Towards a microscopic understanding of shape isomerism in medium-mass nuclei

Silvia Leoni – University of Milano and INFN

In collaboration with:

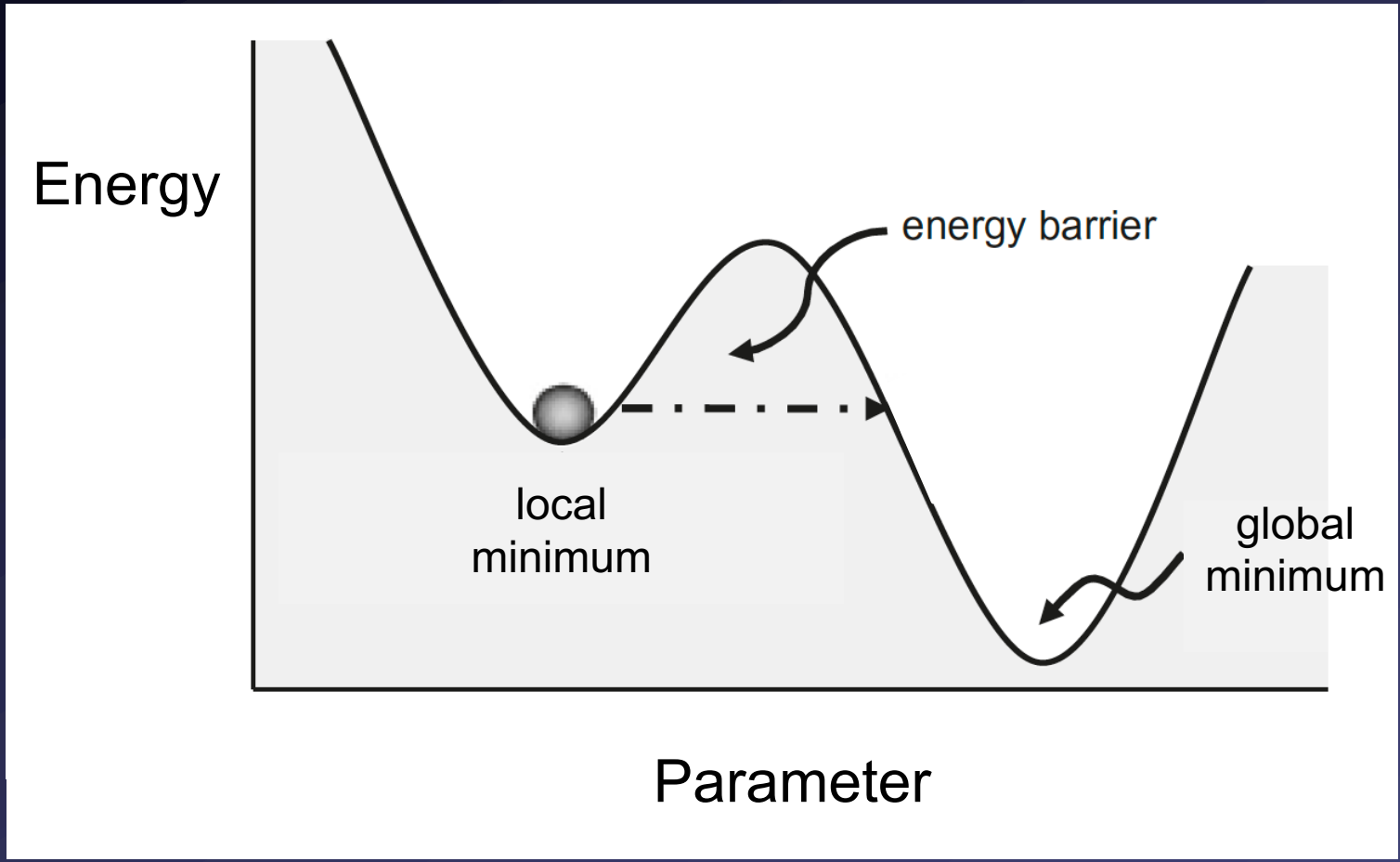
- **B. Fornal** et al., Institute of Nuclear Physics, Krakow, Poland
- **N. Mărginean** et al., IFIN HH, Bucharest, Romania
- **R.V.F. Janssens** et al., University of Noth Carolina, USA
- **C. Michelagnoli** et al., ILL, Grenoble, France
- **M. Sferrazza** et al., Universite libre de Bruxelles, Belgium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

INFN
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI MILANO

The Potential Energy Surface (PES) of a system

a fundamental concept in physics on all scales

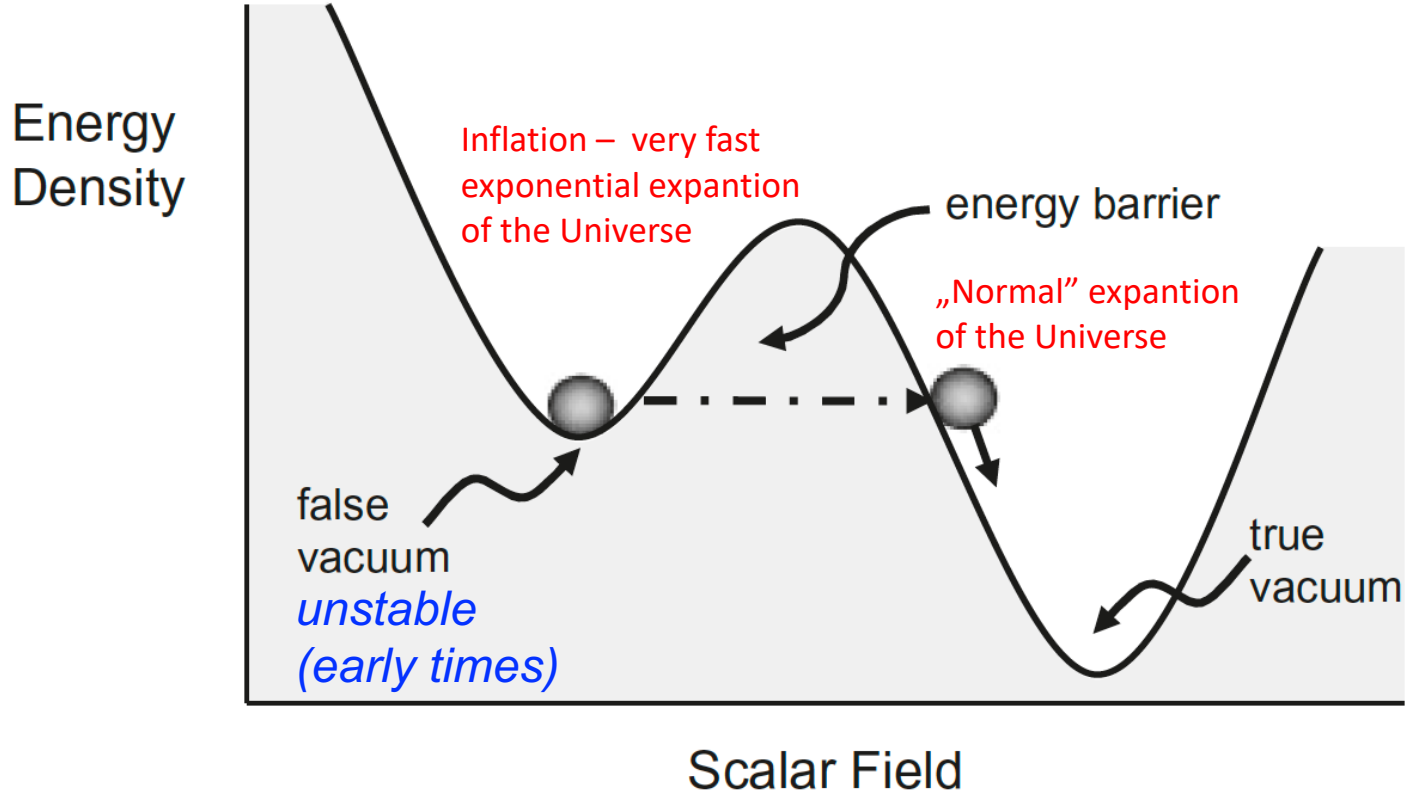


physical systems tend to minimize their potential energy

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

Alan Guth idea on Cosmic inflation – «Expansion of the Universe»



Toy model for Universe expansion

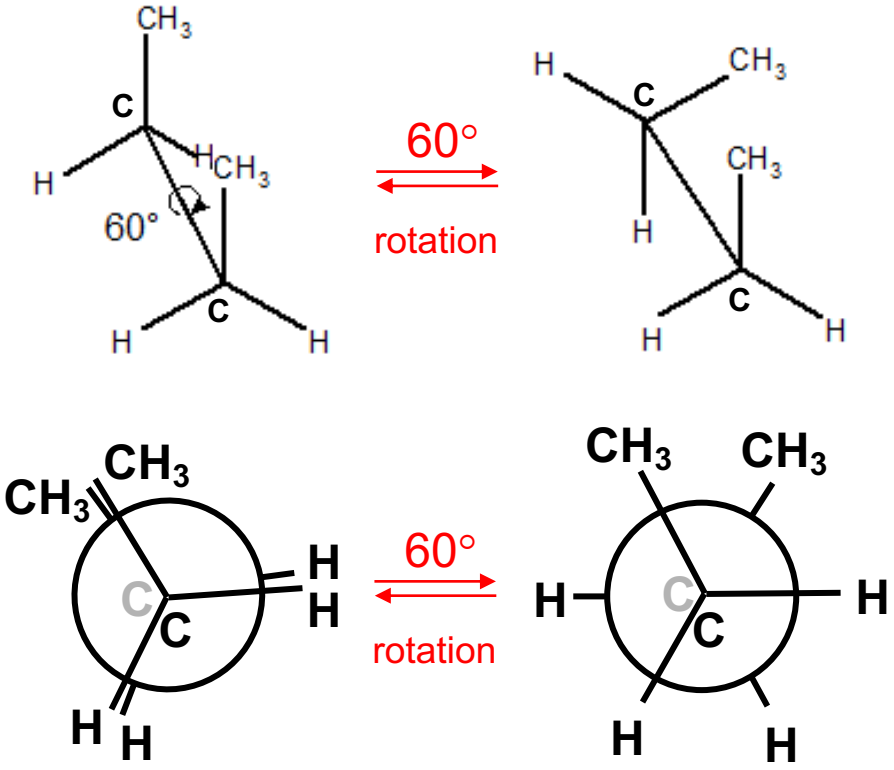
Strong repulsive gravity of the false vacuum causes a period of very fast, accelerated expansion. The inflation period ends when the system decays into the true vacuum

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

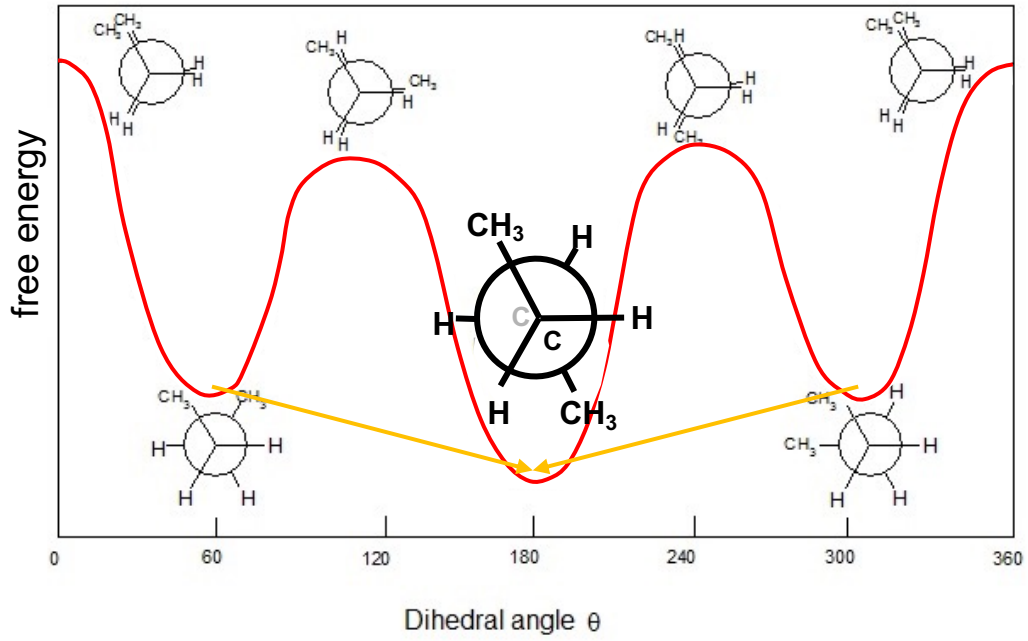
Potential Energy Surface (PES) of MOLECULES

Butane molecule C_4H_{10}

Conformational isomers



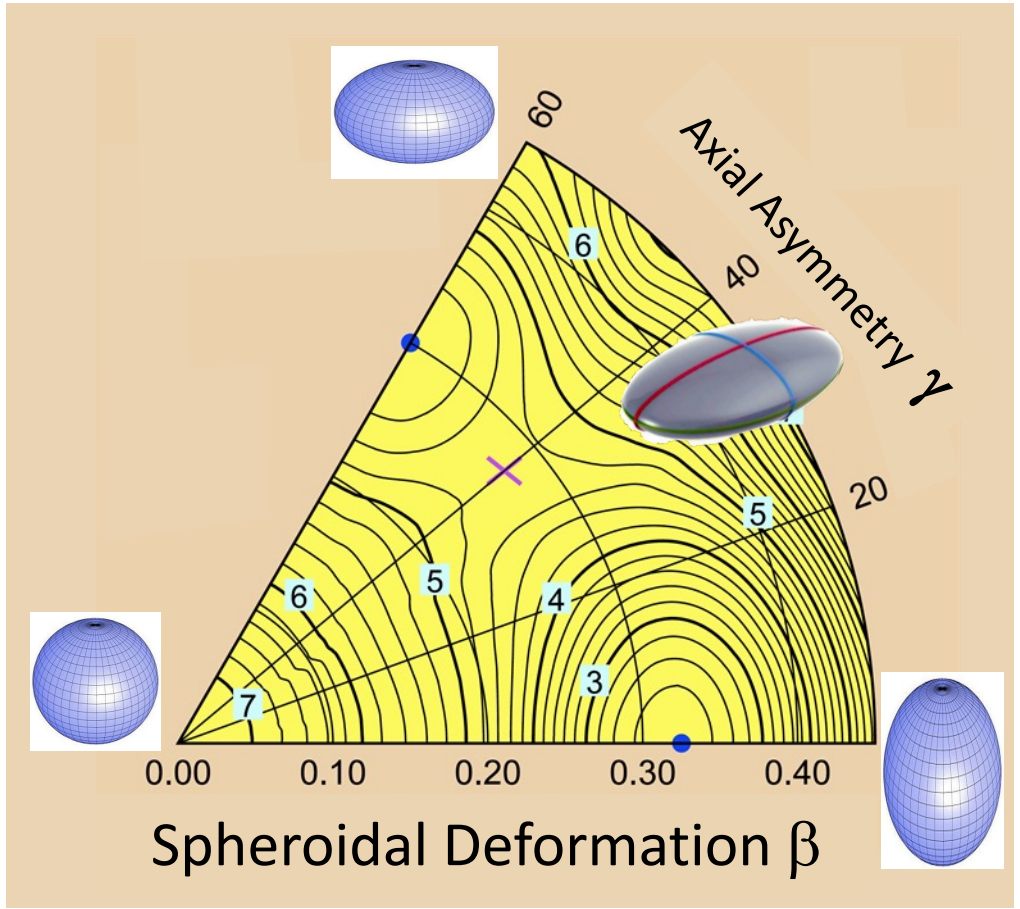
Rotation about single bond of butane



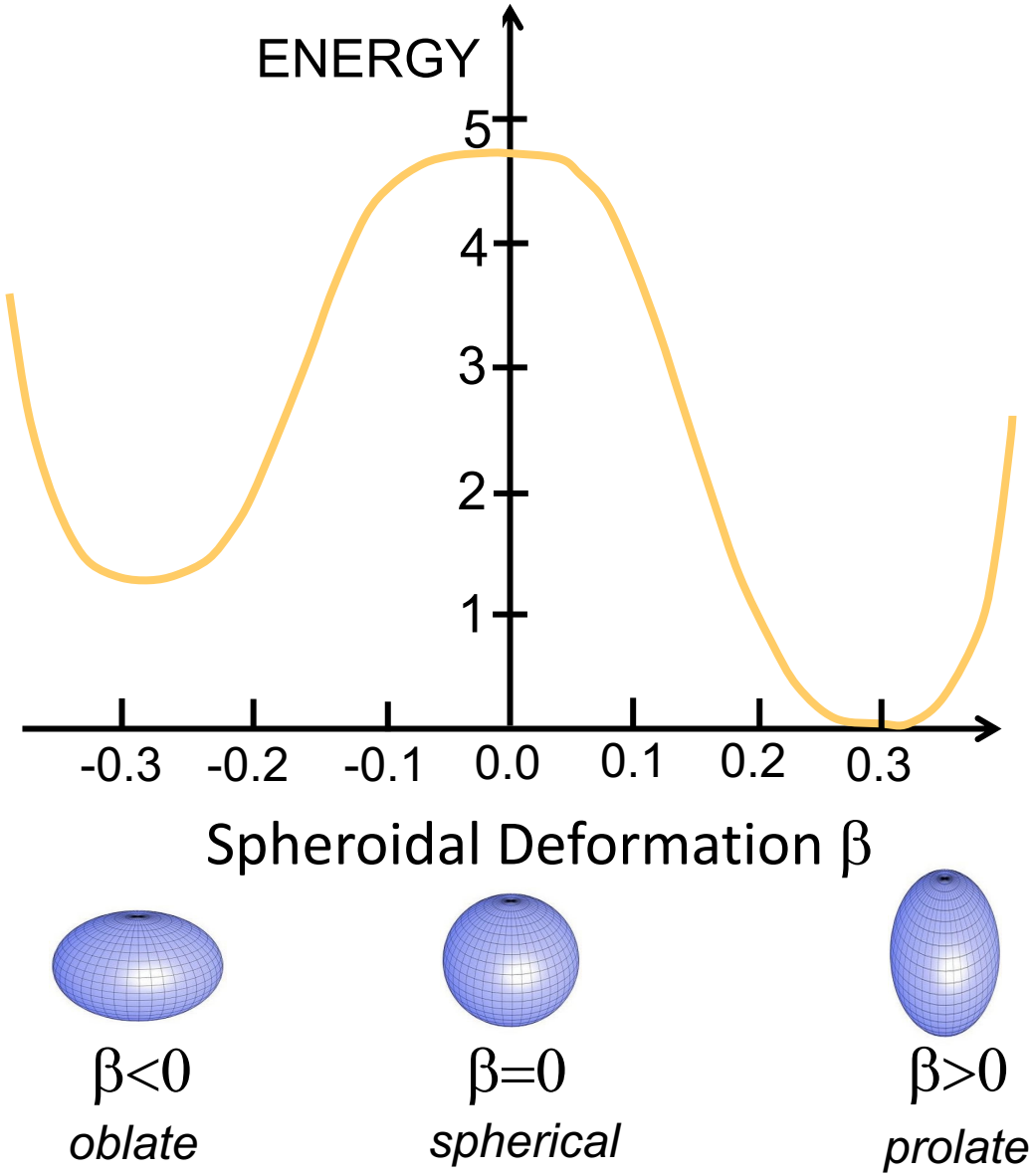
Free energy diagram of butane as a function of dihedral angle

Potential Energy Surface (PES) of a NUCLEUS

two-dimensional contour

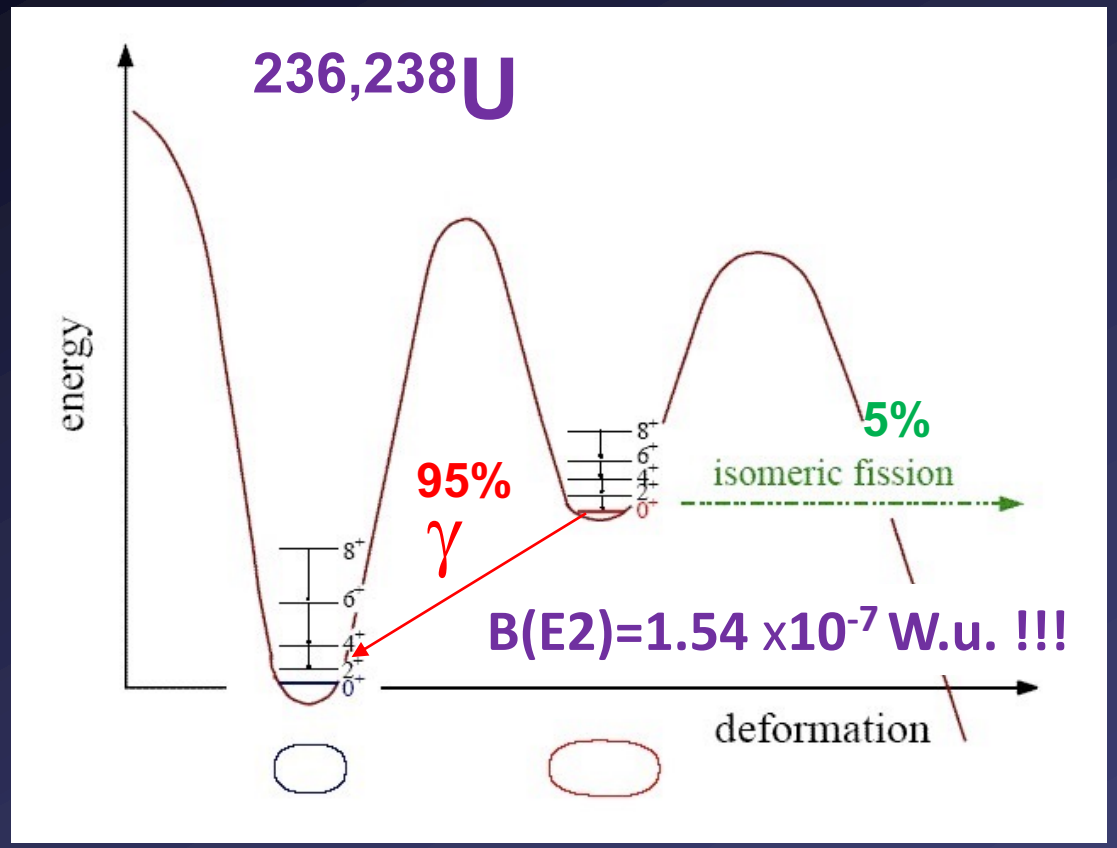


one-dimensional representation



SHAPE ISOMERS - very peculiar metastable states

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



Structures living in "separate worlds"

MAIN FINGER PRINT:
hindrance
of deexciting transitions

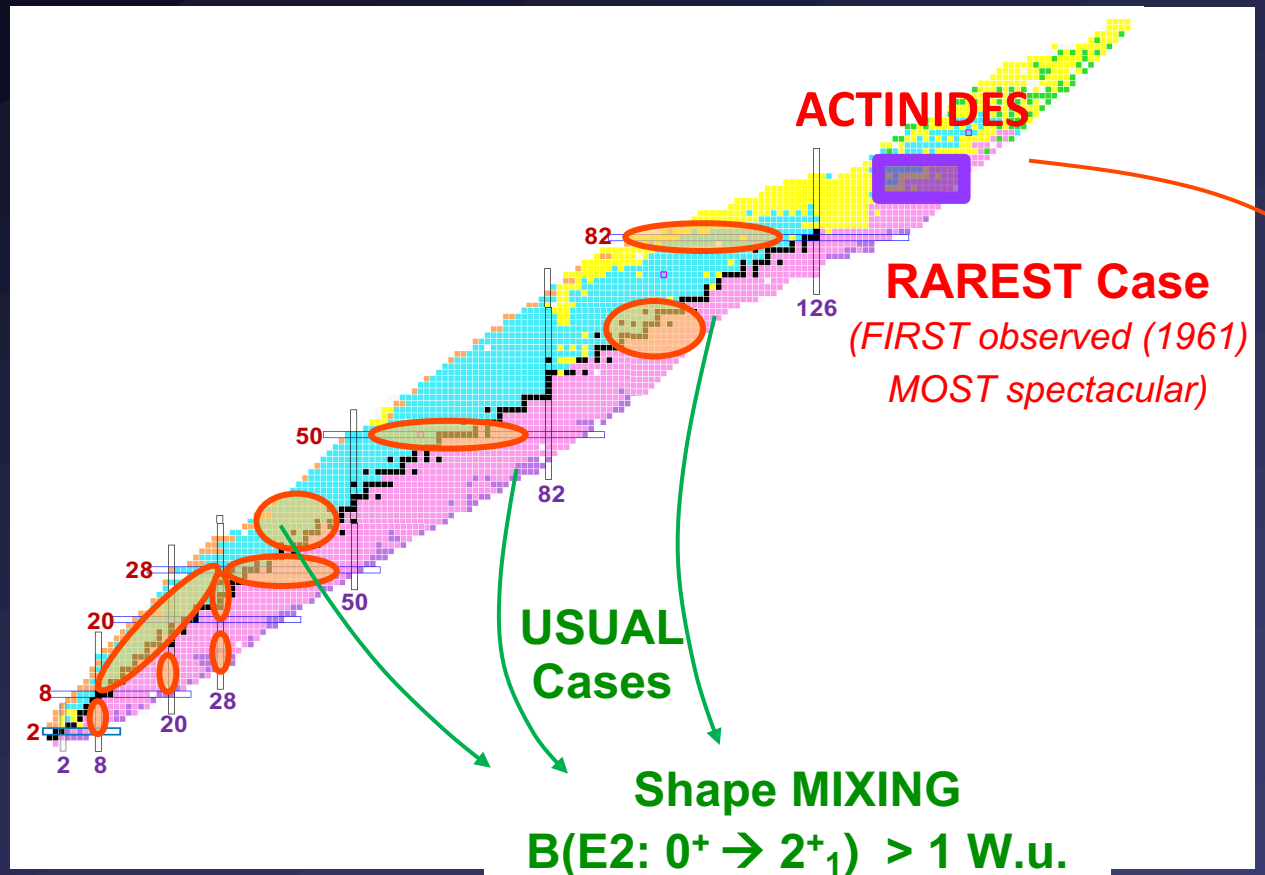
Can OTHER (lighter) nuclei exhibit this feature ?

Shape coexistence in atomic nuclei

Close to spin 0

After 50 years of investigation:

"An ubiquitous phenomenon across the nuclear chart"

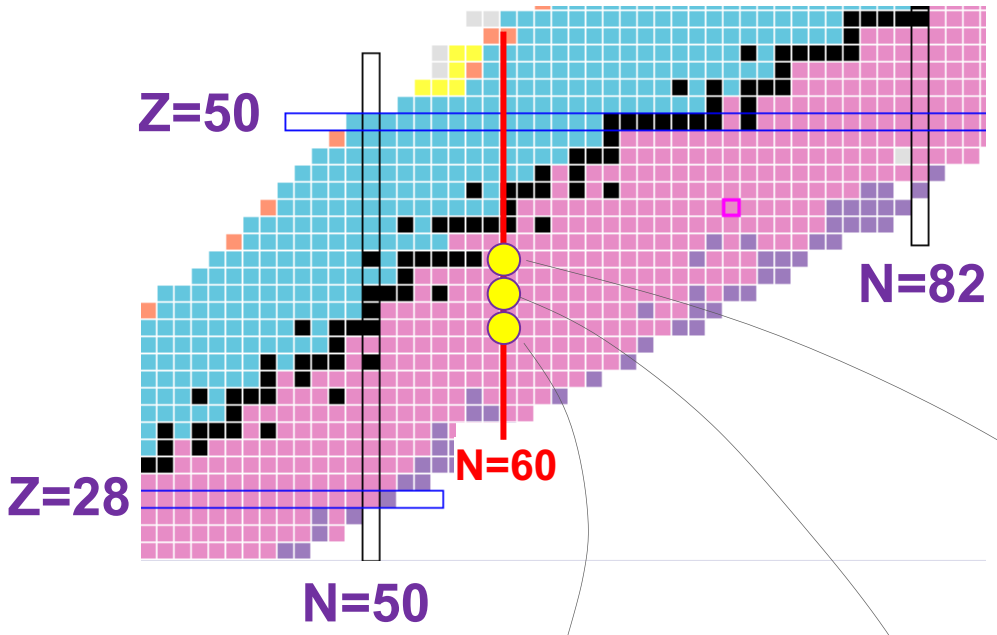


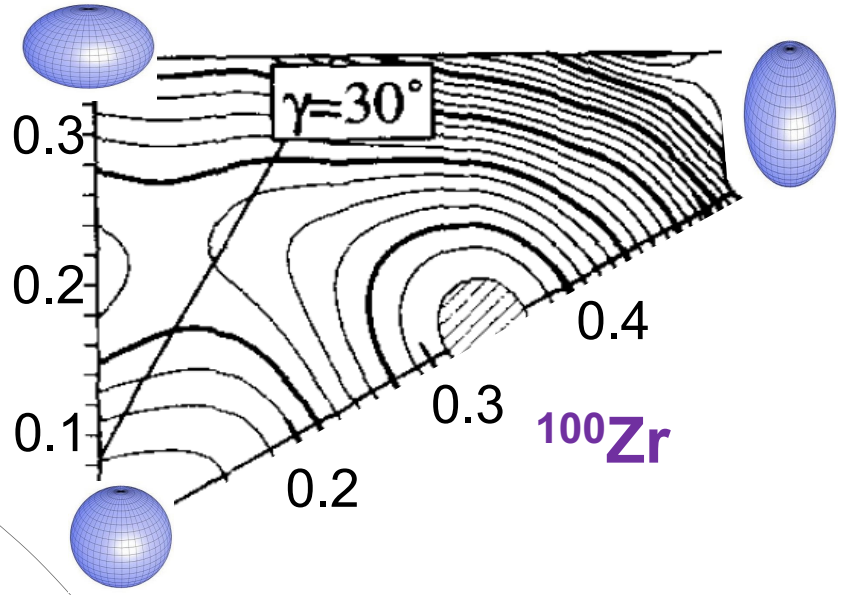
Fission Shape ISOMERS
($T_{1/2}$ ~10^2 ns)

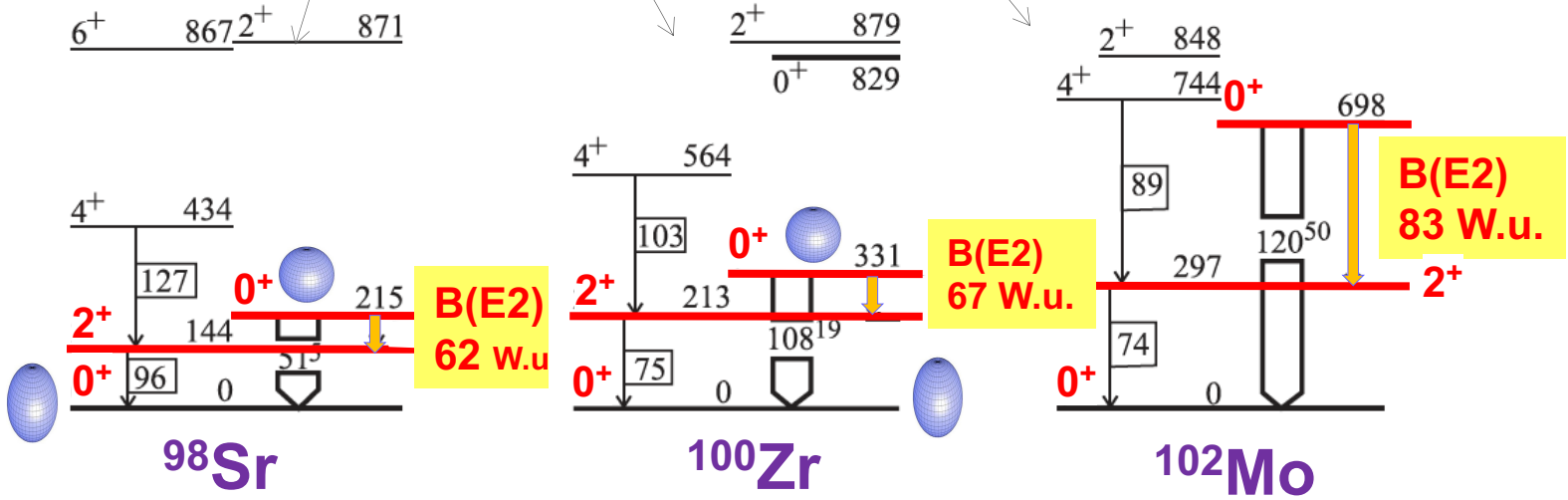
B(E2: $0^+ \rightarrow 2^+_1$) ≤ 10^{-8} W.u.

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)







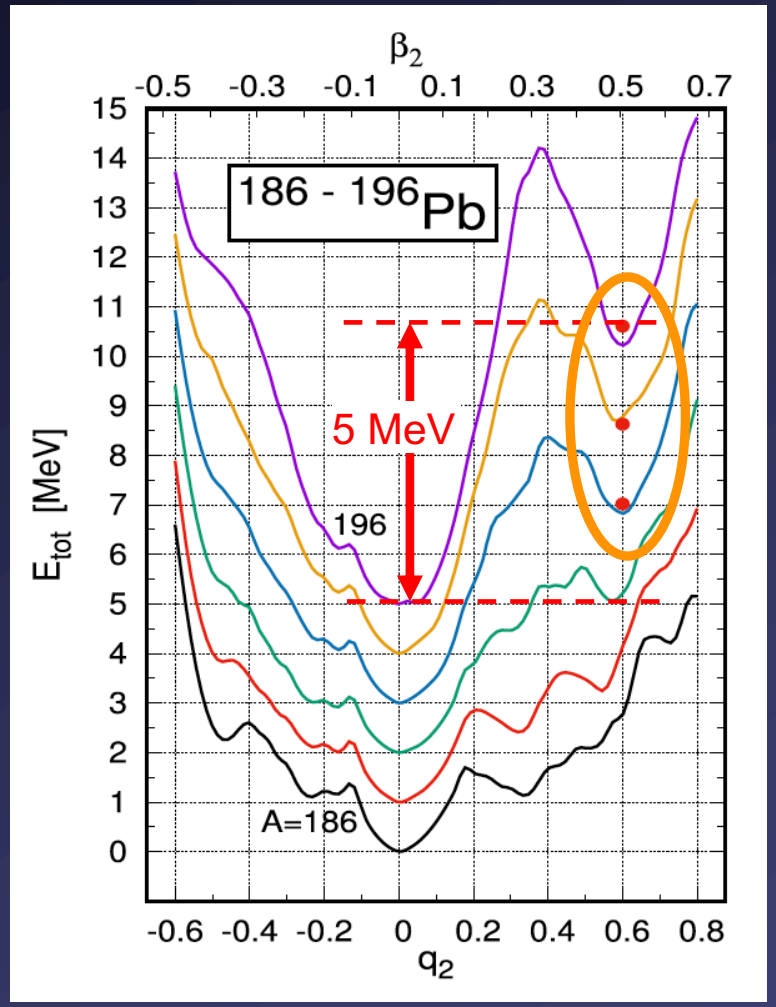
No retardation in γ decay is observed !!!!

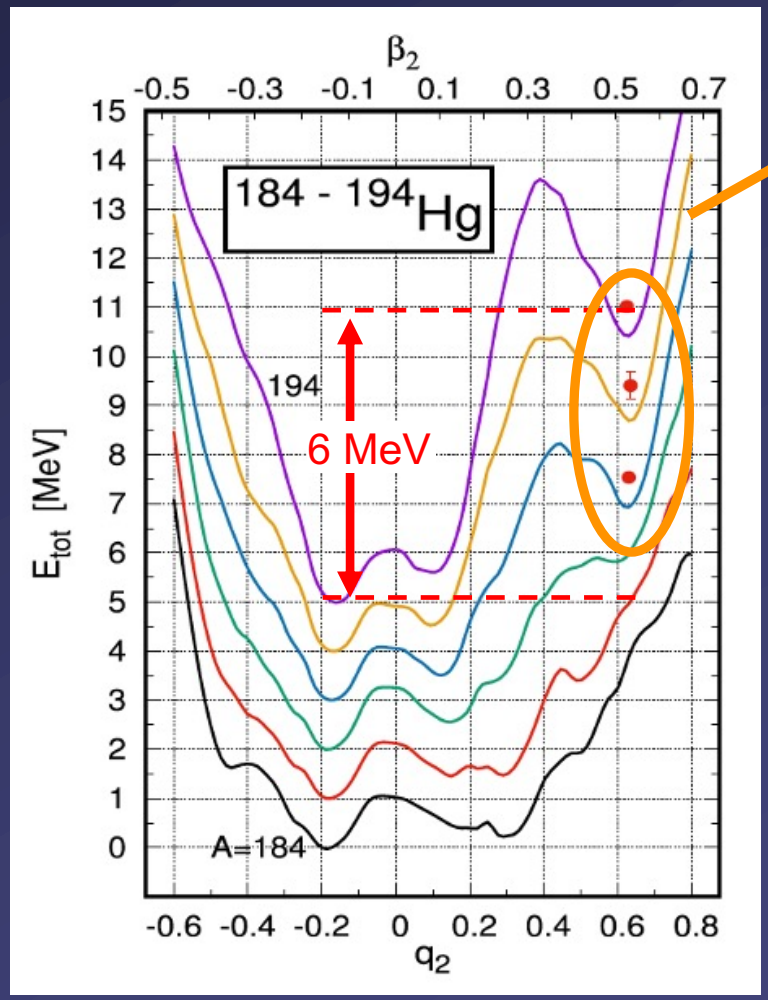
Potential barrier **NOT sizable** enough to prevent fast shape changes

Where to search for other strongly hindered γ decays from 0^+ states located in deep secondary minima ?

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)

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) << 1 W.u., HF > 10

Predictions for SHAPE ISOMERISM at I = 0

(Microscopic Hartree-Fock plus BCS calculations)

Nuclear Physics **A500** (1989) 308–322
North-Holland, Amsterdam **1989**

SUPERDEFORMATION AND SHAPE ISOMERISM AT ZERO SPIN*

P. BONCHE[1], S.J. KRIEGER, P. QUENTIN[2] and M.S. WEISS

Department of Physics, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

J. MEYER, M. MEYER and N. REDON

Institut de Physique Nucléaire (et IN2P3), Université Lyon 1, F-69622 Villeurbanne Cedex, France

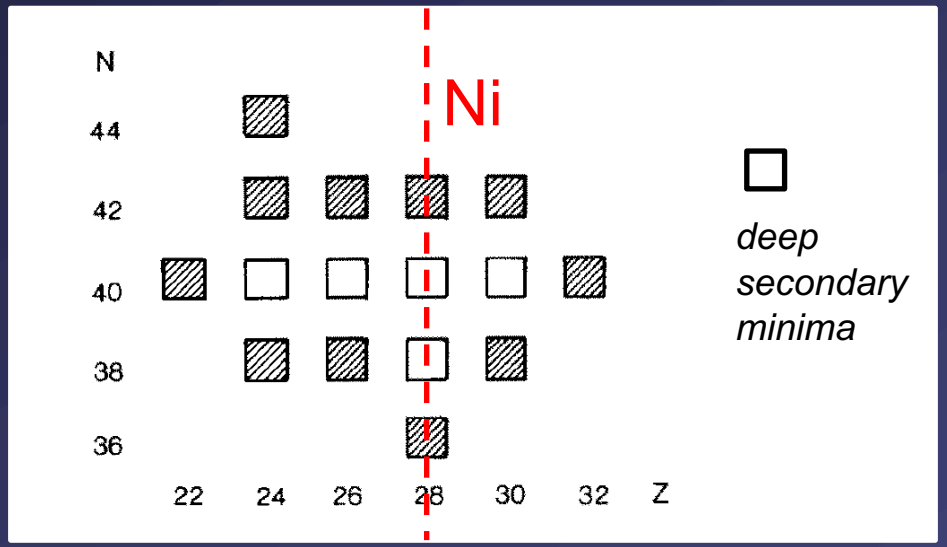
H. FLOCARD

Division de Physique Théorique[3], Institut de Physique Nucléaire, F-91406 Orsay Cedex, France

P.-H. HEENEN[4]

Physique Nucléaire Théorique, Université Libre de Bruxelles, CP 229, B-1050 Brussels, Belgium

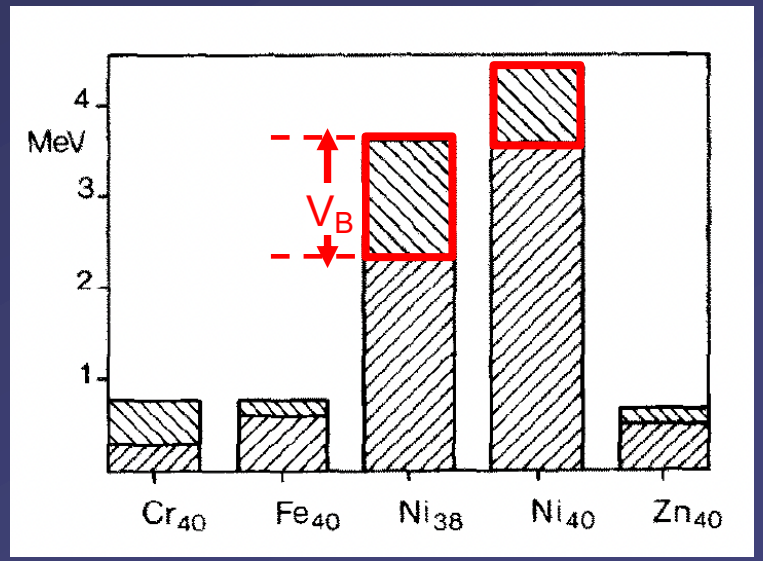
Received 7 March 1989



Candidates for the presence of deep, secondary minima:

^{66}Ni, ^{68}Ni, ^{66}Fe, ^{64}Cr, ^{70}Zn, ^{190,192}Pt, ^{206,208,210}Os, ^{194,196,214}Hg

~Z=28, N=40



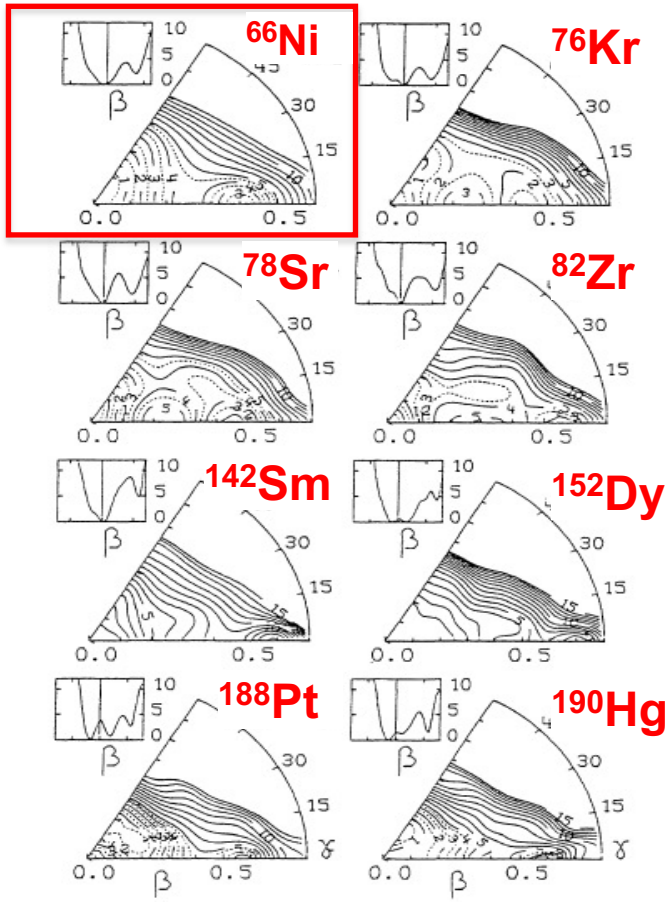
Predictions based on Mean Field and EDF
for existence of DEEP Secondary Minima

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

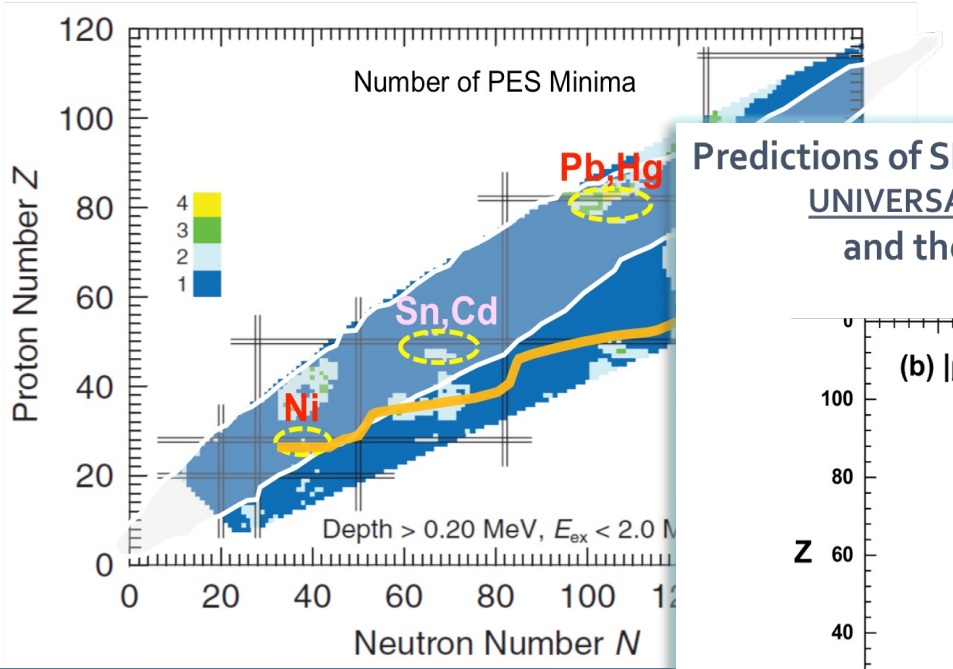
PRL 103, 212501 (2009) PHYSICAL REVIEW LETTERS week ending 20 NOVEMBER 2009

2009

Global Calculation of Nuclear Shape Isomers

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

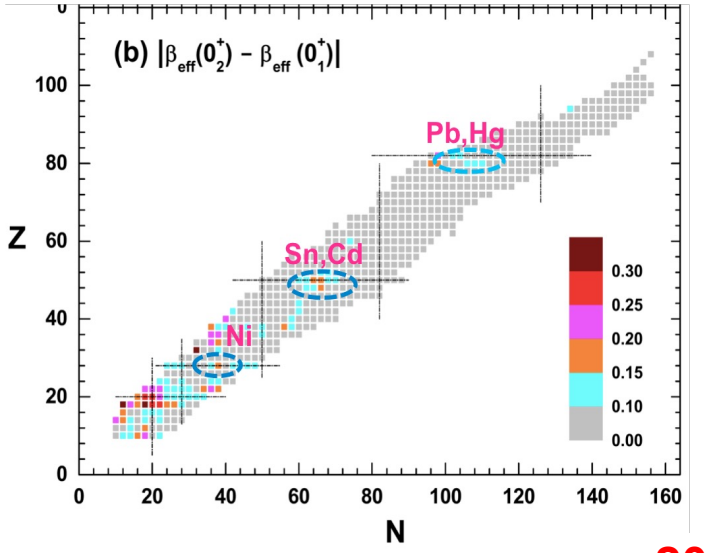
Study of 7206 nuclei from A=31 to A=209



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.



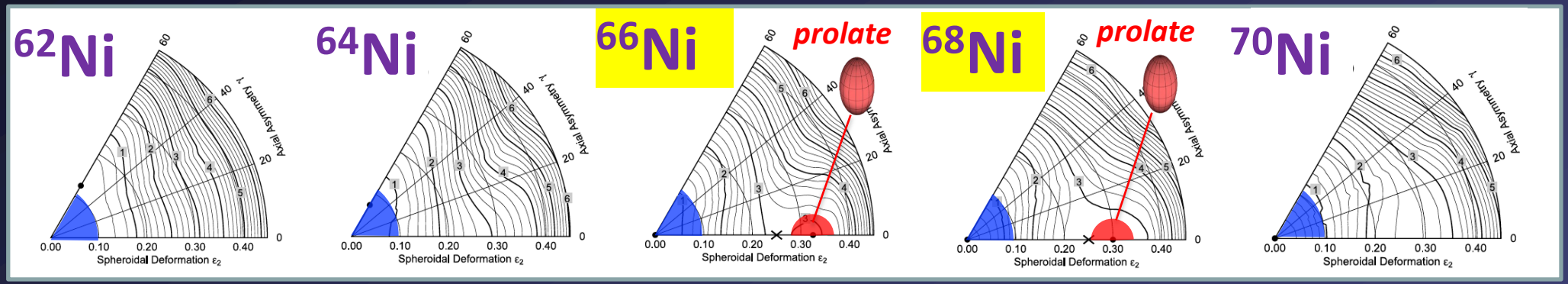
S. Quan et al., PHYSICAL REVIEW C 95, 054321 **2017**

We focus on the Ni chain

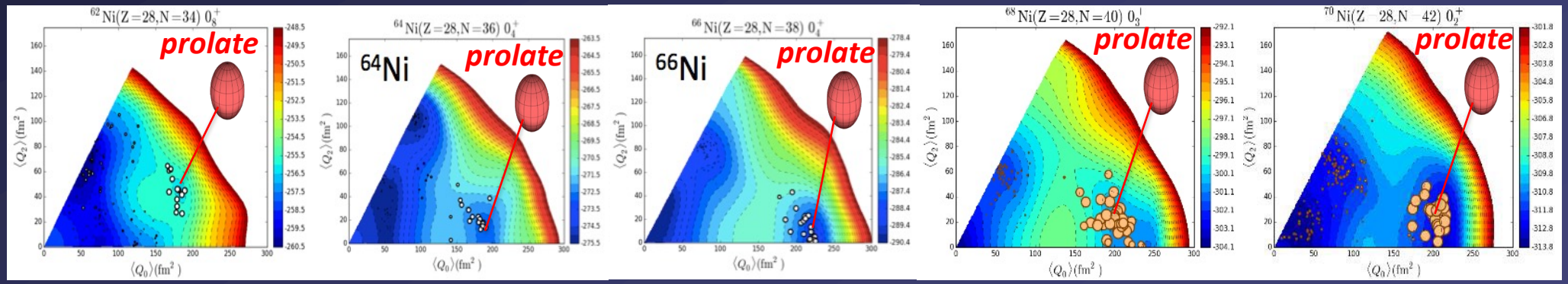
Monte Carlo Shell Model

- 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.



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

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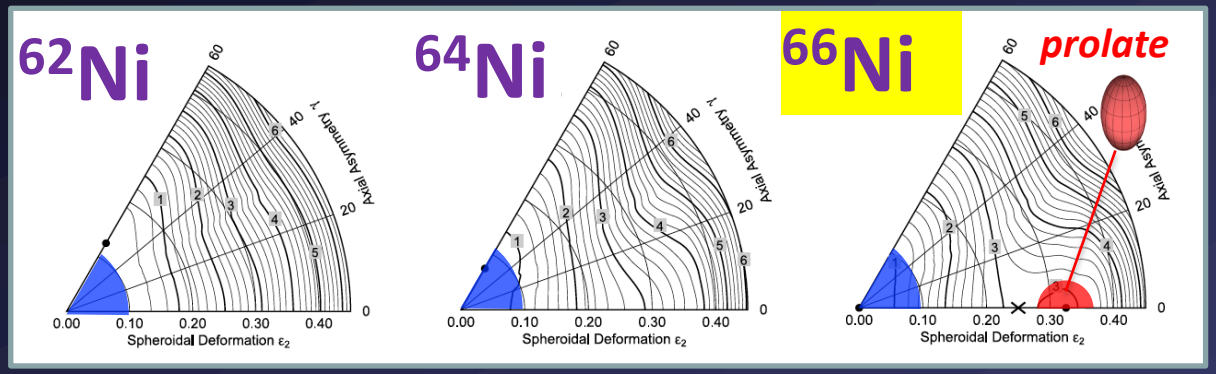
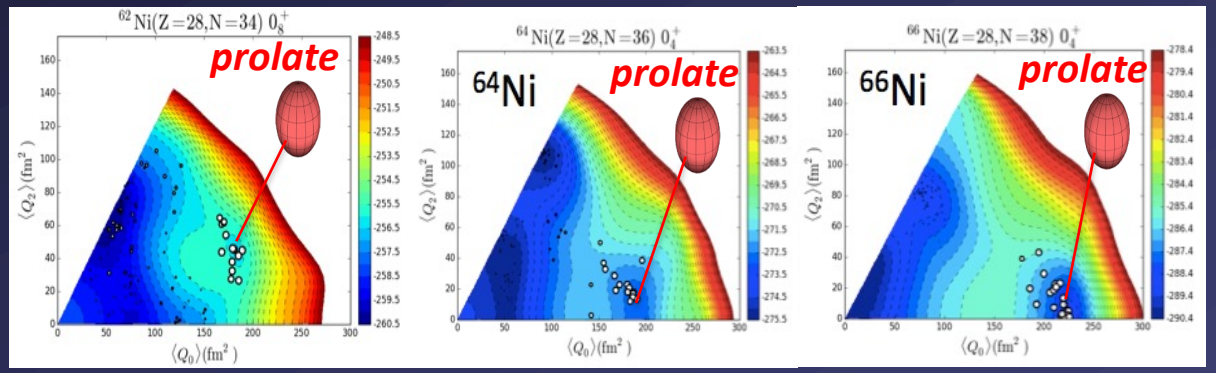




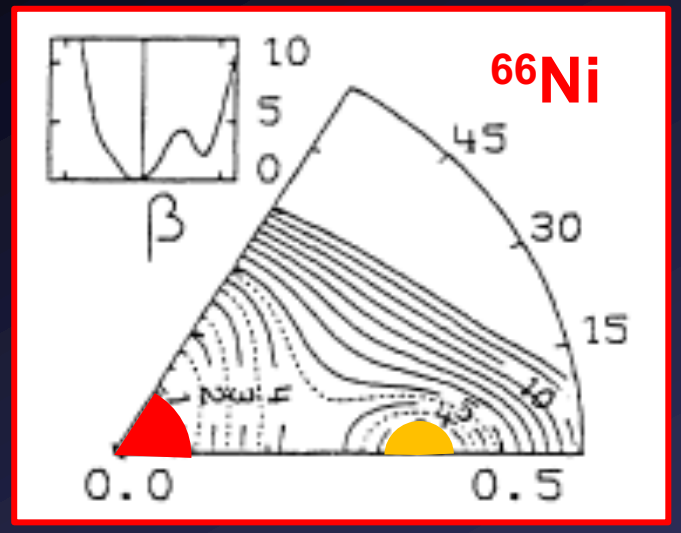
experimental investigation with STABLE beams

Mean Field
Moeller et al.

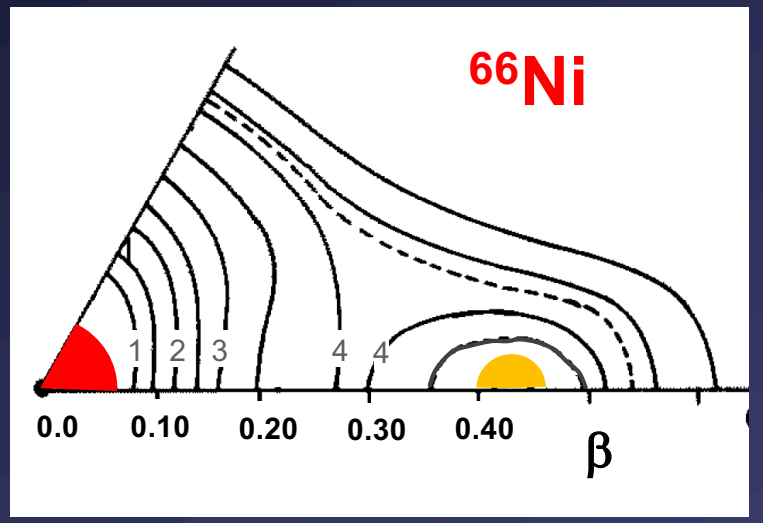
Monte Carlo SHELL Model
Y. Tsunoda,
T. Otsuka et al.

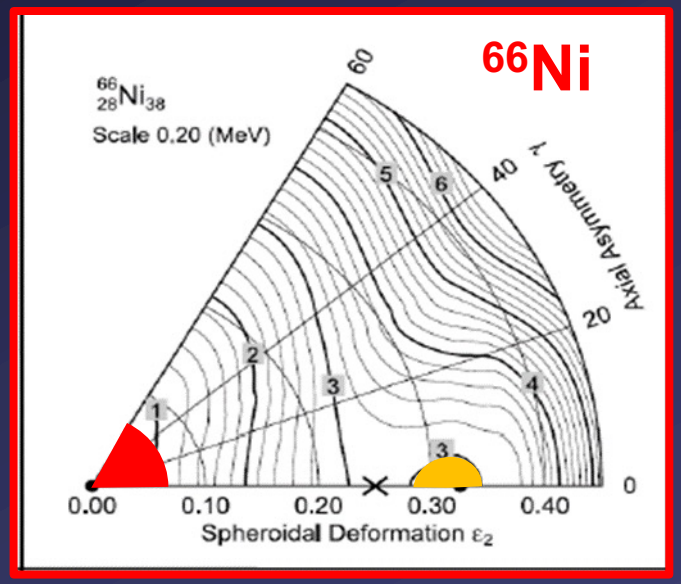
Predictions of the FOUR models for ^{66}Ni

Microscopic Hartree-Fock-Bogoliubov

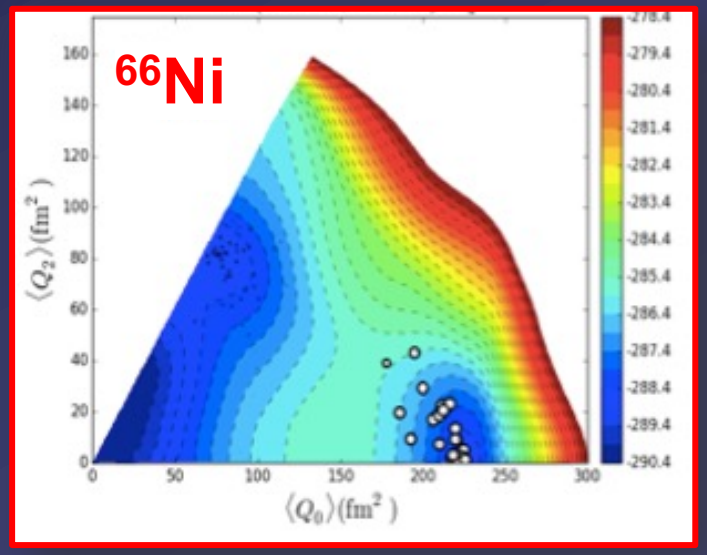


Microscopic Hartree-Fock plus BCS



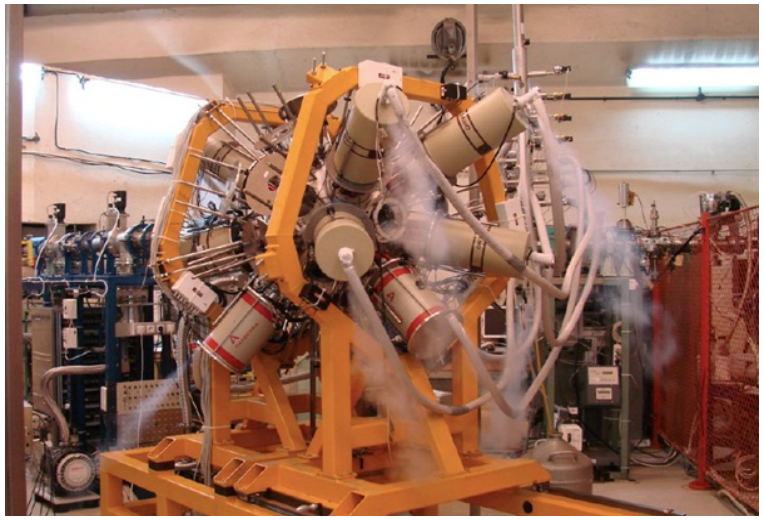


Macro-Microscospic Model



Monte Carlo Shell Model

2016



ROSPHERE

14 HPGe - 1.1% eff

11 $LaBr_3(Ce)$ - 1.75% eff

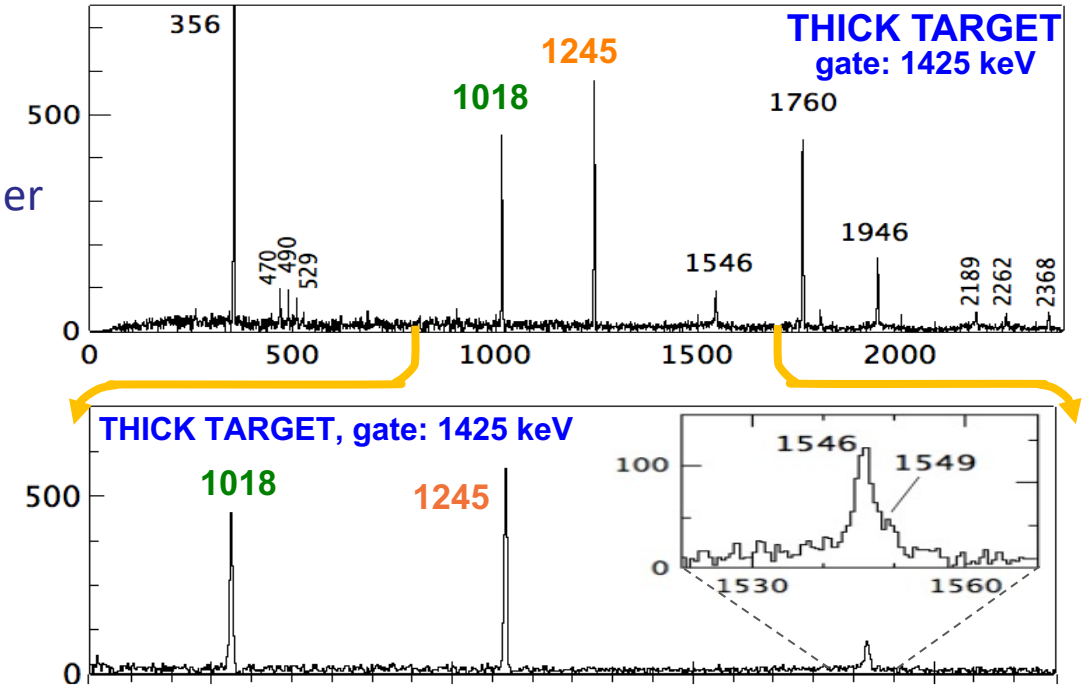
$^{18}O+^{64}Ni \rightarrow ^{16}O+^{66}Ni$

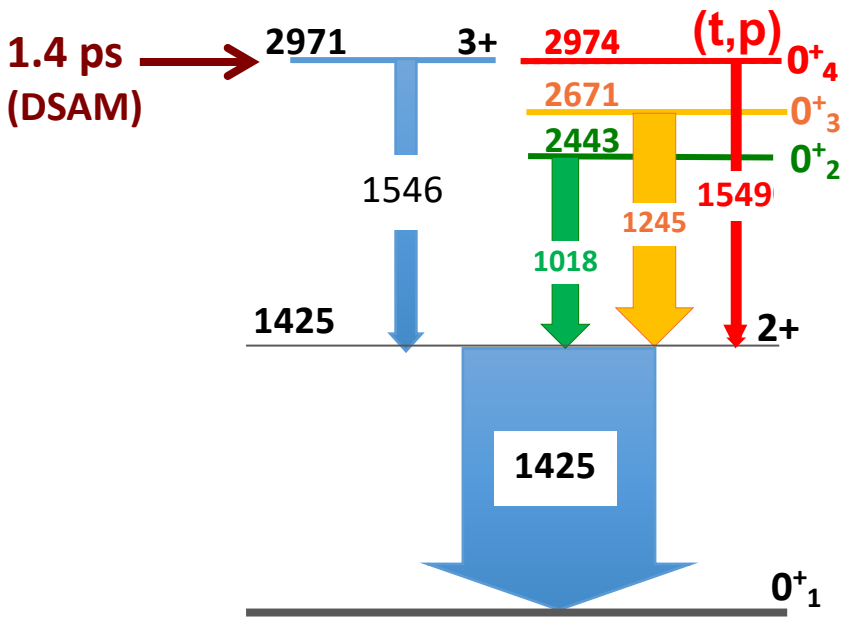
E_{beam} = 39 MeV

2n transfer below Coulomb Barrier

at IFIN HH Bucharest

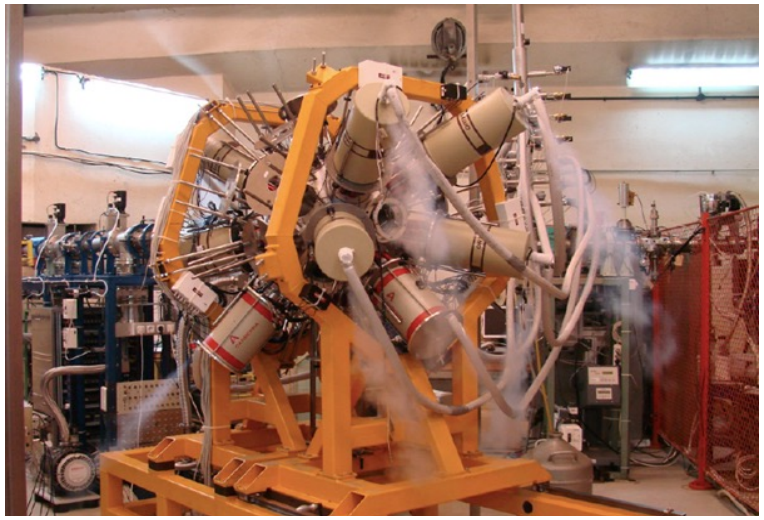
> 1.5 months, 30 pnA





^{66}Ni

2016



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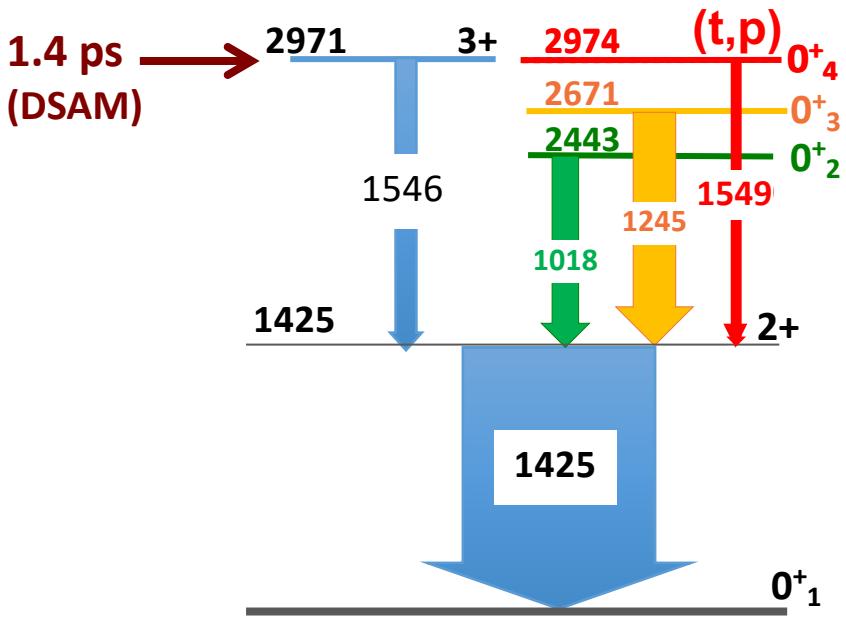
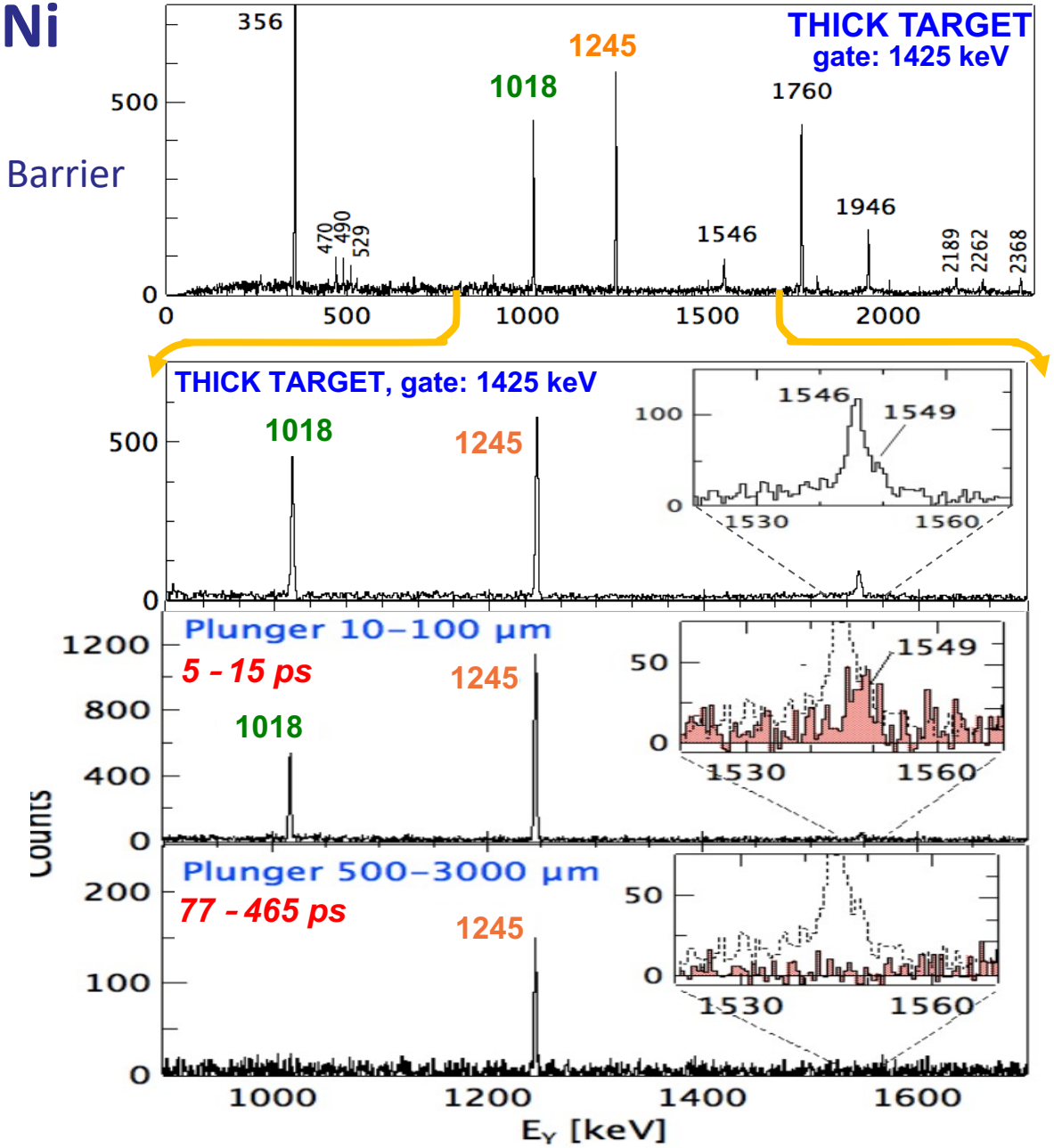
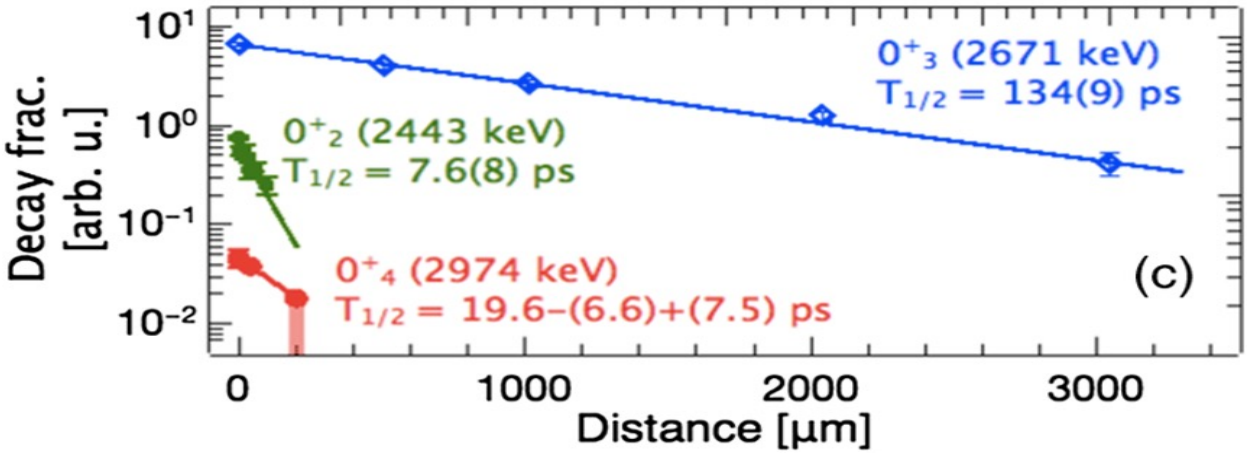
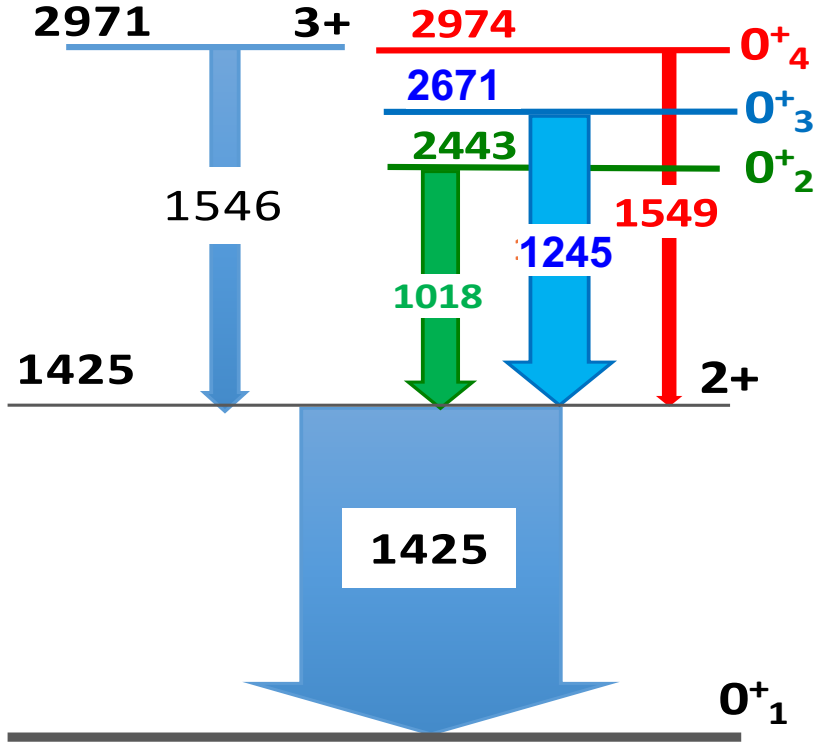


^{66}Ni



SHAPE assignment from comparison with theory predictions (MCSM)





^{66}Ni

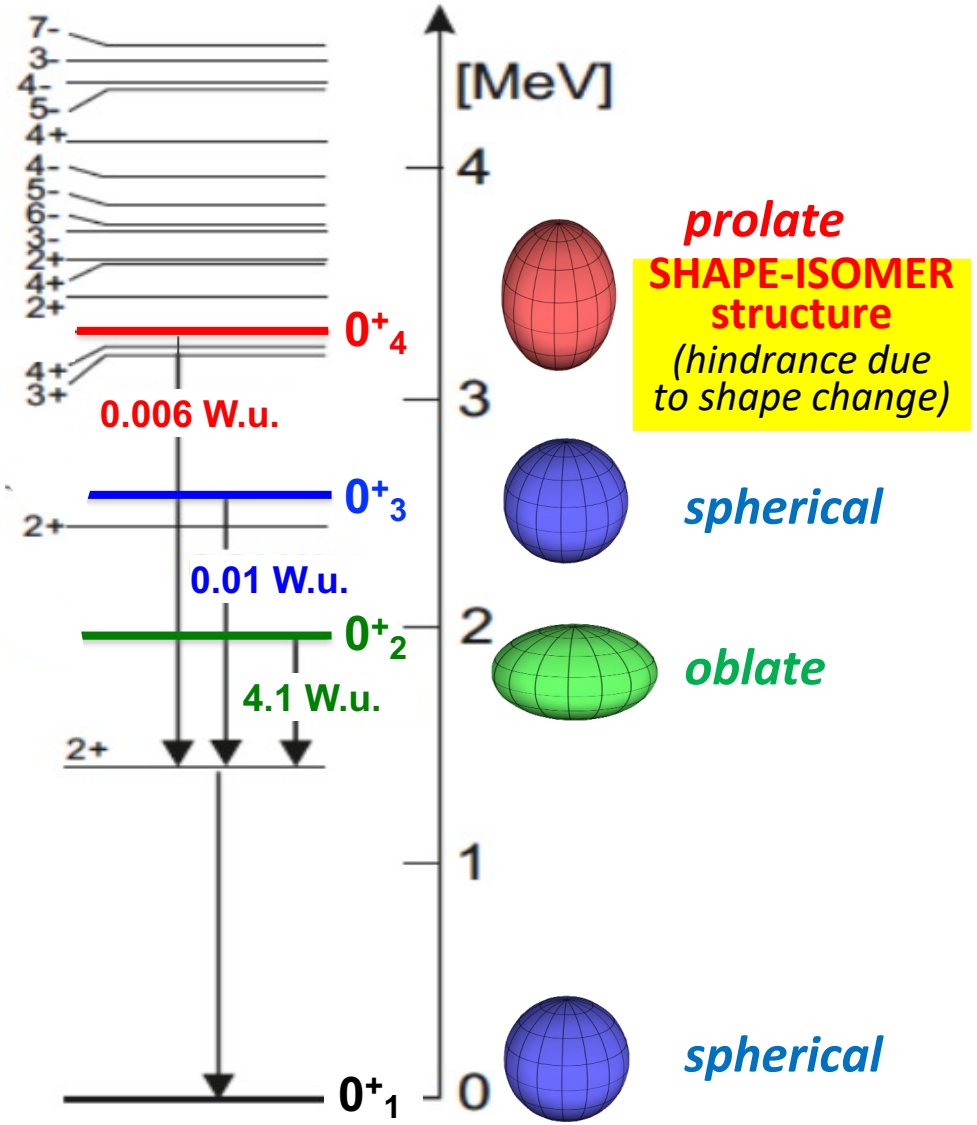
$B(E2) \sim 0.2$ Wu

$B(E2) = 0.1$ Wu

$B(E2) = 4.3$ Wu

2 TRANSITIONS BELOW 1 W.u.

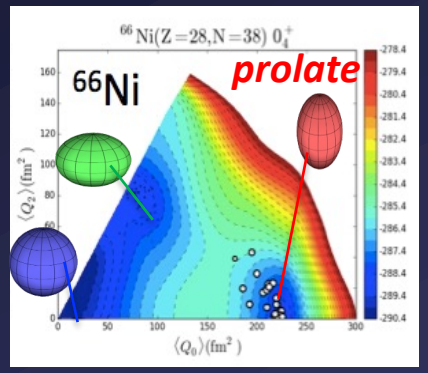
$T_{1/2}$ (0^+_3) confirmed at ISOLDE by B. Olaizola, et al., PRC95, 061303(R) (2017)



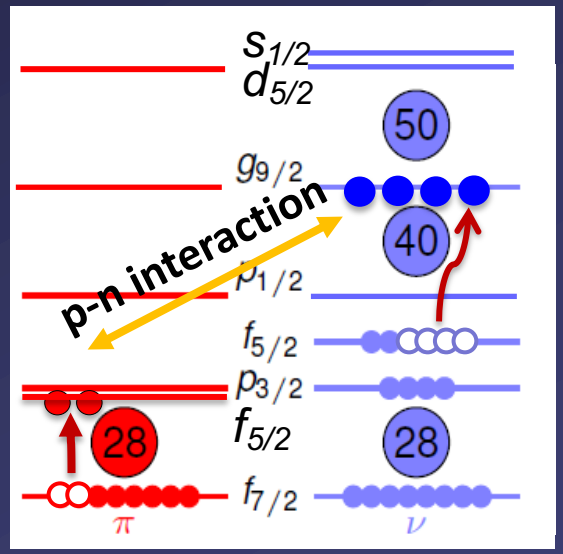
S. Leoni, B. Fornal, N. Marginean et al., PRL118, 162502(2017)

PROLATE 0^+ state

^{66}Ni



0^+_4: well localized wave function in prolate minimum



and proton in $p_{3/2}$, $f_{5/2}$ orbitals

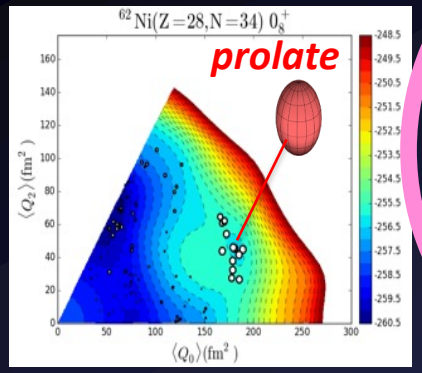
Sizable occupation of neutron in $g_{9/2}$

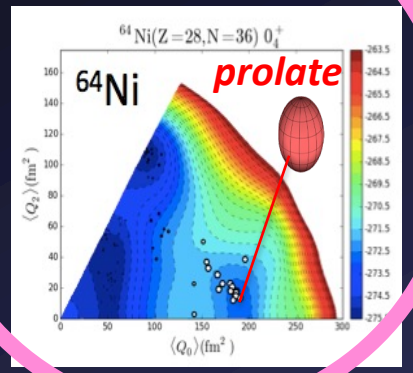
*proton-neutron interaction (**monopole tensor force**)* induces **Spontaneuos Symmetry Breaking**

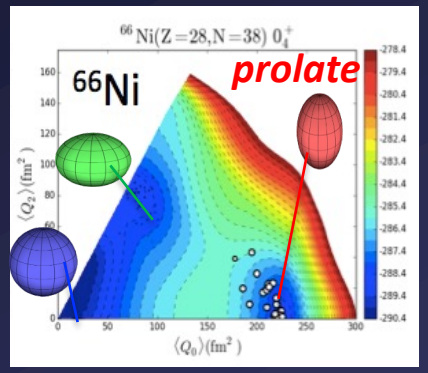
Type II SHELL Evolution - Y. Tsunoda, T. Otsuka

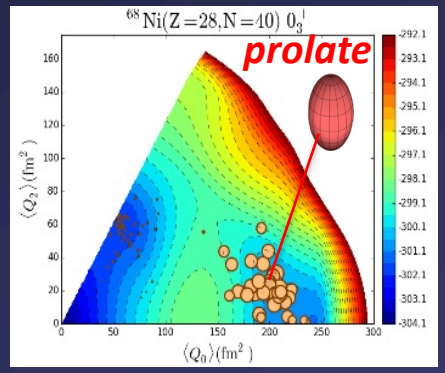
Same features of PROLATE 0^+ states along the Ni chain:

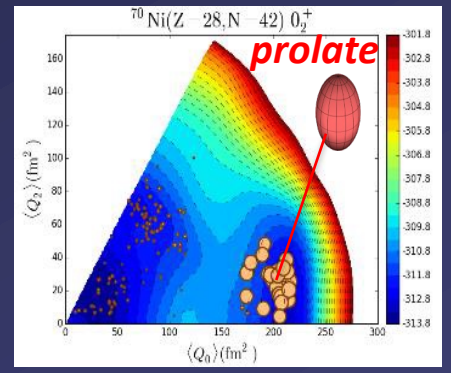
^{62}Ni ^{64}Ni ^{66}Ni ^{68}Ni ^{70}Ni

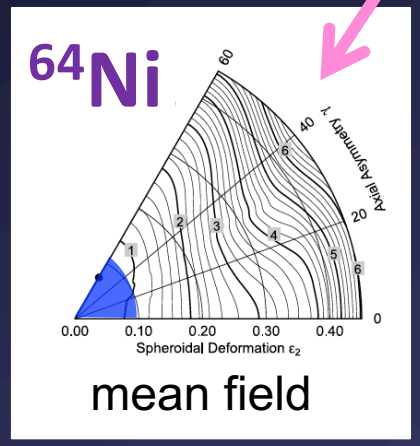




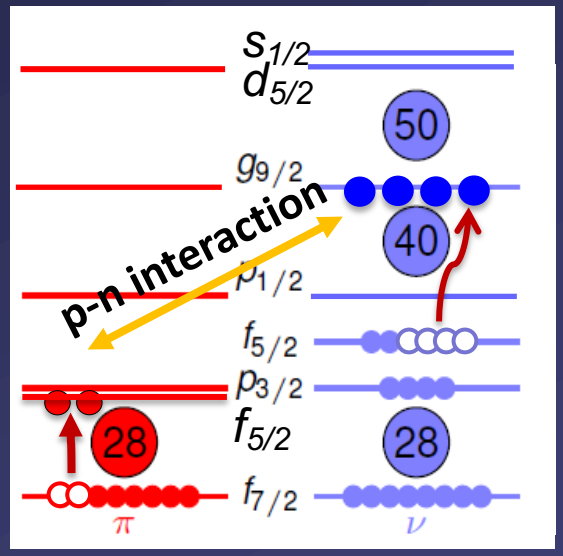








and <u>proton</u> in $p_{3/2}$, $f_{5/2}$ orbitals



Sizable occupation of <u>neutron</u> in $g_{9/2}$

proton-neutron interaction (***monopole tensor force***) induces **Spontaneuos Symmetry Breaking**

Type II SHELL Evolution - Y. Tsunoda, T. Otsuka

^{64}Ni: 4 experiments in 4 laboratories

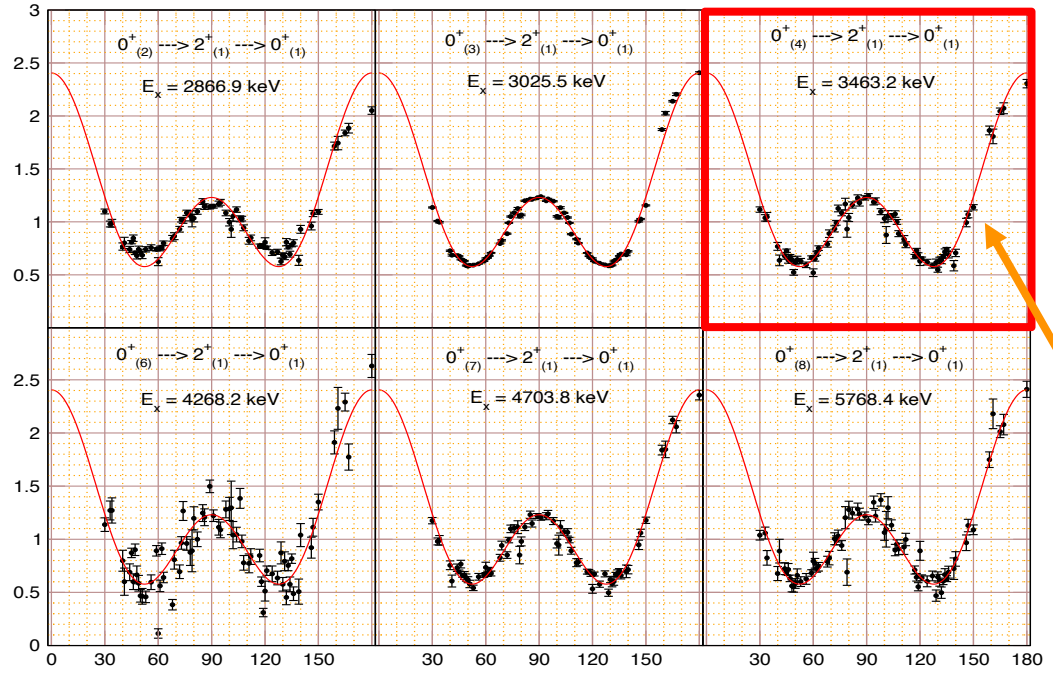
to achieve the required experimental sensitivity

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

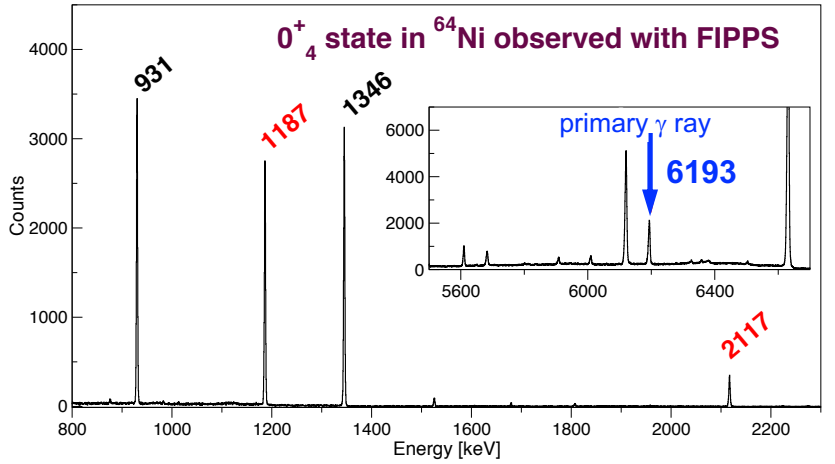
a multimessanger approach …

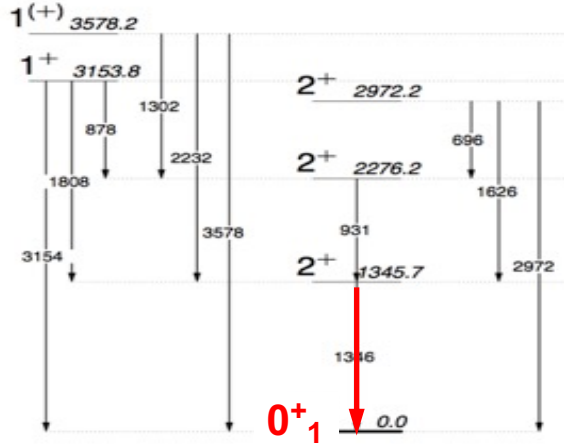
(79 co-authors from 25 Institutions)

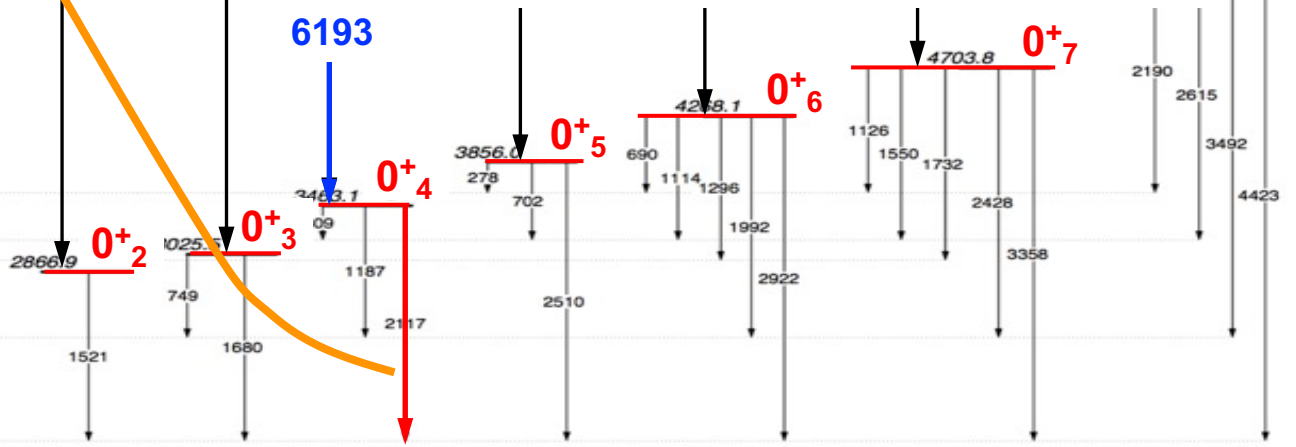
The most complex level scheme:
(n,γ) experiment with FIPPS array at ILL (2019) - 2 GigaBq ^{63}Ni target



S_n= 9657.46 keV







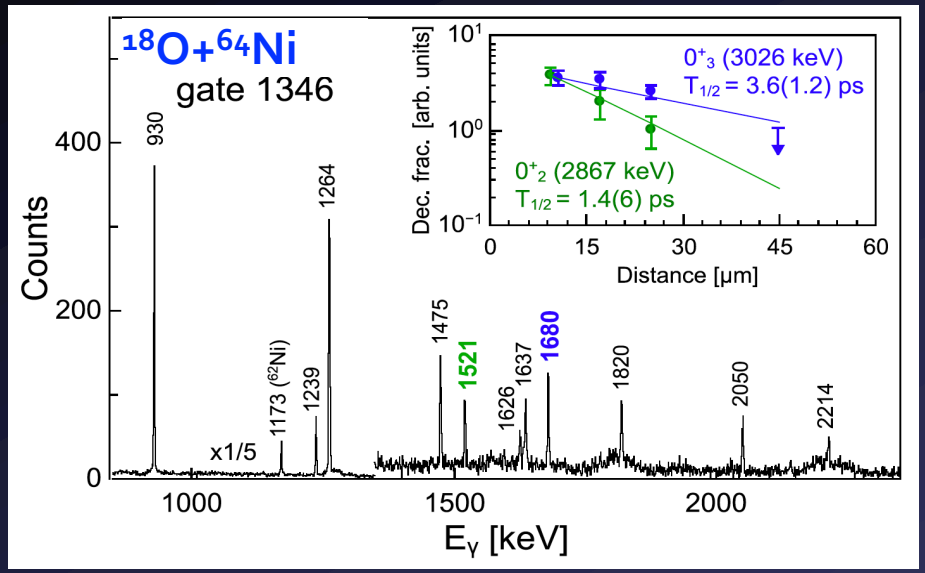
extended decay pattern: seven 0^+ states, six 2^+ states, ...

^{64}Ni

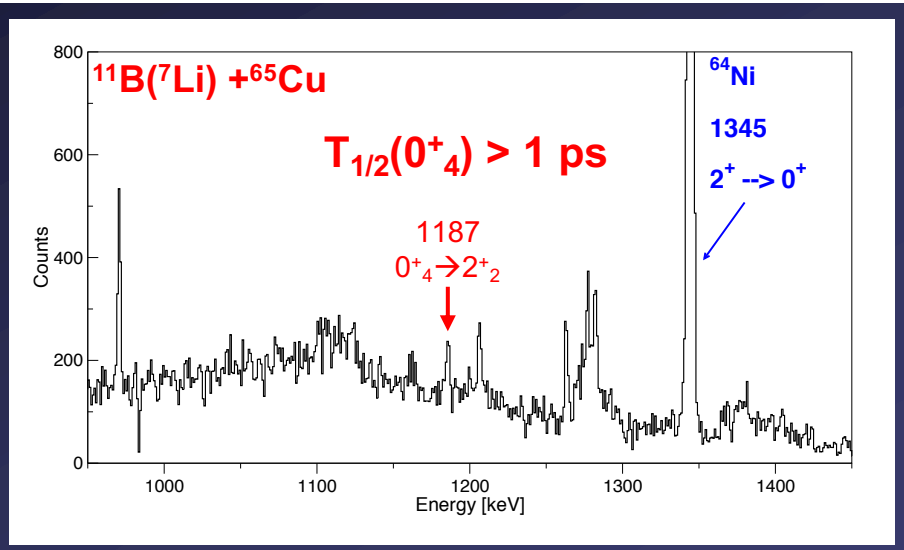
- IFIN-HH – Lifetimes measurements
- Argonne (GRETINA) – Coulomb Excitations

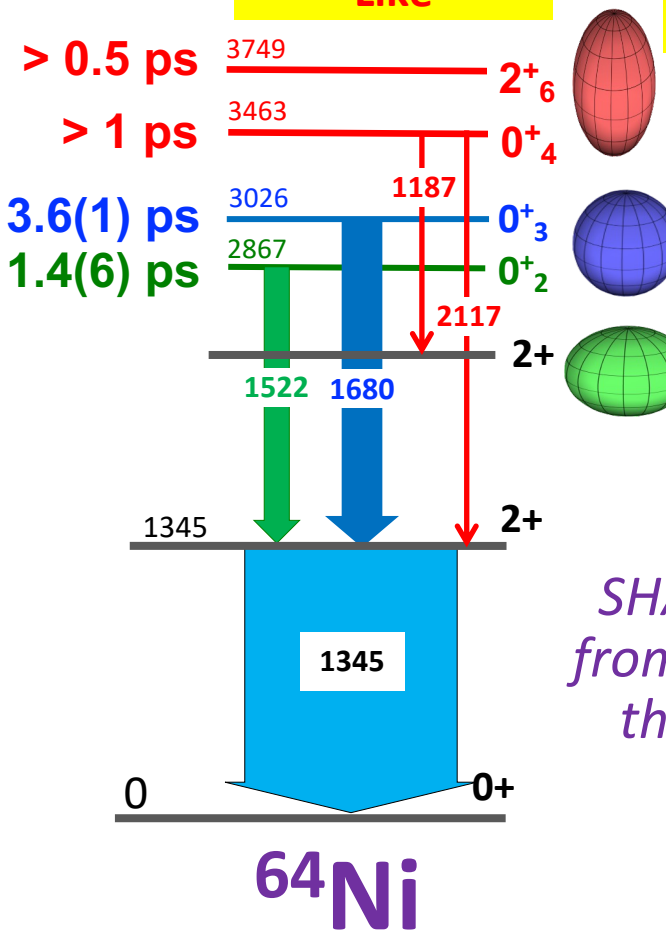
^{64}Ni

2n



1p





HINDRANCE
due to
a **shape change**

B(E2) <0.08 Wu
(Coulex GRETINA)

0.7 Wu

3.2 Wu

SHAPE assignement from comparison with theory predictions (MCSM)

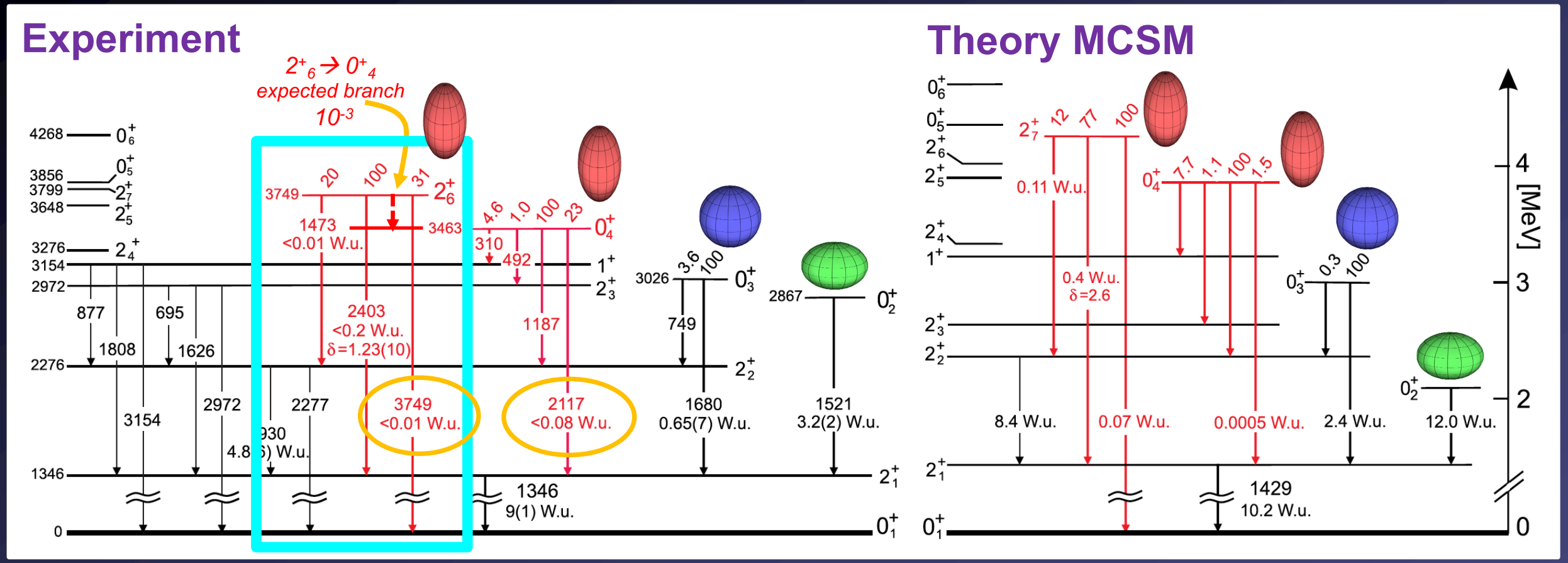
^{64}Ni

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

Extended comparison with Theory

microscopic **interpretation** of the nature of 0^+ excitations

^{64}Ni

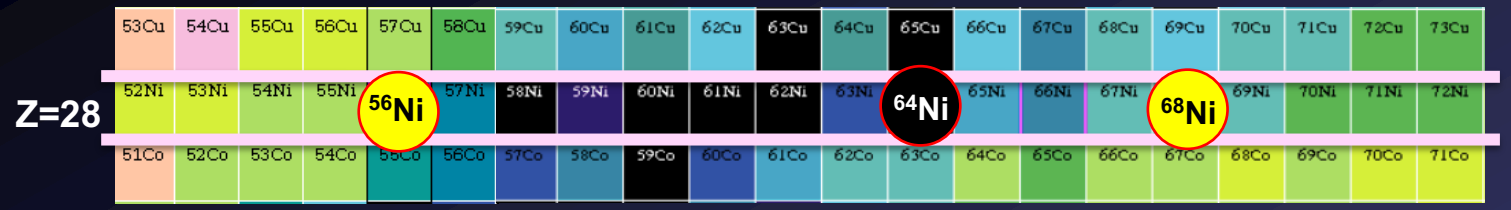


$0^+_4 \rightarrow 2^+_1$ and $2^+_6 \rightarrow 0^+_1$: two transitions strongly hindered !!

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

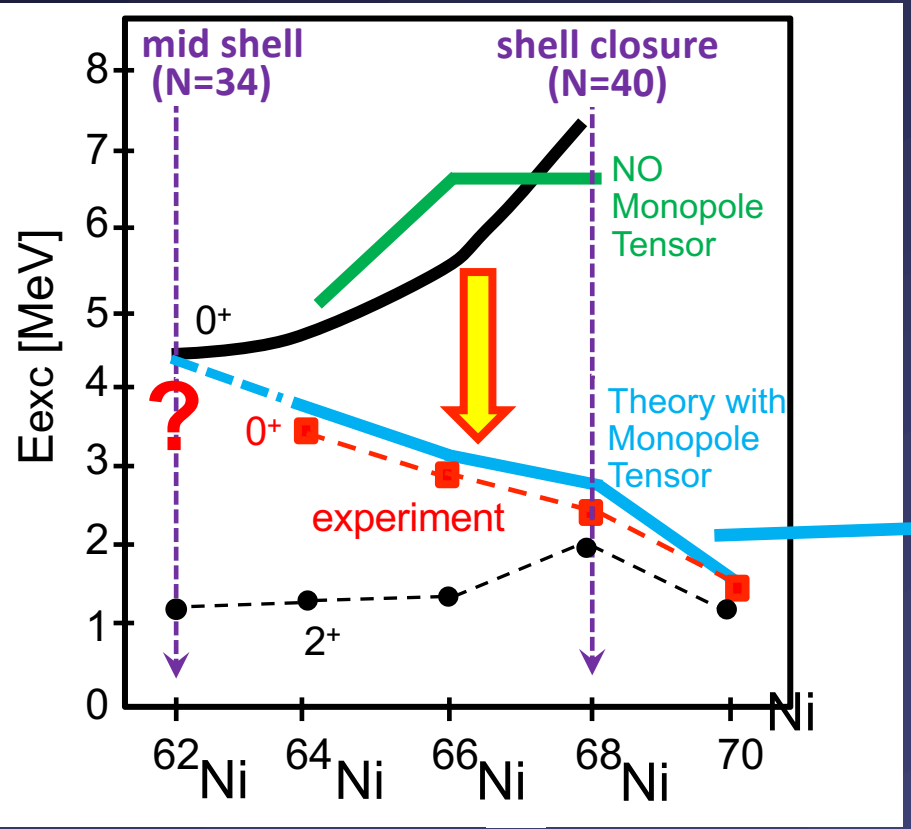
N. Marginean, et al., Phys. Rev. Lett. 125, 102502 (2020)

Evolution of the energies of PROLATE 0^+ states in the Ni chain
Impact of Monopole Tensor Term

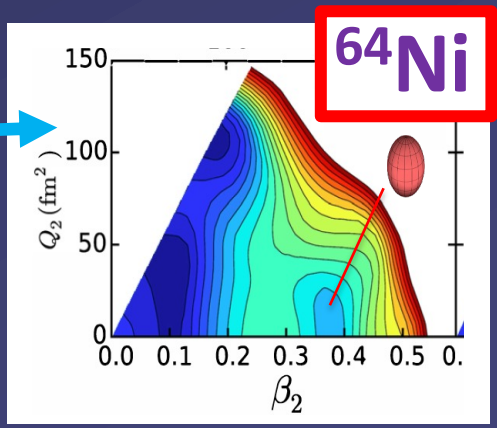


Traditional view of PARABOLA behavior of deformed bands:

2p-2h, 4p-4h , …
excitations across the energy gap



EXTRA BINDING
given by
MONOPOLE-TENSOR PART
of nucleon-nucleon force



DEEP prolate minimum in PES

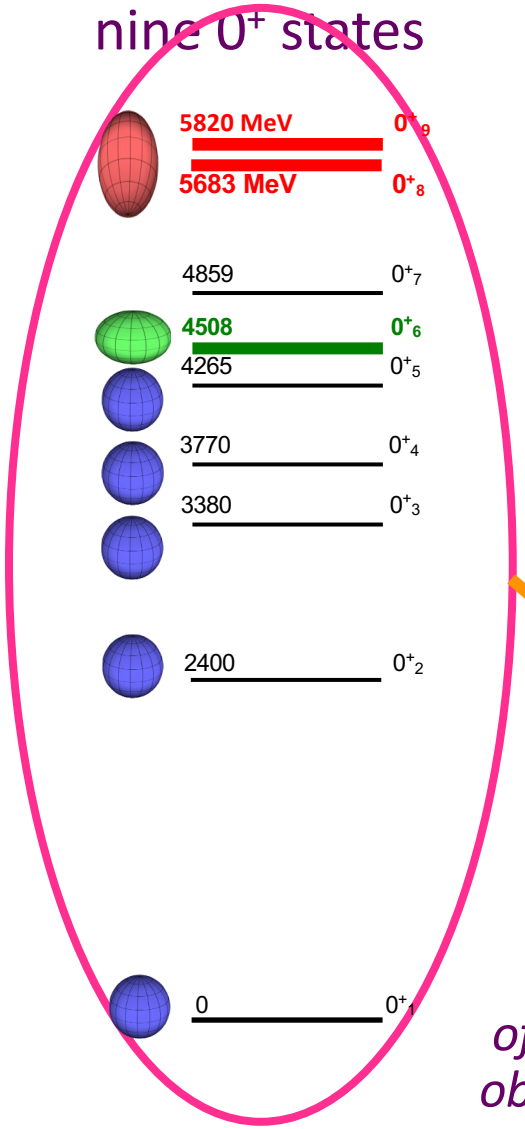
Current Investigation

^{62}Ni

at N=34
mid shell

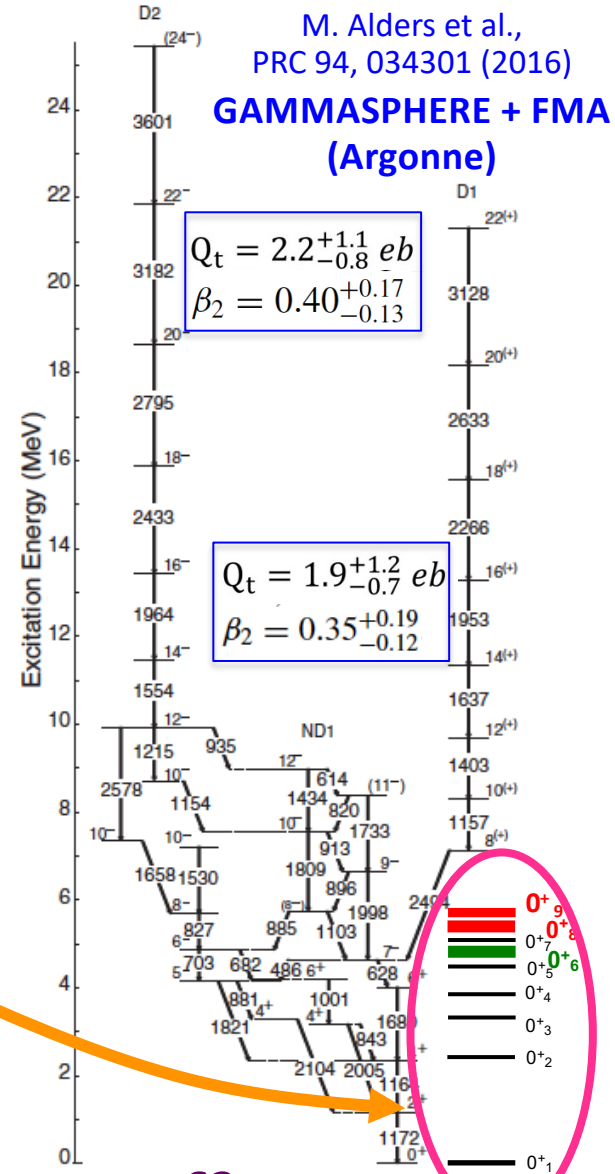
^{62}Ni – MCSM

(very preliminary)
nine 0^+ states



deformed 0^+ states could be the ***BANDHEADS*** *of rotational structures observed at higher spins*

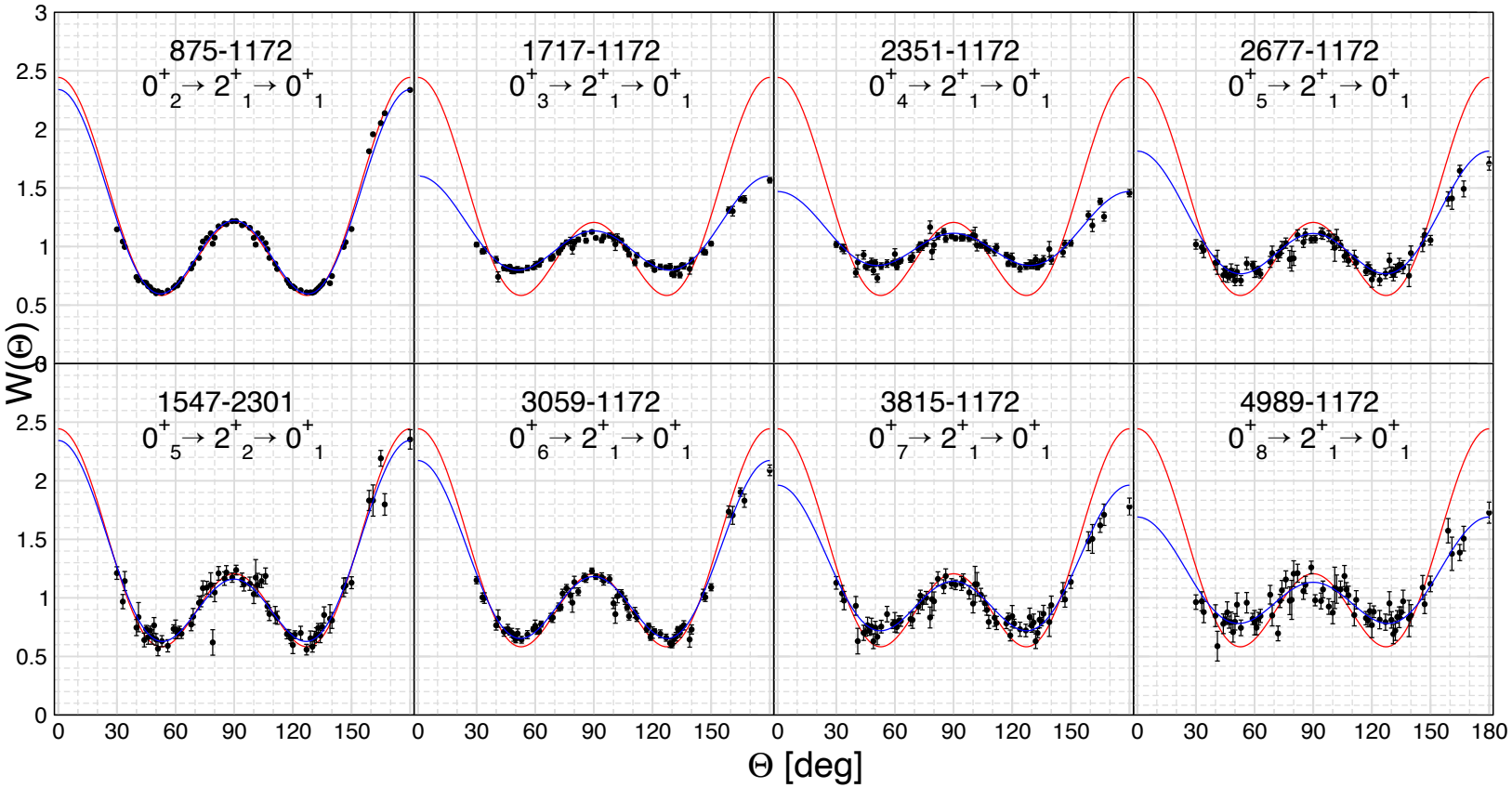
M. Alders et al.,
PRC 94, 034301 (2016)
GAMMASPHERE + FMA (Argonne)



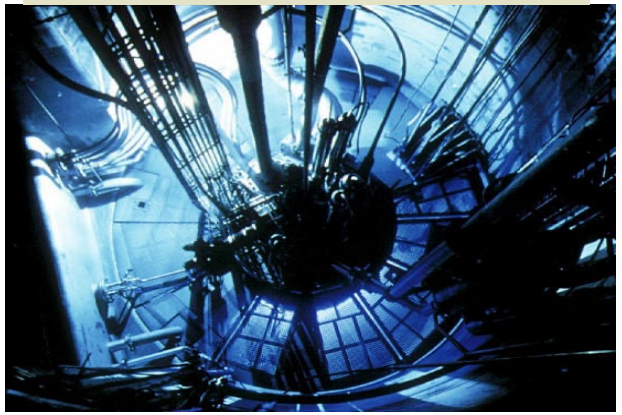
^{62}Ni

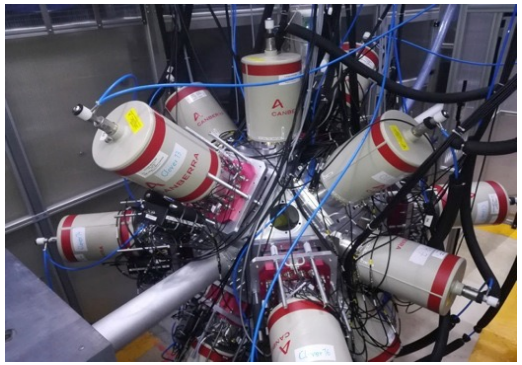
^{62}Ni data from ^{61}Ni(n,γ) reaction with FIPPS at ILL

Large statistics and high-precision angular correlations



Pencil-like intense thermal neutron beam





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

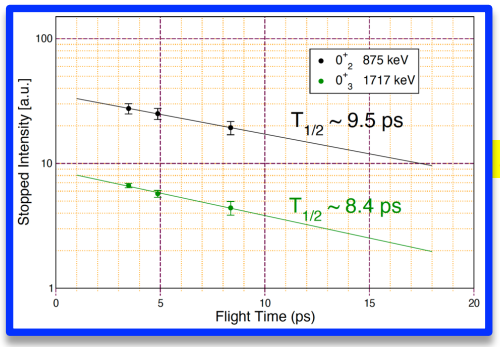
Preliminary, C. Costache and N. Marginean, IFIN-HH, Bucharest

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

Preliminary, C. Costache and N. Marginean, IFIN-HH, Bucharest

*lifetime measurements with **DSAM** **(2n transfer)***
Orsay Data
NUBALL 1
June 2018

*lifetime measurements with **PLUNGER** **(2n transfer)***
ROSPHERE
July 2023-ongoing



S_n= 10595.7 keV

*Preliminary **SHAPE assignment** from comparison with theory (MCSM) in terms of **decay pattern***

weakly def

oblate

prolate-triaxial

8.4 ps
0.3 WU

9.5 ps
8 WU

0^+_1 0^+_2 0^+_3 0^+_4 0^+_5 0^+_6 0^+_7 0^+_8 0^+_9 0^+_{10} 0^+_{11}

6162 keV

$^{62}_{28}$Ni$_{34}$

Lesson learned from Ni studies

1) evidence for shape-isomer-like 0^+ states in ^{64,66}**Ni**
(with B(E2, $0^+ \rightarrow 2^+_1$) < 1 W.u.)

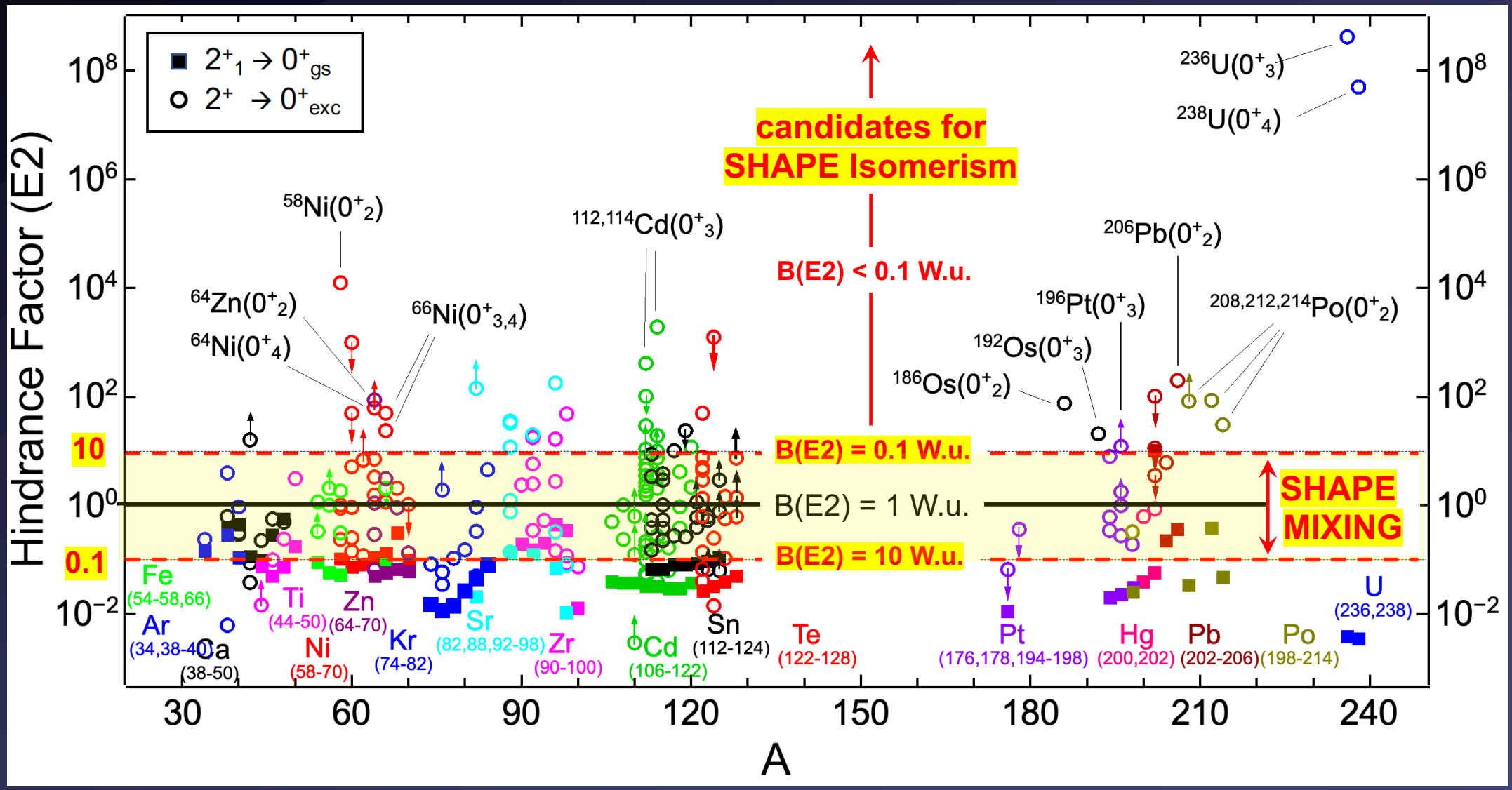
2) Important role played by monopole tensor force
in the origin of deformation

!!! Shape coexistence without parabola **!!!**

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

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, to be published

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

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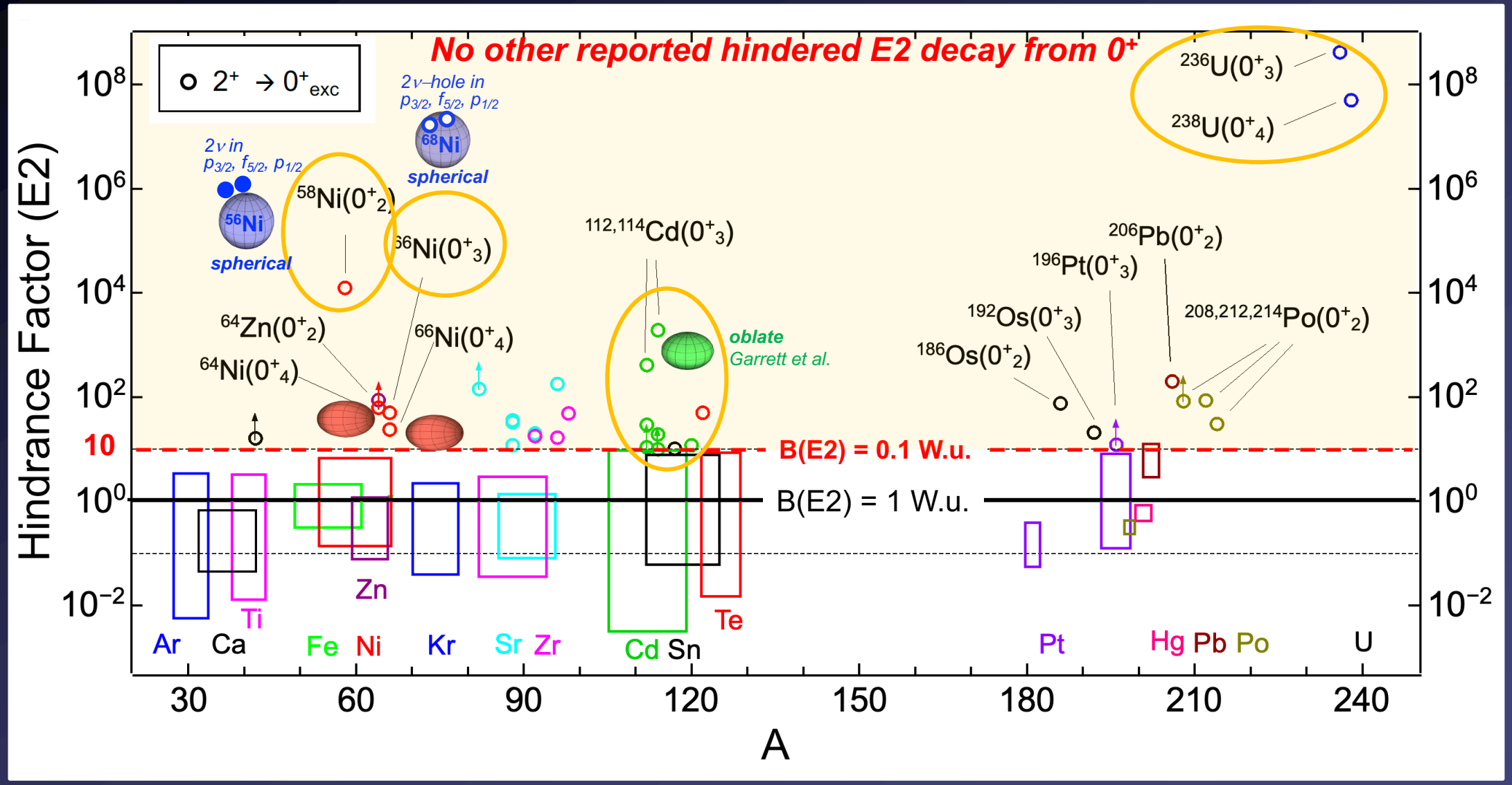
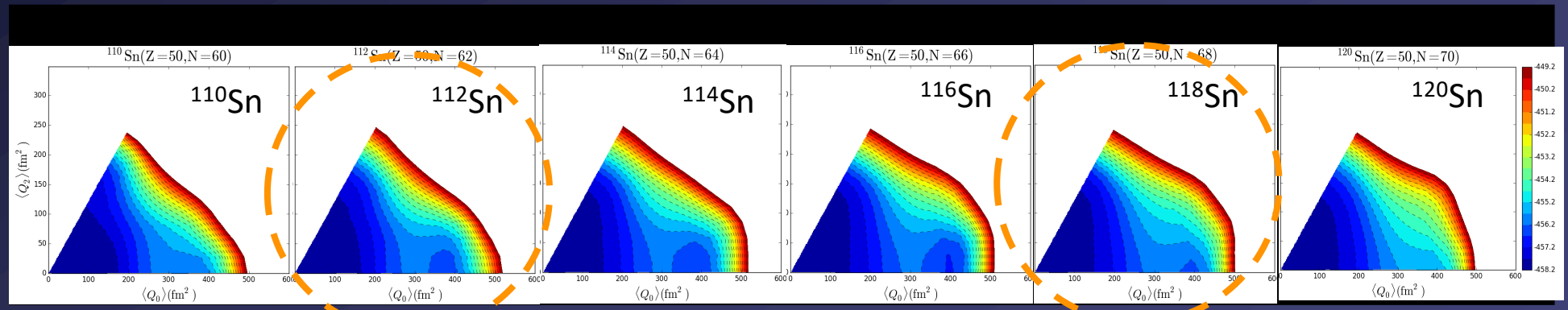


S. Leoni, B. Fornal, A. Bracco, Y. Tsunoda, T. Otsuka, to be published

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

expected scenario similar to Ni

data under analysis

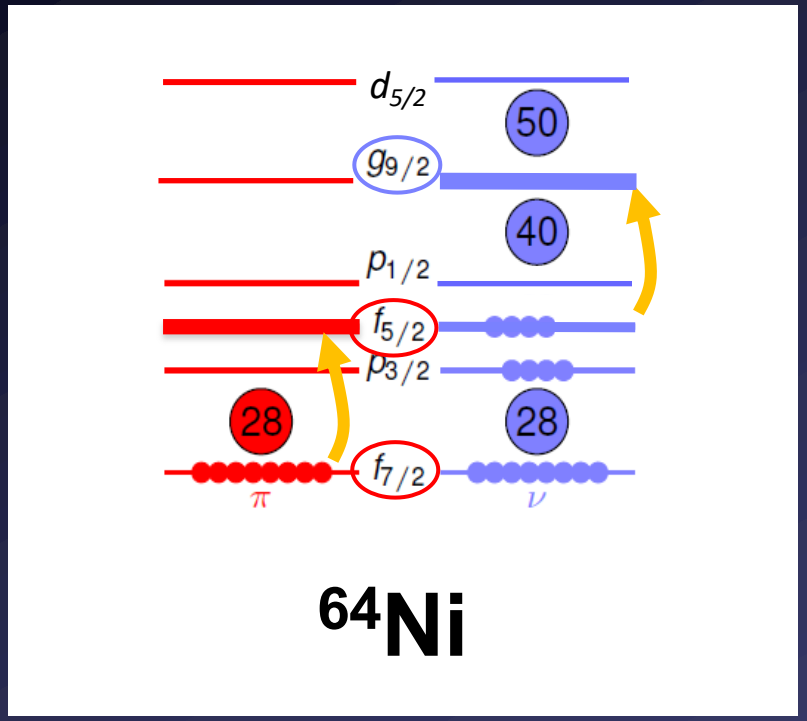


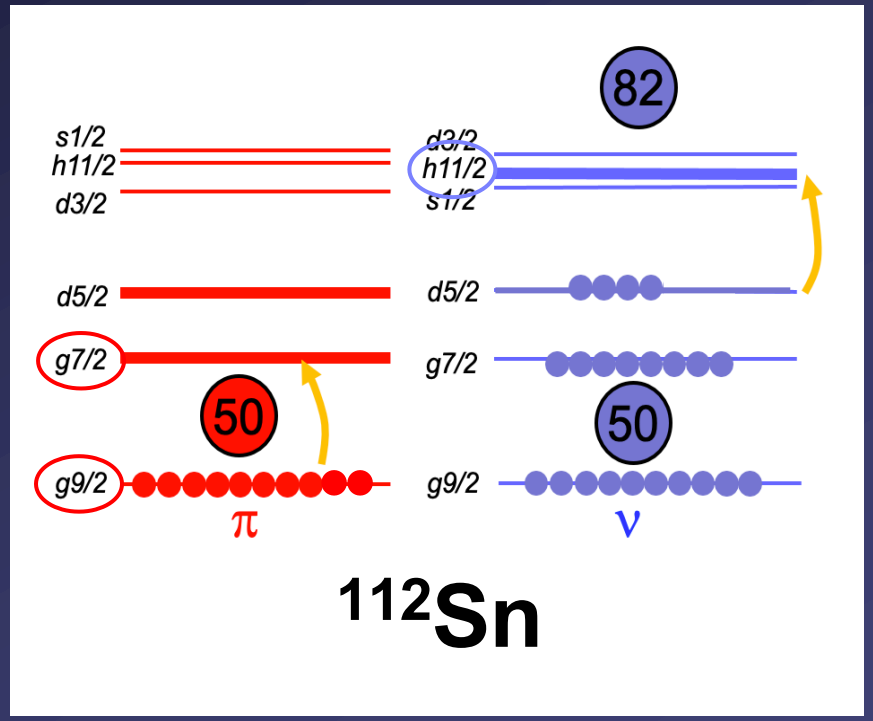
Hartree-Fock-Bogoliubov

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

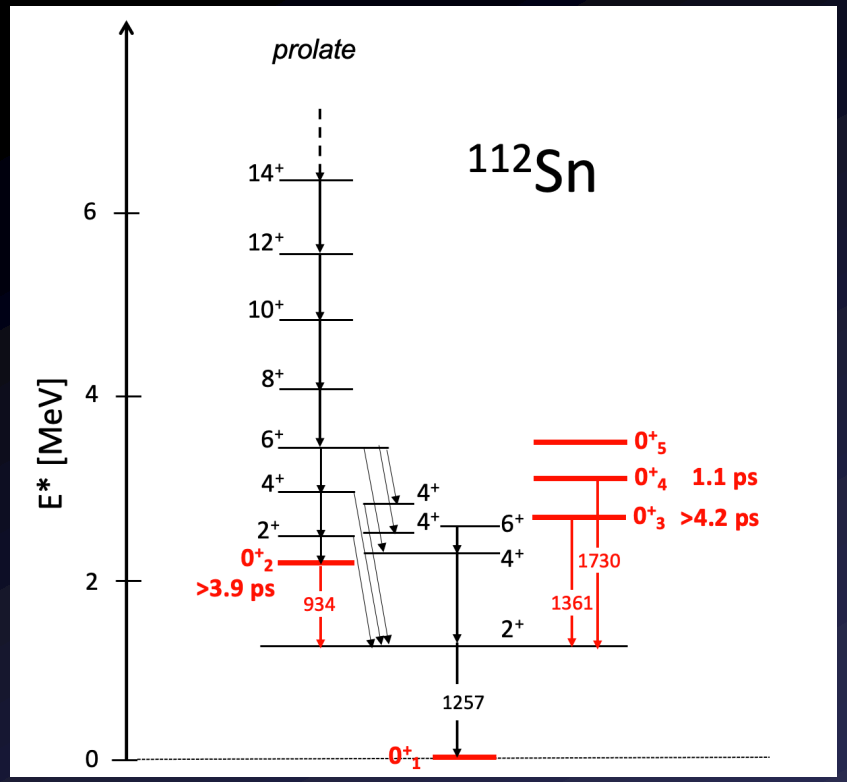
SIMILAR MECHANISM for **Spontaneus Symmetry Breaking** (spherical → deformed) induced by proton-neutron interaction

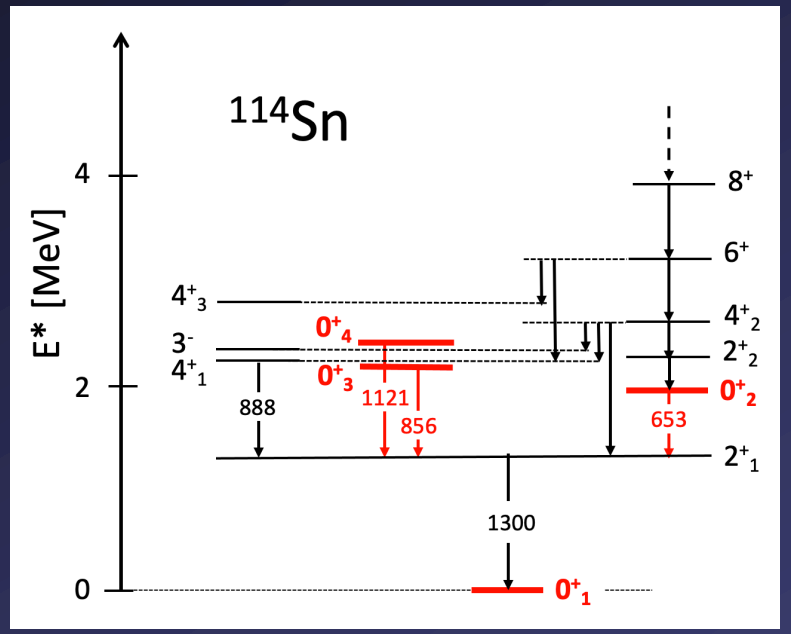


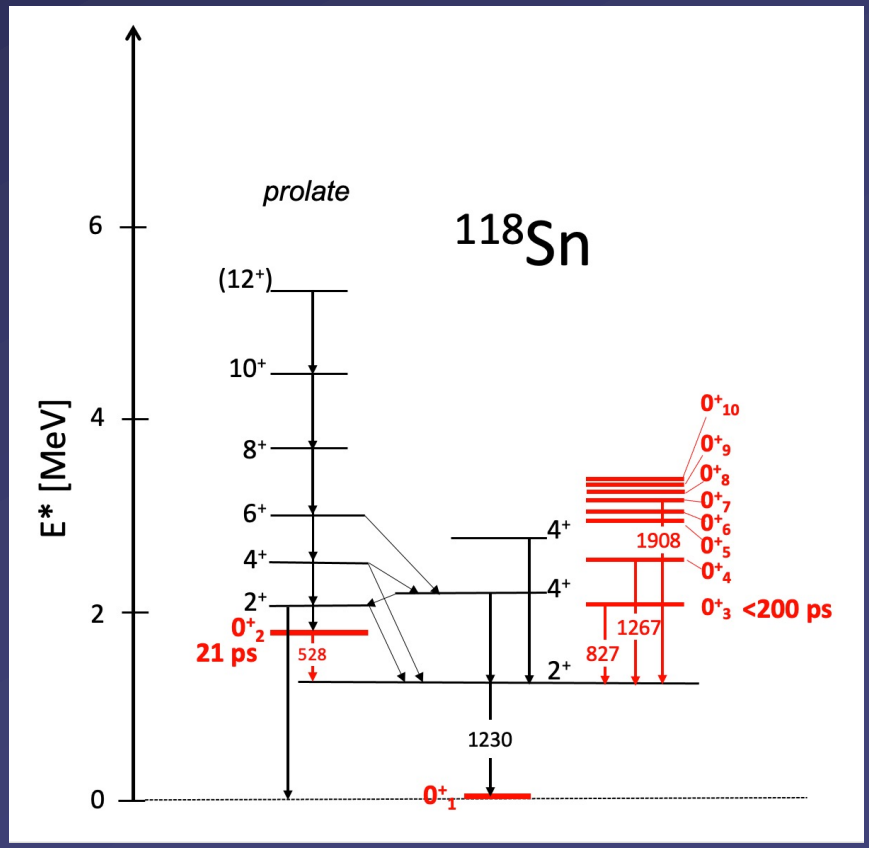


deep prolate minima might be expected
due to monopole tensor force

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







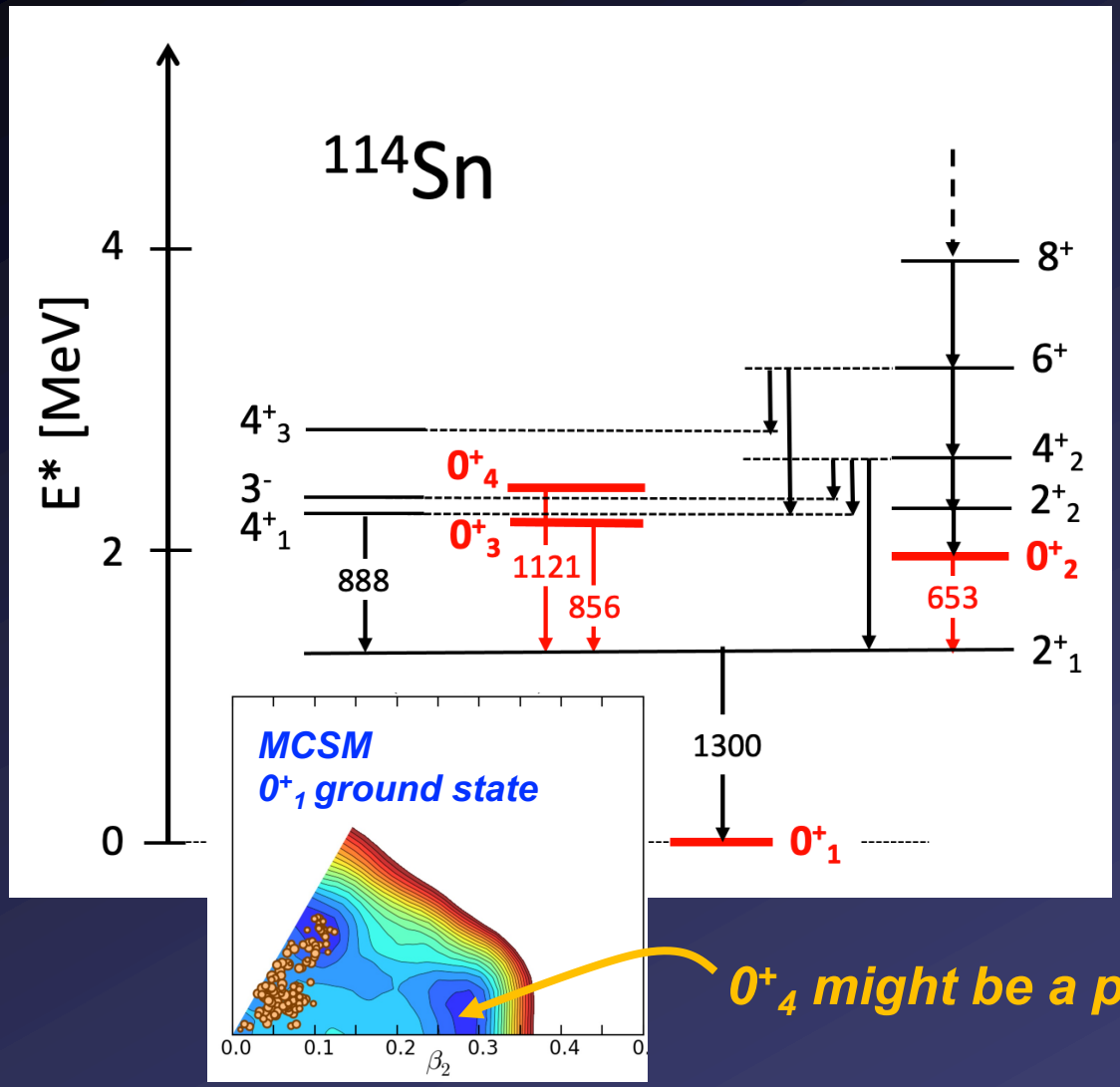
Performed/planned experiments:

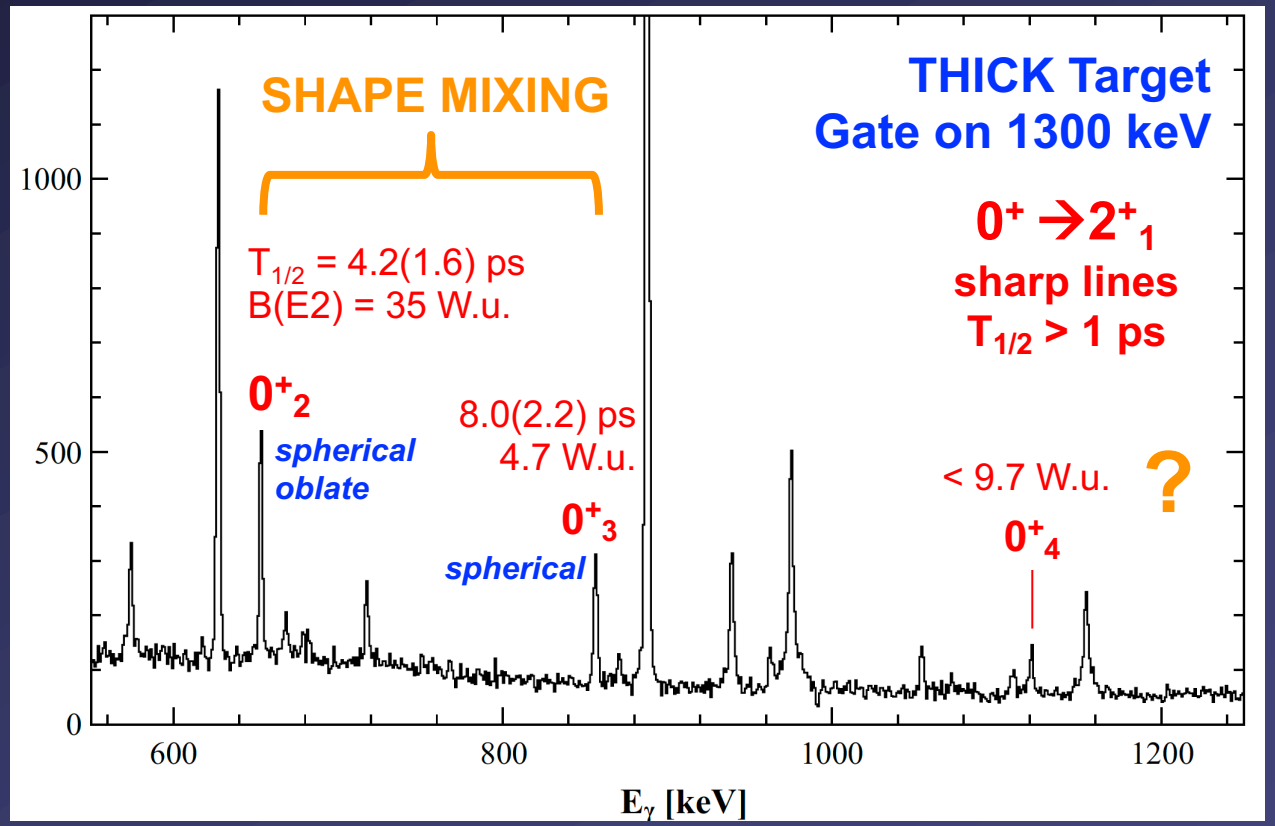
^{18}O+ ^{112}Sn →^{114}Sn: lifetime (DSAM and Plunger), ROSPHERE (2022)
^{32}S+ ^{110}Cd → ^{112}Sn: lifetime (Plunger), AGATA+PRISMA (2022)
1n, 2n, 2p, alpha transfer → ^{118}Sn: ROSPHERE (2023)

Preliminary - ^{114}Sn

G. Corbari PhD, Milano University

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





0^+_4 might be a prolate shape-isomer-like structure !!!

Conclusions: search for **SHAPE ISOMERS** in medium mass nuclei

only few cases exist with γ decay between structures
with different shapes **significantly hindered** (**B(E2) << 1 , HF>10**)

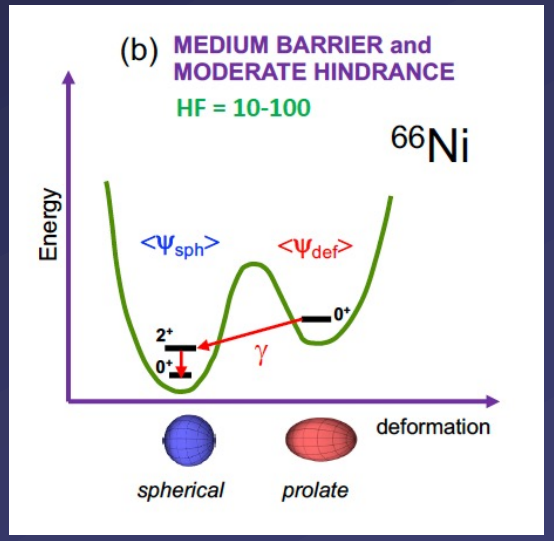
we have focused on ^{64}Ni and ^{66}Ni … ^{62}Ni ongoing

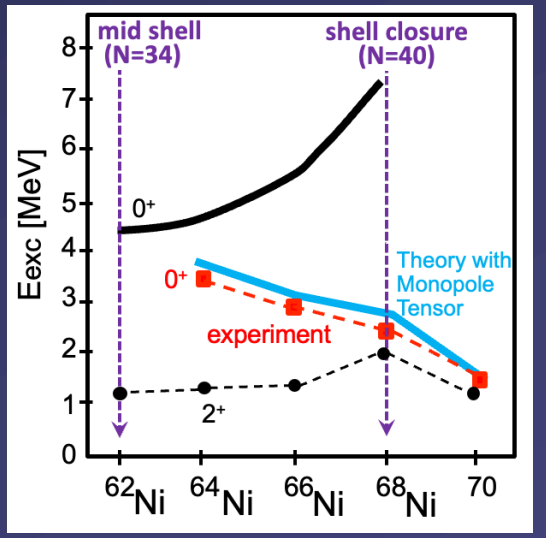
Lesson learned:

1) **Hindrance** results from **wave functions well localized** in different PES minima, separated by a **sizable barrier**

The wave functions «do not talk to each other»
This gives rise to SHAPE ISOMERISM

2) The **TENSOR force** plays a key role, **deepening the minima**:
in Ni isotopes – Shape coexistence WITHOUT PARABOLA





In general, at SPIN 0:

NO HINDRANCE for decay between different shapes
Wave functions NOT well localized → SHAPE MIXING
Such states may still be ISOMERIC for other reasons.

FUTURE PLANS: ^{112}Sn-^{118}Sn chain

with complementary probes
→ expected similarities with Ni isotopes