Probing the island of inversion in heavy N=Z nuclei

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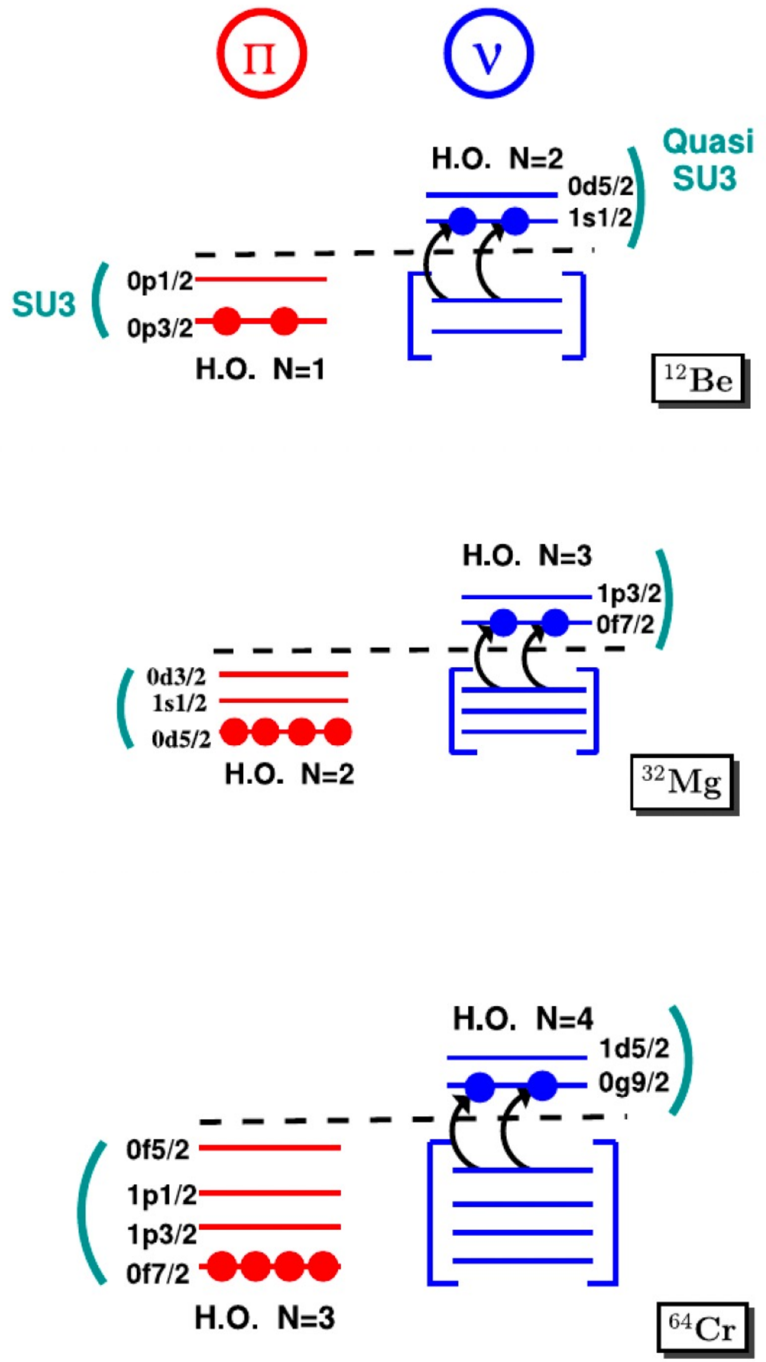
Development of deformation at N=8,20,40

- Experimental evidence of **shell structure with magic numbers - energy gaps:** to promote particles above the Fermi levels costs energy
- Some **intruders configurations** can overwhelm their loss of monopole energy with their **huge gain in correlation energy**
  - ^{12}Be, ^{32}Mg, ^{64}Cr: center of islands of inversion
- In exotic nuclei the effective nuclear interaction weight very differently proton and neutron interaction than they do at the stability line. Therefore leading in some cases to **the vanishing of established shell closures or to the appearance of new ones**



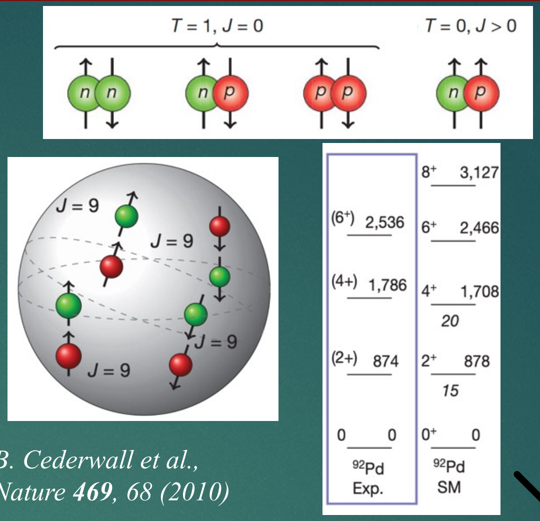
Physics Motivation

- N = Z nuclei play a special role
  - **(np) collectivity** by the proton-neutron interaction
  - **spatial overlap** of their respective wave functions at the Fermi surface
  - proton and neutrons act coherently.
- Competing **isoscalar np pairing** and normal isovector (T = 1, I = 0) pairing modes
  - a nuclear superfluid **analogous to "Cooper Pairs"** may exists in nuclei
  - Isoscalar correlations are predicted to be prominent in the ground states of heavier (A > 76) N = Z nuclei
  - Difficult to find a smoking gun signature
  - shell-model predict that **isoscalar pairing enhances collectivity → measurements of B(E2)**

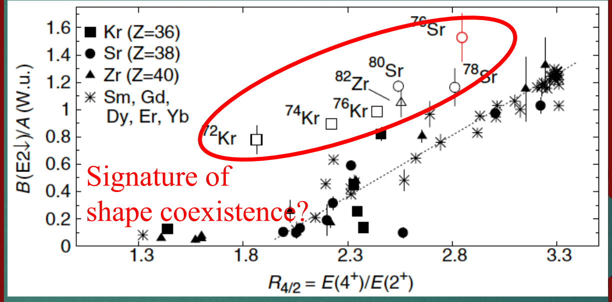
Physics Motivation

- The self-conjugate $N = Z$ nuclei
  - Proton-neutron correlations: role of np-pairing, …
  - Schematic way to understand the phenomena: Nilsson SU3 scheme, …

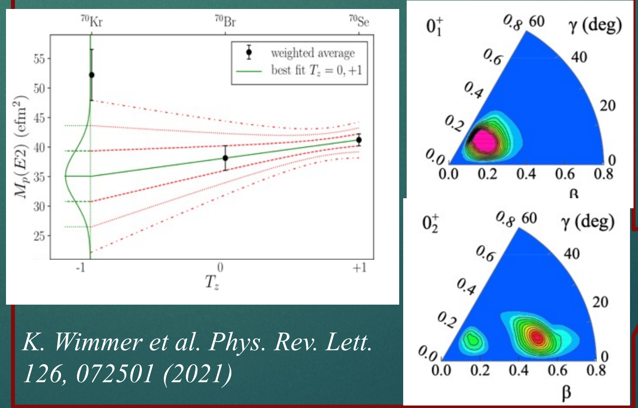
- A significant shape change has been anticipated among the medium-mass nuclides
  → **Competition between shapes is expected**



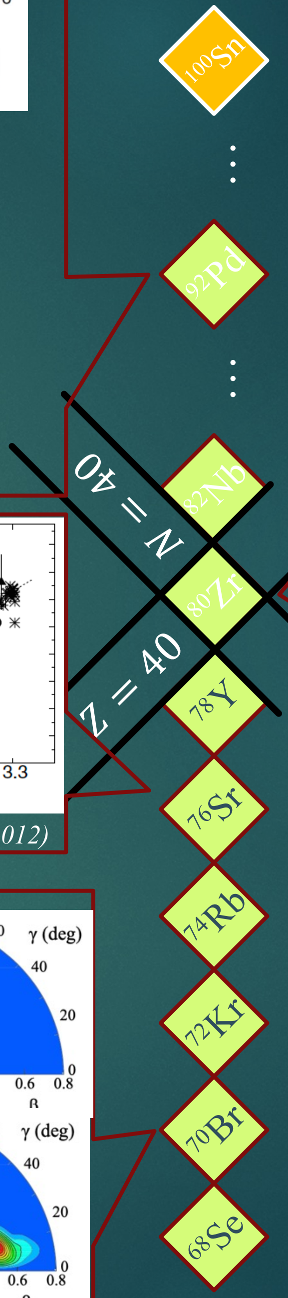
B. Cederwall et al., Nature **469**, 68 (2010)



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

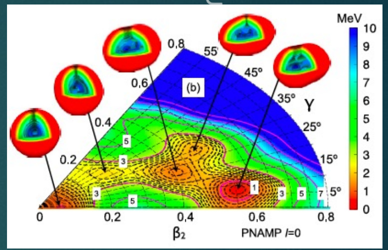


K. Wimmer et al. Phys. Rev. Lett. 126, 072501 (2021)



Multiple shape coexistence?

T. R. Rodríguez and J. L. Egido, Phys. Lett. B **705**, 255 (2011)



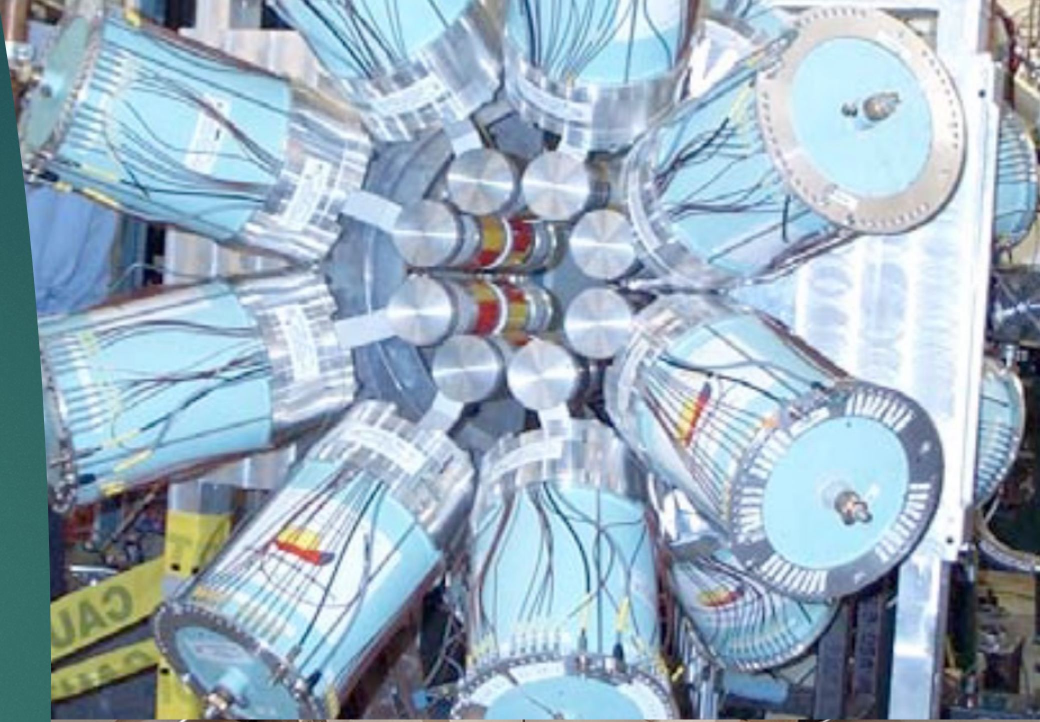
Maximum (prolate) deformation

Prolate-oblate shape coexistence

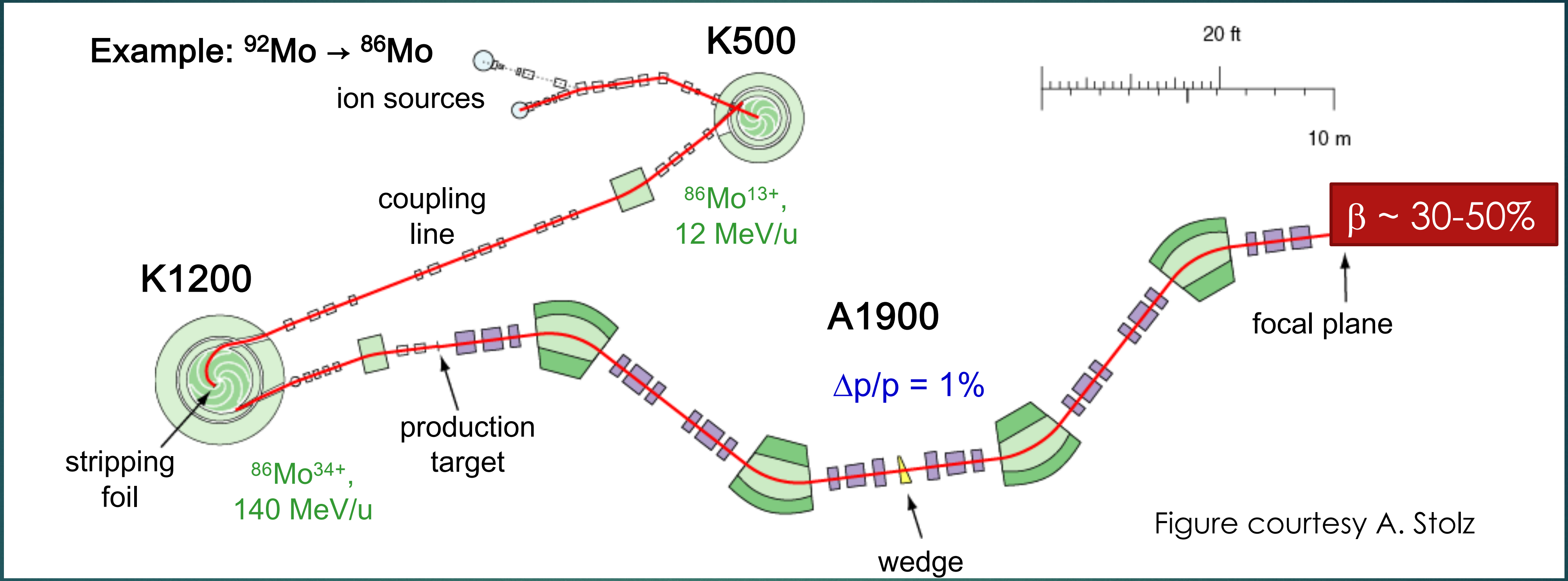
Oblate collectivity

Along N=Z at the NSCL facility

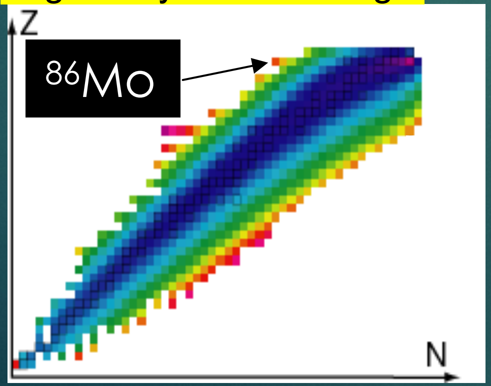
- ^{72}Kr
  - **First GRETINA campaign 2013-14**
  - **H. Iwasaki et al. Phys. Rev. Lett. 112, 142502 (2014)**
- ^{74}Rb: A. Lemasson
- ^{76}Sr
  - **Last SEGA campign ~2010**
  - **A. Lemasson Phys Rev C 85, 0041303(R) (2012)**
- ^{78}Y: R. D. O. Llewellyn
- ^{80}Zr
  - **Last GRETINA campaign at NSCL 2019-20**
  - **R. D. O. Llewellyn et al. Phys. Rev. Lett. 124, 152501 (2020)**



Secondary beams: fragmentation

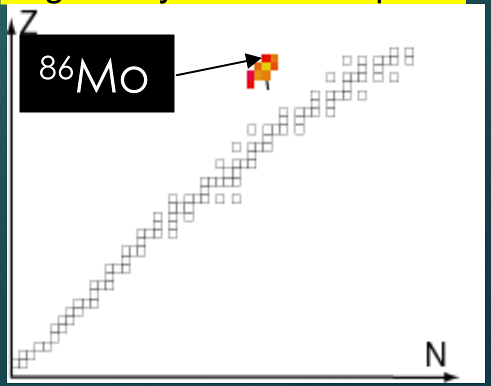


fragment yield after target



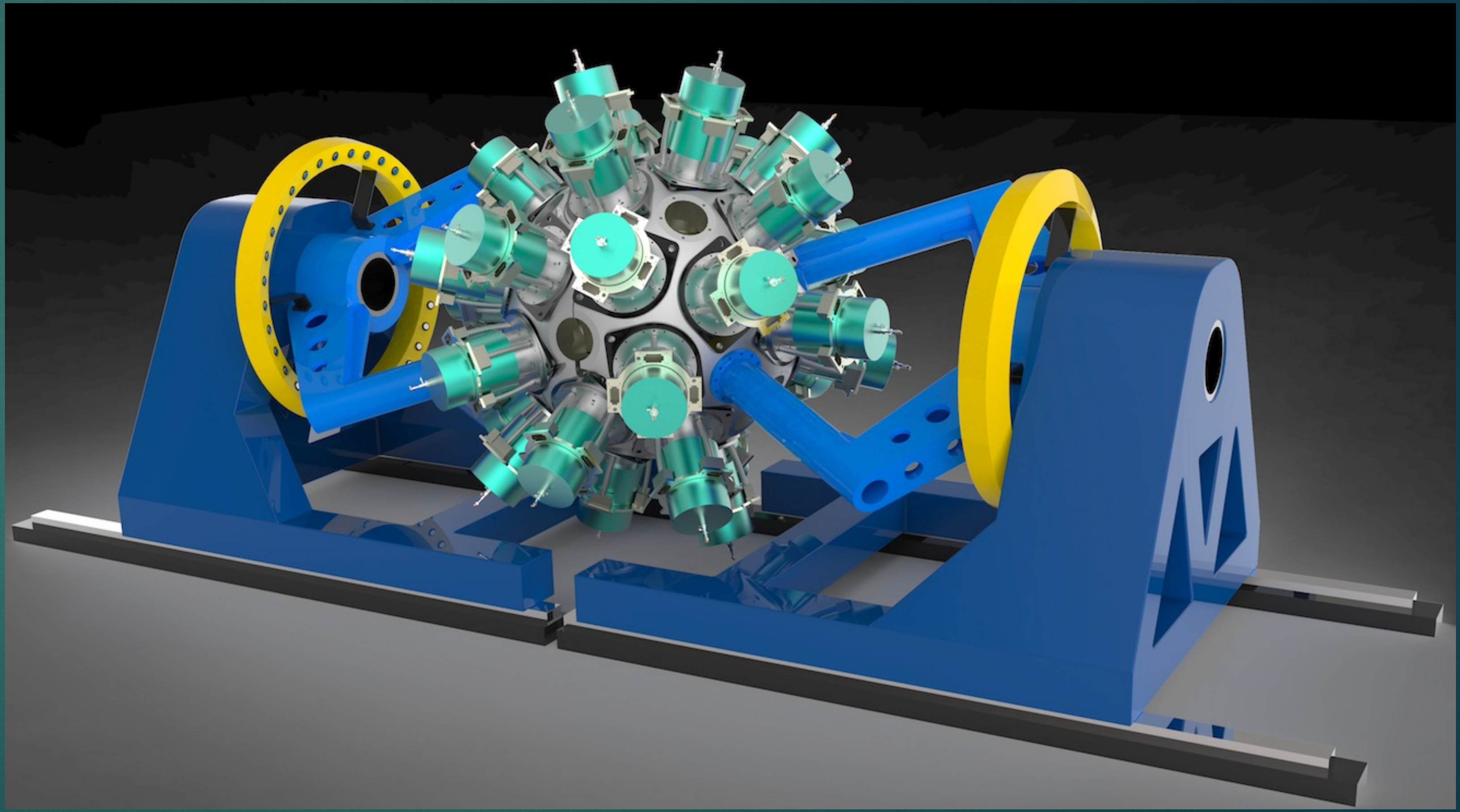
- Identification event-by-event
  - B – Rho
  - TOF

fragment yield at focal plane



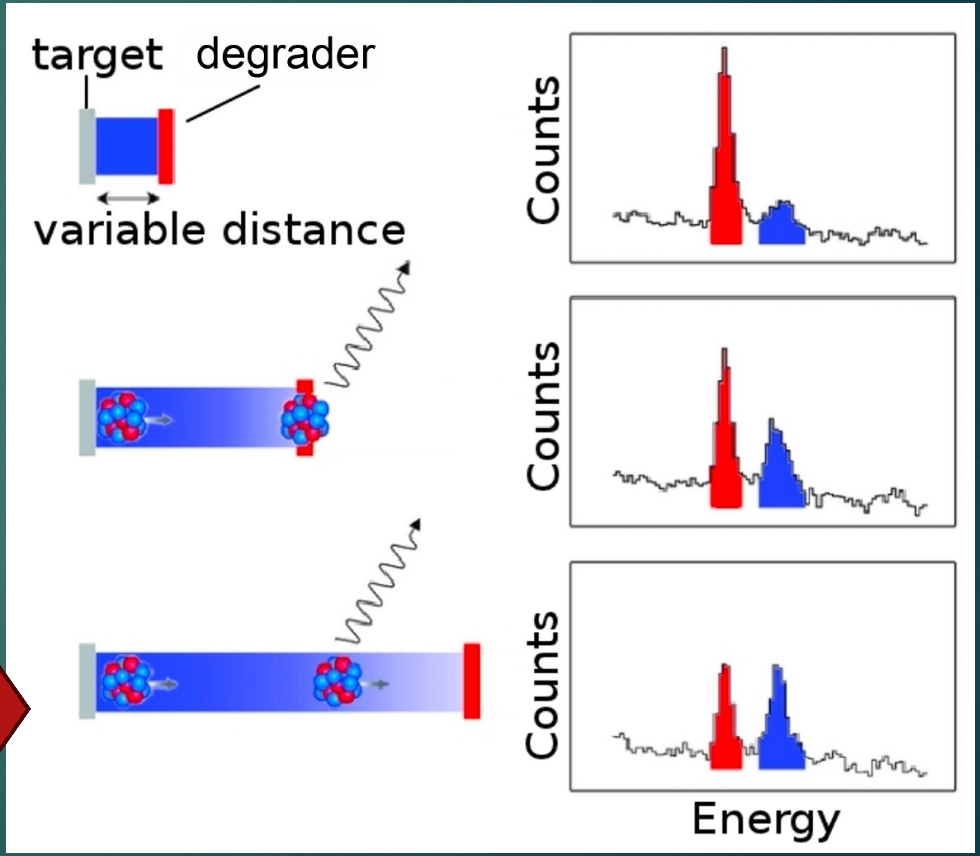
Gamma Ray Energy Tracking Array

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

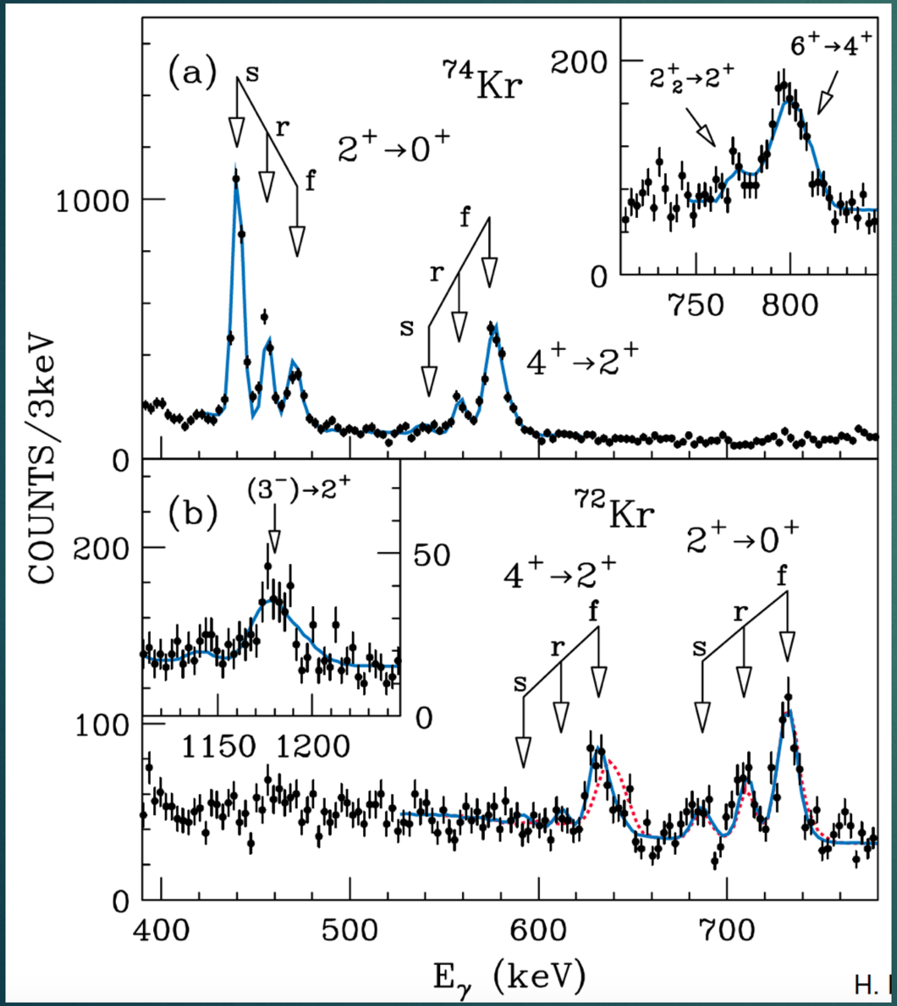


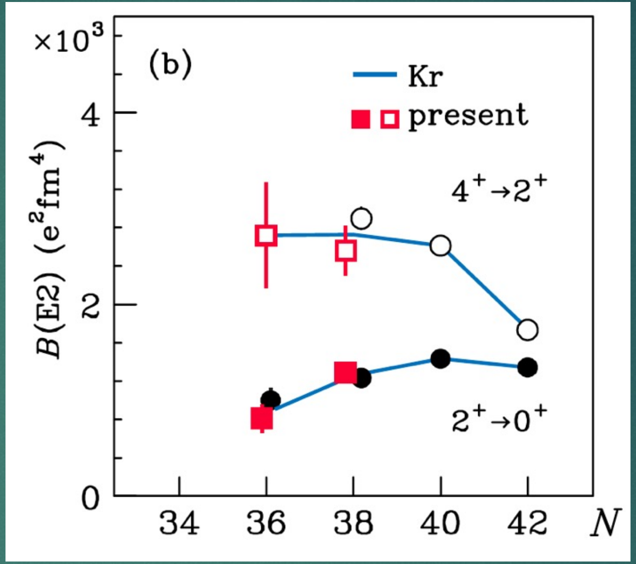
In-beam lifetime measurements .. with radioactive beams

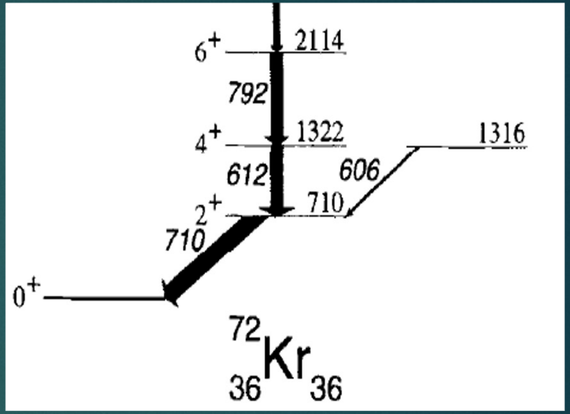
- the beam **intensity is low**, beam time is scarce
- use a **degrader instead of a stopper**→ residual nucleus can be identified event by event
- two different emission velocities, **two peaks** in spectrum
- Variations over distances to adapt to the lifetime(s) of interest



Lifetimes in ^{72}Kr : competition of deformations





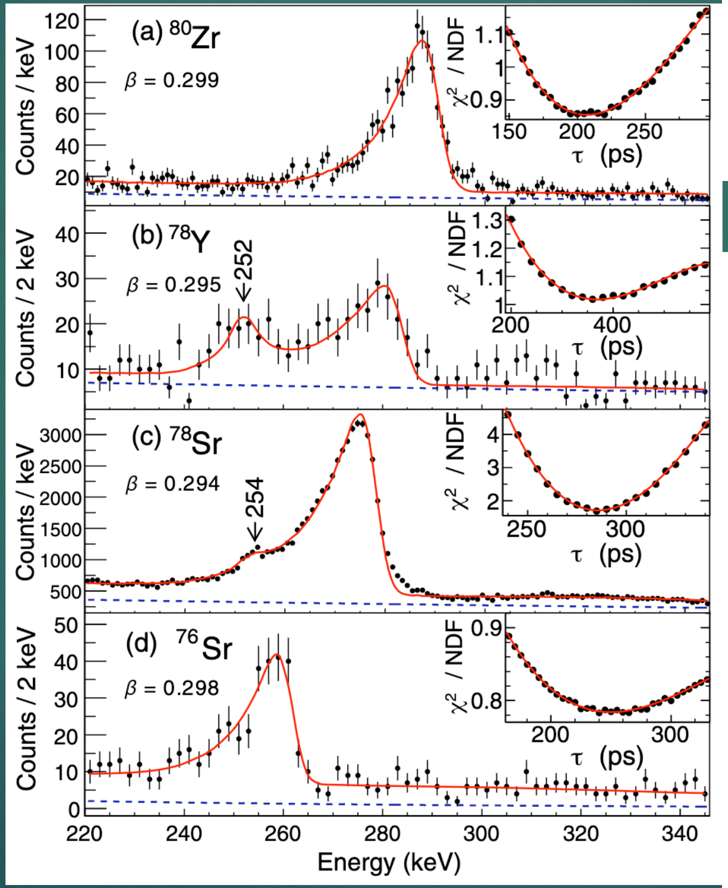


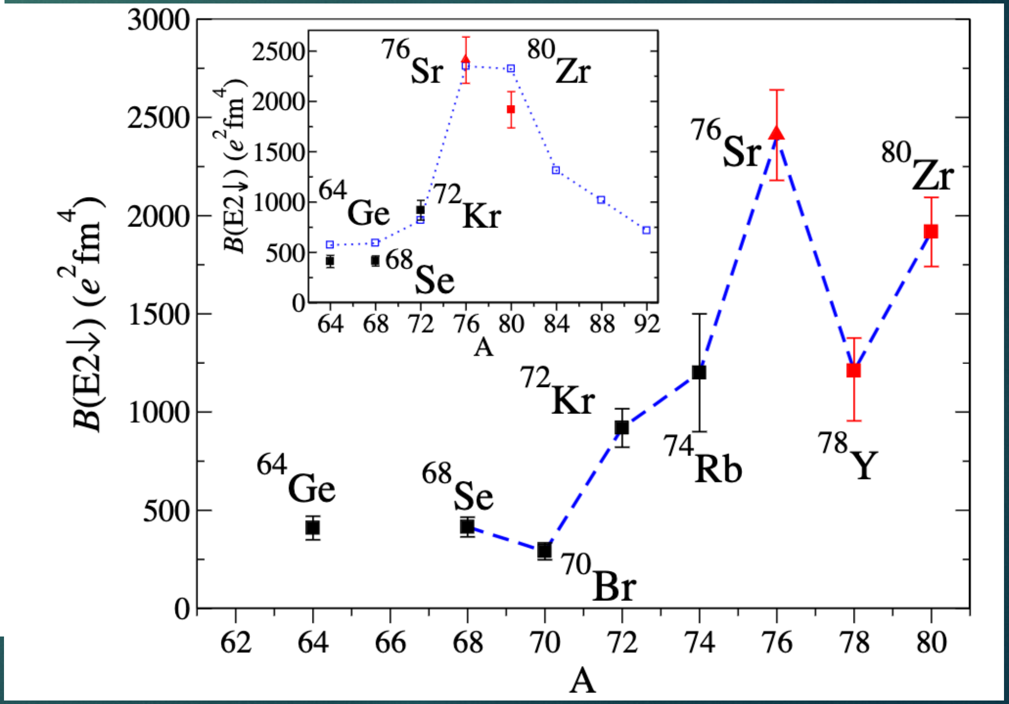
- short lifetime of 4^+ state in ^{72}Kr
  - large B(E2; $4^+ \rightarrow 2^+$)
- **shape transition next to the g.s.**
  - oblate ground state,
  - prolate for higher spins as suggested by LNL experiment that measured level spacing in 1997

Lifetimes extracted from lineshapes for ^{80}Zr and ^{78}Y

- **Very large quadrupole deformation**
  - **Maximum along N=Z**

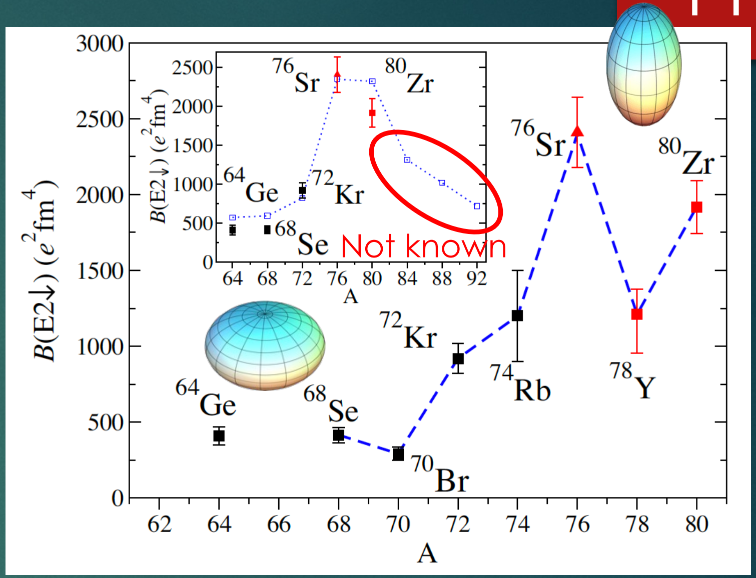
	$E(2^+)$	τ	$\tau_{prev,1}$	$\tau_{prev,2}$	τ_{avg}	$B(E2\downarrow)$
^{80}Zr	290.4(4)	207(19)				1910(180)
^{78}Y	283.6(8)	369^{+77}_{-54}				1200^{+180}_{-250}
^{78}Sr	278.1(3)	286(20)	276(39)[a]	224(27)[b]	266(15)	1840(100)
^{76}Sr	261.6(5)	250(44)	296(36)[a]		278(28)	2390(240)



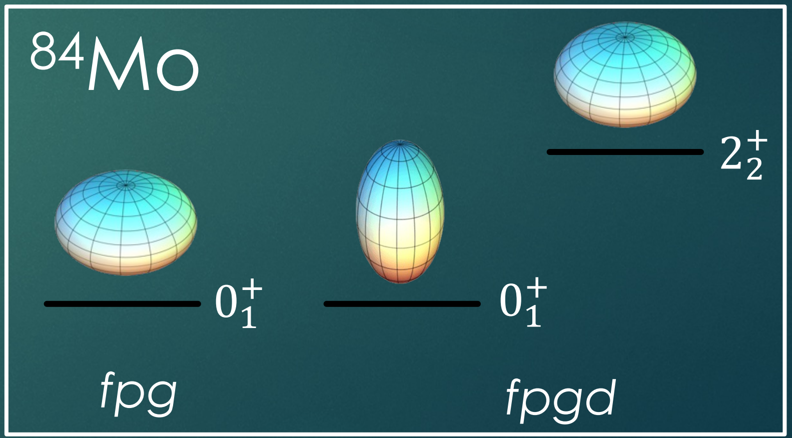


Physics Motivation

- Along $N = Z$: shape change **from oblate** (^{64}Ge, ^{68}Se) **to prolate** around ^{72}Kr
- Large deformation continues up to ^{80}Zr
- Then prolate or oblate??
- Shell model predictions for ^{84}Mo:
  - oblate, $\tau(2_1^+) = 75$ ps
  - prolate , $\tau(2_1^+) = 43$ ps

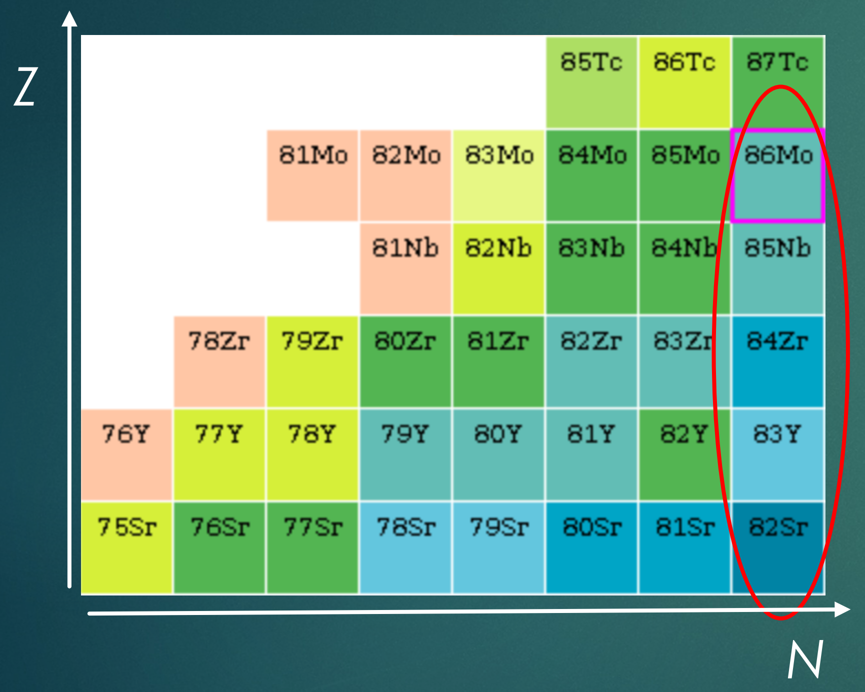


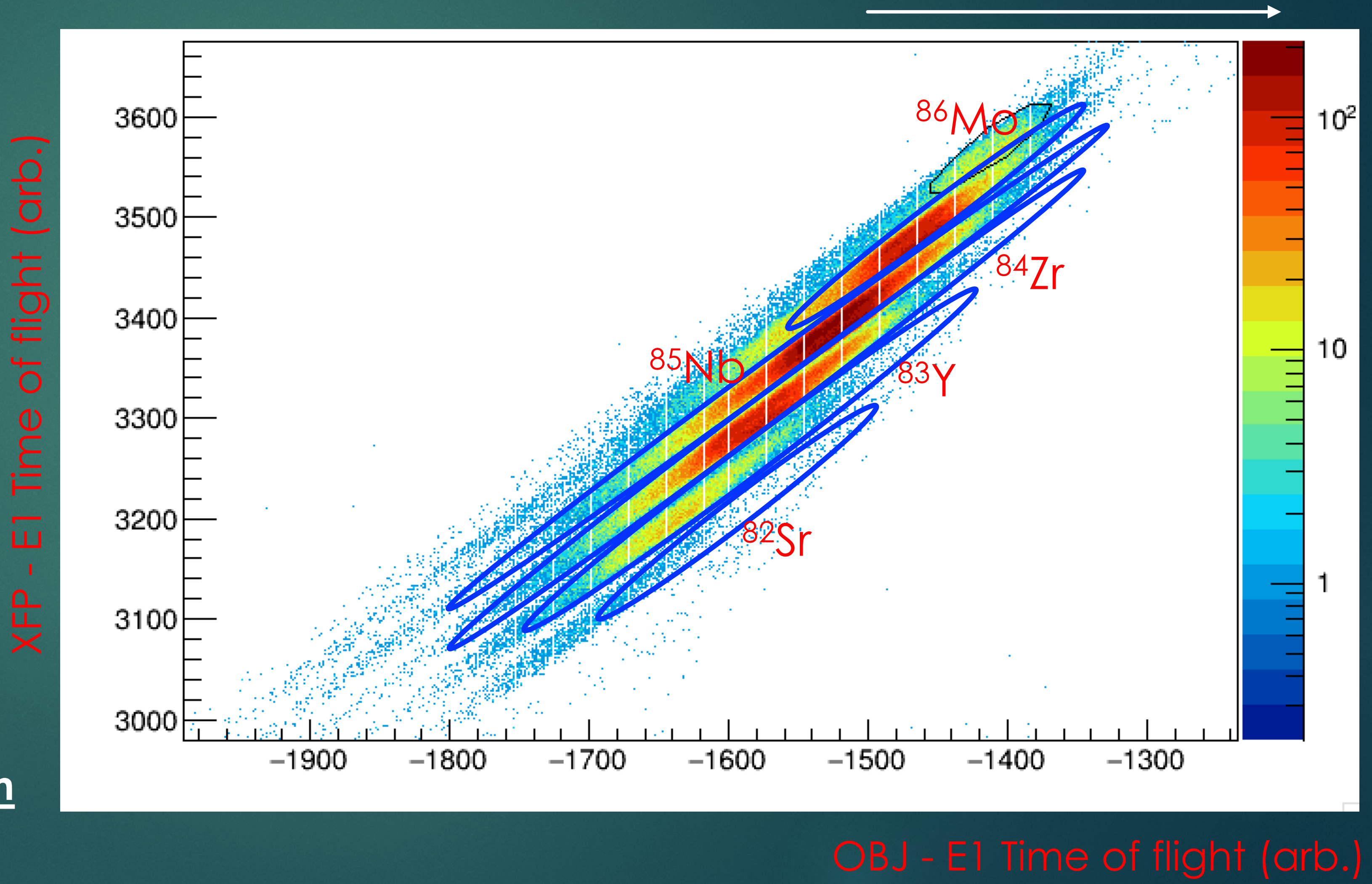
R. D. O. Llewellyn et al., Phys. Rev. Lett. ***124****, 152501 (2020)*



Incoming PID

[Selection of the incoming beam]

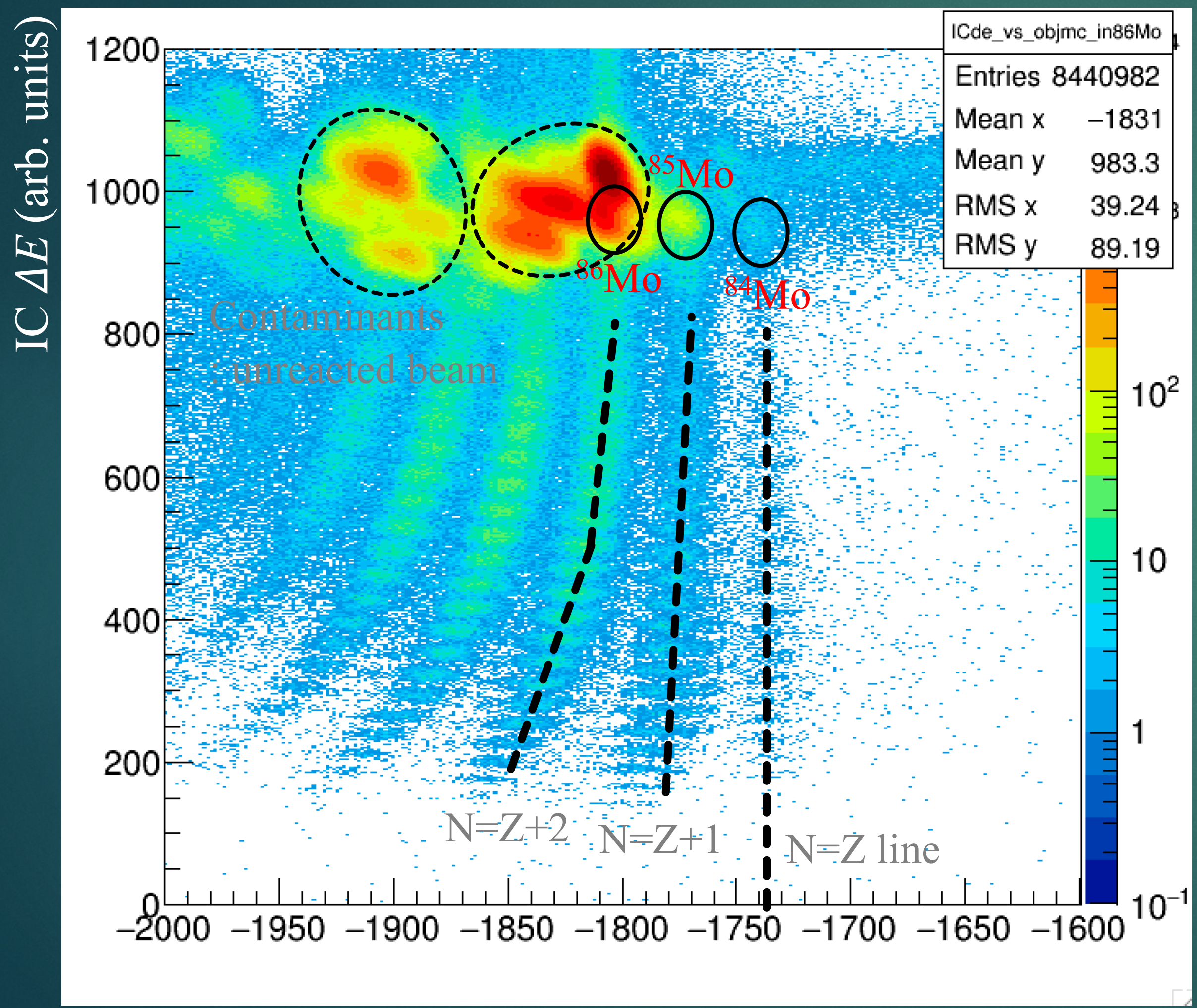


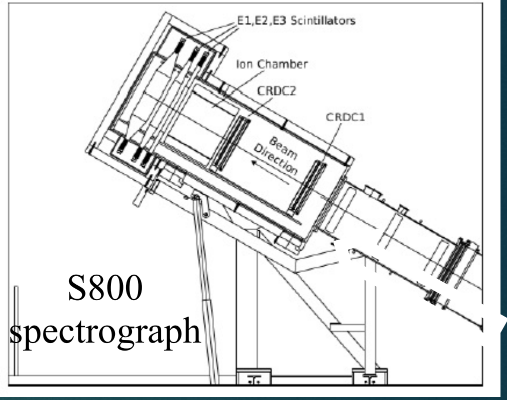


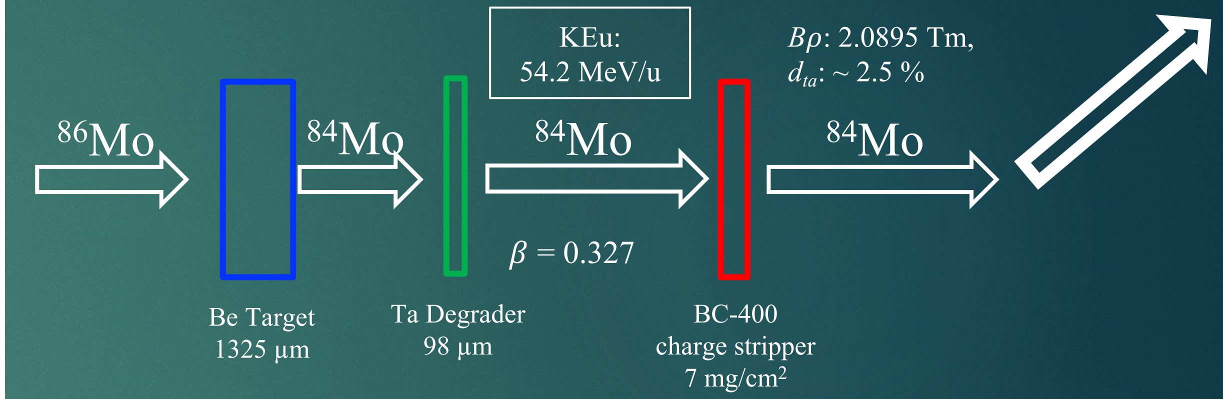
^{86}Mo was 0.8% of incoming beam

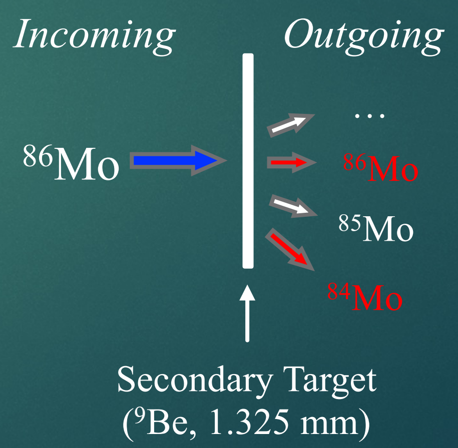
Analysis

[Outgoing beam PID plot for incoming ^{86}Mo beam]









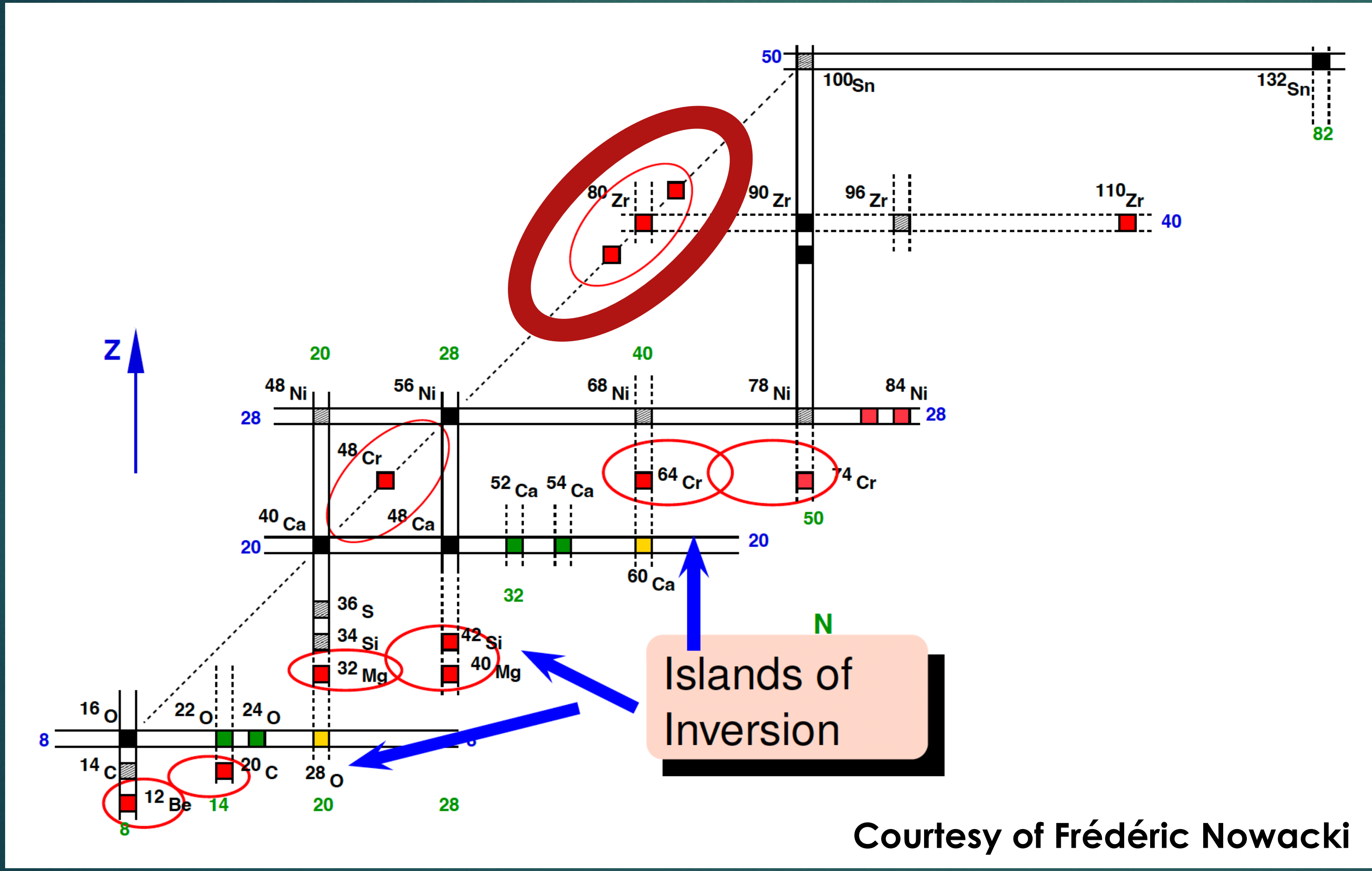
Comparison to full Monte Carlo

- The spatial and energy distribution of the secondary beam are reproduced in the **simulation**
- Strong **direct** population to 2^+
  - Residual population to 4^+ states that decays by a fast transition

Conclusion 1/2

- Advanced RIB Facilities and instrumentation allow progress
  - Measure collectivity by B(E2) along N=Z
  - New challenges for theoretical description of the B(E2) measured in the center of the $g_{9/2}$ shell
  - **Quadrupole correlations beyond expectations;** possible **triaxiality**... calculation still in progress
  - Shell model description: new region of deformation and **sharp transition between ^{84}Mo and ^{86}Mo**

Conclusion 2/2



- **Limit of past facilities is reached.** Looking forward for the new ones, FRIB
  - Heavier nuclei along N=Z: ^{88}Ru, ^{92}Pd, ^{96}Cd
  - odd-odd nuclides (^{82}Nb, ^{86}Tc, …) shape competition and coexistence

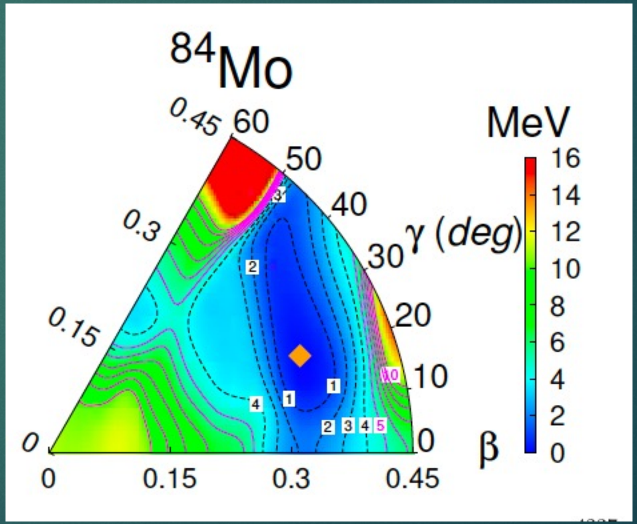
ONLY POSSIBLE THANKS TO:

Jeongsu Ha
Pablo Aguilera
Sara Carollo



WITH CALCULATIONS BY:

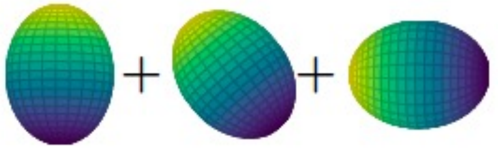
F. Nowacki
D. D. Dao
S. Lenzi
A. Poves



THE FULL NSCL COLLABORATION IS ACKNOWLEDGED

Generator Coordinate Method: $|\Psi_{\text{eff}}\rangle = \sum_i f_i |\Phi_i\rangle$

1) Deformed Hartree-Fock (HF) Slater determinants
2) Restoration of rotational symmetry
3) Mixing of shapes:

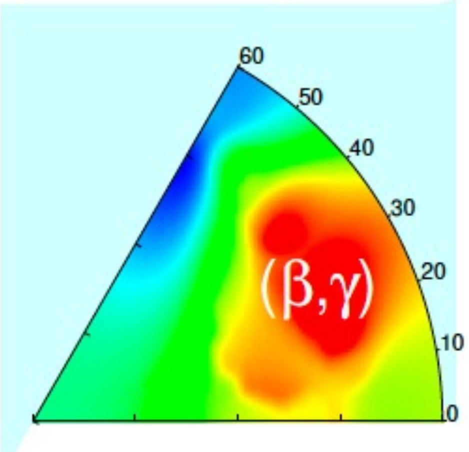
$|\Psi_{\text{eff}}\rangle =$  $\cdots$

Basis Truncation Method

? *choice of relevant deformed Hartree-Fock states*

- **E. Caurier's Minimization Technique**:

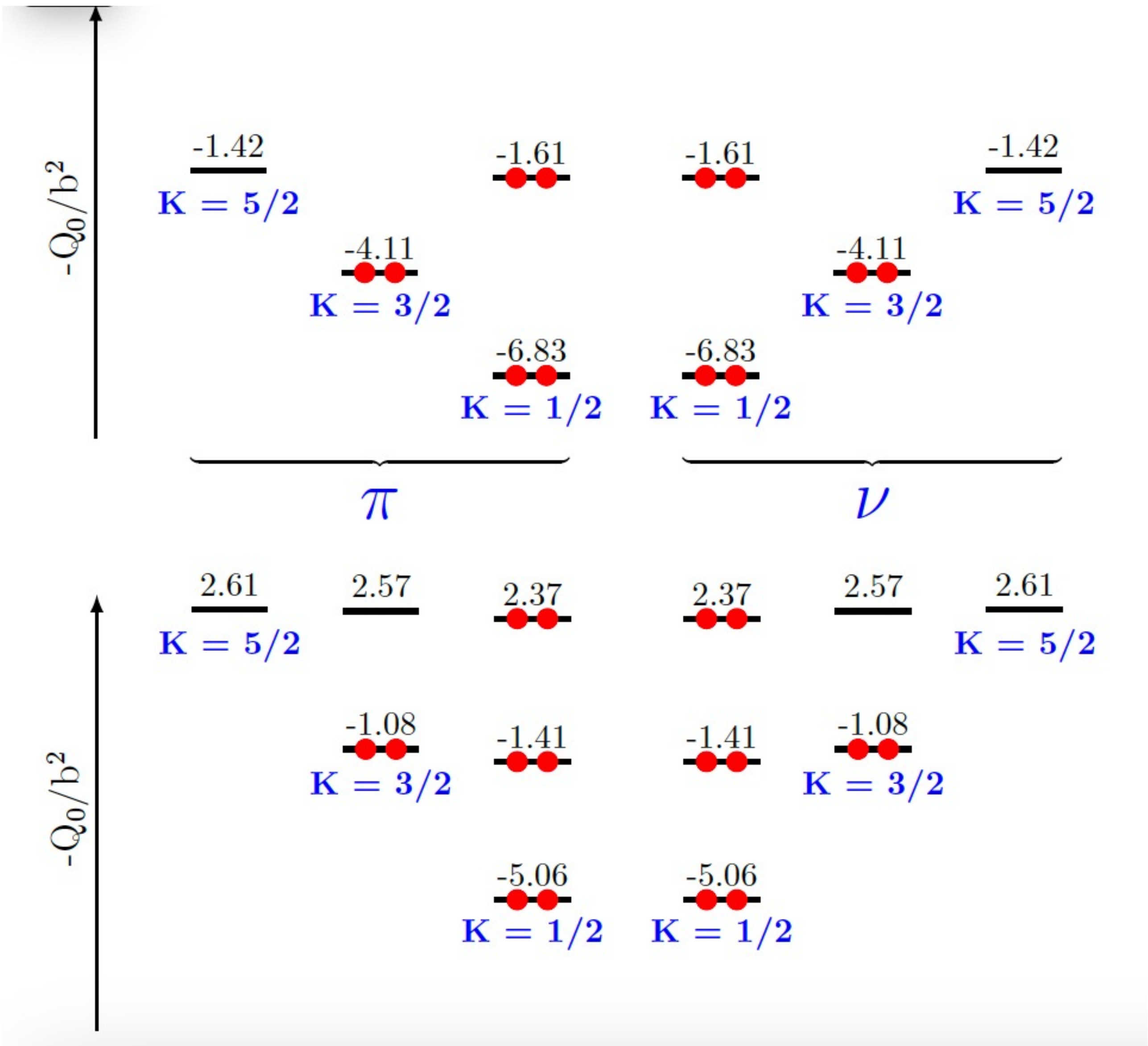
(E. Caurier, Proc. on GCM, BLG report **484** (1975))

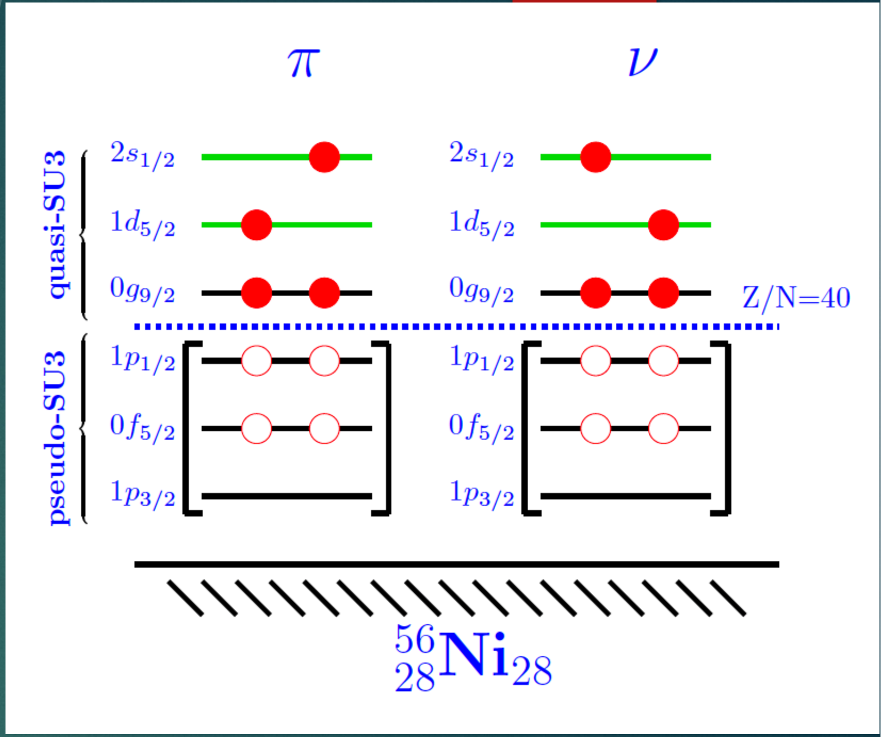


◇ Based on the variational principle

◇ Minimization of the energy of given states $\{J^\pi\}$

Courtesy of F. Nowacki





ZRP w/ ZBM interaction

A. P. ZUKER, B. BUCK, AND J. B. MCGRORY, PHYS. REV. LETT. 21, 39 (1968);