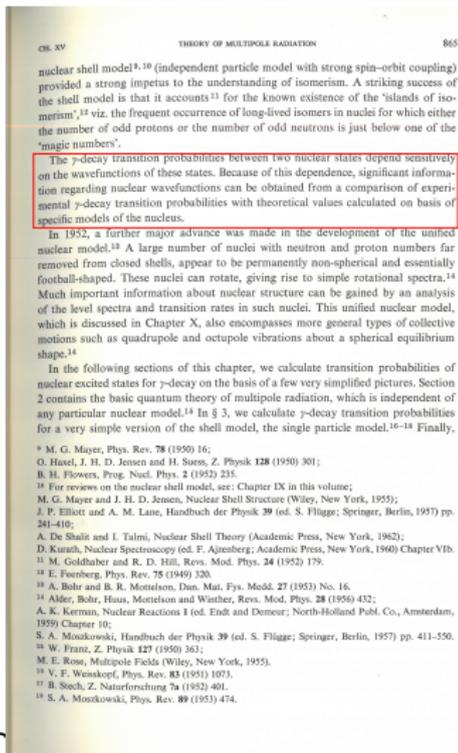


# Electromagnetic transitions, lifetime measurements and the Plunger technique.

J. Ljungvall

December 6, 2021

# Electromagnetic transitions in nuclei - short introduction



## From "Alpha, Beta, and Gamma-ray spectroscopy", K. Siegbahn

- 1 The text in the red square is a good summary of my lecture
- 2 An who is who in nuclear physics in the reference list (2 Nobel Prizes)...

# Electromagnetic transitions in nuclei - short introduction

Hand-waving justification for the statement in the box

$H_0\phi = E_0\phi$ , e.g. an Harmonic Oscillator

Problem we want to solve  $[H_0 + H_1]\varphi = E\varphi$ ,  $\varphi = \sum_0^n c_i\phi_i$

$H_{ij} = \langle \phi_i | H_1 | \phi_j \rangle$ , the interaction

$$\begin{bmatrix} H_{00} & H_{01} & \dots & H_{0n} \\ H_{10} & H_{11} & \dots & H_{1n} \\ \dots & \dots & \ddots & \vdots \\ \dots & \dots & \dots & H_{mn} \end{bmatrix} \begin{bmatrix} c_0 \\ c_1 \\ \vdots \\ c_n \end{bmatrix} = E \begin{bmatrix} \phi_0 \\ \phi_1 \\ \vdots \\ \phi_m \end{bmatrix}$$

Diagonalisation gives E. Eigenvectors, i.e.  $\varphi$ , needed for transition strengths!

# Electromagnetic transitions in nuclei - short introduction

First order time-dependent perturbation theory

$$H = H_{nuc} + H_{EM} + H_{int} = H_0 + H_{int}$$

Eigenstates of  $H_0$  are products of the nuclear states and zero or more photons.

$$\text{Fermi's golden rule } T_{i \rightarrow f} = \frac{2\pi}{\hbar} | \langle f | H_{int} | i \rangle |^2 \frac{dN}{dE}$$

$$H_{int} \propto \mathbf{J} \cdot \mathbf{A}$$

A EM vector potential, "only photons",  $\mathbf{J}$  is current distribution in nucleus, i.e. nuclear physics (wave functions)!

# Electromagnetic transitions in nuclei - short introduction

## First order time-dependent perturbation theory

A comes from solution to the PDE  $\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}\right) A_\mu(\vec{r}, t) = 0$

$$A(\vec{r}, t) \propto \sum_k \sum_\eta \left( b_{k\eta} \epsilon_{k\eta} e^{i(\vec{k}\cdot\vec{r}-\omega t)} + b_{k\eta}^\dagger \epsilon_{k\eta}^* e^{-i(\vec{k}\cdot\vec{r}-\omega t)} \right)$$

we have 0 photons in  $|i\rangle$  and 1 photon in  $|f\rangle$

$$\langle f | H_{int} | i \rangle \propto \langle 1_{k\eta} | b_{k\eta}^\dagger | 0 \rangle \langle f | \mathbf{J} \cdot \epsilon_{k\eta}^* e^{-i(\vec{k}\cdot\vec{r}-\omega t)} | i \rangle$$

# Electromagnetic transitions in nuclei - short introduction

## Multipole expansion of $\vec{A}$

Now expand EM field so it is expressed with definite L,M

$$\begin{aligned} \mathbf{J} \cdot \boldsymbol{\epsilon}_{k\eta}^* e^{-i\vec{k}\cdot\vec{r}} &\propto \sum_{L,M} \sqrt{2L+1} \frac{(-i\omega)^L}{(2L+1)!!} \sqrt{\left(\frac{L+1}{L}\right)} D_{M\eta}^{(L)}(\mathbf{e}_z \rightarrow \mathbf{k}) \\ &\times \left( O_{L,M}^\dagger(EL) - i\eta O_{L,M}^\dagger(ML) \right) \end{aligned}$$

# Electromagnetic transitions in nuclei - short introduction

What did I just try to say?

- We have nuclear states  $|Im\pi\rangle$
- We have  $\langle f|H_{int}|i\rangle$  with  $H_{int}$  written as a sum of terms specified by angular momentum  $L$  and projection  $M$

Using Wigner-Eckart theorem we get for each term in  $\langle f|H_{int}|i\rangle$

$$\begin{aligned} \langle I_f m_f | O_{L,M}^\dagger(E/ML) | I_i m_i \rangle &= (-1)^{I_f - m_f} \begin{pmatrix} I_f & L & I_i \\ -m_f & M & m_i \end{pmatrix} \\ &\times \langle I_f || O_L^\dagger(E/ML) || I_i \rangle \end{aligned}$$

# Electromagnetic transitions in nuclei - short introduction

The reduced transition matrix element  $\langle I_f || O_L^\dagger(E/ML) || I_i \rangle$

If the wavelength of the emitted  $\gamma$ -ray is much larger than the size of the nucleus the following is true

- It contains the nuclear structure information
- Does not depend on energy of emitted  $\gamma$  ray
- Fermi's golden rule  $T_{i \rightarrow f} \propto | \langle I_f || O_L^\dagger(E/ML) || I_i \rangle |^2$

# Electromagnetic transitions in nuclei - short introduction

## Reduced transition probability

Skipping some straightforward but tedious math (as they say;-)

$$B(E/ML; I_i \rightarrow I_f) = \frac{1}{2I_i+1} | \langle I_f || O_L^\dagger(E/ML) || I_i \rangle |^2$$

and

$$\tau_{I_i} \propto 1/B(E/ML; I_i \rightarrow I_f)$$

so the lifetime gives access to the nuclear structure.

# Electromagnetic transitions in nuclei - short introduction

Transition probability, phase-space factors, and Weisskopf units

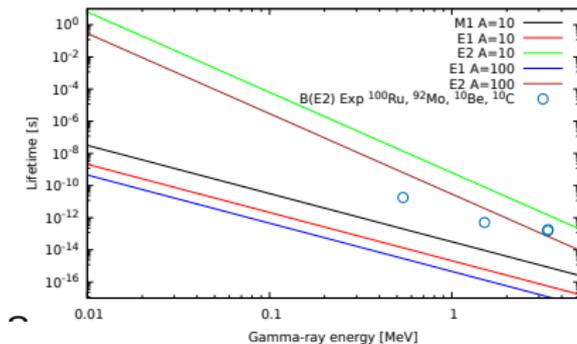
$$\begin{aligned}
 T(E1) &= 1.59 \times 10^{15} E_\gamma^3 B(E1) & T(M1) &= 1.76 \times 10^{13} E_\gamma^3 B(M1) \\
 T(E2) &= 1.23 \times 10^9 E_\gamma^5 B(E2) & T(M2) &= 1.35 \times 10^7 E_\gamma^5 B(M2) \\
 T(E3) &= 5.71 \times 10^2 E_\gamma^7 B(E3) & T(M3) &= 6.31 \times 10^0 E_\gamma^7 B(M3) \\
 T(E4) &= 1.70 \times 10^{-4} E_\gamma^9 B(E4) & T(M4) &= 1.88 \times 10^{-6} E_\gamma^9 B(M4)
 \end{aligned}$$

$$\begin{aligned}
 B_W(EL) &= \frac{1}{4\pi} \left(\frac{3}{3+L}\right)^2 (1.2)^{2L} A^{2L/3} e^2 \text{fm}^{2L} \\
 B_W(ML) &= \frac{10}{\pi} \left(\frac{3}{3+L}\right)^2 (1.2)^{2L-2} A^{(2L-2)/3} \mu_N^2 \text{fm}^{2L-2}
 \end{aligned}$$

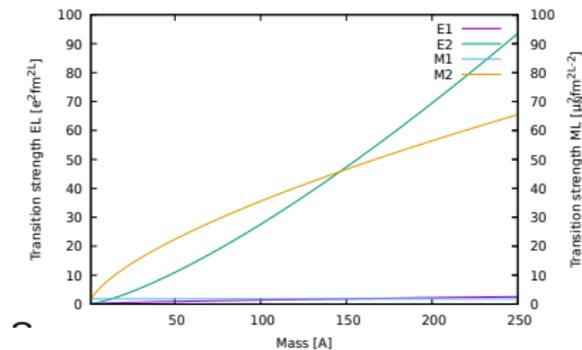
$B/B_W \gg 1$  collective.  $B/B_W \ll 1$  "hindered" transition

# Electromagnetic transitions in nuclei - short introduction

## Lifetimes for 1 W.u.



## W.u vs Mass



$$e^2 \text{fm}^{2L} \approx 90 \mu_N^2 \text{fm}^{2L-2}$$

# Electromagnetic transitions in nuclei - short introduction

Just a reminder of  $\gamma$  decay selection rules

- $E_\gamma = E_i - E_f$  (and a small recoil correction)
- $|I_f - I_i| \leq L \leq I_f + I_i$
- $m_f = M + m_i$
- Parity, i.e.  $\pi_i \pi_\gamma^{E/M} = \pi_f$ ,  $\pi_\gamma^{E/M} = (-1)^{L/L+1}$

If isospin symmetry was exact and in the long wavelength approximation

- No E1 transitions between states with  $T=0$

# Some methods to measure lifetimes (and maybe get a transition strength)

## Measure the lifetime of state

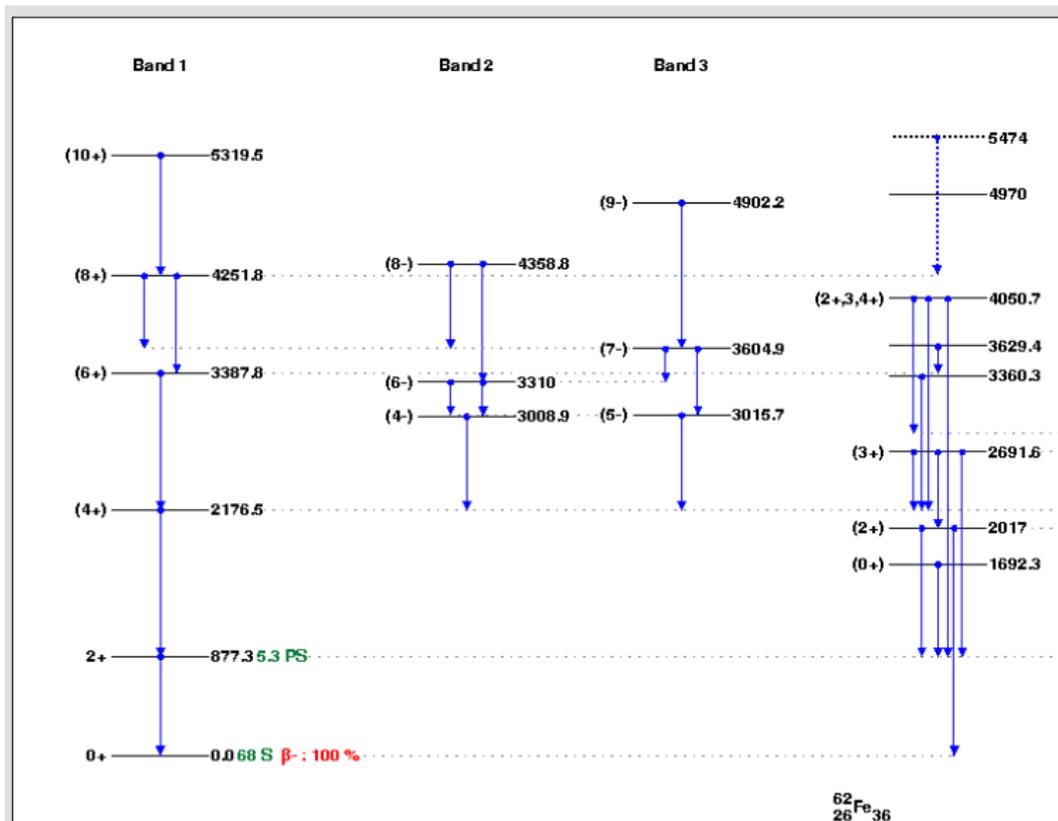
- 1 Fast timing using  $\text{LaBr}_3$  ( $>50$  ps)
- 2 Recoil Distance Doppler Shift ( $>1$  ps)
- 3 Doppler Shift Attenuation Method ( $<1$  ps)

## This give transition strengths if...

- 1 Unmixed  $\gamma$ -ray transition known multipolarity
- 2 Known multipolarities and branching ratios
- 3 Known mixing ratio(s) in transition(s)

So a complete spectroscopy needed

# Lets focus on picosecond lifetimes



# A Plunger



## How to produce excited states in nuclei

We produce excited states by colliding two nuclei:

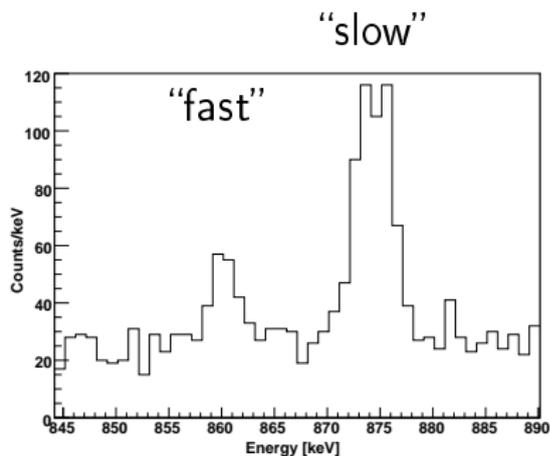
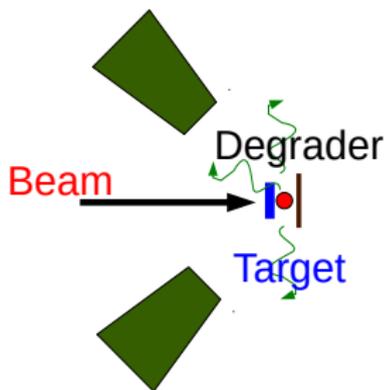
- Scatter off each other, exciting nuclear states via virtual photons
- Fuse together and create a highly excited compound nuclei
- Exchange a few nucleons creating two excited nuclei close to the original nuclei.

We use a thin target so:

- The nucleus has a recoil velocity  $> .5\%$  of  $v/c$   
( $> 1.5 \mu m/ps$ )
- Doppler Shift for the detected  $\gamma$ -ray energies.

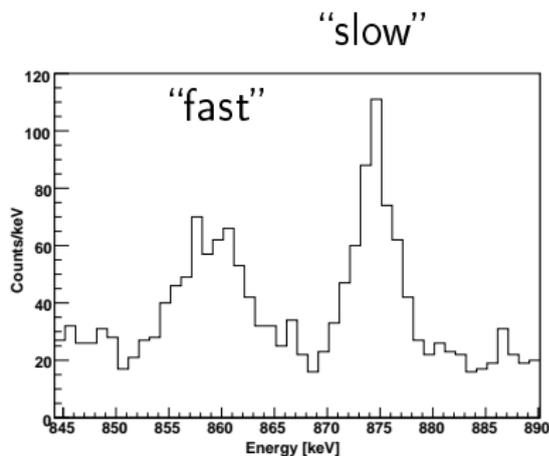
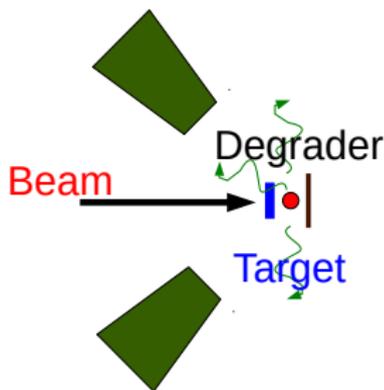
# What is a Plunger

- A device to perform Recoil Distance Doppler Shift (RDDS) measurements to get the lifetime of an excited state



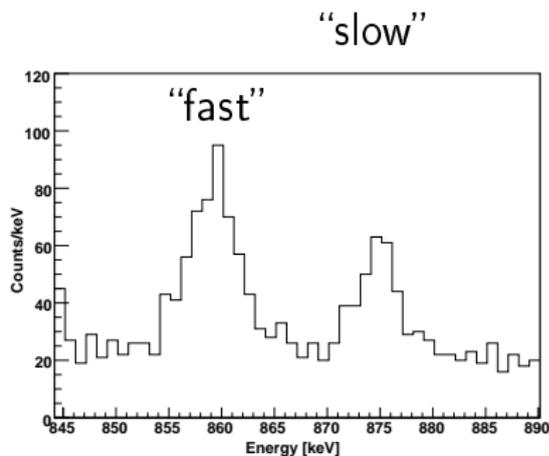
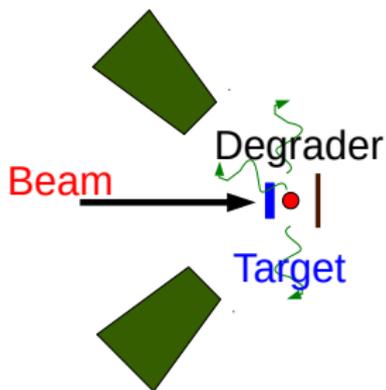
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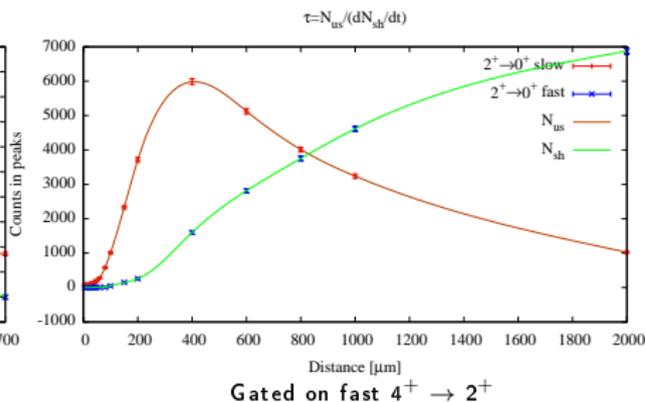
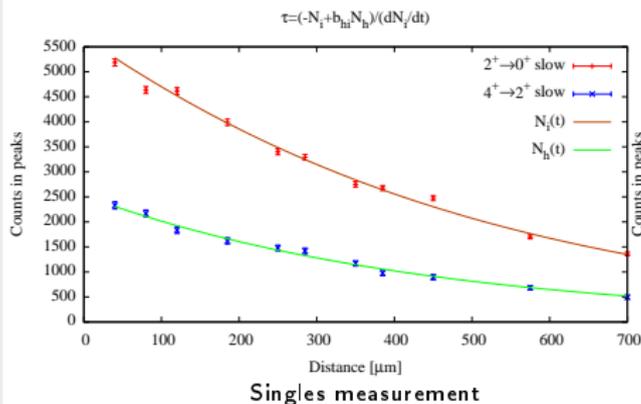
# What is a Plunger

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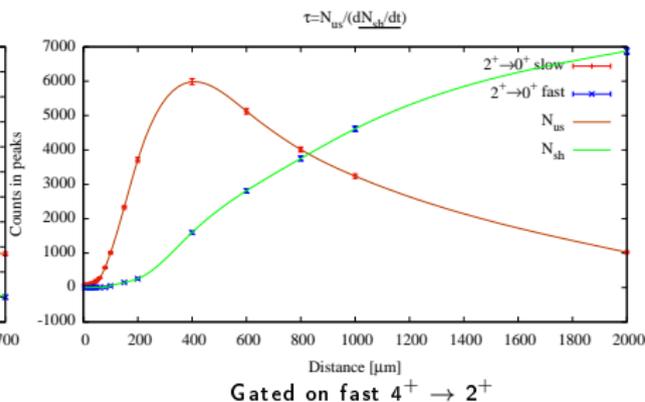
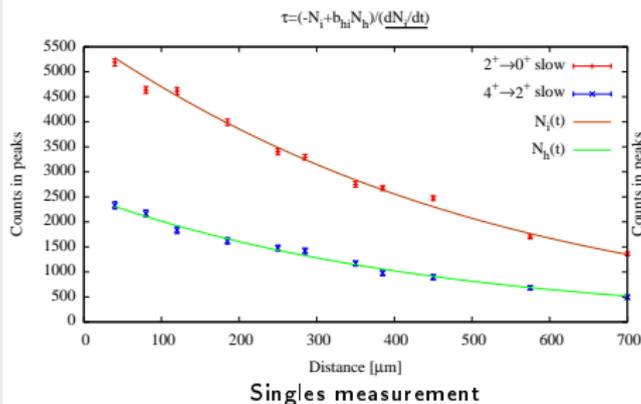
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- A device to perform Recoil Distance Doppler Shift (RDDS) measurements to get the lifetime of an excited state
- Normally data is analysed using so-called Differential Decay Curve Method (DDCM)



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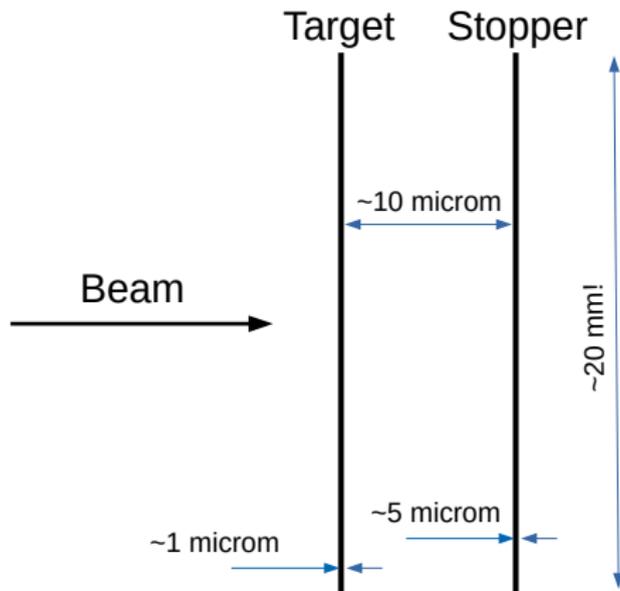
Note  $d/dt$ , removes need to know  $t_0$ !!!

# What is a Plunger

- A device to perform Recoil Distance Doppler Shift (RDDS) measurements to get the lifetime of an excited state
- Normally data is analysed using so-called Differential Decay Curve Method (DDCM)
- High accuracy and precision for lifetimes  $> 1$  picosecond if and only if...

# What is a Plunger

This is a high precision game...



# What is a Plunger

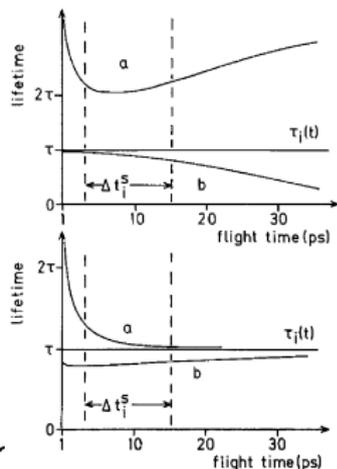
... we can control or correct for:

- ① feeding pattern
- ② assumption of "thin" target and stopper/degrader
- ③ time-dependent angular distributions (recoil-in-vacuum)
- ④ other effects... (not always smaller)

# What is a Plunger

## Feeding pattern

- No problem if one can gate "from above", preferentially on "fast" component
- If statistics does not allow gating,  $\tau(t)$  can be used



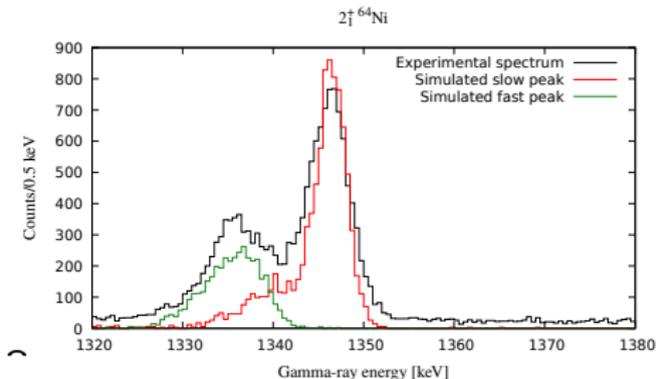
A. Dewald et al. Z. Phys A 334, 163-175 (1989)

# What is a Plunger

## Thin foil assumption

- $A_{fast}(t) \propto \int_0^t N(t') dt'$
- $A_{slow}(t) \propto \int_t^\infty N(t') dt'$

Only true if  $d_{foil}/v < \tau$ .  
 Lifetime of state and feeding history affects peak shapes.  
 Gating on "in-flight" component compromised.

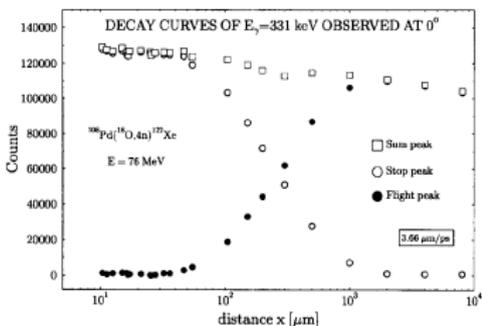


# What is a Plunger

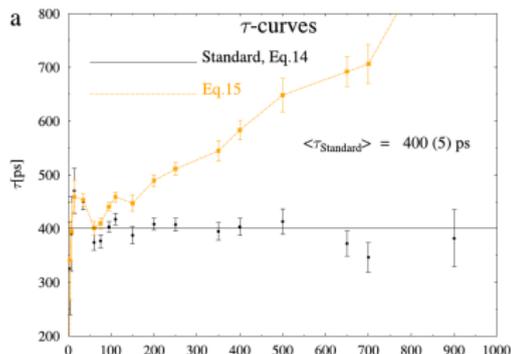
## Recoil-in-Vacuum

Hyper-fine interactions between magnetic moment of nuclear state and electronic spin gives time dependent angular distributions/correlations

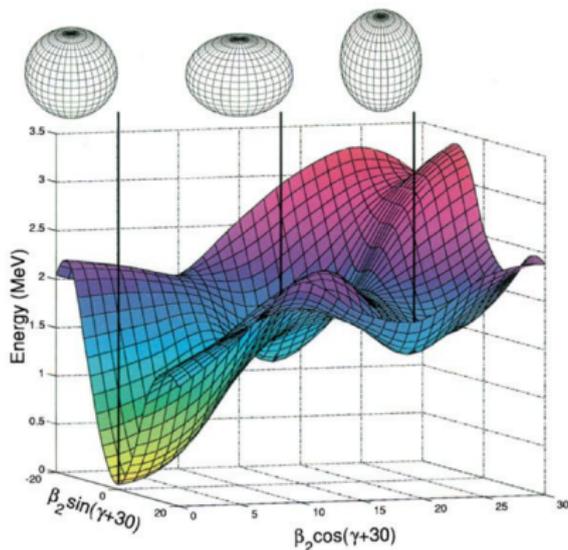
*P. Petkov et al. / Nuclear Physics A 589 (1995) 341–362*



*Nuclear Inst. and Methods in Physics Research, A 877 (2018) 288–292*



# Shape coexistence



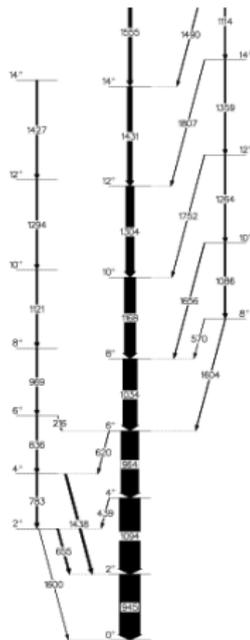
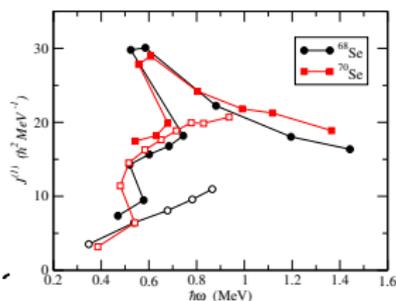
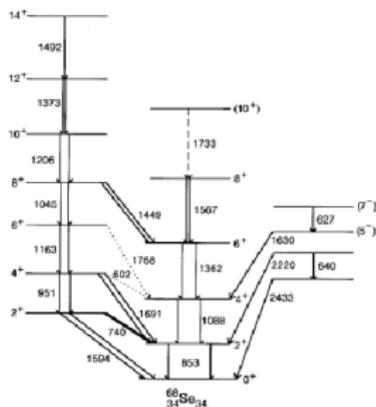
- Close in energy
- Different shapes
- Very stringent test on theoretical descriptions

"Shape coexistence in atomic nuclei", Kris Heyde and John L. Wood, REVIEWS OF MODERN PHYSICS, VOLUME 83, OCTOBER–DECEMBER 2011

A. Andreyev et al., "A triplet of differently shaped spin-zero states in the atomic nucleus  $^{186}\text{Pb}$ ", Nature volume 405, pages 430–433 (25 May 2000)

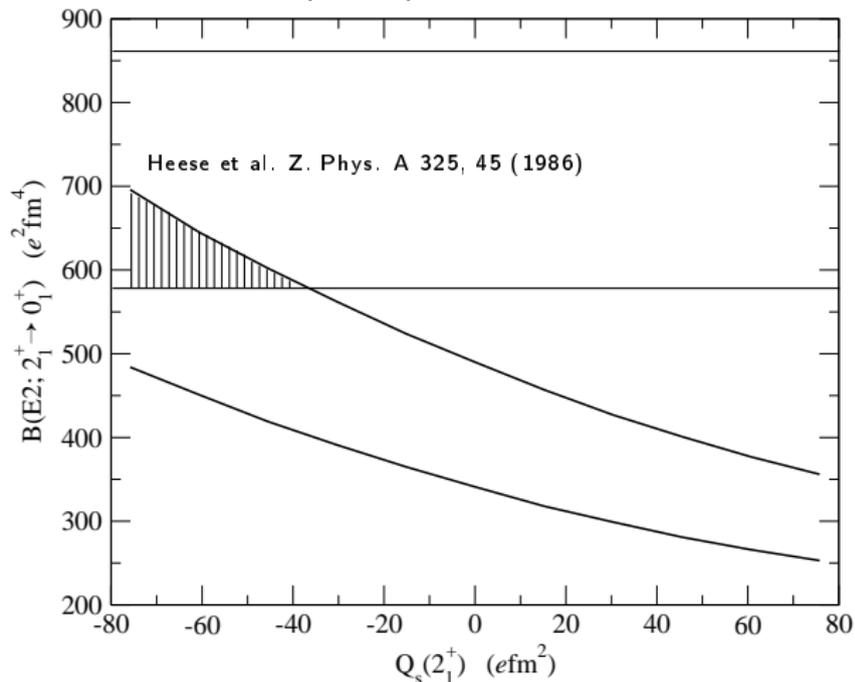
# Shape coexistence at $N \sim Z$ , $^{68-72}\text{Se}$

$^{68}\text{Se}$  considered example of oblate gs and shape-coexistence.  
By similarity  $^{70}\text{Se}$  should also have oblate gs.



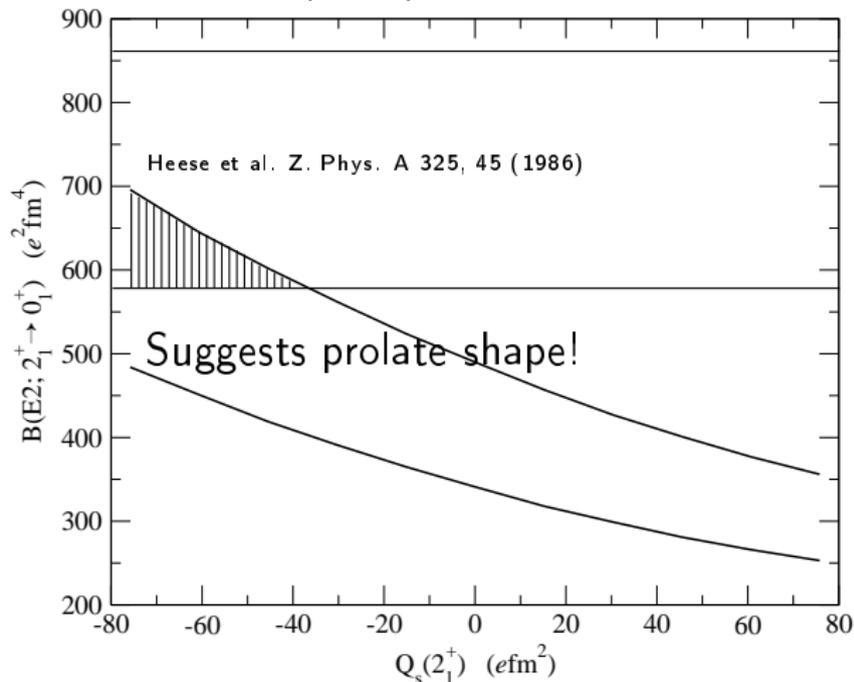
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Coulex measurement at REX-Isolde with MINIBALL, Hurst. et al. PRL 98, 072501 (2007)+lifetime measurement



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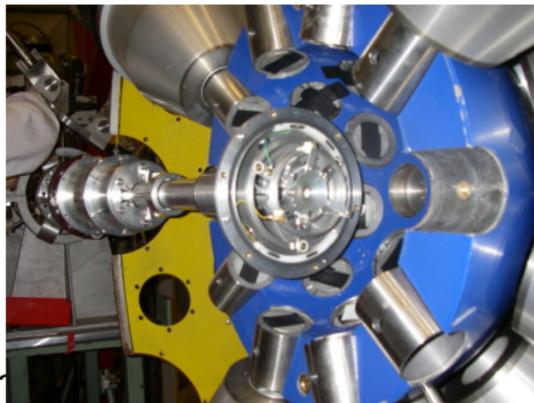
Coulex measurement at REX-Isolde with MINIBALL, Hurst. et al. PRL 98, 072501 (2007)+lifetime measurement



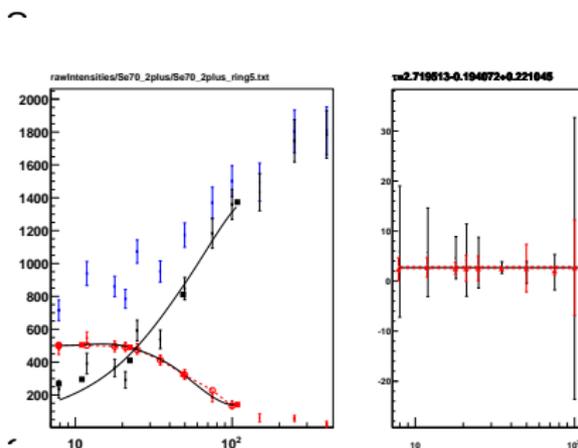
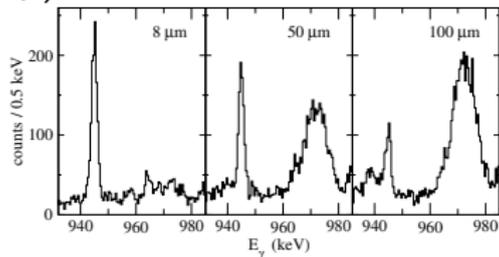
# Shape coexistence at $N \sim Z$ , $^{68-72}\text{Se}$

Surprise, but was old lifetime measurement reliable?

- New experiment  $^{40}\text{Ca}(^{36}\text{Ar}, \alpha 2p)^{70}\text{Se}$

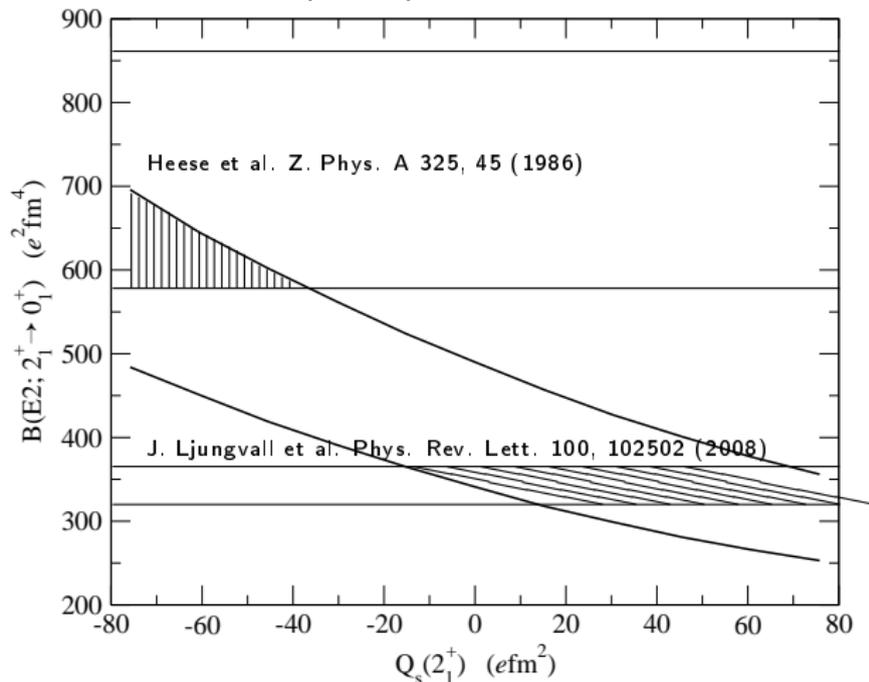


$J^\pi$	$\tau$ (ps)		$B(E2; \downarrow)$ ( $e^2\text{fm}^4$ )	
	new	old	exp.	theo
$^{70}\text{Se}$				
$2^+_{1/2}$	3.2(2)	1.5(3)	342(19)	549
$4^+_{1/2}$	1.4(1)	1.4(3)	370(24)	955
$6^+_{1/2}$	1.9(3)	3.9(9)	530(96)	1404



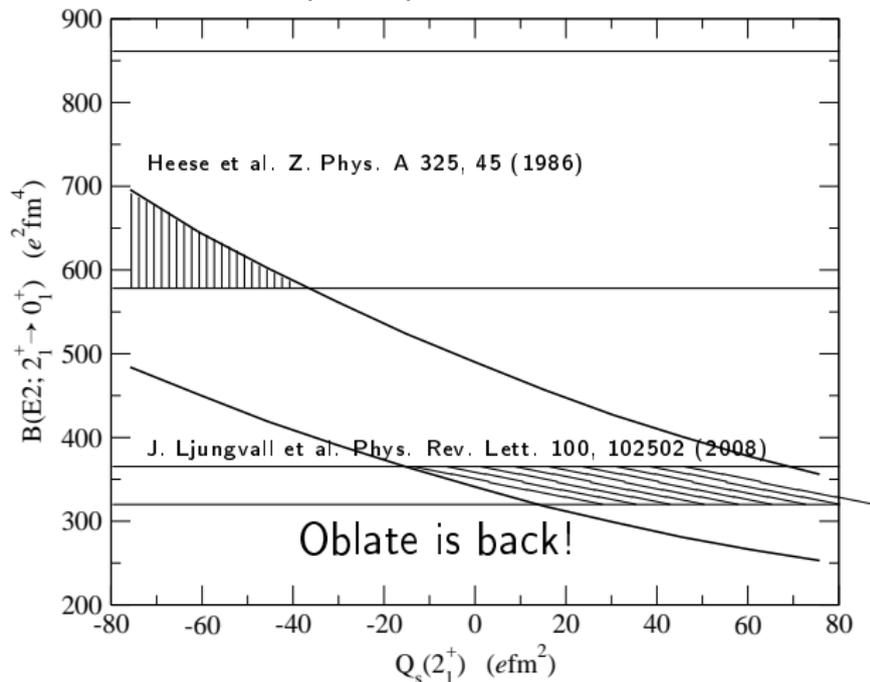
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# Magic numbers always the same? The question of shell evolution

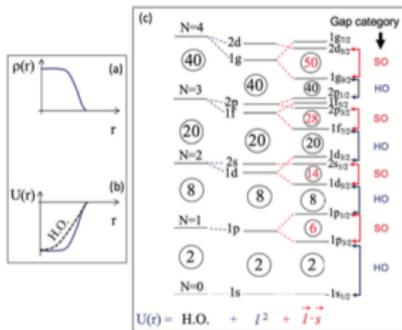


Figure 2 Schematic pictures. (a) Nucleon density distribution  $\rho(r)$  and (b) mean potential  $U(r)$  are shown as a function of the distance from the center of the nucleus,  $r$ . (c) Single-particle energies for a Harmonic Oscillator (HO) potential well, with an added  $l^2$  term and a spin-orbit interaction (SO)  $\vec{l} \cdot \vec{s}$ . Shell-gap categories are shown by HO and SO. The  $N$  label refers here to the oscillator shell  $N = 2(n-1) + \ell$ , with  $(n-1)$  being the number of nodes of the radial wave function and  $\ell$  the orbital angular momentum.

- Not fixed for all  $Z$  and  $N$
- Exotic nuclei probe for N-N interaction

SO density dependence, Tensor force, 3N forces, Pseudo-spin symmetry. . .

"Evolution of nuclear structure in exotic nuclei

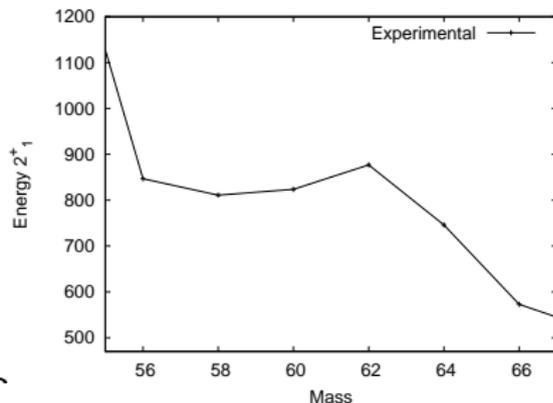
driven by nuclear forces" Rev. Mod. Phys. 92,

015002

# Shell evolution at N=40

What happens as we approach N=40?

- $^{68}\text{Ni}$  is spherical (with multiple examples of shape-coexistence)
- Energy systematics in iron suggest more collectivity
- The way to investigate is to measure the  $B(E2)$ 's

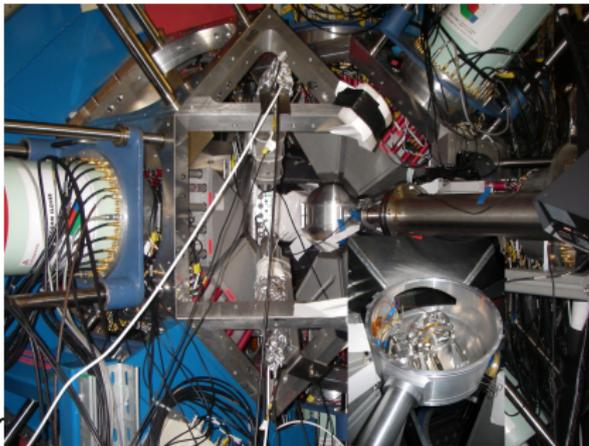


# Shell evolution at $N=40$

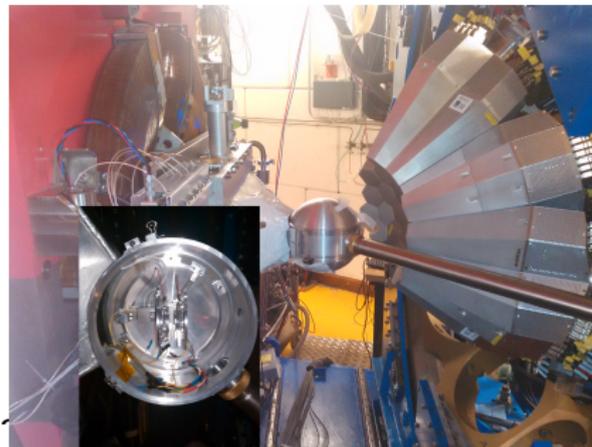
Two experiments using Multi-nucleon transfer reaction  $^{238}\text{U}$  beam@6.5 MeV/A on  $^{64}\text{Ni}$  target and VAMOS.

2009,  $2_1^+$  in  $^{62,64}\text{Fe}$   
EXOAM+Cologne plunger

2015,  $4_1^+$  in  $^{62,64}\text{Fe}$   
AGATA+OUPS

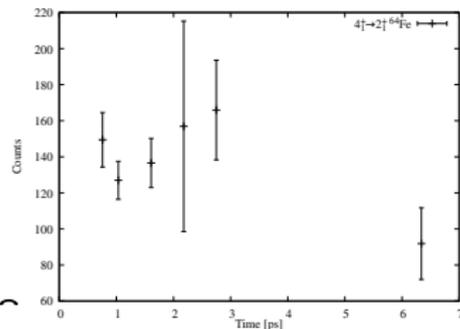
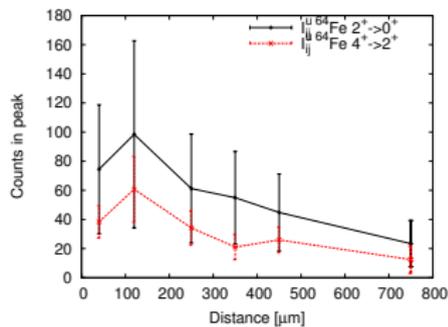
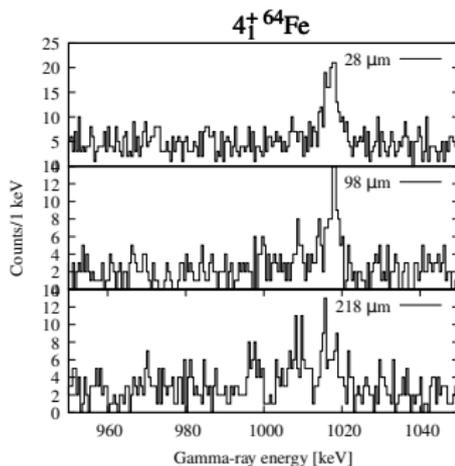
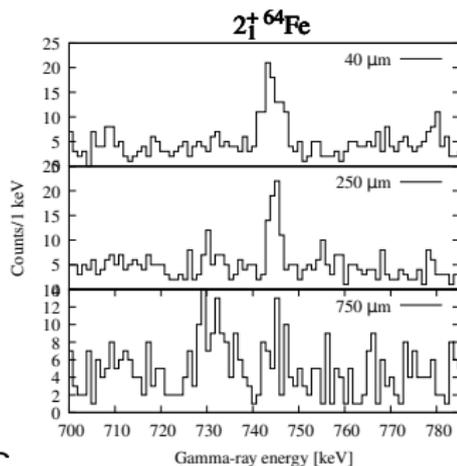


Plunger, Prog. Part. Nucl. Phys. 67, 786 (2012)

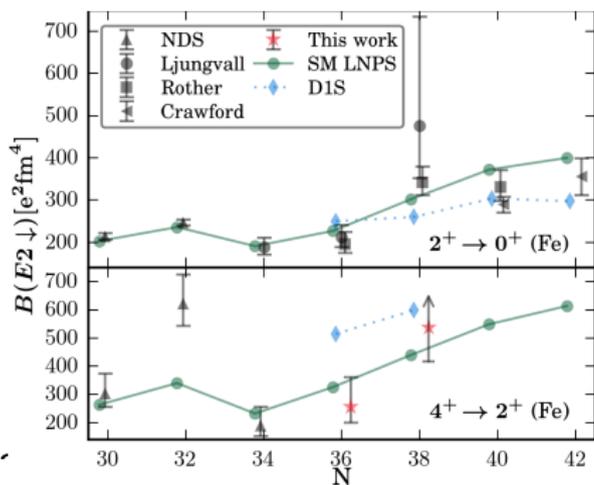


OUPS, NIM A679, 61-66 (2012)

# Shell evolution at N=40



# Shell evolution at N=40



- J. Ljungvall et al. PRC 81, 014310 (2010)
- M. Klintefjord et al. PRC 95, 024313 (2017)

- Monopole drift from tensor force "activates quadrupole partners" **Collectivity**
- This is "SU(3)" behaviour found at N=20,40, and 50 shell closure, "The island of inversions"