Decay studies of exotic A~70 nuclei

Test of nuclear properties at both extremes of the nuclear chart

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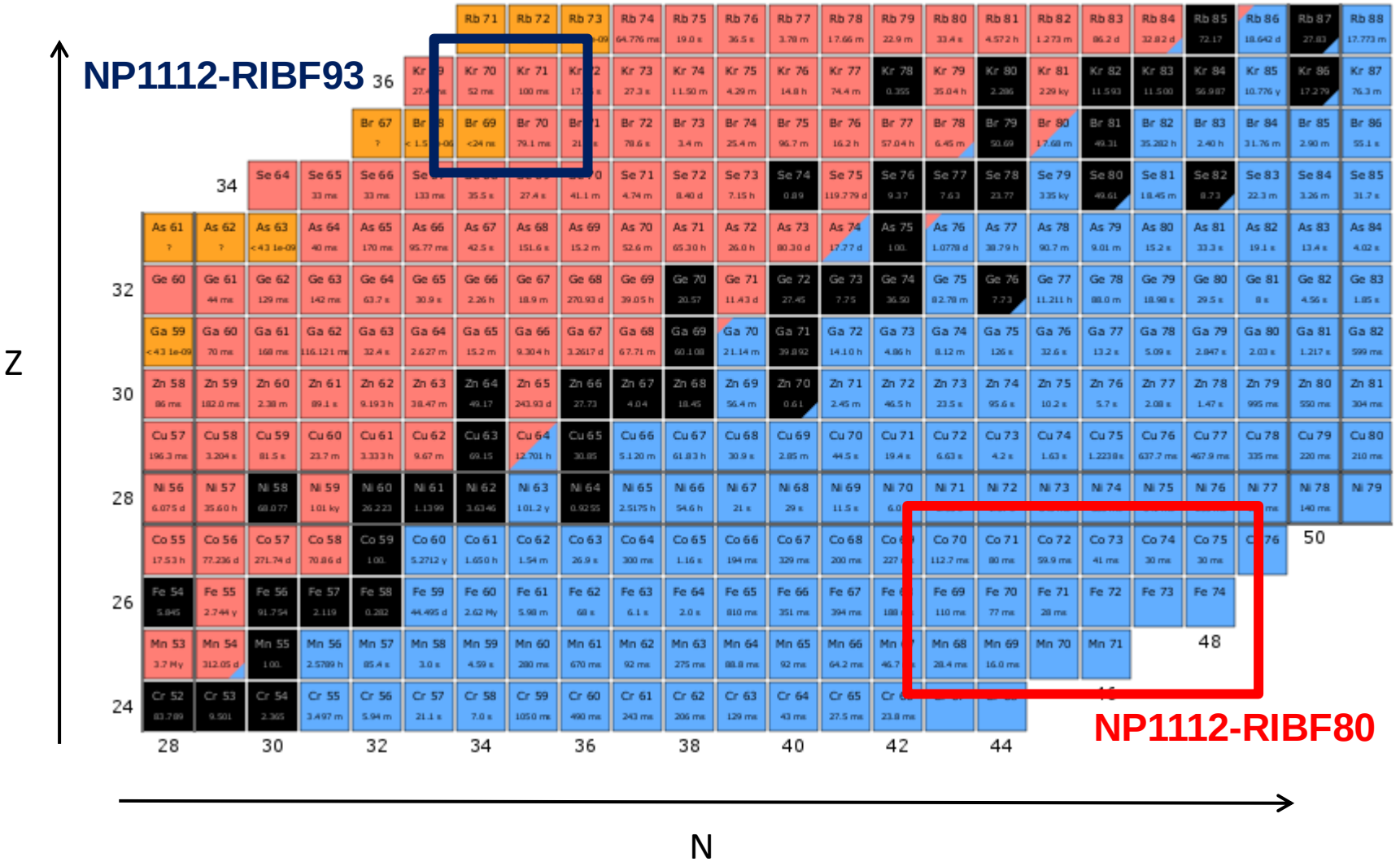
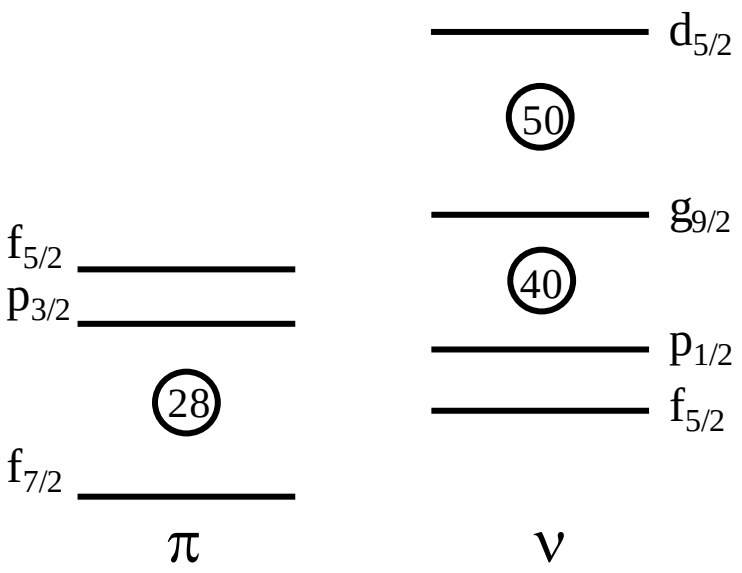
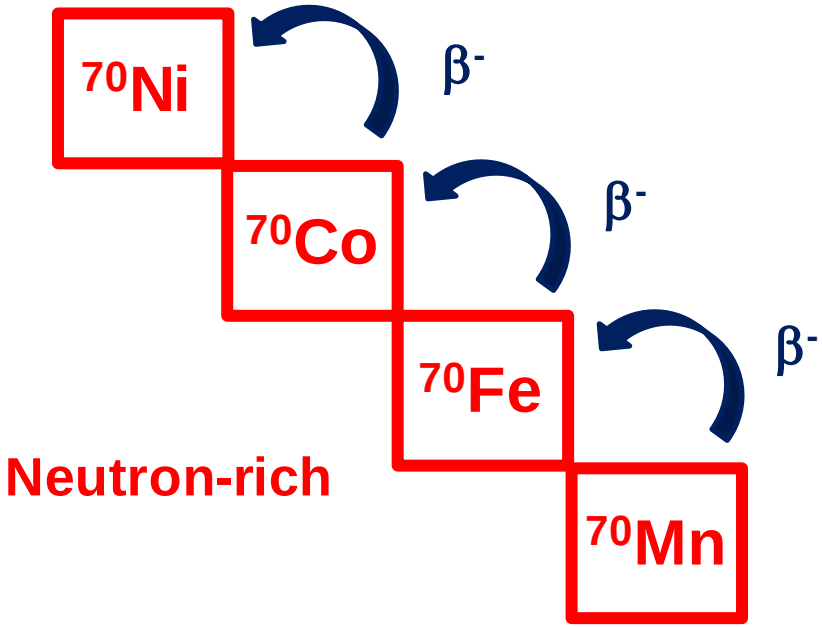
MOTIVATION: Exotic A~70 nuclei

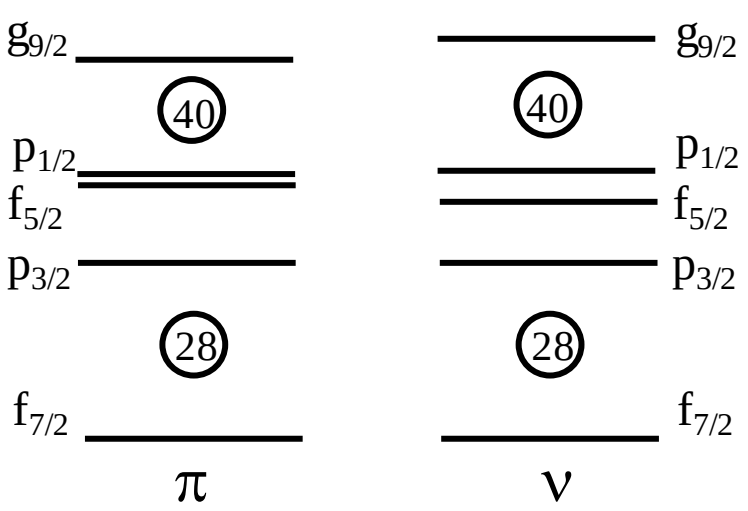
- The most exotic A=70 nuclei could be produced and studied at the RIBF-RIKEN

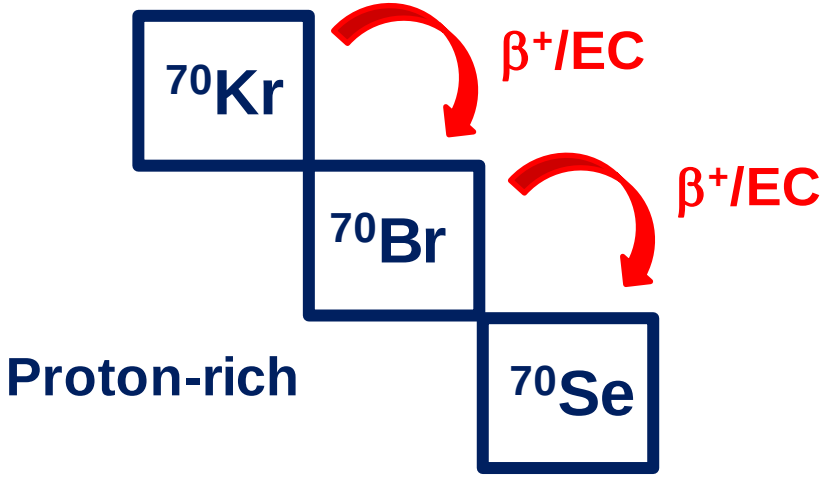


MOTIVATION: Structure of exotic A~70 nuclei



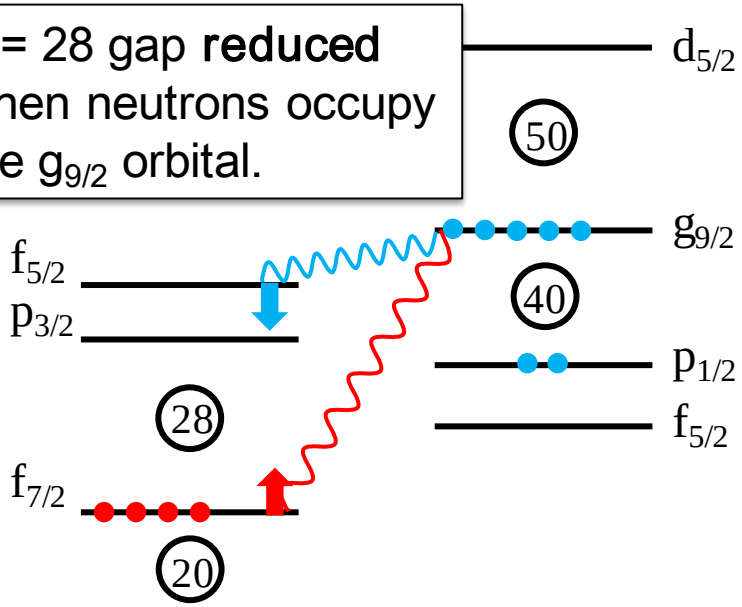




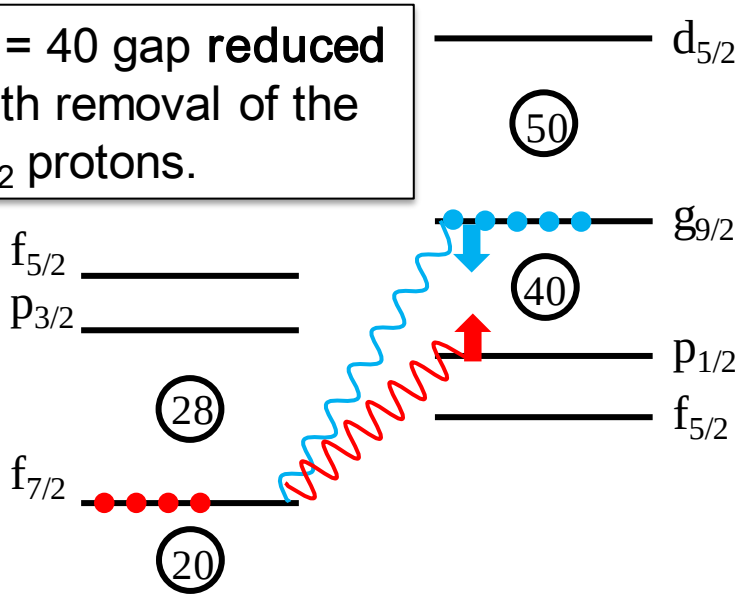


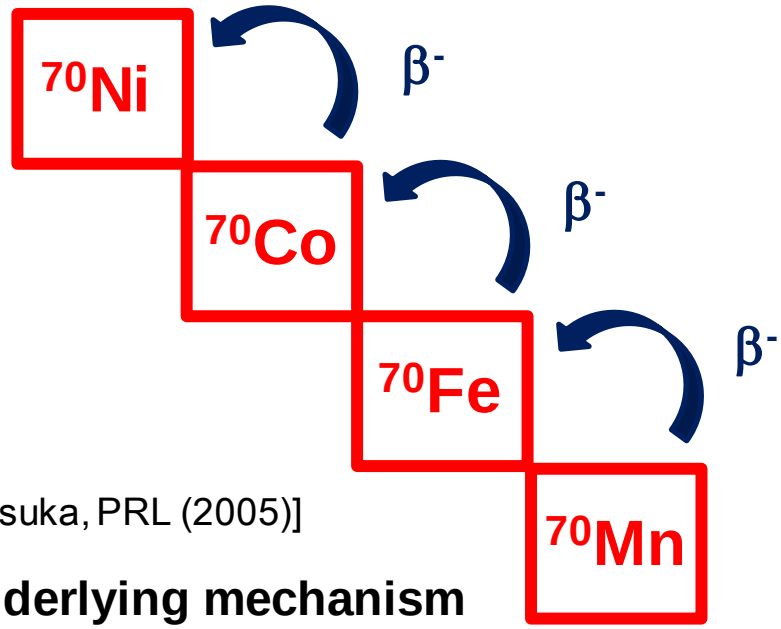
MOTIVATION: Shell evolution in neutron-rich A~70, N>40 nuclei

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



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



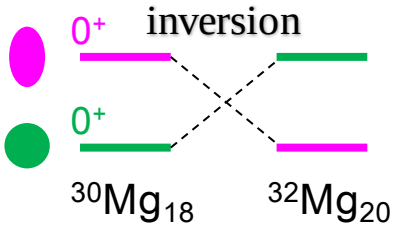


[T. Otsuka, PRL (2005)]

➢ **Underlying mechanism**

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

Deformation
Shape coexistence
Shape inversion

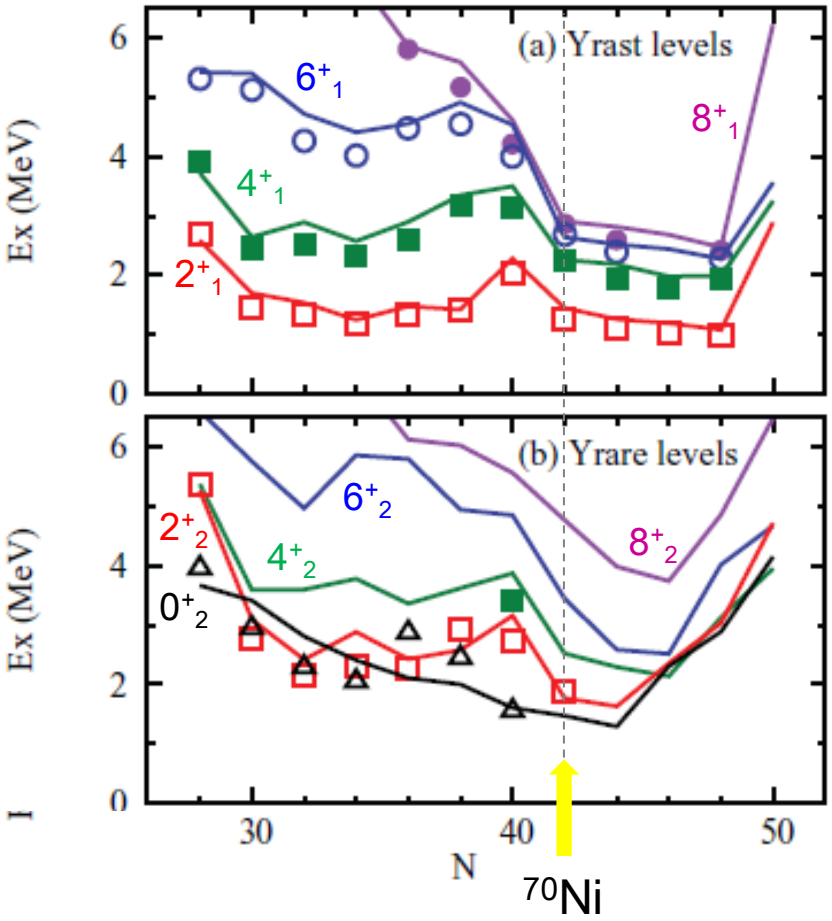


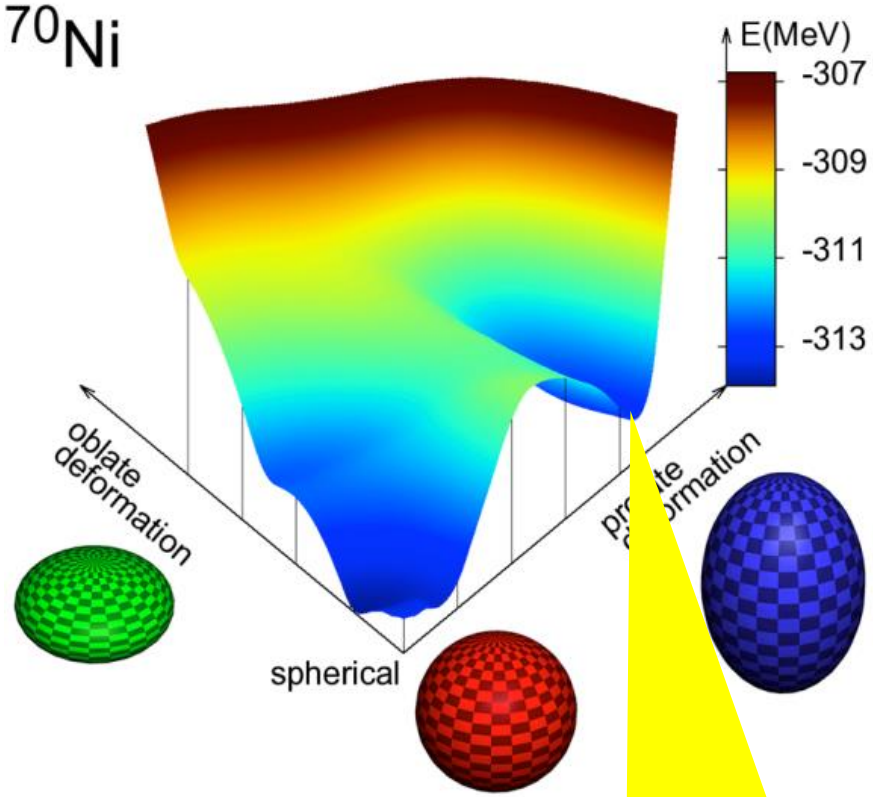
MOTIVATION: Development of shape coexistence in ^{70}Ni

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

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

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



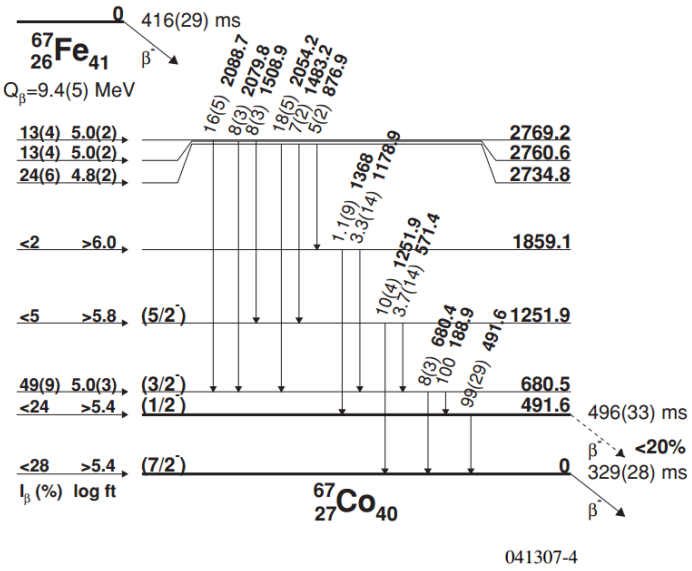


Deeper local minimum at prolate deformation

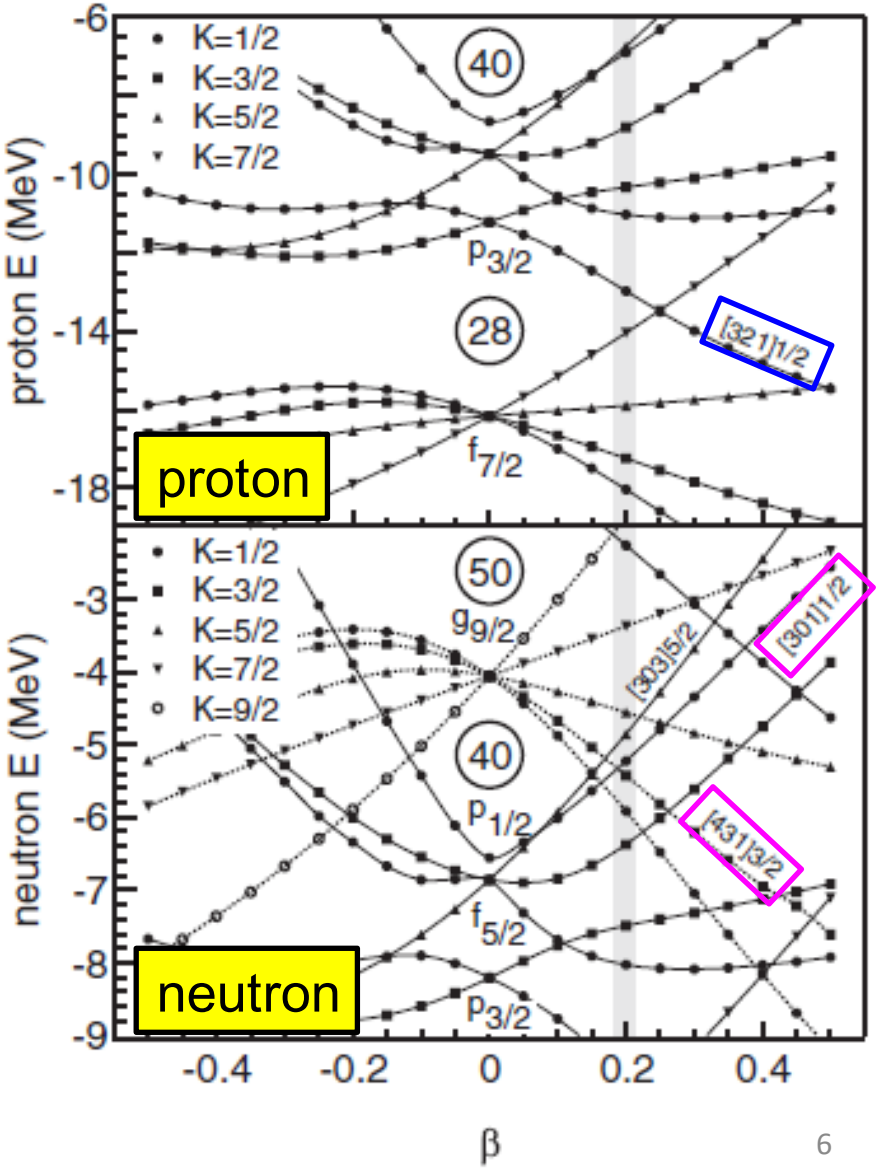
MOTIVATION: Nature of the low-spin β–decaying isomer in Co

- 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 etal., PRC (2012)]
  [F. Flavigny et al., PRC (2015)]

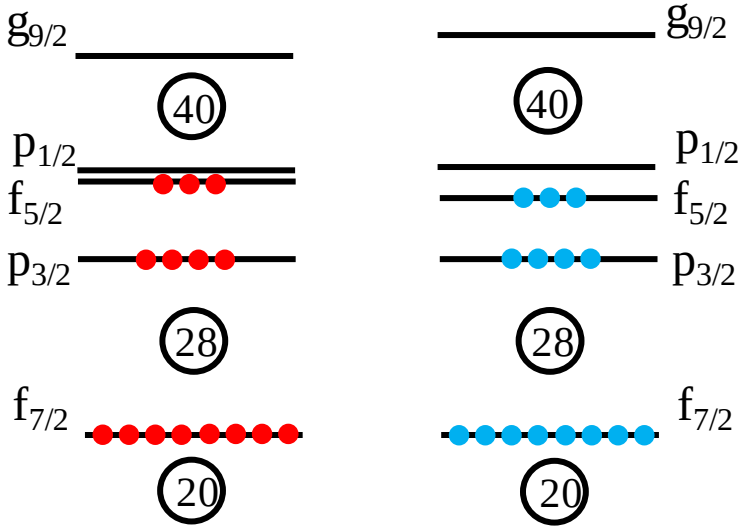


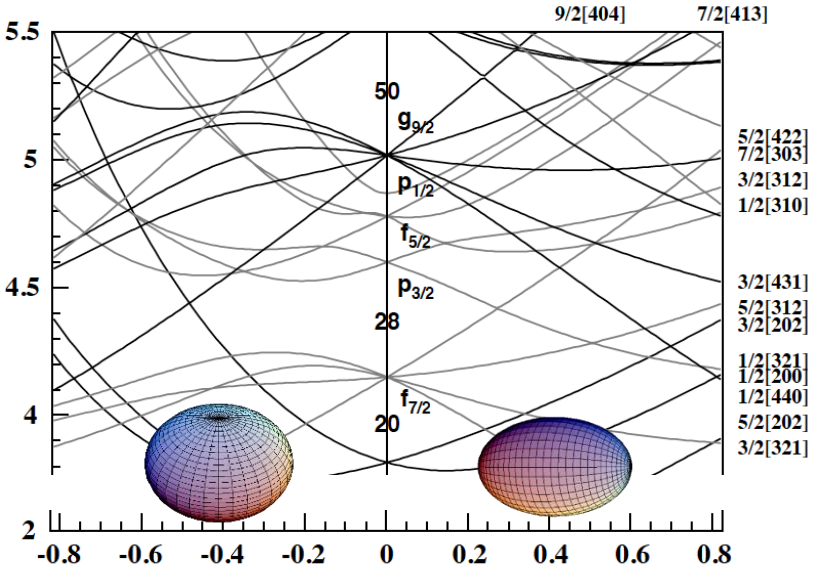
[D. Pauwels et al., PRC (2008)]

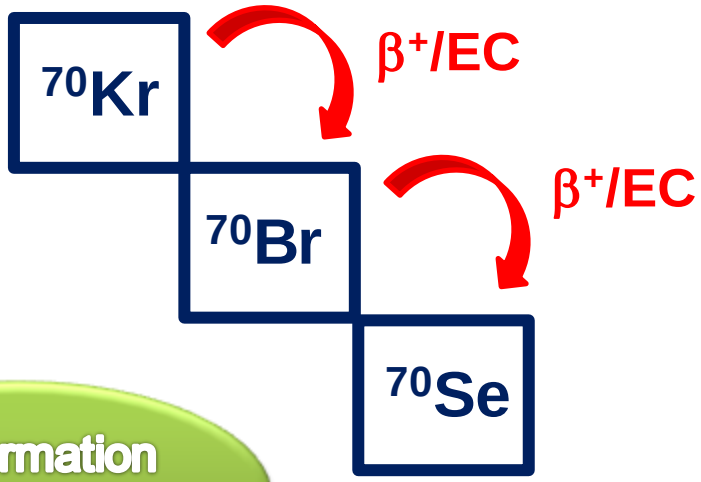


MOTIVATION: Shell evolution in proton-rich A~70 nuclei

➢ **N~Z nuclei**

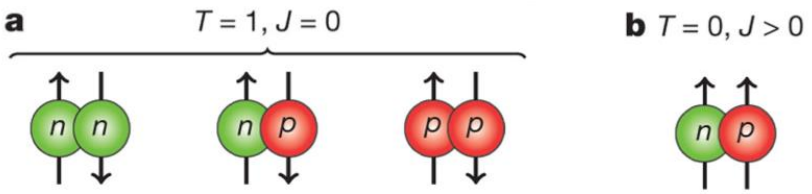




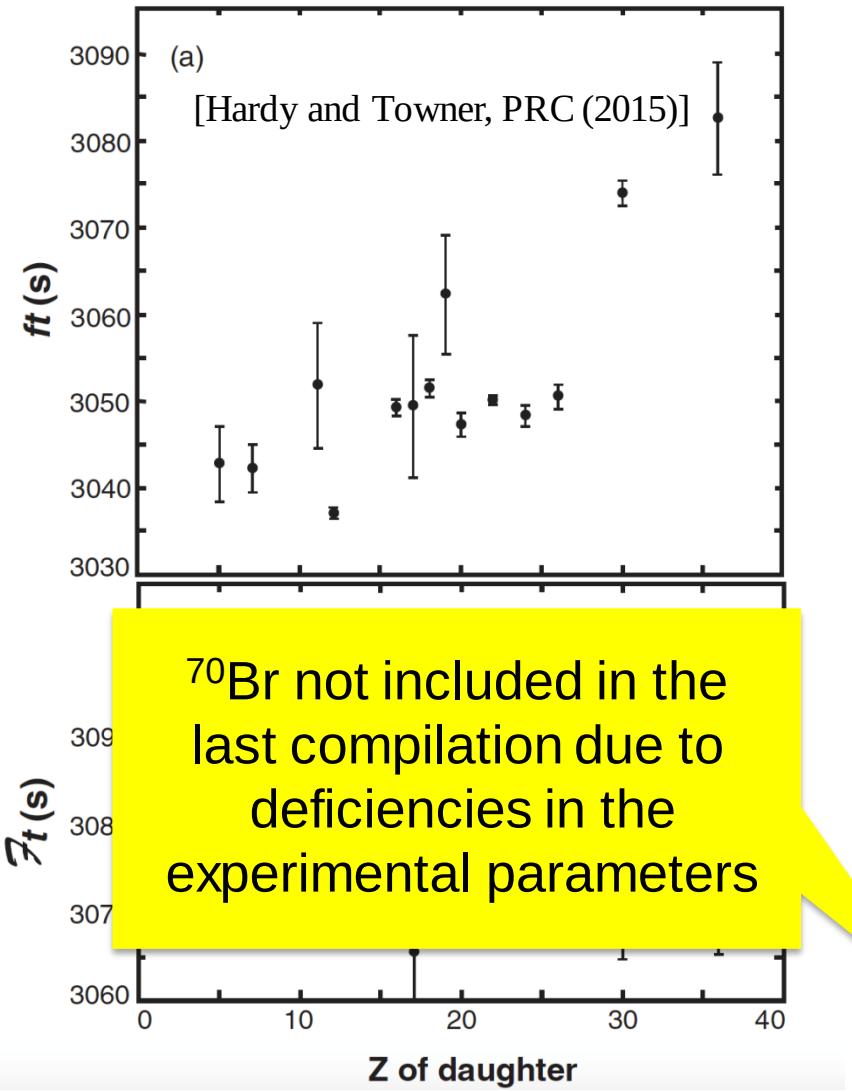


Deformation
Shape coexistence

➢ **Underlying mechanism:** *p-n pairing*



MOTIVATION: Superallowed $0^+ \rightarrow 0^+$ β decay in ^{70}Br



^{70}Br not included in the last compilation due to deficiencies in the experimental parameters

Search for new physics beyond the Standard Model

- ❖ Unitarity of CKM matrix
- ❖ Conserved Vector Current (CVC) hypothesis

$$Ft \propto G_F^2 V_{ud}^2,\ V_{ud} = G_V/G_F$$

- ➢ *Ft* values obtained from:

Experiment

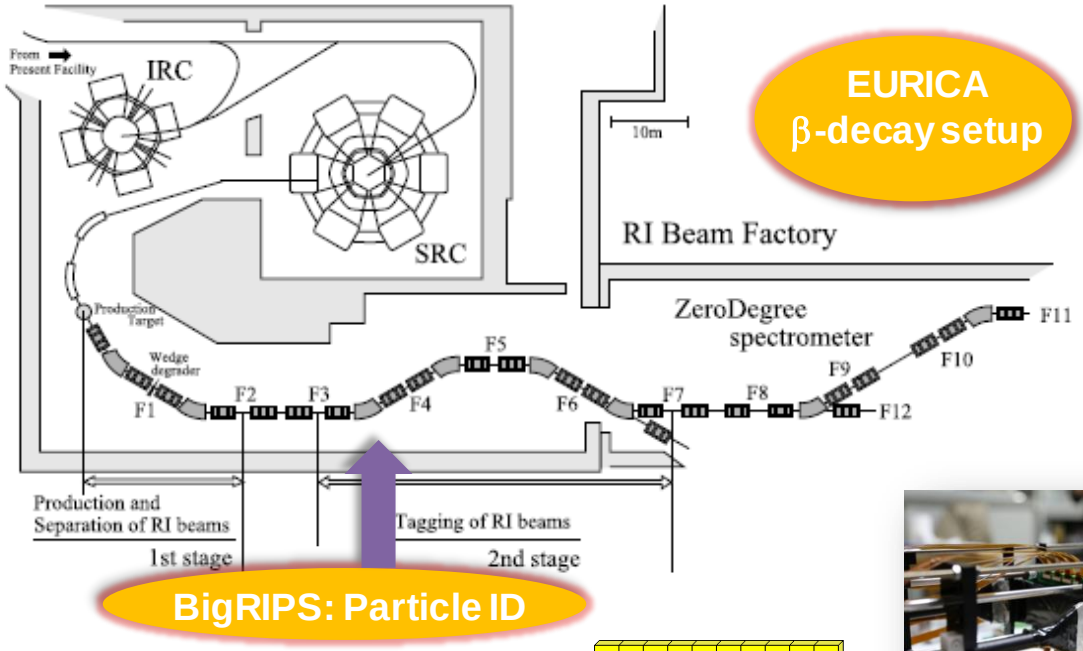
- Half-lives
- Branching ratios
- Masses

Theory

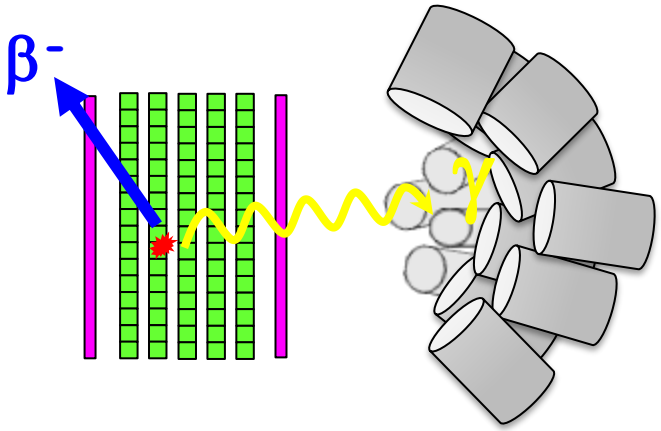
- Isospin impurities
- Radiative corrections

THE BIGRIPS AND EURICA SETUPS

Radioactive Isotope Beam Factory (RIBF) @ RIKEN

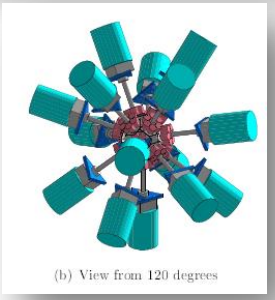


EURICA β-decay setup



➢ WAS3ABI

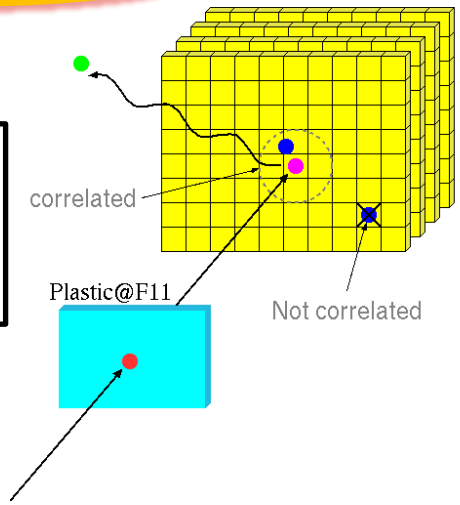
- 5 DSSSDs 60x40 strips
- 1 mm^2 pitch, 1 mm thick
- Ion-β correlations (~ ms)



➢ EURICA

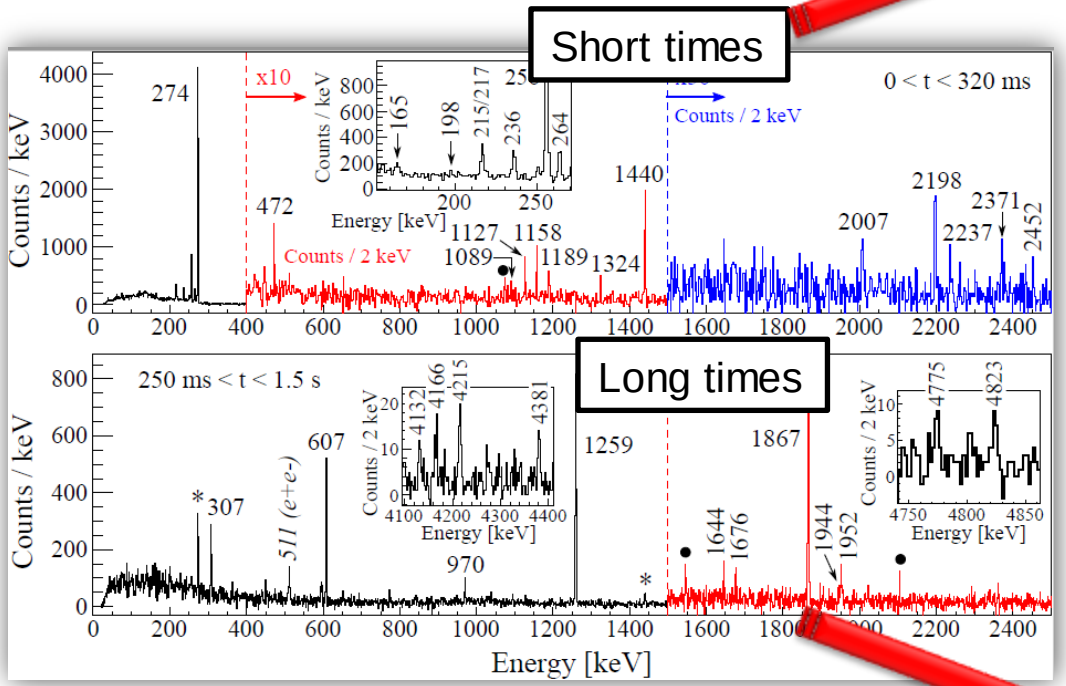
- 12 HPGe clusters
- 84 crystals
- Ion-γ correlations
- β-γ correlations
- Correlation time 110 μs

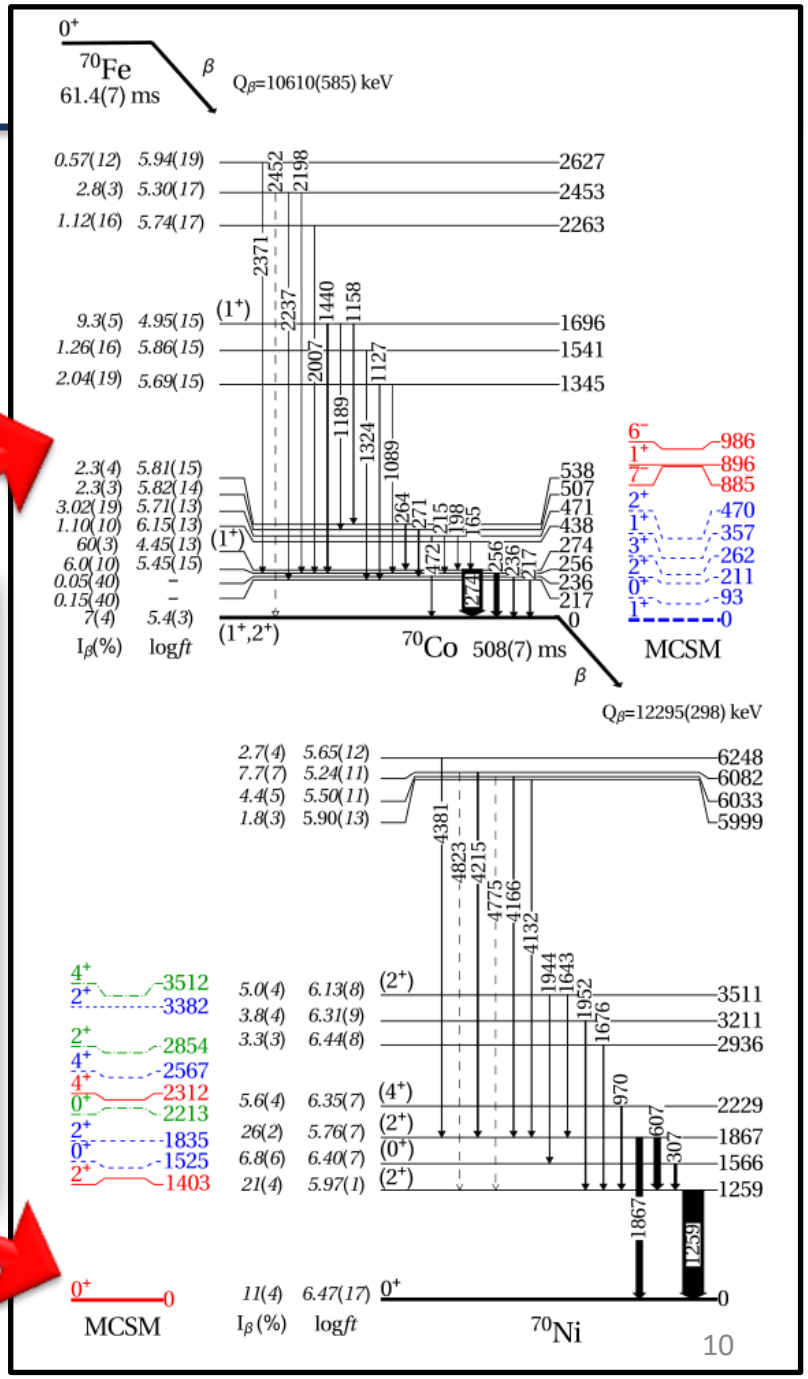
➢ **β-decay information extracted from time and position correlations**



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



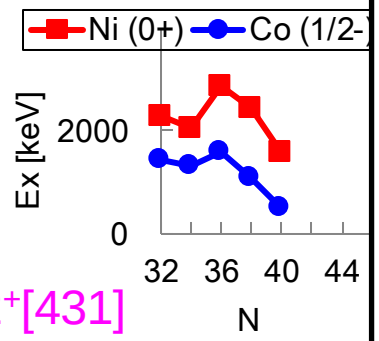


β-decay $^{70}Fe \rightarrow ^{70}Co$

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

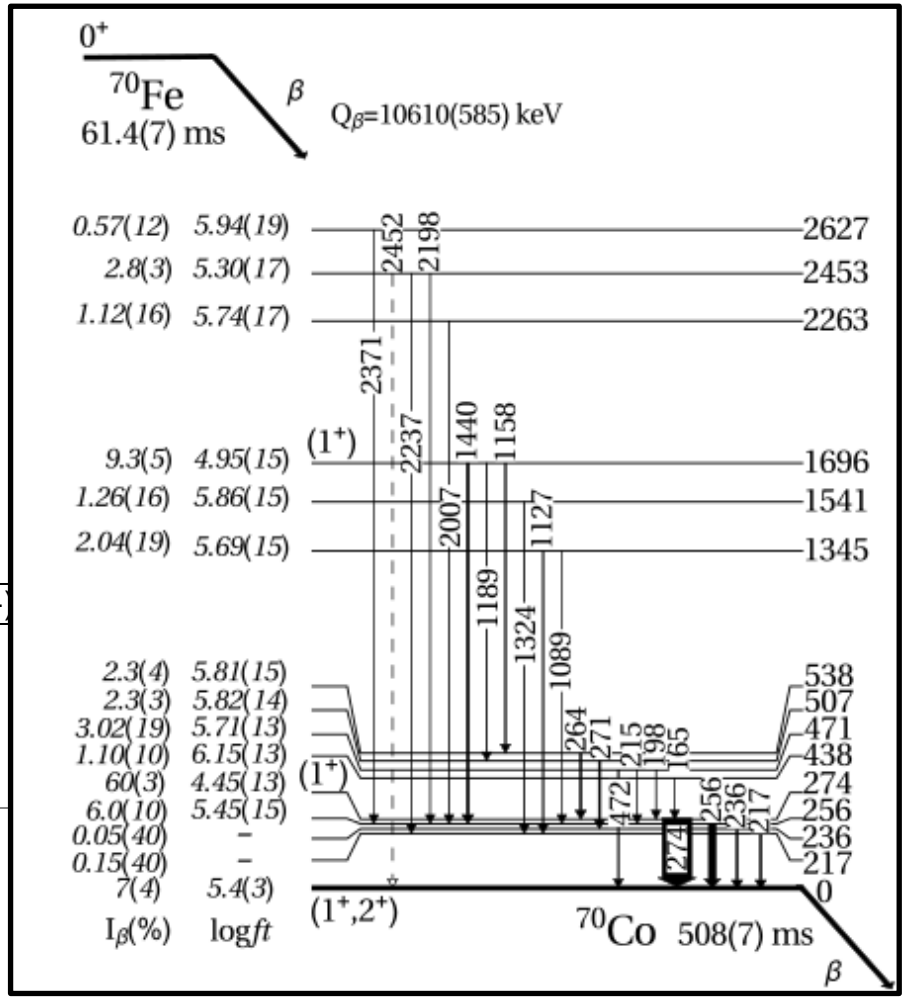
*If **spherical**,*

- 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 ⇒ **$K^{\pi} = 0^{+}, 1^{+}, 2^{+}$**



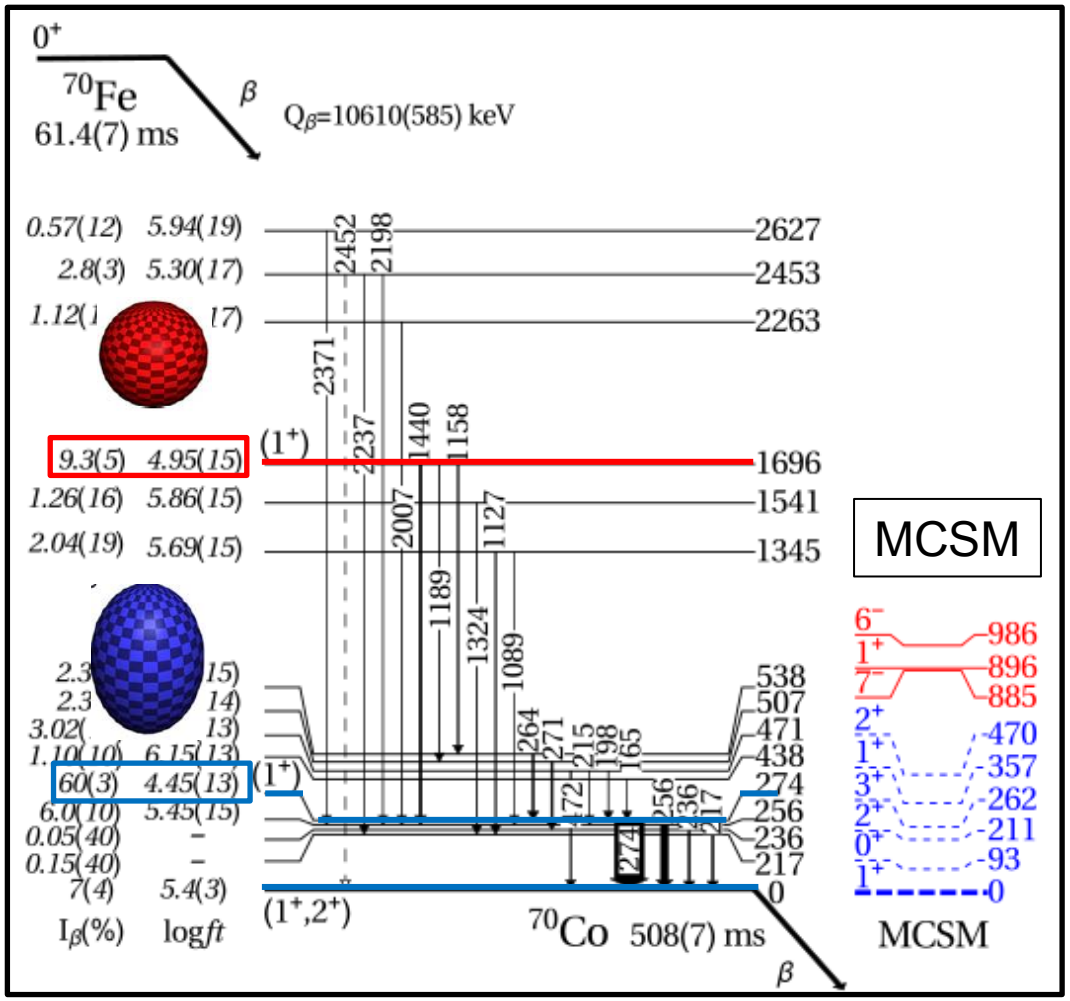
Low-lying 1+ state at 274keV

⇒

Evidence for a deformed configuration

β decay ^{70}Fe→^{70}Co

➢ **MCSM calculations:** A3DA Hamiltonian & pf + $g_{9/2}$ + $d_{5/2}$ orbitals



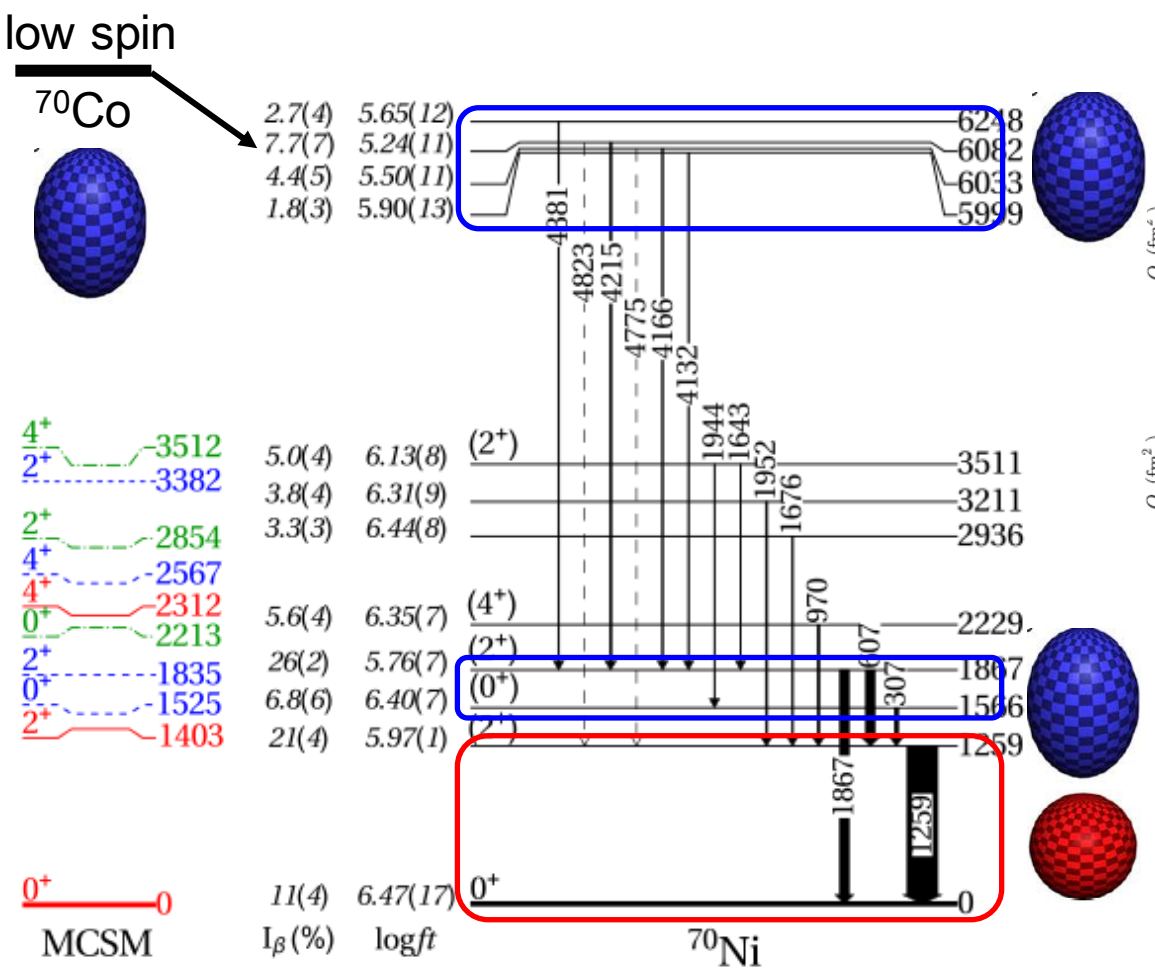
	logft (MCSM)	logft (exp.)
1^+_1	7.9	>5.4(3)
1^+_2	5.02	>4.45(13)
1^+_3	4.33	>4.95(15)

■ **Log*ft***

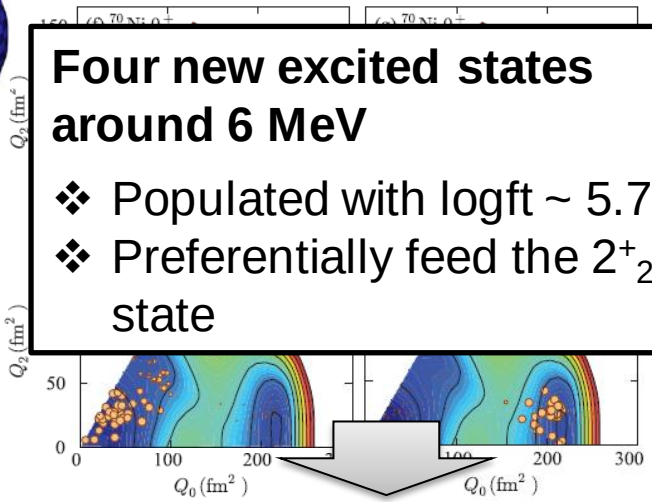
- ❖ Abundance of population of two excited 1^+ states
- ❖ Highly hindered β feeding to the deformed 1^+ ground state

⇒ consistent with the observed decay pattern

β decay ^{70}Co (low spin) → ^{70}Ni



MCSM



Four new excited states around 6 MeV

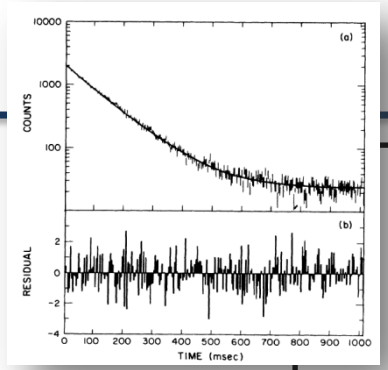
- Populated with logft ~ 5.7
- Preferentially feed the 2^+_2 state

- Similar deformed structure
- Proton 2qp configurations with $K^\pi = 0^+, 1^+, 2^+$

⇒ 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

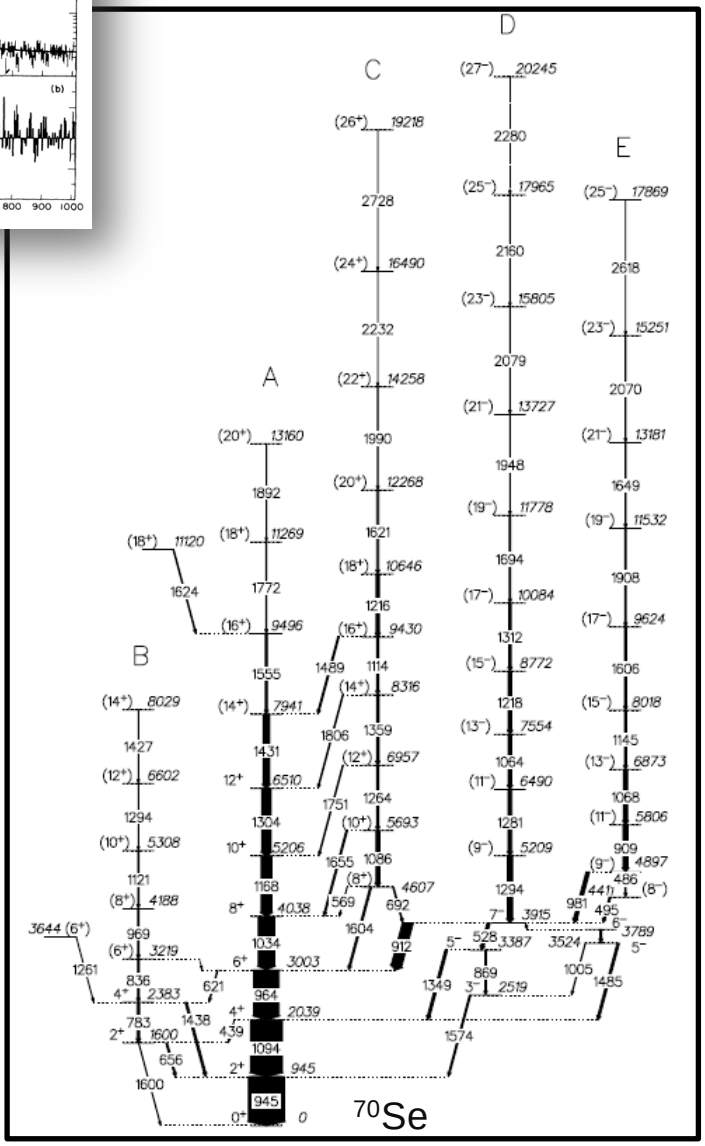
β decay $^{70}Br \rightarrow ^{70}Se$



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

T=1, $J^{\pi} = 0^{+}$			
Ref	$t_{1/2}$ (ms)	Ref	$t_{1/2}$ (ms)
[Al78]	80,2 ± 0.8	[Bur88]	78.54 ± 0.59
[Lop02]	79 ± 36	[Rog14]	70 ± 19
T=0, $J^{\pi} = 9^{+}$			
Ref	t1/2 (ms)	Ref	t1/2 (ms)
[Vos78]	2200 ± 200	[Sch02]	2200 ± 300

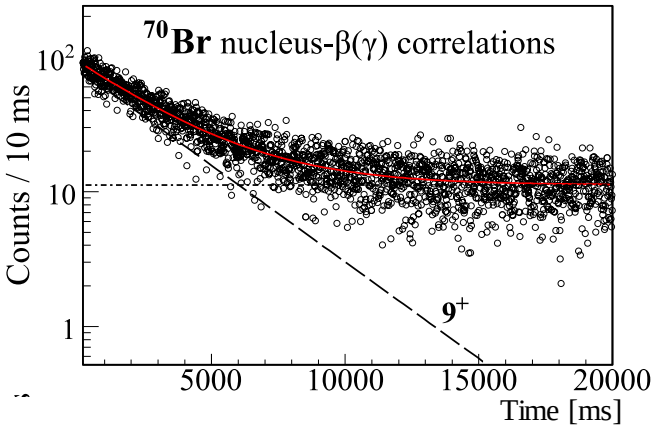
[Al78] D.E. Alburger, PRC (1978)
[Bur88] R.H. Burch, PRC (1988)
[Lop02] M.J. López Jiménez, PRC (2002)
[Rog14] A.M. Rogers, PRC (2014)
[Vos81] B. Vosicki, PRC (1981)
[Sch02] K. Schmidt, PRC (2002)

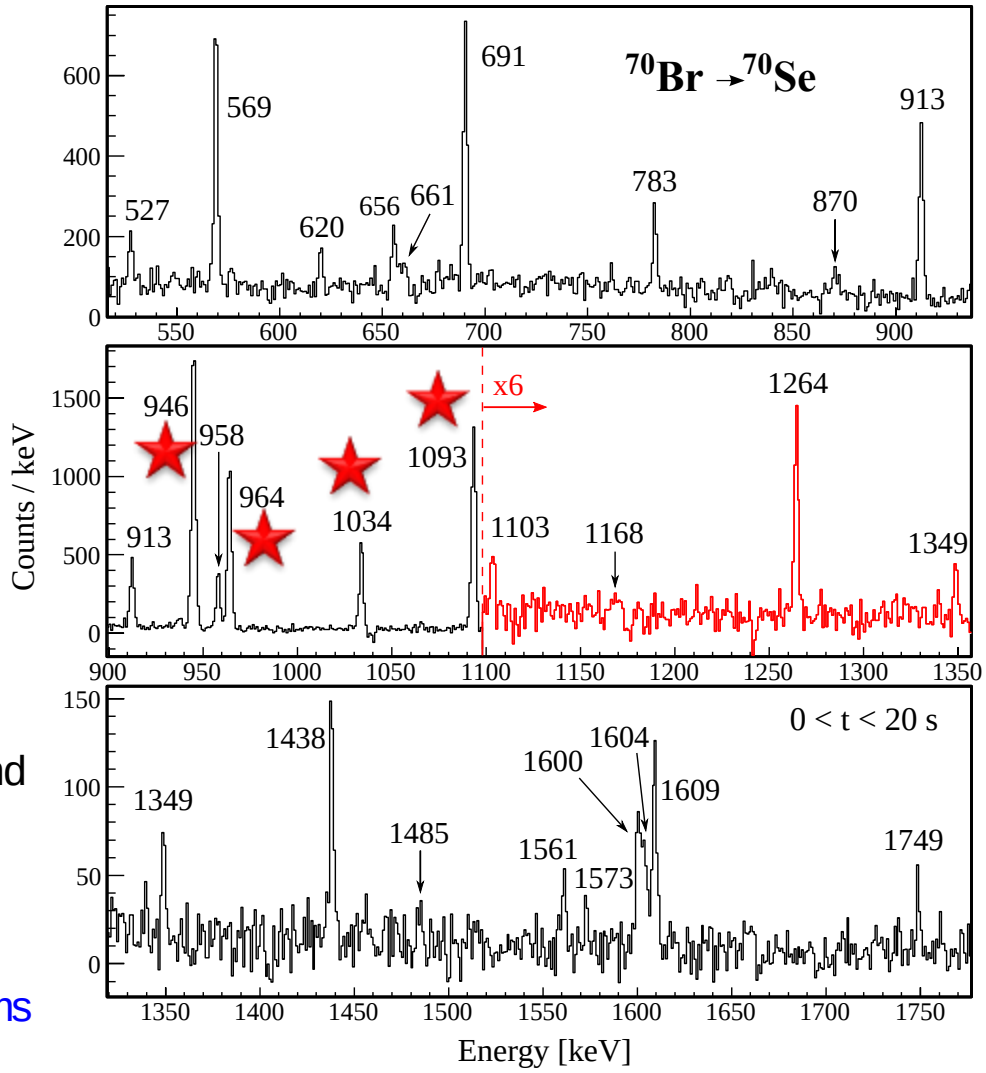


[G. Rainovski ,JPGNPP (2002)]

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

Half-life extracted from time behaviour of transitions at **945**, **964**, **1034**, and **1093** keV





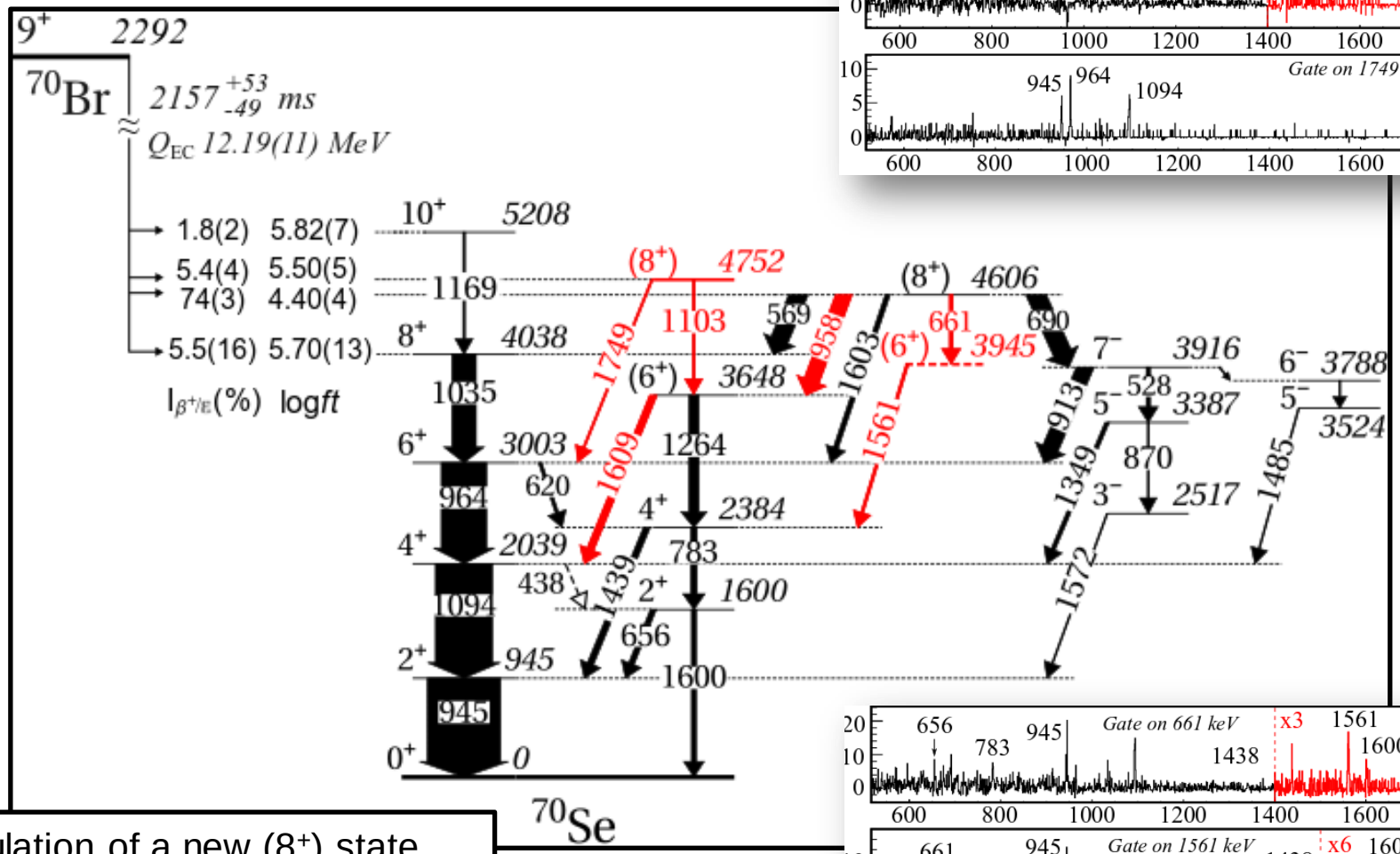
- Exponential function + fixed background
- S

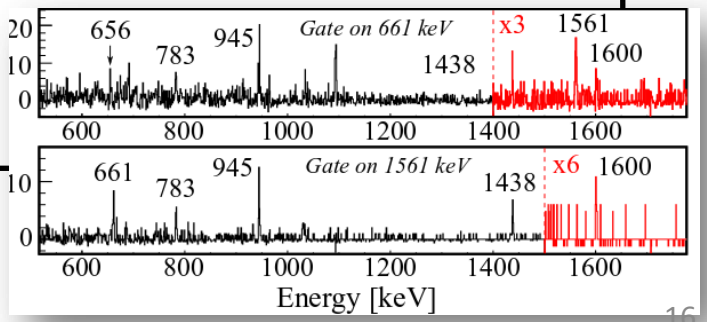
Present value: $t_{1/2} = 2157\ ^{+53}_{-49}$ ms

Old value: $t_{1/2} = 2200 \pm 200$ ms

- Fitting range ⇒ ± 8 ms
- Starting fitting time ⇒ ± 31 ms
- Background ⇒ +44/-38 ms

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



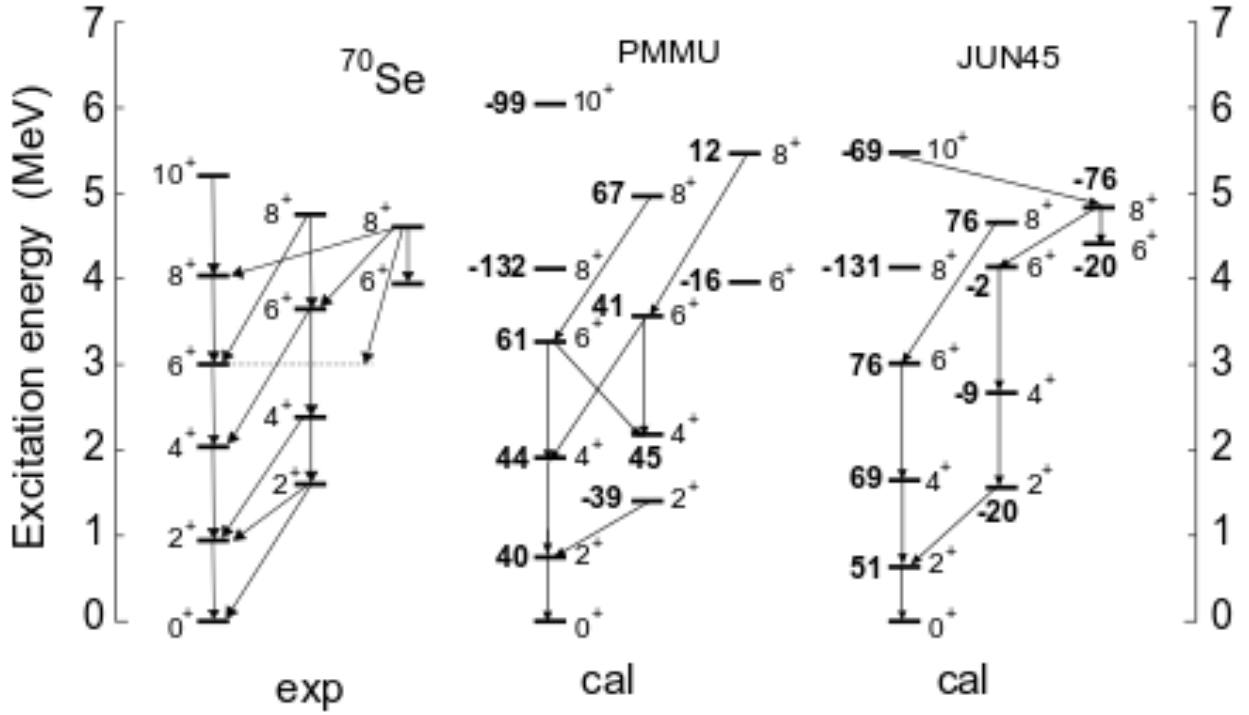


- Population of a new (8^{+}) state
- Observation of a (6^{+}) candidate

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

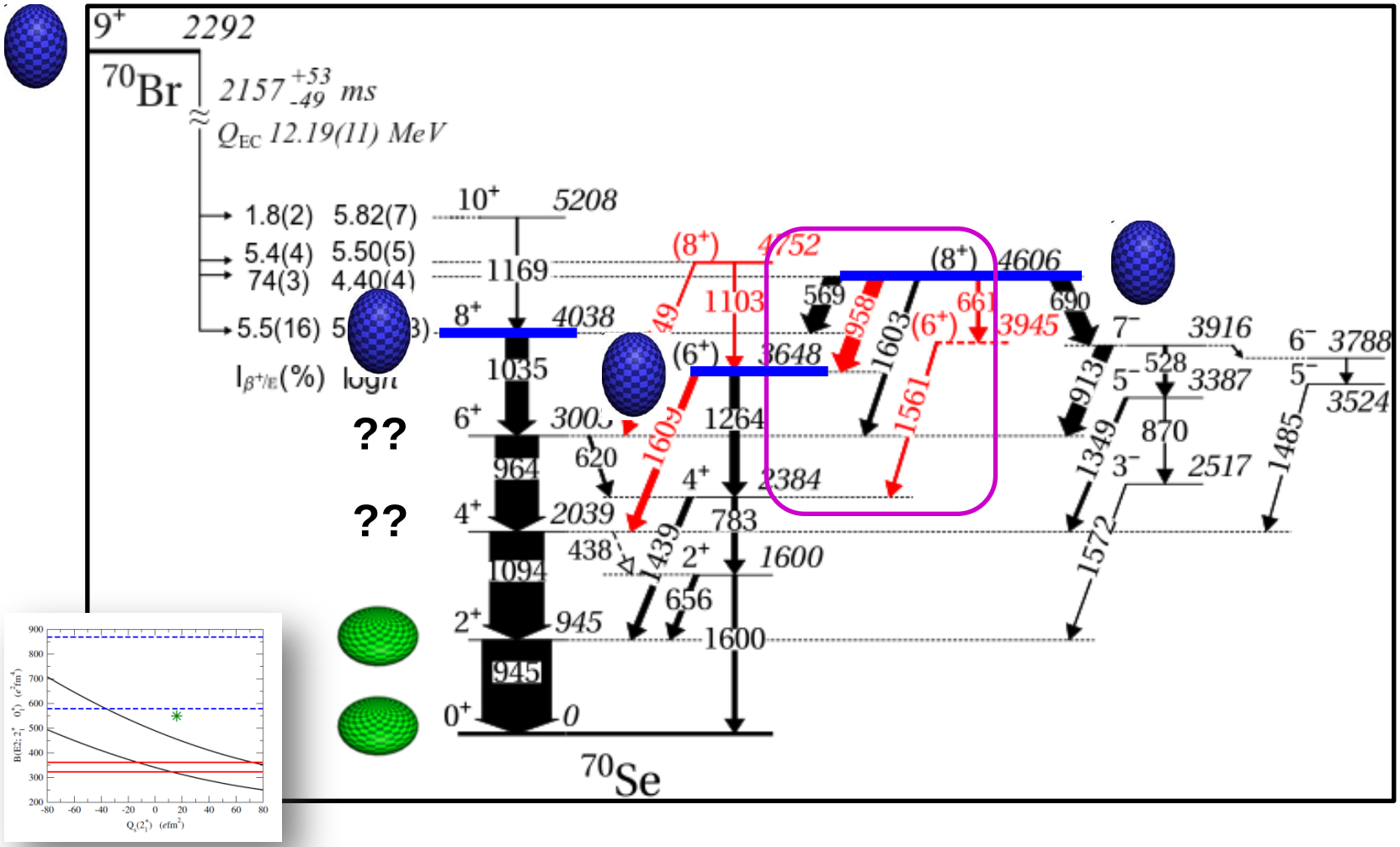
[Kan15] K. Kaneko, PRC (2015)
[Hon09] M. Honma, PRC (2009)

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



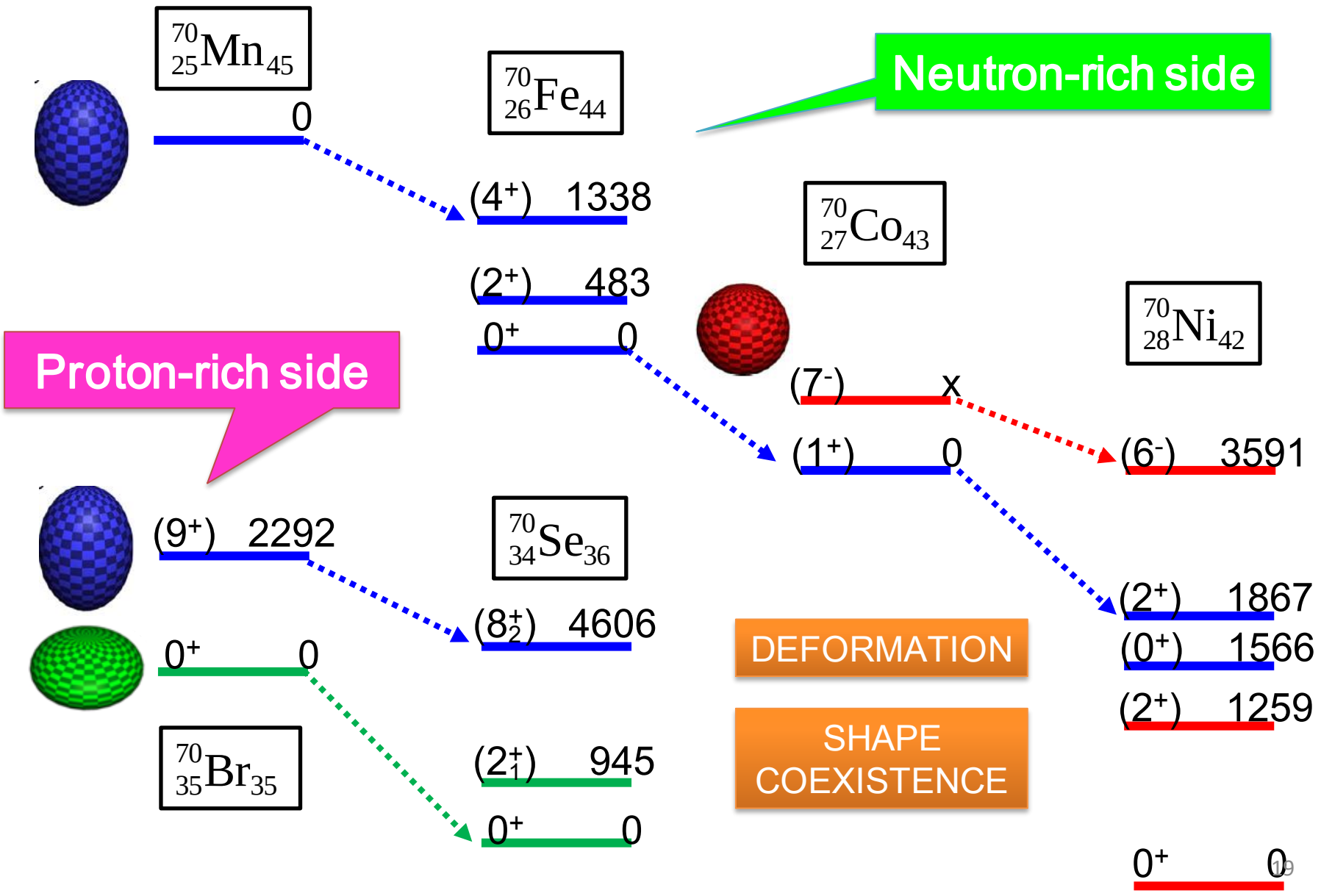
- T=0, $J^\pi = 9^+$ state in ^{70}Br is predicted to be ***prolate*** deformed by both calculations
- Yrast 8^+ state also predicted to be ***prolate*** deformed by both calculations
- Logft to the yrast 8+ states (logft~4.6) consistent with the observed logft=4.40(4) to the (8^+_2) level

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



J. Ljungvall, PRL (2008)

Selective population of shapes in A=70 isobars



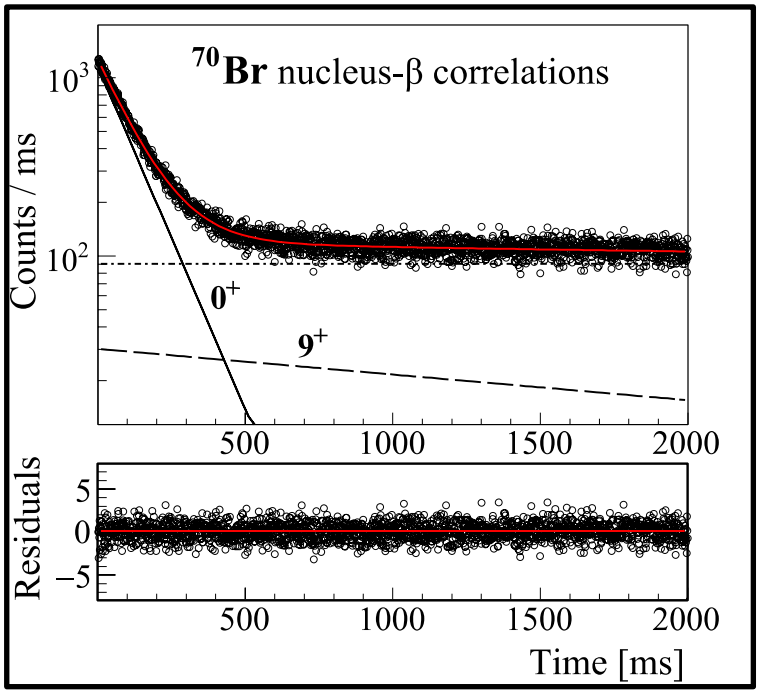
β decay ^{70}Br (T=1, $J^{\pi} = 0^{+}$) → ^{70}Se

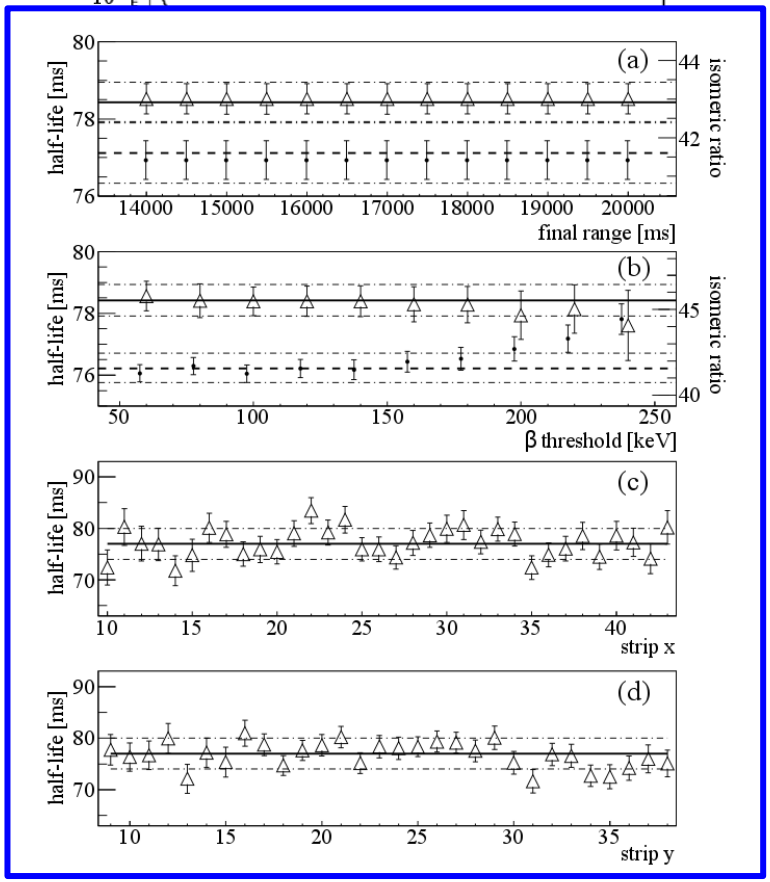
No clear γ rays or protons observed

Half-life extracted from implant-β time-correlated spectrum

Present value: $t_{1/2} = 78.42 \pm 0.51$ ms

Best old value: $t_{1/2} = 78.54 \pm 0.59$ ms





β decay ^{70}Br (T=1, $J^\pi = 0^+$) → ^{70}Se

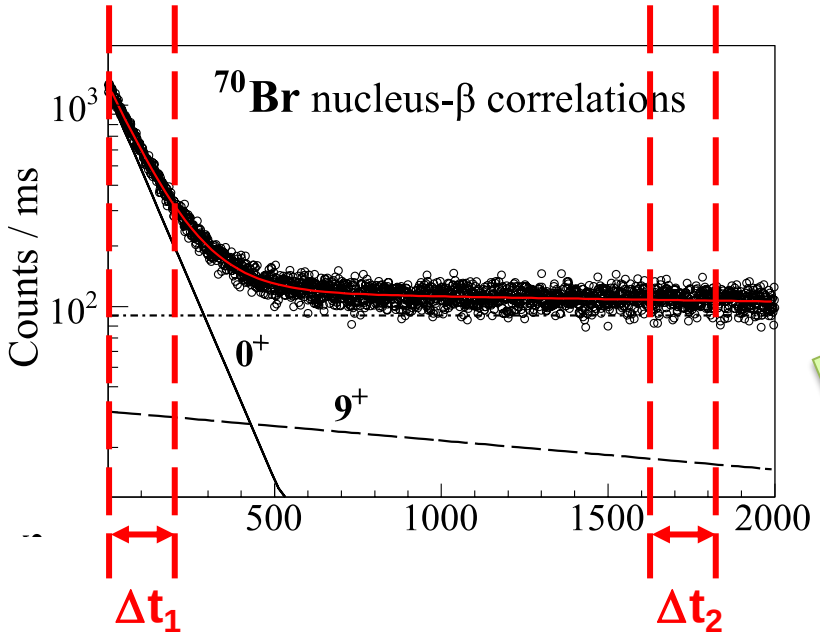
[Har77] J.C. Hardy, PLB (1977)

[Har02] J.C. Hardy, PRL (2002)

- Branching ratio through the 2^+_1 state

  - When the β feeding is strongly fragmented the γ transitions to the ground state might not be observed [Har77].

  - Solution: Measuring the γ imbalance of the 2^+_1 state



T=1, $J^\pi = 0^+$

Multit
0^+, 1^+

$$N_\gamma(\Delta t_2) = N_0^\beta \cdot F(\Delta t_2, 9^+) \cdot R^m \cdot \varepsilon_\gamma \cdot I_\gamma^{T=0}(2_1^+)$$

$$N_\gamma(\Delta t_1) = N_0^\beta \cdot F(\Delta t_1, 9^+) \cdot R^m \cdot \varepsilon_\gamma \cdot I_\gamma^{T=0}(2_1^+) + N_0^\beta \cdot F(\Delta t_1, 0^+) \cdot (1 - R^m) \cdot \varepsilon_\gamma \cdot I_\gamma^{T=1}(2_1^+)$$

"collector state"

R(2⁺₁) = 1.3 ±1.1 %

0^+

- Value estimated by [Har02]: $R^{GT}(2^+_1) = \sim 1\%$

Need to separate contributions from the two β–decaying isomers produced in the fission reaction

β decay ^{70}Br (T=1, $J^\pi = 0^+$) $\rightarrow$ ^{70}Se

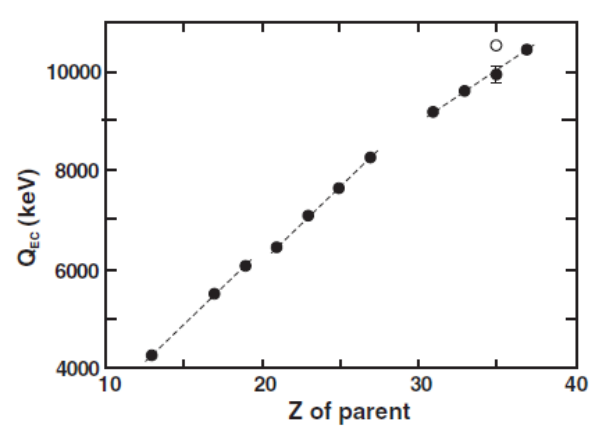
Need of Q_{EC}, $t_{1/2}$ and BR

$$\mathcal{F}t \equiv ft(1+\delta_R')(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

Test of CVC hypothesis

J.C. Hardy and I.S. Towner, PRC (2015)

- For ^{70}Br, there are two conflicting Q_{EC} values:
  1. Positron end-point energy
     ⇒ **Q_{EC} = 9970(170) keV** *[C.N. Davids, AMFC (1980)]*
  2. Penning-trap mass measurement
     ⇒ **Q_{EC} = 10504(15) keV** *[J. Savory, PRL (2009)]*



World average Ft ⇒ 3072.27 ± 0.72 s

Q_{EC} (keV)	$t_{1/2}$ (s)	f	R (%)	P_{EC} (%)	ft (s)	$\mathcal{F}t$ (s)
9970 ± 170 [3]	0.07842 ± 0.00051	38600 ± 3600 [2]	97.94 ± 1.75	0,173	3096 ± 293	3086 ± 293
10504 ± 15 [4]	0.07842 ± 0.00051	50979 ± 385 [65]	97.94 ± 1.75	0,133	4087 ± 83	4078 ± 83

Summary and conclusions

- The β decay of exotic A=70 nuclei 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, howing 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.

- For the superallowed decay of ^{70}Br, the improved half-life measurement and the first estimate of the BR obtained here reveal the need for a new high-precision measurement of the Q_{EC} for this decay. This is particularly relevant to probe the theoretical isospin-symmetry-breaking corrections which are enhanced for N=Z nuclei with large Z.

NP1112-RIBF80 collaboration

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

A.I. Morales [a,b,*], G. Benzoni [a], H. Watanabe [c,d], Y. Tsunoda [e], T. Otsuka [f,g,h], S. Nishimura [d], F. Browne [i,d], R. Daido [j], P. Doornenbal [d], Y. Fang [j], G. Lorusso [d], Z. Patel [k,d], S. Rice [k,d], L. Sinclair [l,d], P.-A. Söderström [d], T. Sumikama [m], J. Wu [d], Z.Y. Xu [f,d], A. Yagi [j], R. Yokoyama [f], H. Baba [d], R. Avigo [a,b], F.L. Bello Garrote [n], N. Blasi [a], A. Bracco [a,b], F. Camera [a,b], S. Ceruti [a,b], F.C.L. Crespi [a,b], G. de Angelis [o], M.-C. Delattre [p], Zs. Dombradi [q], A. Gottardo [o], T. Isobe [d], I. Kojouharov [r], N. Kurz [r], I. Kuti [q], K. Matsui [f], B. Melon [s], D. Mengoni [t,u], T. Miyazaki [f], V. Modamio-Hoybjor [o], S. Momiyama [f], D.R. Napoli [o], M. Niikura [f], R. Orlandi [h,v], H. Sakurai [d,f], E. Sahin [n], D. Sohler [q], H. Schaffner [r], R. Taniuchi [f], J. Taprogge [w,x], Zs. Vajta [q], J.J. Valiente-Dobón [o], O. Wieland [a], M. Yalcinkaya [y]

[Phys. Lett. B, 765 (2017) 328]

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

G. Benzoni [a,*], A.I. Morales [a,b], H. Watanabe [c,d], S. Nishimura [c], L. Coraggio [e], N. Itaco [e,f], A. Gargano [e], F. Browne [g,c], R. Daido [h], P. Doornenbal [c], Y. Fang [h], G. Lorusso [c], Z. Patel [i,c], S. Rice [i,c], L. Sinclair [j,c], P.-A. Söderström [c], T. Sumikama [k], J. Wu [c], Z.Y. Xu [l,c], R. Yokoyama [m], H. Baba [c], R. Avigo [a,b], F.L. Bello Garrote [n], N. Blasi [a], A. Bracco [a,b], F. Camera [a,b], S. Ceruti [a,b], F.C.L. Crespi [a,b], G. de Angelis [o], M.-C. Delattre [p], Zs. Dombradi [q], A. Gottardo [o], T. Isobe [c], I. Kuti [q], K. Matsui [l], B. Melon [r], D. Mengoni [s,t], T. Miyazaki [l], V. Modamio-Hoybjor [o], S. Momiyama [l], D.R. Napoli [o], M. Niikura [l], R. Orlandi [u,v], H. Sakurai [c,l], E. Sahin [n], D. Sohler [q], R. Taniuchi [l], J. Taprogge [w,x], Zs. Vajta [q], J.J. Valiente-Dobón [o], O. Wieland [a], M. Yalcinkaya [y]

[Phys. Lett. B, 751 (2015) 107]

NP1112-RIBF93 collaboration

PHYSICAL REVIEW C 00, 004300 (2017)

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

A. I. Morales,[1,2,3,*] A. Algora,[1,4,†] B. Rubio,[1] K. Kaneko,[5] S. Nishimura,[6] P. Aguilera,[7] S. E. A. Orrigo,[1] F. Molina,[7] G. de Angelis,[8] F. Recchia,[9,10] G. Kiss,[6] V. H. Phong,[6,11] J. Wu,[6] D. Nishimura,[12] H. Oikawa,[13] T. Goigoux,[14] J. Giovinazzo,[14] P. Ascher,[14] J. Agramunt,[1] D. S. Ahn,[6] H. Baba,[6] B. Blank,[14] C. Borcea,[15] A. Boso,[9,10] P. Davies,[16] F. Diel,[17] Zs. Dombrádi,[4] P. Doornenbal,[6] J. Eberth,[17] G. de France,[18] Y. Fujita,[19] N. Fukuda,[6] E. Ganioglu,[20] W. Gelletly,[1,21] M. Gerbaux,[14] S. Grévy,[14] V. Guadilla,[1] N. Inabe,[6] T. Isobe,[6] W. Korten,[22] T. Kubo,[6] S. Kubono,[6] T. Kurtukián Nieto,[14] S. Lenzi,[9,10] D. Lubos,[23] C. Magron,[14] A. Montaner-Pizá,[1] D. R. Napoli,[8,9] H. Sakurai,[6,24] Y. Shimizu,[6] C. Sidong,[6] P.-A. Söderström,[6] T. Sumikama,[24] H. Suzuki,[6] H. Takeda,[6] Y. Takei,[13] M. Tanaka,[19] and S. Yagi[13]

Special mention to:

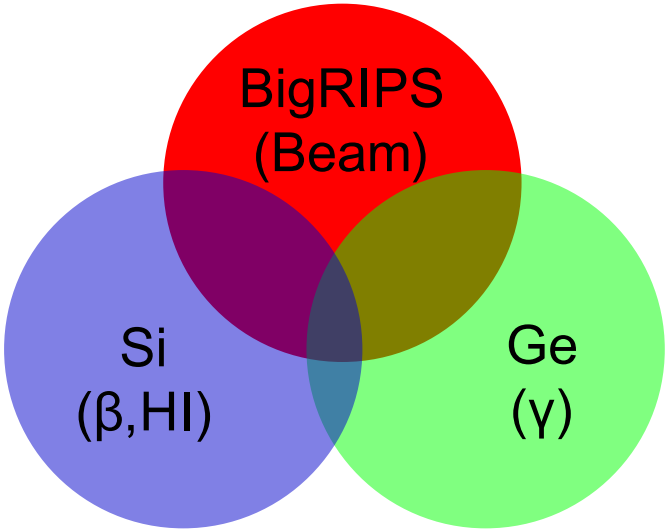
- **NP1112-RIBF80:** **G. Benzoni, H. Watanabe**
  L. Coraggio, N. Itaco, A. Gargano ($^{68\text{-}70}$Mn→$^{68\text{-}70}$Fe)
  T. Otsuka, Y. Tsunoda (^{70}Fe→^{70}Co →^{70}Ni)

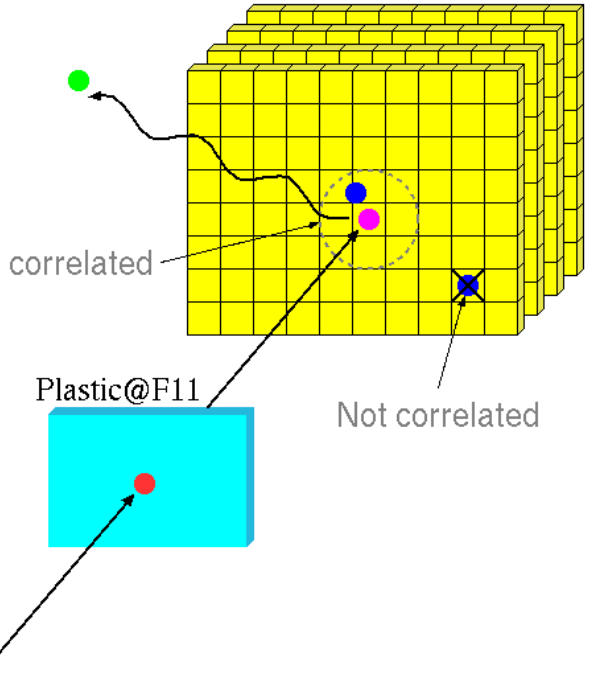
- **NP112-RIBF93:** **A. Algora, B. Rubio**
  K. Kaneko (^{70}Br→^{70}Se)

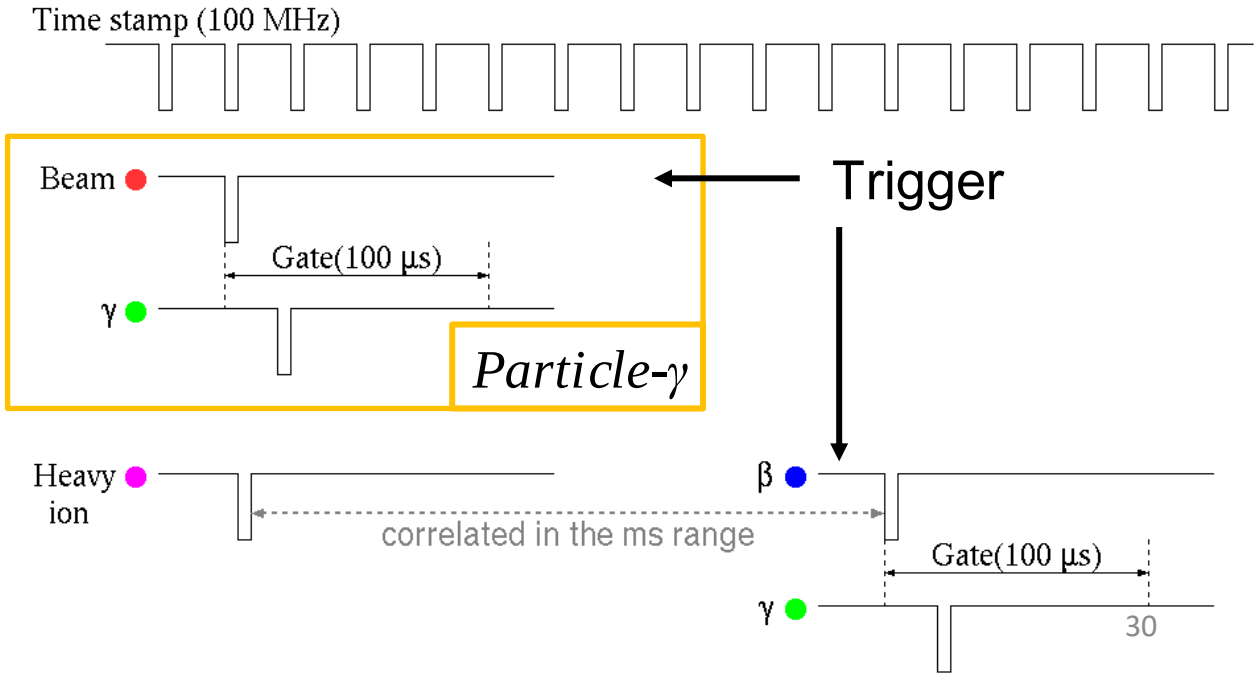
THANK YOU VERY MUCH FOR YOUR ATTENTION

DAQ for decay spectroscopy experiments

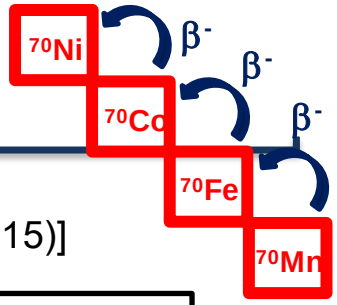
- Independent DAQ systems
- Synchronized using time stamp
- Event build based on time stamp



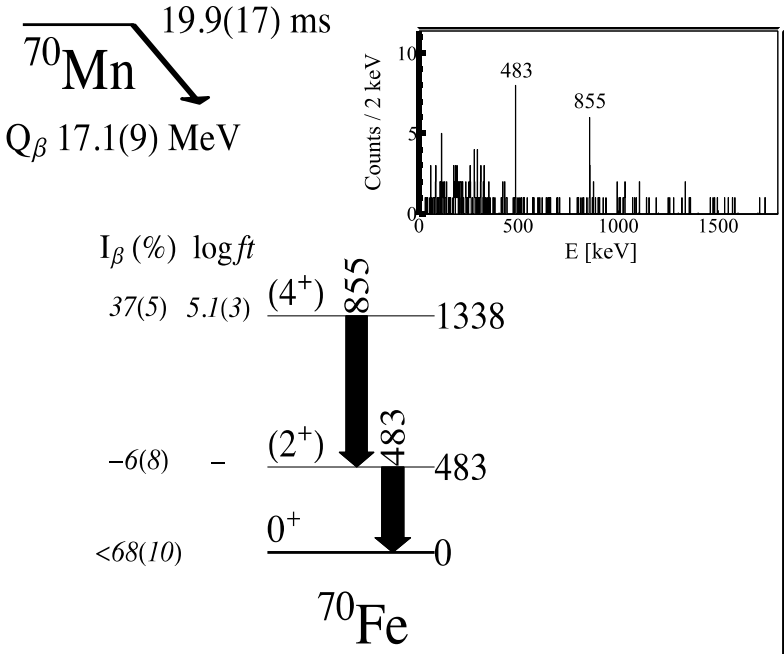


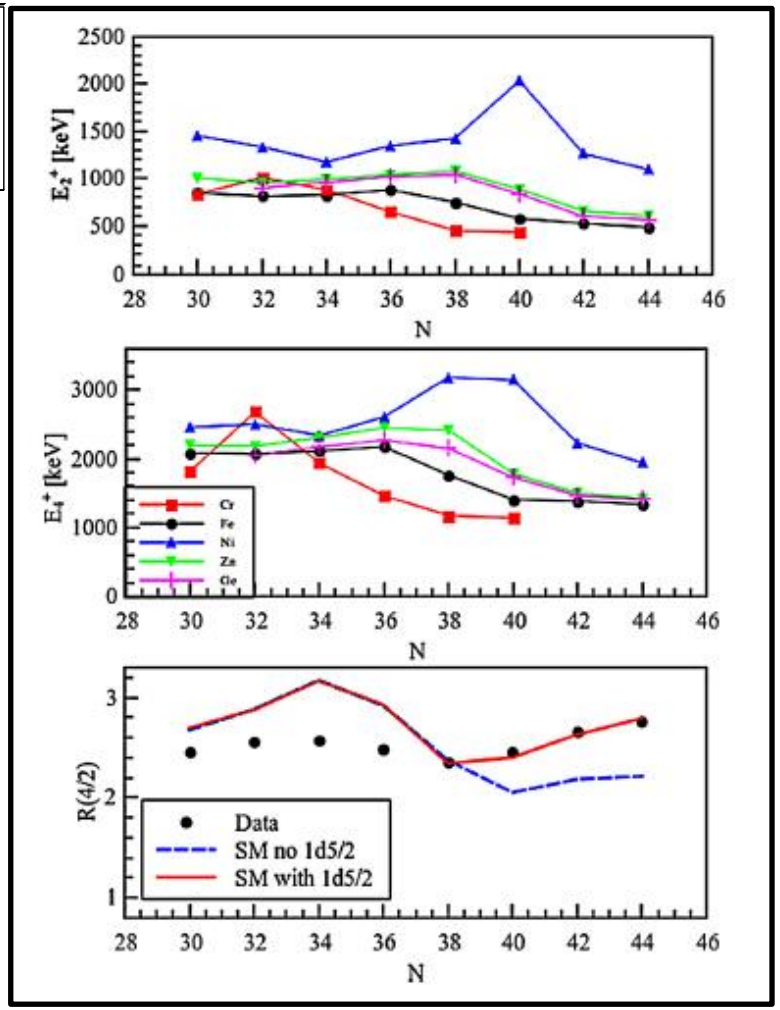


β decay of neutron-rich A=70 isobars



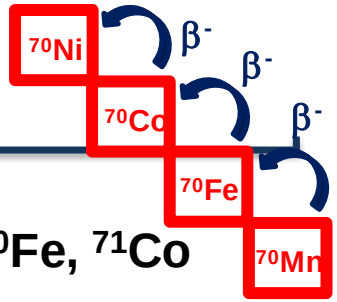
[G. Benzoni et al., PLB (2015)]



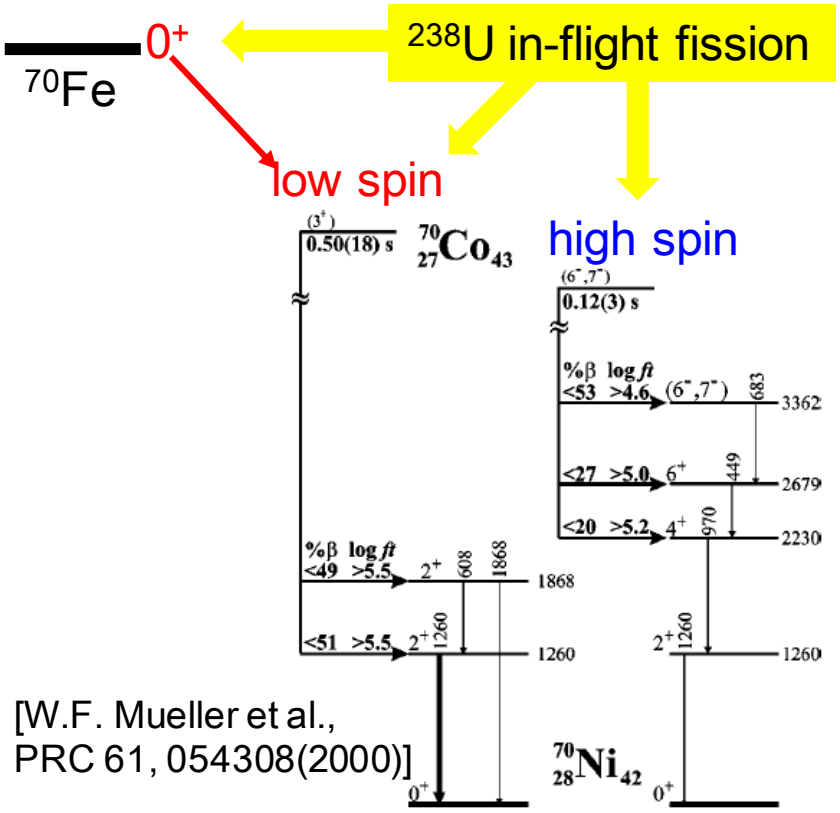


Deformation confirmed in Fe isotopic chain up to N=44 and good comparison with shell-model calculations by group in Naples (Italy)

β decay of neutron-rich A=70 isobars



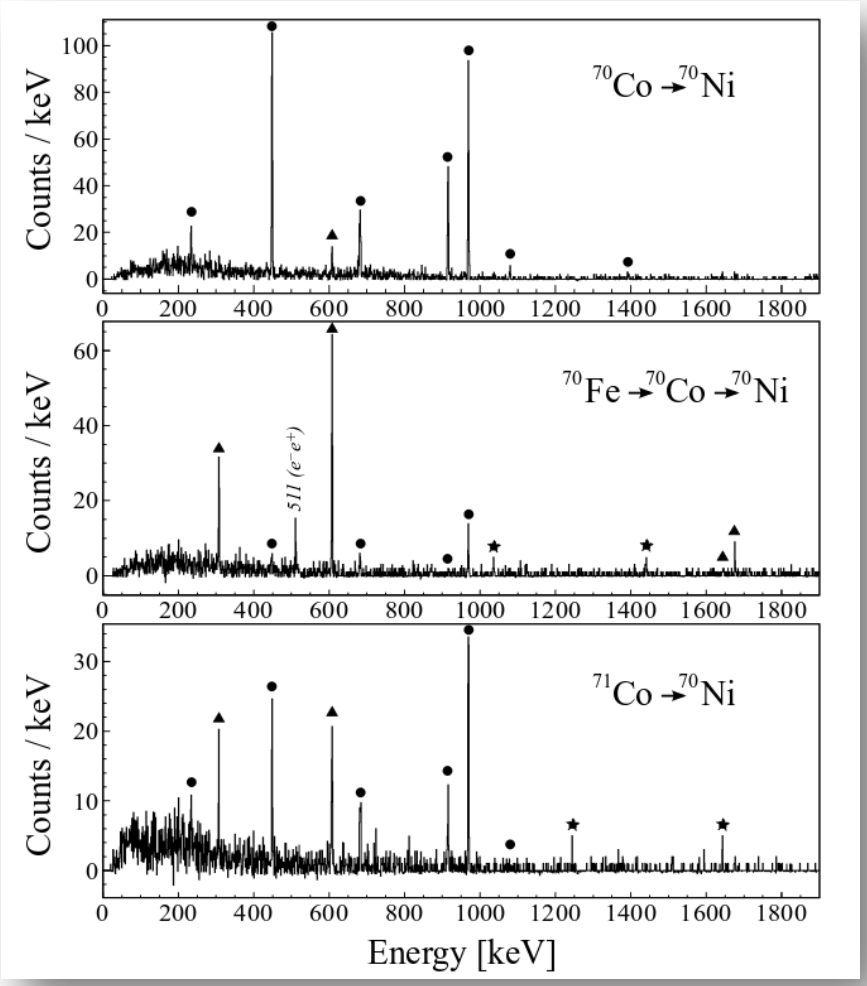
- Two long-lived β-decaying states at high and low spins in ^{70}Co
- Low-spin β-decaying state in ^{70}Co isolated via the β decay of ^{70}Fe
- Selectively populate low-spin states in ^{70}Ni



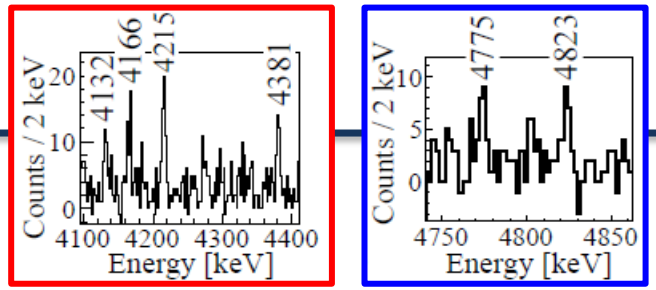
[W.F. Mueller et al., PRC 61, 054308(2000)]

➢ **3 progenitors: ^{70}Co, ^{70}Fe, ^{71}Co**

* Gate on 1259-keV transition



β decay ^{70}Co (low spin) → ^{70}Ni

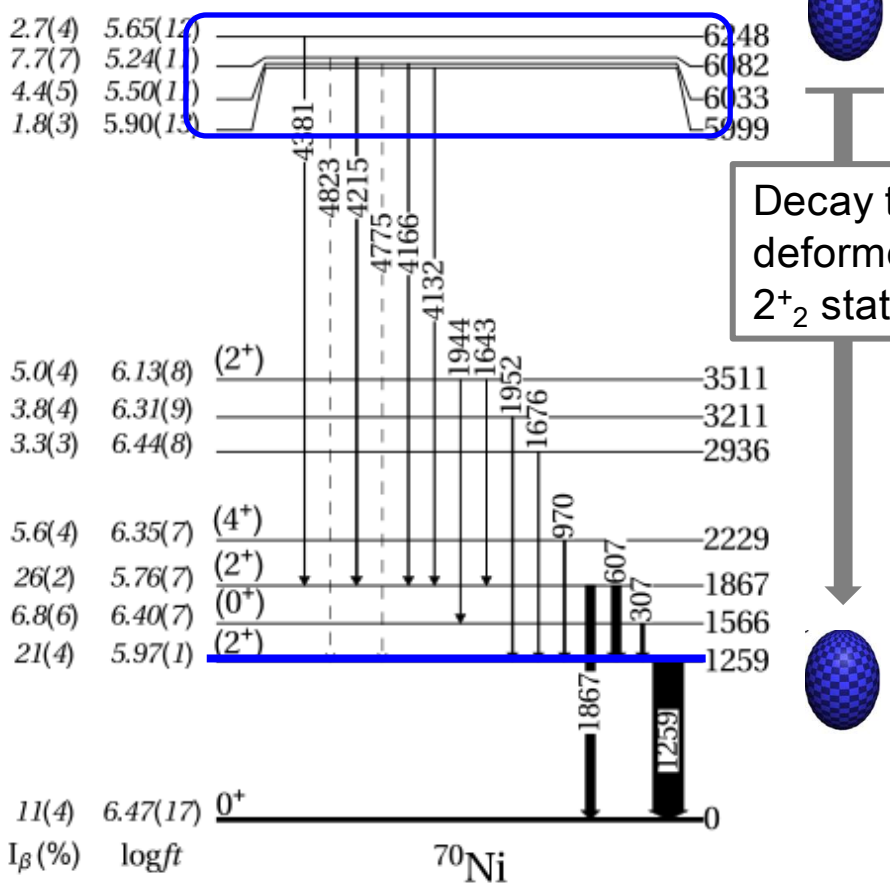


- **Significant population of levels at 6 MeV**

low spin

^{70}Co

$T_{1/2}$ = 508(7) ms

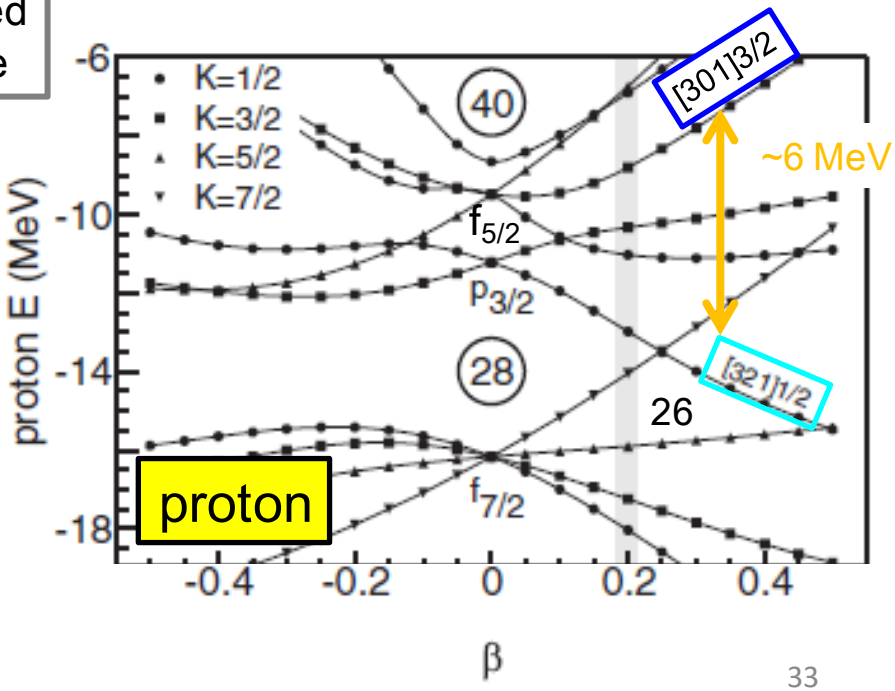


Decay to deformed 2^+_2 state

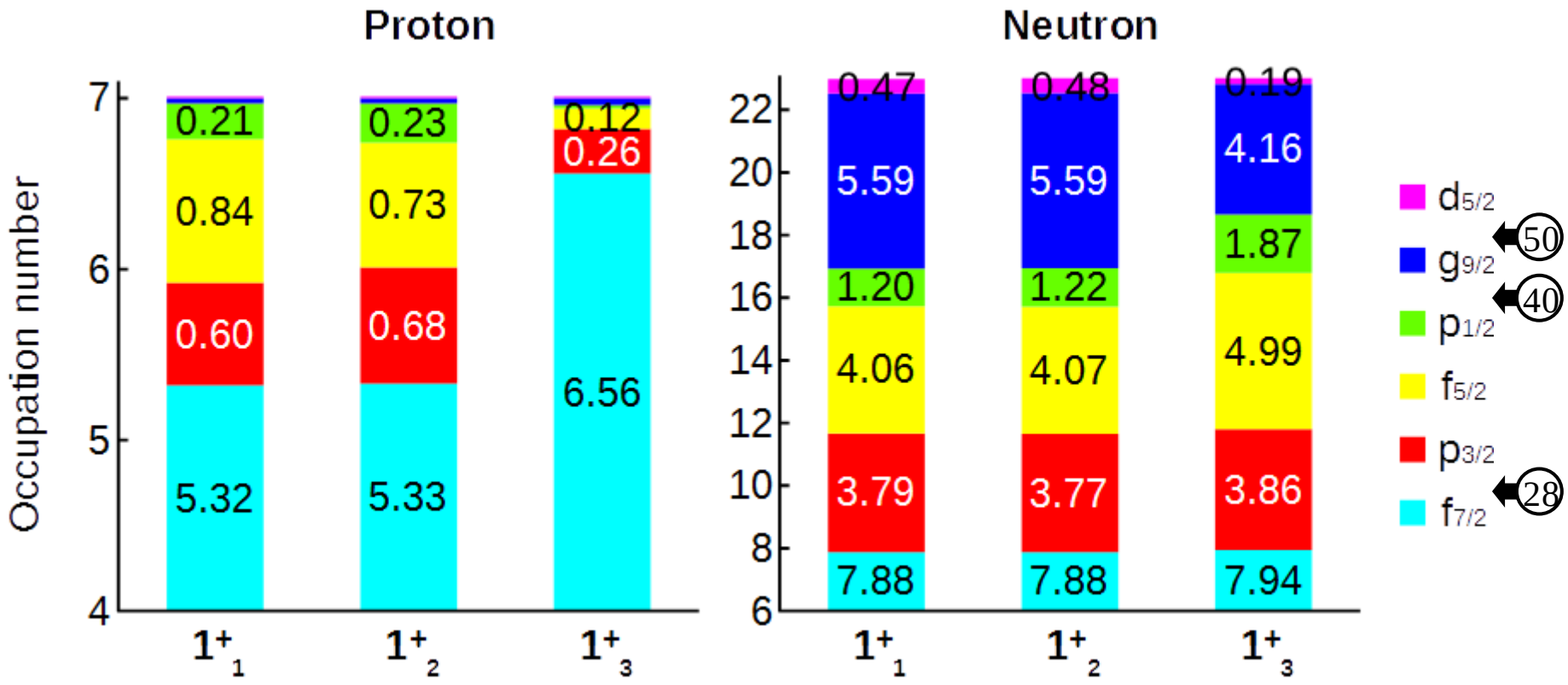
allowed-unhindered

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

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



β decay ^{70}Fe→^{70}Co

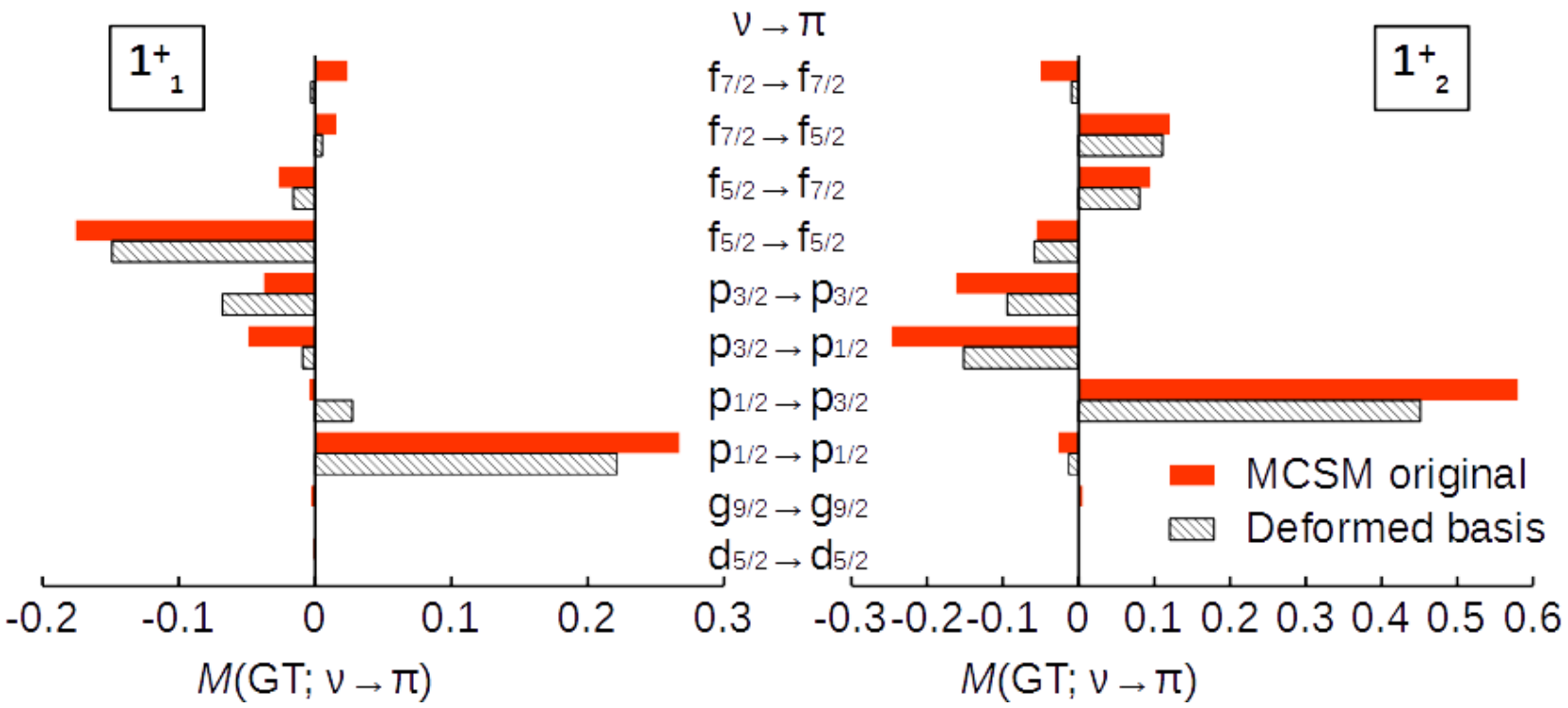


MCSM wave functions of the three 1^+ states in ^{70}Co

- $1^+_{1,2}$: 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→^{70}Co



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