“Shape Isomerism in ^{66}Ni”

S. Leoni, B. Fornal, N. Marginean, M. Sferrazza,
Y. Tsunoda, T. Otsuka, et al., …

University of Milano and INFN sez. ***Milano, Italy***
IFJ-PAN, The Institute of Nuclear Physics, ***Krakow, Poland***
IFIN HH, ***Bucharest, Romania***
Departement de Physique, ***Universite libre de Bruxelles, Belgium***
Center for Nuclear Study, ***University of Tokyo, Japan***

NUSTAR Week 2017

25-29 September 2017
Ljubljana, Slovenia
Europe/Ljubljana timezone

Outline

- **Introduction**

  isomers in molecular chemistry

- **Atomic nucleus**

  shell structure, deformation, potential energy surpace (PES)

- **Discovery of nuclear fission (shape) isomers**
- **Experimental search for shape coexistence/shape isomers**
- **The unique case of ^{66}Ni**
- **Relevance for THEORY – SHELL Model**

  MICROSCOPIC origin of Nuclear Deformation

ISOMERS in chemistry

In chemistry, an isomer is a molecule with the same molecular formula as another molecule, but with different arrangement of the atoms.

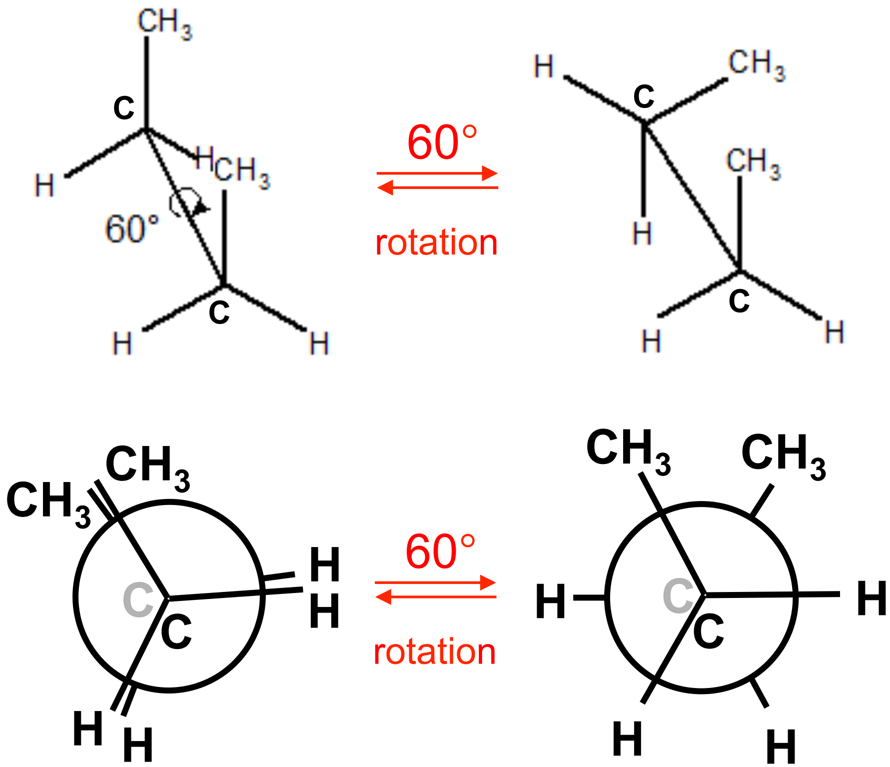
Subgroup: stereoisomers or spatial isomers

Sub-subgroup: conformational isomers (conformers)

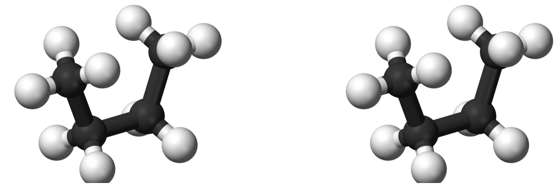
Sub-sub-subgroup: rotamers

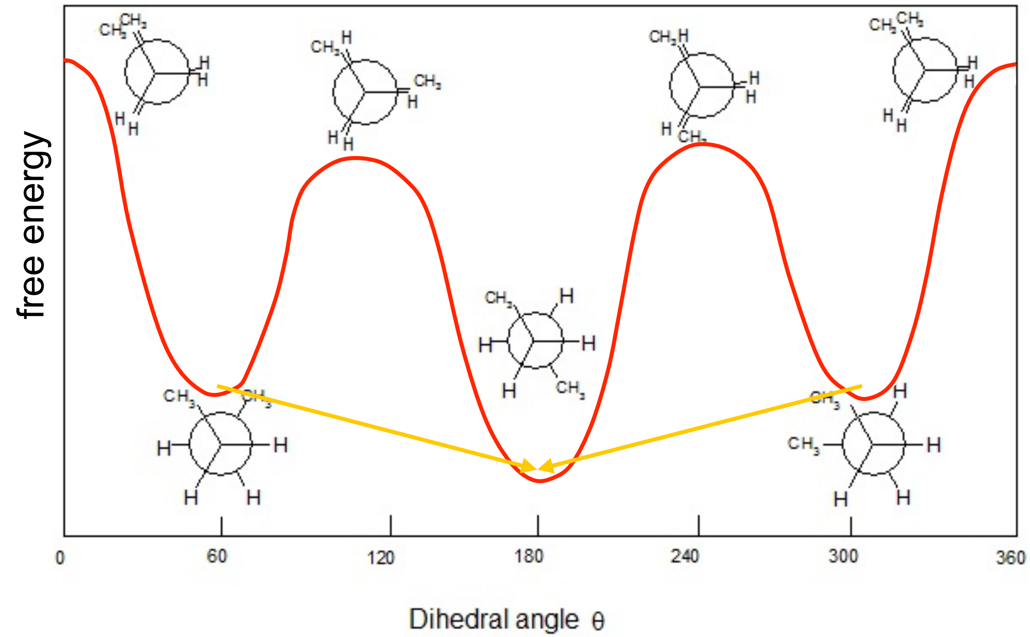
Butane molecule C_4H_{10}

Conformational isomers

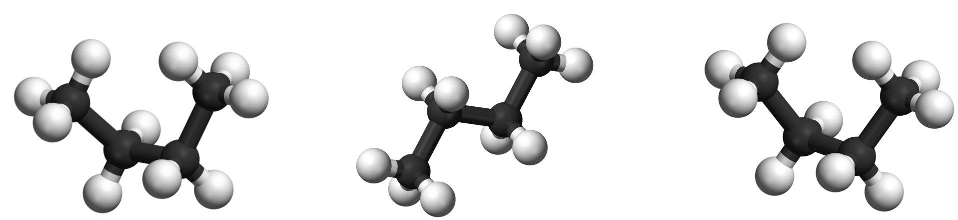


Rotation about single bond of butane





Free energy diagram of butane
as a function of dihedral angle



Potential energy surface (PES) of a nucleus

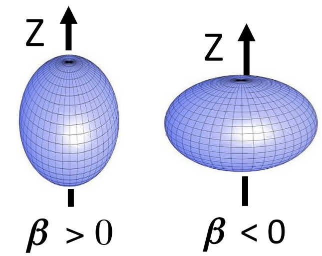
Parametrization
of the NUCLEAR SHAPE

$$R(\theta,\varphi) = R_0[1 + \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)]$$

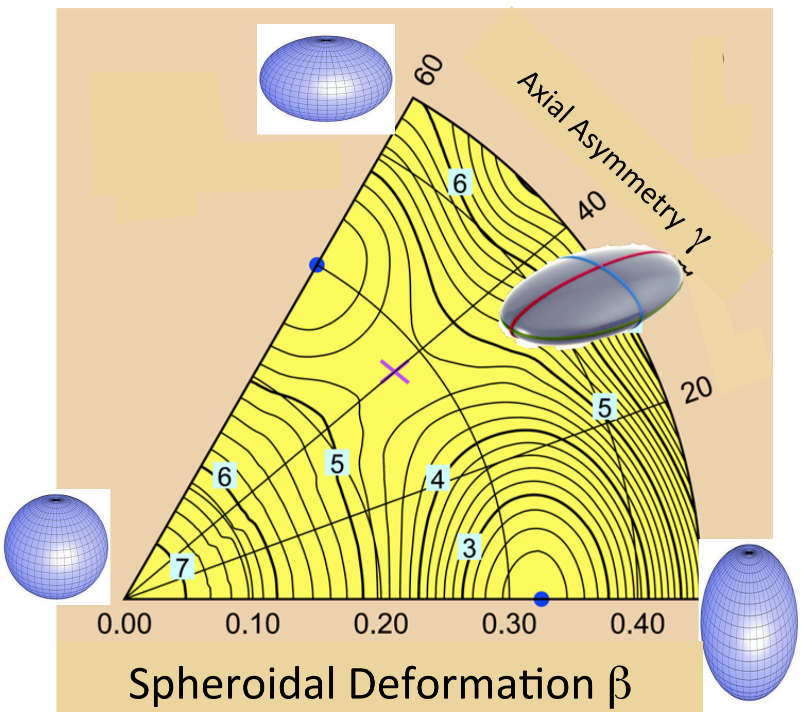
If we consider only
quadrupole deformation

$$a_{20} = \beta \cos\gamma$$

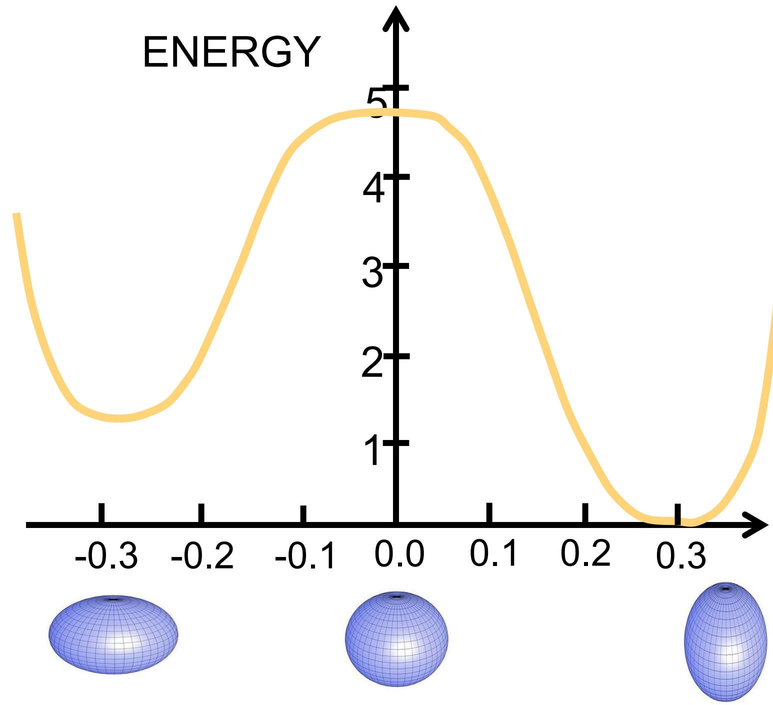
$$a_{22} = (1/\sqrt{2})\beta \sin\gamma$$



TWO-dimensional contour



ONE-dimensional representation



Where do we find secondary minima

in the nuclear chart

considering only static deformation ?

(no additional degree of freedom involved
… angular momentum, excitations …)

PHYSICAL REVIEW VOLUME 89, NUMBER 5 MARCH 1 **1953**

Nuclear Constitution and the Interpretation of Fission Phenomena

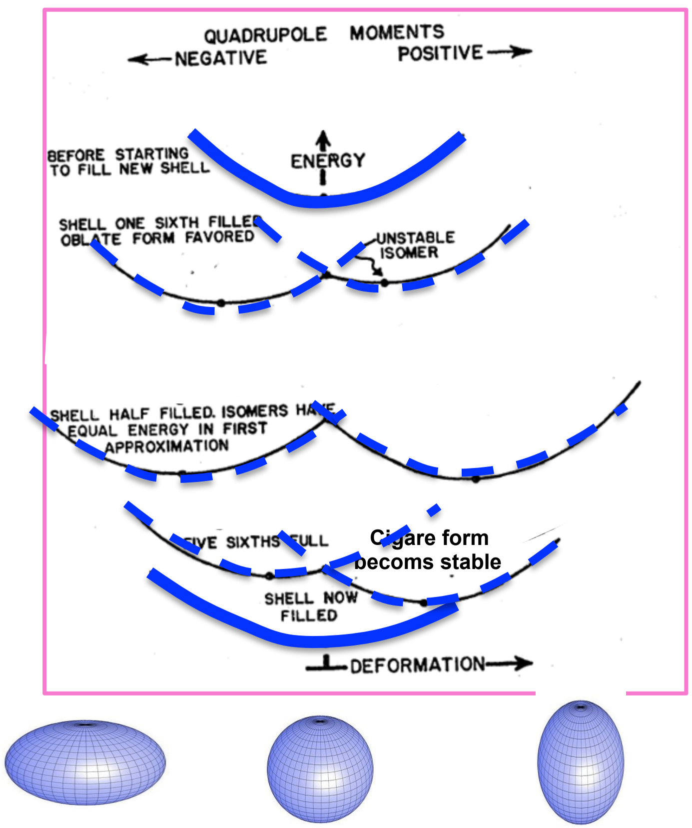
DAVID LAWRENCE HILL*
Vanderbilt University, Nashville, Tennessee, and Los Alamos Scientific Laboratory, Los Alamos, New Mexico

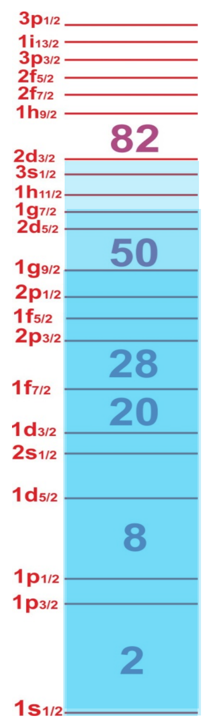
AND

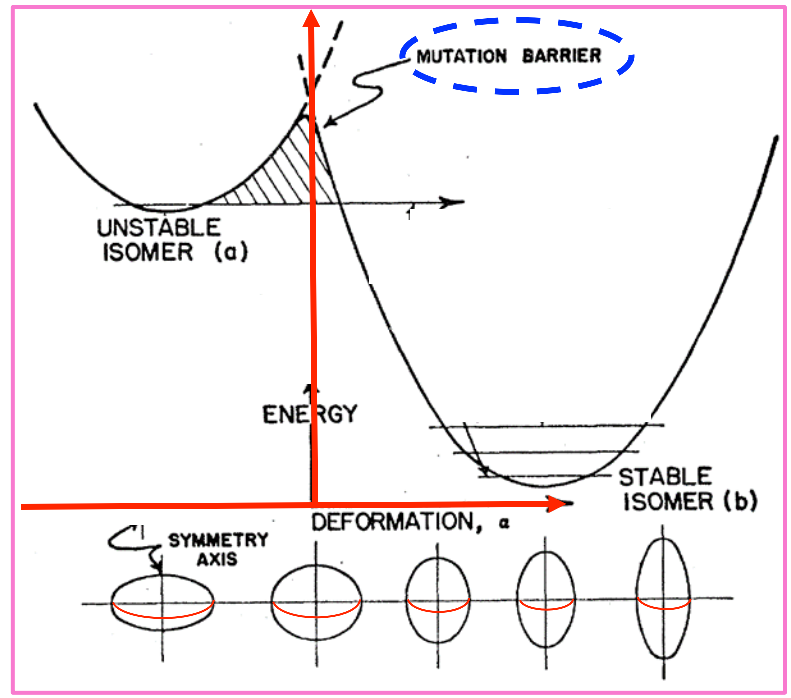
JOHN ARCHIBALD WHEELER†
Princeton University, Princeton, New Jersey, and Los Alamos Scientific Laboratory, Los Alamos, New Mexico

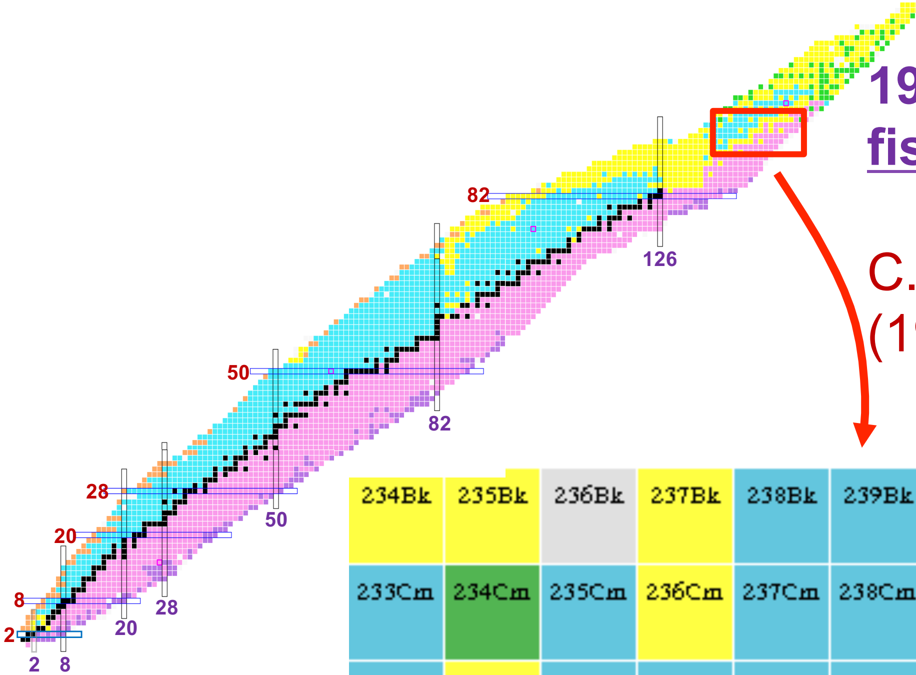
(Received October 14, 1952)

Already in **1953**, **Hill** and **Wheeler** discussed possible consequences of the **existence of two well separated minima** in the potential energy surface **for the ground state** of the system.









1961 - discovery of the first <u>spontaneously fissioning isomer</u> in ^{242}Am with a **half-life 14 msec**

C. M. Polikanov et al., Zh. Eksp. Teor. Fiz. 42, 1464 (1962) [Sov. Phys.- JETP 15, 1016 (1962)].

234Bk	235Bk	236Bk	237Bk	238Bk	239Bk	240Bk	241Bk	242Bk	243Bk	244Bk	245Bk	246Bk	247Bk	248Bk	249Bk	250Bk
233Cm	234Cm	235Cm	236Cm	237Cm	238Cm	239Cm	240Cm	241Cm	242Cm	243Cm	244Cm	245Cm	246Cm	247Cm	248Cm	249Cm
232Am	233Am	234Am	235Am	236Am	237Am	238Am	239Am	240Am	241Am	242Am	243Am	244Am	245Am	246Am	247Am	248Am
231Pu	232Pu	233Pu	234Pu	235Pu	236Pu	237Pu	238Pu	239Pu	240Pu	241Pu	242Pu	243Pu	244Pu	245Pu	246Pu	247Pu
230Np	231Np	232Np	233Np	234Np	235Np	236Np	237Np	238Np	239Np	240Np	241Np	242Np	243Np	244Np	245Np	
229U	230U	231U	232U	233U	234U	235U	236U	237U	238U	239U	240U	241U	242U	243U		
228Pa	229Pa	230Pa	231Pa	232Pa	233Pa	234Pa	235Pa	236Pa	237Pa	238Pa	239Pa	240Pa	241Pa			
227Th	228Th	229Th	230Th	231Th	232Th	233Th	234Th	235Th	236Th	237Th	238Th	239Th				
226Ac	227Ac	228Ac	229Ac	230Ac	231Ac	232Ac	233Ac	234Ac	235Ac	236Ac	237Ac					

SOVIET PHYSICS USPEKHI VOLUME 11, NUMBER 1 JULY-AUGUST 1968

1968

SPONTANEOUSLY FISSIONING ISOMERS

S. M. POLIKANOV

Joint Institute for Nuclear Research, Dubna

Usp. Fiz. Nauk 94, 43–62 (January, 1968)

SOVIET PHYSICS USPEKHI VOLUME 15, NUMBER 4 JANUARY-FEBRUARY 1973

539.144.7

1973

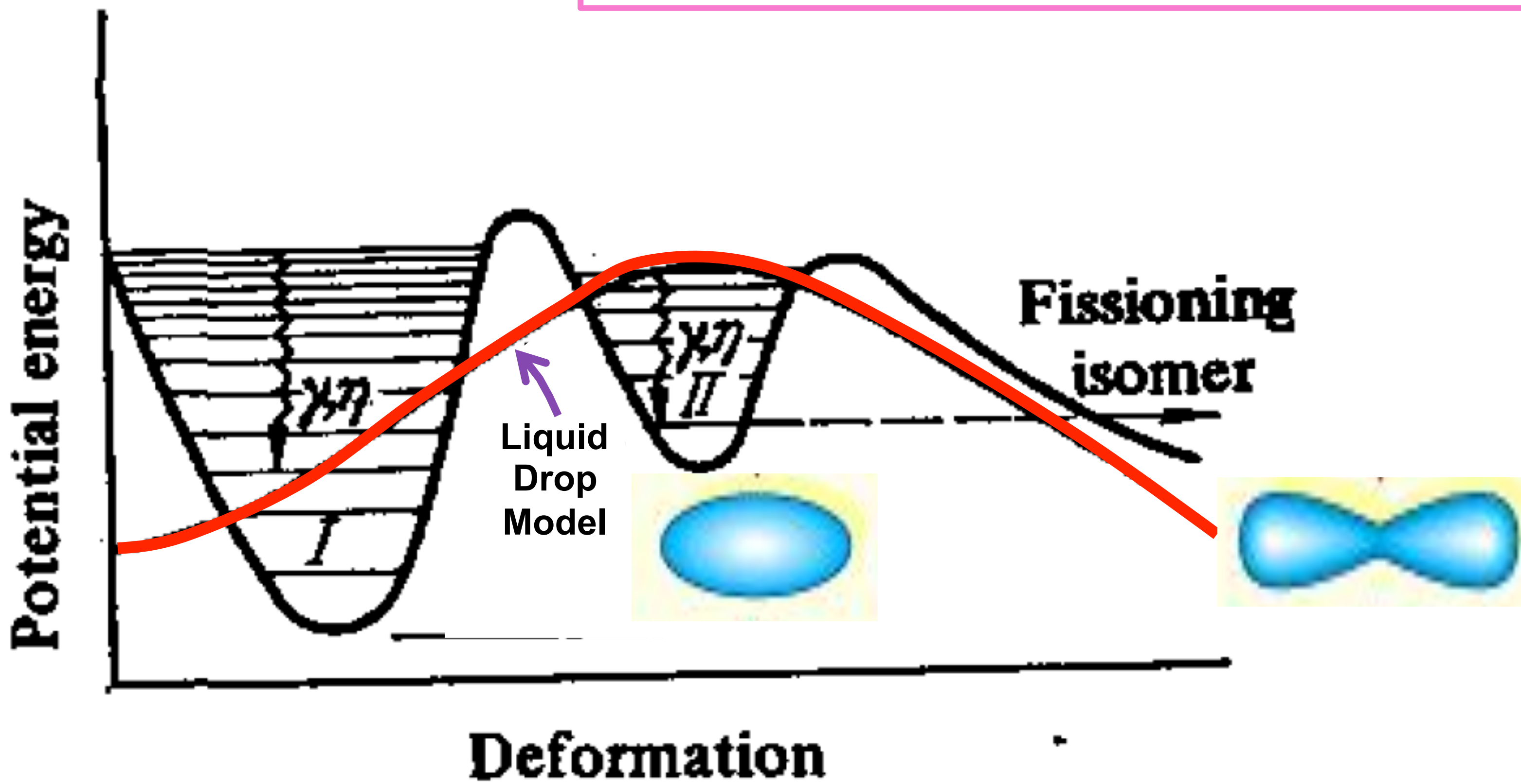
Physics of Our Days

NUCLEAR SHAPE ISOMERS

S. M. POLIKANOV

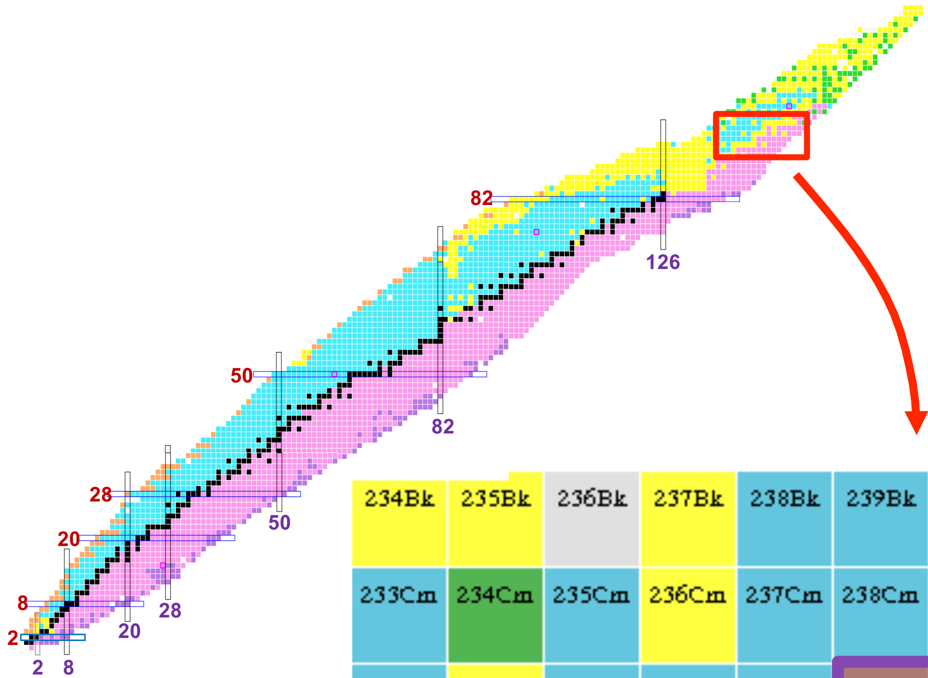
Joint Institute for Nuclear Research, Dubna

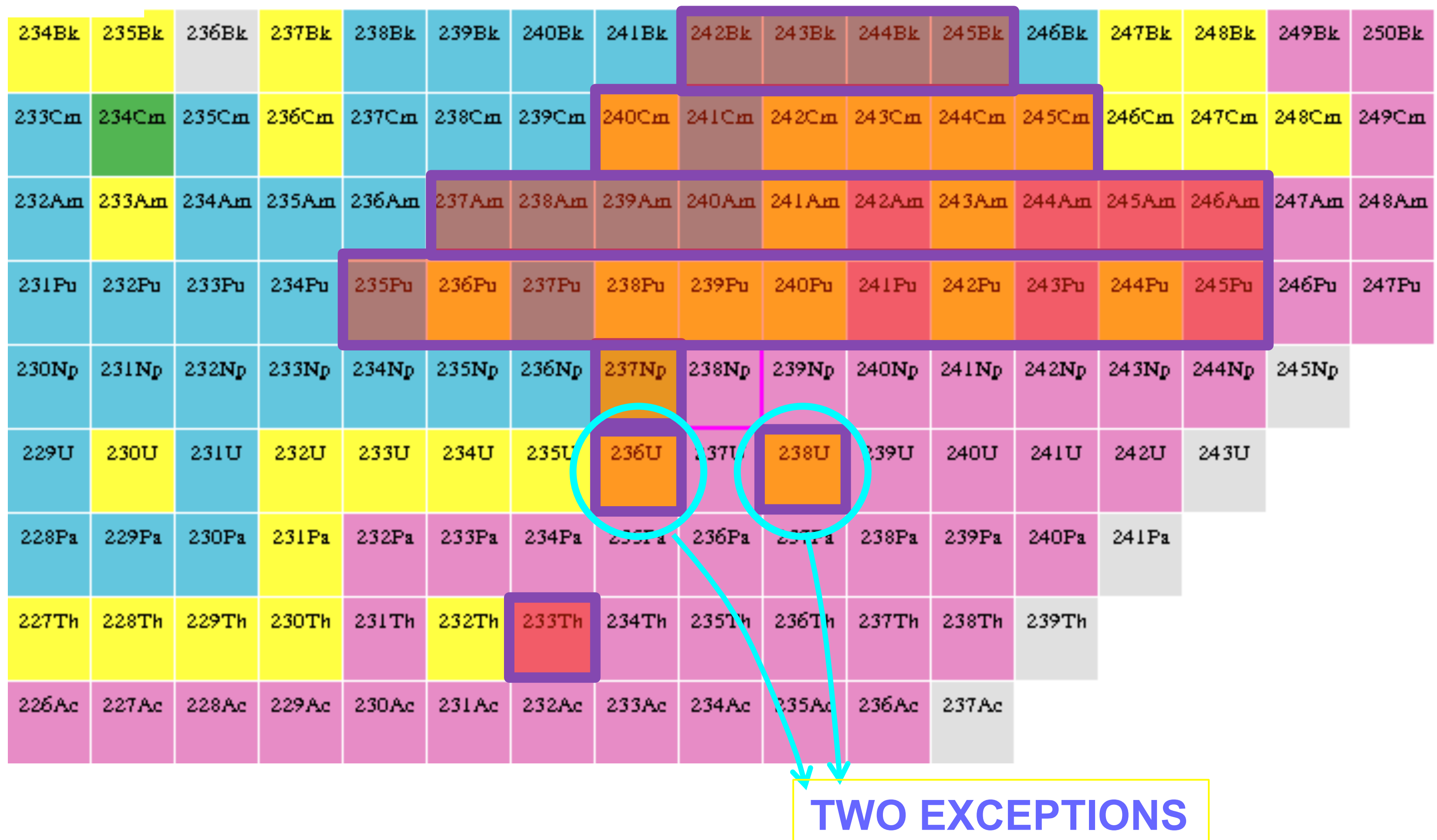
Usp. Fiz. Nauk 107, 685–704 (August, 1974)



Shape isomers in actinides

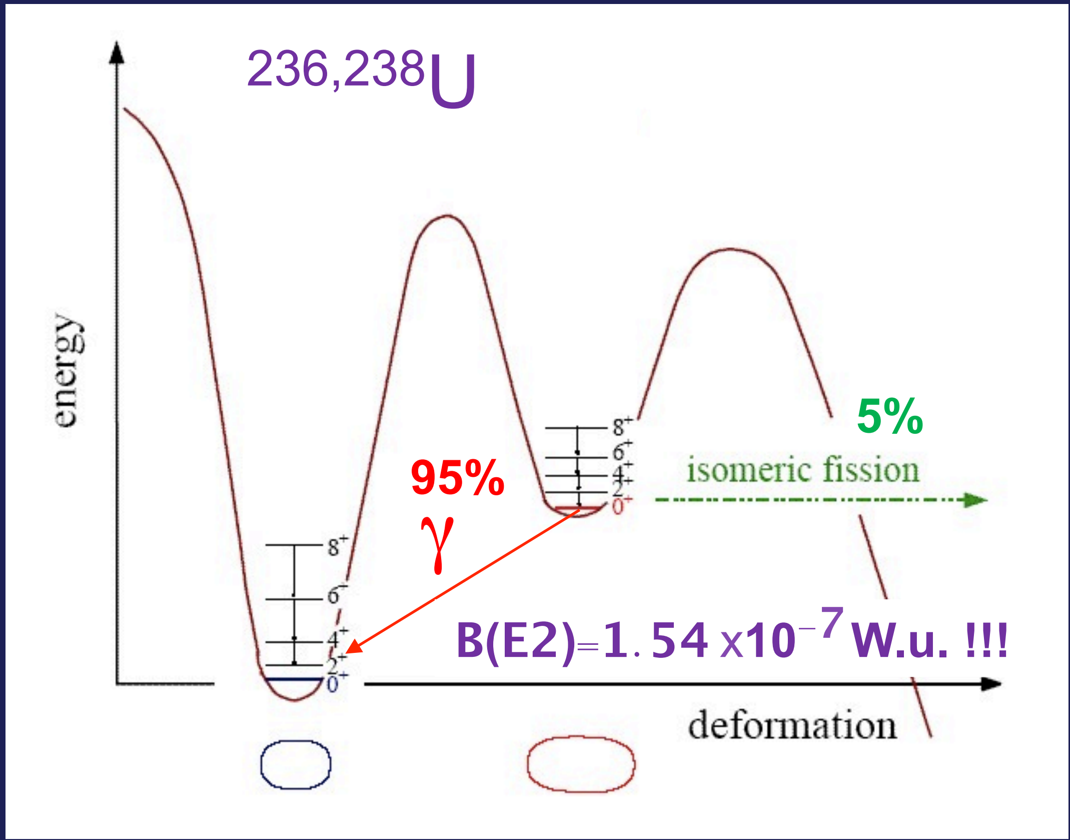
- HIGH Potential BARRIER
- Nucleus trapped In the second minimum
- **Spontaneous fission from the second minimum**





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 these features ?

SEARCH for SHAPE ISOMERS in LIGHTER nuclei:

- MOST CLEAR-CUT cases of SHAPE Coexistence
- a PROBE of MICROSCOPIC origin of nuclear deformation within a pure SHELL Model Approach

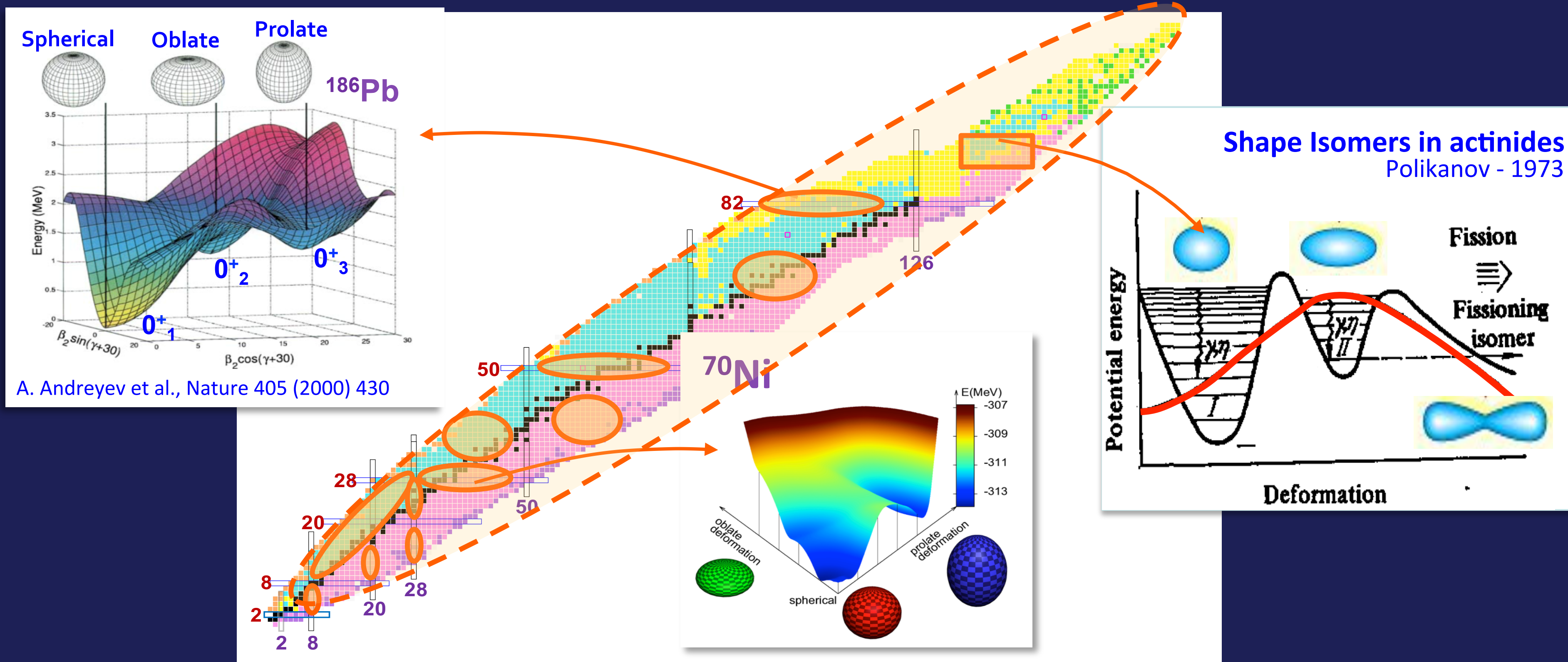
Ideal Cases are 0^+ states – to avoid ambiguity given by spin effects

(Actinides are **NOT doable** by SHELL Model …)

SHAPE Coexistence in Atomic Nuclei

Appearence of different shapes at low excitation energy

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

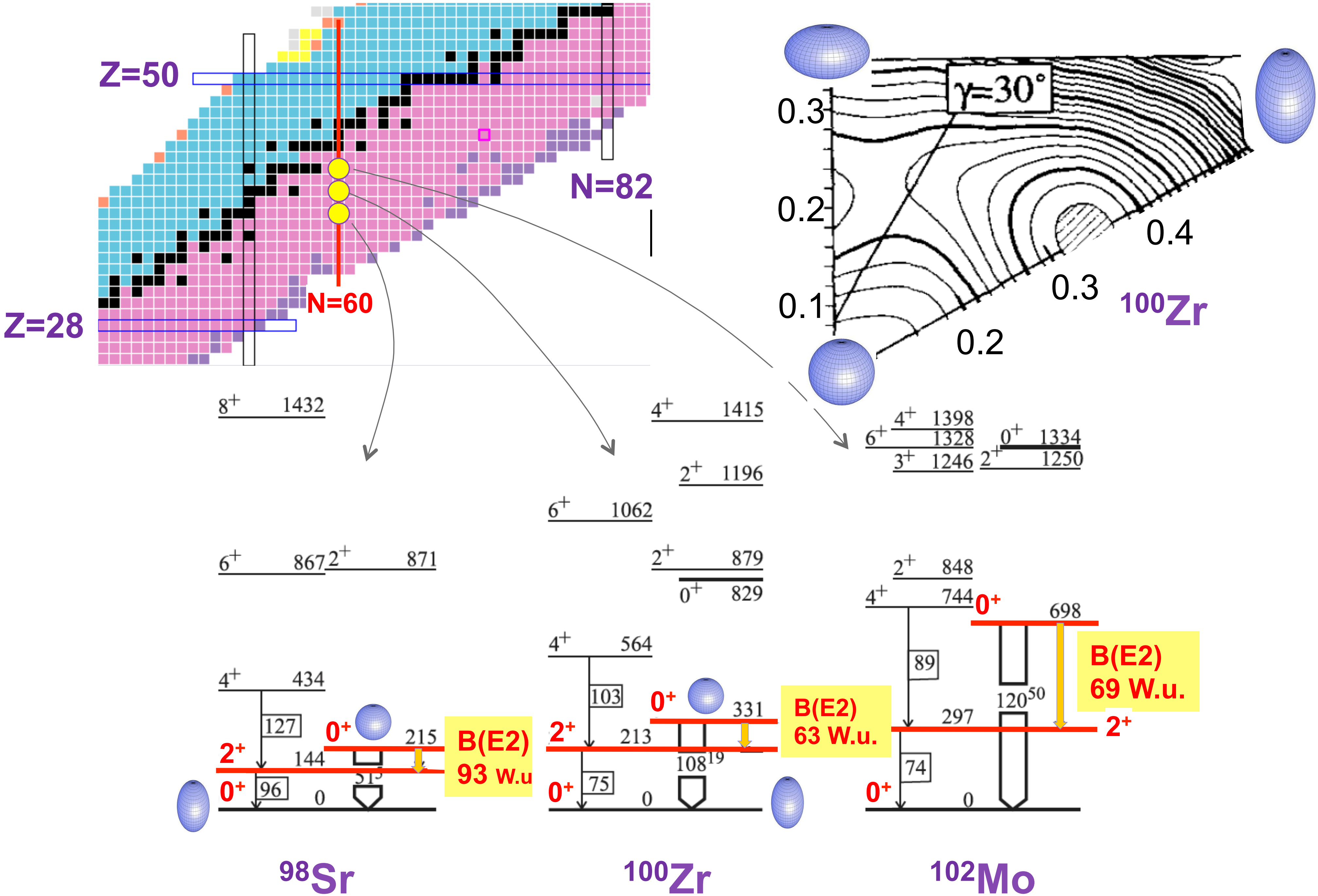


Through the last 40 years of experimental activities, the concept has evolved:

1) exotic rarity (1970')

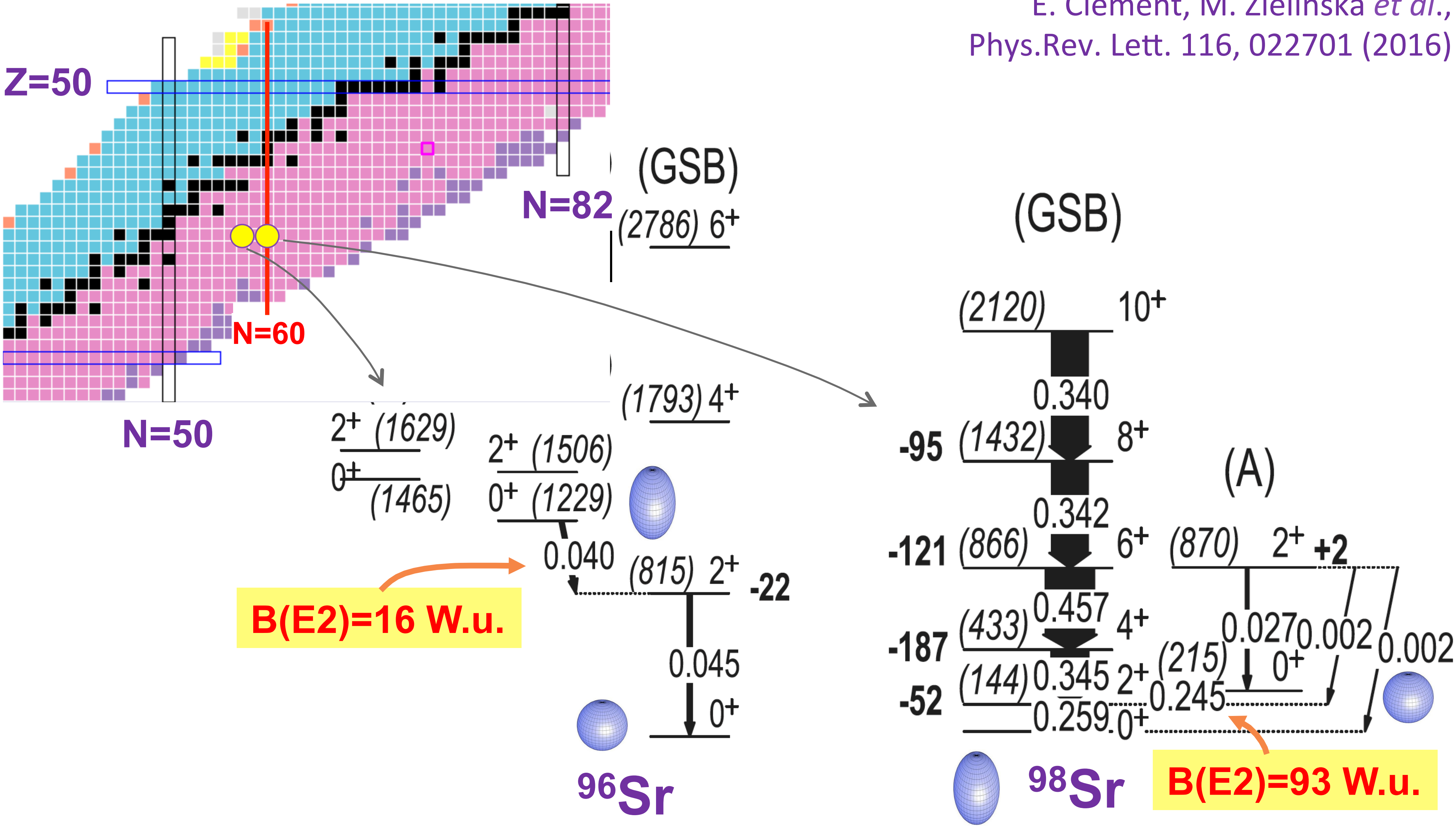
2) islands of occurrence (1990')

3) current believe: occurrence in all (but the lightest) nuclei



Z=50
Z=28
N=60
N=82
γ=30°
0.3
0.2
0.1
0.2
0.3
0.4
100Zr
8+ 1432
6+ 867
2+ 871
4+ 434
127
0+ 215
2+ 144
0+ 96 0
B(E2) 93 W.u
4+ 1415
2+ 1196
6+ 1062
2+ 879
0+ 829
4+ 564
103
0+ 331
2+ 213
108 19
0+ 75 0
B(E2) 63 W.u.
4+ 1398
6+ 1328
3+ 1246
0+ 1334
2+ 1250
2+ 848
4+ 744
0+ 698
89
120 50
297
2+
0+ 74 0
B(E2) 69 W.u.
98Sr
100Zr
102Mo

E. Clément, M. Zielińska *et al.*, Phys.Rev. Lett. 116, 022701 (2016)



No retardation in γ decay is observed !!!!

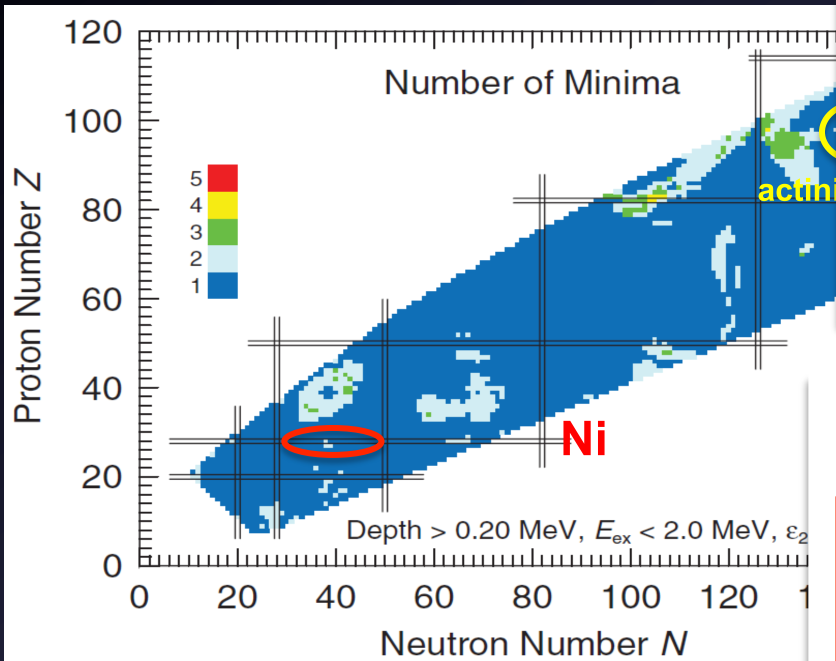
Potential barrier **NOT sizable** enough to prevent fast shape changes

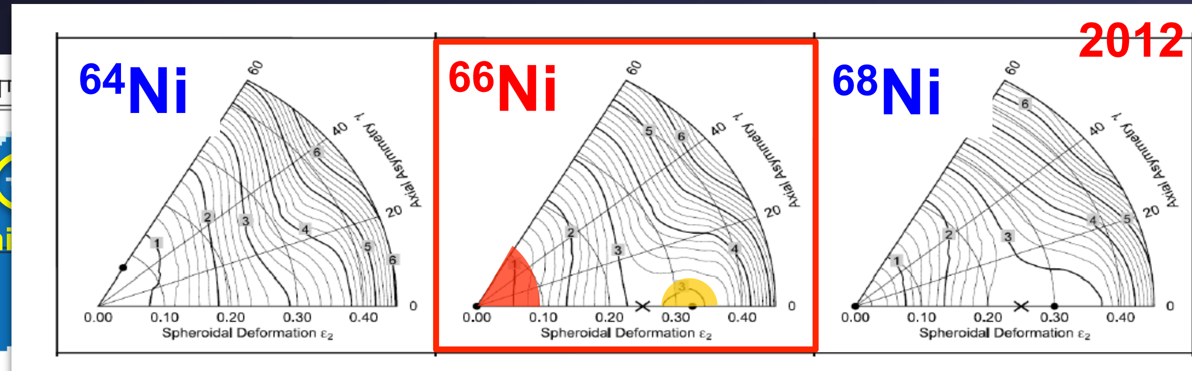
Predictions for SHAPE ISOMERS - Mean Field Based

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

Global Calculation Searching for Nuclear Shape Isomers

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





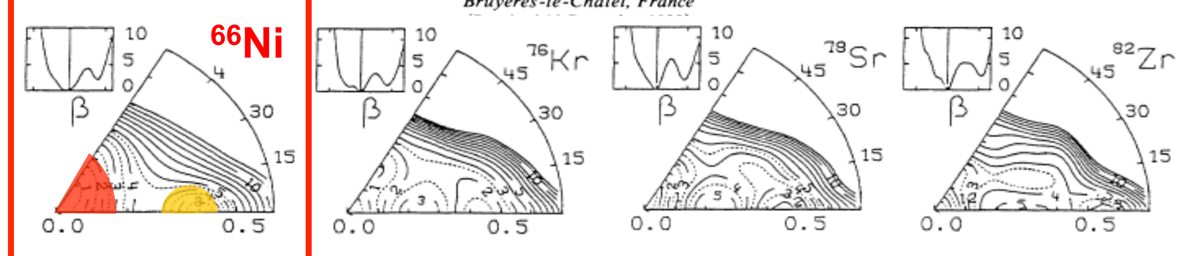
VOLUME 62, NUMBER 21 PHYSICAL REVIEW LETTERS 22 MAY 1989

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



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

Microscopic Hartree-Fock plus BCS calculations

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

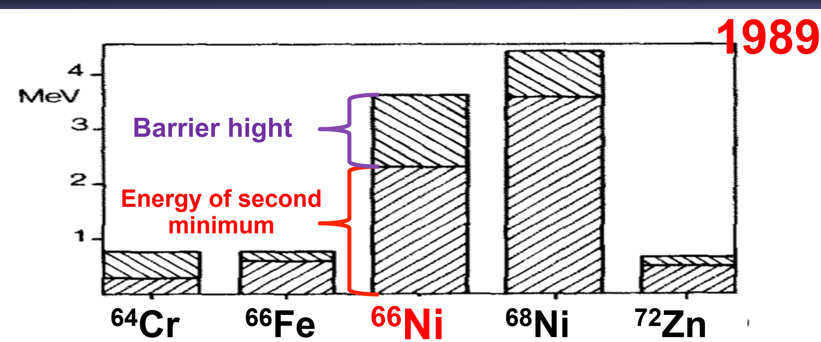
H. FLOCARD

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



Predictions for SHAPE ISOMERS – SHELL Model Based

[Otsuka group and Nowacki, Lenzi, Poves, …]

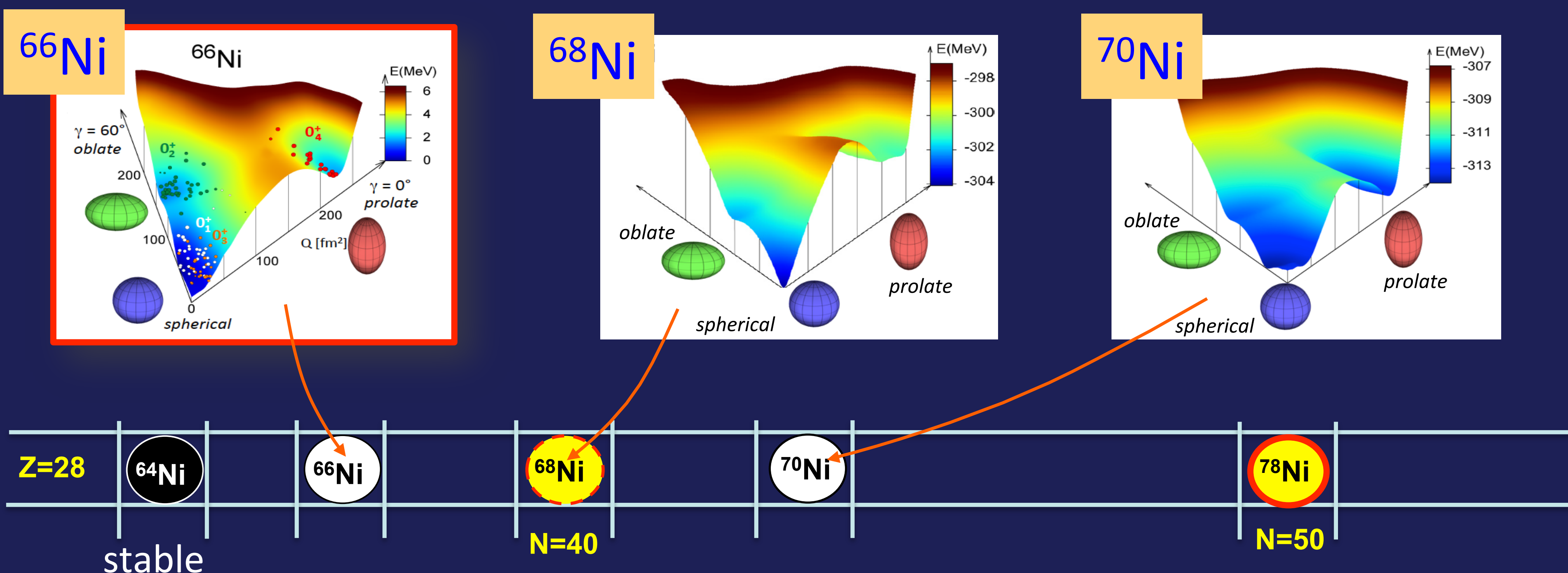
state-of-the-art SHELL Model: possible for A <= 100

new calculations scheme, very powerfull computer

Investigation of MICROSCOPIC NATURE - wave functions, B(Eλ/Mλ), …

Monte Carlo SHELL Model (T. Otsuka's Group – K computer 10^6 processors)

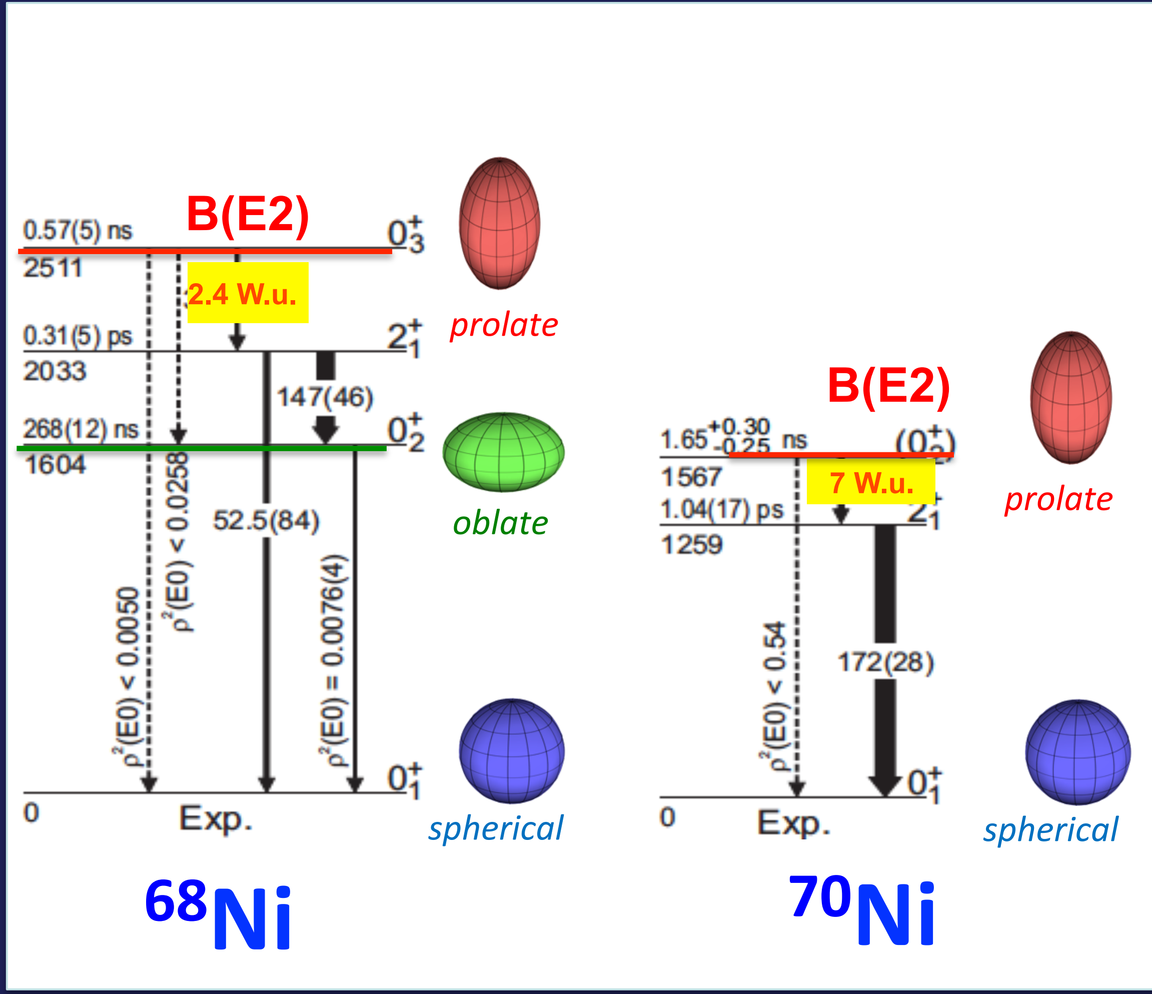
^{66}Ni – ^{78}Ni: FULL pf + $g_{9/2}$ + $d_{5/2}$ for both neutrons and protons



Y. Tsunoda et al., PRC 89 (2014) 031301R

Experimentally …

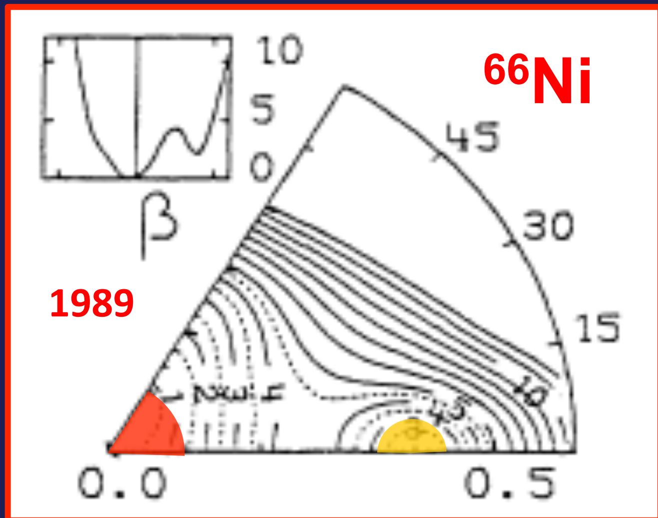
No retardation is found in ^{68}Ni and ^{70}Ni



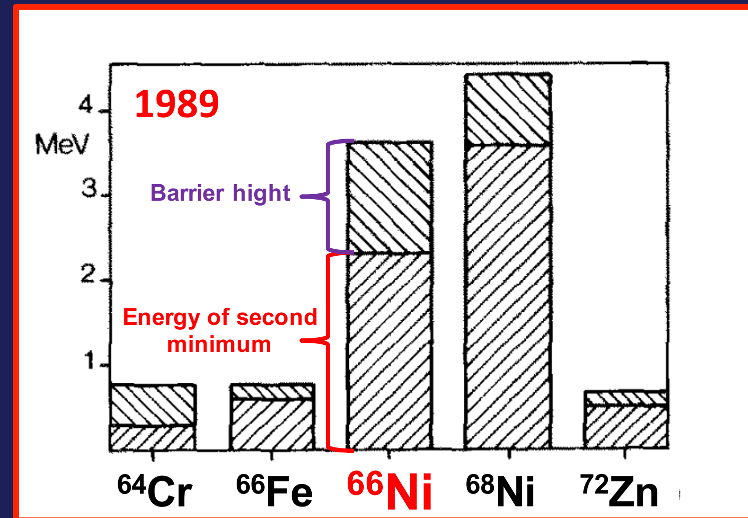
B. P. Crider et al., Phys. Lett. B 763, 108 (2016)

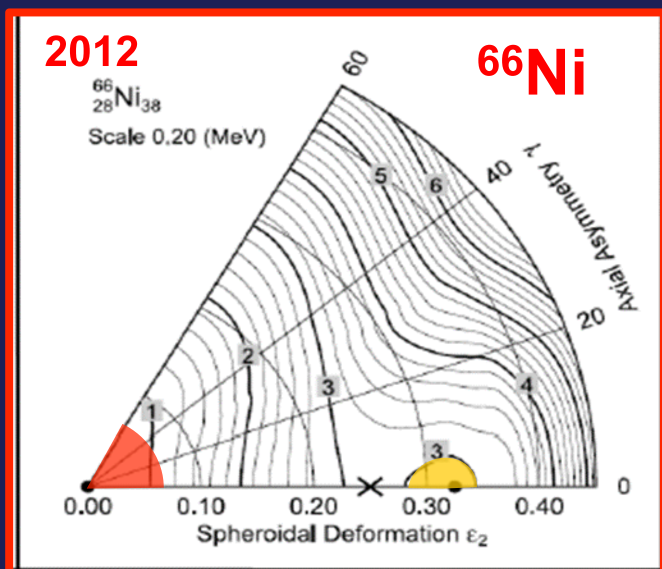
Predictions of four models → shape isomerism in ^{66}Ni

Microscopic Hartree-Fock-Bogoliubov

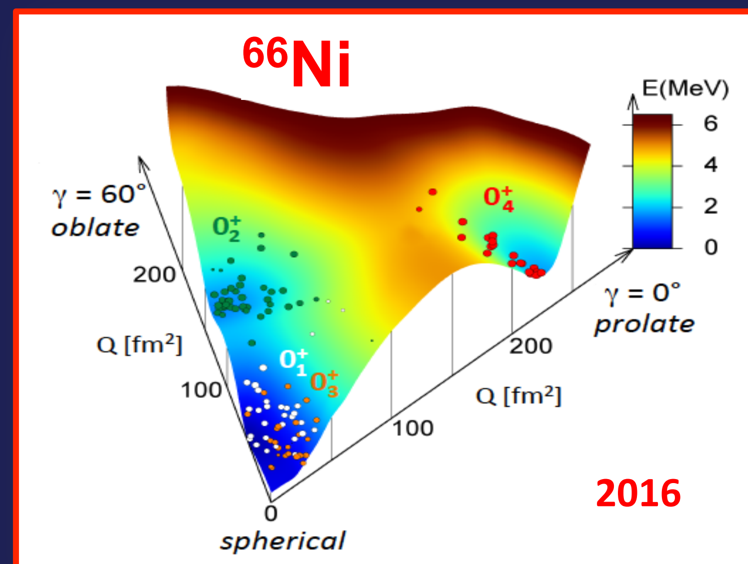


Microscopic Hartree-Fock plus BCS





Macro-Microscospic Model

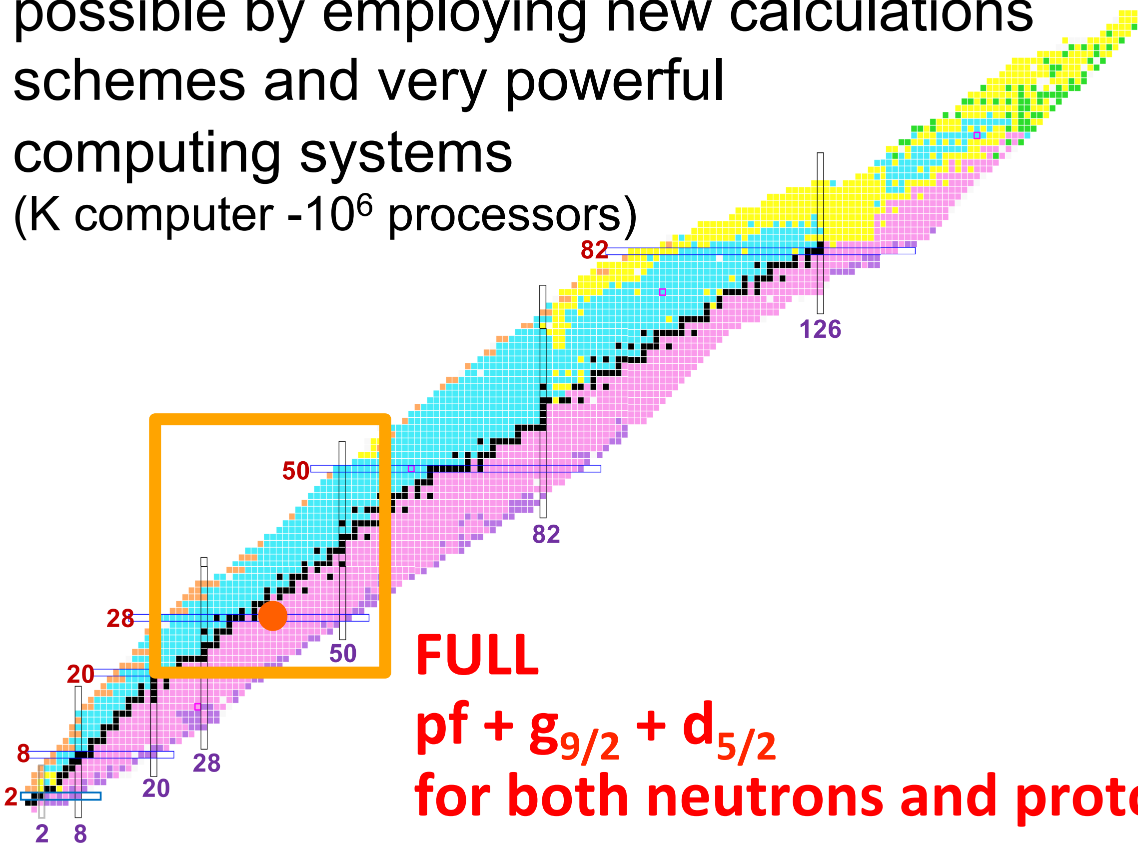


Monte Carlo Shell Model

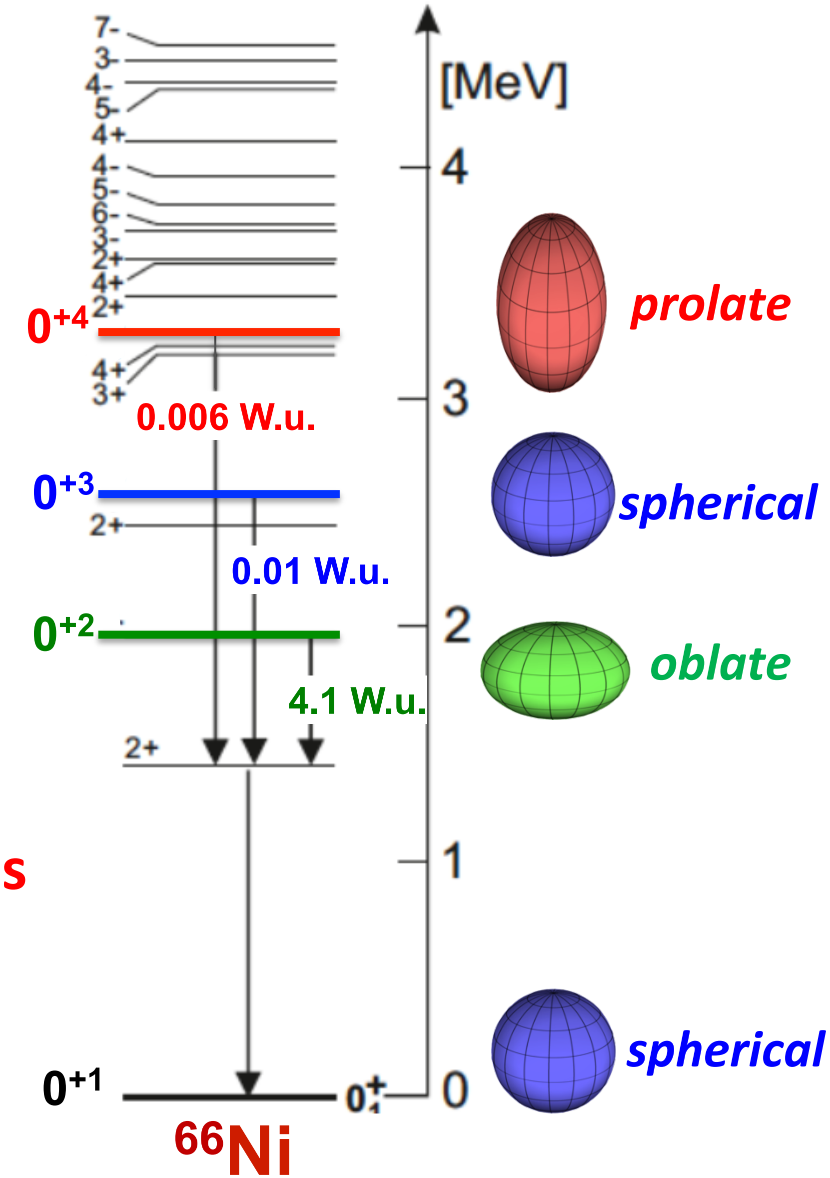
MONTE CARLO SHELL MODEL Calculations

Y. Tsunoda and T. Otsuka, Univ. of Tokyo

State-of-the-art Shell Model calculations possible by employing new calculations schemes and very powerful computing systems
(K computer -10^6 processors)



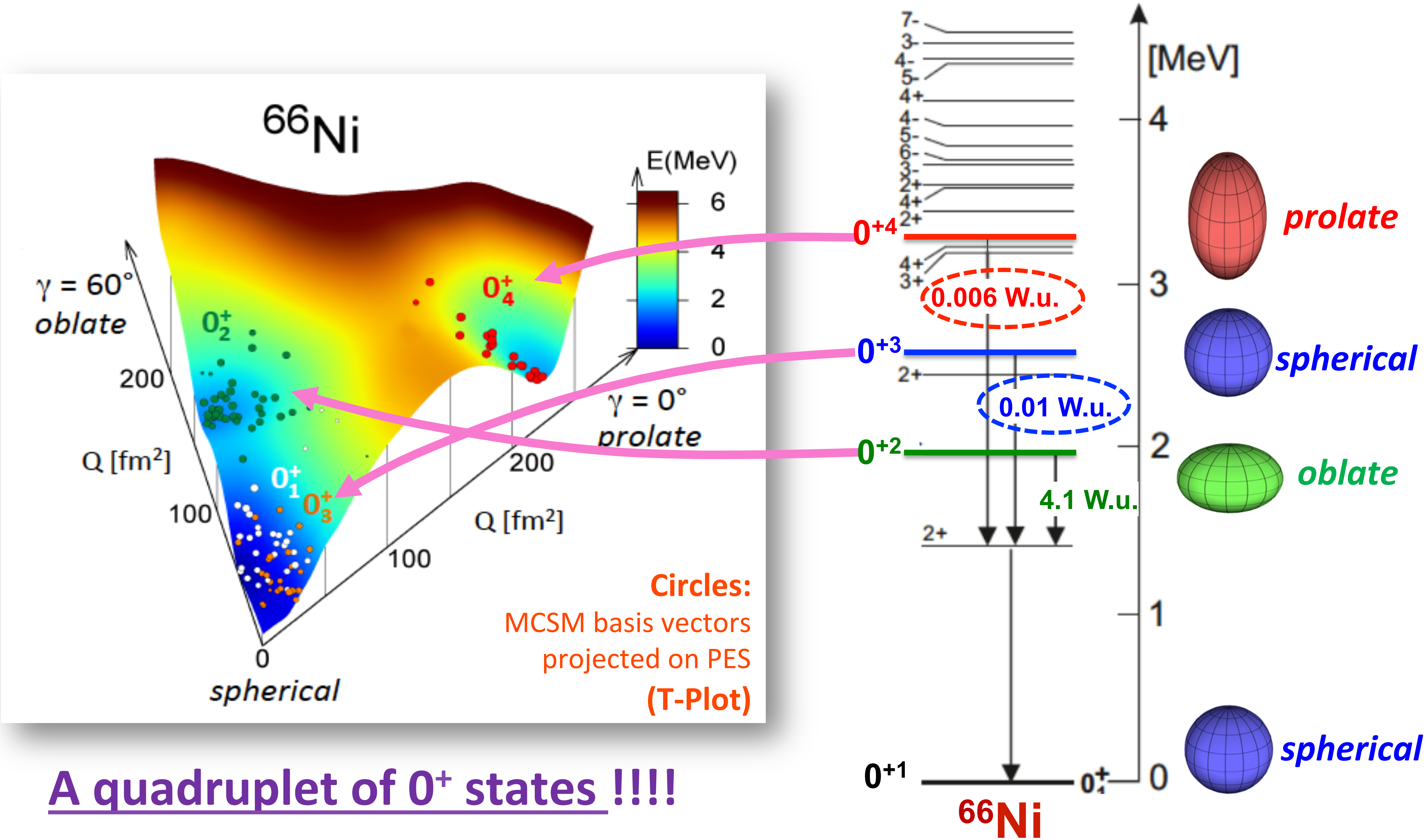
FULL
pf + $g_{9/2}$ + $d_{5/2}$
for both neutrons and protons



Detailed Microscopic Investigation:
- ○ Wave functions
- ○ B(Eλ/Mλ), ...

MONTE CARLO SHELL MODEL Calculations

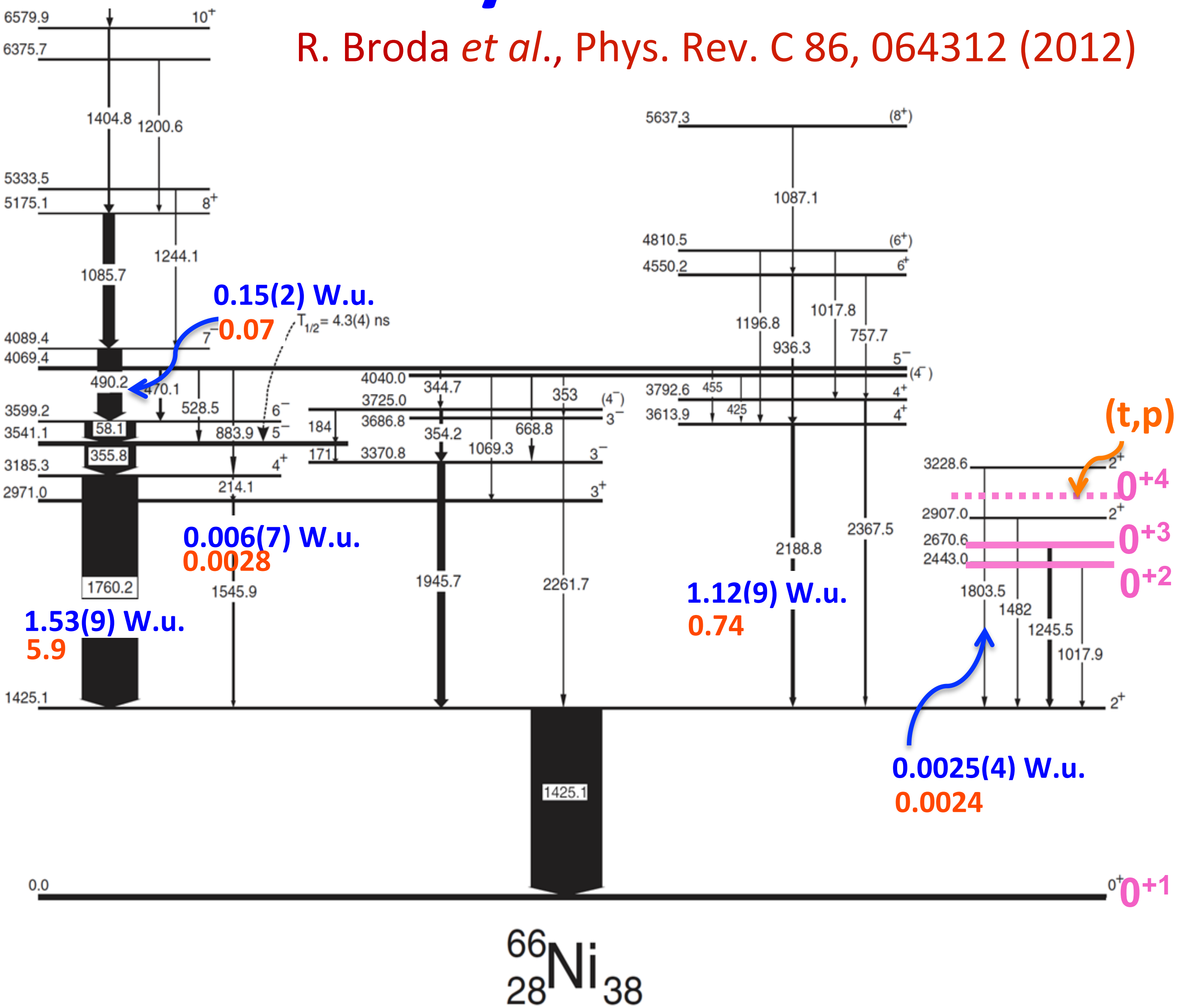
Y. Tsunoda and T. Otsuka, Univ. of Tokyo



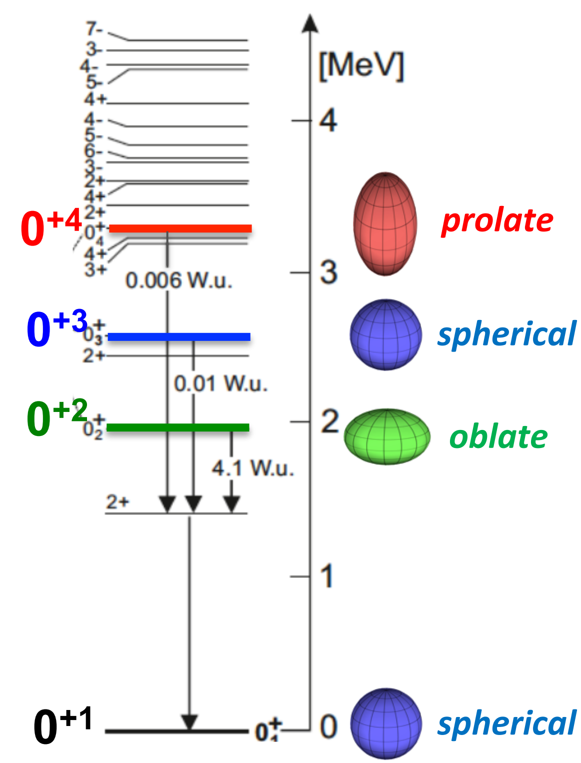
<u>A quadruplet of 0^+ states</u> !!!!

Decay Scheme of ^{66}Ni

R. Broda *et al.*, Phys. Rev. C 86, 064312 (2012)



Monte Carlo SHELL Model

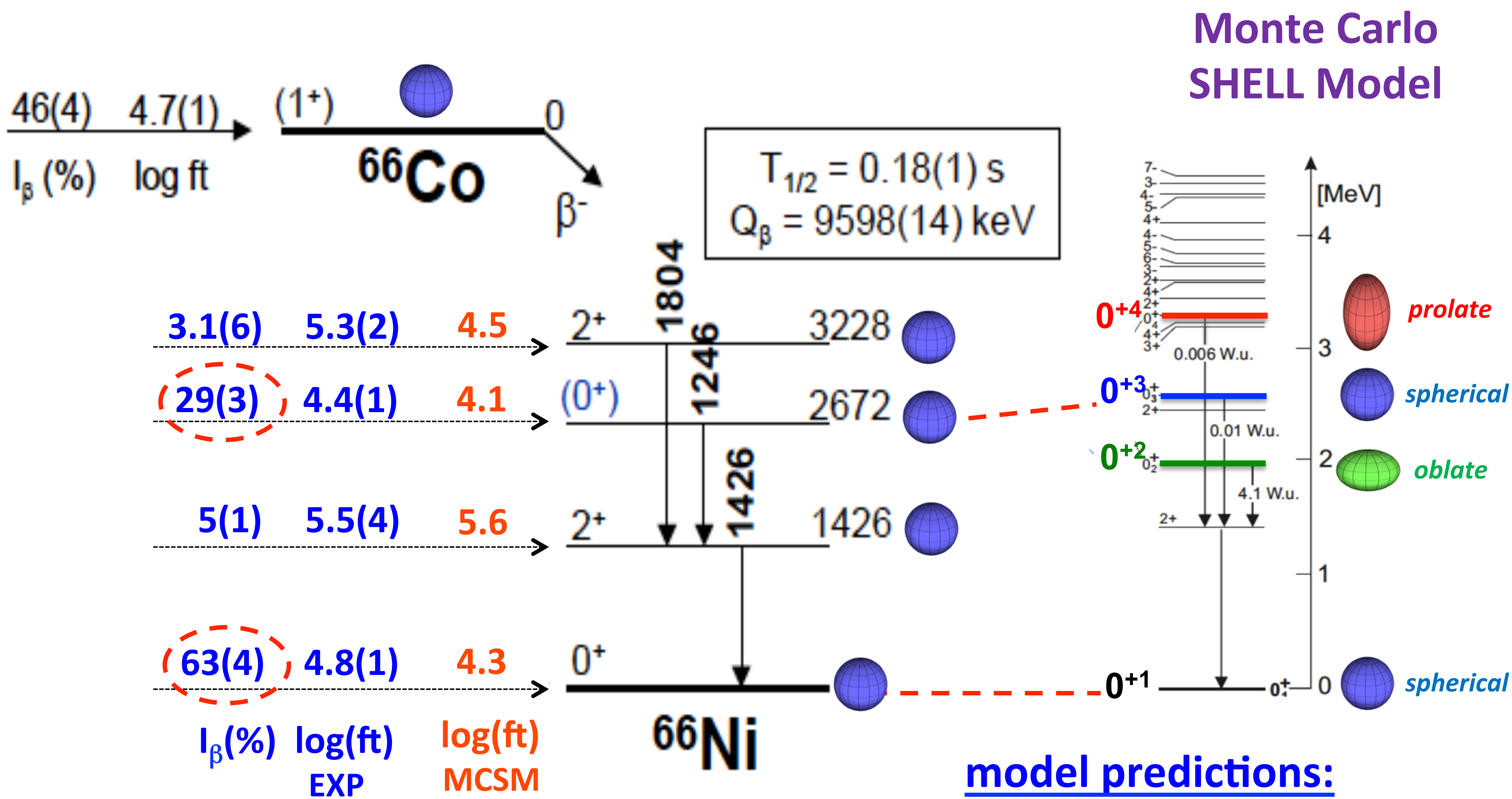


Excited states energies → One-to-one correspondence (**including 0⁺ states** !)

B(E2/M1) (from our Bucharest EXP) → very well reproduced !!

β-decay population of ^{66}Ni

D. Pauwels, P. Van Duppen *et al.*, ARIS-2011 Conference



model predictions:

population of 0^+ and 2^+ **spherical** states from **spherical** ^{66}Co g.s

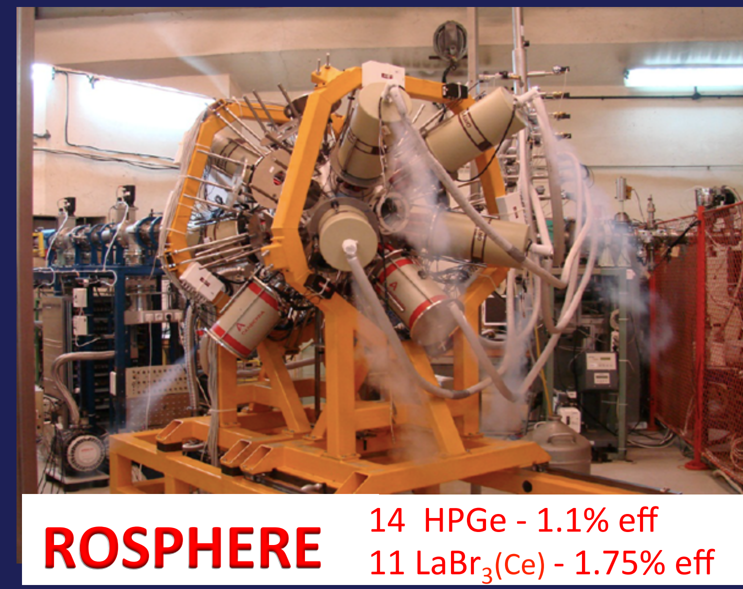
General agreement with **β-decay branches**

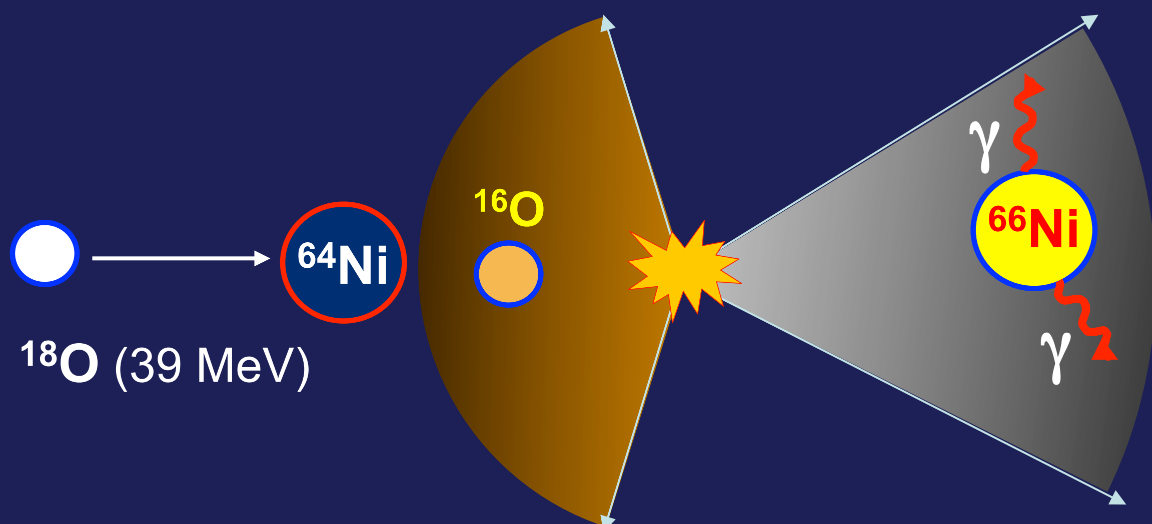
^{66}Fe→ ^{66}Co → ^{66}Ni

Our Bucharest Experiment (@IFIN HH)

$^{18}O + ^{64}Ni \rightarrow ^{16}O + ^{66}Ni$ (2n Transfer - 1 MeV below Coulomb Barrier)

$\sigma(^{66}Ni) \approx$ few mb - FUSION strongly suppressed





- **THICK Target** – 5 mg/cm^2
- **PLUNGER** - 12 distances
  From 10 to 3000 μm
  v/c ≈ 2.2 %
  TOF of 155 ps in 1 mm

> 1.5 month

30 pnA beam current

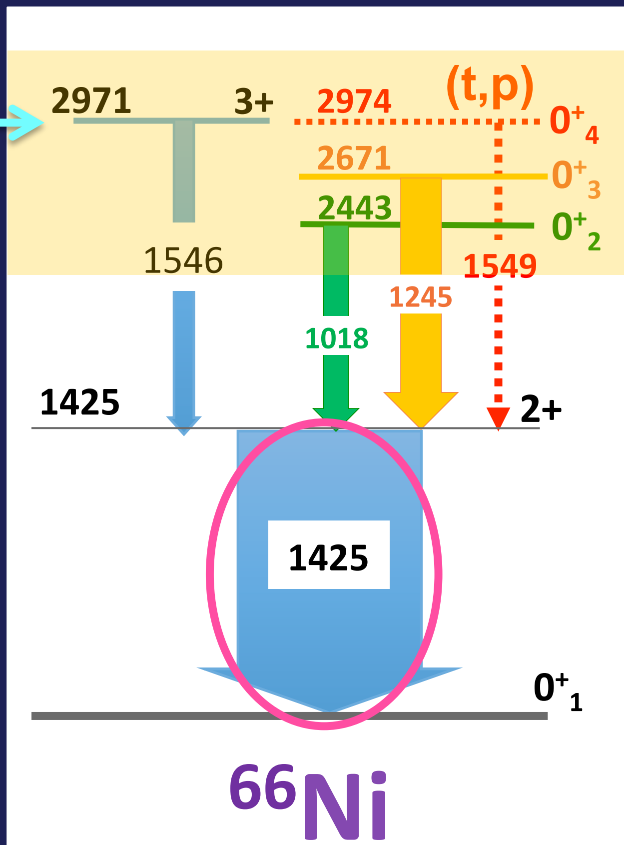
$^{18}O+^{64}Ni \rightarrow ^{16}O+^{66}Ni$

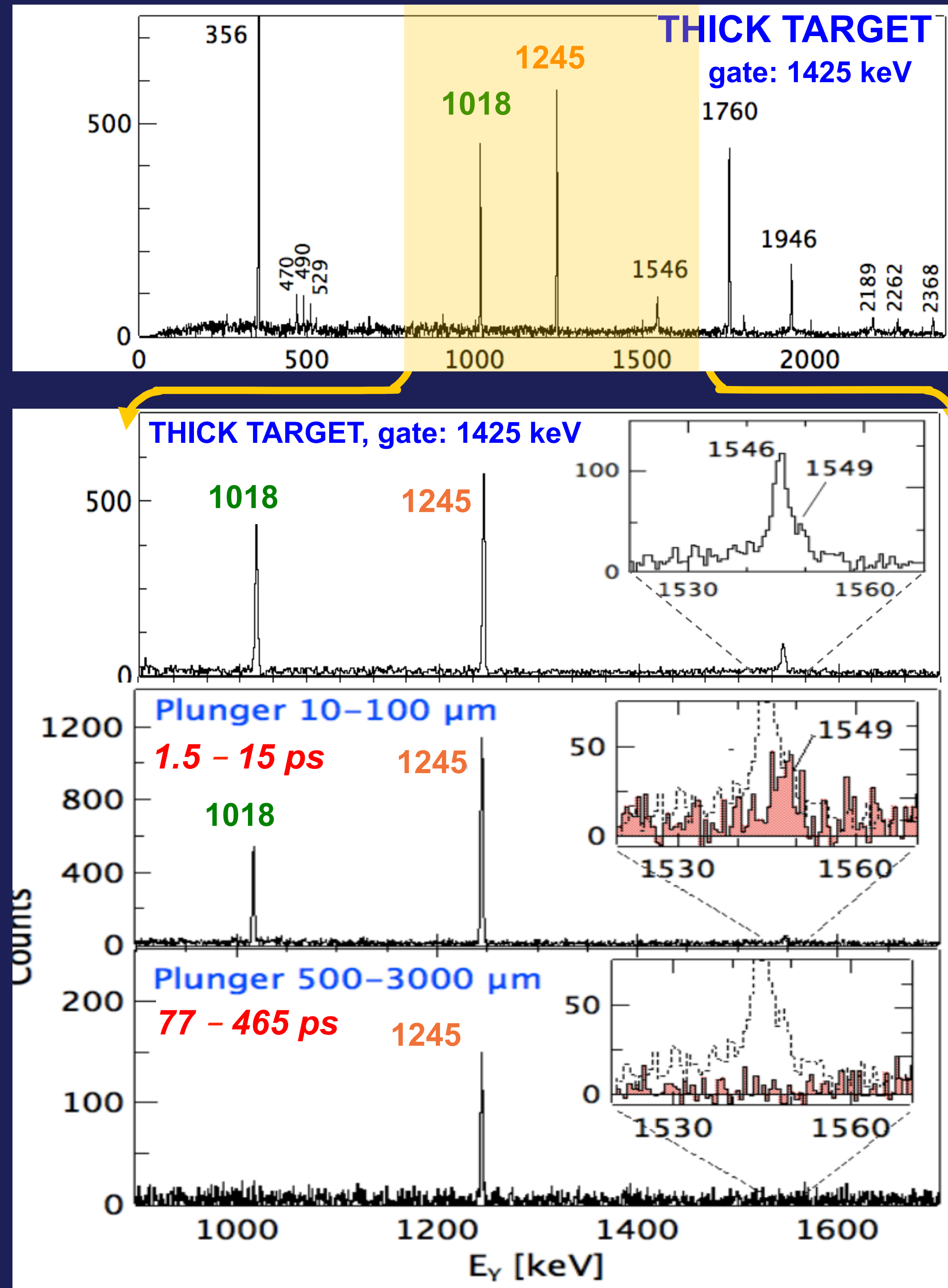
E_{beam} = 39 MeV

2n transfer below Coulomb Barrier

at IFIN HH Bucarest

1.4 ps (DSAM)





All transitions belong to ^{66}Ni !!

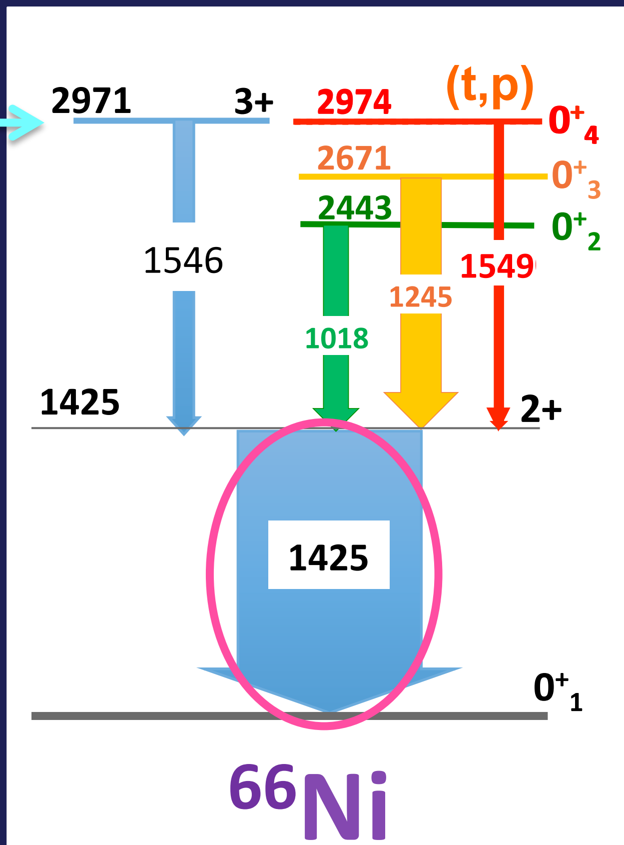
$^{18}O+^{64}Ni \rightarrow ^{16}O+^{66}Ni$

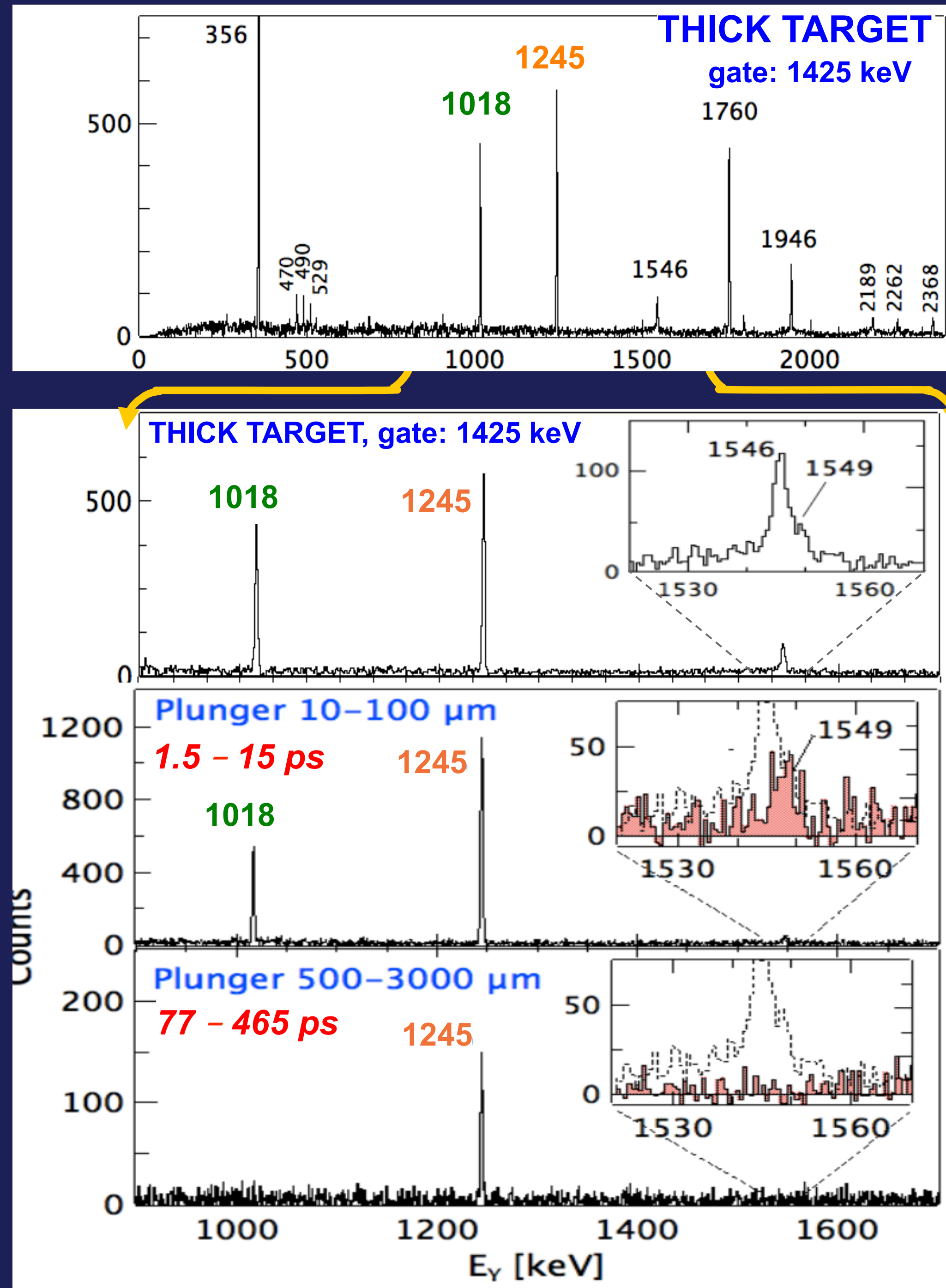
E_{beam} = 39 MeV

2n transfer below Coulomb Barrier

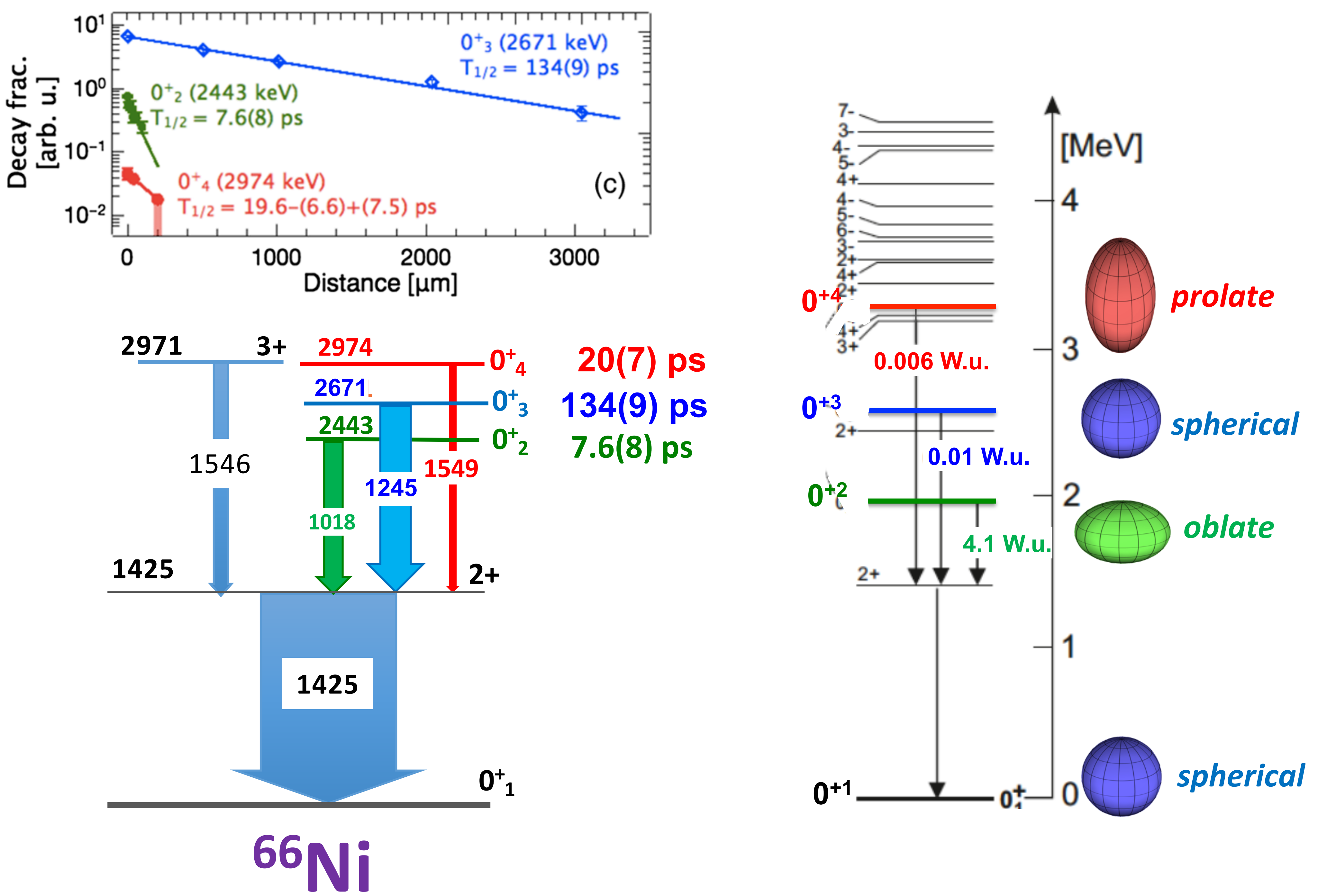
at IFIN HH Bucarest

1.4 ps (DSAM)

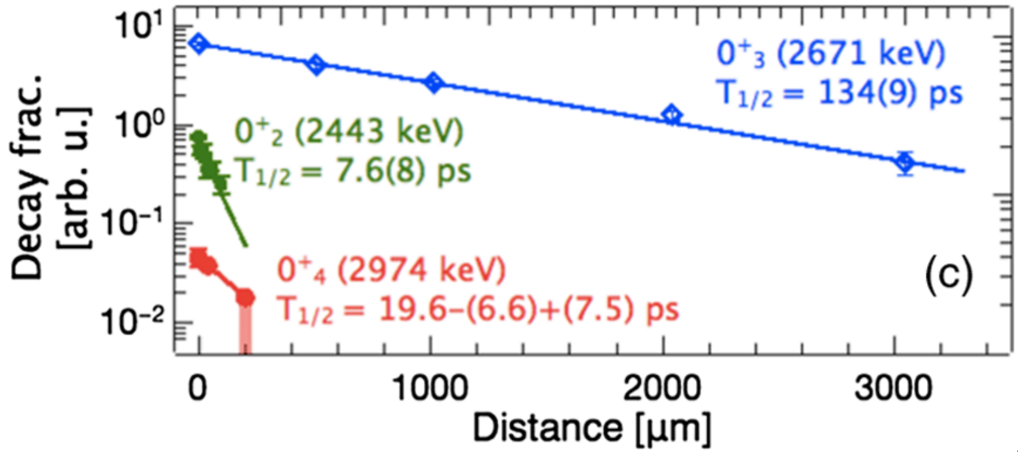


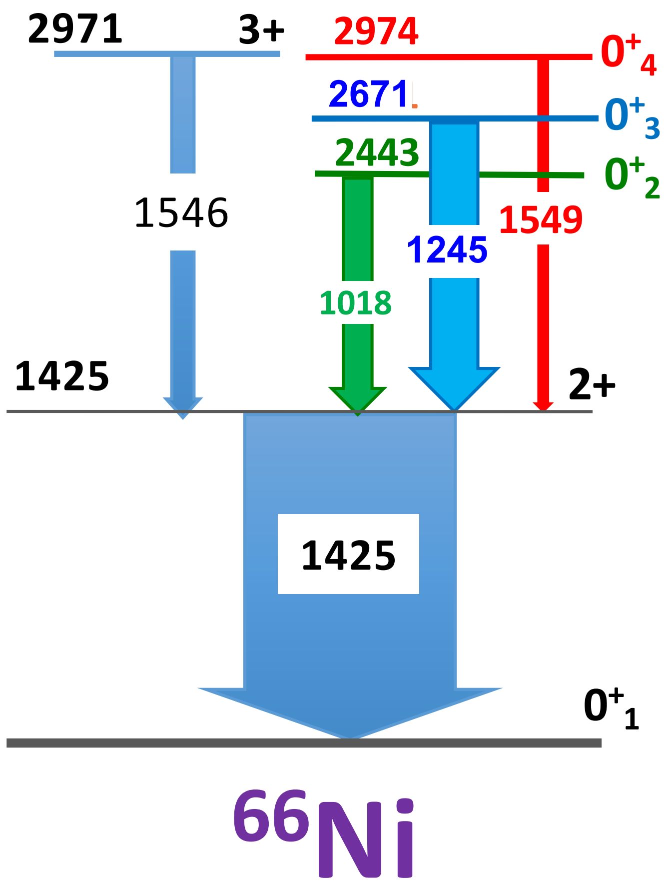


All transitions belong to ^{66}Ni !!



Decay frac. [arb. u.]
10^1
10^0
10^{-1}
10^{-2}
0^+_3 (2671 keV)
$T_{1/2}$ = 134(9) ps
0^+_2 (2443 keV)
$T_{1/2}$ = 7.6(8) ps
0^+_4 (2974 keV)
$T_{1/2}$ = 19.6–(6.6)+(7.5) ps
(c)
0
1000
2000
3000
Distance [µm]
2971
3+
2974
0^+_4
20(7) ps
2671
0^+_3
134(9) ps
2443
0^+_2
7.6(8) ps
1546
1549
1245
1018
1425
2+
1425
0^+_1
^{66}Ni
7-
3-
4-
5-
4+
4-
5-
6-
3-
2+
4+
2+
0^{+4}
4+
3+
0.006 W.u.
0^{+3}
2+
0.01 W.u.
0^{+2}
4.1 W.u.
2+
0^{+1}
0^+_1
[MeV]
4
3
2
1
0
prolate
spherical
oblate
spherical





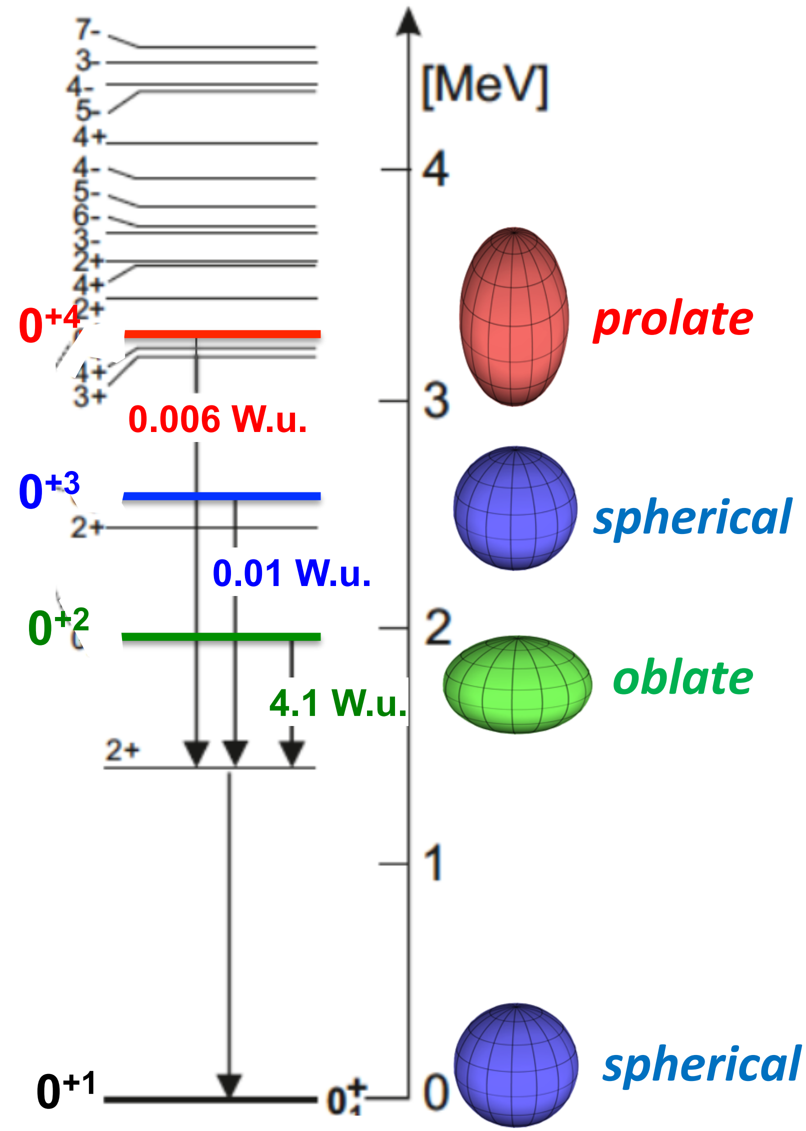
!!!!!!!!!!!!!

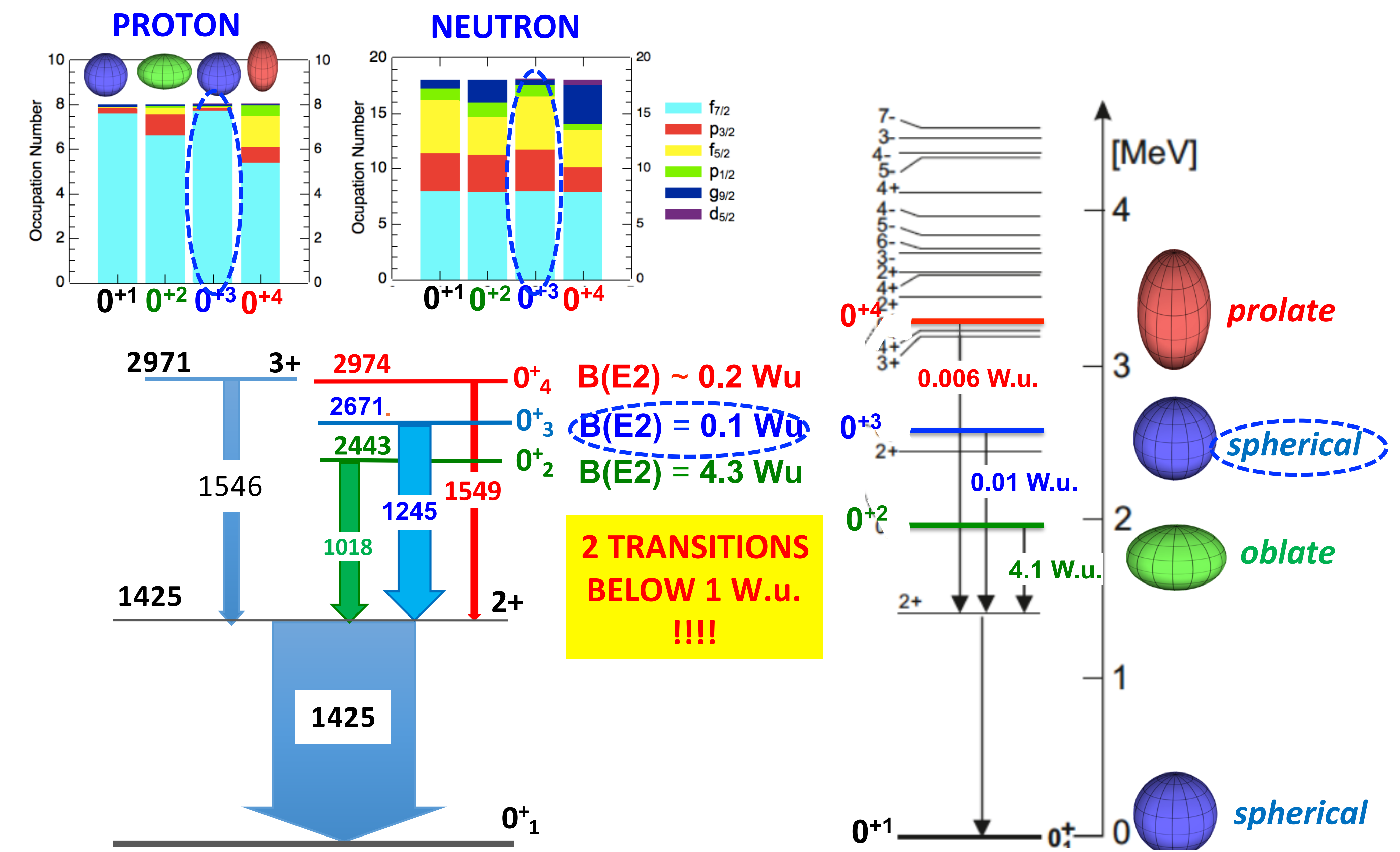
B(E2) ~ 0.2 Wu

B(E2) = 0.1 Wu

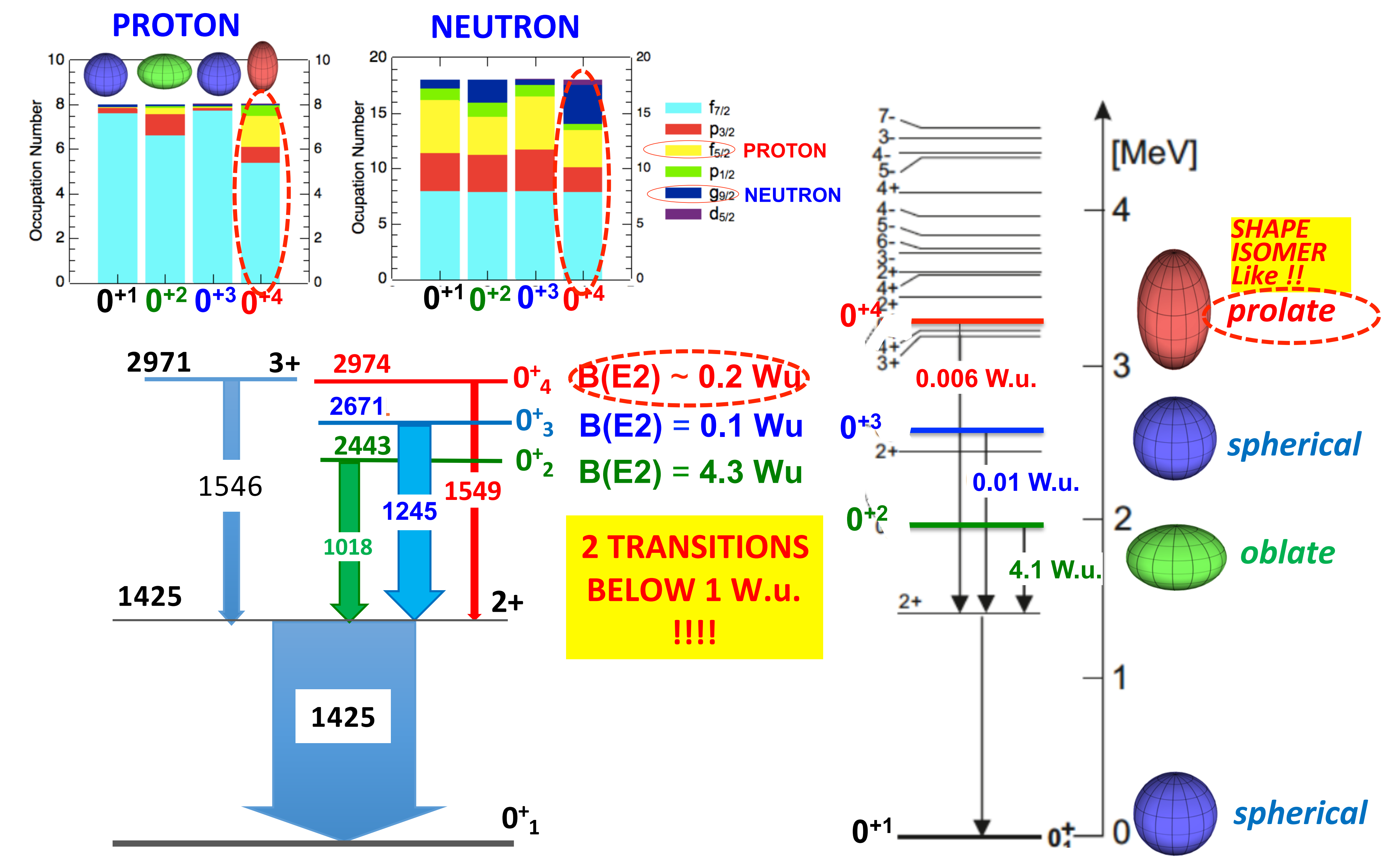
B(E2) = 4.3 Wu

2 TRANSITIONS BELOW 1 W.u. !!!!

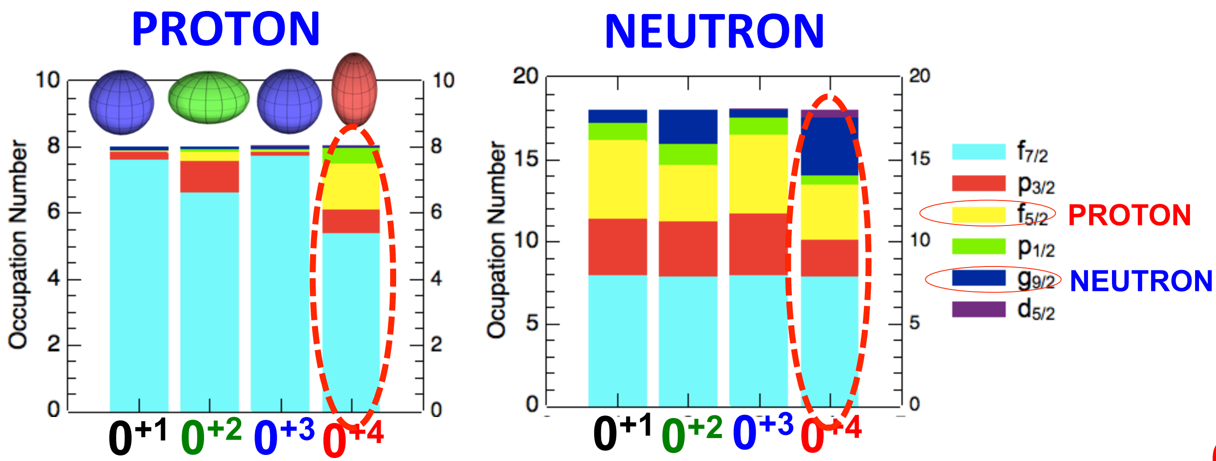




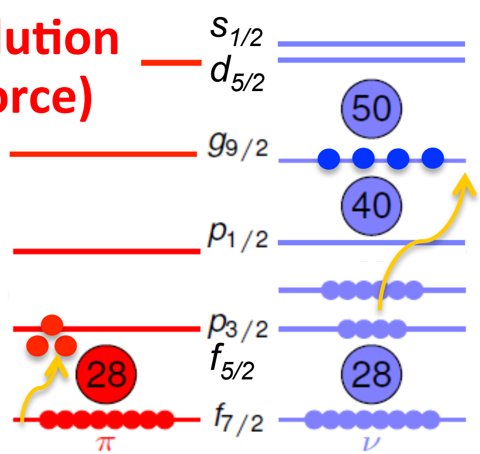
0^+_3 is spherical (very similar to 0^+_1): HINDRANCE due to **cancellation** of matrix elements



0^+_4 **is prolate:** HINDRANCE due to **shape change** through high potential barrier !!!!



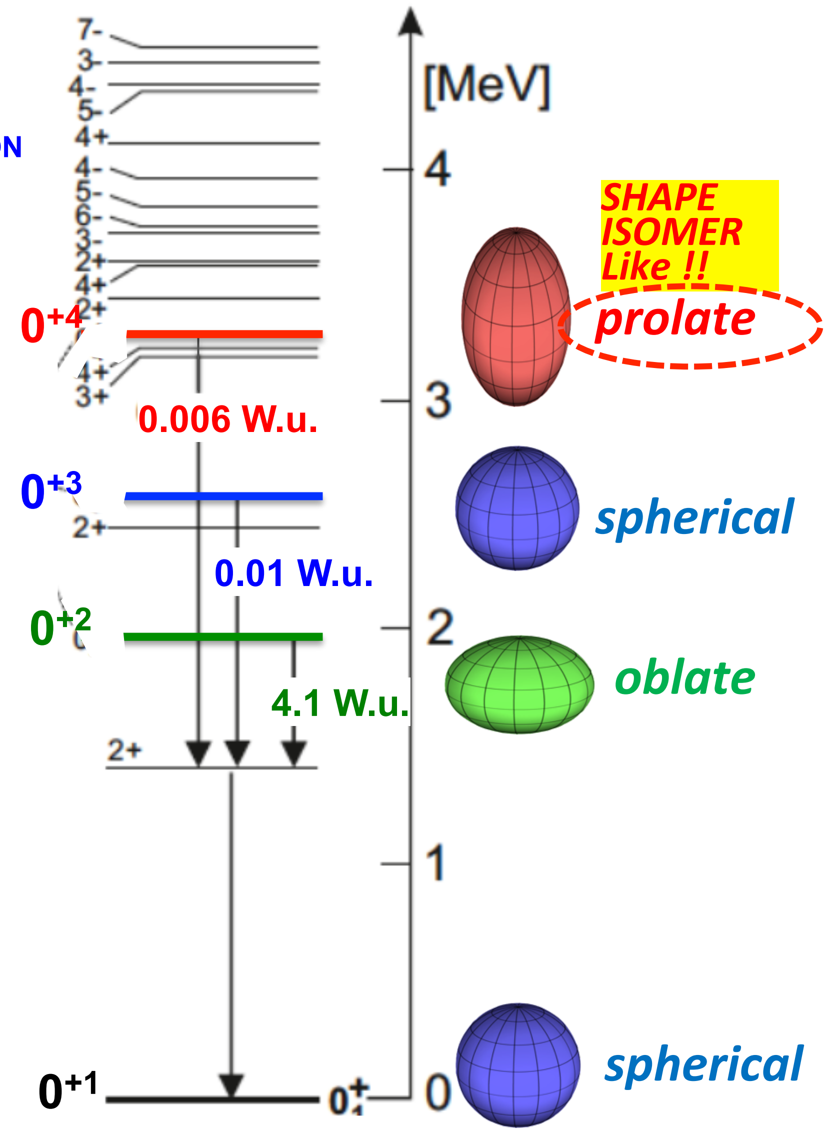
Type II SHELL Evolution (tensor force)



STABILIZATION of DEFORMED Local Minima

↓

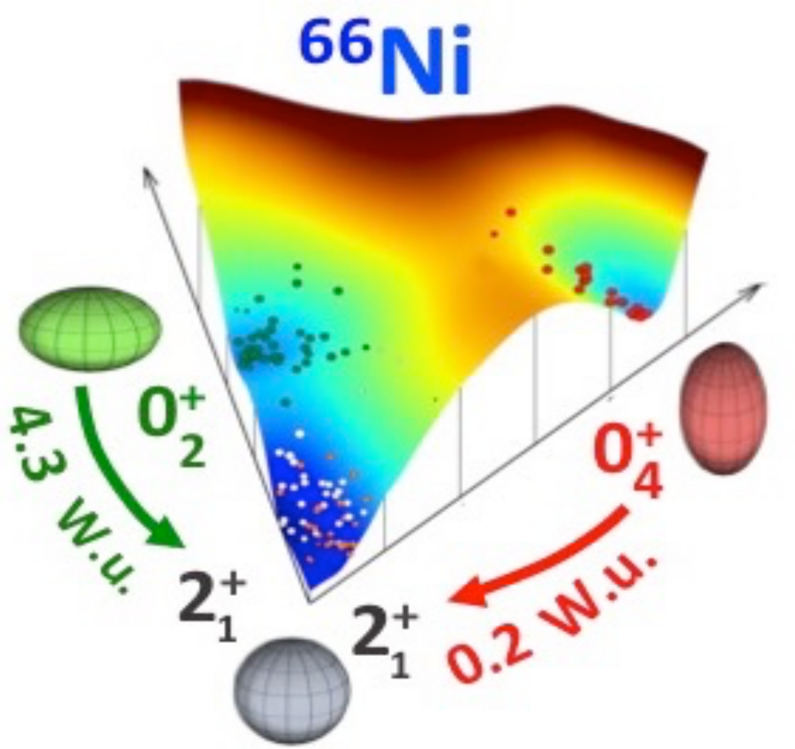
SHAPE COEXISTENCE



WITHIN the SAME nucleus

change of major configurations:
sizable excitations of ν in $g_{9/2}$
reduced proton spin-orbit splitting

0^+_4 is prolate: HINDRANCE due to **shape change** through high potential barrier !!!



^{66}Ni:

lightest and unique example

- apart from the actinides –

of 0^+ deformed state deexciting
via HINDERED γ transition

a SHAPE-ISOMER-like structure !!!!

A probe of TYPE II SHELL Evolution:

rearrengement of nucleons in orbitals
causes emergence of deformation

PRL 118, 162502 (2017) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2017

Multifaceted Quadruplet of Low-Lying Spin-Zero States in ^{66}Ni: Emergence of Shape Isomerism in Light Nuclei

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***** Thank You for the Attention *****

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UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

IVth Topical Workshop on Modern Aspects in Nuclear Structure

The Many Facets of Nuclear Structure

BORMIO 19 - 25 February 2018

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Scient. Secretaries: F. Crespi, X. Roca-Maza

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