UNIVERSITÀ DEGLI STUDI DI MILANO

INFN
Istituto Nazionale di Fisica Nucleare

7th Workshop on Nuclear Fission and Spectroscopy of Neutron-Rich Nuclei

9–13 Mar 2026, Salle Totem, Le Bachat, Chamrousse

From shape isomers to superdeformation at high spins

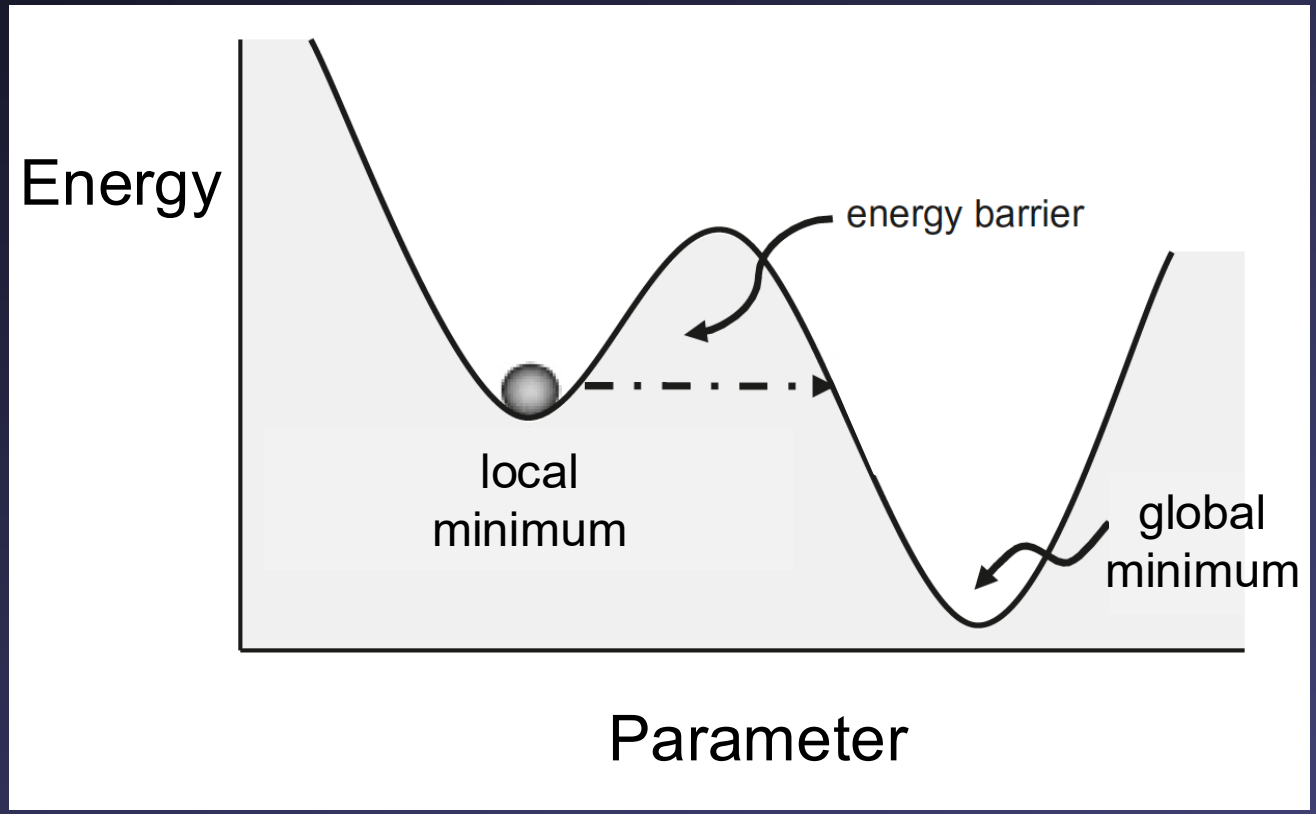
Silvia Leoni – University of Milano and INFN

In collaboration with:

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

The Potential Energy Surface (PES) of a system

a fundamental concept in physics at all scales

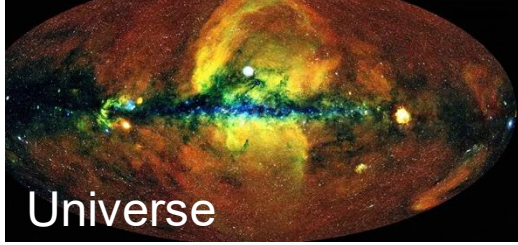


physical systems tend to minimize their potential energy

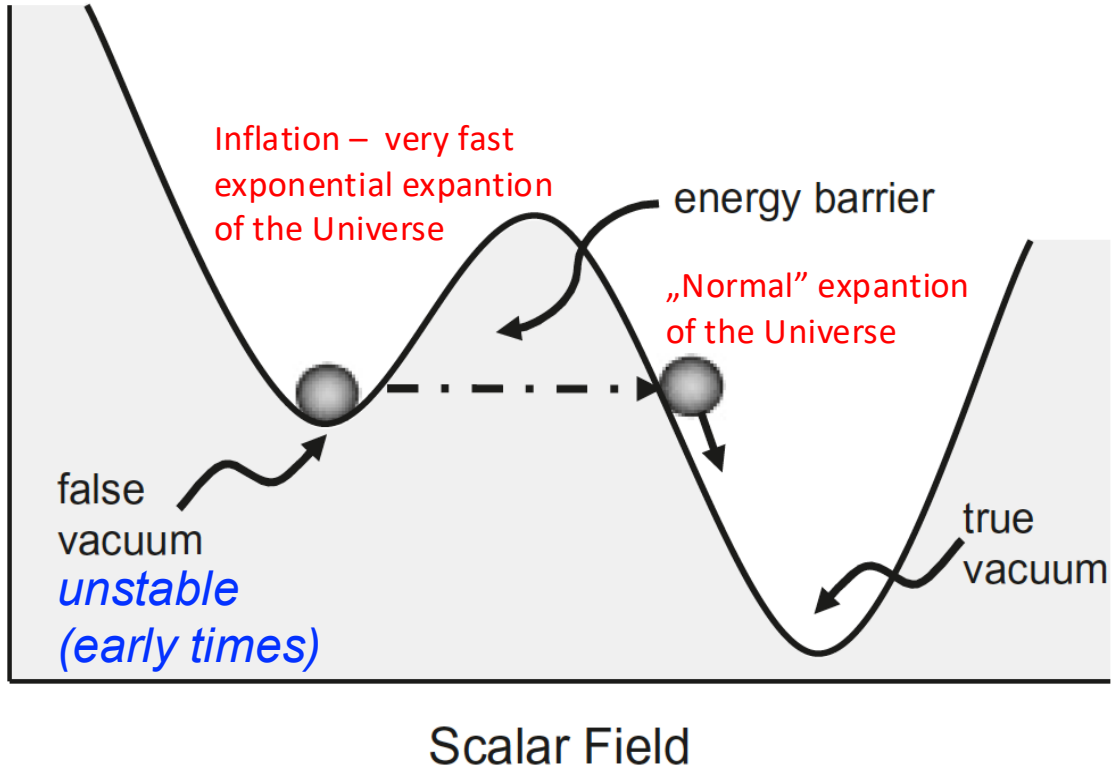
in Quantum Mechanics
a system trapped in a **local minimum** can decay into the **global minimum**,
specifically, into the ground state of the system

Potential Energy Surface (PES) in COSMOLOGY

Expansion of the Universe



Alan Guth idea on Cosmic inflation

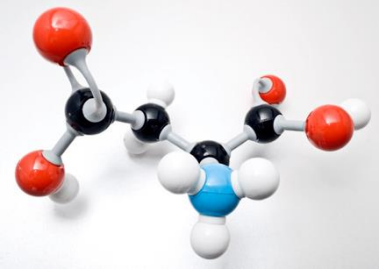


Toy model for Universe expansion

*Strong repulsive gravity of the false vacuum causes a **period of very fast, accelerated expansion**.*
The inflation period ends when the system decays into the true vacuum

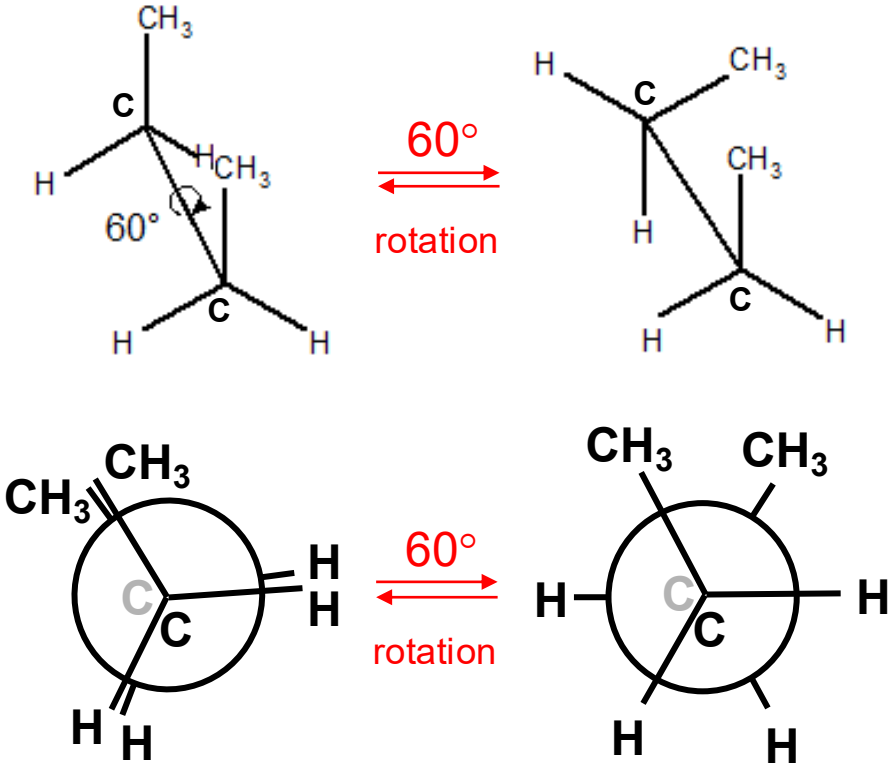
Alan H. Guth, Phys. Rev. D 23, 347 (1981), *Inflationary universe: A possible solution to the horizon and flatness problems*
Figure from the book D. Perlov and A. Vilenkin, *Cosmology for the Curious*, DOI 10.1007/978-3-319-57040-2_16

Potential Energy Surface (PES) of MOLECULES

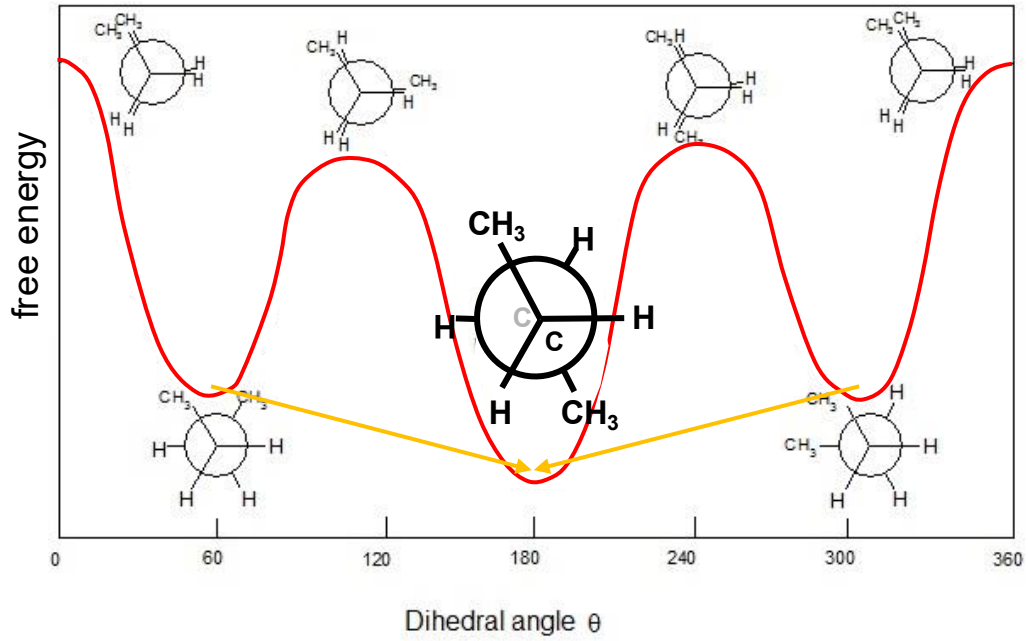


Butane molecule C_4H_{10}

Conformational isomers

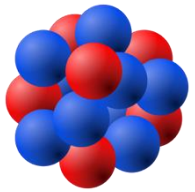


Rotation about single bond of butane

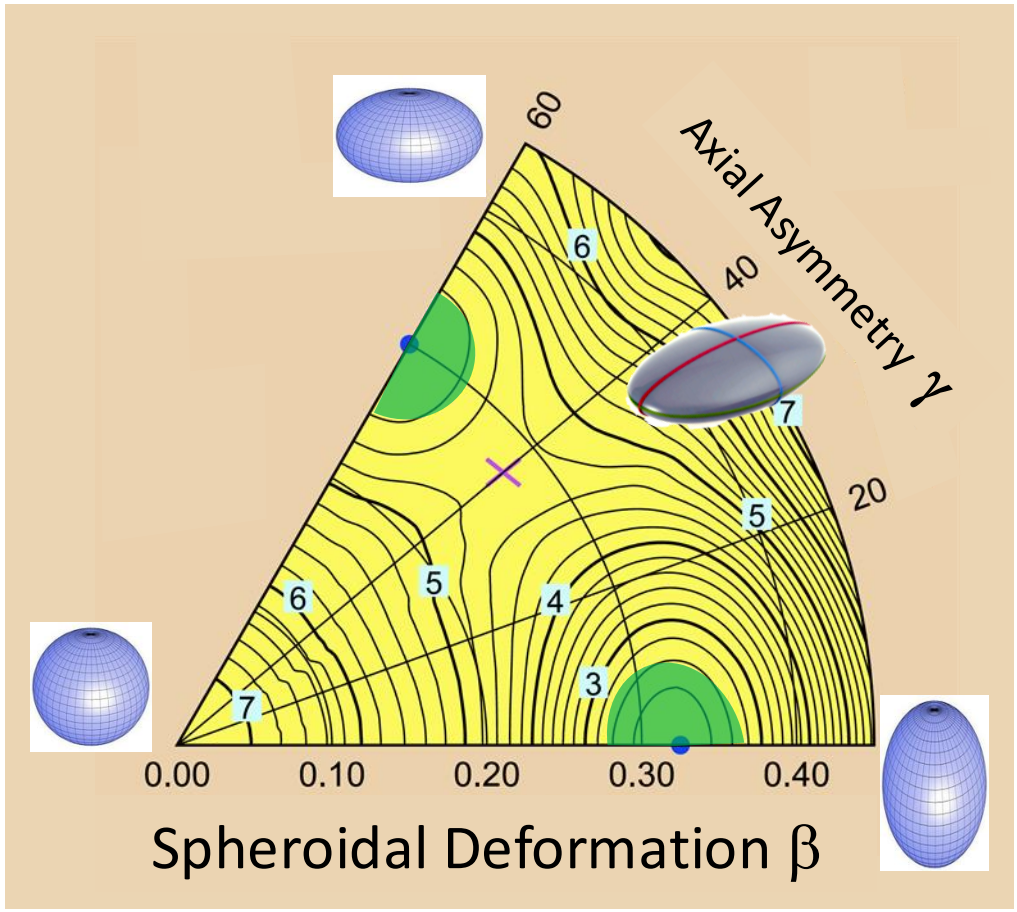


Free energy diagram of butane as a function of dihedral angle

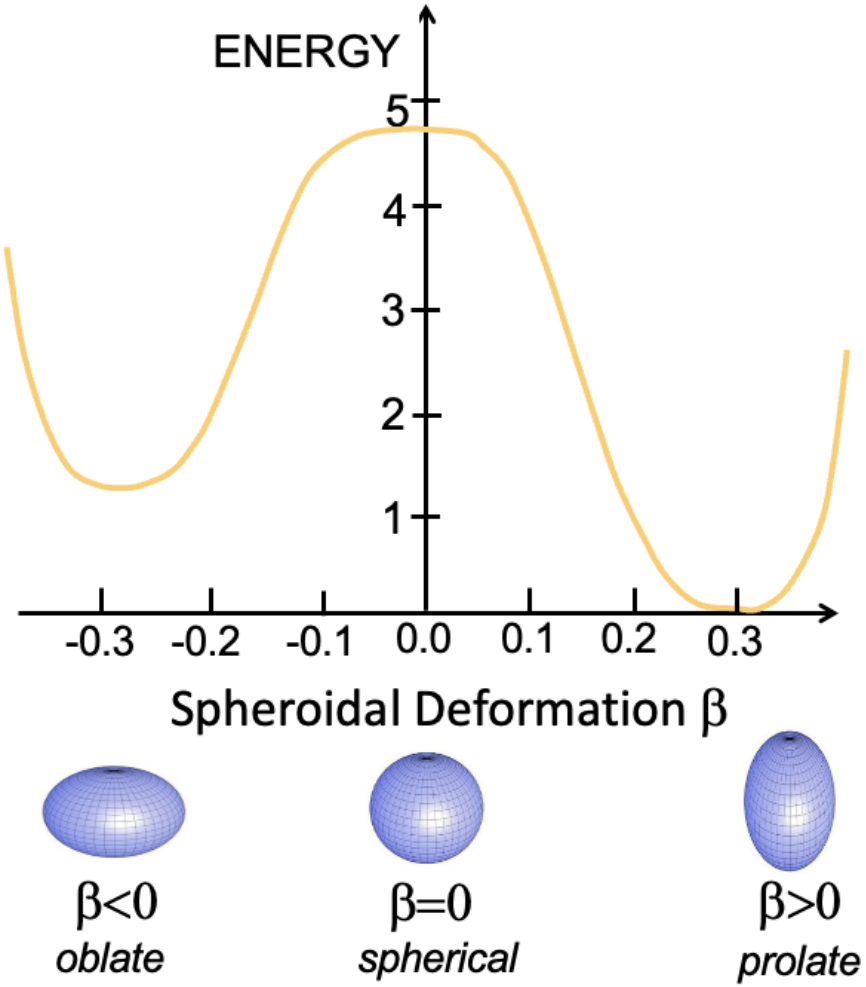
Potential Energy Surface (PES) of a NUCLEUS



two-dimensional contour



one-dimensional representation

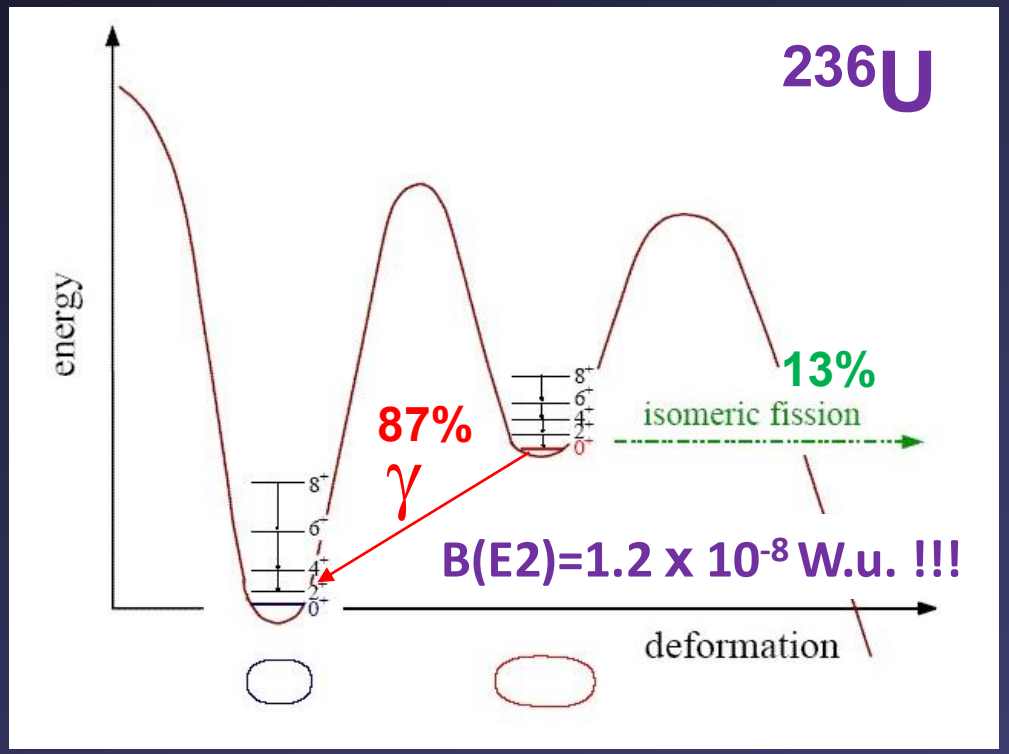


Appearence of <u>different shapes</u>
at comparable excitation energies

First evidence for Shape Coexistence ('60s)

Fission SHAPE ISOMERS in actinides - very peculiar metastable states

- HIGH Potential BARRIER
- Nucleus trapped In the minimum
- very retarded photon decay (***B(E2) << 1 W.u. → 10^8 hindrance***)



Structures living in "separate worlds"

MAIN FINGER PRINT for SHAPE ISOMERISM: LARGE decay HINDRANCE

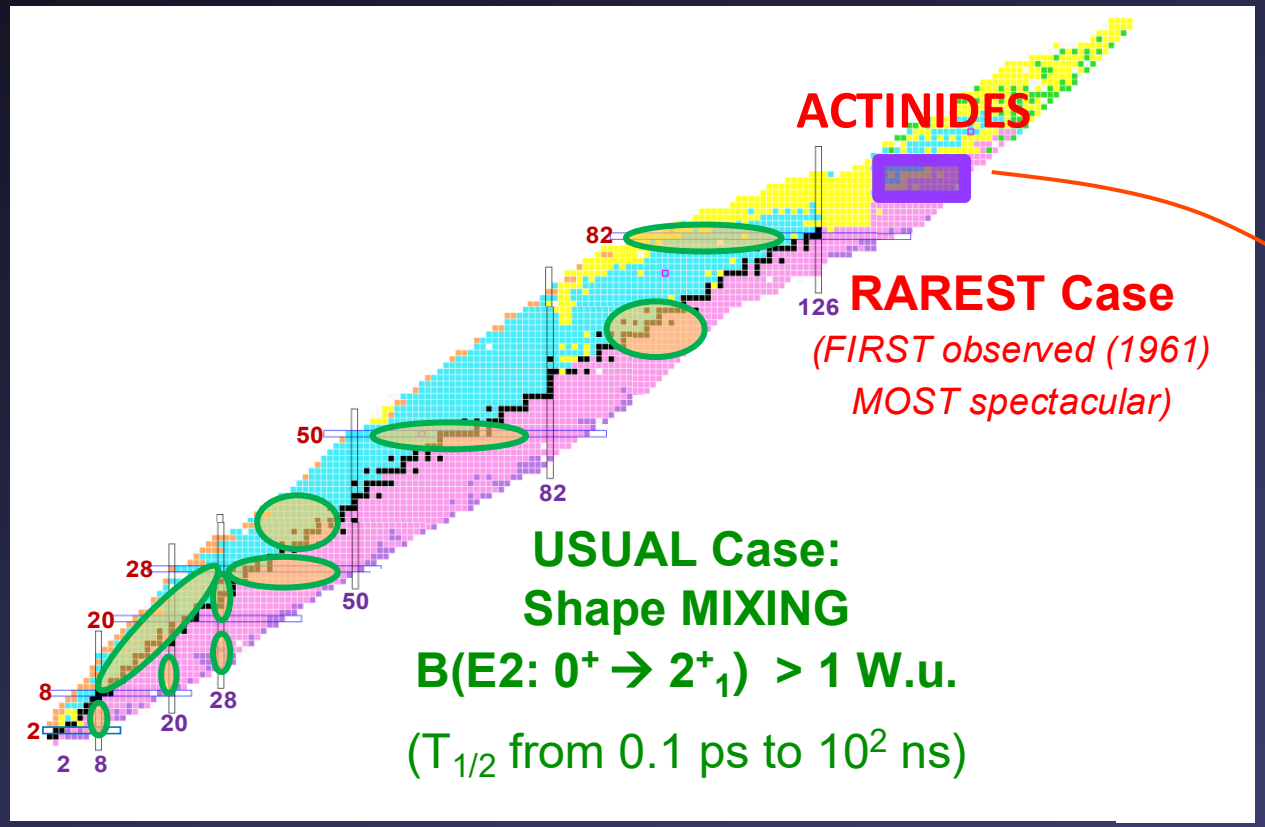
Several TALKS in this conference:

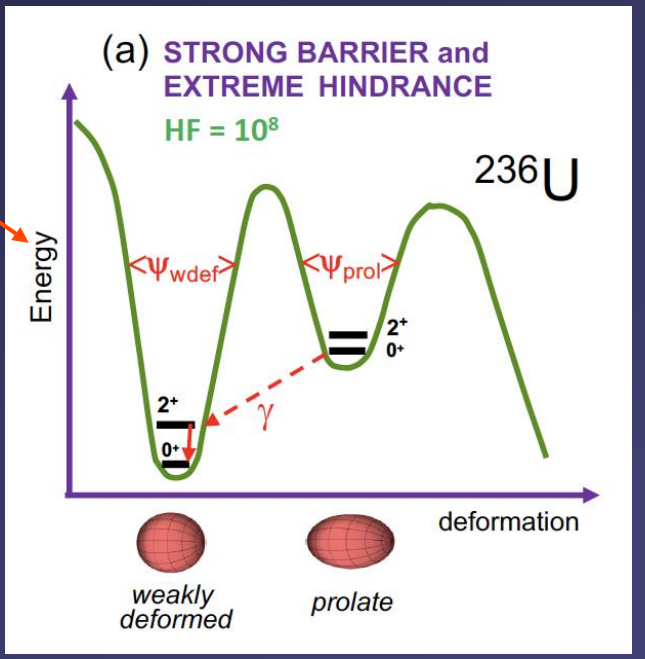
J. Wilson, P. Reiter, C. Hiver, T. Dickel, S. Oberstedt, N. Jovancevic, …

P. Thirolf, D. Habs, Prog. Part. Nucl. Phys. 49 (2) (2002)325
P. Reiter, D. Habs, D. Schwalm, P. Thirolf, EPJA61 (2025)158; EPJA62 (2026)29

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

2024 Review paper on Shape Coexistance and Shape Isomerism

Progress in Particle and Nuclear Physics 139 (2024) 104119

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Multifaceted character of shape coexistence phenomena in atomic nuclei

S. Leoni [a,b,*], B. Fornal [c], A. Bracco [a,b], Y. Tsunoda [d], T. Otsuka [e,f]

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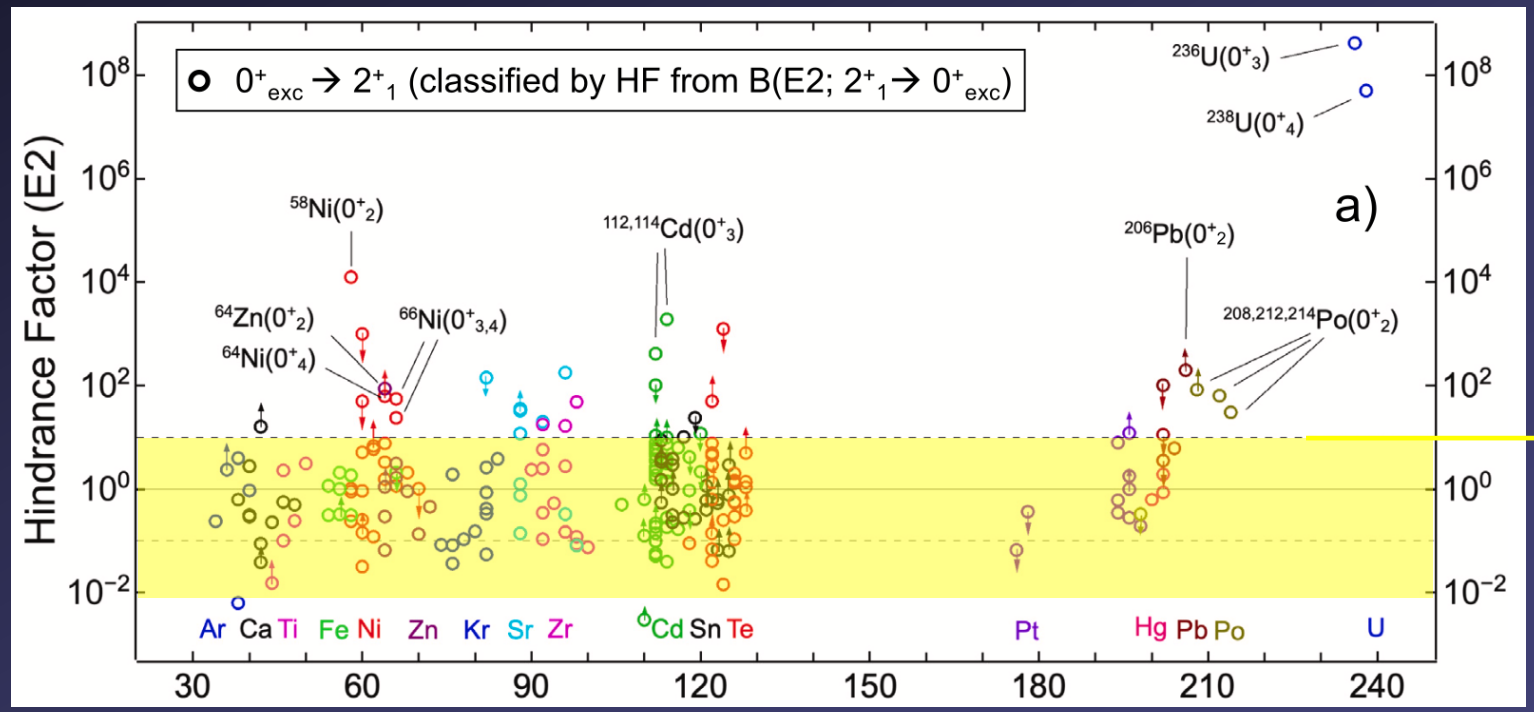
[c] Institute of Nuclear Physics Polish Academy of Sciences, Krakow 31-342, Poland
[d] Center for Nuclear Study, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
[e] Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
[f] RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Survey of 0^+ states from Ca to U
searching for regions of
Shape Isomerism



candidates for SHAPE Isomerism

HF > 10
B(E2) < 0.1 W.u.

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

K.E. Löbner PLB26, 369 (1968)

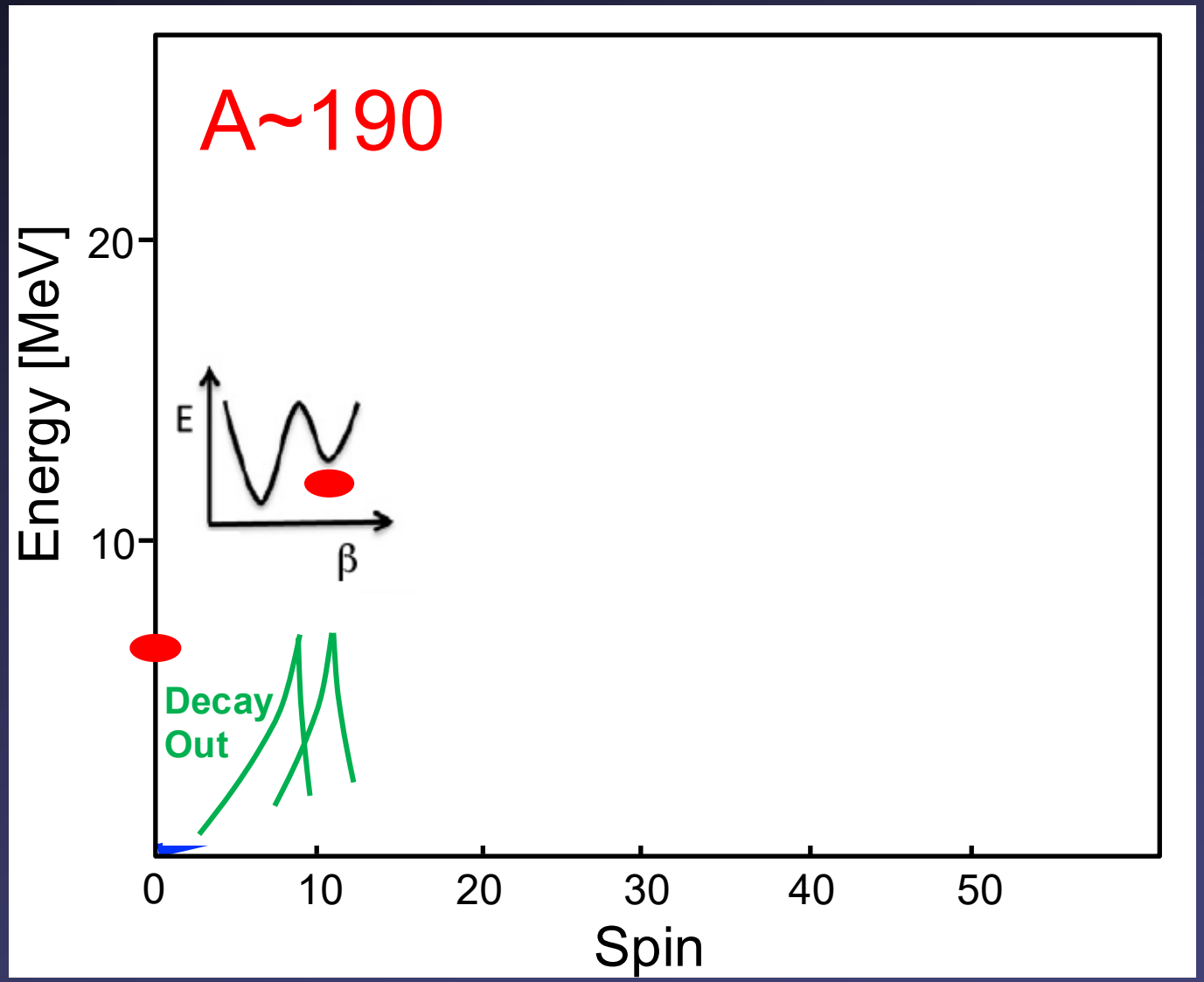
Search for SHAPE ISOMERS at I=0 among Super Def nuclei

SD Nuclei are spectacular examples of extreme shape coexistence

*(ranked among the **top 10** most exciting physics discoveries of last century)*

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

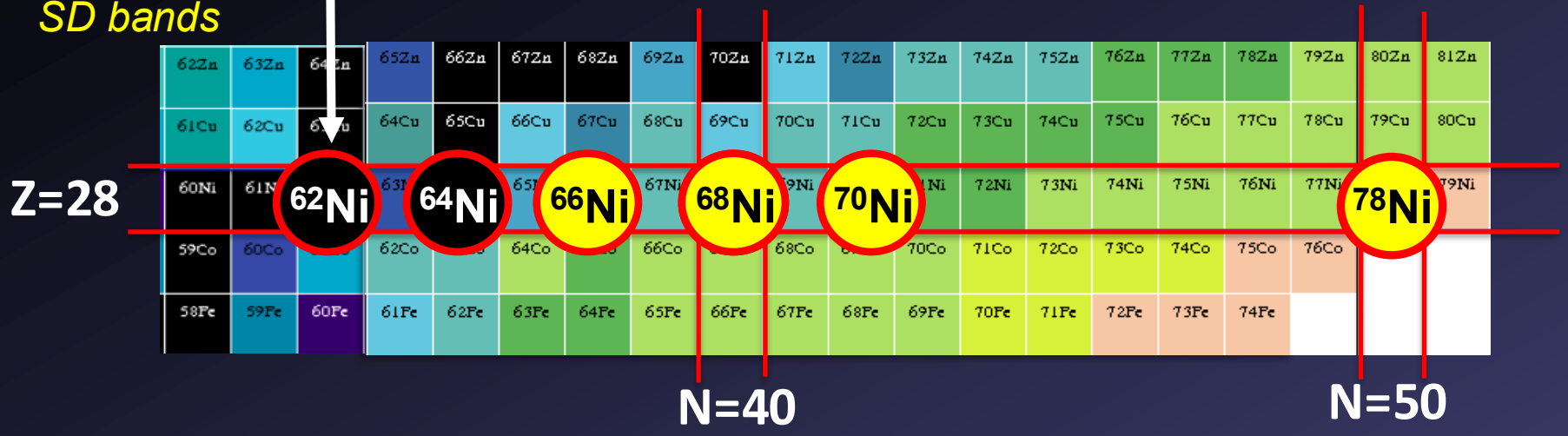
focusing on cases where wave functions are well localized
in different PES minima
separated by a sizable barrier

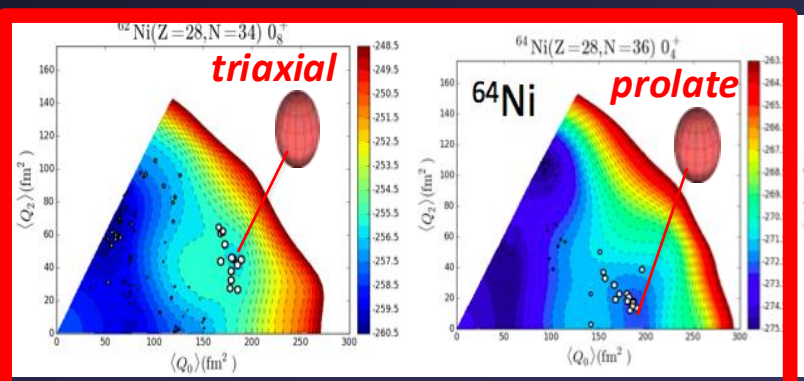
B(E2) << 1 W.u., HF > 10

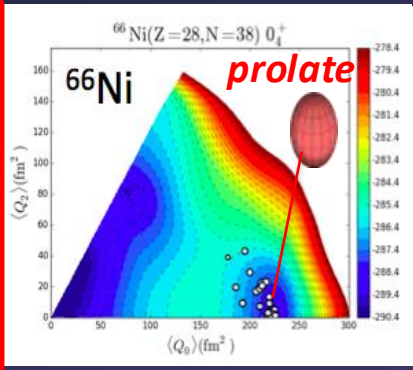
The Ni chain

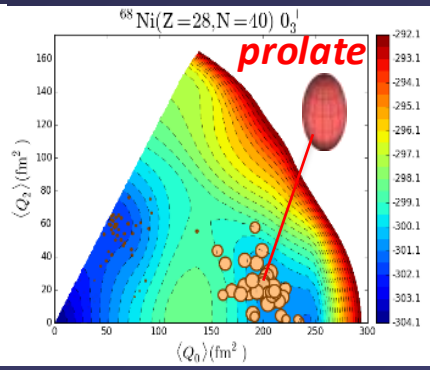
historical region to test Shape Coexistence

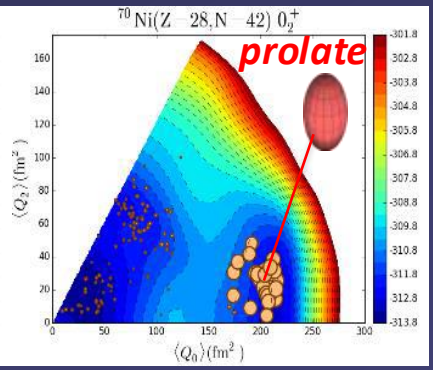
$A \leq 62$ *High Spin SD bands* ◄·····► $A > 62$ *Low Spins data only*

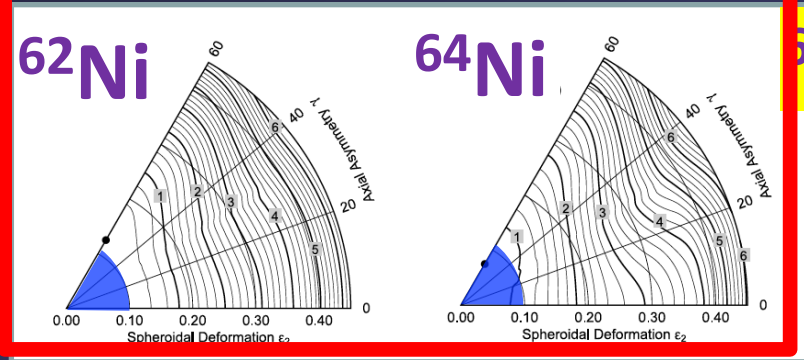


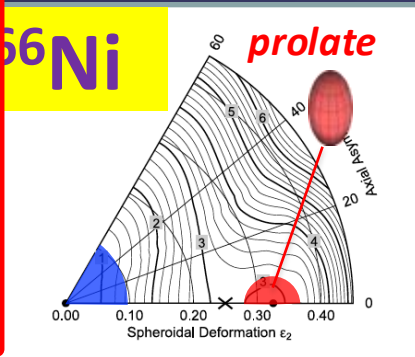


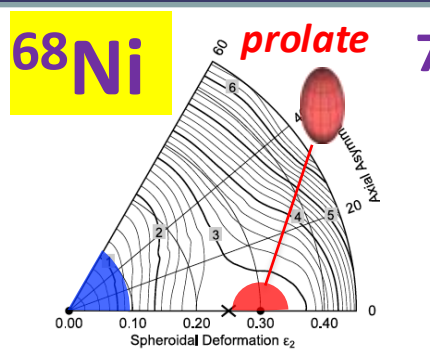


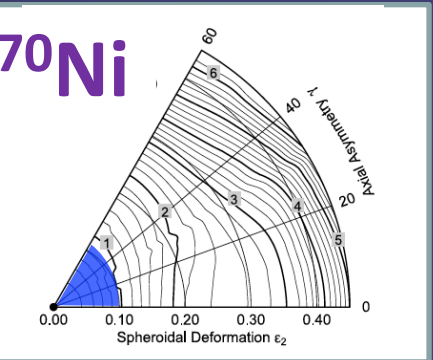












MonteCarlo SHELL Model

Otsuka, Tsunoda

10^{20} configurations
K computer in Tokyo
10^{6} parallel processors

Mean Field

2012: Moeller
'80s: Girod, Gogny

^{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)

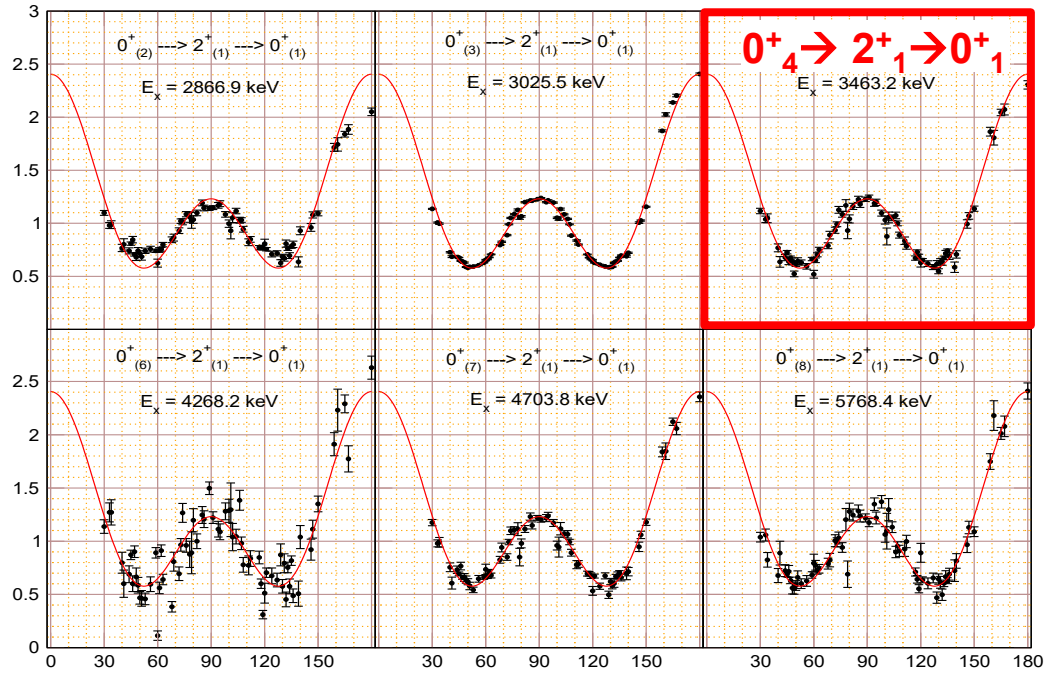
Shape Coexistence at Zero Spin in ^{64}Ni Driven by the Monopole Tensor Interaction

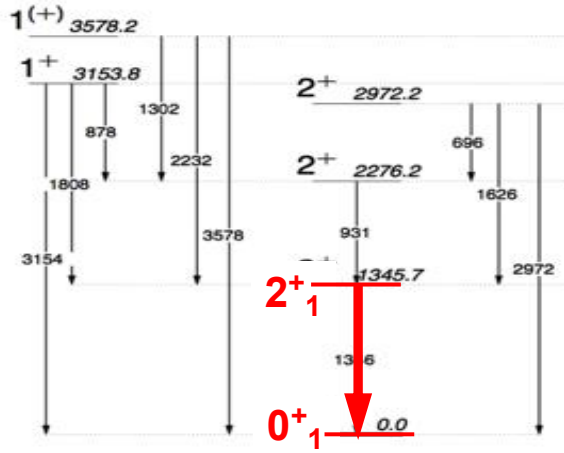
N. Mărginean,[1,*] D. Little,[2,3] Y. Tsunoda,[4] S. Leoni,[5,6,†] R. V. F. Janssens,[2,3,‡] B. Fornal,[7,§] T. Otsuka,[8,9,10,‖] C. Michelagnoli,[11] L. Stan,[1] F. C. L. Crespi,[5,6] C. Costache,[1] R. Lica,[1] M. Sferrazza,[12] A. Turturica,[1] A. D. Ayangeakaa,[13] K. Auranen,[14,¶] M. Barani,[5,6,11] P. C. Bender,[15] S. Bottoni,[5,6] M. Boromiza,[1] A. Bracco,[5,6] S. Călinescu,[1] C. M. Campbell,[16] M. P. Carpenter,[14] P. Chowdhury,[15] M. Ciemała,[7] N. Cieplicka-Oryńczak,[7] D. Cline,[17] C. Clisu,[1] H. L. Crawford,[16]

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

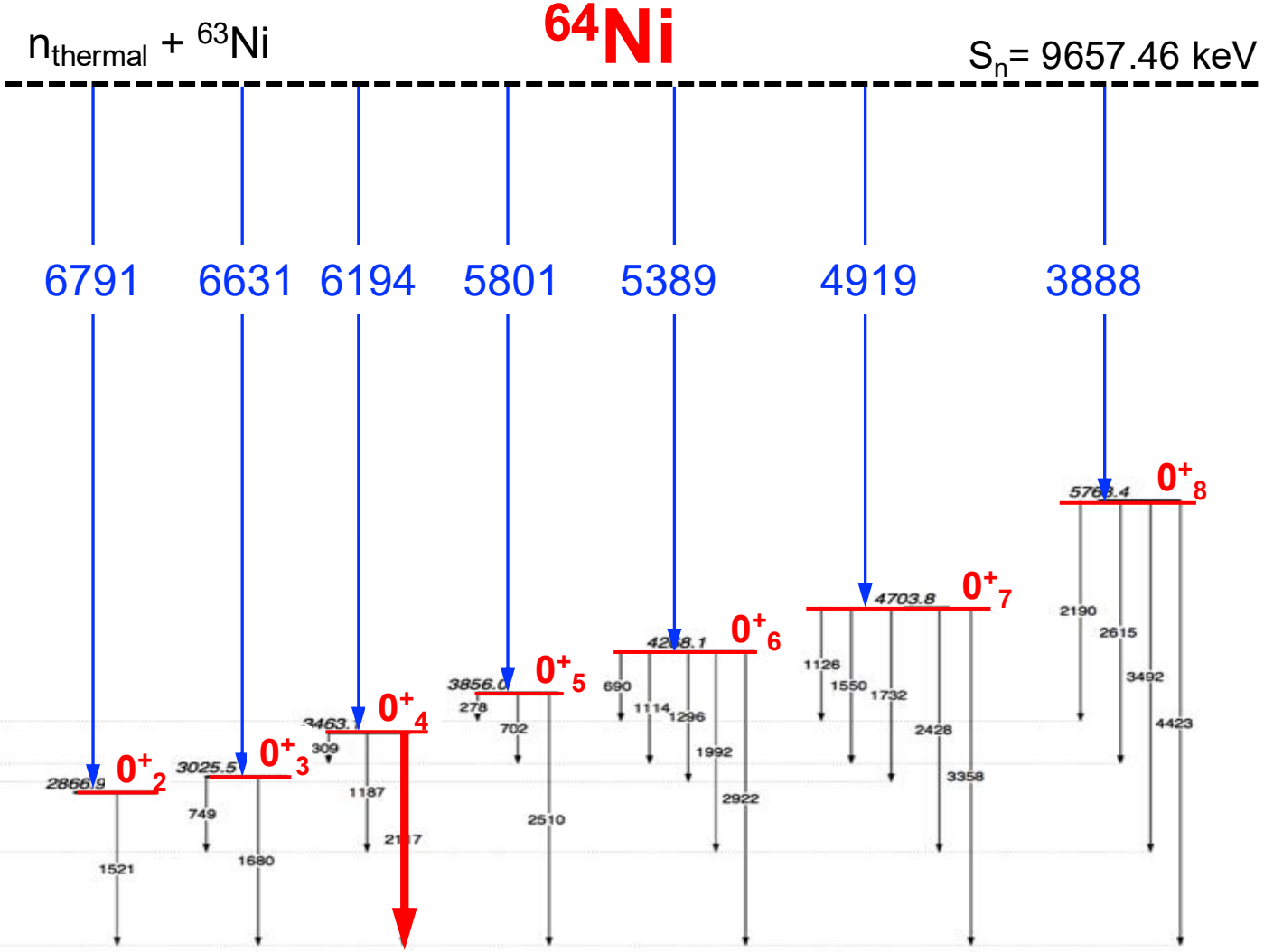
(n,γ) experiment with FIPPS array at ILL (2019) - 2 GigaBq ^{63}Ni target

high-precision γ–γ angular correlations





^{64}Ni



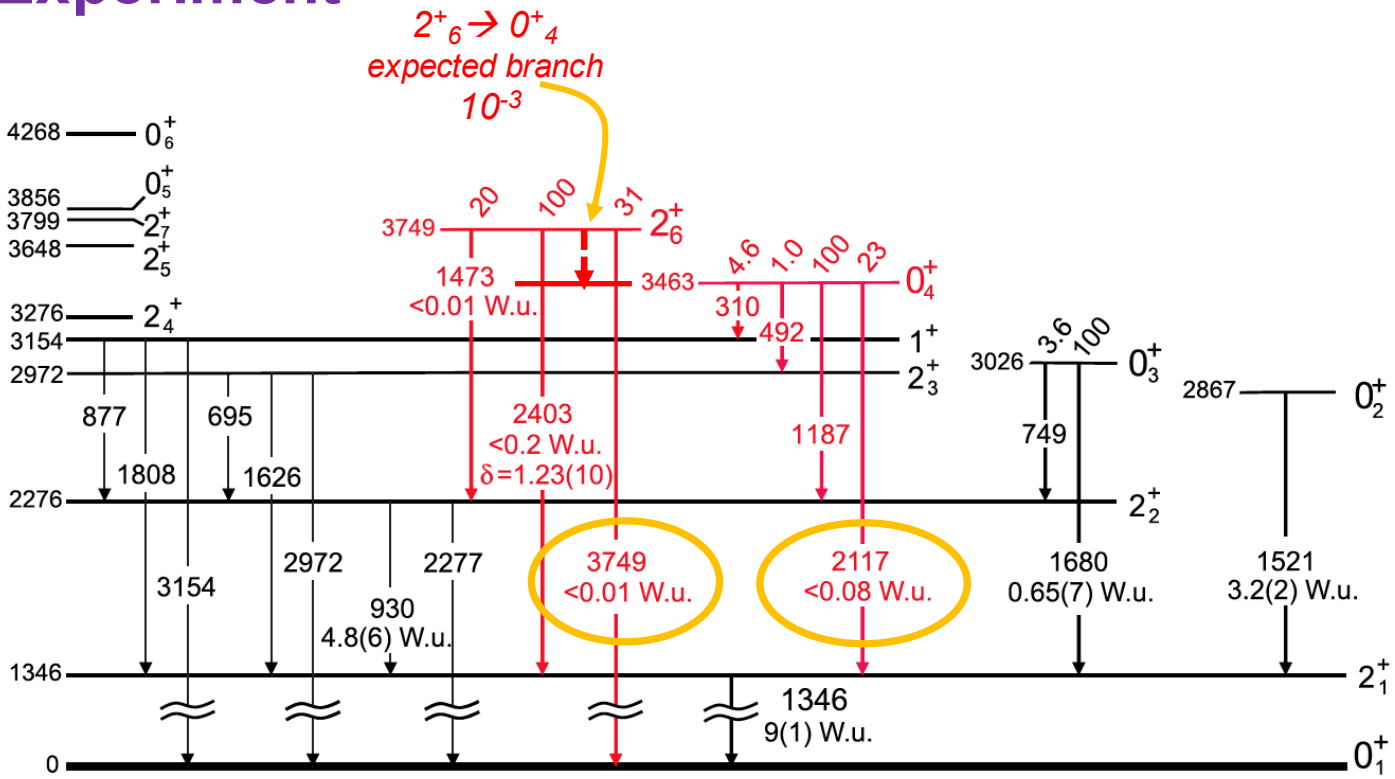
extended decay pattern: *seven 0^+ states, six 2^+ states, ...*

Extended experimental investigation (4 experiments)

decay scheme, state lifetimes, transition rates, …

^{64}Ni

Experiment



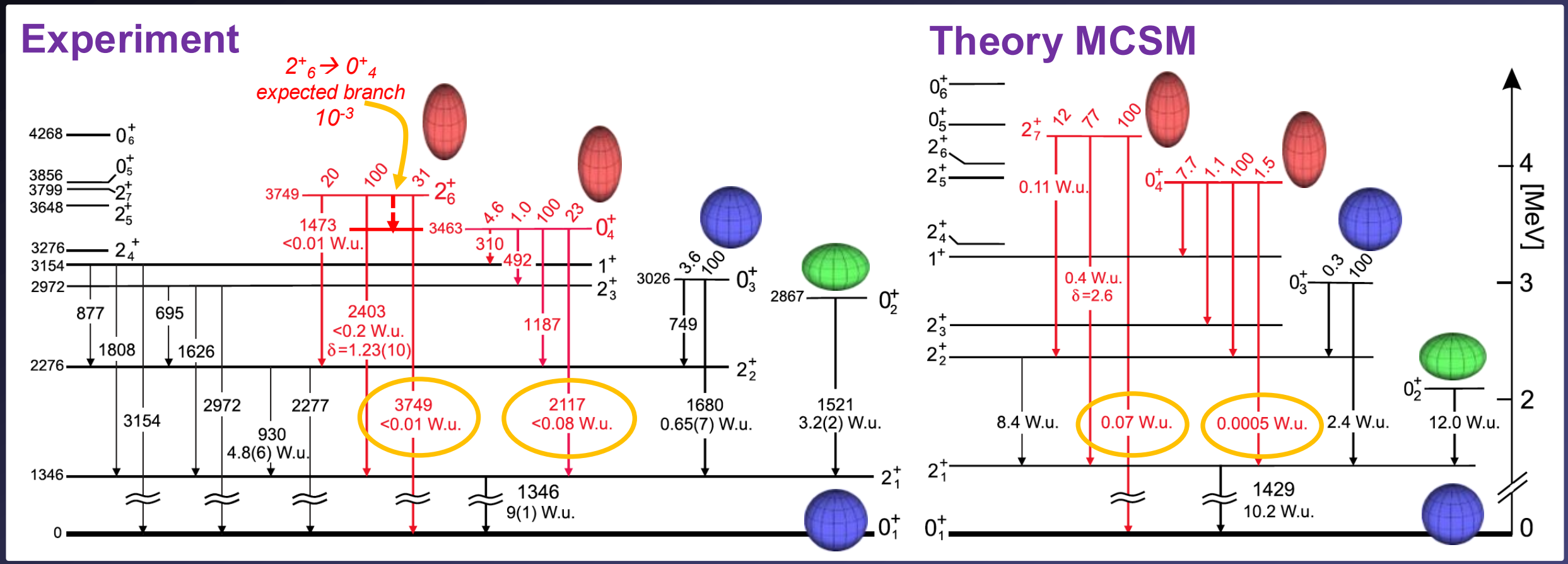
$0^+_4 \rightarrow 2^+_1$ and $2^+_6 \rightarrow 0^+_1$
two E2 transitions strongly hindered !!

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

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

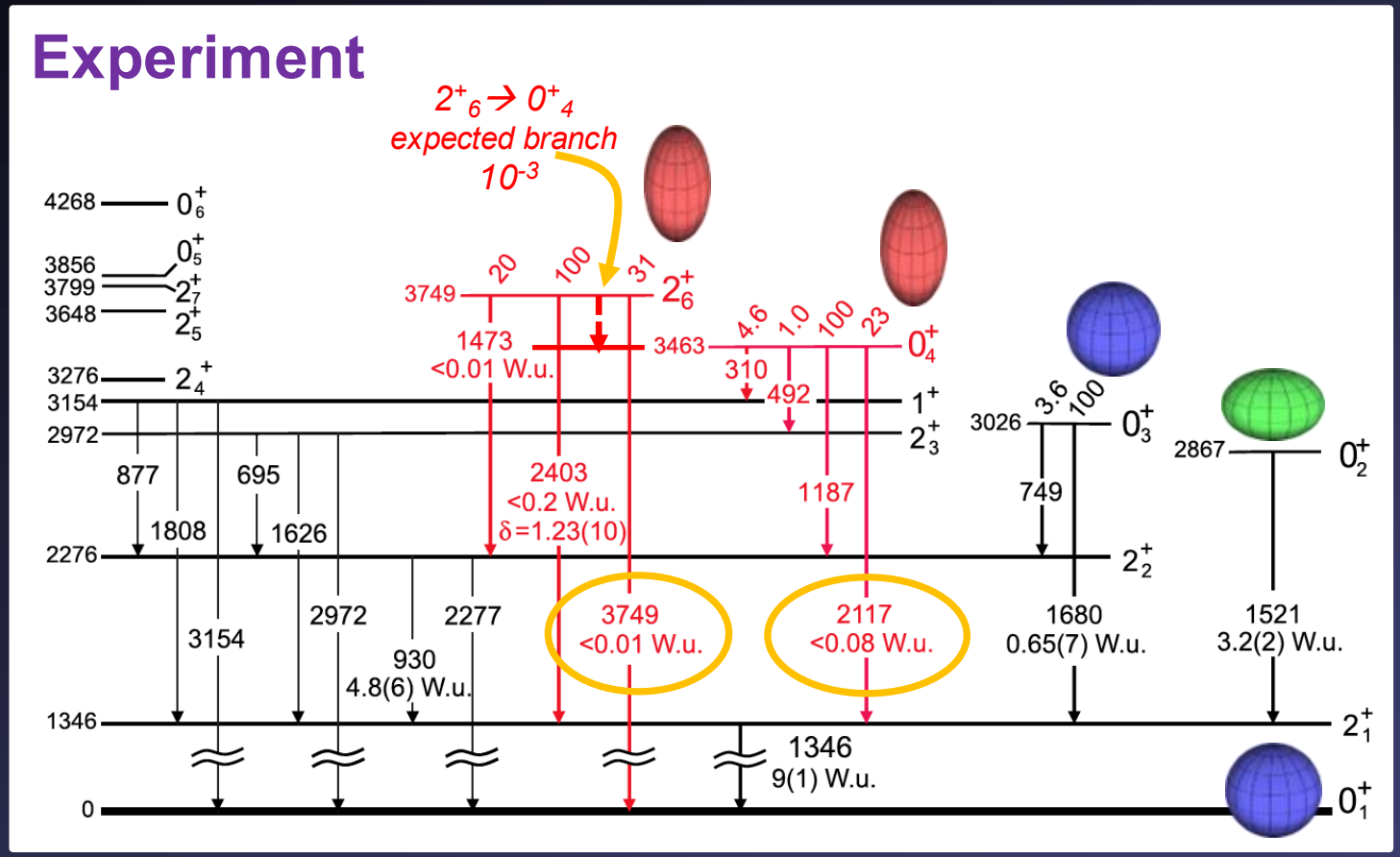
the **TENSOR FORCE** is responsible
for the **coexistence of shapes in ^{64}Ni**
otherwise expected to be spherical !!!

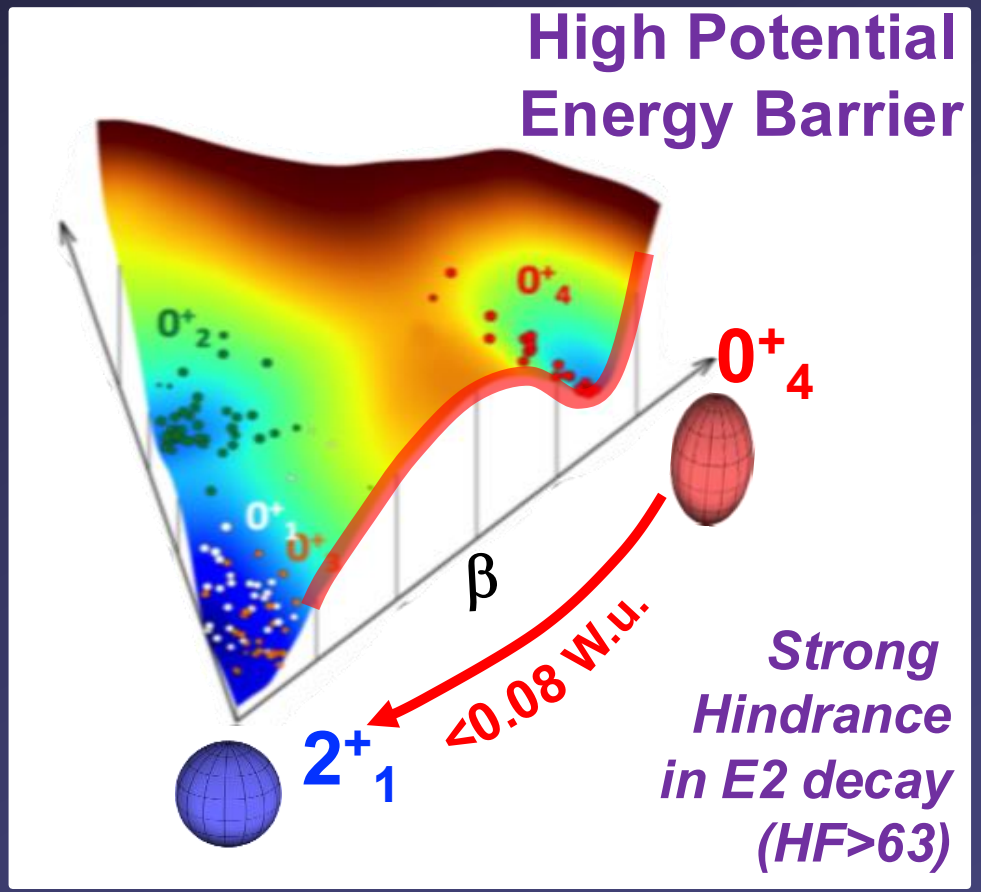
N. Marginean, et al., Phys. Rev. Lett. 125, 102502 (2020)

Extended experimental investigation (4 experiments)

decay scheme, state lifetimes, transition rates, …

^{64}Ni





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

Hindrance caused by
shape change (*prolate → spherical*)

SHAPE-ISOMER-LIKE structure

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

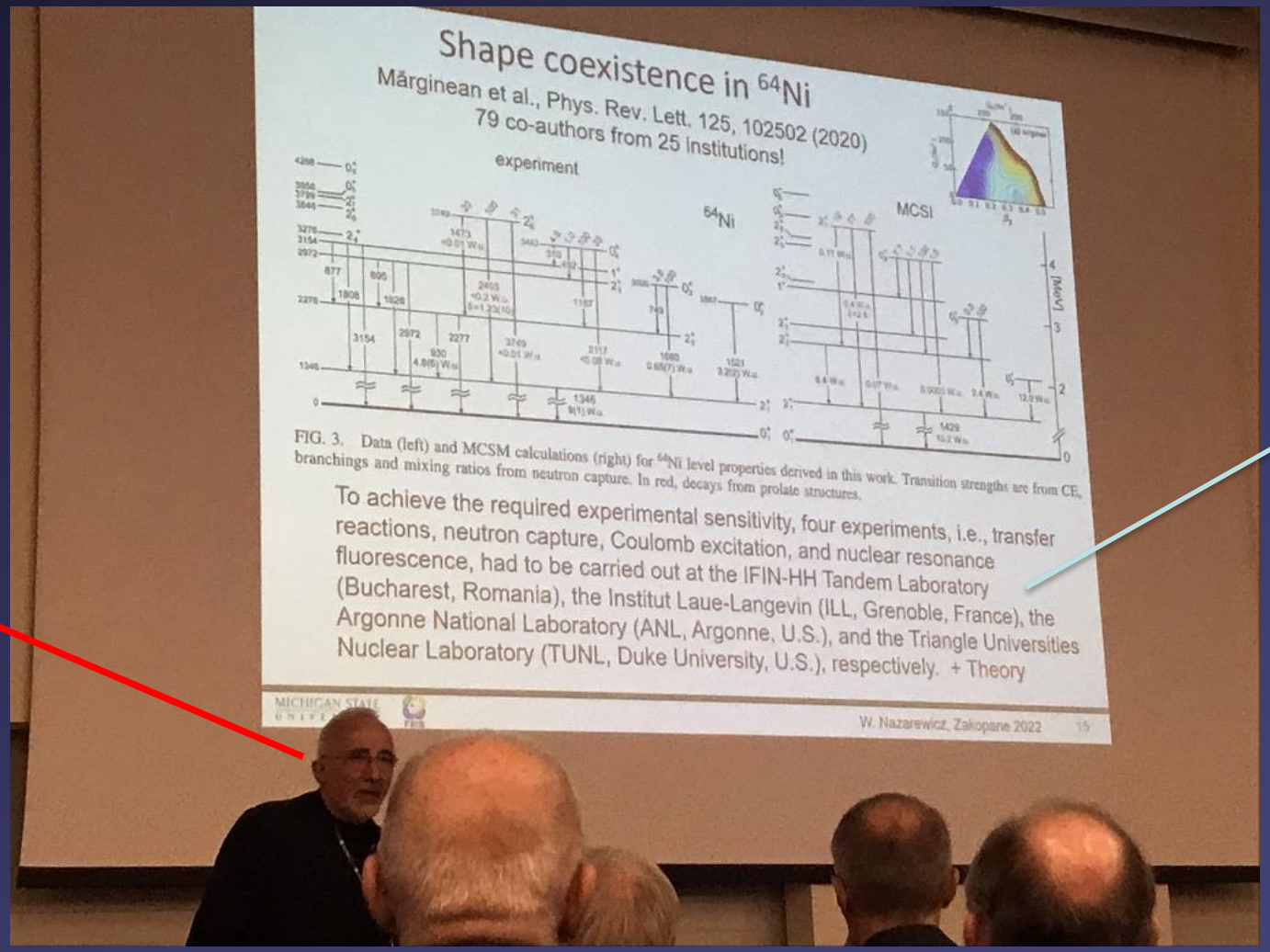
Witold Nazarewicz keynote talk

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 US LONG RANGE PLAN

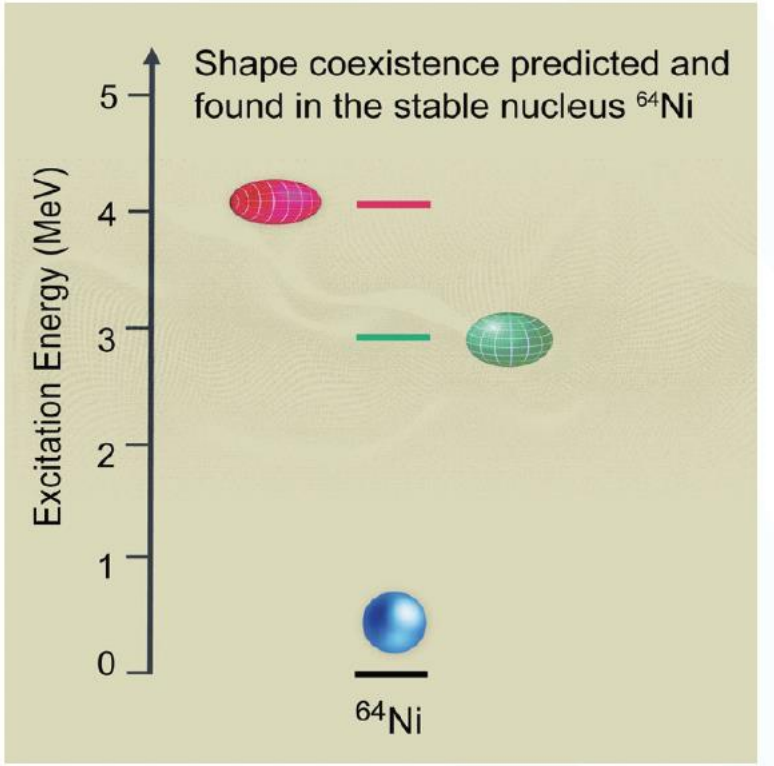
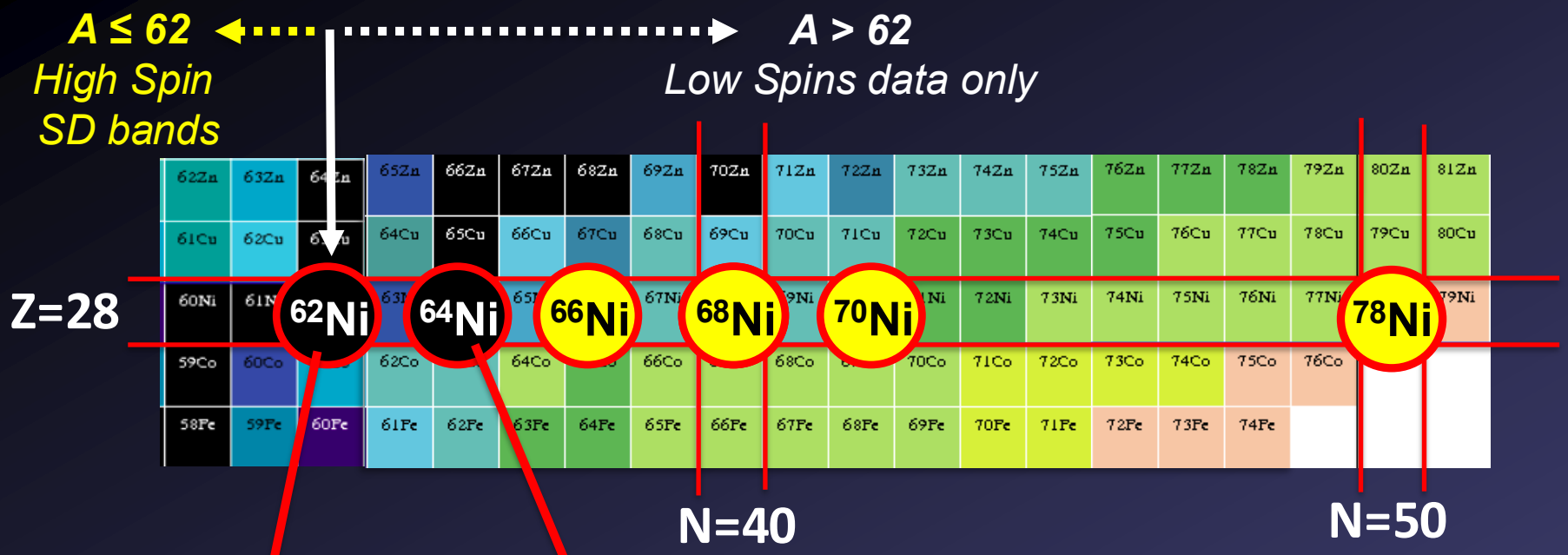


Figure 4.4. The evolution of the nuclear shape in stable nickel-64 as predicted by large-scale nuclear model calculations. *Now, new research has confirmed the coexistence of three nuclear shapes [20].*

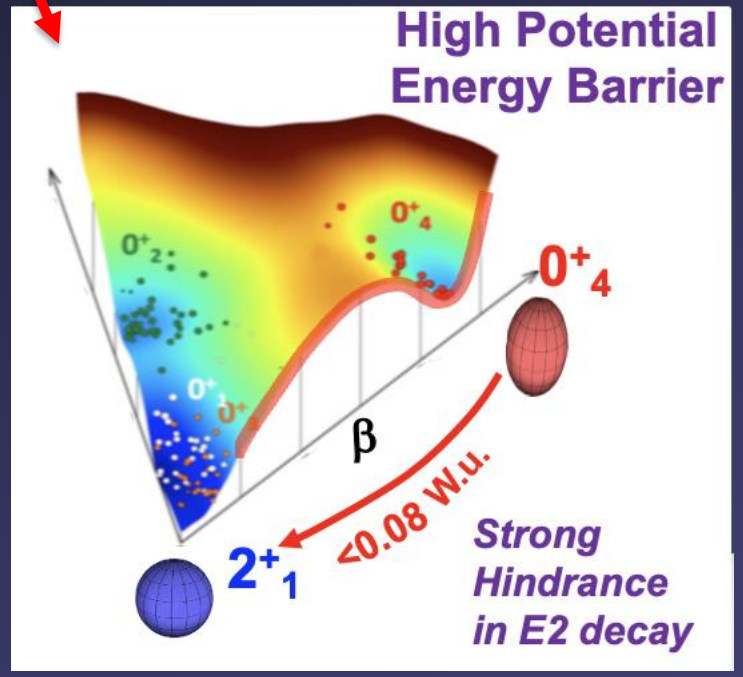
Meanwhile, the study of very elongated shapes in nuclei provides a window into nucleonic shell structure at large deformation. Extensive work earlier this century enabled the characterization of nuclear shapes with 2:1 axis ratio. In the coming decade, GRETA at ATLAS is poised to enable the discovery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

The Ni chain

historical region to test Shape Coexistence



in ^{62}Ni ?



in ^{64}Ni (and ^{66}Ni):

Evidence for
SHAPE-ISOMER-LIKE structure
at Spin 0

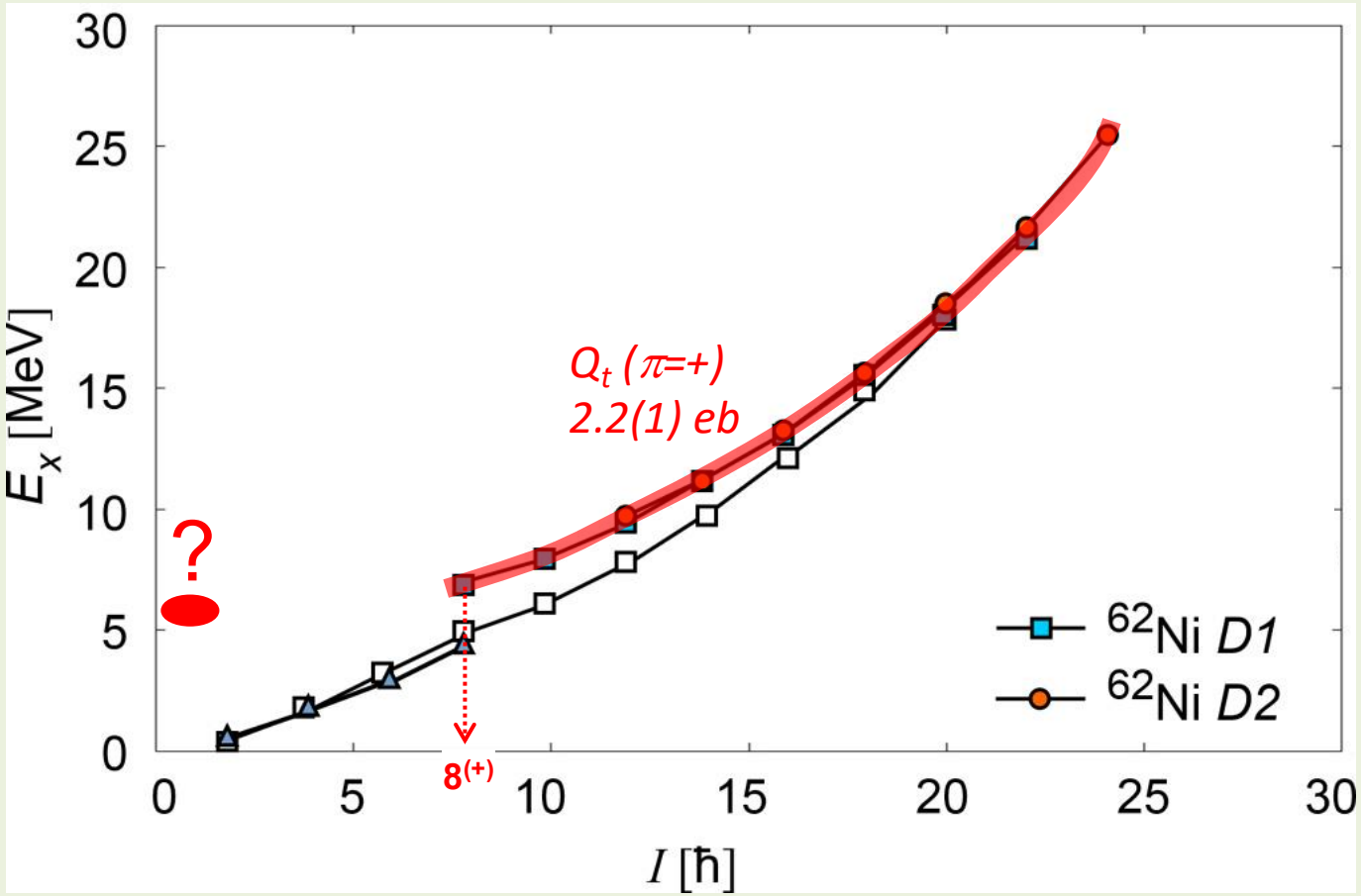
^{66}Ni: *IFIN-HH data, sub-barr. 2n transfer*
Leoni, Fornal, Marginean et al., PRL118, 162502(2017)

HIGH SPIN data in ^{62}Ni

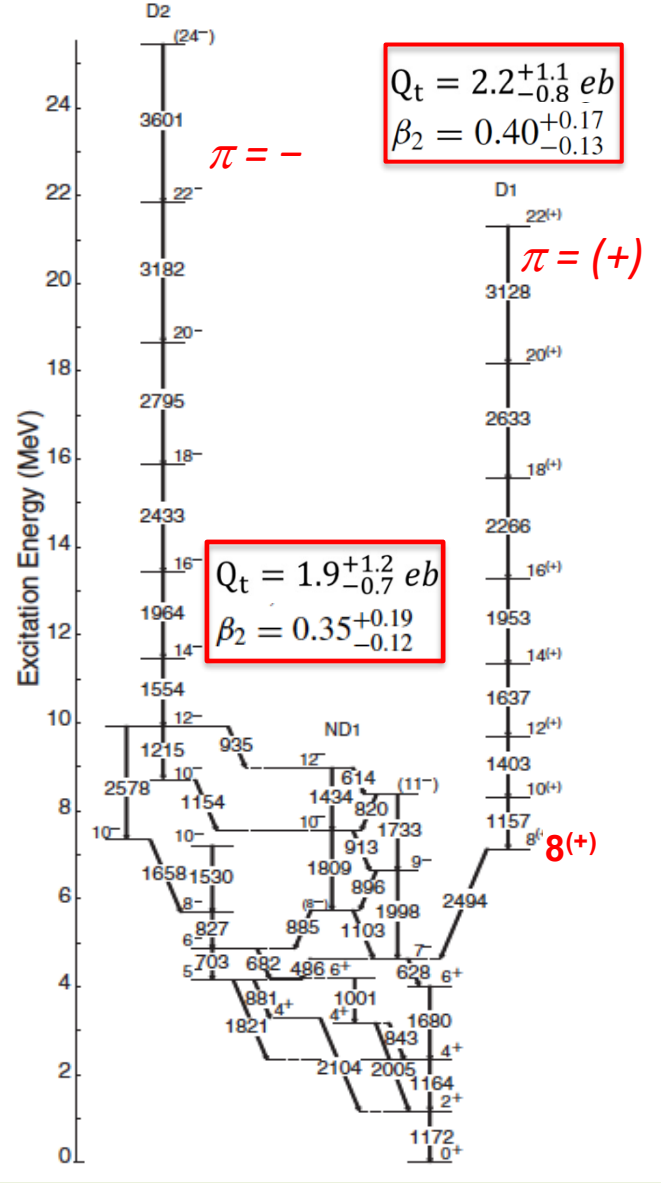
PHYSICAL REVIEW C **94**, 034301 (2016)

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]



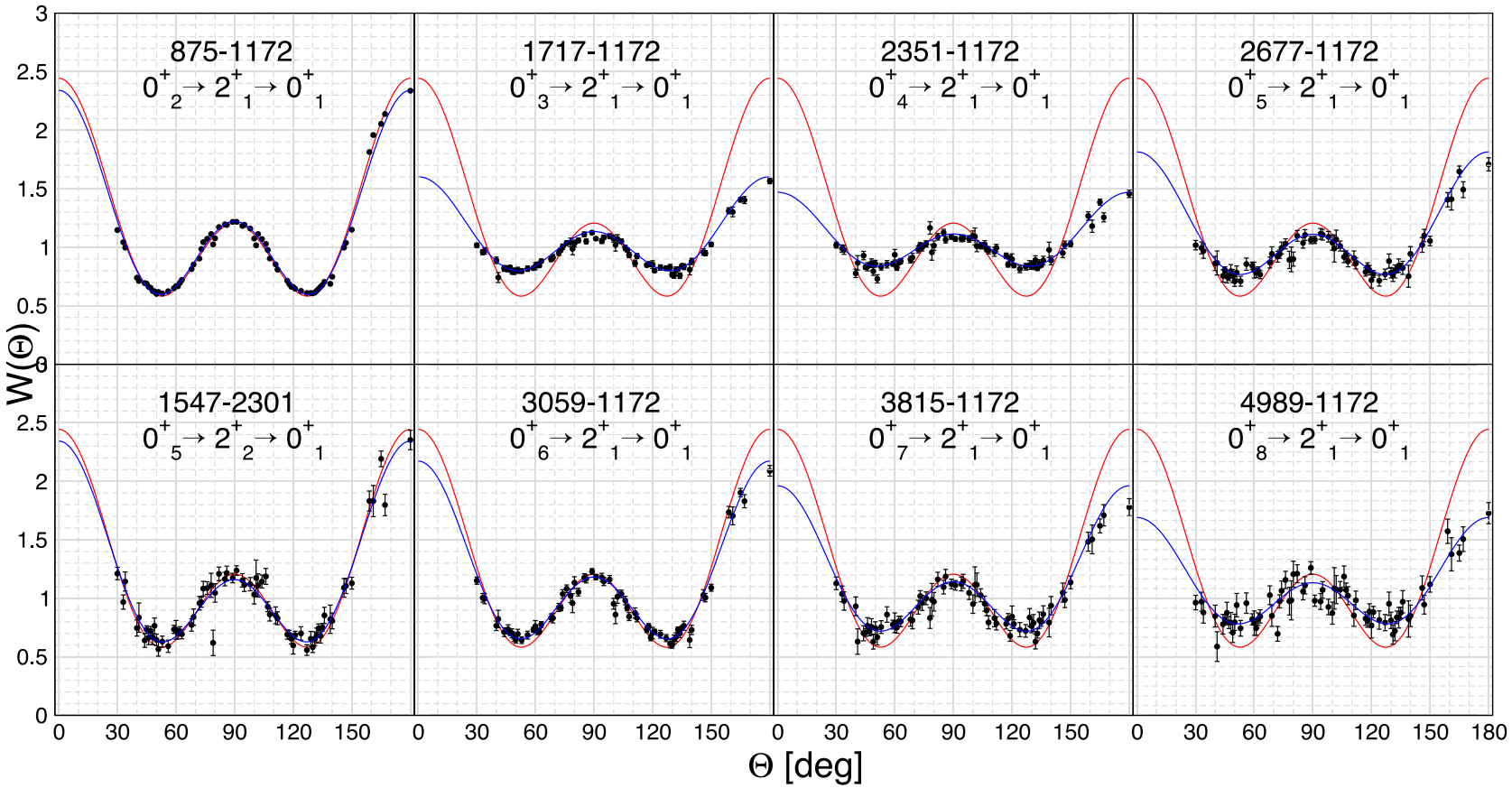
GAMMASPHERE + FMA (Argonne)



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

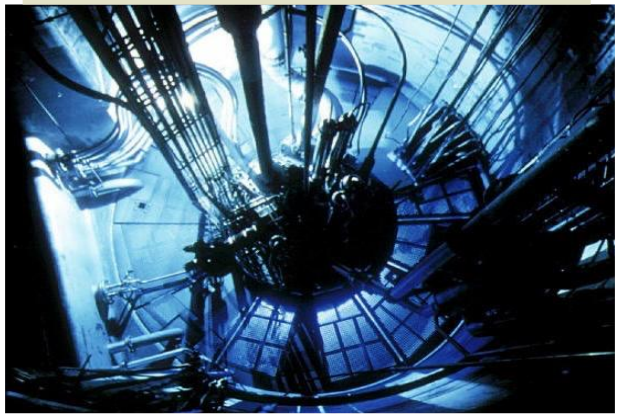
thermal-neutron capture on a 250 mg ^{61}Ni target of metallic powder

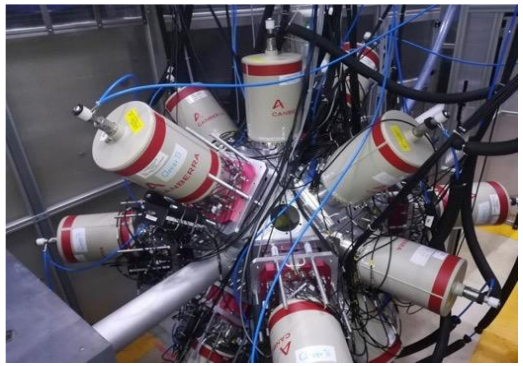
Large statistics and high-precision γ–γ angular correlations



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

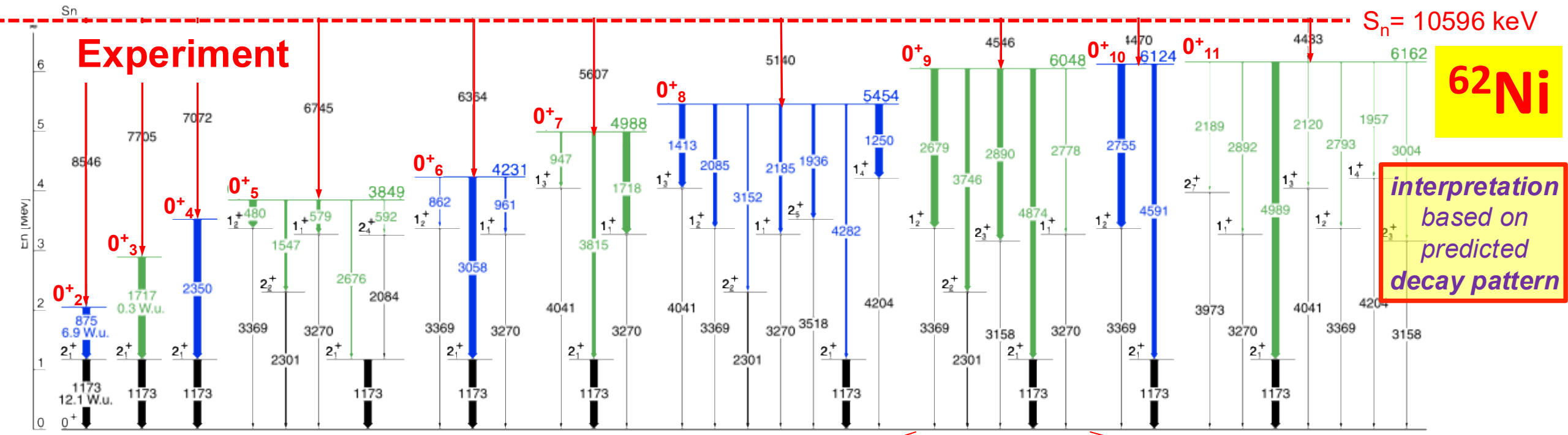
Pencil-like intense thermal neutron beam



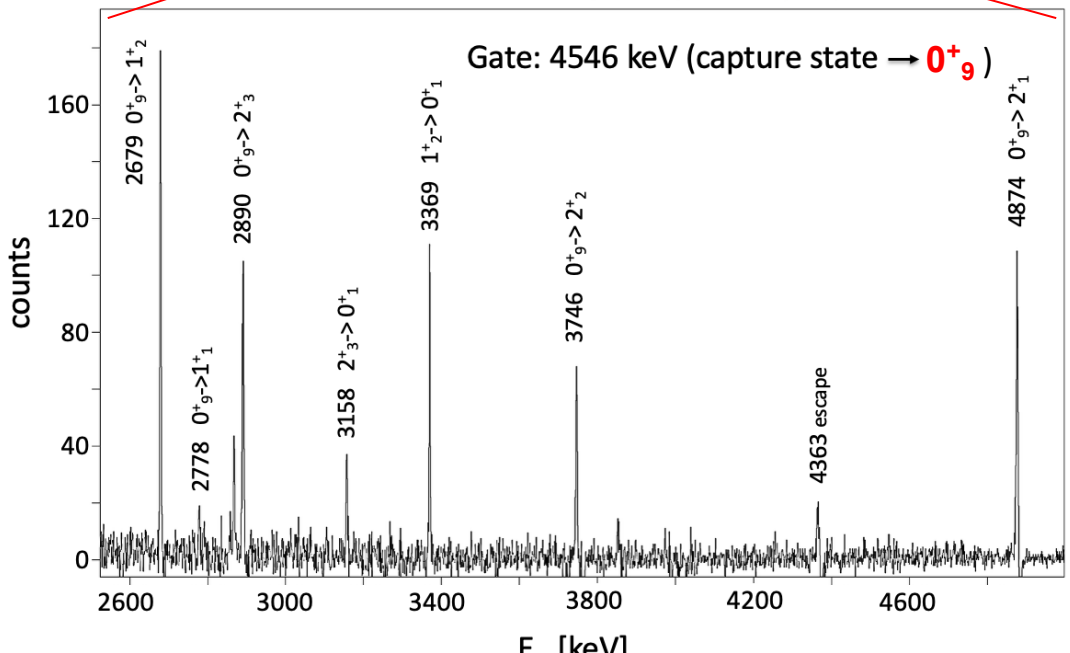


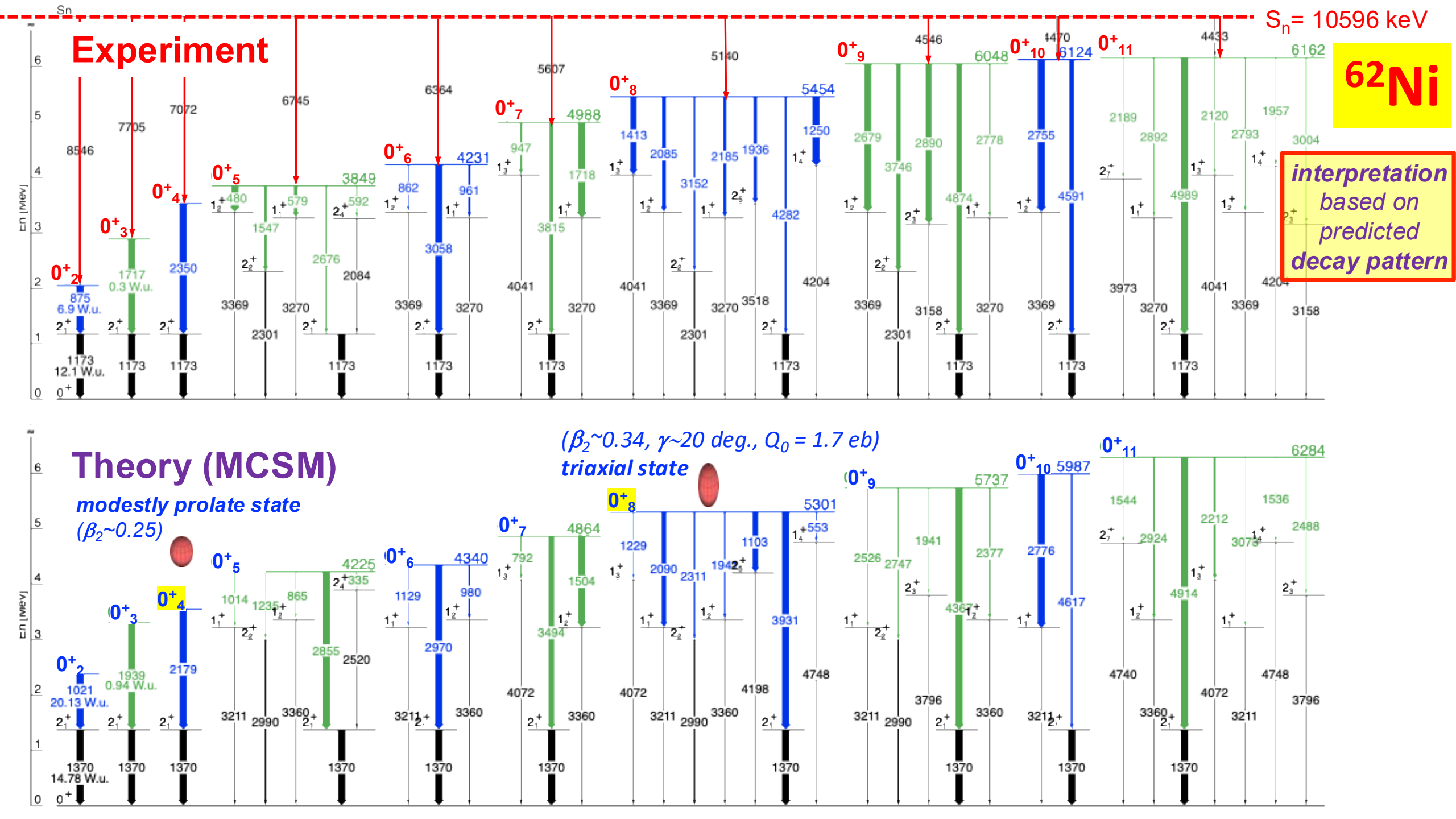
16 HPGe clovers (8 from IFIN-HH) high resolution and efficiency γ detector array

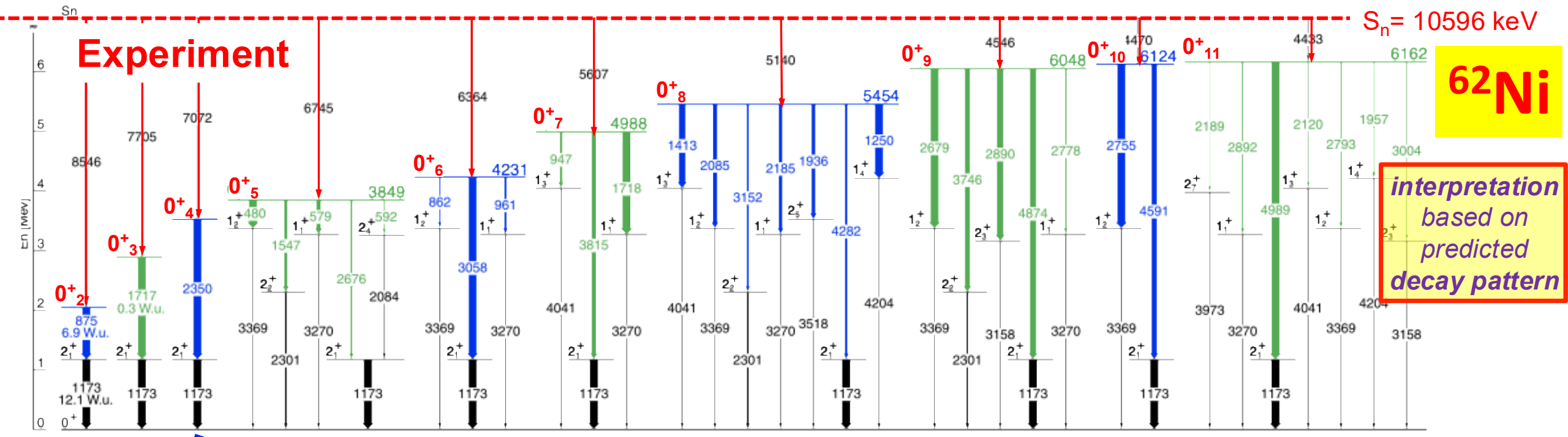
C. Costache, Y. Tsunoda, S. Leoni, B. Fornal, N. Marginean, R. V. F. Janssens, T. Otsuka, … to be submitted



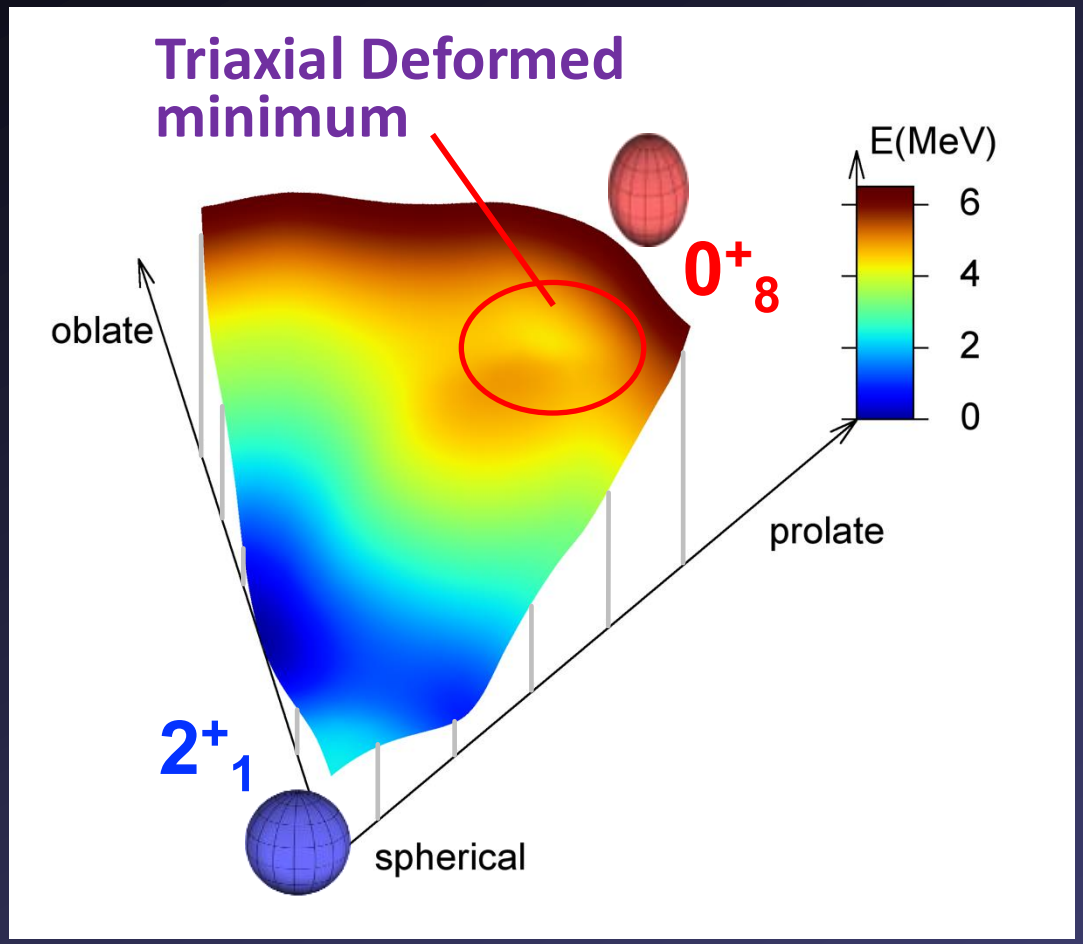
high statistics
extremely clean data
from FIPPS




Sn
S_n= 10596 keV
Experiment
^{62}Ni
interpretation based on predicted decay pattern
Theory (MCSM)
modestly prolate state
(β_2~0.25)
(β_2~0.34, γ~20 deg., Q_0 = 1.7 eb)
triaxial state
Ex [MeV]

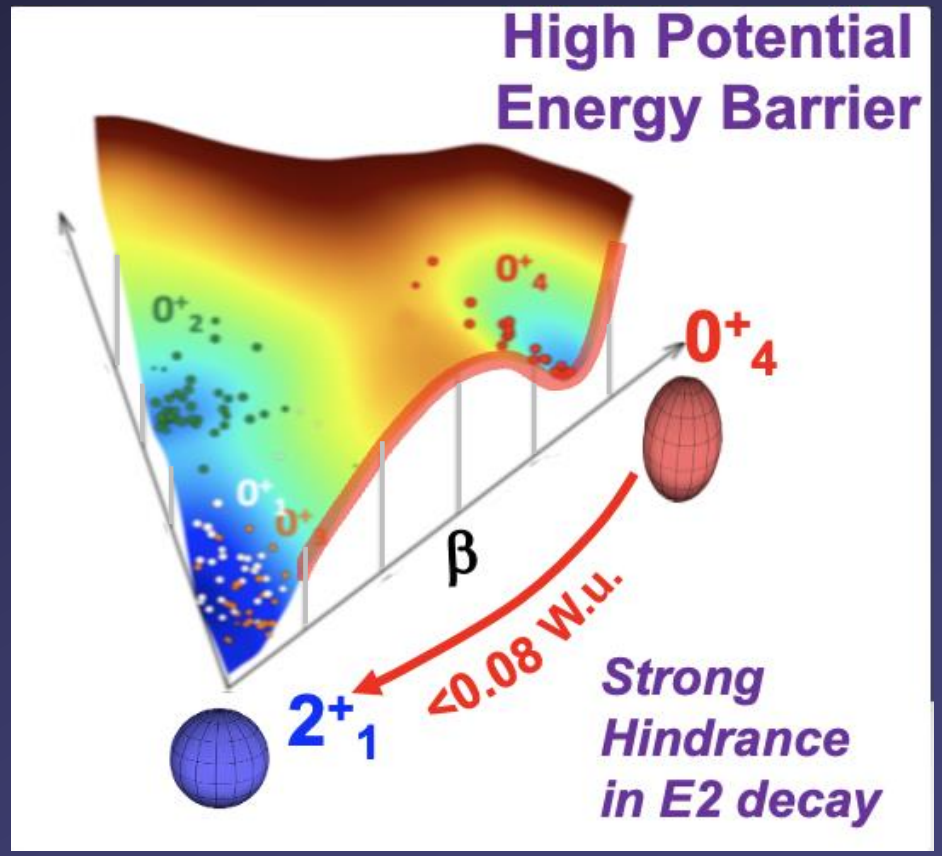

Sn
S_n= 10596 keV
Experiment
^{62}Ni
interpretation based on predicted decay pattern
E_x (MeV)
0^+_2 875 6.9 W.u.
0^+_3 1717 0.3 W.u.
0^+_4 2350
0^+_5
0^+_6 4231
0^+_7 4988
0^+_8 5454
0^+_9 4546
0^+_{10} 6124
0^+_{11} 4433
1173 12.1 W.u.
8546
7705
7072
6745
6364
5607
5140
6048
6162
4470
Theory (MCSM)
0^+_1 ground state
0^+_4 modestly prolate β_2~0.25
3.5 MeV
0^+_8 triaxial prolate β_2~0.34 γ~20°
5.3 MeV
β_2

^{62}Ni



NO expected Hindrance in the E2 decay

^{64}Ni



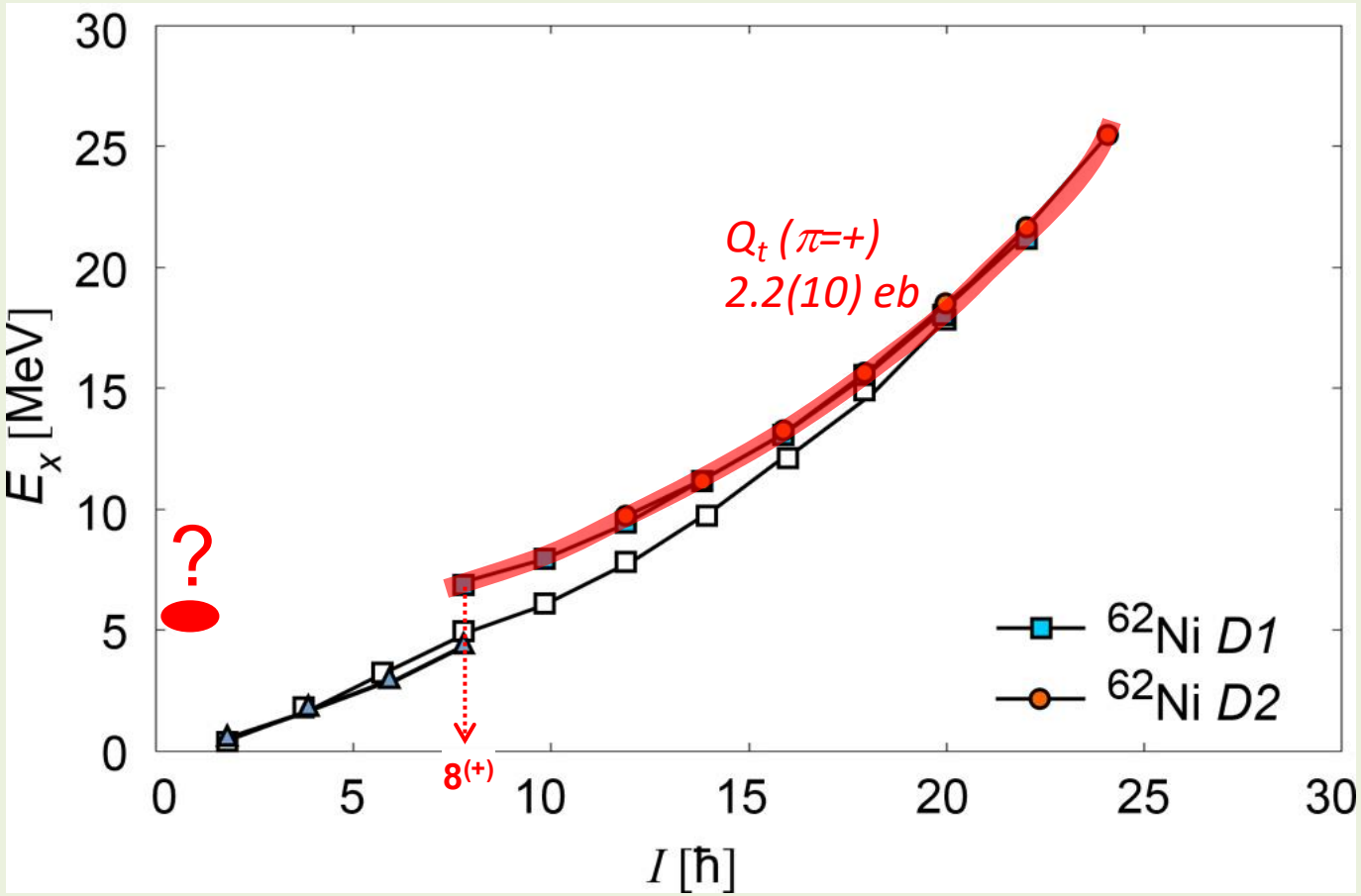
SHAPE-ISOMER-LIKE structure at Spin 0

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

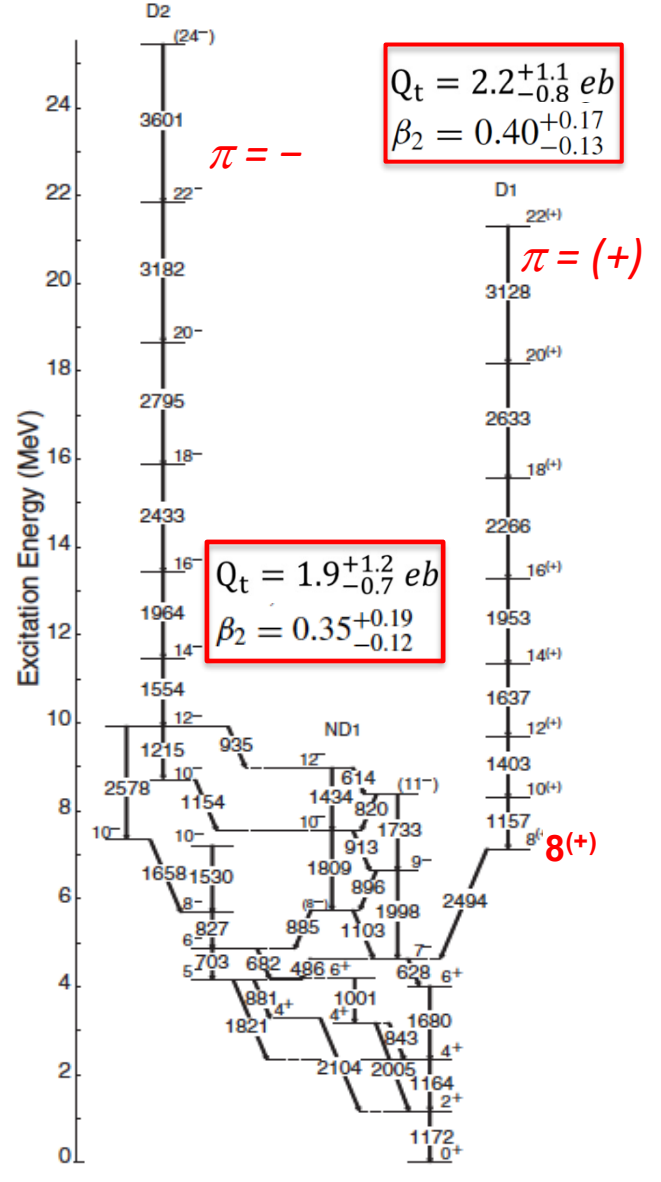
PHYSICAL REVIEW C **94**, 034301 (2016)

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

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)



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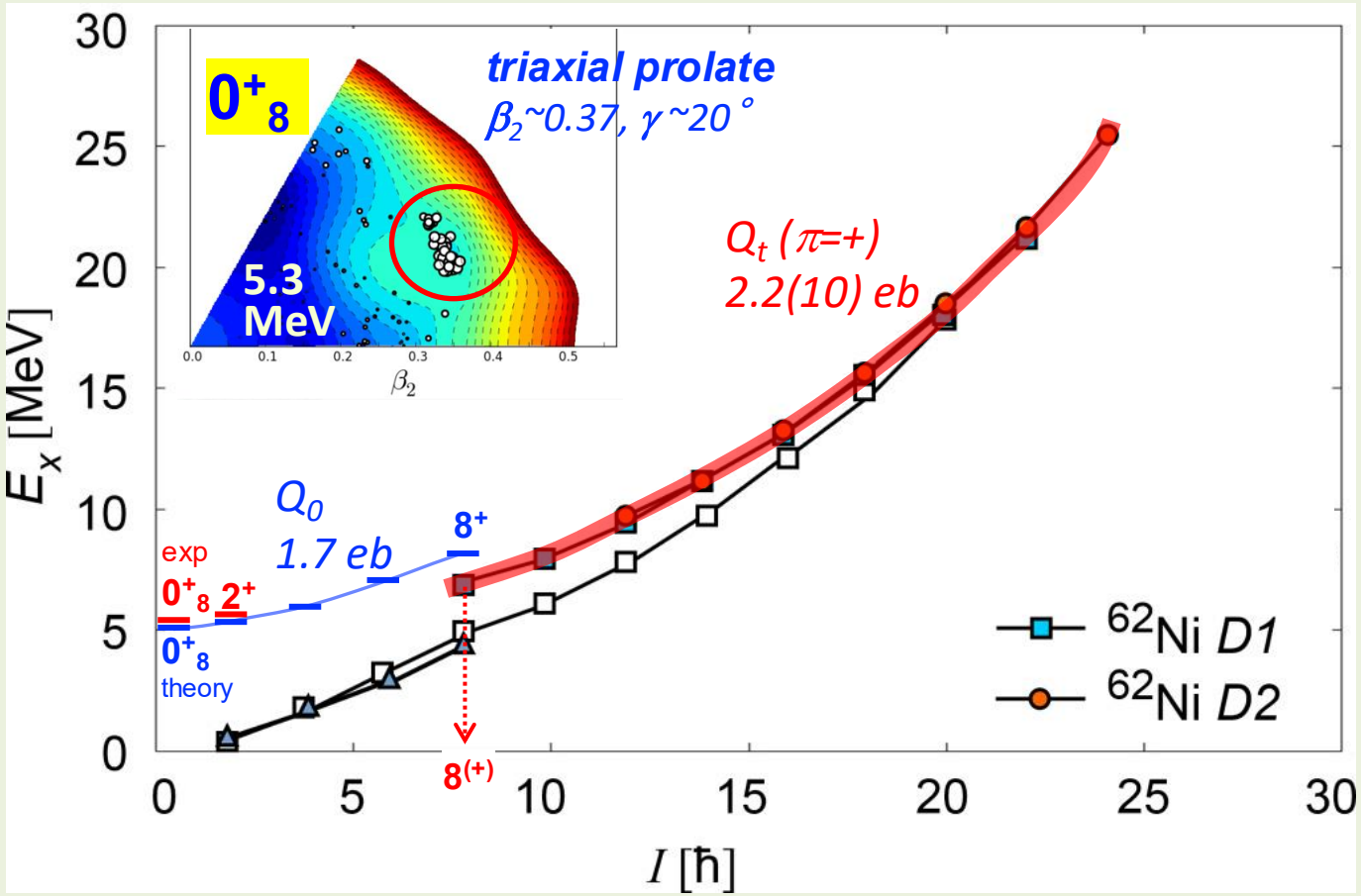
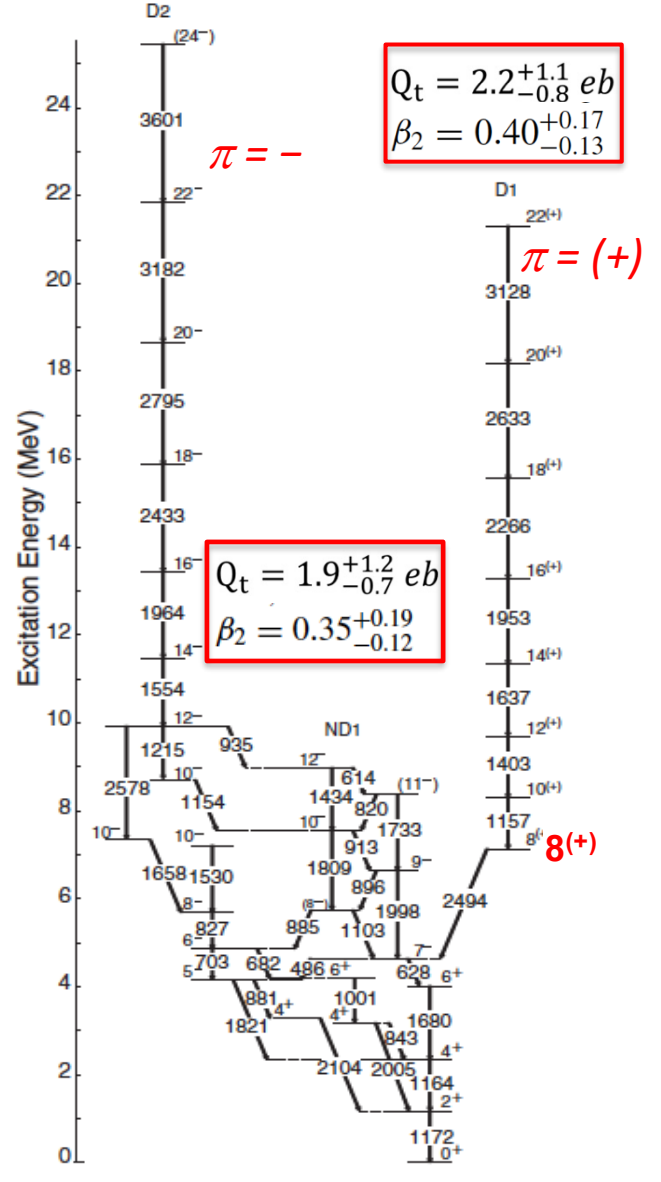
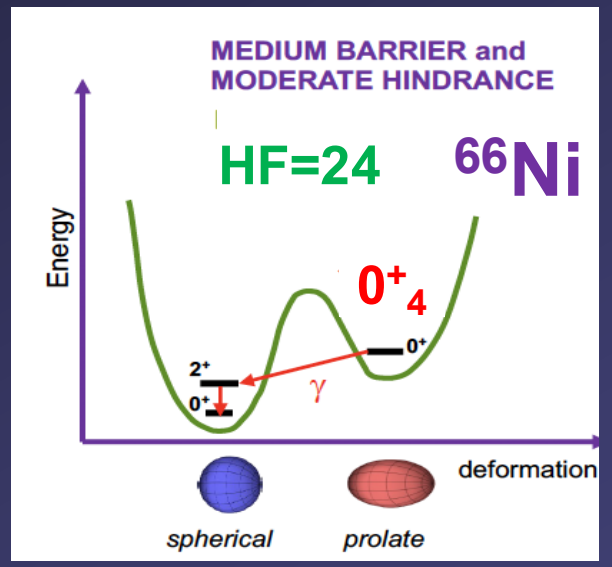


GAMMASPHERE + FMA (Argonne)



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

CONCLUSIONS



- **SHAPE ISOMERISM at I=0 is a very peculiar and rare phenomenon**

it appears when the **wave function is well localized in secondary PES minimum,** separated by a **sizable barrier**

MAIN FINGERPRINT: Large Hindrance (B(E2)<< 1, HF>10)

^{236}U (HF>10^7), $^{64,66}Ni$ (HF ~20-100), …

- **Neutron capture reactions are ideal to search for shape isomers !!!**
- **Search for SHAPE ISOMERISM among SUPER DEFORMED nuclei**

for the first time, **^{62}Ni at FIPPS** offers the possibility to make a connection between shape coexistence at spin 0 and superdeformation at high spins: a long standing issue!

- **Microscopic interpretation must be based on most powerful SHELL Model**

The TENSOR FORCE plays a significant role

Thank you for the attention !