UNIVERSITÀ DEGLI STUDI DI MILANO

INFN
Istituto Nazionale di Fisica Nucleare

Connecting Shape Coexistence at Spin 0 to Superdeformation at High Spins

Silvia Leoni – University of Milano and INFN

In collaboration with:

- **R.V.F. Janssens** et al., University of Noth Carolina and TUNL, USA
- **B. Fornal** et al., Institute of Nuclear Physics, Krakow, Poland
- **N. Mărginean** et al., IFIN HH, Bucharest, Romania
- **C. Michelagnoli** et al., ILL, Grenoble, France
- **T. Otsuka and Y. Tsunoda**, University of Tokyo, Japan

Nuclear Physics Over The Years: From the high spin era to rare isotopes

Sep 19, 2025, 8:00 AM → Sep 20, 2025, 2:00 PM America/New_York

Sun Flower Room (Friday Conference Center, UNC Chapel Hill)

Description CELEBRATING THE CAREER AND CONTRIBUTIONS OF ROBERT V. F. JANSSENS

Dear Robert,

GREETINGS, CONGRATULATIONS and BEST WISHES from the Milano Spectroscopy gruoup - University of Milano and INFN !!!!

Angela Bracco

Benedicte Million

Franco Camera

a lot of excitement even with an ocean in between ! !!

Gianluca Colò

Enrico Vigezzi

Oliver Wieland

Fabio Crespi

Agnese Giaz

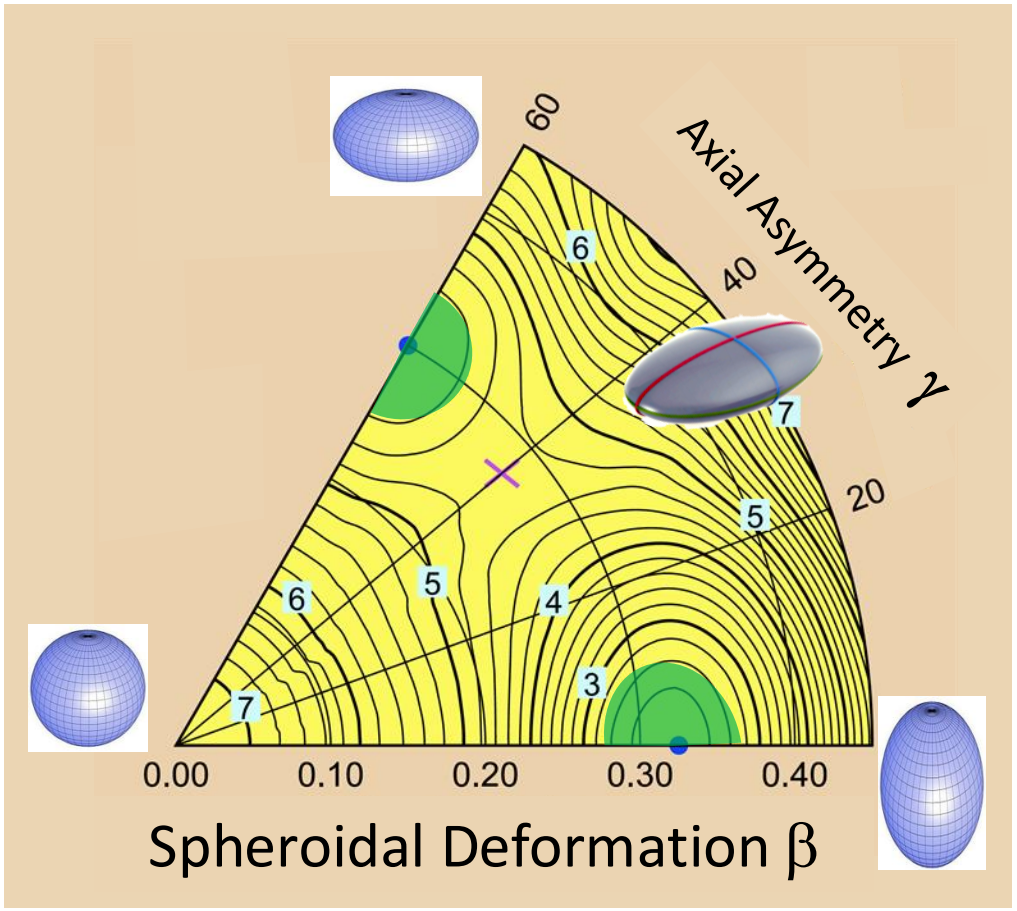
Simone Bottoni (post-doc in Argonne in 2015-2016)

Carlo Barbieri

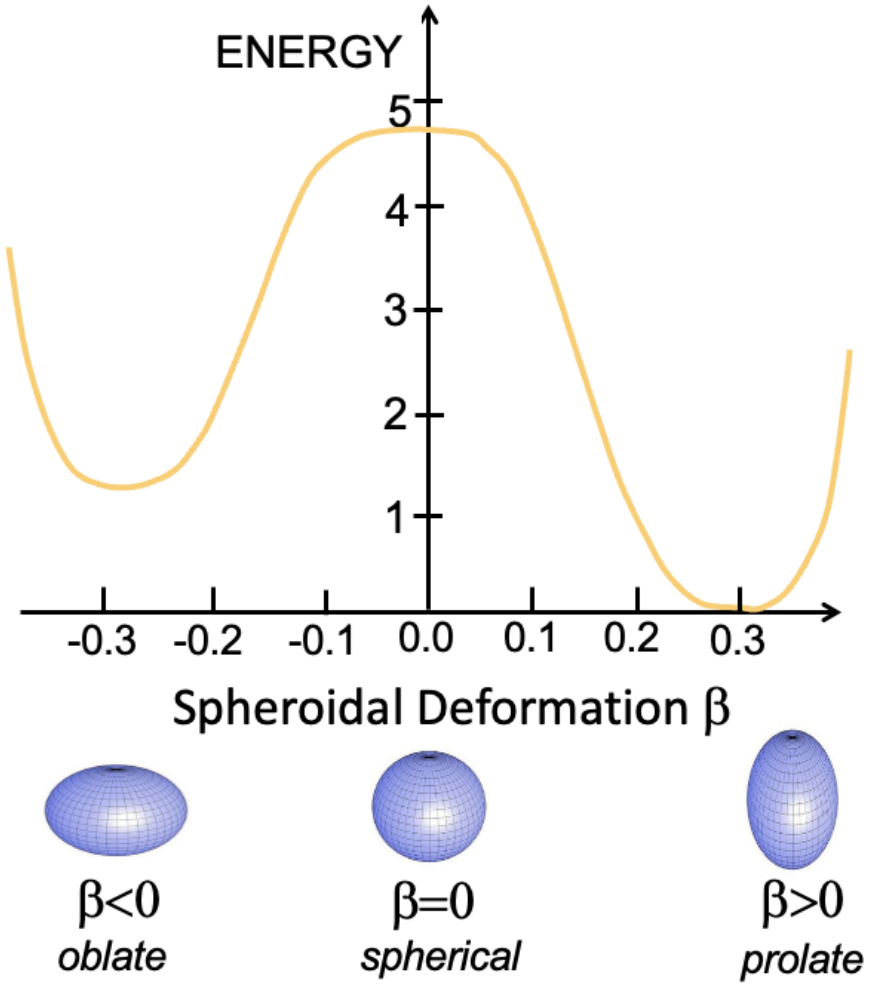
Roca Maza Javier

Potential Energy Surface (PES) of a NUCLEUS

two-dimensional contour



one-dimensional representation

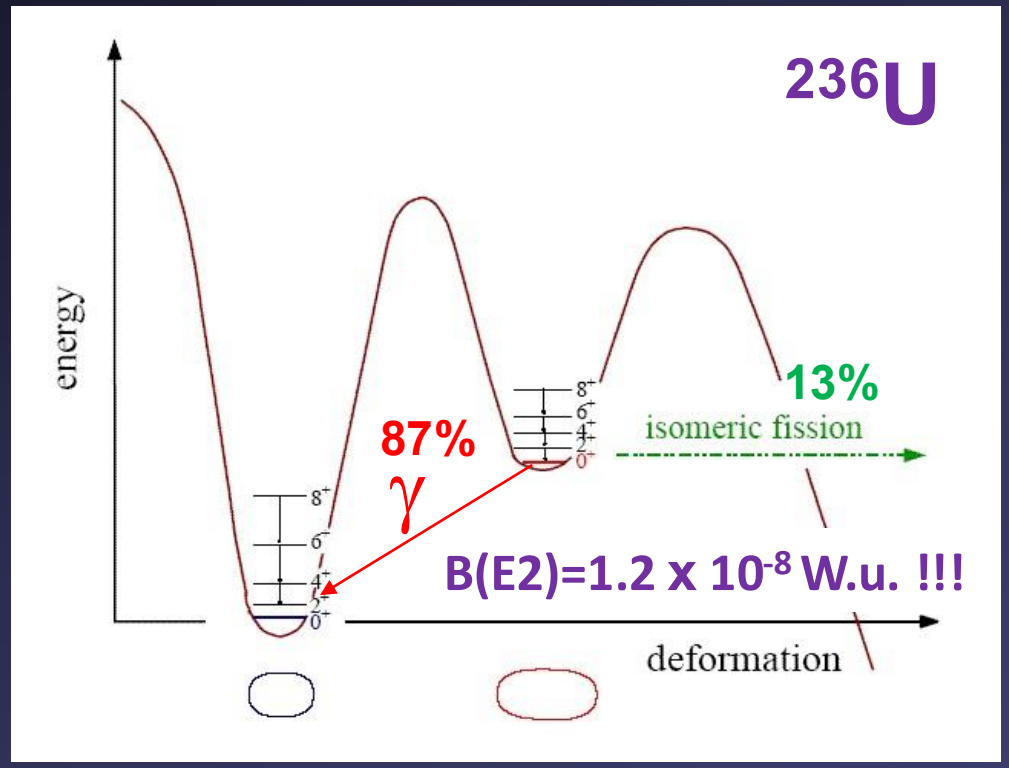


Appearence of <u>different shapes</u>
at comparable excitation energies

First evidence for Shape Coexistence ('60s)

Fission SHAPE ISOMERS - very peculiar metastable states

- HIGH Potential BARRIER
- Nucleus trapped In the minimum
- very retarded photon decay (***10^8 hindrance***)



$$HF = \frac{T_{1/2\gamma}\,(EXP)}{T_{1/2\gamma}\,(1\ W.u.\ estimate)}$$

K.E. Löbner PLB26, 369 (1968)

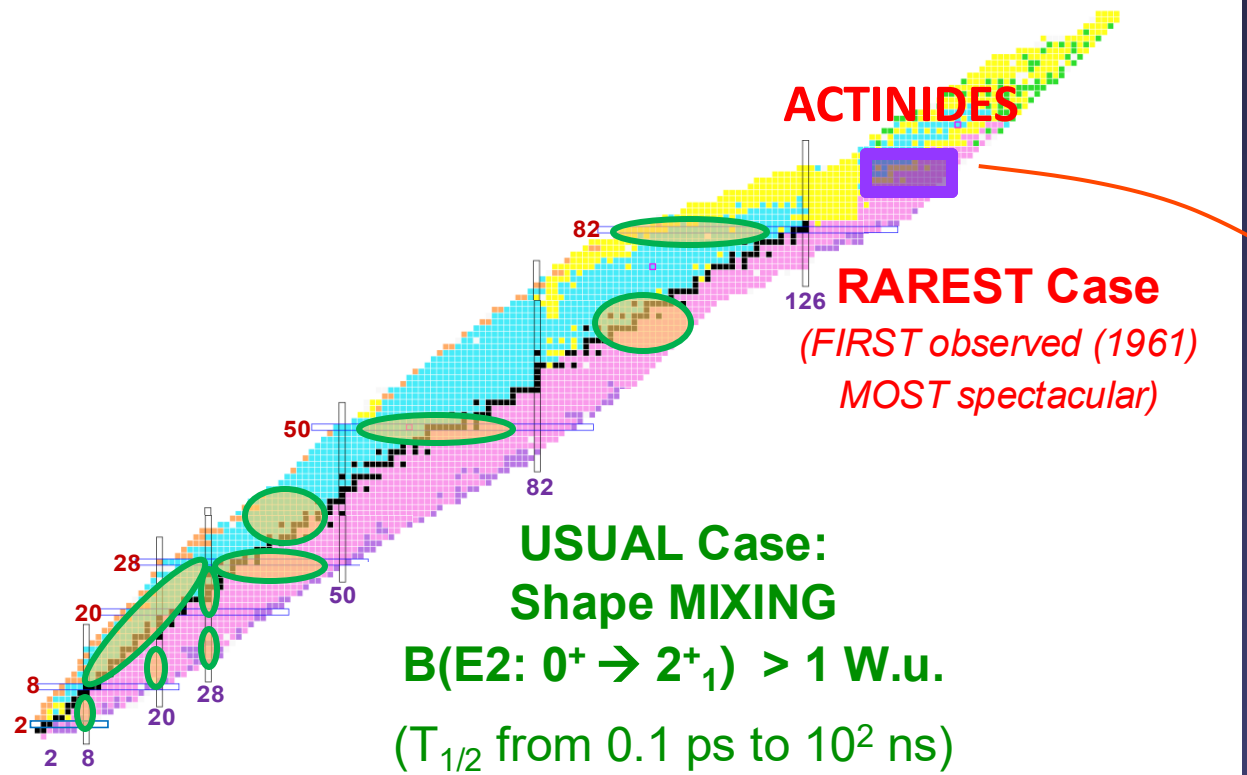
Structures living in "separate worlds"

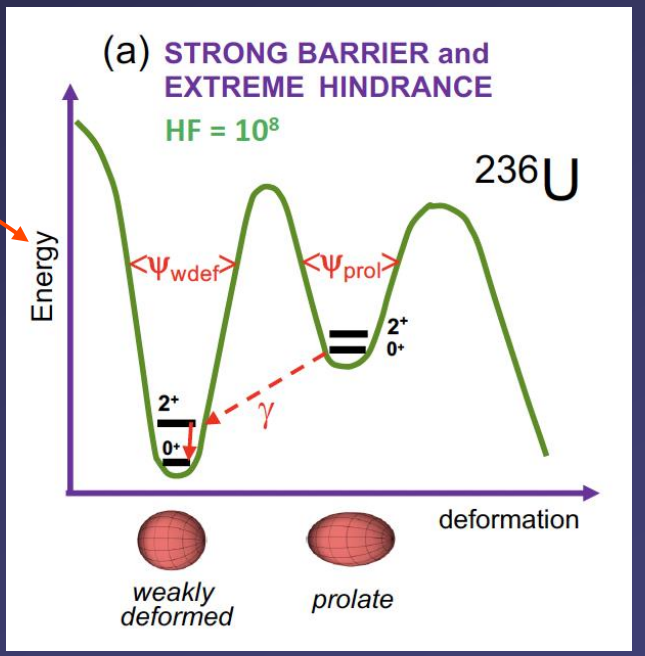
P. Thirolf, D. Habs, Prog. Part. Nucl. Phys. 49 (2) (2002) 325

P. Reiter, D. Habs, D. Schwalm, P. Thirolf, Eur. Phys. J. A61 (2025) 158

60 years of Shape coexistence studies at I≈0

"An ubiquitous phenomenon across the nuclear chart"





Fission Shape ISOMERS

($T_{1/2}$ ~10^2 ns)

B(E2: $0^+ \rightarrow 2^+_1$) ~10^{-8} W.u.

"Two Worlds Apart"

In general, NO HINDRANCE observed
for decay between different shapes, even if isomeric
i.e., B(E2) ≳ 1 W.u.

K. Heyde and J. L. Wood, Rev. Mod. Phys. 83, 1467 (2011)

P.E. Garrett, M. Zielińska, E. Clément, Prog. Part. Nucl. Phys. 124,103931 (2022)

S. Leoni, B. Fornal, A. Bracco, Y. Tsunoda, T. Otsuka, Prog. Part. Nucl. Phys. 139, 104119 (2024) → *SURVEY of 0^+ states from Ca to U*

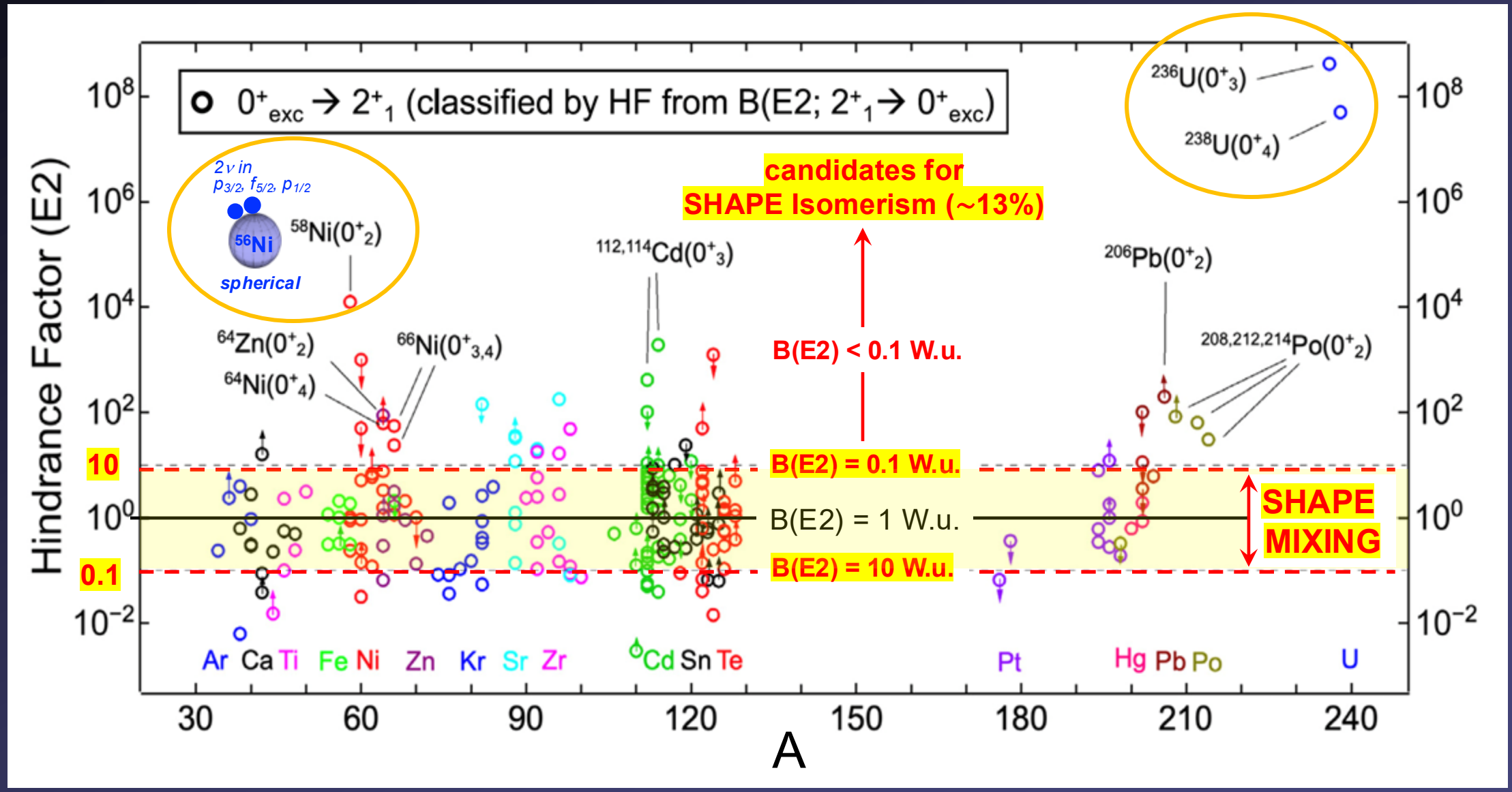
Survey of HINDRANCE (E2) factors for 0^+ states

in the proximity of Z = 20, 28, 40, 50, 82

S. Leoni, B. Fornal, A. Bracco, Y. Tsunoda, T. Otsuka, Prog. Part. Nucl. Phys. 139, 104119 (2024)

$$HF = \frac{T_{1/2\gamma}\,(EXP)}{T_{1/2\gamma}\,(1\ W.u.\ estimate)}$$

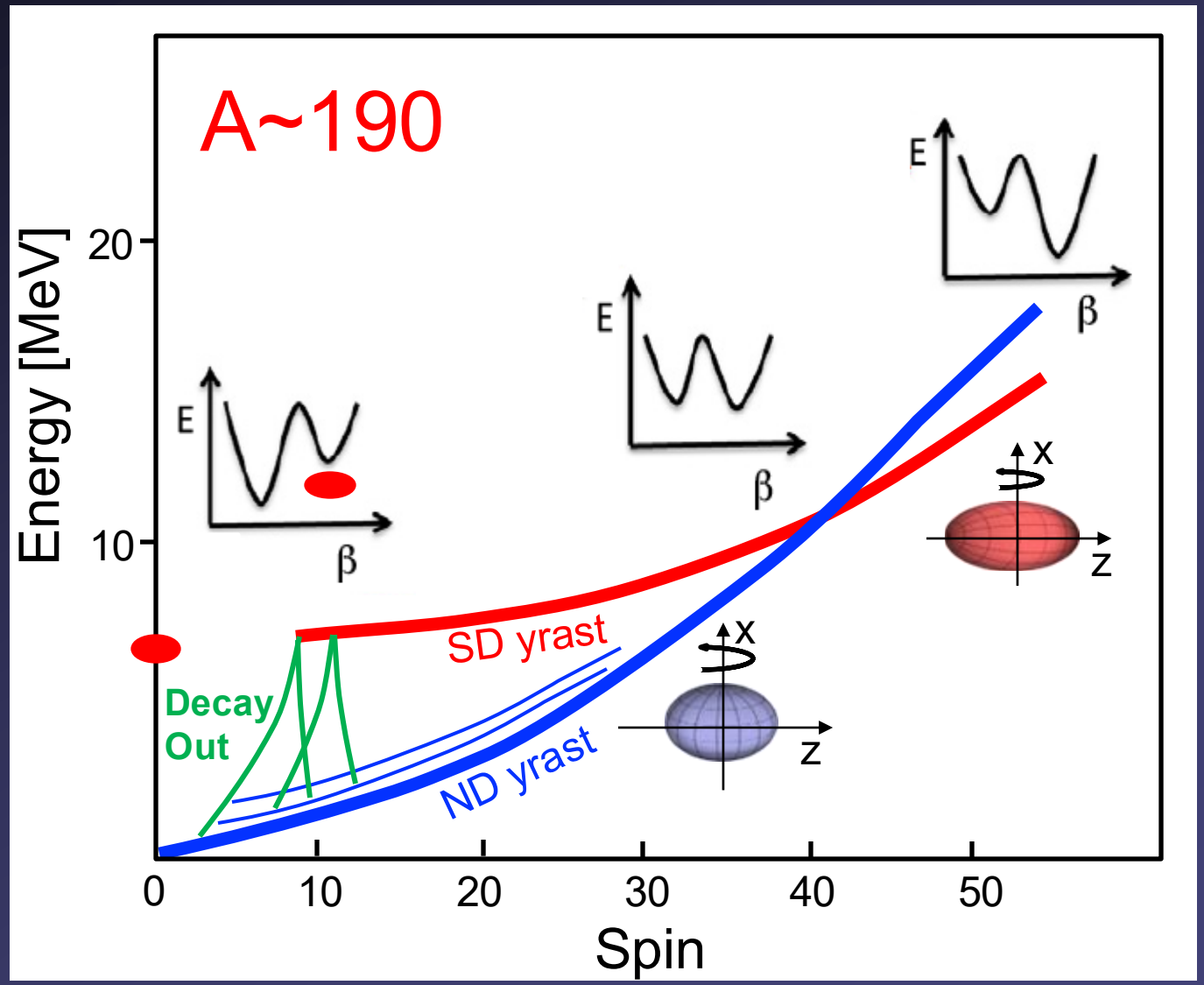
K.E. Löbner PLB26, 369 (1968)



at HIGH spins: enhanced population of states in highly deformed secondary minima

HF
10^2-10^4

Hindrance Factors from LINKING transitions at decay-out Spin
available only for
12 SD bands
(out of >**350**)



*from **Heyde and Wood**, Rev. Mod. Phys. 83(2011):*

Shape coexistence at spin 0 and superdeformation are two faces of the same medal

«Achieving a unified description of SD band structures and low-spin coexistence structures remains a major unsolved problem in nuclear physics»

OUR AIM

CONNECT *in Exp. and Theory*

Shape Coexistence at Spin 0
and Superdeformation at High Spins

focusing on cases where wave functions are well localized
in different PES minima
separated by a sizable barrier

B(E2) << 1 W.u., HF > 10

Predictions based on Mean Field and EDF

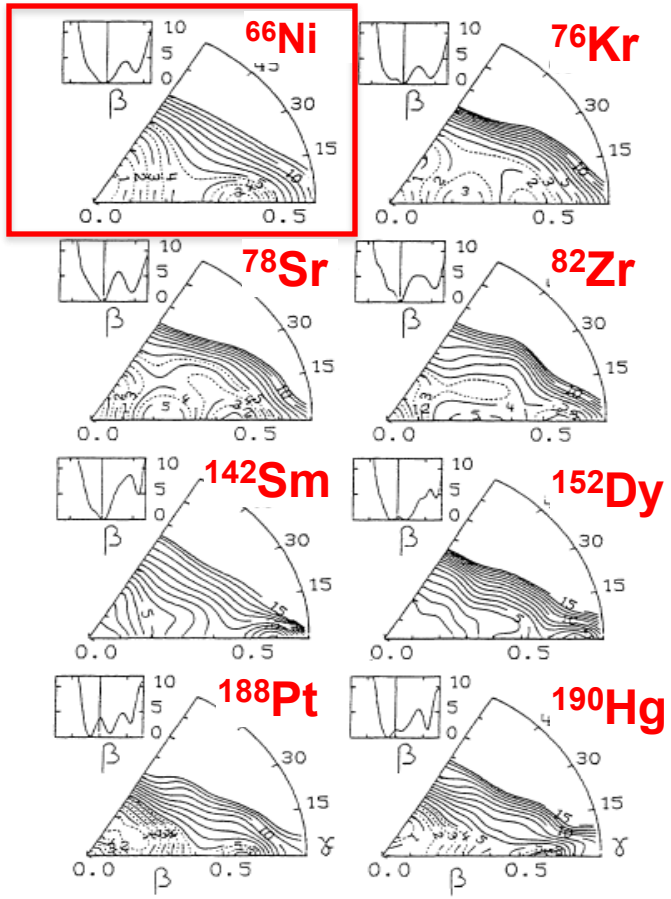
for existence of DEEP Secondary Minima

Mean-Field based predictions

VOLUME 62, NUMBER 21 PHYSICAL REVIEW LETTERS 1989

Hartree-Fock-Bogoliubov Predictions for Shape Isomerism in Neutron-rich Even-Even Nuclei

M. Girod, J. P. Delaroche, D. Gogny, and J. F. Berger
Service de Physique et Techniques Nucléaires, Centre d'Etudes de Bruyères-le-Châtel, BP 12, 91680 Bruyères-le-Châtel, France
(Received 28 December 1988)



Macro-Microscopic Model – P. Moeller et al., 2012

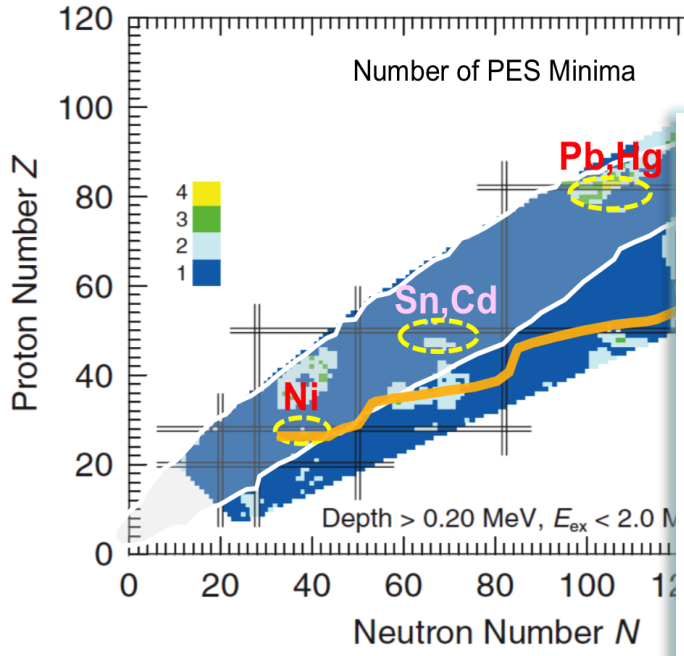
PRL 103, 212501 (2009) PHYSICAL REVIEW LETTERS week ending 20 NOVEMBER 2009

2009

Global Calculation of Nuclear Shape Isomers

Peter Möller,[1,*] Arnold J. Sierk,[1] Ragnar Bengtsson,[2] Hiroyuki Sagawa,[3] and Takatoshi Ichikawa[4,†]

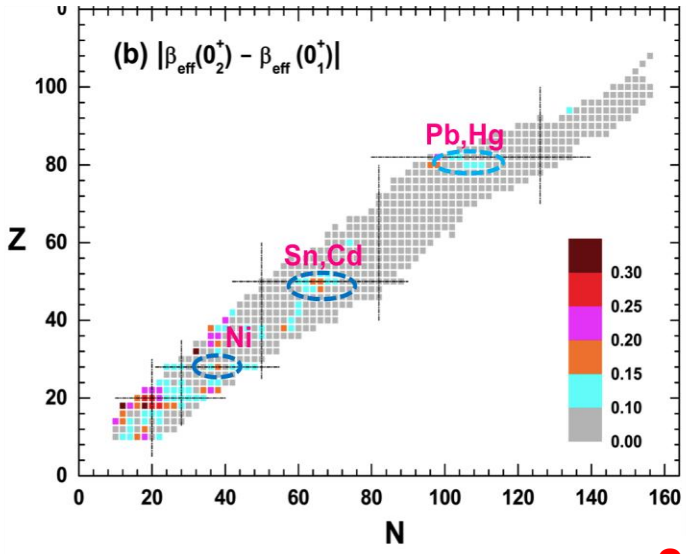
Study of 7206 nuclei from A=31 to A=209



Pb-Hg-Pt	A ~190
Sn-Cd-Pd	A ~110
Ni	A~68

Predictions of SHAPE ISOMERS in Pb-Hg and Sn-Cd by UNIVERSAL ENERGY DENSITY FUNCTIONALS and the quadrupole collective model

D. Vretenar et al.



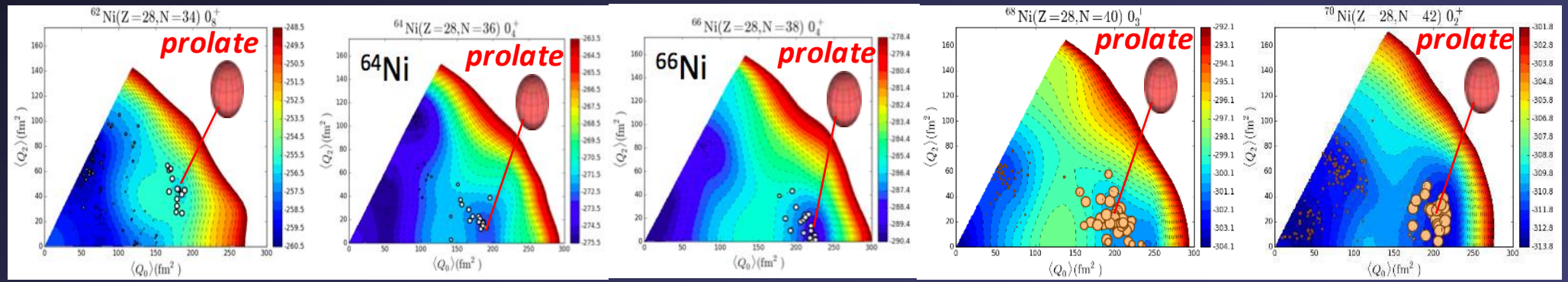
S. Quan et al., PHYSICAL REVIEW C 95, 054321 2017

The Ni chain

historical region to test Shape Coexistence

$A \leq 62$ *High Spin SD bands*

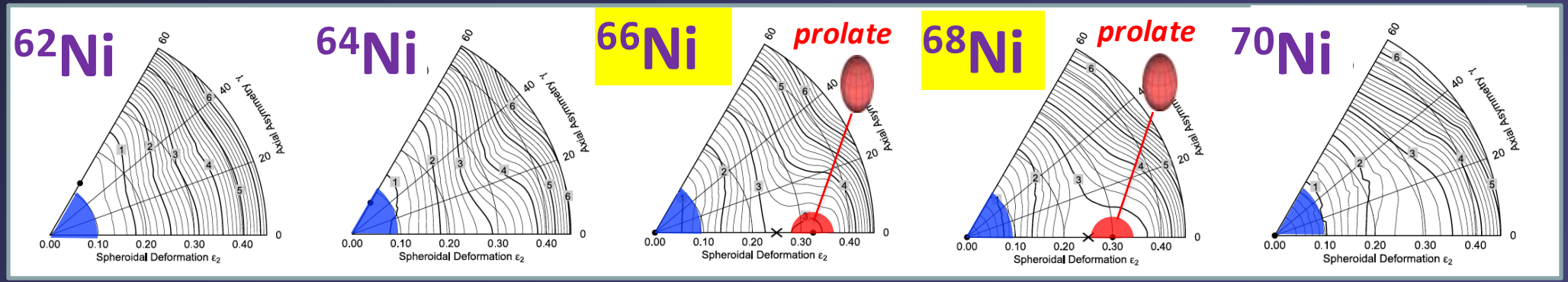
$A > 62$ *Low Spins data only*



SHELL Model

2014 (MCSM): Otsuka, Tsunoda

Lenzi, Nowacki, …



Mean Field

2012: Moeller

'80s: Girod, Gogny

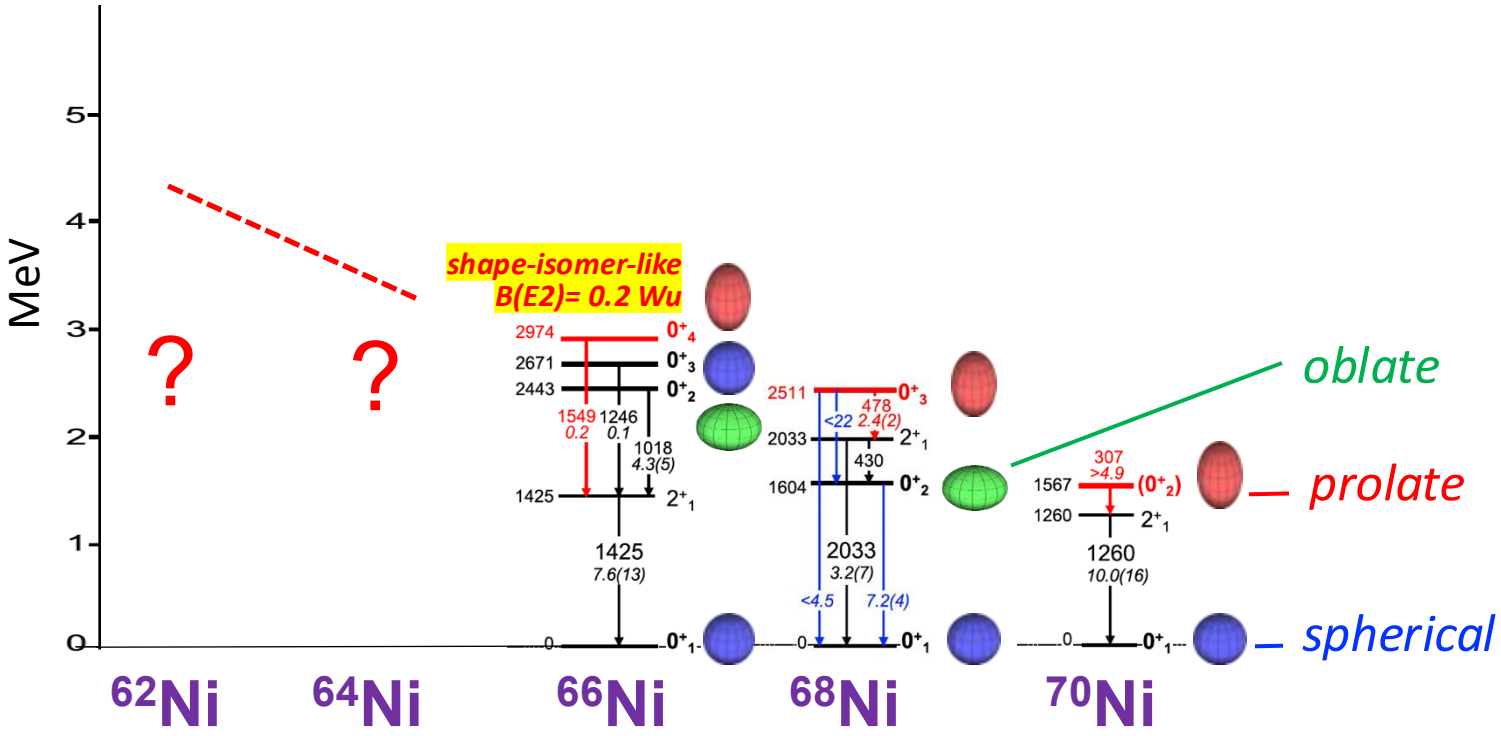
The Ni chain

A ≤ 62 ◄ ····· ► *A > 62*

High Spin SD bands

Low Spins data only

historical region to test Shape Coexistence



68,70Ni: *NSCL data, β decay of 68Co and 70Co*
Crider, ..., Ayangeakaa, …, Janssens et al.,
PLB 763 (2016) 108

66Ni: *IFIN-HH data, sub-barr. 2n transfer*
Leoni, Fornal, Marginean et al.,
PRL118, 162502(2017)

^{64}Ni: 4 experiments in 4 laboratories

to achieve the required experimental sensitivity

1) IFIN-HH (ROSPHERE, Romania): sub-barrier transfer (1p, 2n)
2) ILL (FIPPS, France): neutron capture
3) Argonne (GRETINA,USA): Coulomb excitation
4) TUNL (USA): (γ,γ□)

US tracking array

a multi-observable approach …

(79 co-authors from 25 Institutions)

PHYSICAL REVIEW LETTERS 125, 102502 (2020)

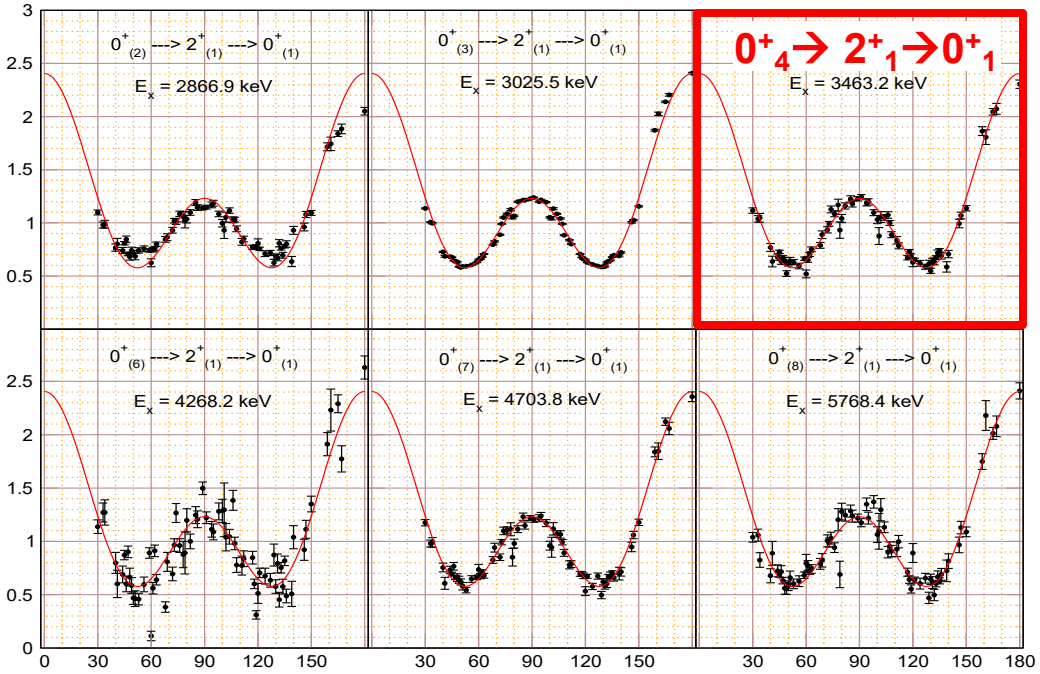
Shape Coexistence at Zero Spin in ^{64}Ni Driven by the Monopole Tensor Interaction

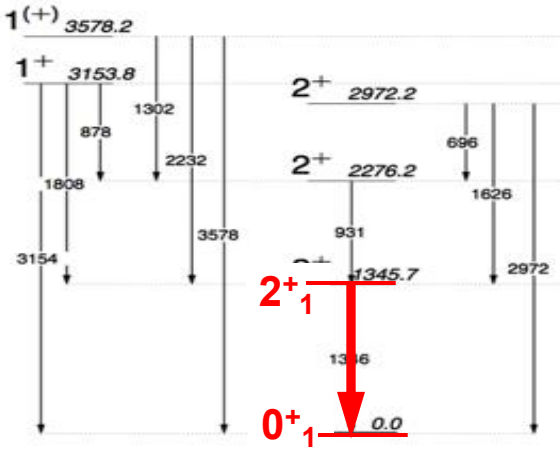
N. Mărginean, D. Little, Y. Tsunoda, S. Leoni, R. V. F. Janssens, B. Fornal, T. Otsuka, C. Michelagnoli, L. Stan, F. C. L. Crespi, C. Costache, R. Lica, M. Sferrazza, A. Turturica, A. D. Ayangeakaa, K. Auranen, M. Barani, P. C. Bender, S. Bottoni, M. Boromiza, A. Bracco, S. Călinescu, C. M. Campbell, M. P. Carpenter, P. Chowdhury, M. Ciemała, N. Cieplicka-Oryńczak, D. Cline, C. Clisu, H. L. Crawford,

Identification of the most impressive set of 0^+ states:

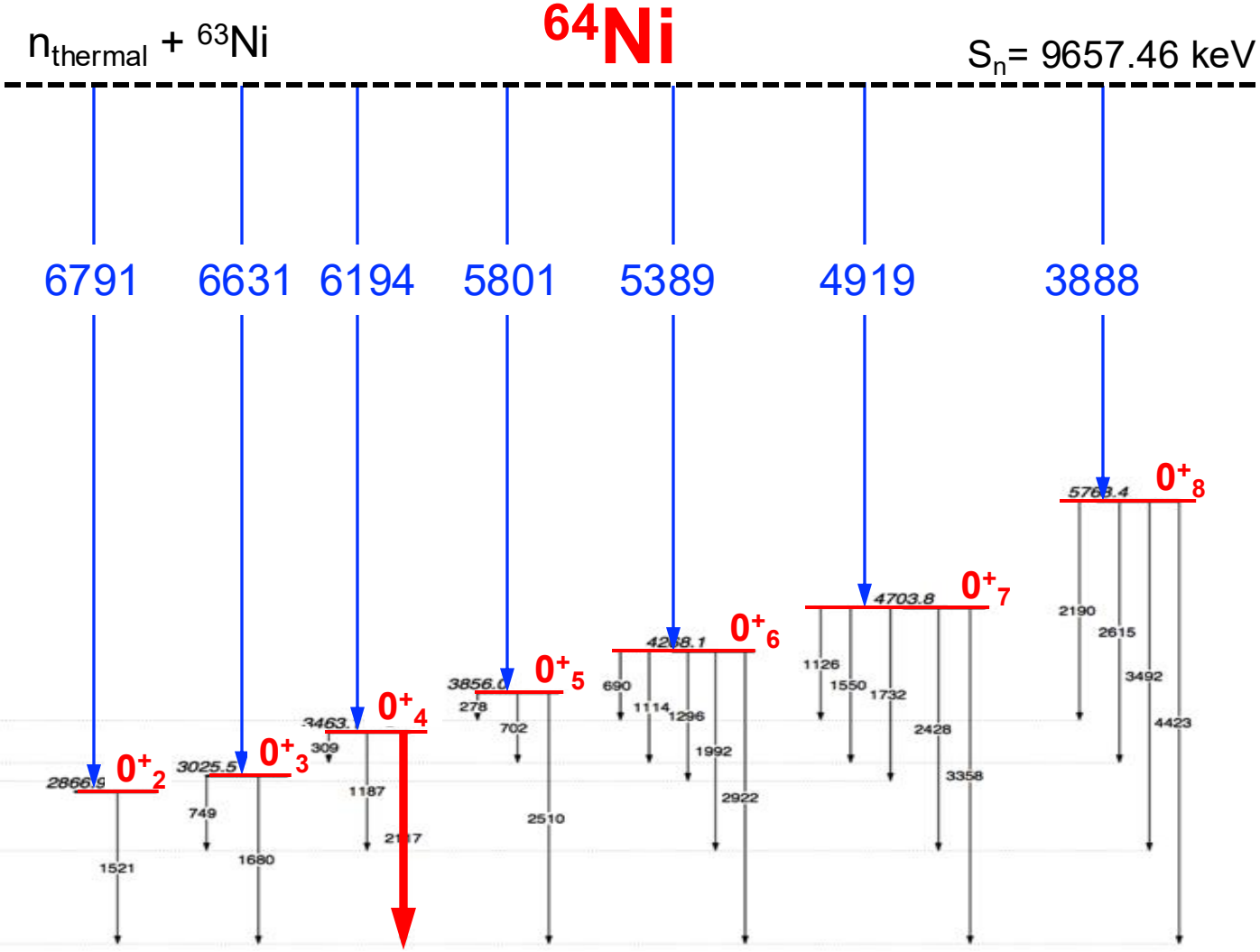
(n,γ) experiment with FIPPS array at ILL (2019) - 2 GigaBq ^{63}Ni target

high-precision γ–γ angular correlations





^{64}Ni

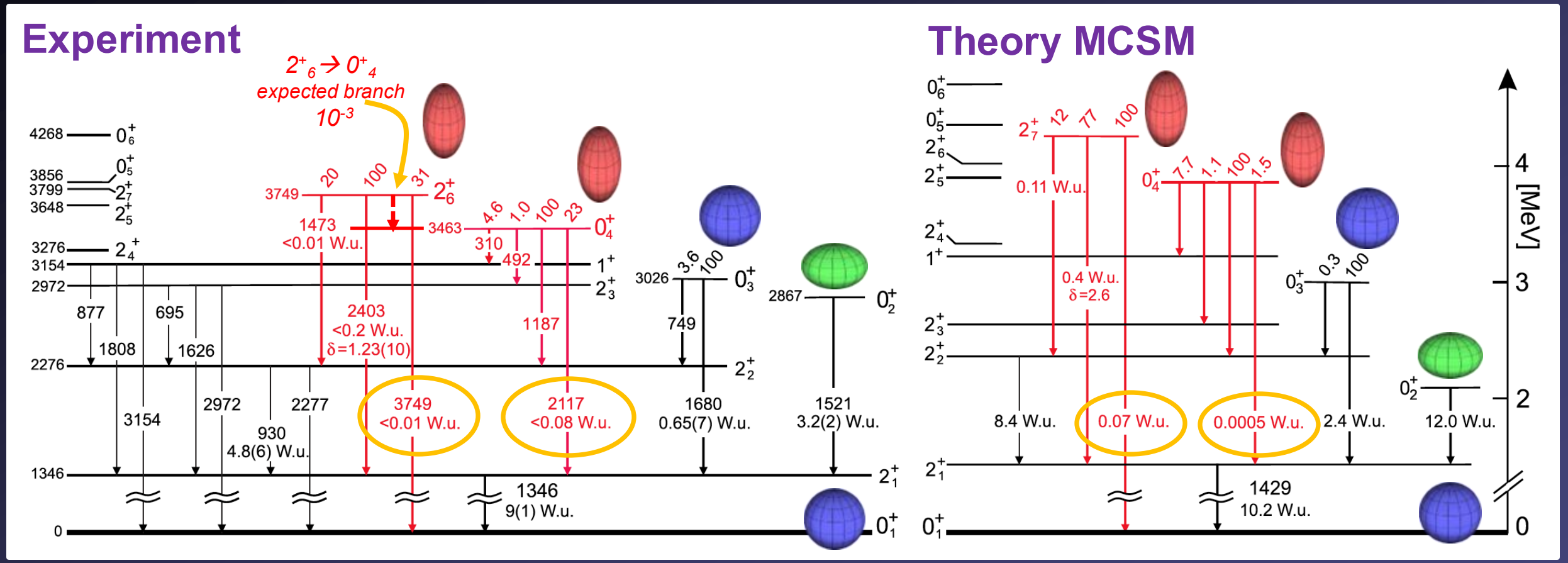


extended decay pattern: *seven 0^+ states, six 2^+ states, ….*

Extended experimental investigation (4 experiments)

decay scheme, state lifetimes, transition rates, …

^{64}Ni



$0^+_4 \rightarrow 2^+_1$ and $2^+_6 \rightarrow 0^+_1$
two E2 transitions strongly hindered !!

Microscopic interpretation

the **TENSOR FORCE** is responsible
for the **coexistence of shapes in ^{64}Ni**
otherwise expected to be spherical !!!

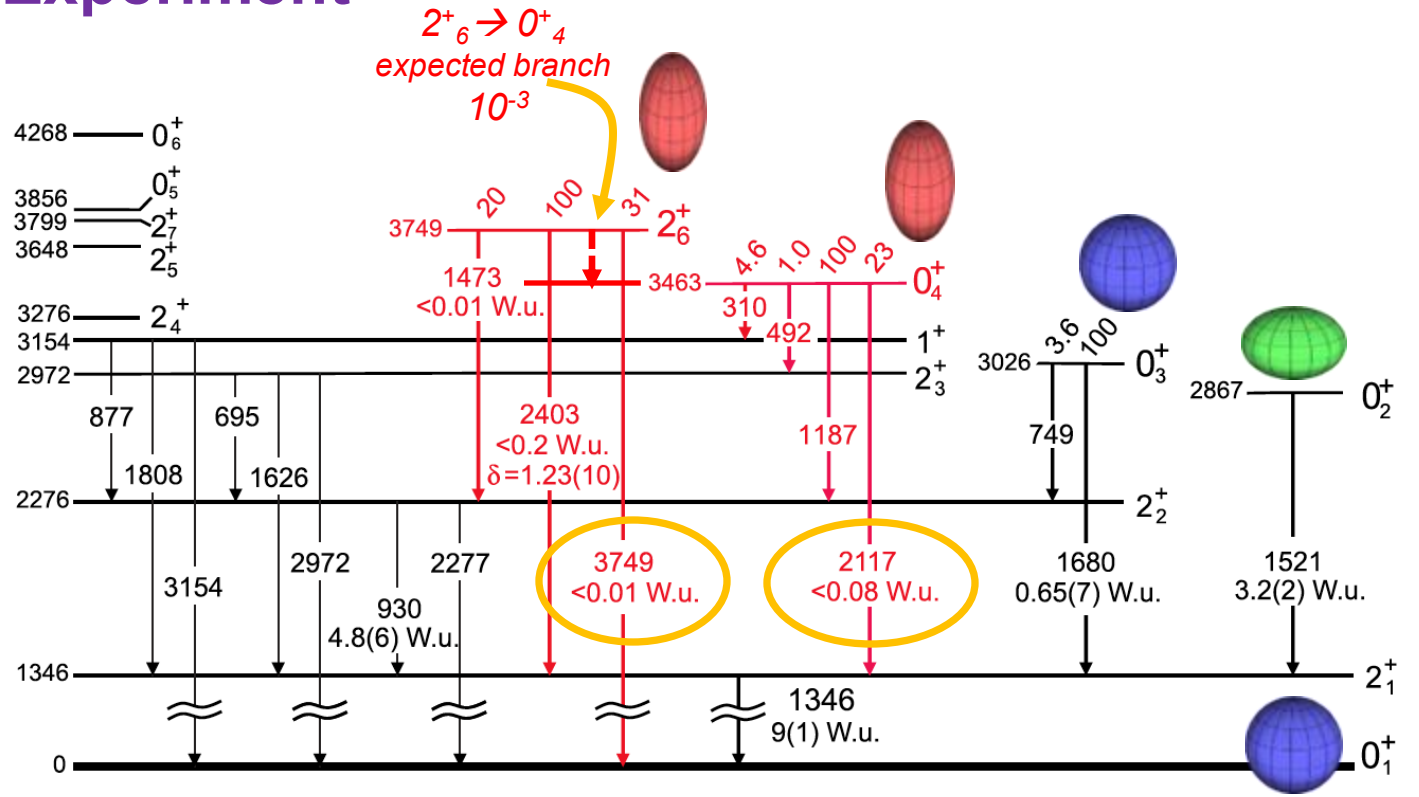
N. Marginean, et al., Phys. Rev. Lett. 125, 102502 (2020)

Extended experimental investigation (4 experiments)

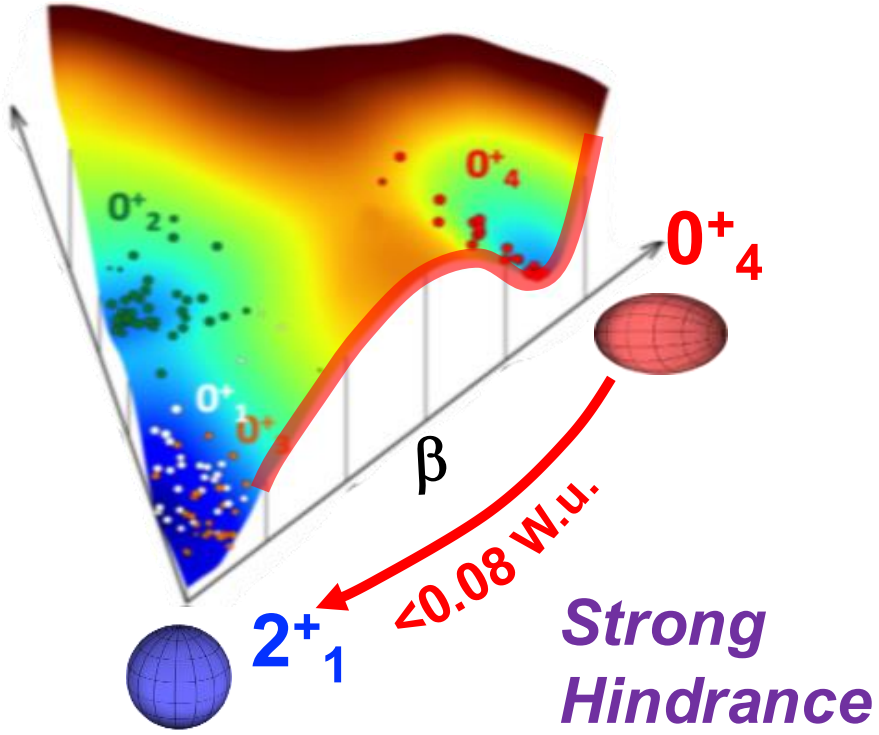
decay scheme, state lifetimes, transition rates, …

^{64}Ni

Experiment



High Potential Energy Barrier



$0^+_4 \rightarrow 2^+_1$ and $2^+_6 \rightarrow 0^+_1$ two E2 transitions strongly hindered !!

Hindrance in the E2 decay caused by shape change: *prolate → spherical*

N. Marginean, et al., Phys. Rev. Lett. 125, 102502 (2020)

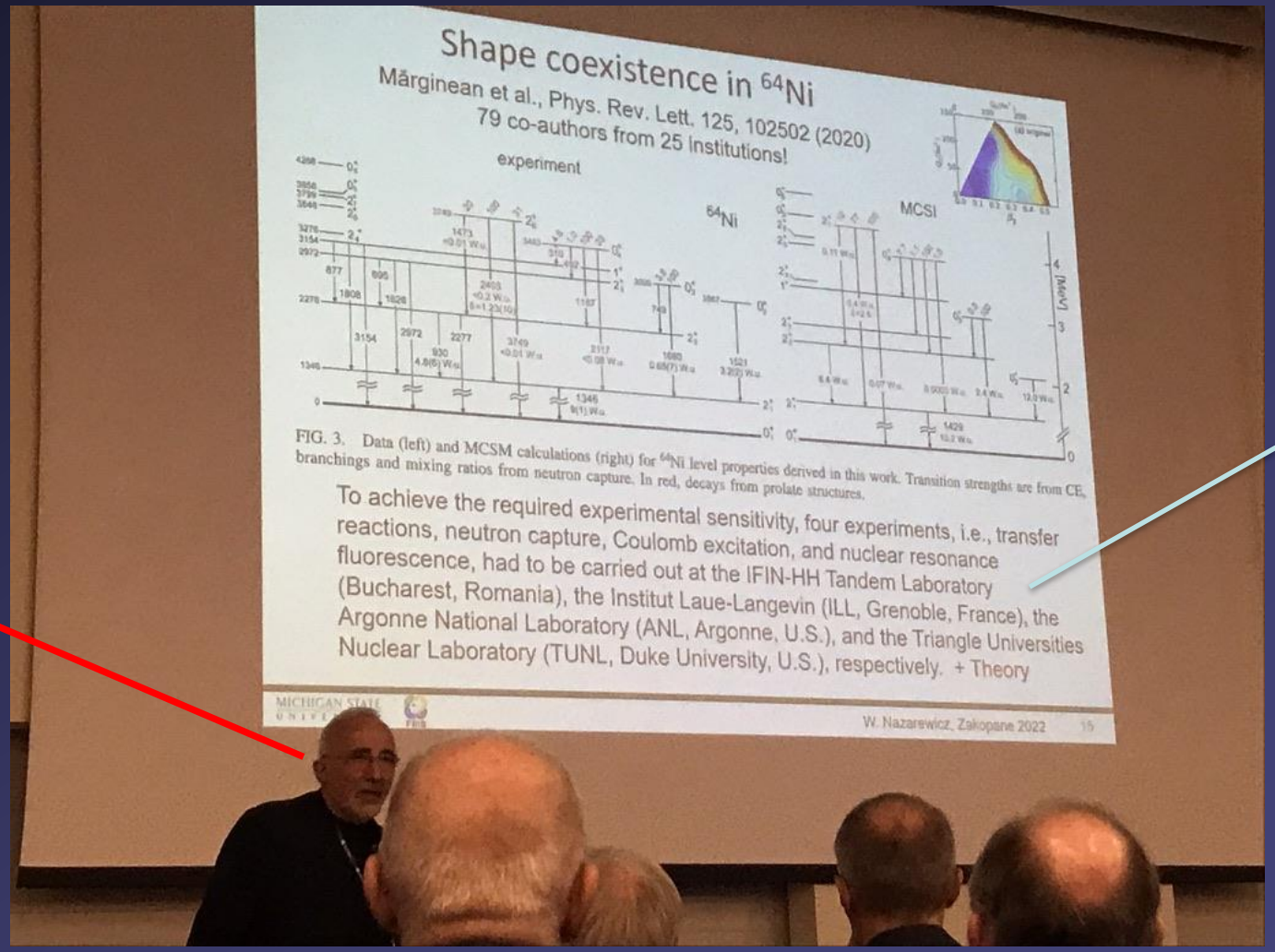
Witold Nazarewicz keynote talk

Zakopane Conference in Nuclear Physics (28/8-3/9 2022)

«Excitement and Challenges in Low-Energy Nuclear Physics: Extending Nuclear Frontiers»

*"... **EXCELLENT EXAMPLE** of **complementarity** of experimental activities ...*

*... **the direction for future experiments of low-energy Nuclear Physics ...**"*



4 experiments in 4 different laboratories !!!

https://zakopane2022.ifj.edu.pl/wp-content/uploads/2022/09/Zakopane2022-WN.pdf

^{64}Ni shape coexistence in 2023 LONG RANGE PLAN

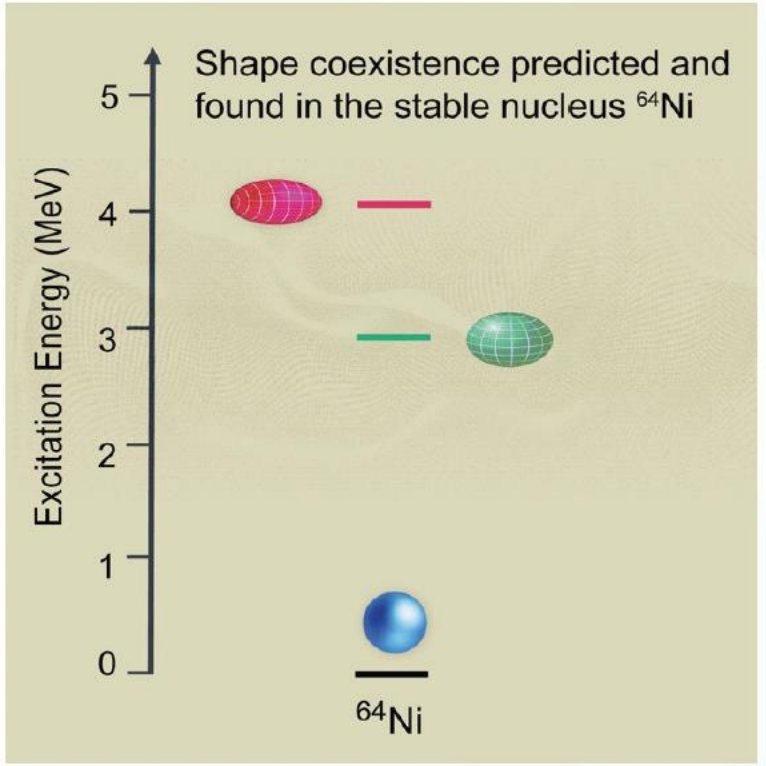
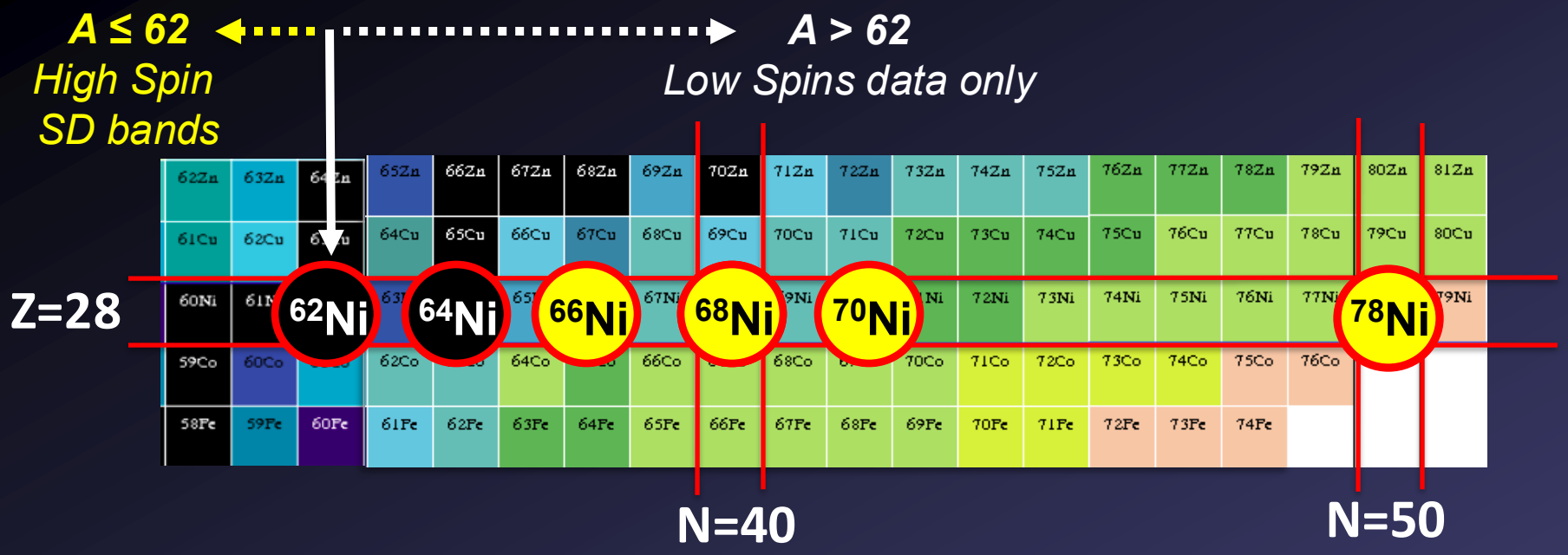


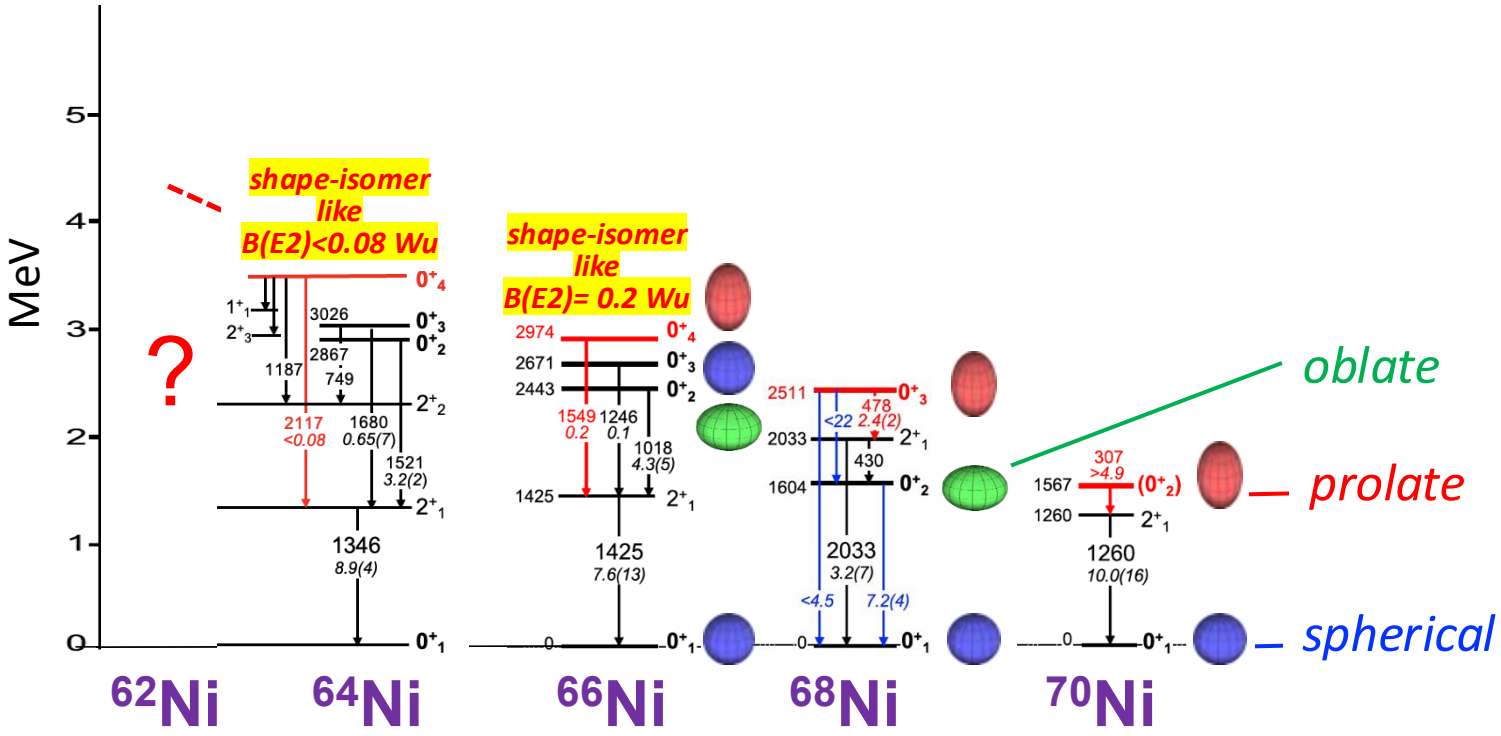
Figure 4.4. The evolution of the nuclear shape in stable nickel-64 as predicted by large-scale nuclear model calculations. *Now, new research has confirmed the coexistence of three nuclear shapes [20].*

Meanwhile, the study of very elongated shapes in nuclei provides a window into nucleonic shell structure at large deformation. Extensive work earlier this century enabled the characterization of nuclear shapes with 2:1 axis ratio. In the coming decade, GRETA at ATLAS is poised to enable the discovery and study of structures with even bigger deviations.

The Ni chain

historical region to test Shape Coexistence





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Crider, ..., Ayangeakaa, …, Janssens et al.,
PLB 763 (2016) 108

66Ni: *IFIN-HH data, sub-barr. 2n transfer*
Leoni, Fornal, Marginean et al.,
PRL118, 162502(2017)

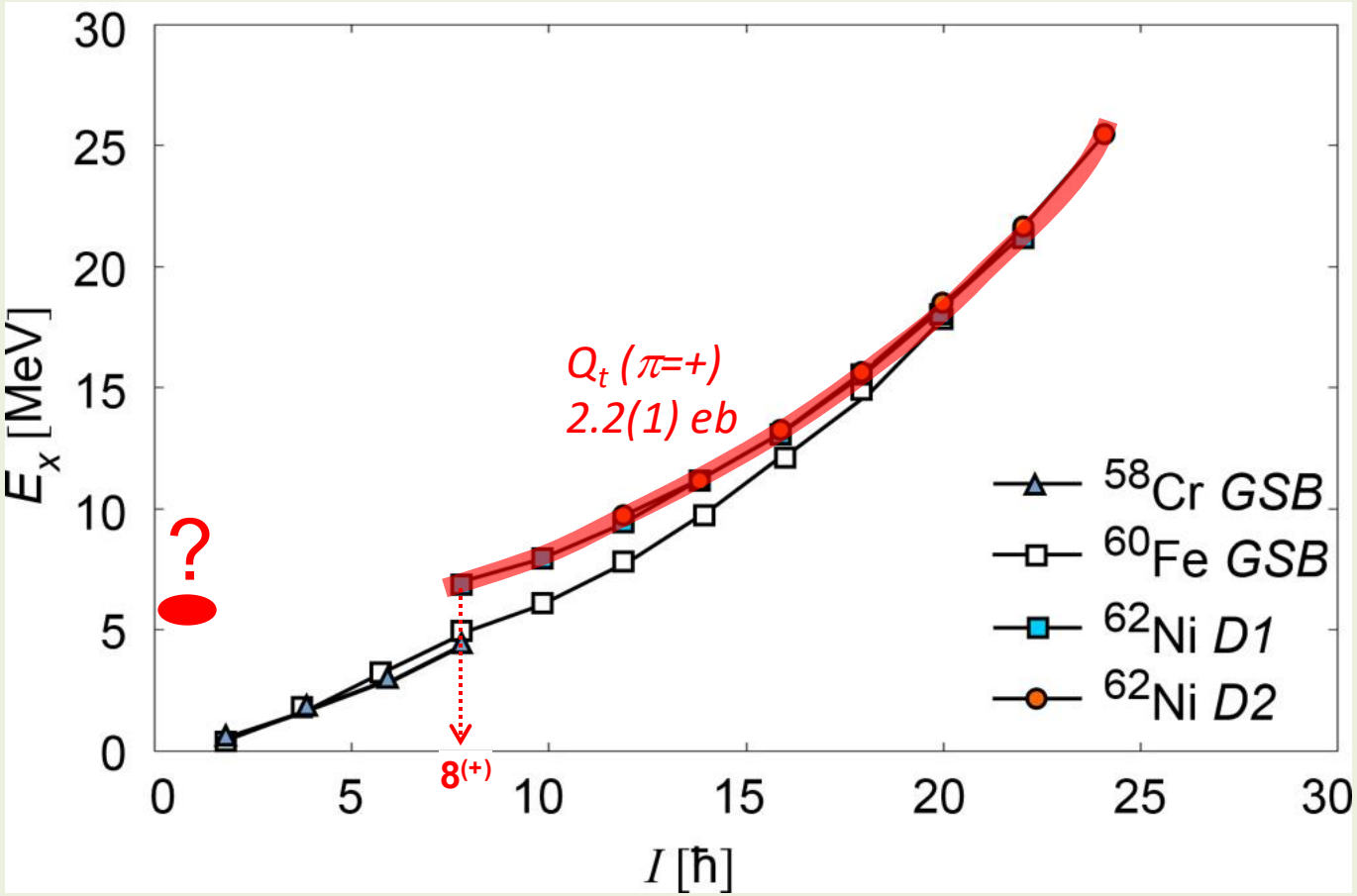
64Ni: *4 experiments*
Marginean et al.,
PRL125, 102502(2020)

HIGH SPIN data in ^{62}Ni

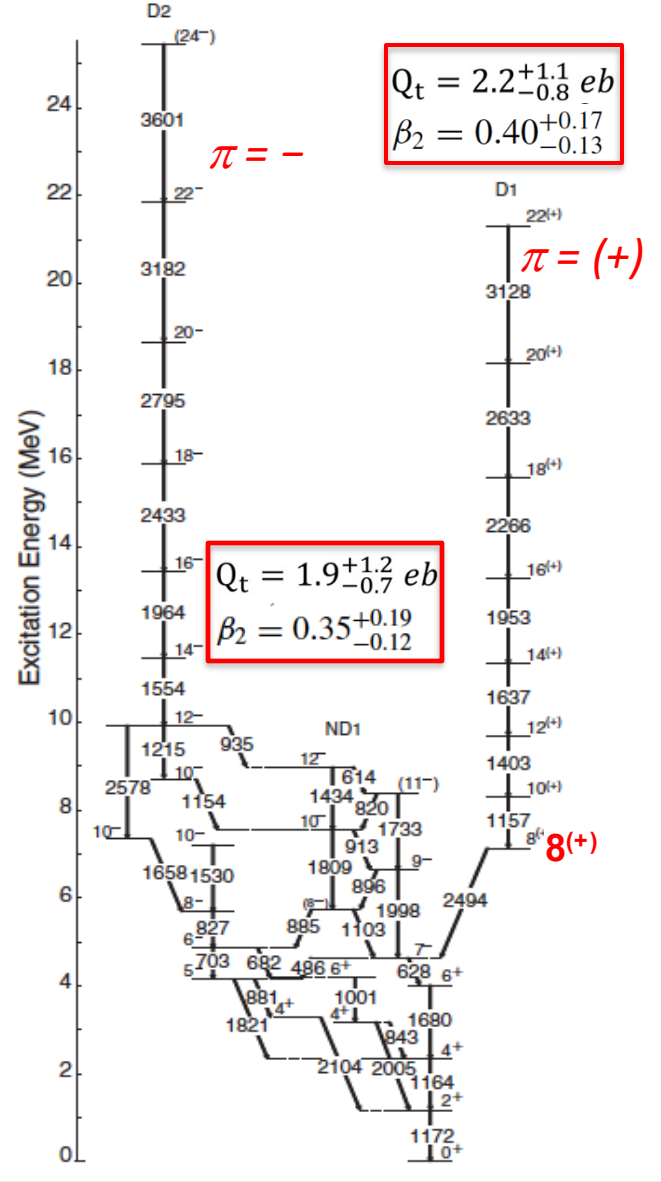
PHYSICAL REVIEW C **94**, 034301 (2016)

Single-particle and collective excitations in ^{62}Ni

M. Albers,[1] S. Zhu,[1] A. D. Ayangeakaa,[1] R. V. F. Janssens,[1] J. Gellanki,[2] I. Ragnarsson,[3] M. Alcorta,[1,*] T. Baugher,[4,5] P. F. Bertone,[1,†] M. P. Carpenter,[1] C. J. Chiara,[1,6,‡] P. Chowdhury,[7] H. M. David,[1,§] A. N. Deacon,[8] B. DiGiovine,[1] A. Gade,[4,5] C. R. Hoffman,[1] F. G. Kondev,[9] T. Lauritsen,[1] C. J. Lister,[1,‖] E. A. McCutchan,[1,¶] C. Nair,[1] A. M. Rogers,[1,‖] and D. Seweryniak[1]



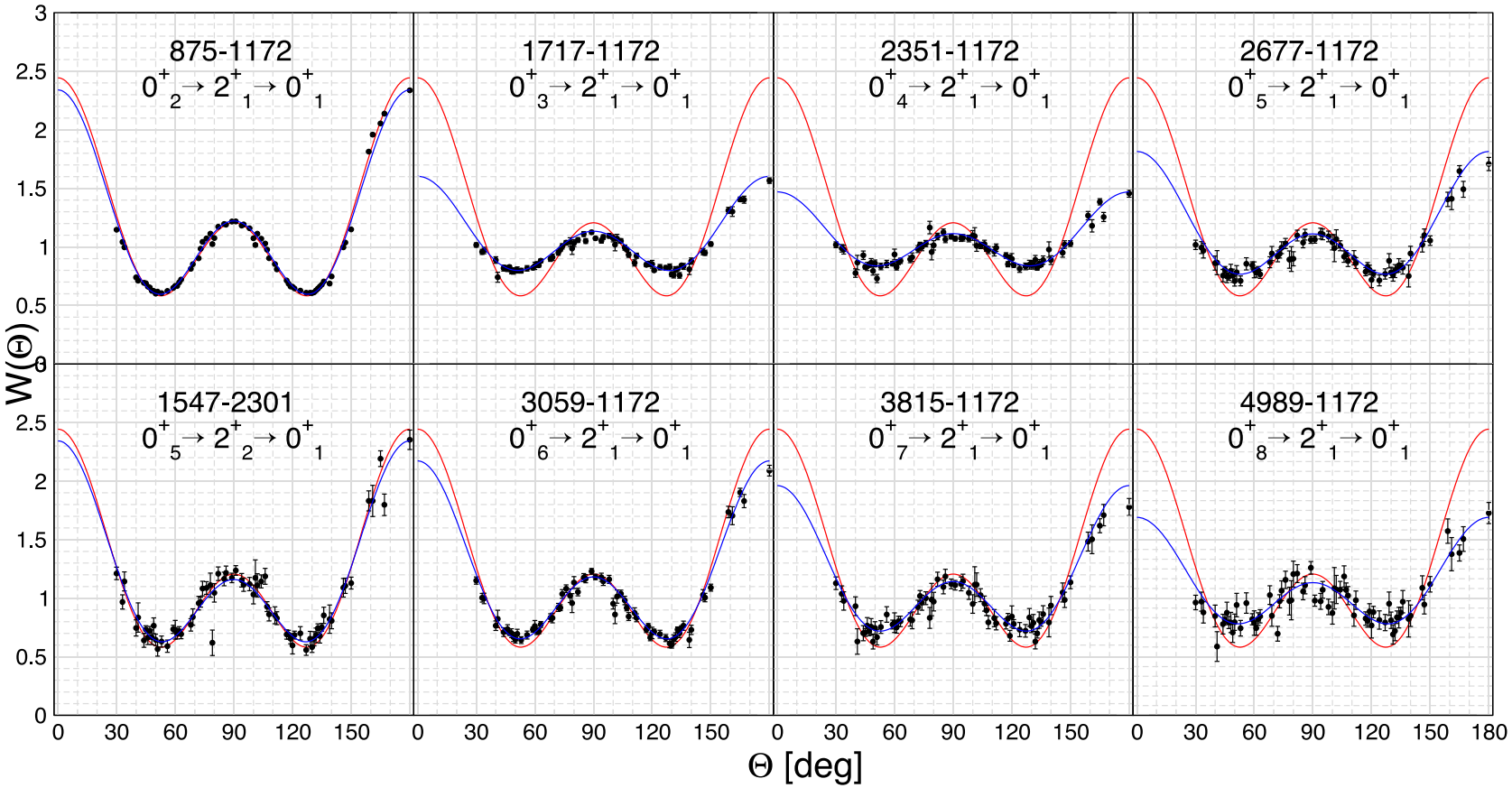
GAMMASPHERE + FMA (Argonne)



^{62}Ni data from ^{61}Ni(n,γ) reaction with FIPPS at ILL

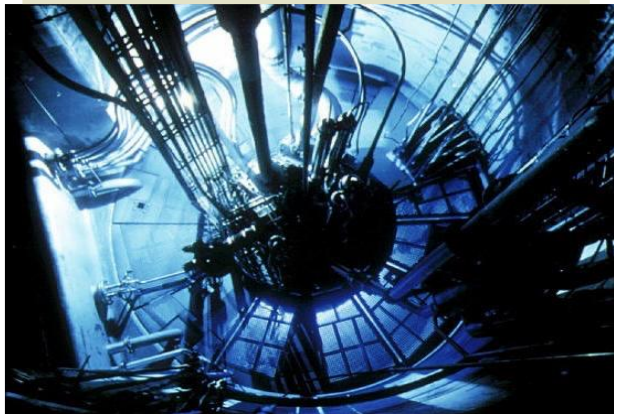
thermal-neutron capture on a 250 mg ^{61}Ni target of metallic powder

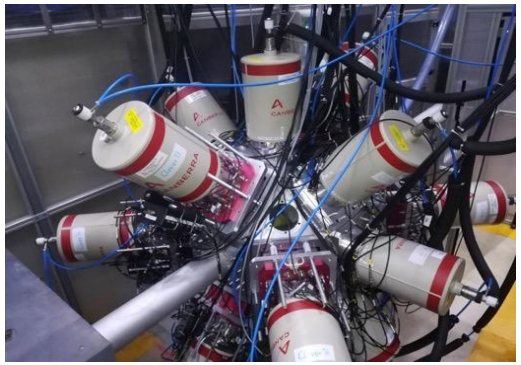
Large statistics and high-precision γ–γ angular correlations



→ *10 excited 0⁺ states observed in ^{62}Ni*

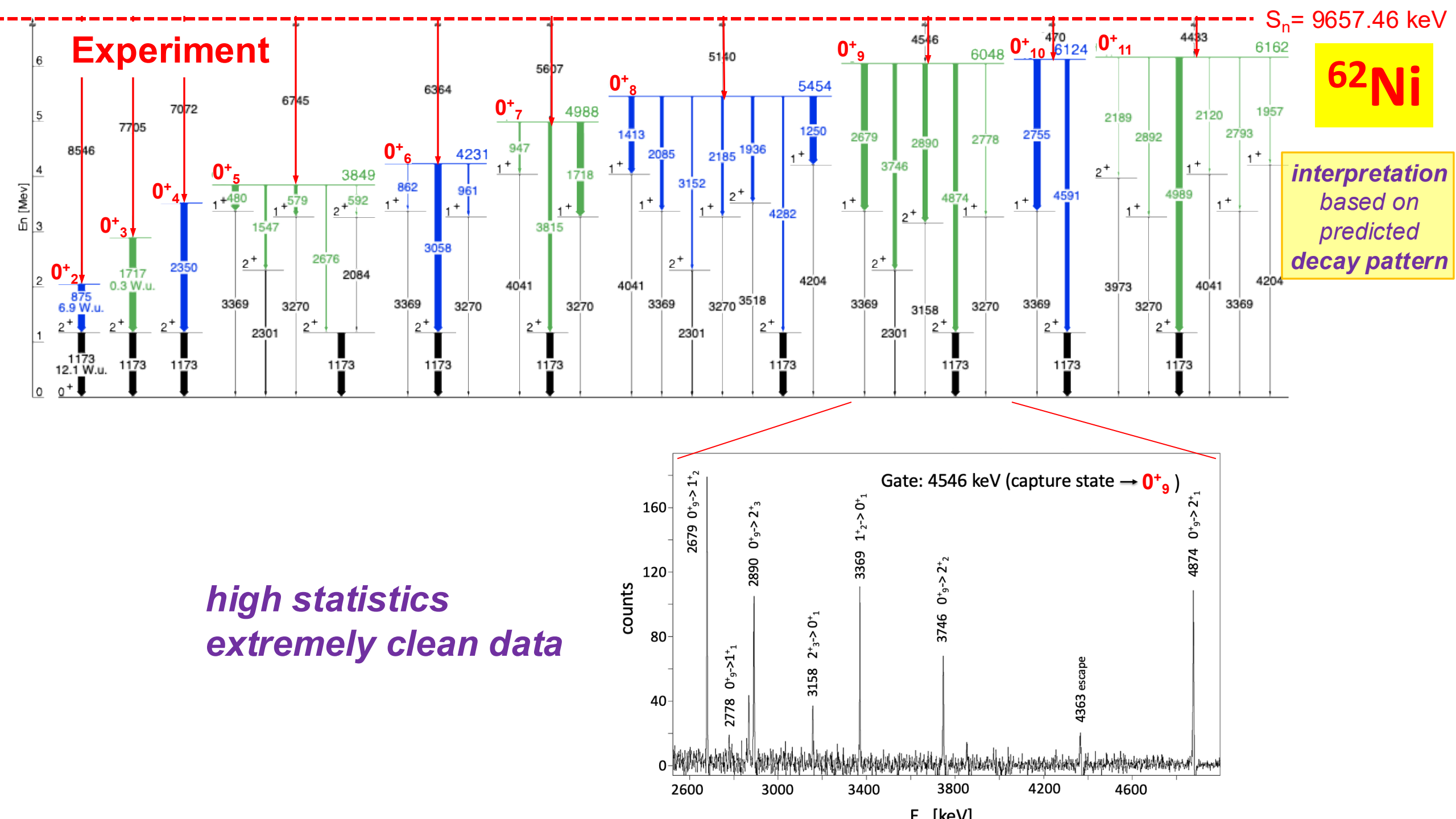
Pencil-like intense thermal neutron beam

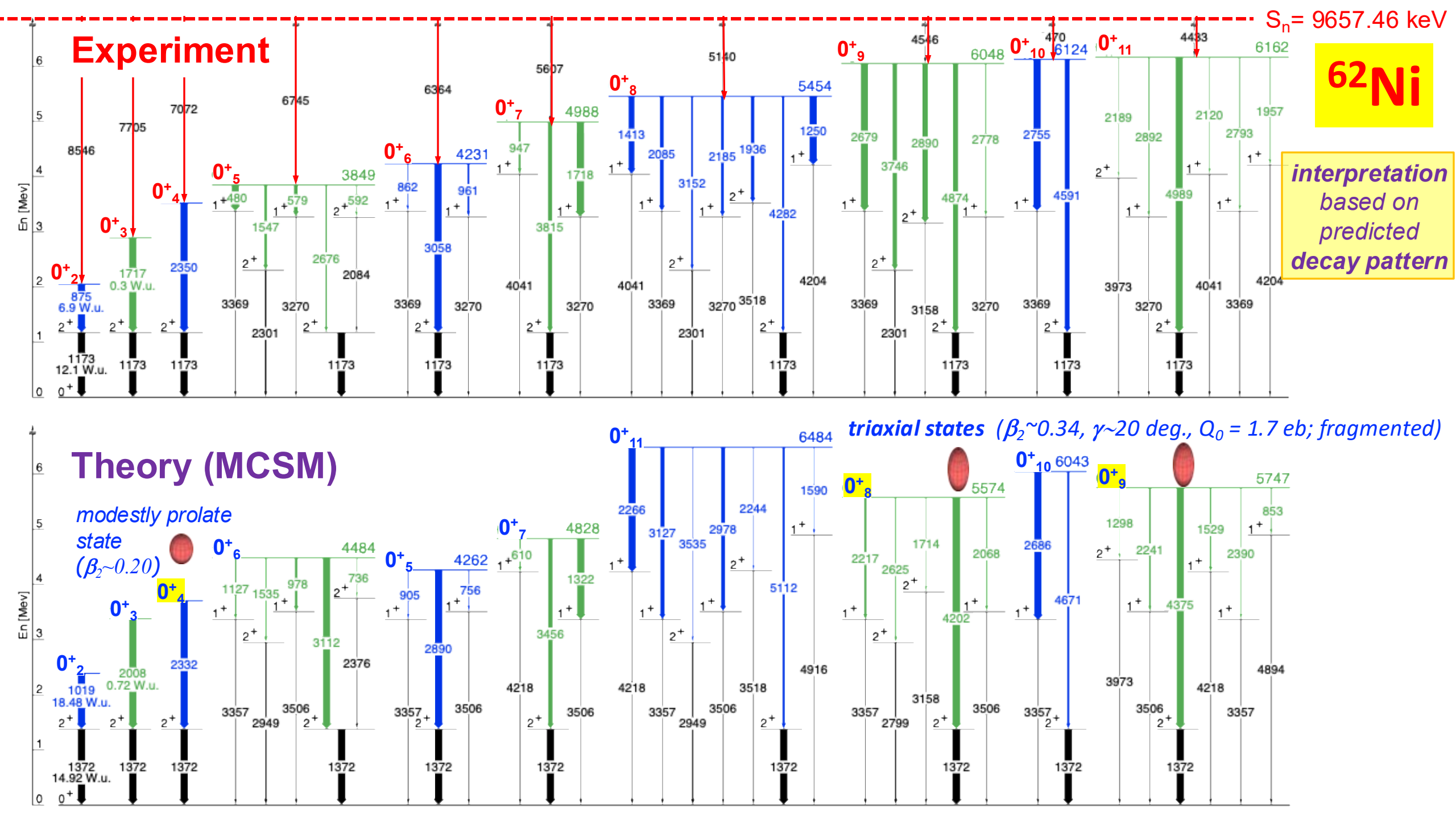




16 HPGe clovers (8 from IFIN-HH) high resolution and efficiency γ detector array

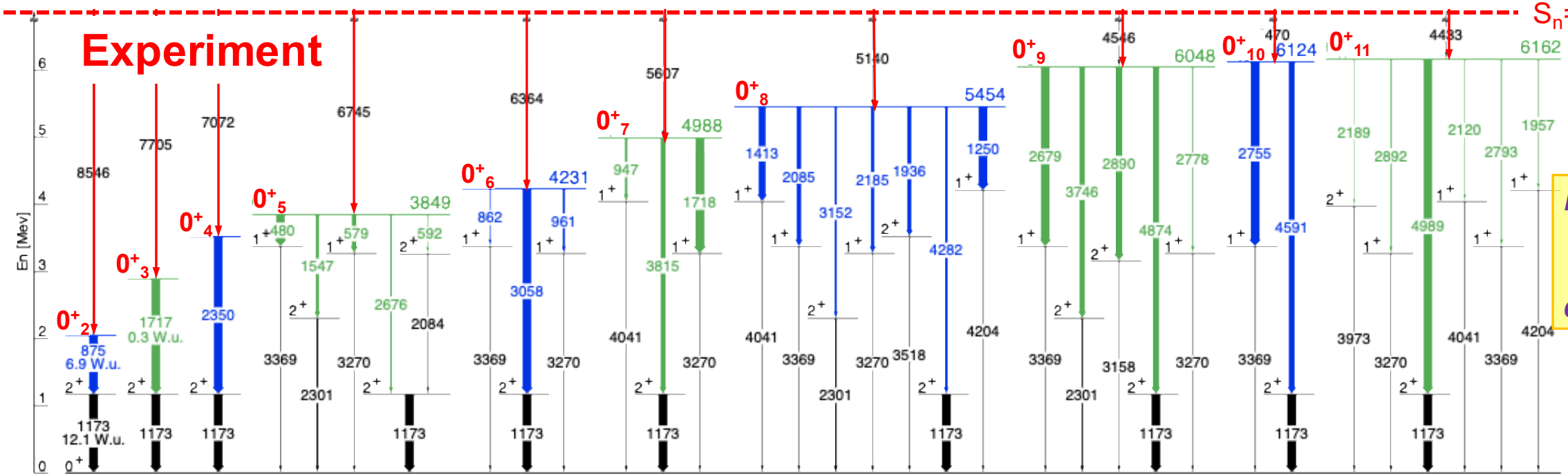
C. Costache, Y. Tsunoda, S. Leoni, B. Fornal, N. Marginean, R. V. F. Janssens, T. Otsuka, … in preparation


Experiment
S_n= 9657.46 keV
^{62}Ni
interpretation based on predicted decay pattern
high statistics
extremely clean data
Gate: 4546 keV (capture state → 0^+_9)
counts
E [keV]
En [Mev]
2679 0^+_9-> 1^+_2
2778 0^+_9->1^+_1
2890 0^+_9-> 2^+_3
3158 2^+_3-> 0^+_1
3369 1^+_2-> 0^+_1
3746 0^+_9-> 2^+_2
4363 escape
4874 0^+_9-> 2^+_1


Experiment
S_n= 9657.46 keV
^{62}Ni
interpretation based on predicted decay pattern
Theory (MCSM)
modestly prolate state (β_2~0.20)
triaxial states (β_2~0.34, γ~20 deg., Q_0 = 1.7 eb; fragmented)
En [Mev]
0+2
0+3
0+4
0+5
0+6
0+7
0+8
0+9
0+10
0+11
875
6.9 W.u.
1173
12.1 W.u.
1717
0.3 W.u.
2350
1019
18.48 W.u.
2008
0.72 W.u.
2332
1372
14.92 W.u.

S_n= 9657.46 keV

Experiment

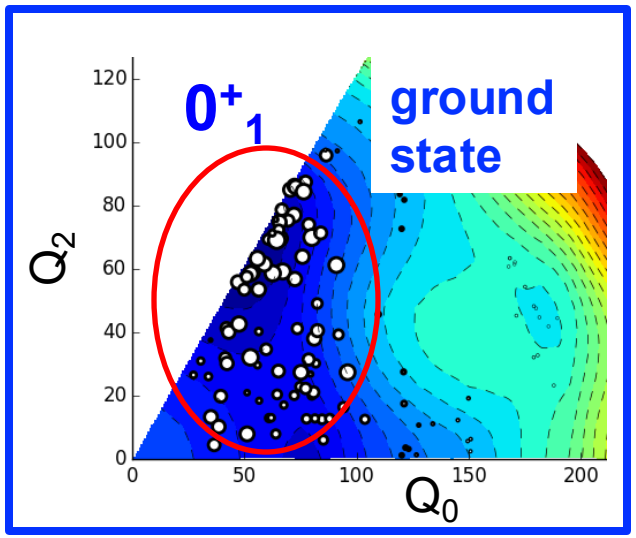


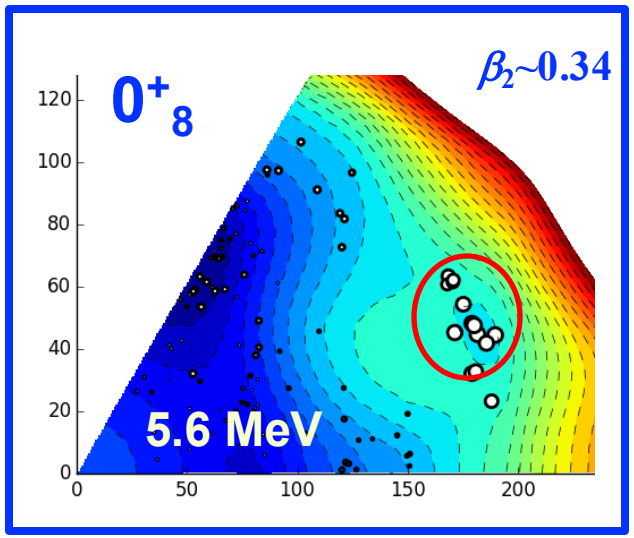
interpretation *based on predicted* **decay pattern**

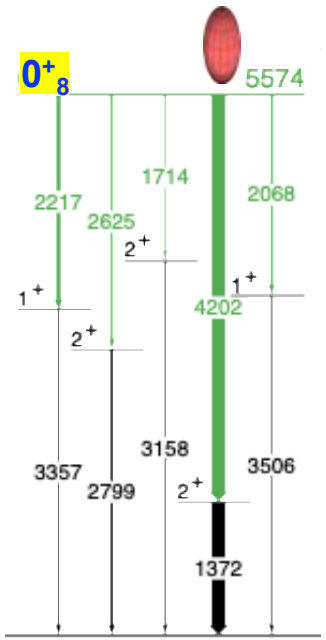
^{62}Ni

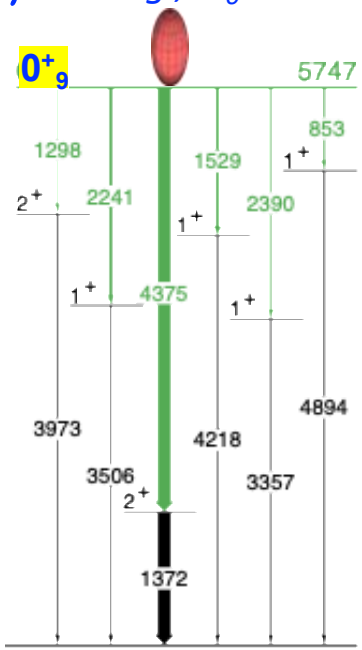
triaxial states *(β_2~0.34, γ~20 deg., Q_0 = 1.7 eb; fragmented)*

Theory (MCSM)









Connecting Shape Coexistence at Spin 0 to Superdeformation at High Spins in ^{62}Ni

PHYSICAL REVIEW C **94**, 034301 (2016)

Single-particle and collective excitations in ^{62}Ni

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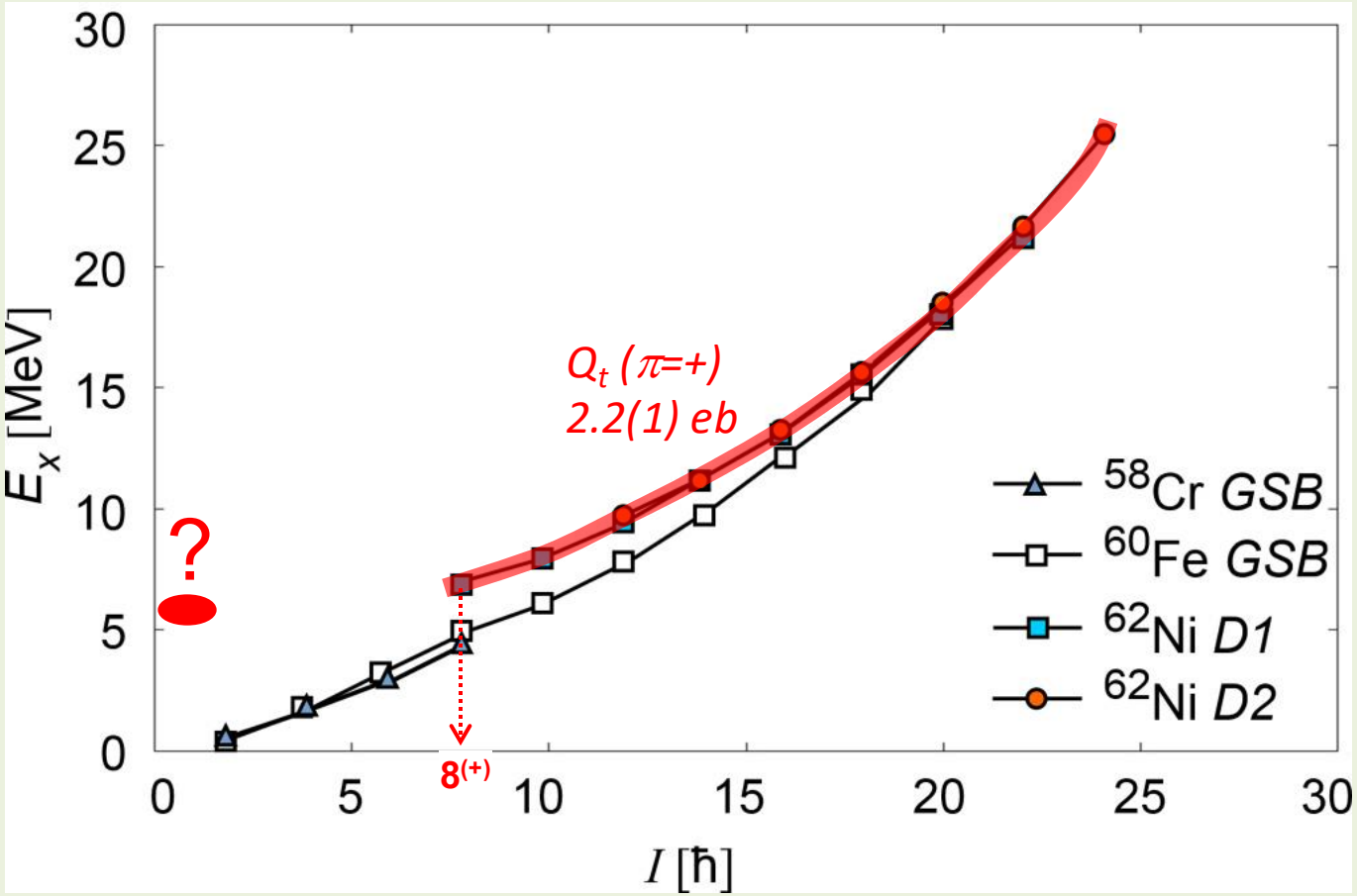
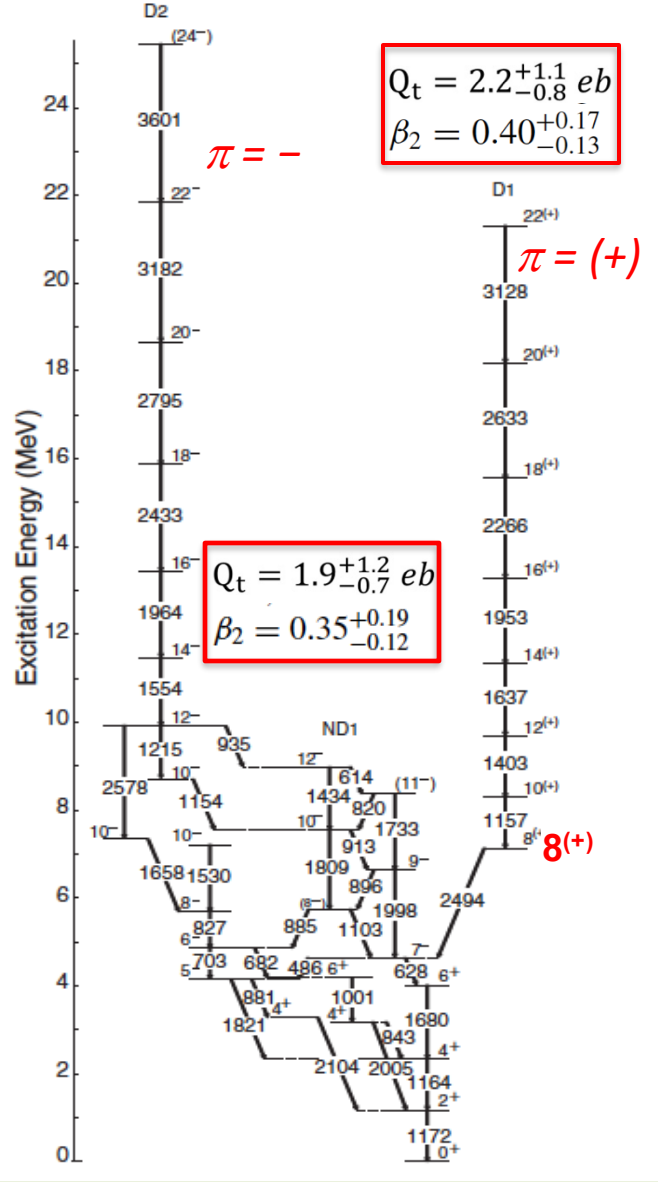


GAMMASPHERE + FMA (Argonne)



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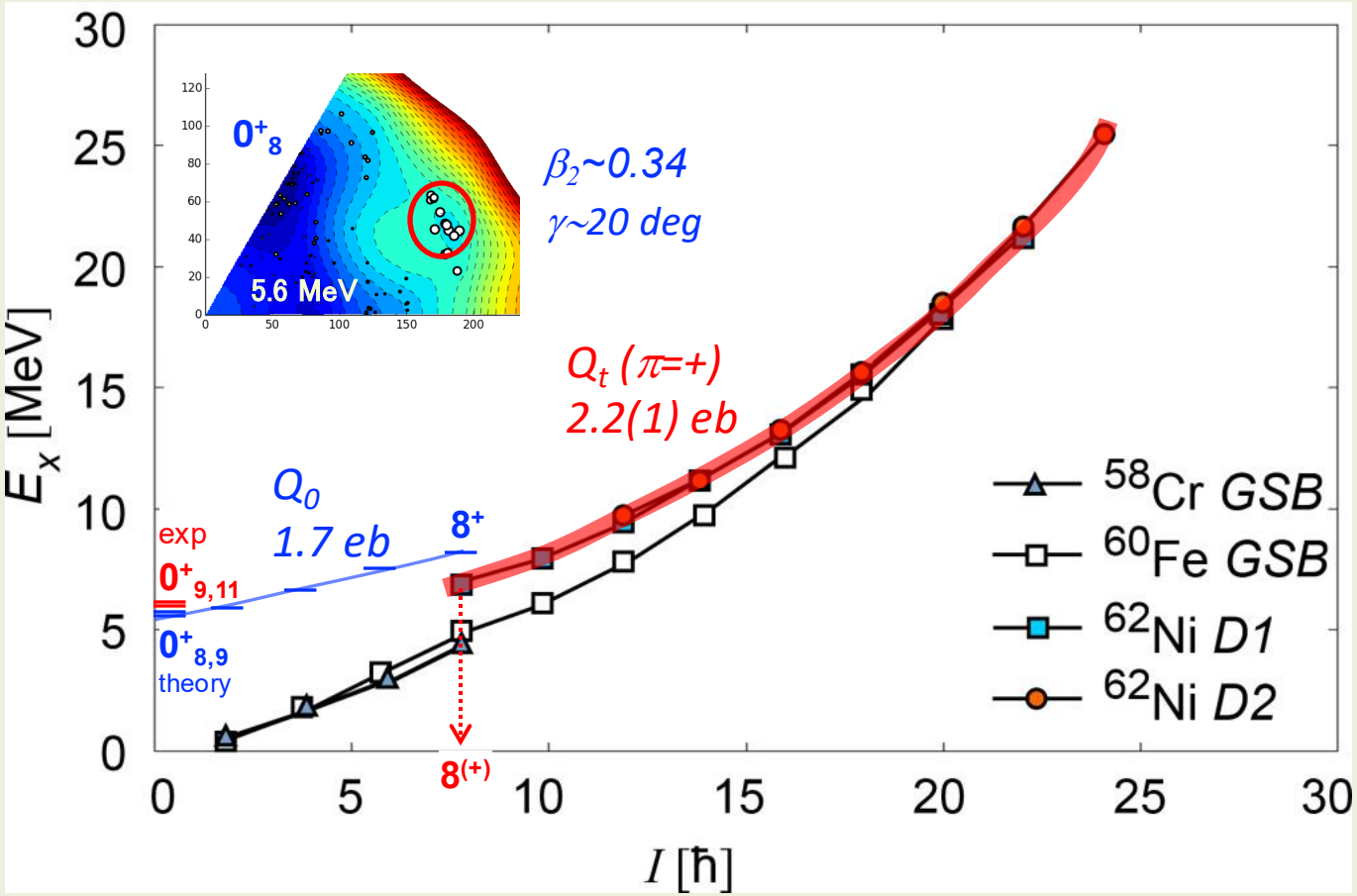

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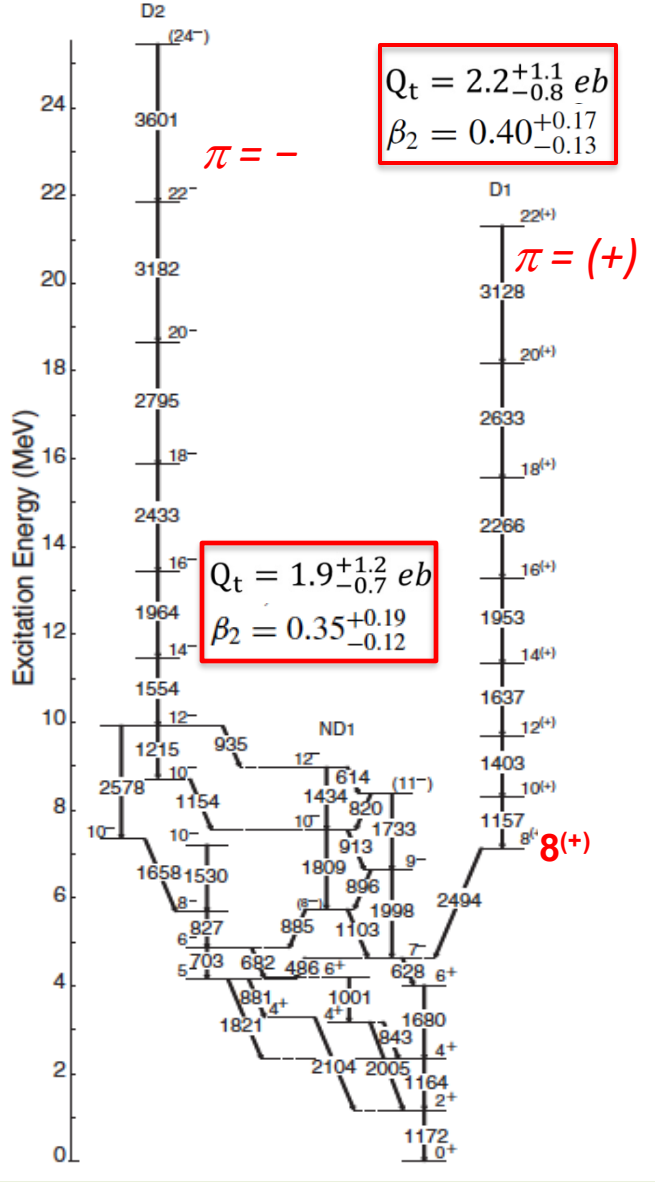
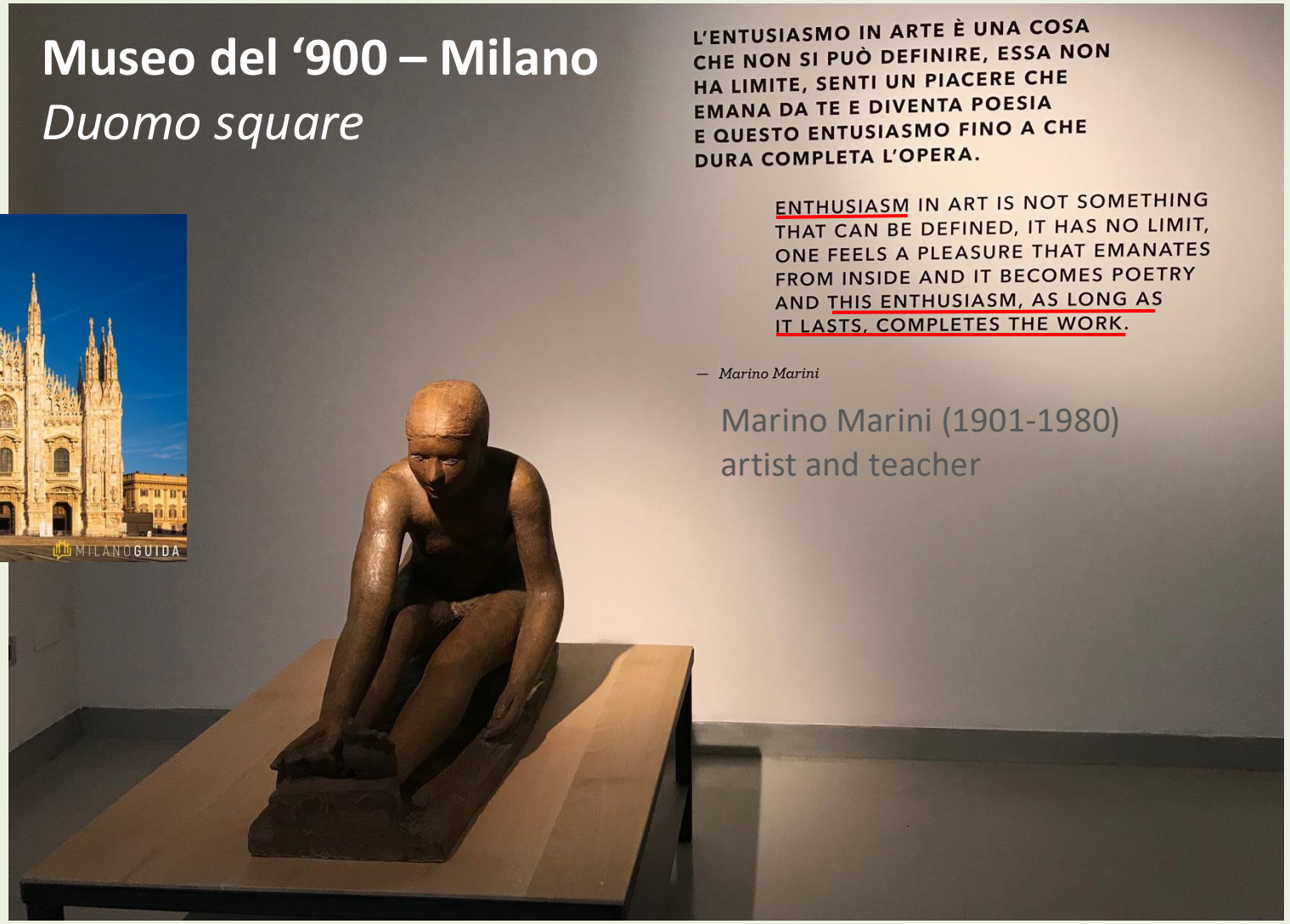


triaxial deformed 0⁺ states *could be the* ***fragmented BANDHEAD*** *of rotational structures observed at high spins*

CONCLUSION: *Thank you **Robert** for bringing me back to my beloved days of high spins: at the end … I am still in this beautiful world !!!*



*It applies very well to **SCIENCE …***

In particular to fruitfull collaborations such as the

Milano-Copenhagen-UK-France-Krakow-Bucharest-US-Japan … collaboration

ongoing since > 35 years

Robert is certainly full of contagious enthusiasm for science and life !!!