Study on nuclear structure of important neutron-rich nuclei related to the *r*-process

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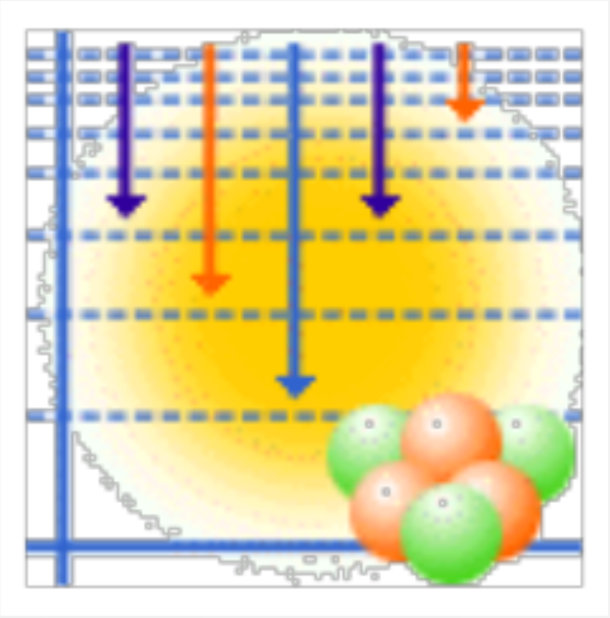
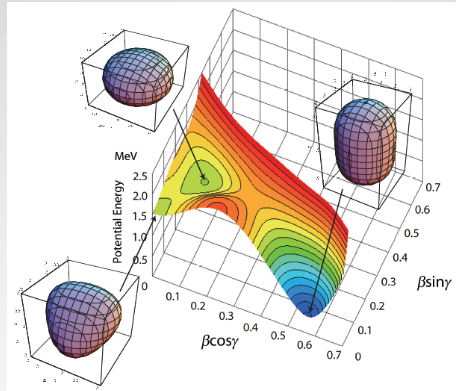
Content

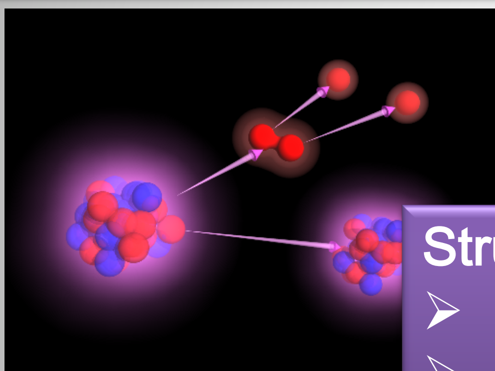


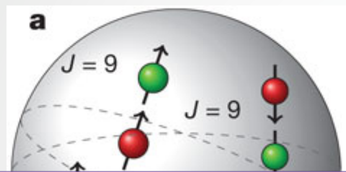
Exploration of the New Frontier in Nuclear Physics

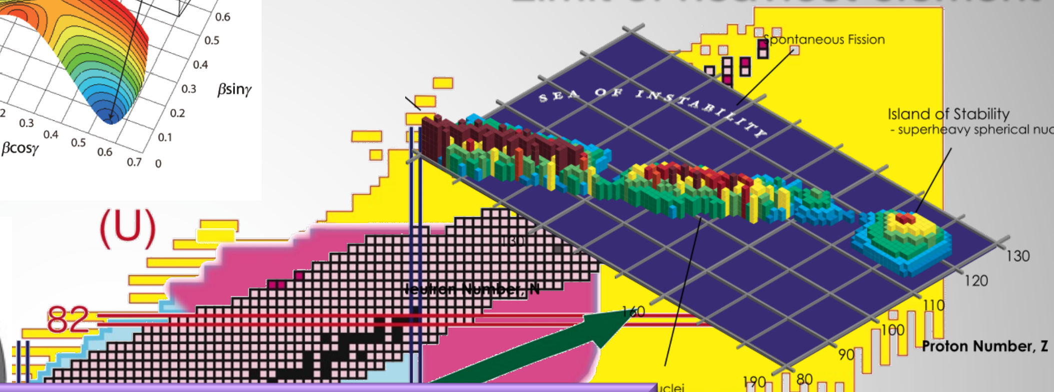
Proton-rich nuclei
- Proton-neutron pairing
- Isospin symmetry
- Proton radioactivity
- rp-process



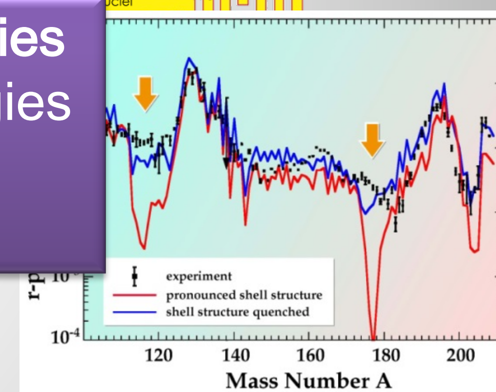
Superheavy nuclei
- Island of stability

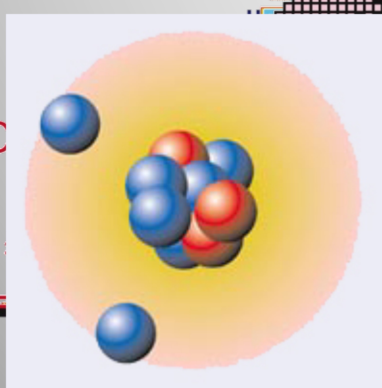


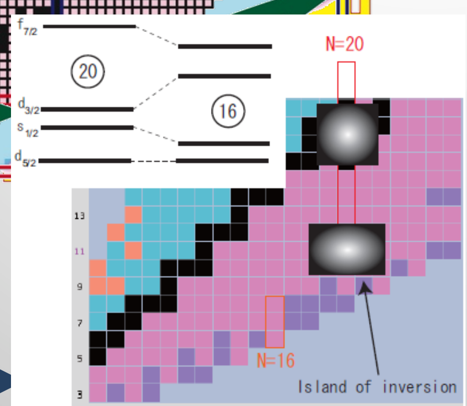




Structural evolution within these boundaries
- Monopole shift of single-particle energies
- Shape-phase transitions

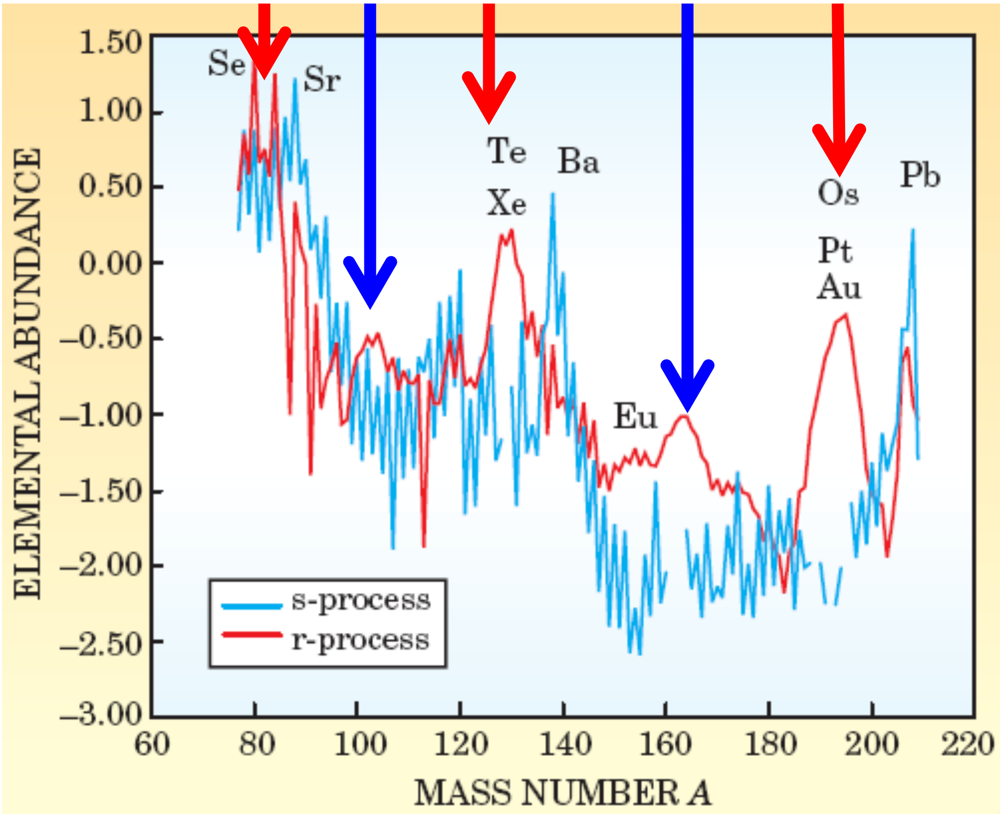






Neutron-rich nuclei
- Shell quenching and new magicity
- Neutron halo/skin
- Loosely bound neutrons
- r-process

Motivation & background



Adapted from Sneden and Cowan, Science (2003)
J. Wu et al., PRL, 118 ,072701 (2017)

Elemental abundance

First peak: A~ 80 → N=50

Second peak: A~ 130 → N=82

Third peak: A~ 195 → N=126

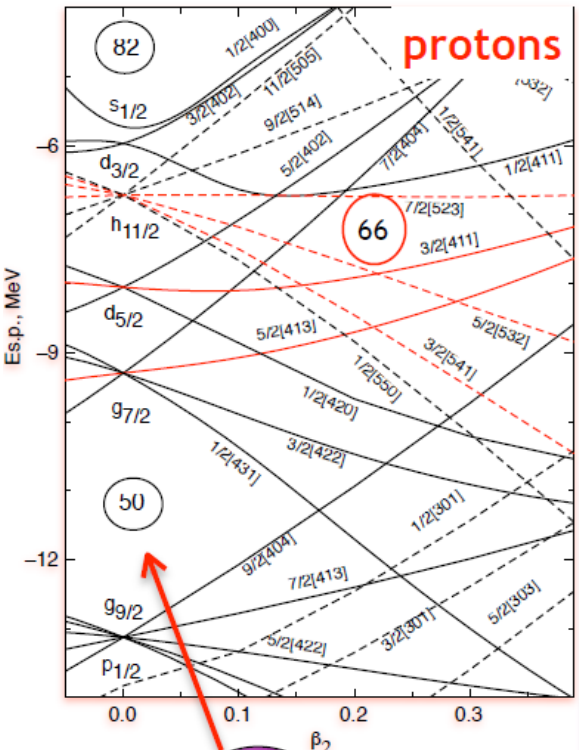
Small and broad peak: A~ 165 → ?

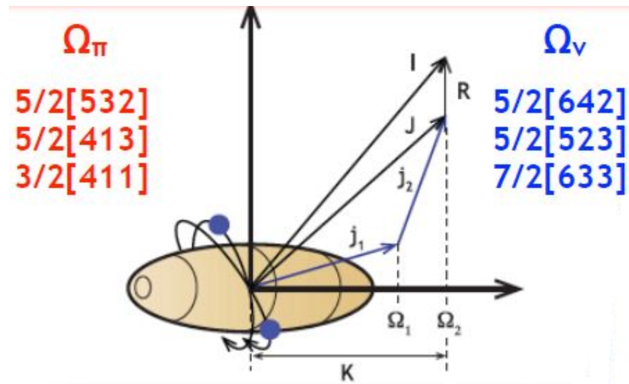
New physics: shape coexistence, midshell collectivities……

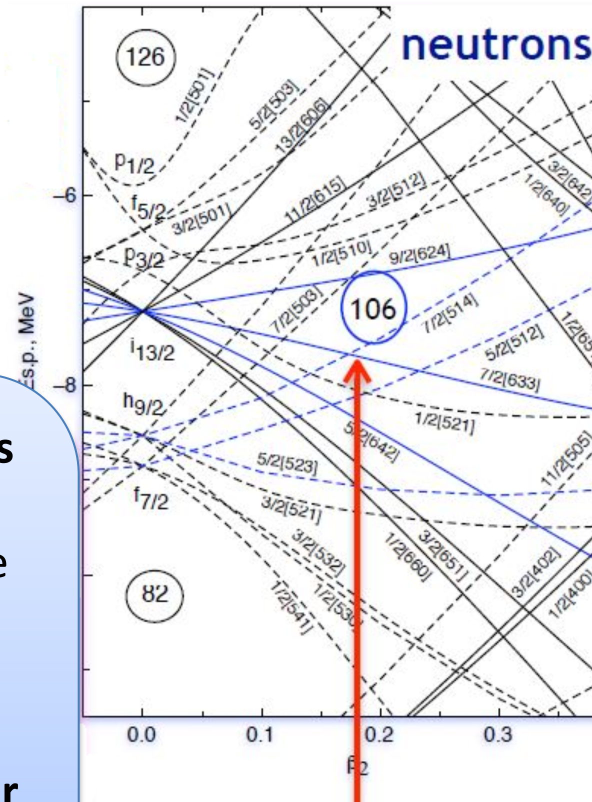
s-process — neutron capture timescale > β-decay timescale

r-process — neutron capture timescale < β-decay timescale

Motivation & background







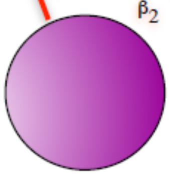
ordering of single-particle levels

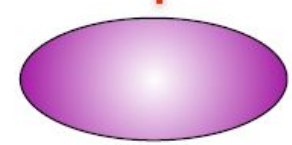
- **size of deformation**

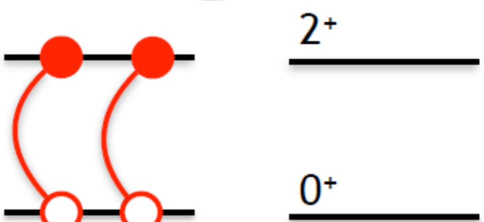
✓ how it evolves with N & Z; are there shape changes?

- **pairing and residual nucleon-nucleon interactions**
- role of the **K-quantum number**

✓ both in γ-decay (K-isomers) and β-decay (spin-trap isomers)







$$E = \frac{\hbar^2}{2\Im(\Delta,\beta)} I(I+1)$$

Results & Discussion-PSM

Intrinsic coordinate

↓

$$|\Phi_{\kappa}\rangle$$

K. Hara and Y. Sun, Int. J. Mod. Phys. E 4，637 (1995).

Results & Discussion-PSM

Intrinsic coordinate

$|\Phi_\kappa\rangle$

$\hat{P}^I_{MK}|\Phi(\kappa)\rangle$

angular
momentum
projection

K. Hara and Y. Sun, Int. J. Mod. Phys. E 4，637 (1995).

Results & Discussion-PSM

Intrinsic coordinate

Laboratory coordinate

$$\left|\Phi_{\kappa}\right\rangle$$

$$\hat{P}^{I}_{MK}\left|\Phi(\kappa)\right\rangle$$

$$\left|\Psi_{IM}\right\rangle = \sum_{\kappa K} F^{I}_{\kappa K}\hat{P}^{I}_{MK}\left|\Phi_{\kappa}\right\rangle$$

angular momentum projection

K. Hara and Y. Sun, Int. J. Mod. Phys. E 4，637 (1995).

Results & Discussion-PSM

Intrinsic coordinate

$$|\Phi_\kappa\rangle$$

Laboratory coordinate

$$\hat{P}^I_{MK}|\Phi(\kappa)\rangle$$

angular momentum projection

$$|\Psi_{IM}\rangle = \sum_{\kappa K} F^I_{\kappa K} \hat{P}^I_{MK} |\Phi_\kappa\rangle$$

PSM

Projection operator：

$$\hat{P}^I_{MK} = \frac{2I+1}{8\pi^2}\int d\Omega D^I_{MK}\hat{R}(\Omega)$$

How to select two-body interaction, single particle basis and model space?

K. Hara and Y. Sun, Int. J. Mod. Phys. E 4，637 (1995).

Results & Discussion-PSM

Two-body Hamiltonian

$$\hat{H} = \hat{H}_0 - \frac{\chi}{2}\sum_{\mu}\hat{Q}^{+}_{\mu}\hat{Q}_{\mu} - G_M\hat{P}^{+}\hat{P} - G_Q\hat{P}^{+}_{\mu}\hat{P}_{\mu}$$

QQ force

QQ force

monopole

qudrupole

Usually, quite satisfactory results can be obtained since the deformed quasiparticle basis already contains important correlations.

Results & Discussion-PSM

$$\hat{H}_0 - \frac{2}{3}\hbar\omega\varepsilon\hat{Q}_0$$

axial symmetry

Nilsson potential

K. Hara and Y. Sun, Int. J. Mod. Phys. E 4, 637 (1995).

Results & Discussion-PSM

Nilsson potential

$$\hat{H}_0 - \frac{2}{3}\hbar\omega\varepsilon\hat{Q}_0$$

axial symmetry

$$\hat{H}_0 - \frac{2}{3}\hbar\omega\left[\varepsilon\hat{Q}_0 + \varepsilon'\frac{\hat{Q}_{+2}+\hat{Q}_{-2}}{\sqrt{2}}\right]$$

triaxial

TPSM

J. A. Sheikh and K. Hara, Phys.Rev.Lett. 82, 3968 (1999).
Y. Sun et al., Phys. Rev. C 61, 064323 (2000).

Results & Discussion-PSM

Nilsson potential

$$\hat{H}_0 - \frac{2}{3}\hbar\omega\varepsilon\hat{Q}_0$$

axial symmetry

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triaxial

TPSM

J. A. Sheikh and K. Hara, Phys.Rev.Lett. 82, 3968 (1999).
Y. Sun et al., Phys. Rev. C 61, 064323 (2000).

Double even nucleus: $|0\rangle, a^+_{\nu 1}a^+_{\nu 2}|0\rangle, a^+_{\pi 1}a^+_{\pi 2}|0\rangle, a^+_{\nu 1}a^+_{\nu 2}a^+_{\pi 1}a^+_{\pi 2}|0\rangle$

Double odd nucleus: $a^+_{\nu}a^+_{\pi}|0\rangle$

Odd neutron nucleus: $a^+_{\nu}|0\rangle, a^+_{\nu}a^+_{\pi 1}a^+_{\pi 2}|0\rangle$

Odd proton nucleus: $a^+_{\pi}|0\rangle, a^+_{\pi}a^+_{\nu 1}a^+_{\nu 2}|0\rangle$

Nilsson+BCS deformed basis

angular momentum projection

$$\hat{P}^I_{MK}|\Phi(\kappa)\rangle$$

Model space

Results & Discussion-PSM

Perform configuration mixing

PSM wave function →

$$|\Psi_{IM}\rangle = \sum_{\kappa K} F^{I}_{\kappa K} \hat{P}^{I}_{MK} |\Phi_{\kappa}\rangle$$

$$\sum_{\kappa' K'} \{H^{I}_{\kappa K \kappa' K'} - E N^{I}_{\kappa K \kappa' K'}\} F^{I}_{\kappa' K} = 0$$

Band energy →

$$E_{\kappa}(I) = \frac{\langle \Phi_{\kappa} | \hat{H} \hat{P}^{I}_{KK'} | \Phi_{\kappa} \rangle}{\langle \Phi_{\kappa} | \hat{P}^{I}_{KK'} | \Phi_{\kappa} \rangle} = \frac{H_{\kappa\kappa}}{N_{\kappa\kappa}}$$

Results & Discussion-PSM

Moment of Inertia (J)

$$J^{(1)} = \frac{2I-1}{E(I)-E(I-2)}$$

B(E2, I→I-2)

$$B(E2, I \rightarrow I-2) = \frac{1}{2I+1}\left|\left\langle \Psi^{I-2} \left\| \hat{Q}_2 \right\| \Psi^{I} \right\rangle\right|^2$$

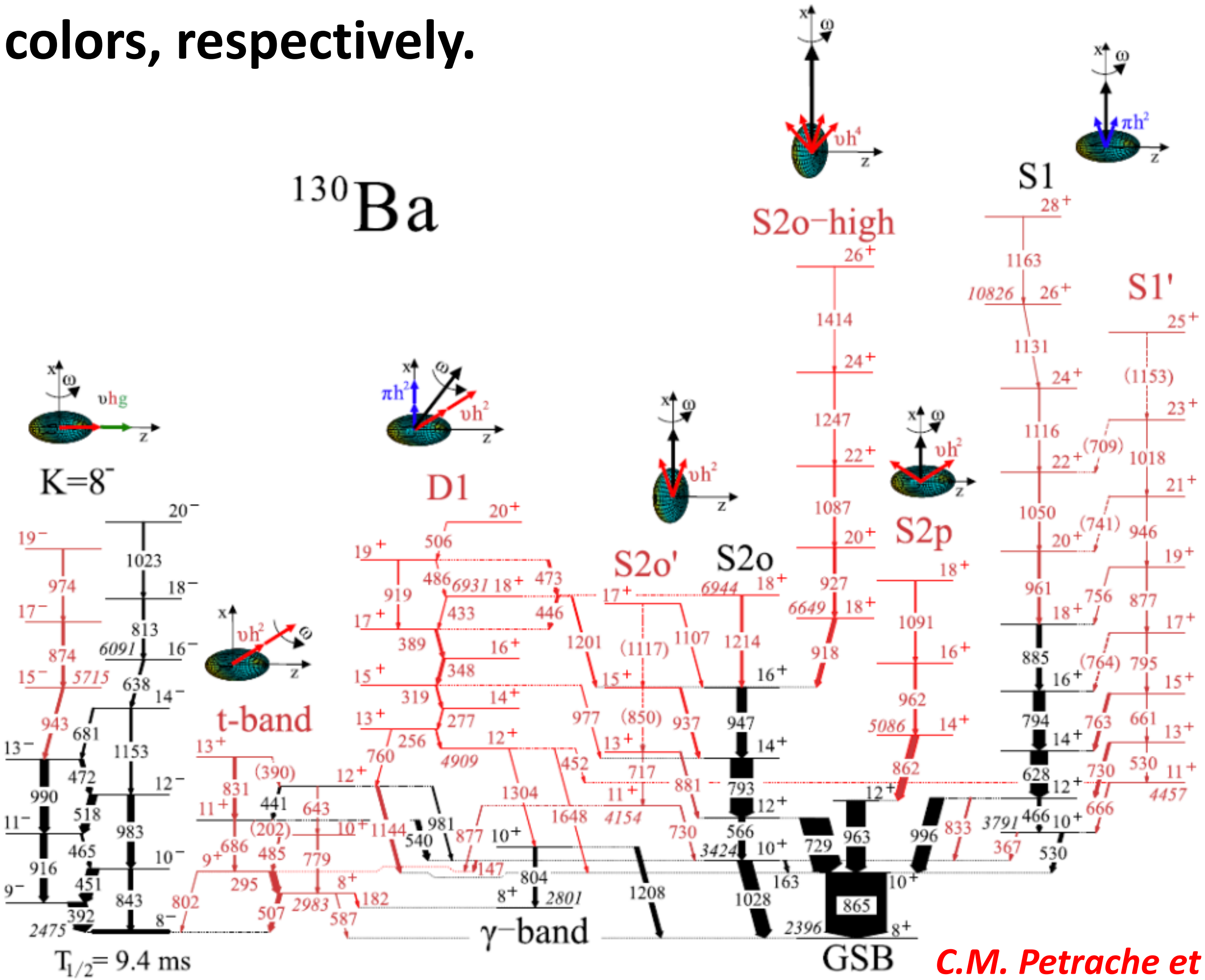
g factor

$$g(I) = \frac{\mu(I)}{\mu_N I} = \frac{1}{\mu_N I}\left[\mu_\pi(I) + \mu_\nu(I)\right]$$

Results & Discussion-A~130 region

□ Experiment

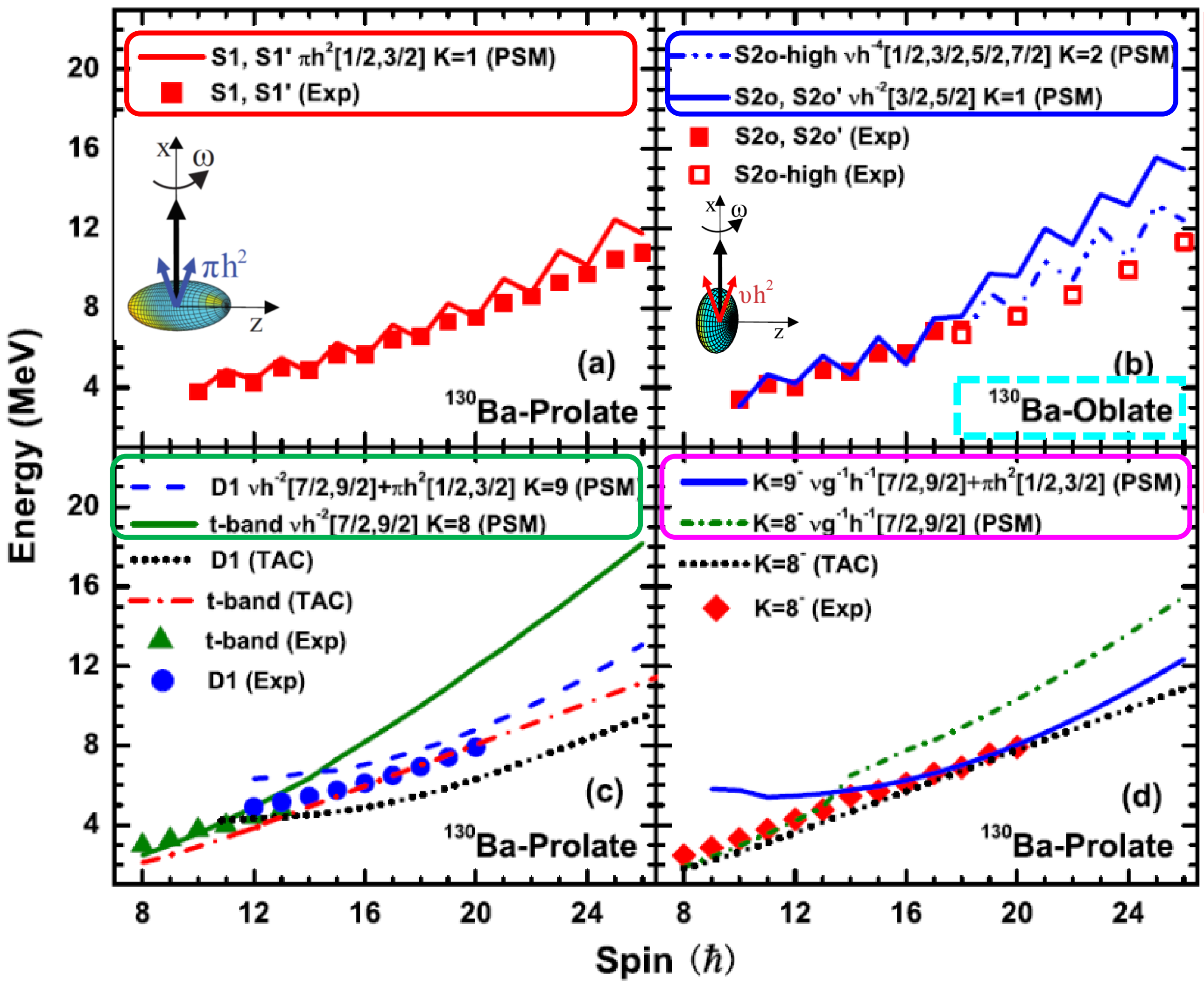
Known (new) levels and transitions are drawn with black (red) colors, respectively.



C.M. Petrache et al. PLB 795 (2019) 241

Results & Discussion-A~130 region

☐ Energy



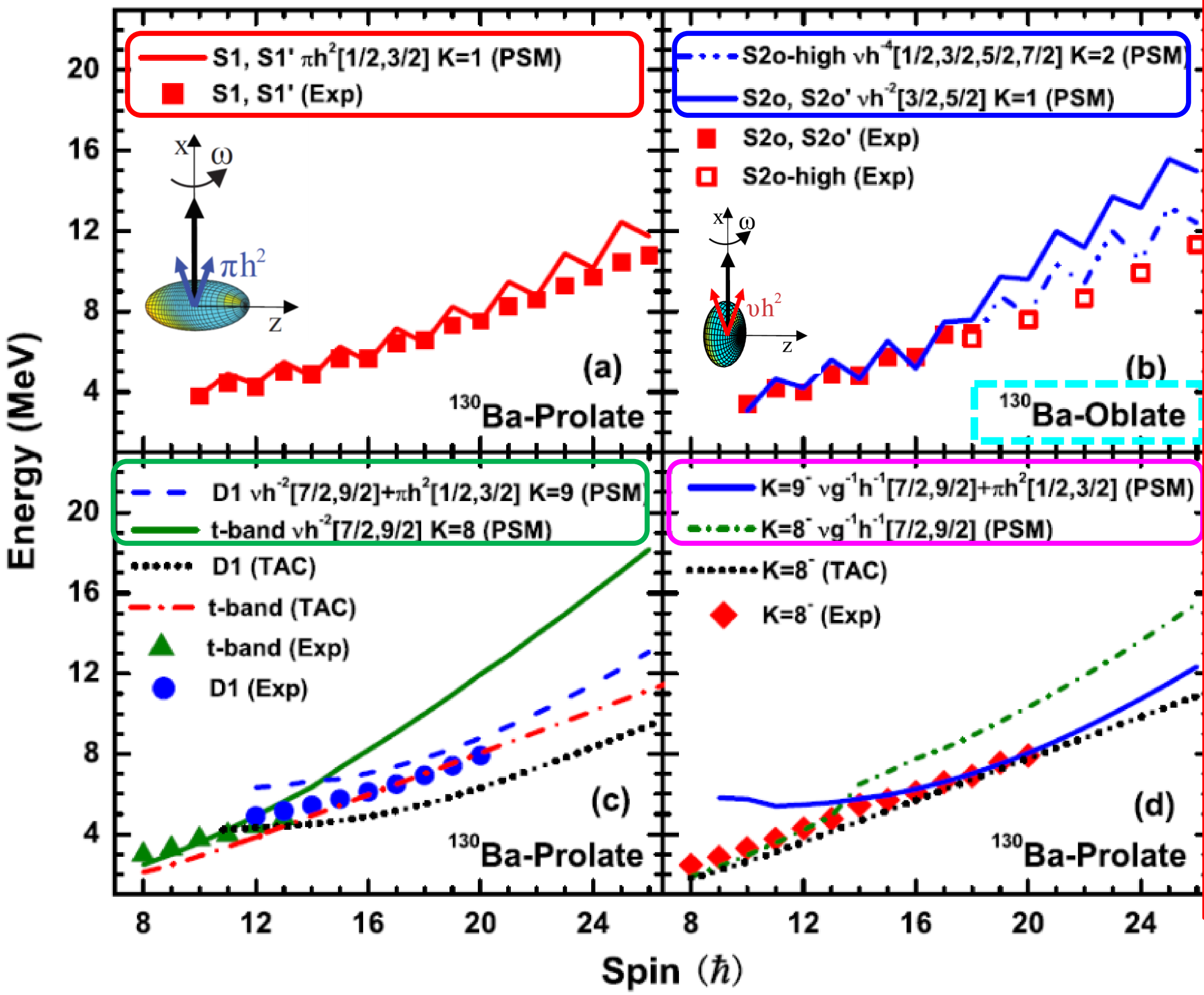
- The theoretical results are in good agreement with the available experimental data for all rotational bands.

Prolate shape:
$\varepsilon_2 = 0.22$,
oblate shape:
$\varepsilon_2 = -0.18$

Comparison of the calculated PSM energies with available data for ^{130}Ba. For the *t*-band, *D*1and $K^{\pi}=8^{-}$ bands, also the calculated TAC energies are included in panes (c) and (d).

Results & Discussion-A~130 region

Energy

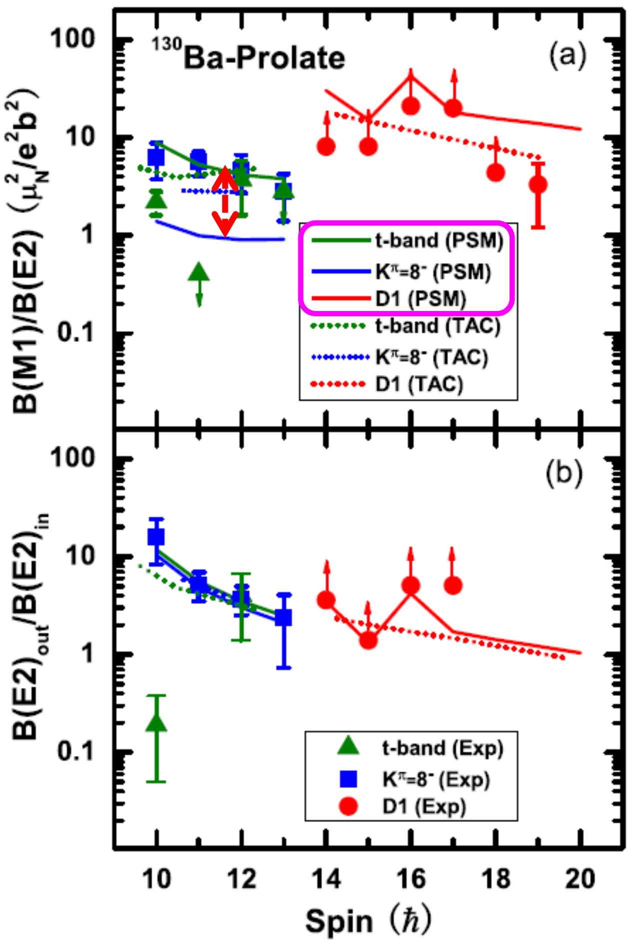


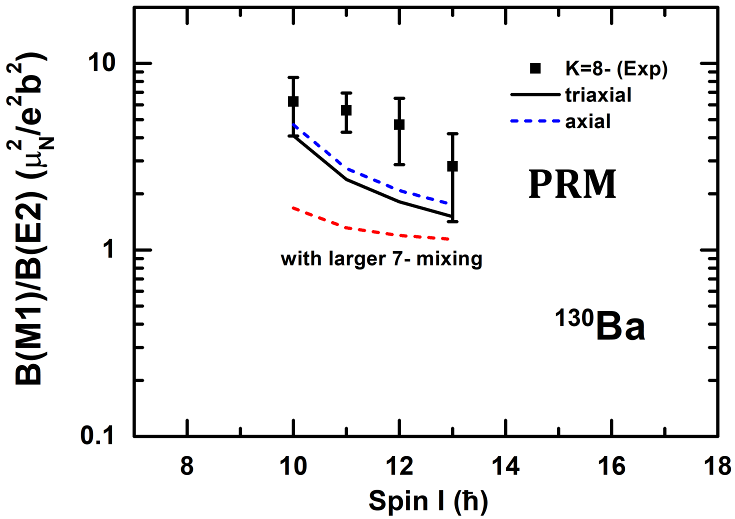
Comparison of the calculated PSM energies with available data for ^{130}Ba. For the *t*-band, *D*1and $K^{\pi}=8^{-}$ bands, also the calculated TAC energies are included in panes (c) and (d).

- The 2-quasiparticle neutron configuration $K = 8^{+}$ component is assigned to the t-band.
- The 4-quasiparticle configuration K = 9 component is assigned to band D1.
- The difference between calculated and experimental energies for D1 band can be reduced by taking into account the triaxial deformation.

Results & Discussion-A~130 region

□ B(E2)out/B(E2)in and B(M1)/B(E2)





- The calculated $B(E2)_{out}/B(E2)_{in}$ values are in good agreement with the experimental data for all bands.
- The discrepancy is caused by too small calculated B(M1)values. The analysis of the PSM wave functions shows that the $K^{\pi}=8^{-}$band is strongly mixed with the neutron 2-qp band $\nu h_{11/2}[7/2] \otimes \nu g_{7/2}[7/2]$, $K^{\pi}=7^{-}$band.

Results & Discussion-A~160 region

□ Deformed shell gap in light rare-earth nuclei

- Z. Patel et al. Phys. Rev. Lett. 113(2014) 262502, the predicted deformed shell closure is at N=100.
- R. Yokoyama et al. Phys. Rev. C 95(2017) 034313, new isomers can be explained without the predicted N=100 shell gap.
- J. Wu et al. Phys. Rev. Lett. 118(2017) 072701, the authors could not find a convincing signature in the half-life trend to confirm the evidence for a deformed subshell gap at N=100.
- D. J. Hartley et al. Phys. Rev. Lett. 120(2018) 182502, the existence of the N= 98 deformed subshell gap.

□ Question

The existence of neutron shell gap at N=98 or N=100 is currently a question under debate, which needs to be investigated further by theoretical and experimental studies.

Y. X. Liu et al. Changes of deformed shell gaps at N~100 in light rare-earth, neutron-rich nuclei, J.Phys. G 47 (2020) 055108.

✓ propose a modification for the "standard" Nilsson parameters,

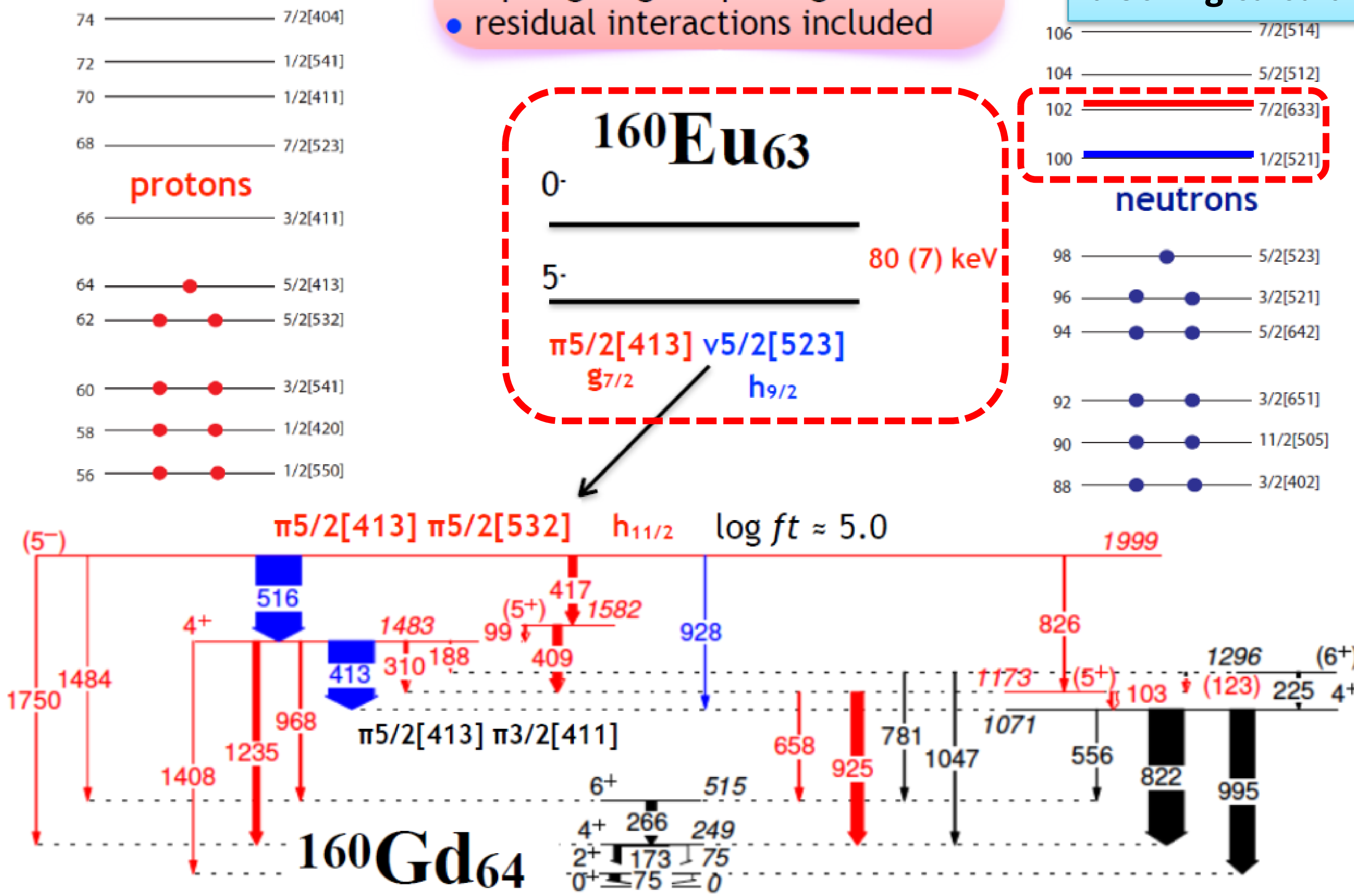
✓ ground state configuration in odd-neutron nuclei, upbending of the yrast moment of inertia at higher spins and the energies of 2-quasineutron 6^- and 4^- isomers in even-even nuclei

Results & Discussion-A~160 region

D. J. Hartley et al. Phys. Rev. Lett. 120(2018) 182502 (Isomer states of ^{160,162}Eu)

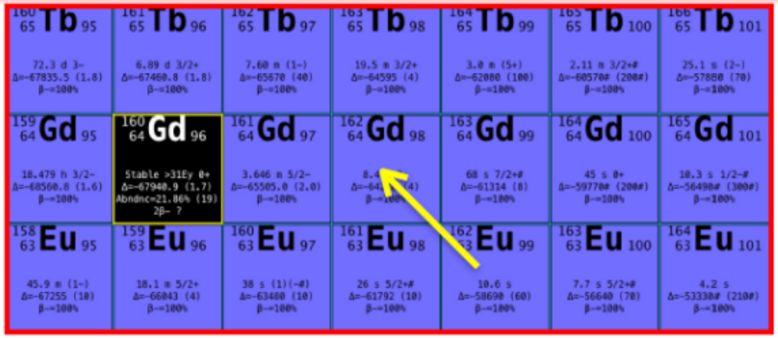
- deformed Woods-Saxon potential
- Lipking-Nogami pairing model
- residual interactions included

Multi-qp pairing-blocking calculations



Results & Discussion-A~160 region

Studies of $^{162}Eu_{63}$ (N=99)



PRL 118, 072701 (2017) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2017

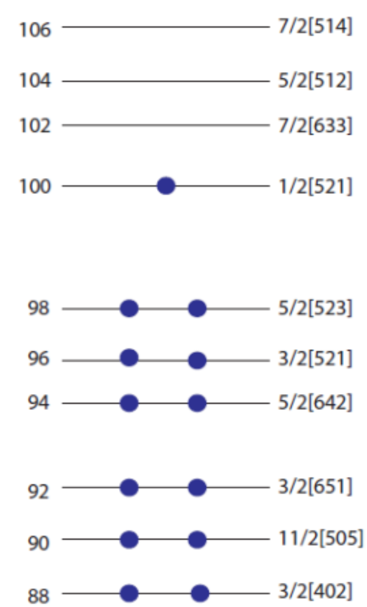
94 β-Decay Half-Lives of Neutron-Rich $_{55}$Cs to $_{67}$Ho: Experimental Feedback and Evaluation of the r-Process Rare-Earth Peak Formation

J. Wu,[1,2,*] S. Nishimura,[2] G. Lorusso,[2,3,4] P. Möller,[5] E. Ideguchi,[6] P.-H. Regan,[3,4] G. S. Simpson,[7,8,9] P.-A. Söderström,[2] P. M. Walker,[4] H. Watanabe,[10,2] Z. Y. Xu,[11,12] H. Baba,[2] F. Browne,[13,2] R. Daido,[14] P. Doornenbal,[2] Y. F. Fang,[14] G. Gey,[7,15,2] T. Isobe,[2] P. S. Lee,[16] J. J. Liu,[11] Z. Li,[1] Z. Korkulu,[17] Z. Patel,[4,2] V. Phong,[18,2] S. Rice,[4,2] H. Sakurai,[2,12] L. Sinclair,[19,2] T. Sumikama,[2] M. Tanaka,[6] A. Yagi,[14] Y. L. Ye,[1] R. Yokoyama,[20] G. X. Zhang,[10] T. Alharbi,[21] N. Aoi,[6] F. L. Bello Garrote,[22] G. Benzoni,[23] A. M. Bruce,[13] R. J. Carroll,[4] K. Y. Chae,[24] Z. Dombradi,[17] A. Estrade,[25] A. Gottardo,[26,27] C. J. Griffin,[25] H. Kanaoka,[14] I. Kojouharov,[28] F. G. Kondev,[29] S. Kubono,[2] N. Kurz,[28] I. Kuti,[17] S. Lalkovski,[4] G. J. Lane,[30] E. J. Lee,[24] T. Lokotko,[11] G. Lotay,[4] C.-B. Moon,[31] H. Nishibata,[14] I. Nishizuka,[32] C. R. Nita,[13,33] A. Odahara,[14] Zs. Podolyák,[4] O. J. Roberts,[34] H. Schaffner,[28] C. Shand,[4] J. Taprogge,[35,36] S. Terashima,[10] Z. Vajta,[17] and S. Yoshida[14]

^{152}Ba	0.139(8)	^{156}Pr	0.444(6)	^{161}Eu	30.1(90)	^{172}Dy	$3.94(^{+28}_{-37})$
^{153}Ba	0.116(52)	^{157}Pr	$0.295(^{+20}_{-11})$	^{162}Eu	11.8(14)	^{172m}Dy	0.674(66)

10.6 (1) s from Gd X-rays
Greenwood et al. PRC 35 (1987) 1065

What to expect:
π5/2[413] ν1/2[521] configuration
$K^{\pi}=3^{-}$ ground state - no isomers

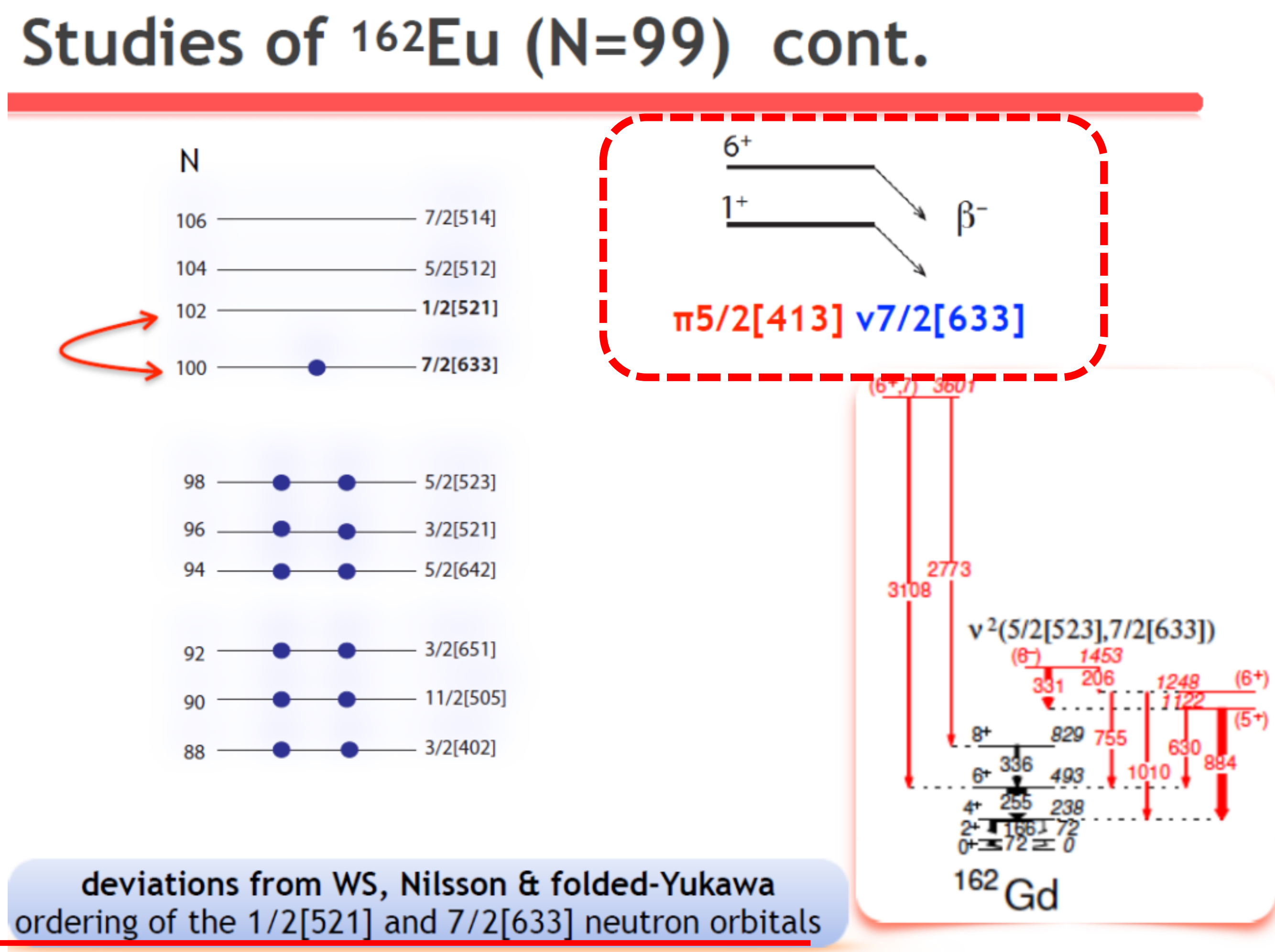


WS, Nilsson & folded-Yukawa

However, such interpretations cannot account for the existence of 3^{-} and 2^{-} long-lived states in ^{162}Eu.

Results & Discussion-A~160 region

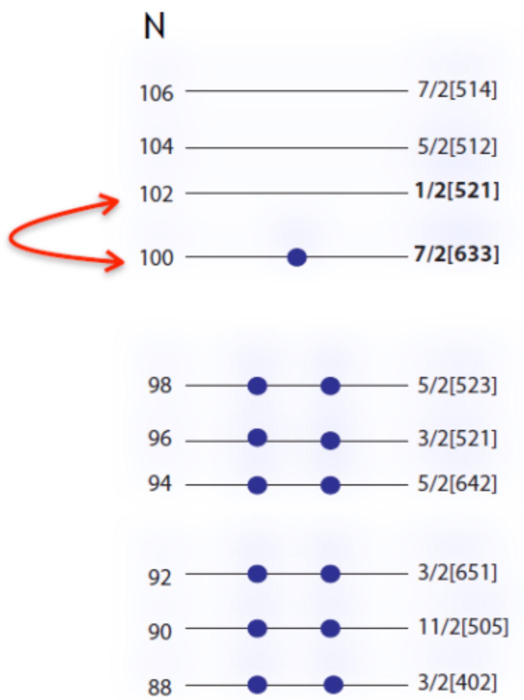
The long-lived levels in ^{162}Eu can be assigned the π5/2[413] ⊗ ν7/2[633] configuration with $K^{\pi}=1^{+}$ assigned to the ground state and $K^{\pi}= 6^{+}$ to the isomer. This interpretation is consistent with the observed decay pattern in ^{162}Eu and can explain the observed isomerism in this nucleus.

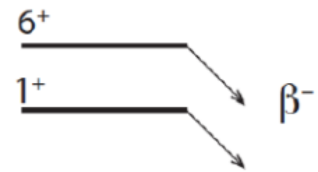


F. G. Kondev et al., Nucl. Phys. A617 (1997), 91.

Results & Discussion-A~160 region

Studies of ^{162}Eu (N=99) cont.





π5/2[413] ν7/2[633]

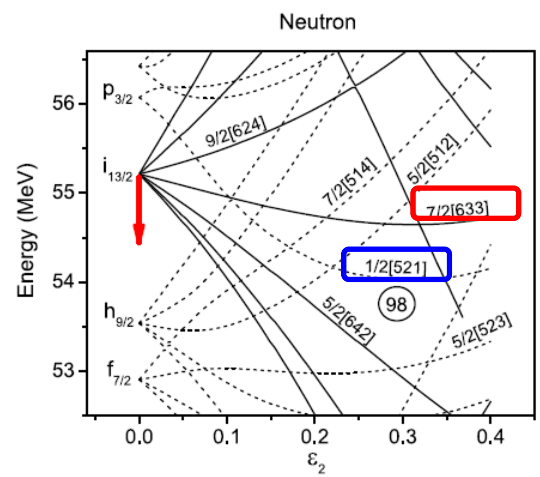


Figure 3. Nilsson diagram generated with the 'standard' set of parameters (κ, μ) of Bengtsson and Ragnarsson [26]. The values for the neutron $n = 6$ shell are $\kappa = 0.062$, $\mu = 0.34$.

deviations from WS, Nilsson & folded-Yukawa
ordering of the 1/2[521] and 7/2[633] neutron orbitals

^{162}Gd

How can we interchange the ordering of 1/2[521] and 7/2[633] neutron orbitals? A simple modification can be achieved to move the neutron $i_{13/2}$ intruder state down properly while keeping the other nearby orbitals unchanged.

Results & Discussion-A~160 region

□ Reproduce correct order of single particle orbit

$(\kappa, \mu)_{New} = (1 - 0.015|N - 102|)(\kappa, \mu)_{N=102}$

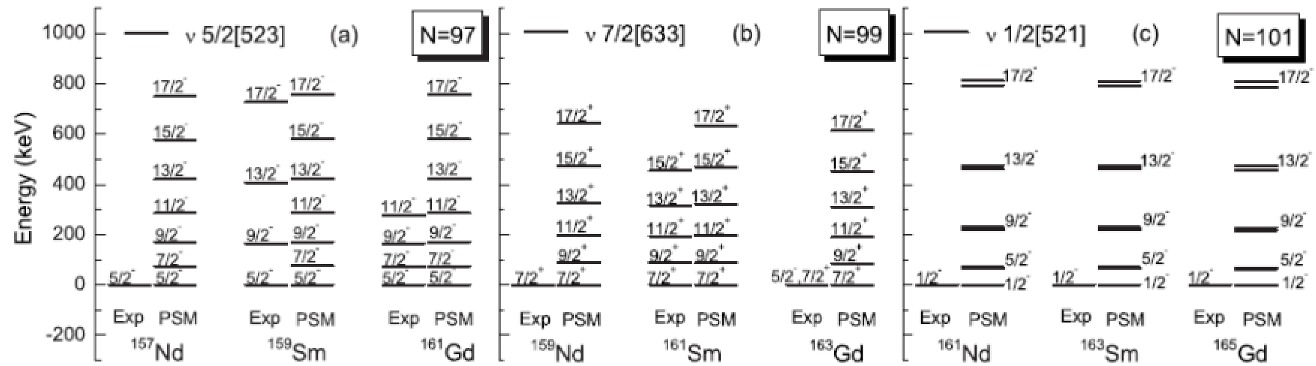


FIG. 1: Calculated ground state bands of odd-neutron nuclei with neutron number N = 97, 99 and 101 at Z = 60 (Nd), 62 (Sm) and 64 (Gd) with new set of Nilsson parameters. Data are taken from Refs. [2, 15, 26–29]

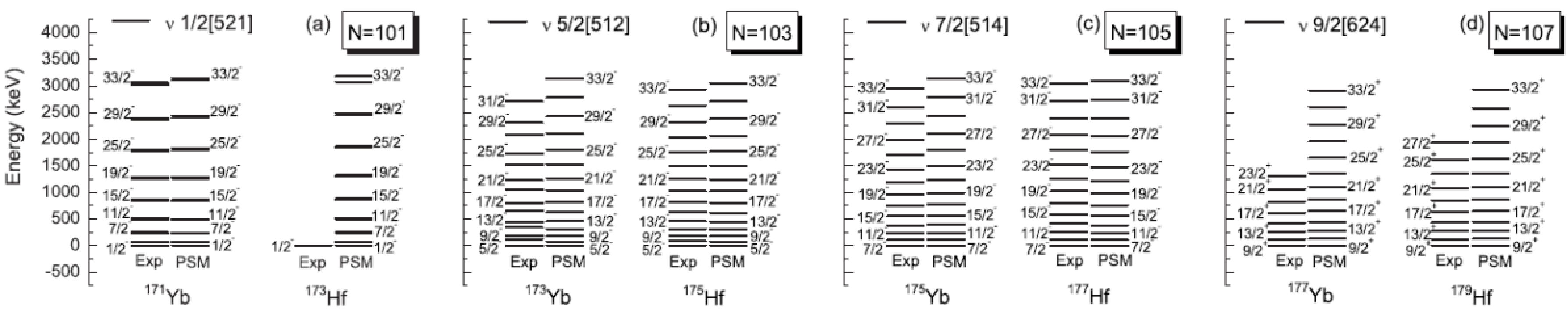


FIG. 2: Calculated ground state bands of odd-neutron nuclei with neutron number N = 101, 103, 105, and 107 at Z = 70 (Yb) and 72 (Hf) with new set of Nilsson parameters. Data are taken from Refs. [30–35]

Results & Discussion-A~160 region

□ Reproduce correct order of single particle orbit

$(\kappa, \mu)_{New} = (1 - 0.015|N - 102|)(\kappa, \mu)_{N=102}$

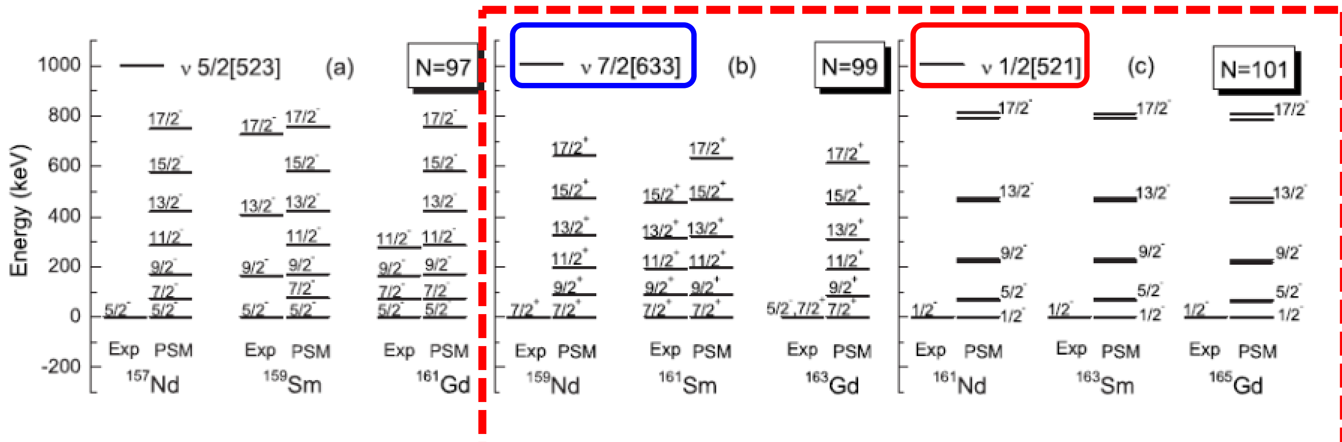


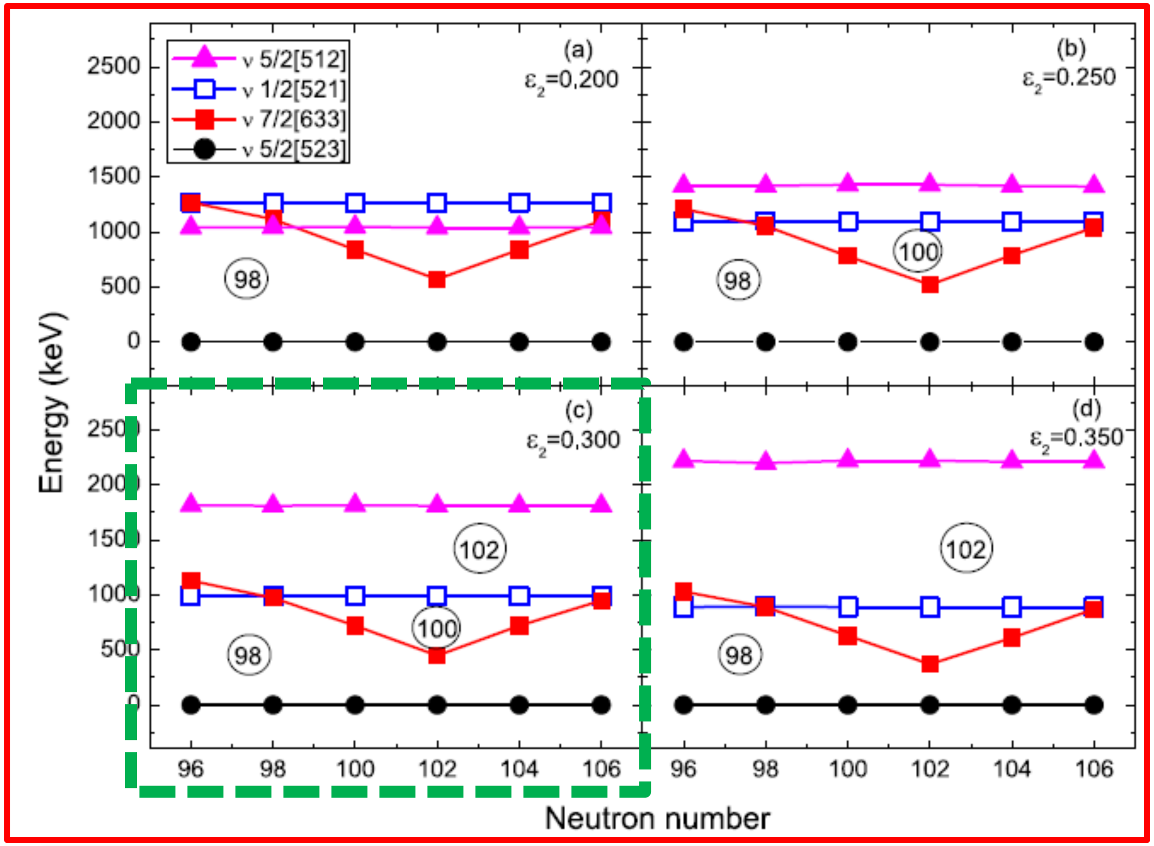
FIG. 1: Calculated ground state bands of odd-neutron nuclei with neutron number N = 97, 99 and 101 at Z = 60 (Nd), 62 (Sm) and 64 (Gd) with new set of Nilsson parameters. Data are taken from Refs. [2, 15, 26–29]

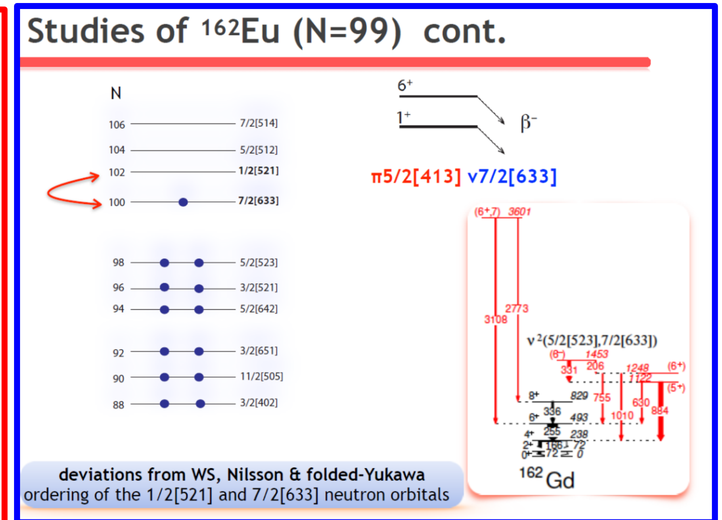
- **Especially, for neutron number N=99 and 101, the order of $1/2^-$[521] and$7/2^+$[633] is interchanged and consistence with the experimental observation.**
- **These represent a clear example that due to changes in neutron/proton ratio, the traditional Nilsson model for the stable mass region cannot be directly applied for the neutron-rich region.**

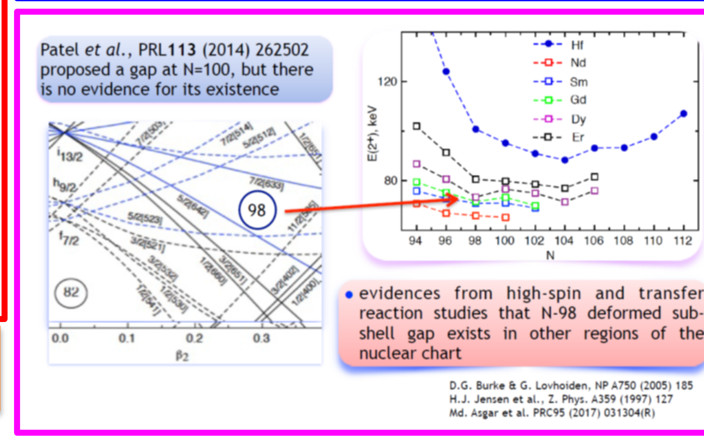
FIG. 2: Calculated ground state bands of odd-neutron nuclei with neutron number N = 101, 103, 105, and 107 at Z = 70 (Yb) and 72 (Hf) with new set of Nilsson parameters. Data are taken from Refs. [30–35]

Results & Discussion-A~160 region

□ Deformed shell gap at N~100







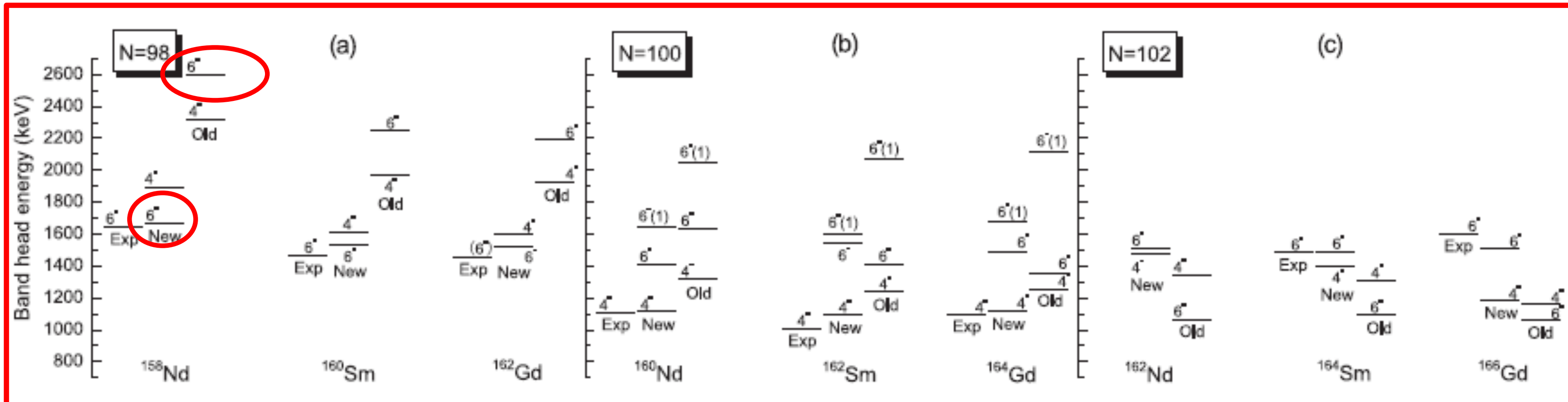
$$(\kappa, \mu)_{New} = (1 - 0.015|N - 102|)(\kappa, \mu)_{N=102}$$

- The **correct placement of the 1/2⁻ [521]** neutron orbital opens a subshell closure at **N=98** with neutron number N=96 – 100. The location and size of the shell gaps change with **neutron number and deformation**.

Results & Discussion-A~160 region

□ Isomer states for N~100 nuclei

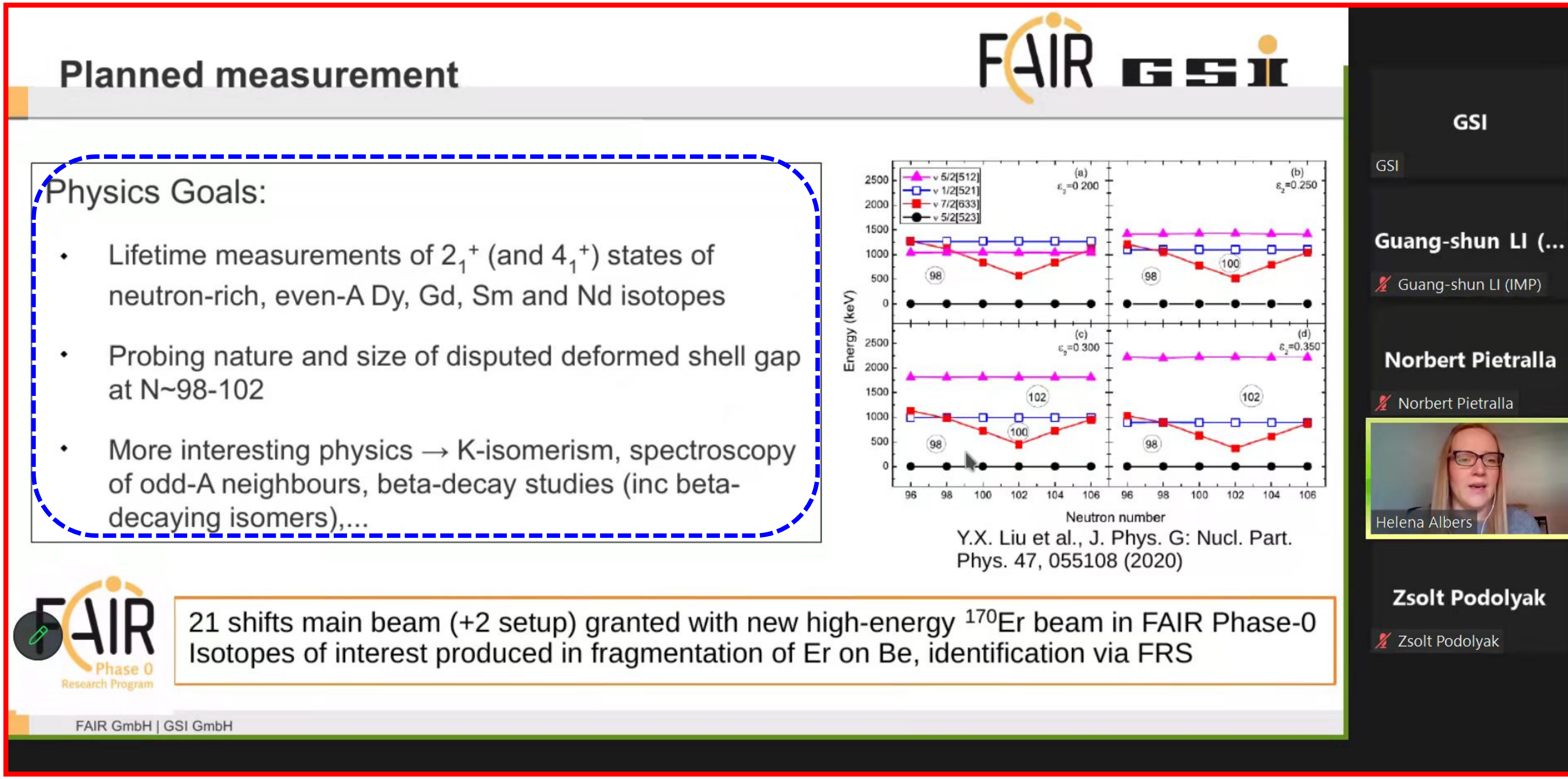
- This disagreement with data can be understood as mainly due to the wrong calculation for the N=98 shell gap and its relative size to the N=100 shell gap.
- We emphasize that the 2-qp isomer energy can be sensitively related to deformed shell gaps in the neutron-rich regions as well as precise locations of the quasiparticles that build the isomeric states. Systematical experimental data for such isomers are much desired.



The calculated bandhead energies of isomer states for Nd, Sm, and Gd isotopes with new and standard (labeled by 'Old') Nilsson parameter and comparison with the available data for (a) at N=98, (b) N=100 and (c) N=102. The configuration of $K^{\pi}=4^{-}$ is $\nu1/2[521]+\nu7/2[633]$. The configuration of $K^{\pi}=6^{-}$ is $\nu5/2[523]+\nu7/2[633]$ for (a) and (b), $\nu5/2[512]+\nu7/2[633]$ for (c). The configuration of $K^{\pi}=6^{-}(1)$ in (b) is $\nu5/2[512]+\nu7/2[633]$.

Results & Discussion-A~160 region

□ Isomer states for N~100 nuclei



Summary & Outlook

✓ Confirmation of the S-bands built on prolate 2qp-proton and oblate 2qp-neutron configurations.
✓ Good description of t-band and D-band.

A~130

✓Deformed shell gap is dependent on the order of single particle orbit, deformation and neutron number.
✓The new formulation need to be checked in other nuclear region.

New order of 1/2−[521] and7/2+[633] single particle orbit was confirmed.

C. J. Zachary et al., Phys.RevC. C 101, 054312 (2020)
E. H. Wang et al., Phys.RevC. 103, 014317 (2021)
R. Yokoyama et al., Phys.RevC. 104, L021303 (2021)
M. J. Burns et al., Phys.RevC. 106, 054308 (2022)

A~160

Thank you for your attention!

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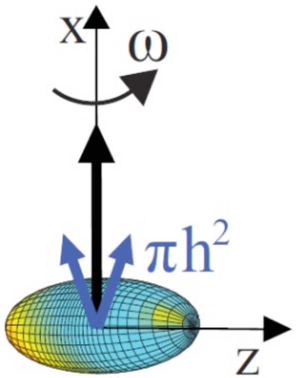
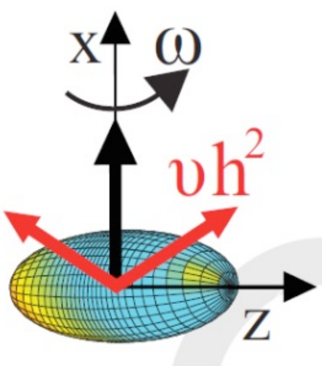
Results & Discussion-A~130 region



low-Ω protons at the prolate

rotation-aligned (RAL) bands

S-bands

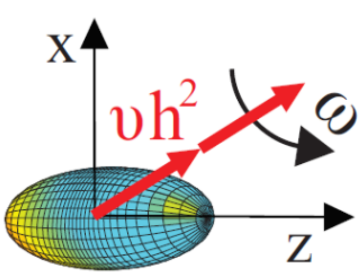


high-Ω neutrons

Deformation aligned (DAL)

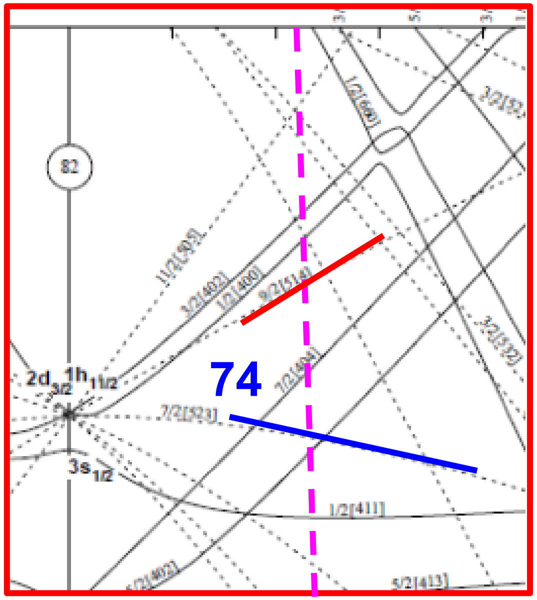
K-bands

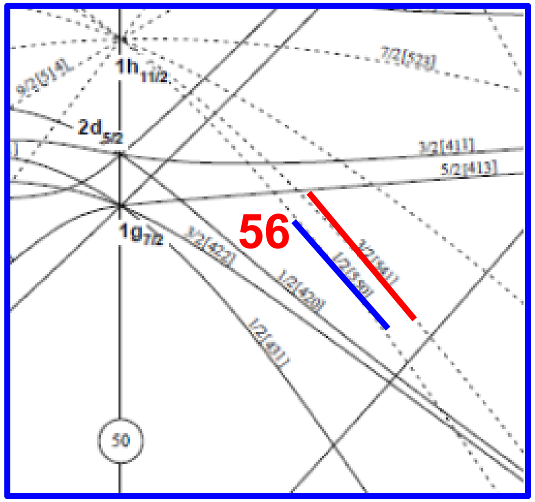
Between the DAL and RAL regimes



Fermi-aligned (FAL)

t-bands





First t-band in A~130 region

C.M. Petrache et al. PLB 795 (2019) 241