Experimental Evidence of Type II Shell Evolution

and shape coexistence in the $g_{9/2}$ shell

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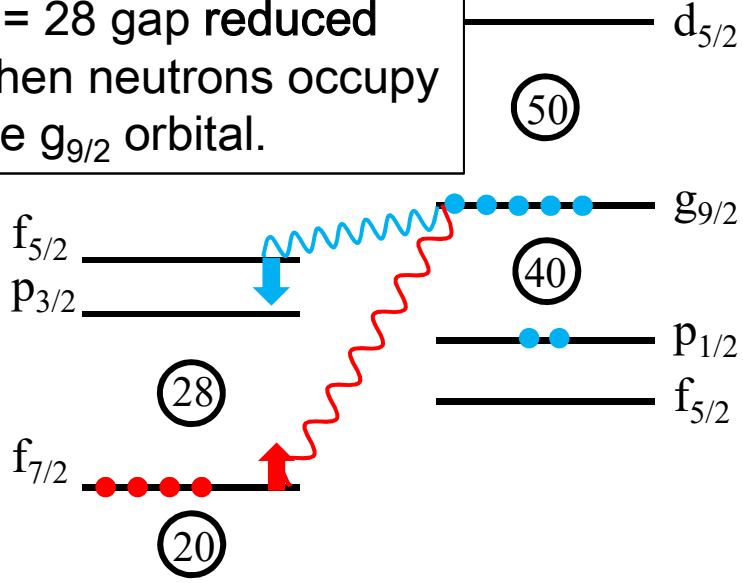
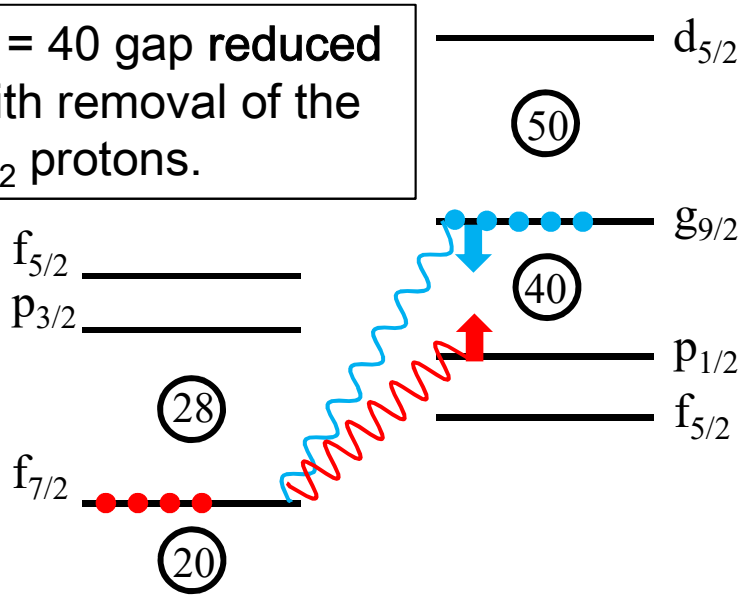
MOTIVATION: Type-II Shell evolution and the tensor force

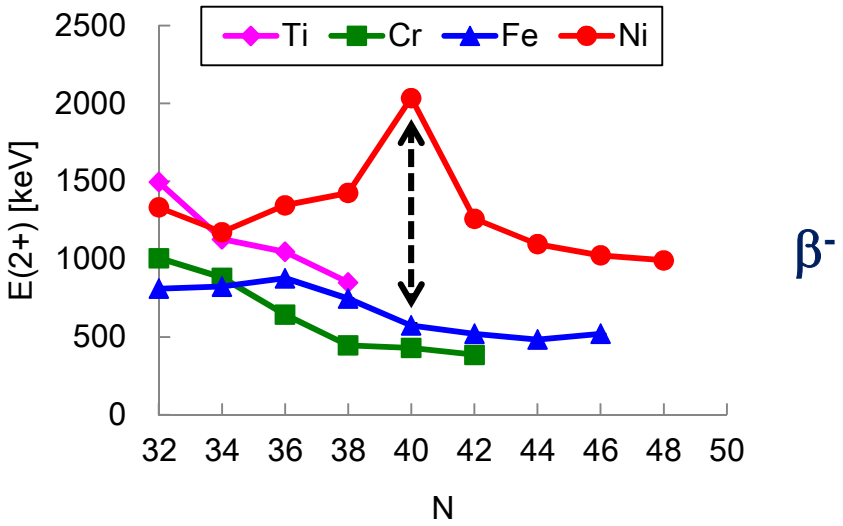
Z = 28 gap reduced when neutrons occupy the $g_{9/2}$ orbital.



N = 40 gap reduced with removal of the $f_{7/2}$ protons.

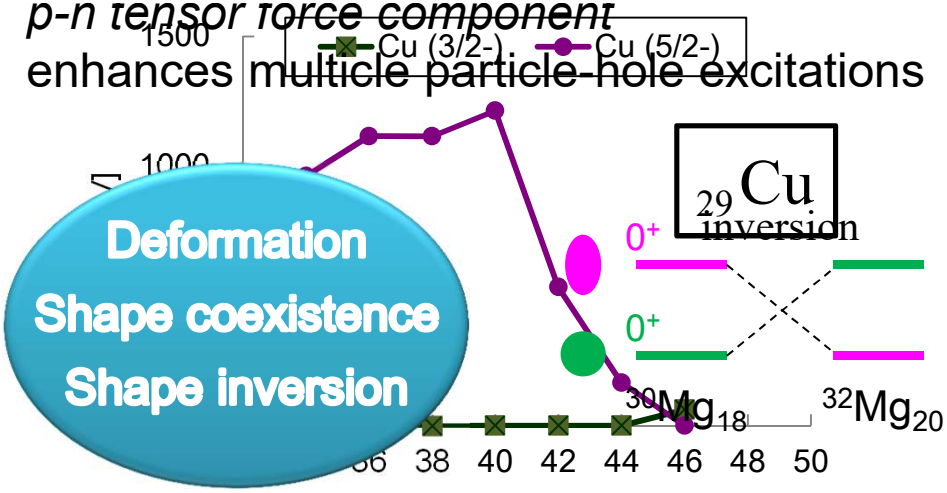


New island of inversion



β-

p-n tensor force component enhances multicle particle-hole excitations

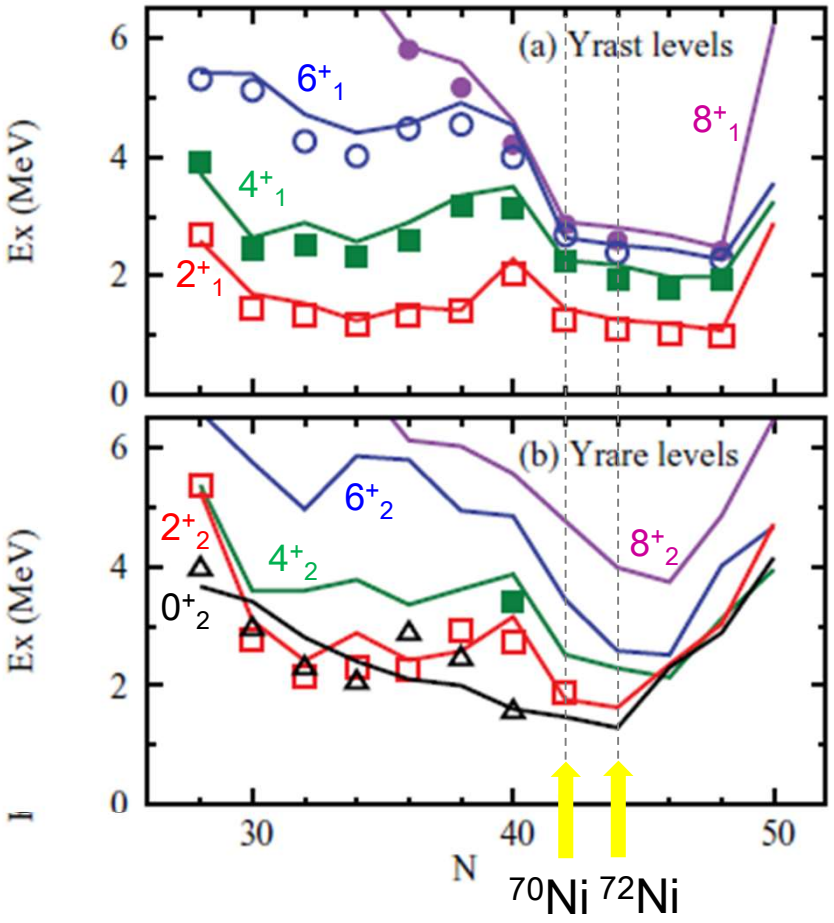


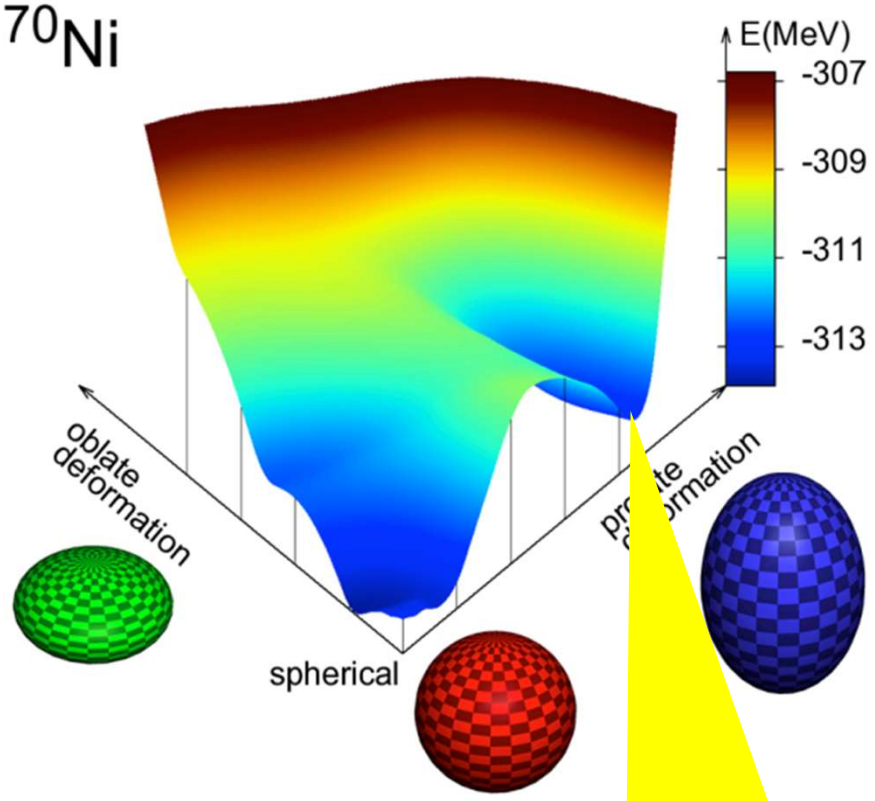
MOTIVATION: Development of shape coexistence in Ni

Monte Carlo shell-model (MCSM)
- Full pf-g9/2-d5/2 model space
- A3DA Hamiltonian

Tensor-force component of proton-neutron interactions plays crucial roles in the shape coexistence

[Y. Tsunoda et al., PRC 89, 031301(R) (2014)]



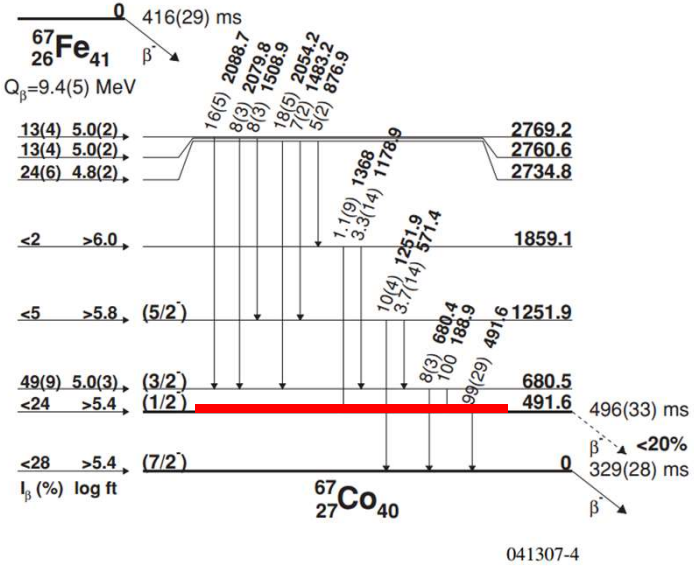


Deeper local minimum at prolate deformation

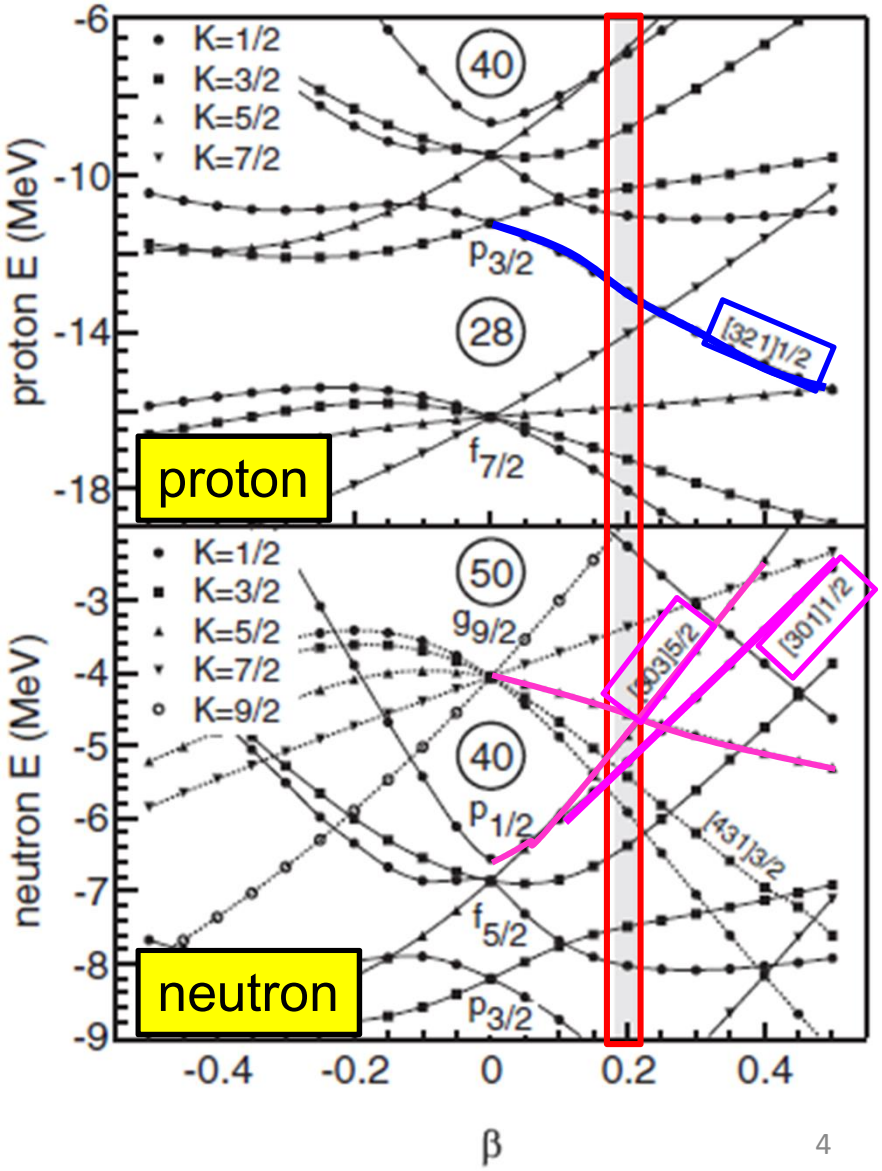
MOTIVATION: Nature of the low-spin β–decaying isomer in Co

- Coupling of the $f_{7/2}$ proton-hole to the $1/2^-$ β-decaying isomer in Ni → (3^+)
  [W.F. Mueller et al., PRC (2000)]

- Coupling of deformed shells:
  (1^+), (2^+), (2^-)
  [Liddick et al., PRC (2012)]
  [F. Flavigny et al., PRC (2015)]

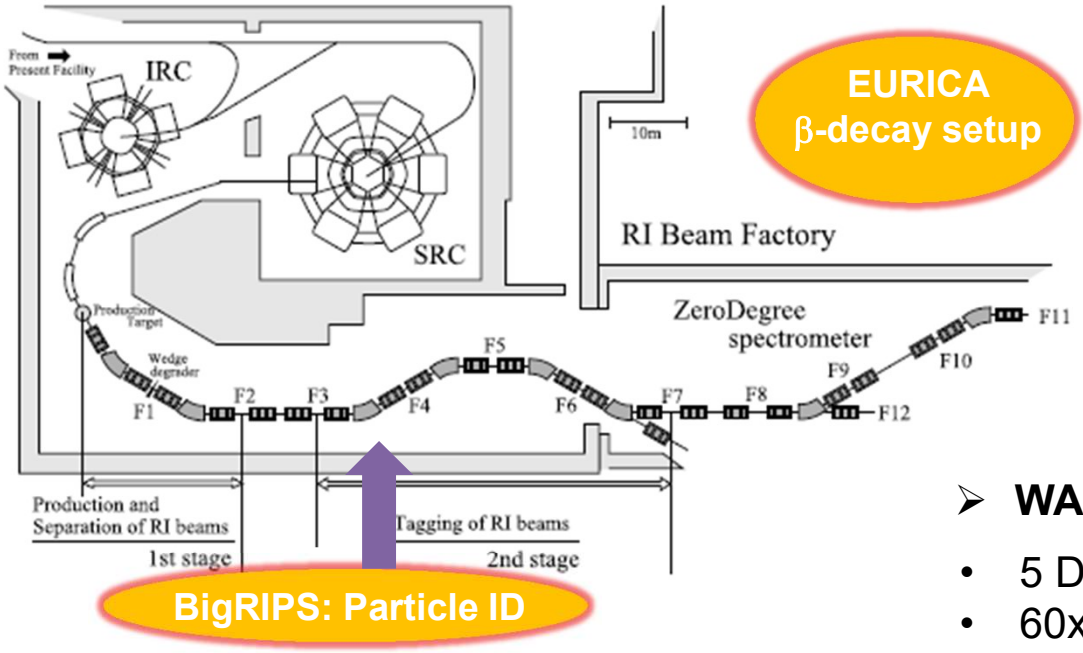


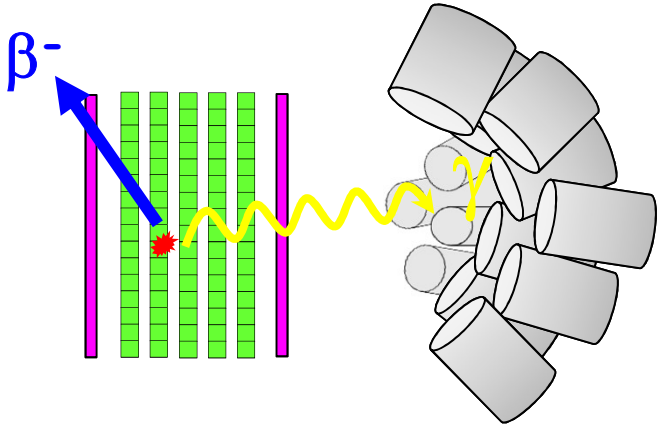
[D. Pauwels et al., PRC (2008)]



EXPERIMENTAL SETUP: BiGRIPS and EURICA

Radioactive Isotope Beam Factory (RIBF) @ RIKEN



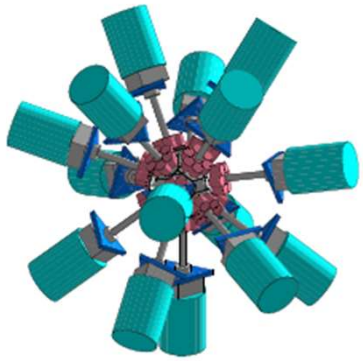


➢ **WAS3ABI**

- 5 DSSSDs
- 60x40 strips
- 1 mm^2 pitch
- 1 mm thick

➢ **EURICA**

- 12 HPGe clusters
- 84 crystals
- 11% eff @ 662 keV

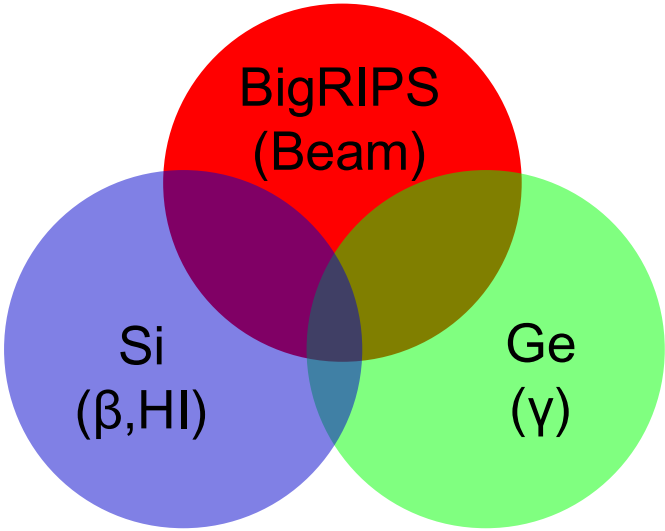


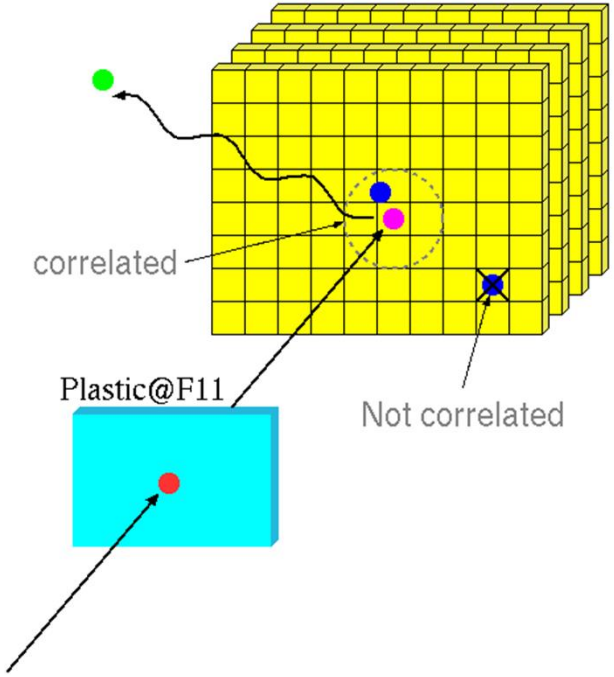
(b) View from 120 degrees

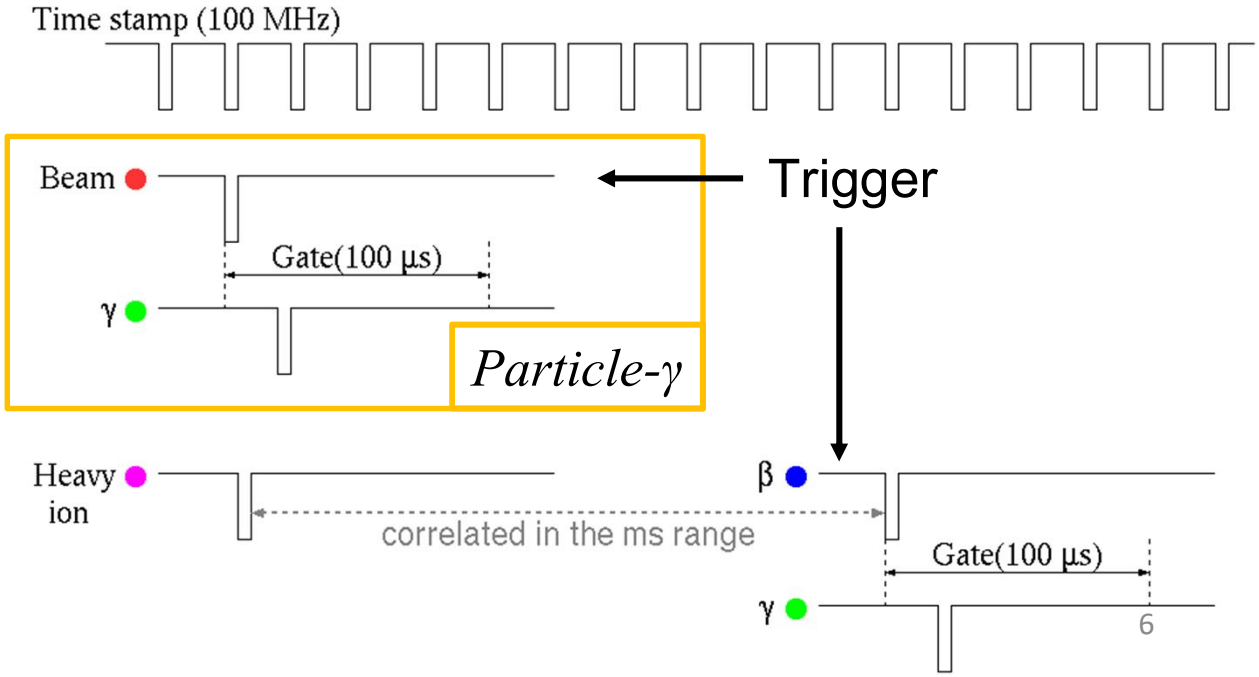
Ion-γ correlations (~ms)
β-γ correlations (~ns-μs)
Ion-β-γ-γ correlations (~100ns)

DAQ for decay spectroscopy experiments

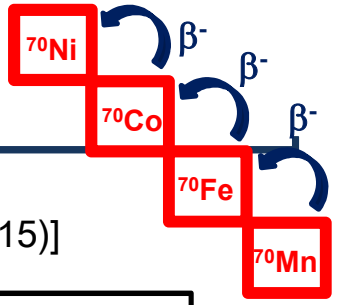
- Independent DAQ systems
- Synchronized using time stamp
- Event build based on time stamp

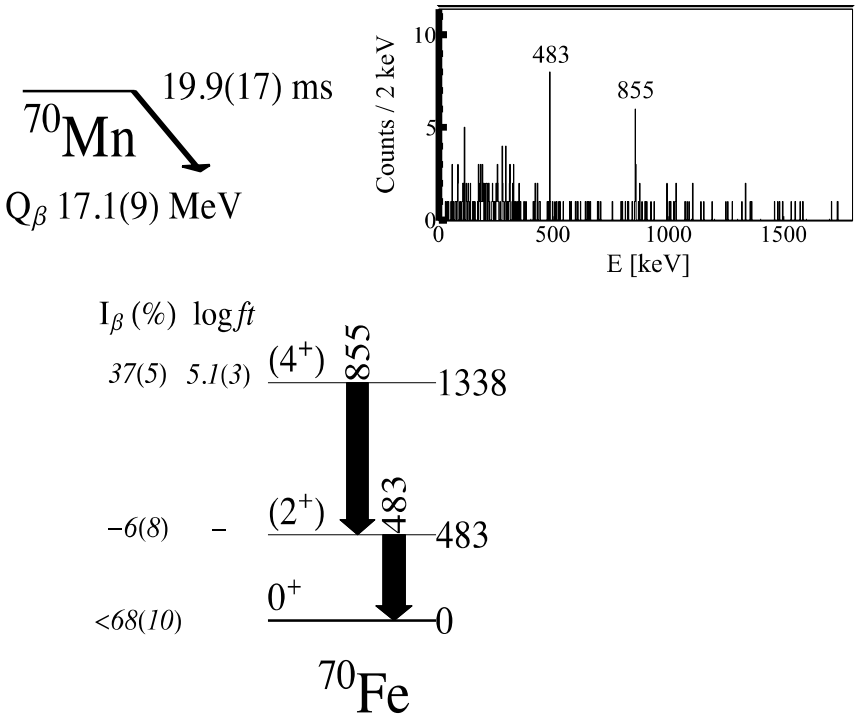






β decay of neutron-rich A=70 isobars

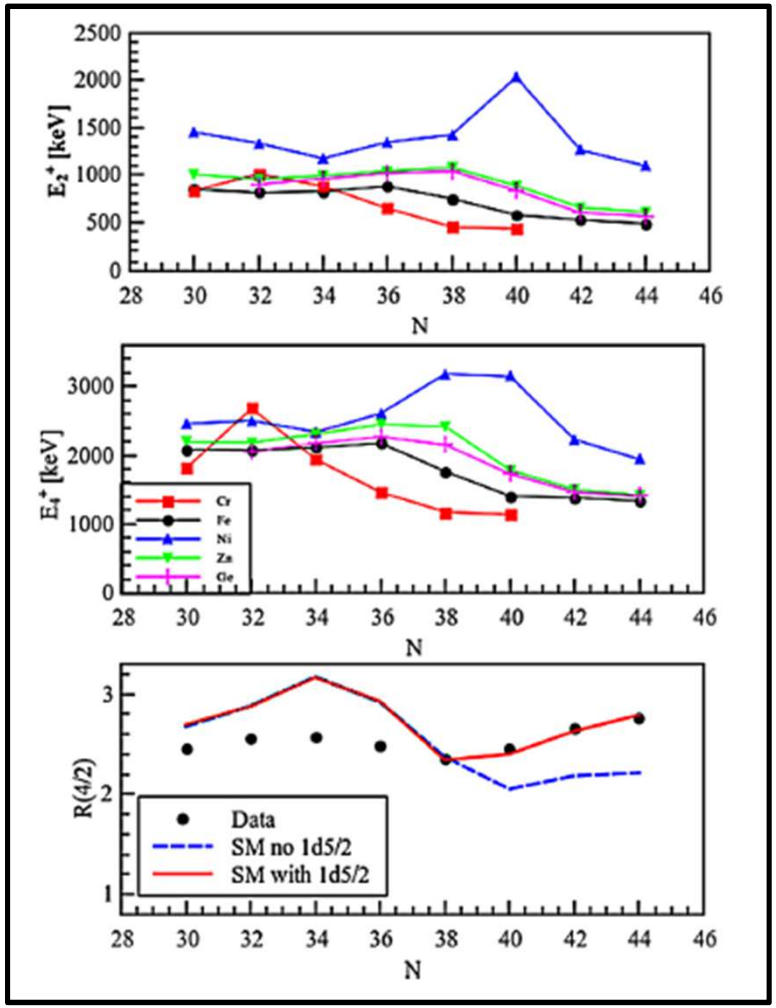




Deformation confirmed in Fe isotopic chain up to N=44 and good comparison with shell-model calculations by group in Naples

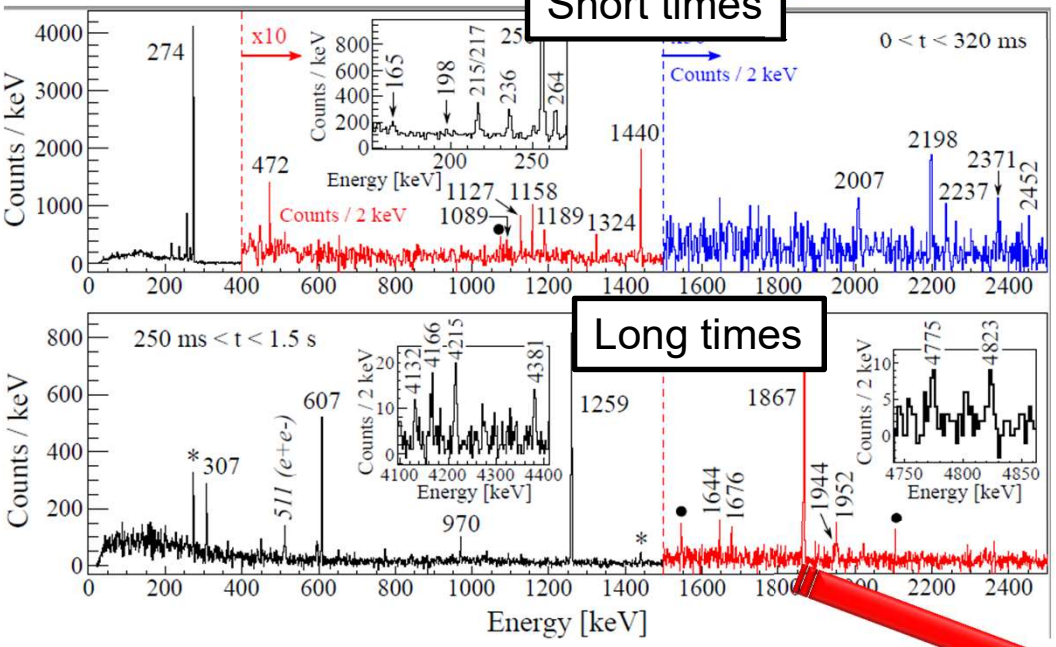
[L. Coraggio et al., PRC 89, 024319 (2014)]

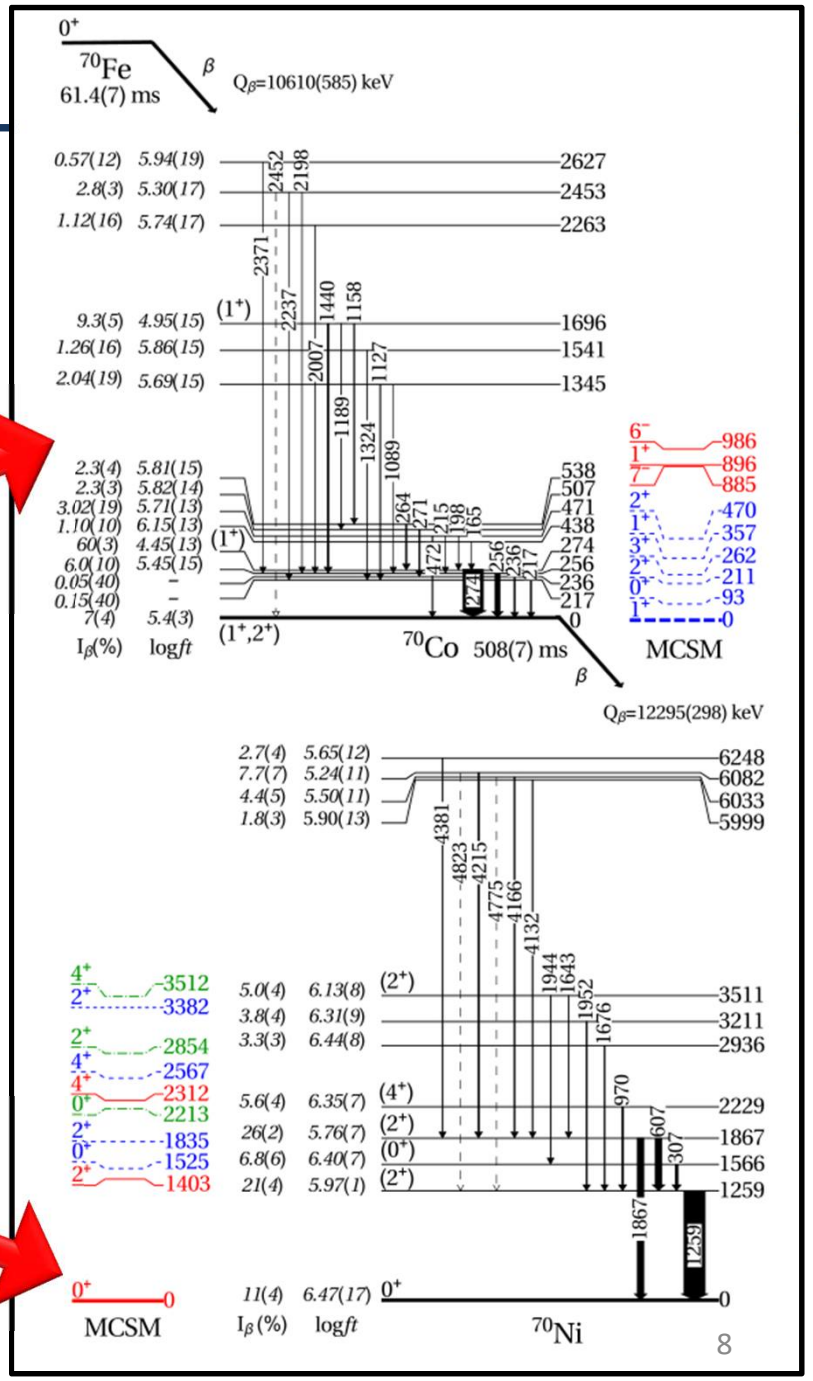
[G. Benzoni et al., PLB (2015)]



β decay ^{70}Fe→^{70}Co→^{70}Ni

- Two long-lived β-decaying states at high and low spins in ^{70}Co
- Low-spin β-decaying state in ^{70}Co isolated via the β decay of ^{70}Fe
- Selectively populate low-spin states in ^{70}Ni





β-decay $^{70}Fe \rightarrow ^{70}Co$

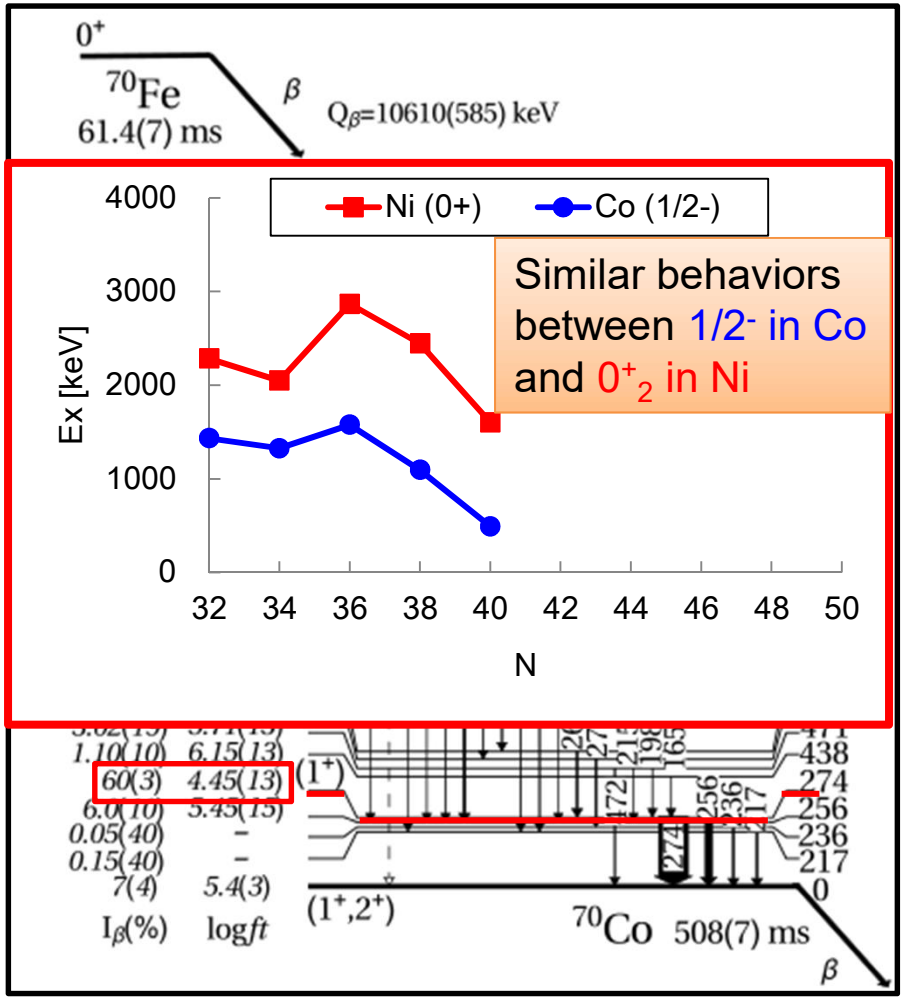
- Strong population of the states at
  - 274 keV: logft = 4.45(13)
  - 1696 keV: logft = 4.95(15)
- Gamow-Teller transition ⇒ $J^{\pi} = 1^{+}$

*If **spherical**,*

- Low-lying levels: $\pi f_{7/2}^{-1} \otimes \nu g_{9/2}$
  ⇒ Negative parity
- 1^{+} state: $\pi f_{7/2}^{-1} \otimes \nu f_{5/2}^{-1}$
  ⇒ E_x ~ 1 MeV

*If **deformed**,*

- Proton: $1/2^{-}[321]$
- Neutron: $1/2^{-}[301]$, $3/2^{+}[431]$
  - Odd-odd ⇒ **$K^{\pi} = 0^{+}, 1^{+}, 2^{+}$**

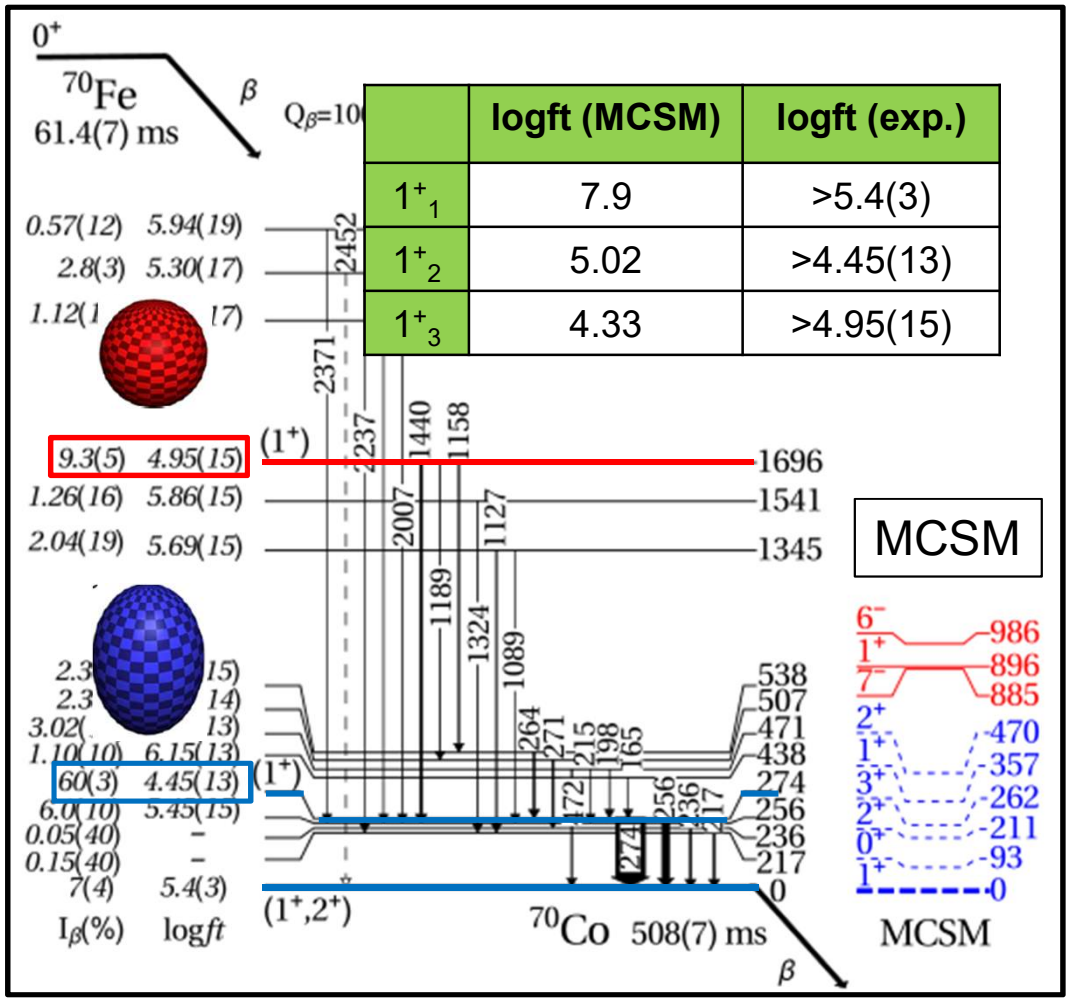


Low-lying 1+ state at 274keV

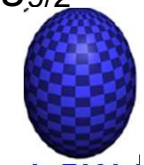
⇒ Evidence for a deformed configuration

β decay ^{70}Fe→^{70}Co

➢ **MCSM calculations:** A3DA Hamiltonian & pf + $g_{9/2}$ + d_5



	logft (MCSM)	logft (exp.)
1^+_1	7.9	>5.4(3)
1^+_2	5.02	>4.45(13)
1^+_3	4.33	>4.95(15)



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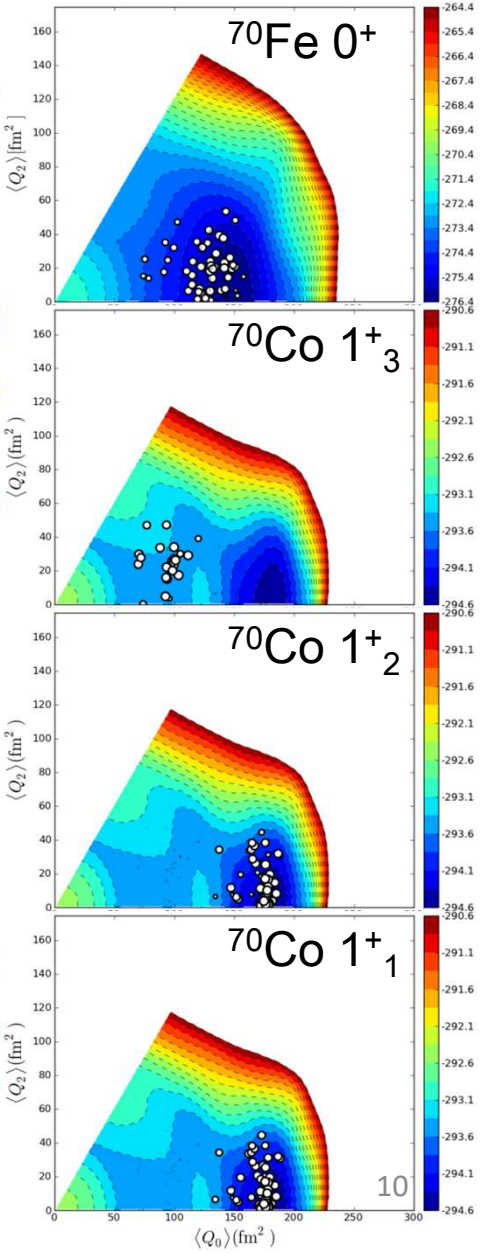
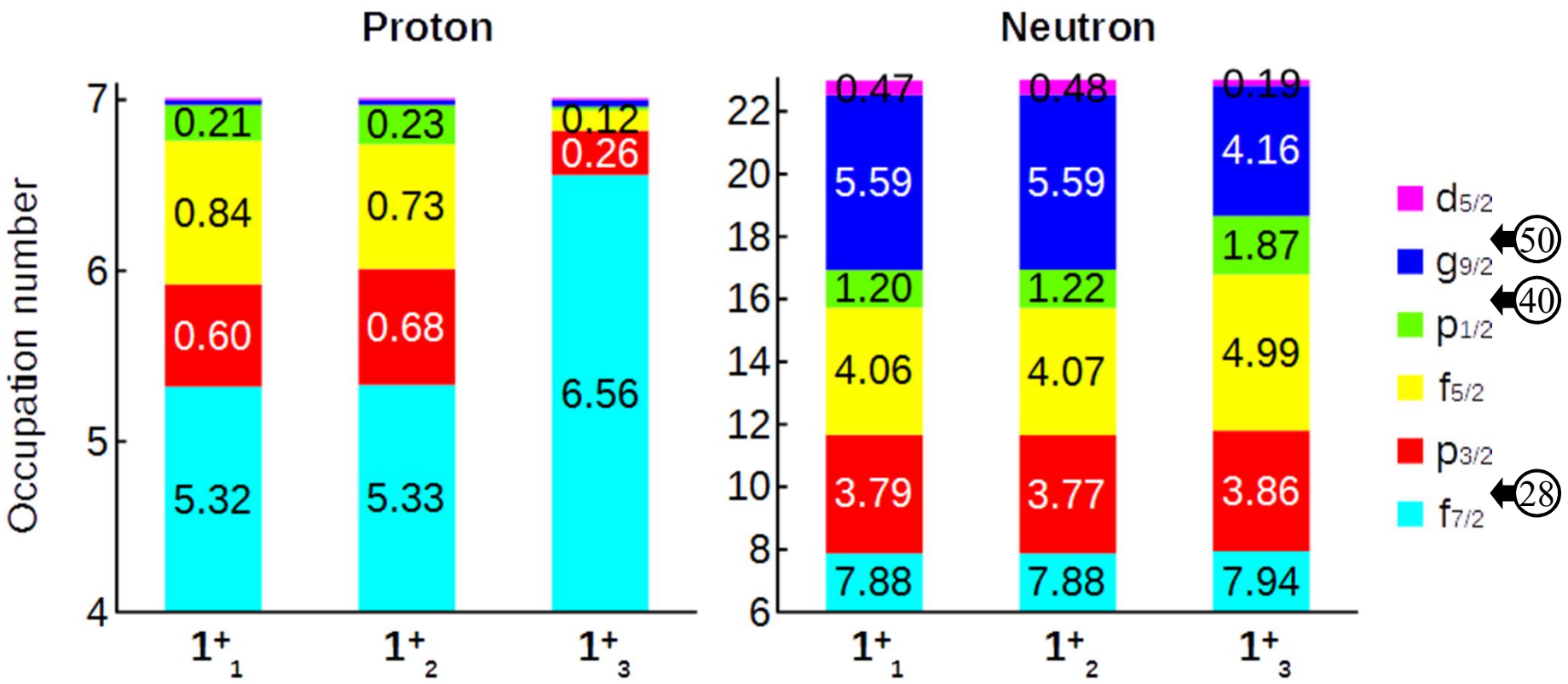


β decay ^{70}Fe→^{70}Co



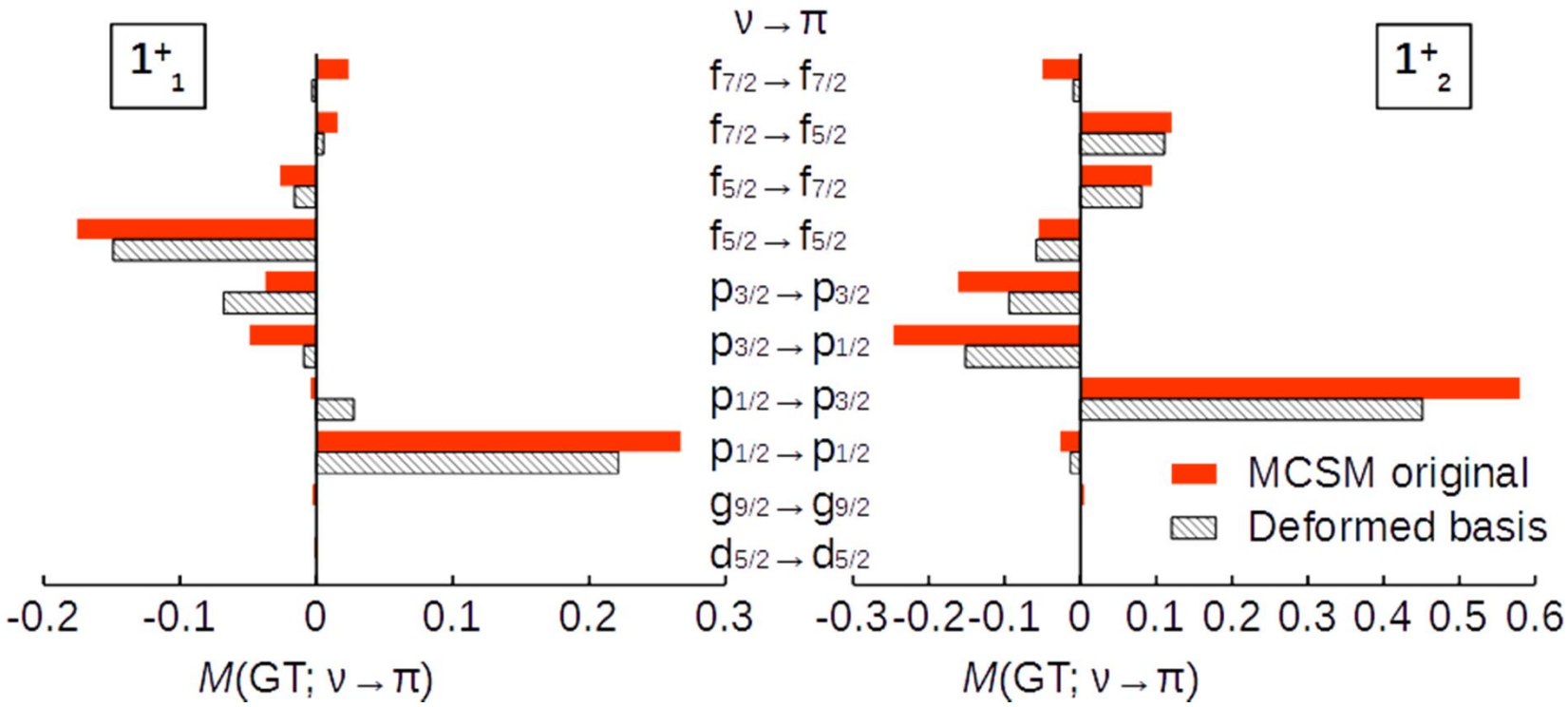
MCSM wave functions of the three 1^+ states in ^{70}Co

- $1^+_{1,2}$: almost identical, involving multiple p-h excitations across the Z = 28 and N = 40 gaps (**Type-II shell evolution**) ⇒ Largely prolate deformed shape
- 1^+_3: dominated by $\pi \mathbf{f_{7/2}}^{-1}\, \nu \mathbf{f_{5/2}}^{-1} g_{9/2}^{+4}$ ⇒ Near spherical shape

Gamow-Teller

β-decay $^{70}Fe \rightarrow ^{70}Co$

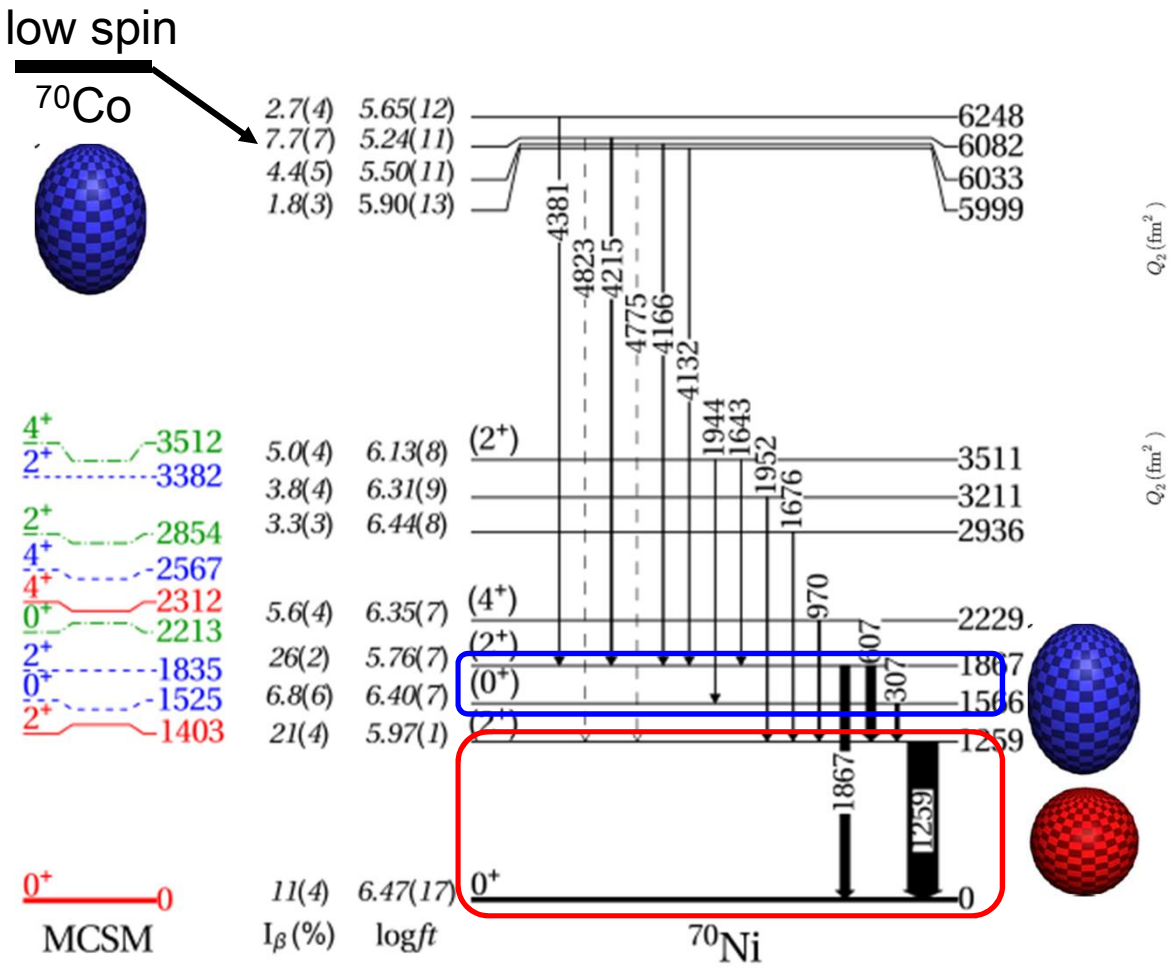
	logft (MCSM)	logft (exp.)
1^+_1	7.9	>5.4(3)
1^+_2	5.02	>4.45(13)



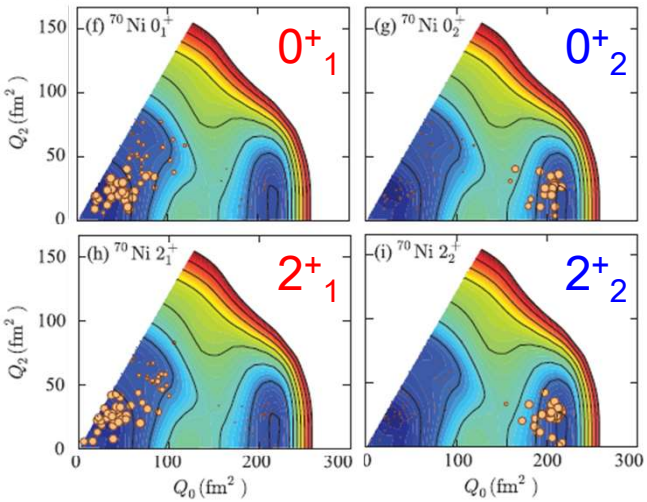
Despite very similar occupancies, there is a discrepancy in B(GT) (logft) between the 1^+_1 and 1^+_2 states

- Difference in the Gamow-Teller matrix elements M(GT)
  - 1^+_1: the main (positive) $\nu p_{1/2} \rightarrow \pi p_{1/2}$ component almost canceled out by the other components
  - 1^+_2: contribution of the $\nu p_{1/2} \rightarrow \pi p_{3/2}$ transition remains predominant

β decay ^{70}Co (low spin) → ^{70}Ni



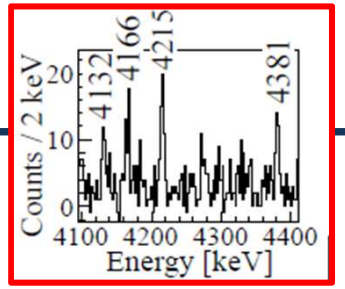
MCSM

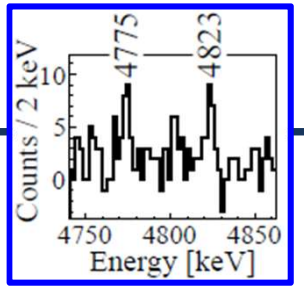


- 0^+_1, 2^+_1 ⇒ Near spherical
- 0^+_2, 2^+_2 ⇒ Prolate deformed

- MCSM ⇒ Much higher population of 2^+_2 than 2^+_1
- Experiment ⇒ Slightly prefer to feed 2^+_2 than 2^+_1, but almost comparable

β decay ^{70}Co (low spin) → ^{70}Ni

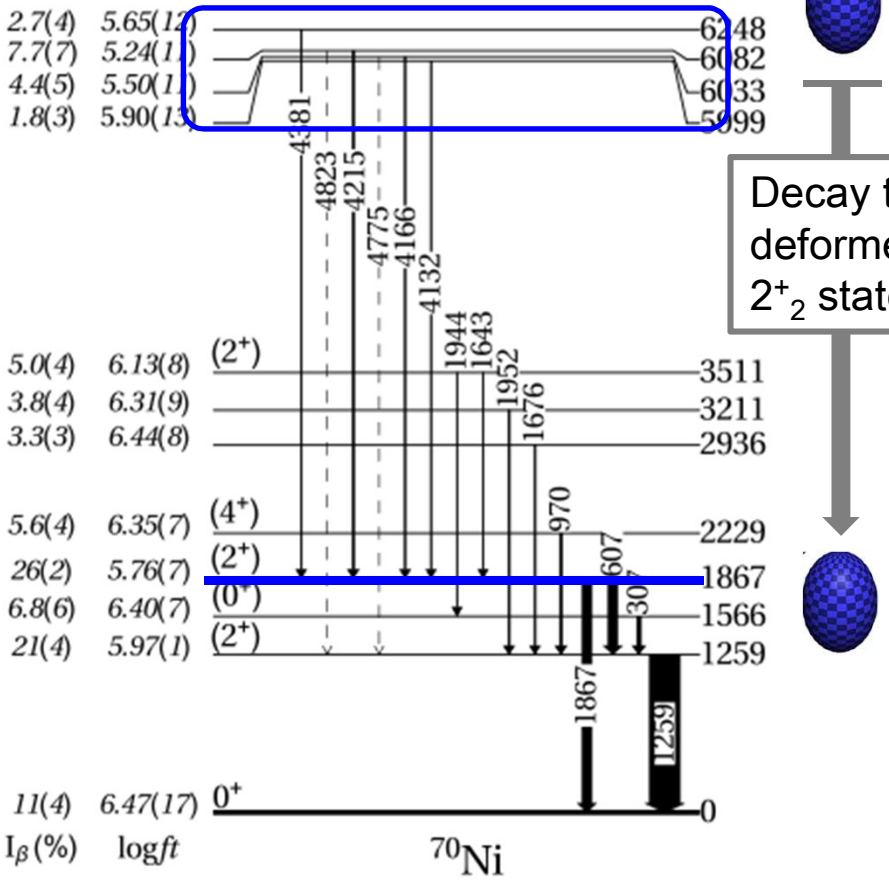




- **Significant population of levels at 6 MeV**

low spin

^{70}Co → $T_{1/2}$ = 508(7) ms



Decay to deformed 2^+_2 state

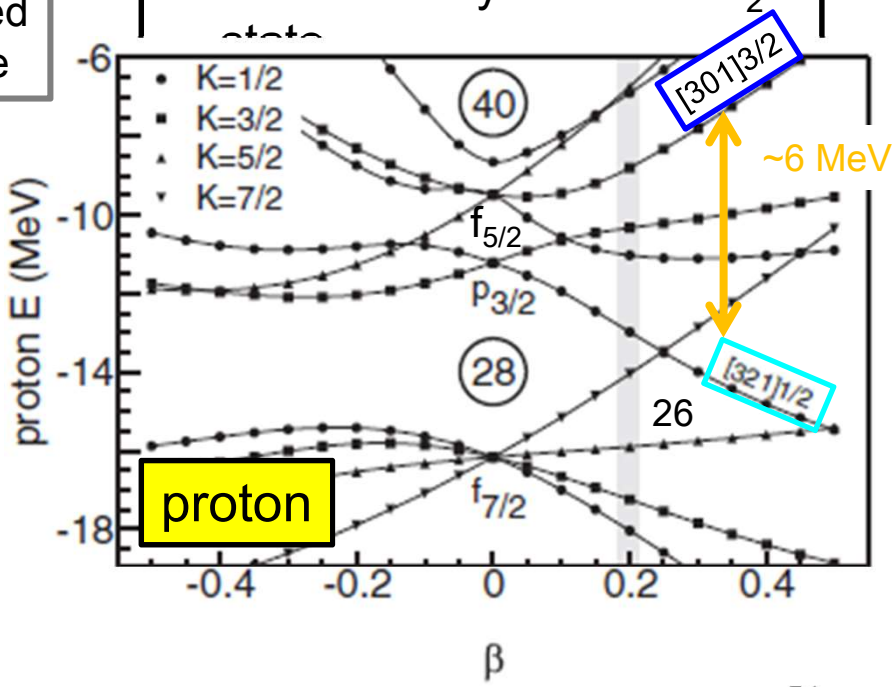
allowed-unhindered

$K^\pi = 1^+_1 : \pi 1/2^-[321]\nu 1/2^-[301]$

around 6 Me

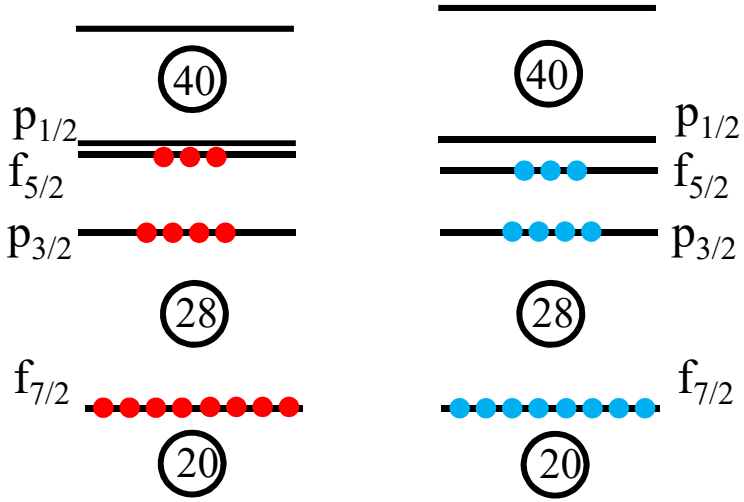
$K^\pi = 1^+, 2^+ : \pi 1/2^-[321]\pi 3/2^-[301]$

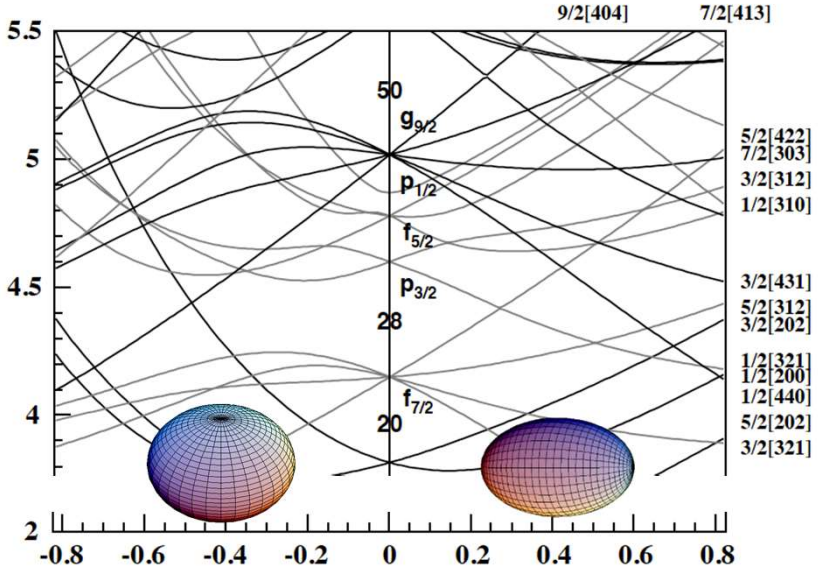
❖ Preferentially feed the 2^+_2 state

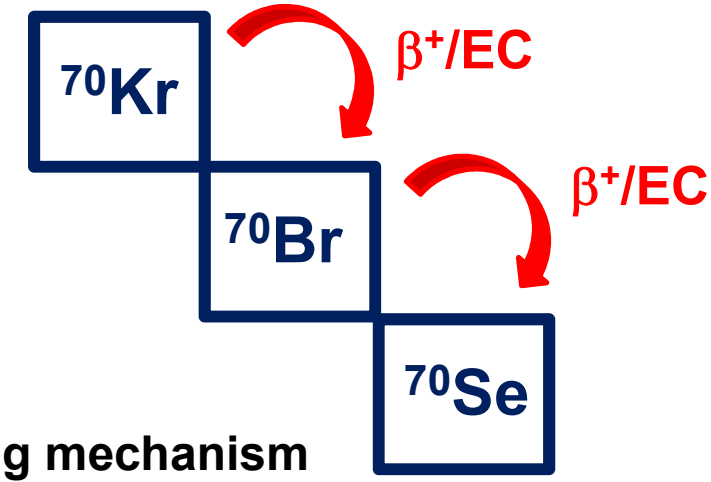


MOTIVATION: Shell evolution in proton-rich A~70 nuclei

➢ **N~Z nuclei**

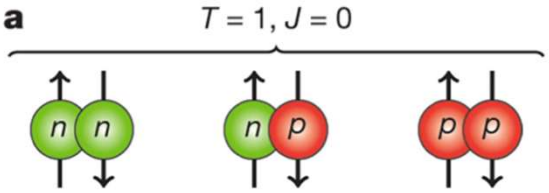




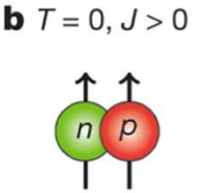


➢ **Underlying mechanism**

p-n pairing induces shell evolution

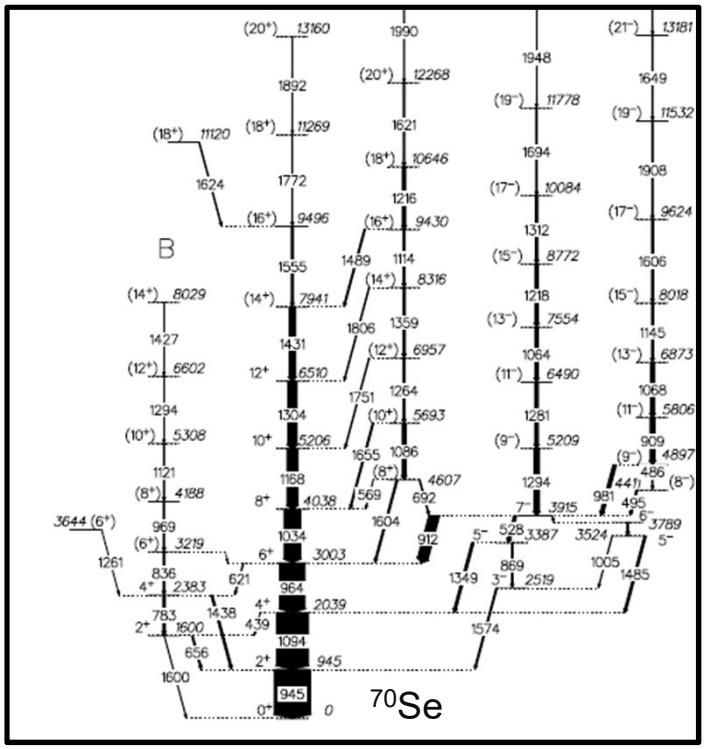


Deformation
Shape coexistence
Isospin symmetry

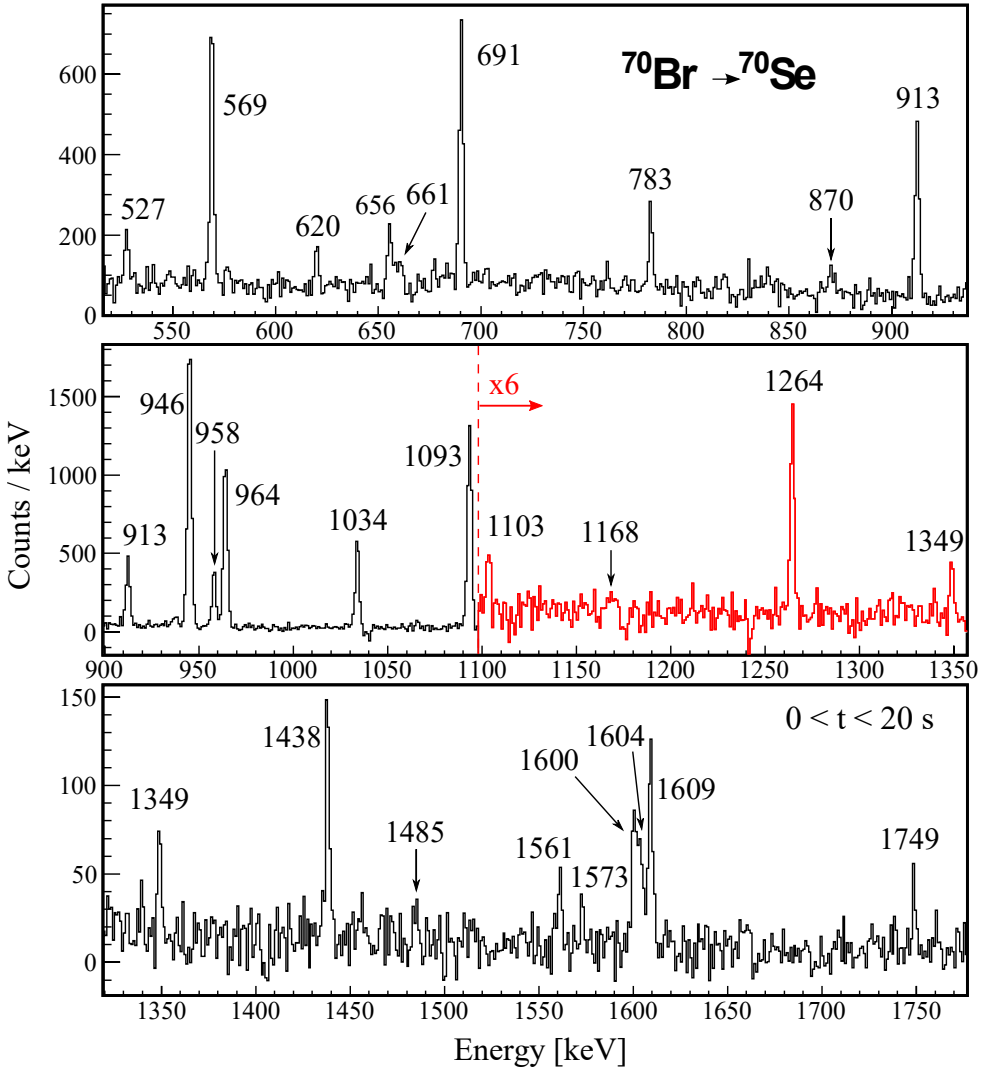


β decay ^{70}Br (T=0, $J^\pi = 9^+$) $\rightarrow$ ^{70}Se

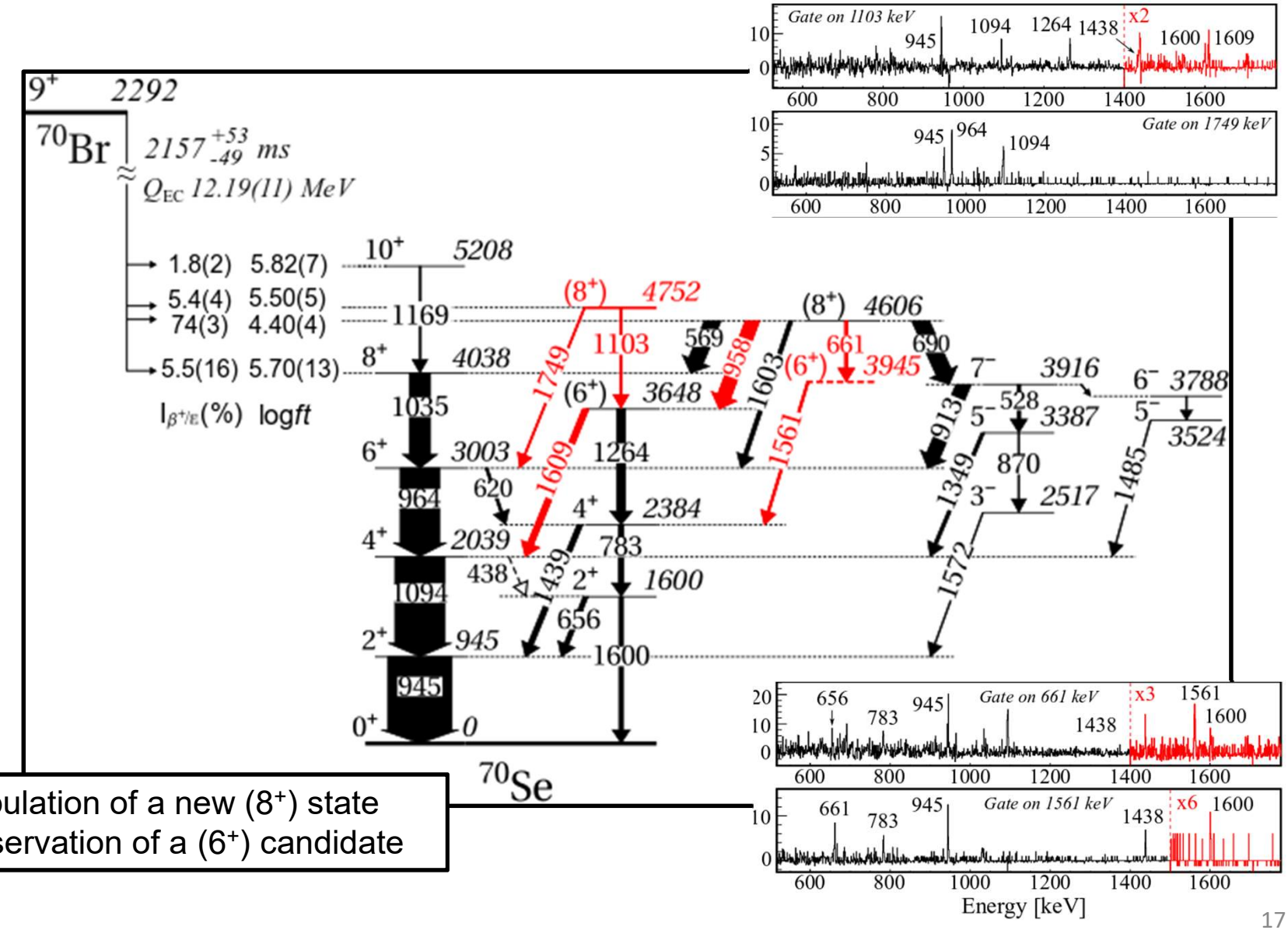
- ❖ **Two long-lived β-decaying states**
- ⇒ T=1, $J^\pi = 0^+$
- ❑ Superallowed β decay
- ⇒ T=0, $J^\pi = 9^+$
- ❑ Selective population of deformed structures



[G. Rainovski ,JPGNPP (2002)]



β decay ^{70}Br (T=0, $J^{\pi} = 9^{+}$) $\rightarrow$ ^{70}Se

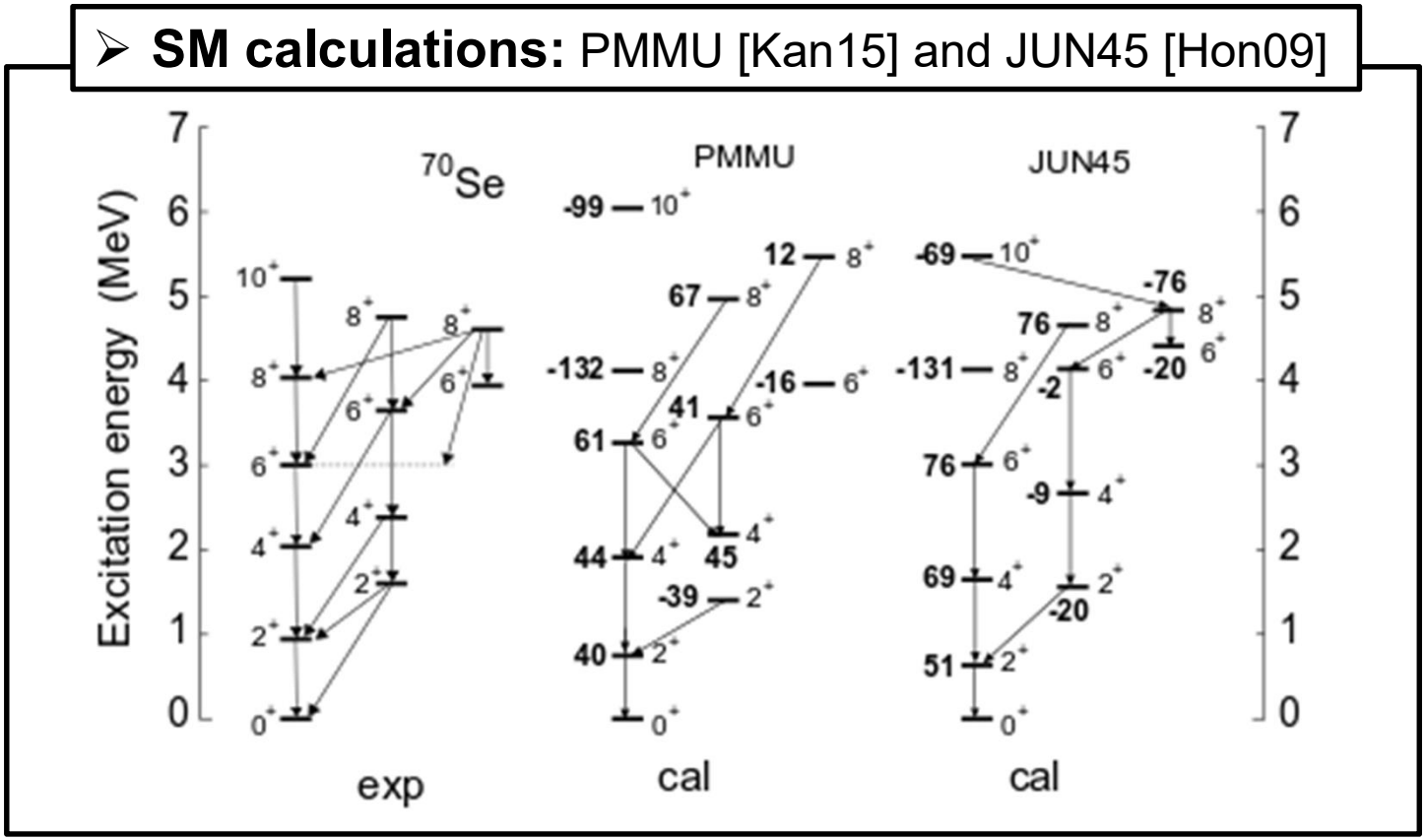


- Population of a new (8^{+}) state
- Observation of a (6^{+}) candidate

β decay ^{70}Br (T=0, $J^\pi = 9^+$) $\rightarrow$ ^{70}Se

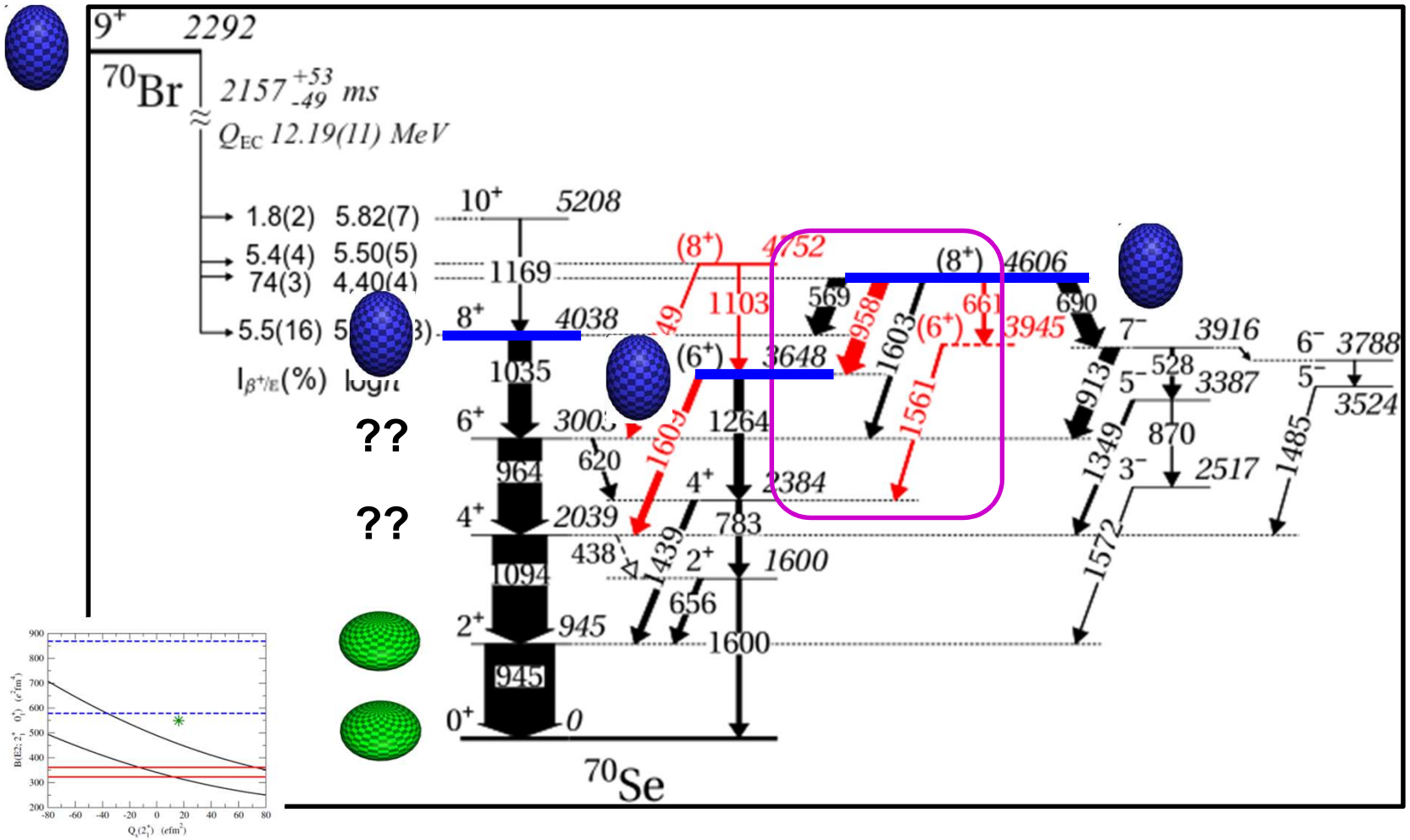
[Kan15] K. Kaneko, PRC (2015)
[Hon09] M. Honma, PRC (2009)

➢ **SM calculations:** PMMU [Kan15] and JUN45 [Hon09]



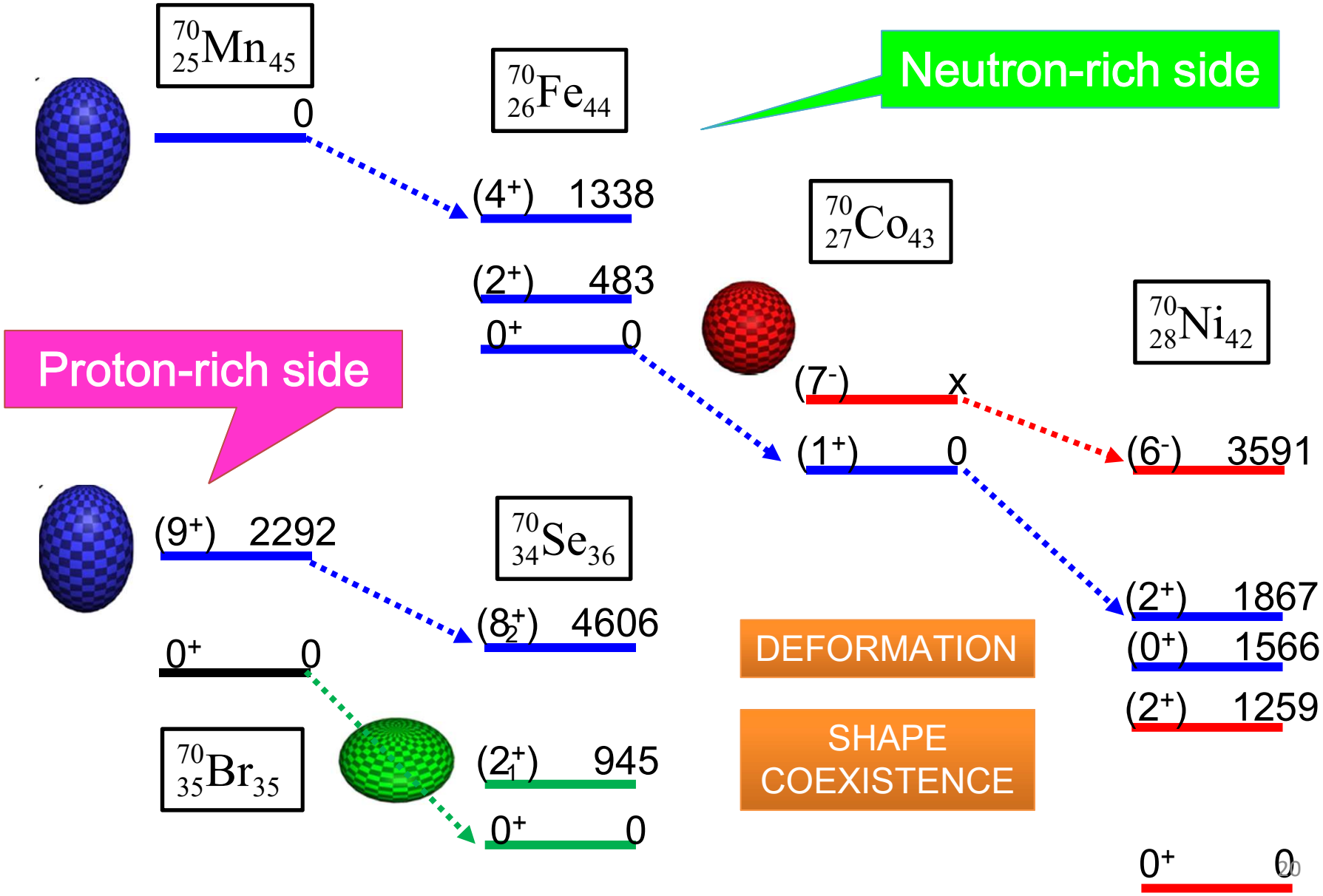
- T=0, $J^\pi = 9^+$ state in ^{70}Br is predicted to be ***prolate*** deformed by both calculations
- Yrast 8^+ state also predicted to be ***prolate*** deformed by both calculations
- Logft to the yrast 8+ states (logft~4.6) consistent with the observed logft=4.40(4) to the (8^+_2) level

β decay ^{70}Br (T=0, $J^{\pi} = 9^{+}$) $\rightarrow$ ^{70}Se



J. Ljungvall, PRL (2008)

Selective population of shapes in A=70 isobars



Summary and conclusions

- The β decay of exotic A=70 nuclei and $g_{9/2}$ Ni isotopes has been exploited by the EURICA collaboration at RIBF (RIKEN) to investigate the nuclear properties of nuclei at both extremes of the chart of nuclides.

- On the neutron-rich side, evidence for the stabilization of prolate deformed structures in the ground states of ^{70}Mn, ^{70}Fe, and ^{70}Co has been found. Shape coexistence in ^{70}Co and ^{70}Ni has been described in terms of **"Type II"** shell evolution, showing an excellent agreement between experimental results and theoretical predictions.

- On the proton-rich side, shape coexistence and mixing result in a complex interpretation of the low-energy spectrum of ^{70}Se.

- First intruder deformed candidates have been presented for ^{72}Ni and ^{74}Ni, with 4 and 6 neutrons in the g9/2 shell. The disagreement with the powerful predictions of the MCSM calculations suggest that the real first yrare states have not been studied in our beta-decay study

NP1112-RIBF80 collaboration

Decay properties of ^{68,69,70}Mn: Probing collectivity up to N = 44 in Fe isotopic chain

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Type II shell evolution in $A = 70$ isobars from the $N \geq 40$ island of inversion

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NP1112-RIBF93 collaboration

Simultaneous investigation of the T = 1 ($J^\pi = 0^+$) and T = 0 ($J^\pi = 9^+$) β decays in ^{70}Br

VICS (Very Important Collaborators)




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THANK YOU VERY MUCH FOR
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