Spectroscopy of Shape Isomers: status and perspectives

Silvia Leoni – University of Milano and INFN

In collaboration with:

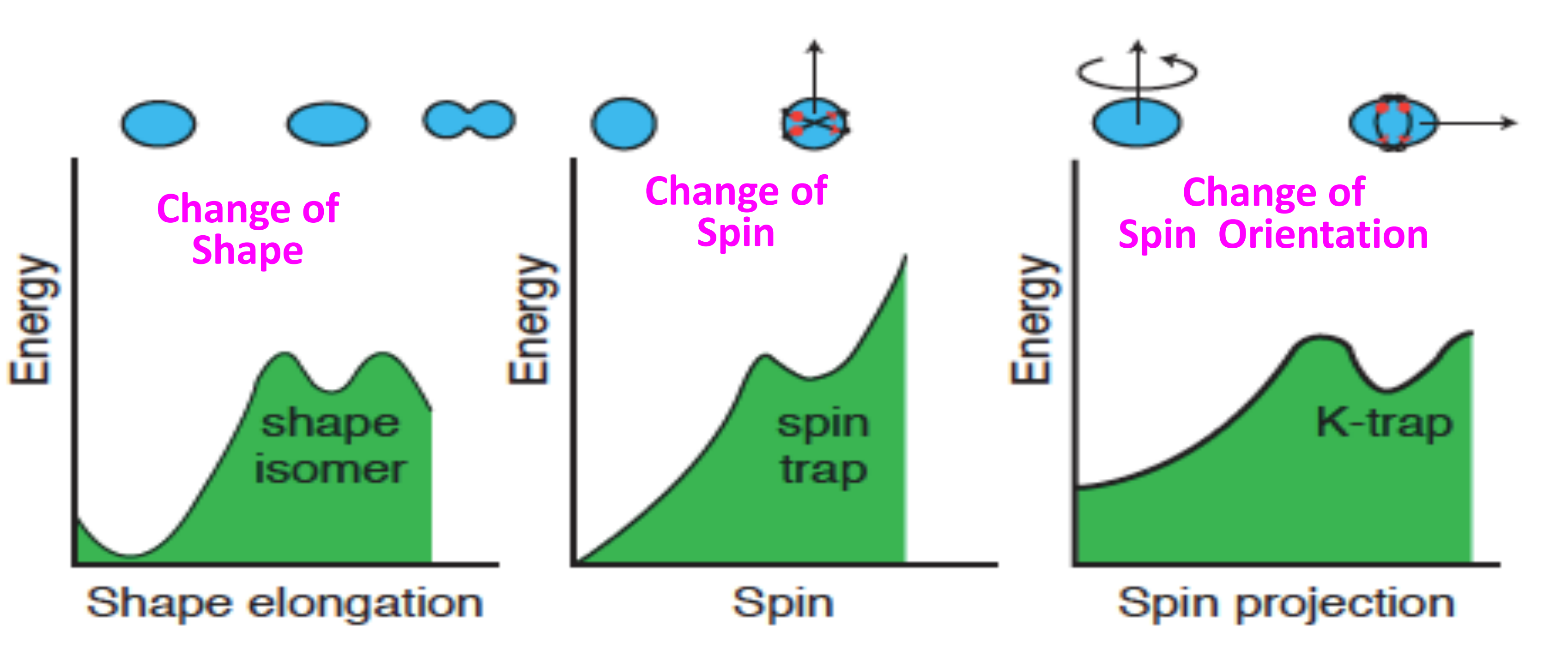
- **B. Fornal** et al., Institute of Nuclear Physics, Krakow, Poland
- **N. Mărginean** et al., IFIN HH, Bucharest, Romania
- **R.V.F. Janssens** et al., University of Noth Carolina, USA
- **C. Michelagnoli** et al., ILL, Grenoble, France
- **M. Sferrazza** et al., Universite libre de Bruxelles, Belgium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

Understanding of isomers

Metastable Quantum States at High Excitation Energy

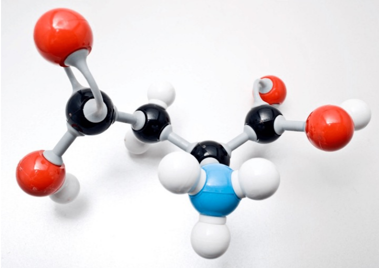
Dependence on **shell structure** of neutron and proton orbits:

→ Very **stringent test** for theoretical models
→ Important Consequences in **Applications**



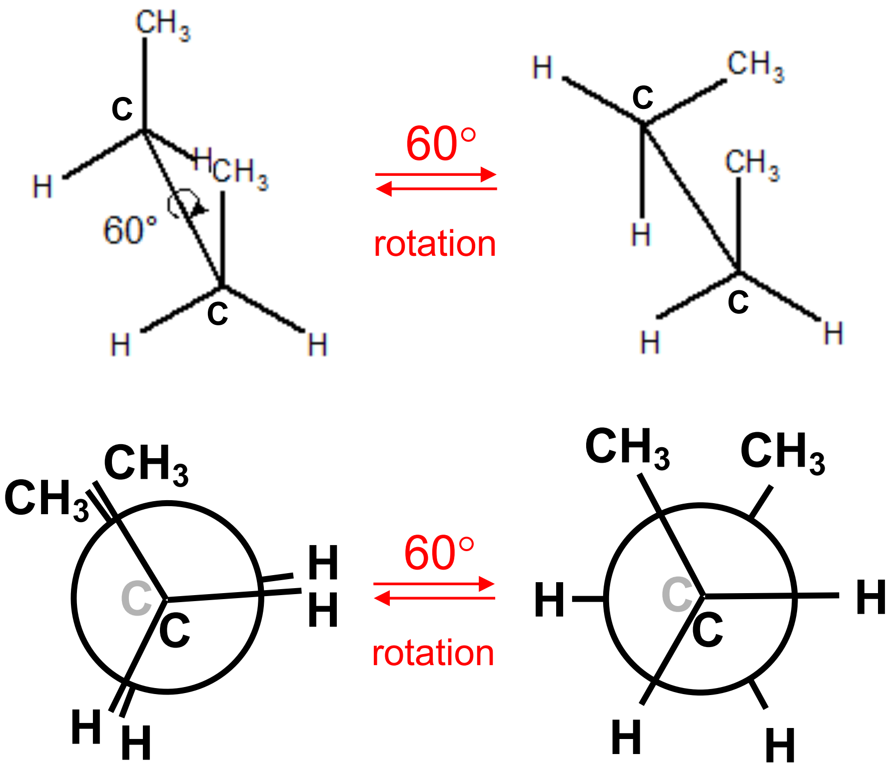
P. Walker and G. Dracoulis, Nature 399(1999)35

Potential Energy Surface (PES) of MOLECULES

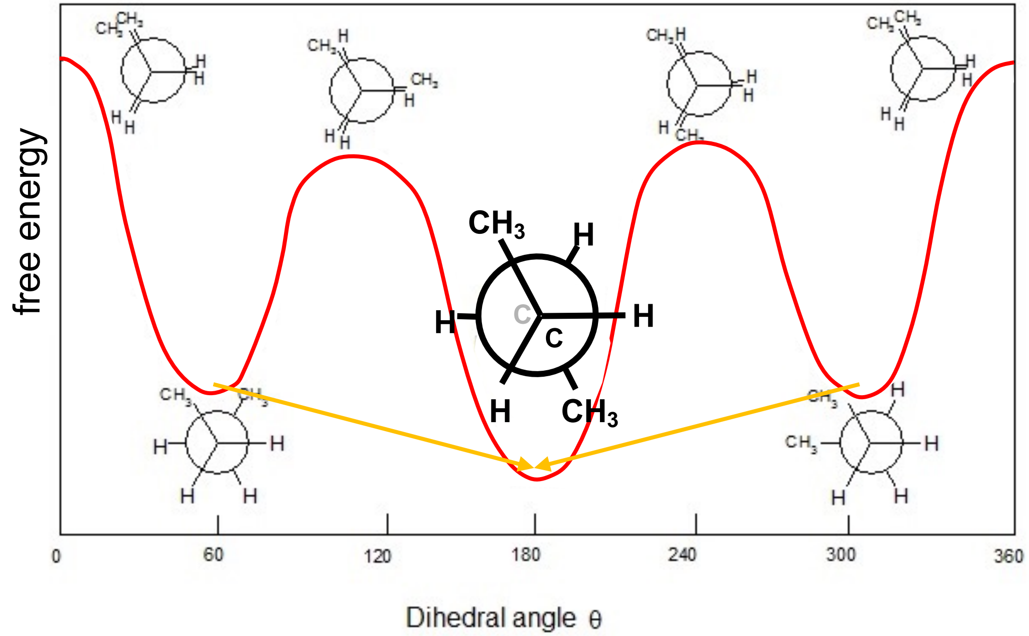


Butane molecule C_4H_{10}

"Conformational isomers"



Rotation about single bond of butane



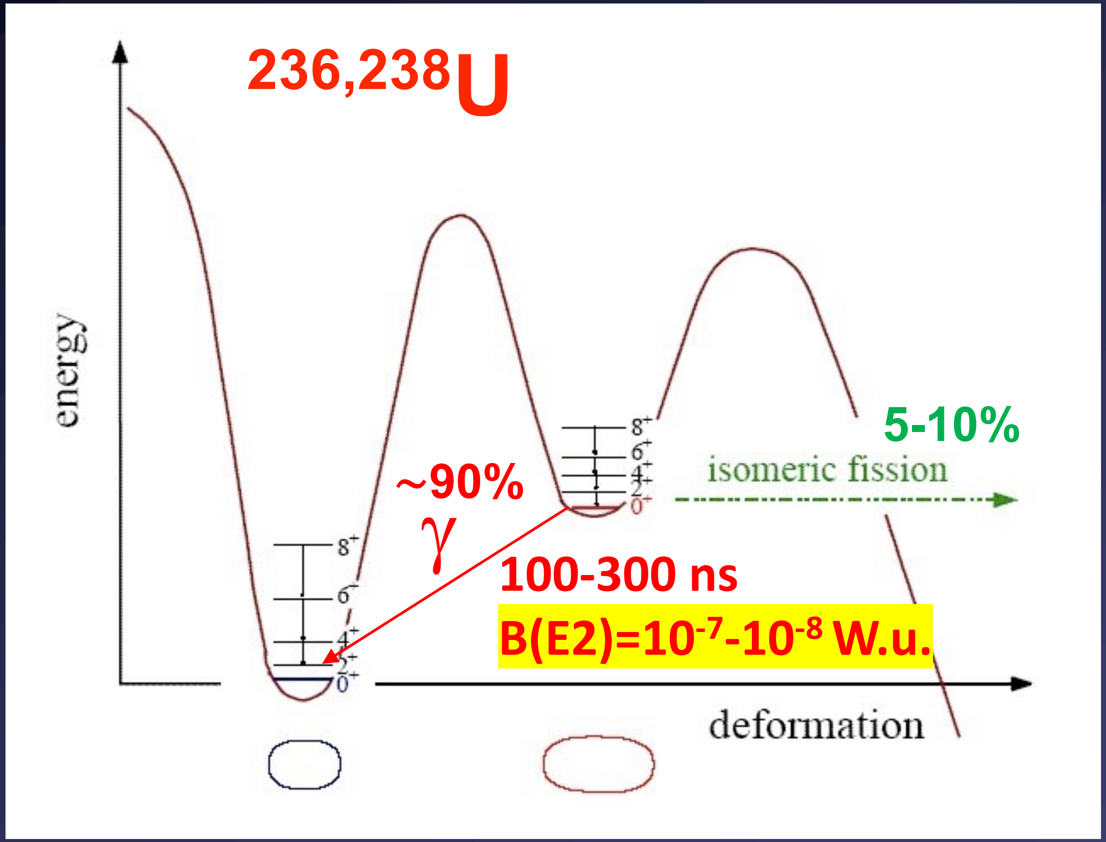
Free energy diagram of butane as a function of dihedral angle

FISSION SHAPE ISOMERS: a case of extreme shape coexistence

- HIGH Potential BARRIER
- Nucleus trapped In the minimum
- very retarded photon decay (**10^7 hindrance**)

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

K.E. Löbner PLB26, 369 (1968)



Structures living in "separate worlds"

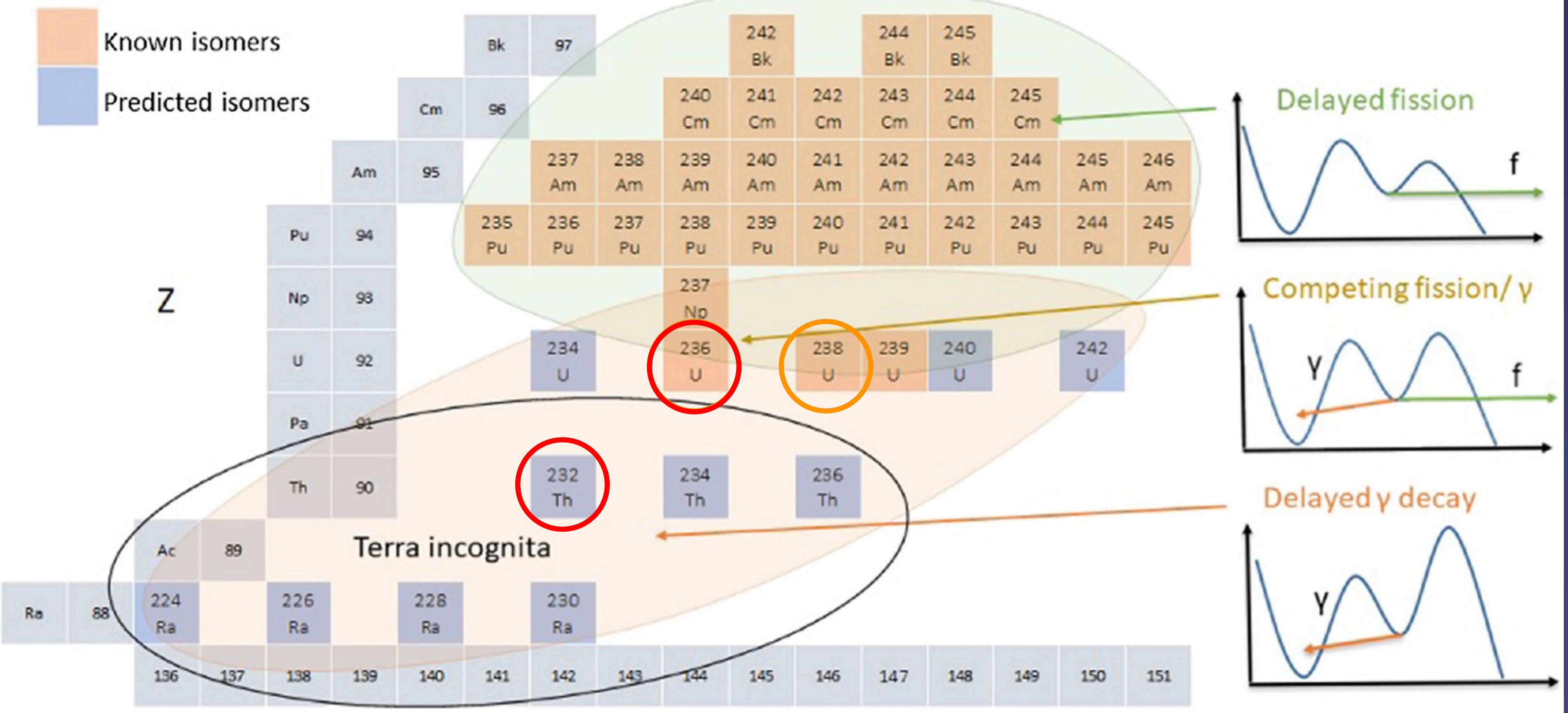
Wave Functions well localized in different PES minima separated by a sizable barrier

MAIN FINGER PRINT for SHAPE ISOMERISM: LARGE decay HINDRANCE

Can OTHER (lighter) nuclei exhibit this feature ?

Map of known “fission” shape isomers

Difficulties in finding γ decay from fission shape isomers



Recent experiments (2022-23) with NUBALL@IJCLAB (Orsay)
J. Wilson at al., ^{232}Th(d,x), ^{235}U(d,x)
Data under analysis

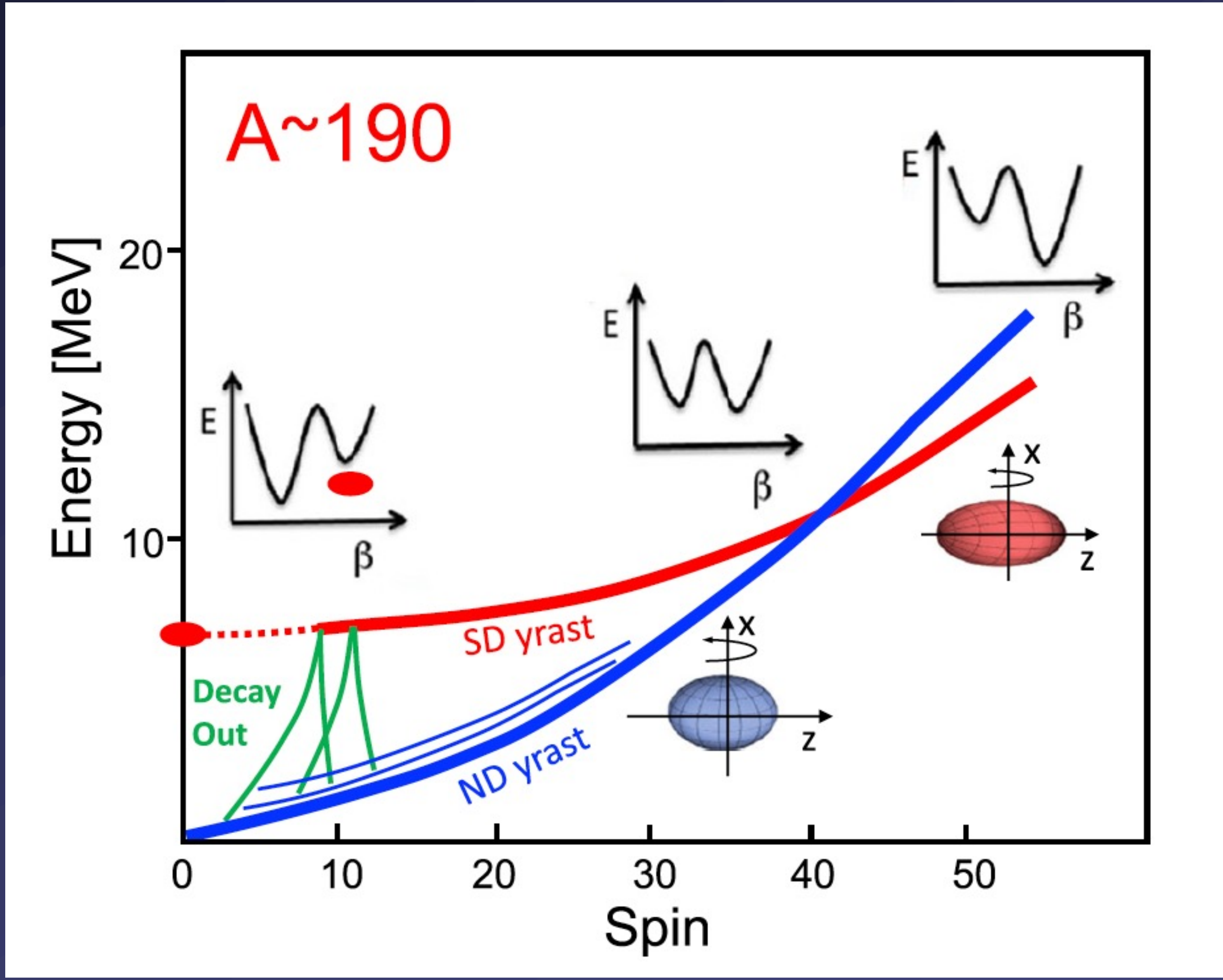
Leoni, Fornal, Marginean, Wilson, EPJ Spec. Top. 233, 1061(2024)

Search for SHAPE ISOMERS at I=0 among SD nuclei

SD Nuclei are spectacular examples of extreme shape coexistence

- Very difficult to follow SD states to spin 0
- Large Hindrance already at the decay-out in A=150 and 190

HF ~ 10^2-10^4

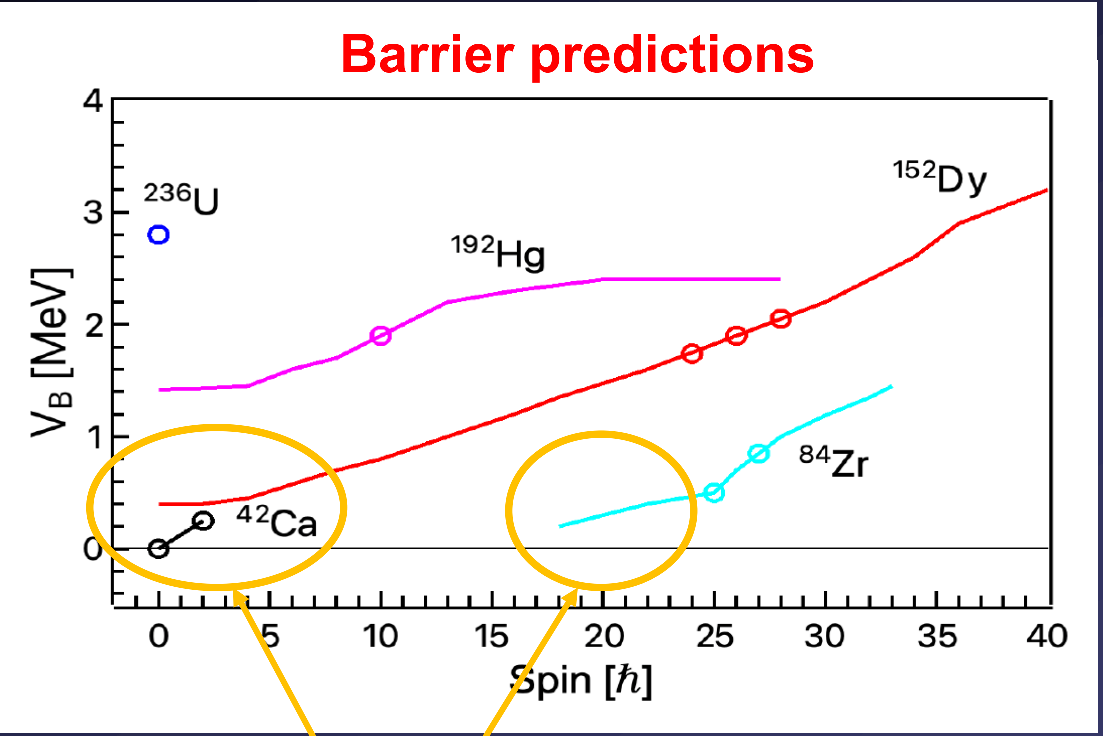


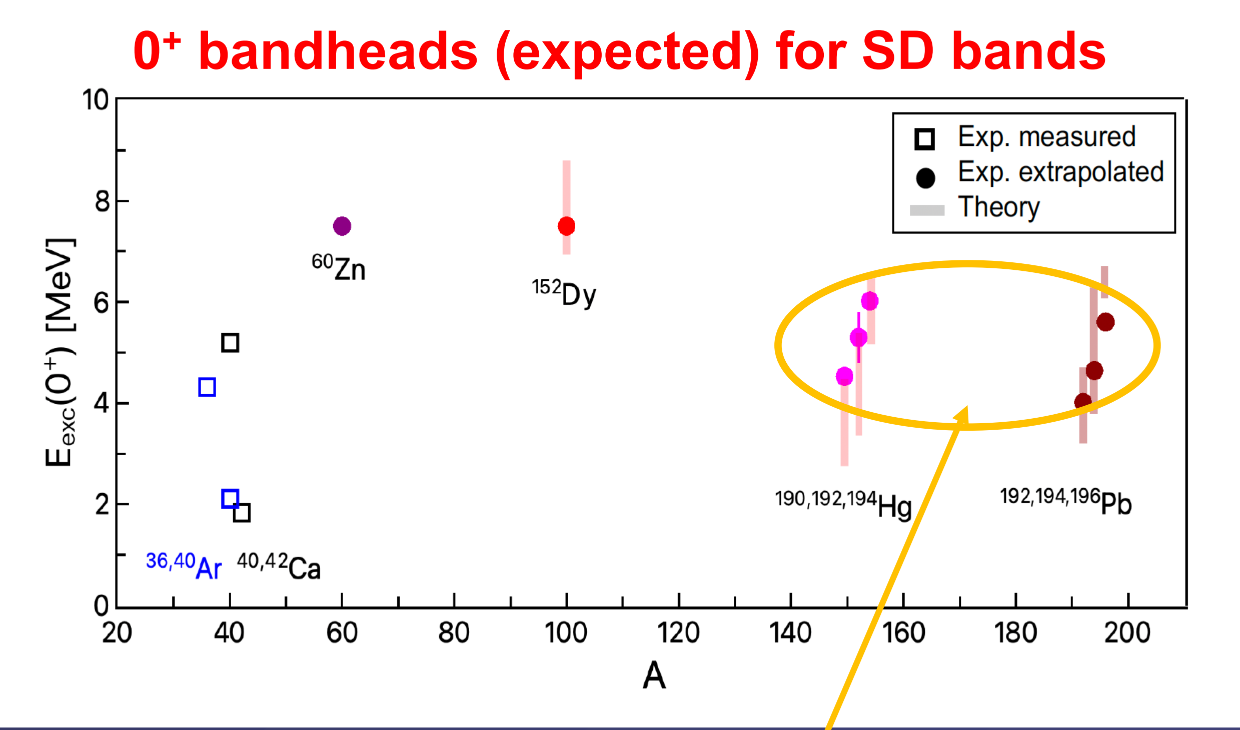
→ Need for new experimental approaches to explore SD at low spins

Searching for Hindered decay at Spin 0

Shape-isomer-like structures (B(E2) << 1 W.u., HF > 10)

Expectation from Superdeformation





vanishing barriers *(SHAPE MIXING)*

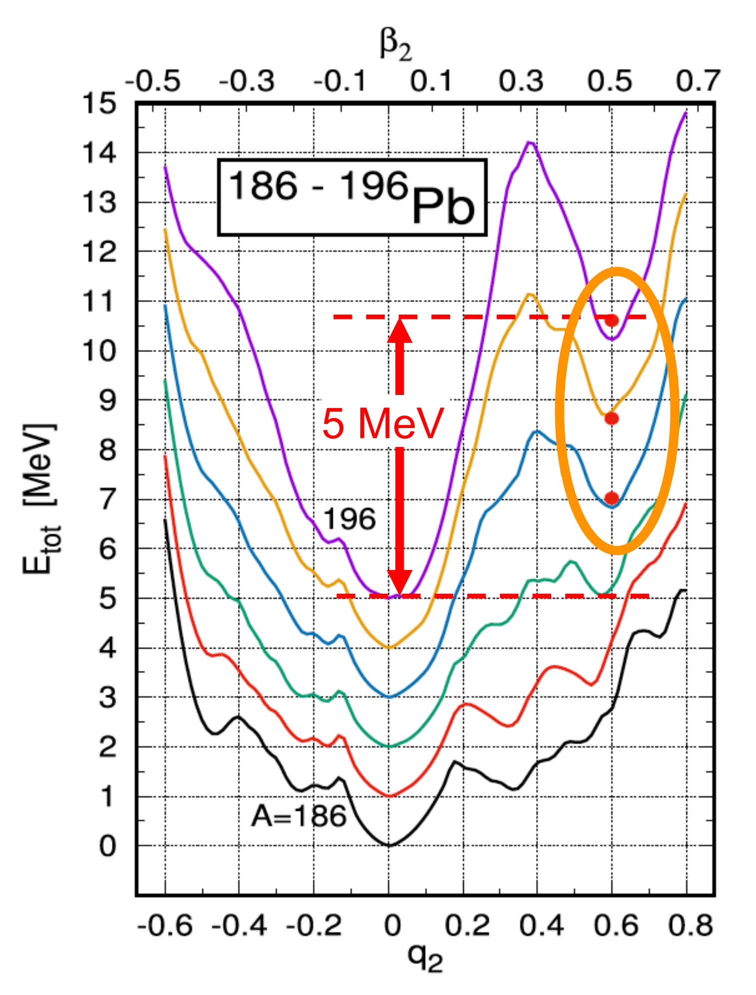
possible candidates for SHAPE ISOMERS
very difficult to populate

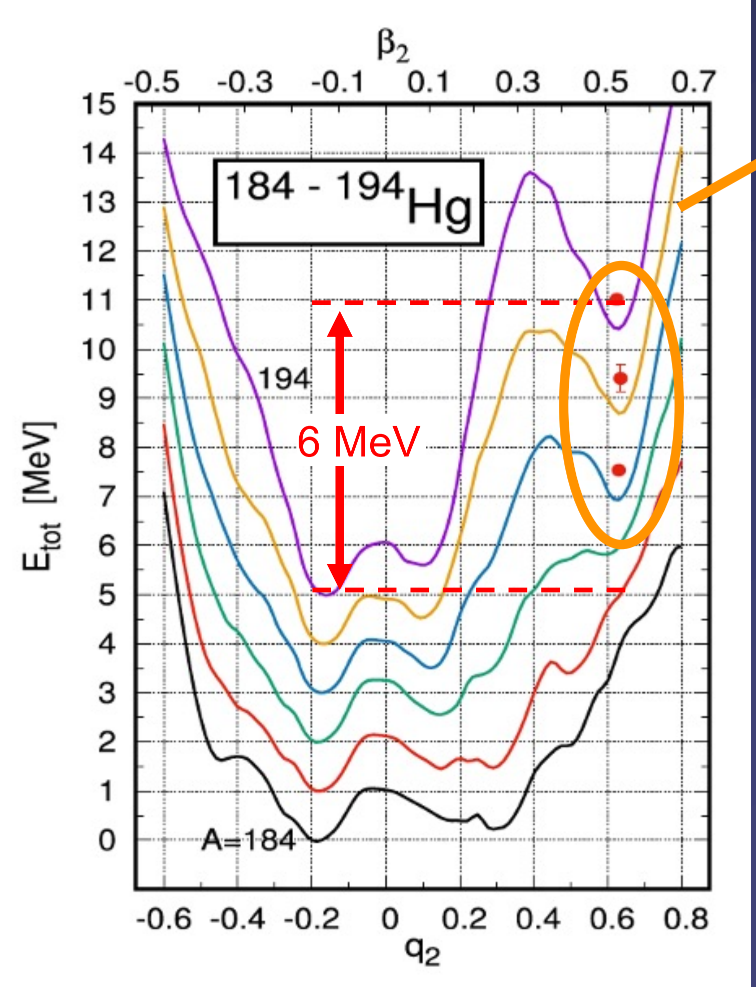
Searching for Hindered decay at Spin 0

Shape-isomer-like structures (B(E2) << 1 W.u., HF > 10)

Several predictions for heavy systems

- **very difficult to populate** (high density of states)
- **No specific tagging** (delayed γ rays on huge background, no fission tag)





HIGH fission barrier

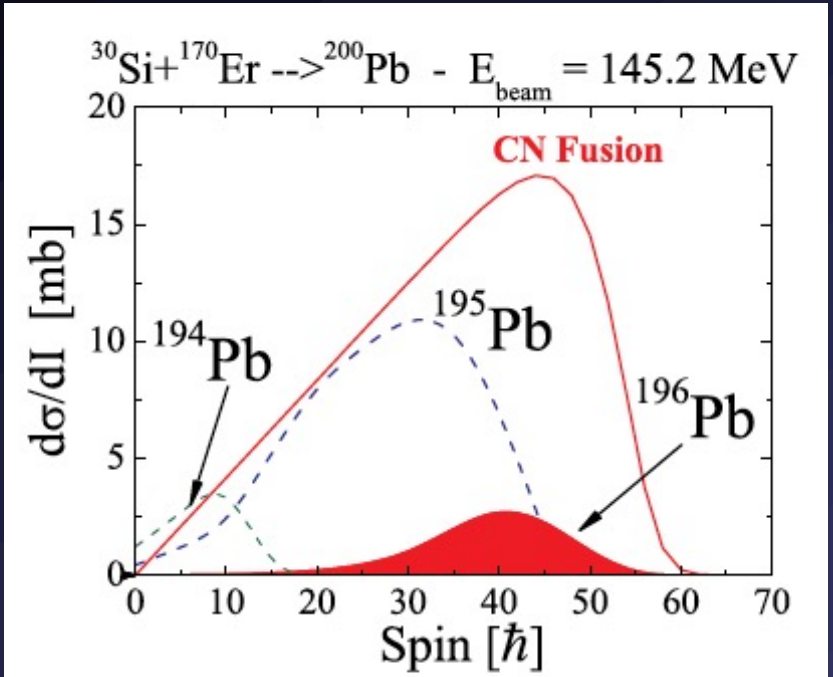
expected band heads of SD structures

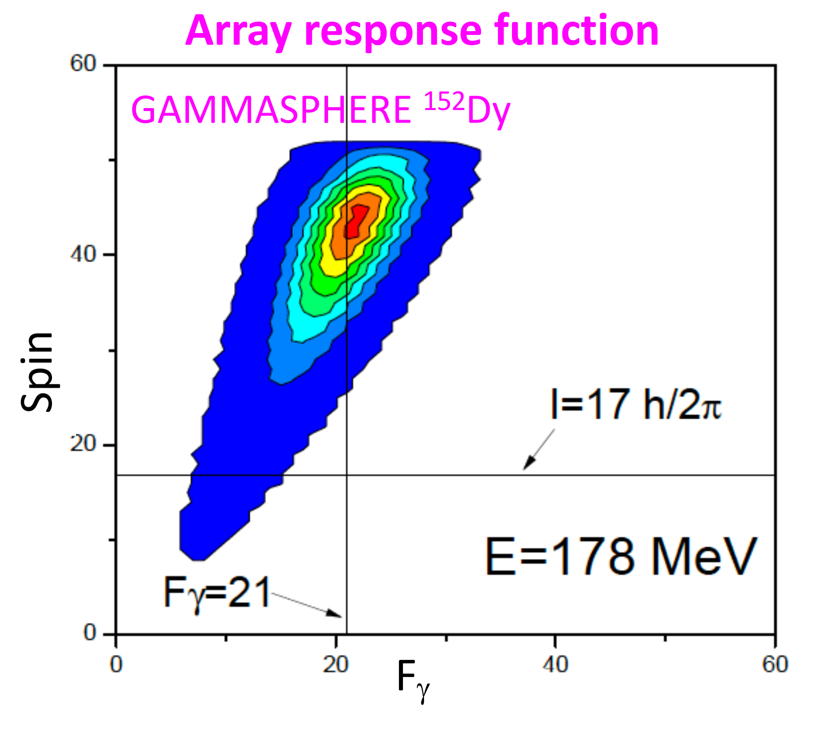
at I=0

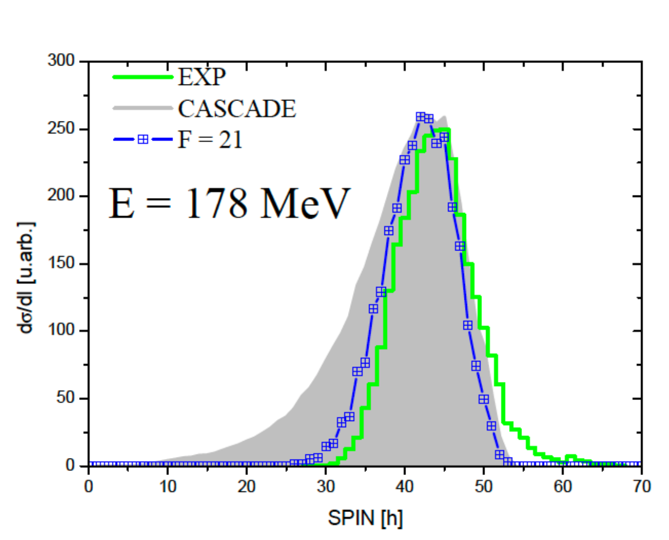
K. Pomorski et al., Eur. Phys. J. A56, 107 (2020)

Need to exploit low-spin reaction mechanisms

1) Fusion reactions favoring low spins







One should focus on **low multiplicity** typically rejected in high-spin experiments

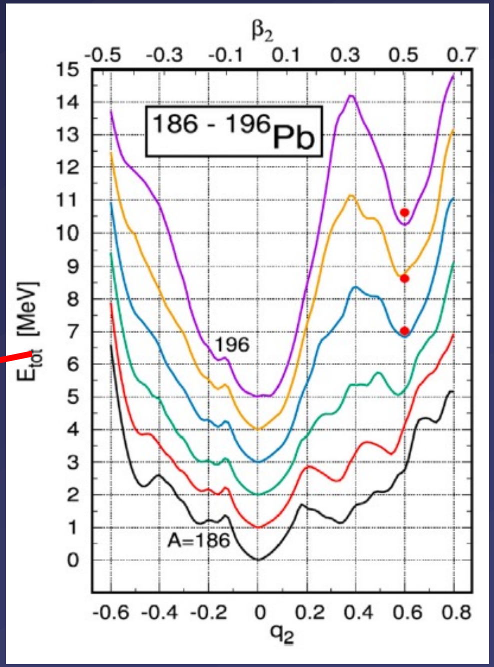
S. Leoni et al., Phys. Rev. C 79, 064307 (2009)

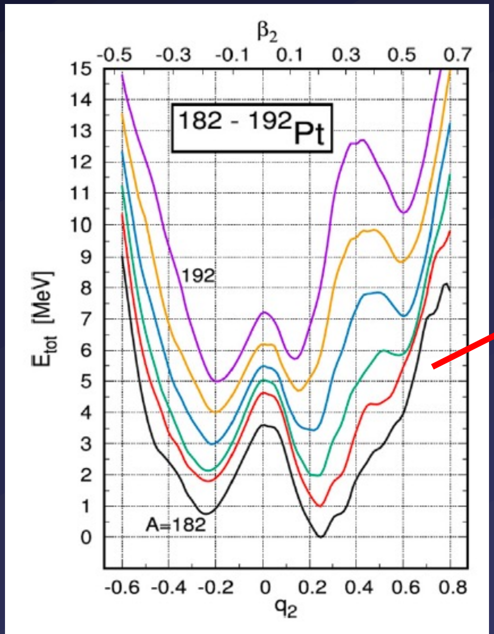
2) Direct population of low-spin states by Heavy-Ion transfer reactions

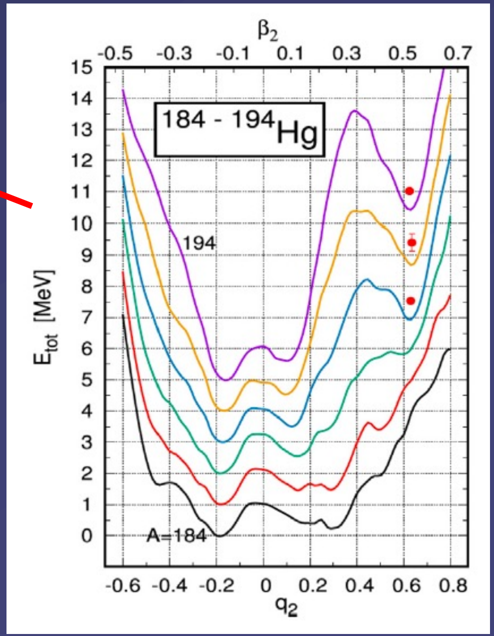
Difficulty in finding feasible HI projectile-target combination

e.g., 2 neutron transfer (^{18}O,^{16}O), at/below Coulomb barrier
2 proton transfer (^{16}O,^{14}C), at/above Coulomb barrier

Z																	
	188Po	189Po	190Po	191Po	192Po	193Po	194Po	195Po	196Po	197Po	198Po	199Po	200Po	201Po	202Po	203Po	204Po
	187Bi	188Bi	189Bi	190Bi	191Bi	192Bi	193Bi	194Bi	195Bi	196Bi	197Bi	198Bi	199Bi	200Bi	201Bi	202Bi	203Bi
82	186Pb	187Pb	188Pb	189Pb	190Pb	191Pb	192Pb	193Pb	194Pb	195Pb	196Pb	197Pb	198Pb	199Pb	200Pb	201Pb	202Pb
	185Tl	186Tl	187Tl	188Tl	189Tl	190Tl	191Tl	192Tl	193Tl	194Tl	195Tl	196Tl	197Tl	198Tl	199Tl	200Tl	201Tl
80	184Hg	185Hg	186Hg	187Hg	188Hg	189Hg	190Hg	191Hg	192Hg	193Hg	194Hg	195Hg	196Hg	197Hg	198Hg	199Hg	200Hg
	183Au	184Au	185Au	186Au	187Au	188Au	189Au	190Au	191Au	192Au	193Au	194Au	195Au	196Au	197Au	198Au	199Au
78	182Pt	183Pt	184Pt	185Pt	186Pt	187Pt	188Pt	189Pt	190Pt	191Pt	192Pt	193Pt	194Pt	195Pt	196Pt	197Pt	198Pt
	181Ir	182Ir	183Ir	184Ir	185Ir	186Ir	187Ir	188Ir	189Ir	190Ir	191Ir	192Ir	193Ir	194Ir	195Ir	196Ir	197Ir
76	180Os	181Os	182Os	183Os	184Os	185Os	186Os	187Os	188Os	189Os	190Os	191Os	192Os	193Os	194Os	195Os	196Os
	104		106		108		110		112		114		116		118		N



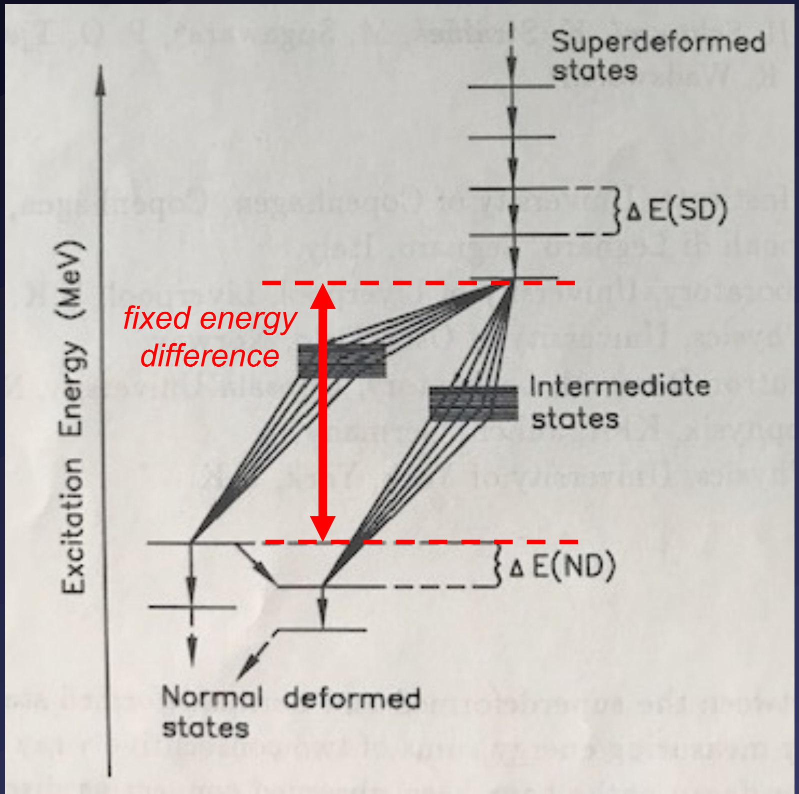


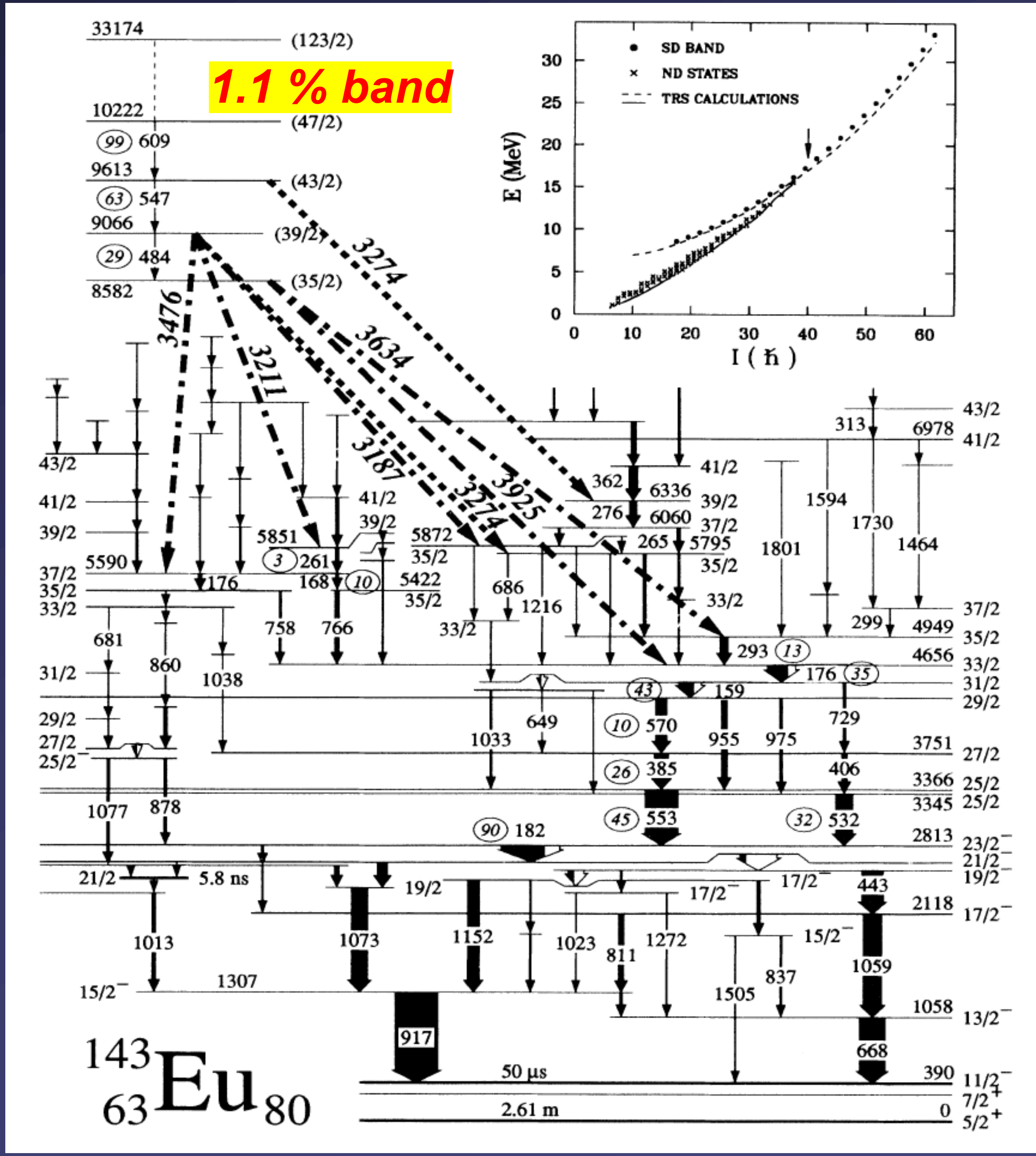


Summing technique used to search for SD-ND linking transitions

^{143}Eu

^{37}Cl + ^{110}Pd
NORDBALL





the energy sum ($E_{\gamma1}+E_{\gamma2}$)
should be constant

A. Atac, B. Herskind et al., Phys. Rev. Lett. 70(1993)1069

Searching for SHAPE ISOMERS at Spin 0 in other regions

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

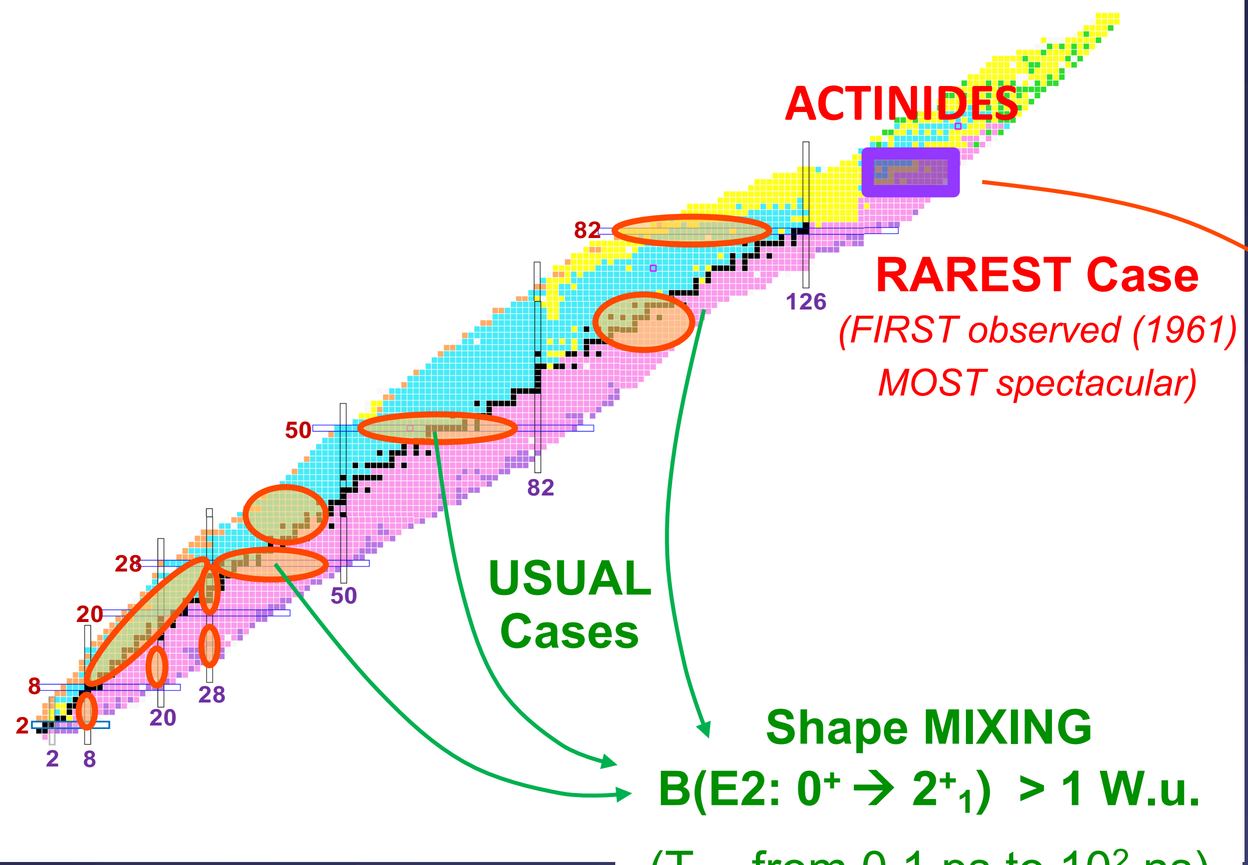
$B(E2;0^+ \rightarrow 2^+_1) << 1$ W.u., HF > 10

Regions of shape coexistence in atomic nuclei

Close to spin 0

After 50 years of investigation:

"An ubiquitous phenomenon across the nuclear chart"



Fission Shape ISOMERS

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

B(E2: $0^+ \rightarrow 2^+_1$) $\lesssim 10^{-7}$ W.u.

HF ≥ 10^7

Shape MIXING

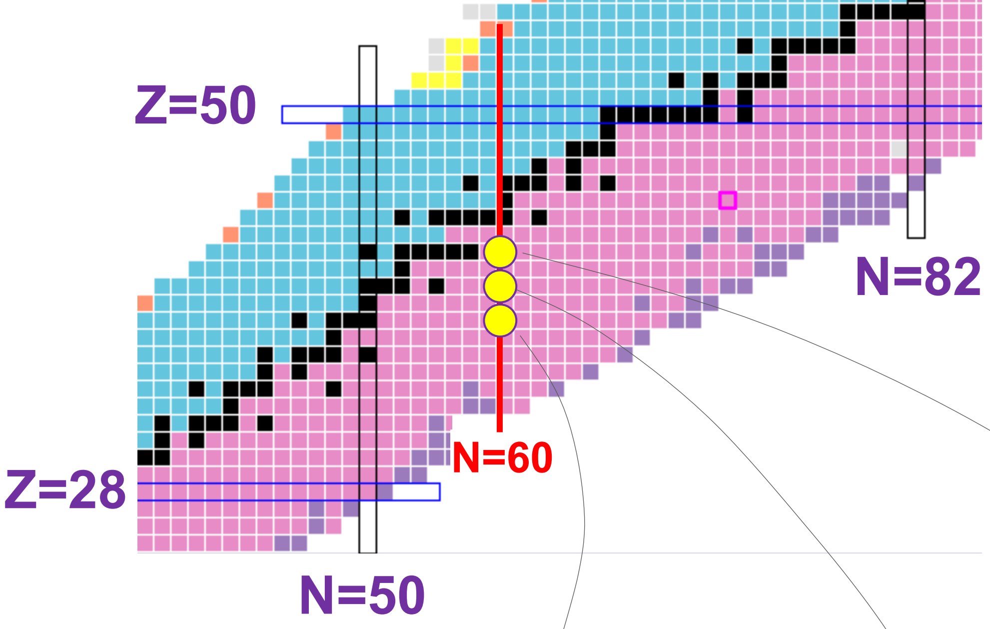
B(E2: $0^+ \rightarrow 2^+_1$) > 1 W.u.

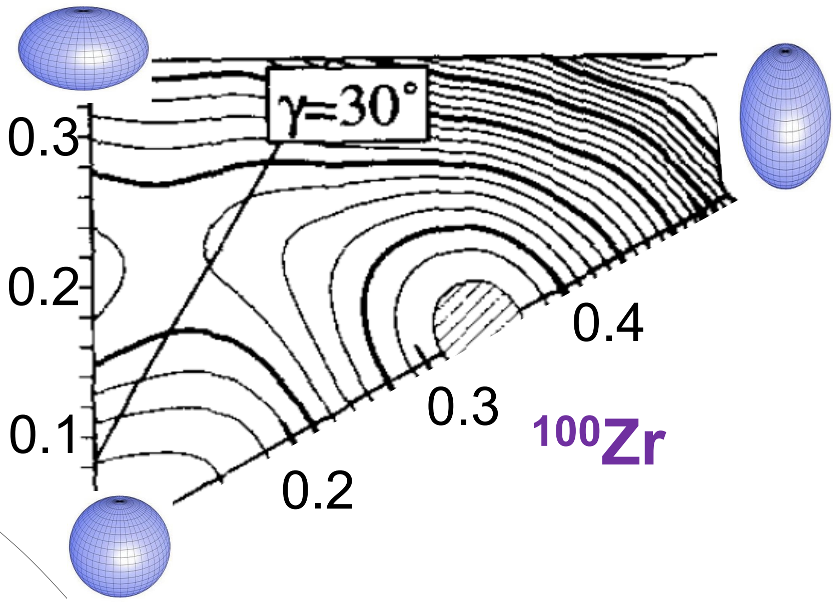
($T_{1/2}$ from 0.1 ps to 10^2 ns)

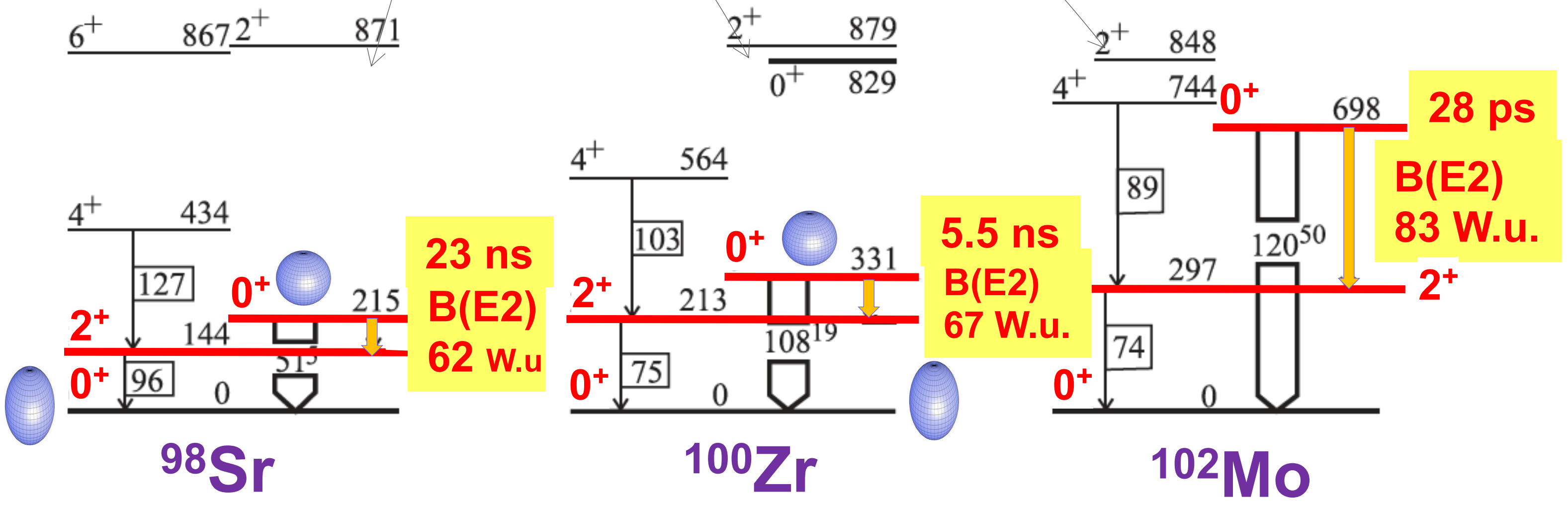
In general, NO HINDRANCE observed for decay between different shapes, even if isomeric

B(E2) ≳ 1 W.u. , HF < 10

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







Examples of SHAPE MIXING NOT SHAPE ISOMERISM

No retardation in γ decay is observed - B(E2)>> 1W.u., HF << 1

→ Potential Barrier **NOT sizable** enough to prevent fast shape changes

→ Wave Functions **NOT well localized** in (β,γ) plane

Predictions based on Mean Field and EDF
for existence of DEEP Secondary Minima

Mean-Field based predictions

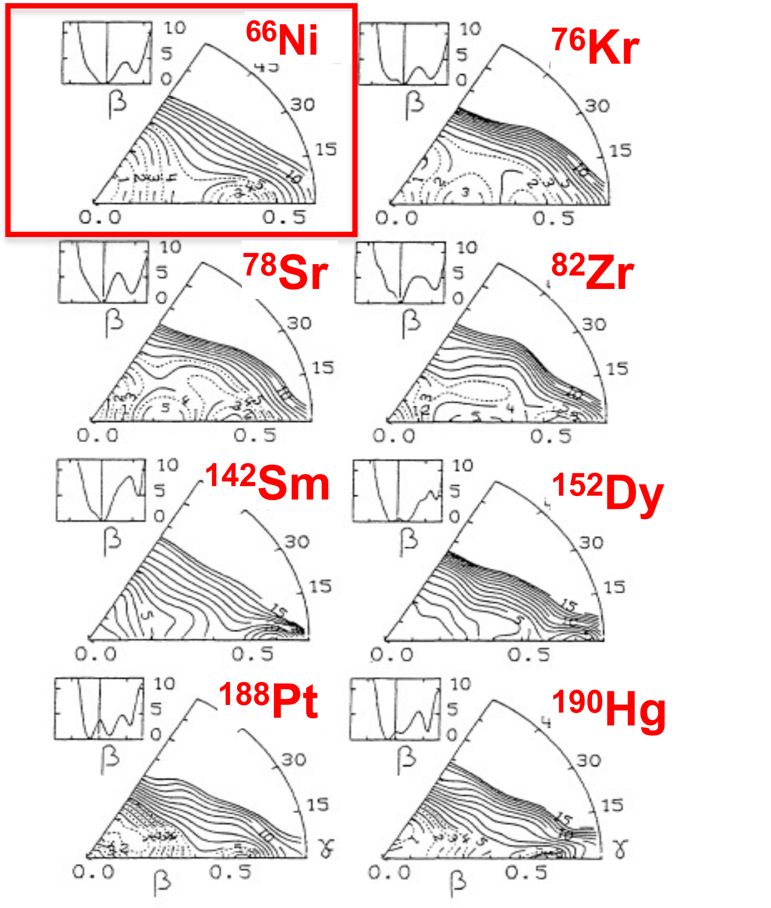
VOLUME 62, NUMBER 21 PHYSICAL REVIEW LETTERS **1989**

Hartree-Fock-Bogoliubov Predictions for Shape Isomerism in Nonfissile 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

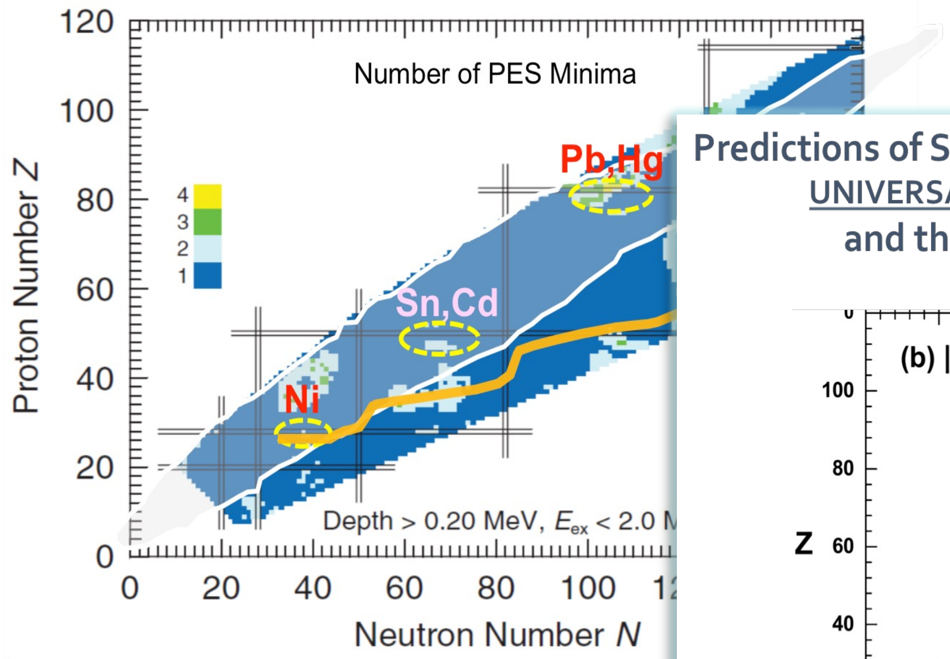
PRL 103, 212501 (2009) PHYSICAL REVIEW LETTERS week ending 20 NOVEMBER 2009

2009

Global Calculation of Nuclear Shape Isomers

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

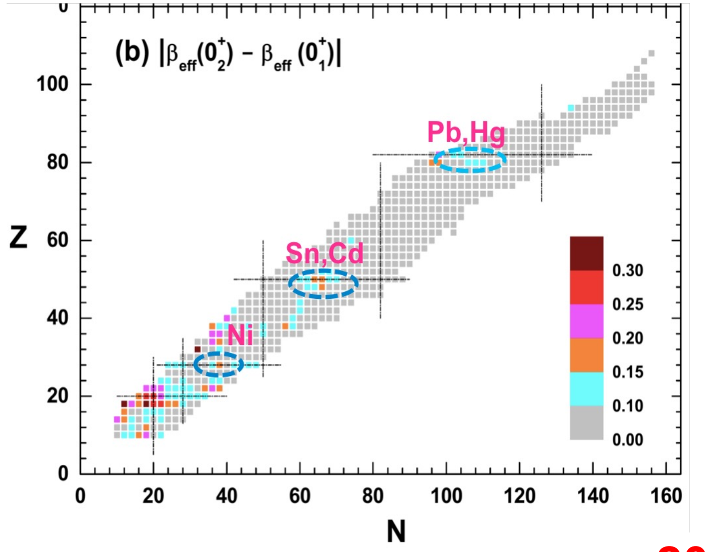
Study of 7206 nuclei from A=31 to A=209



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.



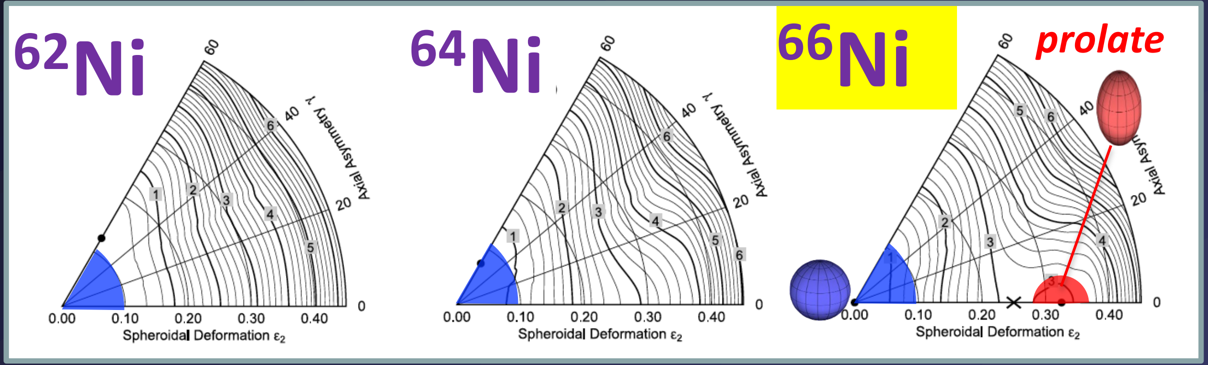
S. Quan et al., PHYSICAL REVIEW C 95, 054321 **2017**

The Ni chain

Monte Carlo Shell Model

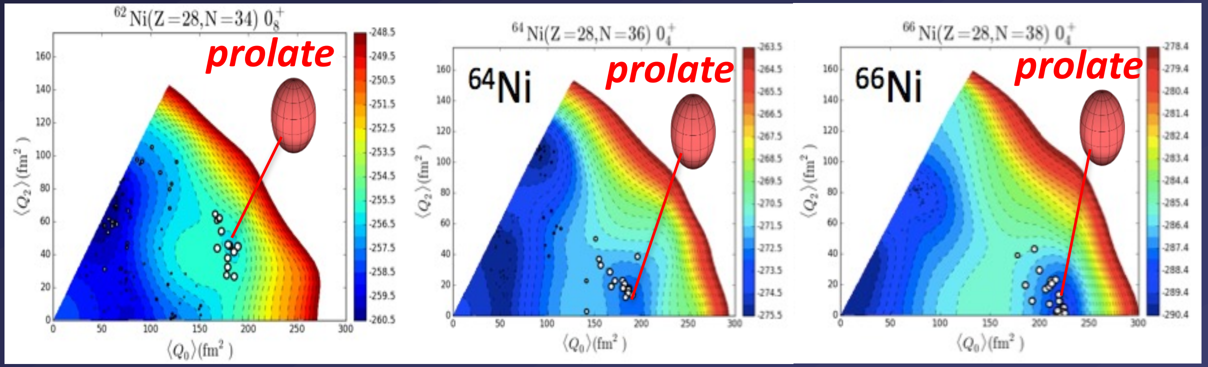
- Large configuration space:
  $f_{7/2}, p_{3/2}, f_{5/2}, p_{1/2}, g_{9/2}, d_{5/2}, g_{7/2}$
- Number of configurations 10^{20}

MICROSCOPIC understanding
wave functions, B(Eλ/Mλ) ...



Mean Field
Moeller et al.

experimental investigation with STABLE beams



Monte Carlo SHELL Model
Y. Tsunoda,
T. Otsuka et al.

Study of 0^+ states in ^{64,66}Ni isotopes

^{64}Ni: 4 experiments in 4 laboratories

to achieve the required experimental sensitivity

… a **multimessanger approach** …

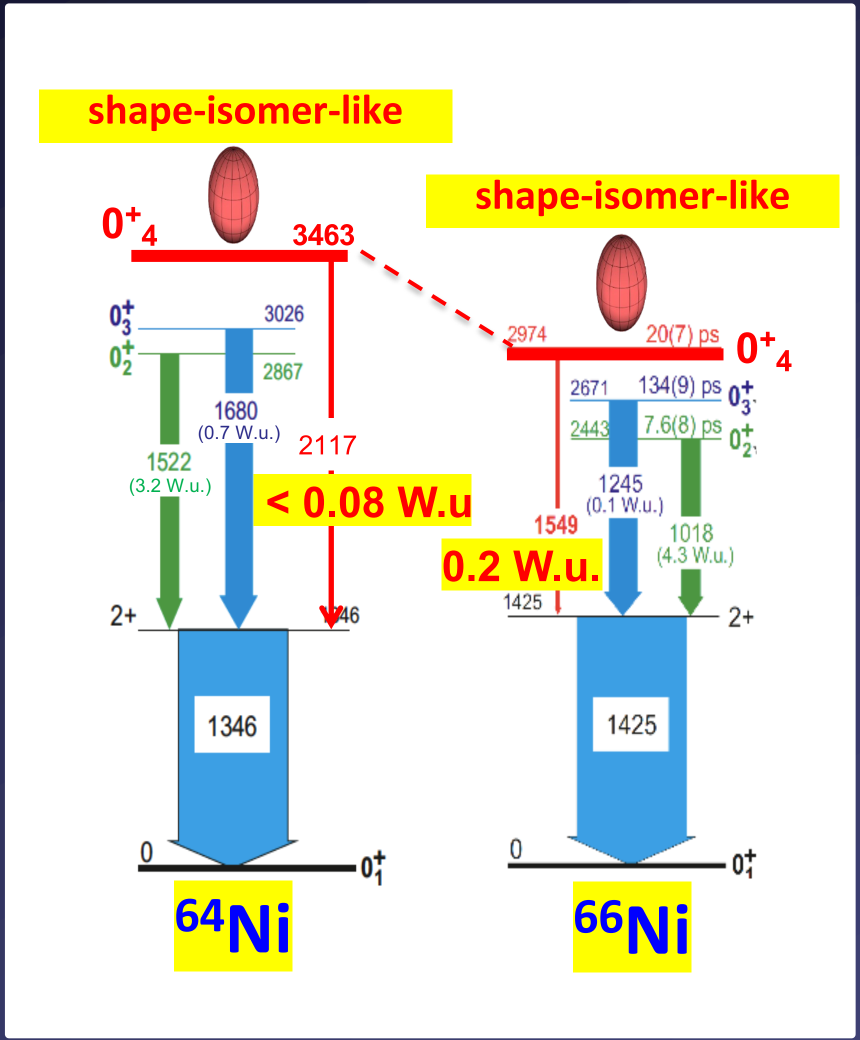
1) **IFIN-HH (ROSPHERE)**
   sub-barrier transfer (1p, 2n)
2) **ILL reactor (FIPPS)**
   neutron capture
   (with 1 GBq target)
3) **Argonne (GRETINA)**
   Coulomb excitation
4) **TUNL (USA):** *(γ,γ')*

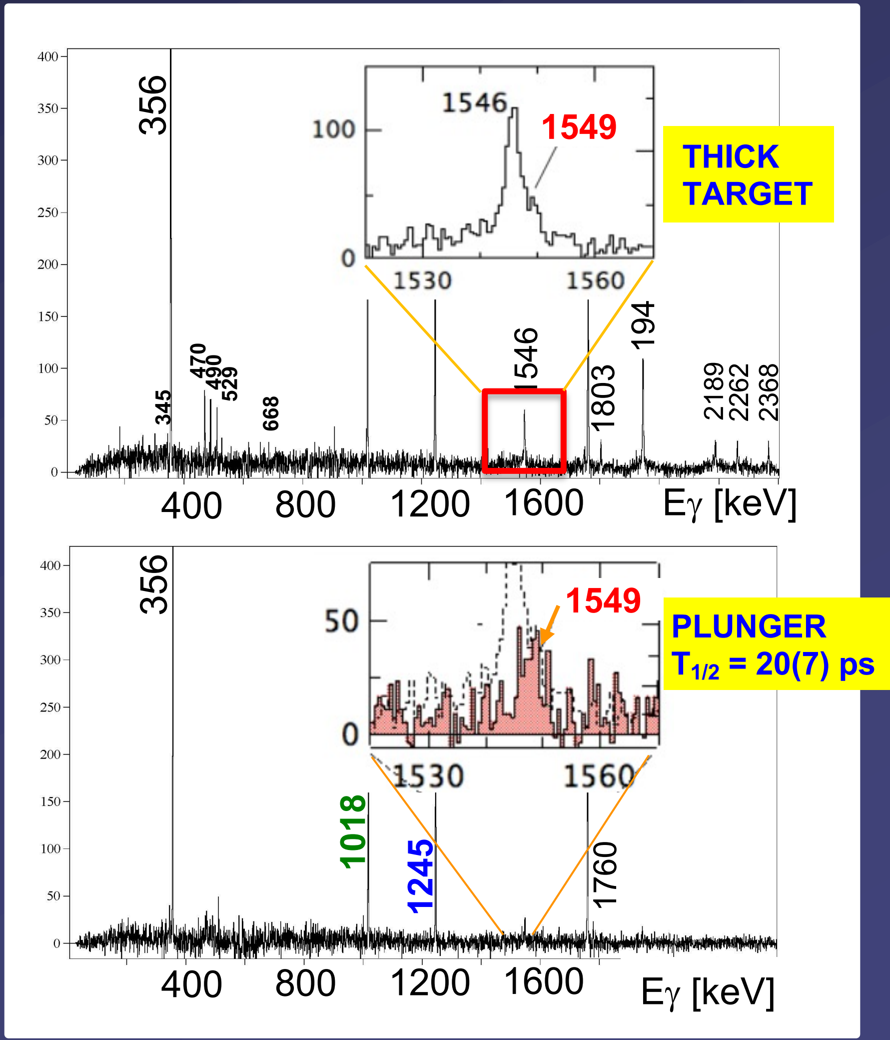
example used for American LONG RANGE PLAN

^{66}Ni: > 1 month Beam Time

sub-barrier transfer ^{64}Ni(^{18}O,^{16}O)^{66}Ni

ROSPHERE Array (IFIN-HH)





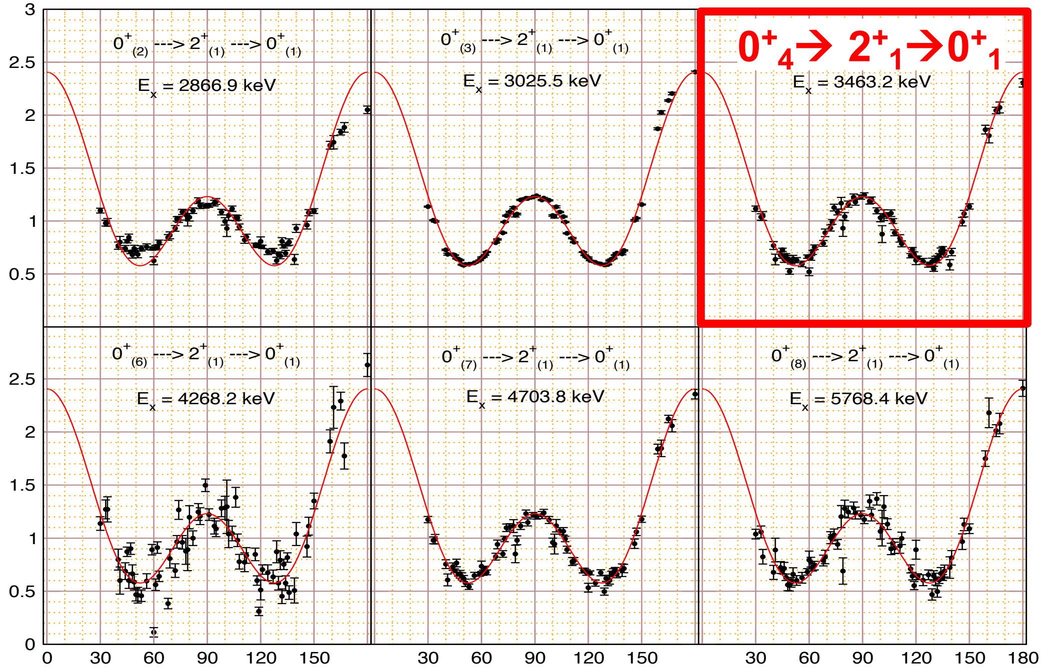
N. Marginean, et al., Phys. Rev. Lett. 125, 102502 (2020)

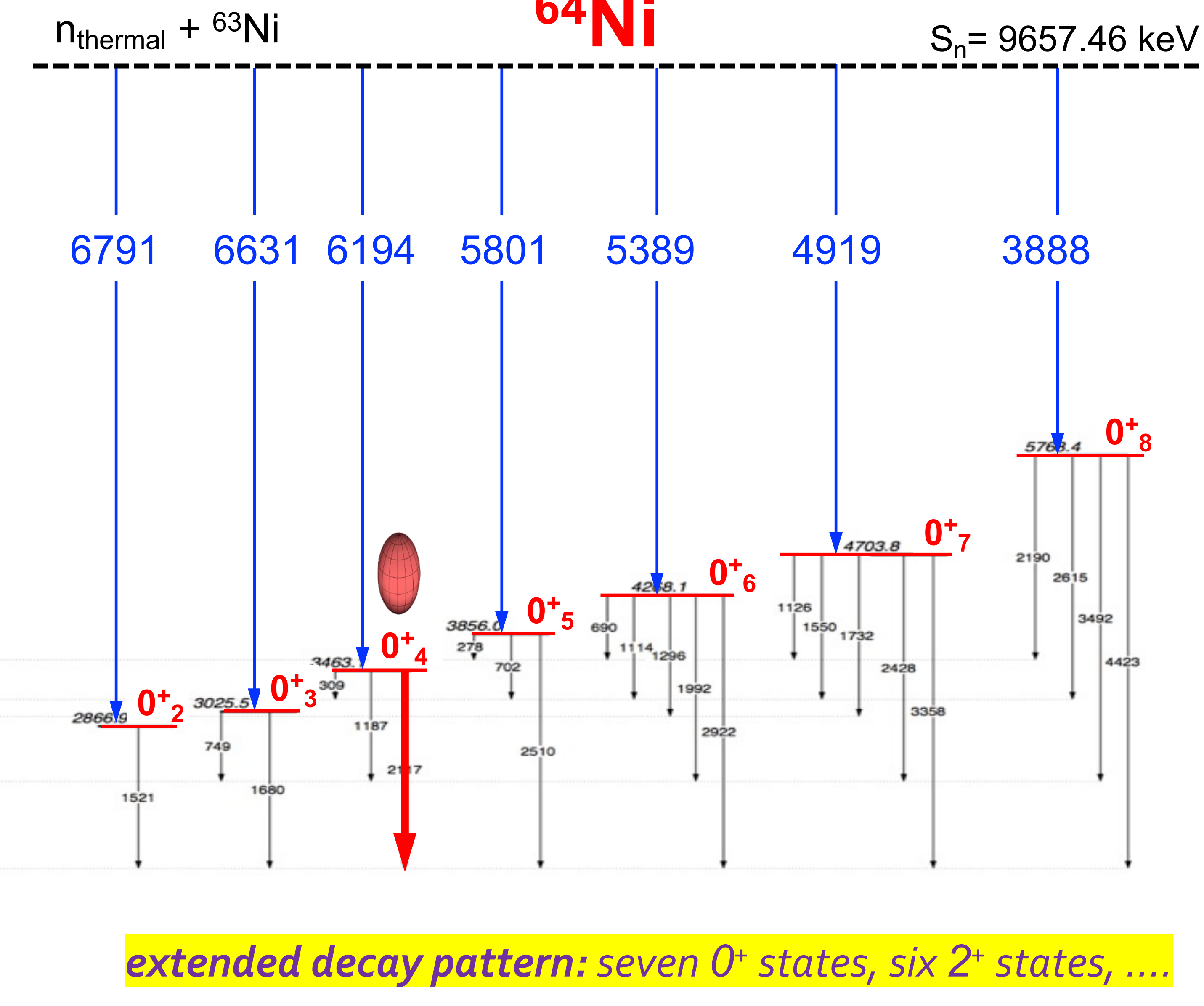
S. Leoni, B. Fornal, N. Marginean, et al., Phys. Rev. Lett. 118, 162502 (2017)

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





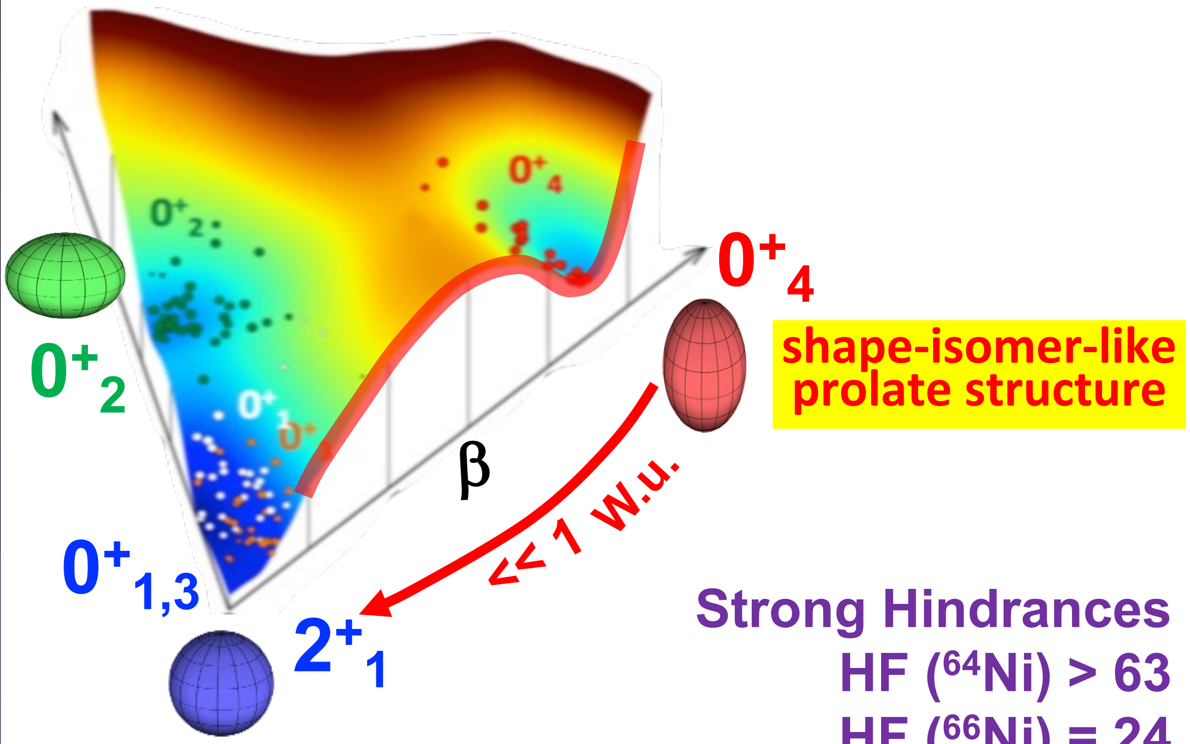
^{64}Ni

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

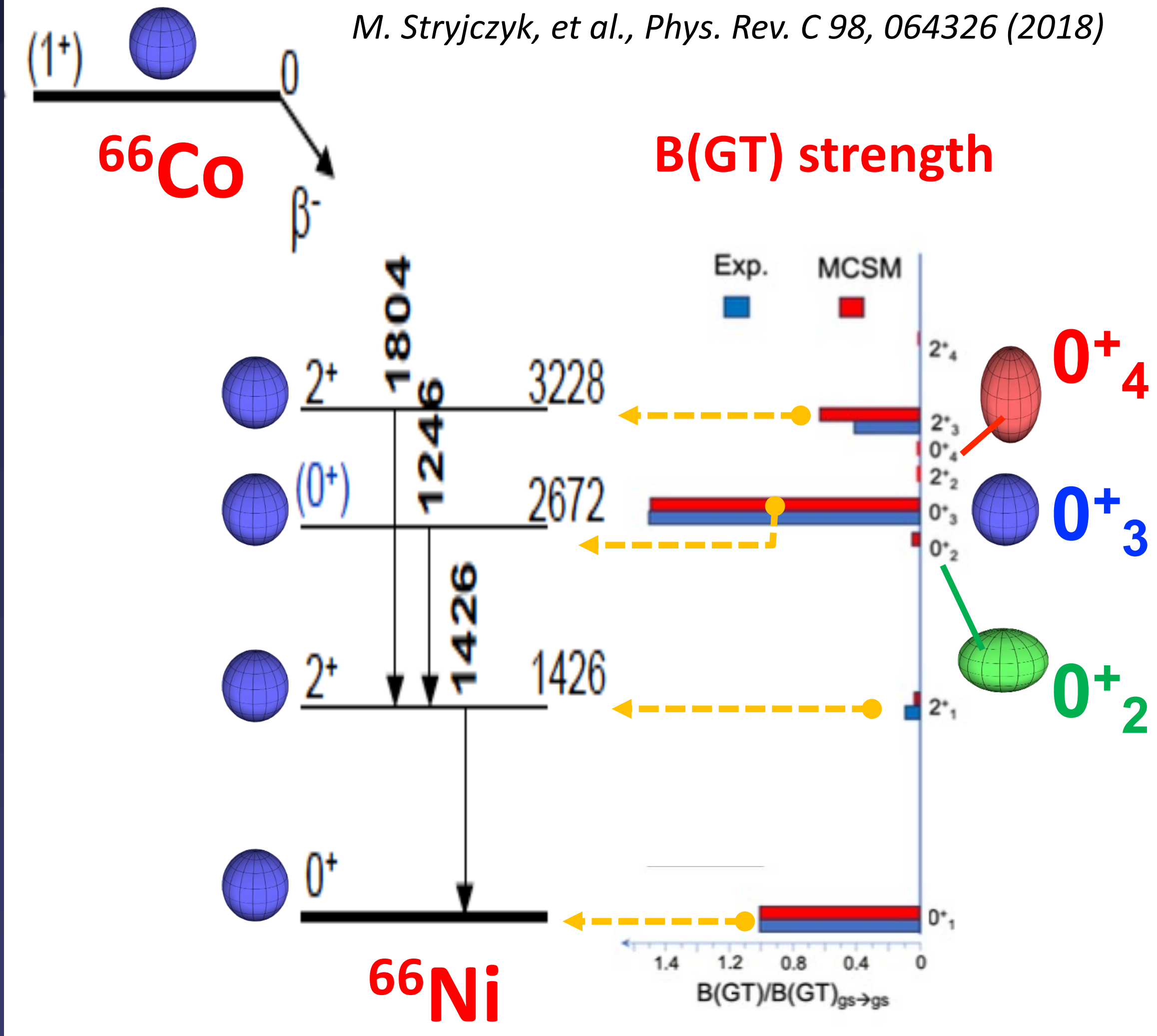
^{64,66}Ni

β-decay studies support the MCSM shape assignments

High Potential Energy Barrier



Strong Hindrances
HF (^{64}Ni) > 63
HF (^{66}Ni) = 24



According to MCSM calculations, the <u>Strong Hindrance</u> in the E2 decay of 0^+_4 is caused by a <u>shape change</u>: prolate → spherical

Where to search for other shape-isomer-like 0^+ states?

Eur. Phys. J. Spec. Top. (2024) 233:1061–1074
https://doi.org/10.1140/epjs/s11734-024-01175-6

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Check for updates

Review

Shape isomers: status and perspectives across the nuclear chart

S. Leoni[1,2,a], B. Fornal[3], N. Mărginean[4], and J. N. Wilson[5]

[1] Dipartimento di Fisica, Università di Milano, Milan 20133, Italy
[2] Istituto Nazionale di Fisica Nucleare, Milan 20133, Italy
[3] Niewodniczanski Institute of Nuclear Physics PAN, Radzikowskiego 152, Krakow 31-342, Poland
[4] Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH, Bucharest 077125, Romania
[5] IJC Lab, CNRS/IN2P3, Université Paris-Saclay, Orsay 91406, France

Received 1 March 2024 / Accepted 17 April 2024 / Published online 2 May 2024

Abstract The paper reviews the searches for shape isomers, which are "extreme" example of shape-coexistence phenomena in nuclei. They may appear when highly deformed structures, well localized in the nuclear Potential Energy Surface (PES) in the deformation space, undergo a significant change in shape to match the final state shape, thus leading to a substantially hindered γ decay. This is in sharp contrast to the vast majority of shape-coexistence phenomena, where significant mixing in the initial and final state wave functions is found. So far, the most spectacular examples of shape isomerism are known in fissioning systems in the actinides, although only scarce experimental information is available from experiments conducted more than 20 years ago. Searches in lighter mass regions, guided by theory predictions based on different approaches and experimental investigations on superdeformed systems, are also presented. They point to ^{64,66}Ni as additional examples of prolate deformed shape-isomer-like structures, although with much reduced hindrance with respect to the actinides. Their origin is strictly related to the action of the monopole component of the tensor force of the nucleon-nucleon interaction, which is expected to favor the appearance of deep secondary minima also in the PES of Sn nuclei with masses 112–118. Perspectives in current searches of shape isomerism with modern detection systems, in the actinides regions and in lighter masses, are discussed.

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

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

ELSEVIER

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]

[a] Dipartimento di Fisica dell'Università degli Studi di Milano, Italy
[b] INFN, Sezione di Milano, Italy
[c] Institute of Nuclear Physics PAN, Krakow, 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

IN PRINT

ARTICLE INFO

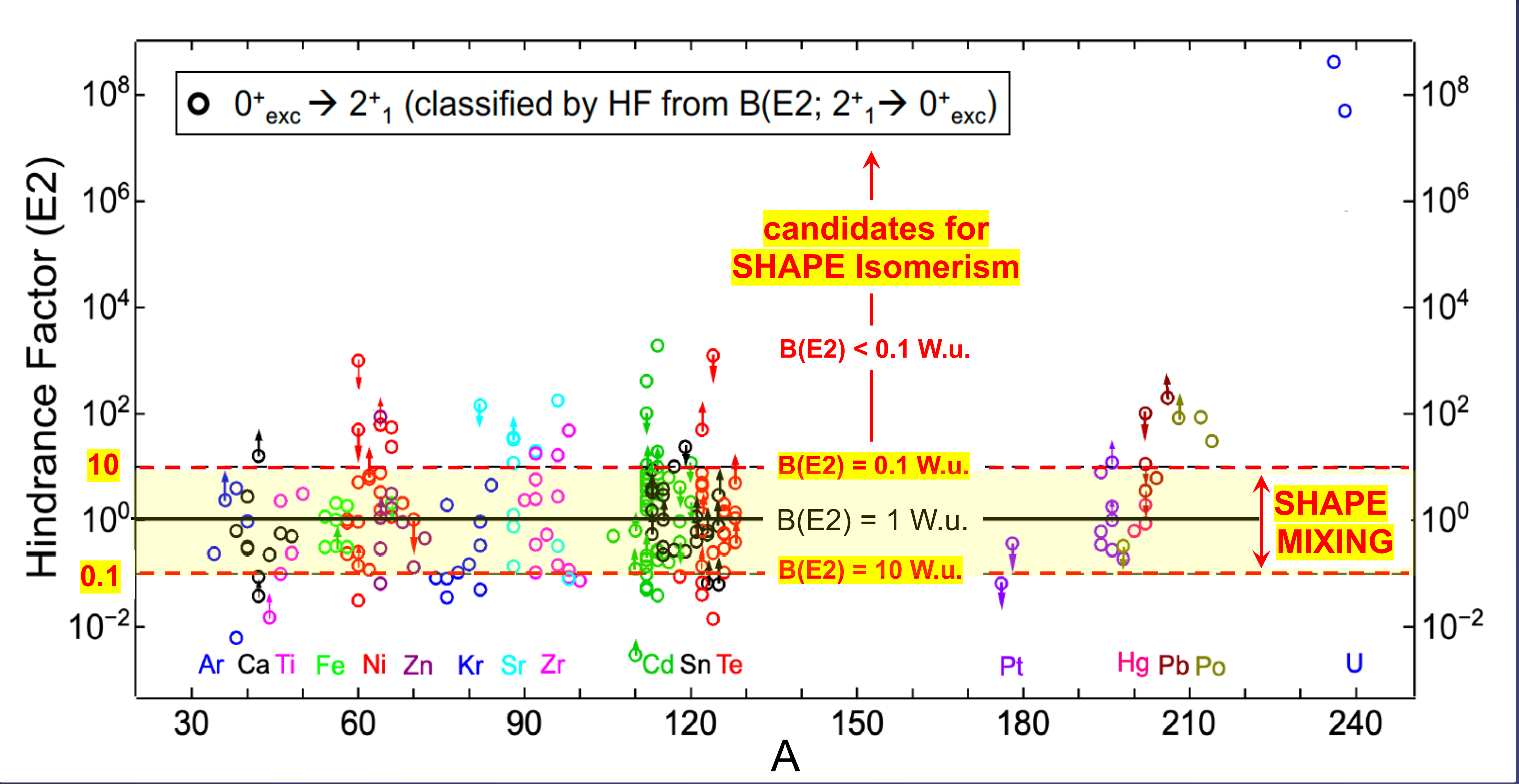
Keywords:
Nuclear structure
Shape coexistence
Shape isomers
Superdeformed bands

ABSTRACT

This article is devoted to a review of decay properties of excited 0^+ states in regions of the nuclear chart well known for shape coexistence phenomena. Even–even isotopes around the Z=20 (Ca), 28 (Ni), 50 (Sn), 82 (Pb) proton shell closures and along the Z=36 (Kr), Z=38 (Sr) and Z=40 (Zr) isotopic chains are mainly discussed. The aim is to identify examples of *extreme shape coexistence*, namely highly deformed structures, well localized in the Potential Energy Surface in the deformation space, which could lead to γ decays substantially hindered. This is in analogy to the 0^+ fission shape isomers in the actinides region and to the superdeformed (SD) states at the decay-out spin in medium/heavy mass systems. In this survey, the Hindrance Factor (HF) of the E2 transitions de-exciting 0^+ states or SD decay-out states is a primary quantity which is used to differentiate between types of shape coexistence. The 0^+ states, examined with the help of the hindrance factor, reveal a multifaceted scenario of shape coexistence. A limited number of 0^+ excitations (in the Ni, Sr, Zr and Cd regions) exhibit large HF values (>10), some of which are associated with the clear separation of coexisting wave functions, while in most cases the decay is not hindered, due to the mixing between different configurations. Comparisons with theory predictions based on various models are also presented, some of which shed light on the microscopic structure of the considered states and the origin of the observed hindrances. The impact of shape ensembles at finite temperature on the decay properties of highly-excited states (Giant Dipole Resonances) is also discussed. This research area offers a complementary approach for identifying regions where extreme shape coexistence phenomena may appear.

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

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

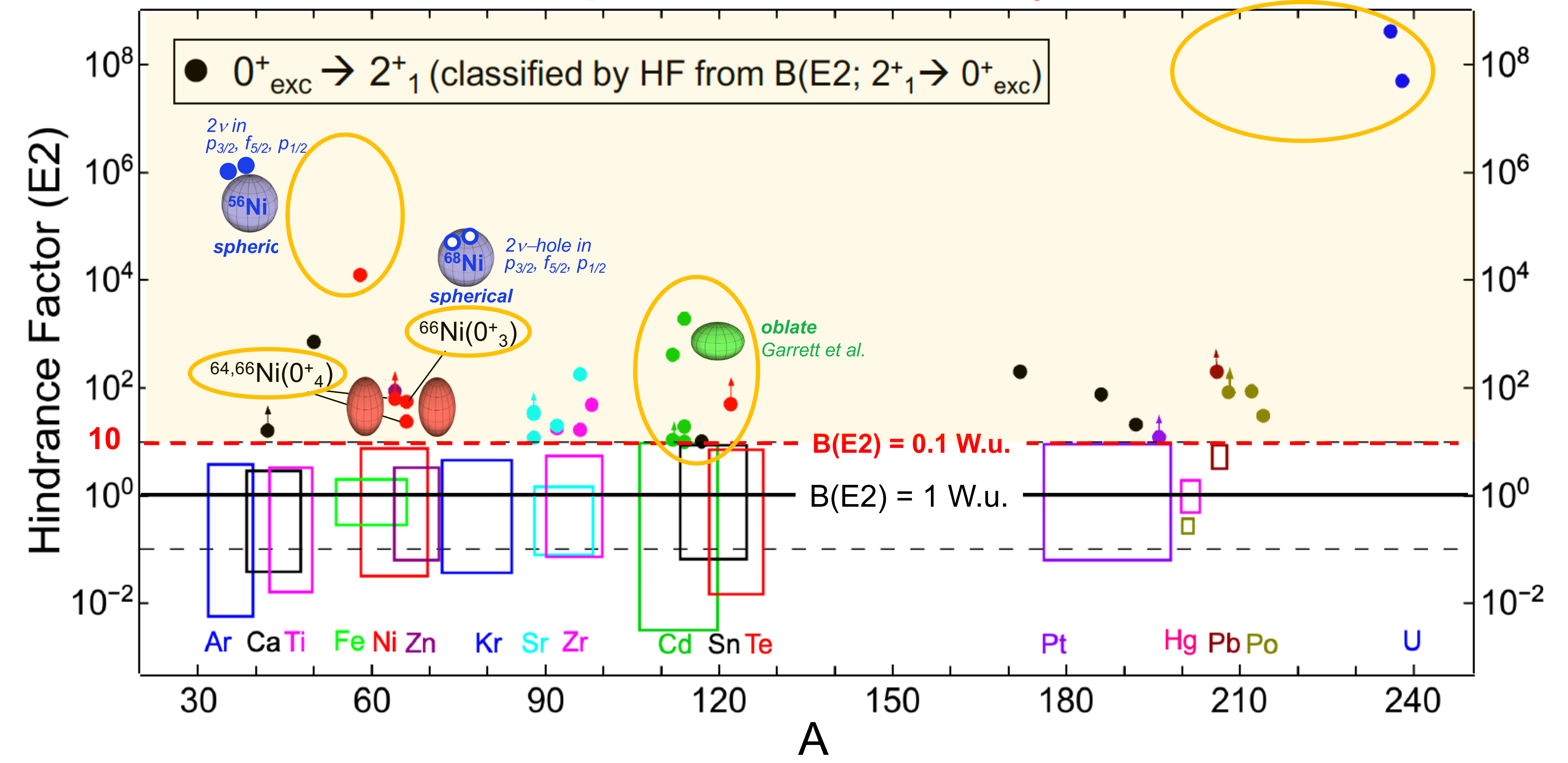


S. Leoni, B. Fornal, A. Bracco, Y. Tsunoda, T. Otsuka, in print in Prog. Part. Nucl. Phys. (2024)

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

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

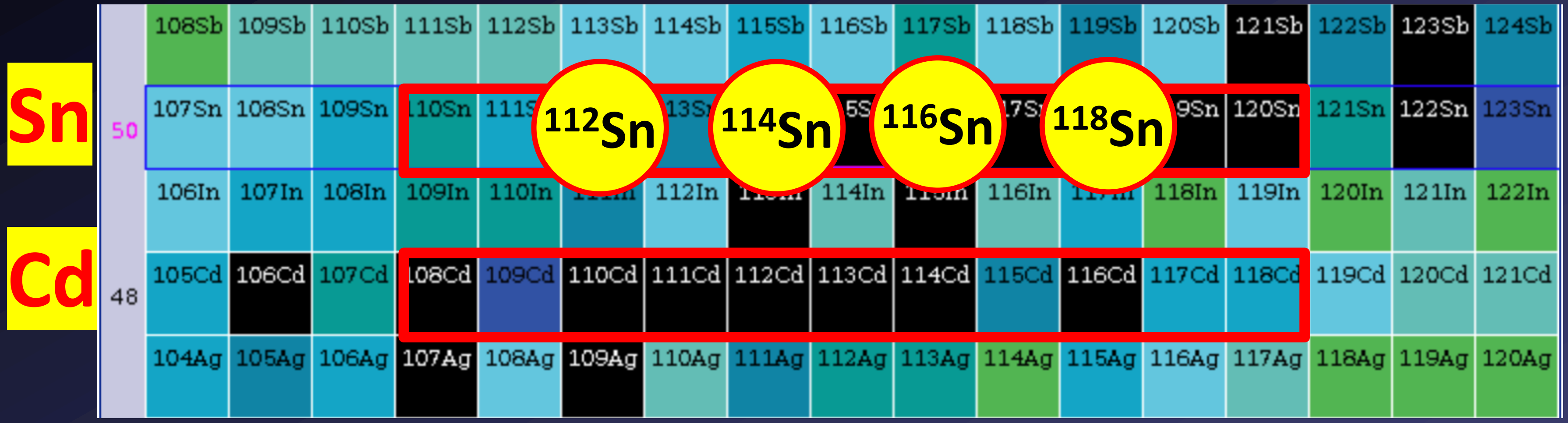
No other reported hindered E2 decay from 0^+



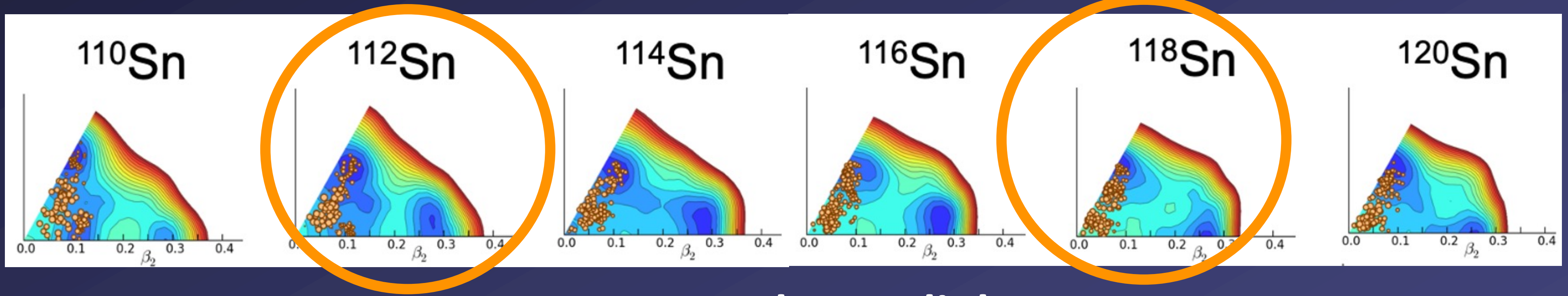
S. Leoni, B. Fornal, A. Bracco, Y. Tsunoda, T. Otsuka, in print in Prog. Part. Nucl. Phys. (2024)

Our new project: Systematic Study of Shape coexistence in Sn nuclei

expected scenario similar to Ni



data under analysis

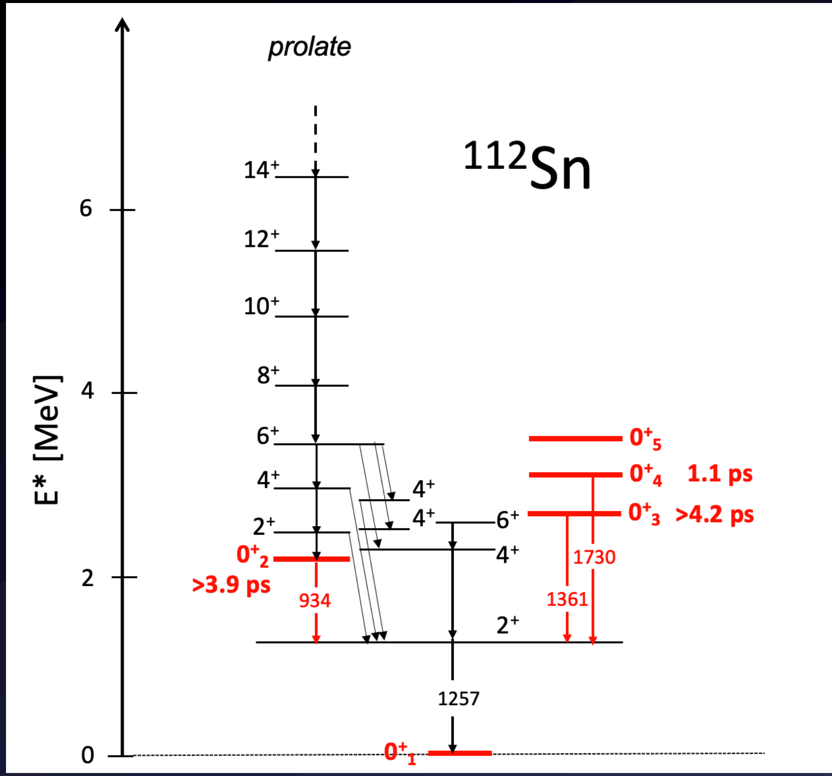


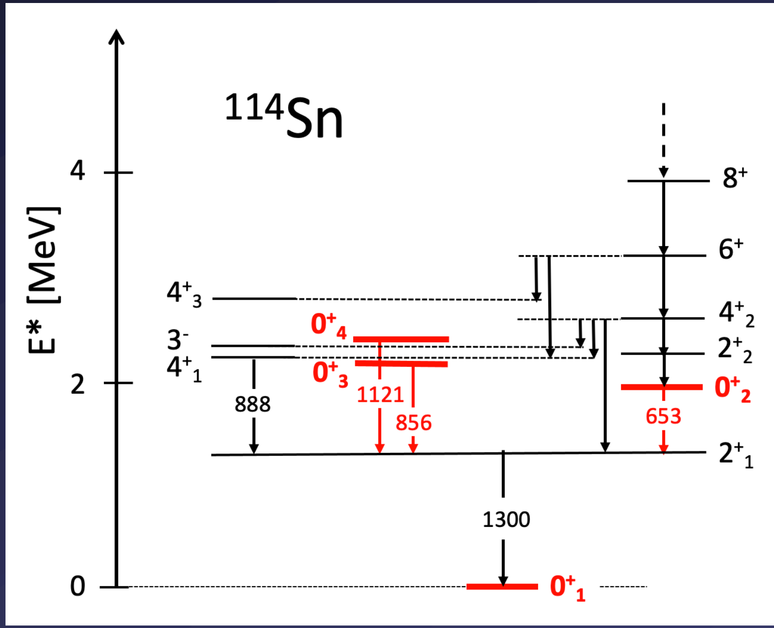
Hartree-Fock-Bogoliubov

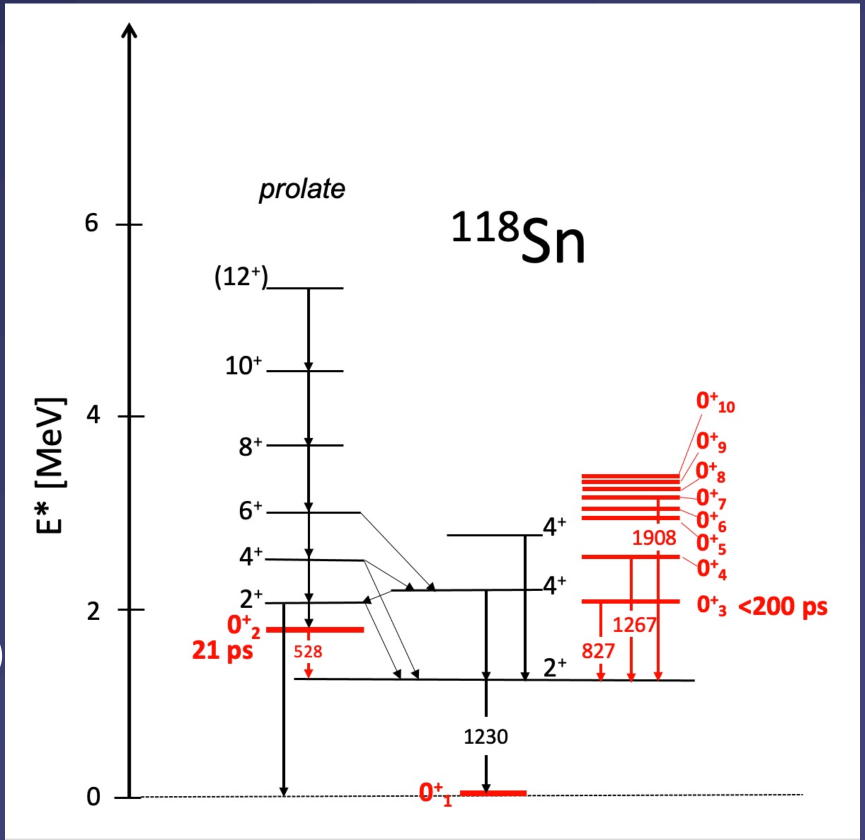
interaction from Togashi et al., PRL121, 062501 (2018)

^{112}Sn and ^{118}Sn are first and last isotopes with an expected well-developed prolate minimum

Several excited 0^+ states identified in $^{112,114,116,118}Sn$, but no lifetimes measured







Performed/planned experiments:

^{18}O+ ^{112}Sn → ^{114}Sn: lifetime (DSAM and Plunger), ROSPHERE (2022)

^{32}S+ ^{110}Cd → ^{112}Sn: lifetime (Plunger), AGATA+PRISMA (2022)

1n, 2n, 2p, (alpha) transfer → $^{114,116,118.120}Sn$: DSAM, ROSPHERE (2023)

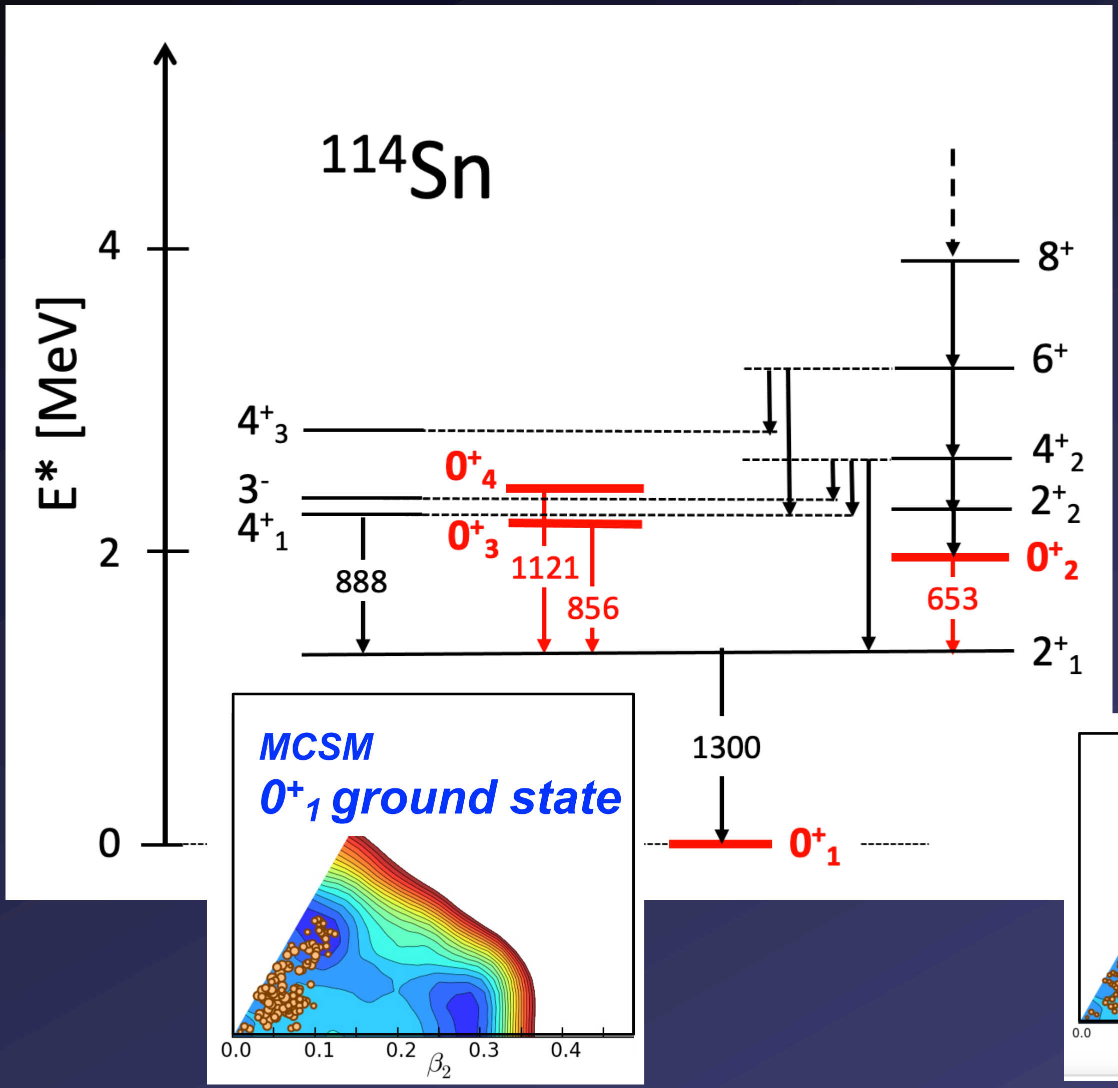
1n transfer → $^{114,116,118.120}Sn$: lifetime (Plunger), ROSPHERE (2024)

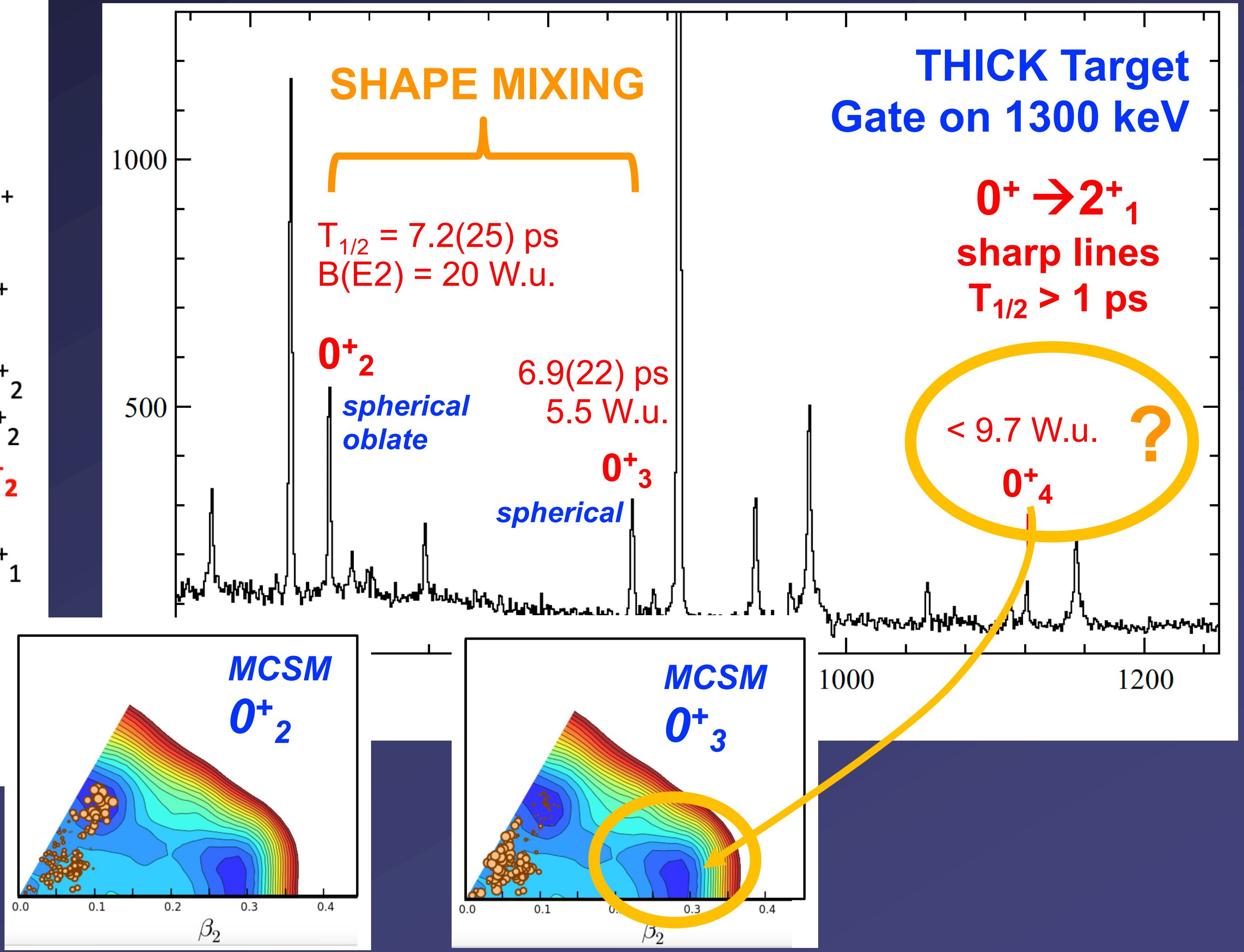
^{112}Sn to ^{118}Sn : All Lifetimes measured up to at least 0^+_4

Preliminary - ^{114}Sn

G. Corbari PhD, Milano University

^{18}O+ ^{112}Sn → ^{114}Sn:
lifetime (DSAM and Plunger)
ROSPHERE @ IFIN (2022)



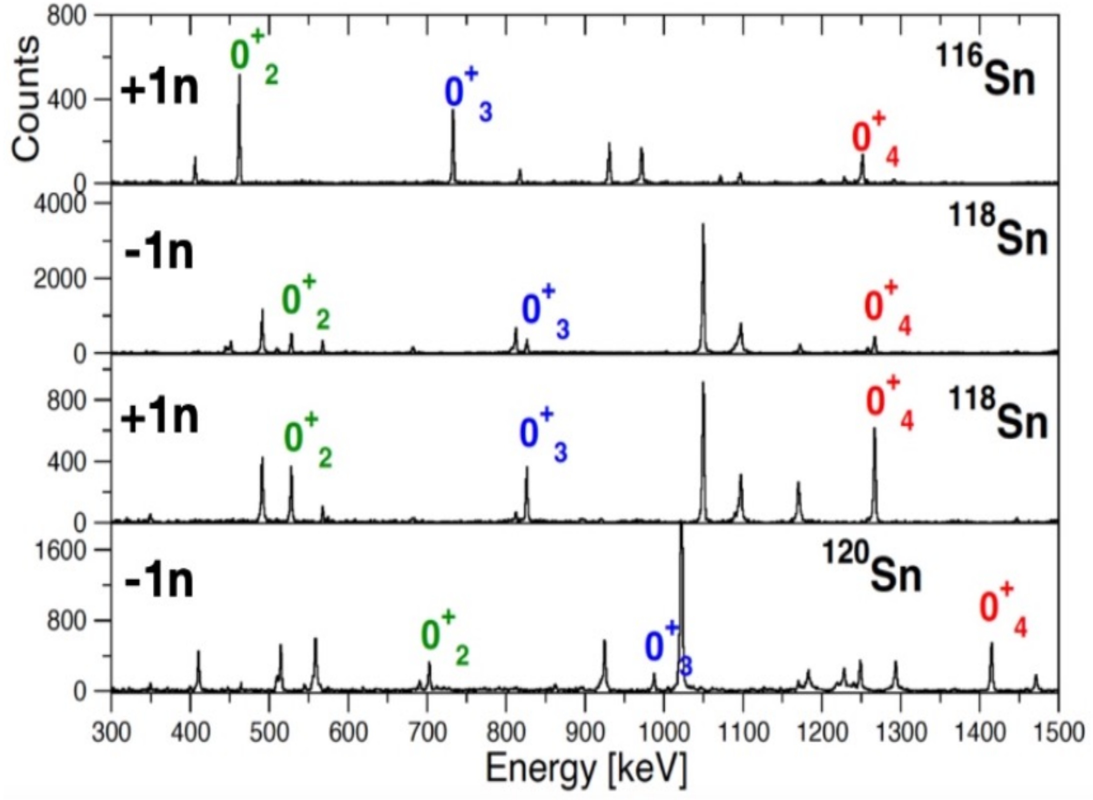


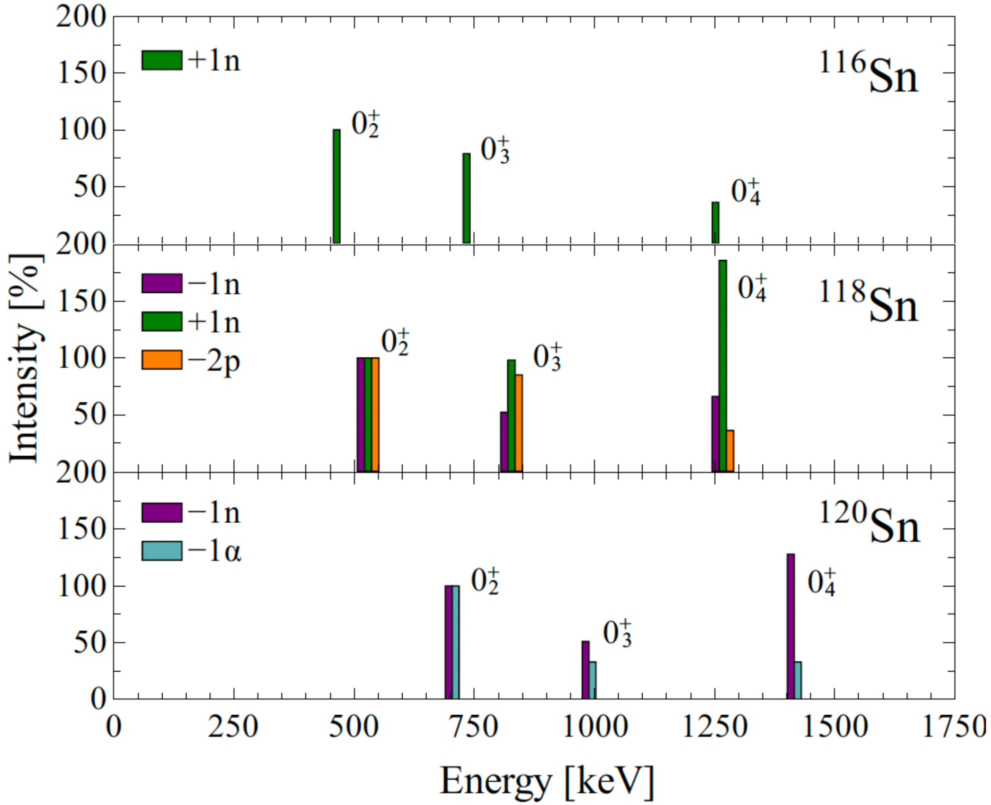
$^{116\text{-}118\text{-}120}$Sn DSAM

October **2023**

13C+117Sn @ 43 MeV
13C+119Sn @ 43 MeV
16O+116Cd @ 56 MeV

ROSPHERE + particle detector
IFIN-HH Bucharest





Analysis ongoing

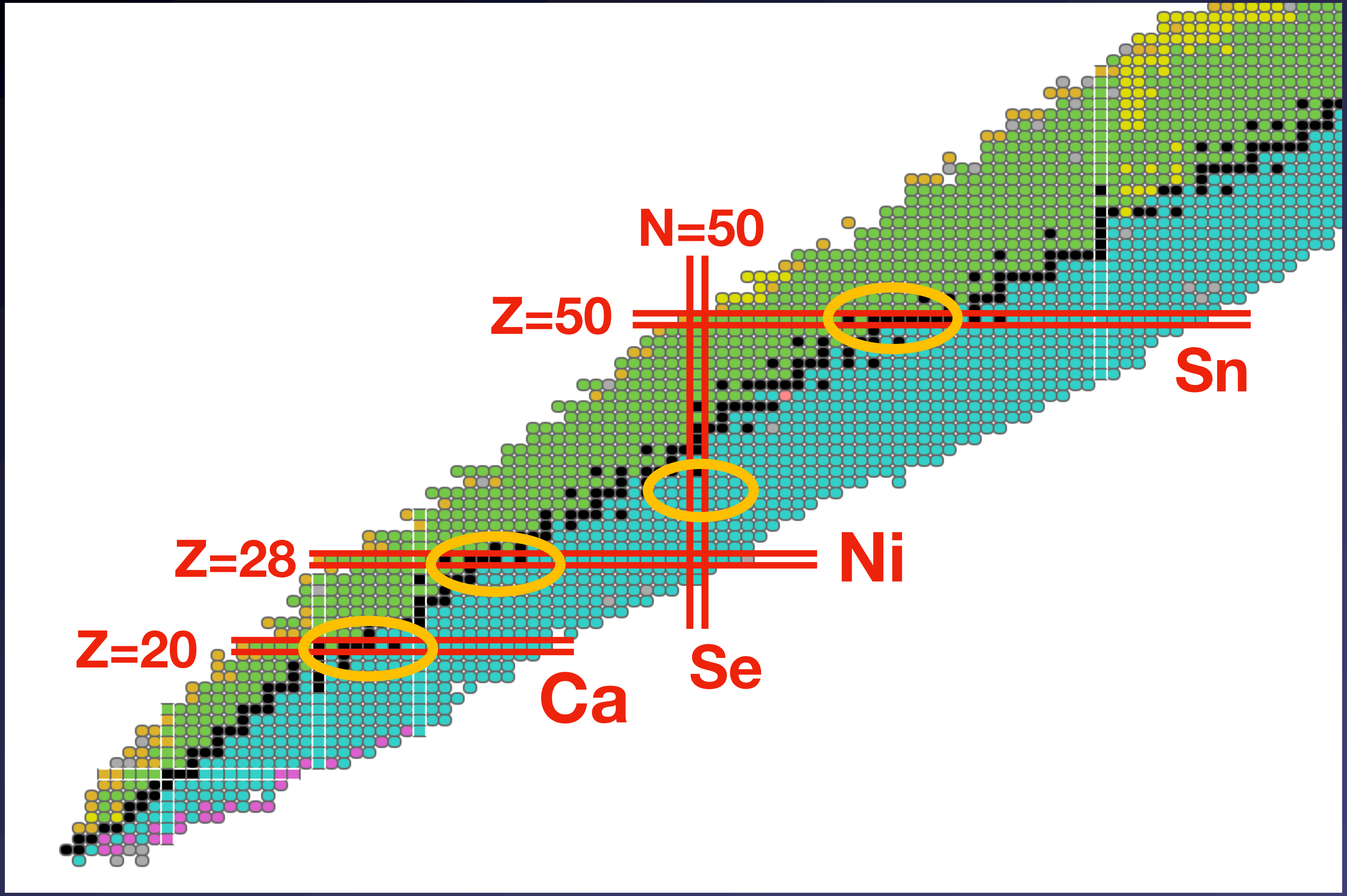
G. Corbari, PhD thesis, ongoing

New Experiments

PLUNGER measurements in 114,116,118,120Sn

13C+115Sn @ 43 MeV
13C+117Sn @ 43 MeV
13C+119Sn @ 43 MeV

Summary of our research program – close to stability



Sn (Z=50)

$^{112,114,116,118}Sn$

Ni (Z=28)

$^{62,64,66}Ni$

Se (N=50)

$^{83,84}Se$

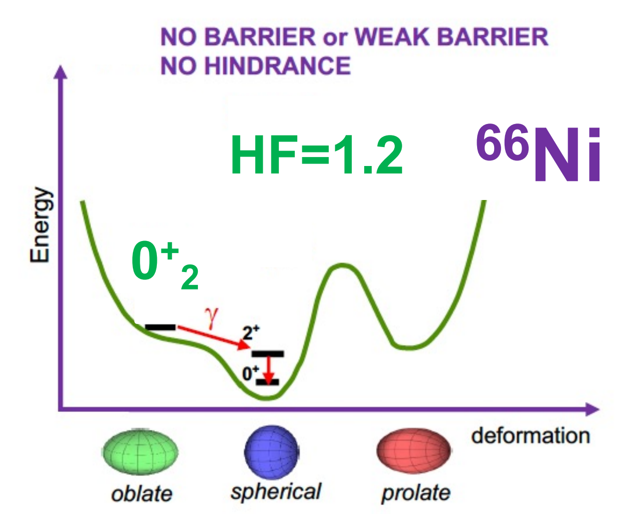
Ca (Z=20)

$^{42,43,44,45}Ca$

Conclusions: SHAPE COEXISTENCE is a multifaceted phenomenon

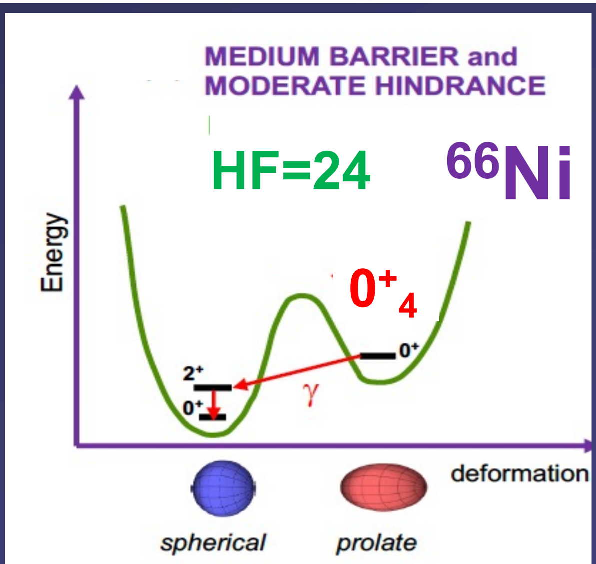
1) In general, at Spin 0, NO HINDRANCE is observed (HF<10)
for decay between different shapes
Wave functions NOT well localized → SHAPE MIXING

Such states may still be ISOMERIC for other reasons !!



2) Shape isomerism is very rare:
it appears when the wave function is well localized
in secondary PES minimum, separated by a sizable barrier

→ primary requisit is LARGE HINDRANCE (HF>10)
examples: ^{236,238}U (HF>10^7), ^{64,66}Ni (HF~20-100), …



Perspectives: Searches in the A=190 Hg, Pt region, among SD systems

THANK YOU FOR THE ATTENTION !!!!!