



# Experimental Nuclear Physics I

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2 July 2026



**MICHIGAN STATE**  
UNIVERSITY

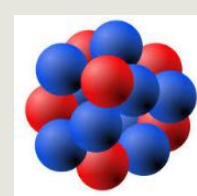


U.S. DEPARTMENT  
*of* **ENERGY**

Office of  
Science



# Complexity vs Simplicity



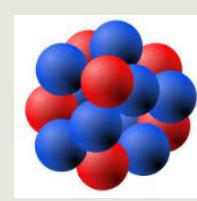
Nuclei are governed by very **‘complicated’** strong force, while nuclei exhibit surprisingly **‘simple’** and **‘beautiful’** patterns such as shell structure and rotational bands.



**Nuclei** ~60% of the volume is occupied  
nucleon moves at 10~20% speed of light  
structure is governed by the strong force

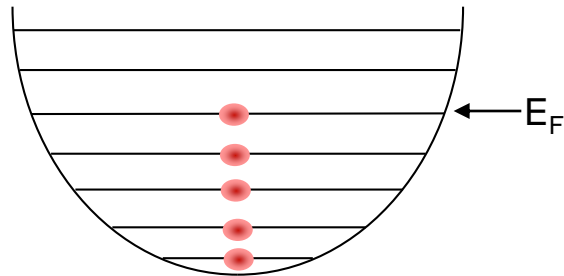


# Complexity vs Simplicity

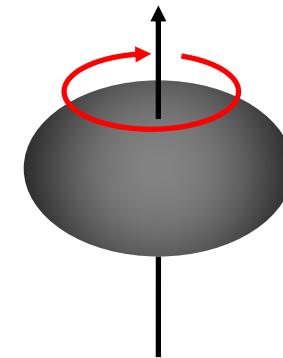


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individual nucleon motion (shell structure)

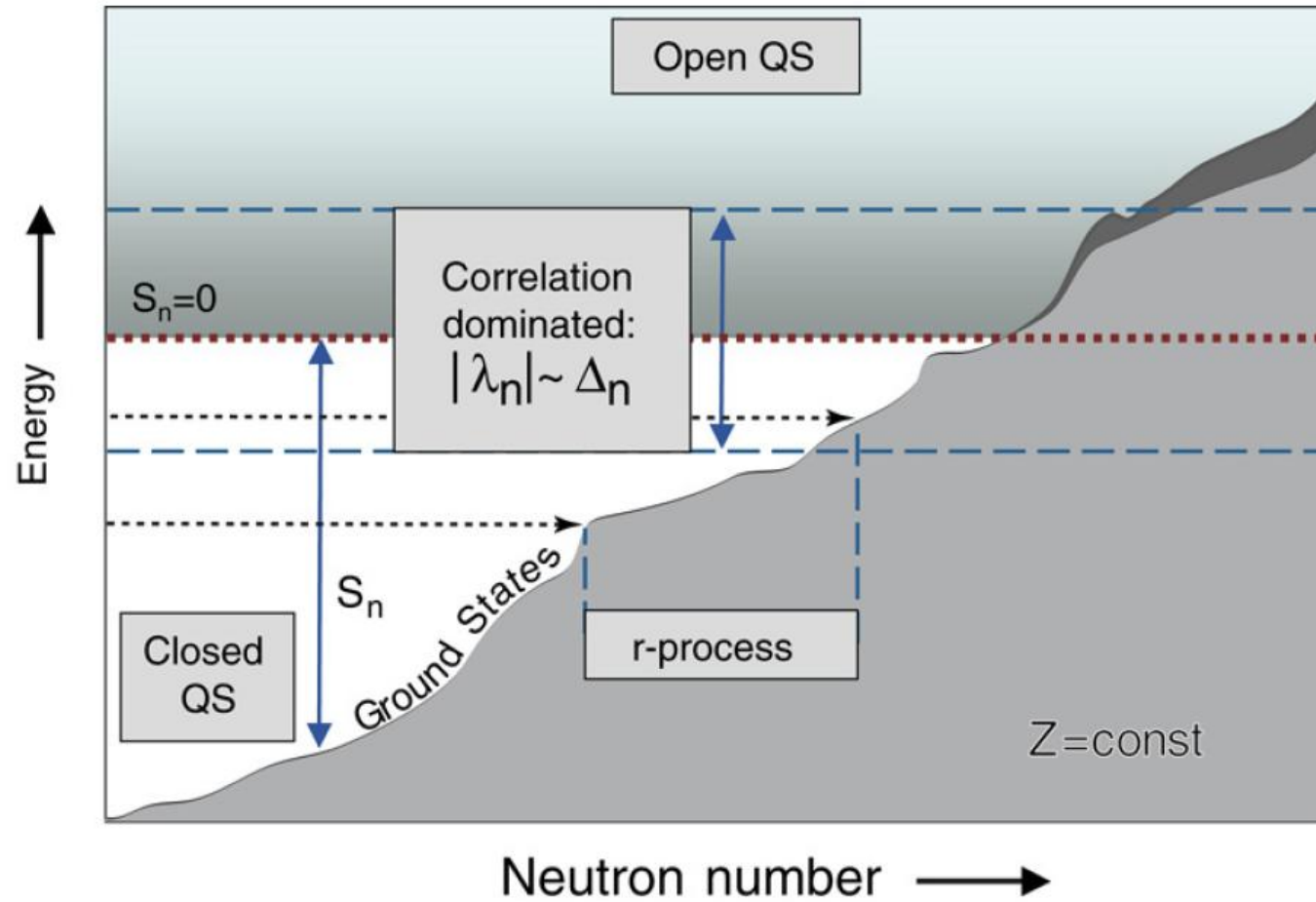


collective nuclear behavior

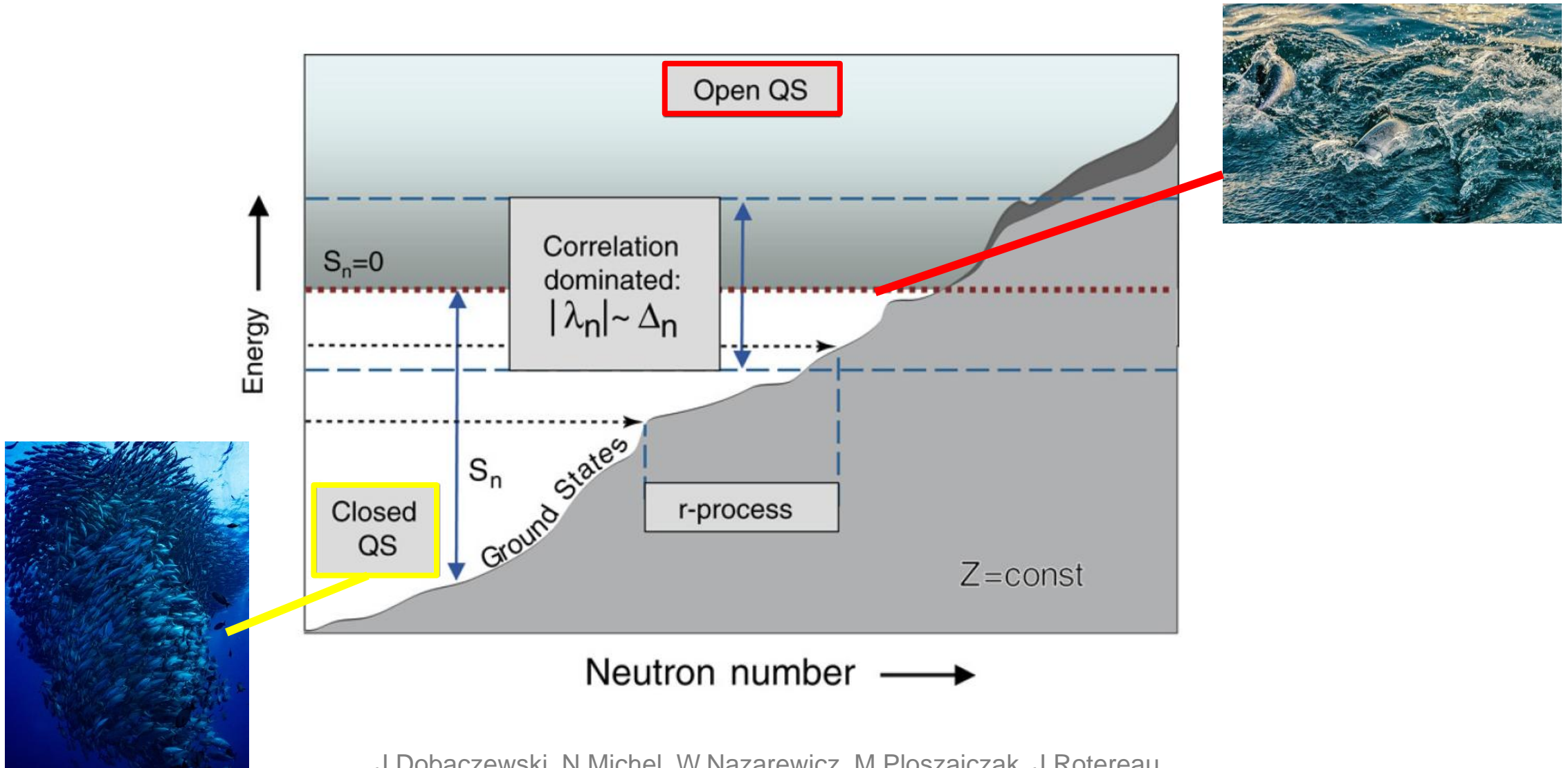


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# Weakly-bound Nuclei as Open Quantum System



# Weakly-bound Nuclei as Open Quantum System



J.Dobaczewski, N.Michel, W.Nazarewicz, M.Ploszajczak, J.Rotureau,  
Prog. Part. Nucl. Phys. 59, 432 (2007)

# Overarching questions in nuclear physics

**U.S. Department of Energy Office of Science Office of Nuclear Physics mission is accomplished by supporting scientists who answer overarching questions in major scientific thrusts of basic nuclear physics research**

**Science Drivers from the National Research Council (NRC)  
Rare-Isotope Science Assessment Committee (RISAC)**

**Nuclear Structure**

**Nuclear Astrophysics**

**Tests of  
Fundamental Symmetries**

**Applications of Isotopes**

**Intellectual challenges from 2013 NRC Decadal Study and the 2015 NSAC Long Range Plan**

How does subatomic matter organize itself and what phenomena emerge?

How did visible matter come into being and how does it evolve?

Are fundamental interactions that are basic to the structure of matter fully understood?

How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

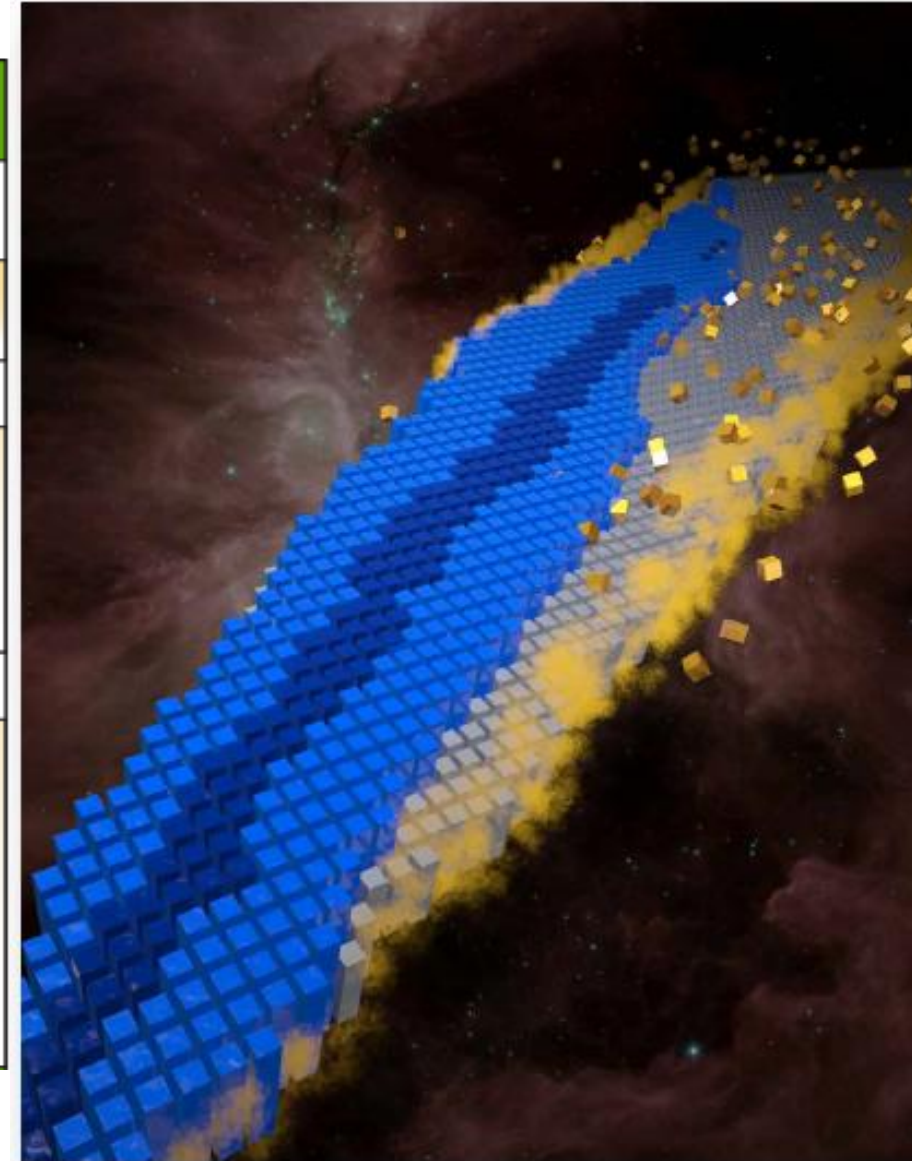
**Specific questions included in the challenges**

What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?  
  
What is the origin of simple patterns in complex nuclei?

What is the nature of neutron stars and dense nuclear matter?  
  
What is the origin of the elements in the Cosmos?  
  
What are the nuclear reactions that drive stars and stellar explosions?

Why is there now more matter than antimatter in the Universe?

What are new applications of isotopes to meet the needs of society?



# Today's menu for experimental nuclear physics I & II

- To understand complex structure of atomic nuclei, various experimental methods need to be combined
- Experiments with rare isotopes pose additional challenges to achieve required precision and sensitivity

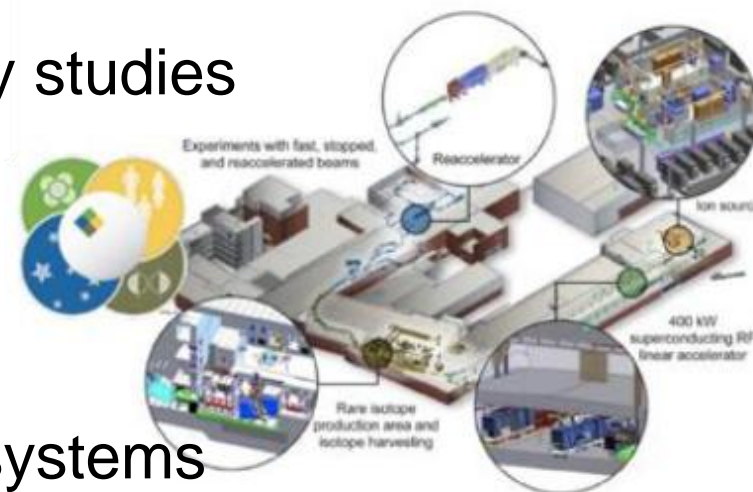
Be familiar with representative experimental methodology and approaches  
Be aware of recent highlights in our field at FRIB era

This (first) lecture :

- RI-beam production for new isotope search and decay studies
- In-beam Gamma Spectroscopy with fast RI beams to track structural changes

Next (second) lecture:

- Invariant-mass Spectroscopy to study weakly bound systems



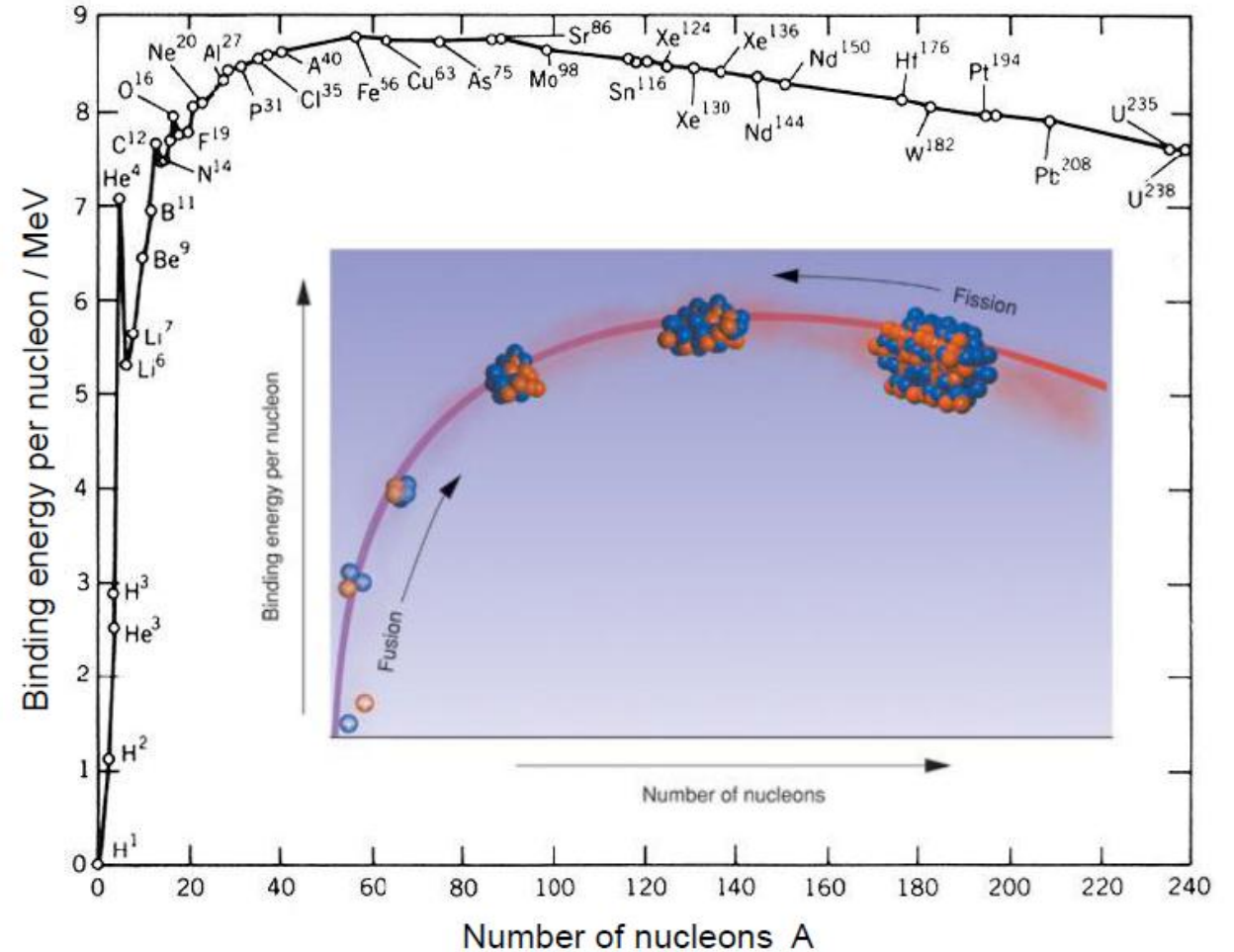
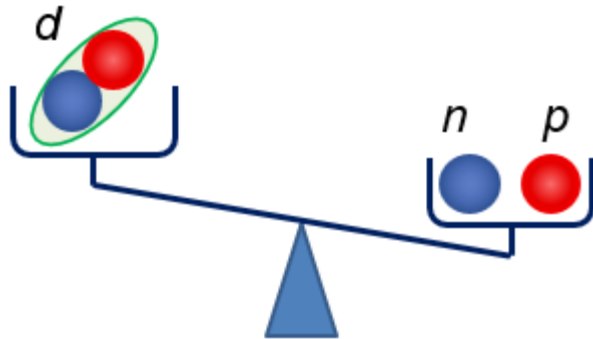
# Binding energies of atomic nuclei

The binding energy  $B(N,Z)$  is defined as:

$$B(N,Z)/c^2 = Z \cdot (M_p + m_e) + N \cdot M_n - M(N,Z)$$

[ B in MeV ]

Mass excess =  $\Delta(N,Z) = M(N,Z) - u \cdot A$   
 with mass unit  $u = M(^{12}\text{C})/12 = 931.5 \text{ MeV}/c^2$



# Semi-empirical mass formula and shell effects

Semi-empirical Mass Formula is given by:

$$M(Z,A) = Z \cdot (M_p + m_e) + N \cdot M_n - a_v A + a_s A^{2/3} + a_c \frac{Z^2}{A^{1/3}} + a_a \frac{(Z-N)^2}{A} + \Delta$$

corresponds  
to “  $-B/c^2$  “

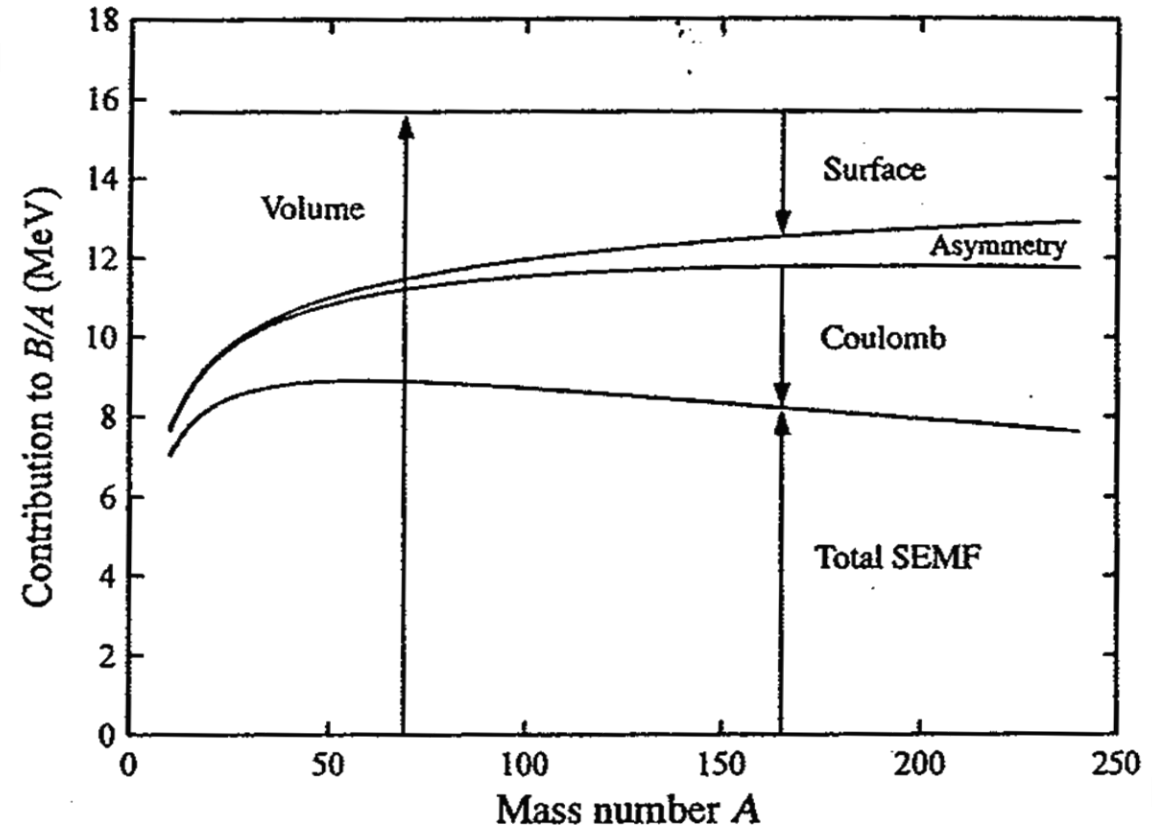
**Volume** term;  $a_v = 15.3$  MeV  
each nucleon feels the effect of the nucleons surrounding

**Surface** term;  $a_s = 16.1$  MeV  
volume term overestimates the effect at the surface

**Coulomb** term;  $a_c = 0.69$  MeV  
Repulsive force among the charged particles (protons)

**Asymmetry** term;  $a_a = 22.5$  MeV  
Nuclei tend to have  $N = Z$

**Pairing** term;  $\Delta = 12A^{-1/2}$  for even-even nuclei,  
 $+ 12A^{-1/2}$  for odd-odd nuclei, 0 for others



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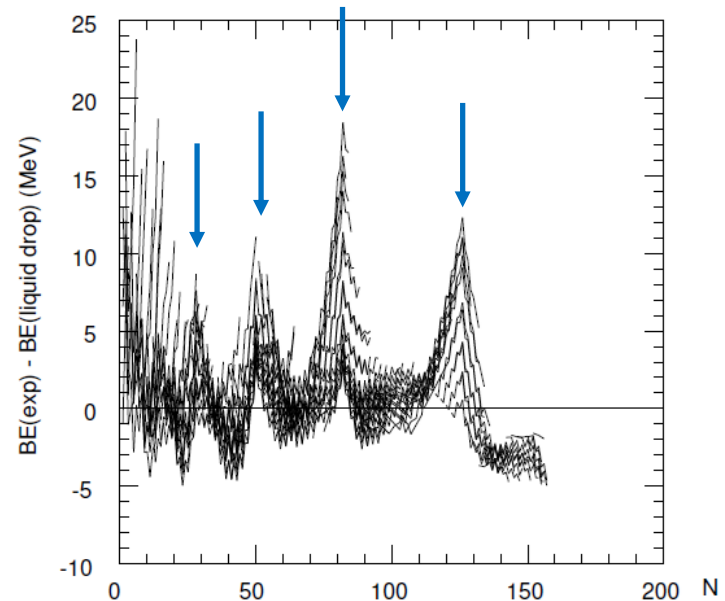
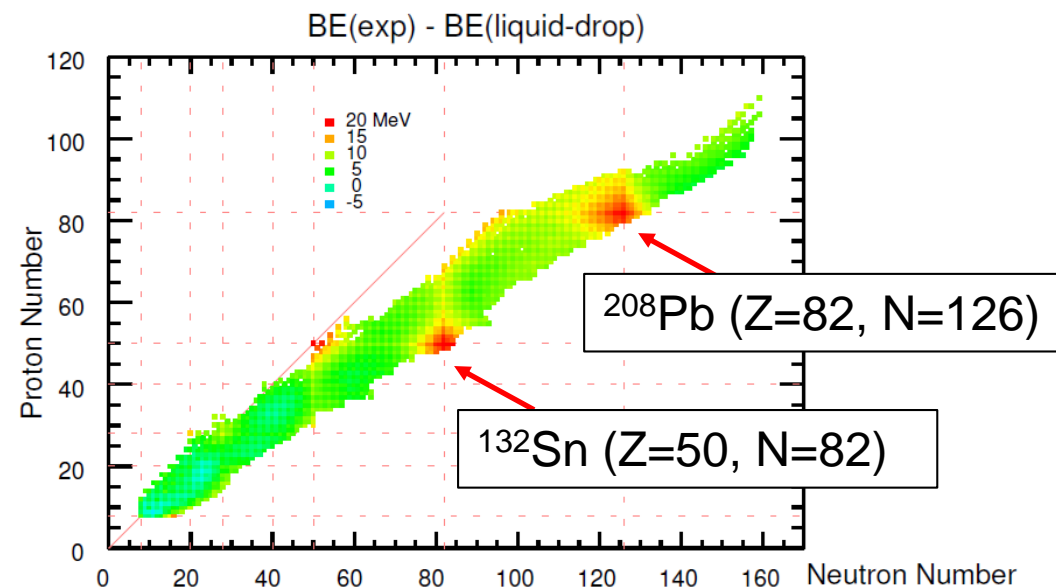
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# Separation energies and shell effects

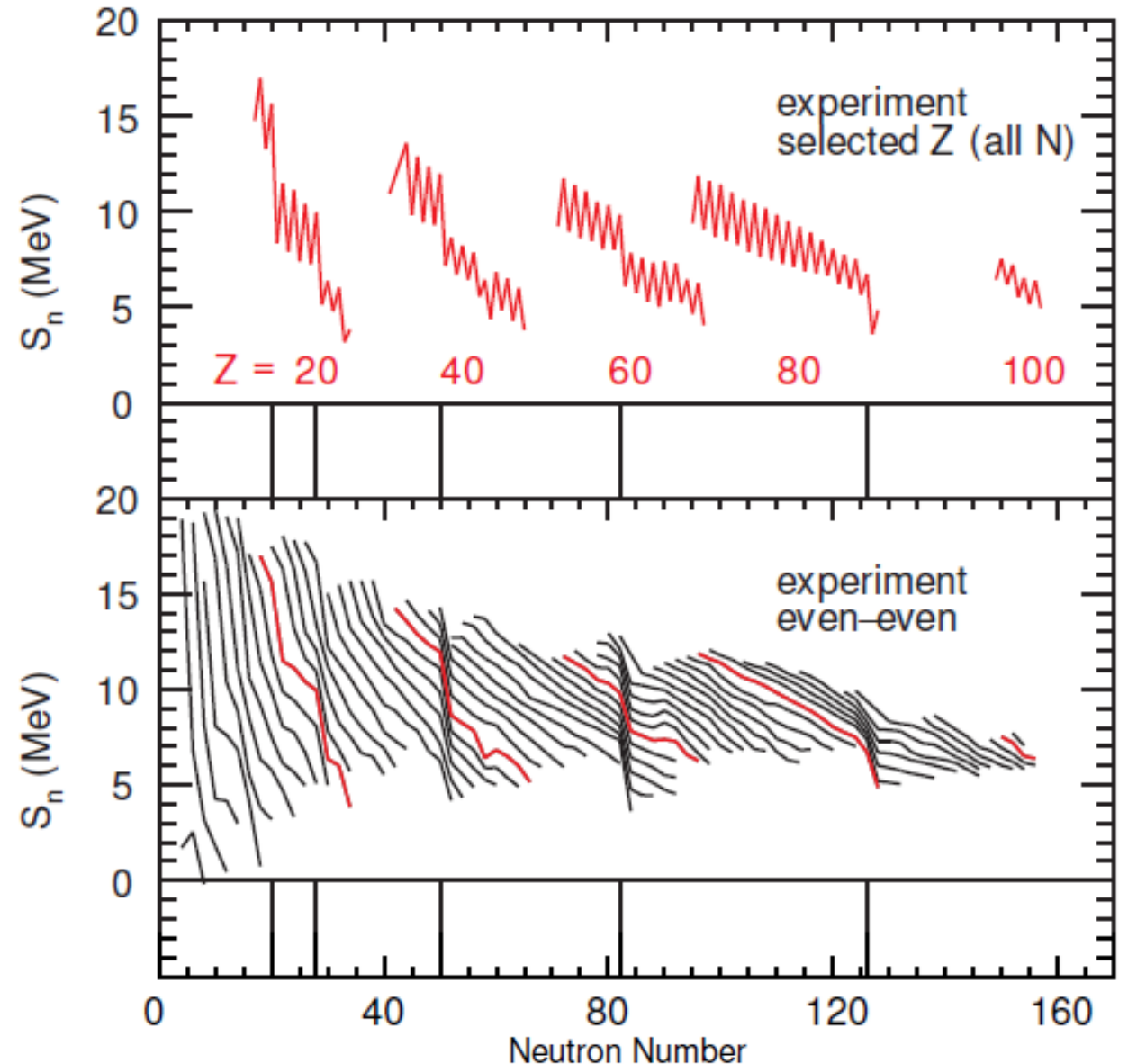
The **separation energy** is the energy to remove a nucleon (neutron or proton) from a nucleus (e.g. ionization energy for atom);

**neutron**

$$S_n(N,Z) = B(N,Z) - B(N-1,Z)$$

**proton**

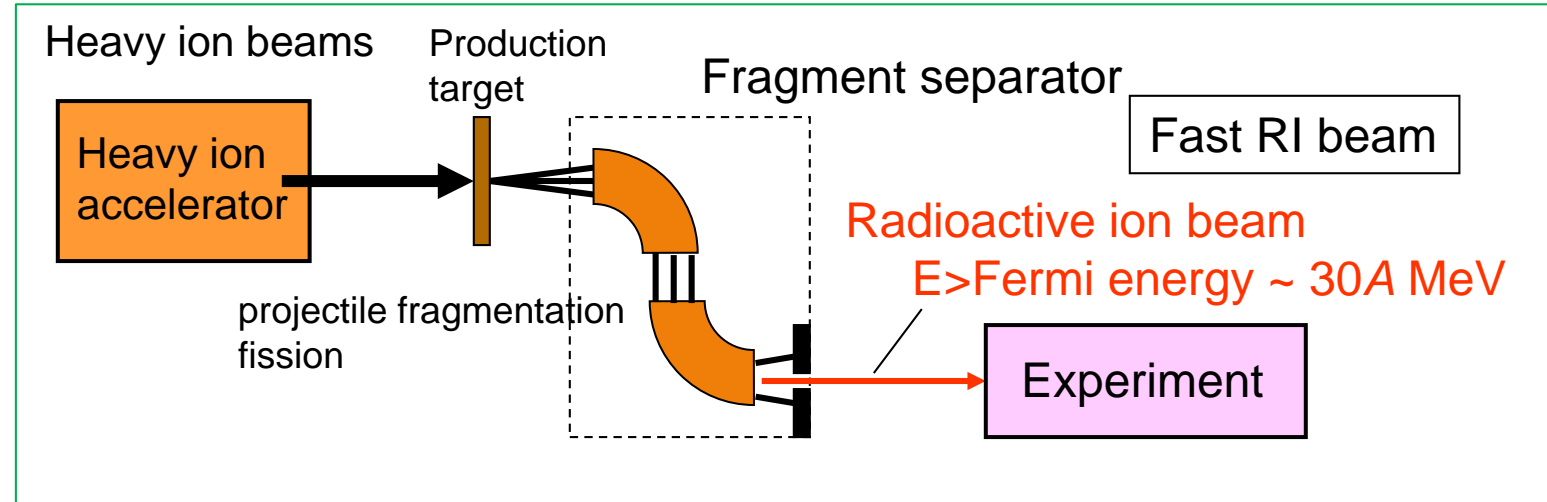
$$S_p(N,Z) = B(N,Z) - B(N,Z-1)$$



# Rare (Radioactive) Isotope Beam production

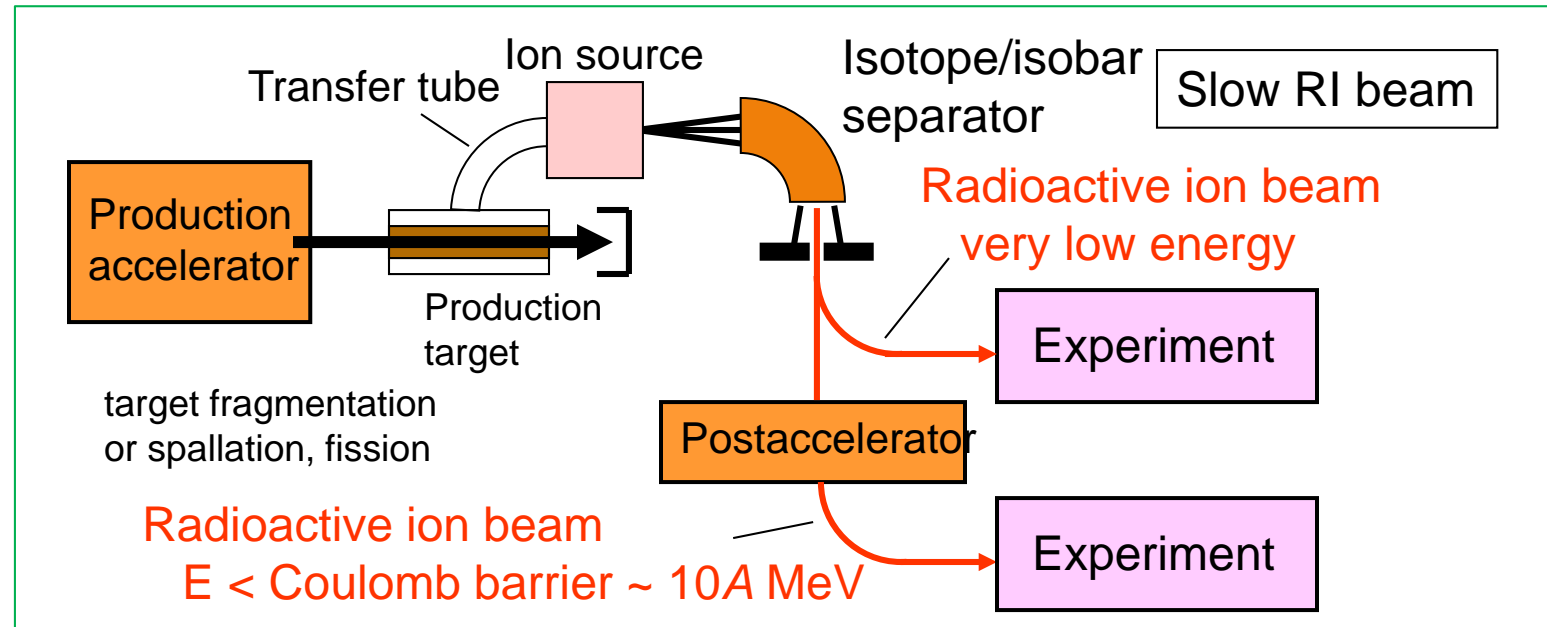
## In-Flight Method

@FRIB/MSU, LISE/GANIL,  
GSI/FAIR, RIBF/RIKEN ...



## ISOL Method

@ISOLDE, TRIUMF  
SPIRAL ...

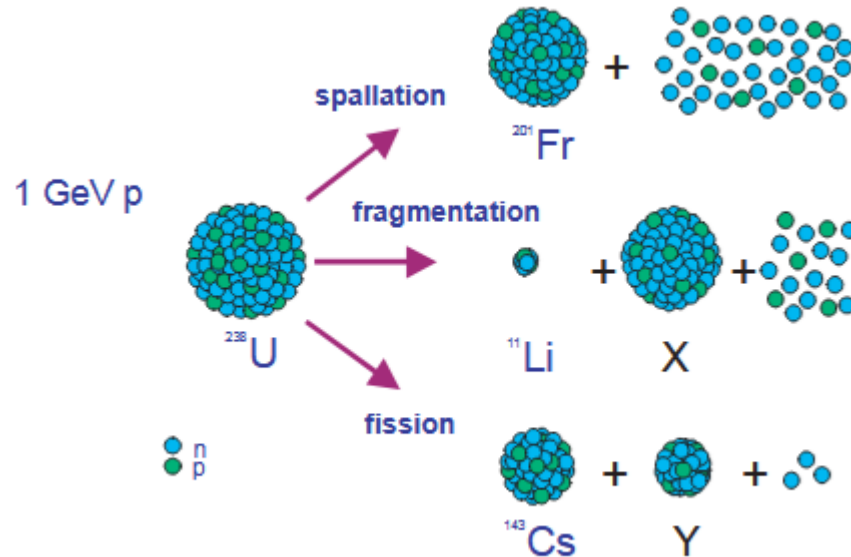


# ISOL

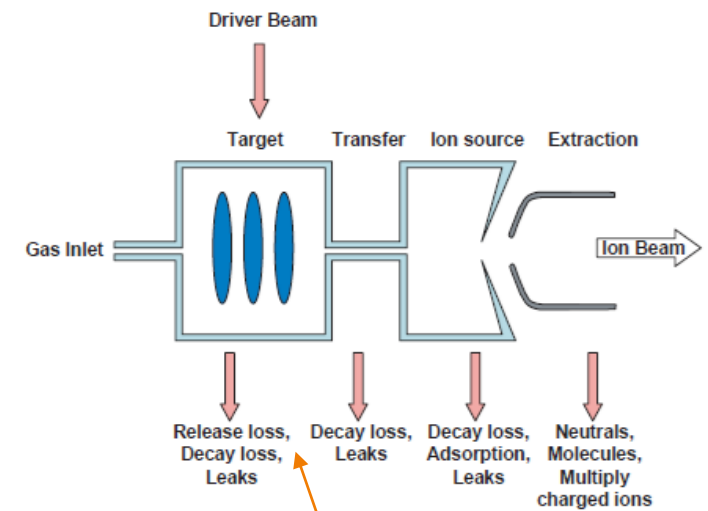
Invented in Copenhagen over >70 years ago and migrated to CERN

K.O.Nielsen, Nuclear Instruments 1 (1957) 289 R. Klapisch et al., PRL23, 652 (1969) T1/2( $^{11}\text{Li}$ )

ISOL (Isotope Separation On-Line) defined as an instrument which is essentially a target, ion source, and an electromagnetic mass analyzer coupled in series.



M.Lindroos, EPAC2004 Proceedings, 45, 2004



Pro: High intensity and quality of rare isotope beams

Con: Half-life limitation (time for diffusion/transport)

Chemical limitation (e.g. refractory elements)



Laser techniques to achieve selectivity and efficiency

(e.g. Resonance Ionization Laser Ion Source)



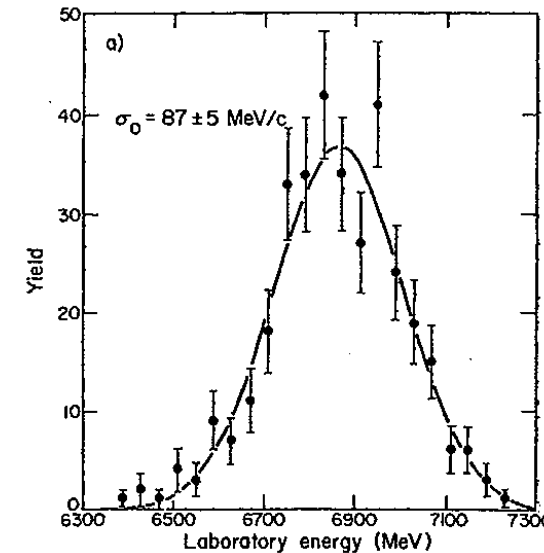
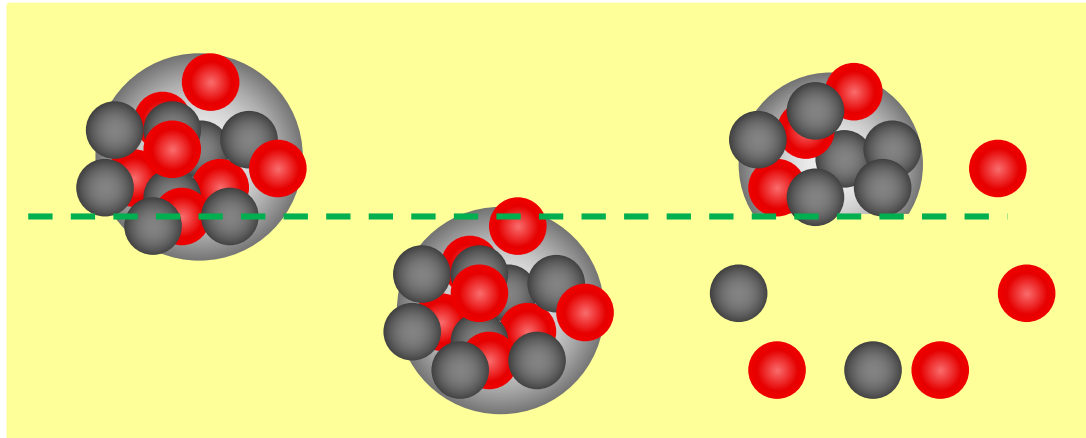
# Projectile Fragmentation

## Discovery of projectile-fragmentation reaction

at Bevalac @ LBL (Lawrence Berkeley Laboratory)

D.E.Greiner et al., Phys. Rev. Lett. 35 (1975) 152

$^{12}\text{C}$ ,  $^{16}\text{O}$  (2.1 AGeV) + Target (Be, C, Al, Cu, Ag, Pb)



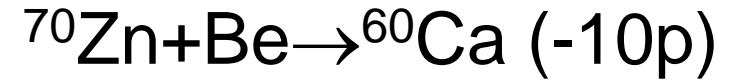
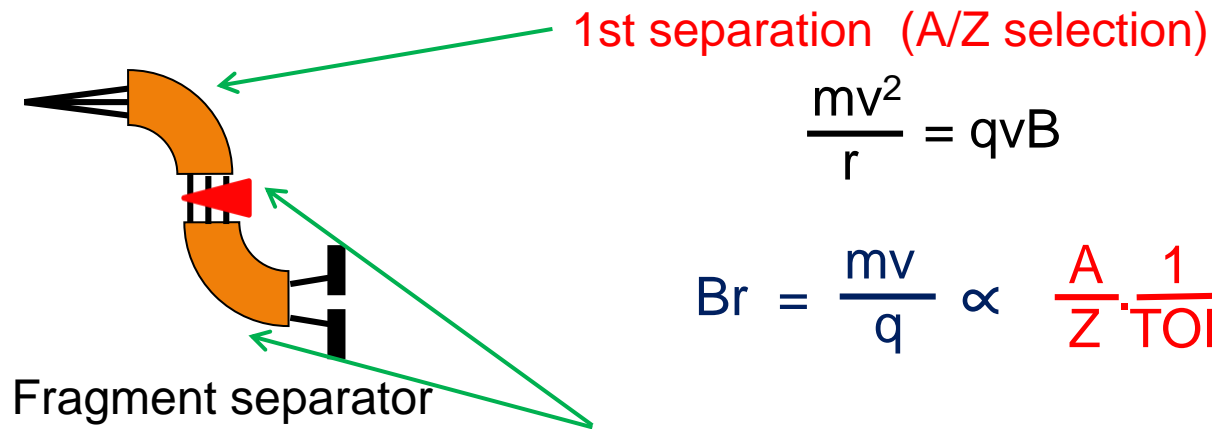
Momentum distribution of fragments are well represented by a simple formula from the Goldhaber model

$$\sigma = \sigma_0 \sqrt{\frac{F(A-F)}{(A-1)}}$$

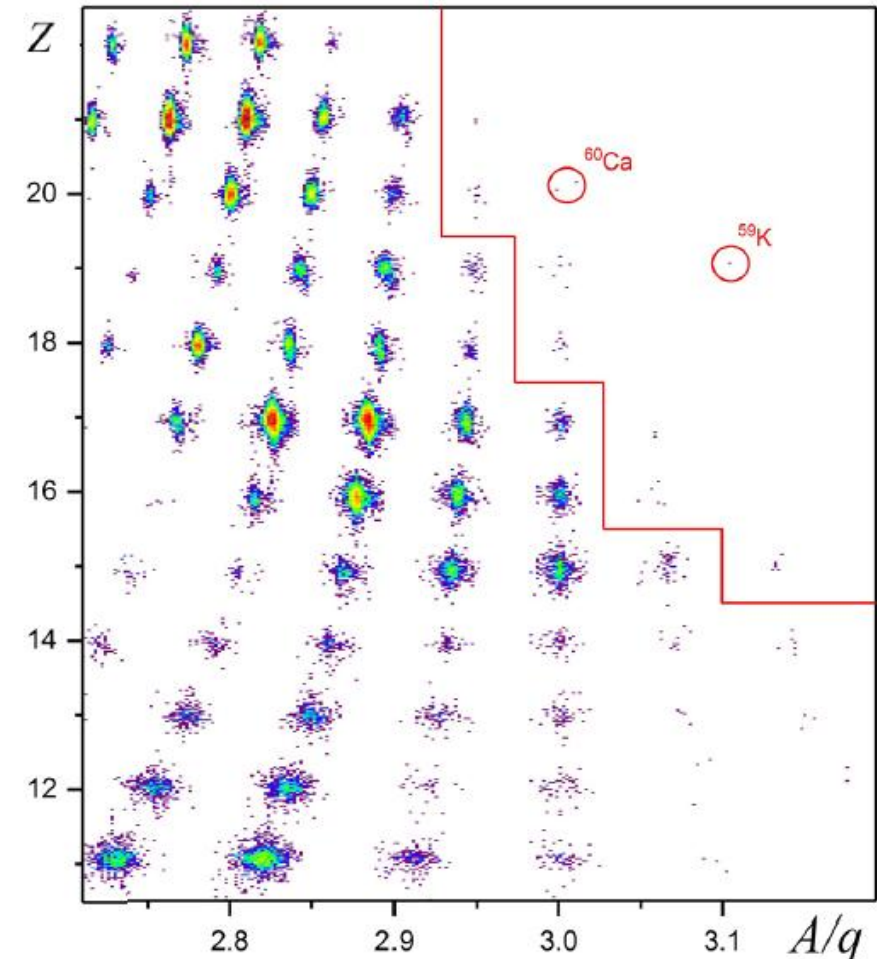
- Several fragments are produced in reactions
- Velocity of fragments is almost the same as that of the beam
- Momentum distribution is narrow, and has no significant correlation with target mass and beam energies

# Discovery of $^{60}\text{Ca}$ ( $Z=20$ , $N=40$ )

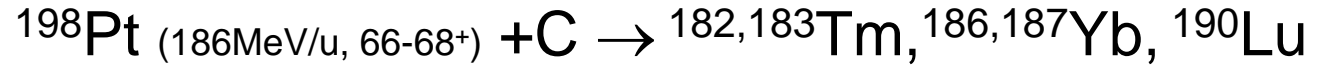
Unambiguous identification of  $^{60}\text{Ca}$  and more based on TOF vs dE plot



8 new isotopes  $^{47}\text{P}$ ,  $^{49}\text{S}$ ,  $^{52}\text{Cl}$ ,  $^{54}\text{Ar}$ ,  $^{57}\text{K}$ ,  $^{59,60}\text{Ca}$ ,  $^{62}\text{Sc}$

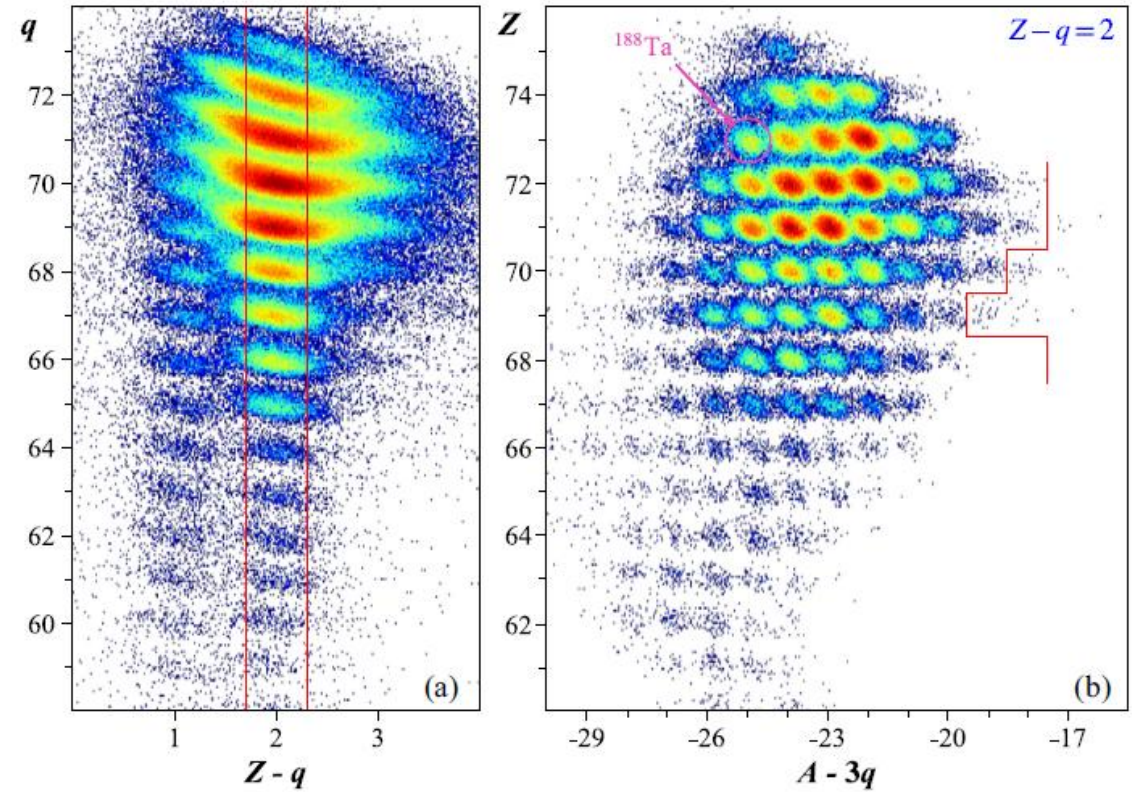
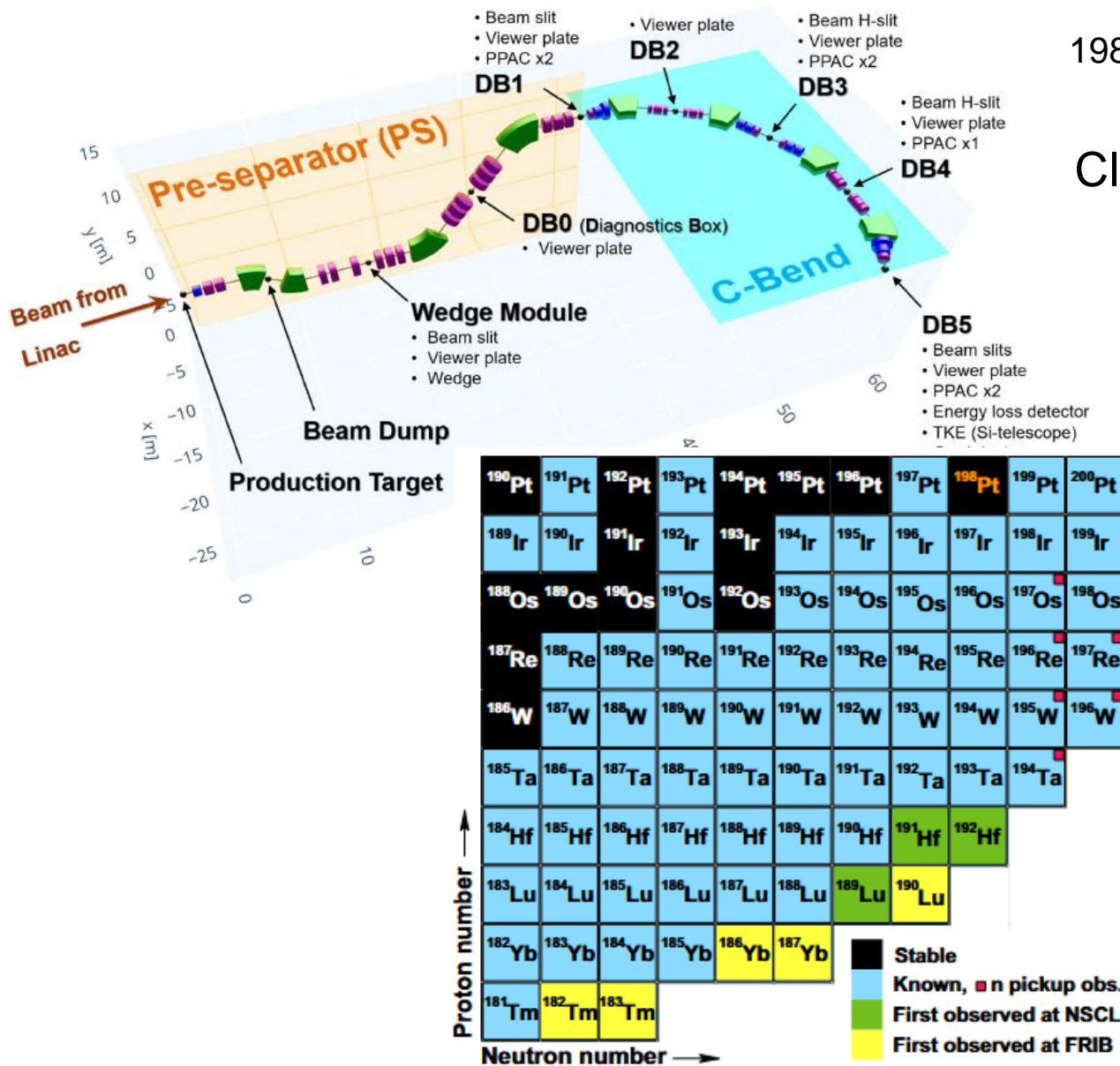


# New isotopes from $^{198}\text{Pt}$ fragmentation at FRIB



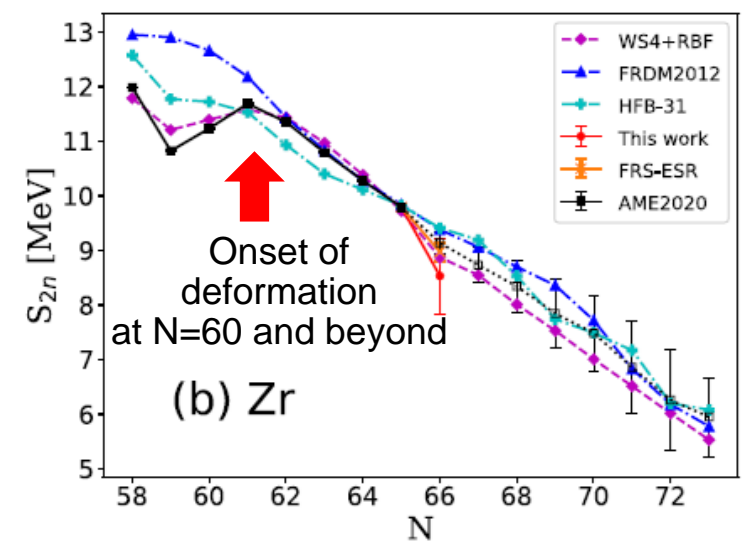
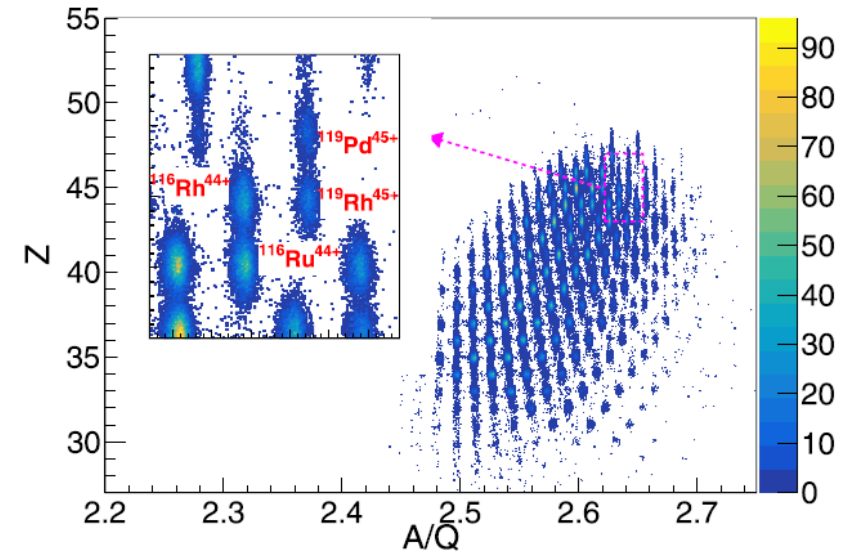
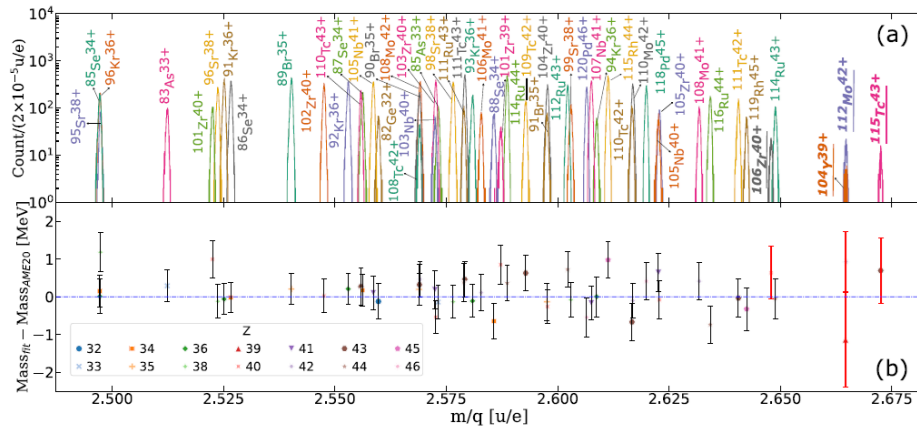
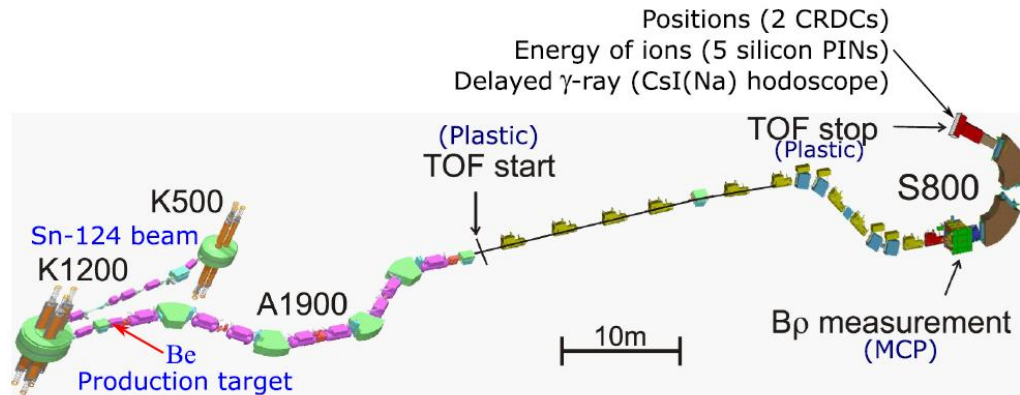
Clear identification based on

$$\begin{aligned} \text{TOF} &\sim L/v \sim A/q \\ dE &\sim Z^2 \\ \text{TKE} &\sim A \end{aligned}$$



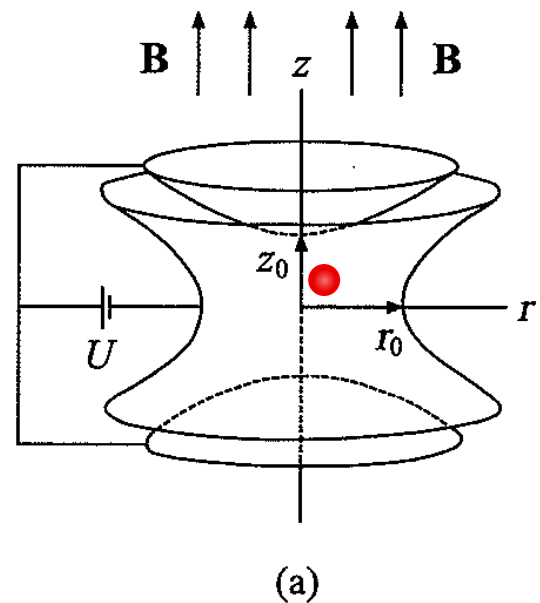
# TOF mass measurement – isospin frontier

High-resolution TOF-Brho measurements can achieve  $A(\text{mass})$  resolution of a few  $10^{-5}$

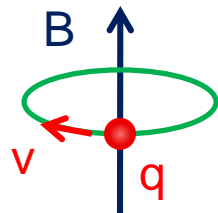


# Penning Trap mass measurement for $^{22}\text{Al}$

High-resolution mass measurement for the proton-dripline nucleus  $^{22}\text{Al}$  was performed at FRIB. The measured mass value corresponds to an exceptionally small proton separation energy of  $S_p = 100.4(8)$  keV, indicating a possible halo structure for  $^{22}\text{Al}$ .



Cyclotron oscillations ( $\omega_c$ )



$$\frac{mv^2}{r} = qvB$$

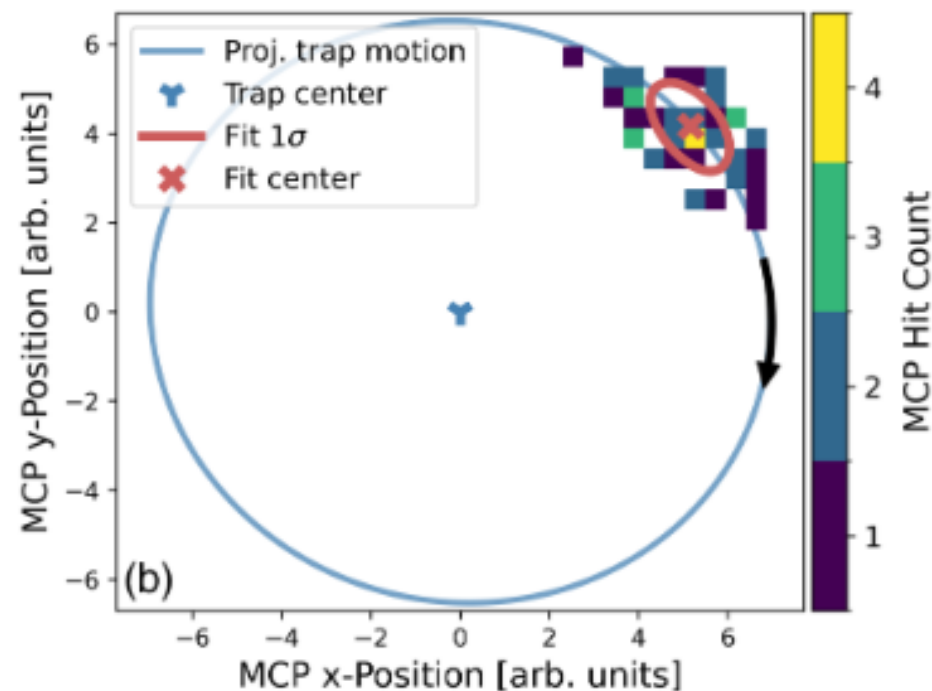
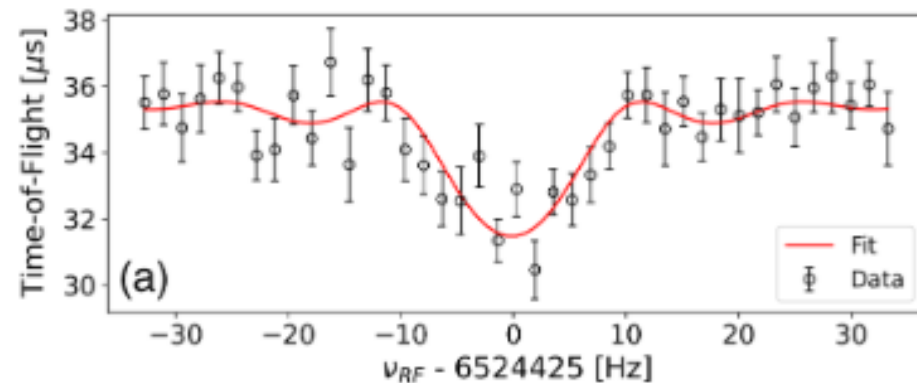
$$v = \frac{qBr}{m}$$

$$t = 2\pi r/v = \frac{2\pi m}{qB}$$

$$\omega_c = 2\pi f$$

$$= 2\pi/T$$

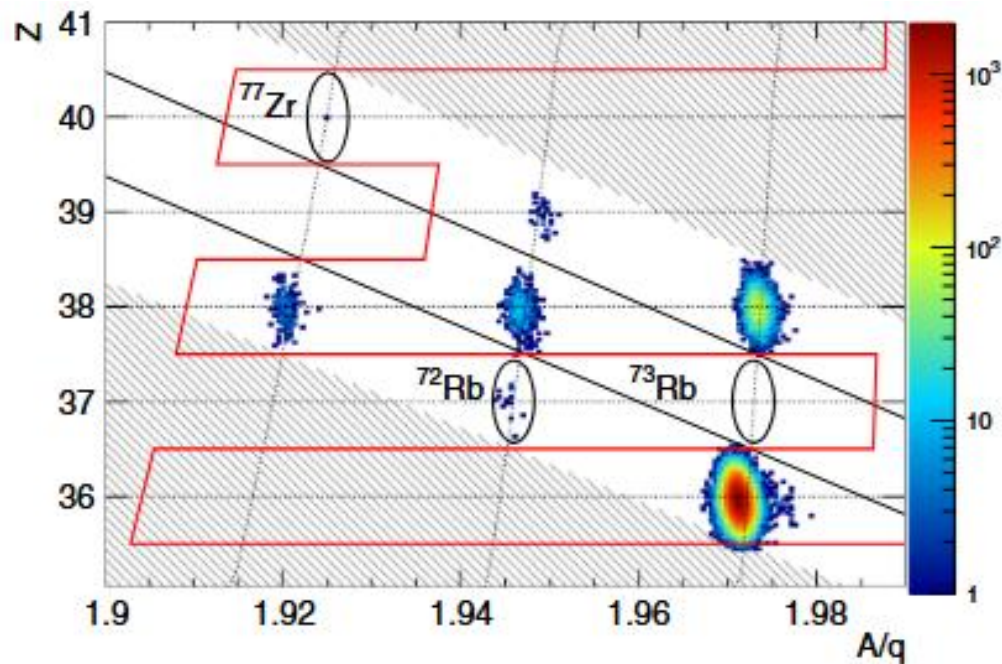
$$= \frac{qB}{m}$$



# Identification of $^{72}\text{Rb}$ ( $Z=37$ , $N=35$ )

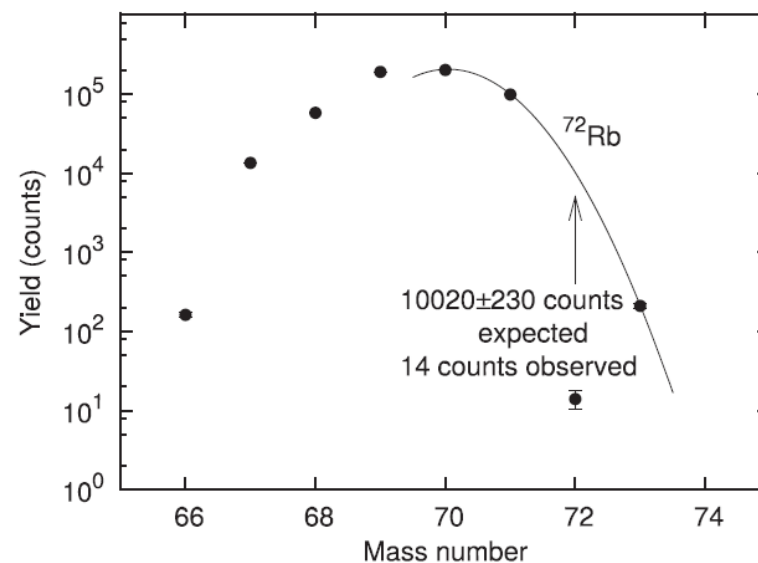
Due to the presence of Coulomb barrier ( $\sim Z^2$ ) and centrifugal barrier ( $\sim \ell(\ell+1)$ ), proton emission can have finite lifetimes ( $10^{-21}$ - $10^{-3}$  s), extending the nuclear chart beyond the dripline.

Unexpected! observation of a relatively long-lived odd-odd nucleus  $^{72}\text{Rb}$



$\text{Sp}(^{72}\text{Rb}) = -710\text{keV}$  (SY,ENSDF)

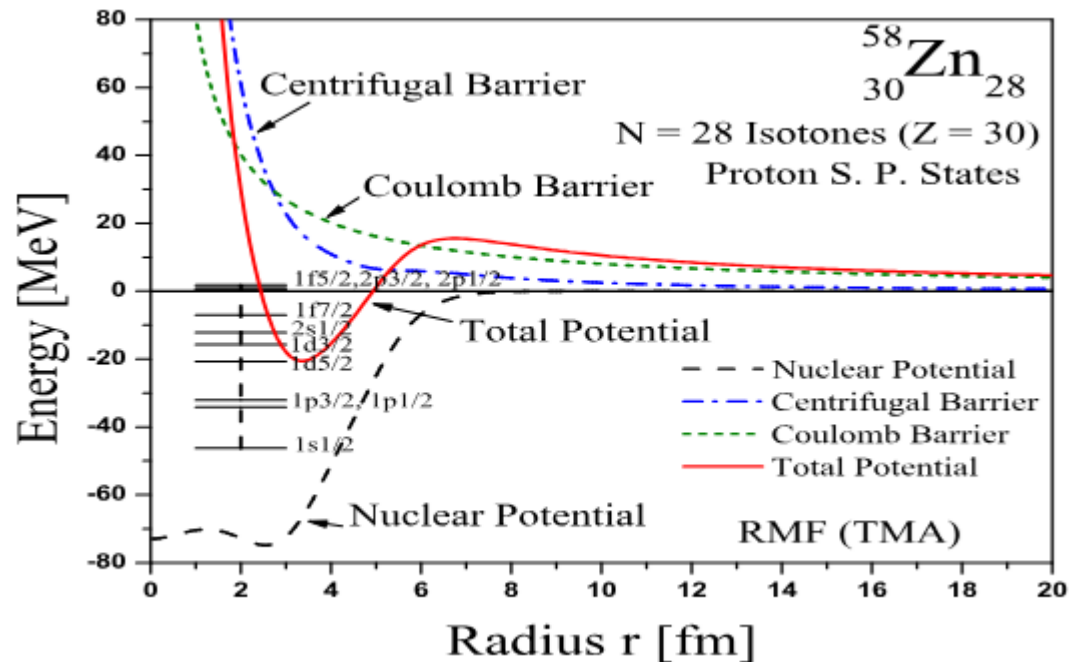
The number of events compared to expectation



H. Suzuki et al., Phys. Rev. Lett. 119, 192503 (2017)

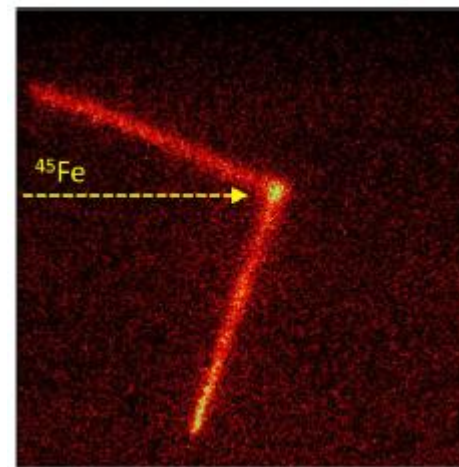
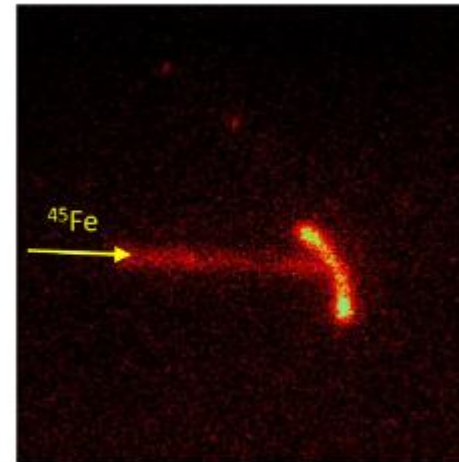
# Natural trap (Coulomb barrier) and exotic proton decays

The interplay between the attractive nuclear potential and repulsive Coulomb potential forms the Coulomb barrier at the surface.

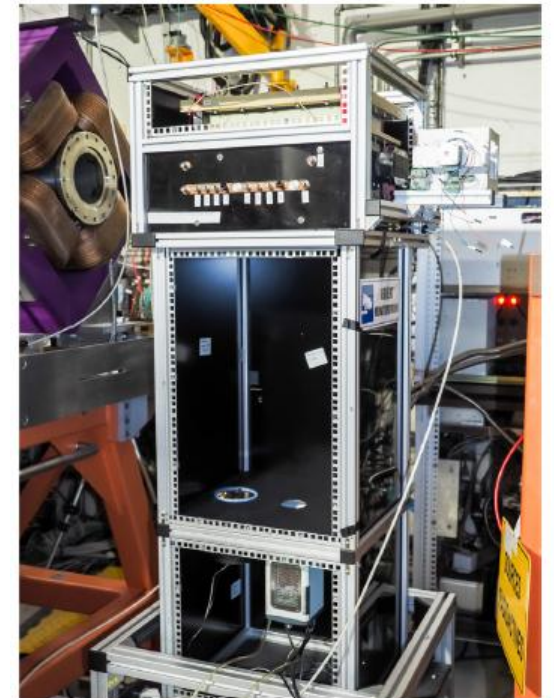


Example of potential energy for  $^{58}\text{Zn}$   
(G.Saxena et al., arXiv 1310.3924)

At the proton dripline, two proton decay modes have been directly observed.

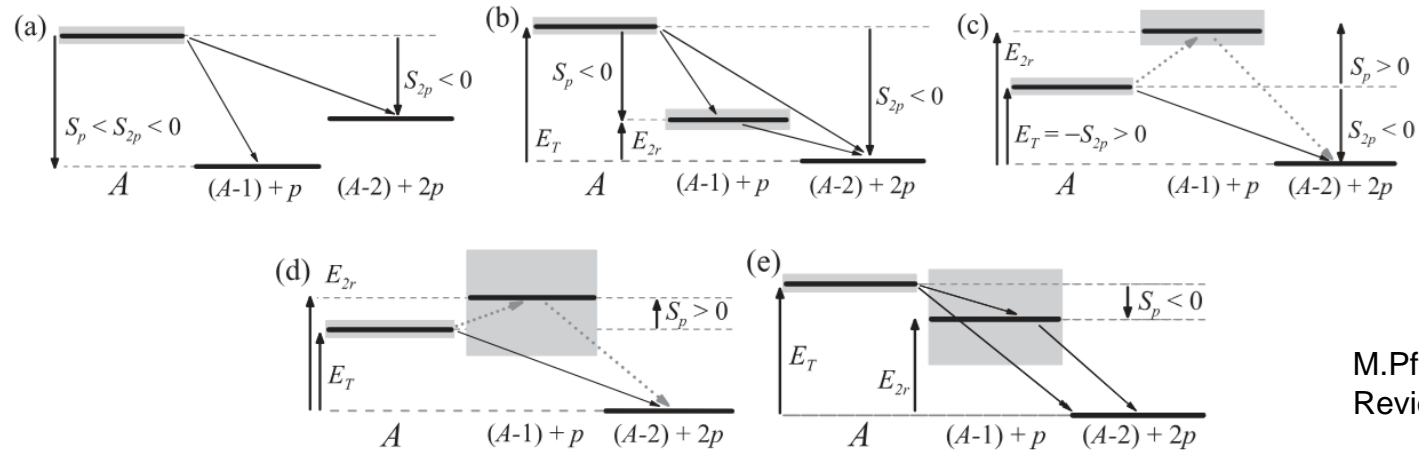


Example of optical images of  $^{45}\text{Fe}$  decays by the OTPC detector.



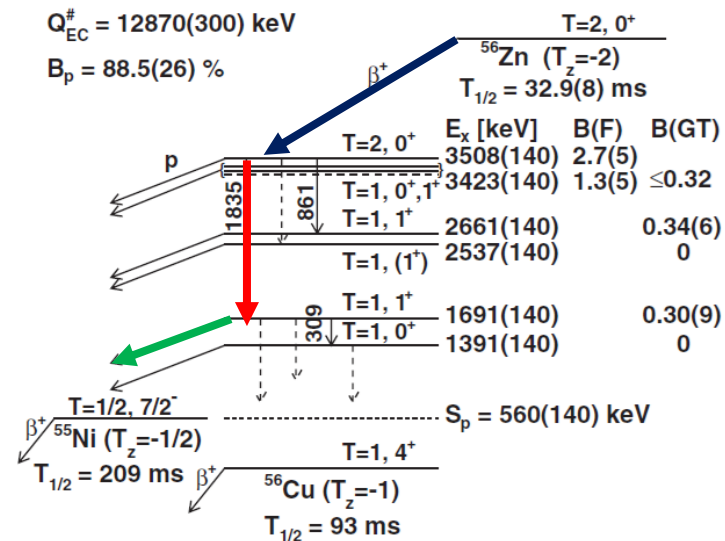
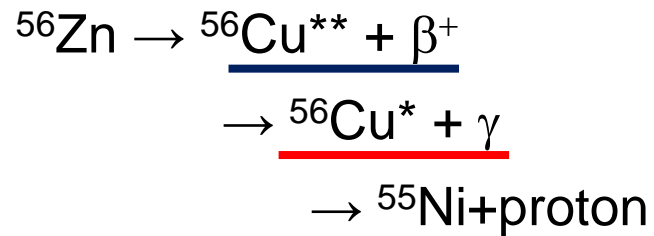
# Various exotic decay modes

## Two proton decays: $A \rightarrow (A-2) + 2p$



M.Pfutzner, et al.,  
Reviews of Modern Physics 84, 567 (2012)

## Beta-delayed gamma proton decay

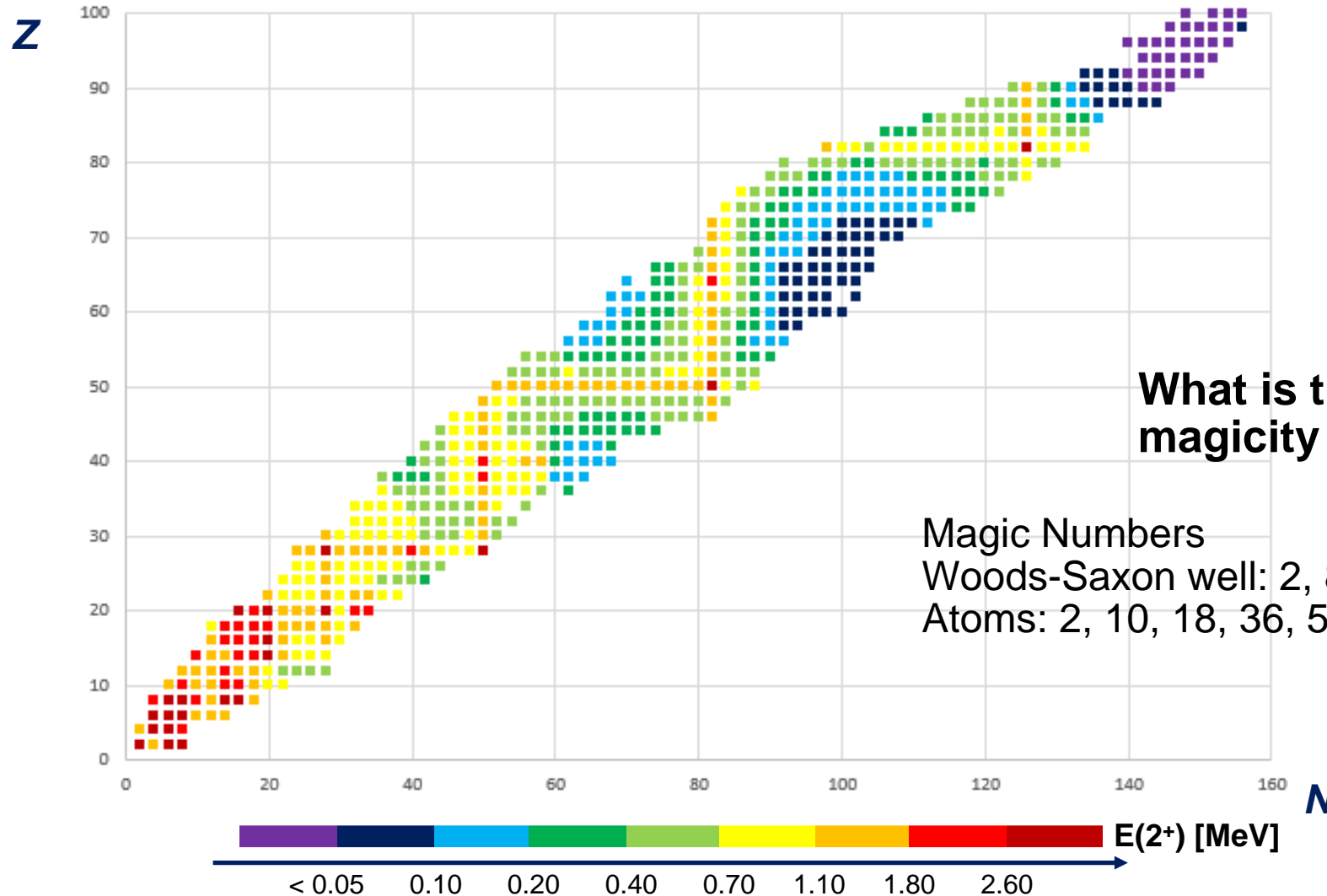


S.E.A.Orrigo et al., PRL112, 222501 (2014)

# Magic numbers in Atomic Nuclei

**N or Z = 2, 8, 20, 28, 50, 82, 126**

$$V_{ls}(r) \sim -\lambda \frac{1}{r} \frac{dV}{dr}$$



**What is the origin of the magicity in atomic nuclei?**

Magic Numbers

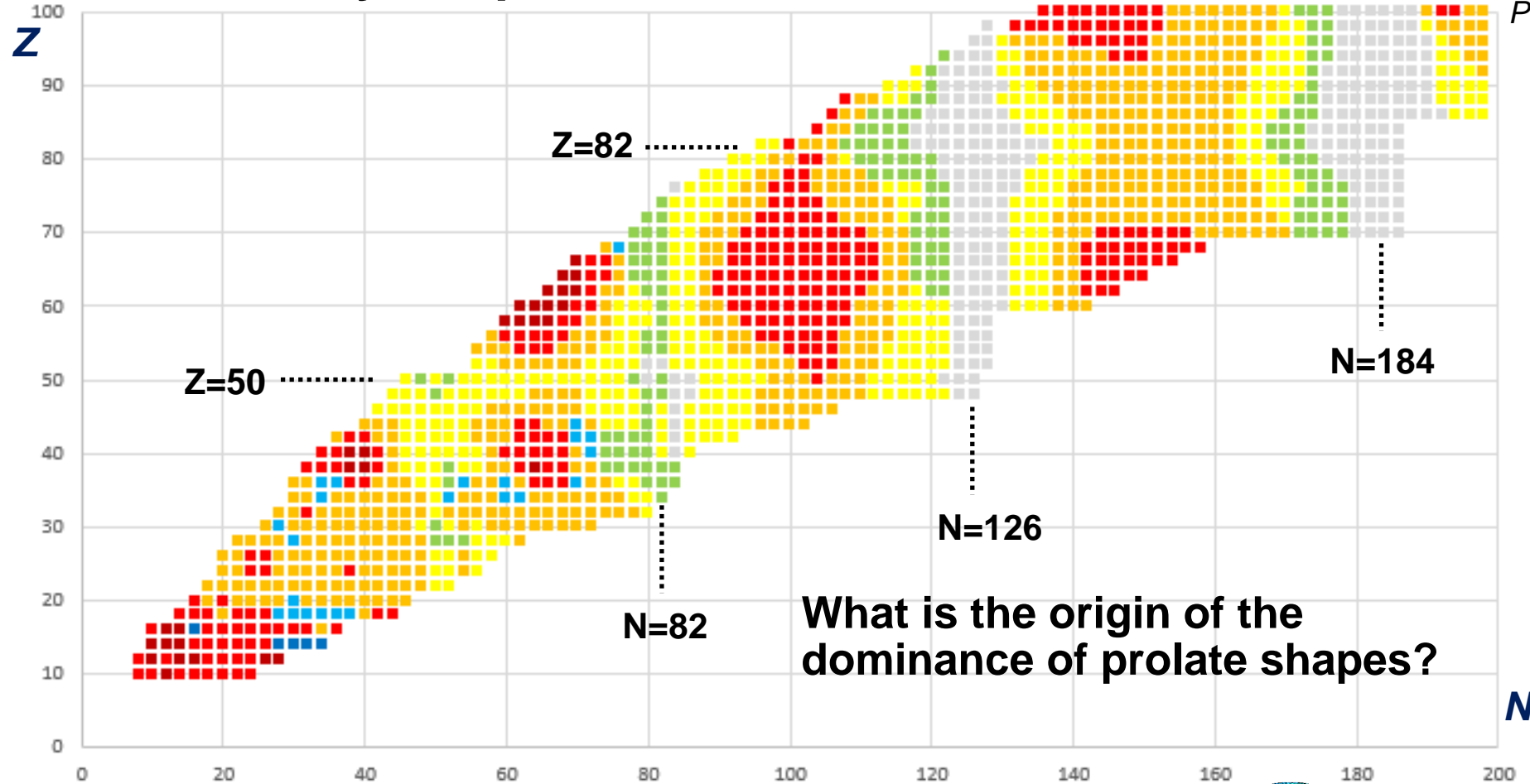
Woods-Saxon well: 2, 8, 20, 40, 58, 92, 112, 138

Atoms: 2, 10, 18, 36, 54, 86, 118

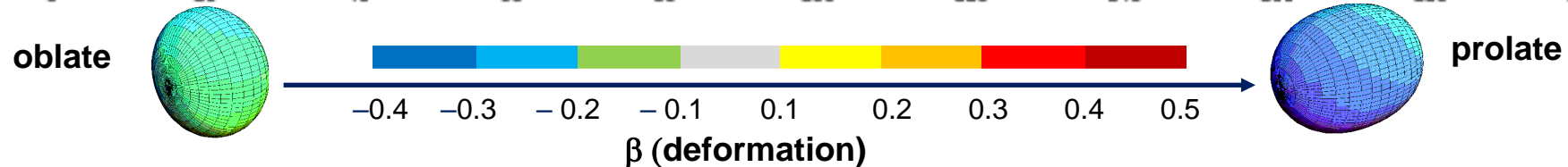
# Nuclear deformation from theory

## Emergence of collectivity at open shell

Data from J.-P. Delaroche et al.,  
PRC81, 014303 (2010)



What is the origin of the dominance of prolate shapes?



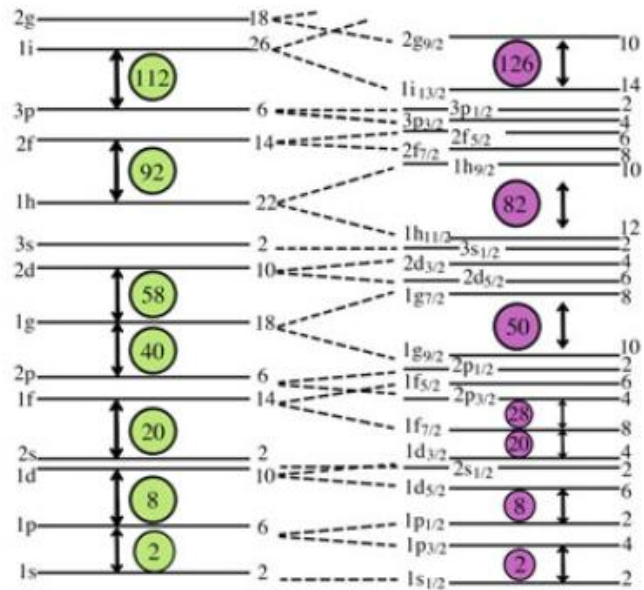
# Nuclear Shell Structure

The shell structure of atomic nuclei can be explained by the mean field with the spin-orbit potential which is a surface term.

$$V_{MF}(r) = V(r) + V_{ls}(r)$$

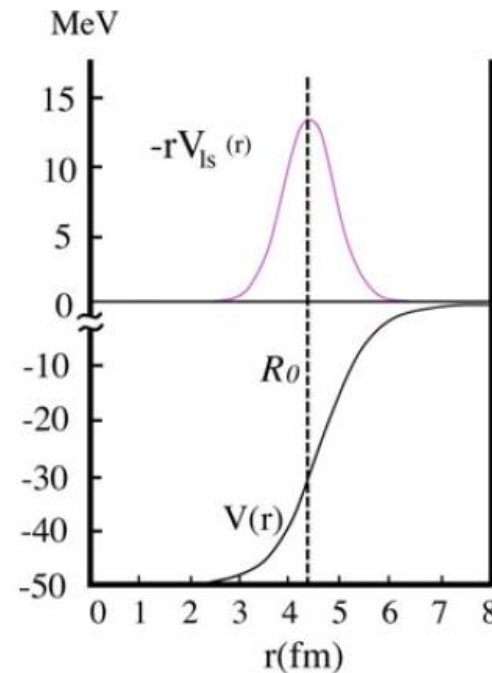
$$V(r) = V_0 f(r) = V_0 \frac{1}{1 + \exp\left(\frac{r-R_0}{a}\right)}$$

$$V_{ls}(r) = V_{ls} r_0^2 \frac{1}{r} \frac{df(r)}{dr} \ell \cdot s$$



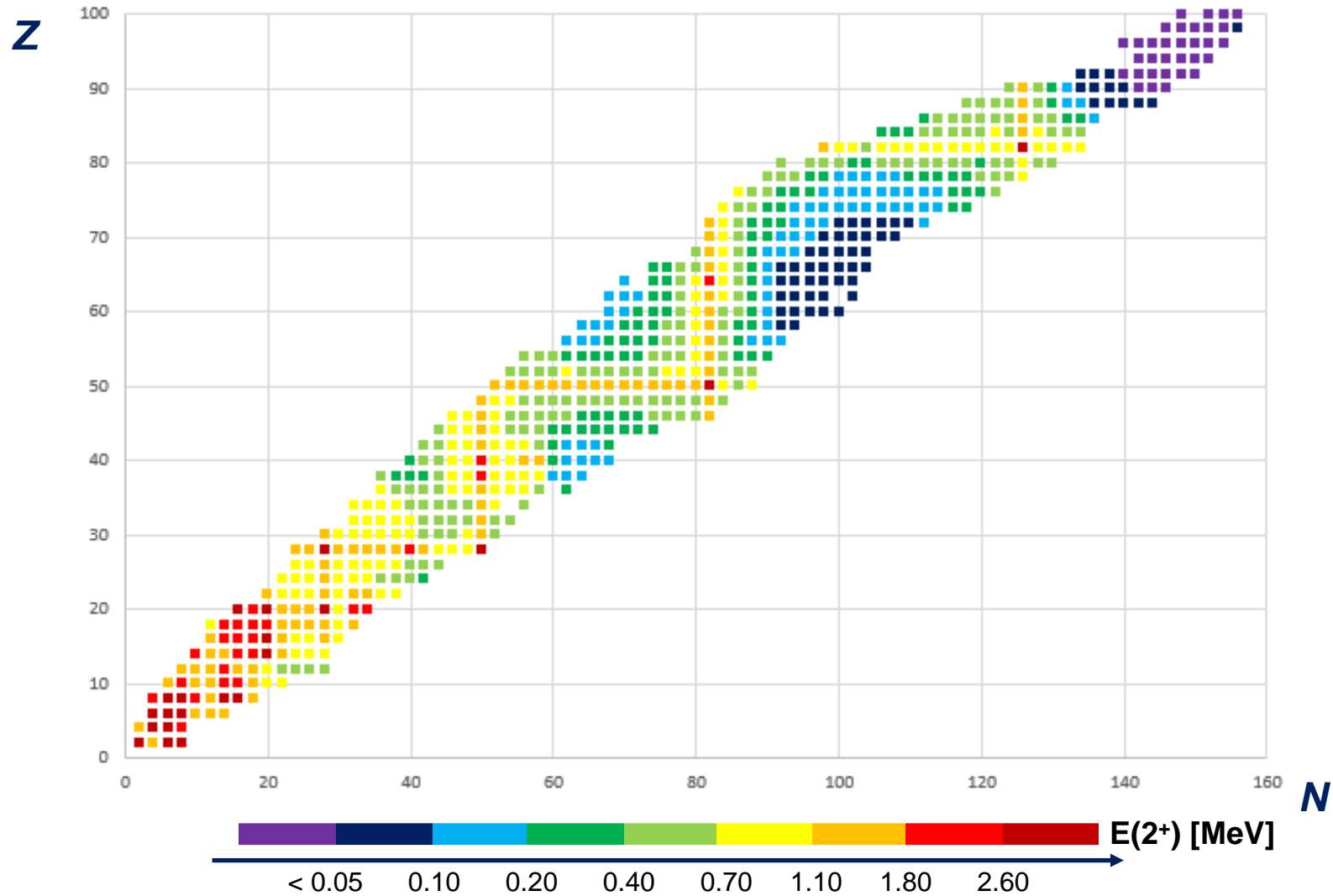
Without spin-orbit  
( $V_{ls}=0\text{MeV}$ )

With spin-orbit  
( $V_{ls}=22\text{MeV}$ )

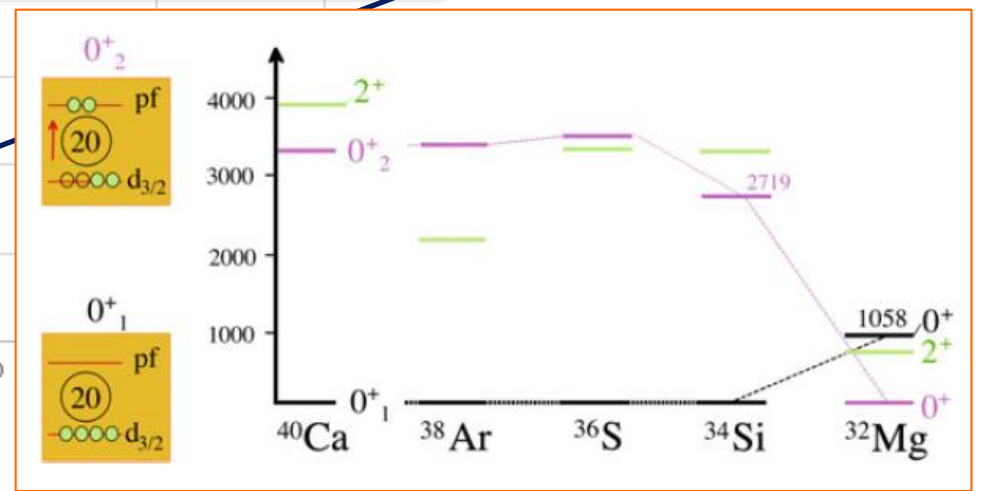
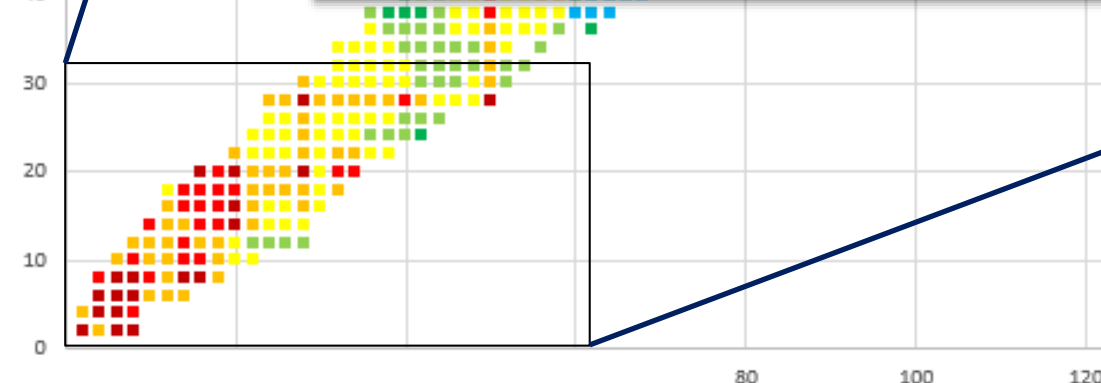
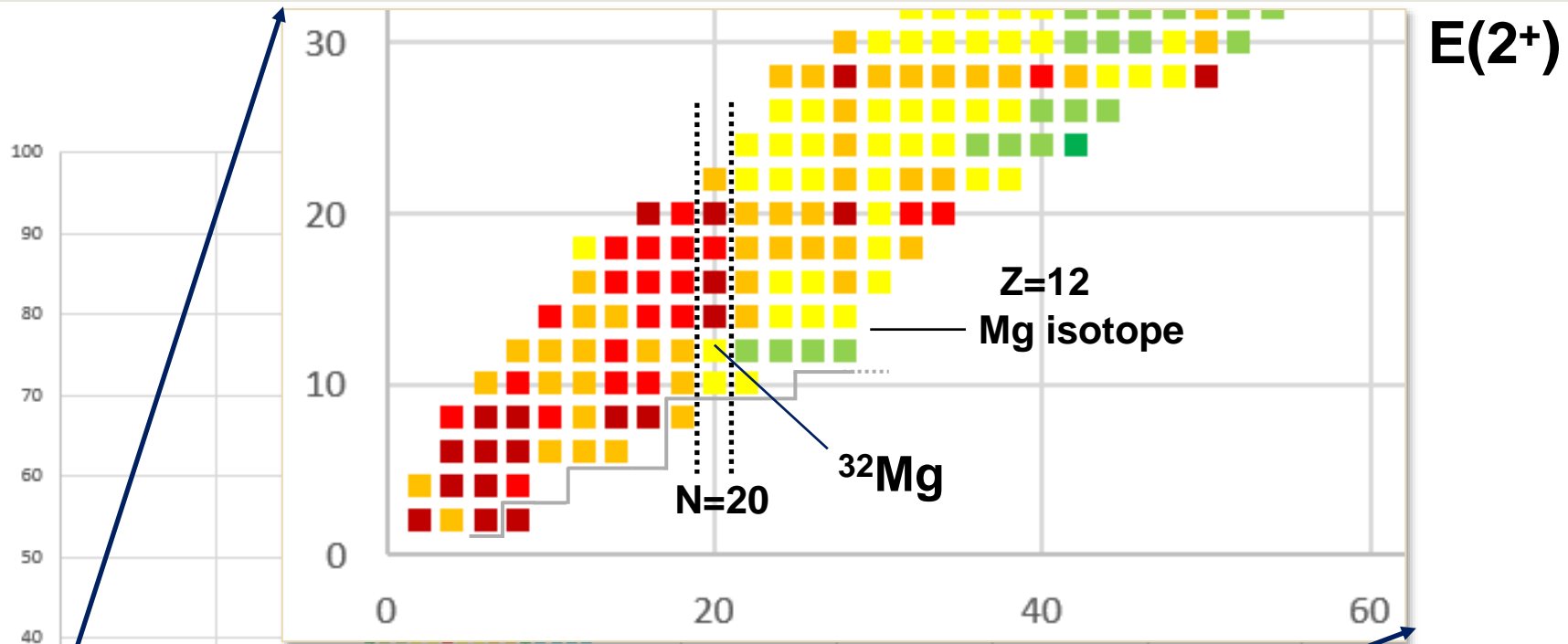


# Island of inversion

Any region for possible onset of deformation?



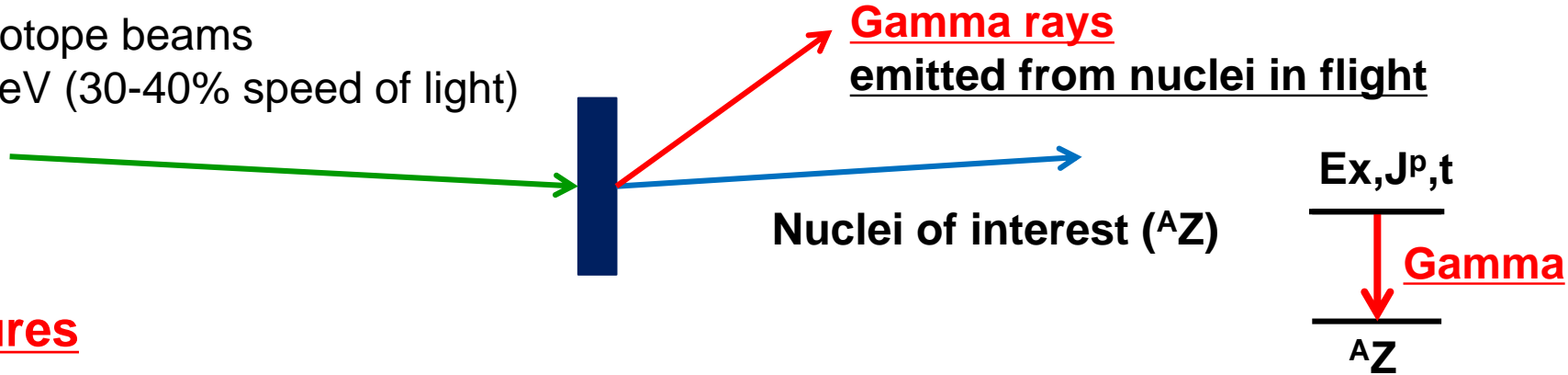
# Zoom in ...



Onset of deformation  
Disappearance of N=20 magic number

# In-beam Gamma Spectroscopy with Exotic Beams

Rare Isotope beams  
>50 A MeV (30-40% speed of light)



## Features

- In-beam gamma spectroscopy with rare isotope beams is studied in inverse kinematics
- Gamma rays are emitted from nuclei in flight and gamma-ray energies are Doppler shifted

## Advantages

- Energetic beams allow for the use of thick targets (up to g/cm<sup>2</sup>), that offsets low intensities of exotic beams
- Resolutions to 'tag' inelastic reaction processes are scaled by gamma-ray energies, and not by total momentum of ejectiles

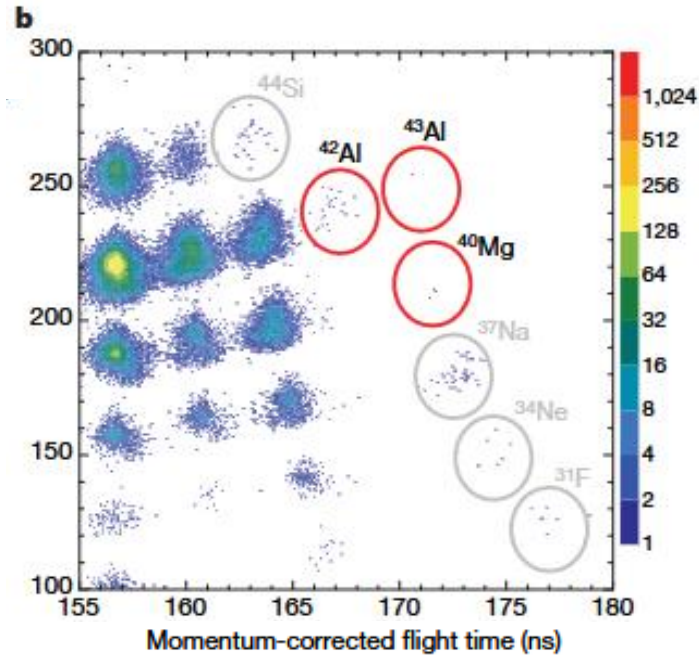


# First gamma-ray energy spectrum for $^{40}\text{Mg}$

12 years after the discovery of the  $^{40}\text{Mg}$  isotope, gamma-ray transitions were identified for the first time.

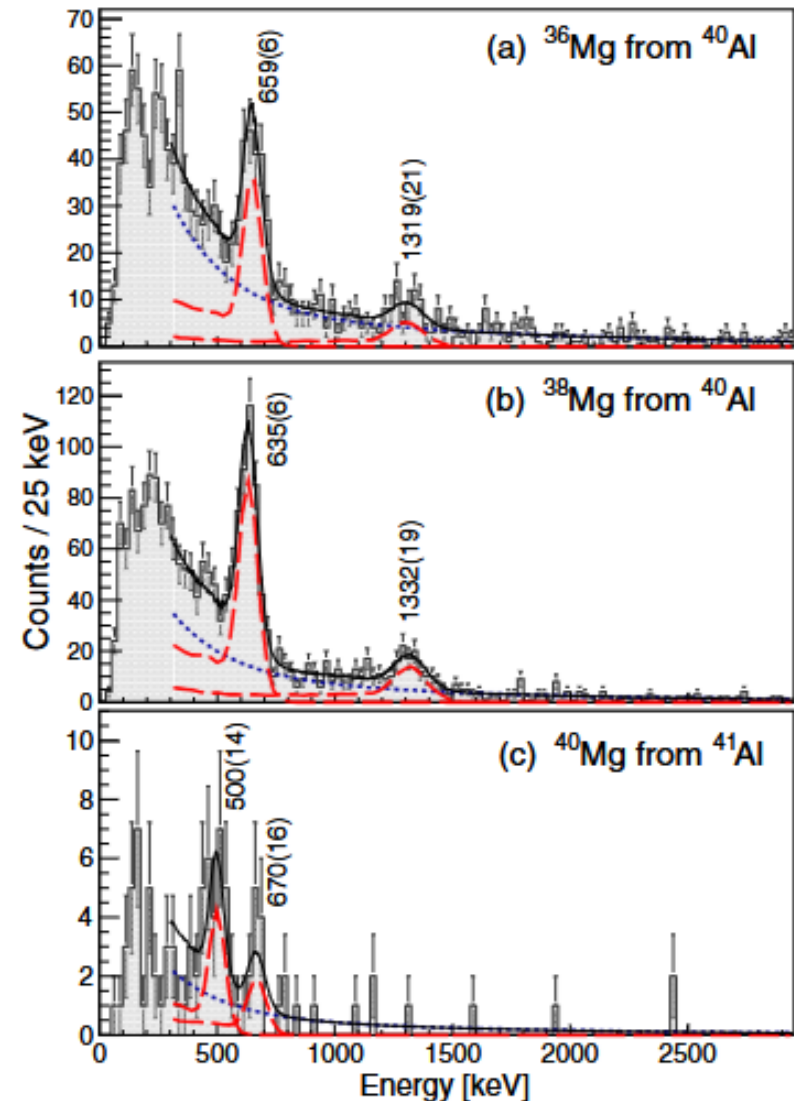
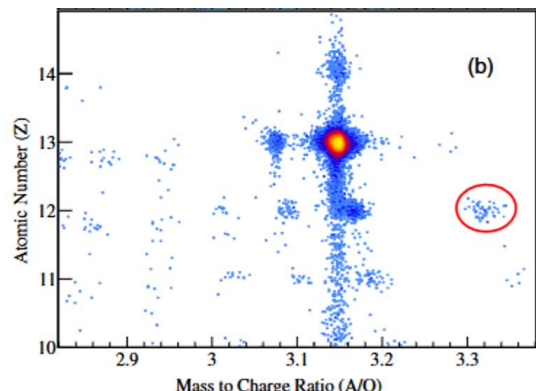
First observation of  $^{40}\text{Mg}$   
(3 counts/2 weeks)  
from  $^{48}\text{Ca}$  fragmentation

T.Baumann et al.,  
Nature 449, 1022 (2007)



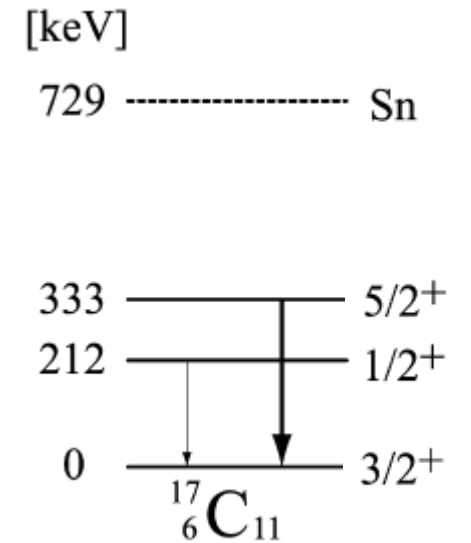
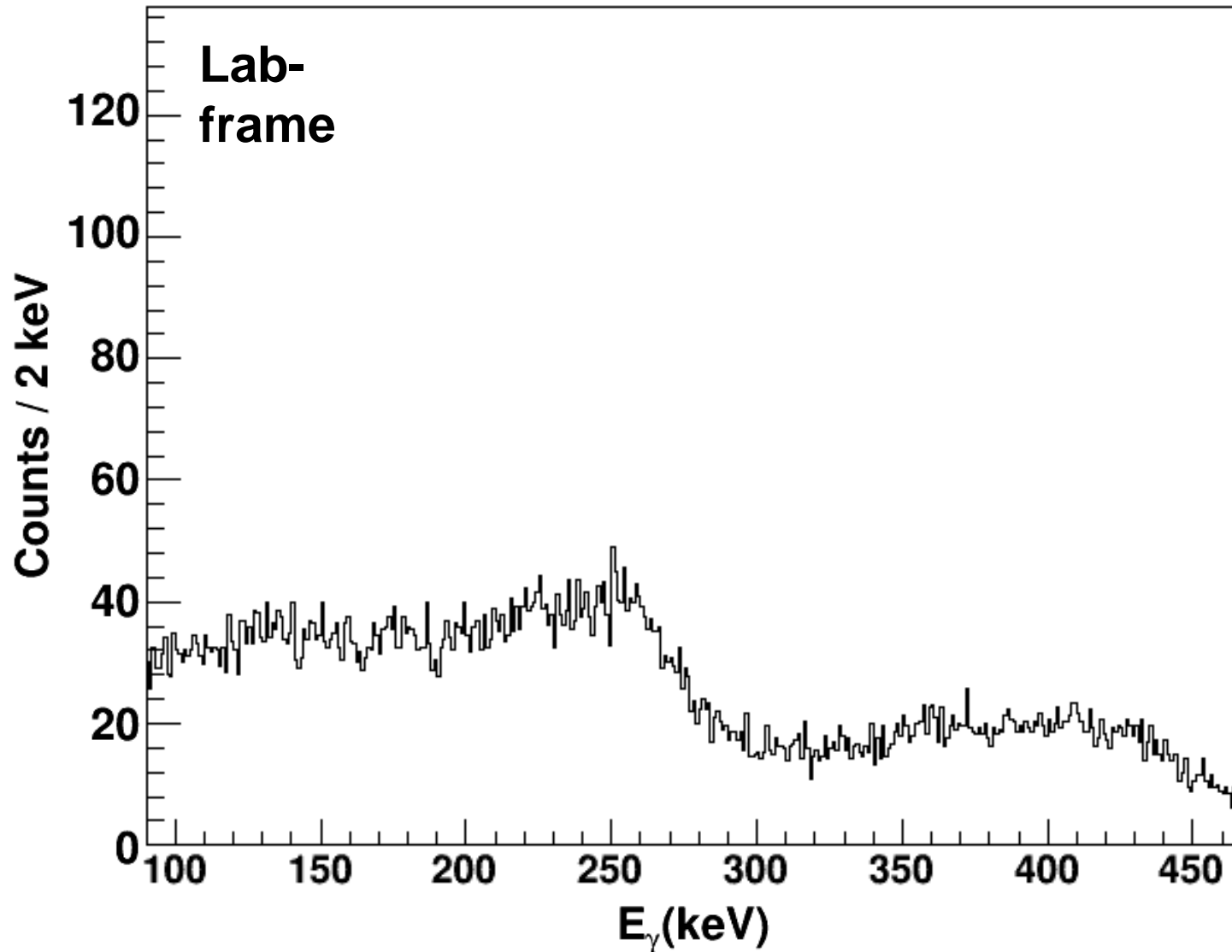
PID to measure  
gamma rays in coincidence  
with  $^{40}\text{Mg}$  produced  
in  $^{41}\text{Al}$  -1p reaction

H.L.Crawford et al.,  
PRL122, 052501 (2019)

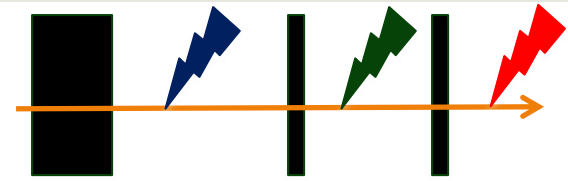


# Gamma spectrum with $^{17}\text{C}$ (lab frame)

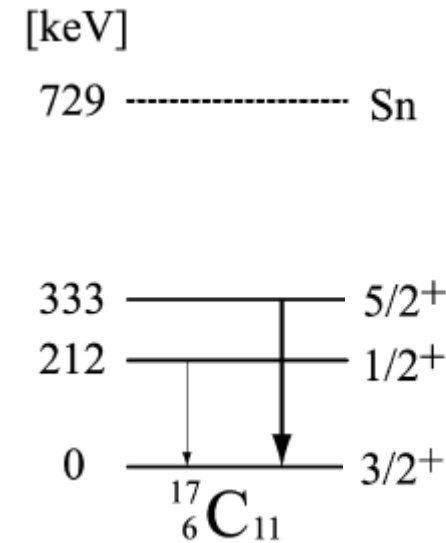
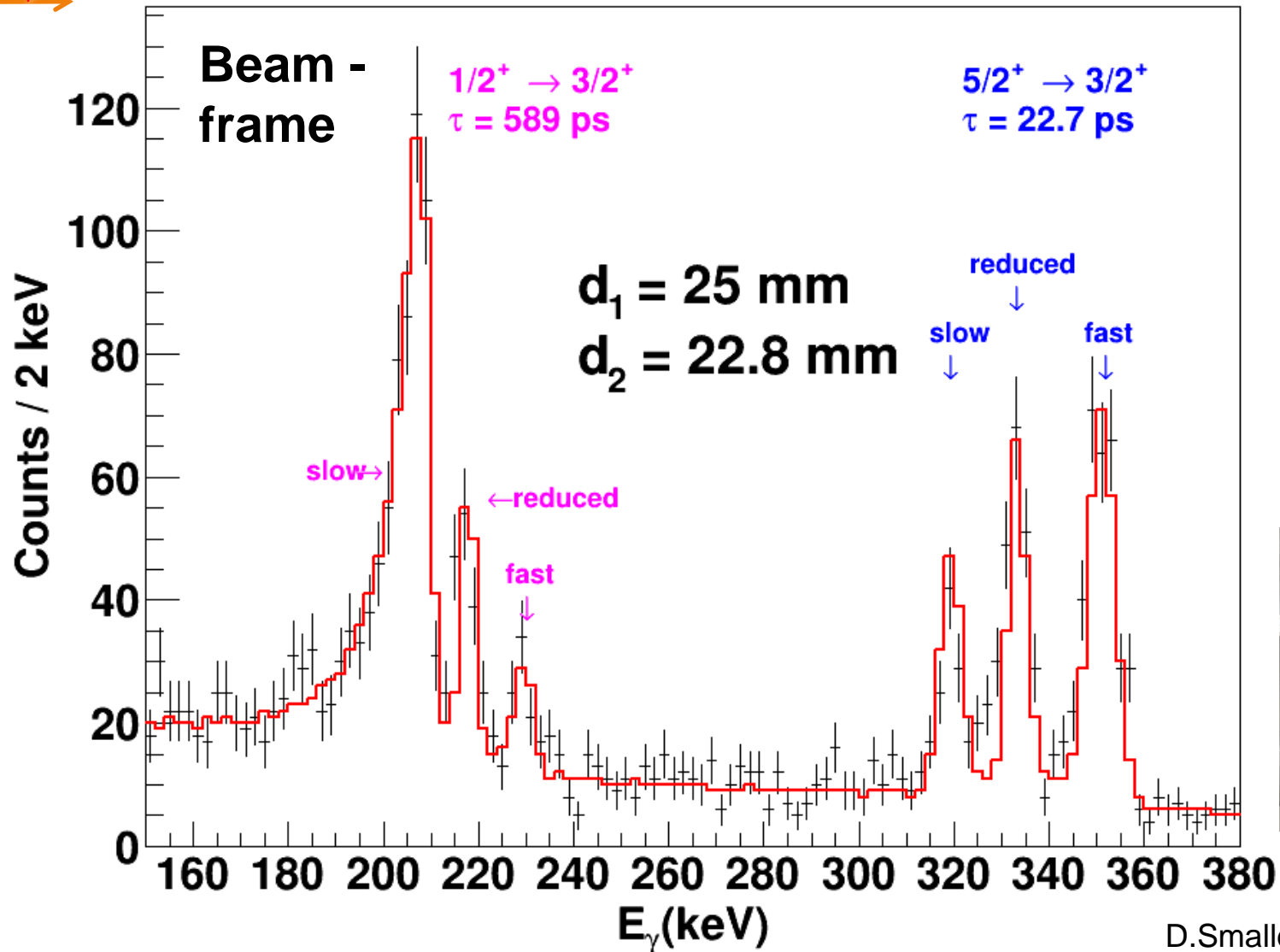
No distinct peak structure (Doppler shifts)



# Gamma spectrum with $^{17}\text{C}$ (beam frame)

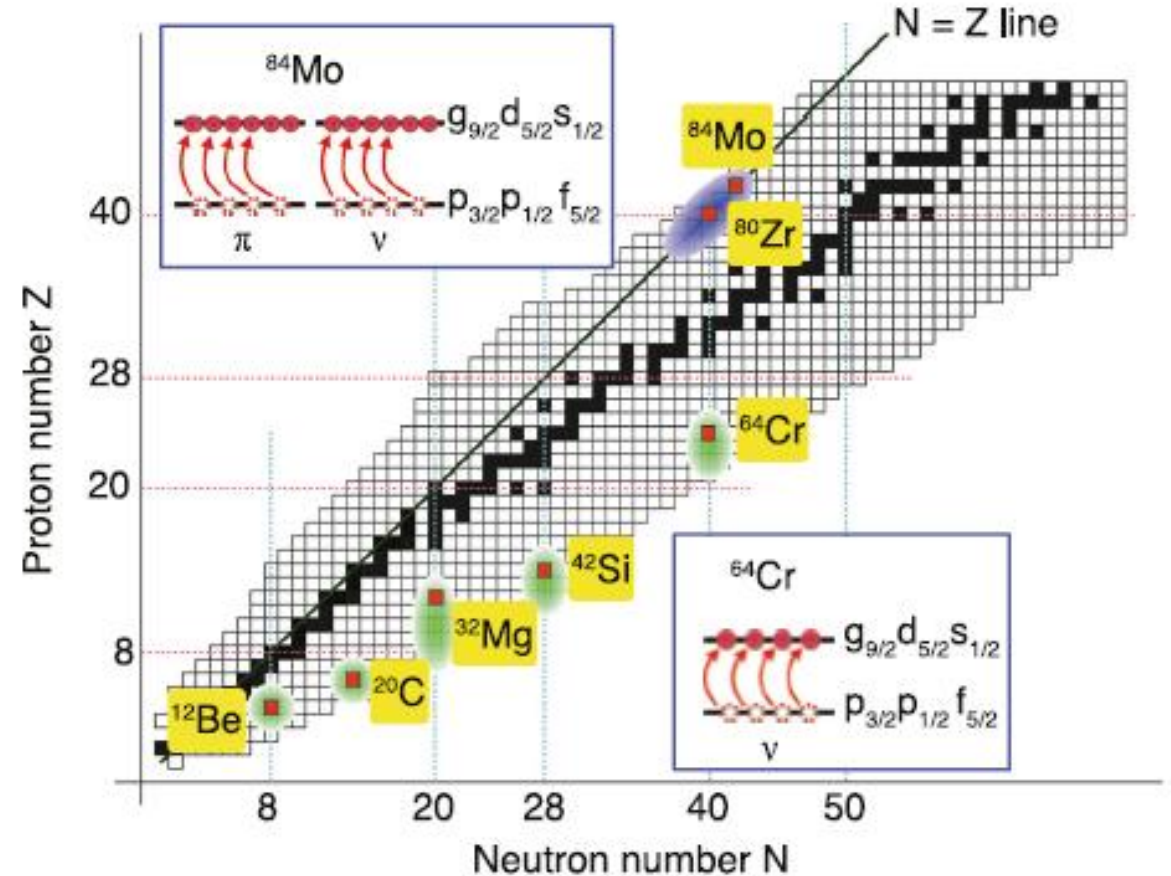
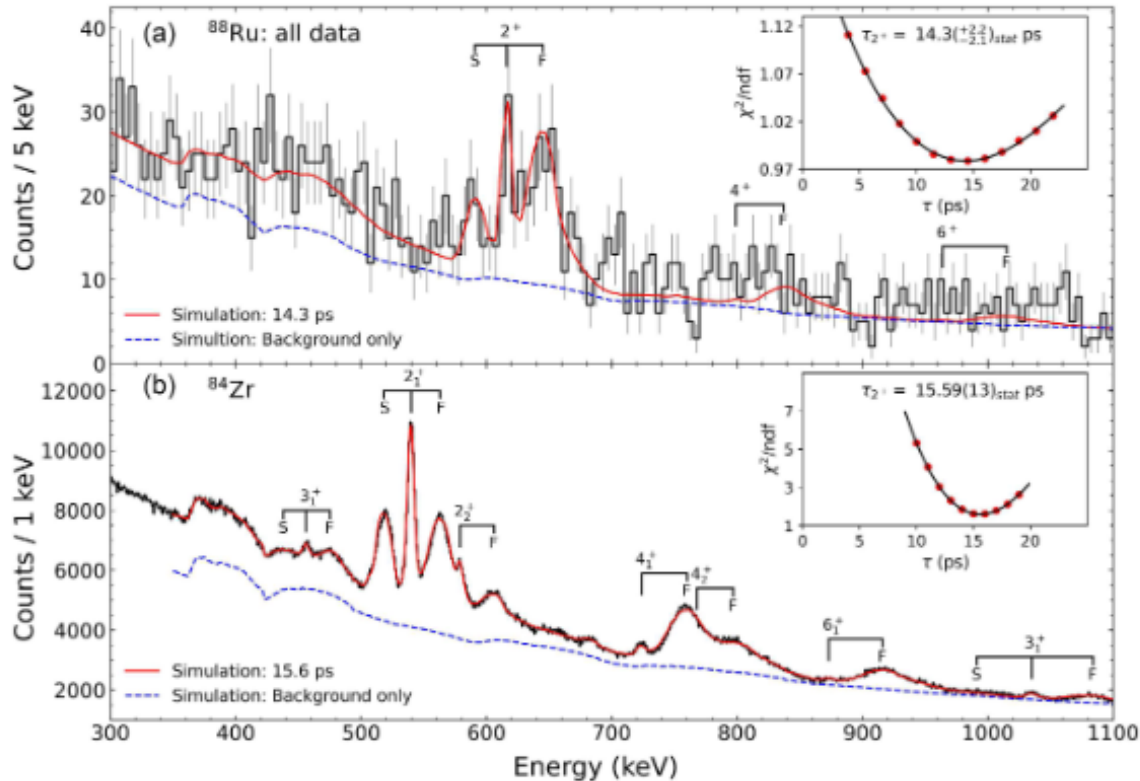
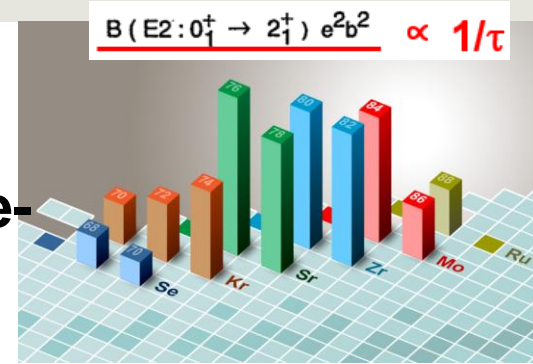


Three Doppler-shift components for lifetime measurements



# Lifetime measurements for maximum deformation at N=Z

Triple-foil lifetime measurements were performed at FRIB for  $^{88}\text{Ru}$  at  $N=Z=44$ . A region of large deformation at  $N=Z$  is defined to cover  $^{76}\text{Sr}$  ( $N=Z=38$ ),  $^{80}\text{Zr}$  ( $N=Z=40$ ), and  $^{84}\text{Mo}$  ( $N=Z=42$ ), which is explained by large-scale shell model calculations with enhanced particle hole excitations.



M.A.Bentley et al., PRL136, 152501 (2026)

J.Ha et al., Nature Communications 16, 10631 (2025)

**Questions before Lunch Break ...**