TOPTIER-CNS Summer School 2026, August 23-29, 2026, IBS Science Culture Center

# Nuclear structure studies by decay spectroscopy

Hiroshi Watanabe
CENS, IBS

# self-intro


- **Hiroshi WATANABE**
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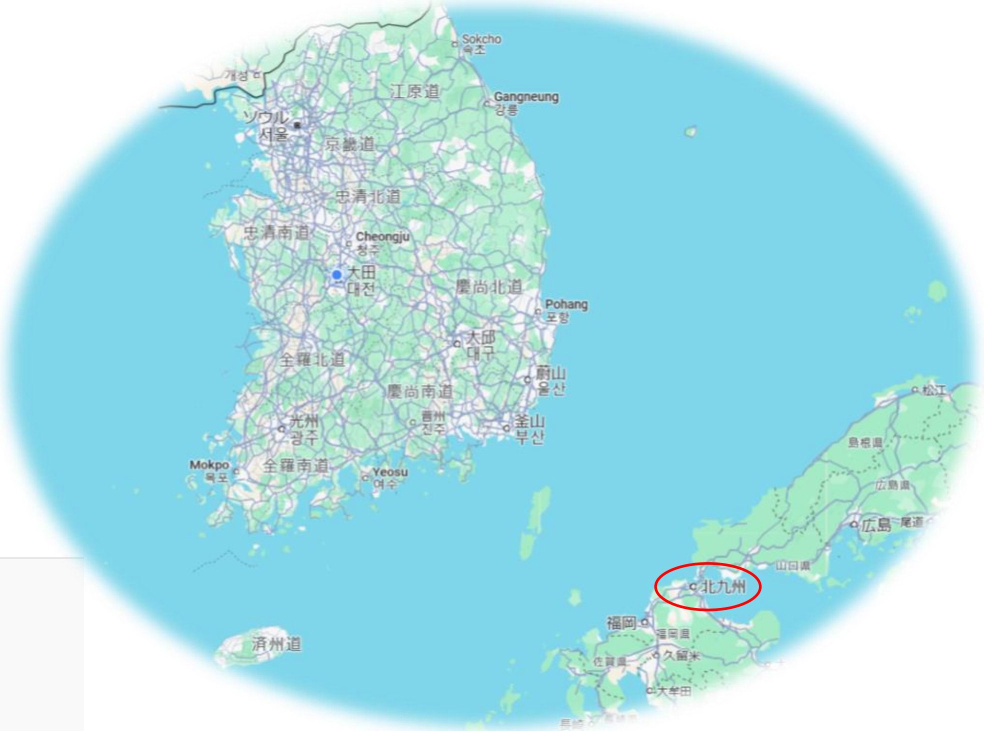
Detail




- **Information**

  Research experience

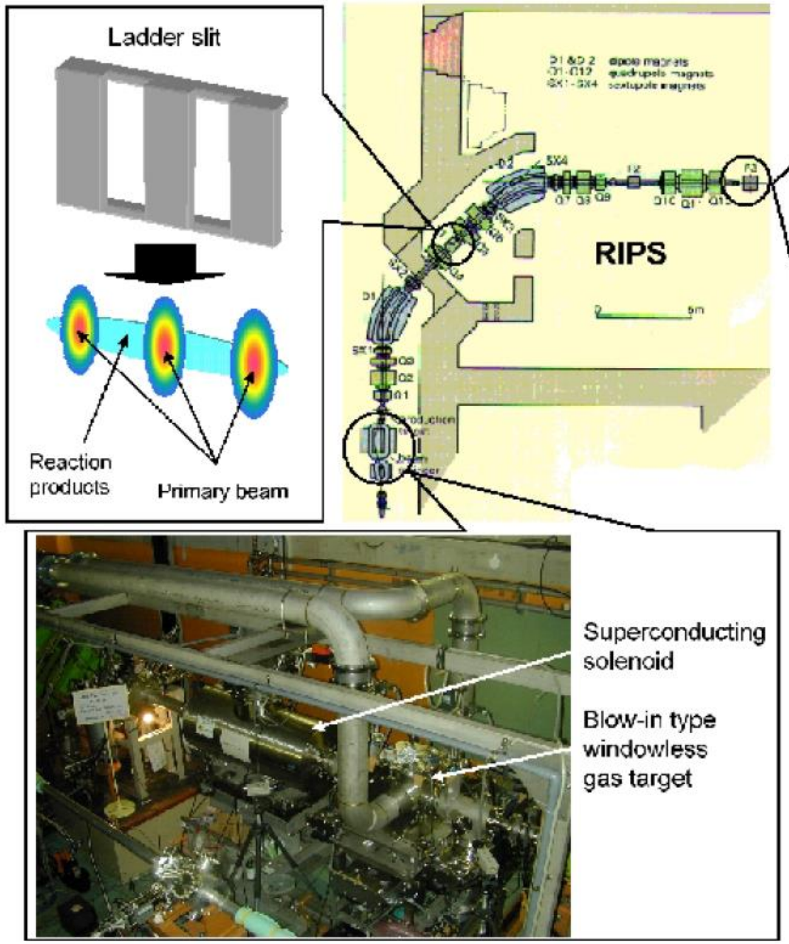
  - Senior Research Fellow, Center for Exotic Nuclear Studies at IBS, Korea (Mar. 2025 - Present) → IDATEN project at RIBF, γ-ray spectroscopy at RAON
  - Visiting Professor, Wako Nuclear Science Center at KEK (Apr. 2021 - Present)
  - Professor, School of Physics at Beihang University, China (Jan. 2013 - Feb. 2025) → Decay spectroscopy with EURICA, KISS, and IDATEN
  - Research Associate, Nishina Center at RIKEN, Japan (Aug. 2007 - Dec. 2012) → First decay spectroscopy at RIBF
  - Postdoctoral Fellow, Department of Nuclear Physics at ANU, Australia (May 2004 - Jul. 2007) → γ-ray and electron spectroscopy at ANU and ANL
  - Contract Research Scientist, Applied Nuclear Physics Laboratory at RIKEN, Japan (Jul. 2000 - Apr. 2004) → Nuclear moment measurements at RIKEN

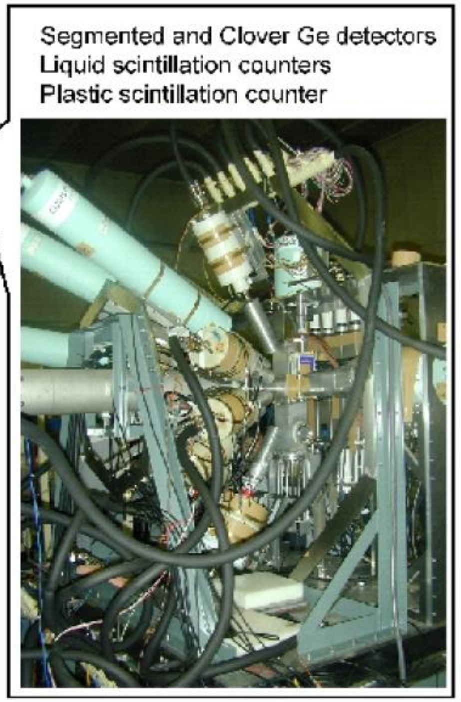
  Education

  - Ph.D. in Physics, Kyushu University, Japan → Secondary fusion reactions using high-spin isomer beams
  - MSc in Physics, Kyushu University, Japan → Development of unstable $^{6}$He beams
  - BSc in Physics, Kyushu University, Japan

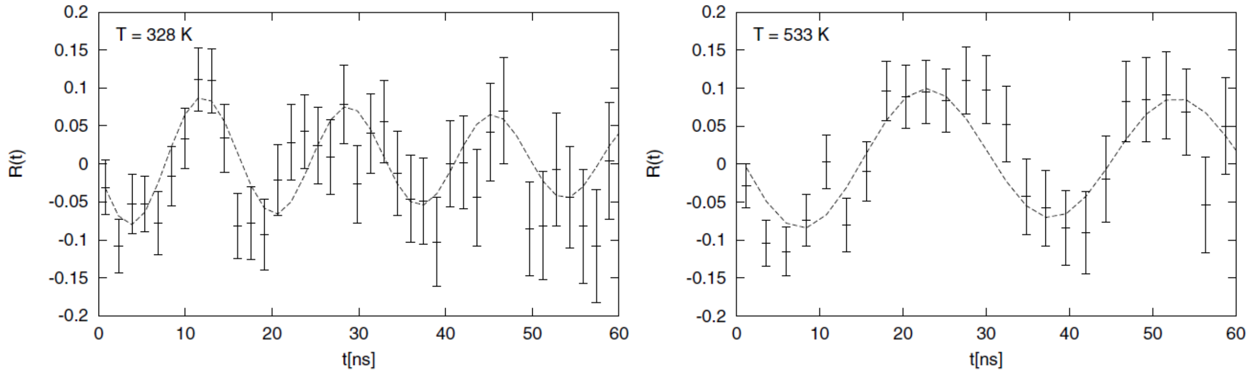
# self-intro

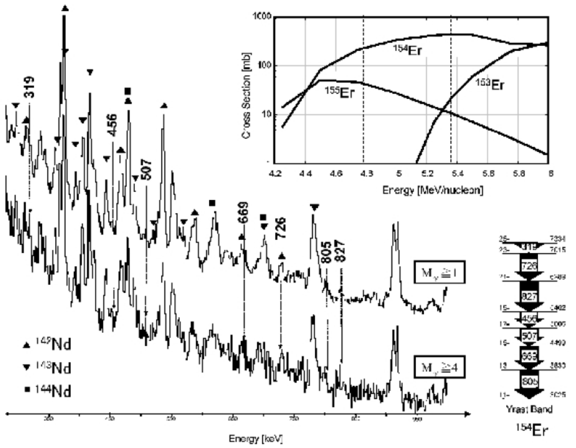
Research using high-spin isomer beams at RIKEN




g-factor measurement of the $49/2^+$ isomer in $^{149}$Dy



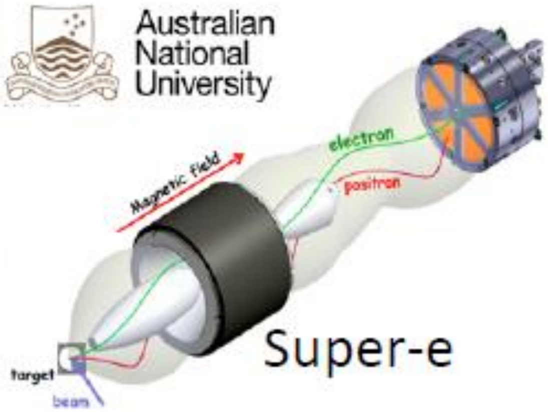

Secondary fusion reaction with $^{145}$Sm HSIB

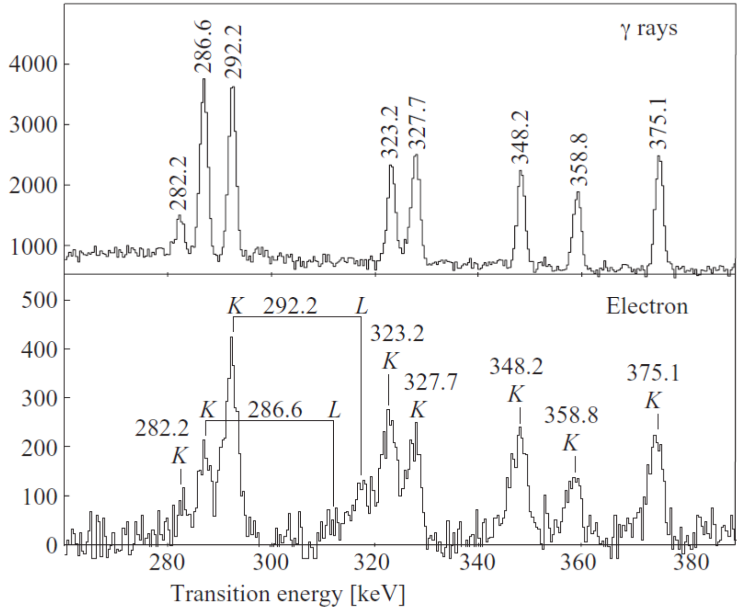
# self-intro

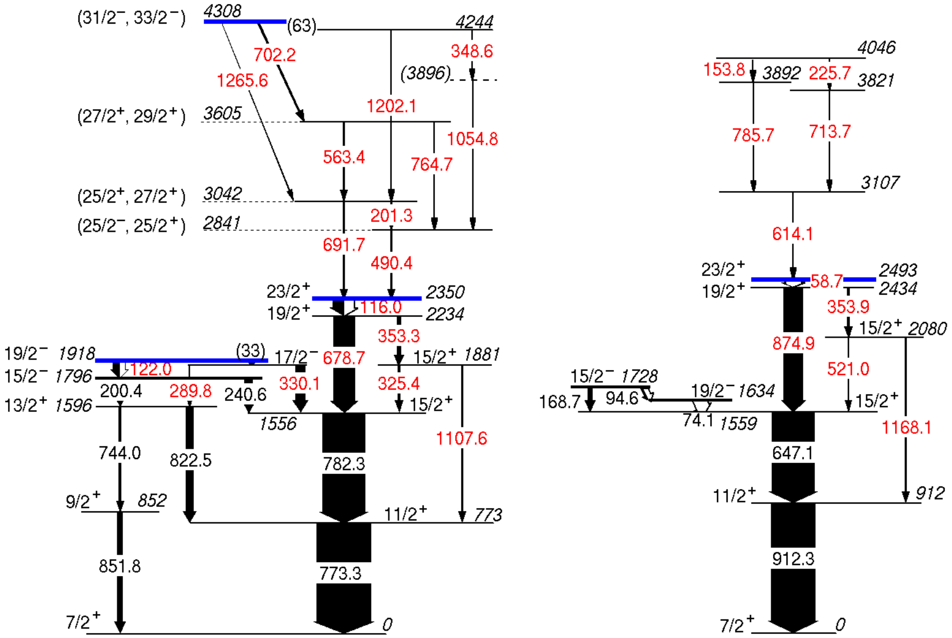
## Gamma-ray and electron spectroscopy at ANU and Argonne

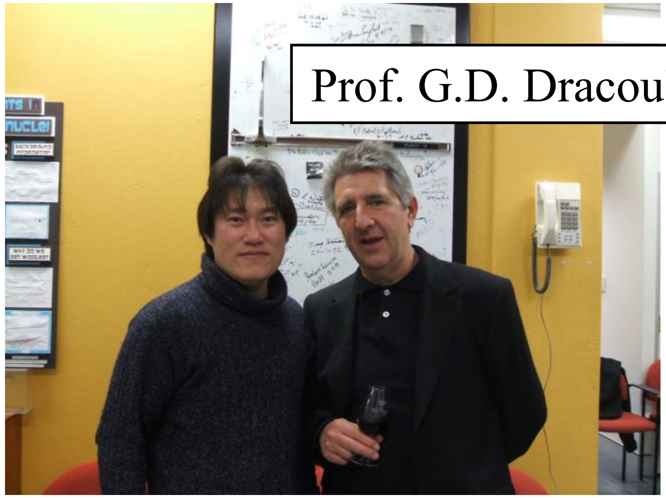
GAMMASPHERE

CAESAR



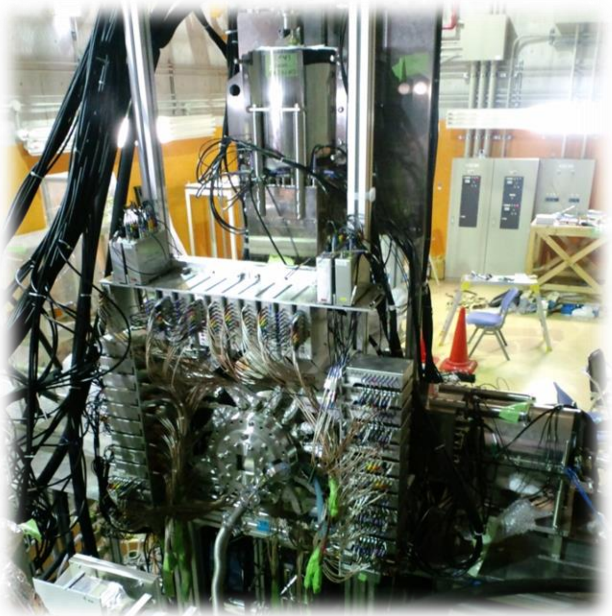



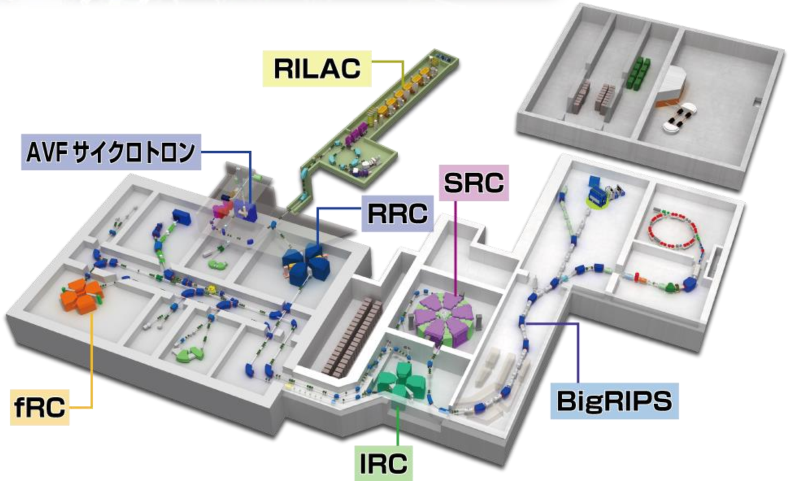



Prof. G.D. Dracoulis

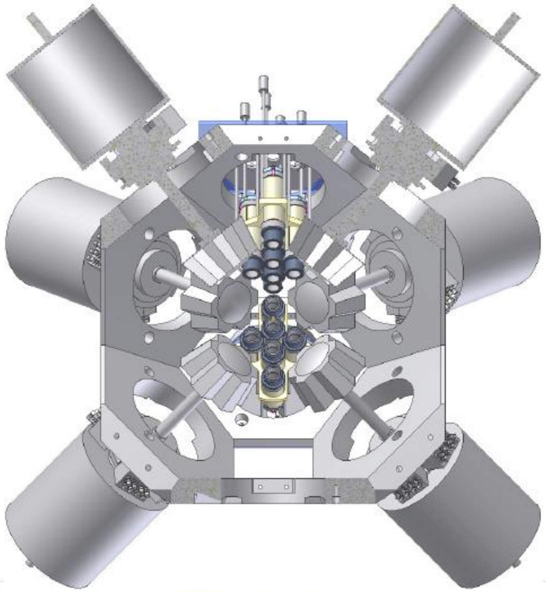
# self-intro

First decay spectroscopy at RIBF

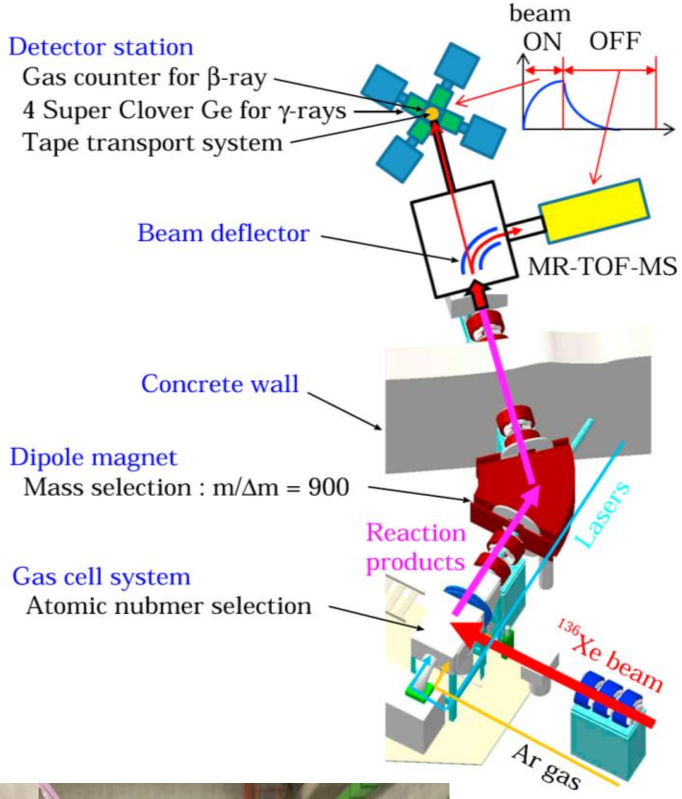





EURICA project at RIBF



Decay spectroscopy at KISS

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Review

published in 2017

# Exotic nuclei explored at in-flight separators

T. Nakamura[a,b,*], H. Sakurai[b,c], H. Watanabe[b,d]

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[b] RIKEN Nishina Center, Saitama, Japan
[c] Department of Physics, University of Tokyo, Tokyo, Japan
[d] IRCNPC, School of Physics and Nuclear Energy Engineering, Beihang University, Beijing, China

- Overview of in-flight separators
- Experiments by particle identification
- Experiments with stopped beams
- Experiments with reactions
- Future perspectives

Eur. Phys. J. A (2019) **55**: 19
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THE EUROPEAN PHYSICAL JOURNAL A


Review

published in 2019

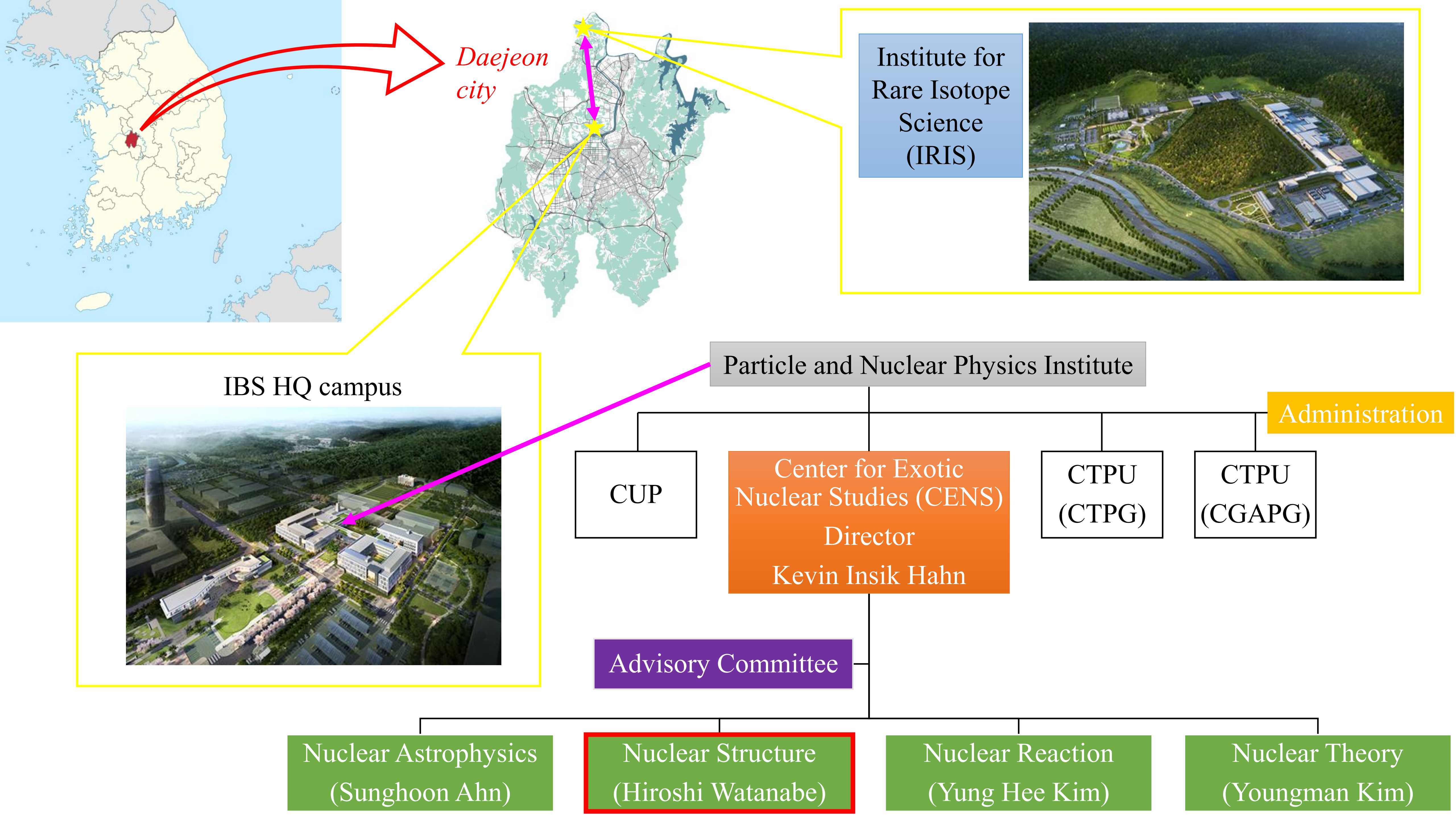
# Nuclear decay studies of rare isotopes

## Overview of decay spectroscopy at RIBF

Hiroshi Watanabe[1,2,a]

[1] IRCNPC, School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191 China
[2] RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

- Experimental details
- Decay spectroscopy of neutron-rich nuclei
- Decay spectroscopy of proton-rich nuclei
- Ongoing projects and future perspectives


Daejeon city
Institute for Rare Isotope Science (IRIS)
IBS HQ campus
Particle and Nuclear Physics Institute
Administration
CUP
Center for Exotic Nuclear Studies (CENS)
Director
Kevin Insik Hahn
CTPU (CTPG)
CTPU (CGAPG)
Advisory Committee
Nuclear Astrophysics (Sunghoon Ahn)
Nuclear Structure (Hiroshi Watanabe)
Nuclear Reaction (Yung Hee Kim)
Nuclear Theory (Youngman Kim)

# Research interest of Nuclear Structure group at CENS

■ **Probing the mechanism of a quantum many-body system:**

- Magicity loss and new magic numbers (shell evolution)
- Shape co-existence and higher-order deformation
- Isospin breaking, seniority (non-)conservation
- Proton-neutron (T=0) pairing

■ **Filtering/enhancing specific interactions relevant to fundamental symmetries:**

- β/γ asymmetry and correlations from polarized nuclei
- γ-ray circular polarization from parity-mixed nuclear levels

■ **Exploring exotic nuclei and their sensitivity to nucleosynthesis:**

- Decay properties (β-$T_{1/2}$, $P_n$, etc.) and masses
- Isomers on s/i/r-process pathways

Hiroshi WATANABE

Yung Hee KIM

Byul MOON

Xesus PEREIRA-LOPEZ

Arunita MUKHERJEE

Zhiqiang CHEN

Youngseub JANG

Jaehwan LEE

Minju KIM

# Contents of today's lecture

- Basic properties of atomic nuclei
  - Scale in physics; Shell structure; Deformation

- Decay spectroscopy and related topics

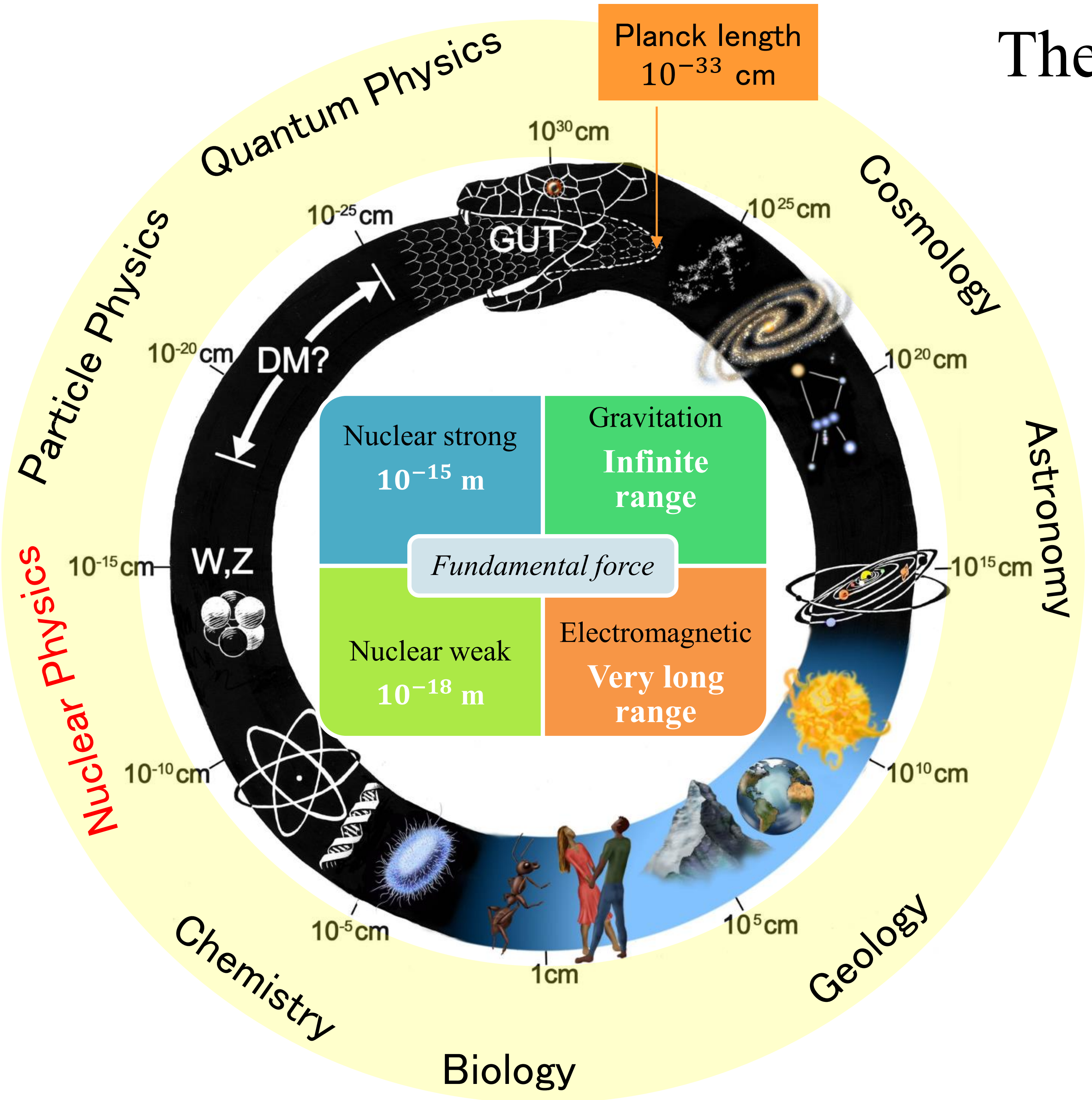
- β decay
- γ-ray emission
- Isomeric transition

⇒

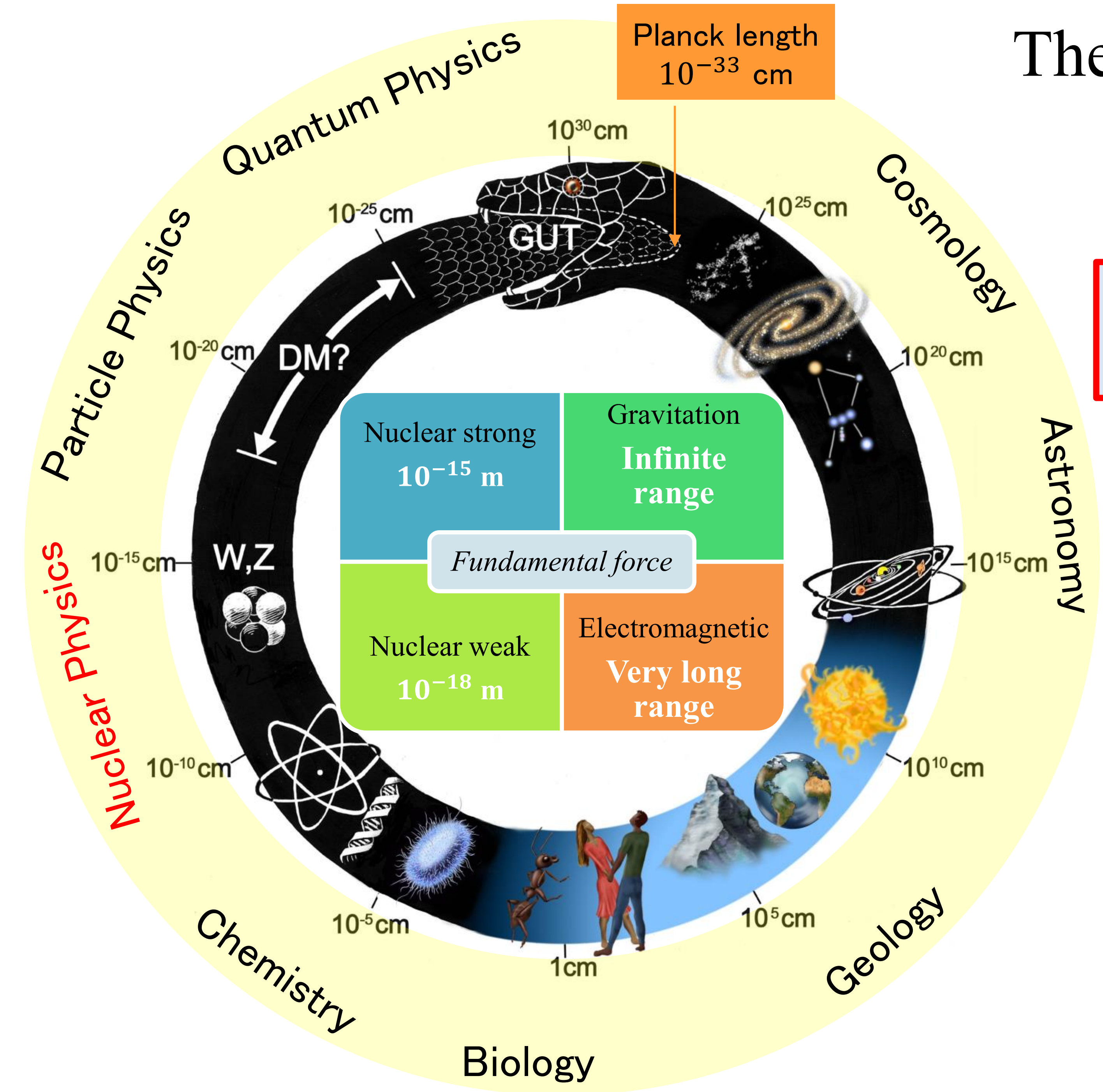
- ✓ Single-particle structure
- ✓ Nuclear shapes and collectivity
- ✓ Symmetry breaking (parity, seniority, axial/rotational symmetry)

# The cosmic Uroboros by Glashow

Cyclic nature of scientific subjects from very large scale to extremely small scale




Sheldon Glashow
Nobel Prize in
Physics (1979)




# The cosmic Uroboros by Glashow

Cyclic nature of scientific subjects from very large scale to extremely small scale

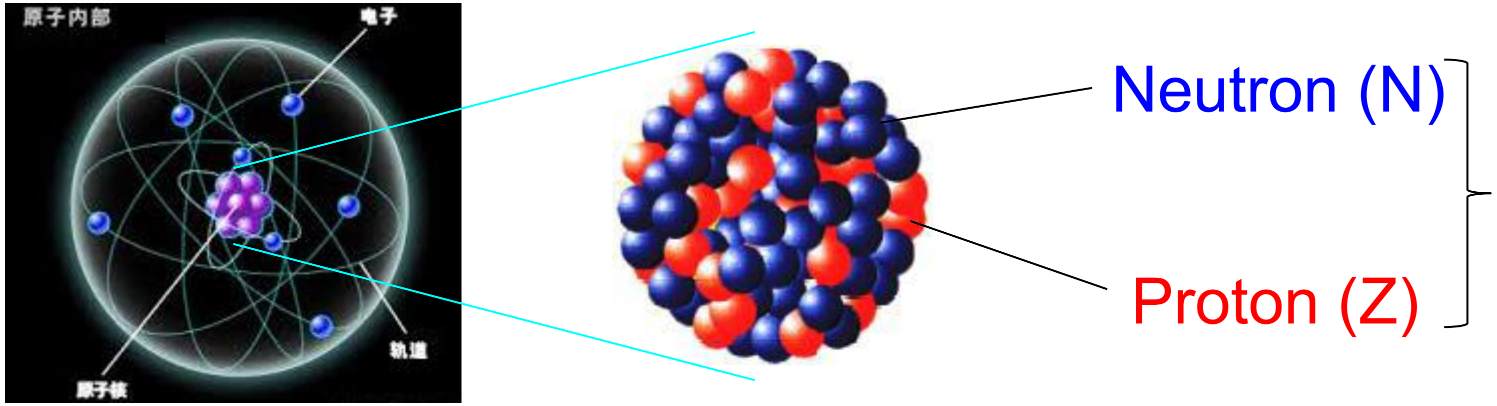
## Fundamental forces relevant to Nuclear Physics

### Nuclear strong
- Strongest force
- Mediated by gluon and pion
- **Binds quarks and nucleons**

### Gravitation
- Weakest force
- Mediated by graviton (hypothetical)
- Influential in massive objects

### Nuclear weak
- Second weakest force
- Mediated by $W^{\pm}$ and Z bosons
- **Responsible for β decay**

### Electromagnetic
- Second strongest force
- Mediated by photon
- **Affects charged particles and magnetism**




Mass number
N + Z = A

$^{A}_{Z}X_{N}$

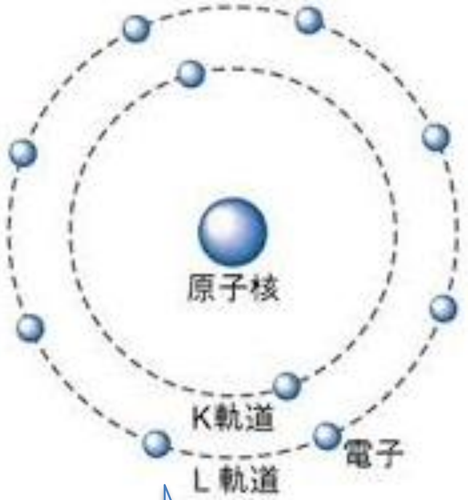
**Many-body quantum system consisting of protons and neutrons in a confined space**

Self-aggregated by strong nuclear force

| Macroscopic (classical) aspects | Microscopic (quantum) aspects |
|---|---|
| Surface and volume | Pairing correlation |
| Shape and deformation | Quantized energy levels |
| Mean–field potential | Shell effect |
| Collectivity motion | Effective interactions |

**A rich variety of phenomena emerge according to the combination of Z and N, energy, angular momentum, etc.**

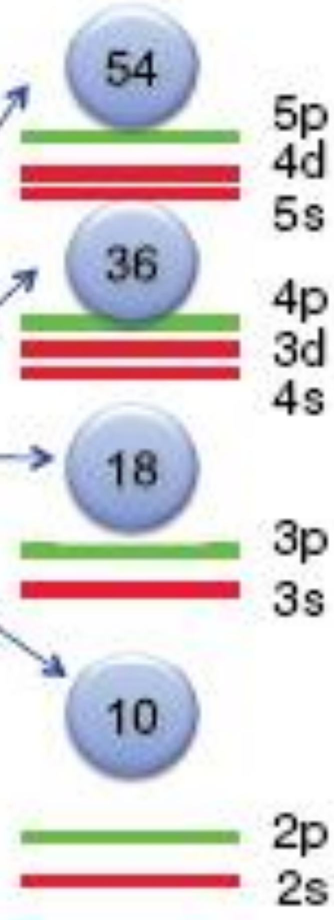
# Various aspects of atomic nuclei: Shell structure




Mean field made by the **nucleus** (Coulomb force)

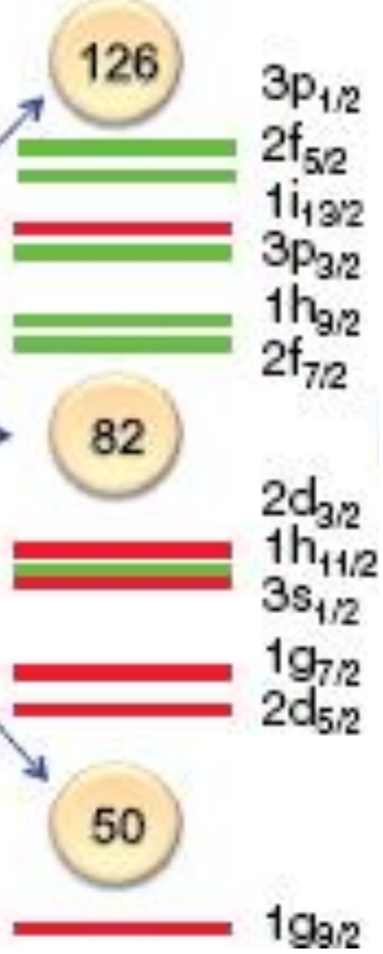
Electronic shells of the atom

Noble gases (Closed shells)

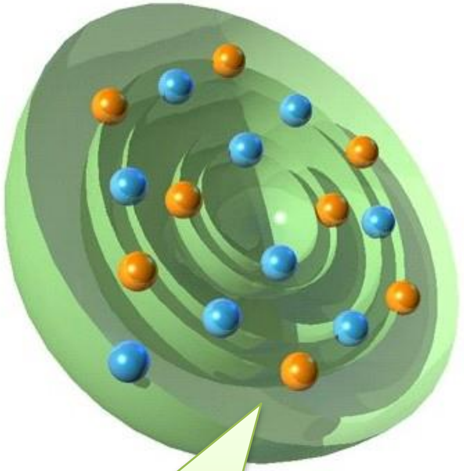



Nucleonic shells of the nucleus

Magic numbers (Closed shells)



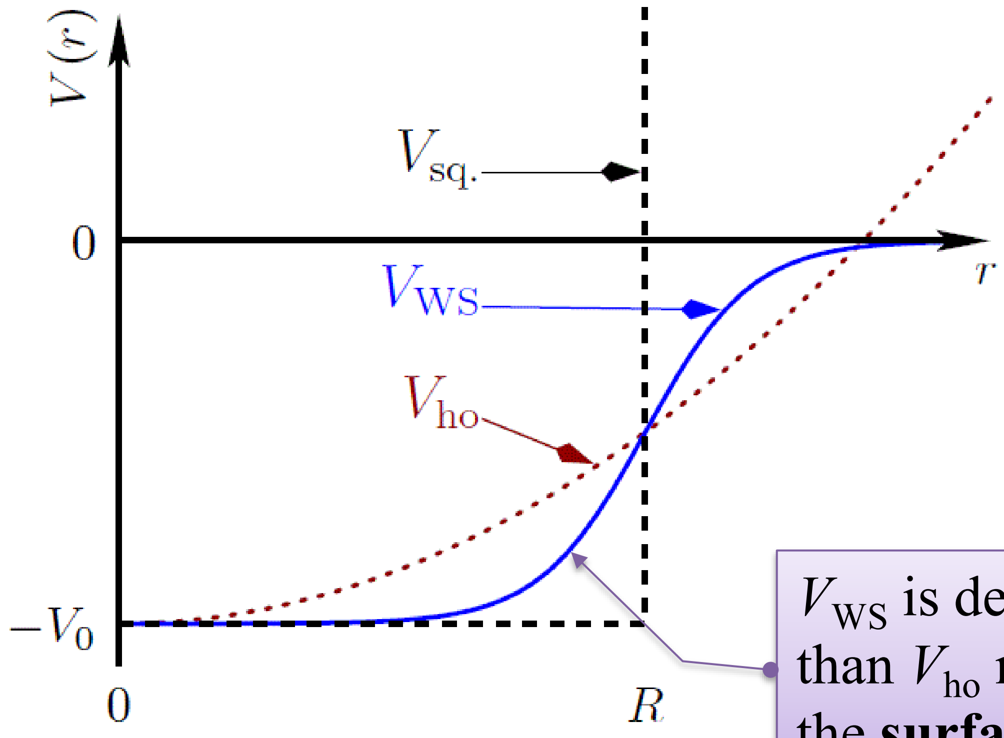




Self-consistent

Mean field made by the **nucleons** (Nuclear force)

# Phenomenological nuclear potential



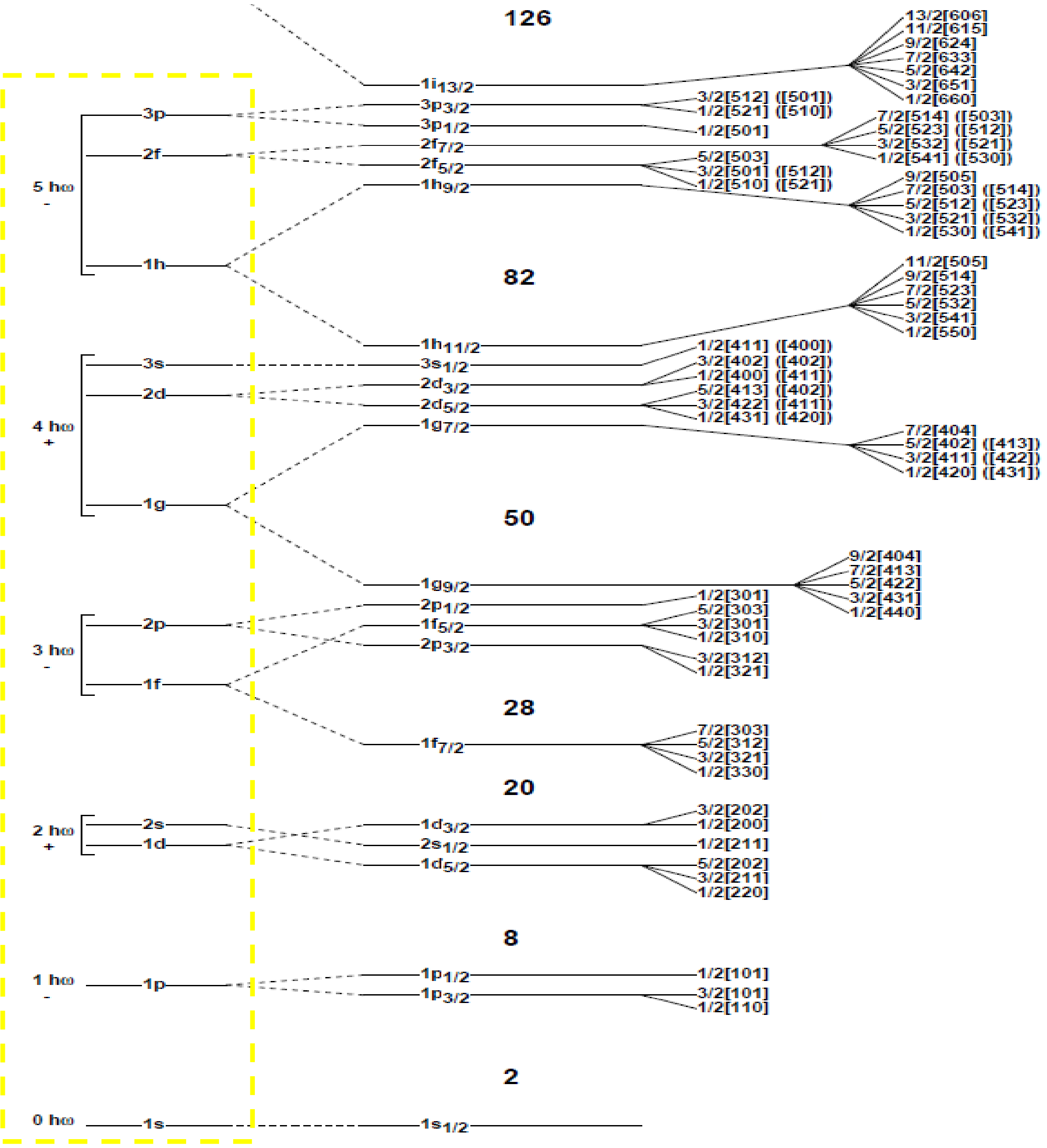

| | ℓ |
|---|---|
| s | 0 |
| p | 1 |
| d | 2 |
| f | 3 |
| g | 4 |
| h | 5 |

$V_{\rm WS}$ is deeper than $V_{\rm ho}$ near the **surface**

Intermediate between the harmonic oscillator (HO) and square well

**Woods-Saxon type**
$\equiv$ HO + $\ell^2$

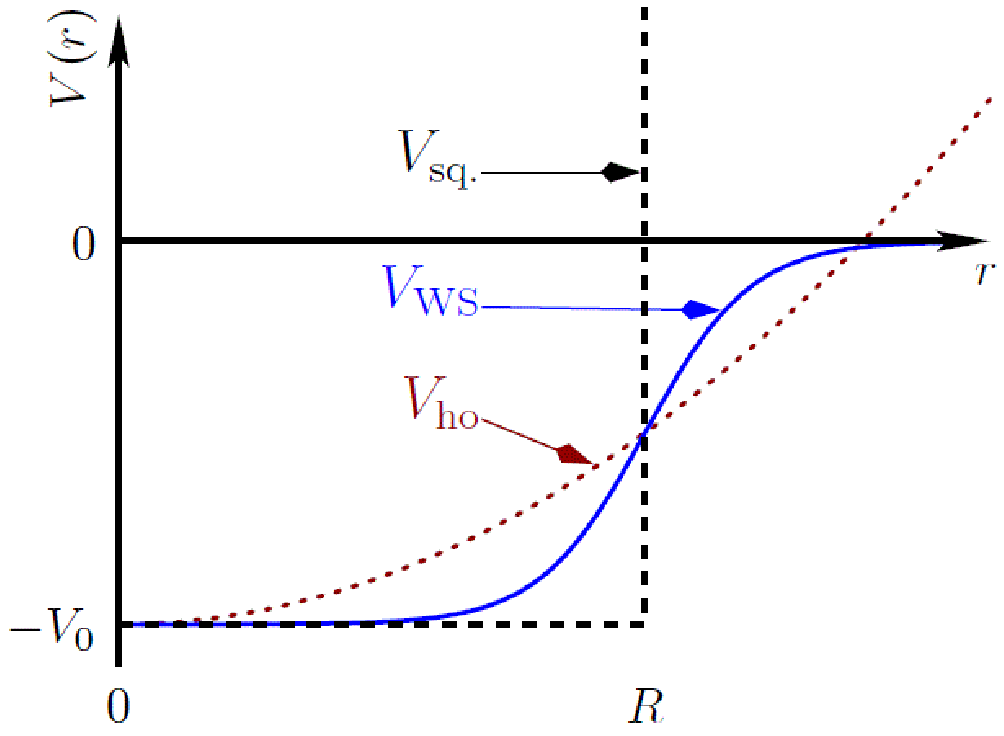
High-ℓ levels are pushed out to larger radii and lowered in energy




HO

$+\ell^2$

# Phenomenological nuclear potential



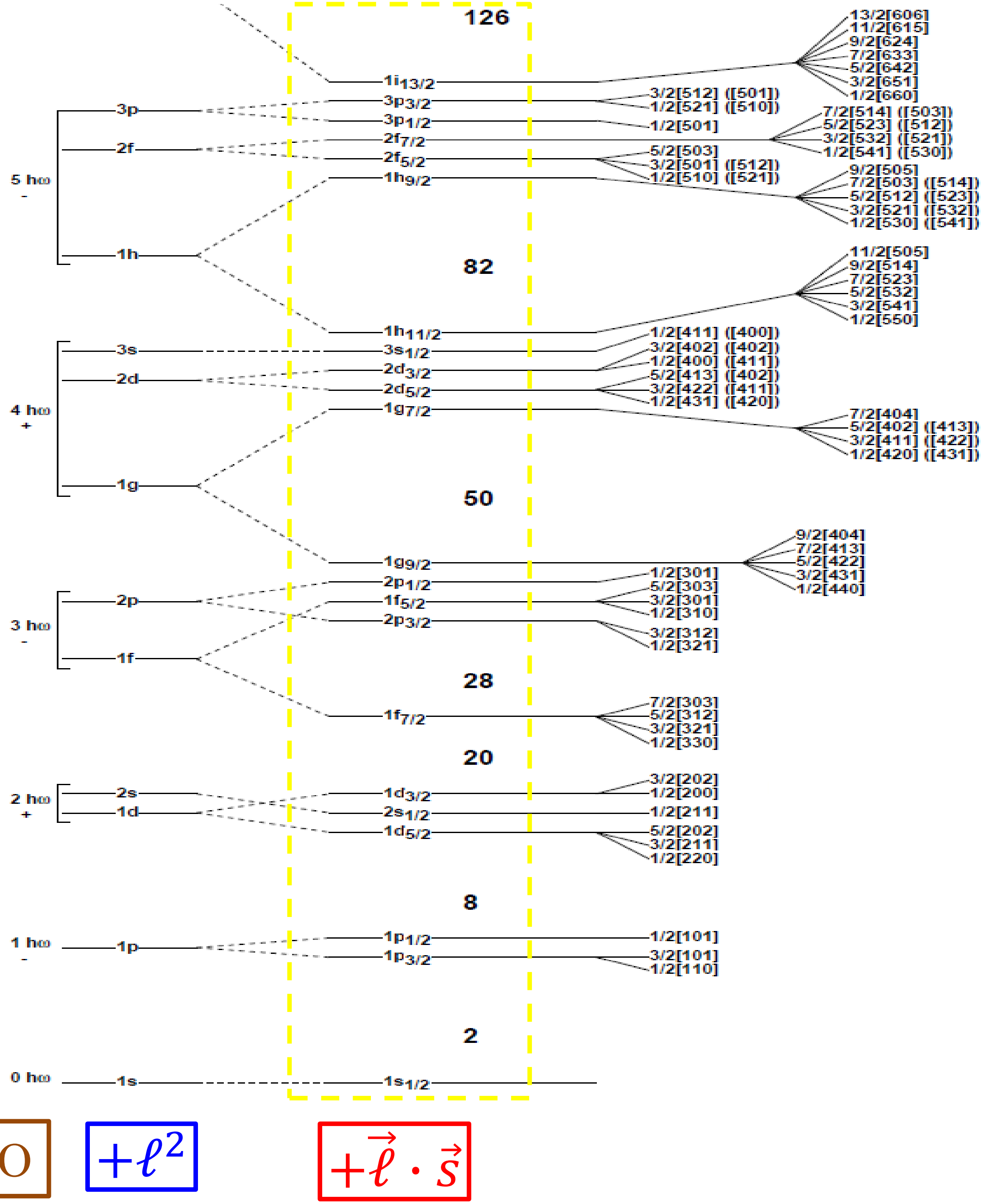

| | $\ell$ |
|---|---|
| s | 0 |
| p | 1 |
| d | 2 |
| f | 3 |
| g | 4 |
| h | 5 |

Spin-orbit force: $-V_{\ell s}\dfrac{\partial V(r)}{\partial r}\vec{\ell}\cdot\vec{s}$

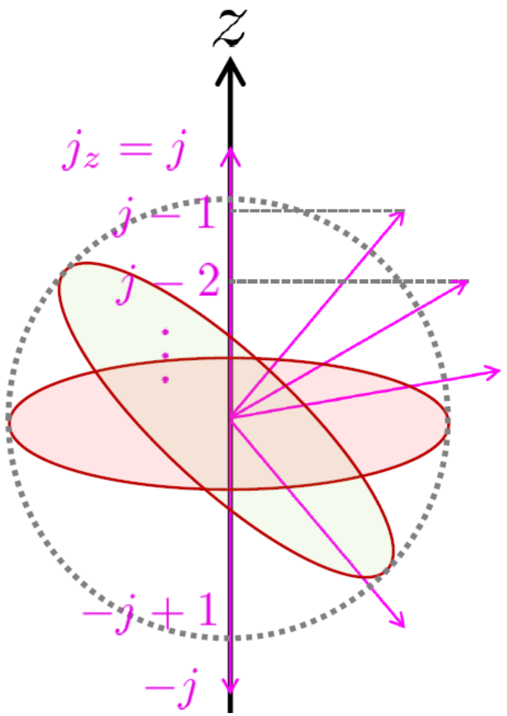
- ✓ Surface phenomena
- ✓ $\boldsymbol{E(j_>) < E(j_<)}$

※Intrinsic spin $s = 1/2$


Magic numbers are produced



# Phenomenological nuclear potential (spherical)



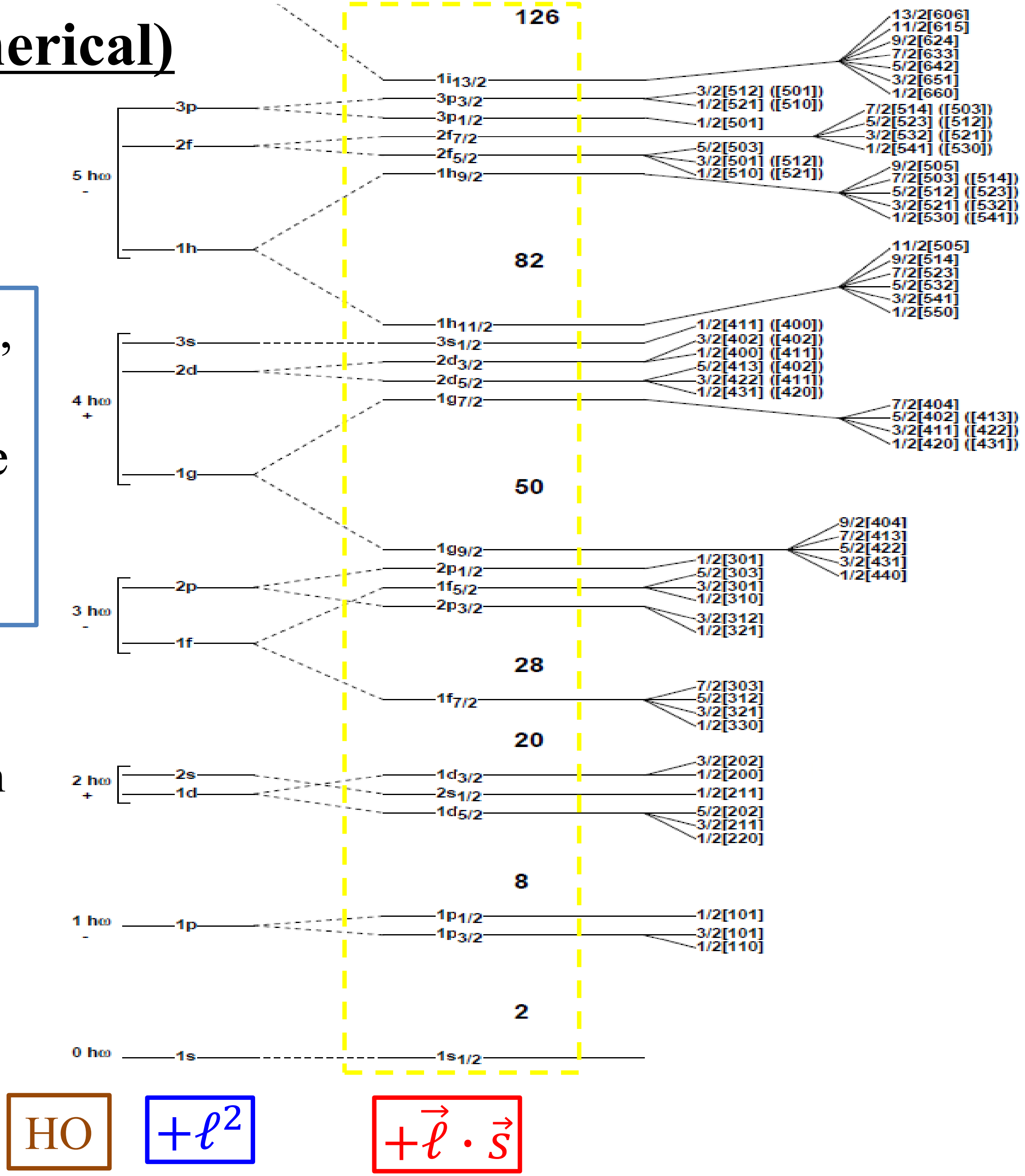

If nuclear shape is **spherical**, each of the shell orbitals has **"2j+1"-fold degeneracy** due to no angle dependence of the potential.

Spin-orbit force: $-V_{\ell s}\frac{\partial V(r)}{\partial r}\vec{\ell}\cdot\vec{s}$

- ✓ Surface phenomena
- ✓ $E(j_>) < E(j_<)$

※Intrinsic spin $s = 1/2$

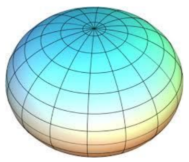

Magic numbers are produced

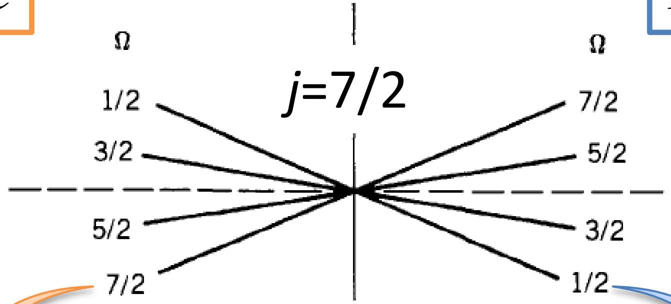


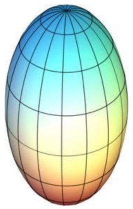
# Phenomenological nuclear potential (deformed)

The energy levels in a deformed potential depends on the projection of *j* on the symmetry axis (Ω).

*Oblate* ⟵ Deformation β ⟶ *Prolate*

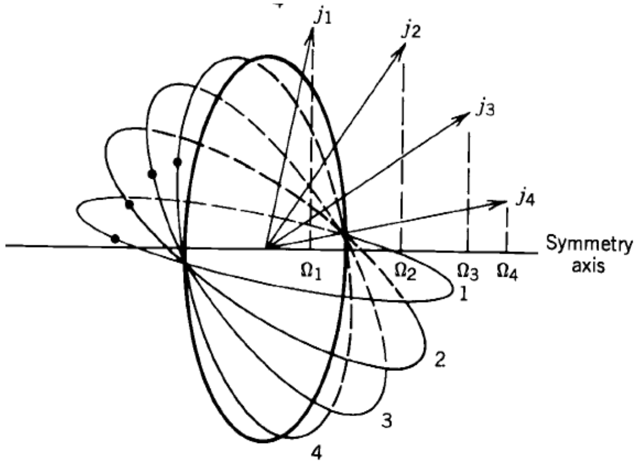


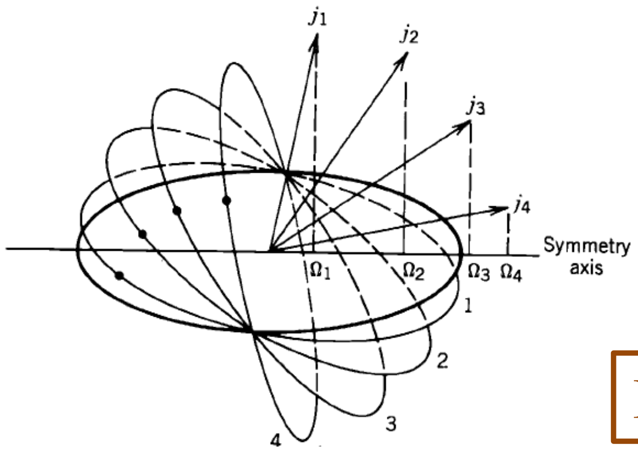


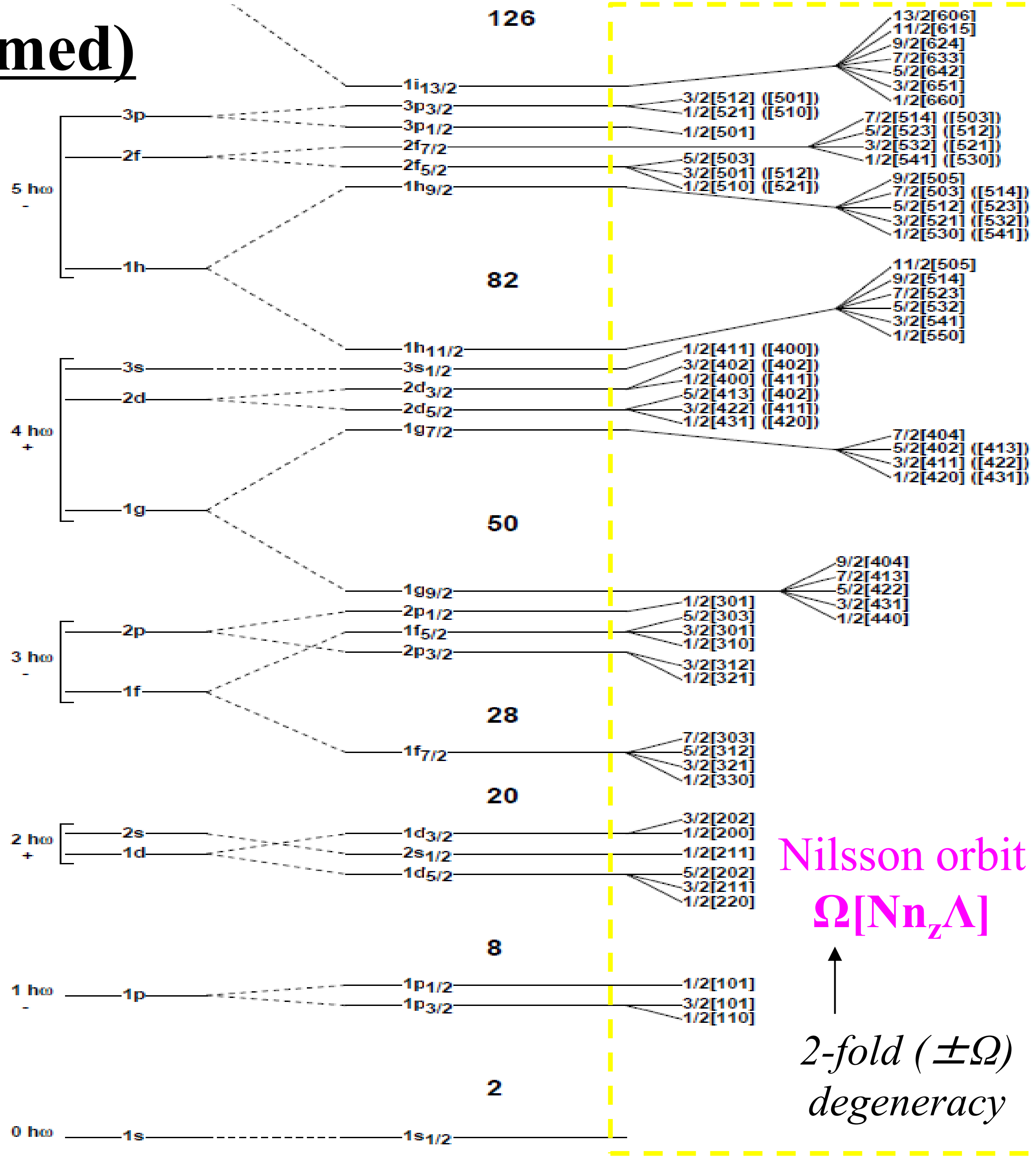



Largest interaction with the oblate core

Largest interaction with the prolate core



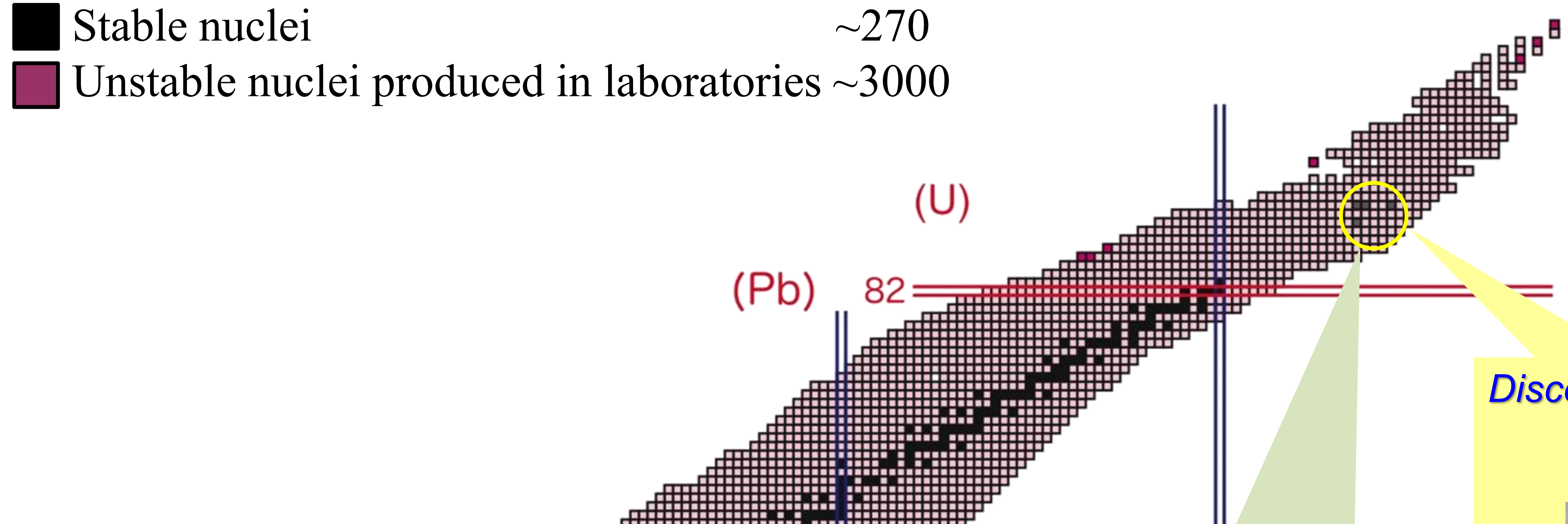

Nilsson orbit

**$\Omega[Nn_z\Lambda]$**

↑

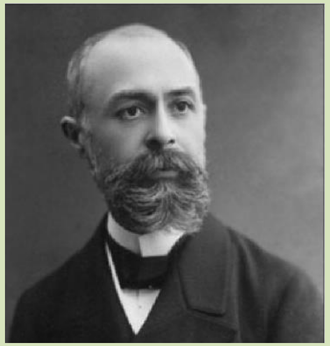
*2-fold (±Ω) degeneracy*

HO | $+\ell^2$ | $+\vec{\ell}\cdot\vec{s}$ | $+\beta r^2 Y_{20}(\theta,\phi)$




## *Discovery of radioactivity*

$_{92}U$ — 1896, H. Becquerel

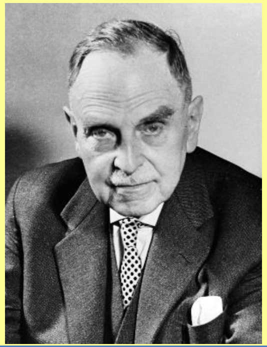


$_{90}Th$ — 1898, M. Curie

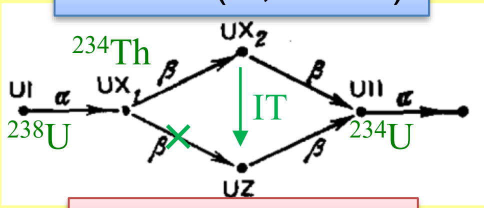
## *Discovery of isomer*

1921

O. Hahn



$^{234m}$Pa ($0^-$, 1.2 m)




$^{234}$Pa ($4^+$, 6.7 h)

O. Hahn, 1921 *Chem. Ber.* **54** 1131

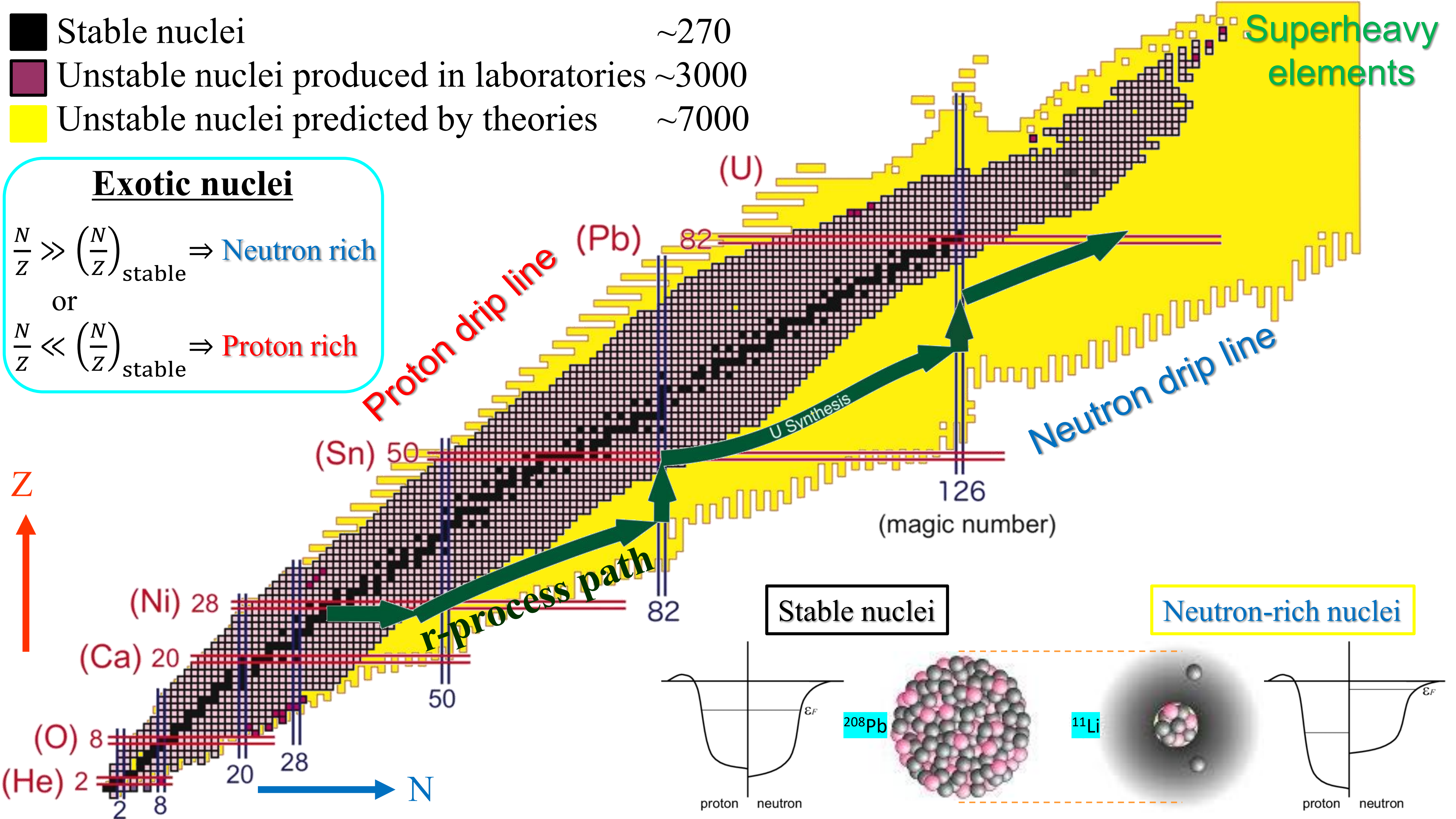
| | | |
|---|---|---|
| ■ (black) | Stable nuclei | ~270 |
| ■ (purple) | Unstable nuclei produced in laboratories | ~3000 |
| ■ (yellow) | Unstable nuclei predicted by theories | ~7000 |

**Exotic nuclei**

$\frac{N}{Z} \gg \left(\frac{N}{Z}\right)_{\text{stable}} \Rightarrow$ Neutron rich

or

$\frac{N}{Z} \ll \left(\frac{N}{Z}\right)_{\text{stable}} \Rightarrow$ Proton rich



- ■ Stable nuclei ~270
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## Exotic nuclei

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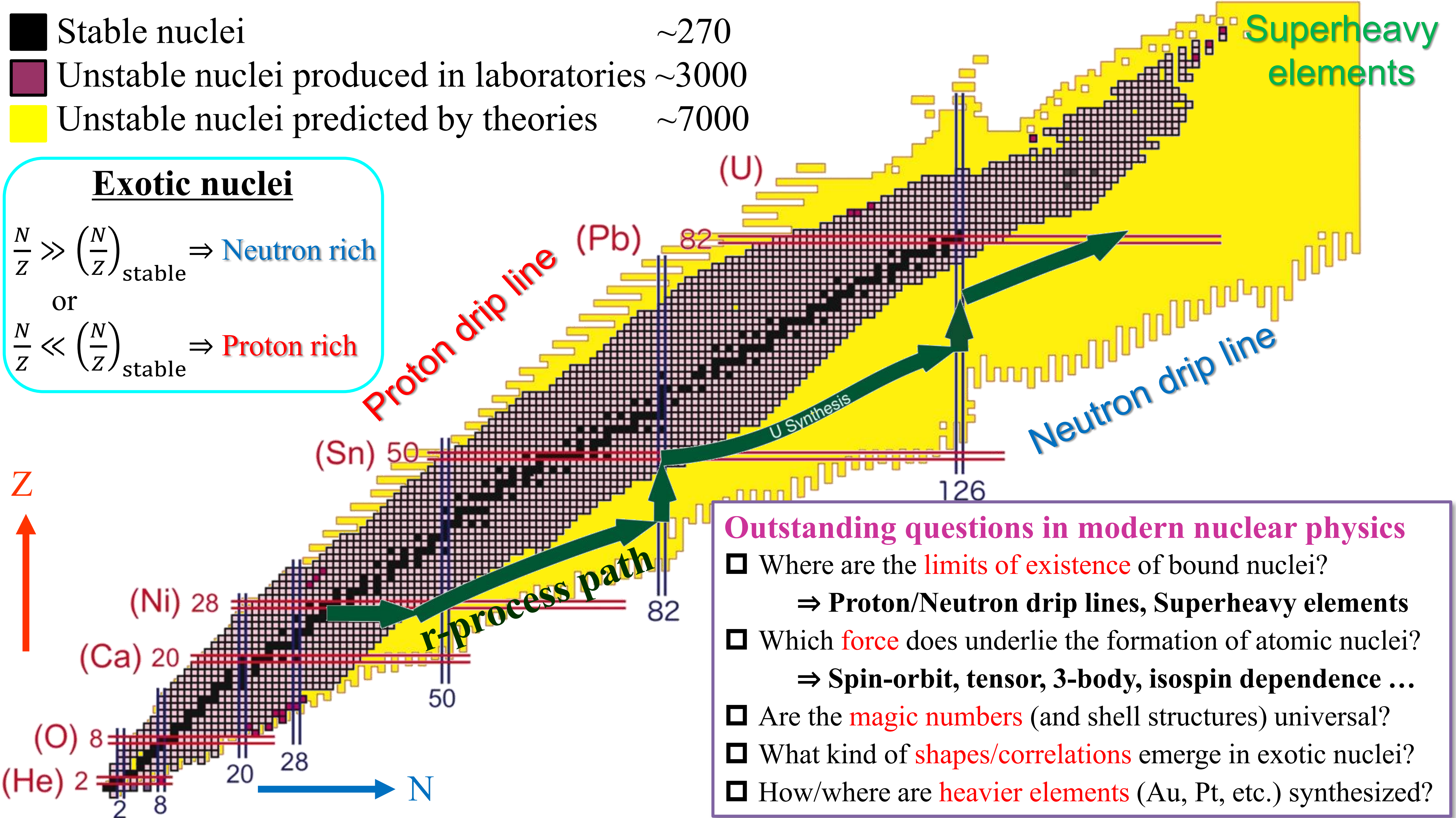
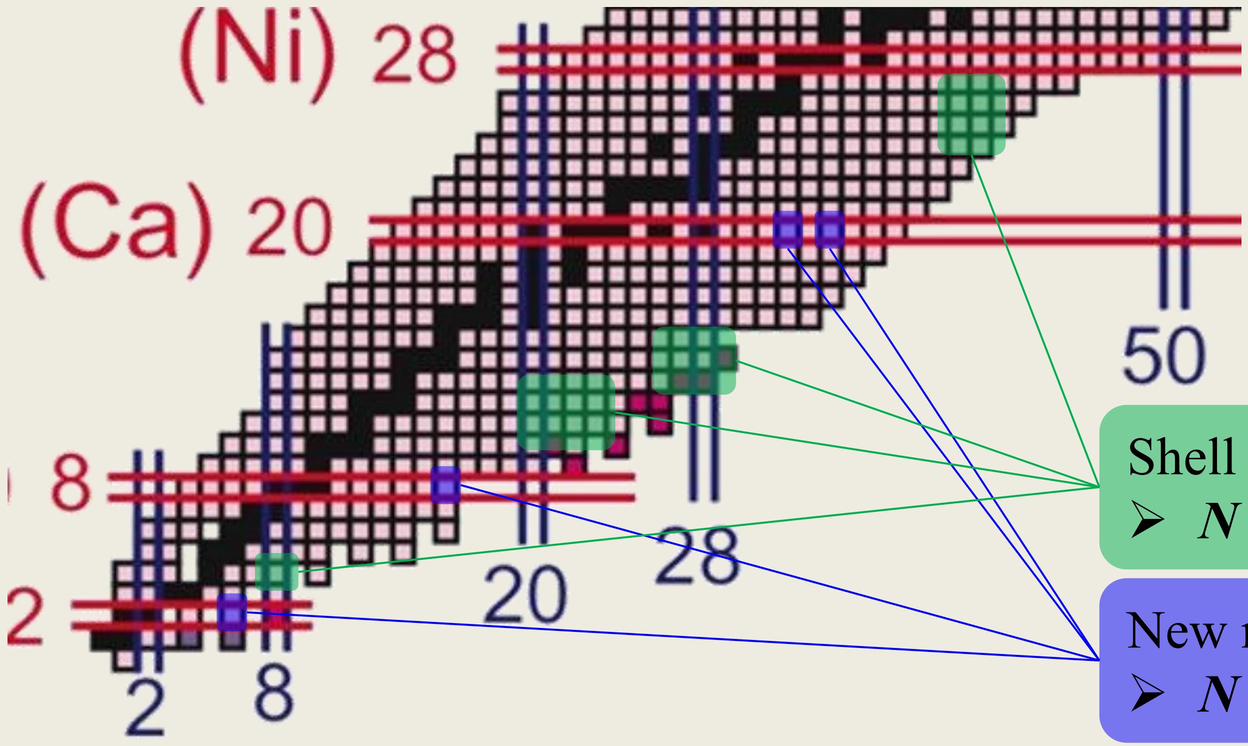



**Outstanding questions in modern nuclear physics**

- ☐ Where are the limits of existence of bound nuclei?
  - ⇒ **Proton/Neutron drip lines, Superheavy elements**
- ☐ Which force does underlie the formation of atomic nuclei?
  - ⇒ **Spin-orbit, tensor, 3-body, isospin dependence …**
- ☐ Are the magic numbers (and shell structures) universal?
- ☐ What kind of shapes/correlations emerge in exotic nuclei?
- ☐ How/where are heavier elements (Au, Pt, etc.) synthesized?

# Shell evolution: New and lost magic numbers

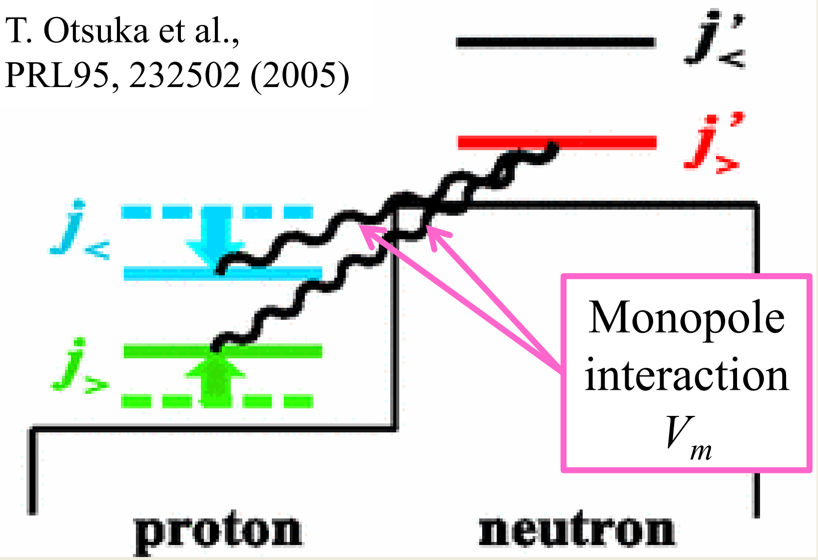


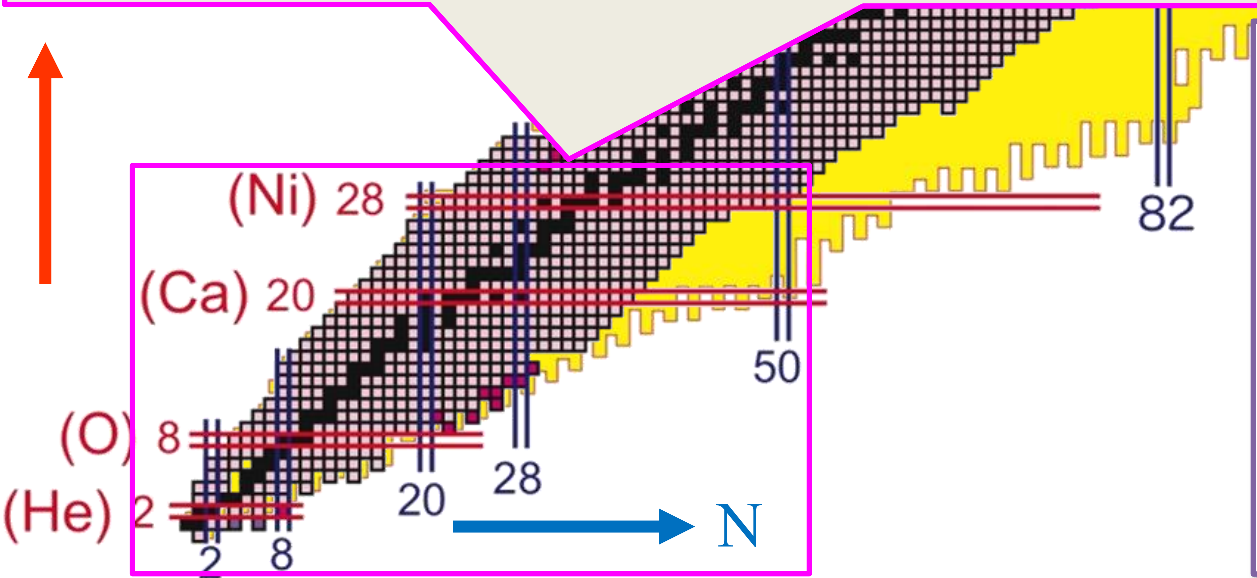

Shell quenching
➢ $N$ = 8, 20, 28, (40)

New magic numbers
➢ $N$ = 6, 16, 32, 34

**Monopole-driven shell evolution**
⇒ More prominent in exotic nuclei

T. Otsuka et al., PRL95, 232502 (2005)




**Outstanding questions in modern nuclear physics**

- ☐ Where are the limits of existence of bound nuclei?
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- ☐ Which force does underlie the formation of atomic nuclei?
  - ⇒ **Spin-orbit, tensor, 3-body, isospin dependence …**
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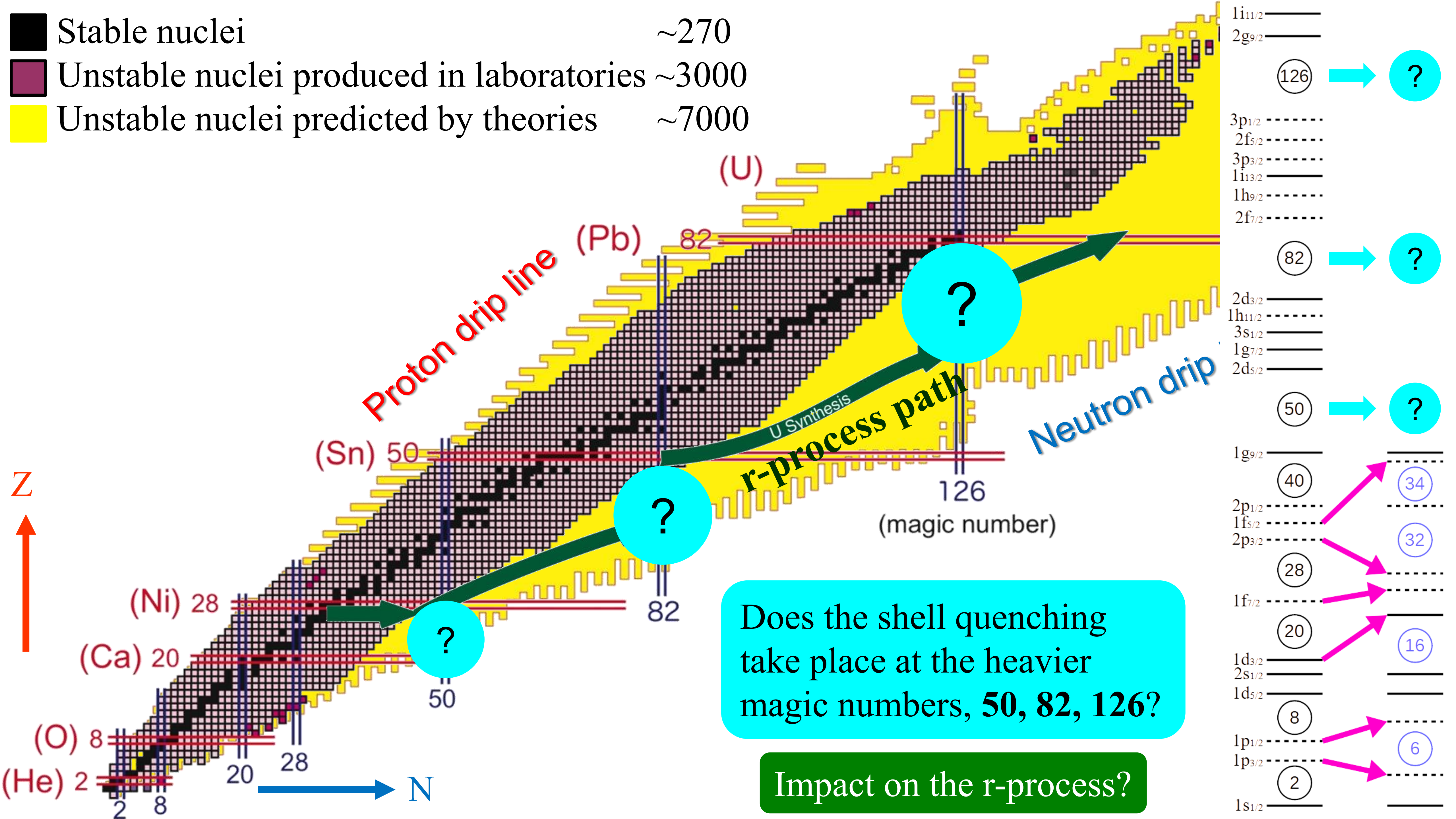
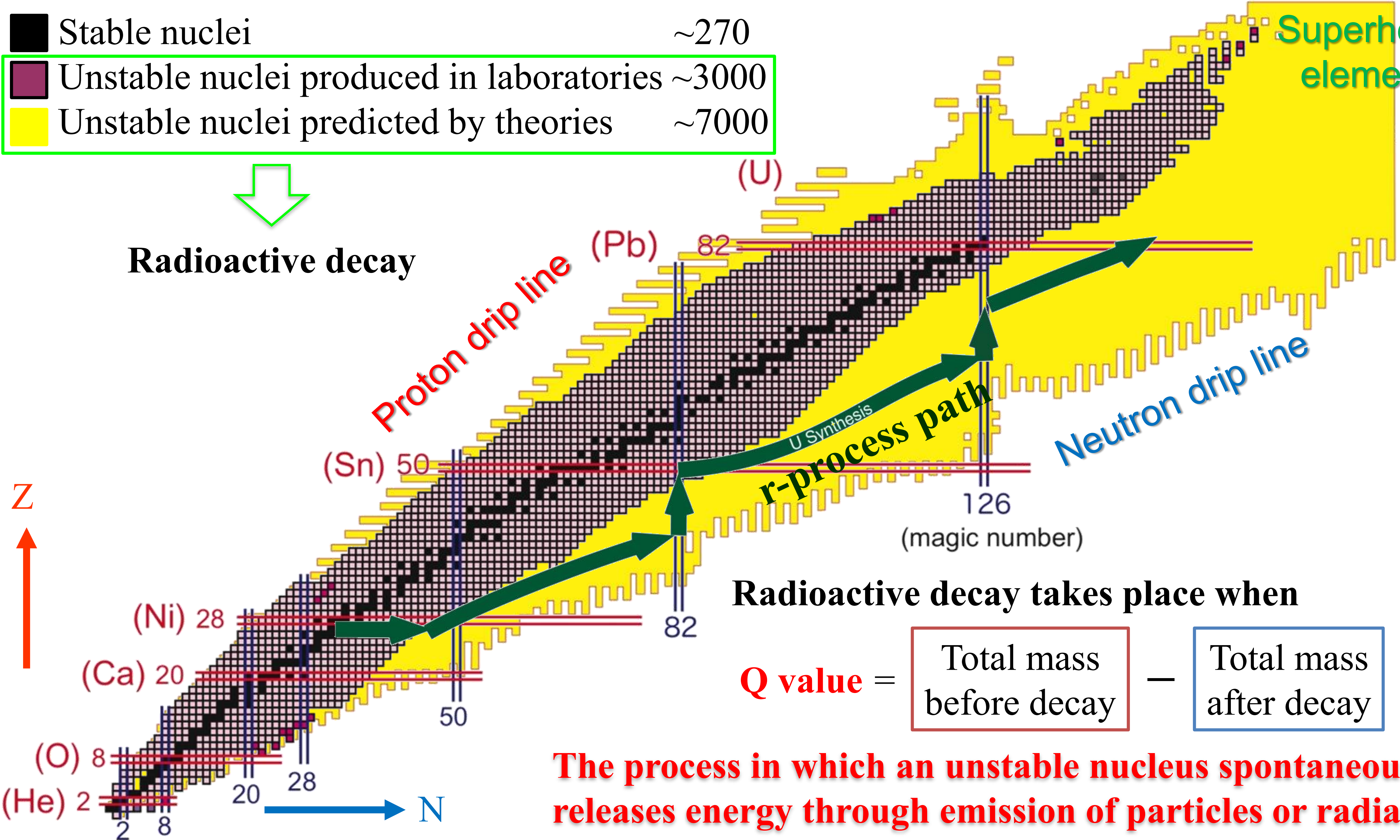


Stable nuclei ~270
Unstable nuclei produced in laboratories ~3000
Unstable nuclei predicted by theories ~7000
Proton drip line
(U)
(Pb) 82
(Sn) 50
(Ni) 28
(Ca) 20
(O) 8
(He) 2
2
8
20
28
50
82
126
(magic number)
Z
N
U Synthesis
r-process path
Neutron drip
?
1i11/2
2g9/2
126
3p1/2
2f5/2
3p3/2
1i13/2
1h9/2
2f7/2
82
2d3/2
1h11/2
3s1/2
1g7/2
2d5/2
50
1g9/2
40
2p1/2
1f5/2
2p3/2
28
1f7/2
20
1d3/2
2s1/2
1d5/2
8
1p1/2
1p3/2
2
1s1/2
34
32
16
6
Does the shell quenching take place at the heavier magic numbers, **50, 82, 126**?
Impact on the r-process?

| | | |
|---|---|---|
| ■ | Stable nuclei | ~270 |
| ■ | Unstable nuclei produced in laboratories | ~3000 |
| ■ | Unstable nuclei predicted by theories | ~7000 |

**Radioactive decay**



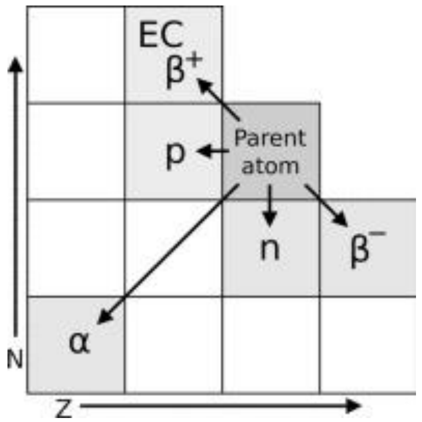

**Radioactive decay takes place when**

**Q value** = Total mass before decay − Total mass after decay > 0

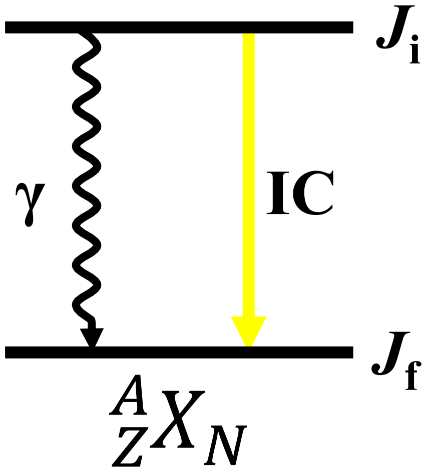
**The process in which an unstable nucleus spontaneously releases energy through emission of particles or radiations**

# Types of radioactive decay

| Decay mode | Symbol | Daughter Z |
|---|---|---|
| Spontaneous fission | SF | Various |
| Neutron emission | n | Z |
| Proton emission | p | Z-1 |
| Alpha ($^4$He) emission | α | Z-2 |
| Positron emission | β+ | Z-1 |
| Electron capture | EC | Z-1 |
| Beta-ray emission | β- | Z+1 |
| Gamma-ray emission | γ | Z |
| Isomeric transition | IT | Z |
| Internal conversion | IC,e- | Z |

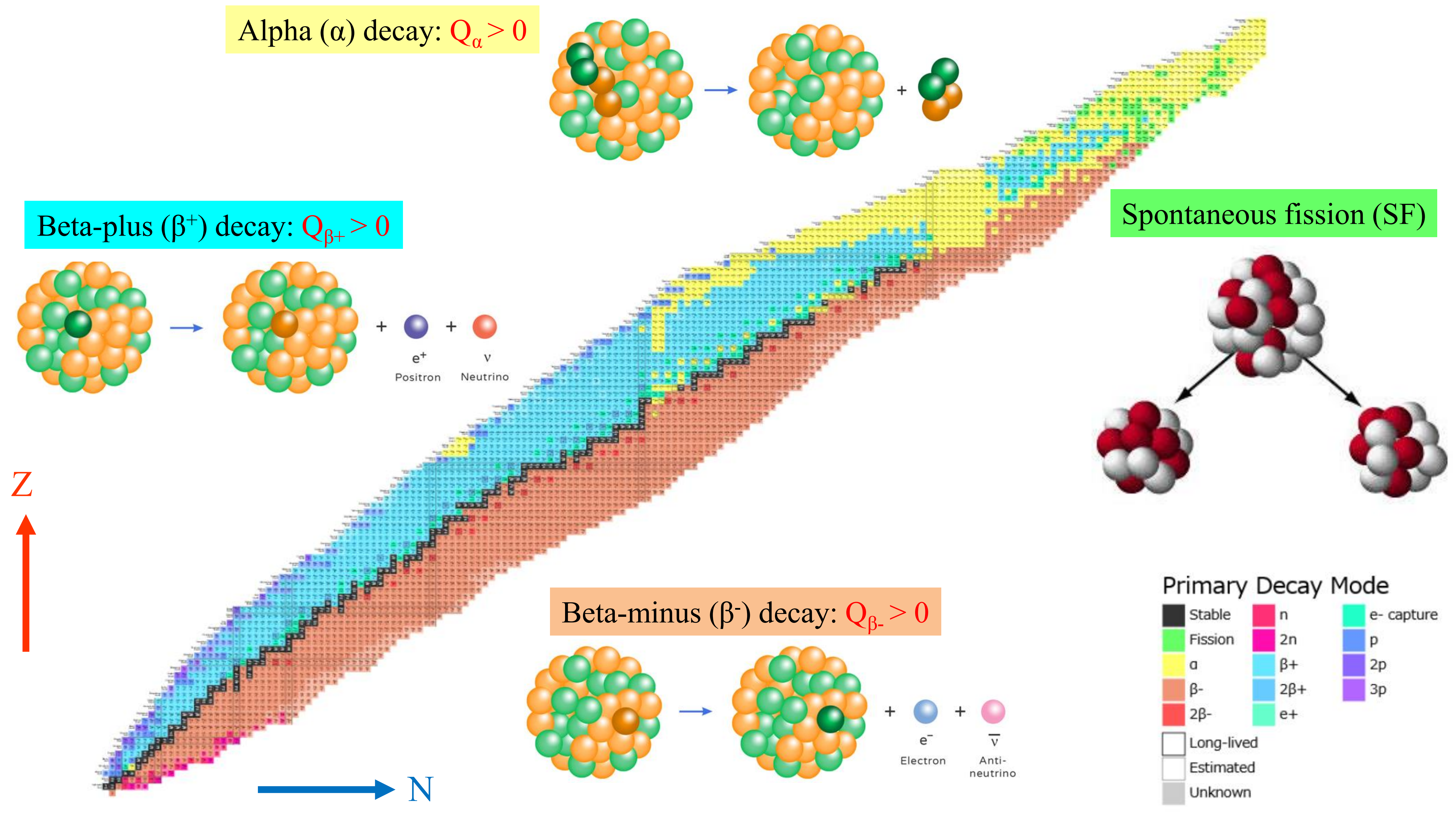



**External decay**
(The number or type of nucleons changed)

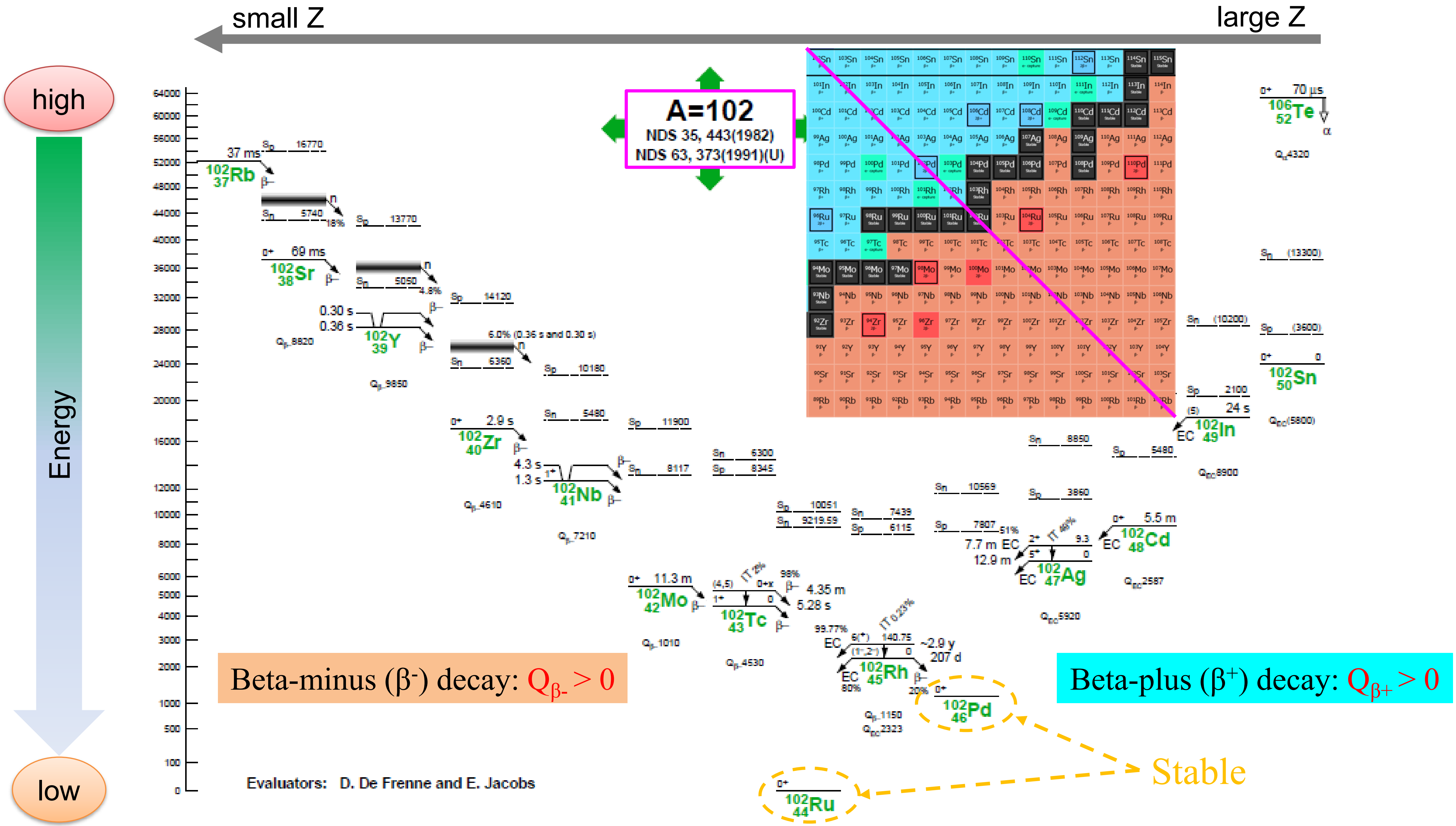



**Internal decay**
(No change in Z, N, and A)

**The process in which an unstable nucleus spontaneously releases energy through emission of particles or radiations**

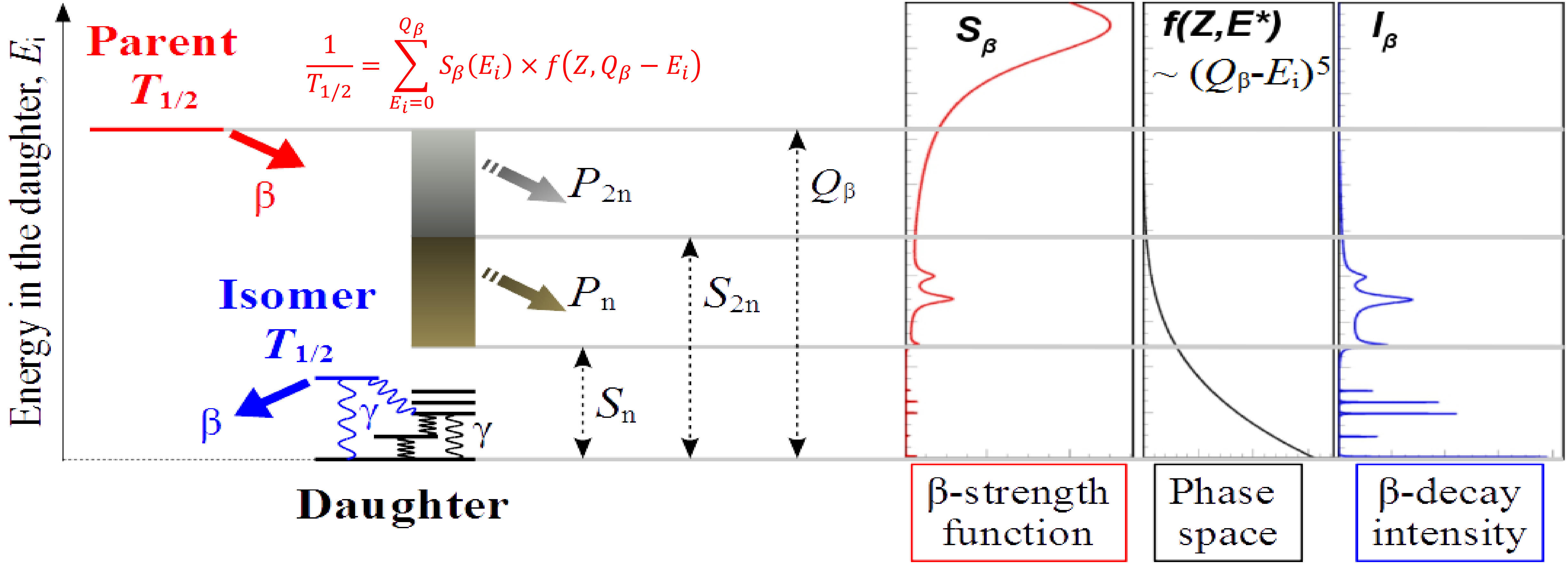


Alpha (α) decay: $Q_{\alpha} > 0$
Beta-plus ($\beta^+$) decay: $Q_{\beta+} > 0$
+ $e^+$ + ν
Positron
Neutrino
Spontaneous fission (SF)
Beta-minus ($\beta^-$) decay: $Q_{\beta-} > 0$
+ $e^-$ + $\bar{\nu}$
Electron
Anti-neutrino
Z
N
Primary Decay Mode
Stable
Fission
α
β-
2β-
n
2n
β+
2β+
e+
e- capture
p
2p
3p
Long-lived
Estimated
Unknown



small Z
large Z
high
Energy
low
A=102
NDS 35, 443(1982)
NDS 63, 373(1991)(U)
102 37 Rb
102 38 Sr
102 39 Y
102 40 Zr
102 41 Nb
102 42 Mo
102 43 Tc
102 44 Ru
102 45 Rh
102 46 Pd
102 47 Ag
102 48 Cd
102 49 In
102 50 Sn
106 52 Te
Beta-minus (β-) decay: Qβ- > 0
Beta-plus (β+) decay: Qβ+ > 0
Stable
Evaluators: D. De Frenne and E. Jacobs

# What can we learn from decay spectroscopy?




- **β-decay half-lives** ⇒ Nuclear matrix elements ($S_\beta$)
- **Decay energies** ⇒ Mass differences ($Q_\beta$)
- **Decay schemes** ⇒ Energies of excited states
- **Delayed particles** ⇒ Emission probabilities ($P_{n,2n}$)
- **Delayed fission** ⇒ Fission barriers ($B_f$)
- **Isomeric states** ⇒ Details of nuclear structure

Good testing ground for nuclear models

Key nuclear physics inputs to astrophysical simulations

# Common feature of radioactive decays

- Transitions take place between two (initial and final) “quantum” states ⇒ Quantum process

**Fermi’s golden rule**: *Transition probability per unit time*

$$\lambda = \frac{1}{\tau} = \frac{2\pi}{\hbar} \left|\langle \phi_f | H' | \phi_i \rangle\right|^2 \rho(E_f)$$

**Decay constant** ($\lambda$)

**Mean lifetime** ($\tau$)

**Final state density** ($\rho(E_f)$)

**Matrix element** (representing quantum process)

- Weak interactions that create an electron and neutrino ⇒ **β decay**
- Variation of EM fields leading to creation of a photon ⇒ **γ decay**

- Radioactive decay is stochastic, in which
  - The time when the decay happens is random (i.e., independent on history)
  - Only the expectation (average) values of quantities can be evaluated

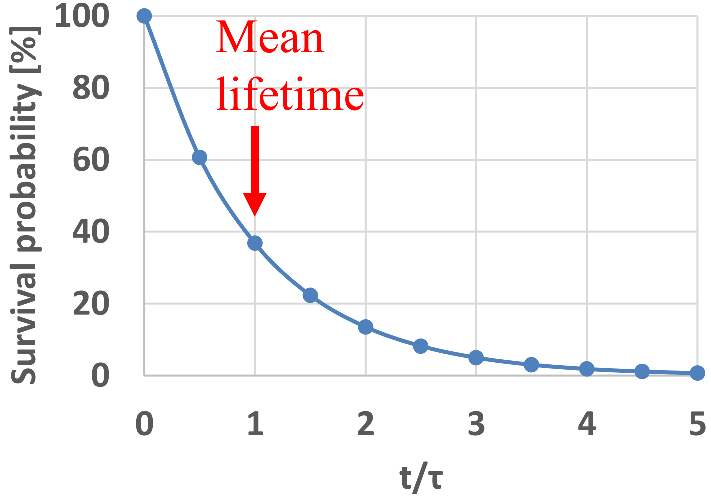
The number of nuclides that decay per unit time

$$\frac{dN}{dt} = -\lambda N(t)$$

⇒

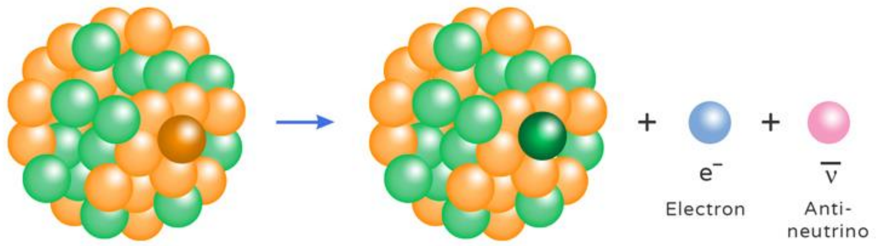
The **average number** of decaying nuclides at time *t*

$$N(t) = N(0)e^{-\lambda t}$$



# Types of β decay

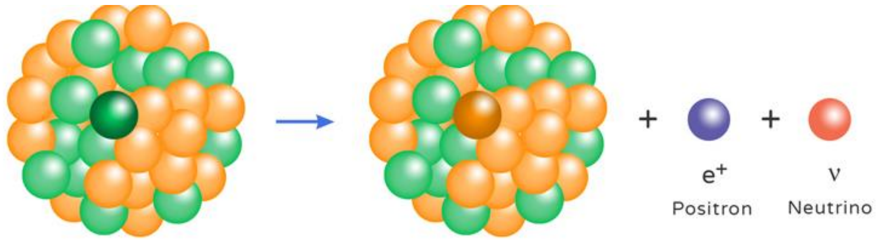
Beta-minus ($\beta^-$) decay




$$Q_{\beta^-} = [M_n(^A_ZX_N) - \{M_n(_{Z+1}^{\ A}Y_{N-1}) + m_e + m_\nu\}]c^2$$
$$\cong [M(^A_ZX_N) - M(_{Z+1}^{\ A}Y_{N-1})]c^2$$

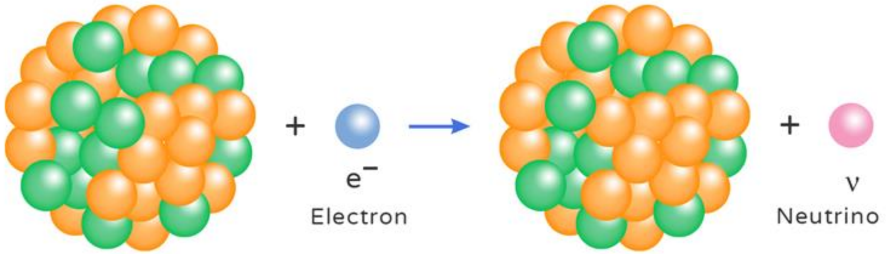
↑ Neglecting the differences in electron binding energy

Beta-plus ($\beta^+$) decay




$$Q_{\beta^+} = [M_n(^A_ZX_N) - \{M_n(_{Z-1}^{\ A}Y_{N+1}) + m_e + m_\nu\}]c^2$$
$$\cong [M(^A_ZX_N) - M(_{Z-1}^{\ A}Y_{N+1})]c^2 - 2m_ec^2$$

Electron-capture (EC) decay




$$Q_{EC} = [\{M_n(^A_ZX_N) + m_e\} - \{M_n(_{Z-1}^{\ A}Y_{N+1}) + m_\nu\}]c^2$$
$$\cong [M(^A_ZX_N) - M^*(_{Z-1}^{\ A}Y_{N+1})]c^2$$
$$= [M(^A_ZX_N) - M(_{Z-1}^{\ A}Y_{N+1})]c^2 - B_e$$

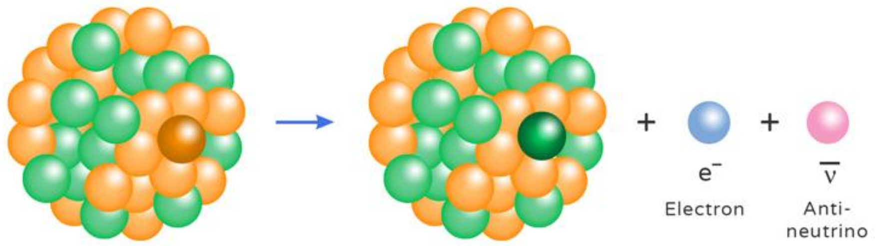
***Important!***
**β decay is 3-body decay**

$$M(^A_ZX_N)c^2 = M_n(^A_ZX_N)c^2 + Zm_ec^2 - \sum_{i=1}^{Z} B_i$$

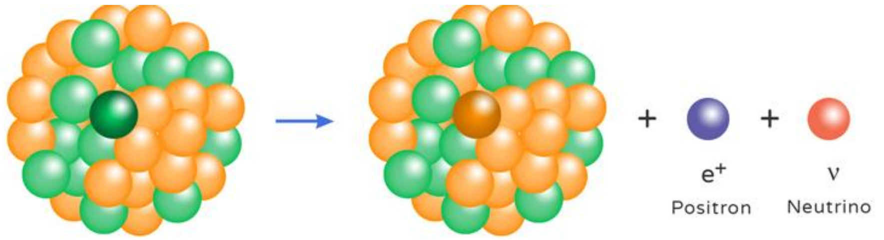
↑ Atomic mass ↑ Nuclear mass ↑ Electron binding energy

# Momentum/Energy spectrum in β decay

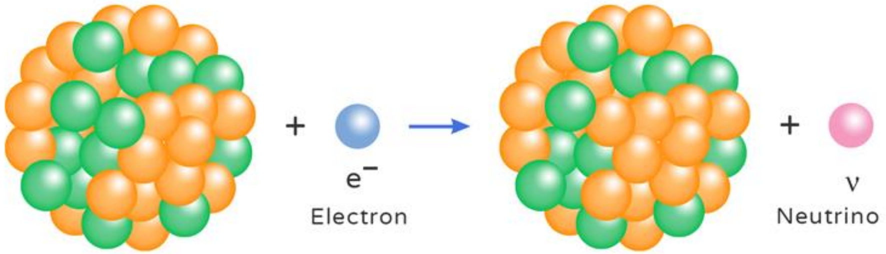
Beta-minus ($\beta^-$) decay




Beta-plus ($\beta^+$) decay




Electron-capture (EC) decay




***Important!***

**β decay is 3-body decay**

**Final state density** ➡ Energy spectrum

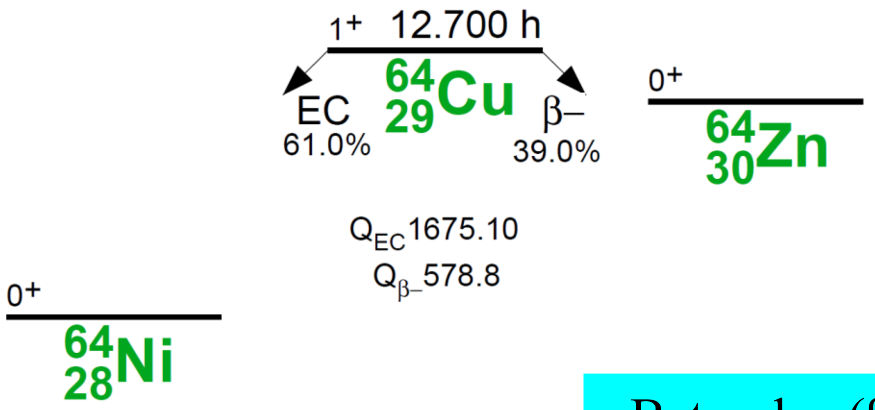
$$\rho(E_f) = \frac{dn_\nu dn_e}{dE_f}$$

$$\approx \frac{V^2}{(2\pi^2\hbar^3)^2 c^3} p_e^2 (E_0 - E_e)^2 F(Z, E_e) dp_e$$

**Fermi function**:
Correction factor for distortion of the electron wave function by the Coulomb field

$n_\nu$: Number of states of neutrino
$n_e$: Number of states of electron
$E_0$: End-point energy

# Momentum/Energy spectrum in β decay

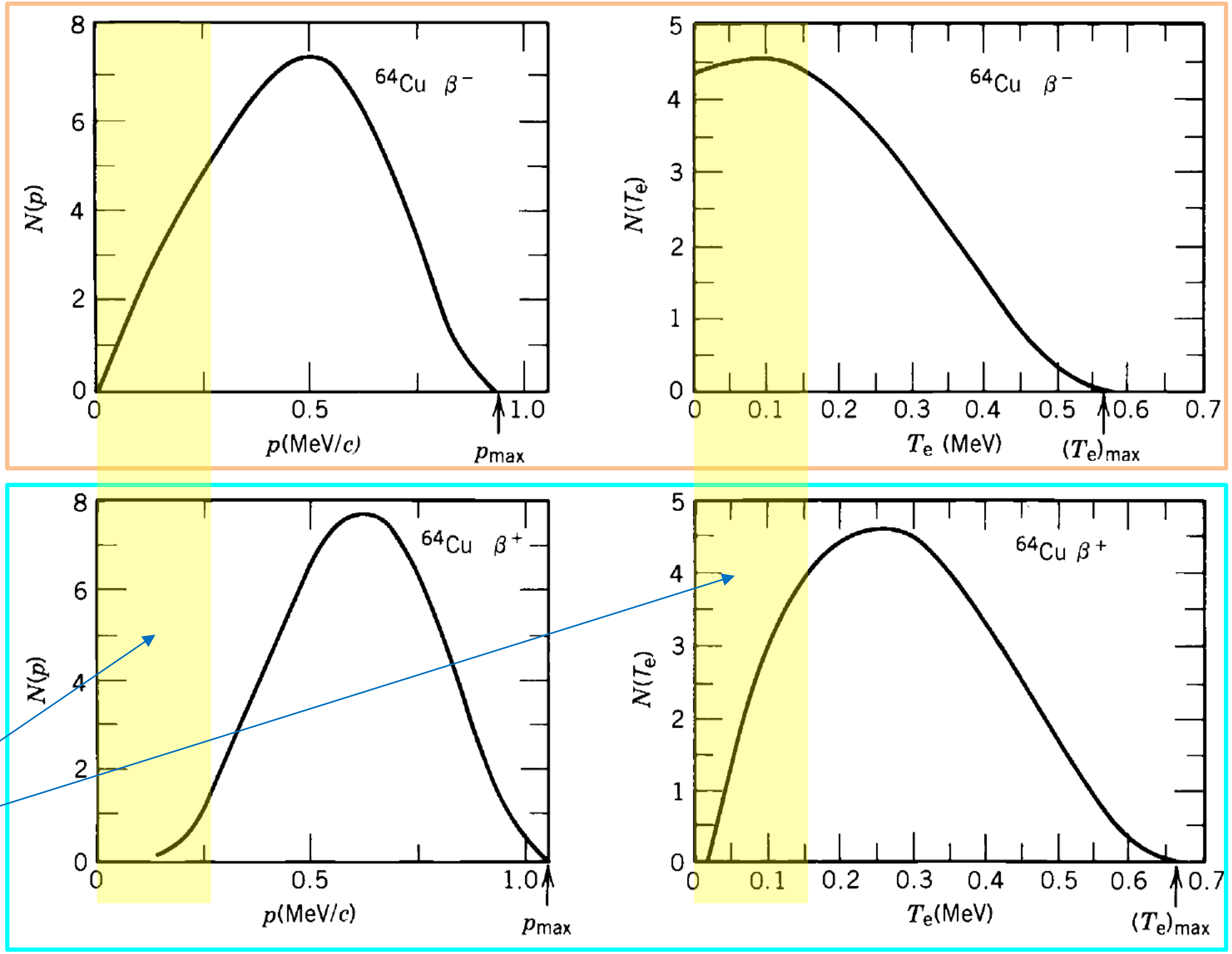



Momentum distribution

Energy distribution

Beta-minus ($\beta^-$) decay

Beta-plus ($\beta^+$) decay



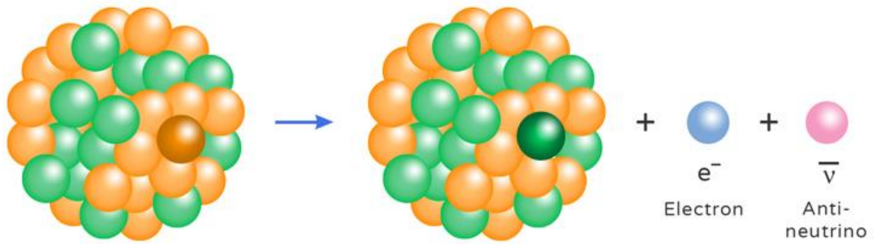

***Important!***

**β decay is 3-body decay**

Effect of Coulomb force
(Fermi function)

# Selection rules for β decays

Beta-minus ($\beta^-$) decay



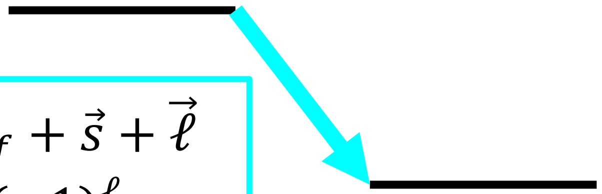

$J_i, \pi_i$ $J_f, \pi_f$ $s_e, \ell_e$ $s_\nu, \ell_\nu$

$$\vec{s} = \vec{s}_e + \vec{s}_\nu$$

$$\vec{\ell} = \vec{\ell}_e + \vec{\ell}_\nu$$

$$s = s_e + s_\nu = \begin{cases} 0 \cdots \uparrow\downarrow & \Rightarrow \text{Fermi transition} \\ 1 \cdots \uparrow\uparrow, \downarrow\downarrow & \Rightarrow \text{Gamow-Teller transition} \end{cases}$$

$|\ell| \equiv n$: Degree of forbiddenness



$$\vec{J}_i = \vec{J}_f + \vec{s} + \vec{\ell}$$

$$\pi_i = (-1)^{\ell} * \pi_f$$

| $n$ | $\pi_i * \pi_f$ | Transition types | | $\|J_i - J_f\|$ |
|---|---|---|---|---|
| 0 | +1 | Allowed | F | 0 |
| | | | GT | 0, 1 |
| 1 | -1 | 1st forbidden | F | 0, 1 |
| | | | GT | 0, 1, 2 |
| 2 | +1 | 2nd forbidden | F | 0, 1, 2 |
| | | | GT | 0, 1, 2, 3 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

Pure Fermi decay when $J_i = J_f = 0$

Pure Gamow-Teller transitions

$n^{th}$ forbidden unique transitions

# β-decay transition rate and *ft* value

$$T_{1/2} = \frac{\ln 2}{w} = \frac{1}{f_n(Z,E_0)} \frac{2\pi^3\hbar^7}{m_e^5 c^4} \frac{\ln 2}{|\langle\psi_f|O_X|\psi_i\rangle|^2}$$

$$ft \equiv f_n(Z,E_0)T_{1/2} = \frac{2\pi^3\hbar^7}{m_e^5 c^4} \frac{\ln 2}{|\langle\psi_f|O_X|\psi_i\rangle|^2}$$

*Information of nuclear structure*

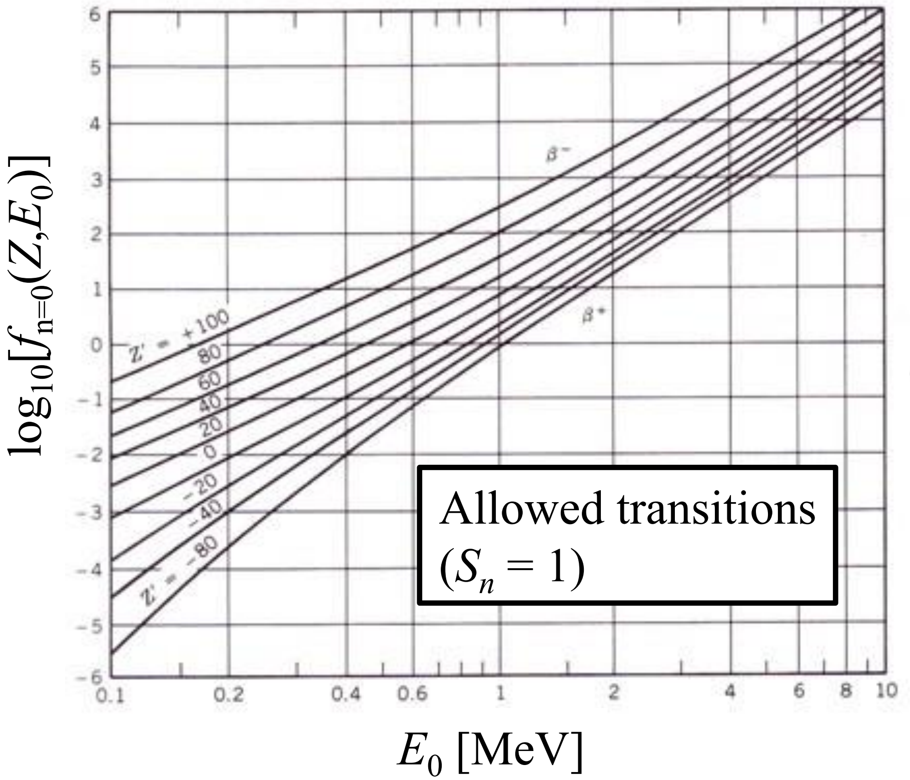
**Fermi integral**:

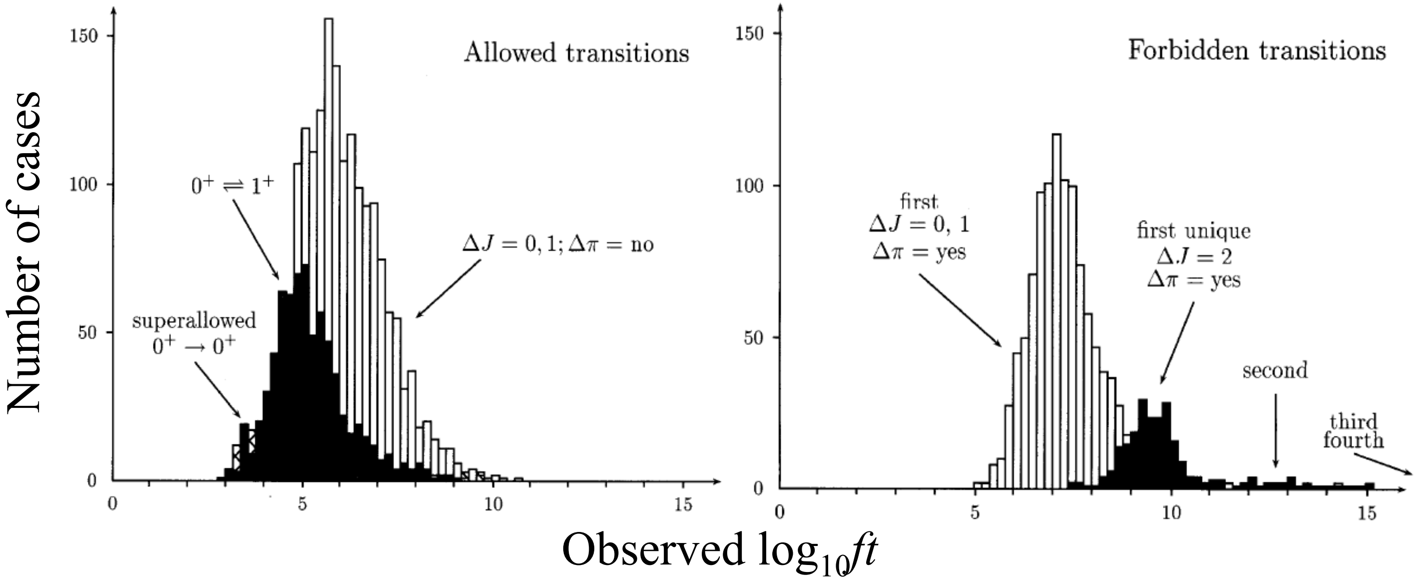
$$f_n(Z,E_0) = \frac{1}{m_e^5 c^7} \int F(Z,E_e) p_e^2 (E_0 - E_e)^2 S_n(p_e,p_\nu) dp_e$$

$$\log_{10} ft = \log_{10} f + \log_{10} t$$

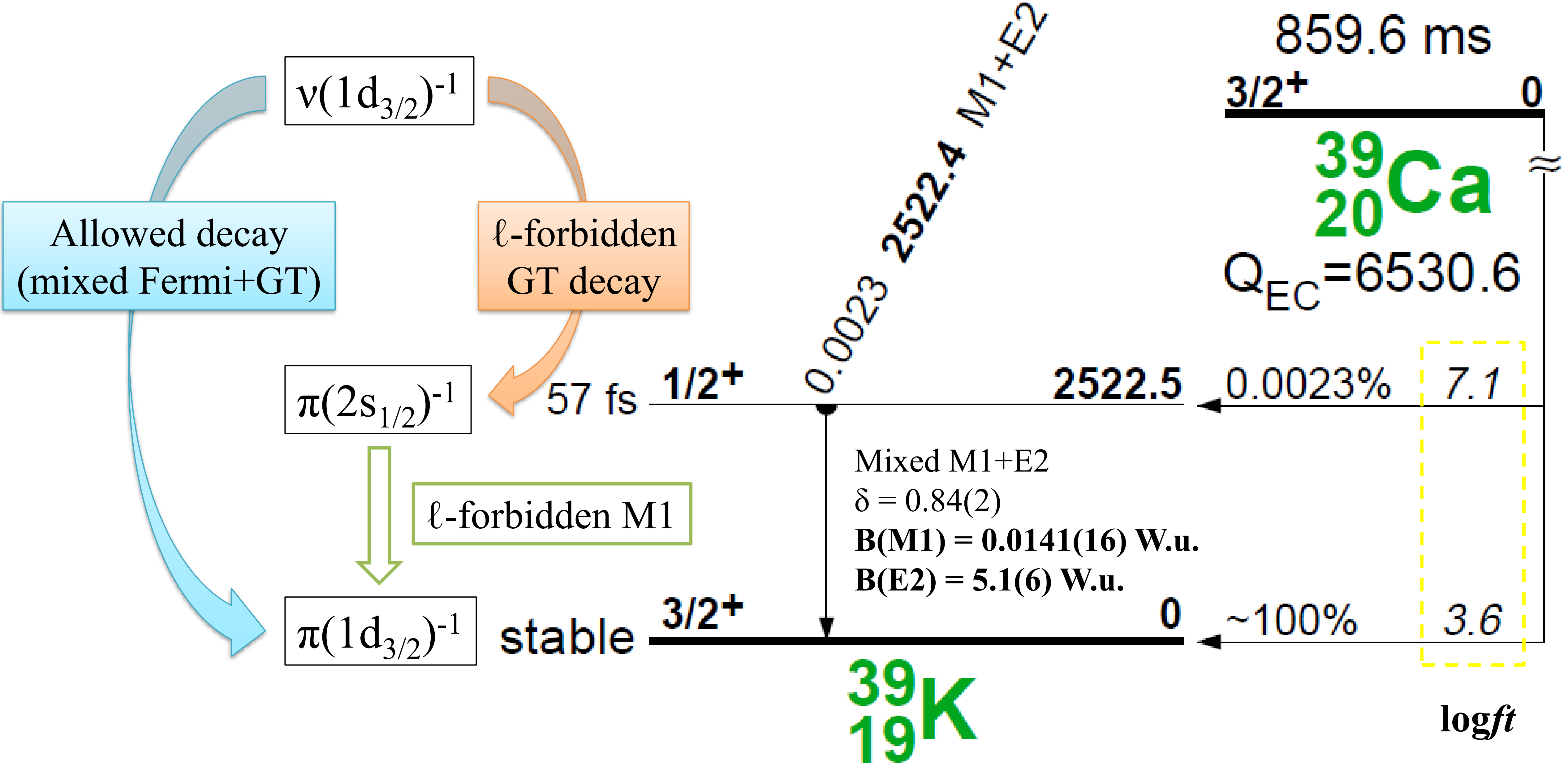
by calculation

by measurement



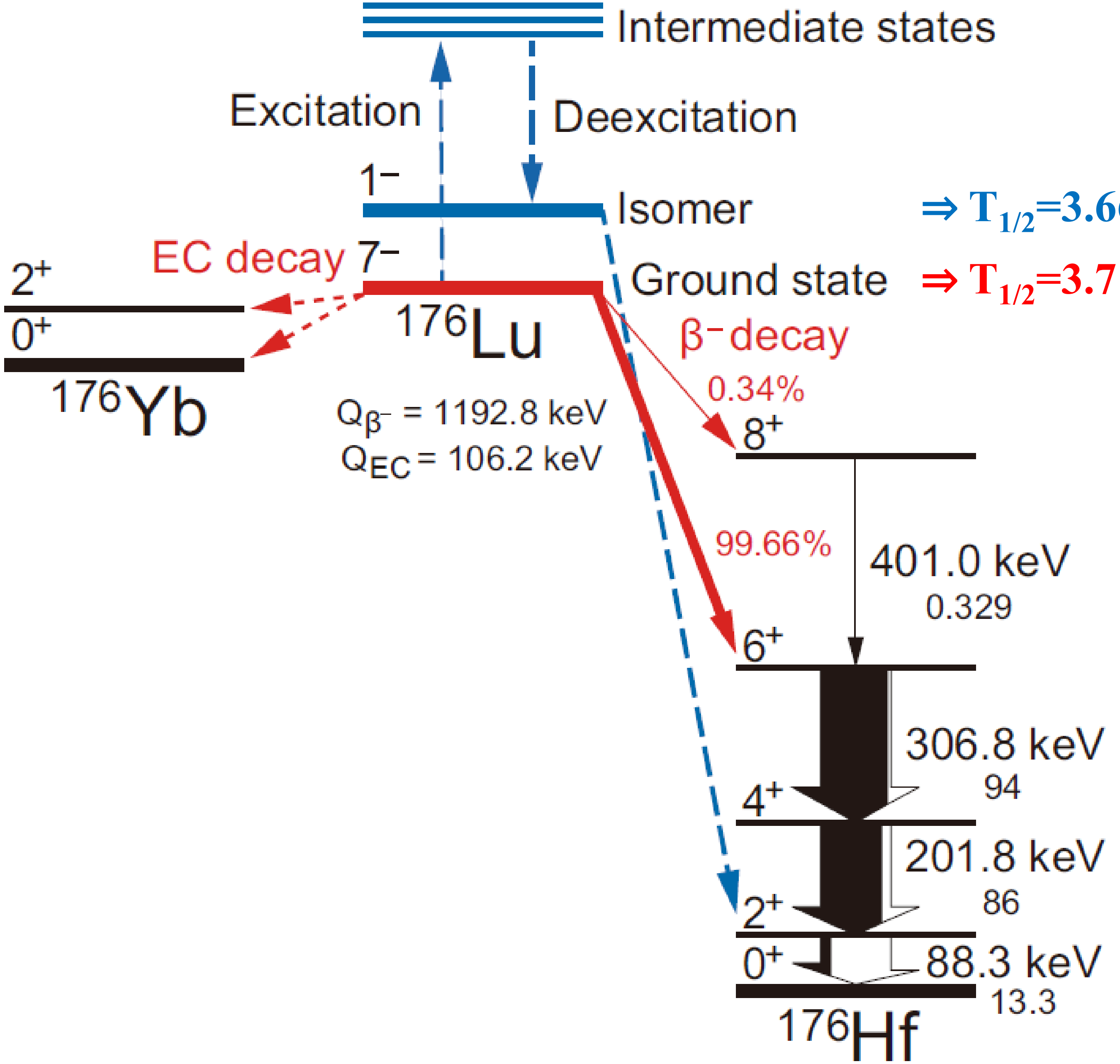



# Effect of nuclear structure on β decay: ℓ-forbidden



# Effect of nuclear structure on β decay: K-forbidden

First forbidden → log*ft* ~ 6 – 10

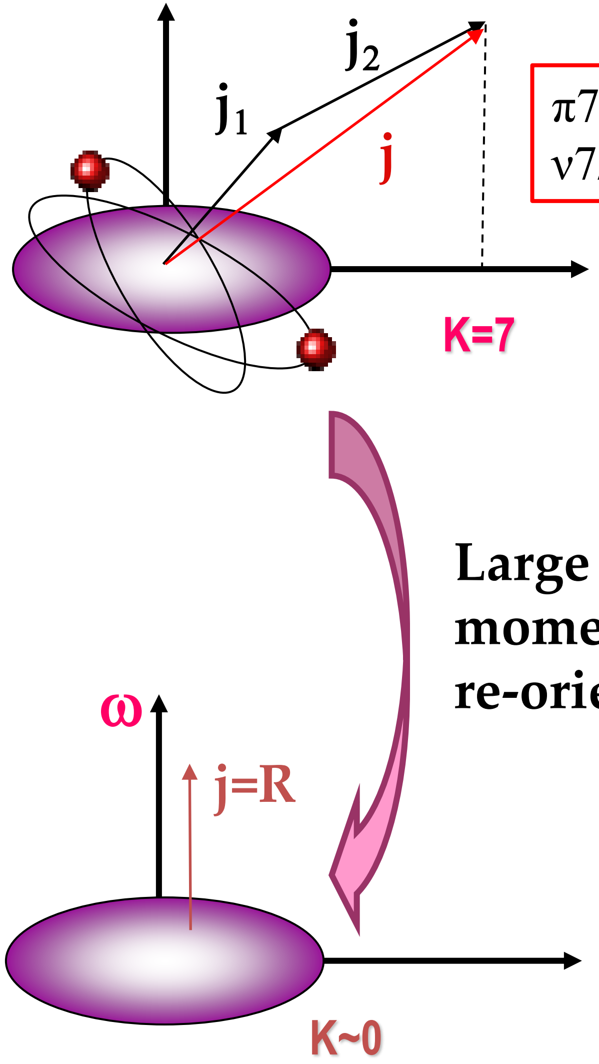



⇒ $T_{1/2}$=3.664 h, K = 1

⇒ $T_{1/2}$=3.7 × $10^{10}$ yr, K = 7

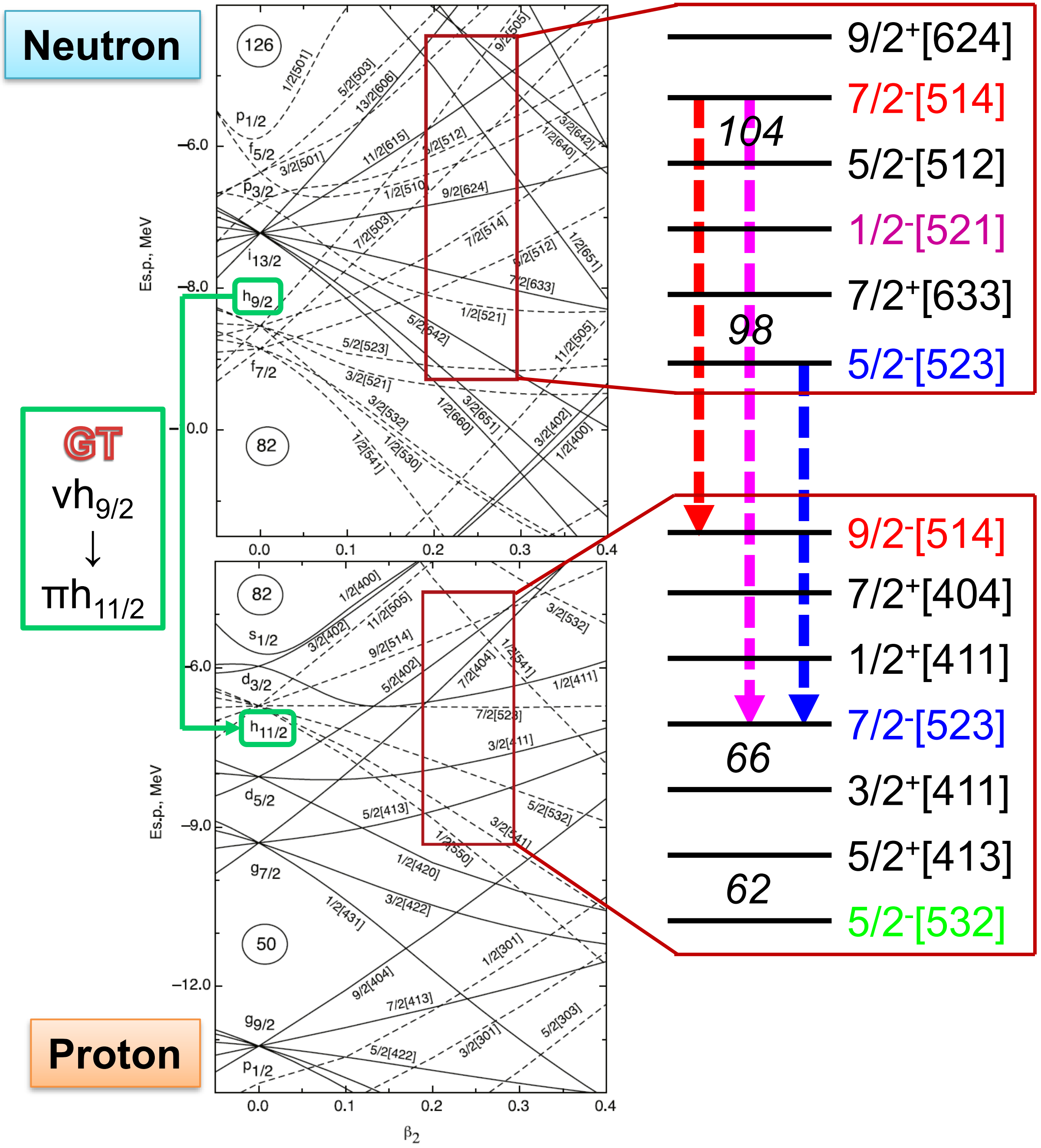
| log*ft* |
| --- |
| 19.98 |
| 19.17 |
| 6.54 |
| 6.85 |

$\pi 7/2^+[404] \otimes$
$\nu 7/2^-[514]$




Large angular momentum re-orientation

# Effect of nuclear structure on β decay: Nilsson orbits

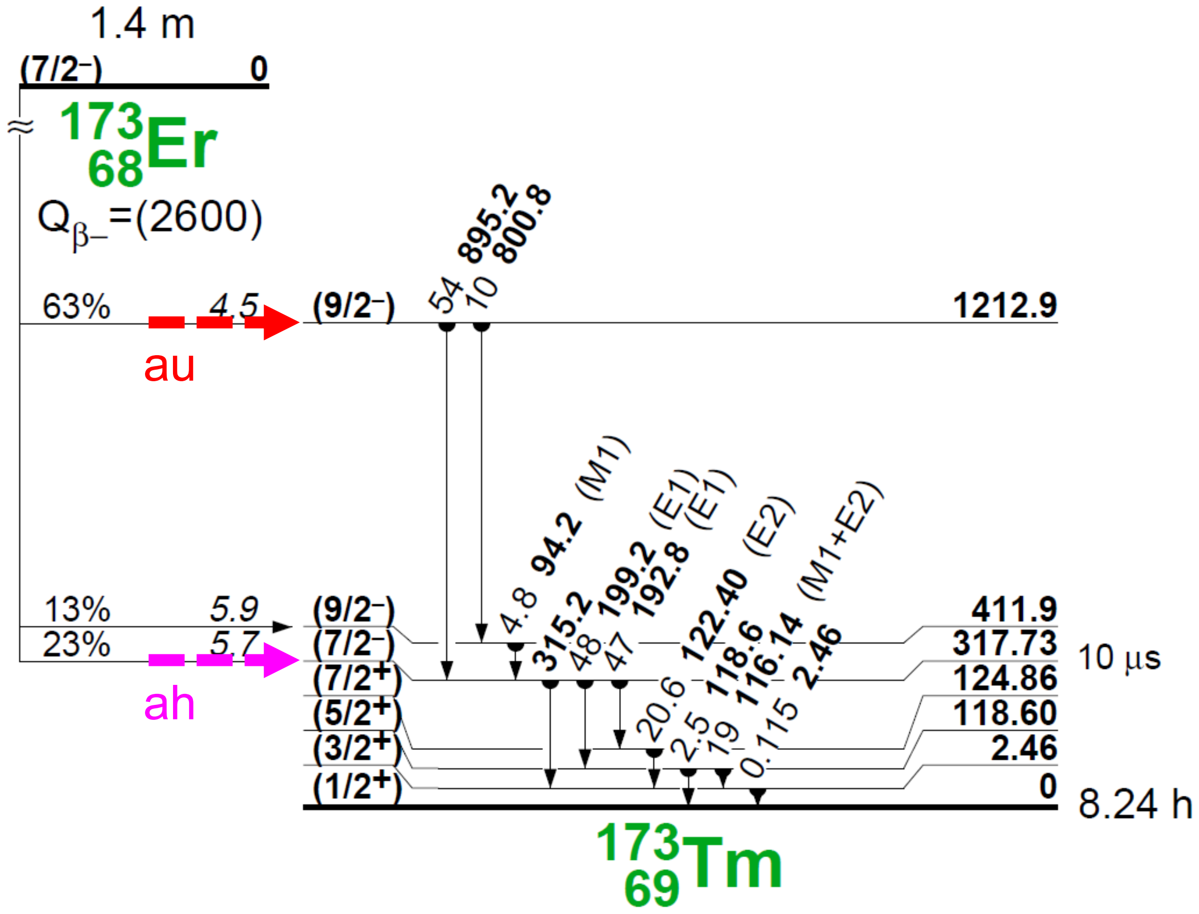



allowed-unhindered (au) $\log ft \le 5$

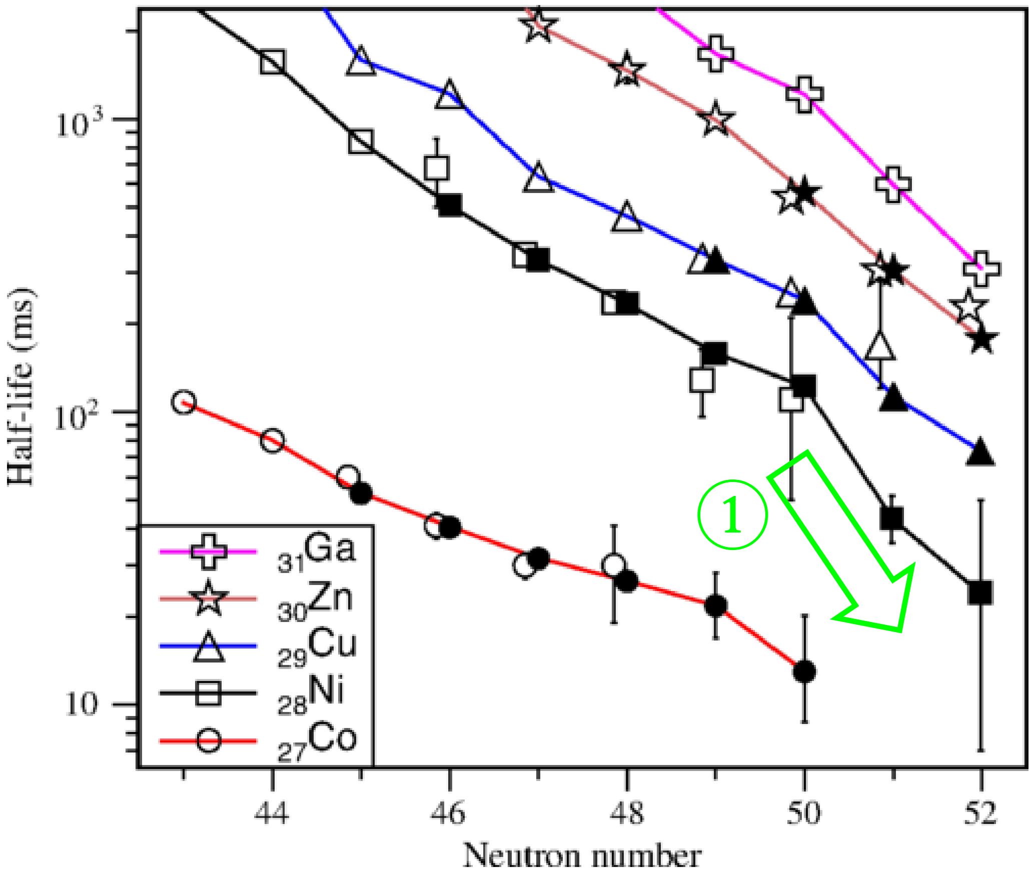
$$\Delta N = \Delta n_z = \Delta\Lambda = 0$$

allowed-hindered (ah) $\log ft \ge 5.5$

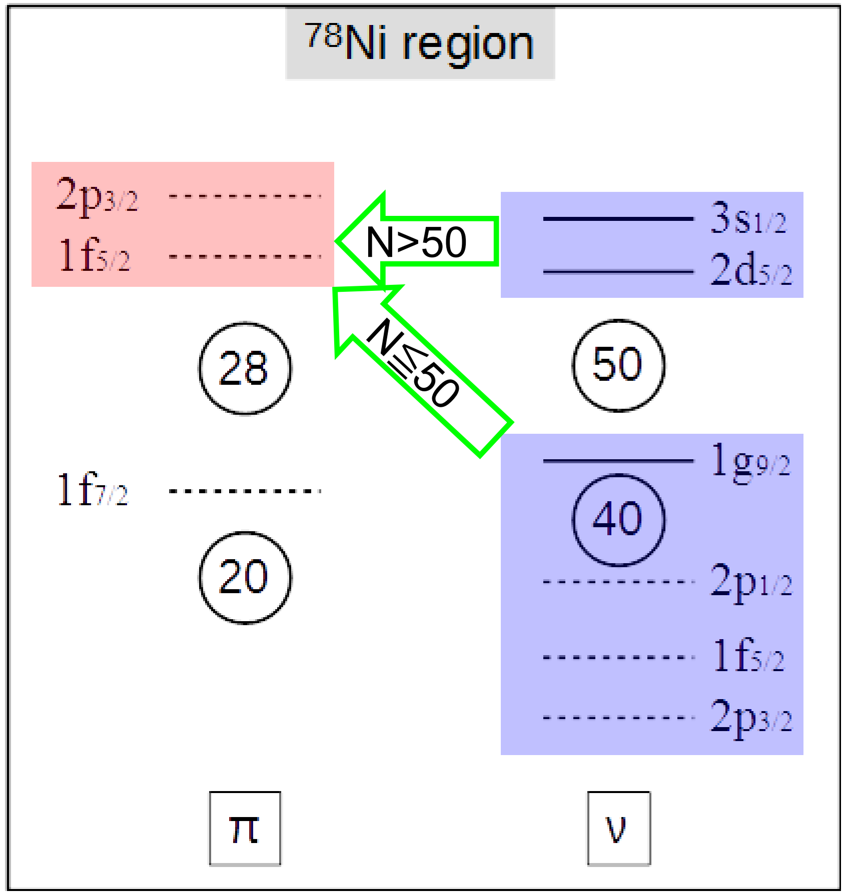
$$\Delta N = 0, \Delta n_z \ne 0, \Delta\Lambda \ne 0$$



# Effect of nuclear structure on β decay: Shell gap

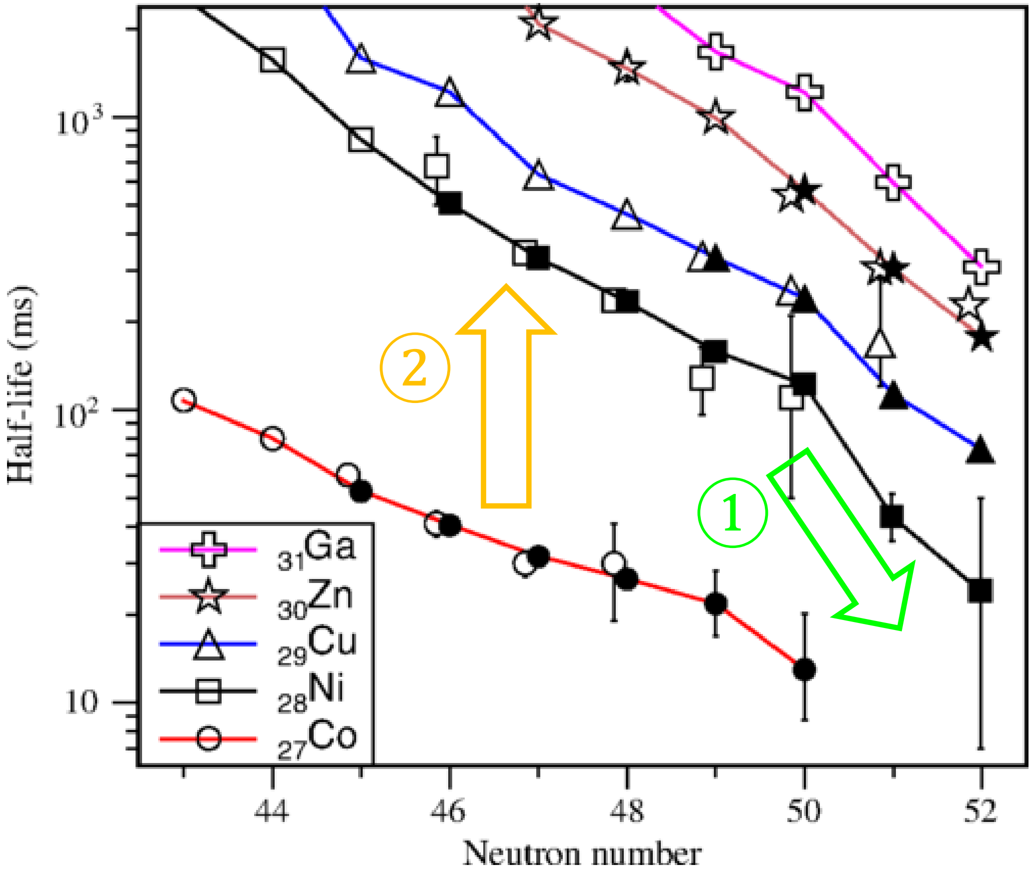



Z.Y. Xu et al., PRL113, 032505 (2014)




① Abrupt drop for Ni isotopes N > 50 → N = 50 shell gap

# Effect of nuclear structure on β decay: Shell gap

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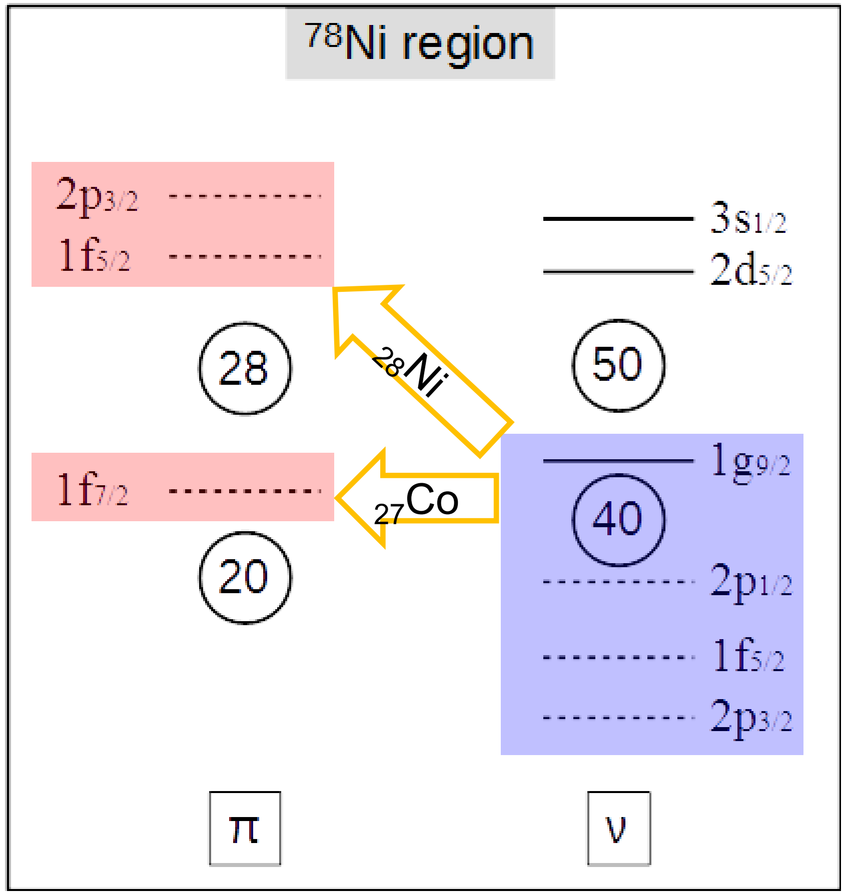


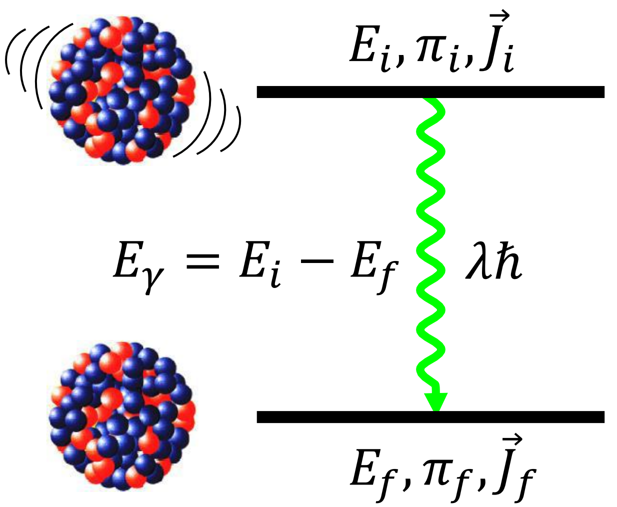

① Abrupt drop for Ni isotopes N > 50 → N = 50 shell gap

② Sizable gap between $_{28}$Ni and $_{27}$Co → Z = 28 shell gap

Robust nature of doubly-magic nucleus $^{78}$Ni

# Gamma-ray emission

**Charge/current distribution changes in a nucleus** → **Extra-nuclear field varies** → **Energy released as a photon (emission of an EM wave)**




$$|J_f - J_i| \le \lambda \le J_f + J_i$$

**Electric transition**

$$O_{\lambda\mu}(E\lambda) = \sum_{i=1}^{A} e(i) r_i^{\lambda} Y_{\lambda\mu}(\theta_i, \varphi_i)$$

Charge distribution: $e(i)$

$$e(i) = \begin{cases} 1 \\ 0 \end{cases} \quad g_\ell(i) = \begin{cases} 1 \\ 0 \end{cases} \quad g_s(i) = \begin{cases} 5.586 \\ -3.826 \end{cases}$$

**Magnetic transition**

$$O_{\lambda\mu}(M\lambda) = \sum_{i=1}^{A} \left\{ g_s(i) s_i + g_\ell(i) \frac{2\ell_i}{\lambda + 1} \right\} \cdot \nabla_i \left( r_i^{\lambda} Y_{\lambda\mu}(\theta_i, \varphi_i) \right) \mu_N$$

Intrinsic spin (1/2ħ): $g_s(i) s_i$

Proton orbital motion: $g_\ell(i) \frac{2\ell_i}{\lambda + 1}$

Parity selection rule

$$\pi_i \pi_f = (-1)^{\lambda}$$ (electric)

$$\pi_i \pi_f = (-1)^{\lambda+1}$$ (magnetic)

Transition rate

$$w(\lambda; J_i \to J_f) = \frac{8\pi(\lambda + 1)}{\lambda[(2\lambda + 1)!!]^2} \frac{1}{\hbar} \left( \frac{E_\gamma}{\hbar c} \right)^{2\lambda+1} B(\lambda; J_i \to J_f)$$

→ Depend on energy

Reduced transition probability

$$B(\lambda; J_i \to J_f) = \sum_{\mu M_f} \left| \langle J_f M_f | O_{\lambda\mu} | J_i M_i \rangle \right|^2 = \frac{1}{2J_i + 1} \left| \langle J_f \| O_\lambda \| J_i \rangle \right|^2$$

→ Not depend on energy

# Gamma-ray spectroscopy in nuclear physics

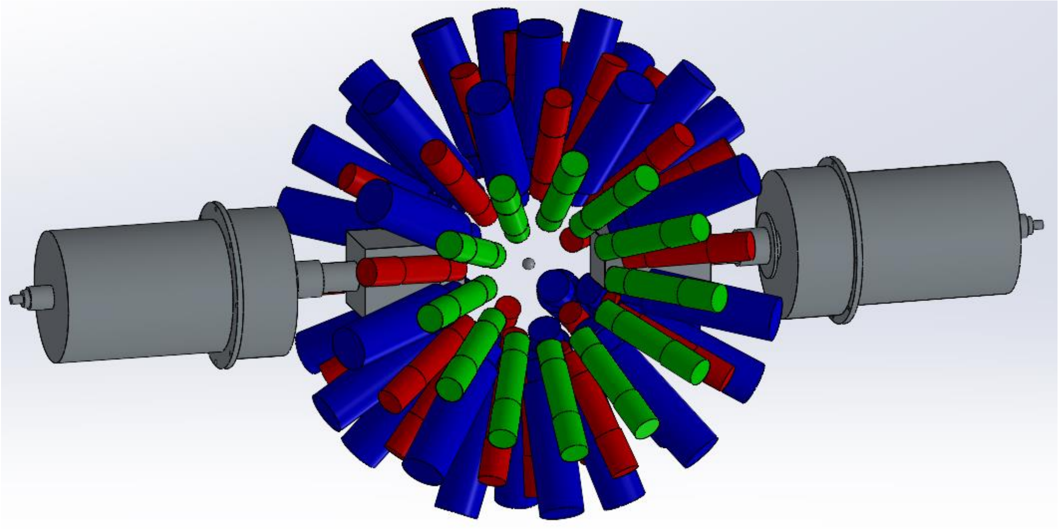
**Powerful experimental means to investigate (bound) excited states**

| **Observables/techniques** | | **Physics outputs** |
| --- | --- | --- |
| ■ Full-energy (photo) peak | ⇒ | Level and transition energy |
| ■ Time distribution, Doppler shift | ⇒ | Lifetime of excited states |
| ■ Coincidence relationship | ⇒ | Level scheme |
| ■ Angular distribution and correlation | ⇒ | Spin, multipolarity (λ) |
| ■ Linear polarization | ⇒ | Parity (Eλ or Mλ) |

High resolution γ-ray spectroscopy with **large detector arrays** has been a cornerstone in nuclear structure studies

# Two main research gears for γ-ray spectroscopy at CENS

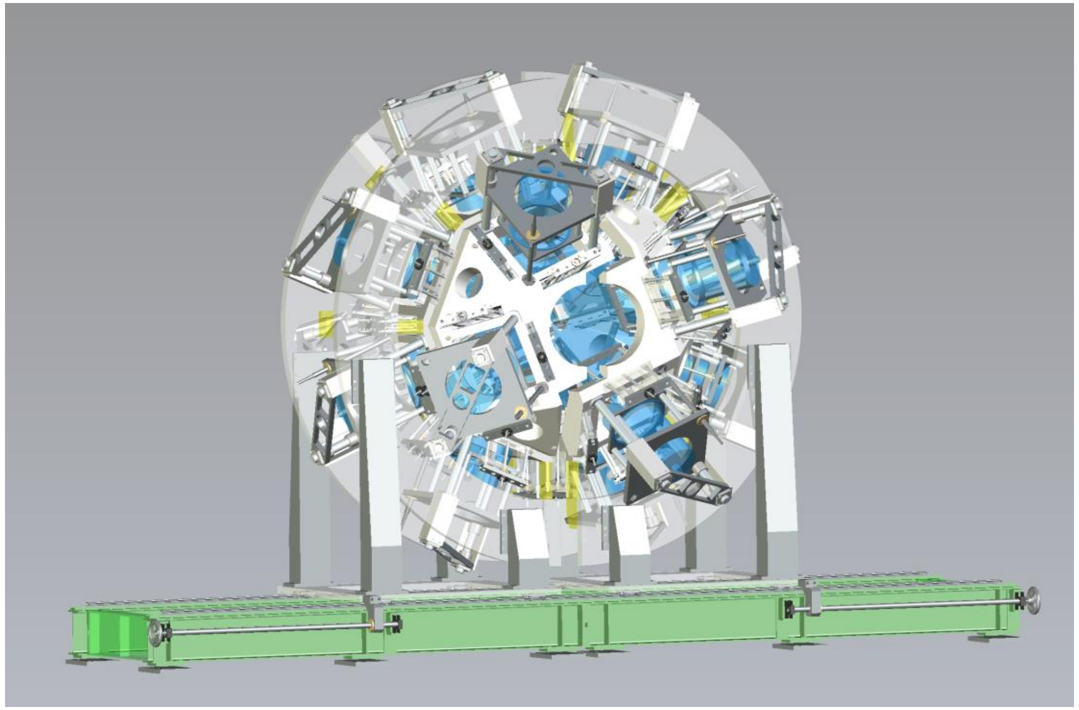
IDATEN
(International Detector Assembly for fast-Timing measurements of Exotic Nuclei)



$LaBr_3(Ce)$-based array
⇓
**Fast time response**

5 proposals from CENS (spokesperson/co-spokesperson) approved by RIBF PAC in 2022/2023

ASGARD
(Array of Super clover GAmma-Ray Detectors)



Hyper-pure Ge detectors
⇓
**High energy resolution**

4 experiments proposed by the CENS members scheduled at RAON in Oct-Nov 2025

# Scientific motivation for measuring excited-state lifetime

Lifetime of an excited state is one of the most important observables in nuclear structure studies

$$\frac{1}{\tau} = \frac{\Gamma}{\hbar} = \frac{8\pi(\lambda+1)}{\lambda[(2\lambda+1)!!]^2} \frac{1}{\hbar} \left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda+1} B(\sigma\lambda; I_i \to I_f)$$

**$B(\sigma\lambda)$ contains information of the wave functions of the initial and final states**

- *More sensitive to the intrinsic structure than level energies*
- *In-depth study of the underlying nuclear structure aspects, such as single-particle and collective motion*
- *Probe for the "hidden" mechanism of structural change (e.g., shell/shape evolution)*
- *Good testing ground for theoretical nuclear structure models*

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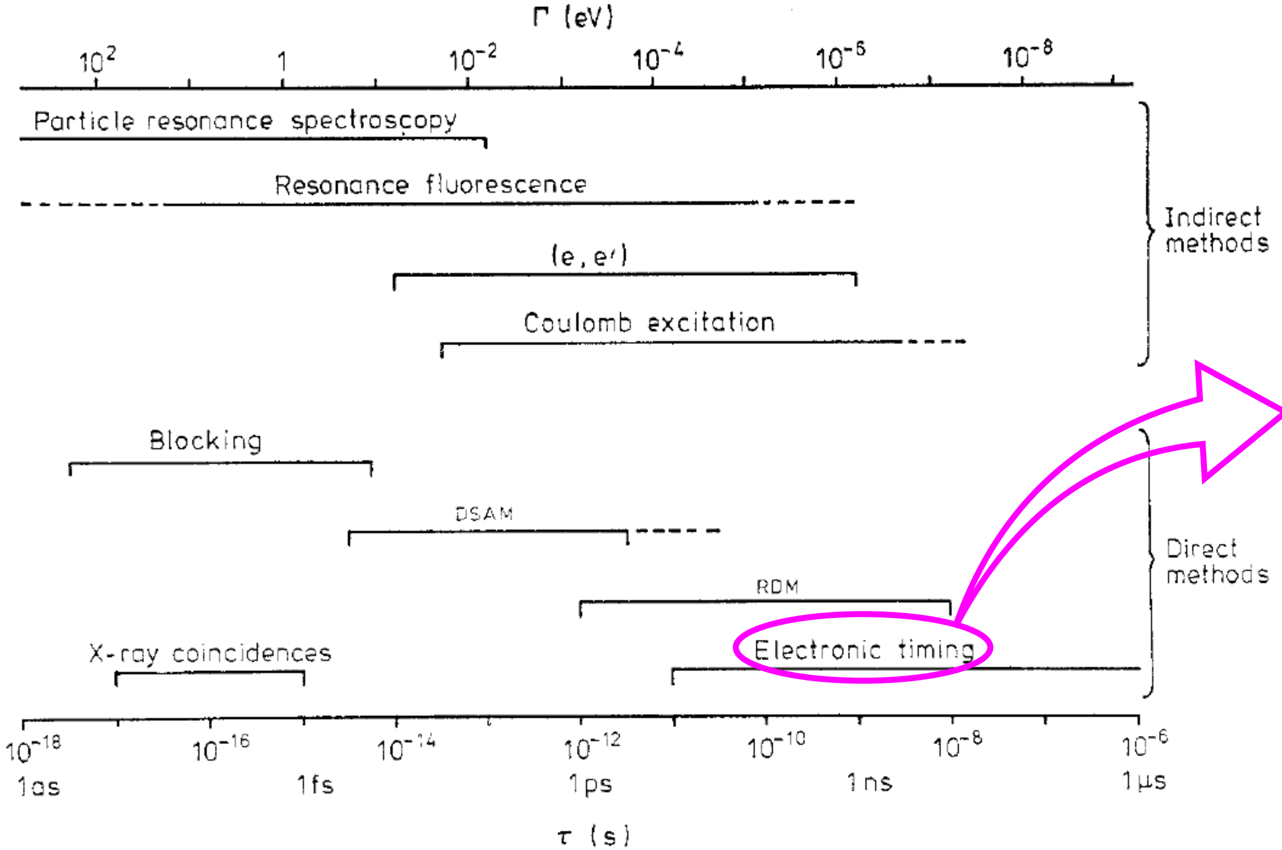
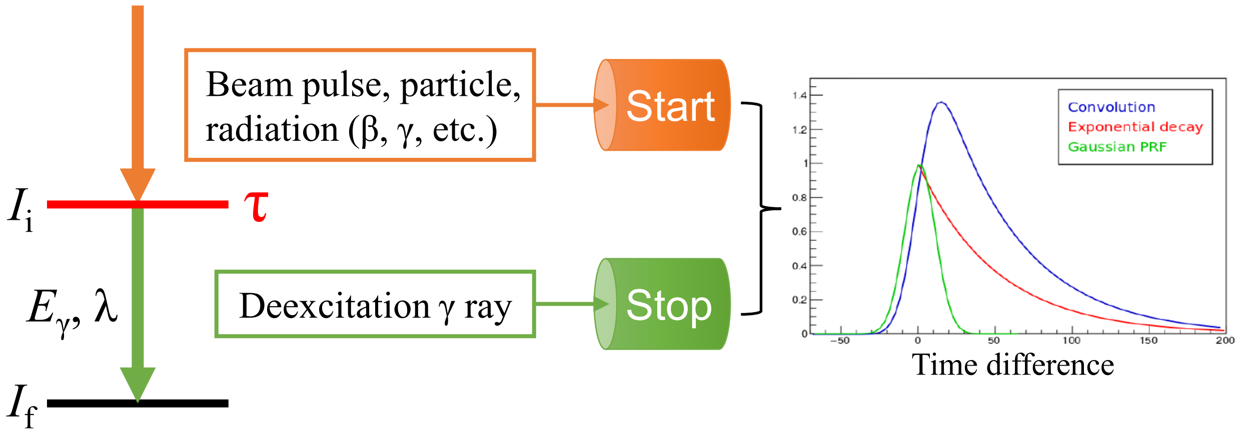
P.J. Nolan and J. F. Sharpey-Schafer, Rep. Prog. Phys. 42, 1 (1979)




The mean lifetime can be determined directly from the slope or the shift of centroids of the time differential spectrum.

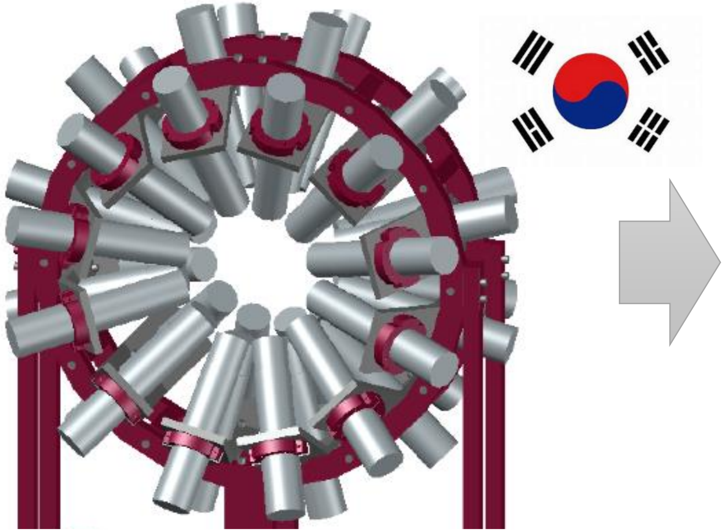
# International Detector Assembly for fast-Timing measurements of Exotic Nuclei: IDATEN

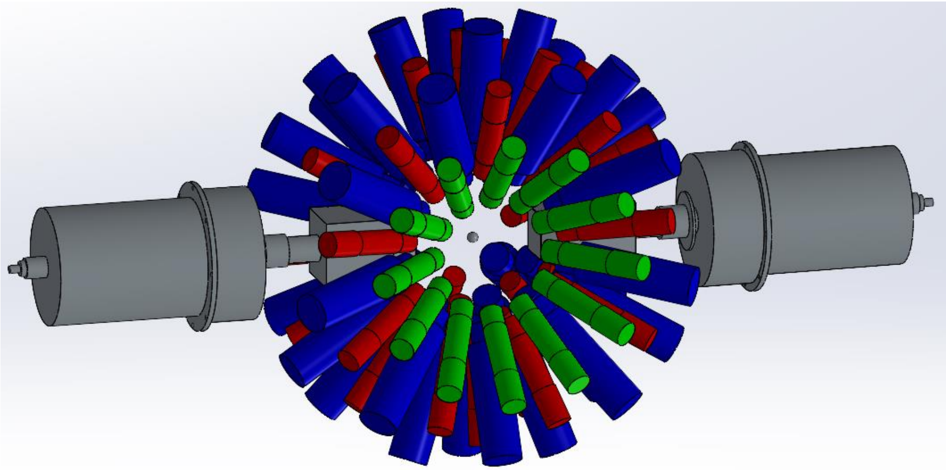
**FATIMA**
***FA**st-**TIM**ing **A**rray*

**KHALA**
***K**orea **H**igh-resolution **A**rray of **LA**Br$_3$(Ce)*

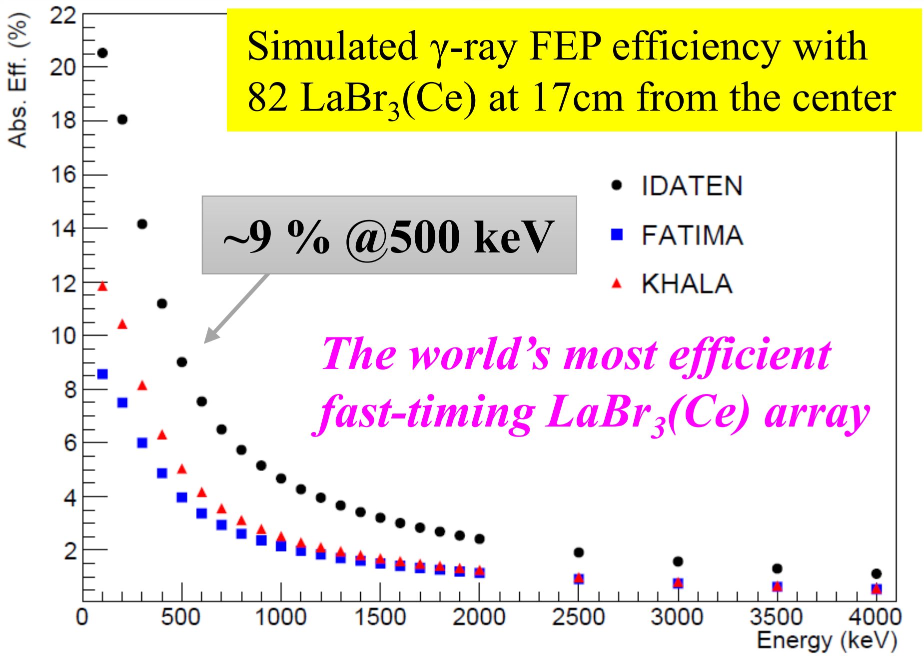
**IDATEN**
82 LaBr$_3$(Ce) + 2 Clover HPGe detectors

+





| | FATIMA | KHALA |
|---|---|---|
| Quantity | 36 units | 48 units |
| Crystal size | $\phi$1.5” × 2”-length | $\phi$1.5” × 1.5”-length |
| PMT | R9779 | R13408 |
| $\delta E_\gamma/E_\gamma$ | 3.4 % @779 keV | 3.3 % @662 keV |
| $\delta T_\gamma$ in FWHM (γ-γ coin.) | 334.3(4) ps (1332-1173 keV) | 335(1) ps (511-511 keV) |
| Owners | U. of Surrey<br>U. of Brighton | Korea U.<br>Seoul National U. |

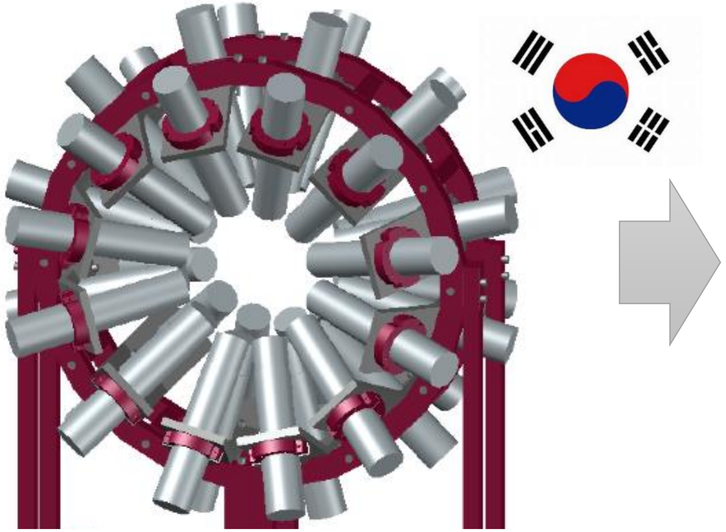


# International Detector Assembly for fast-Timing measurements of Exotic Nuclei: IDATEN

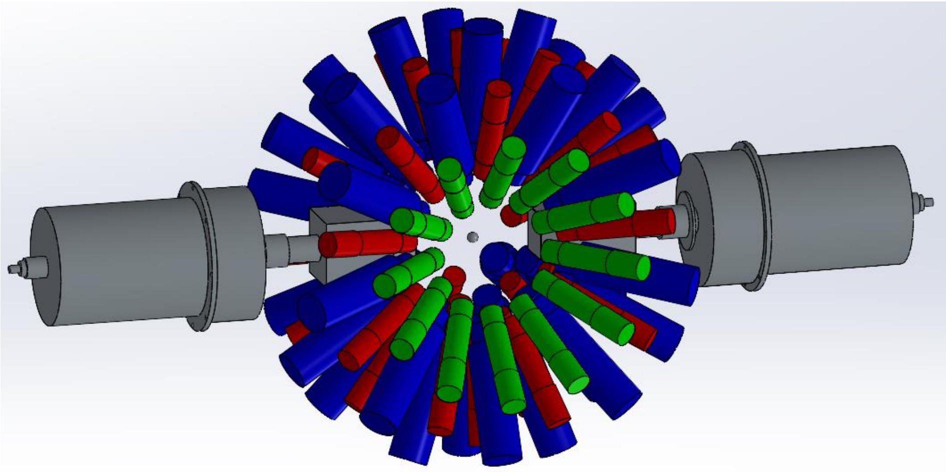
**FATIMA**
***FA**st-**TIM**ing **A**rray*

+

**KHALA**
***K**orea **H**igh-resolution **A**rray of **LA**Br$_3$(Ce)*



**IDATEN**
82 LaBr$_3$(Ce) + 2 Clover HPGe detectors

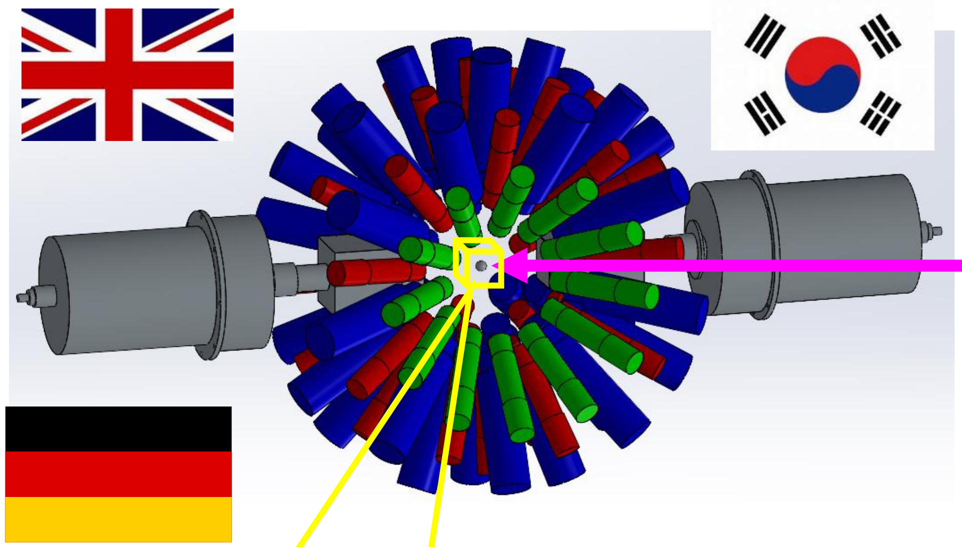


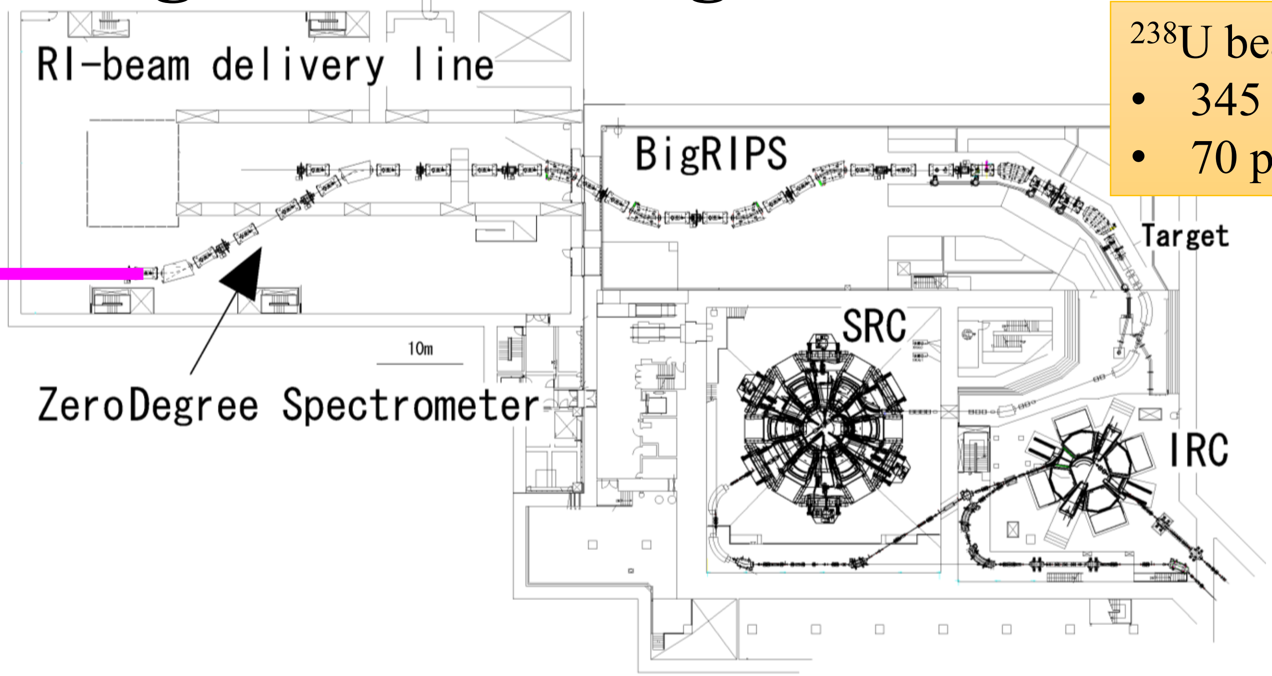
| | FATIMA | KHALA |
|---|---|---|
| Quantity | 36 units | 48 units |
| Crystal size | $\phi$1.5” × 2”-length | $\phi$1.5” × 1.5”-length |
| PMT | R9779 | R13408 |
| $\delta E_\gamma / E_\gamma$ | 3.4 % @779 keV | 3.3 % @662 keV |
| $\delta T_\gamma$ in FWHM ($\gamma$-$\gamma$ coin.) | 334.3(4) ps (1332-1173 keV) | 335(1) ps (511-511 keV) |
| Owners | U. of Surrey<br>U. of Brighton | Korea U.<br>Seoul National U. |

## Scope of IDATEN

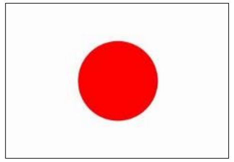
- Measurement of 10 ps - 10 ns lifetimes using the electronic fast-timing methods
- Study of new levels and γ rays by β-γ spectroscopy
- Search for previously unexplored isomers

# Experimental setup: SRC → BigRIPS/ZeroDegree → IDATEN



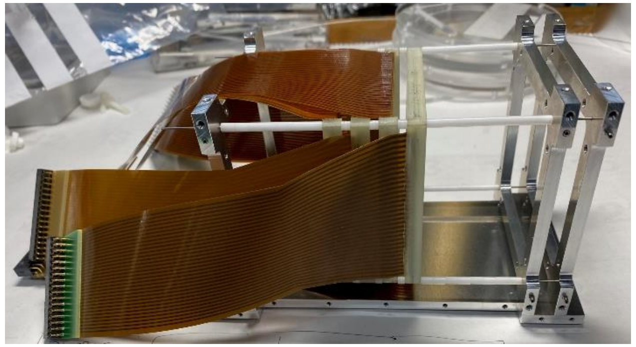



$^{238}U$ beam
- 345 MeV/u
- 70 pnA

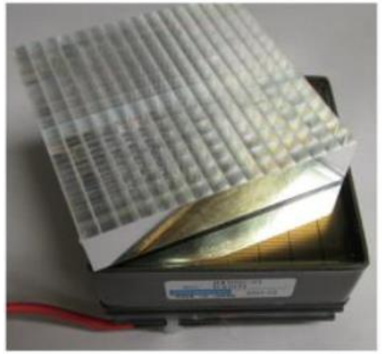


Active stopper system

DSSSD (Micron BB-7)



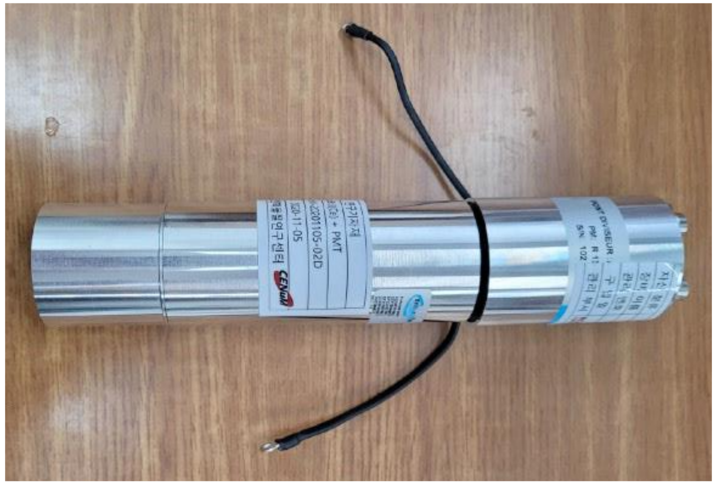
Segmented plastic



## Scope of IDATEN

- Measurement of 10 ps - 10 ns lifetimes using the electronic fast-timing methods
- Study of new levels and γ rays by β-γ spectroscopy
- Search for previously unexplored isomers

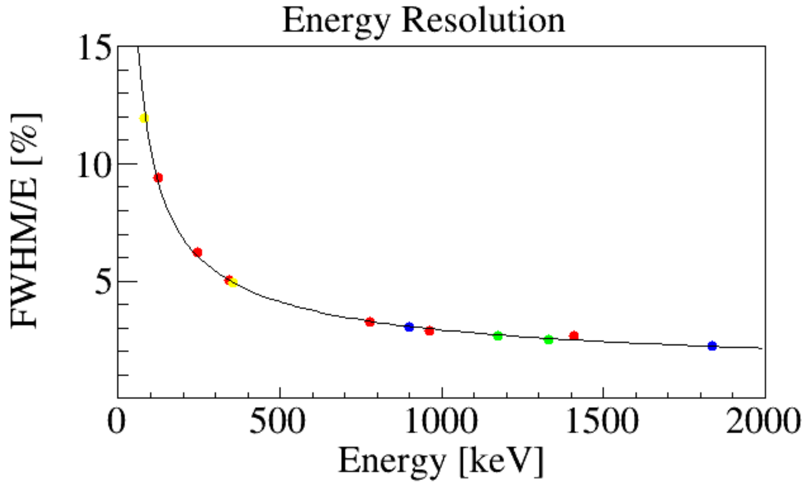
# $LaBr_3(Ce)$ detectors

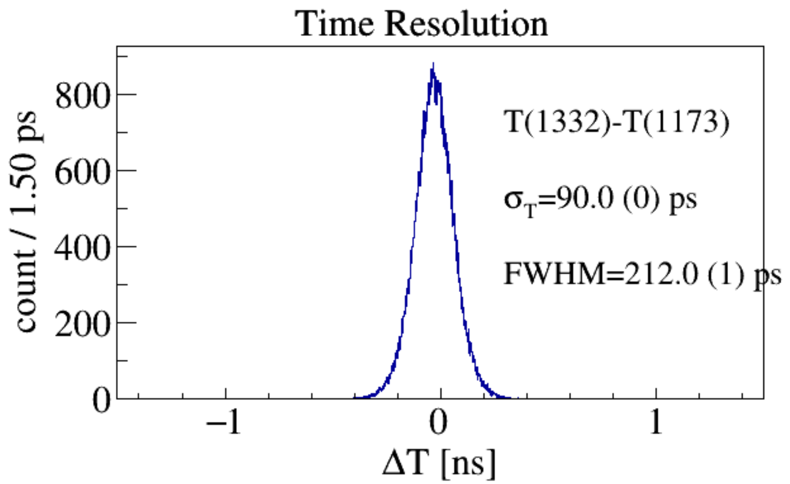


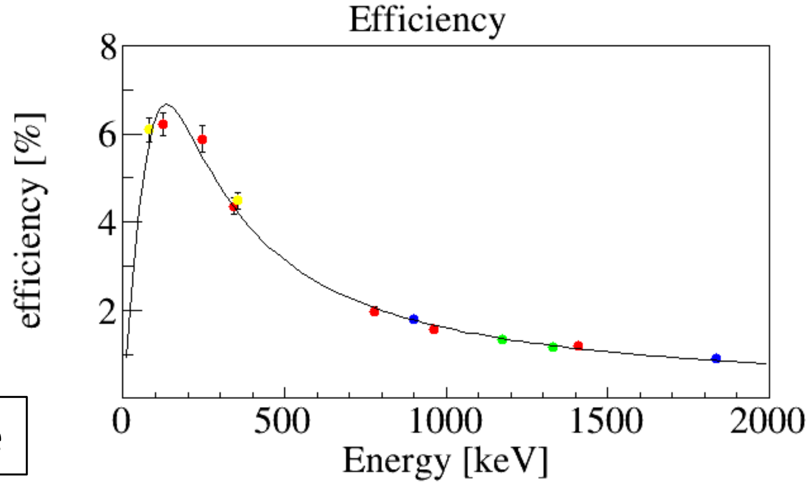
KHALA: Korea High-resolution Array of $LABr_3$(Ce)

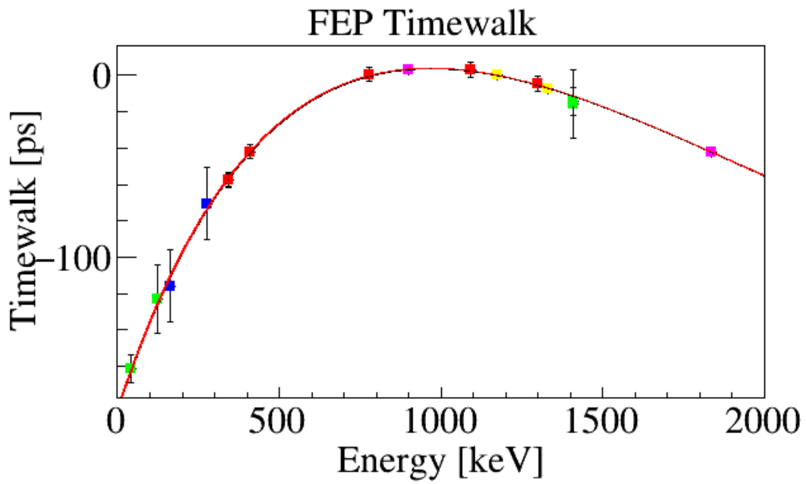
B. Moon et al., NIMB 541 (2023) 253

- $\phi$1.5” × 1.5” crystal (BrilLanCe380) from Saint-Gobain
- HAMAMATSU R13408 PMT assembly
- 36 units from Korea U., 12 units from SNU



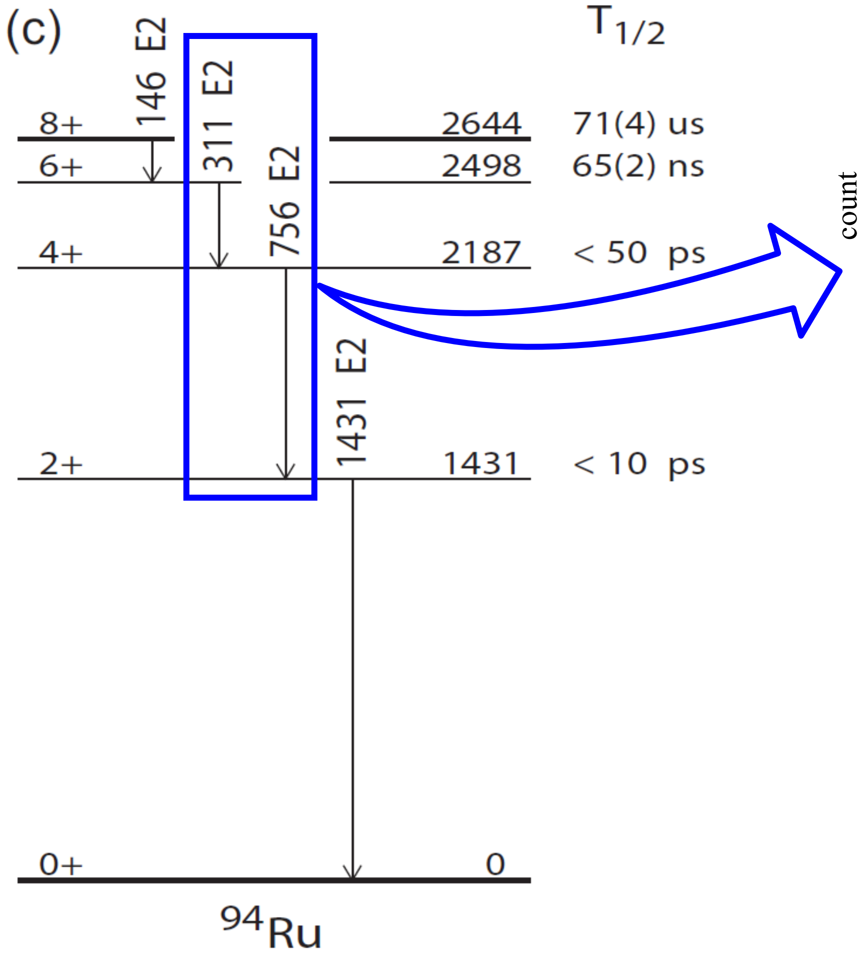



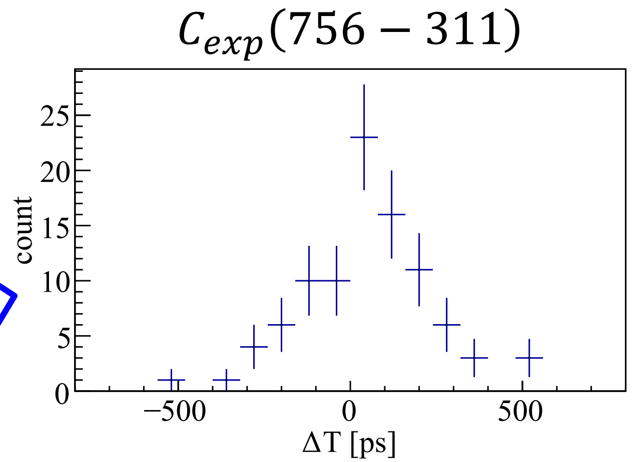

Courtesy of J. Lee

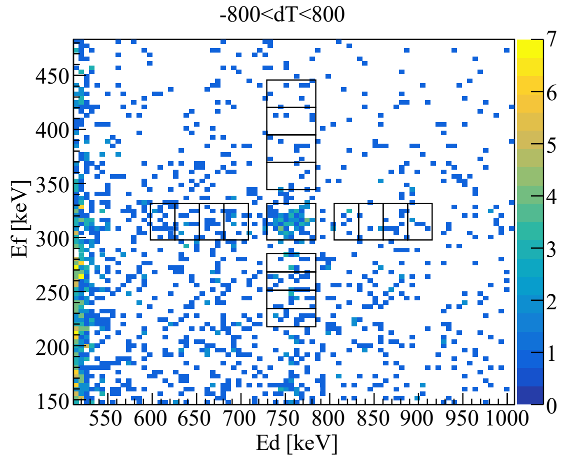
# Analysis technique: Generalized Centroid Difference (GCD)

Lifetimes comparable with time resolution (10 – 100 ps) can be determined by means of the GCD method using fast-response γ-ray detectors such as $LaBr_3(Ce)$.




H. Mach et al., PRC95, 014313 (2017)

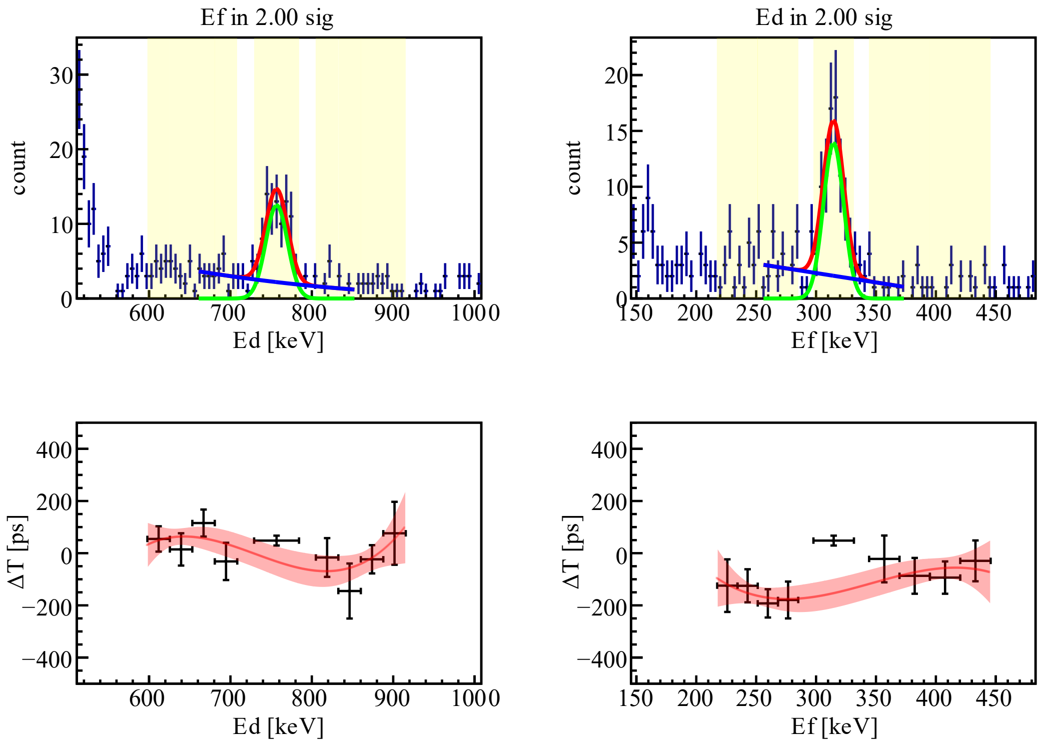



$$C_{p,p} = C_{exp} + \frac{R_d \times Tcor_d + R_f \times Tcor_f}{R_d + R_f}$$

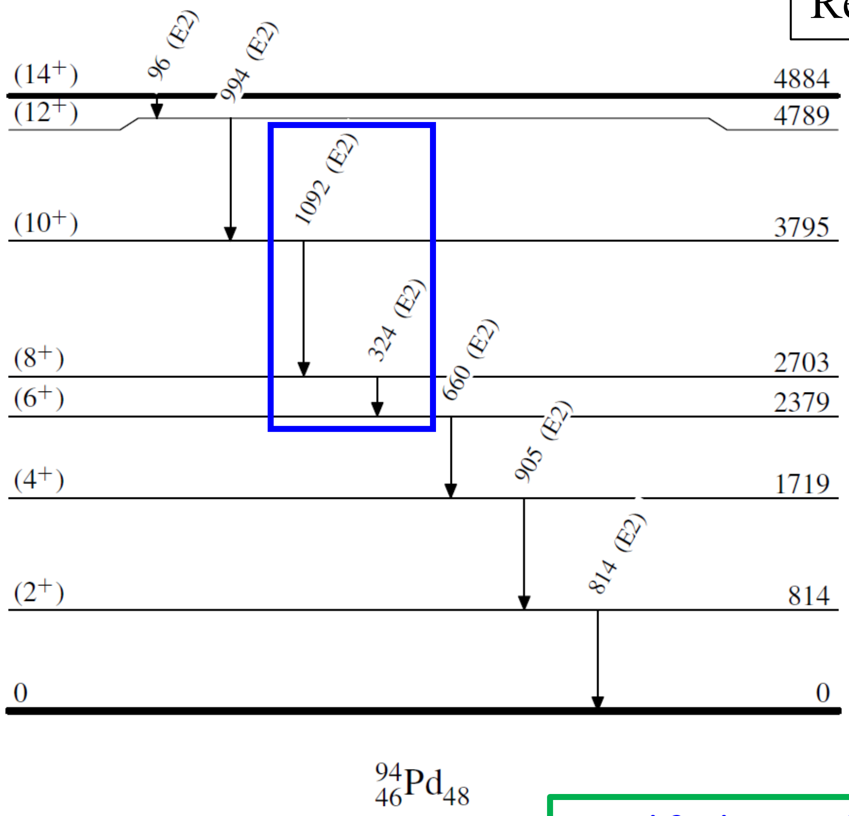
BG-to-Peak ratio: $R_i = B_i / P$

BG correction factor: $Tcor_i = \left(C_{exp} - C_{BG,i}\right) \times R_i$

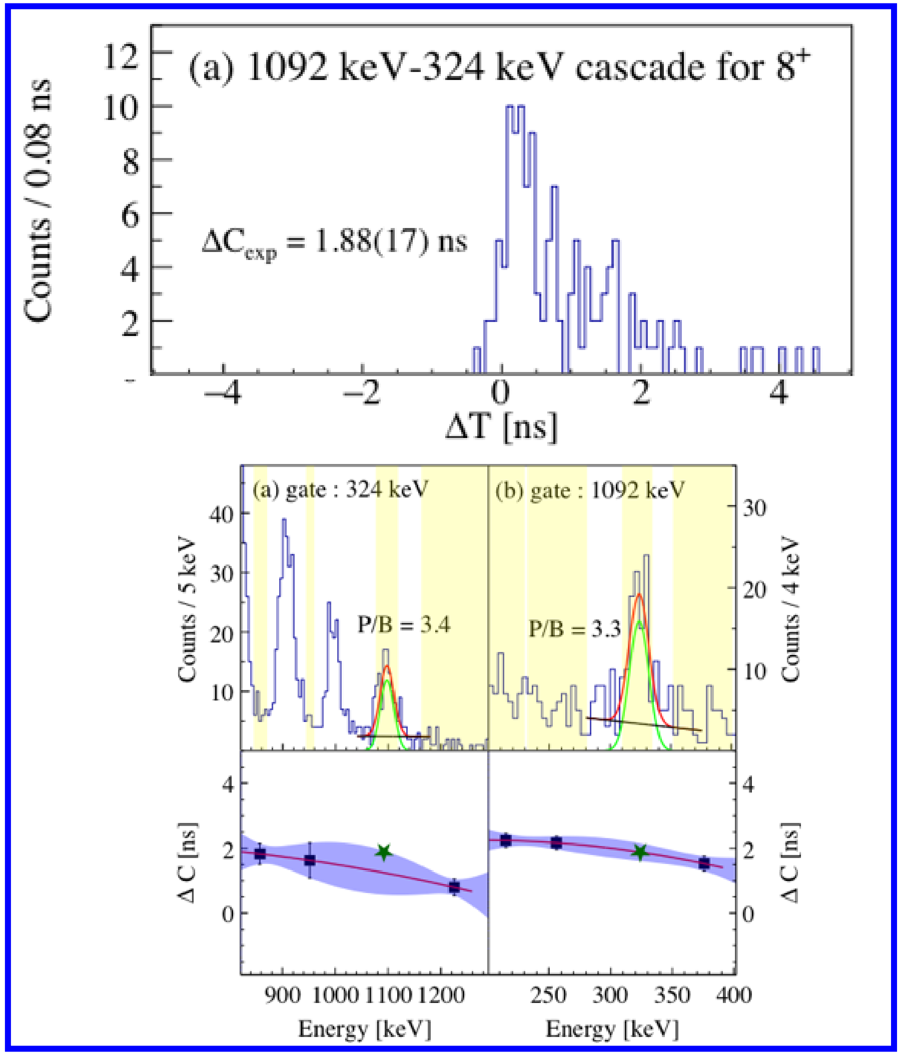


# First physics result from IDATEN: Excited-state lifetime of $^{94}$Pd

- IDATEN commissioning experiment (26-27 June 2024)
- Primary beam: $^{124}$Xe, 345 MeV/u, ~140 pnA



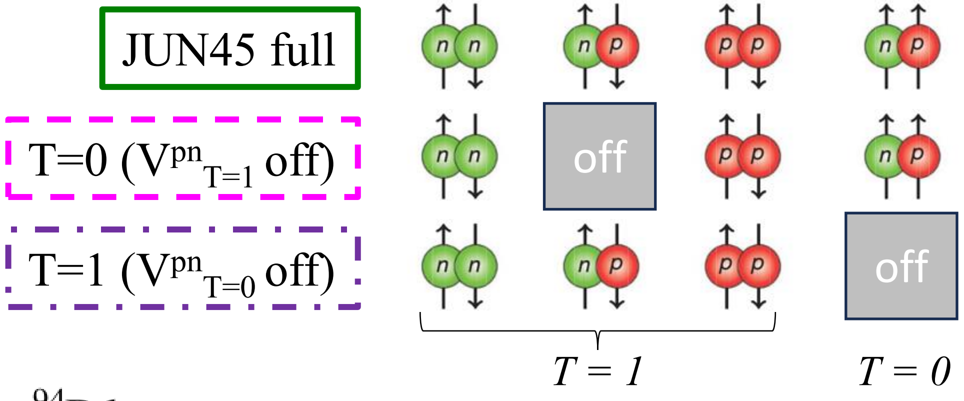

| Level | Reference | Present work |
|---|---|---|
| (14+) 4884 | 515 ns *1* | 560(10) ns |
| (10+) 3795 | | < 19 ps |
| (8+) 2703 | 7.6×10$^2$ ps *11* | **693(72) ps** |
| (6+) 2379 | <40 ps | < 13 ps |
| (4+) 1719 | | 13(11) ps |
| (2+) 814 | | < 15 ps |

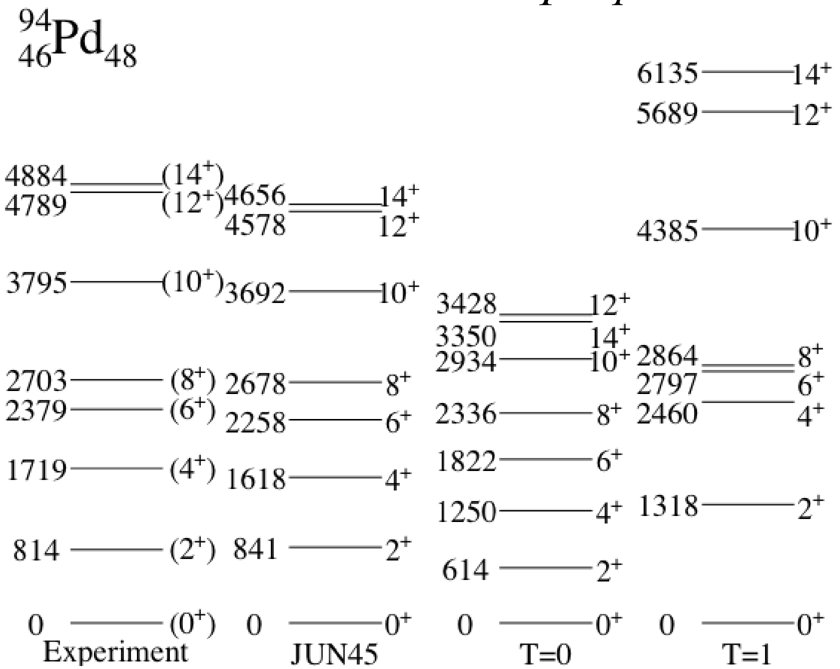


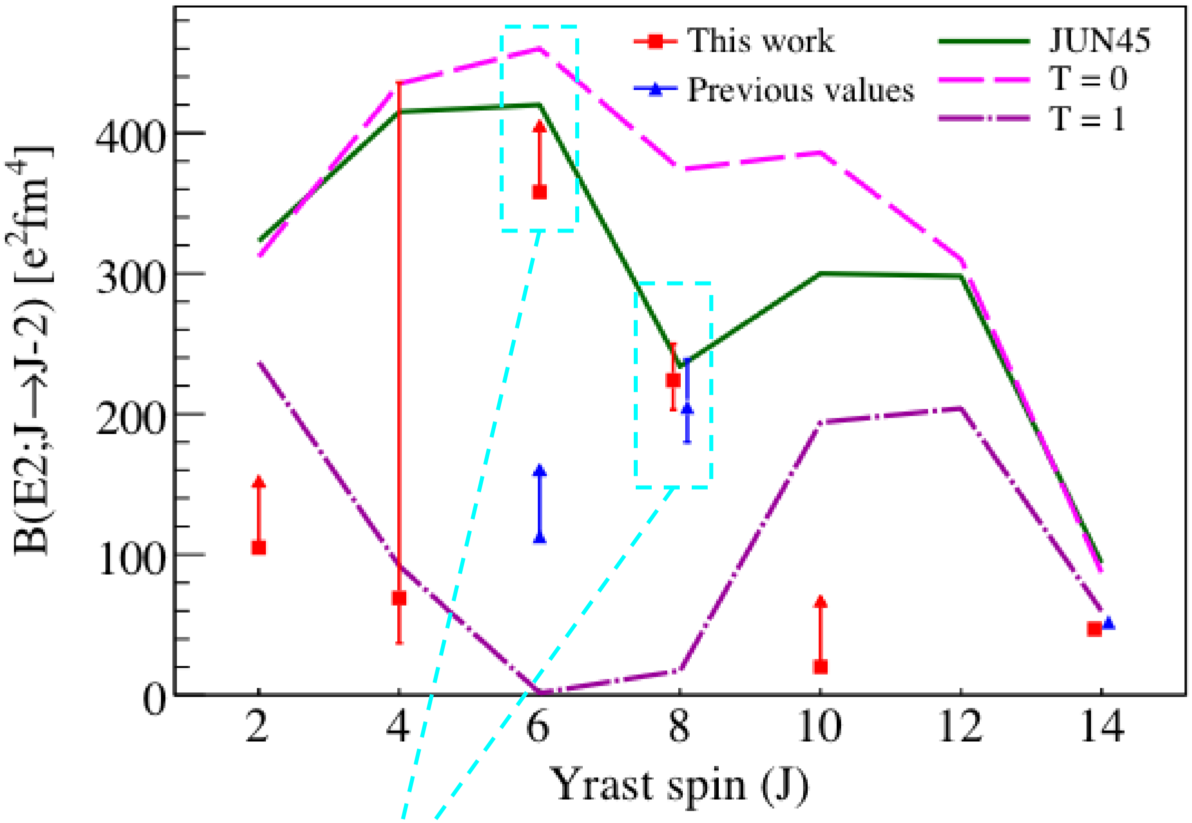

- Lifetime of the (8$^+$) level measured in better precision
- Lifetime of the (4$^+$) level measured for the first time
- Upper limit of lifetime defined for the (2$^+$), (6$^+$), and (10$^+$) levels

# $^{94}$Pd results: compared to shell-model calculations

- Model space: $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$ for protons and neutrons
- Interactions: JUN45 (optimized using experimental data)
- Effective charges: 1.5e for protons, 1.1e for neutrons
- Three types of calculation using the KSHELL code:



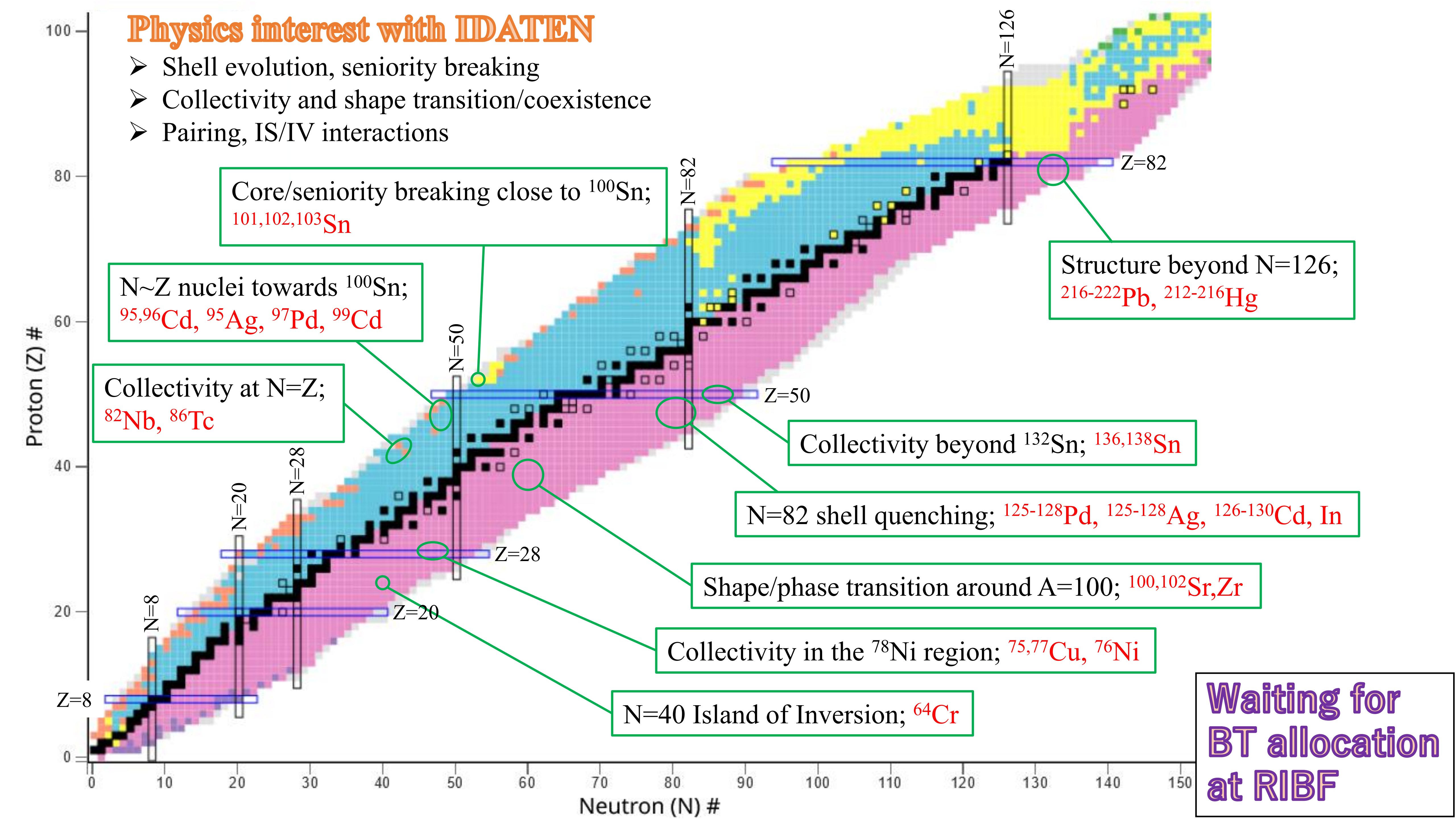




Newly measured B(E2) values can put a stricter constraint on the p-n interactions

- T = 0 component plays a dominant role in **the 6$^+$ state**
- Both T = 0 and T = 1 components contribute to **the 8$^+$ state**

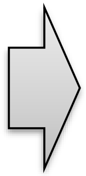
Accepted for publication in PRC


Physics interest with IDATEN
Shell evolution, seniority breaking
Collectivity and shape transition/coexistence
Pairing, IS/IV interactions
Core/seniority breaking close to 100Sn; 101,102,103Sn
N~Z nuclei towards 100Sn; 95,96Cd, 95Ag, 97Pd, 99Cd
Collectivity at N=Z; 82Nb, 86Tc
Structure beyond N=126; 216-222Pb, 212-216Hg
Collectivity beyond 132Sn; 136,138Sn
N=82 shell quenching; 125-128Pd, 125-128Ag, 126-130Cd, In
Shape/phase transition around A=100; 100,102Sr,Zr
Collectivity in the 78Ni region; 75,77Cu, 76Ni
N=40 Island of Inversion; 64Cr
N=8
N=20
N=28
N=50
N=82
N=126
Z=8
Z=20
Z=28
Z=50
Z=82
Proton (Z) #
Neutron (N) #
0
20
40
60
80
100
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Waiting for BT allocation at RIBF

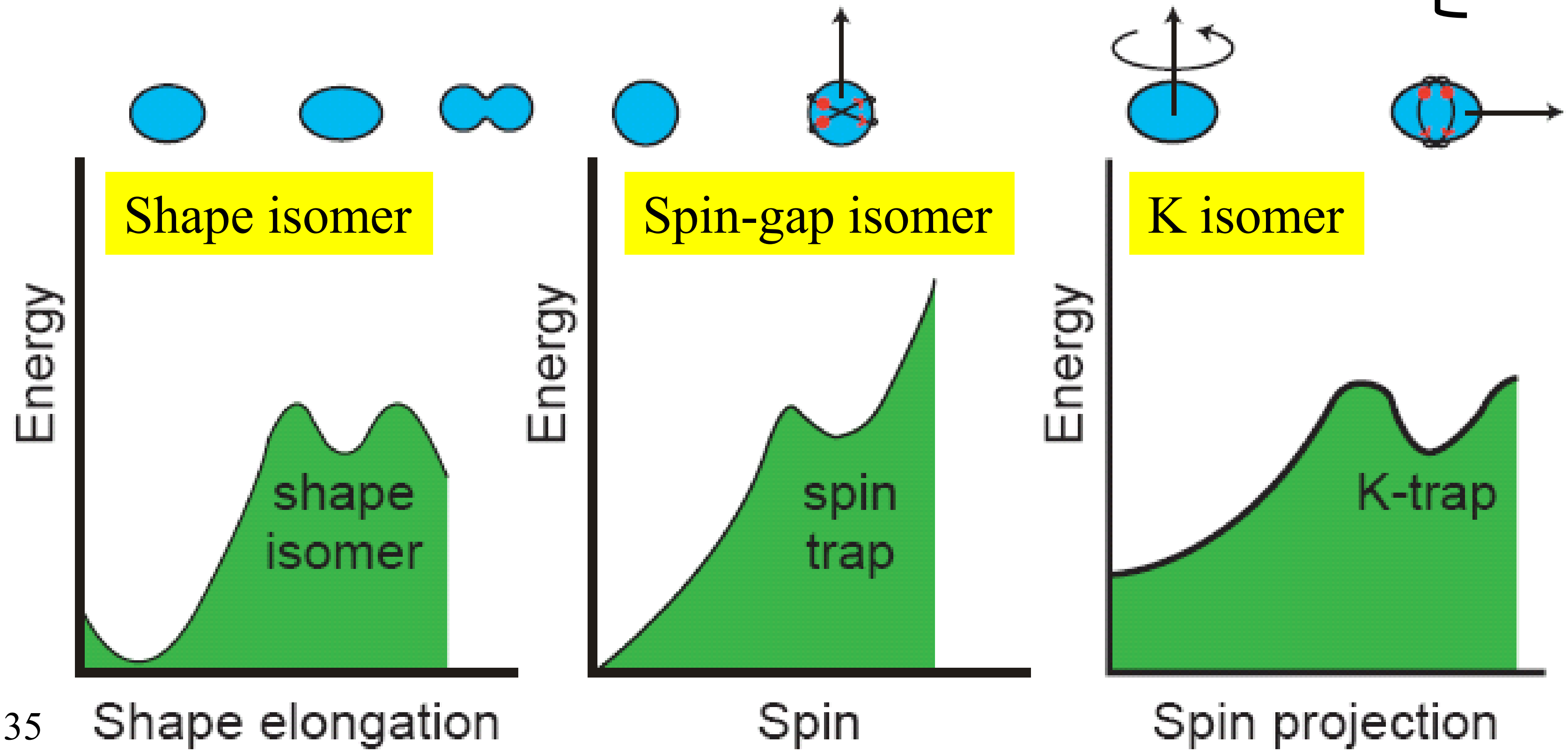
# Nuclear isomers as a probe of the underlying nuclear structure

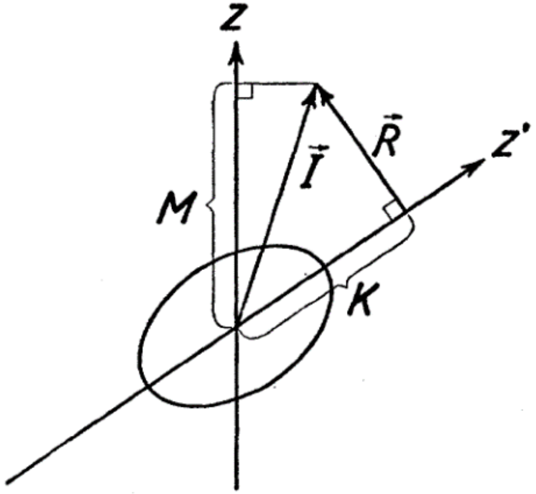
**Metastable with $\tau$>1 ns ⇒** facilitate identification/separation by various experimental techniques

$$T(\sigma\lambda) = \frac{\ln 2}{T_{1/2}} = \frac{8\pi(\lambda+1)}{\lambda[(2\lambda+1)!!]^2}\frac{1}{\hbar}\left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda+1} B(\sigma\lambda; I_i \rightarrow I_f)$$



Longer $\tau$ when
- Low energy transition
- Large spin gap
- Small matrix element



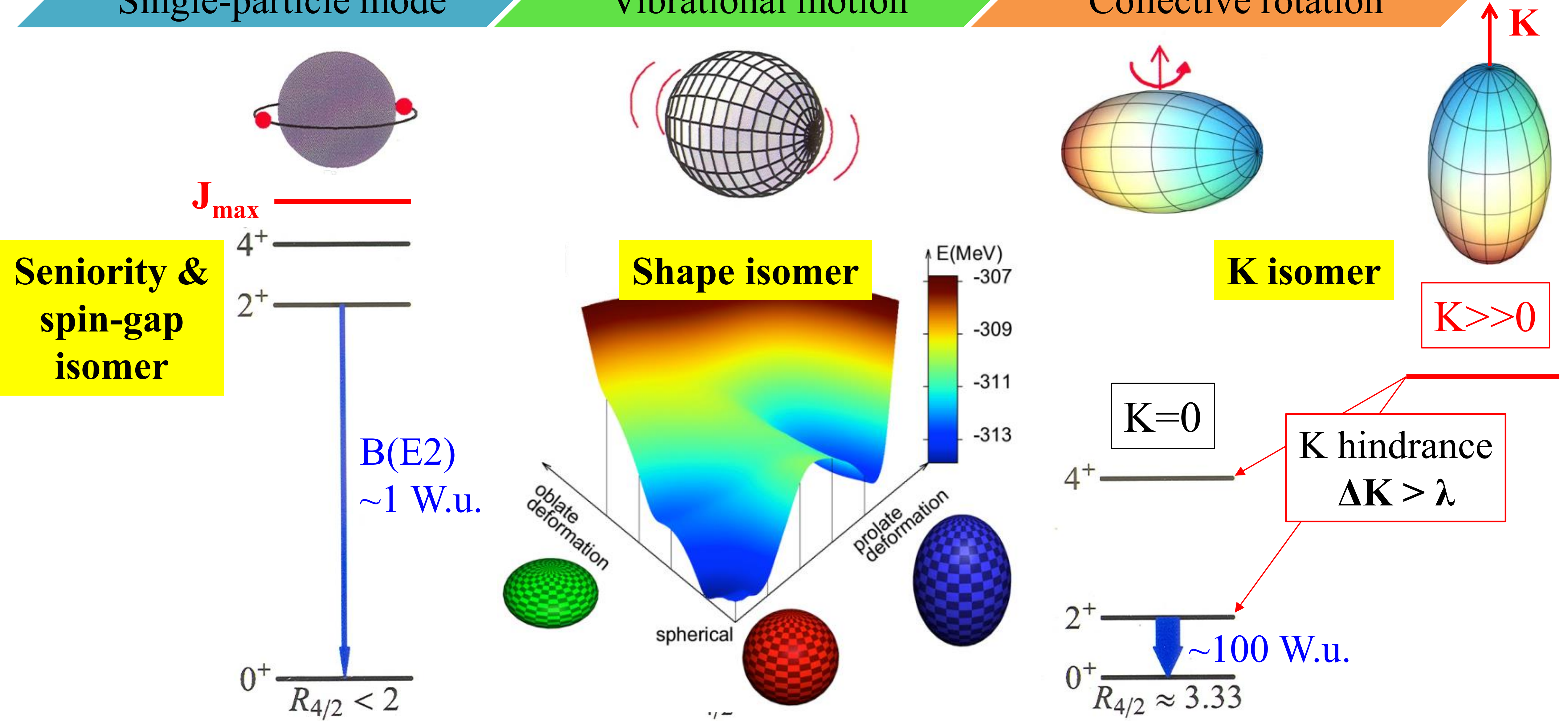

P.M. Walker and G.D. Dracoulis, Nature 399 (199) 35

# Nuclear shape transitions and characteristic isomers

**Closed-shell region** — Single-particle mode

**Transitional region** — Vibrational motion

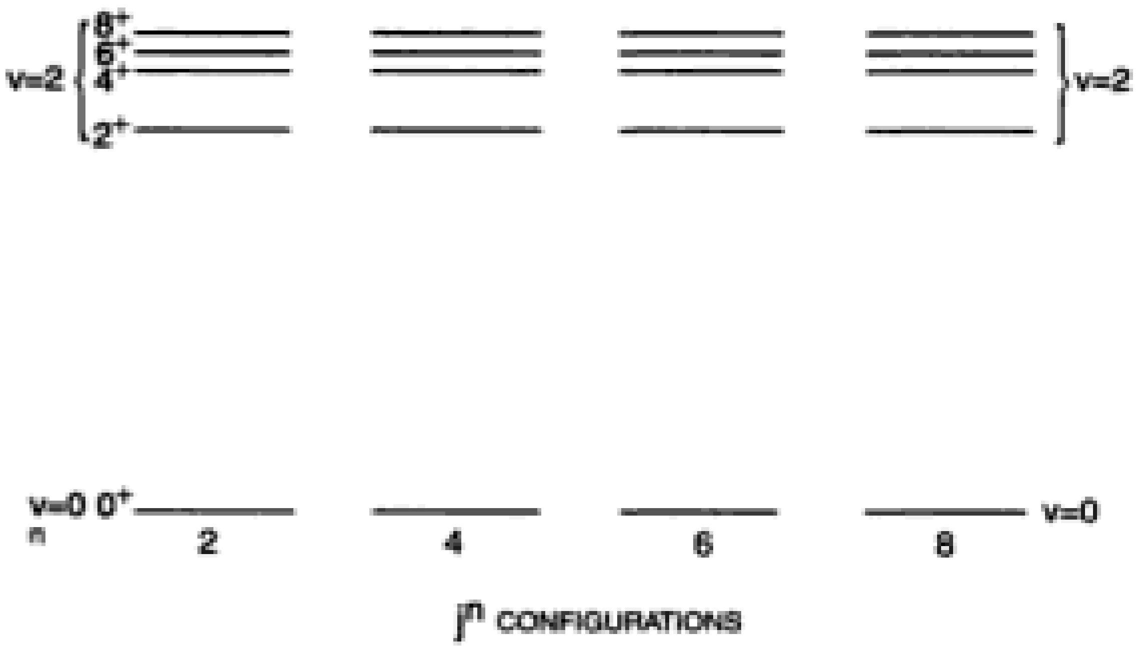
**Mid-shell region** — Collective rotation



# Seniority isomer: Signature of the robustness of shell closure

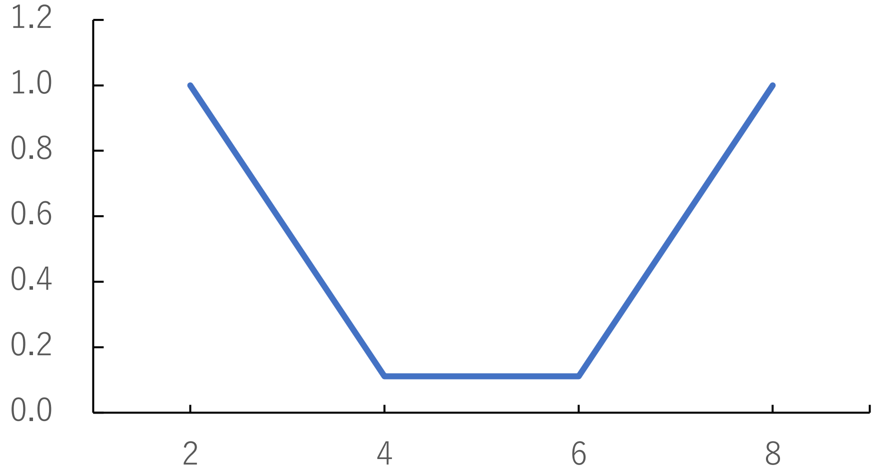
Seniority quantum number (ν)

- The number of nucleons that are **not in pairs coupled to $J = 0$**
- Adopted in *jj*-coupling for many like nucleons (protons or neutrons) in a **single-*j* shell** for the classification and characterization of excitation spectra



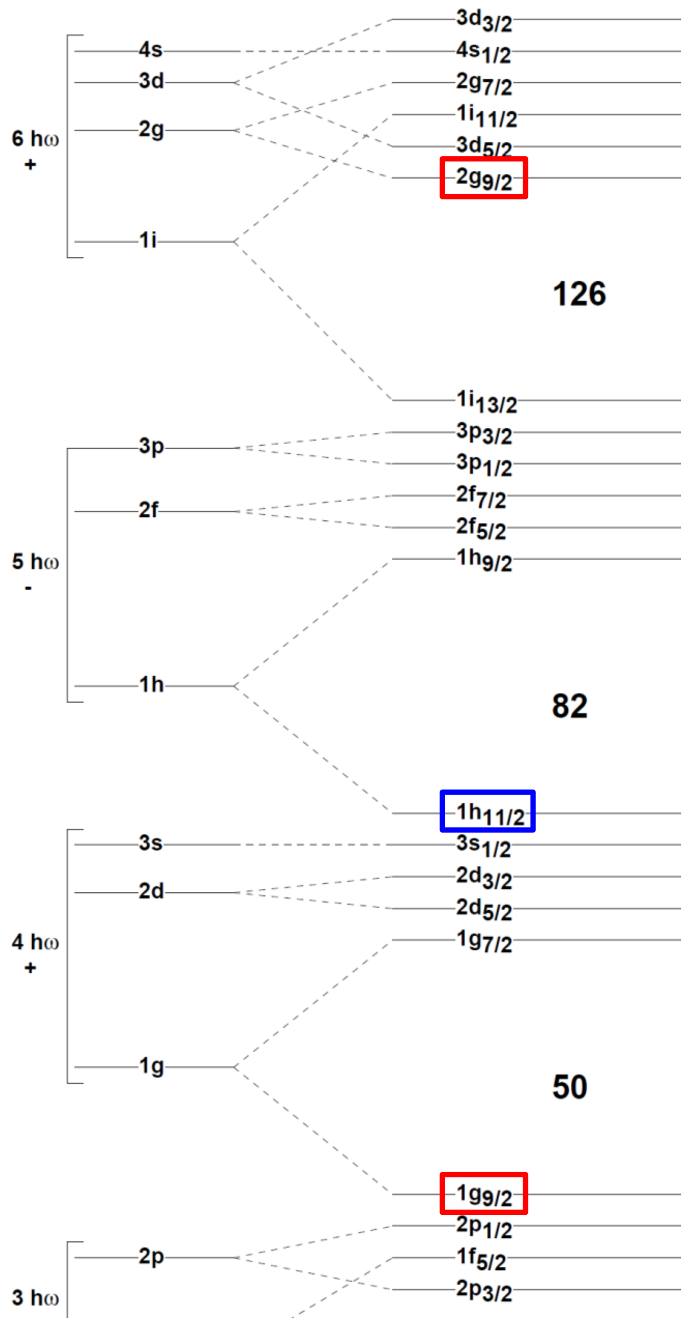

Level energies with identical $J$ and seniority are independent of $n$

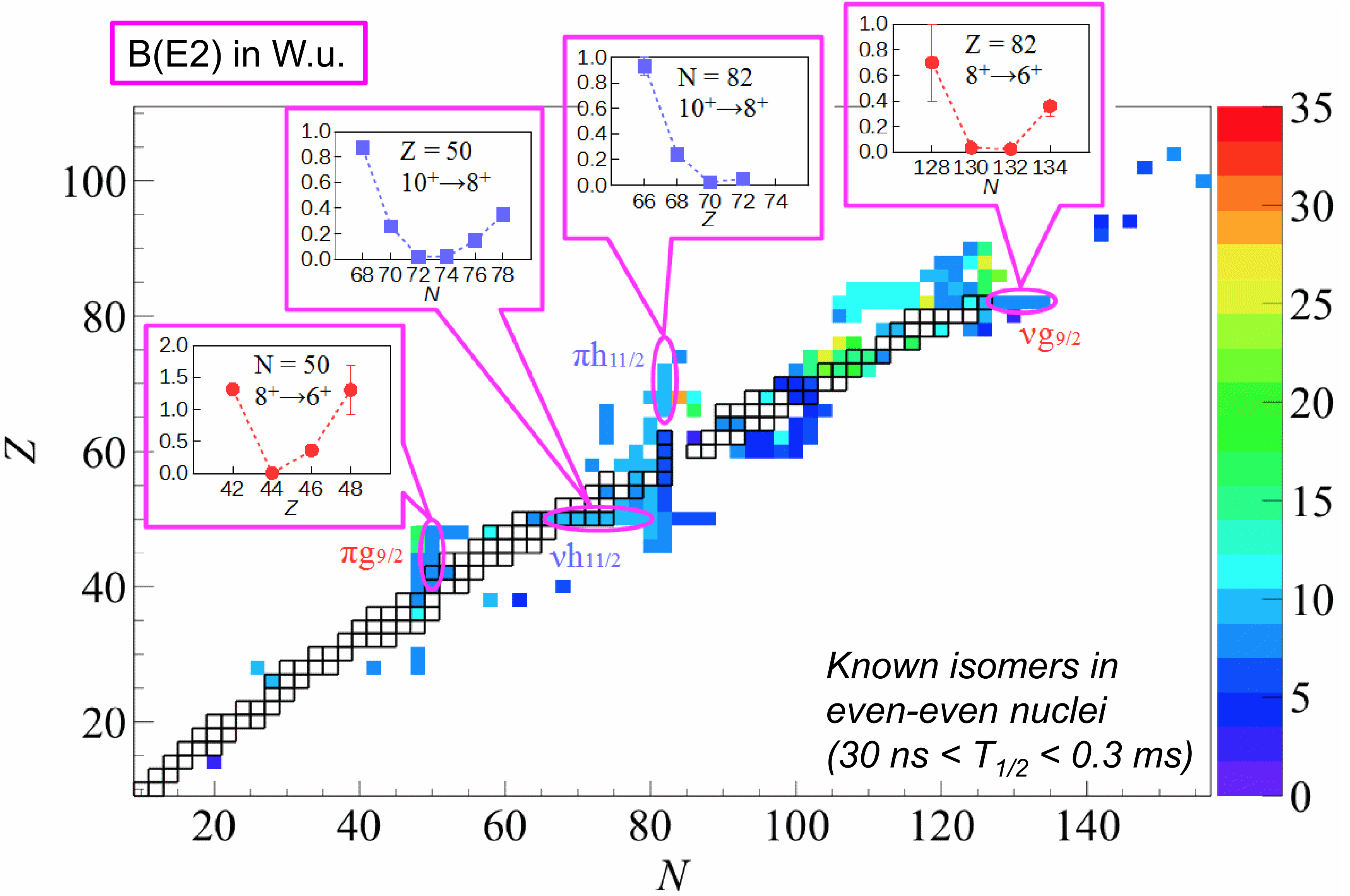
$$B(E2; J \to J-2) \propto \left(\frac{2j+1-2n}{2j+1-2\nu}\right)^2 \times e_{eff}^{\,2}$$




*E*2 matrix elements connecting the same seniority multiplet members are close to zero near the middle of the valence subshell

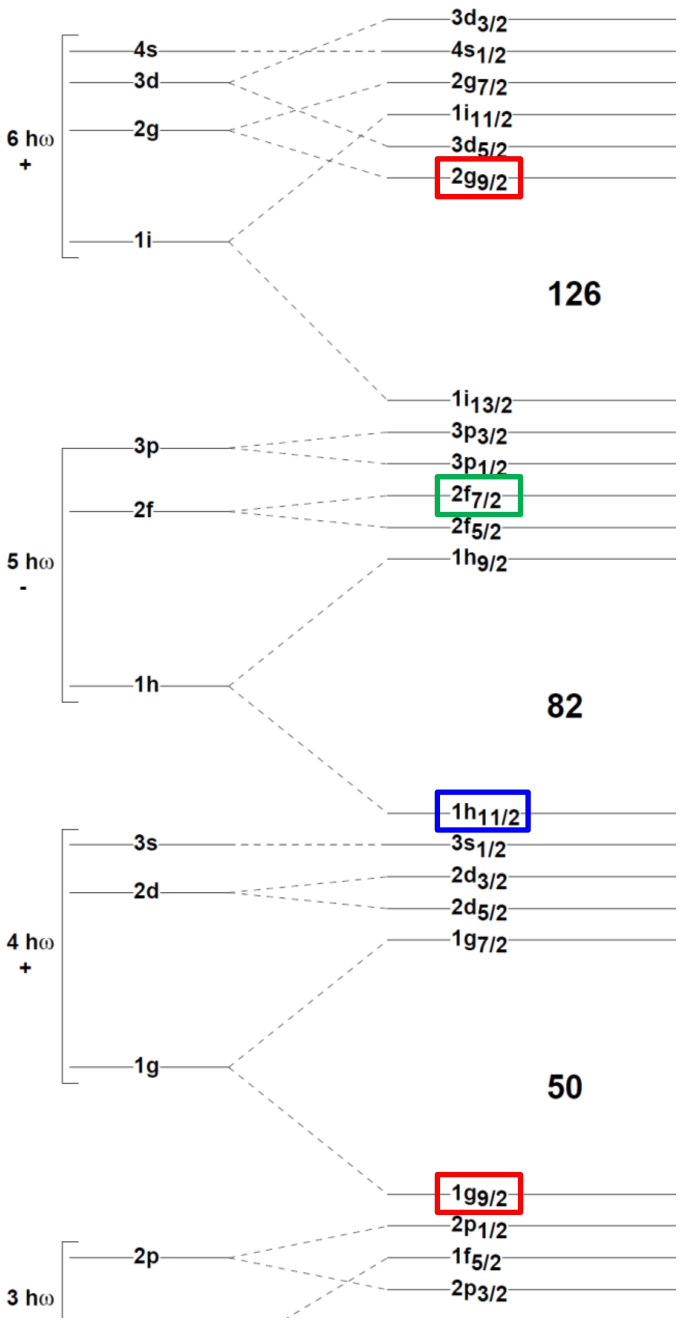
# Seniority isomer: Signature of the robustness of shell closure

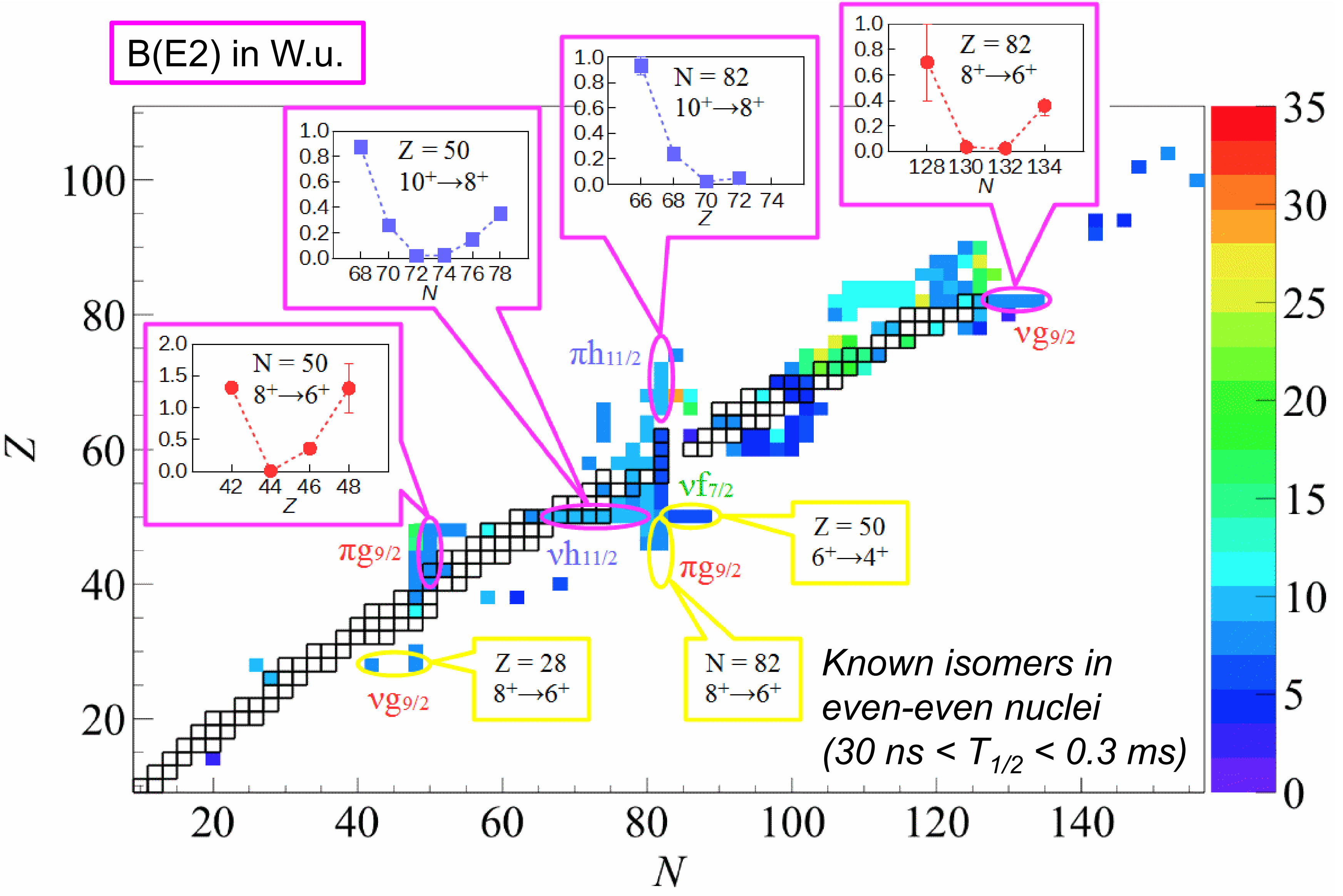



- ✓ Testing **interaction matrix elements** ⇒ conserve or mix seniorities
- ✓ Significant insight into **the underlying shell closures** in semi-magic nuclei

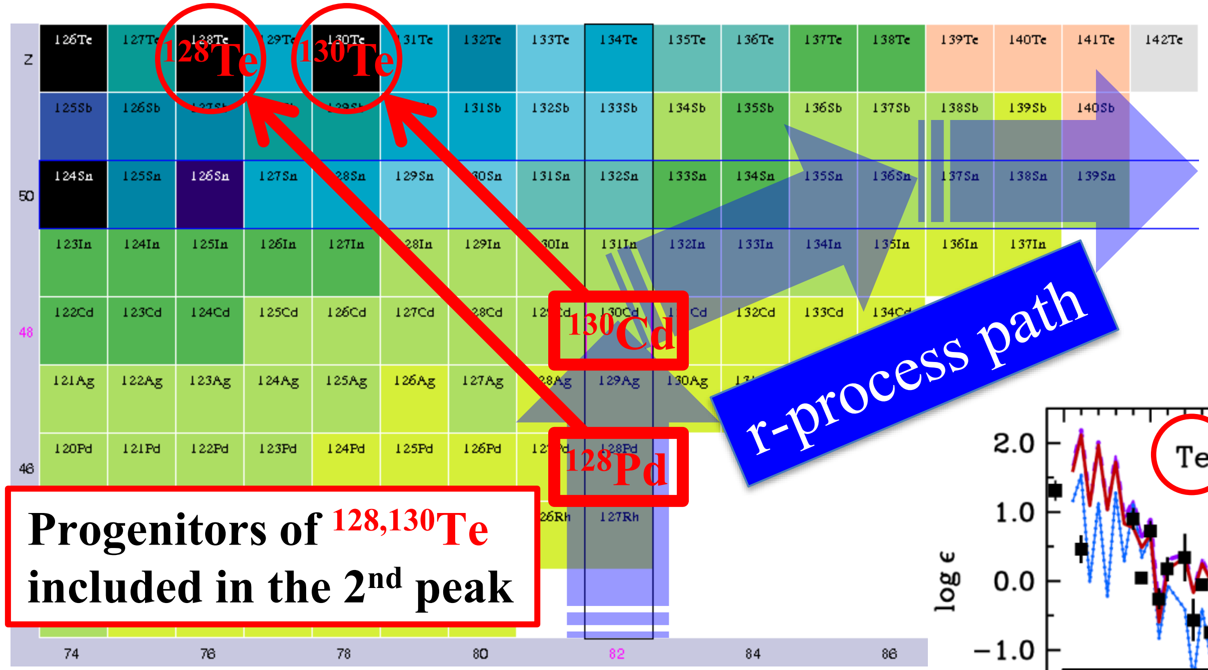
# Seniority isomer: Signature of the robustness of shell closure



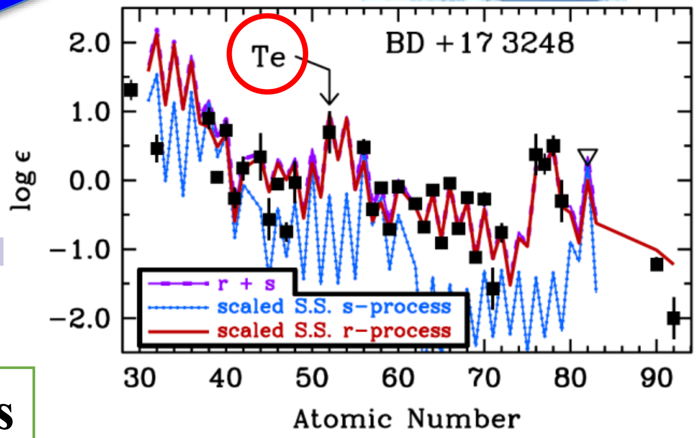




- ✓ Testing **interaction matrix elements** ⇒ conserve or mix seniorities
- ✓ Significant insight into **the underlying shell closures** in semi-magic nuclei

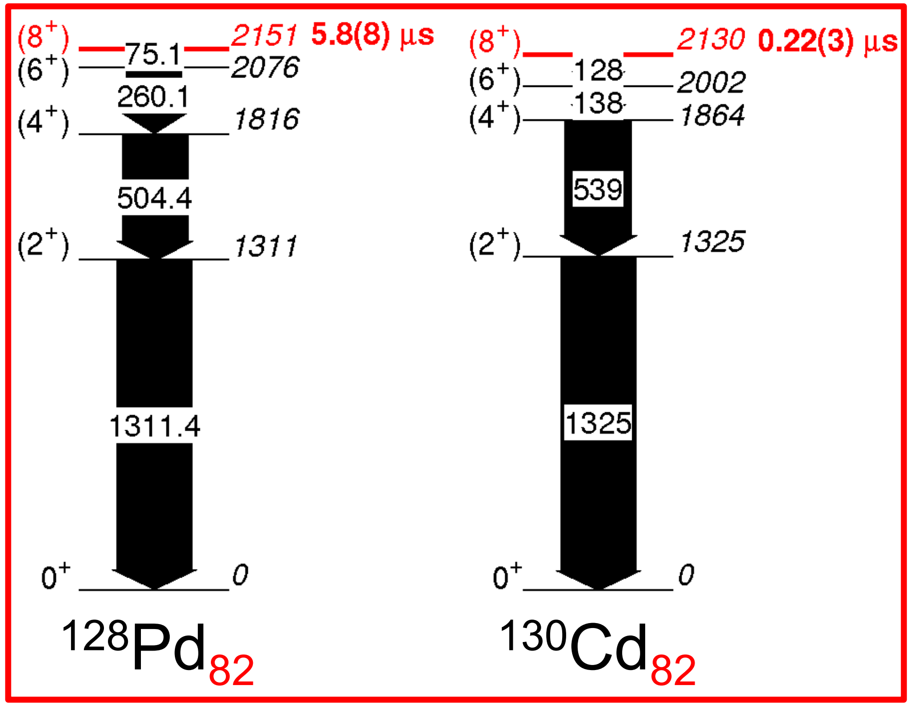
# Seniority isomers in the N = 82 isotones on the r-process path




**Progenitors of $^{128,130}$Te included in the 2$^{nd}$ peak**




$_{52}$Te observed by HST
I.U. Roederer, ApJL 747 (2012)




**Nuclear structure effect on the r-process nucleosynthesis**

- Size of the N=82 shell gap
  - ⇨ 2$^{nd}$ peak position & shape?
- Location of the $1g_{7/2}$ neutron orbit
  - ⇨ Speed of the r-process?
- Presence of long-lived isomers
  - ⇨ Constraint on β-decay pathway?

Level sequences below the 8$^{+}$ isomer in the N=82 isotones

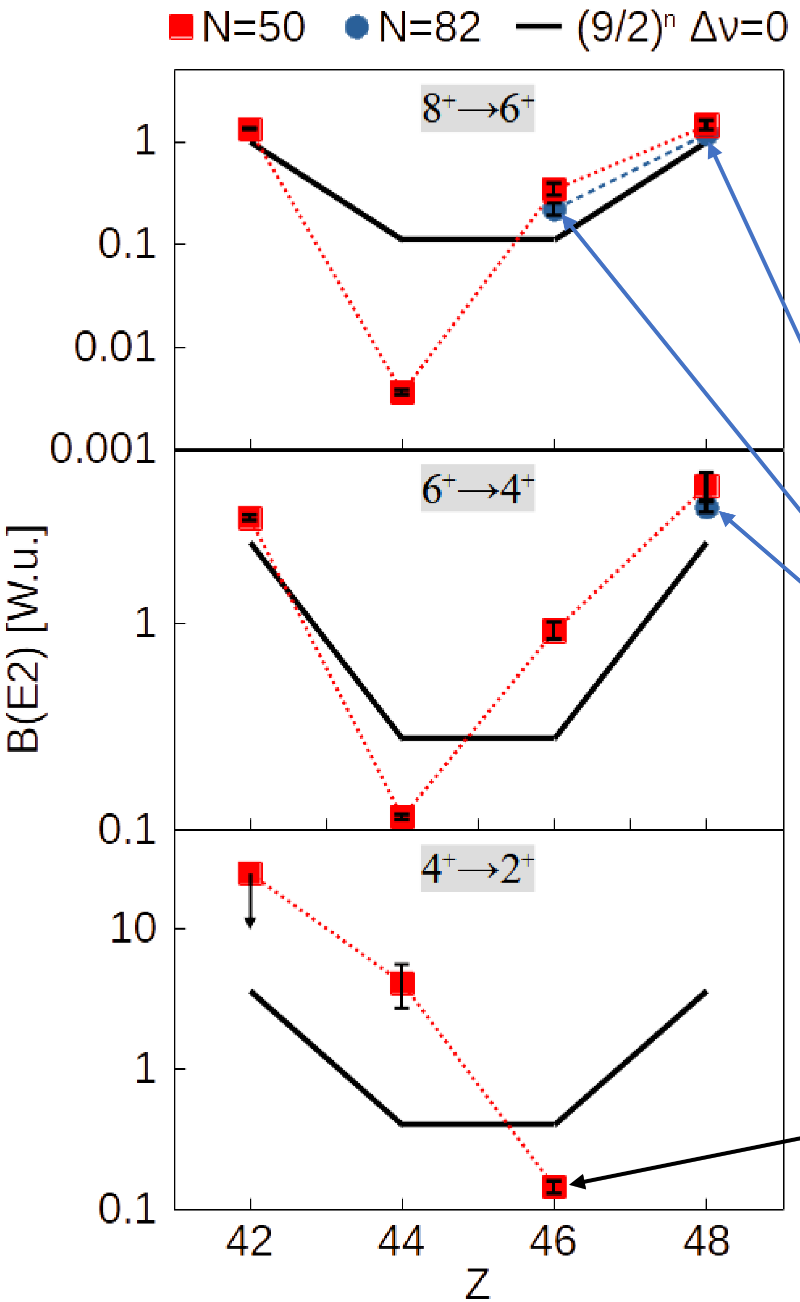
**HW et al., PRL113 (2014) 042502**

A. Jungclaus et al., PRL99 (2007) 132501

➢ Seniority-two (ν=2) coupling in the isolated **$1g_{9/2}$** proton subshell

***⇨ Indirect evidence for the robust nature of the N=82 core***

# Lifetime measurements for the low-spin states in $^{128}$Pd, $^{130}$Cd ➡ IDATEN




**B(E2) in single closed-shell nuclei**

Deviation from the simple seniority scheme is ascribed to:

① Presence of other orbitals near the Fermi surface

② Configuration mixing between different seniorities (e.g., ν=2 and 4)

③ Core excitation across the shell gaps

⇨ Test of **the model space** used in nuclear model calculations

⇨ Development of **effective nucleon-nucleon interactions**

● N=82 with EURICA

HW et al., PRL111 (2013) 152501

A. Jungclaus et al., PRL132 (2024) 222501

B(E2) consistent with

– Δν=0 transitions for j=9/2

■ N=50 isotones

■ N=50 isotones in the middle of the proton shell (Z=44, 46)

➢ *Significant distortions of the seniority scheme for 6$^+$→4$^+$ and 4$^+$→2$^+$*

**※B(E2;4$^+$→2$^+$) < B(E2;8$^+$→6$^+$) ≲ B(E2;6$^+$→4$^+$) in $^{96}$Pd**

⇨ Conservation of seniority is violated

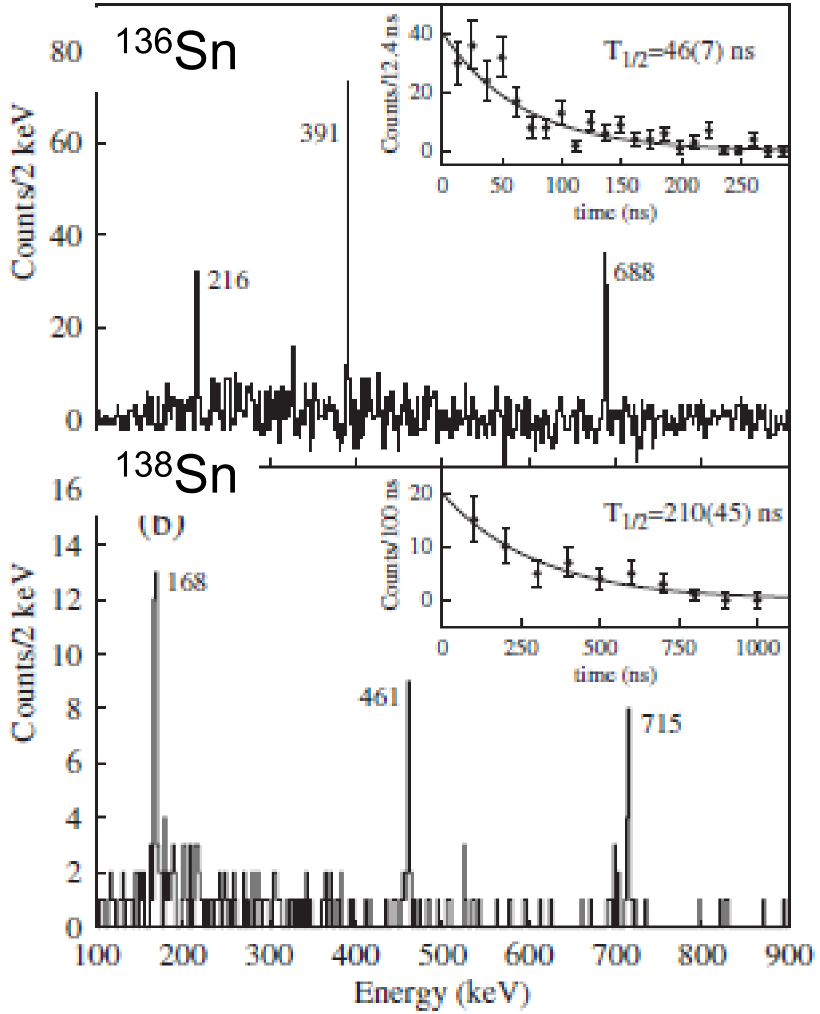
*Question*

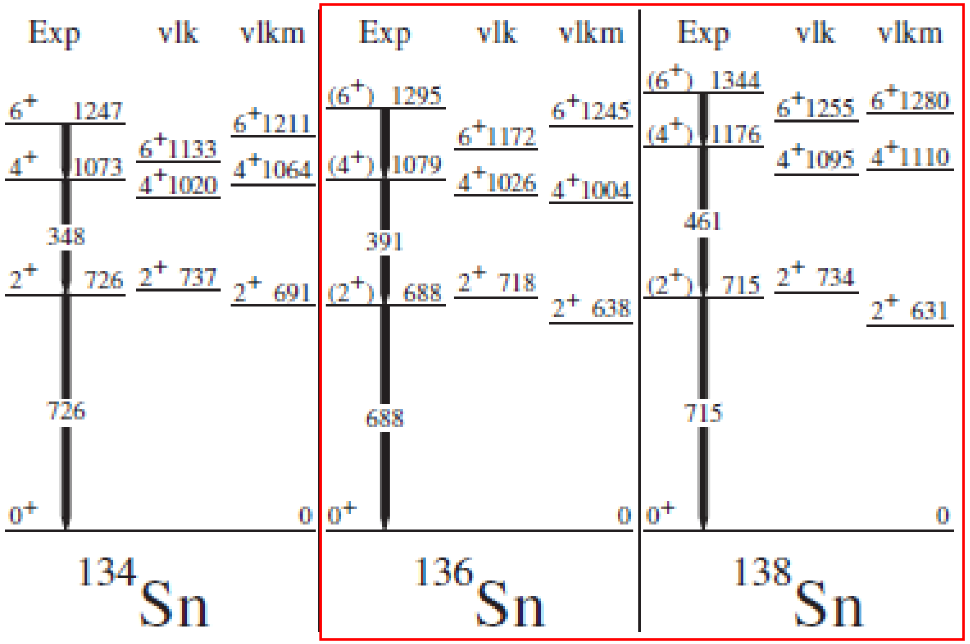
**Seniority breaking takes place as well in the N=82 counterpart $^{128}$Pd?**

# Yrast $6^+$ seniority isomers of $^{136,138}$Sn

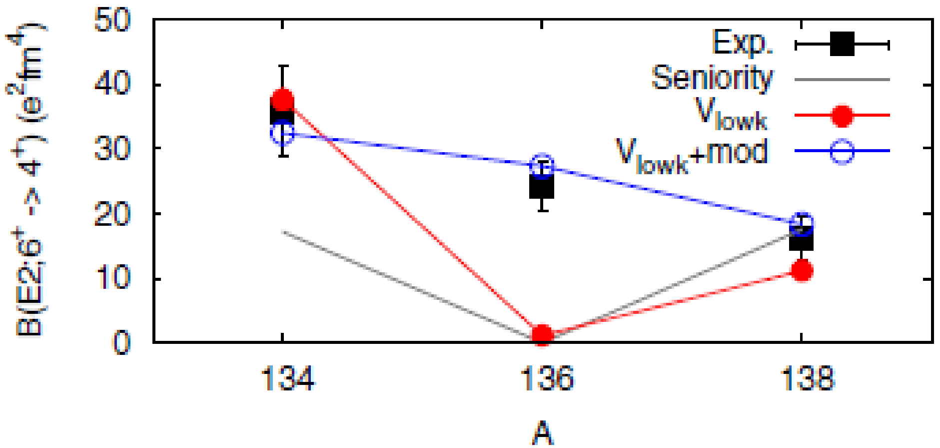
G. Simpson et al., PRL 113, 132502 (2014)

$6^+$ isomers in the ns range




IDATEN

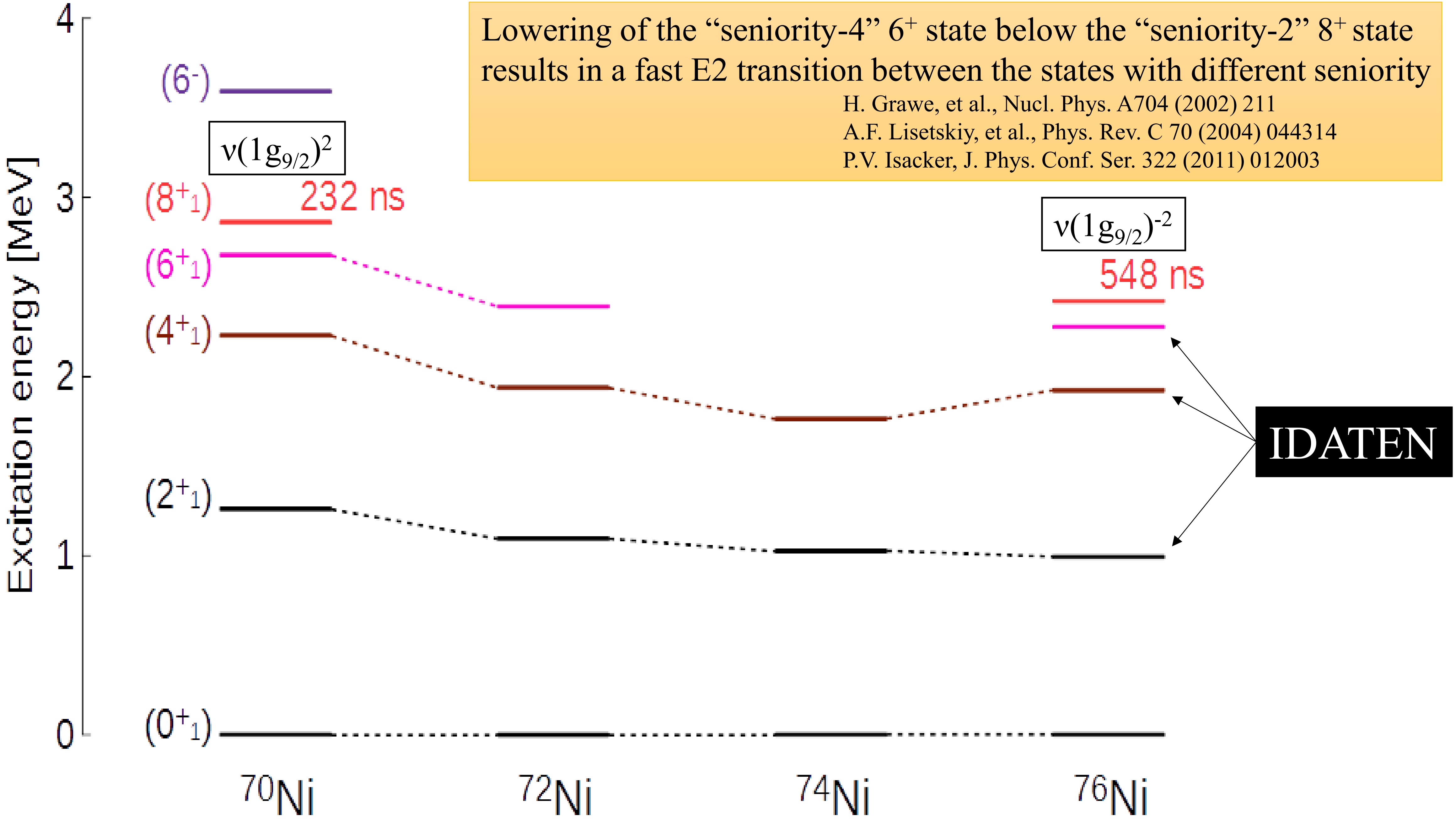



Experimental $B(E2;6^+\rightarrow4^+)$ in $^{136}$Sn reproduced by modifying the $\nu 2f_{7/2}^2$ TBMEs **(reduce neutron pairing)** ⇒ Seniority-mixed 4+ state

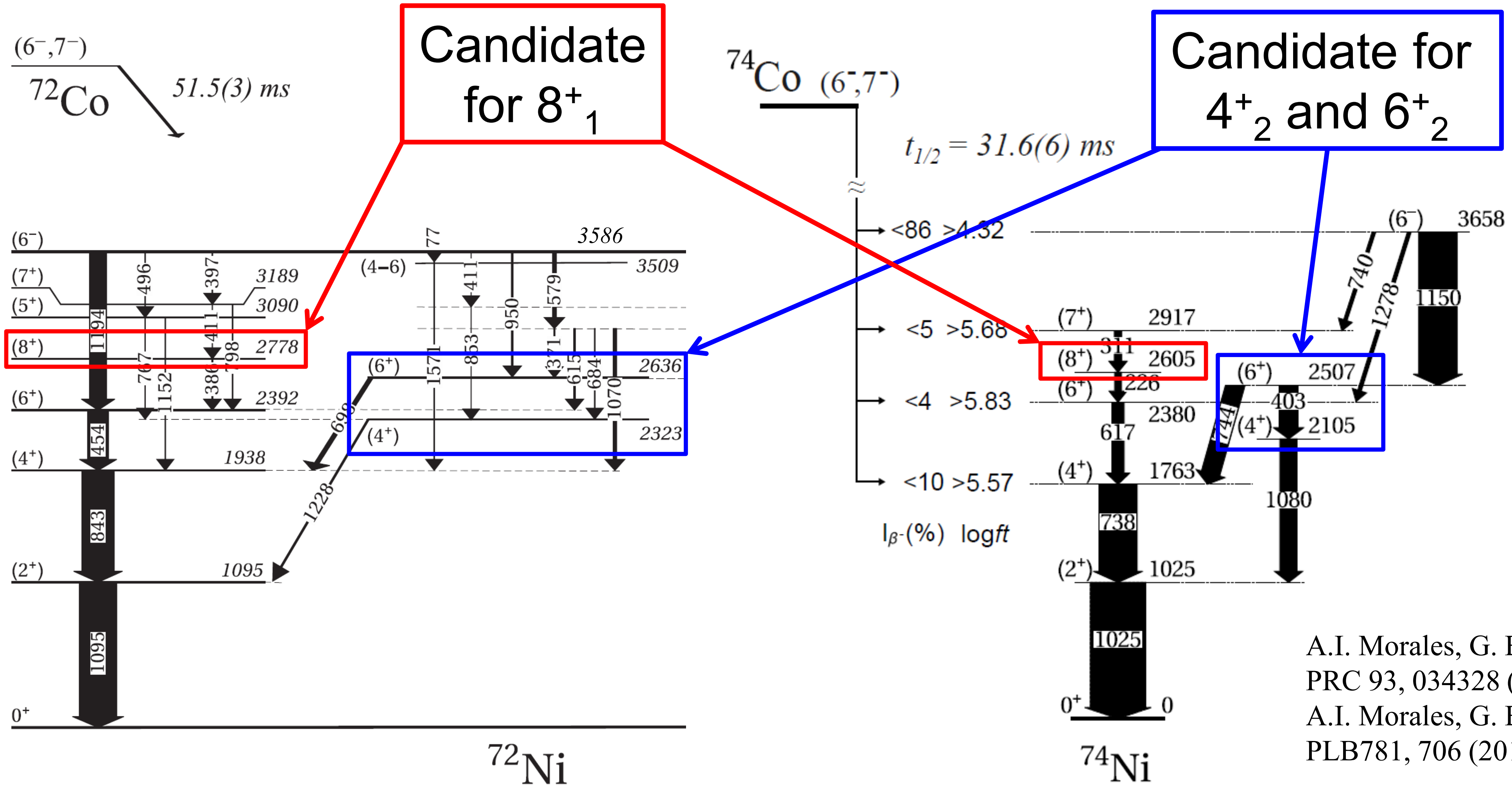
# Absence of the $8^+$ seniority isomers in $^{72,74}$Ni

Lowering of the "seniority-4" $6^+$ state below the "seniority-2" $8^+$ state results in a fast E2 transition between the states with different seniority

H. Grawe, et al., Nucl. Phys. A704 (2002) 211
A.F. Lisetskiy, et al., Phys. Rev. C 70 (2004) 044314
P.V. Isacker, J. Phys. Conf. Ser. 322 (2011) 012003



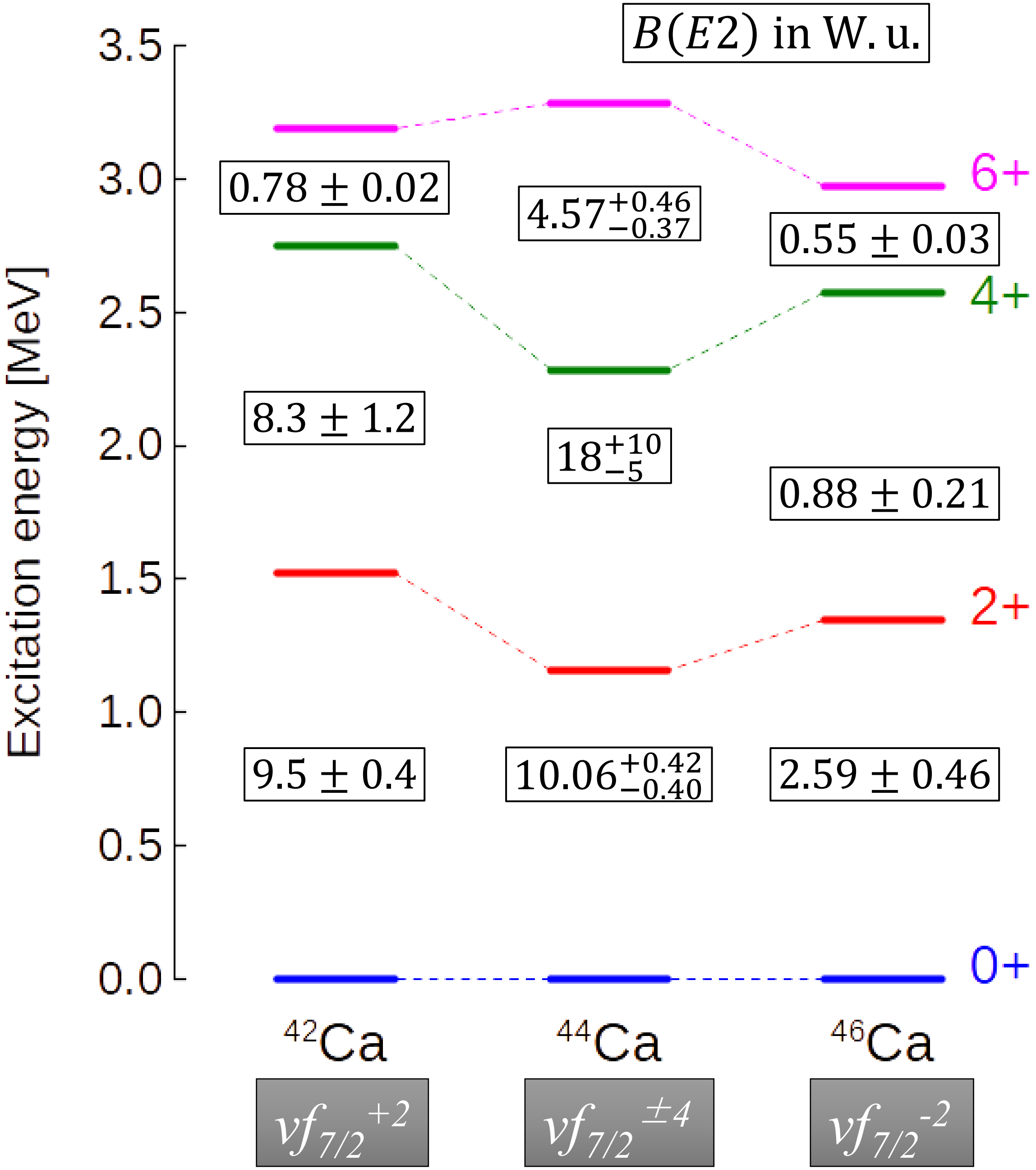
# Absence of the $8^+$ seniority isomers in $^{72,74}$Ni




A.I. Morales, G. Benzoni, HW, et al., PRC 93, 034328 (2016)
A.I. Morales, G. Benzoni, HW, et al., PLB781, 706 (2018)

- ■ Strong β feeding via Gamow-Teller ($\nu f_{5/2} \rightarrow \pi f_{7/2}$) transition ⇒ **$6^-$ ($\nu g_{9/2} \otimes f_{5/2}^{-1}$)**
- ■ **$8^+_1$ (v=2)** state: decays to ($6^+_1$), but not to ($6^+_2$) ⇒ **$6^+_1$ (v=4), $6^+_2$ (v =2)**
- ■ **$6^+_2$ (v=2)** state: decays only to ($4^+_1$) in $^{72}$Ni ⇒ **$4^+_1$ (v=4), $4^+_2$ (v=2)**
  strongly feeds ($4^+_2$) in $^{74}$Ni ⇒ **$4^+_1$ (v=2), $4^+_2$ (v=4)**

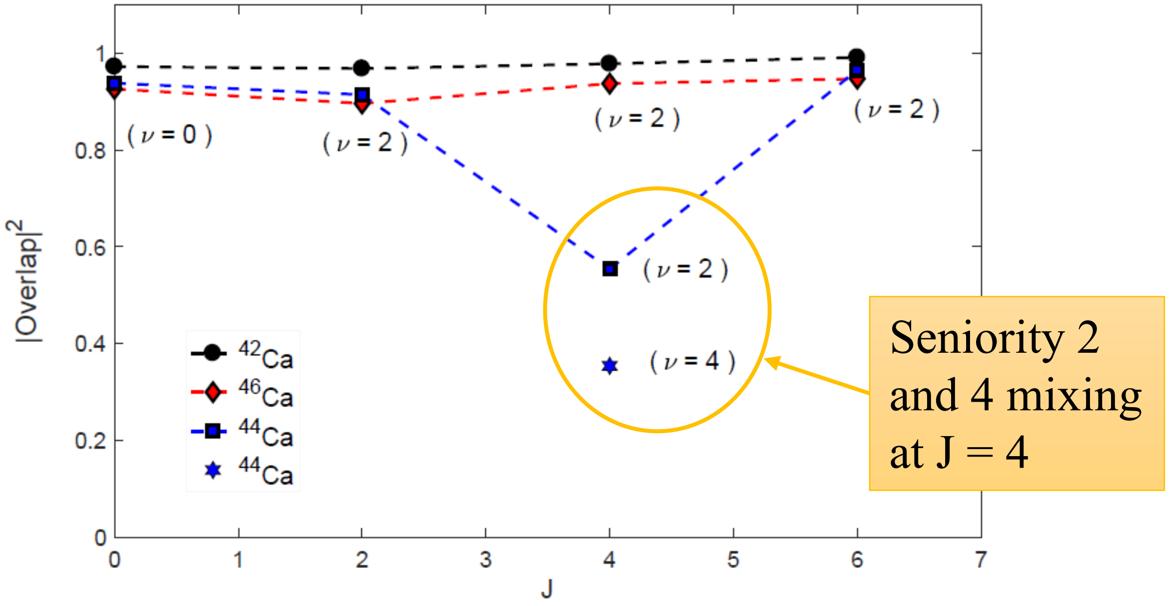
# Mid-shell anomaly in Ca isotopes




➢ $\nu(f_{7/2})^n$ dominance in the low-lying levels

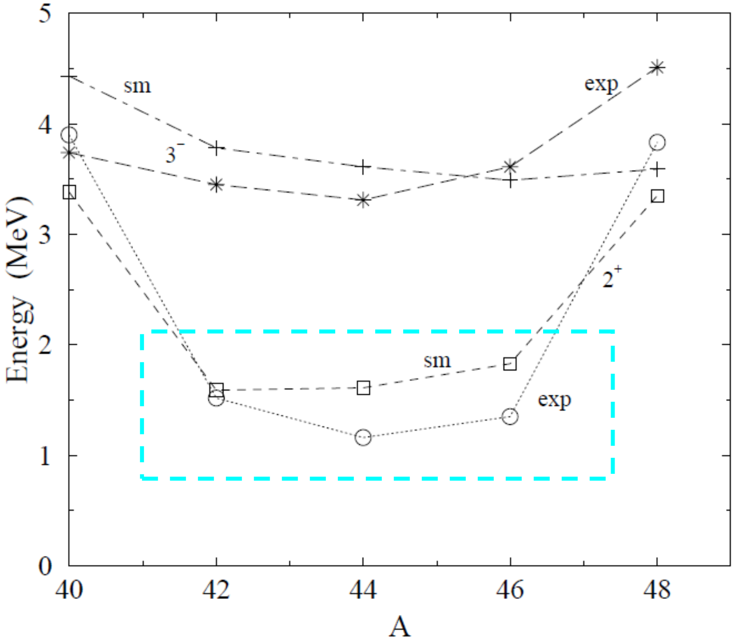
- $^{42,46}$Ca have similar $E_x(J)$ ⇒ **Particle-hole symmetry**
- $2^+$ and $4^+$ states are lower in $^{44}$Ca than in $^{42,46}$Ca

Squared overlap of the wave functions between the CI+GXPF1 and seniority models
L. Kovács et al., Phys. Rev. C **106**, 024303



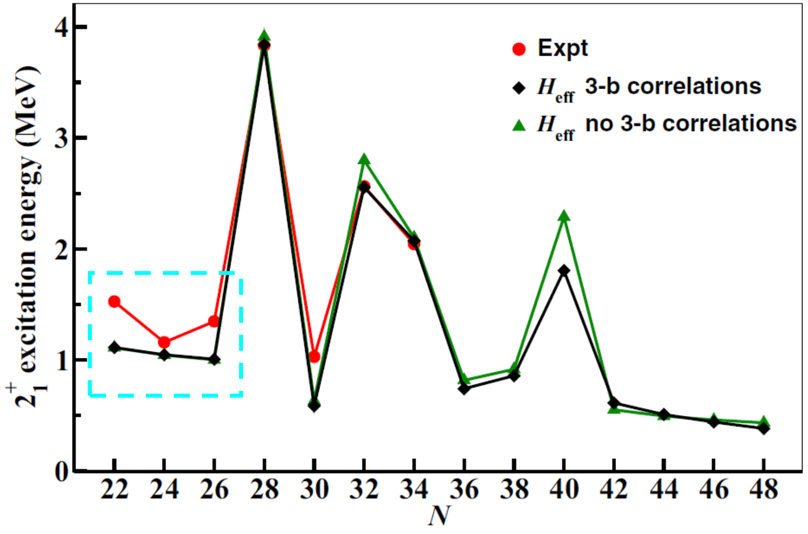

■ Lowering of $4^+$ in $^{44}$Ca is ascribed to seniority mixing

# Mid-shell anomaly in Ca isotopes



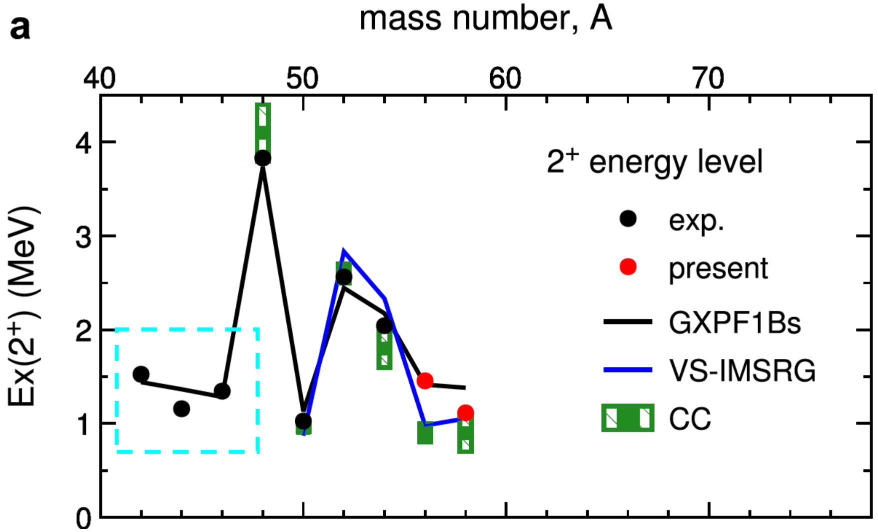

- $d_{3/2}$, $s_{1/2}$, $f_{7/2}$, $p_{3/2}$ ($^{16}O$ core)
- sd→fp 2p-2h excitations incorporated

E Caurier et al., Phys. Lett. B 522 (2001) 240




- fp+$g_{9/2}$ model space
- Chiral NN + 3N force

L. Coraggio et al., Phys. Rev. C 102, 054326 (2020)



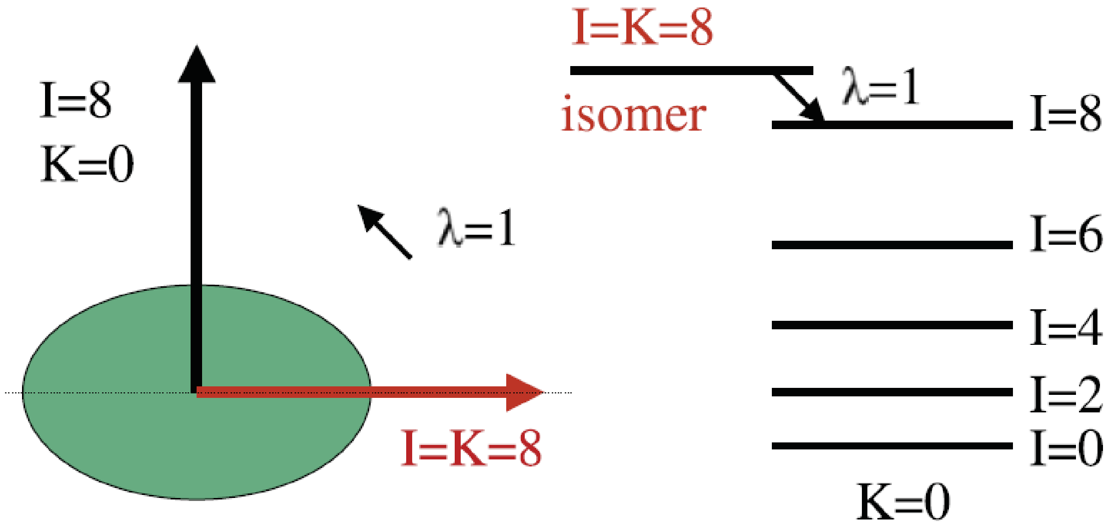

- Full pf shell
- GXPF1Bs

S. Chen et al., Phys. Lett. B 843 (2023) 138025

**Remain unsolved**

- Lowering of $4^+$ in $^{44}Ca$ is ascribed to seniority mixing
- Shell-model calculations can not provide reasonable explanation for the lowering of the $2^+$ state in $^{44}Ca$

# Intrinsic excitations in deformed nuclei: K isomer




$\lambda \geq |I_i - I_f|$ **Spin selection** ⇒ Yes

$\lambda \geq |K_i - K_f|$ **K selection** ⇒ Sort of !

Often violated due to
- **Coriolis effects**
- **Axial asymmetry**
- **Random mixing**

K-forbidden γ-ray transitions

Weisskopf hindrance: $F = \frac{\tau_\gamma^{\exp}}{\tau_W}$

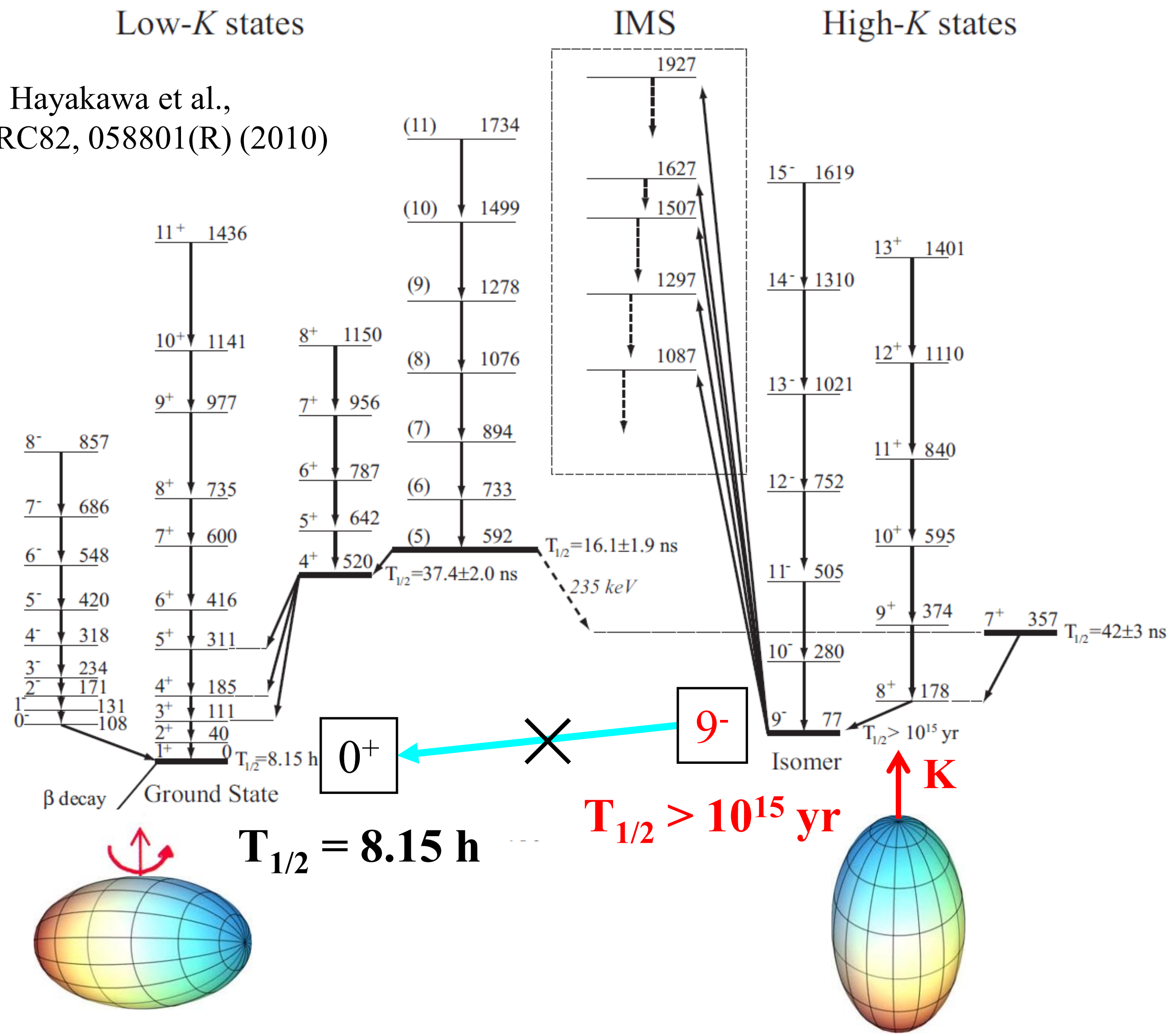
Degree of K forbiddenness $\nu = \Delta K - \lambda$

Reduced hindrance: $f_\nu = F^{1/\nu}$

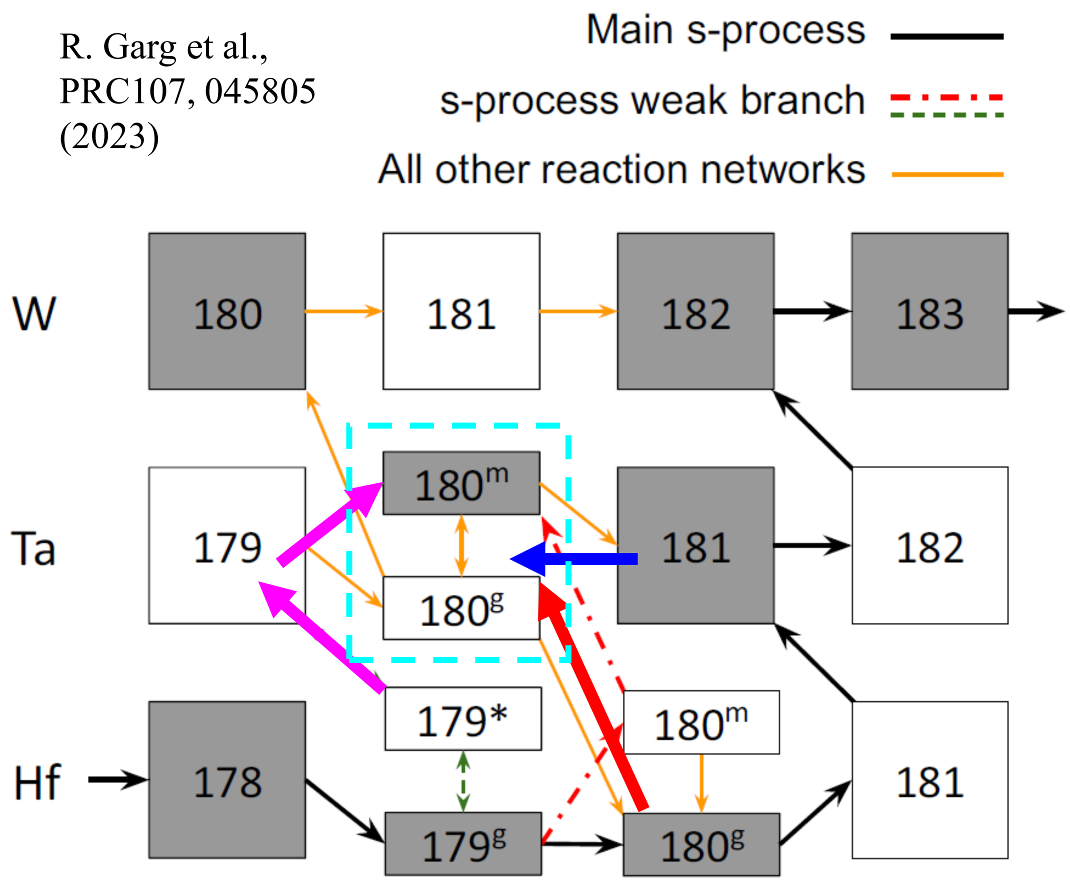
Measure of the hindrance per degree of K forbiddenness

# Origin of naturally occurring isomer $^{180m}$Ta ($T_{1/2} > 10^{15}$ yr)

T. Hayakawa et al., PRC82, 058801(R) (2010)




R. Garg et al., PRC107, 045805 (2023)



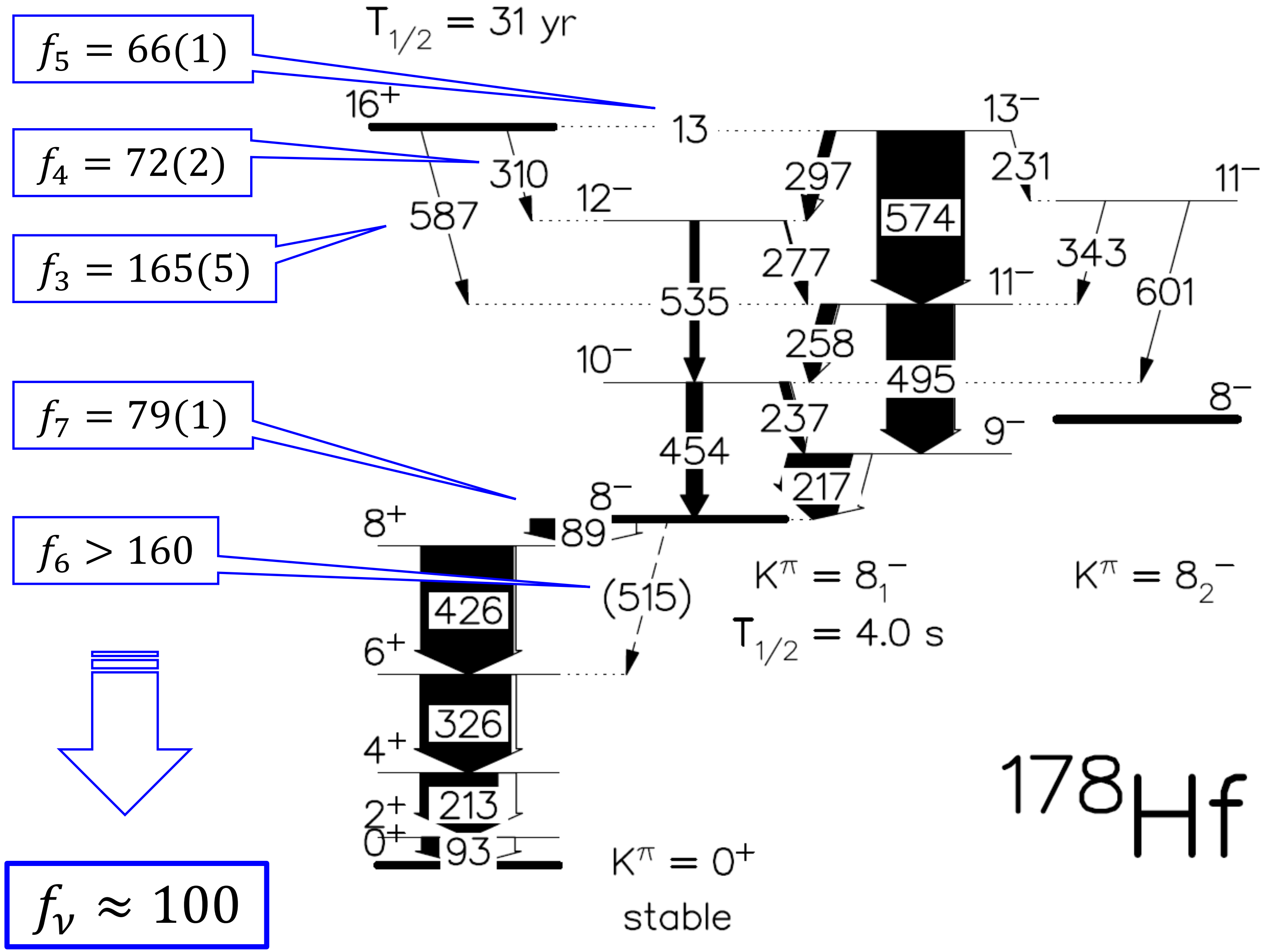

The abundance of $^{180m}$Ta results not only from the production process, but also from the thermalization/freeze-out processes

Synthesis of $^{180}$Ta

※Contribution from the main s/r-process blocked

- **ν-process** in SNe: $^{180}$Hf($\nu_e$,$e^-$), $^{181}$Ta(ν,ν'n)
- **p/γ-process** in type-II SNe: $^{181}$Ta(γ,n)
- **Weak s-process** in AGB: $^{179}$Hf*($\beta^-$)$^{179}$Ta(n,γ)

# High-K isomers in $^{178}$Hf




$f_{\nu} \approx 100$

**K is well conserved**

M. B. Smith et al., PRC 68, 031302(R) (2003)

$\nu^2(7/2^-[514] \otimes 9/2^+[624])$ → $\boldsymbol{K^{\pi} = 8_1^-}$

*mixed*

$\pi^2(7/2^+[404] \otimes 9/2^-[514])$ → $\boldsymbol{K^{\pi} = 8_2^-}$

*coupled*

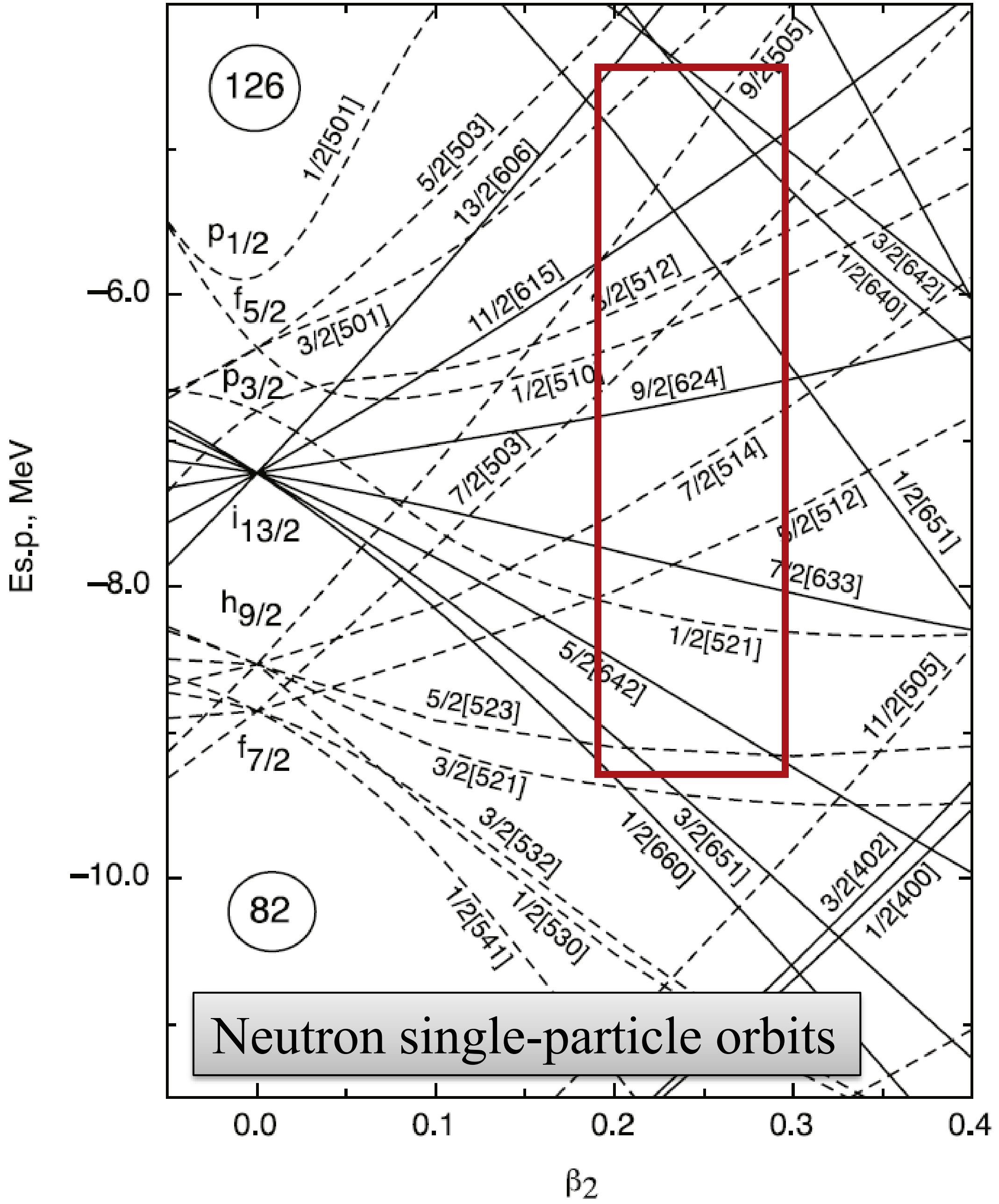
$\boldsymbol{K^{\pi} = 16^+}$

High-K MQP states

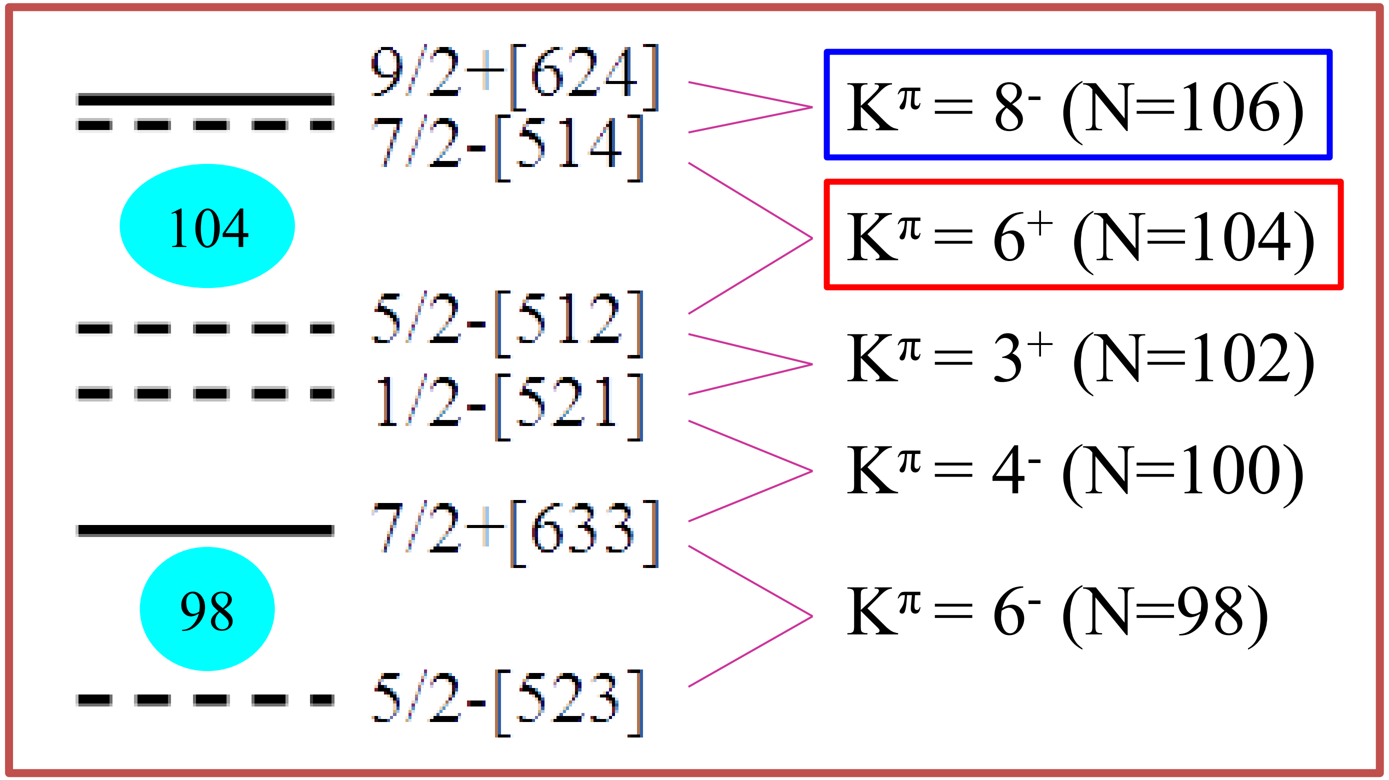
$$K = \sum_j \Omega_j$$

- ✓ Single-particle orbits near the Fermi surface
- ✓ Pairing and other residual interactions
- ✓ Axial (a)symmetry (γ degree of freedom)

# Two quasiparticle K isomer and sub-shell closure




Neutron single-particle orbits




$$E_{2qp} = \sqrt{(\varepsilon_1 - \lambda)^2 + \Delta^2} + \sqrt{(\varepsilon_2 - \lambda)^2 + \Delta^2} \geq 2\Delta$$

- The excitation energy of a 2qp K isomer depends on an energy difference between deformed single-particle orbitals involved, as well as the pairing gap.

# Two quasiparticle K isomer and sub-shell closure

$^{170}_{66}Dy_{104}$

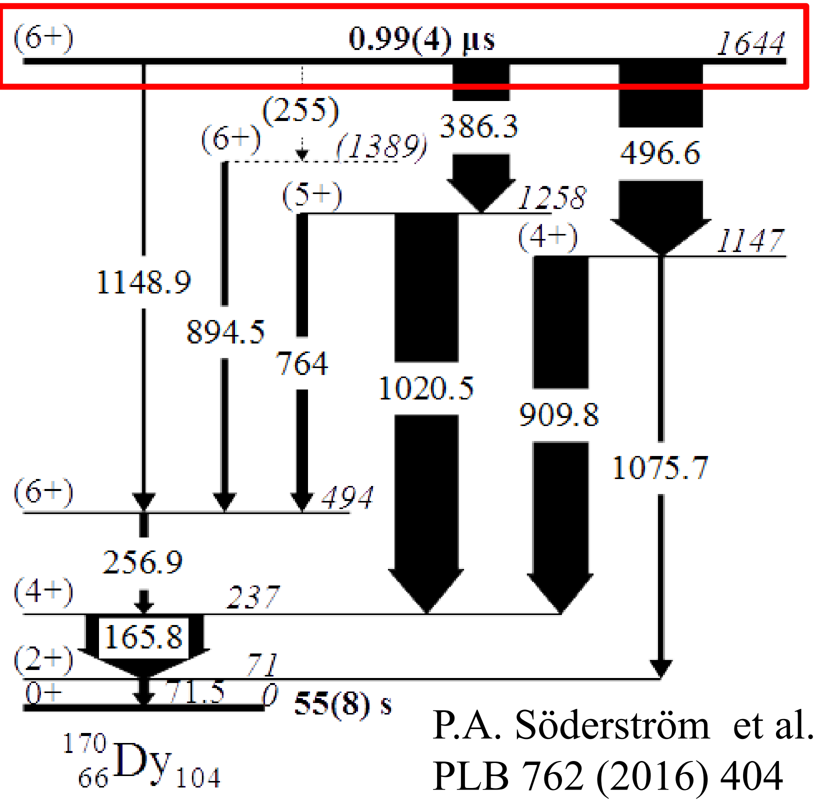
**$K^{\pi}=6^{+}$; ν7/2⁻[514]ν5/2⁻[512]**

$^{172}_{66}Dy_{106}$

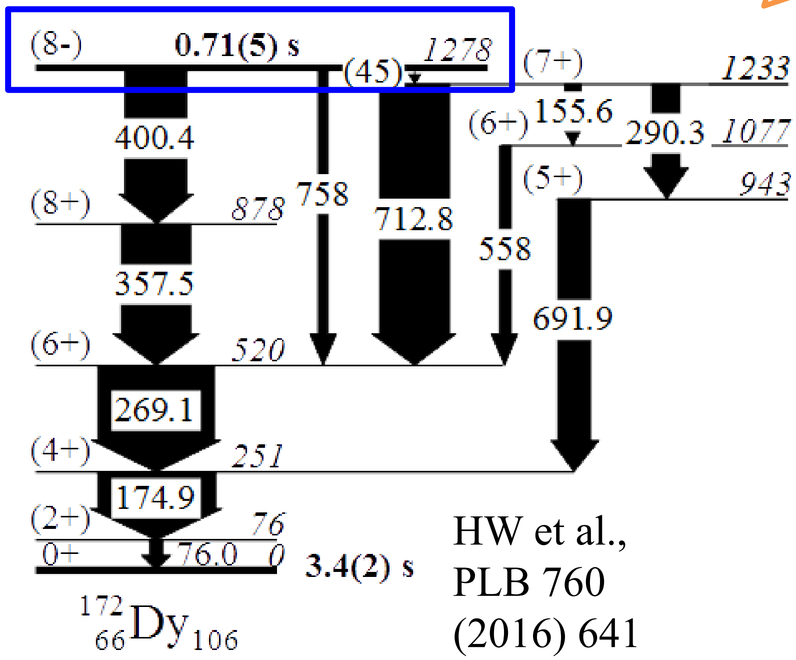
**$K^{\pi}=8^{-}$; ν7/2⁻[514]ν9/2⁺[624]**

$K^{\pi} = 8^{-}$ (N=106)

$K^{\pi} = 6^{+}$ (N=104)

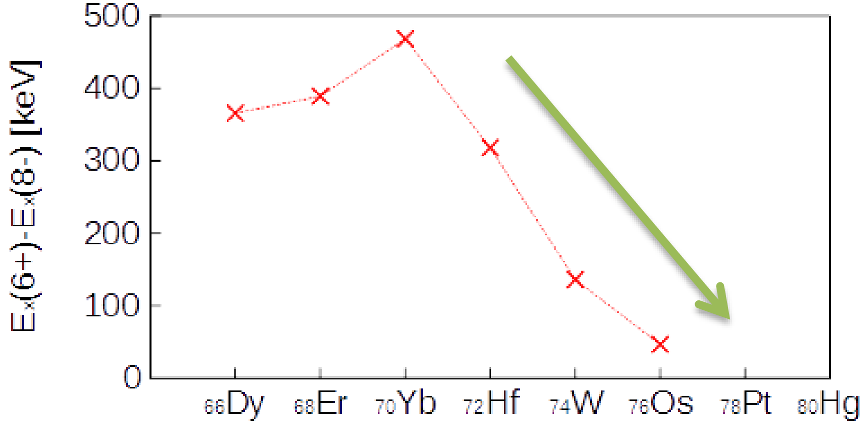



P.A. Söderström et al., PLB 762 (2016) 404




HW et al., PLB 760 (2016) 641

Energy difference between the $K^{\pi} = 6^{+}$ and $8^{-}$ neutron 2qp K isomers

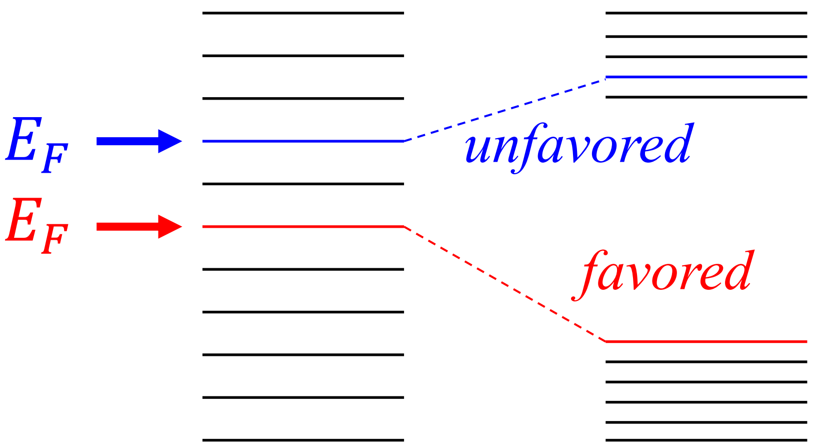



**N=104 sub-shell gap rapidly decreases beyond Yb (Z=70)**

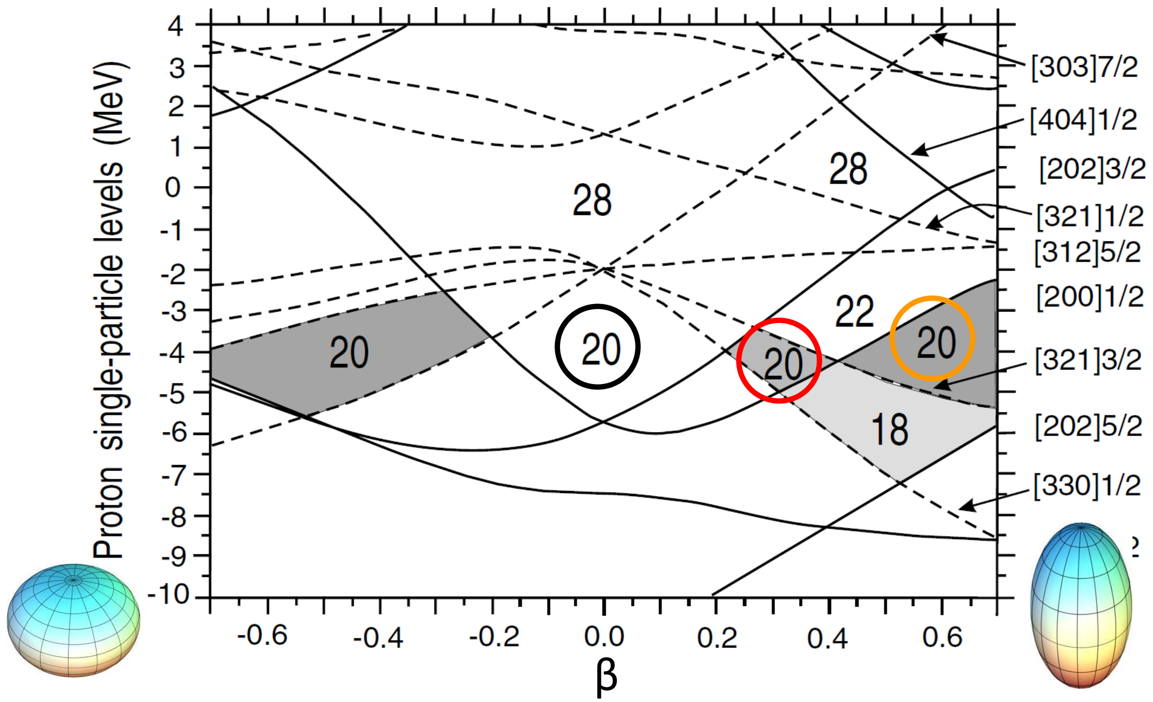
# Why is the nucleus deformed?

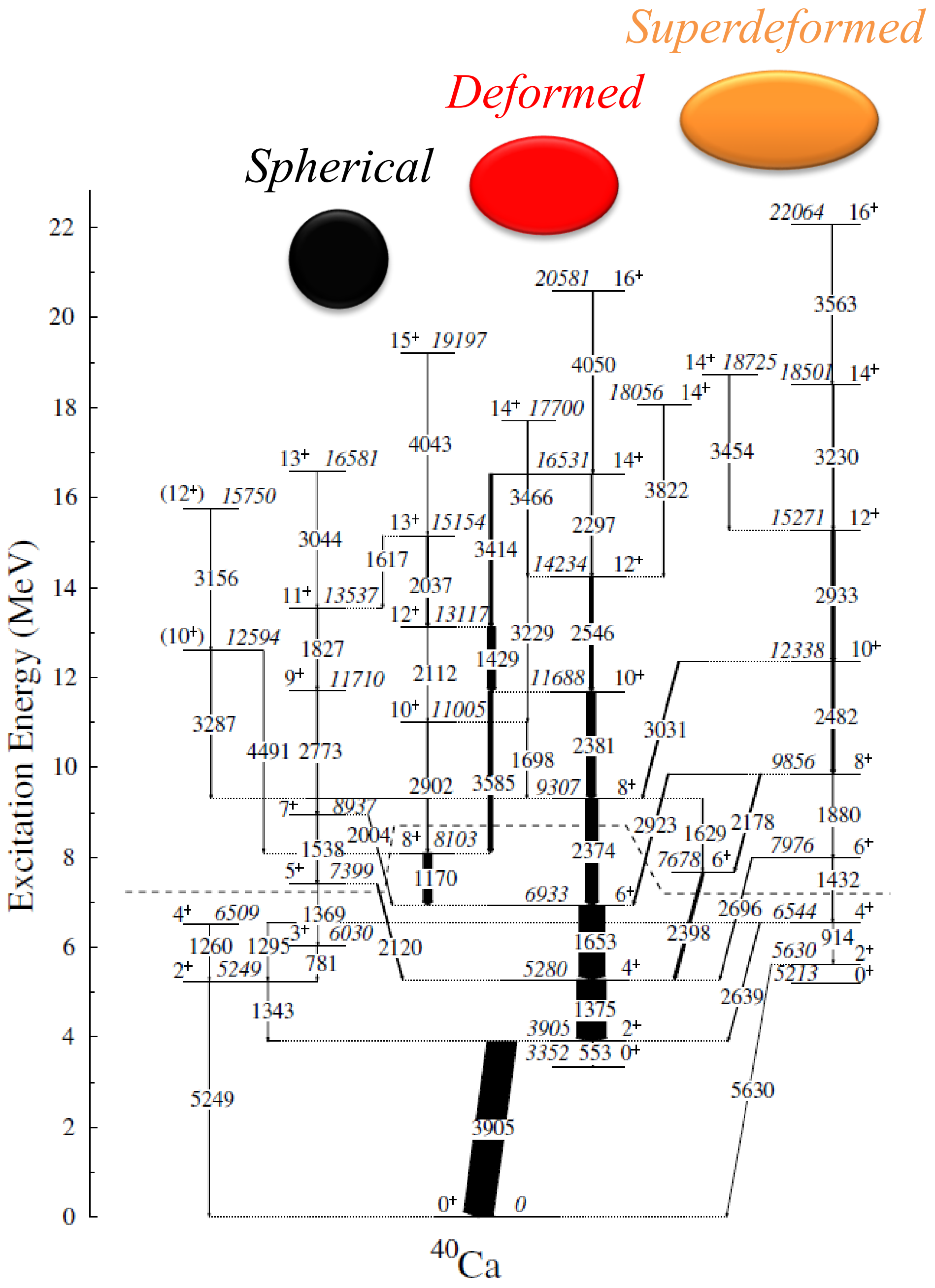
E. Ideguchi et al., PRL87 (2001) 222501

Uniform | Non-uniform ⇨ **Shell effect**



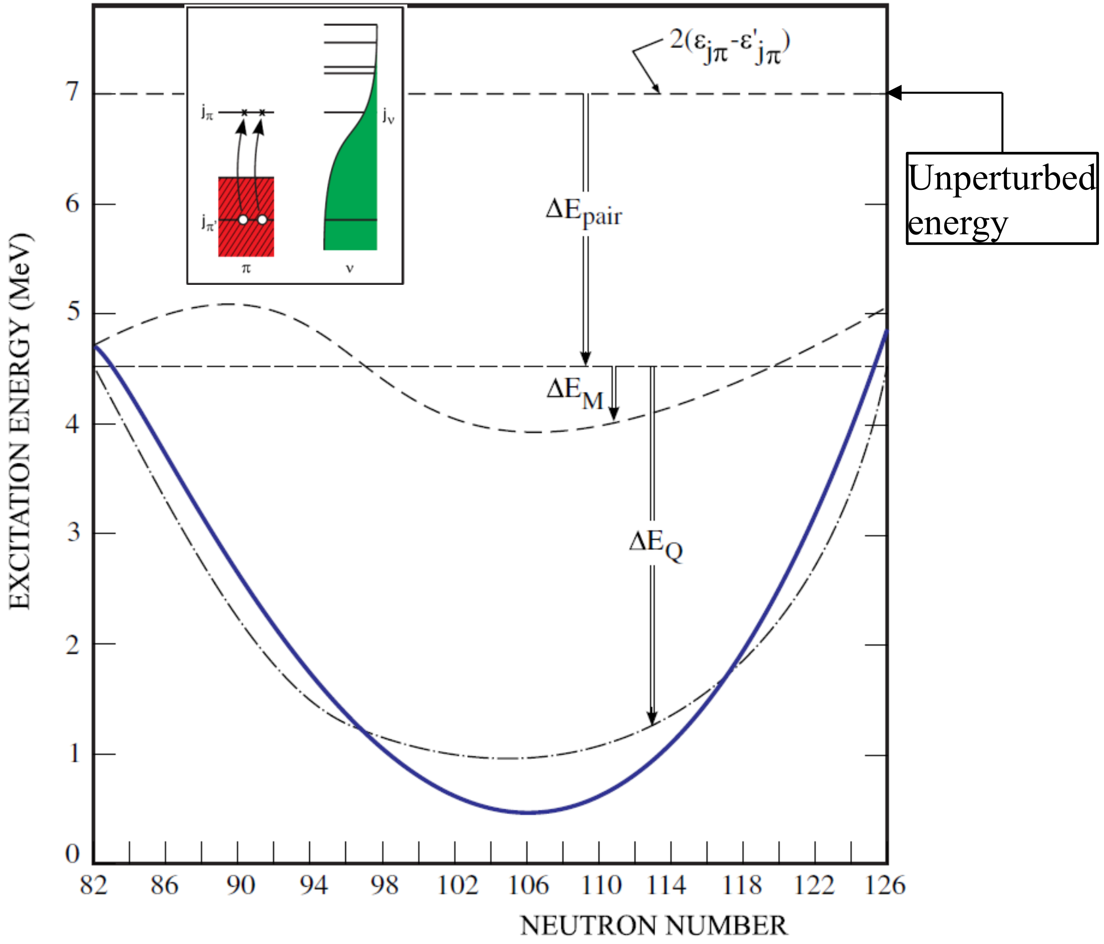

Nucleus favors a shape where the level density near the Fermi level is reduced.



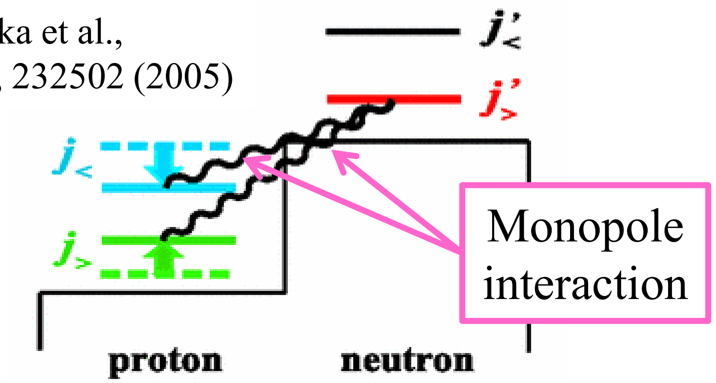
# Shape transitional phenomena take place owing to correlations

Schematic drawing of energy correlations that contribute to $0^+$ **intruder** states
K. Hyde and J.L. Wood, Rev. Mod. Phys. 83 (2011) 1467




- $\Delta E_{pair}$**: Pairing energy**
  - Immediately dominate in closed-shell nuclei
- $\Delta E_Q$**: Quadrupole energy gain**
  - Crucial for producing nuclear deformation
- $\Delta E_M$**: Monopole energy contribution**
  - Play an important role in changing the shell structure
  - Enhanced in the regions far from stability

T. Otsuka et al., PRL95, 232502 (2005)

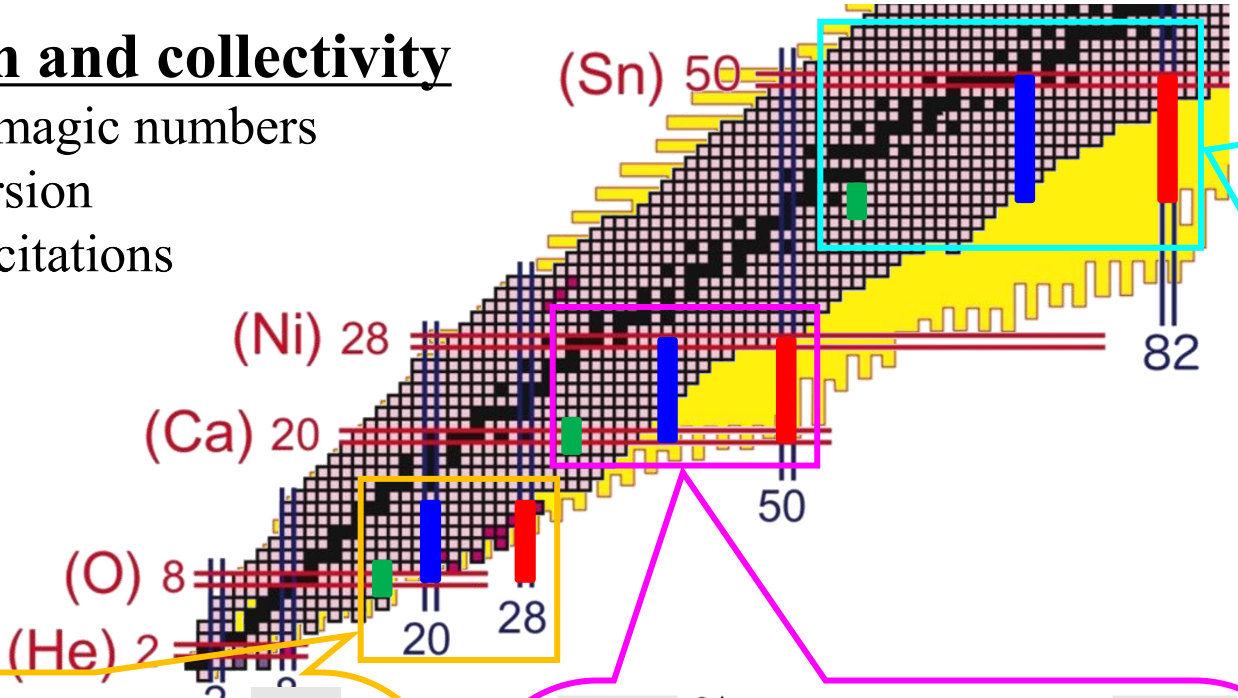


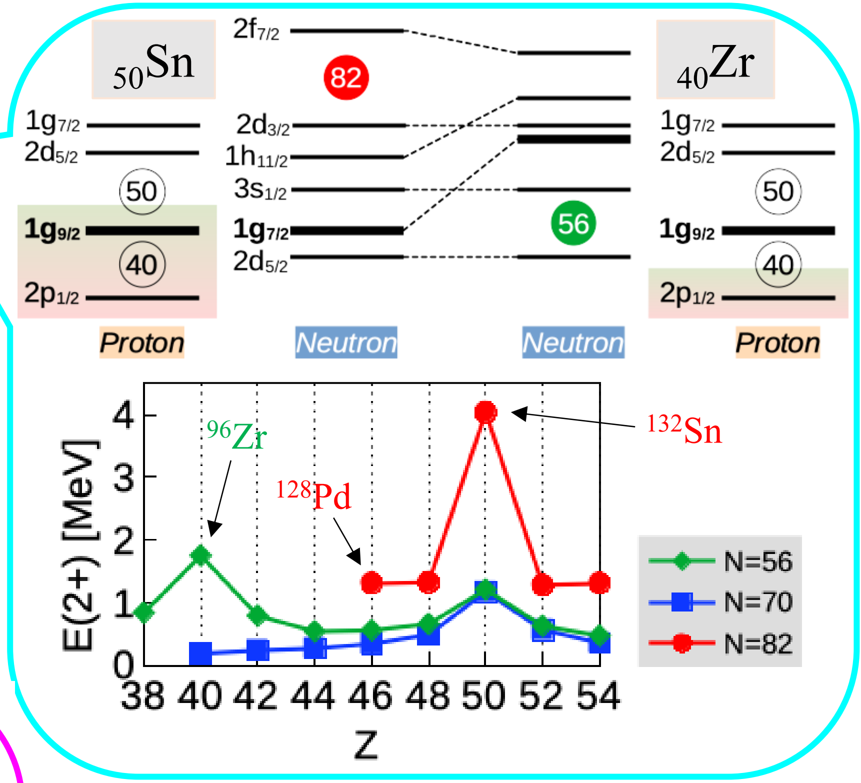

*Tensor-force effect in the proton-neutron interactions*

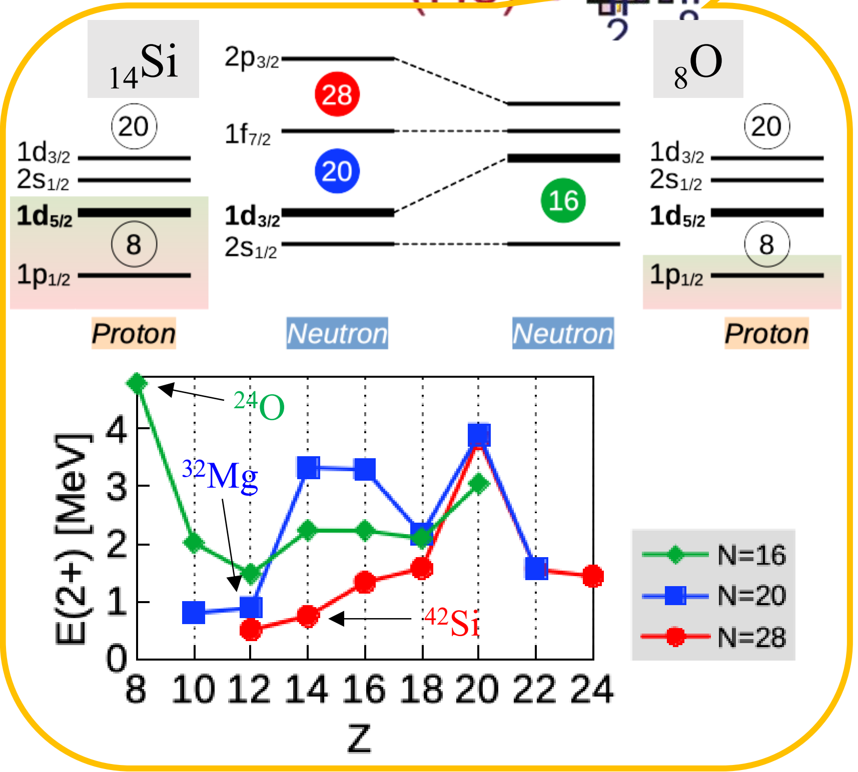
- Many of closed-shell nuclei (both singly and doubly closed shells) that have the spherical ground states exhibit low-energy "**intruder**" deformed states ⇨ **Shape coexistence**

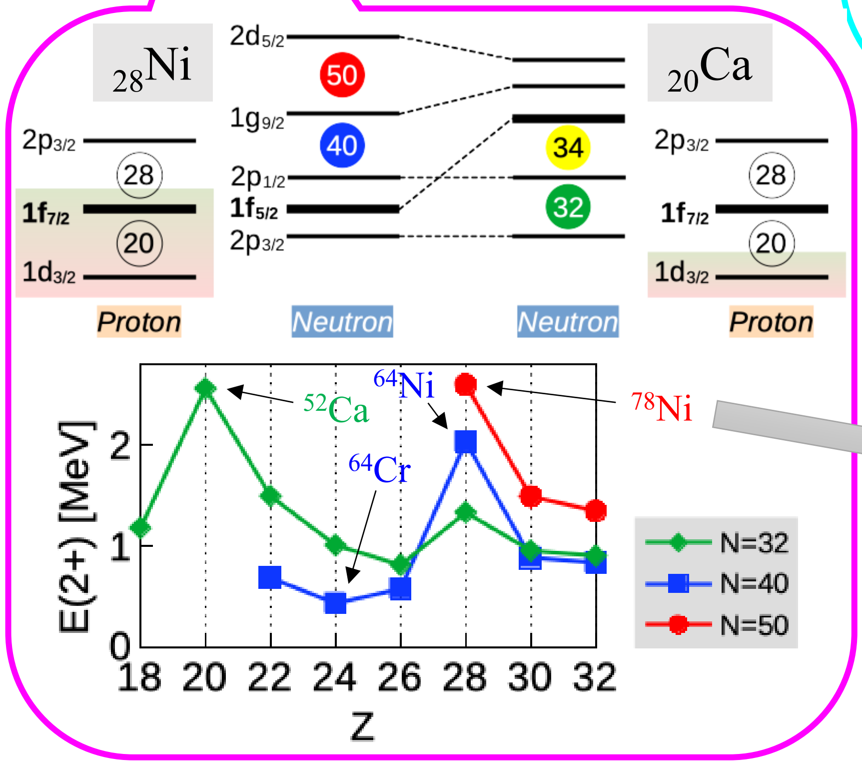
# Shell evolution and collectivity

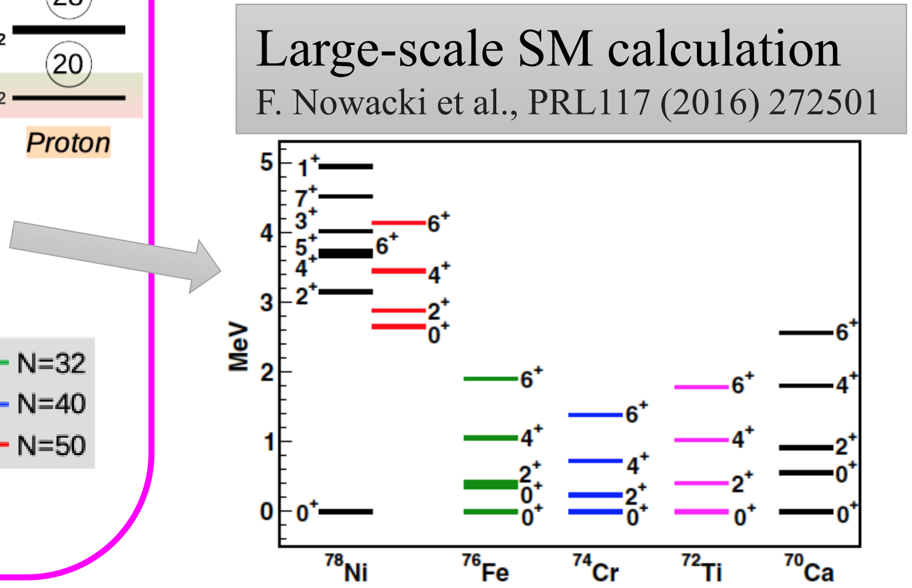
- Lost and new magic numbers
- Island of Inversion
- Cross-shell excitations



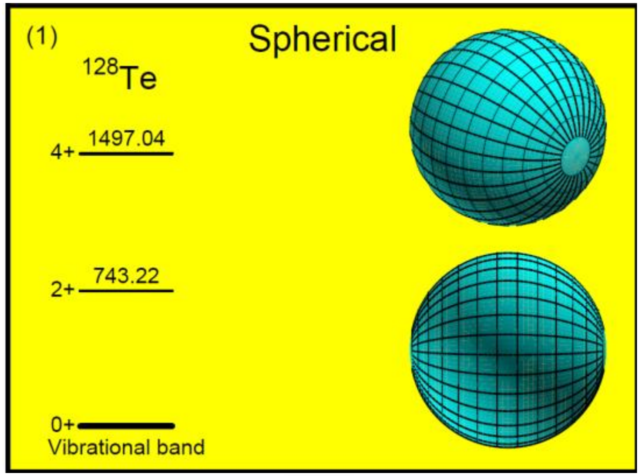



# Low-lying level structures associated with the broken symmetry

Lost symmetry is restored by collective rotational motion

**Characteristic band structures**

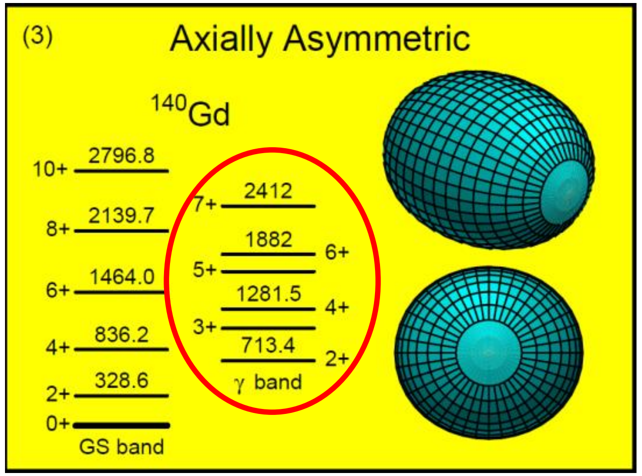
Figures taken from
P. Möller et al., ADNDT98 (2012) 149

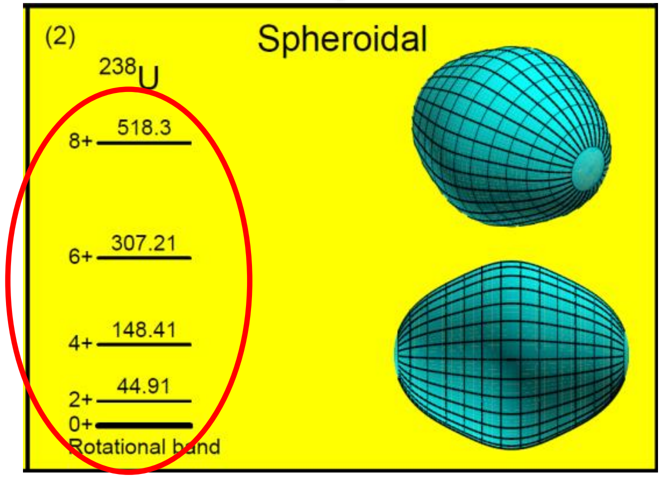


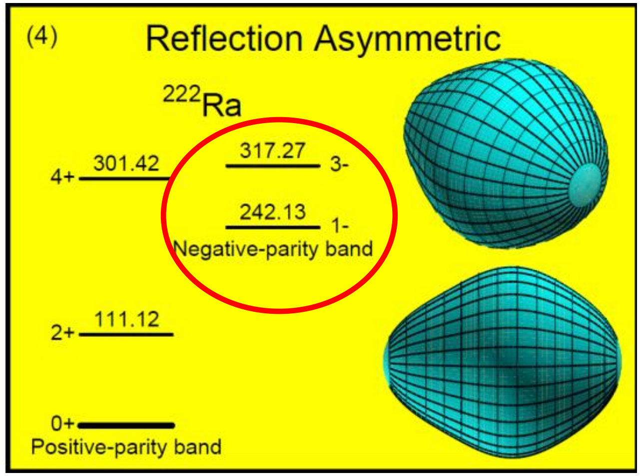

Axial symmetry broken
(Triaxial deformation)

Rotational invariance broken
(Quadrupole deformation)

Parity symmetry broken
(Octupole deformation)




**Atomic nuclei serve as laboratories that enable studying the dynamical mechanism of SSB**

# Basic symmetries of nuclear mean-field Hamiltonian

Operators associated with ***self-consistent symmetries*** in a "non-rotating" frame

A.L. Goodman, Nucl. Phys. A230 (1974) 466

- $\mathcal{T}$: Time reversal
- $\mathcal{P}$: Space inversion (Parity)
- $\mathcal{R}_k = e^{-i\pi j_k}$: Rotations by 180° about the three principal axes of the mean field
- $\mathcal{S}_k = \mathcal{P} \cdot \mathcal{R}_k^{-1}$: Reflections through planes containing the two principal axes of the mean field

When deformed,

- Rotation around the symmetry axis
  → Good K quantum number

In a rotating frame, $\boldsymbol{H^{\omega} = H - \omega I_x}$

■ $\mathcal{T}$, $\mathcal{R}_y$, $\mathcal{R}_z$, $\mathcal{S}_y$, $\mathcal{S}_z$ are violated

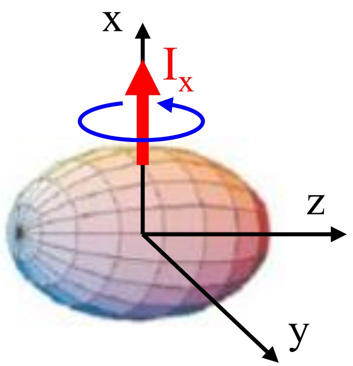
***Coriolis force***

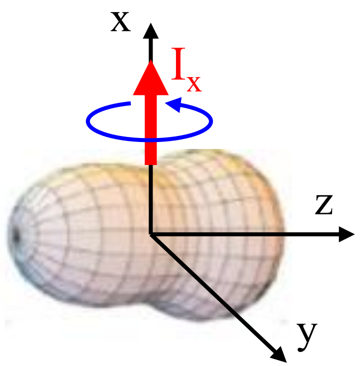
■ $\mathcal{P}$, $\mathcal{R}_x$, $\mathcal{S}_x$ remain

⇒ Provide a classification of the description

λ=even deformation: Parity ($p$) and Signature ($r_x$)

λ=odd deformation: Simplex ($s_x$) only




| | Quadrupole deformation | | Octupole deformation | |
|---|---|---|---|---|
| | $r_x$ | $I$ | $s_x$ | $I^p$ |
| Even mass | +1 | 0, 2, 4, 6, … | +1 | $0^+, 1^-, 2^+, 3^-, 4^+$, … |
| | -1 | 1, 3, 5, 7, … | -1 | $0^-, 1^+, 2^-, 3^+, 4^-$, … |
| Odd mass | -i | 1/2, 5/2, 9/2, … | -i | $1/2^-, 3/2^+, 5/2^-, 7/2^+$, … |
| | +i | 3/2, 7/2, 11/2, … | +i | $1/2^+, 3/2^-, 5/2^+, 7/2^-$, … |

# Signature quantum number and Triaxiality

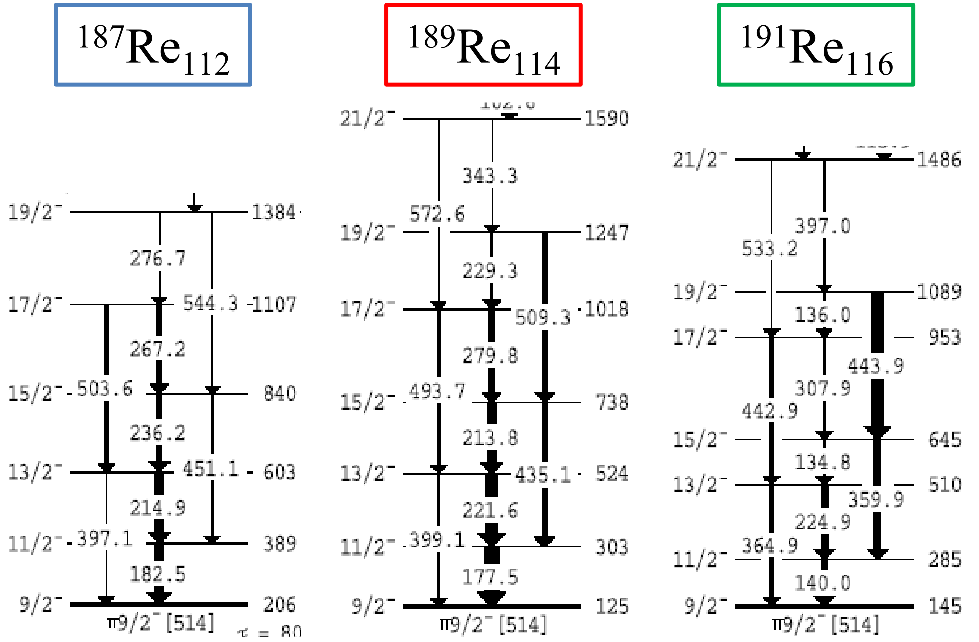
$$E_J = \frac{\hbar^2}{2\mathcal{J}}[J(J+1) - K^2]$$

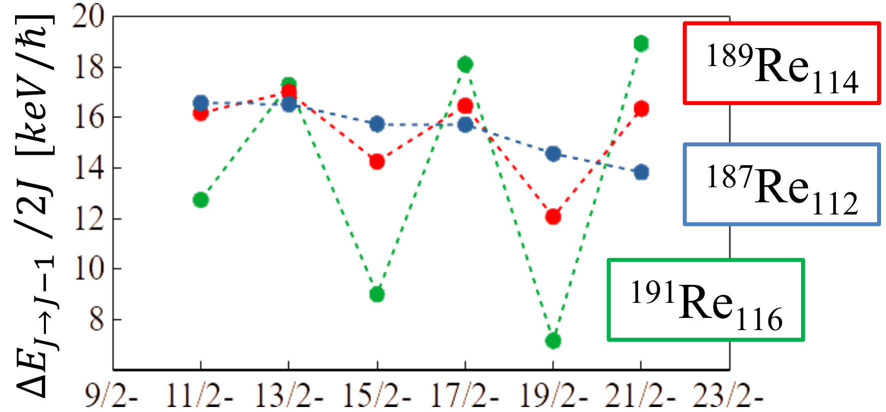
- The rotational band separates into two $\Delta J = 2$ sequences according to signature ($r = \pm 1$ for even-A, $r = \pm i$ for odd-A nuclei)
  - K, K+2, K+4 …
  - K+1, K+3, K+5 …
  - ※Different Coriolis effect between the signature partners
  - ※Signature splitting (energy staggering) caused by Coriolis coupling, which is enhanced for high-j/low-Ω orbits

$$\frac{E_J - E_{J-1}}{2J} = \frac{\Delta E_{J\to J-1}}{2J} = \frac{\hbar^2}{2\mathcal{J}}$$

- Axially symmetric rotor: $\mathcal{J}_x = \mathcal{J}_y \neq \mathcal{J}_z$
  - ⇒ $K$ ($\Omega$) approximately conserved ⇒ **Constant $\Delta E_{J\to J-1}/2J$**
- Asymmetric (Triaxial) rotor: $\mathcal{J}_x \neq \mathcal{J}_y \neq \mathcal{J}_z$
  - ⇒ $\Delta K = \pm 2$ mixing ⇒ Coriolis coupling through "mixed" low-Ω components ⇒ **Staggering in $\Delta E_{J\to J-1}/2J$**

M.W. Reed et al., PLB752, 311 (2016)

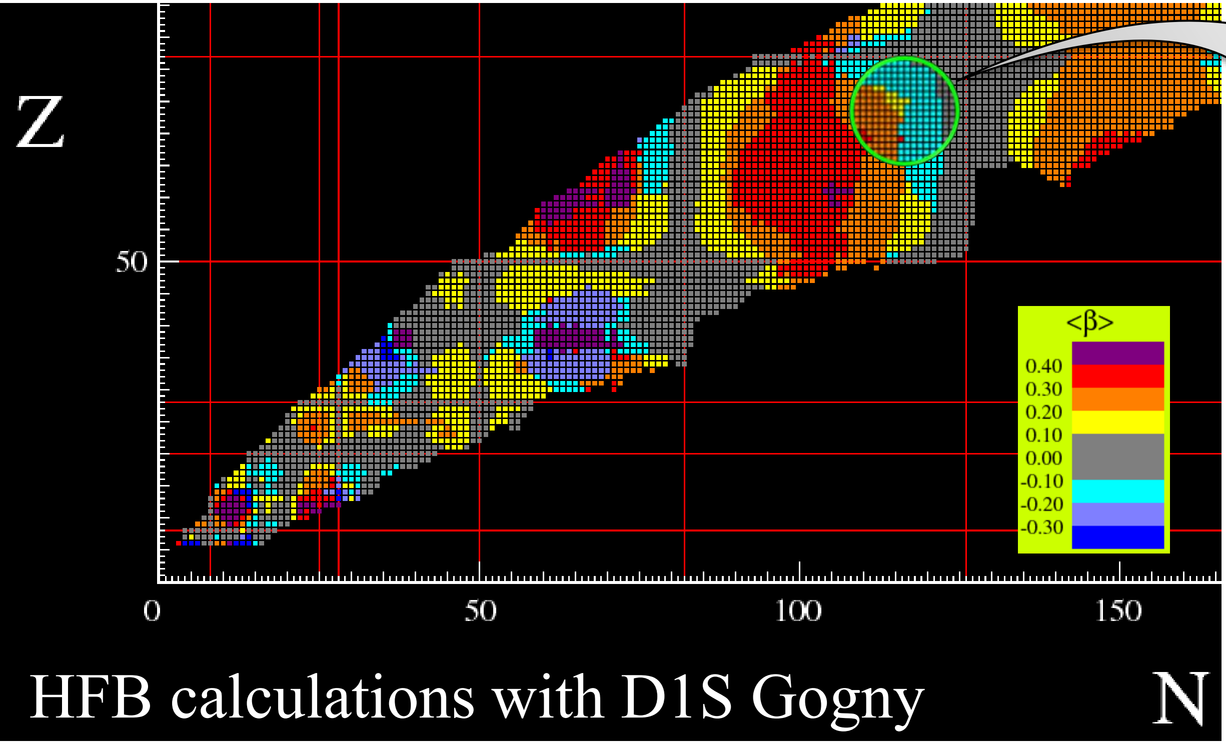


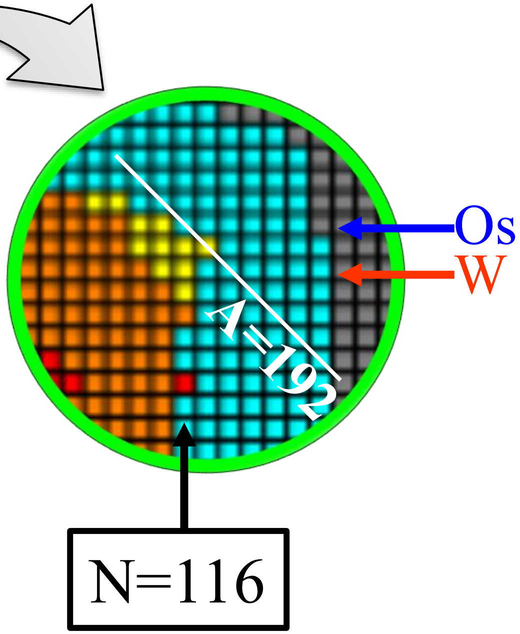



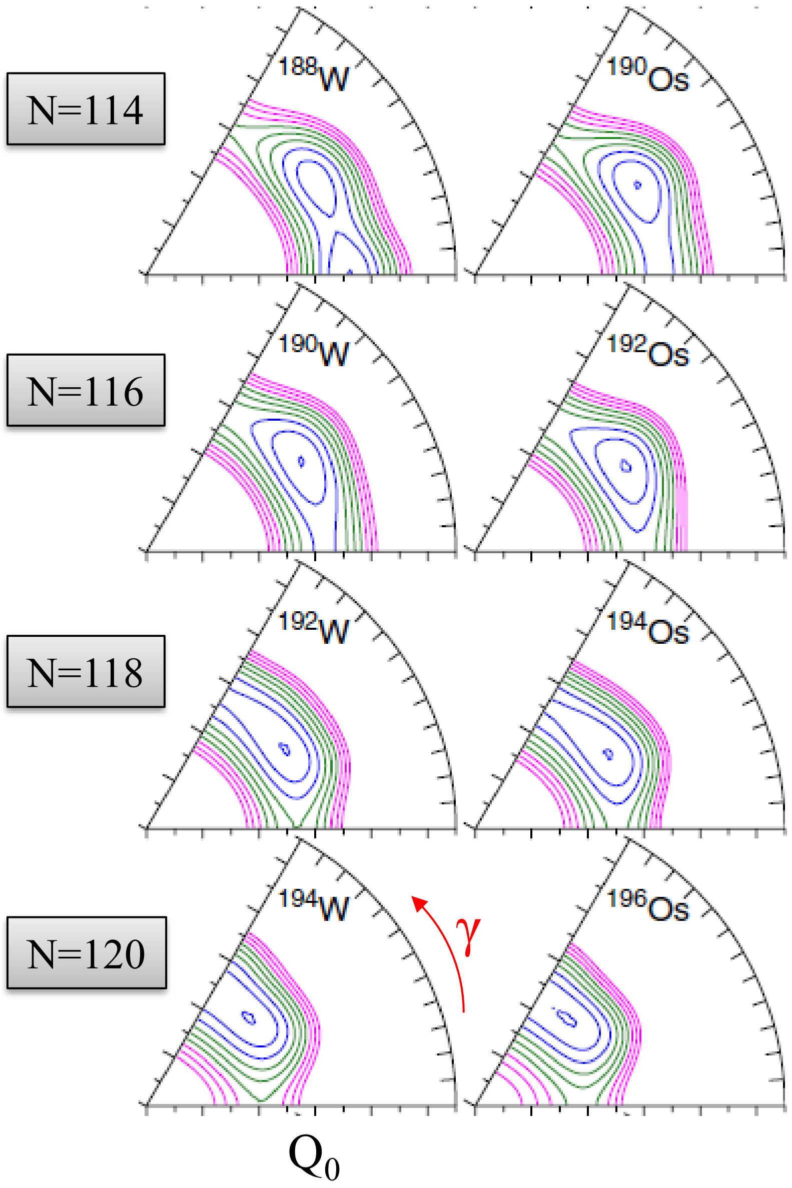

Signature splitting is sensitive to triaxiality

Axial asymmetry enhanced in $_{75}$Re isotopes towards N=116

# What is happening around N = 116, A = 192?



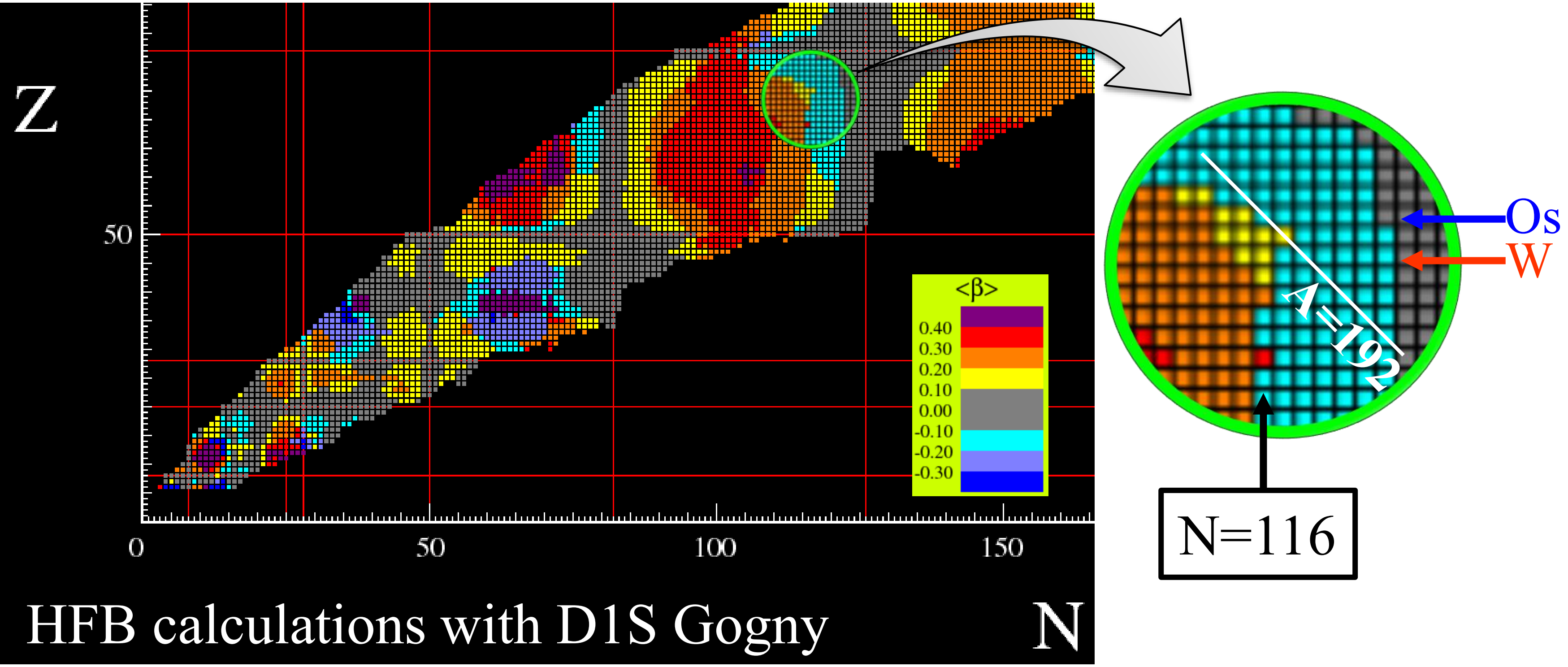



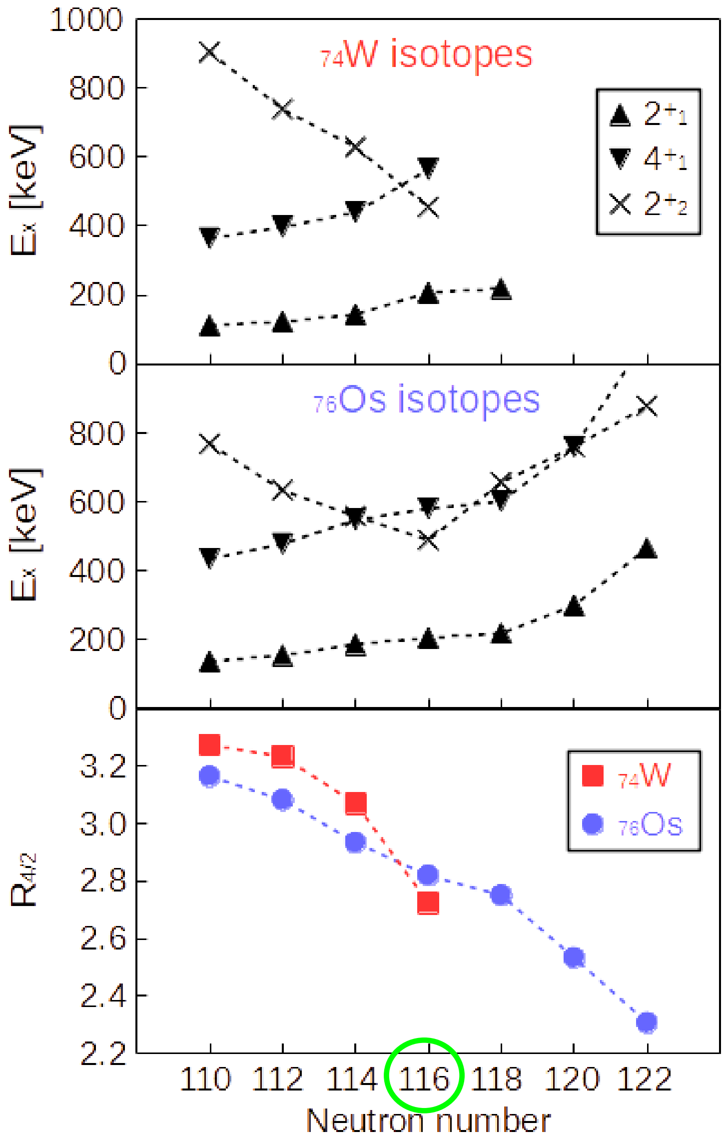

Theoretical arguments

- Transition from prolate to oblate shape
- Soft potential energy surface in the γ direction

L.M. Robledo et al, J. Phys. G: Nucl. Part. Phys. 36 (2009) 115104

# What is happening around N = 116, A = 192?

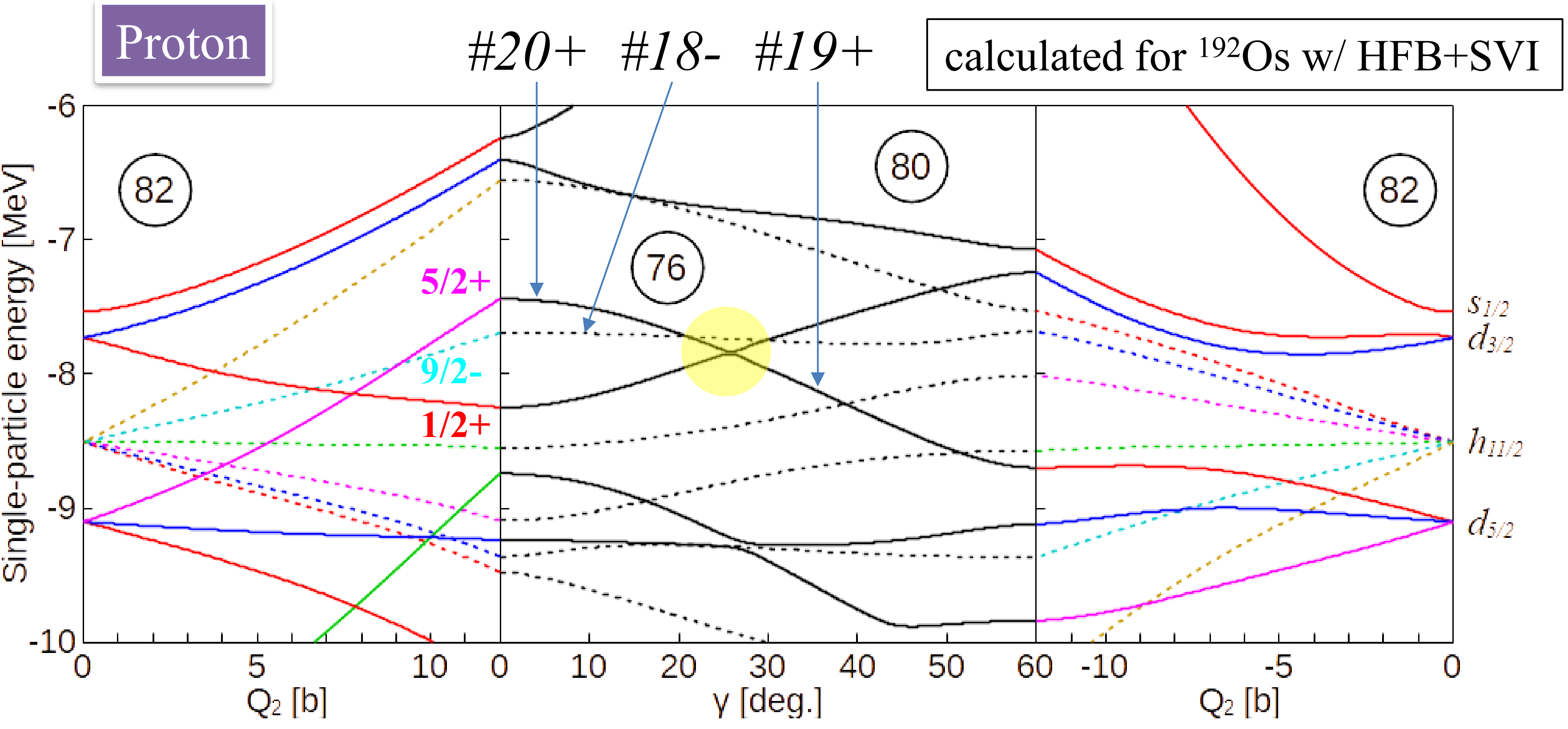


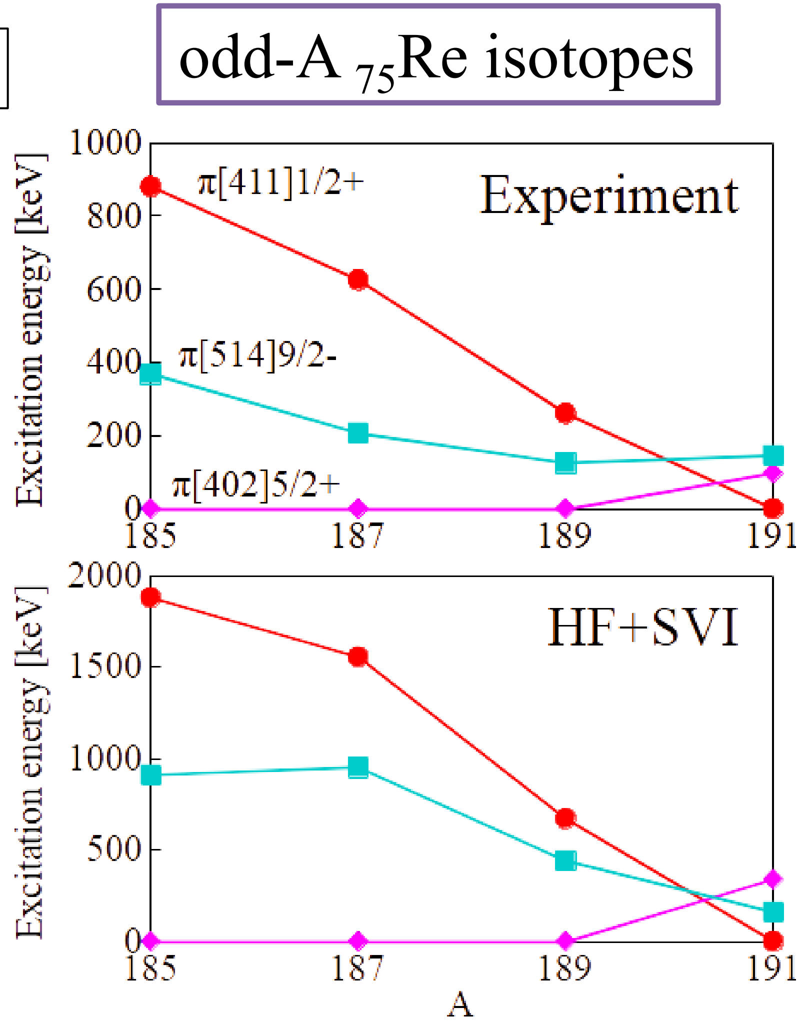




Experimental arguments

- Low-lying $2^+_2$ ($K^\pi = 2^+$) state ⇒ **Axial asymmetry is enhanced**
- Rapid fall in $R_{4/2}$ for $_{74}$W ⇒ **Dramatic change in nuclear shape**
- **Large signature splitting** for rotational bands in odd-A nuclei
- E2 matrix elements measured by Coulomb excitation indicating γ-soft nature
- Anomalously small *K* hindrances measured for the decay from $K^\pi = 10^-$ isomer

# Interpretation of low-lying levels of odd-A $_{75}$Re by Skyrme-HF model




Expected deformation and spin of **the lowest-lying (#20+) state of odd-A Re isotopes** by HFODD

| A | 185 | 187 | 189 | 191 |
|---|---|---|---|---|
| Spin | 2.50 | 2.40 | 2.18 | 0.32 |
| Main $K^{\pi}$ | $5/2^{+}$ | $5/2^{+}$ | $5/2^{+}$ | $1/2^{+}$ |
| $Q_2$ [b] | 15.2 | 15.2 | 13.8 | 13.0 |
| γ [deg.] | 0.0 | 8.8 | 15.3 | 34.5 |

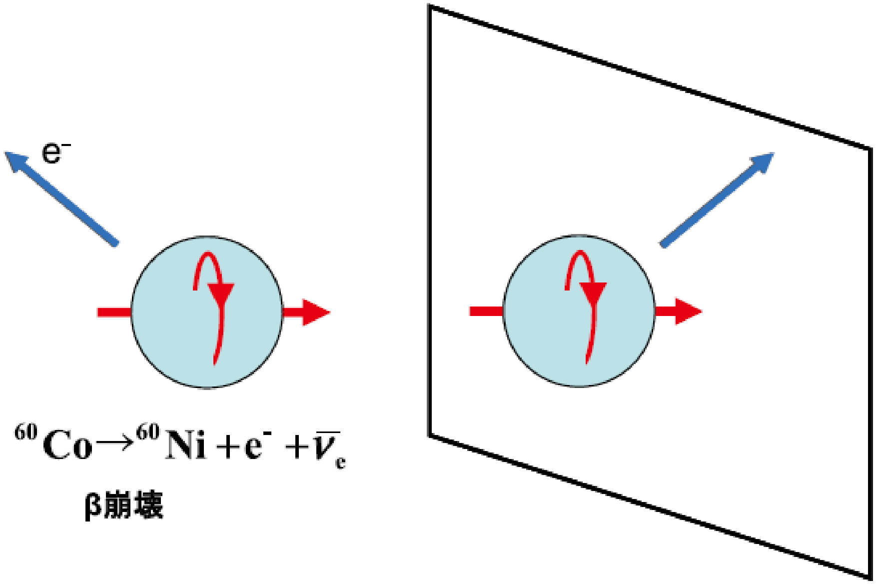
⇨ Shape transition from axial symmetry to asymmetry

# Space inversion (parity) symmetry breaking in weak interaction

**T.D. Lee & C.N. Yang**

Predicted P-symmetry violation

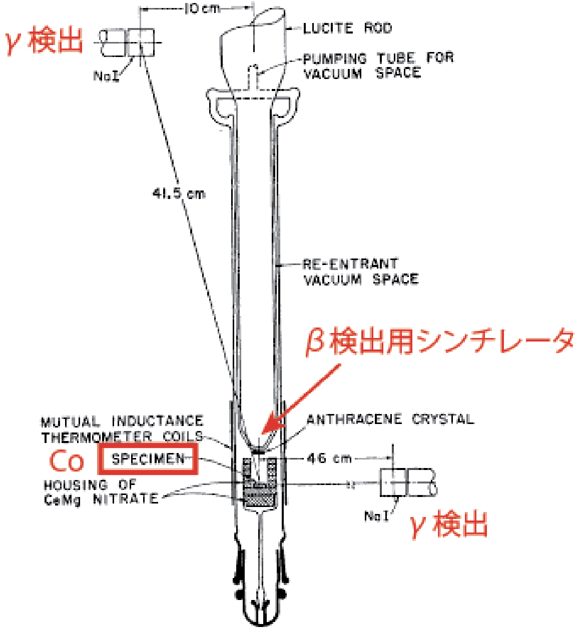
Nobel Prize in Physics 1957

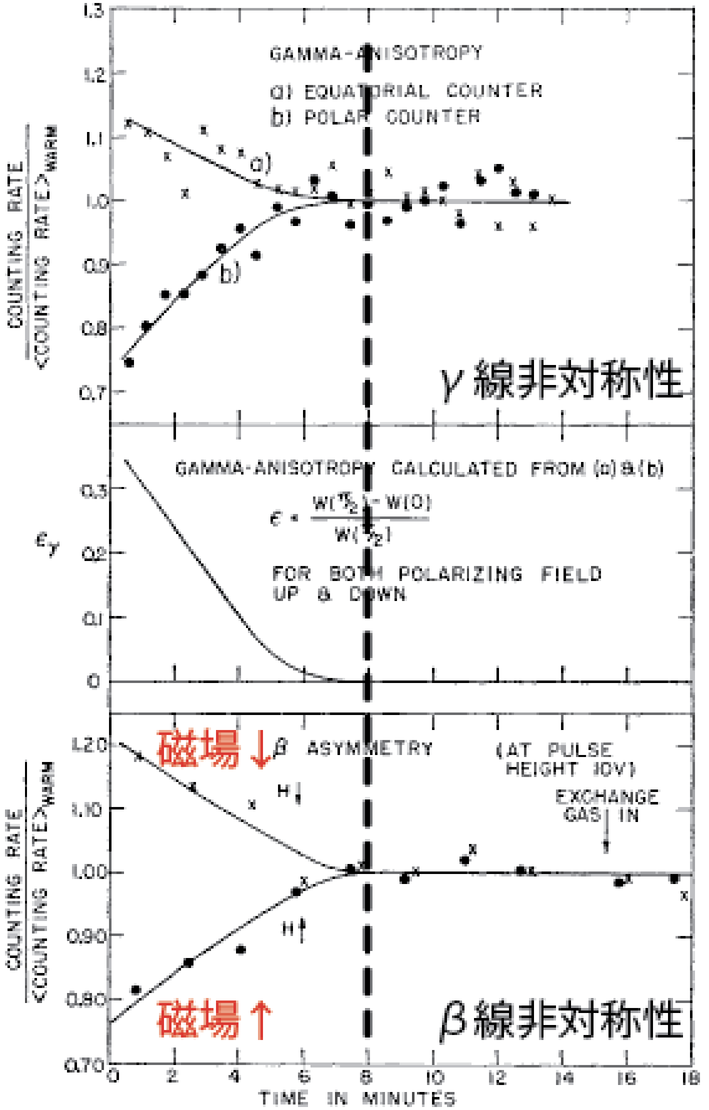



**C.S. Wu**

Discovered P-symmetry violation

in β-decay of spin-polarized $^{60}$Co



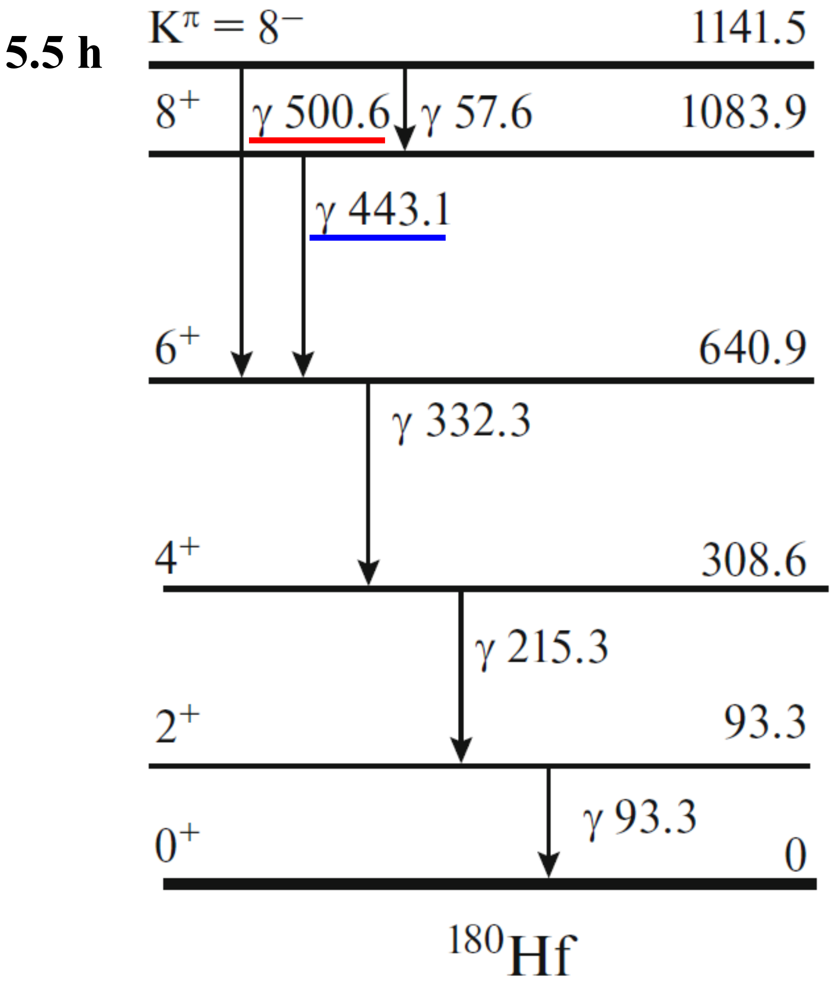

**P-symmetry is violated in nuclear β decay**

# Nuclear structure and Parity non-conservation (PNC)

| | | | |
|---|---|---|---|
| 58 keV | ΔK=8 | E1 | $3.5 \times 10^{-17}$ W.u. |
| 501 keV | ΔK=8 | M2 | $9.8 \times 10^{-15}$ W.u. |
| | | E3 | $7.1 \times 10^{-10}$ W.u. |
| 443 keV | ΔK=0 | E2 | $2.45 \times 10^{2}$ W.u. |

Mix

Parity mixing in bound nuclear states is caused by **weak (parity violating) interaction terms** in the nuclear Hamiltonian, $\boldsymbol{H}_{\mathbf{PNC}}$




$$|\widetilde{8^-}\rangle = |8^-\rangle + \eta|8^+\rangle$$
$$|\widetilde{8^+}\rangle = |8^+\rangle - \eta|8^-\rangle$$

$$\boldsymbol{\eta} = \frac{\langle \mathbf{8^+}|\boldsymbol{H}_{\mathbf{PNC}}|\mathbf{8^-}\rangle}{\boldsymbol{E_x}(\mathbf{8^-}) - \boldsymbol{E_x}(\mathbf{8^+})}$$

The smaller energy gap, the larger mixing

If parity is NOT conserved, **P-odd quantities** change the sign;

- $\boldsymbol{J} \cdot \boldsymbol{k}_{\gamma} \rightarrow \theta = 0°/180°$ asymmetry ($A_\gamma$) from polarized nuclei ($P_N$)

$$P_N A_\gamma \cong \frac{N_\gamma(0°) - N_\gamma(180°)}{N_\gamma(0°) + N_\gamma(180°)} \qquad A_\gamma(501\text{keV}) \cong 2C\eta\frac{\langle E2\rangle}{\langle M2\rangle}$$

- $\boldsymbol{\sigma}_{\gamma} \cdot \boldsymbol{k}_{\gamma} \rightarrow$ Circular polarization ($P_\gamma$) from non-polarized nuclei

$$P_\gamma = \frac{I_R - I_L}{I_R + I_L} \qquad P_\gamma(501\text{keV}) \cong 2\eta\frac{\langle E2\rangle}{\langle M2\rangle}$$

Enhancement due to EM transition matrix

$$\eta\frac{\langle E2\rangle}{\langle M2\rangle} = \epsilon(E2/M2) = -0.0324(16)(19)$$

J.R. Stone et al., PRC76 (2007) 025502

# Nuclear structure and Parity non-conservation (PNC)

| | | | |
|---|---|---|---|
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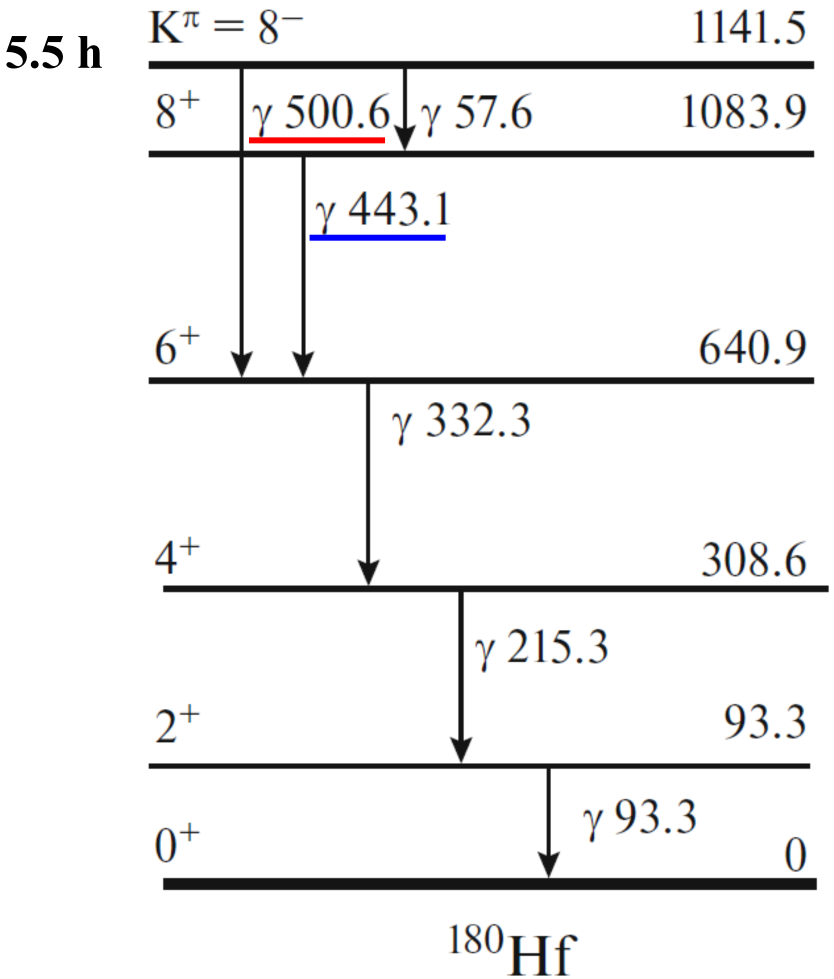
| 443 keV | ΔK=0 | E2 | $2.45 \times 10^{2}$ W.u. |

Mix

Parity mixing in bound nuclear states is caused by **weak (parity violating) interaction terms** in the nuclear Hamiltonian, $\boldsymbol{H}_{\mathbf{PNC}}$




$$|\widetilde{8^-}\rangle = |8^-\rangle + \eta|8^+\rangle$$
$$|\widetilde{8^+}\rangle = |8^+\rangle - \eta|8^-\rangle$$

$$\boldsymbol{\eta} = \frac{\langle \mathbf{8}^+|\boldsymbol{H}_{\mathbf{PNC}}|\mathbf{8}^-\rangle}{\boldsymbol{E}_{\boldsymbol{x}}(\mathbf{8}^-) - \boldsymbol{E}_{\boldsymbol{x}}(\mathbf{8}^+)}$$

The smaller energy gap, the larger mixing

| | $^{180}$Hf |
|---|---|
| $\Delta E_x$ | 57.6 keV |
| $\delta(E3/M2)$ | $-5.3$ |
| $\langle M2\rangle$ | $4.12 \times 10^{-4}$ s$^{-1/2}$ |
| $\langle E2\rangle$ | $7.51 \times 10^{5}$ s$^{-1/2}$ |
| $\lvert\epsilon\rvert$ | $3.24 \times 10^{-2}$ |
| $\lvert\eta\rvert$ | $1.8 \times 10^{-11}$ |
| $\lvert H_{\mathrm{PNC}}\rvert$ | $1.0 \times 10^{-6}$ eV |

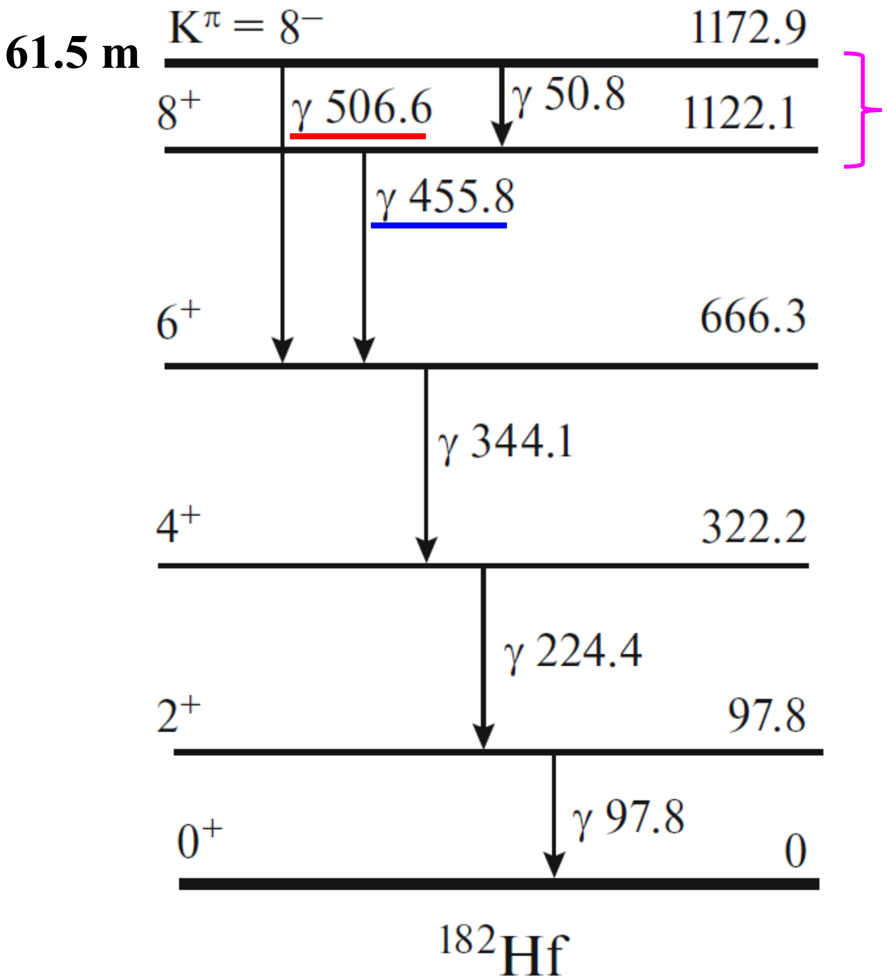
Extremely small (K mismatch)

# Nuclear structure and Parity non-conservation (PNC)

| | | | |
|---|---|---|---|
| 51 keV | ΔK=8 | E1 | $1.3 \times 10^{-16}$ W.u. |
| 507 keV | ΔK=8 | M2 | $4.0 \times 10^{-12}$ W.u. |
| | | E3 | ? |
| 456 keV | ΔK=0 | E2 | ? |

Less hindered compared to $^{180m}$Hf due to **K mixing**?

Small (common) K components in the $8^+$ and $8^-$ states cause $\langle 8^+ | H_{PNC} | 8^- \rangle \neq 0$




$$|\widetilde{8^-}\rangle = |8^-\rangle + \eta|8^+\rangle$$
$$|\widetilde{8^+}\rangle = |8^+\rangle - \eta|8^-\rangle$$

$$\boldsymbol{\eta} = \frac{\langle 8^+ | H_{PNC} | 8^- \rangle}{E_x(8^-) - E_x(8^+)}$$

The smaller energy gap, the larger mixing

| | $^{180}$Hf | $^{182}$Hf |
|---|---|---|
| $\Delta E_x$ | 57.6 keV | 50.8 keV |
| $\delta(E3/M2)$ | −5.3 | ? |
| $\langle M2 \rangle$ | $4.12 \times 10^{-4}$ s$^{-1/2}$ | ? |
| $\langle E2 \rangle$ | $7.51 \times 10^{5}$ s$^{-1/2}$ | ? |
| $\|\epsilon\|$ | $3.24 \times 10^{-2}$ | ? |
| $\|\eta\|$ | $1.8 \times 10^{-11}$ | ? |
| $\|H_{PNC}\|$ | $1.0 \times 10^{-6}$ eV | ? |

**Plan at RAON**

$W_{507}(\theta)$ or $\alpha_{507}$

$\tau_{8^+}$ (or $\tau_{2^+,4^+}$)

$A_{507}$ and/or $P_{507}$

# Summary

Decay spectroscopy is an experimental technique to investigate nuclear structure by measuring the energy, lifetime, multipolarity etc. of radioactive decays, such as

- **β decay**: Selection rule, log*ft* ⇒ Effect of nuclear structure in the β strength function
- **γ-ray emission**: Excited-state lifetime measurement by electronic fast-timing (IDATEN)
- **Isomeric transition**: Deviation from seniority scheme, K quantum number and mixing

Radioactive decay measurements can provide significant information on

- Evolution of shell structure
- Shape transition and co-existence
- Specific interactions, e.g., parity violating term in the nuclear Hamiltonian

Thank you for your listening!