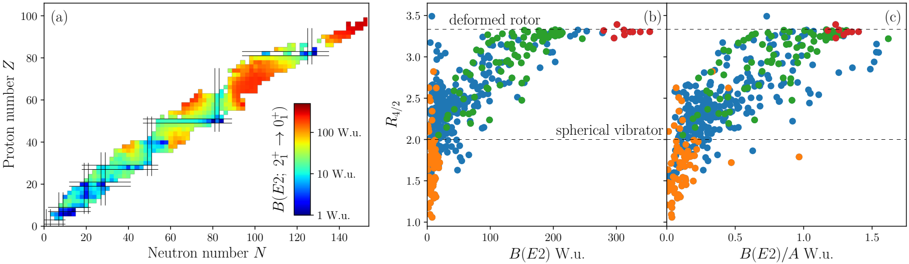

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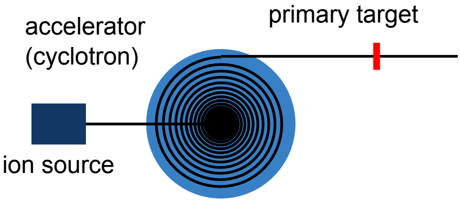
- reduced transition probability $B(E2)$
- direct measure of nuclear collectivity
- in Weisskopf units: how many nucleons participate in the excitation
- experimental observable:
  excitation cross section or probability, lifetime and decay branching
- main techniques (for exotic nuclei): Coulomb excitation and direct lifetime measurements (this talk)

In-beam γ-ray Spectroscopy of Exotic Nuclei

Making radioactive nuclei

- projectile fragmentation of heavy beams on a light primary reaction target



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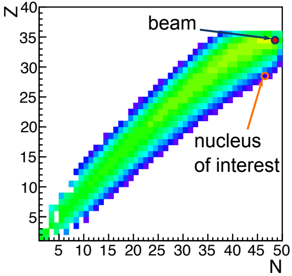
- using dipole magnets and slits
- Z specific energy loss in a wedge shaped degrader



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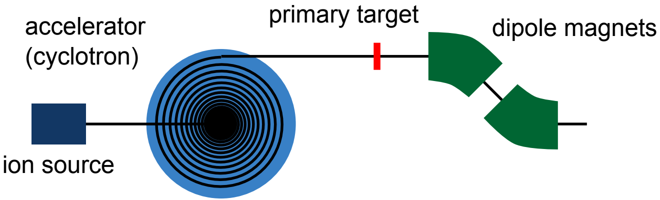

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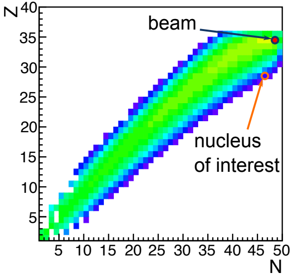

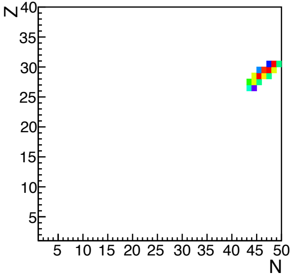

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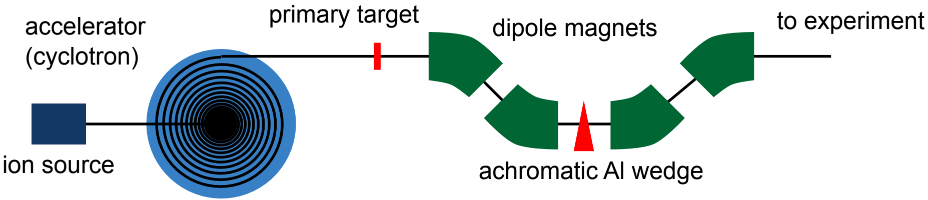

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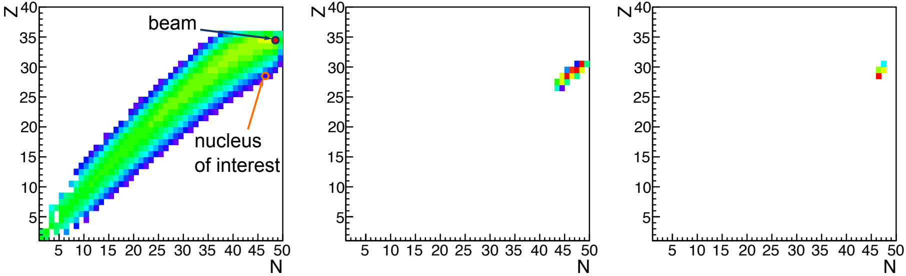


Identification of beam particles

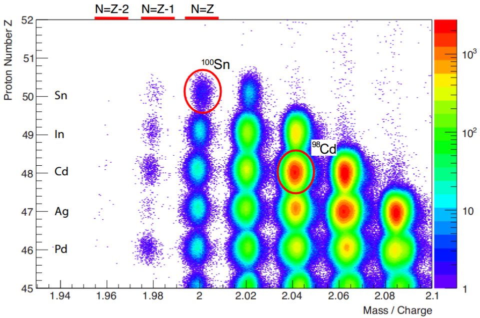
- $B\rho - \Delta E - TOF$ method

$$\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi e^4 Z^2}{m_e v^2} Nz \left[ln\left(\frac{2m_e v^2}{I}\right) - ln(1-\beta^2) - \beta^2 \right]$$

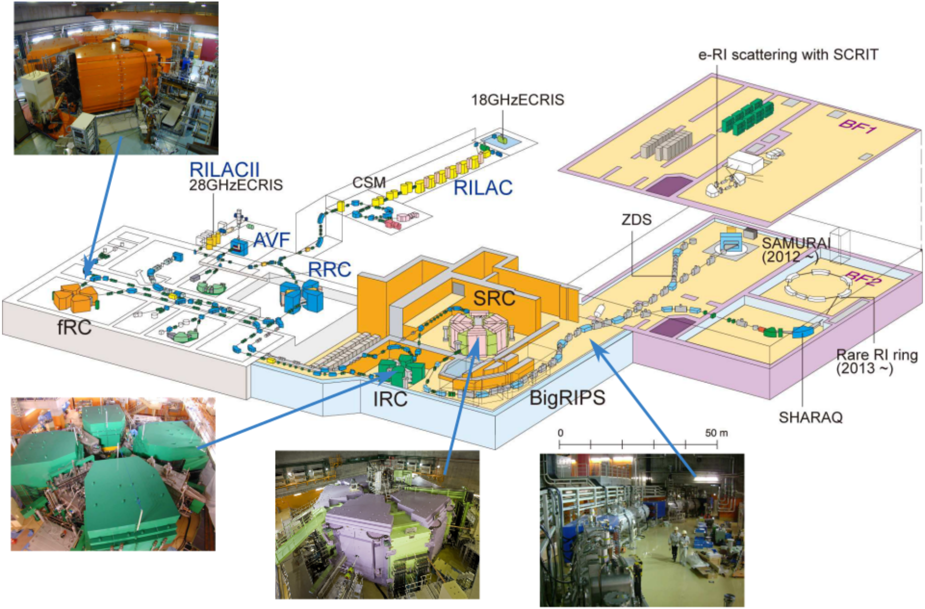
$$TOF = \frac{L}{\beta c}$$

$$\frac{A}{Q} = \frac{B\rho}{\beta\gamma}\frac{c}{m_u}$$

- measure trajectory (position and angles at focal planes), time-of-flight, and energy loss
  $\rightarrow$ unique A/Q and Z identification

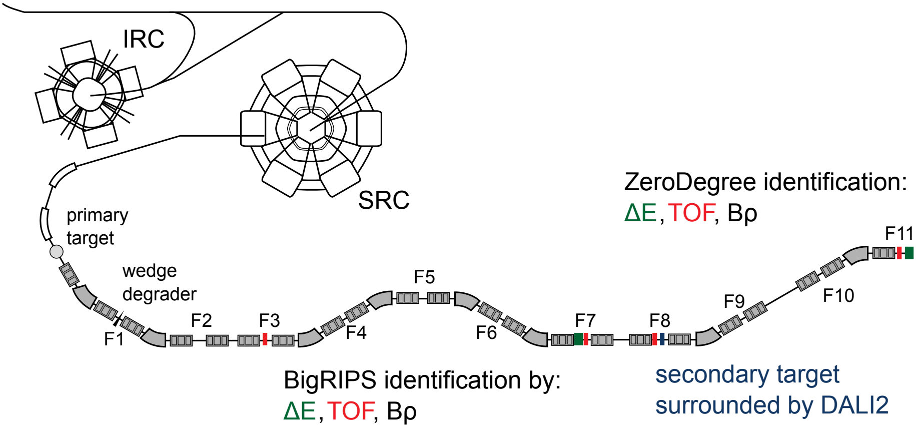


Example: RIBF facility at RIKEN/Japan



Example: RIBF facility at RIKEN/Japan

- 345 *A*MeV primary beams fragmented on a Be target
- 2-stage separation and identification
- decay and in-beam γ-ray spectroscopy



Doppler-effect

- γ rays are emitted in flight from a moving nucleus with velocity β
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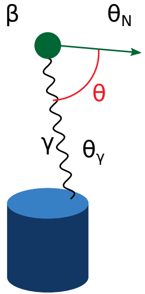

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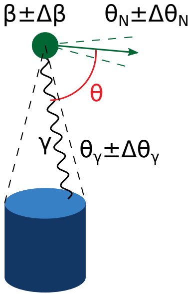

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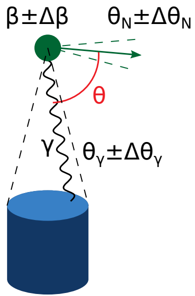

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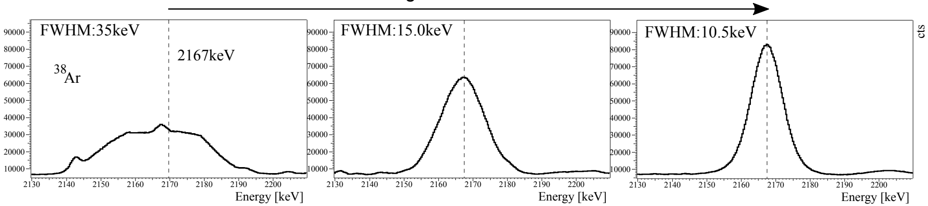
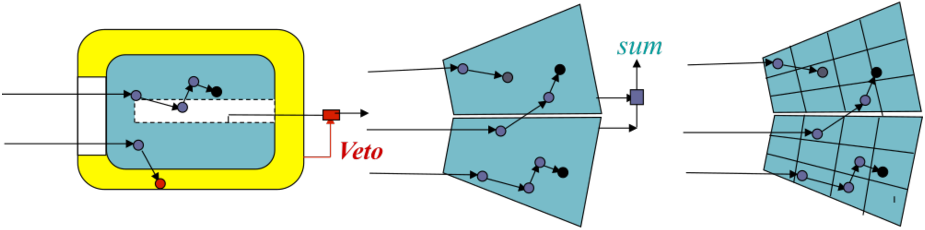
$\rightarrow$ ideally small detectors to minimize $\Delta\theta_\gamma$

decreasing effective detector size



Evolution of Ge detectors



$N \sim 100$
$N\Omega\varepsilon \sim 0.1$
limited efficiency,
suppressor cover space

$N \sim 1000$ (small)
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many detectors

$N \sim 100$ (large)
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with segmentation to
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- ideal: a 4π sphere of highly segmented Ge detectors
- allows to sum Compton events (instead of rejecting)
- signal decomposition for sub-segment position resolution
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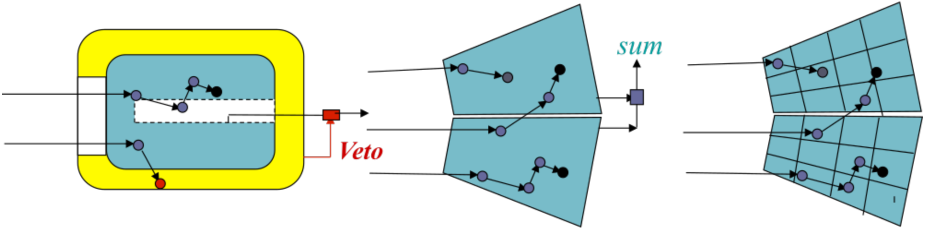

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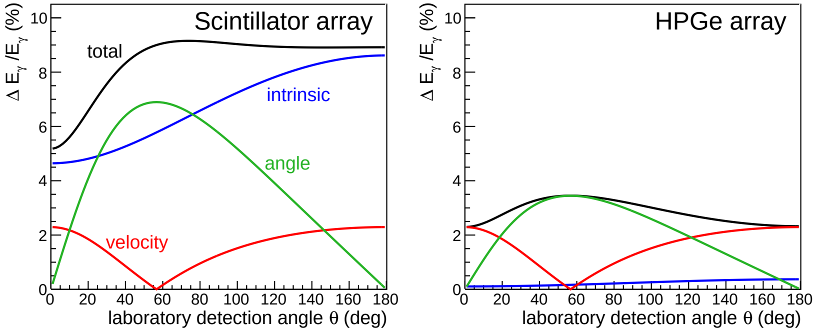
In-beam energy resolution

- depends on intrinsic resolution
- uncertainty from velocity (where in the target happened the reaction)

$$\left(\frac{\Delta E}{E}\right)_\beta = \frac{\cos\theta - \beta}{(1-\beta\cos\theta)(1-\beta^2)} \cdot \Delta\beta$$

- position resolution $\rightarrow$ signal decomposition and tracking

$$\left(\frac{\Delta E}{E}\right)_\theta = \frac{\beta\sin\theta}{(1-\beta\cos\theta)} \cdot \Delta\theta$$



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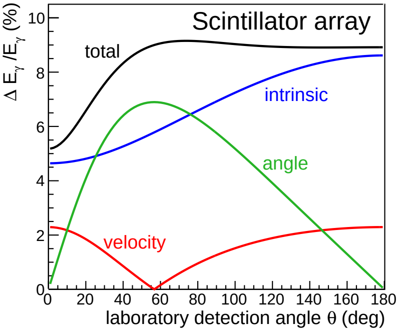
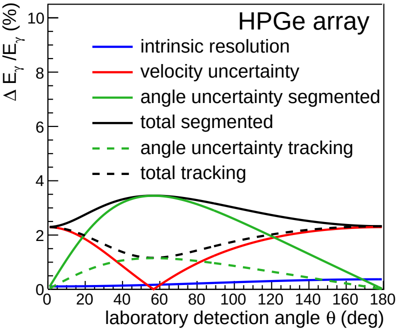
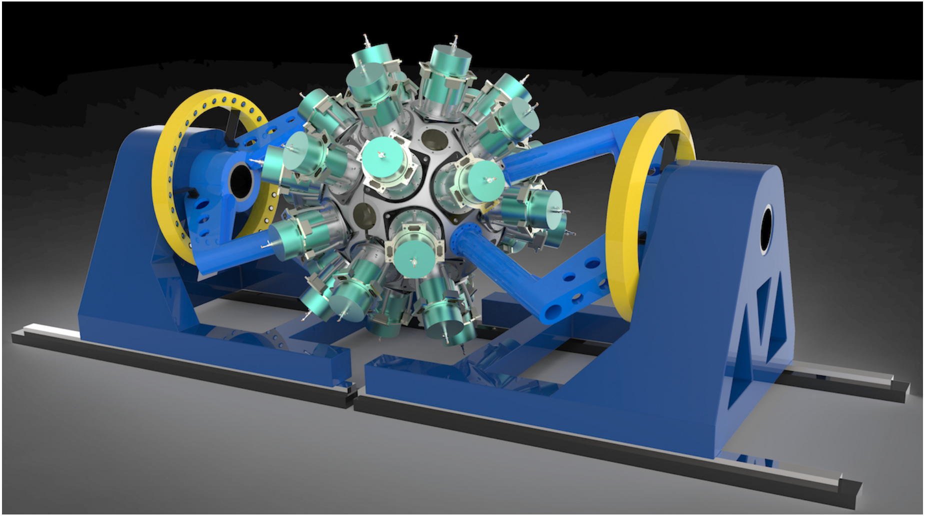


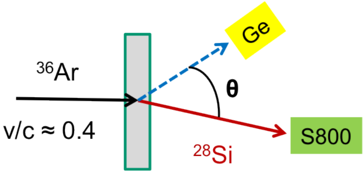


Gamma-Ray Energy Tracking Array

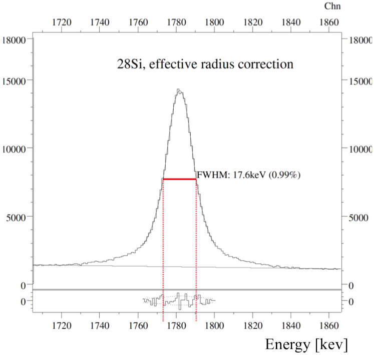


- GRETA: 4π array of 120 HPGe detectors with 36 segments each (USA)
- AGATA: Advanced GAmma Tracking Array in Europe

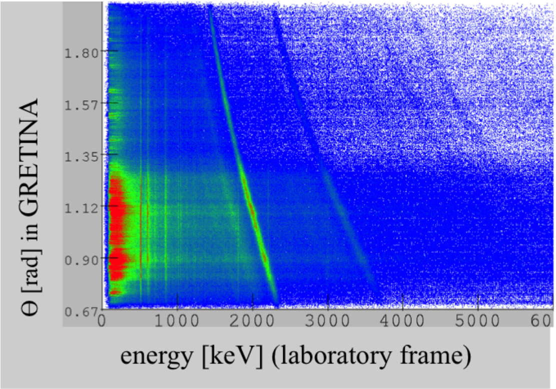
Example: GRETINA at NSCL



- ^{28}Si from ^{36}Ar on a 47 mg/cm^2 Be target
- $v = 0.38$ c
- measured FWHM 1.00 % meets expectations
- 2 mm position resolution



from D. Weisshaar et al.



How to measure the lifetime of an excited nuclear state

In-beam lifetime measurements

- excited states produced in the target decay in flight
- measure distance instead of time
- place a stopper a certain distance after the target
- two components to the spectrum: shifted (in-flight) and stopped

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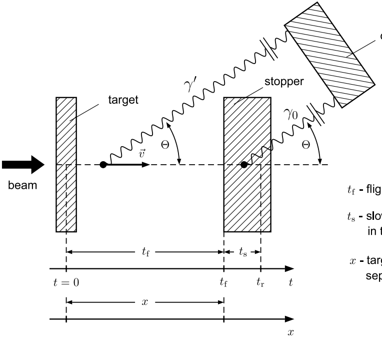

t_{f} - flight time

t_{s} - slowing-down time in the stopper

x - target-stopper separation

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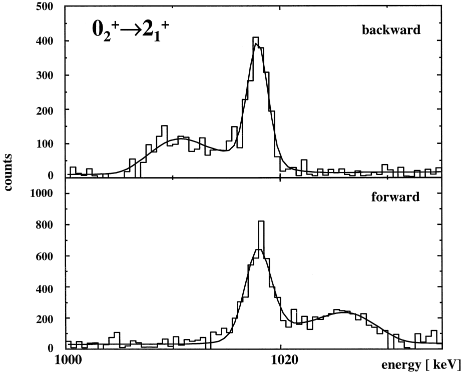

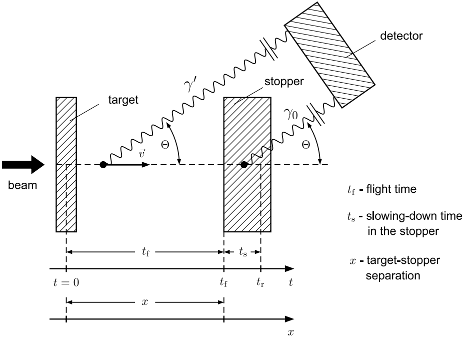

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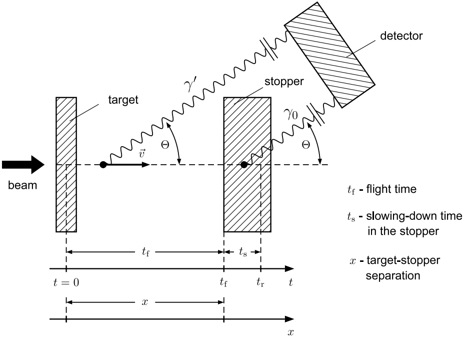
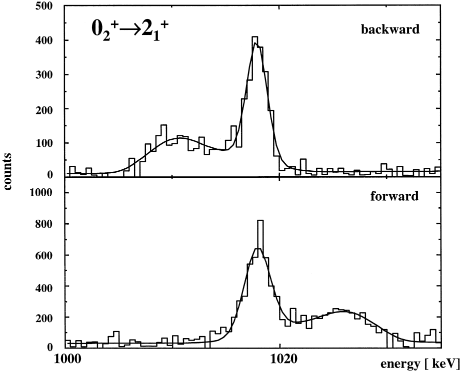
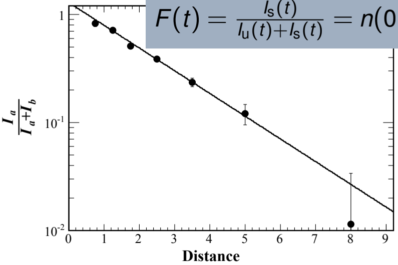


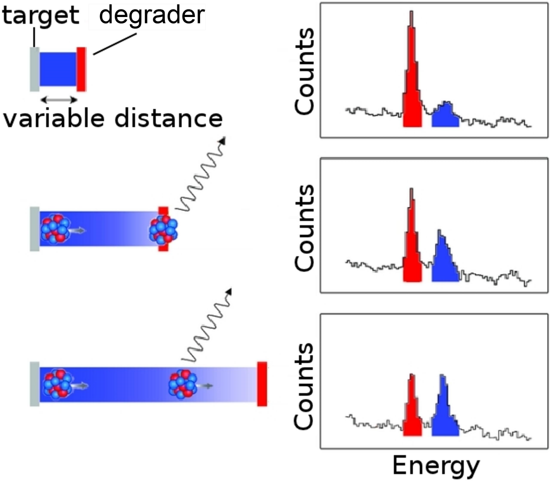


$$F(t) = \frac{I_s(t)}{I_u(t)+I_s(t)} = n(0)e^{-t/\tau}$$



With radioactive beams

- you do not want to stop the beam in your target chamber, this will create a lot of background from decay
- use a degrader instead of a stopper
  → only change velocity β
- two different emission velocities, two peaks in spectrum
- vary distance and measure the relative yields of the two peaks
  → decay curve → lifetime τ



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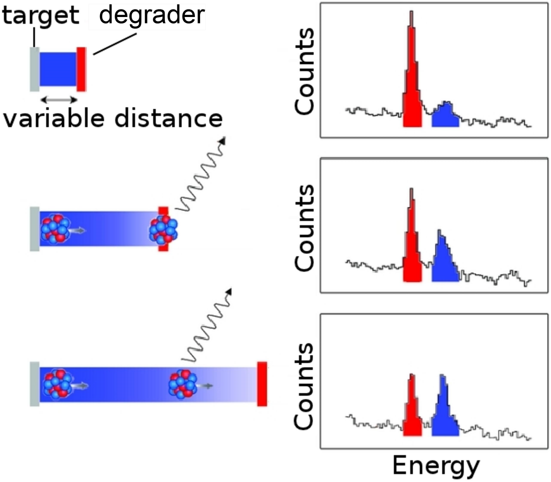

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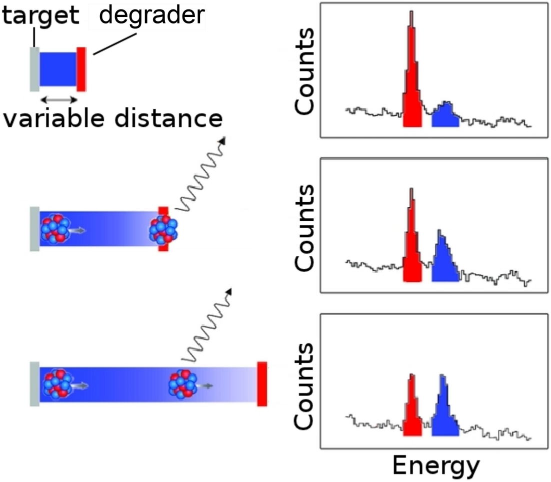

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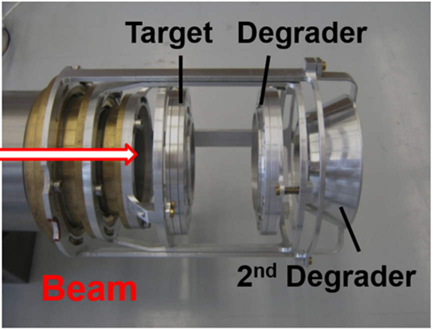

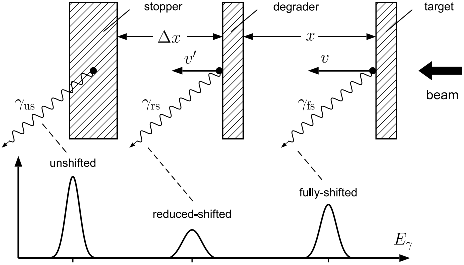

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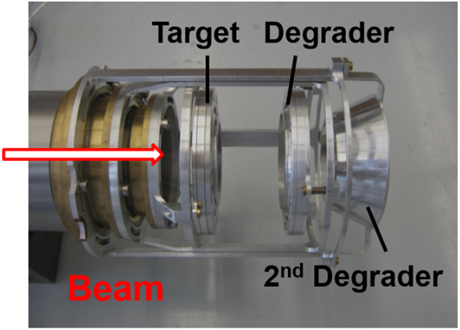
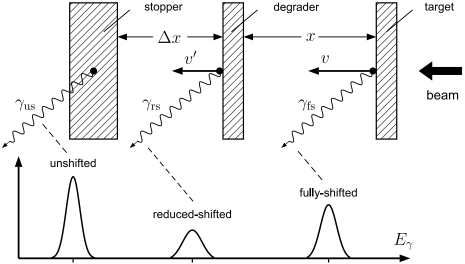
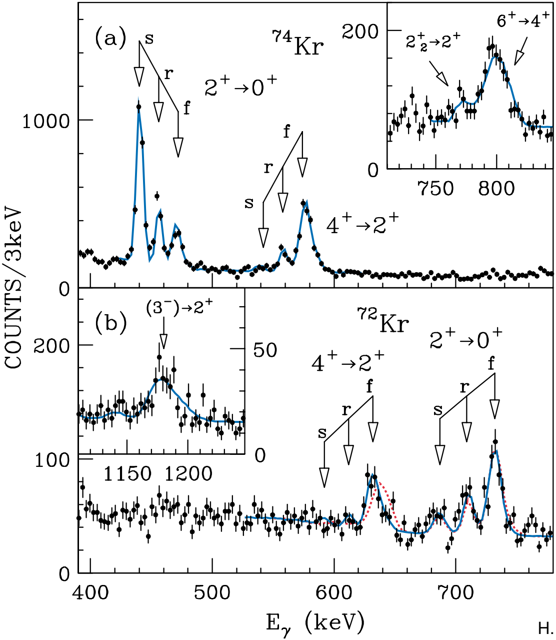
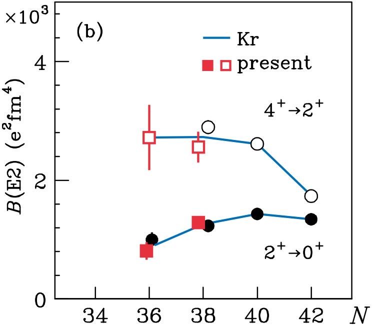




$$\tau = \left| \frac{\exp(-t/\tau)}{\frac{\mathrm{d}}{\mathrm{d}t}\exp(-t/\tau)} \right| \approx \frac{\Delta x}{v} \frac{I_s}{I_r}$$

Lifetimes in ^{72}Kr



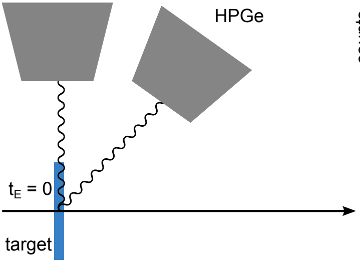


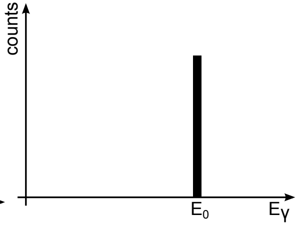
- short lifetime of 4^+ state in ^{72}Kr
  $\rightarrow$ large $B(E2;\ 4^+ \rightarrow 2^+)$
- indicates shape transition in the yrast band
  $\rightarrow$ oblate ground state, prolate for higher spins

H. Iwasaki et al., Phys. Rev. Lett. **112** (2014) 142502

Line-shape method

- method to extract level lifetimes without a degrader
- emission at target position → Doppler correction gives correct energy E_0





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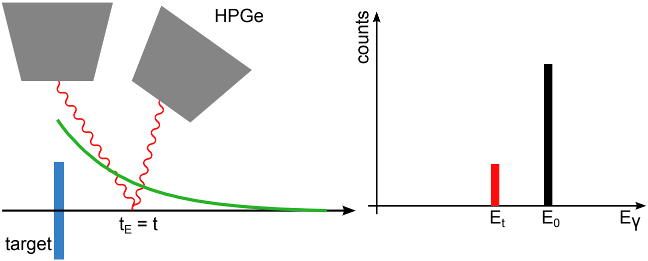

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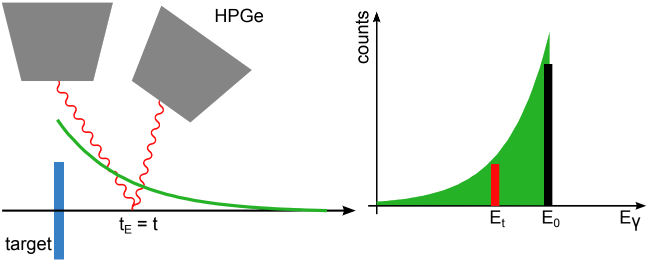

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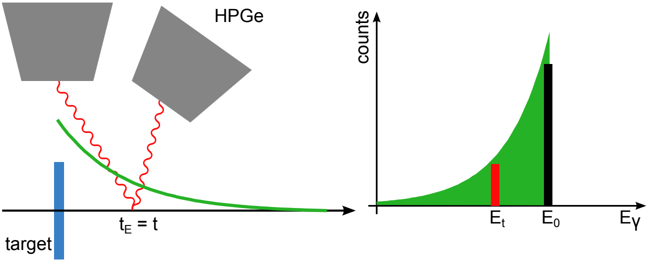

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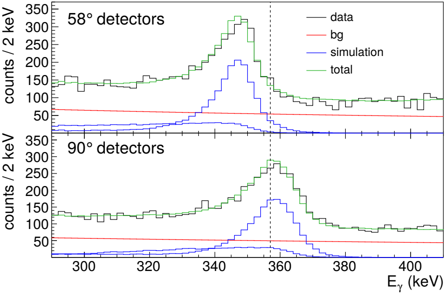

K. Wimmer et al., NSCL experiment.

- lifetime determination through χ^2 fit with simulation
- lifetime measurement at $N = Z = 38$: ^{76}Sr
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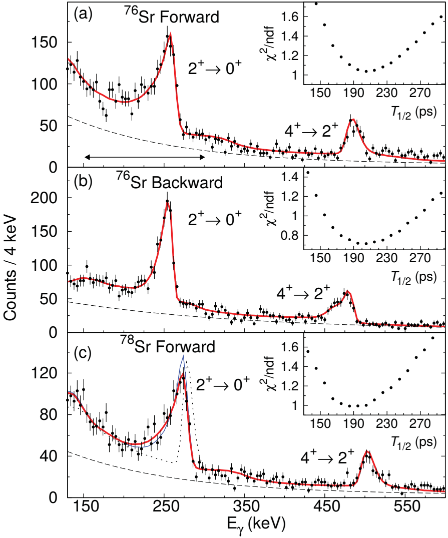

A. Lemasson et al., Phys. Rev. C **85** (2012) 041303.

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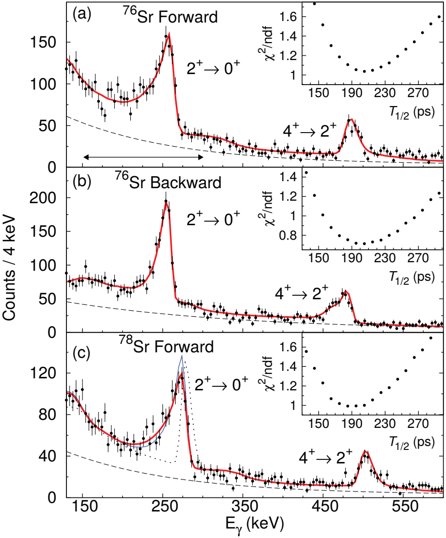

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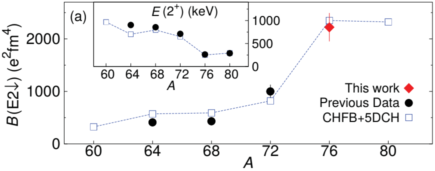

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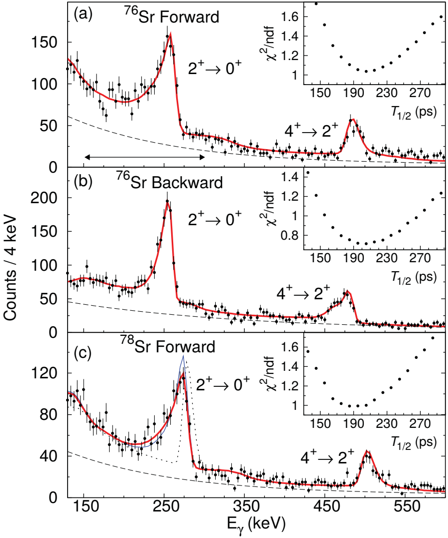

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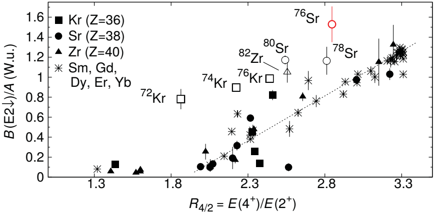
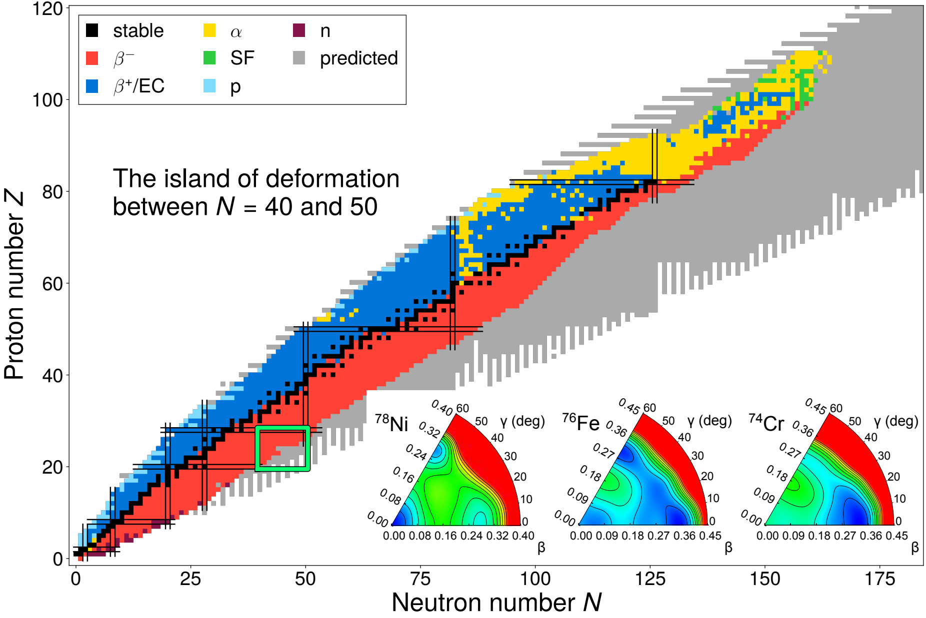


LISA:

LIfetime measurements with Solid Active targets

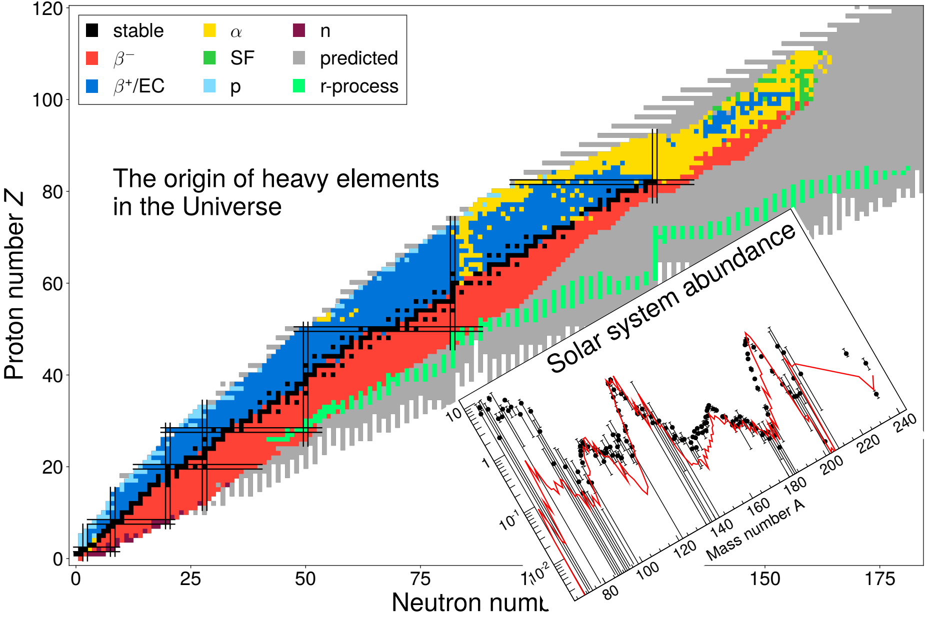
European Research Council
Established by the European Commission

Physics cases for LISA



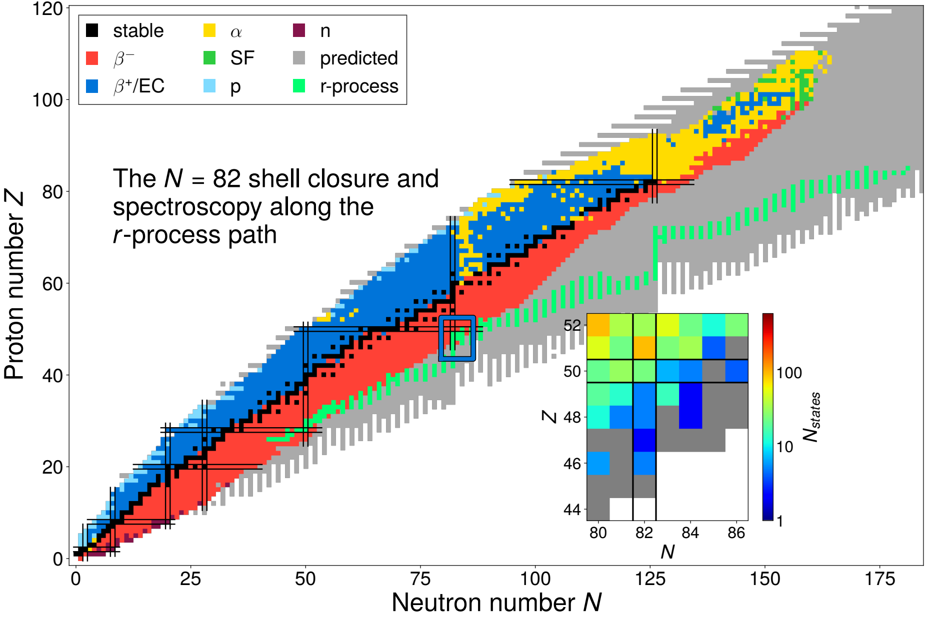
F. Nowacki et al., Phys. Rev. Lett. **117** (2016) 272501.

Physics cases for LISA



G. Lorusso et al., Phys. Rev. Lett. **114** (2015) 192591.

Physics cases for LISA



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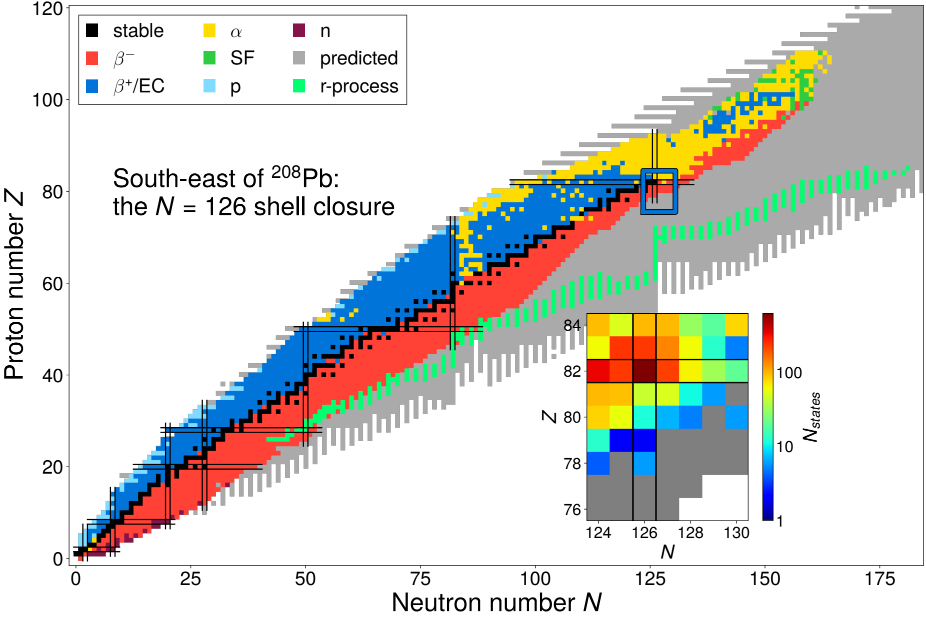

LISA concept

- γ rays emitted at a velocity β are subject to the Doppler effect

$$E_{\text{lab}} = E_0 \cdot \frac{\sqrt{1-\beta^2}}{1-\beta\cos\alpha}$$

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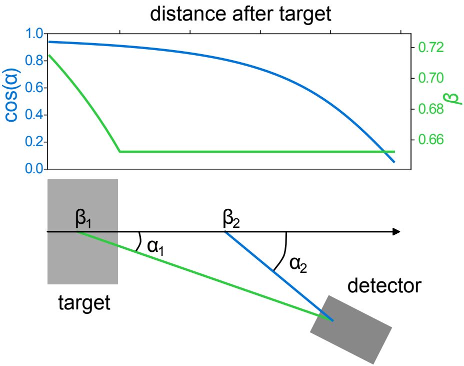

a finite lifetime affects both

- ejectile looses energy in target, smaller velocity β
- decay further downstream, emission at larger angle α

LISA concept

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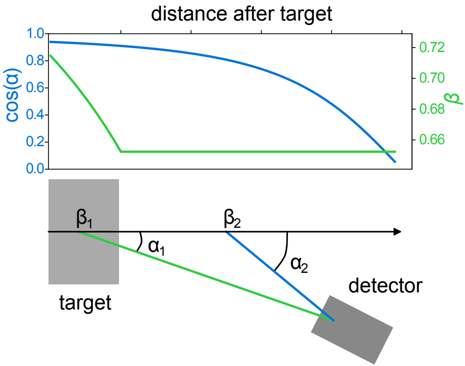
$$E_{\text{lab}} = E_0 \cdot \frac{\sqrt{1-\beta^2}}{1-\beta\cos\alpha}$$

- need to know velocity β and emission angle α to reconstruct transition energy E_0 from measured E_{lab}



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- ejectile looses energy in target, smaller velocity β
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→ change in Doppler reconstructed energy
→ sensitive to the lifetime of states

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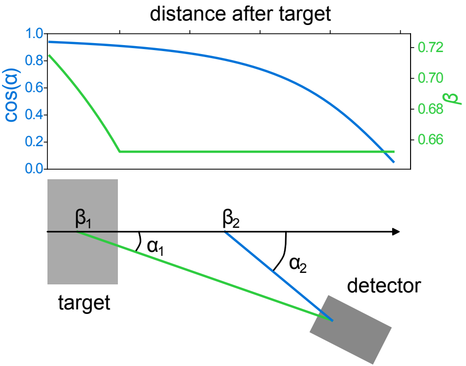

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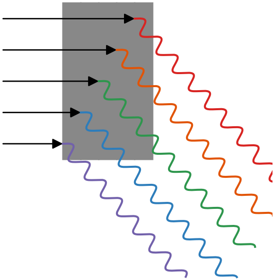
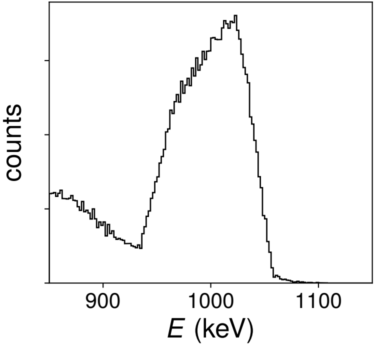
need very good energy and position resolution for γ rays

LISA concept

with the Advanced Gamma-ray Tracking Array AGATA, the achievable resolution is now given by the target ($\sim$g/cm^2 or few mm thick)

- reaction and emission at different velocities
- (angle dependent) spread in Doppler reconstructed spectrum
- different mean decay velocities and different depths in the target
- with an active target resolution can be greatly improved
- use proper position and velocity for Doppler reconstruction





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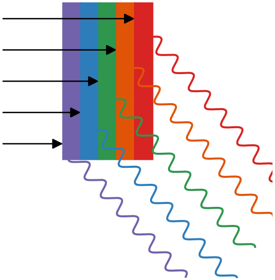

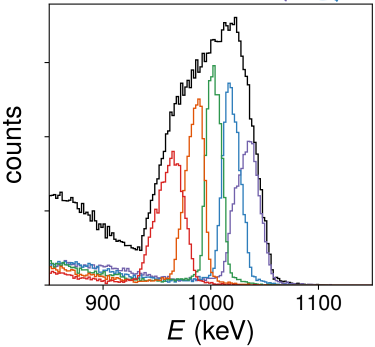

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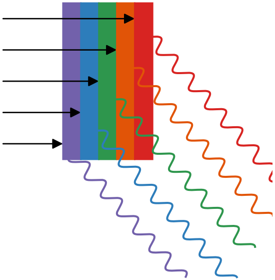

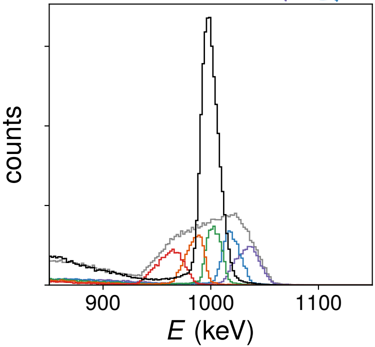

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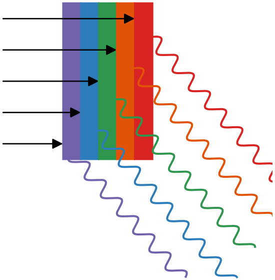
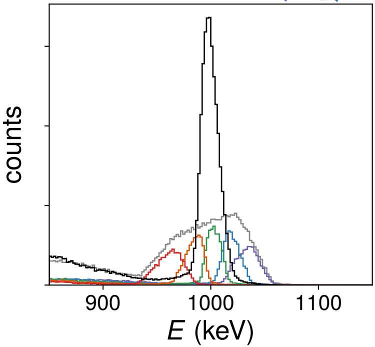
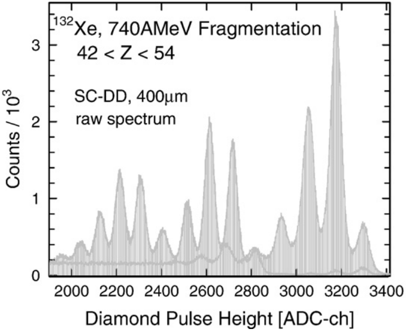




LIfetime measurements with Solid Active targets

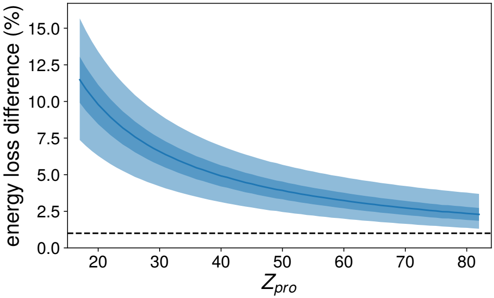
Active targets

- proton removal, change in $Z \rightarrow$ different energy loss
- with single-crystalline diamond a unique Z identification is possible



E. Berdermann et al., Dia. Rel. Mat. **17** (2008) 1159.

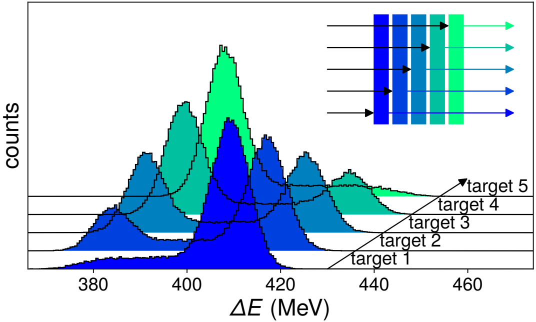
differential energy loss for proton removal at 200 and 800 *A*MeV



- required resolution for Z identification is few %
- new technology based on poly- and single-crystalline CVD diamond detectors

Active targets

- each layer measures the *Z*-dependent energy loss of the beam-like particles
- event-by-event *Z* identification in each layer

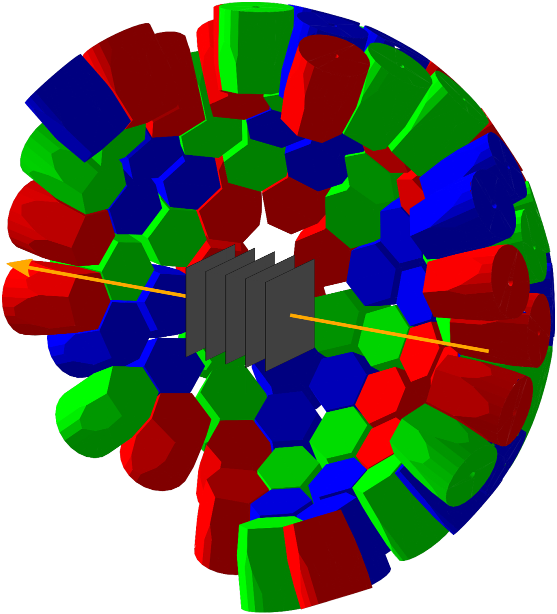


- proton removal reaction $\rightarrow$ change in *Z* and energy loss ΔE
- analysis with machine learning techniques
- simulation study: improved accuracy for layer identification from 70 to 90% for challenging cases compared to simple gating

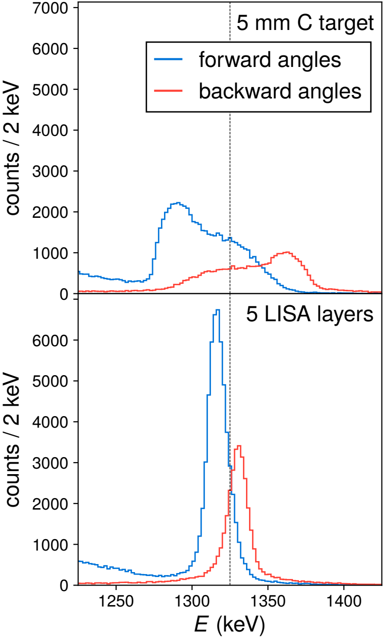
- Doppler-correction with position of reaction layer and corresponding velocity

match target position resolution to resolution of modern γ-ray tracking detectors for improved lifetime measurements

LISA and AGATA



An example: Collectivity of ^{130}Cd at $N = 82$



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- knockout from high-intensity ^{132}Sn beam
- assumption: 1 W.u. $\rightarrow \tau = 5$ ps
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- LISA improves resolution significantly (5 targets, equivalent thickness)
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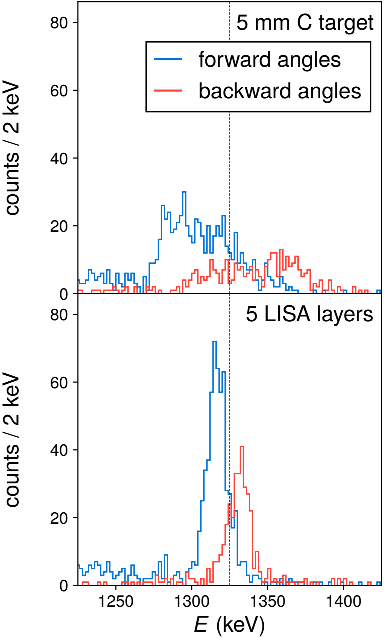

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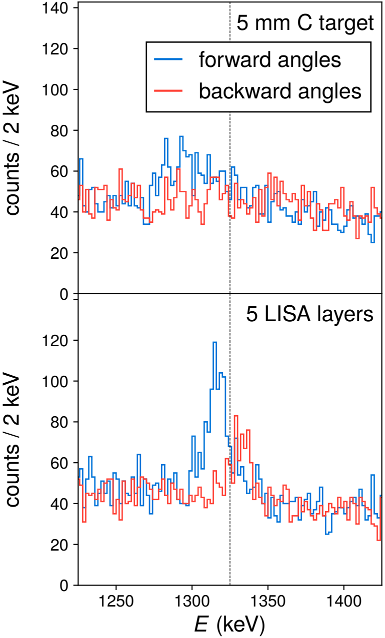

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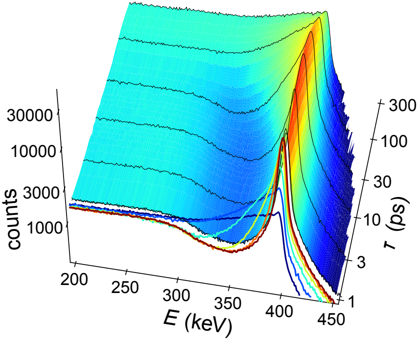
- lifetime measurements to explore collectivity in Islands of Inversion and shell closures in exotic nuclei



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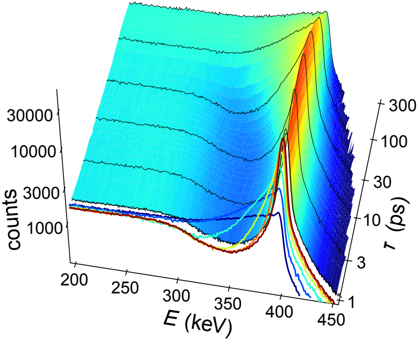

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Lots of opportunities for future experiments