From shape isomers to superdeformation at high spins

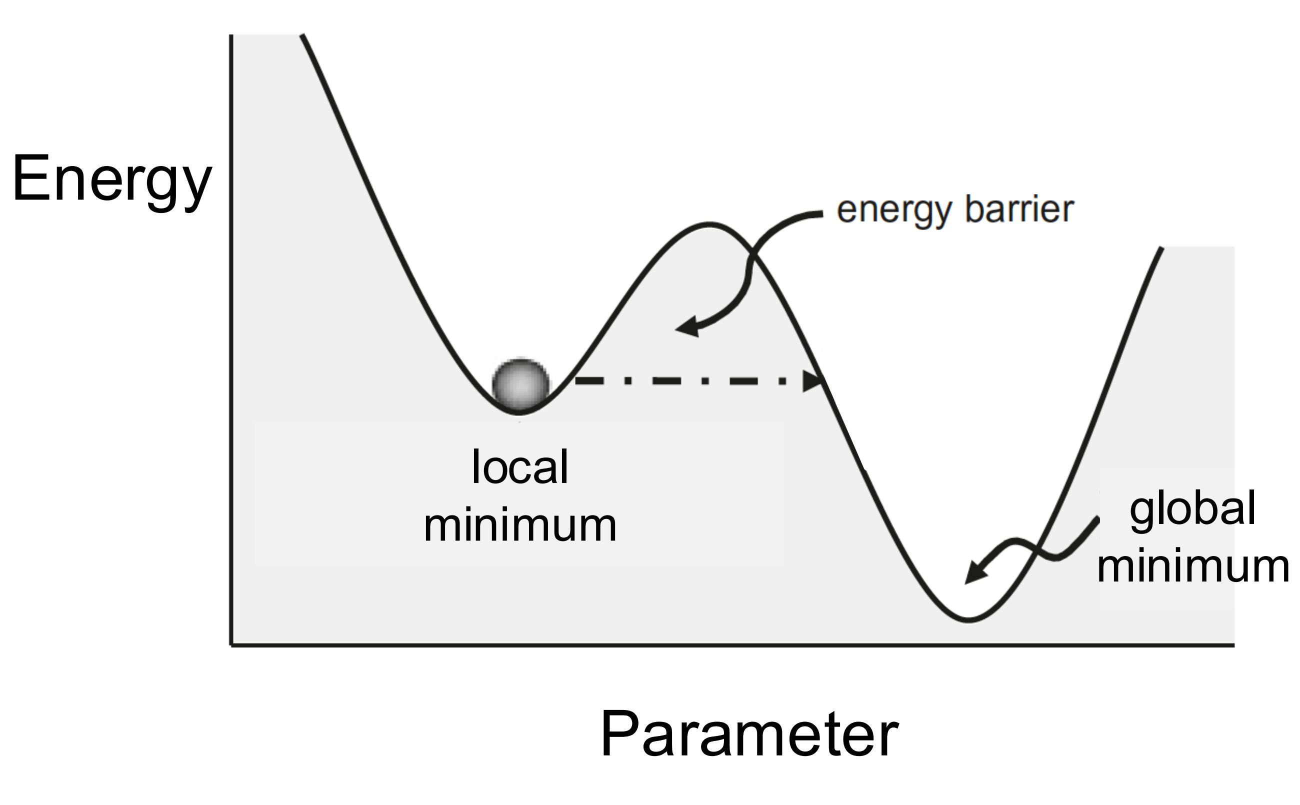
Silvia Leoni – University of Milano and INFN

In collaboration with:

- **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
- **C. Michelagnoli** et al., ILL, Grenoble, France
- **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



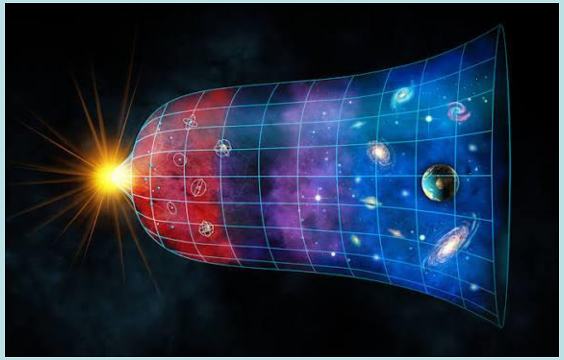
physical systems tend to minimize their potential energy

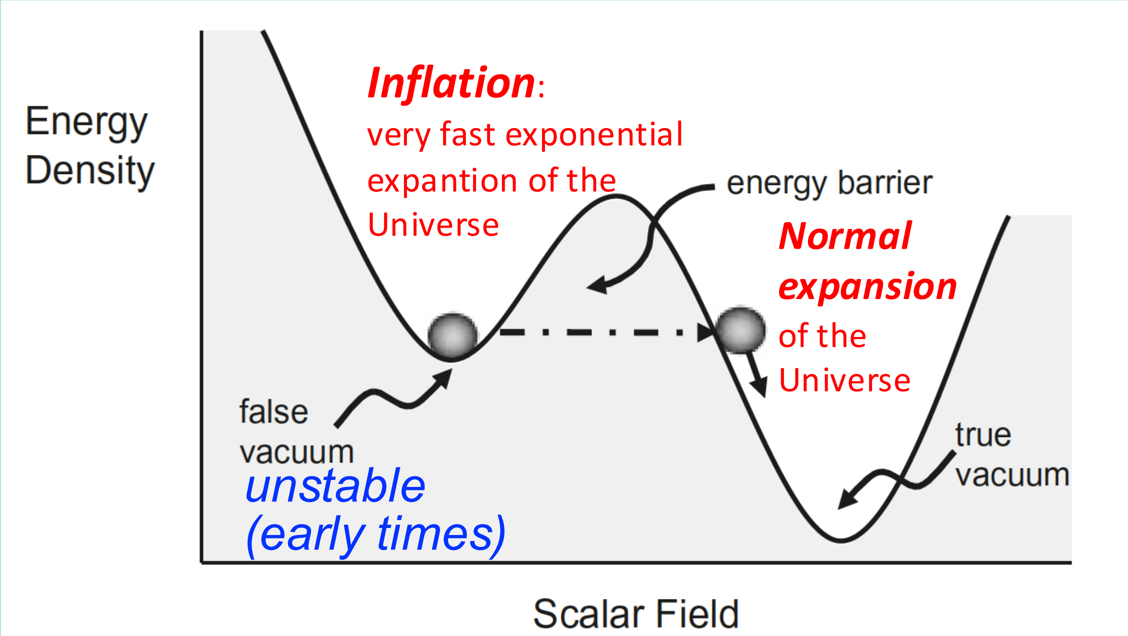
in Quantum Mechanics

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

Selected Examples

COSMOLOGY
Expansion of the Universe

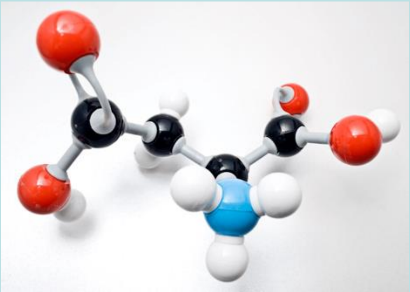




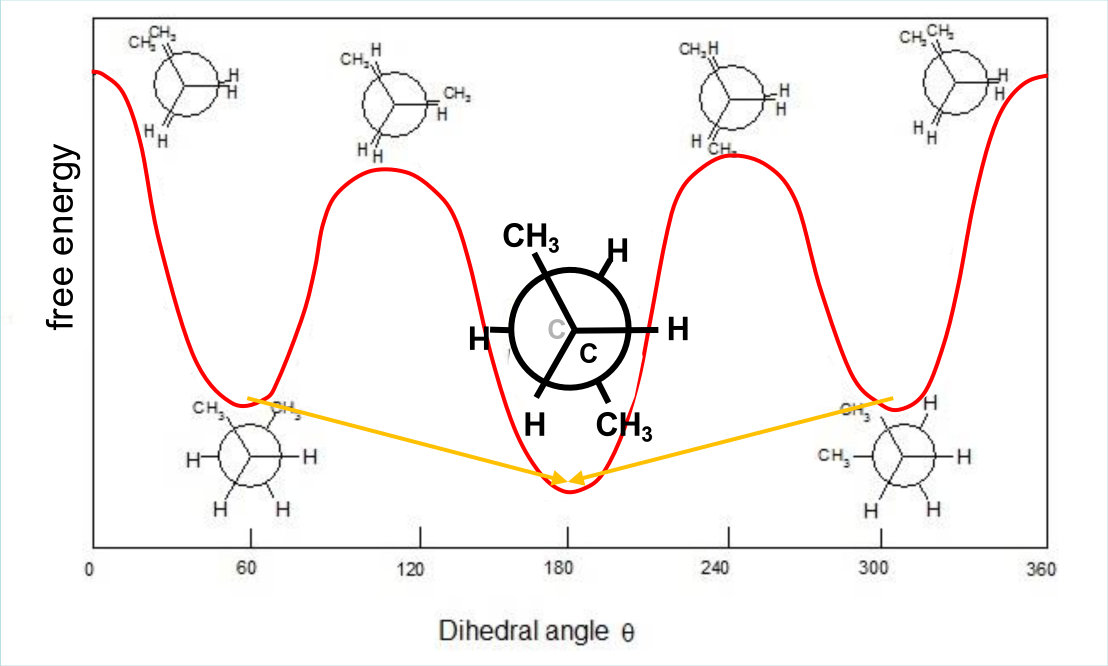
Alan Guth toy model for Universe expansion: ***cosmic inflation***

Alan H. Guth, Phys. Rev. D 23, 347 (1981)

ATOMIC Physics
Conformational isomers



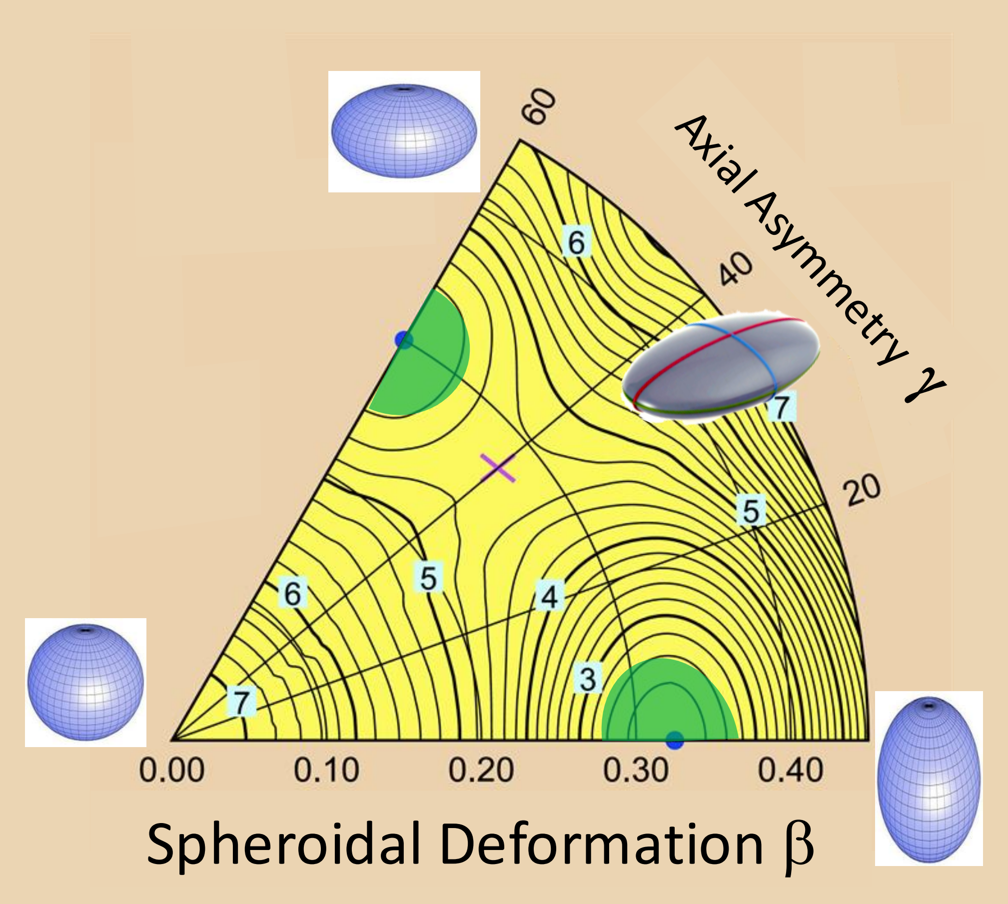
Butane molecule C_4H_{10}



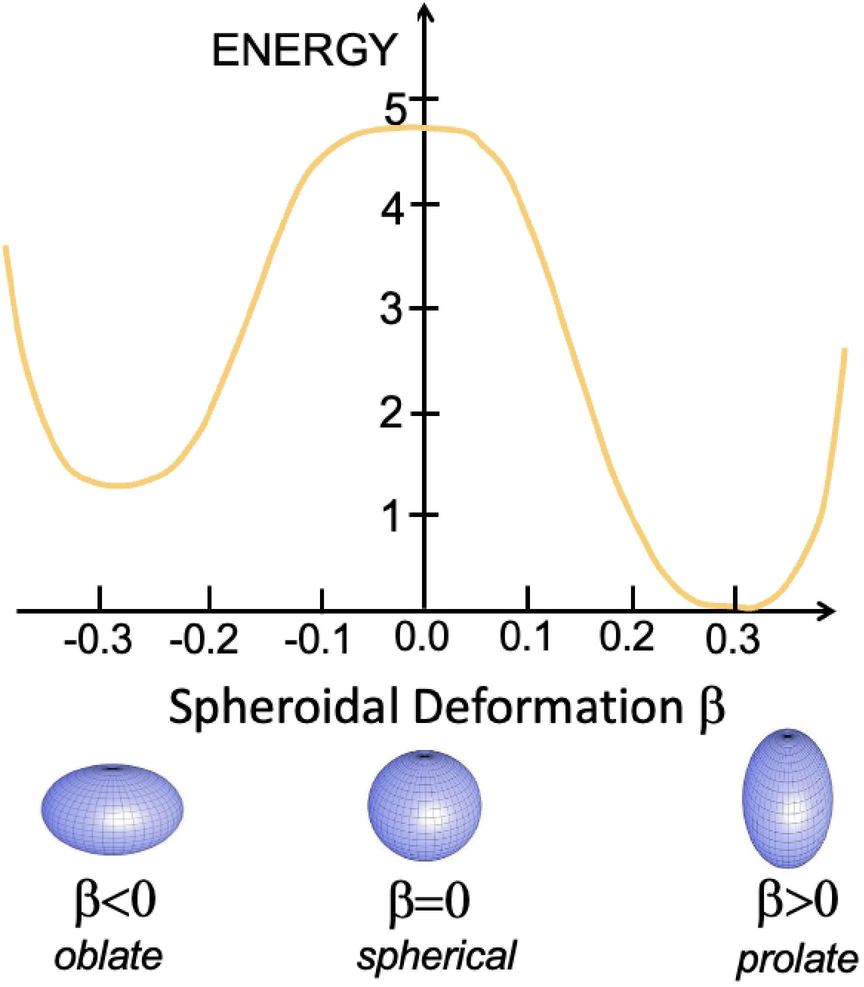
Free energy diagram of butane as a function of dihedral angle (rotation about single bond)

Potential Energy Surface (PES) of a NUCLEUS

two-dimensional contour



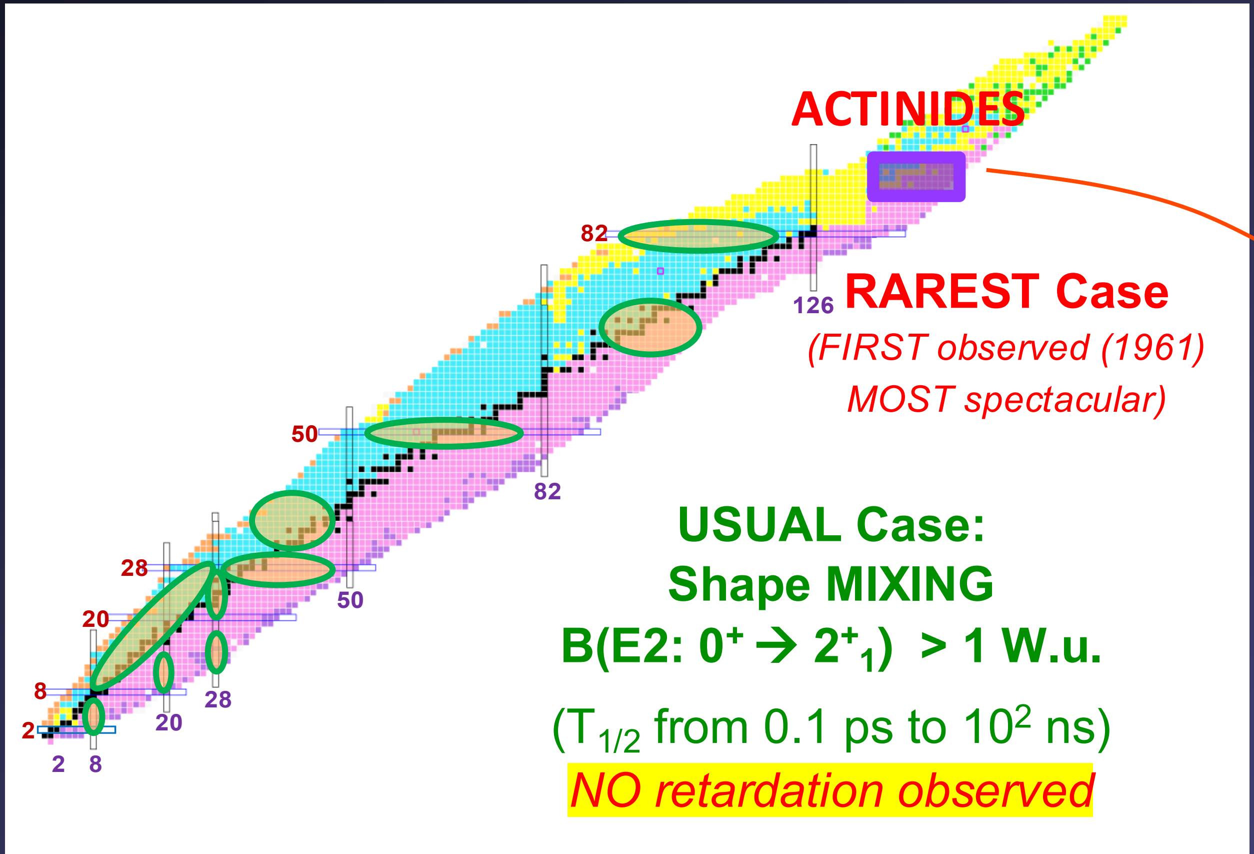
one-dimensional representation

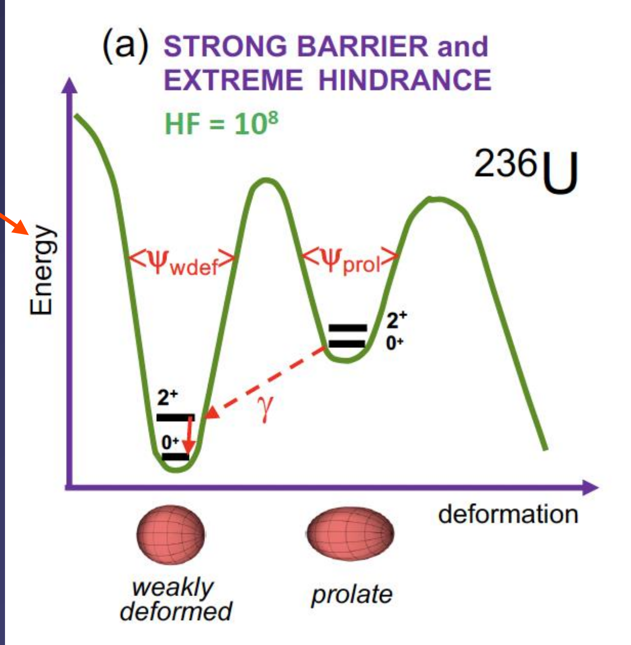


Appearence of <u>different shapes</u>
at comparable excitation energies

>60 years of Shape Coexistence studies at I≈0

“An ubiquitous phenomenon across the nuclear chart”





Fission Shape ISOMERS

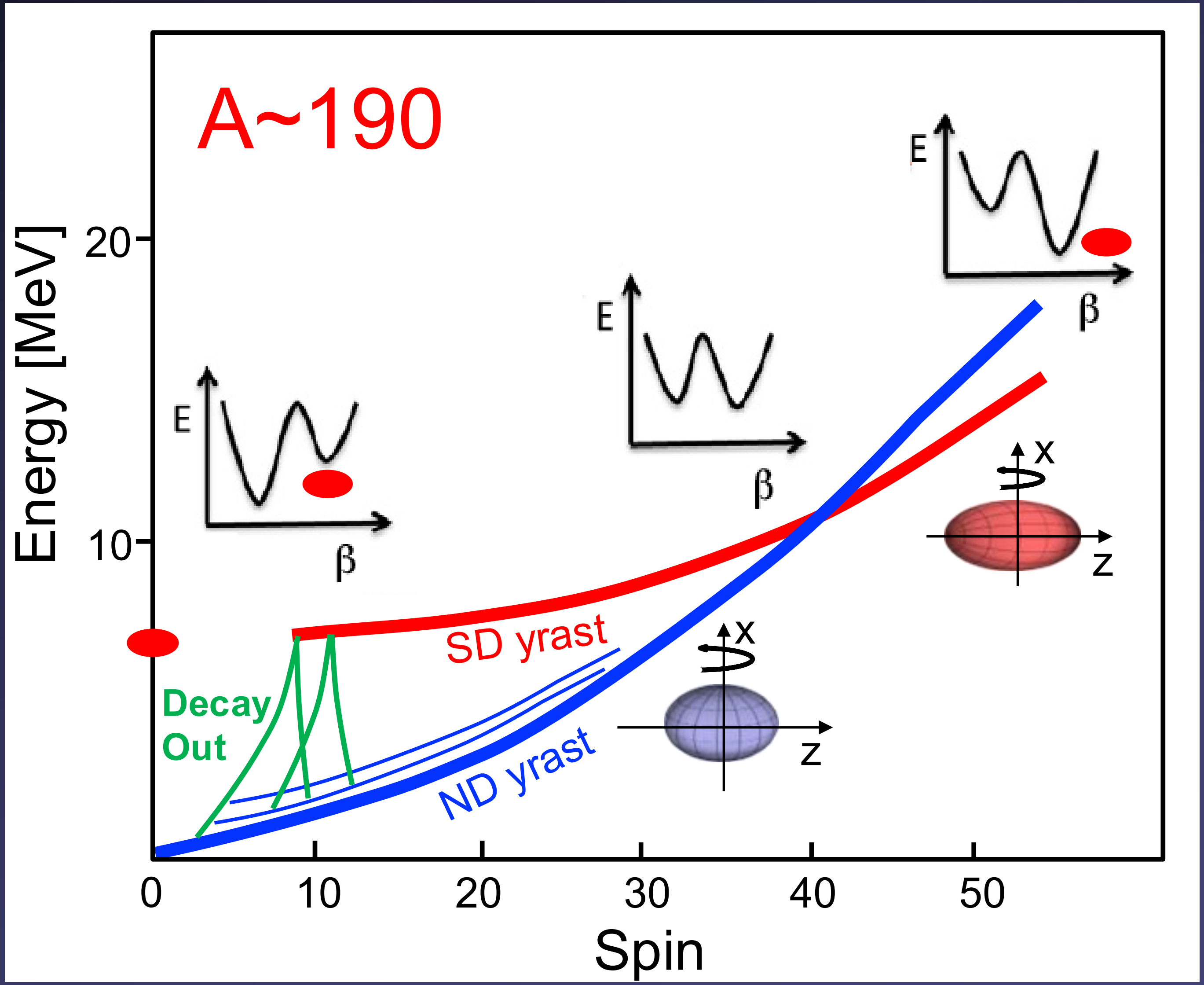
($T_{1/2}$ ~10^2 ns)

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

very retarded Decay

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, N. Marginean, J, Wilson, Eur. Phys. J. Spec. Top. 233, 1061 (2024)
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*

Superdeformation at High Spin:
a spectacular example of Shape Coexistence
> 350 cases discovered with EUROBALL and GAMMASPHERE



B(E2)
10^{-3}-10^{-4} W.u.

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

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

We are missing a unified description from 0 to high spins: a major unresolved problem in nuclear physics

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

OUR AIM

CONNECT *in Exp. and Theory*

Shape Coexistence at Spin 0
and Superdeformation at High Spins

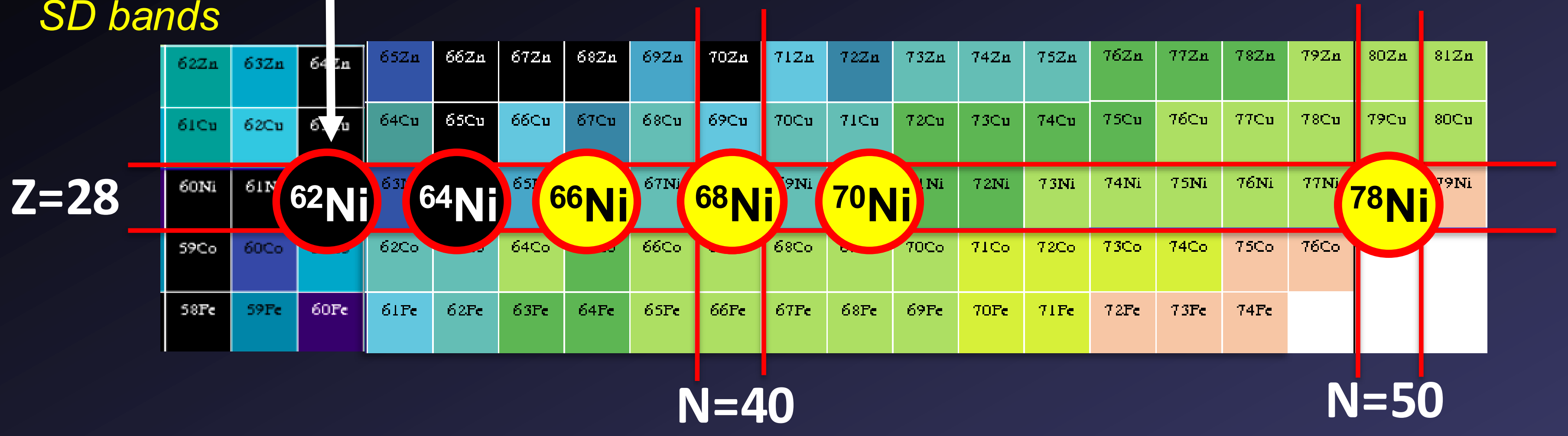
focusing on cases where wave functions are well localized
in different PES minima
separated by a sizable barrier

retarded decay: ***B(E2) << 1 W.u.***

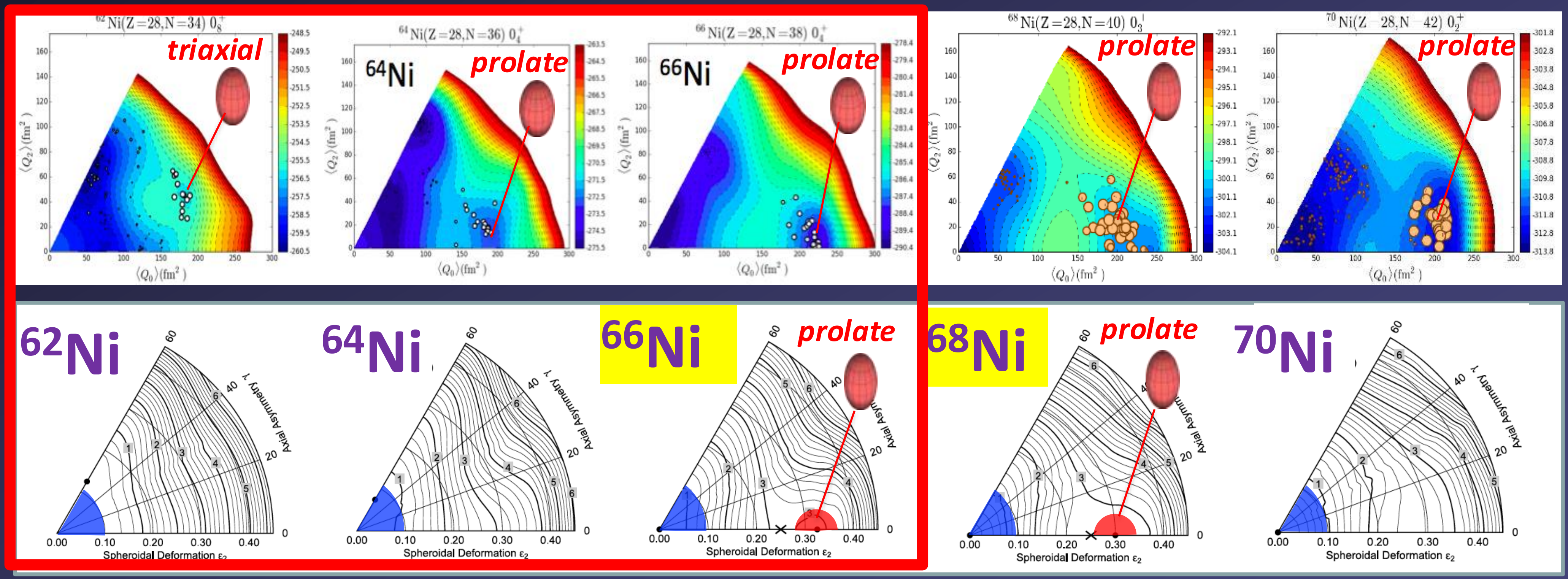
The Ni chain

A ≤ 62
High Spin
SD bands

A > 62
Low Spins data only



historical region to test Shape Coexistence



MonteCarlo SHELL Model

Otsuka, Tsunoda

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

Mean Field

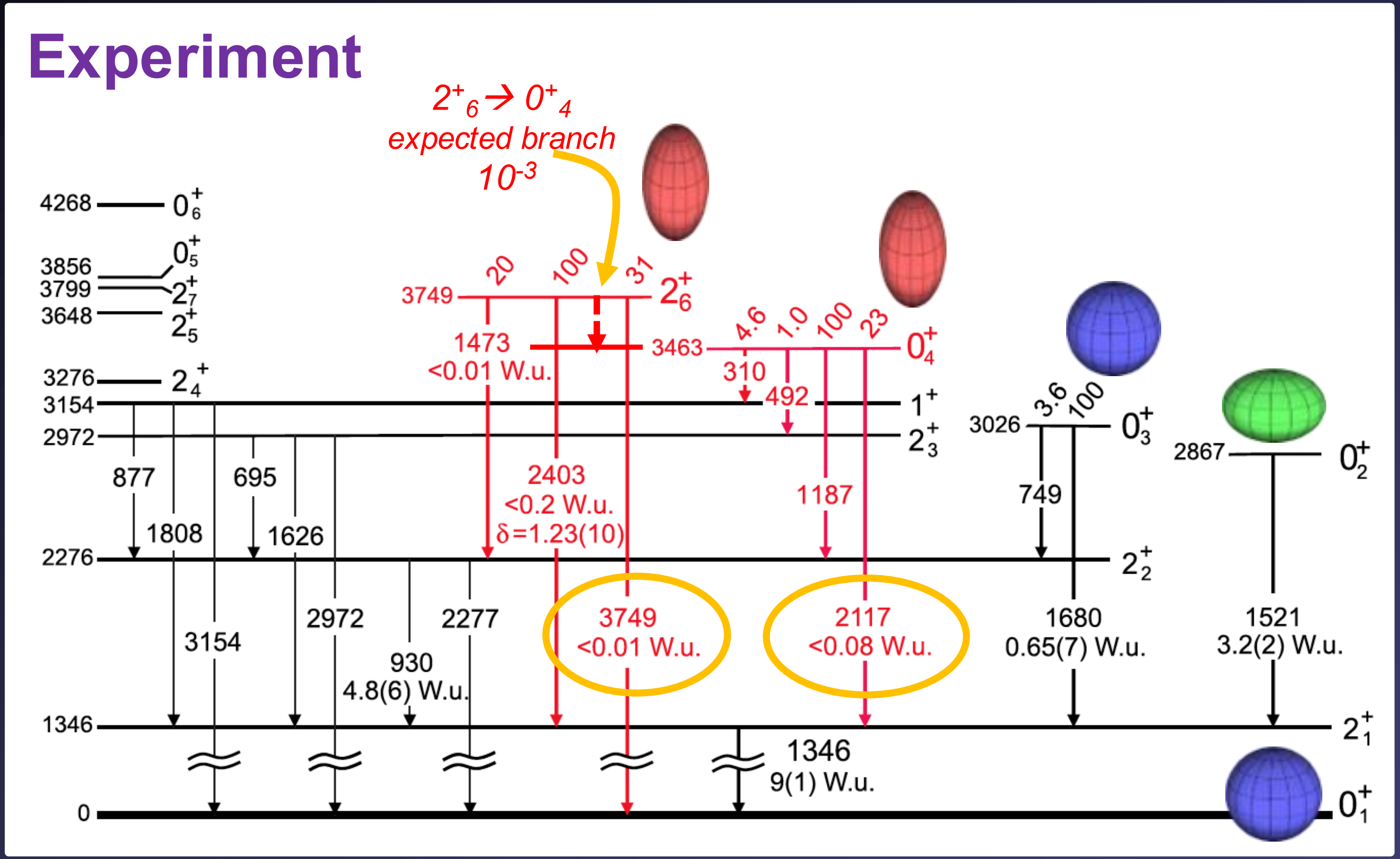
2012: Moeller
'80s: Girod, Gogny

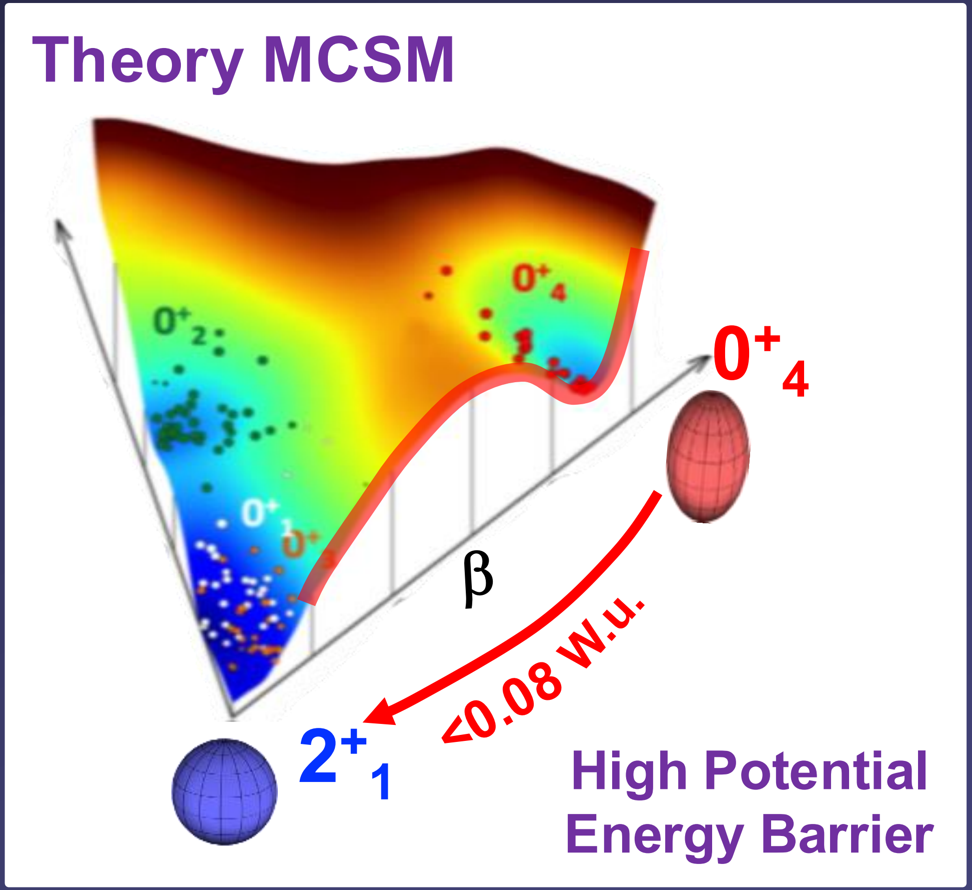
Extended experimental investigation: 4 Exps in 4 Labs

^{64}Ni

transfer@(IFIN-HH), (n,γ)@ILL, Coulex@ANL, (γ,γ')@TUNL

decay scheme, state lifetimes, transition rates, …





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

Strong E2 Hindrance caused by **shape change** (*prolate → spherical*)

SHAPE-ISOMER-LIKE structure

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

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

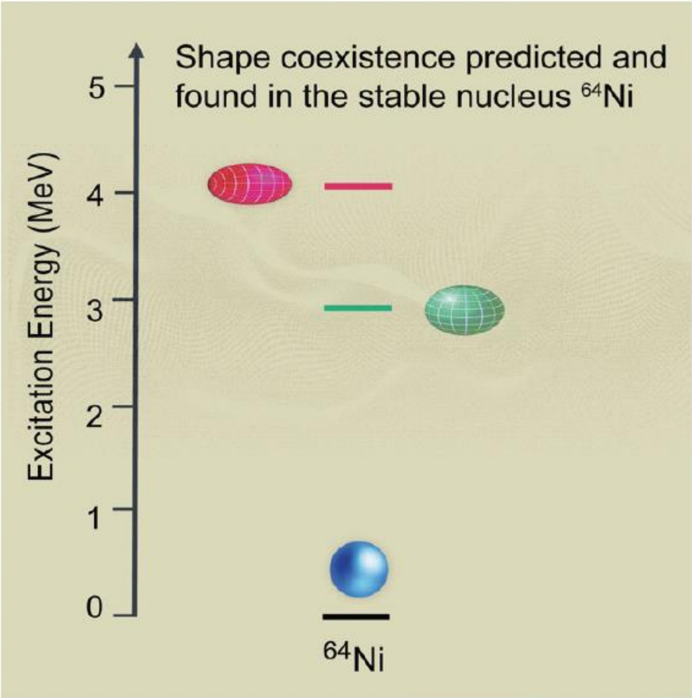


Figure 4.4. The evolution of the nuclear shape in stable nickel-64 as predicted by large-scale nuclear model calculations. *Now, new research has confirmed the coexistence of three nuclear shapes [20].*

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.

"… Complementarity of experimental activities …
the direction for future experiments of low-energy Nuclear Physics …"

The Ni chain

A ≤ 62
High Spin
SD bands

A > 62
Low Spins data only

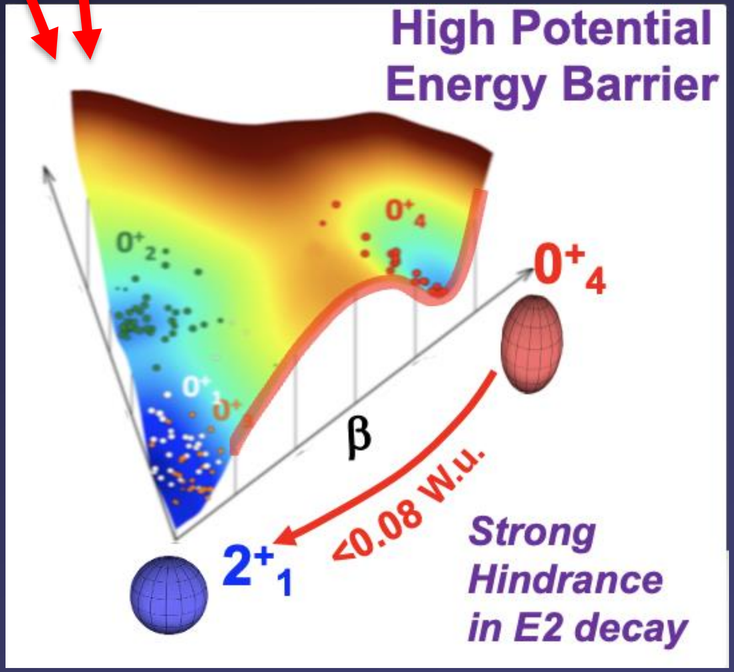
Z=28

N=40

N=50

historical region
to test
Shape Coexistence

in ^{62}Ni ?



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

Evidence for

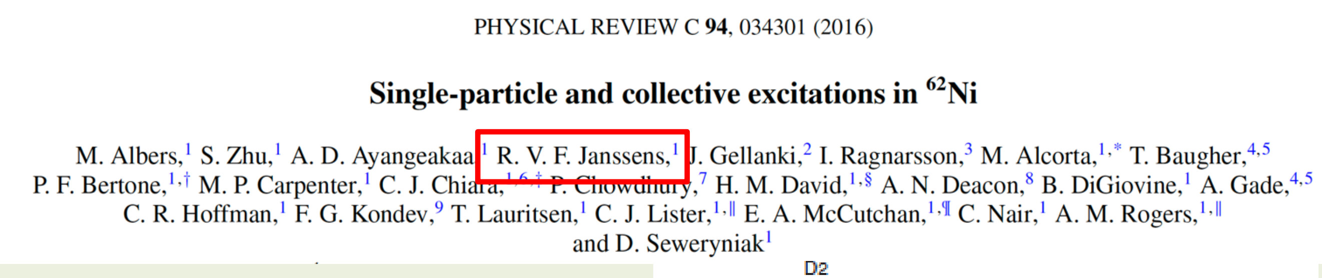
SHAPE-ISOMER-LIKE structure

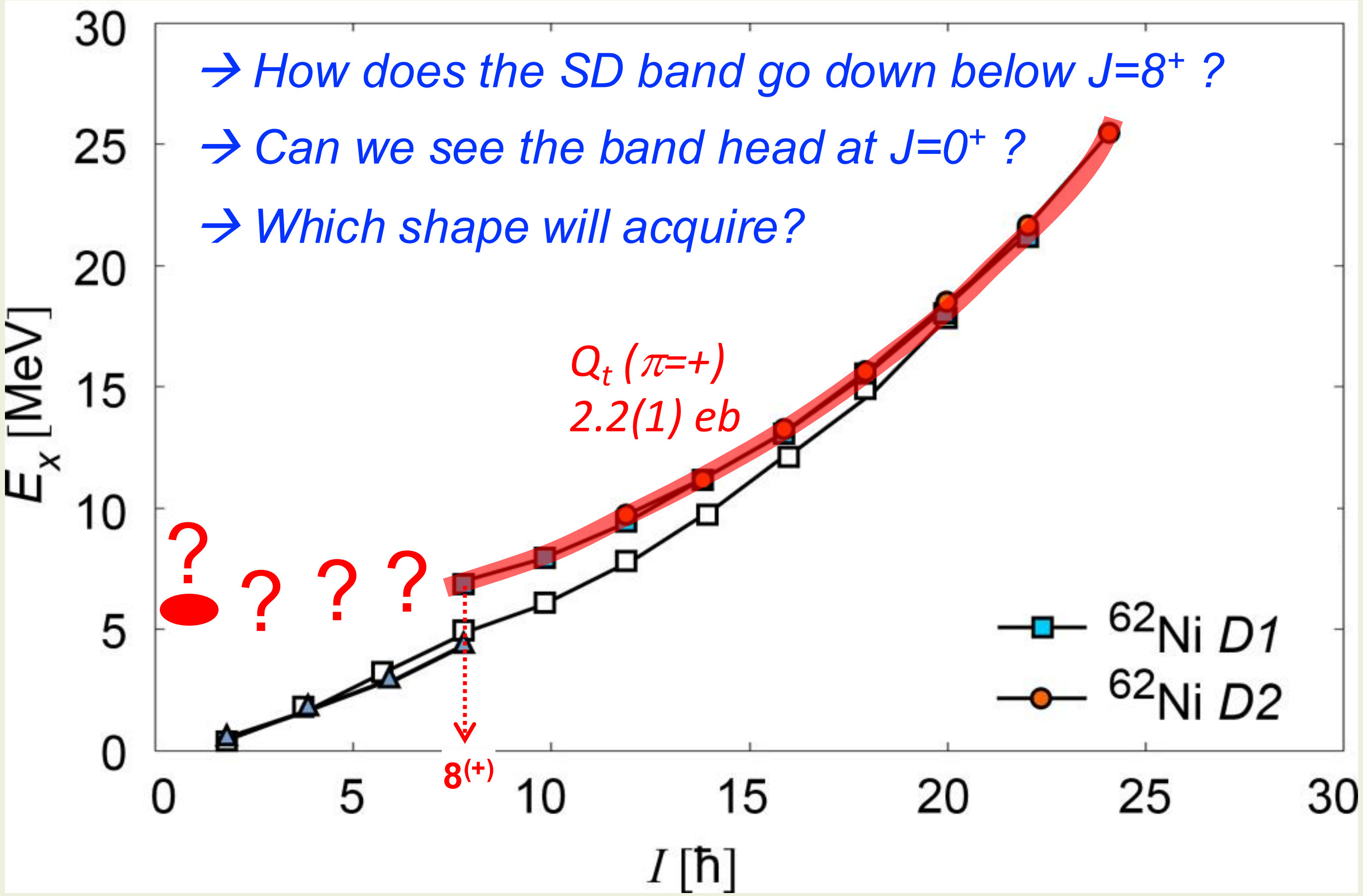
at Spin 0

***^{66}Ni:** IFIN-HH data, sub-barr. 2n transfer*

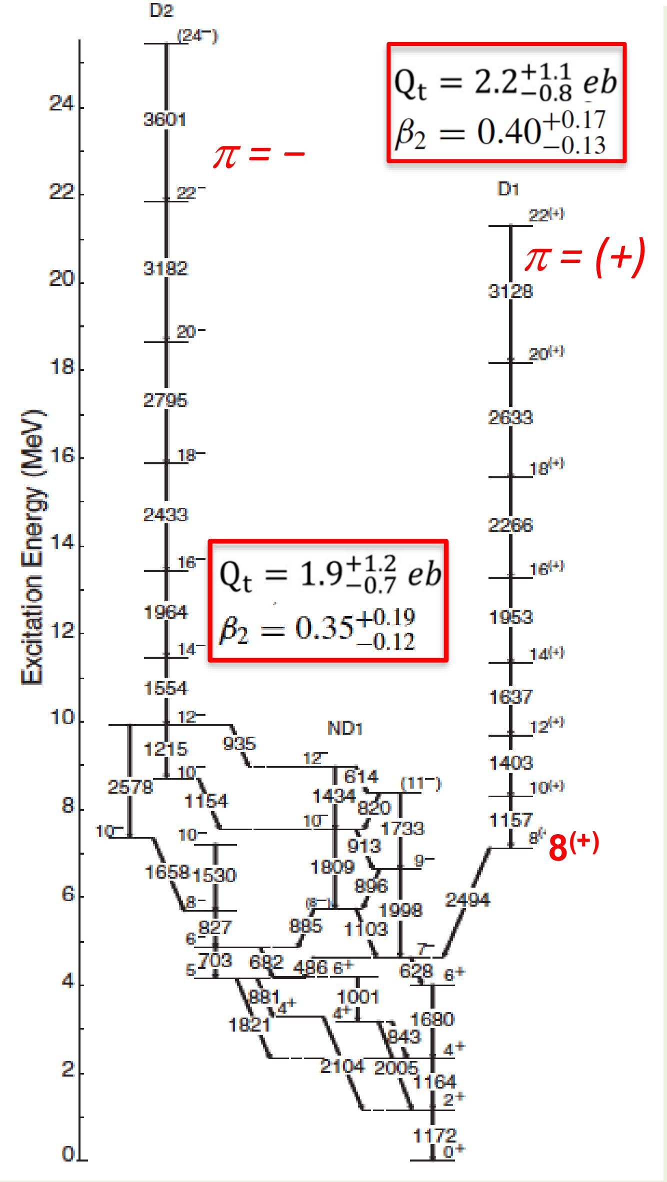
Leoni, Fornal, Marginean et al., PRL118, 162502(2017)

HIGH SPIN data in ^{62}Ni





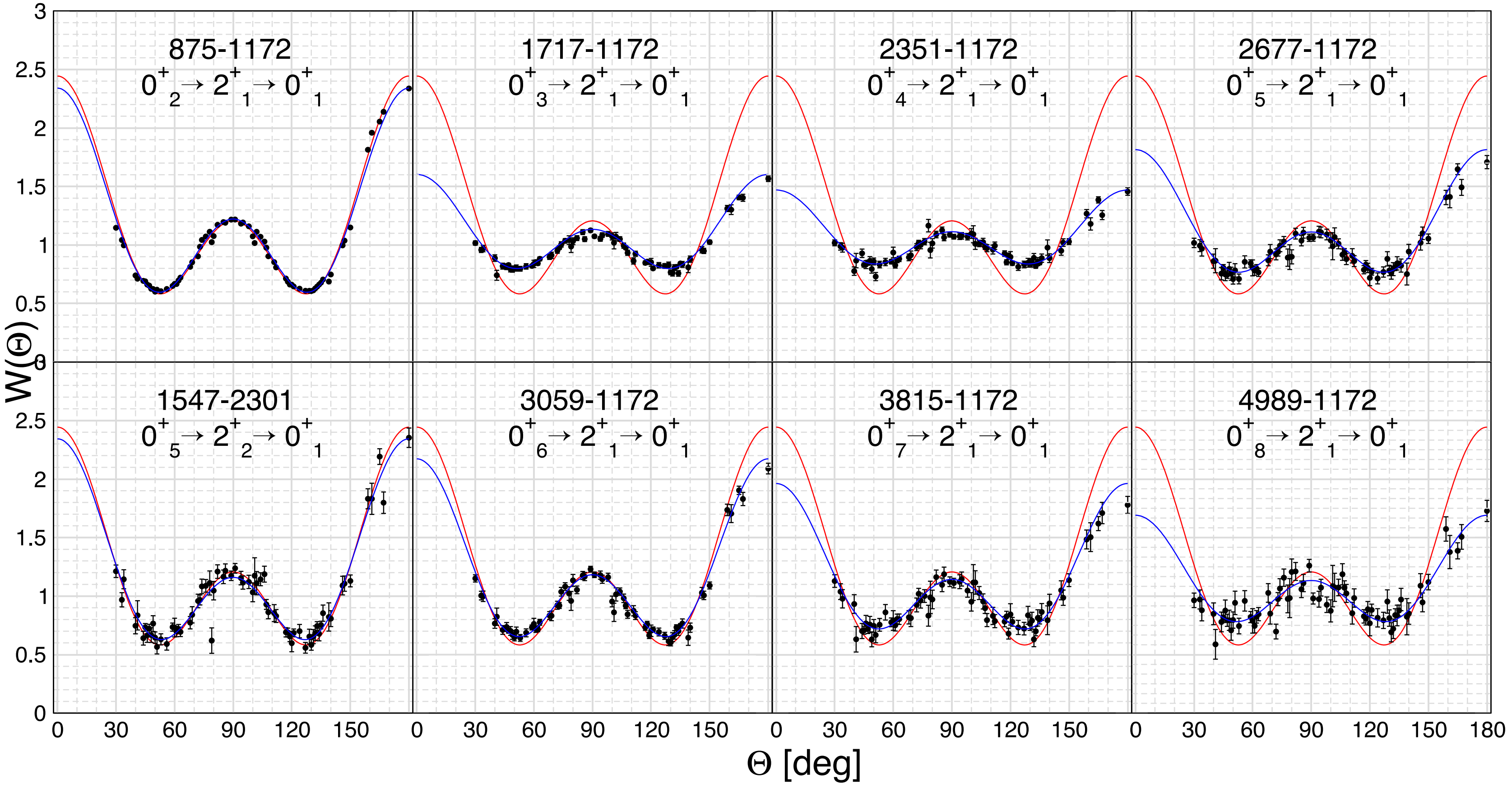
GAMMASPHERE + FMA (Argonne)



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

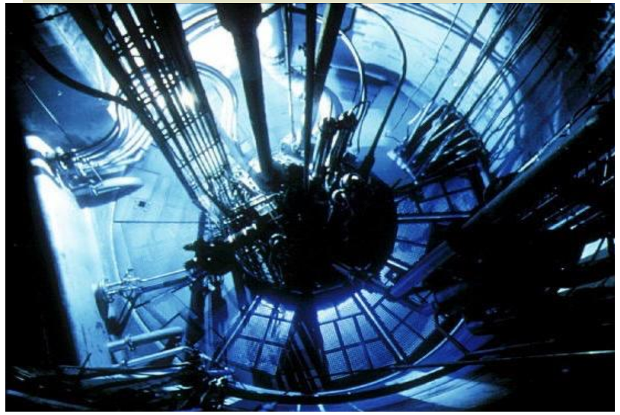
thermal-neutron capture on a 250 mg ^{61}Ni target of metallic powder

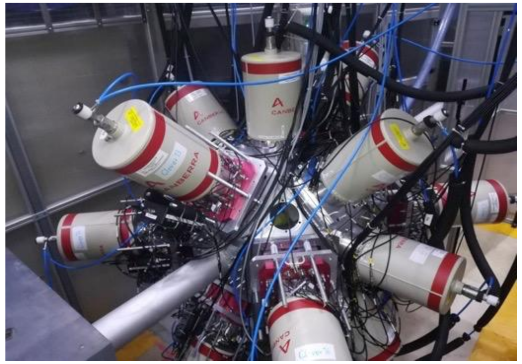
Large statistics and high-precision γ–γ angular correlations



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

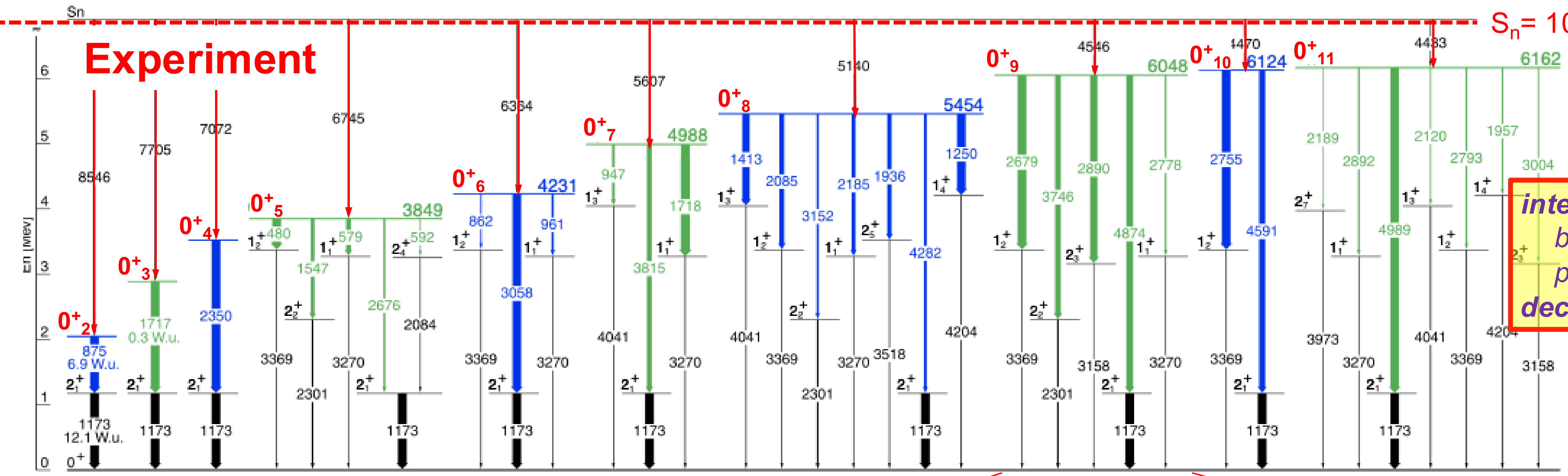
Pencil-like intense thermal neutron beam





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

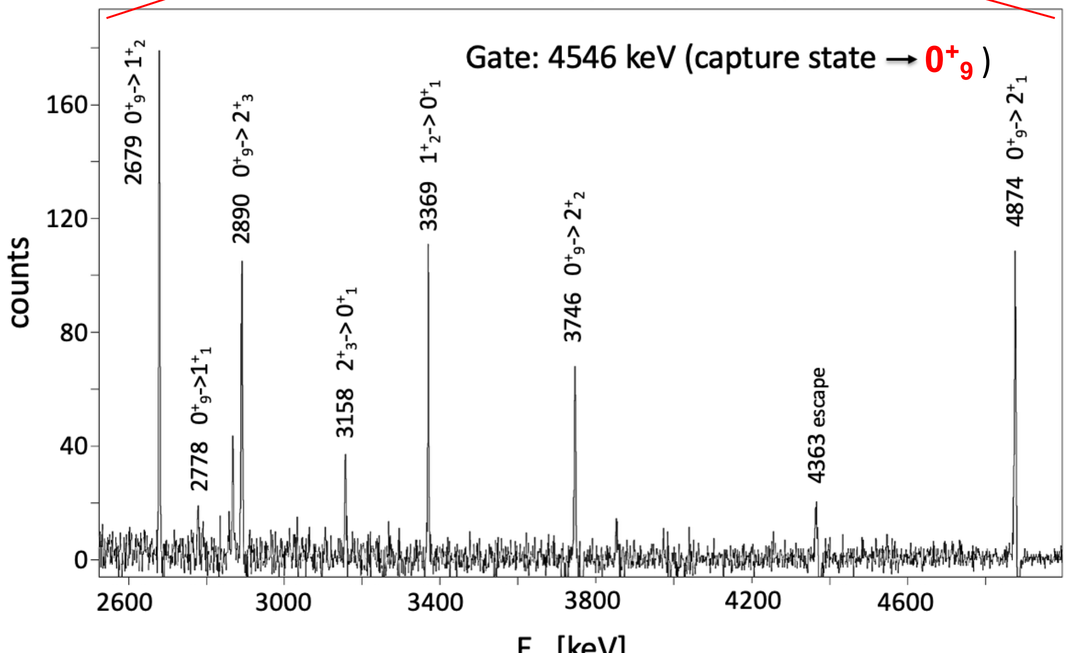


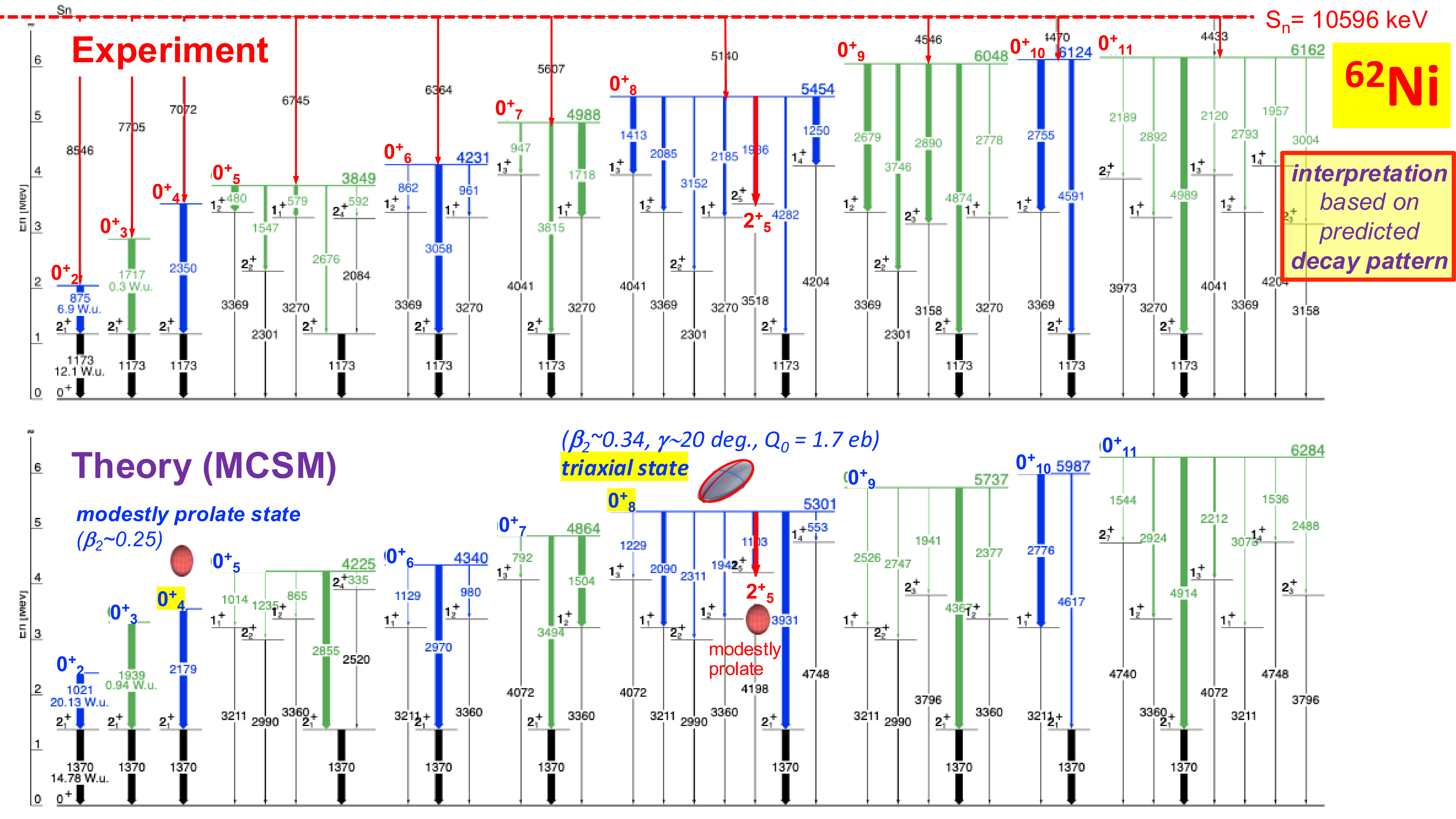
^{62}Ni

interpretation
based on
predicted
decay pattern

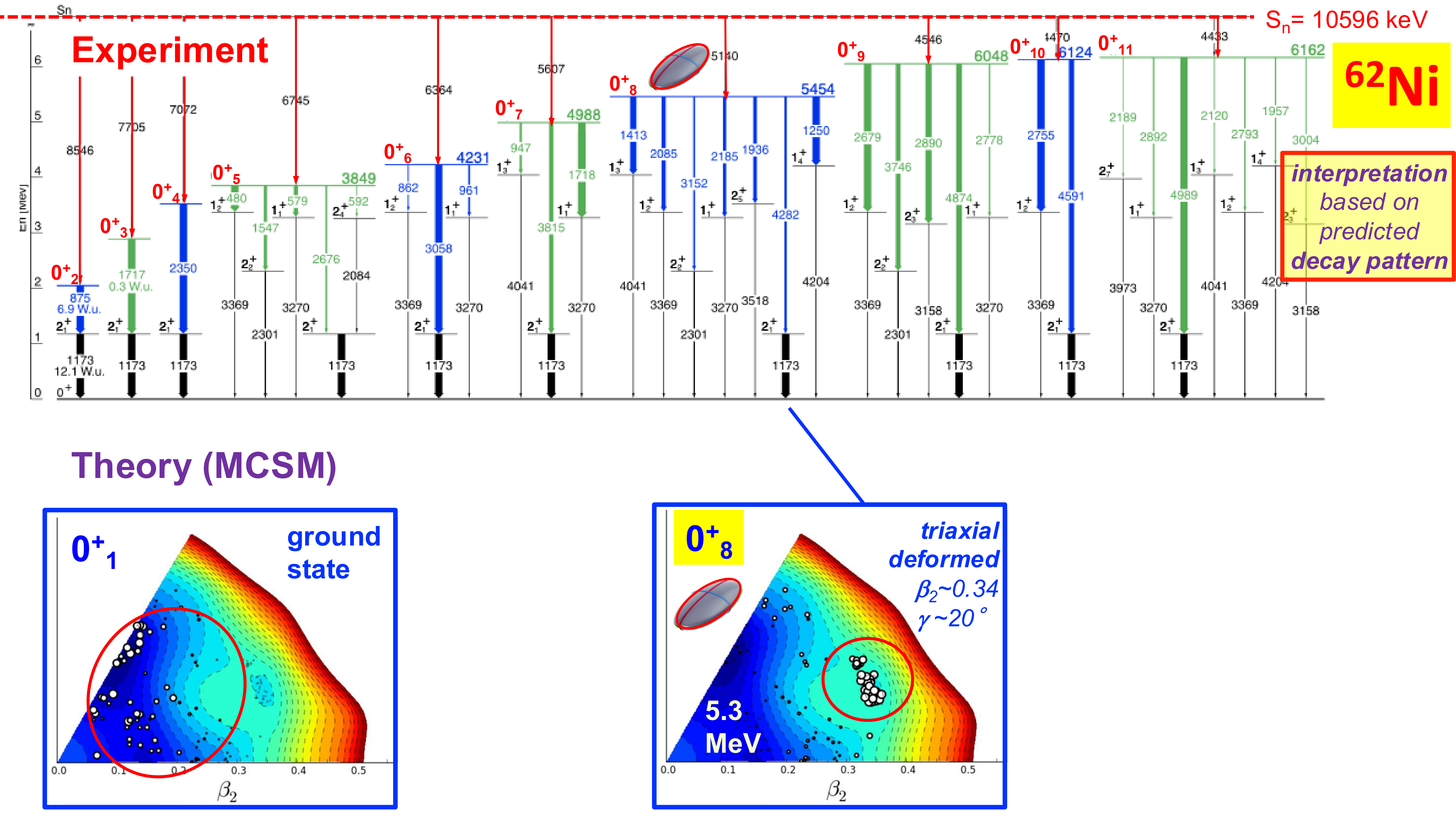
high statistics
extremely clean data
from FIPPS

***Branching ratios** extracted*
from analysis of gamma cascades
in coincidence with
primary transitions
from the capture state





S_n= 10596 keV
Experiment
^{62}Ni
interpretation based on predicted decay pattern
0+2 0+3 0+4 0+5 0+6 0+7 0+8 0+9 0+10 0+11
3849 4231 4988 5454 6048 6124 6162
2+5
875 6.9 W.u.
1717 0.3 W.u.
1173 12.1 W.u.
Theory (MCSM)
modestly prolate state
(β_2~0.25)
(β_2~0.34, γ~20 deg., Q_0 = 1.7 eb)
triaxial state
modestly prolate
4225 4340 4864 5301 5737 5987 6284
1021 20.13 W.u.
1939 0.94 W.u.
1370 14.78 W.u.



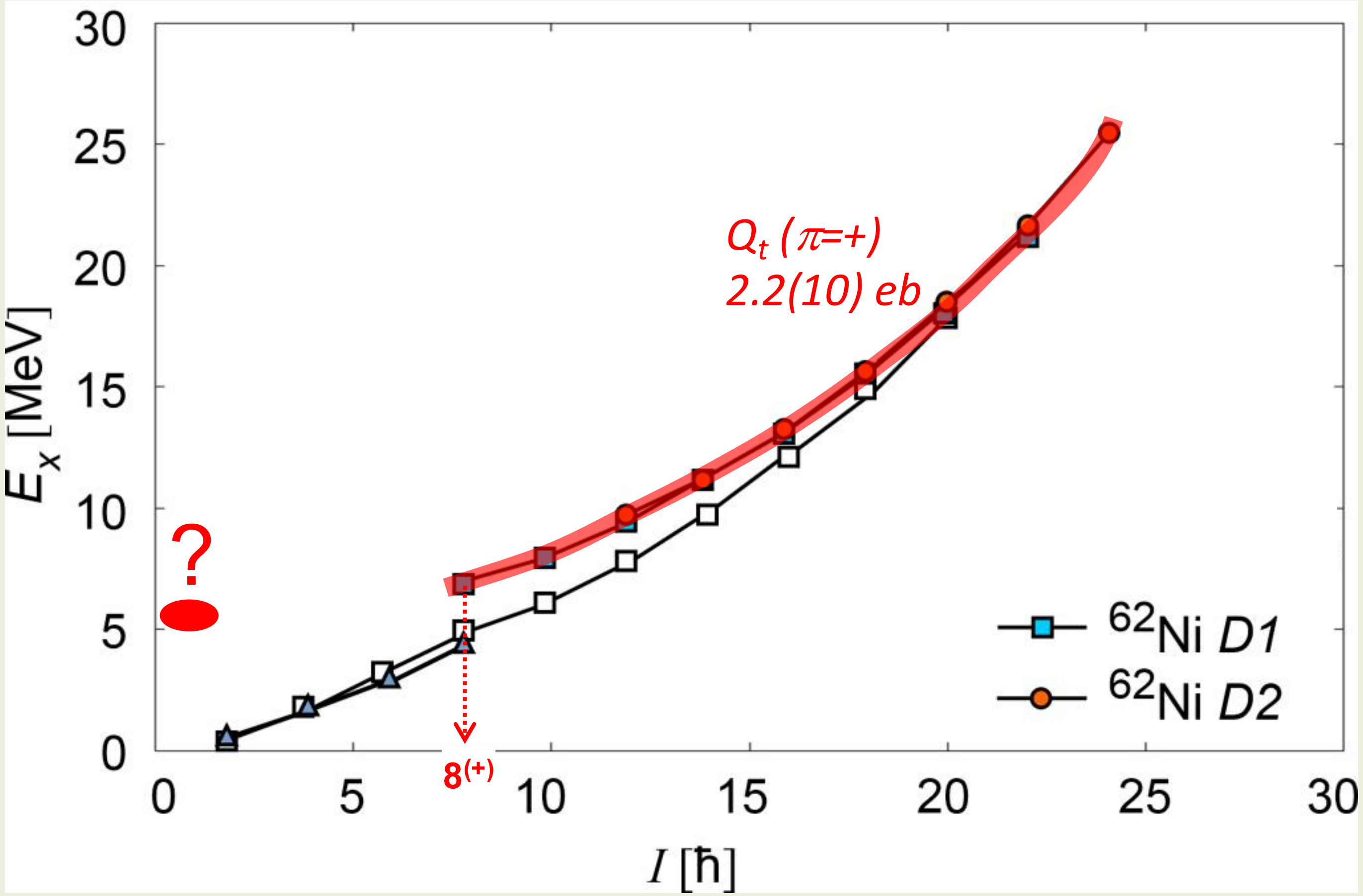
Experiment
S_n= 10596 keV
62Ni
interpretation based on predicted decay pattern
0+2 875 6.9 W.u.
0+3 1717 0.3 W.u.
0+4 2350
0+5 3849
0+6 4231
0+7 4988
0+8 5454
0+9 6048
0+10 6124
0+11 6162
1173 12.1 W.u.
8546
7705
7072
6745
6364
5607
5140
4546
4470
4433
Theory (MCSM)
0+1 ground state
0+8 triaxial deformed
β_2~0.34
γ~20 °
5.3 MeV
β_2

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]



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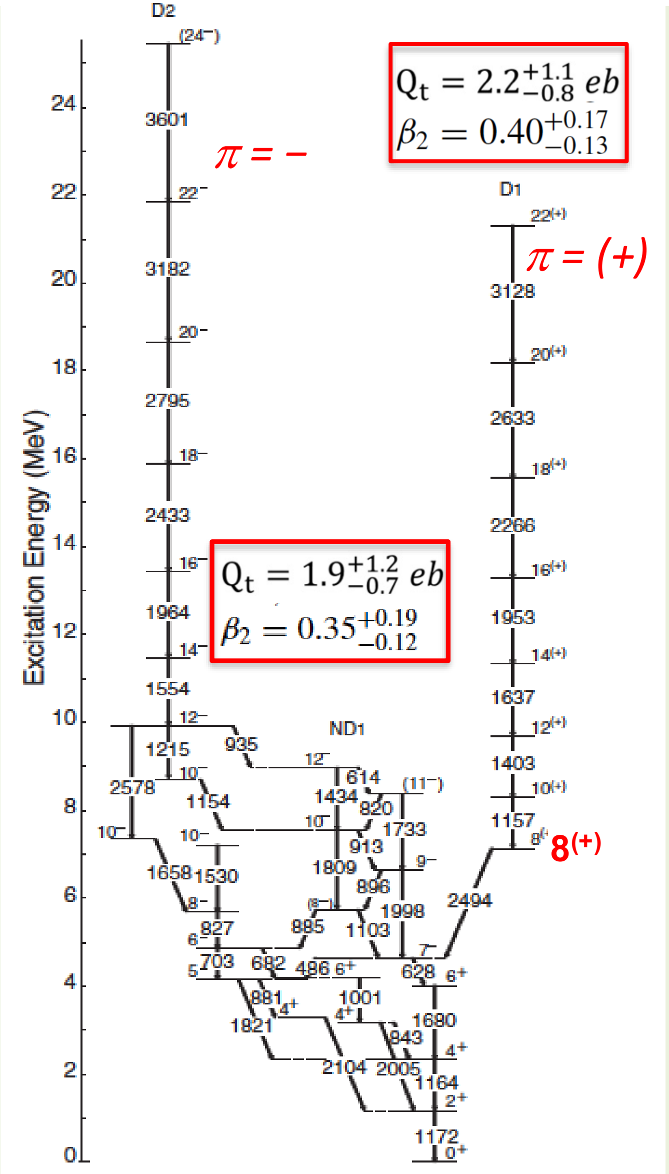

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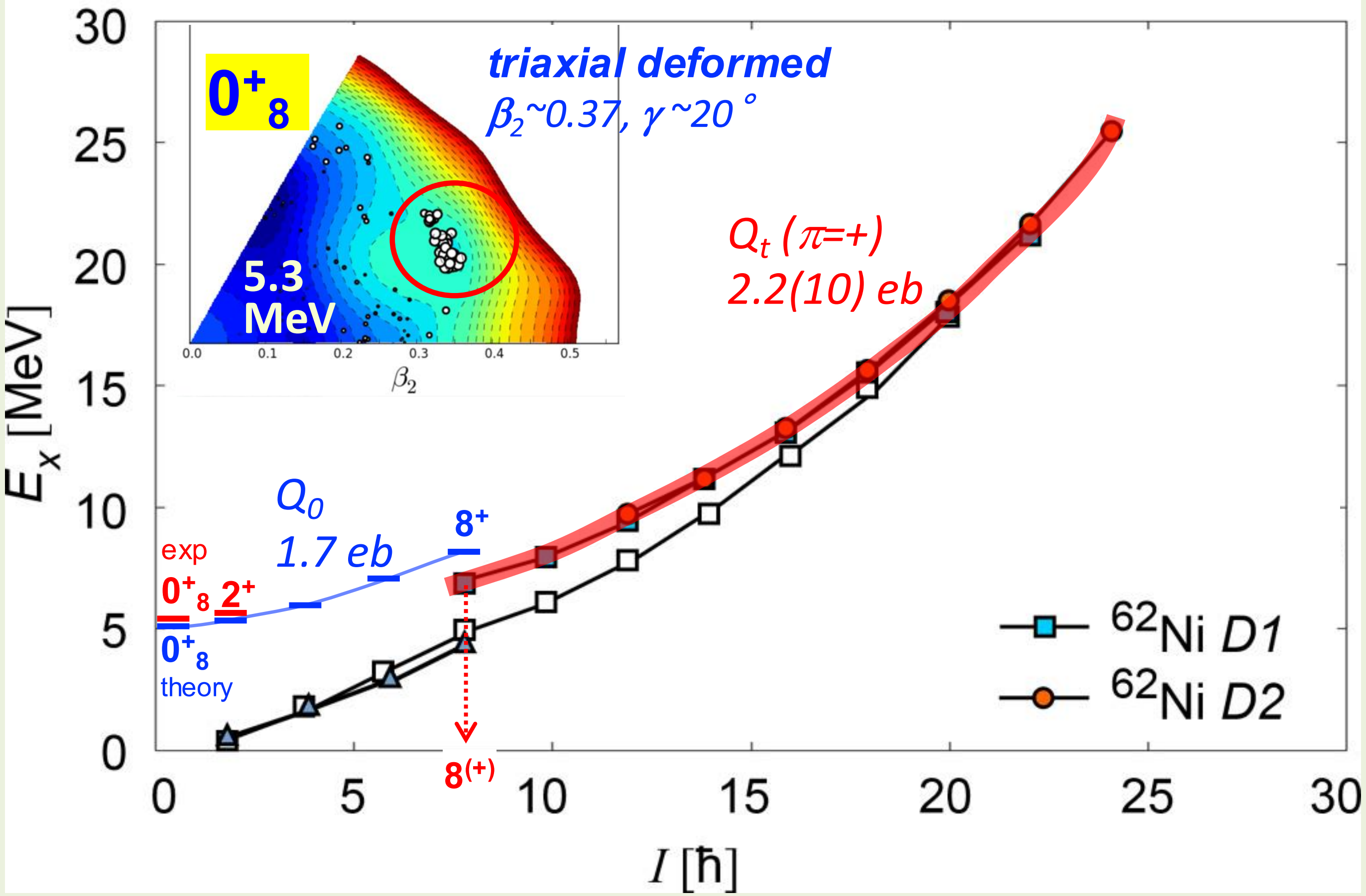
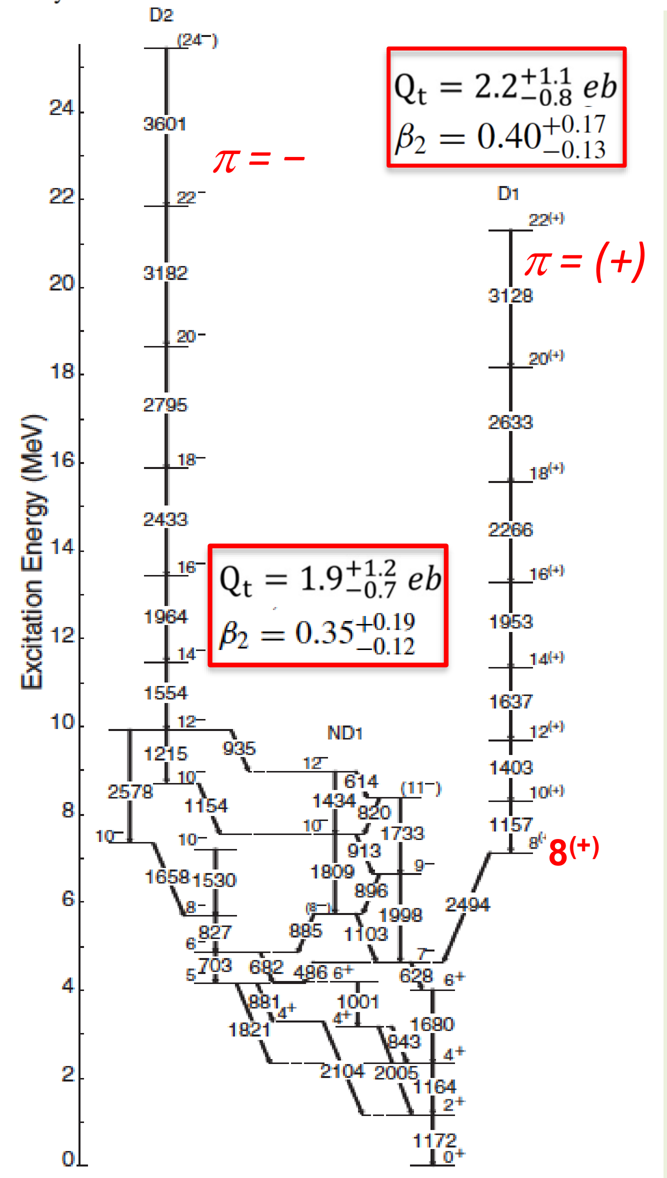
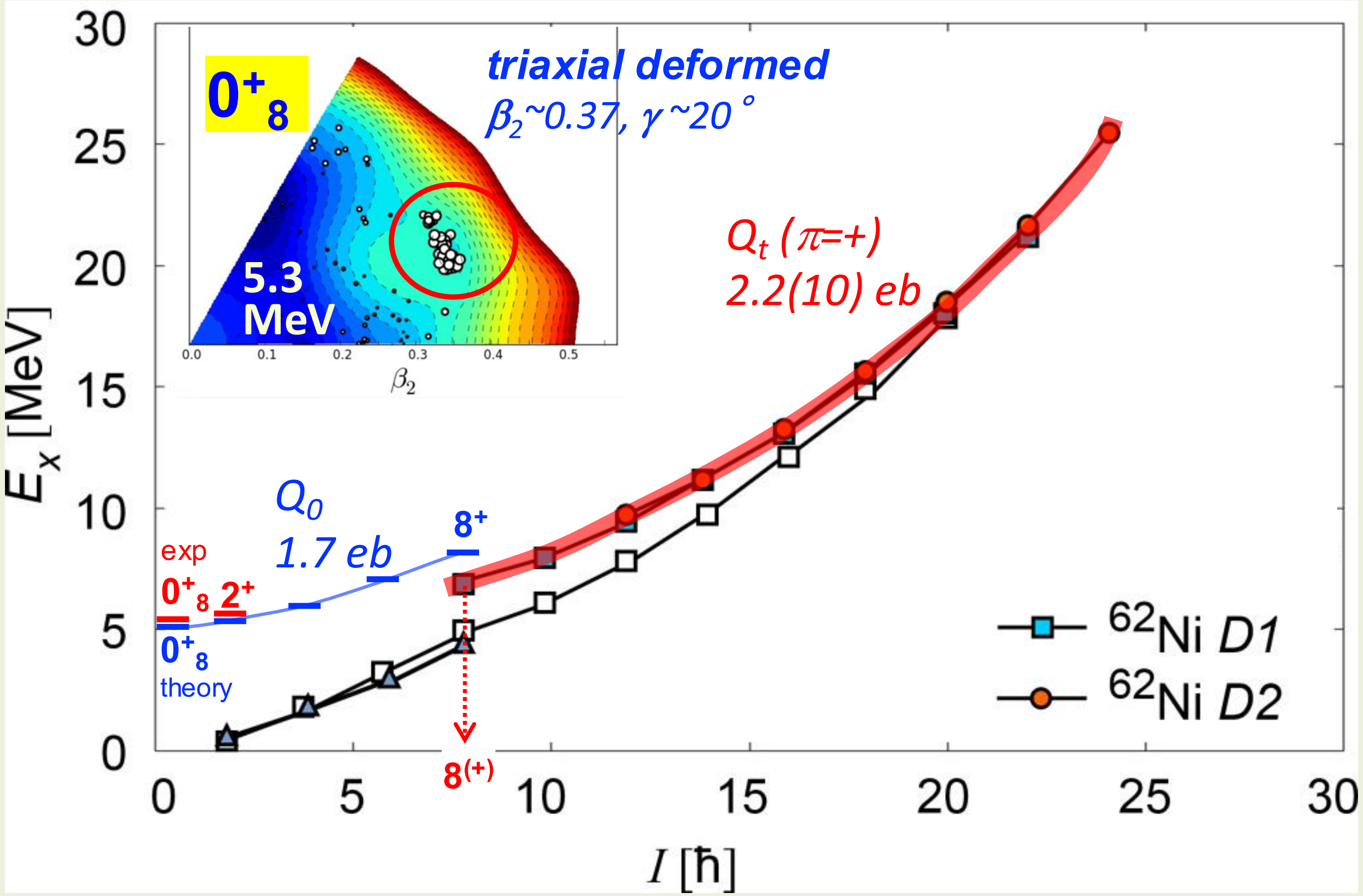


GAMMASPHERE
+
FMA
(Argonne)



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

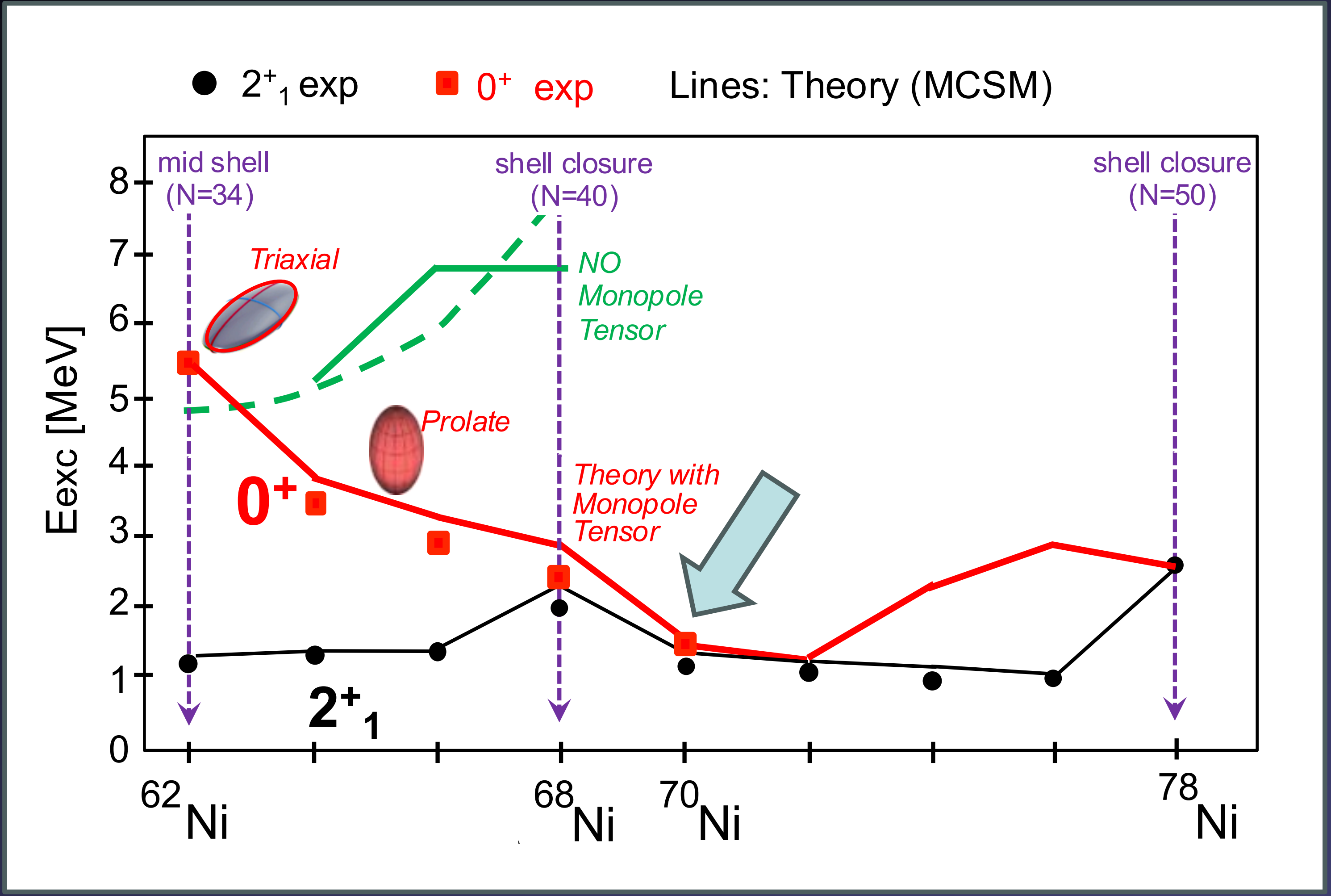
Connecting Shape Coexistence at Spin 0 to Superdeformation at High Spins in ^{62}Ni



We are getting closer to a unified description of shape coexistence at spin 0 and superdeformation at high spins

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

Perspectives



In neutron-rich Ni isotopes SD bands are expected to come down in energy, making it possible to observe the complete SD bands

In ^{70}Ni: the band head is at E_x ~ 1.5 MeV

Thank you for the attention !

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

VIIIth Topical Workshop on Modern Aspects in Nuclear Structure

The Many Facets of Nuclear Structure

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Bormio, Italy

22–27 feb 2027
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Università degli Studi di Milano and **Istituto Nazionale di Fisica Nucleare** (sez. Milano) are pleased to announce the **Eighth Edition** of the series of **Topical Workshops on Modern Aspects of Nuclear Structure.**

The meetings are organized every second year in the month of **February** in **Bormio**, focusing on specific topics which are relevant for the nuclear physics community and related areas.

Within the workshop, **experimental** and **theoretical** collaborations will have the opportunity to present and discuss their latest development on physics and more technical issues (Link to Previous Edition Bormio 2025).

In this edition, the first day **Monday 22nd February** will be devoted to

Nuclear structure and reactions of light nuclei

Additional **SATELLITE** Meetings:

To be announced

Inizio 22 feb 2027, 09:00
Finisce 27 feb 2027, 19:30
Europe/Rome

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Bormio Terme Auditorium
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Deadline for abstract submission: 15th October (not extendable)

Special Prizes for Young Speakers offered by CAEN

As in the previous editions chash prizes will be awarded to best talks given by young speakers (PhD students and early Post-Docs)

Invited Speakers (preliminary)

Mitch Allmond (ORNL, USA)
Mia Au (CERN, Switzerland)
Michael Block (GSI, Germany)
Michal Ciemala (IFJ PAN Krakow, Poland)
Ian Cox (University of Tennessee, USA)
Irene Dedes (IFJ PAN Krakow, Poland)
Timo Dickel (GSI, Germany)
César Domingo-Pardo (IFIC Valencia, Spain)
Paul Fallon (LBNL, USA)
Christian Forssen (University of Chalmers, Sweden)
Franco Galtarossa (University of Padua/INFN, Italy)
Francesca Gulminelli (University of Caen, France)
Andreas Heinz (University of Chalmers, Sweden)
Matthias Heinz (ORNL, USA)
Jack Henderson (University of Surrey, UK)
Ania Kwiatkowski (TRIUMF, Canada)
Marco La Cognata (LNS-INFN, Italy)
Bing-Nan Lu (GSCAEP Beijing, China)
Naomi Marchini (INFN-Florence, Italy)
Chiara Mazzocchi (University of Warsaw, Poland)
Javier Menéndez (University of Barcelona, Spain)
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Gregory Potel (University of Seville, Spain)
Riccado Raabe (KU Leuven, Belgium)
Ante Ravlić (MSU, USA)
Hiroyuki Sagawa (RIKEN/Aizu University, Japan)
Christelle Schmitt (IPHC CNRS/IN2P3 Strasbourg, France)
Mark Spieker (University of Florida, USA)
Ubirajara van Kolck (ECT*, Italy)
Liss Vazquez Rodriguez (MPIK Heidelberg, Germany)
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Jon Wilson (IJCLAB, Orsay, France)
Kathrin Wimmer (University of Cologne, Germany)
Xinhui Wu (University of Fuzhou, China)
Zhiyuan Zhang (IMP-Lanzhou, China)
Pengwei Zhao (University of Peking, China)
Magda Zielinska (CEA, Saclay, France)

http://www.mi.infn.it/WSBormio-Milano2027/