W poszukiwaniu jądrowych izomerów kształtu
(In search of nuclear shape isomers)

Bogdan Fornal

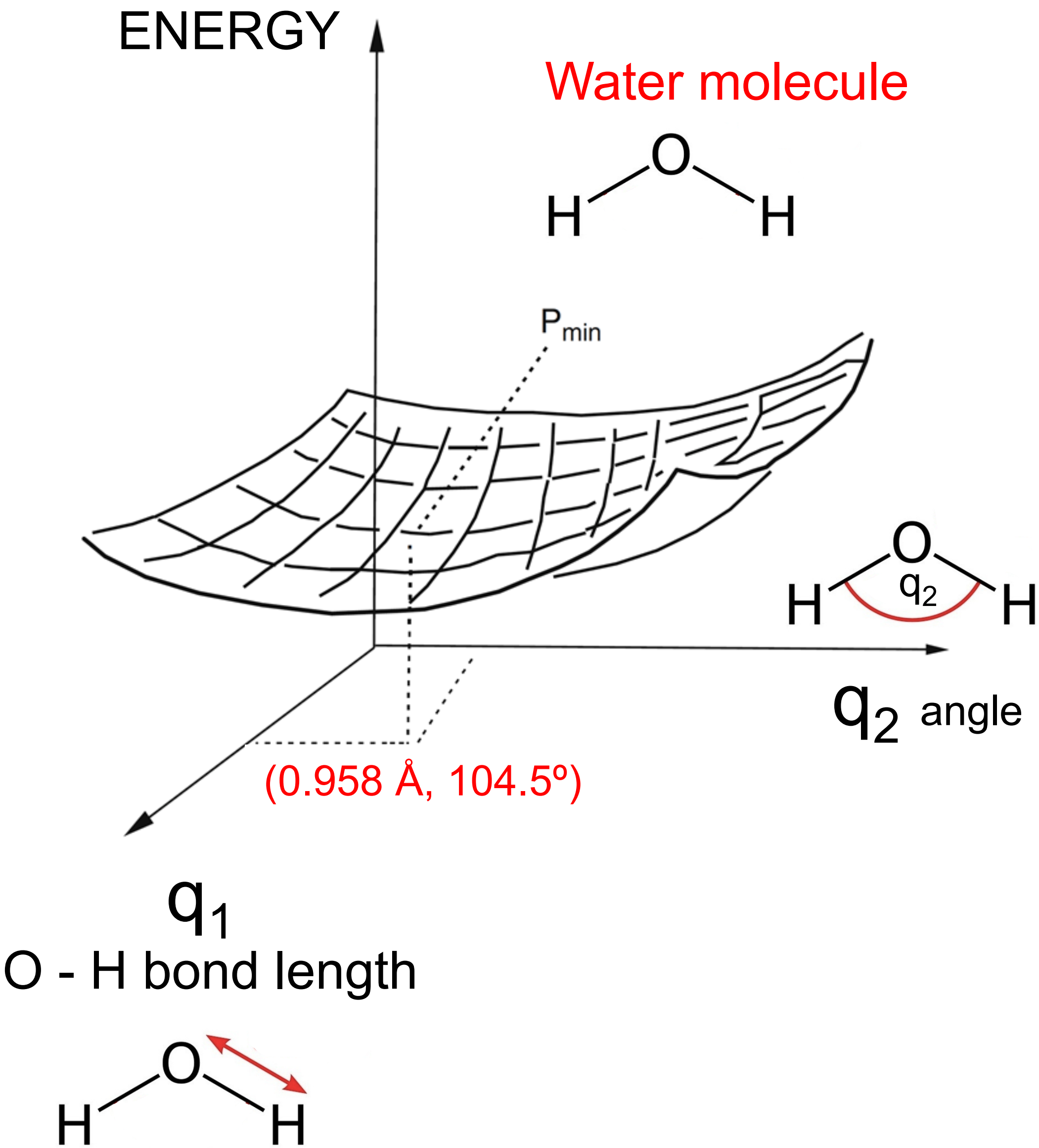
Institute of Nuclear Physics,Polish Academy of Sciences
Krakow, Poland

Collaboration with: University of Milan and INFN Milan, Italy
Universite libre de Bruxelles, Belgium
IFIN HH and ELI, Bucharest, Romania
University of Tokyo, Japan

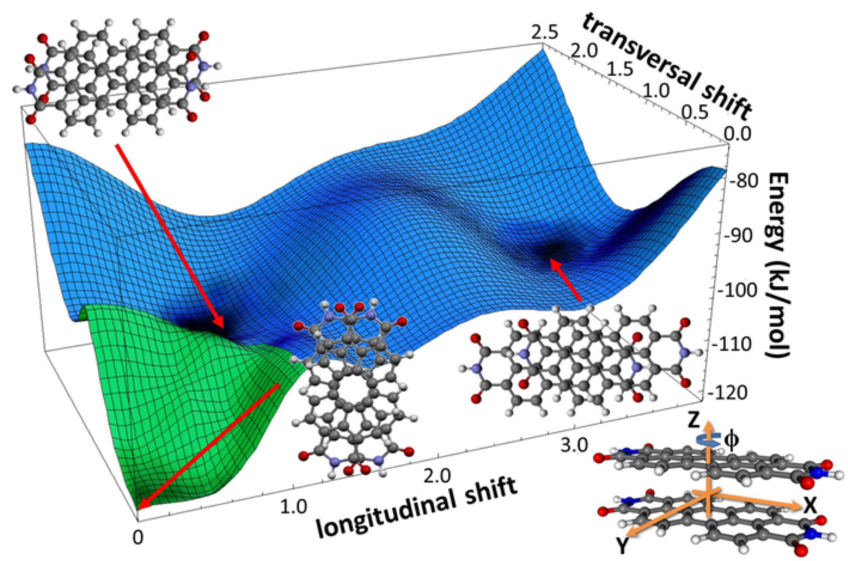
Plan

- Introduction
- Fission isomers – shape isomers.
- Shape coexistence vs. shape isomerism.
- Model predictions of secondary minima in the nuclear potential energy surfaces (PES).
- Candidates for deep minima in PES.
- Experiment – exploration of decay from the secondary PES minima in ^{66}Ni.
- Summary

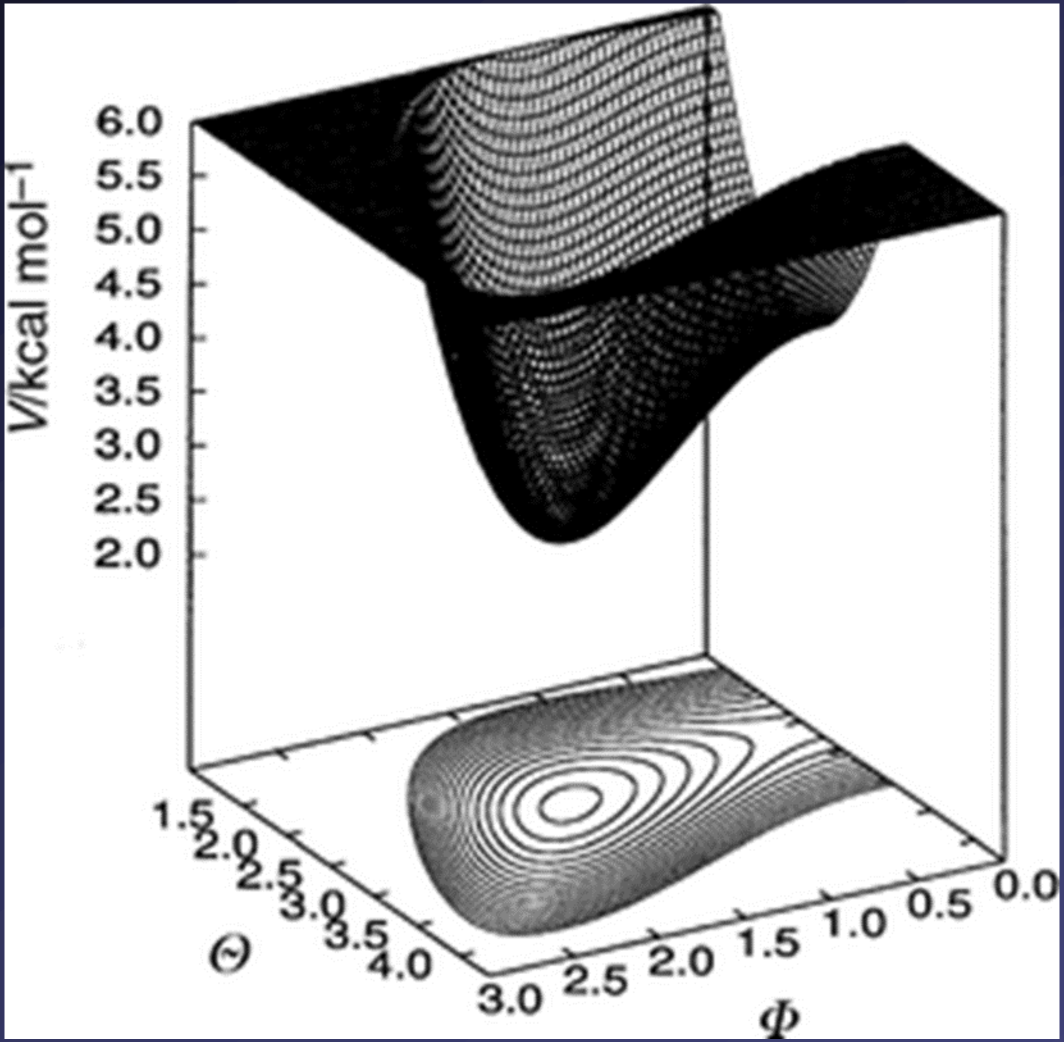
Potential energy surface (PES) (molecules)



Complex molecule



Representation of potential energy surface by two-dimensional contour

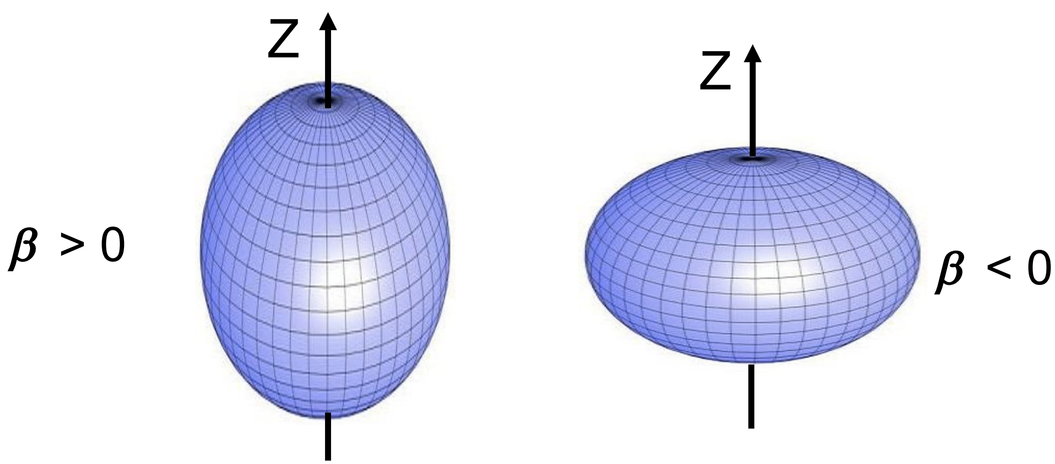


Parametrization of the nuclear shape

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

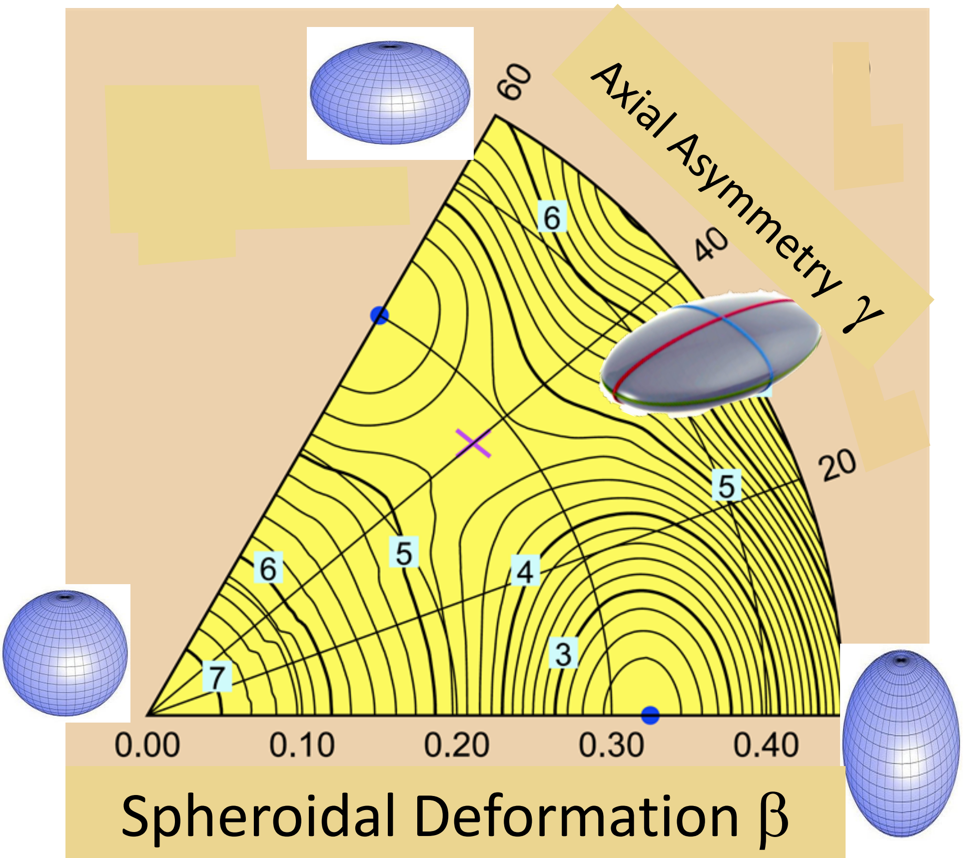
In case we consider only quadrupole deformation

$$a_{20} = \beta\cos\gamma \qquad a_{22} = (1/\sqrt{2})\beta\sin\gamma$$

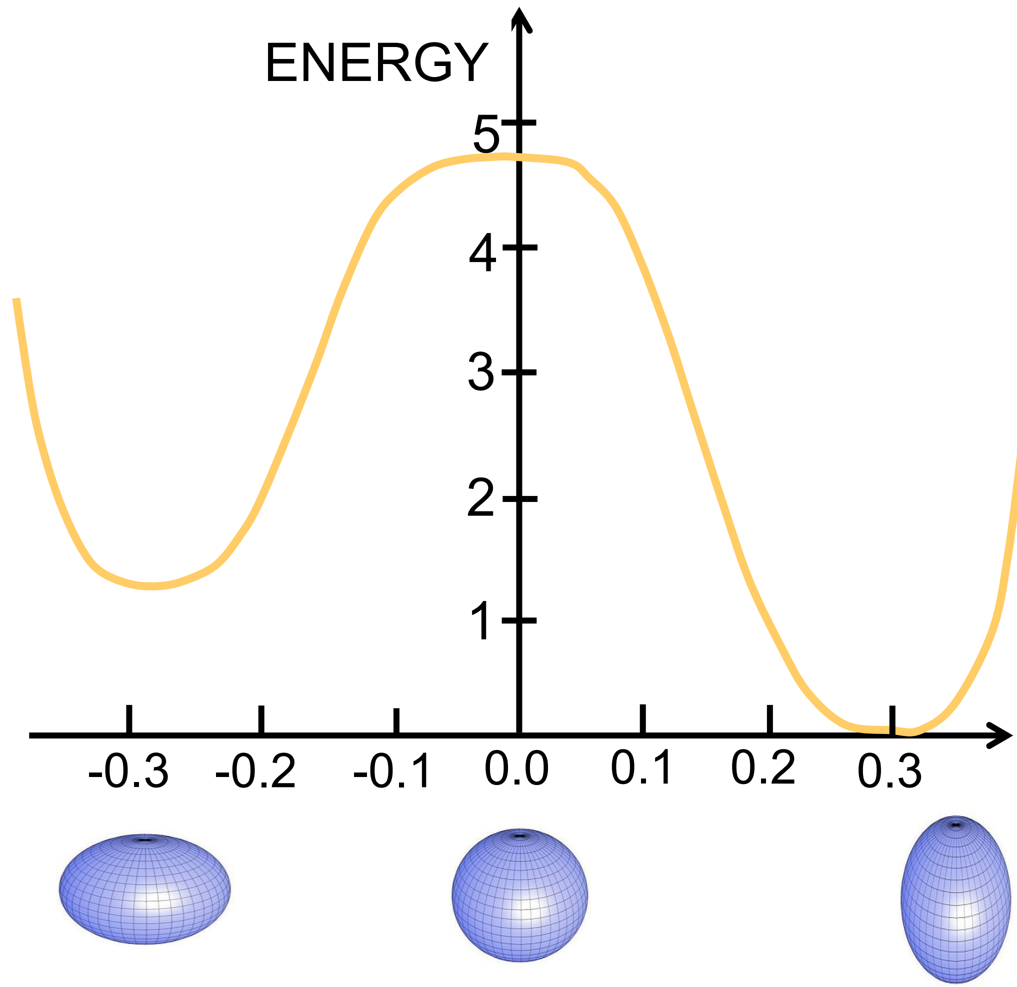


Potential energy surface (PES) of a nucleus

two-dimensional contour



one-dimensional representation



PHYSICAL REVIEW VOLUME 89, NUMBER 5 MARCH 1 1953

Nuclear Constitution and the Interpretation of Fission Phenomena

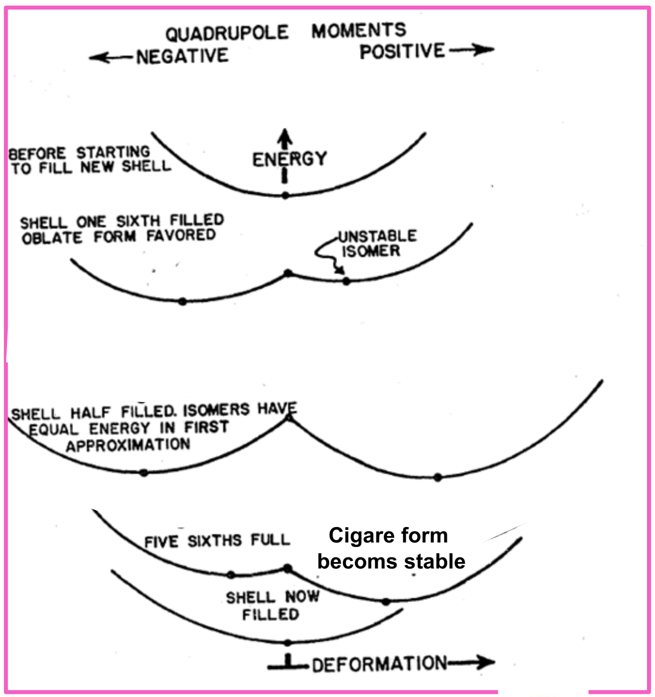
DAVID LAWRENCE HILL*
Vanderbilt University, Nashville, Tennessee, and Los Alamos Scientific Laboratory, Los Alamos, New Mexico

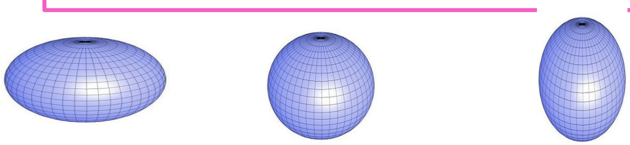
AND

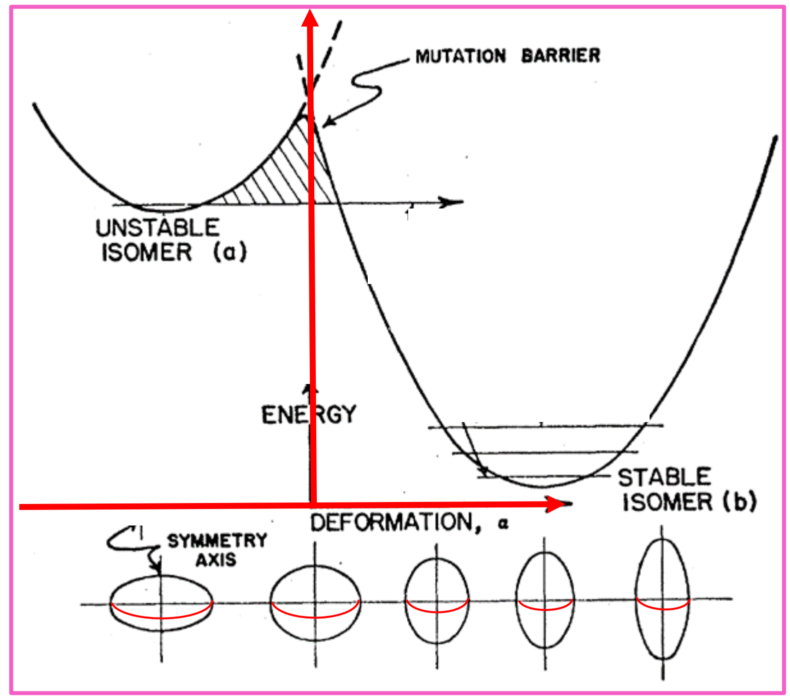
JOHN ARCHIBALD WHEELER†
Princeton University, Princeton, New Jersey, and Los Alamos Scientific Laboratory, Los Alamos, New Mexico

(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.

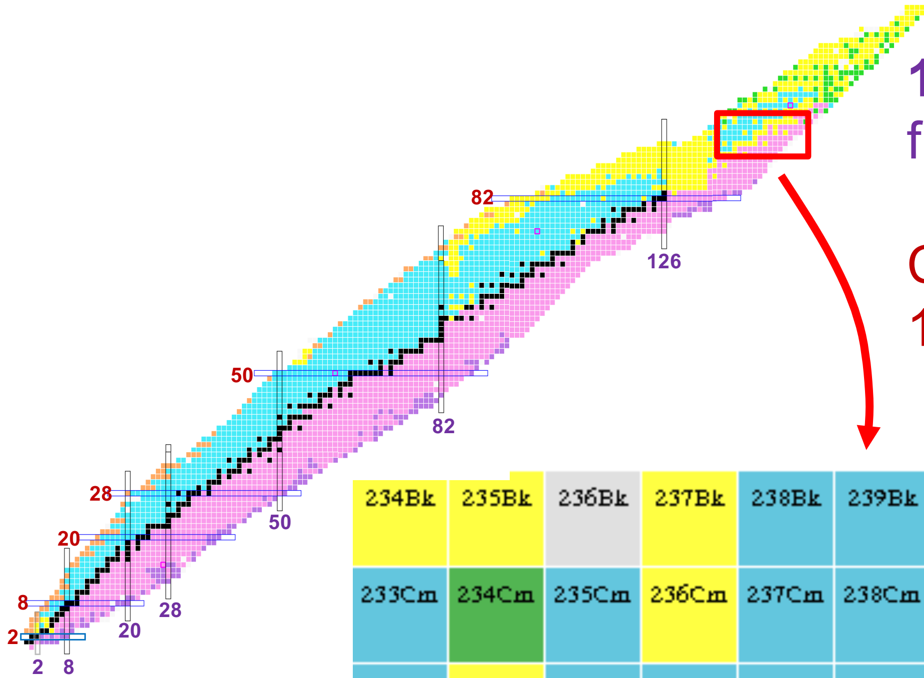






1961 - discovery of the first spontaneously fissioning isomer in ^{242}Am with a half-life 14 msec.

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

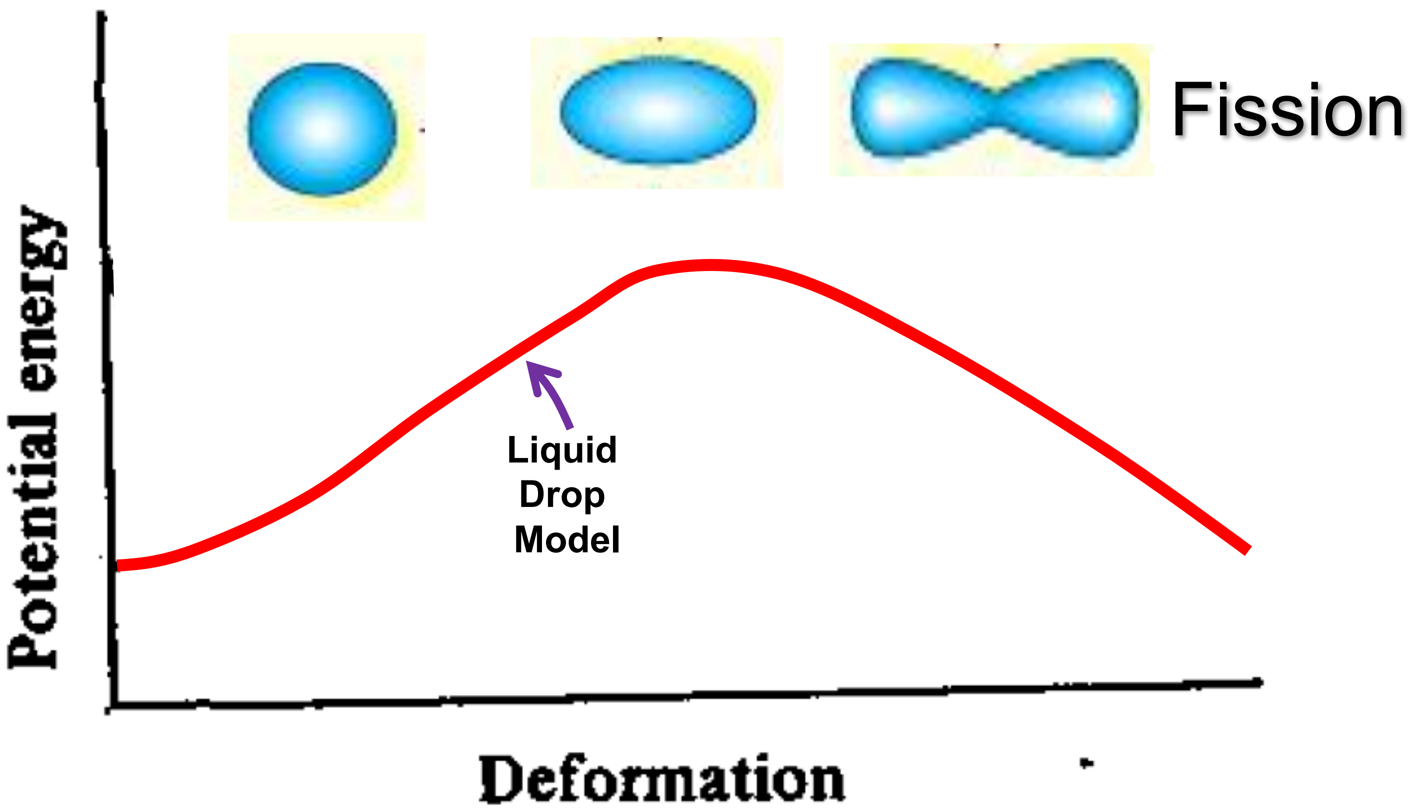
Physics of Our Days

NUCLEAR SHAPE ISOMERS

S. M. POLIKANOV

Joint Institute for Nuclear Research, Dubna

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



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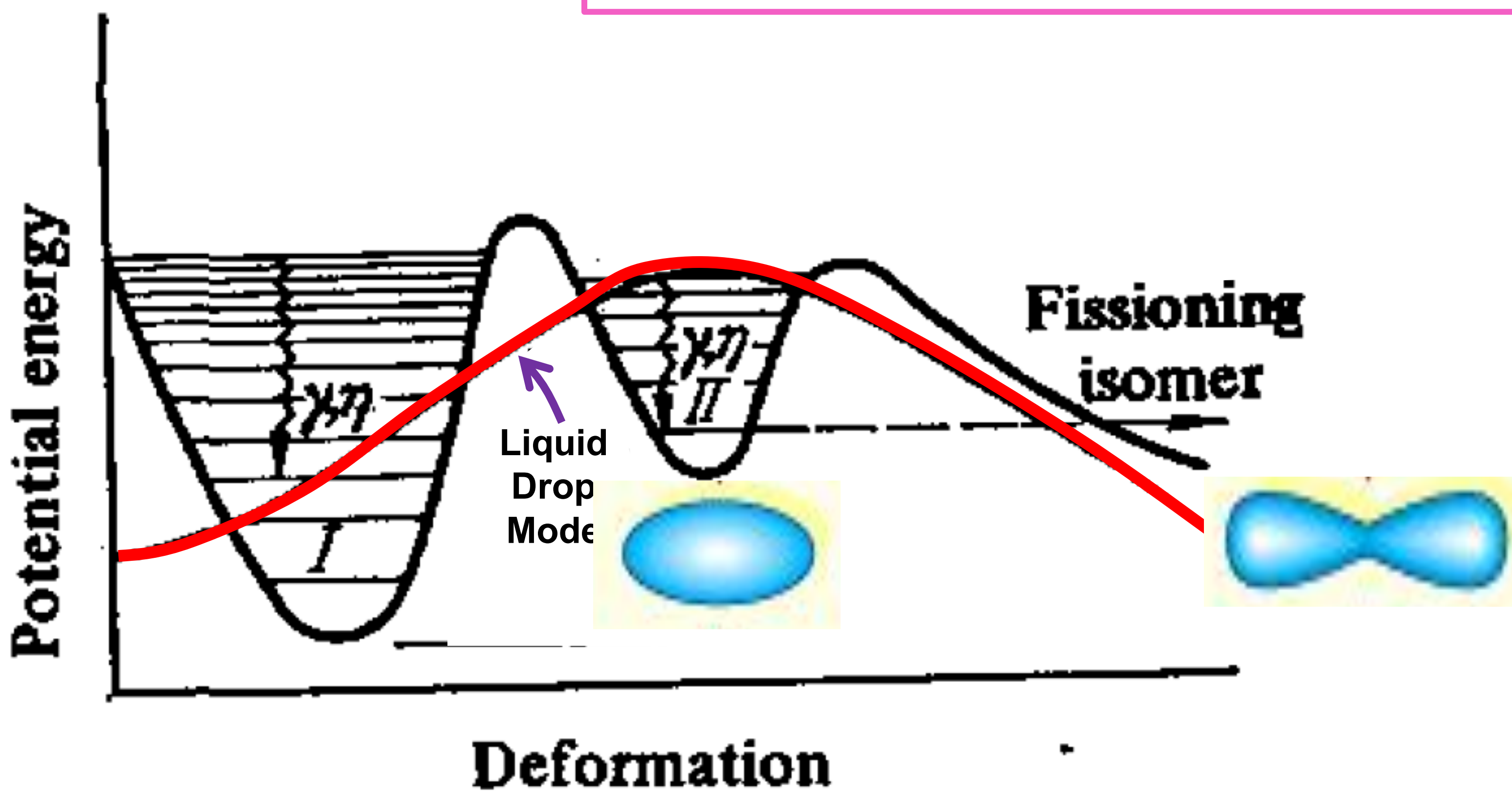
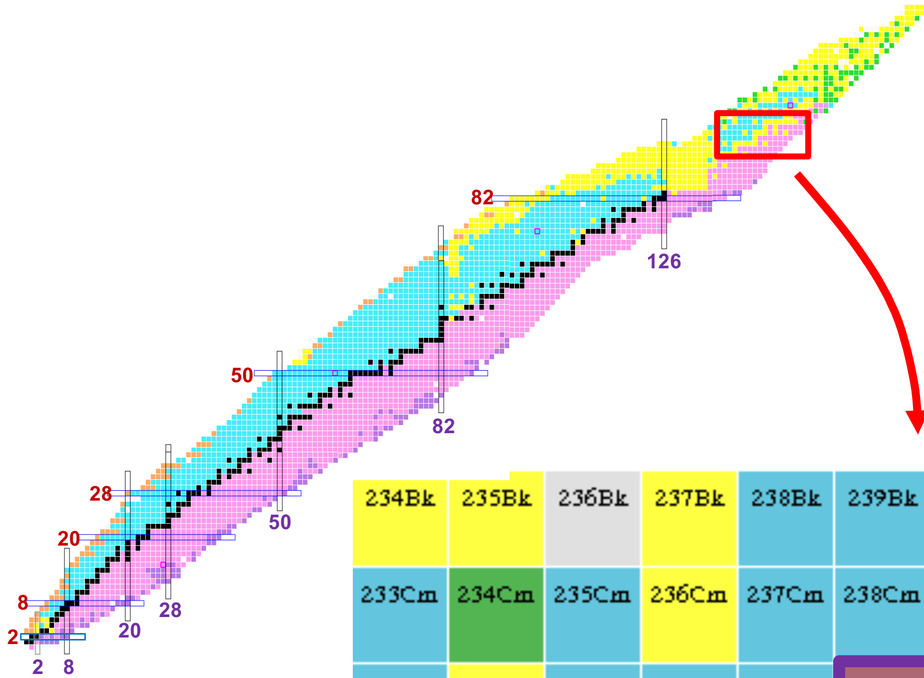
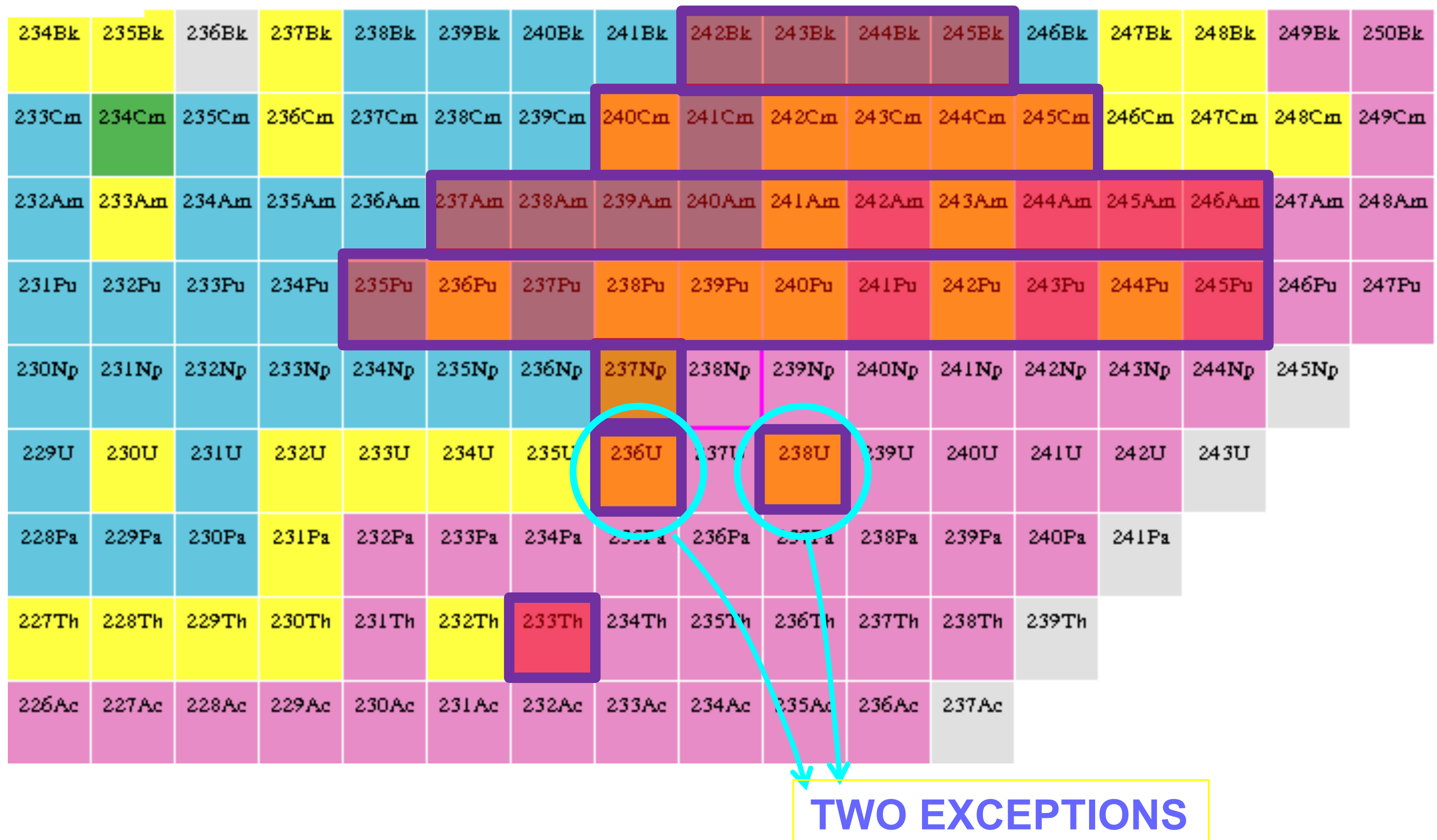


Shape isomers in actinides

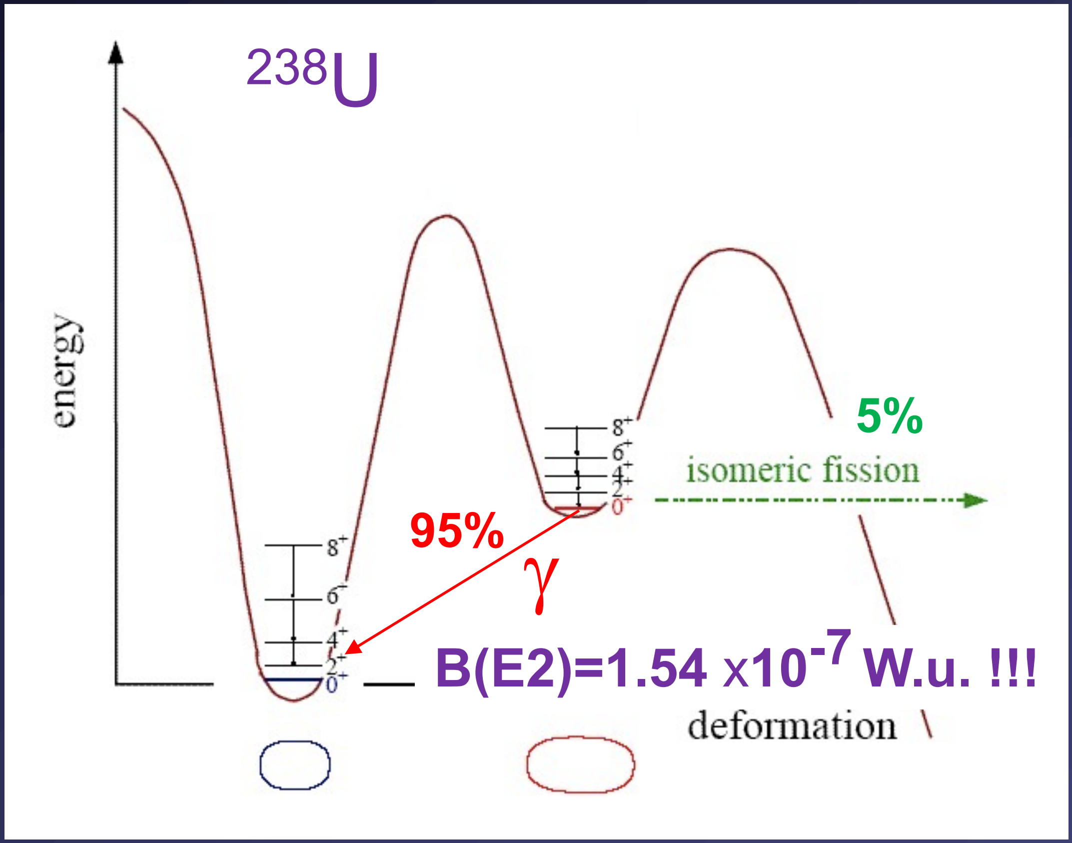
- HIGH Potential BARRIER
- Nucleus trapped In the second minimum
- Spontaneous fission from the second minimum





SHAPE ISOMERS:

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



Can OTHER (lighter) nuclei exhibit these features ?

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)

REVIEWS OF MODERN PHYSICS, VOLUME 83, OCTOBER–DECEMBER 2011

Shape coexistence in atomic nuclei

Kris Heyde*

Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Gent, Belgium

John L. Wood†

School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430, USA

(published 30 November 2011; publisher error corrected 6 December 2011)

The status of shape coexistence in nuclei has evolved:

i) **from an exotic rarity (1980'),**

ii) **via the perception that it is a phenomenon which exhibits "islands of occurrence" (1990')**

iii) **to the current position in which it seems to occur in all** (but the lightest) **nuclei.**

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2016

Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **43** (2016) 020402 (4pp)

doi:10.1088/0954-3899/43/2/020402

Editorial

CrossMark

A focus on shape coexistence in nuclei

edited by: K Heyde and J L Wood

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Unique and complementary information on shape coexistence in the neutron-deficient Pb region derived from Coulomb excitation

K Wrzosek-Lipska and L P Gaffney

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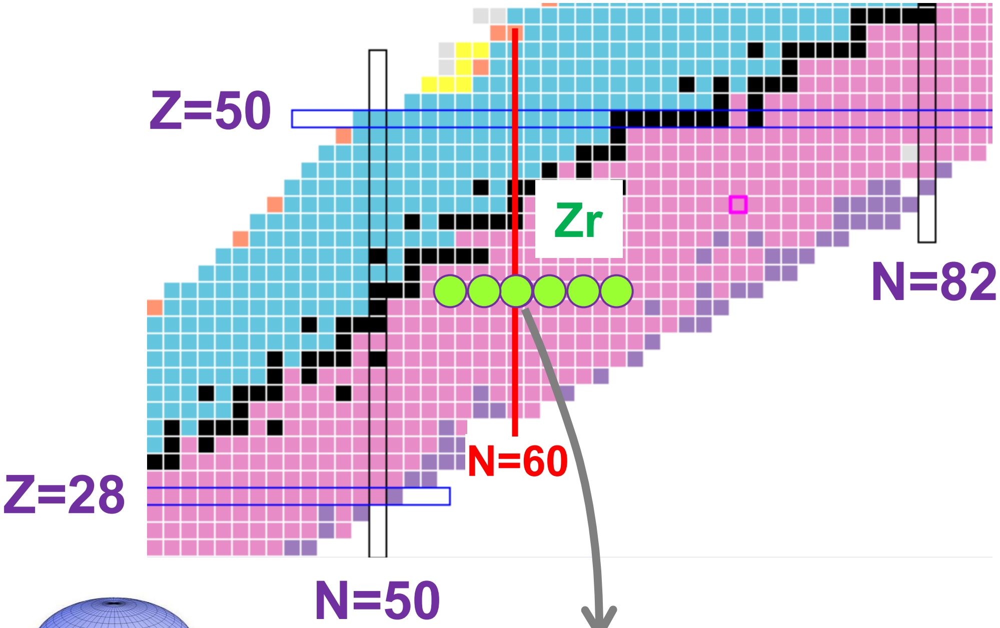


N·H
ELSEVIER

1997

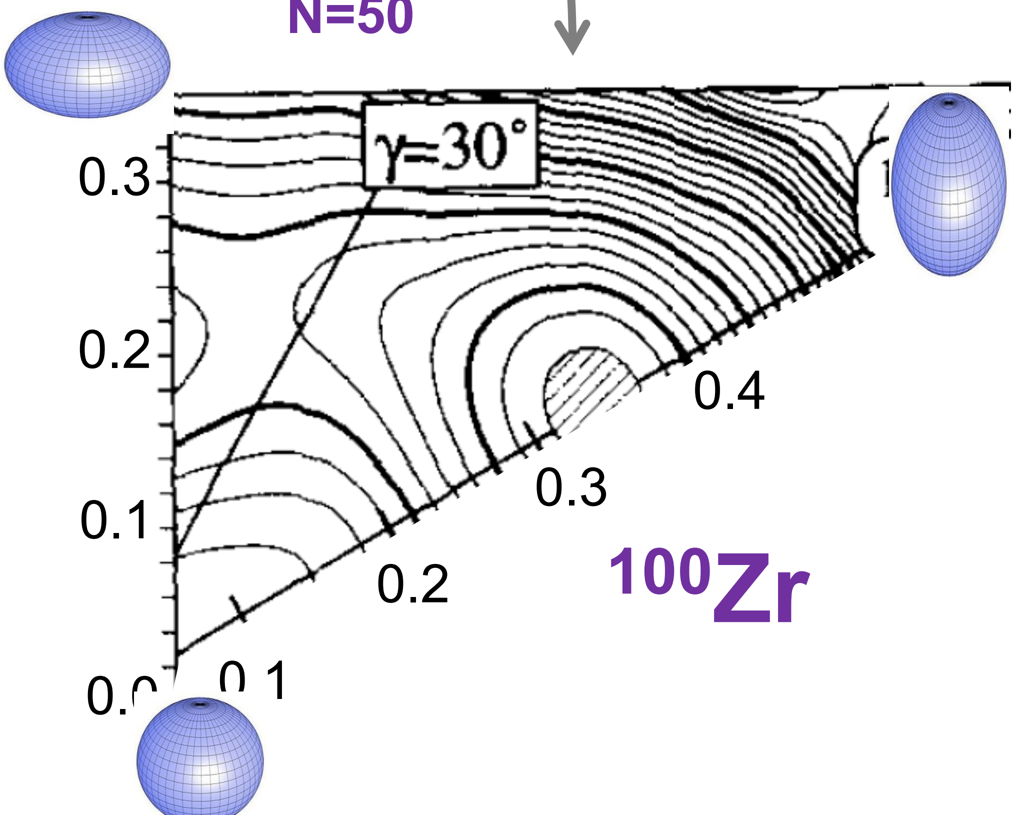
Nuclear Physics A 617 (1997) 282–315

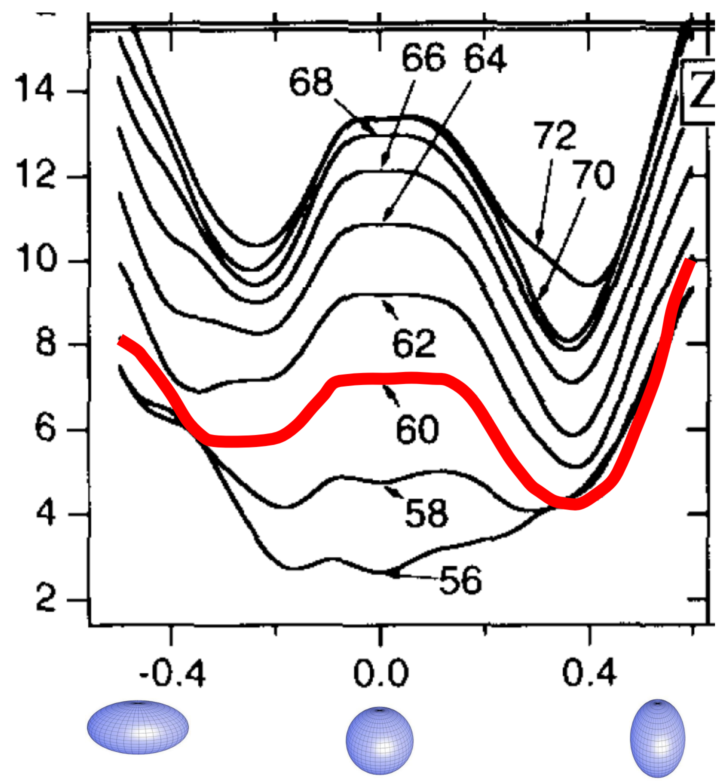
NUCLEAR
PHYSICS A

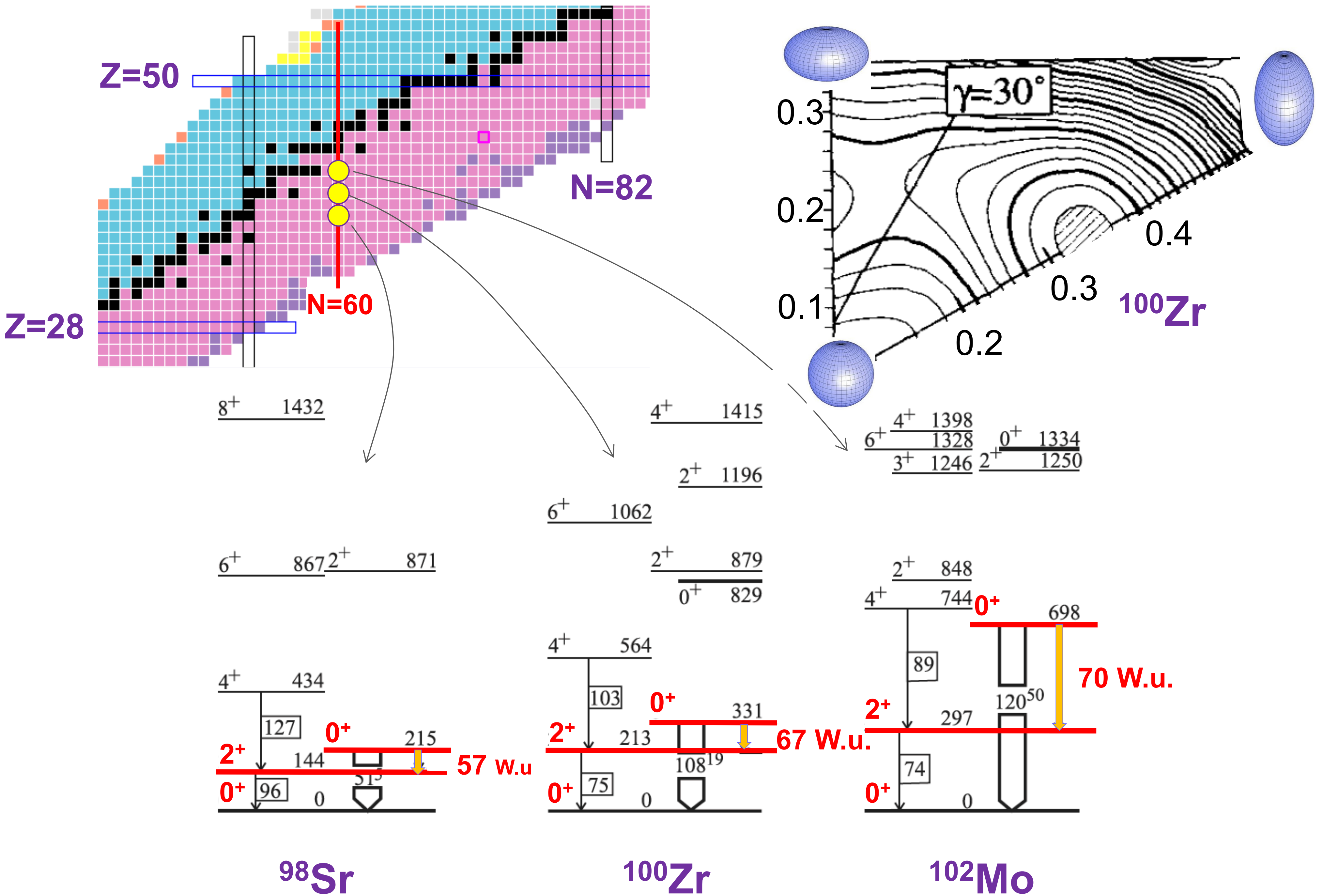
Equilibrium shapes and high-spin properties of the neutron-rich $A \approx 100$ nuclei

J. Skalski [a,b], S. Mizutori [a,c], W. Nazarewicz [c,d,e]

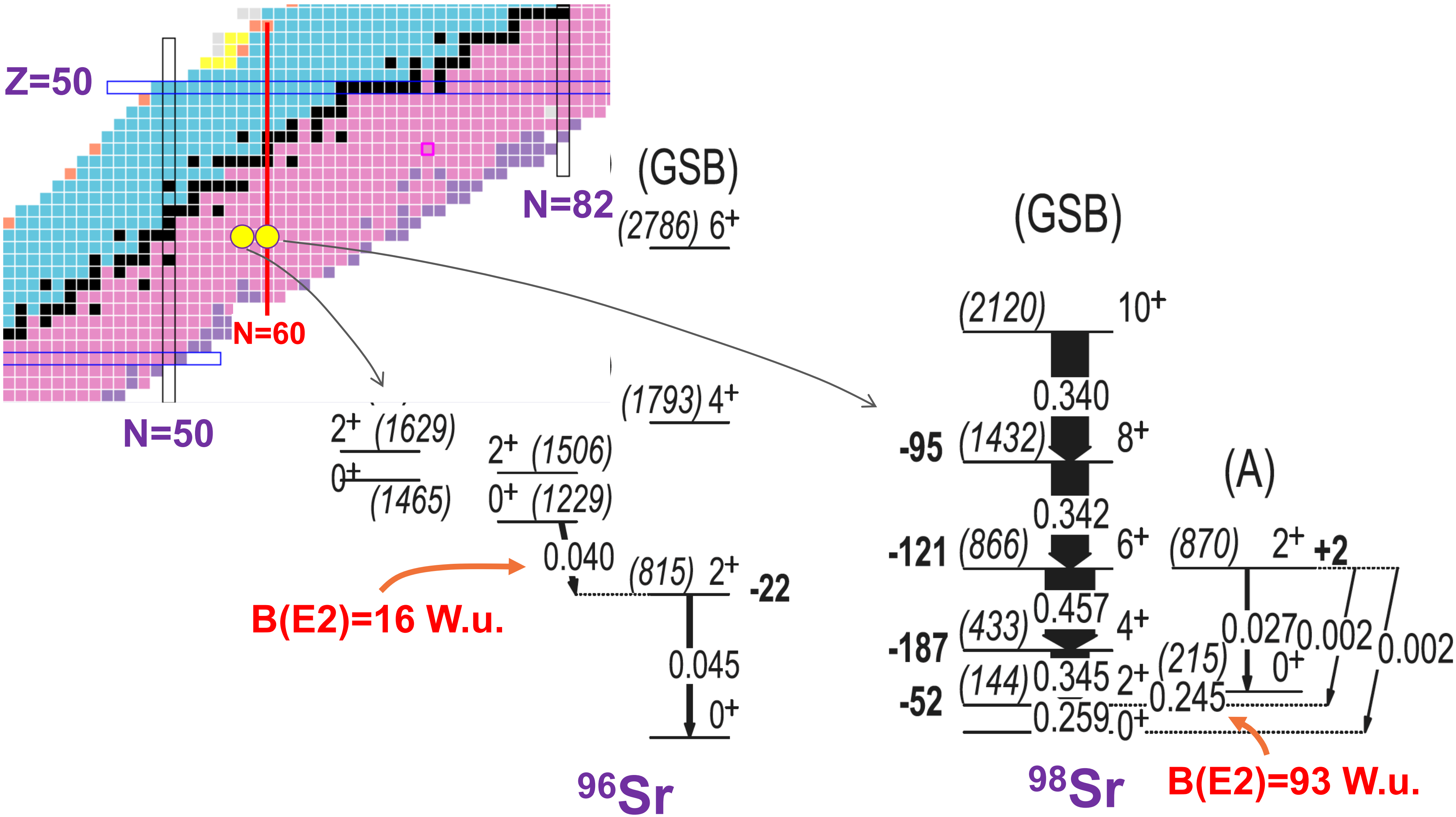
J. Skalski, S. Mizutori, W. Nazarewicz







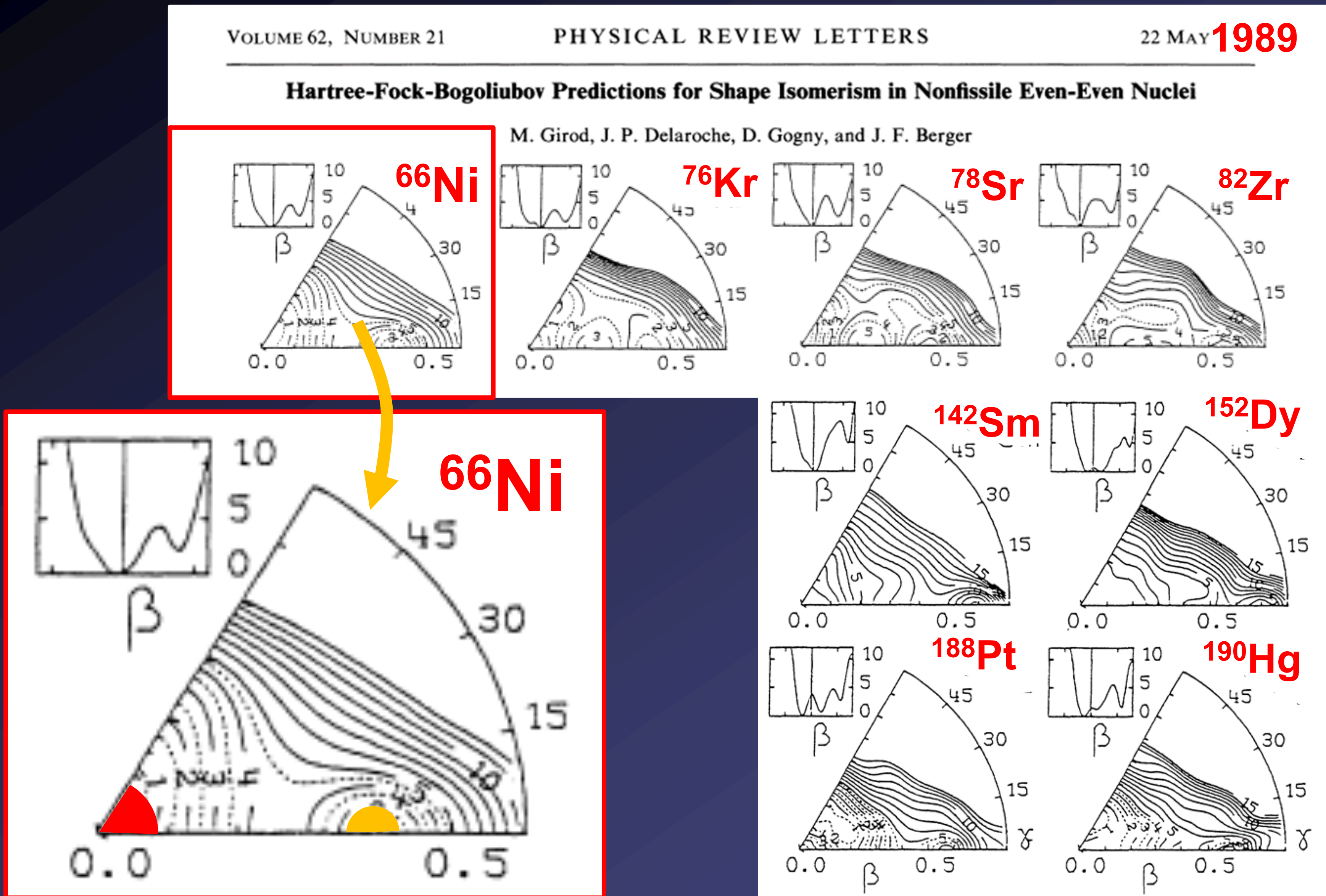
Z=50
Z=28
N=82
N=60
γ=30°
0.3
0.2
0.1
0.2
0.3
0.4
100Zr
8+ 1432
6+ 867
2+ 871
4+ 434
127
0+ 215
2+ 144
57 W.u
0+ 96
51
0
4+ 1415
2+ 1196
6+ 1062
2+ 879
0+ 829
4+ 564
103
0+ 331
2+ 213
108
67 W.u.
0+ 75
0
4+ 1398
6+ 1328
3+ 1246
0+ 1334
2+ 1250
2+ 848
4+ 744
0+ 698
89
70 W.u.
120
2+ 297
74
0+ 0
98Sr
100Zr
102Mo



E. Clément, M. Zielińska (J. Iwanicki, P. Napiorkowski, J. Srebrny, K. Wrzosek-Lipska) *et al.*, Phys.Rev. Lett. 116, 022701 (2016)

Hartree-Fock-Bogoliubov Predictions for Shape Isomerism in Nonfissile Even-Even Nuclei

M. Girod, J. P. Delaroche, D. Gogny, and J. F. Berger, PRL 64 (1989) 2452



SUPERDEFORMATION AND SHAPE ISOMERISM AT ZERO SPIN
(Microscopic Hartree-Fock plus BCS calculations)

P. Bonche et al., Nucl. Phys. A 500 (1989) 308

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

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

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P.-H. HEENEN[4]

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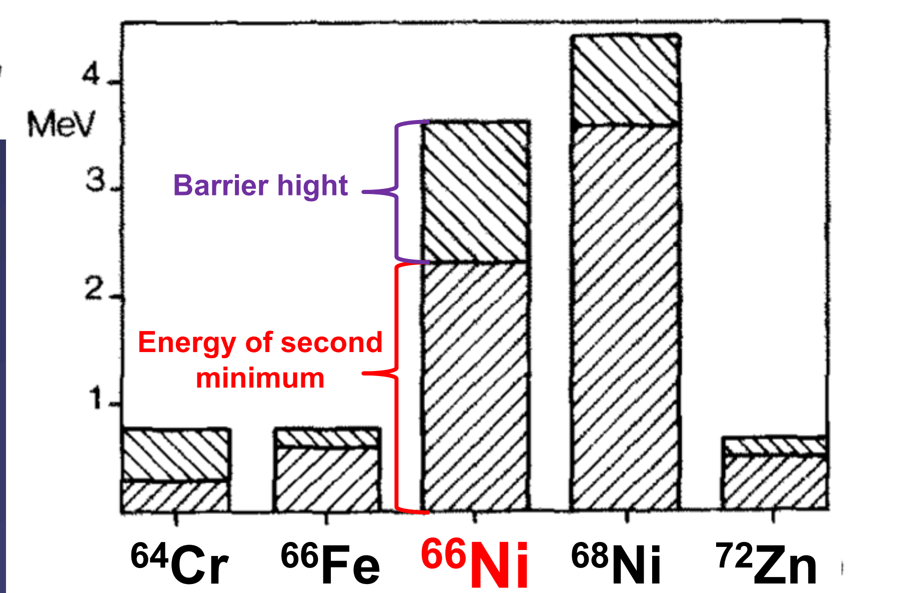
Received 7 March 1989



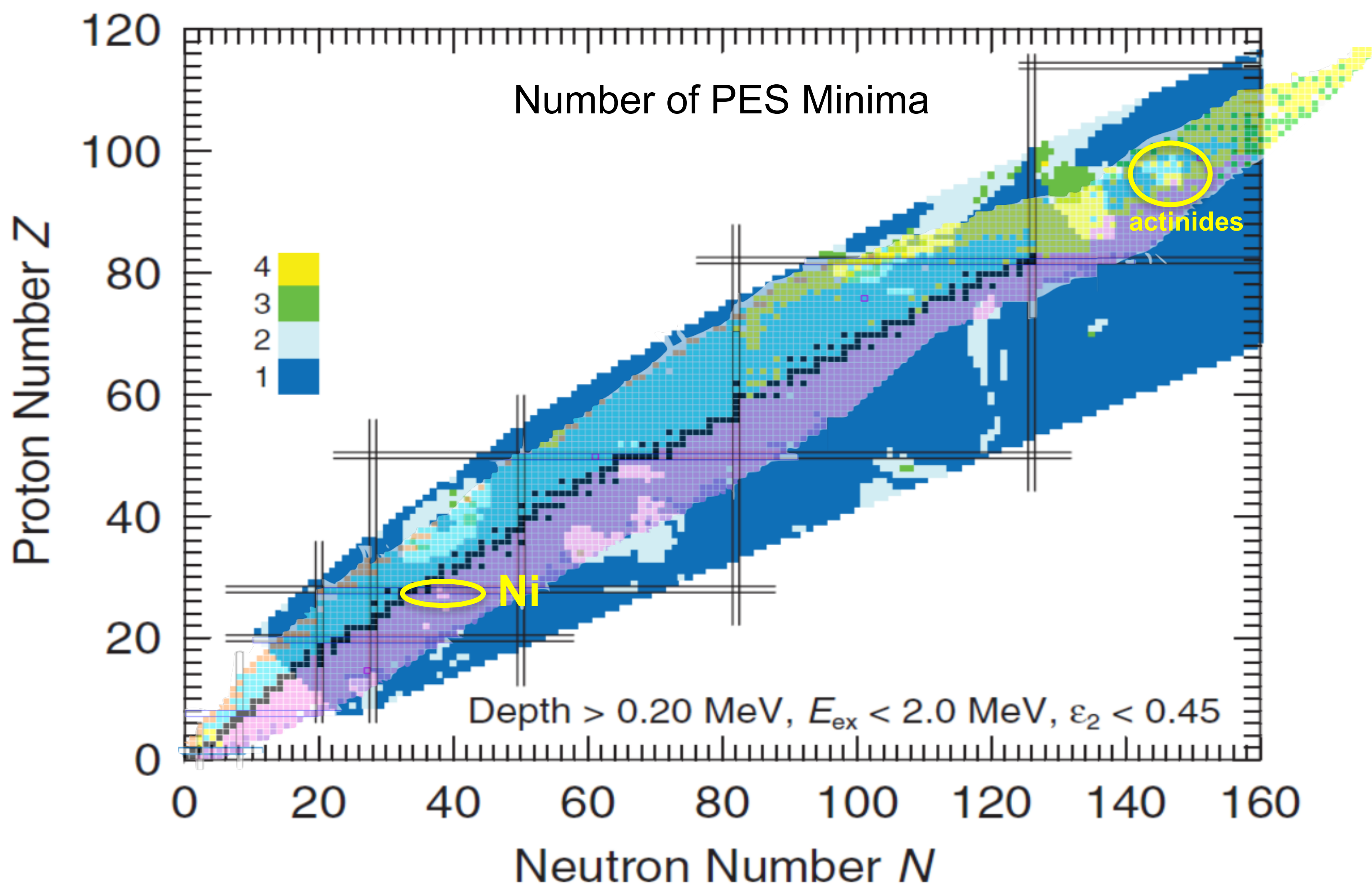
Candidates for the presence of deep, secondary minima:

^{66}Ni, ^{68}Ni, ^{190,192}Pt, ^{206,208,210}Os, ^{194,196,214}Hg

Macro-Microscospic Model – P. Moeller et al., 2012

Global Calculation Searching for secondary PES minima

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

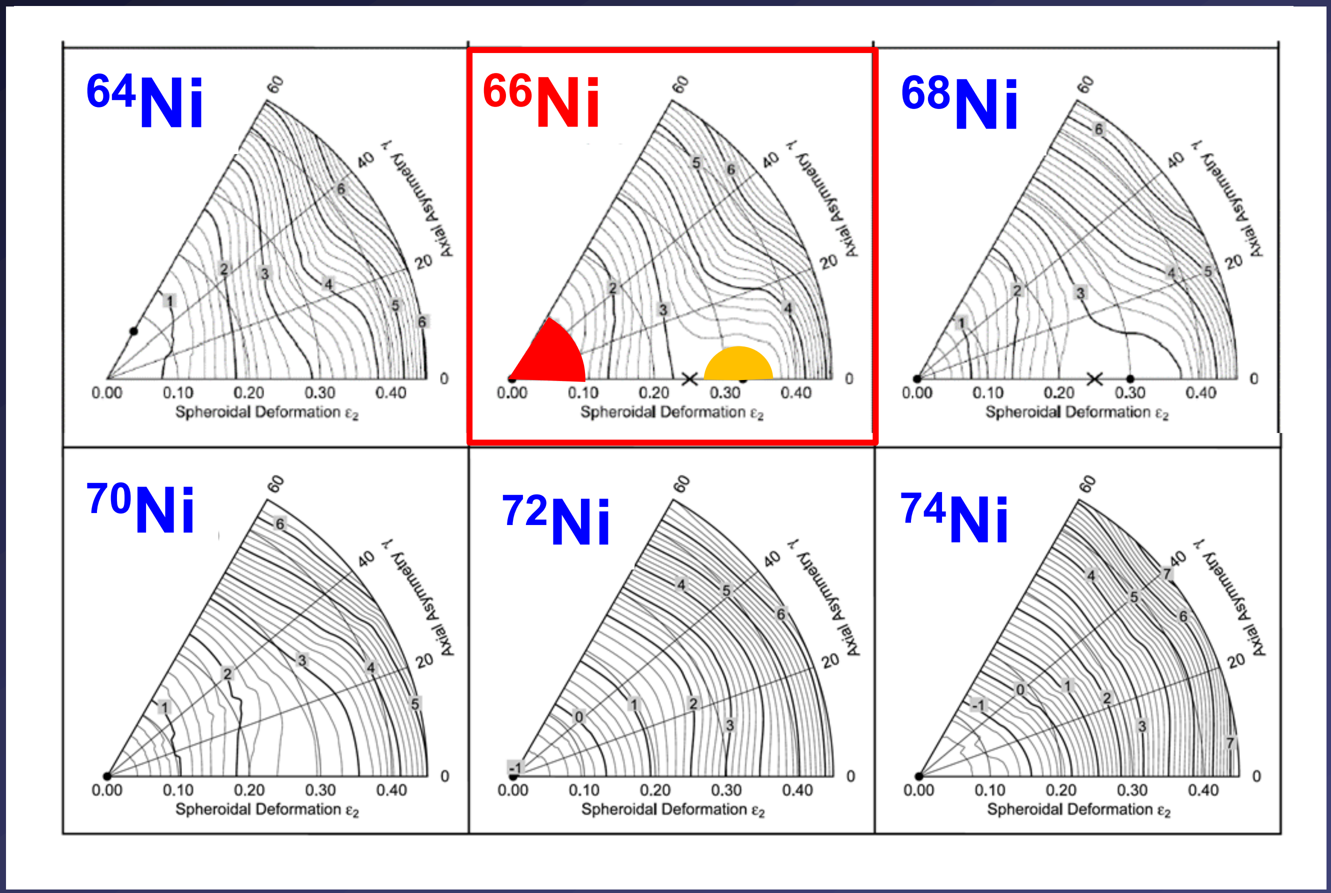


Global Calculation of Nuclear Shape Isomers

P. Moeller et al., Phys. Rev. Lett. 103, (2009) 212501

Nuclear Shape Isomers

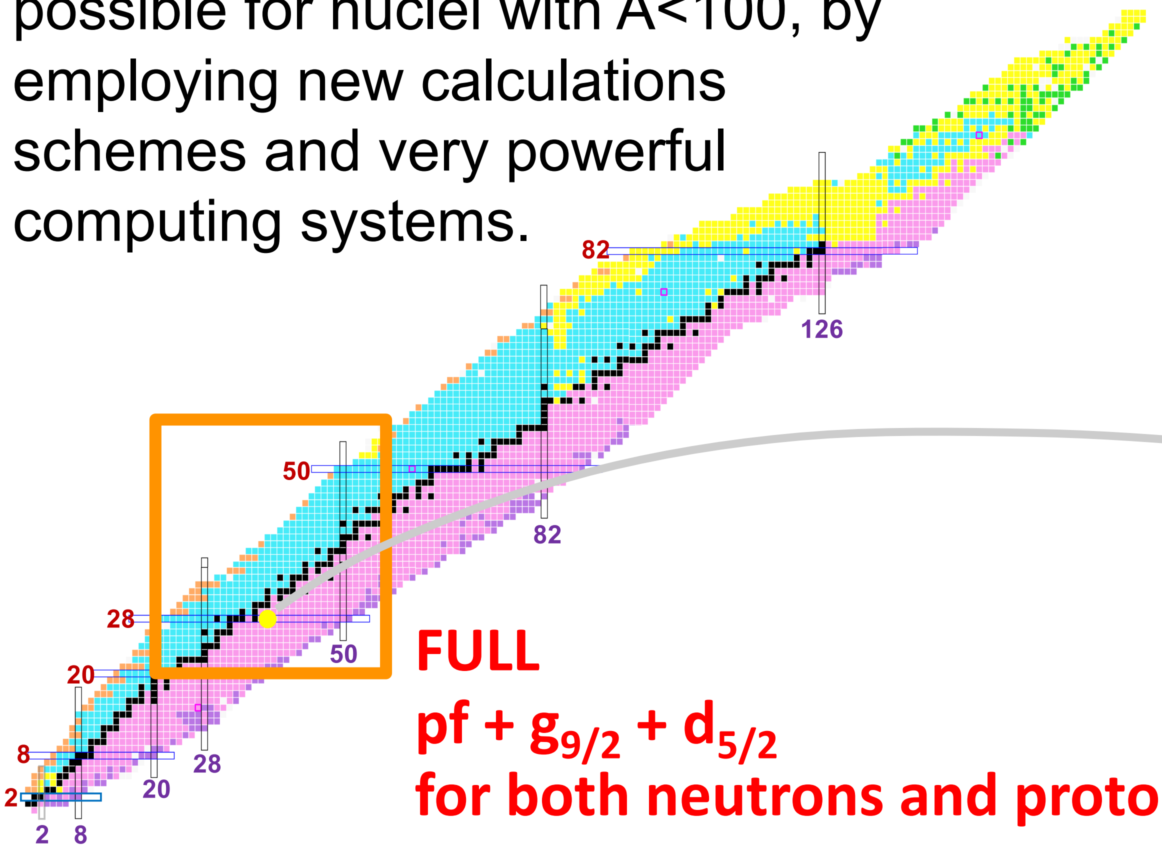
P. Moeller et al., Atomic Data and Nuclear Data Tables 98 (2012) 149



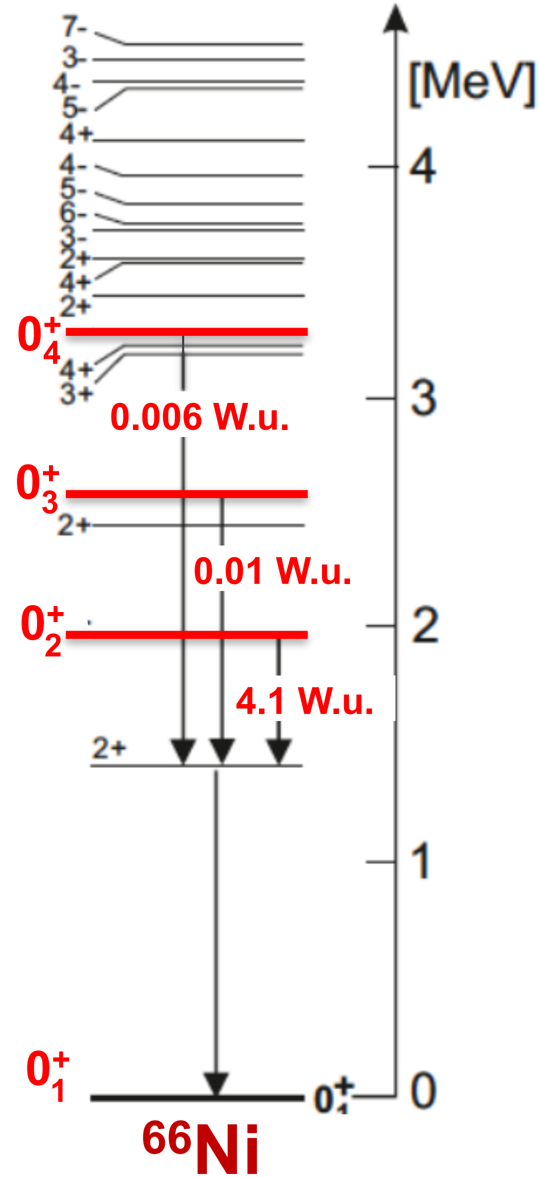
MONTE CARLO SHELL MODEL Calculations

Takaharu Otsuka's Group, Univ. of Tokyo

State-of-the-art Shell Model calculations possible for nuclei with A<100, by employing new calculations schemes and very powerful computing systems.



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

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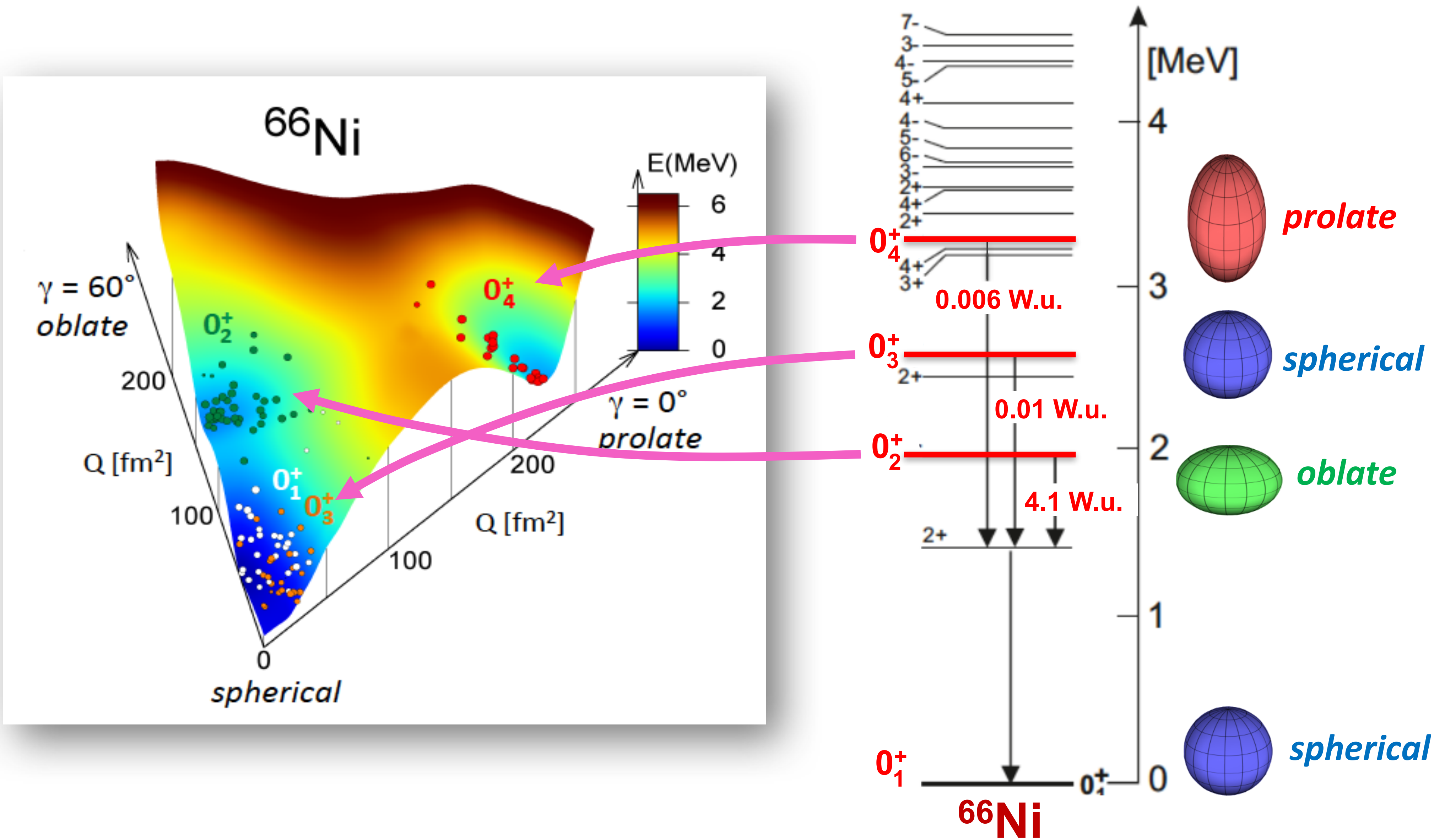
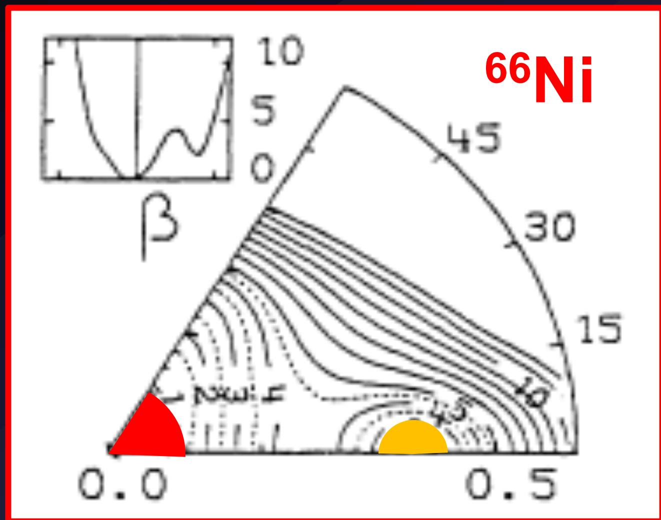
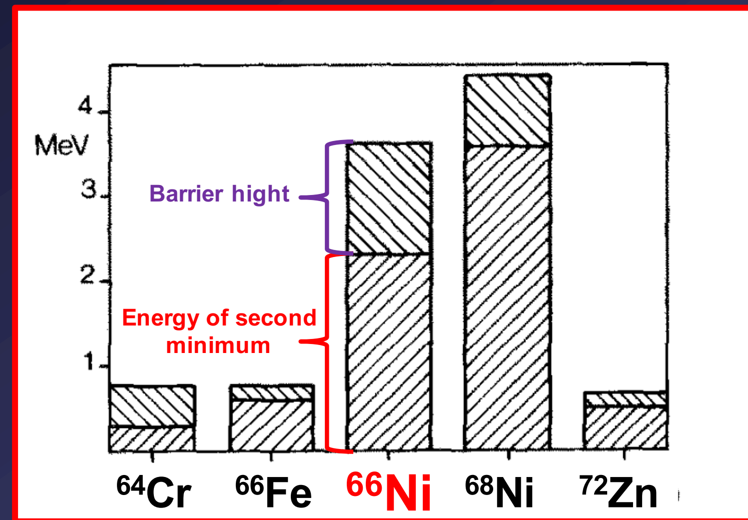


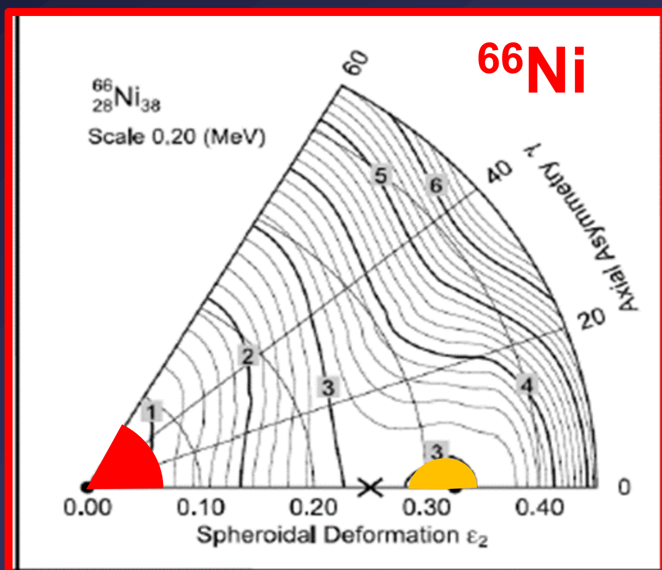
Predictions of four models

Microscopic Hartree-Fock-Bogoliubov

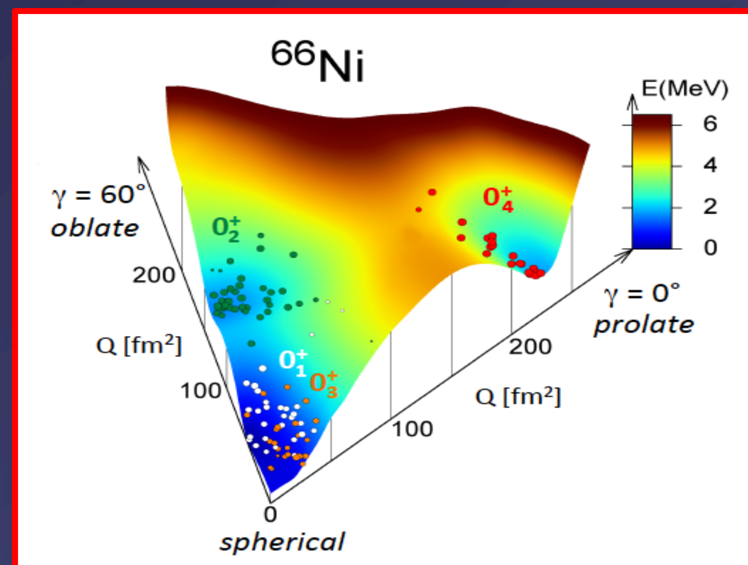


Microscopic Hartree-Fock plus BCS



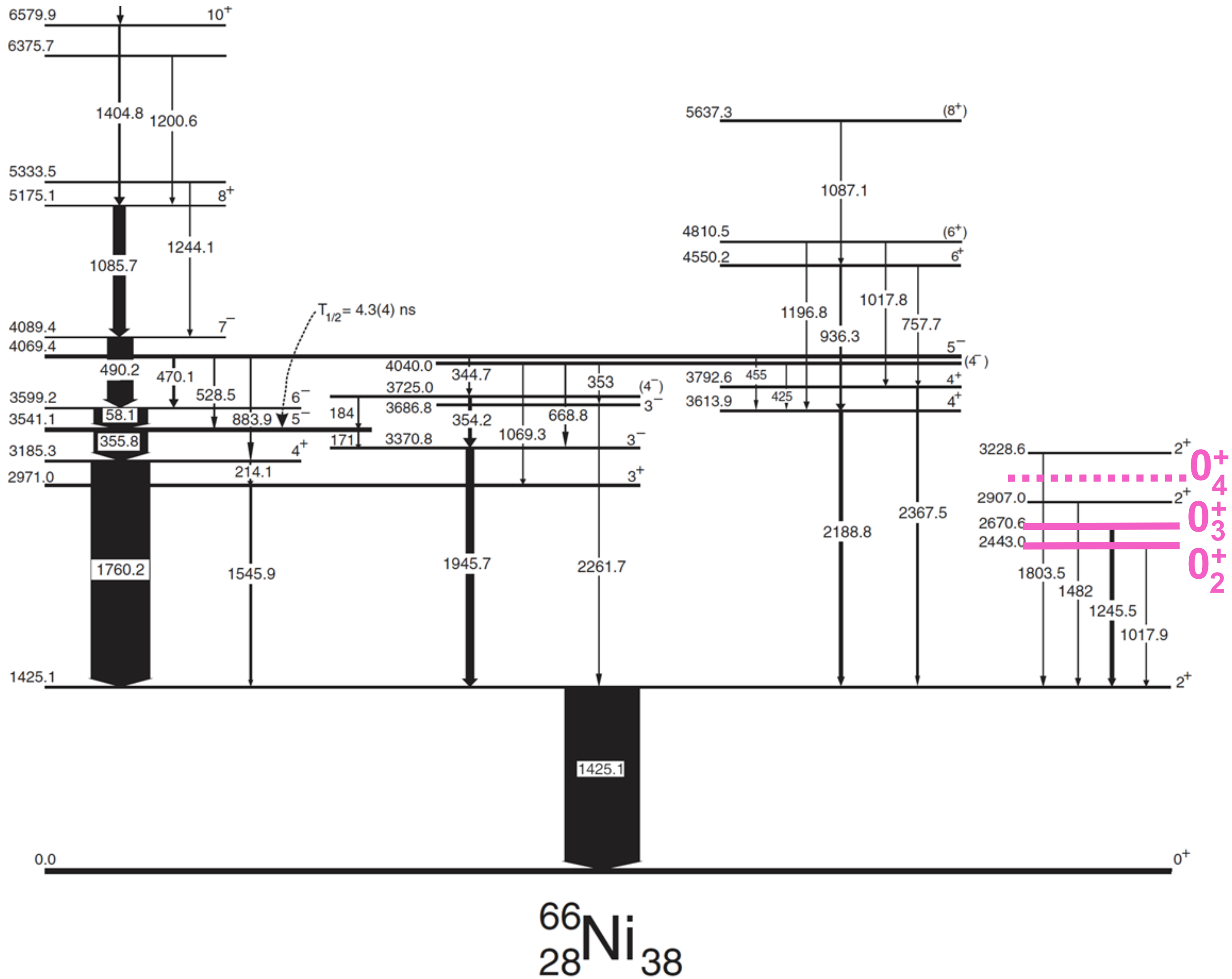


Macro-Microscospic Model

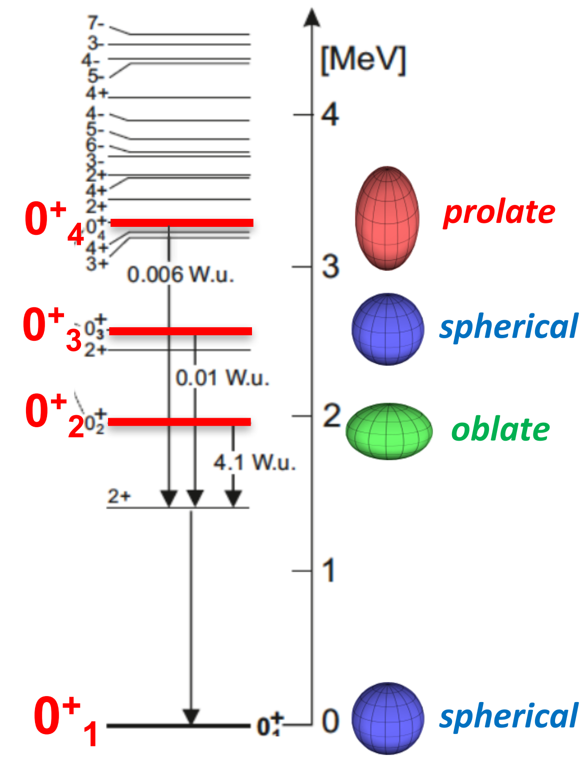


Monte Carlo Shell Model

Decay Scheme of ^{66}Ni:

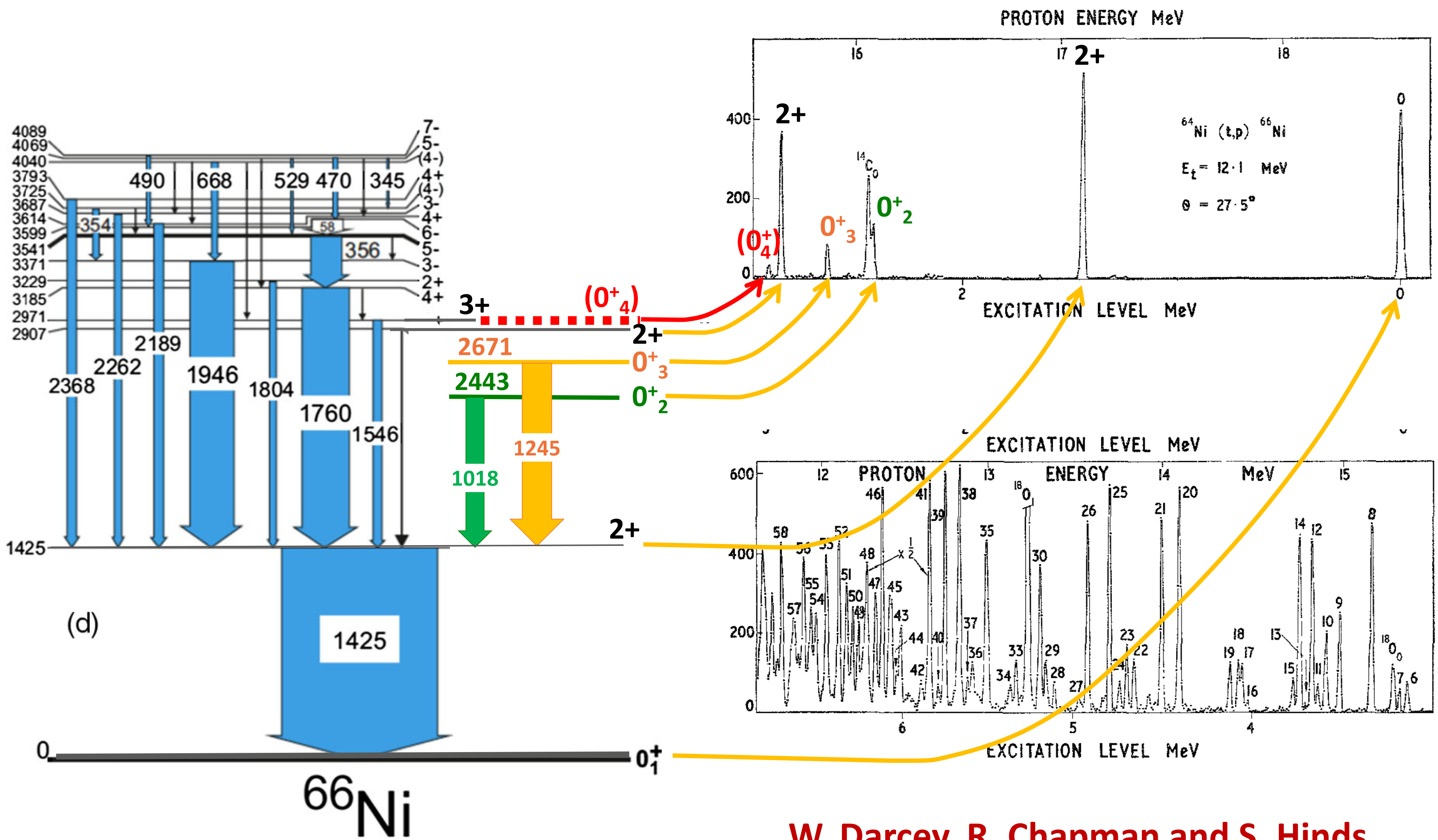


Monte Carlo SHELL Model



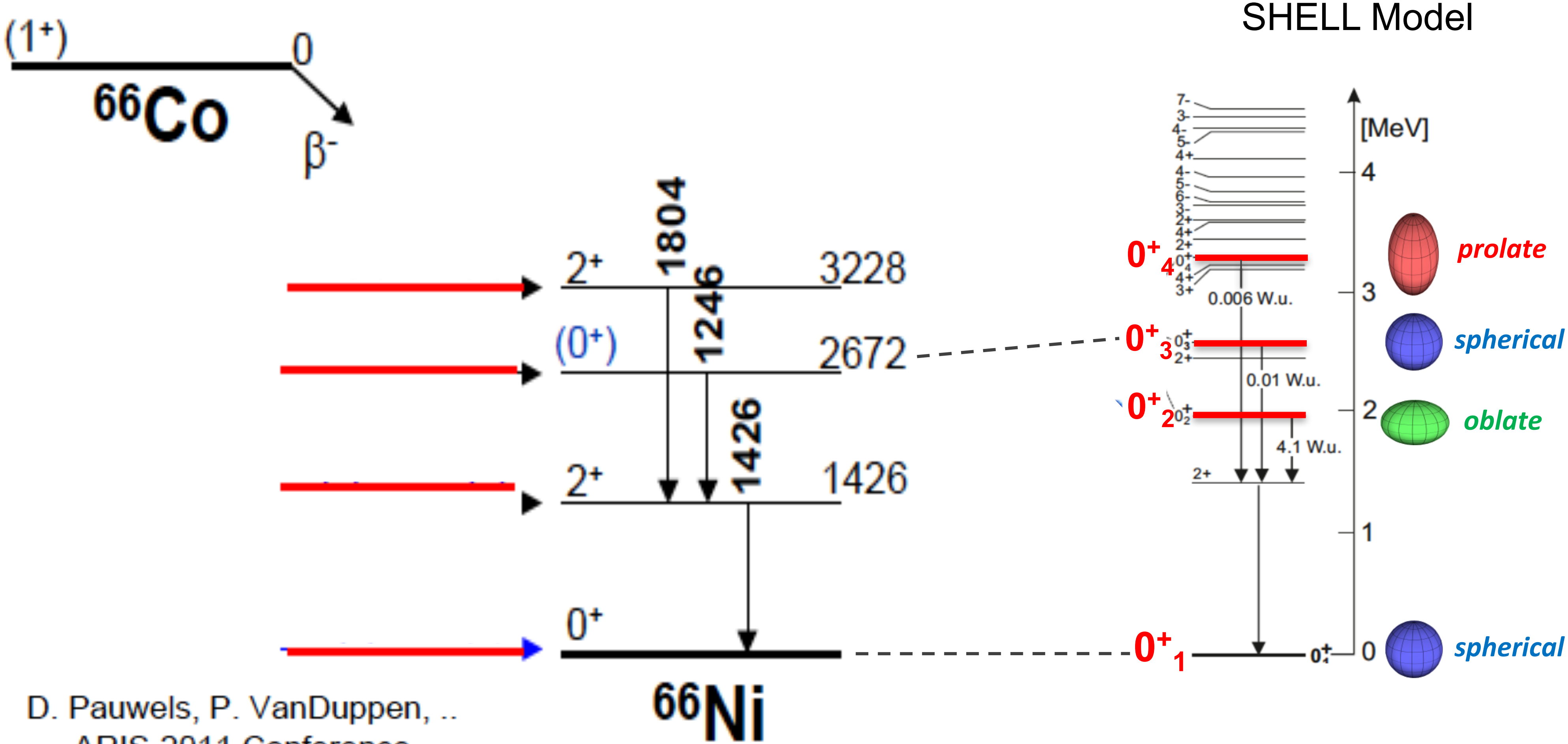
R. Broda *et al.*, Phys. Rev. C 86, 064312 (2012).

$^{64}Ni(t,p)^{66}Ni$



W. Darcey, R. Chapman and S. Hinds
Nuclear Physics A170 (1971) 253

^{66}Co β decay



D. Pauwels, P. VanDuppen, ..
ARIS-2011 Conference
(Leuven, Belgium)

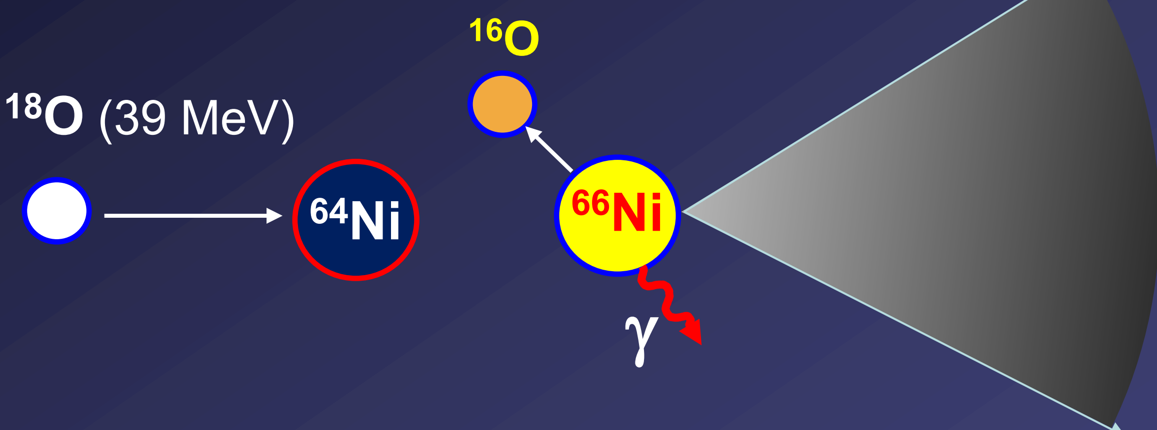
Our Recent Bucharest Experiment:

^{18}O + ^{64}Ni → ^{16}O + ^{66}Ni (1 MeV below Coulomb Barrier)

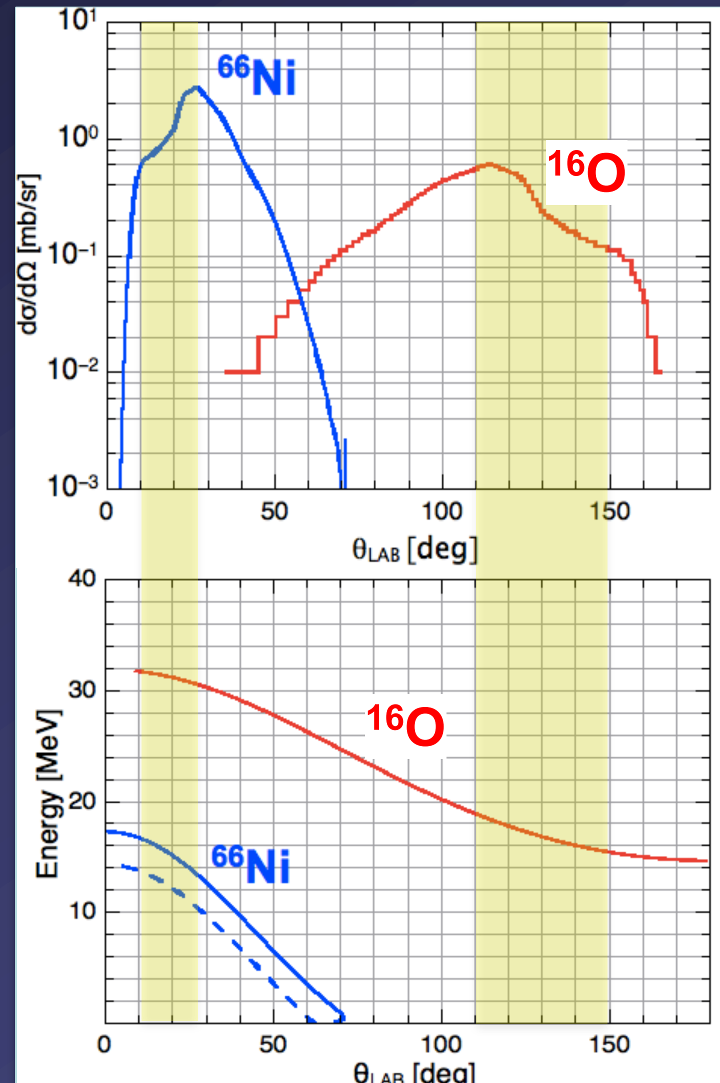
^{62}Ge	^{63}Ge	^{64}Ge	^{65}Ge	^{66}Ge	^{67}Ge	^{68}Ge	^{69}Ge	^{70}Ge	^{71}Ge	^{72}Ge	^{73}Ge	^{74}Ge	^{75}Ge	^{76}Ge	^{77}Ge	^{78}Ge
^{61}Ga	^{62}Ga	^{63}Ga	^{64}Ga	^{65}Ga	^{66}Ga	^{67}Ga	^{68}Ga	^{69}Ga	^{70}Ga	^{71}Ga	^{72}Ga	^{73}Ga	^{74}Ga	^{75}Ga	^{76}Ga	^{77}Ga
^{60}Zn	^{61}Zn	^{62}Zn	^{63}Zn	^{64}Zn	^{65}Zn	^{66}Zn	^{67}Zn	^{68}Zn	^{69}Zn	^{70}Zn	^{71}Zn	^{72}Zn	^{73}Zn	^{74}Zn	^{75}Zn	^{76}Zn
^{59}Cu	^{60}Cu	^{61}Cu	^{62}Cu	^{63}Cu	^{64}Cu	^{65}Cu	^{66}Cu	^{67}Cu	^{68}Cu	^{69}Cu	^{70}Cu	^{71}Cu	^{72}Cu	^{73}Cu	^{74}Cu	^{75}Cu
^{58}Ni	^{59}Ni	^{60}Ni	^{61}Ni	^{62}Ni	^{63}Ni	^{64}Ni	^{65}Ni	^{66}Ni	^{67}Ni	^{68}Ni	^{69}Ni	^{70}Ni	^{71}Ni	^{72}Ni	^{73}Ni	^{74}Ni
^{57}Co	^{58}Co	^{59}Co	^{60}Co	^{61}Co	^{62}Co	^{63}Co	^{64}Co	^{65}Co	^{66}Co	^{67}Co	^{68}Co	^{69}Co	^{70}Co	^{71}Co	^{72}Co	^{73}Co
^{56}Fe	^{57}Fe	^{58}Fe	^{59}Fe	^{60}Fe	^{61}Fe	^{62}Fe	^{63}Fe	^{64}Fe	^{65}Fe	^{66}Fe	^{67}Fe	^{68}Fe	^{69}Fe	^{70}Fe	^{71}Fe	^{72}Fe
^{55}Mn	^{56}Mn	^{57}Mn	^{58}Mn	^{59}Mn	^{60}Mn	^{61}Mn	^{62}Mn	^{63}Mn	^{64}Mn	^{65}Mn	^{66}Mn	^{67}Mn	^{68}Mn	^{69}Mn	^{70}Mn	^{71}Mn
^{54}Cr	^{55}Cr	^{56}Cr	^{57}Cr	^{58}Cr	^{59}Cr	^{60}Cr	^{61}Cr	^{62}Cr	^{63}Cr	^{64}Cr	^{65}Cr	^{66}Cr	^{67}Cr	^{68}Cr		

Z=28

N=40



GRAZING – A. Winter, N. Pollarolo



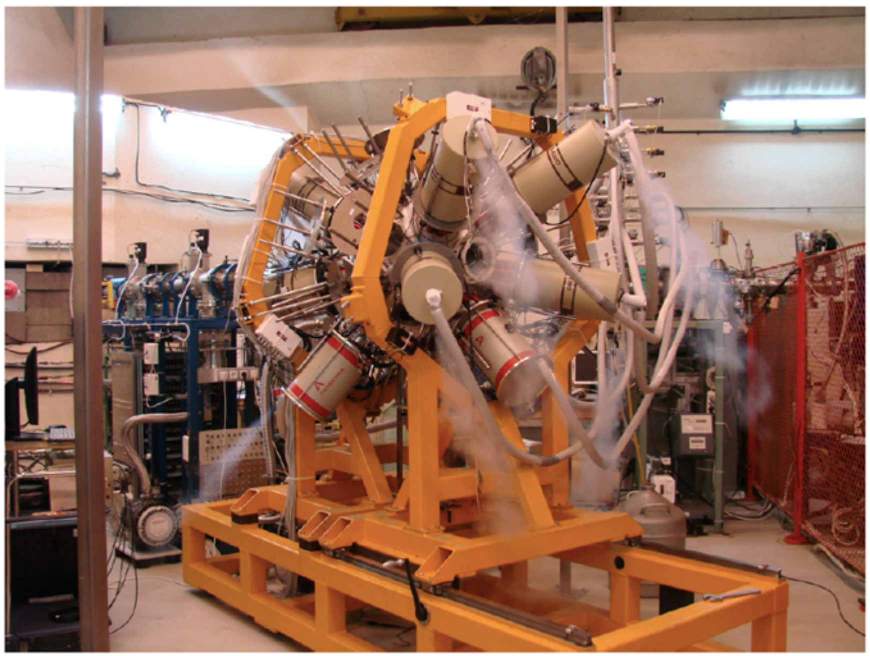
ROmanian array for SPectroscopy in HEavy ion REactions

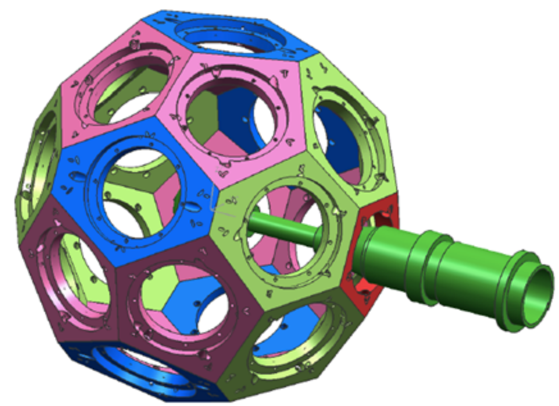
IFIN-HH

Mixed array with

- **14 50% HPGe detectors** with BGO shields (IFIN-HH)
- **11 $LaBr_3$(Ce) scintillators**: currently 7 of 2"x2" (IFIN-HH) and 4 of 1.5"x2" (UK)

25 positions, 5 symmetric rings of 5 detectors



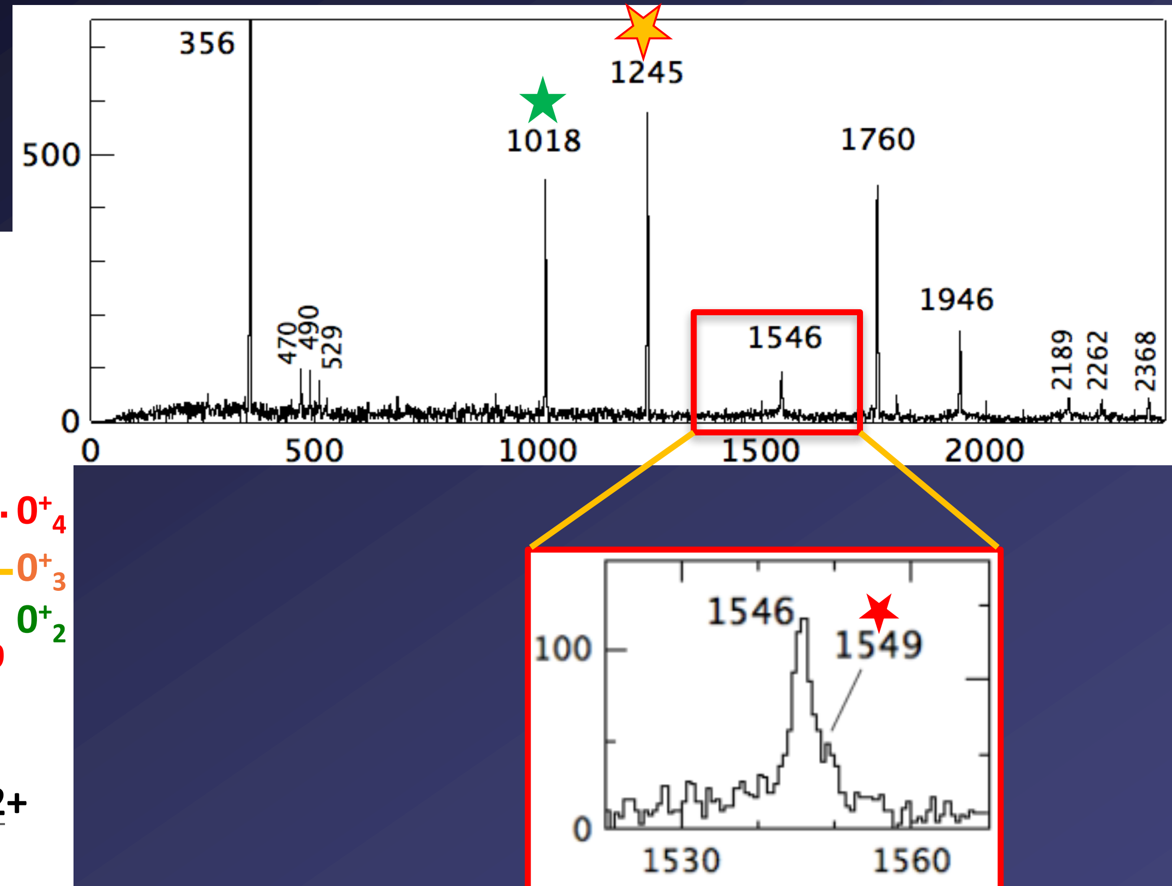


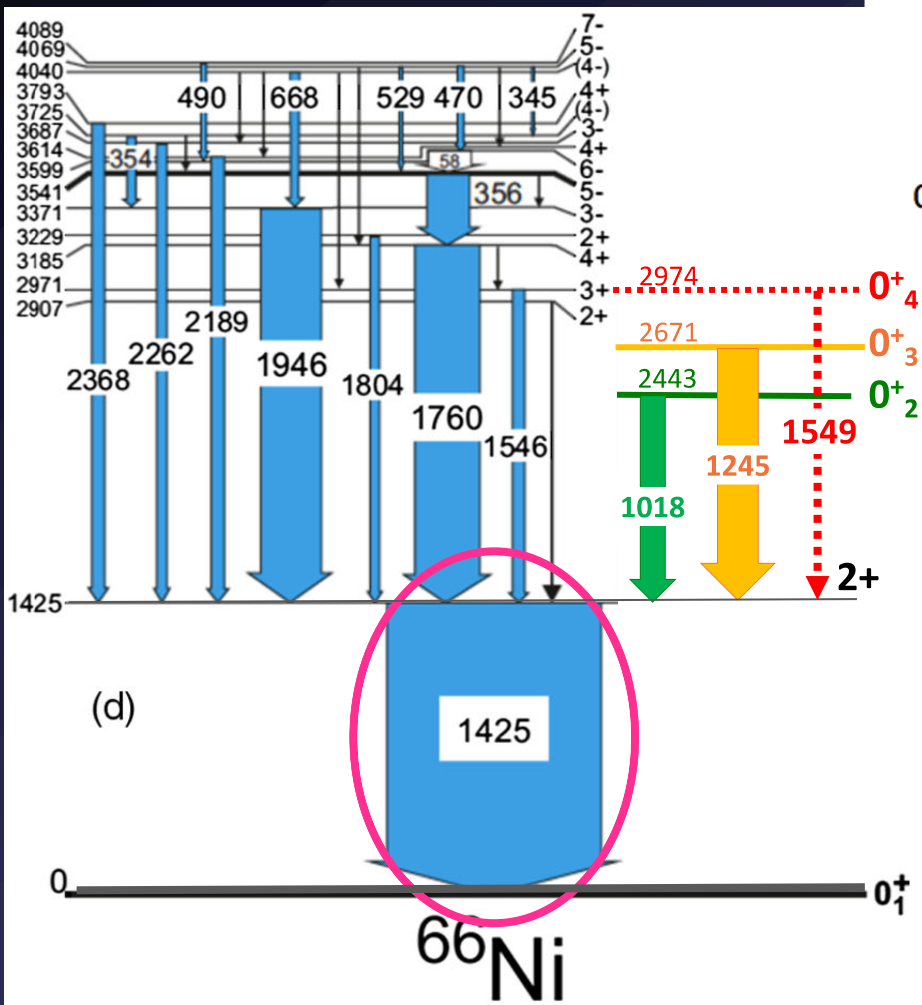
Absolute HPGe efficiency: ~ 1.1%

$LaBr_3$(Ce) efficiency ~ 1.75%

Our Recent Bucharest Experiment:

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





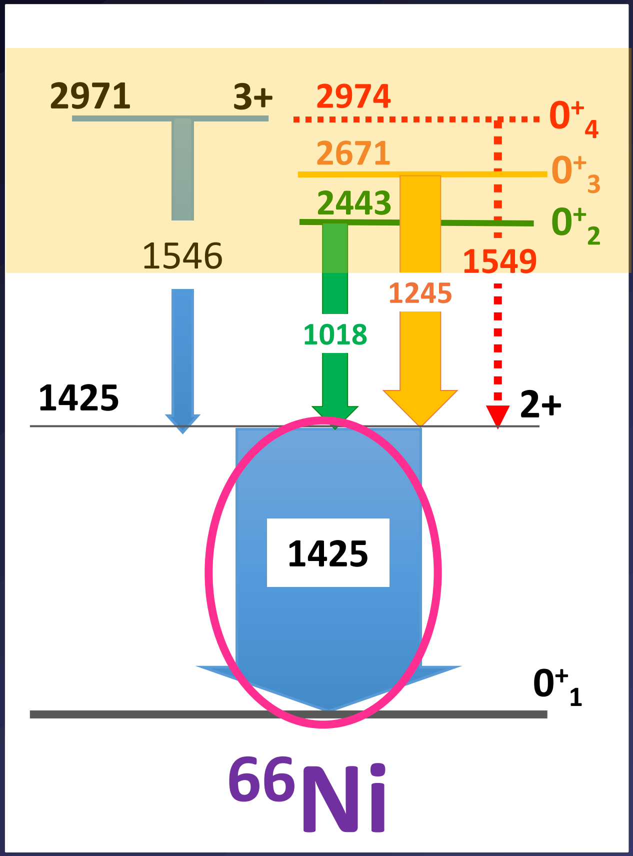
We concentrate on γ-decay from 0^+ states and perform lifetime measurement with PLUNGER

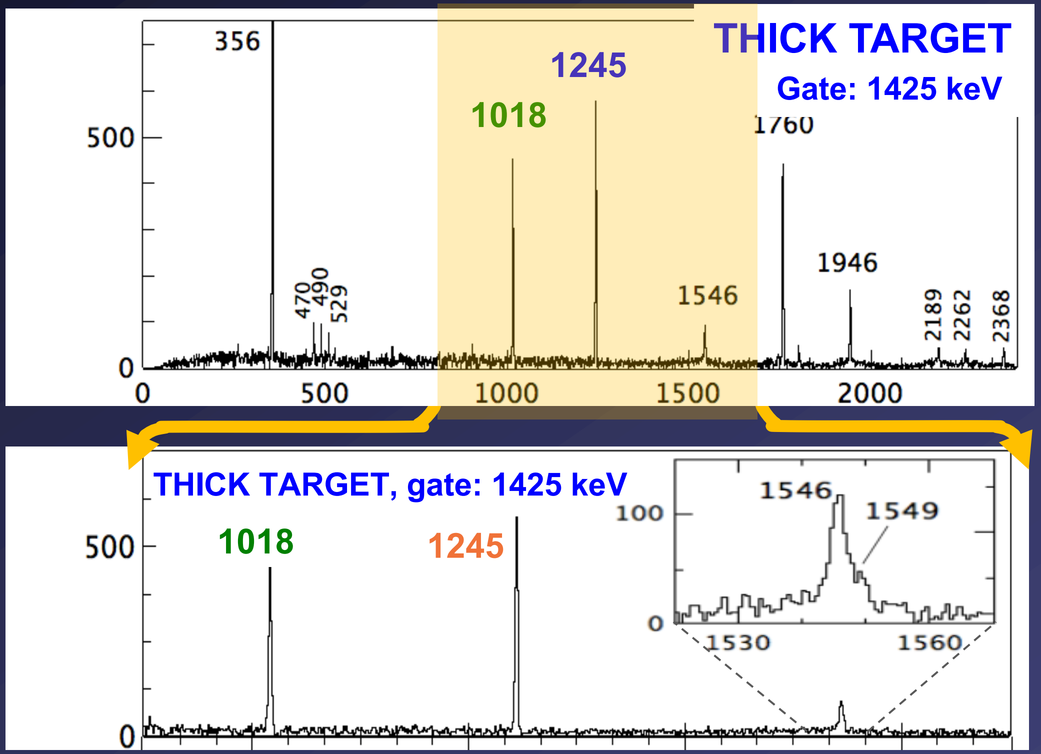
$^{18}O+^{64}Ni \rightarrow ^{16}O+^{66}Ni$

E_{beam} = 39 MeV

2n transfer below Coulomb Barrier

at IFIN HH Bucarest



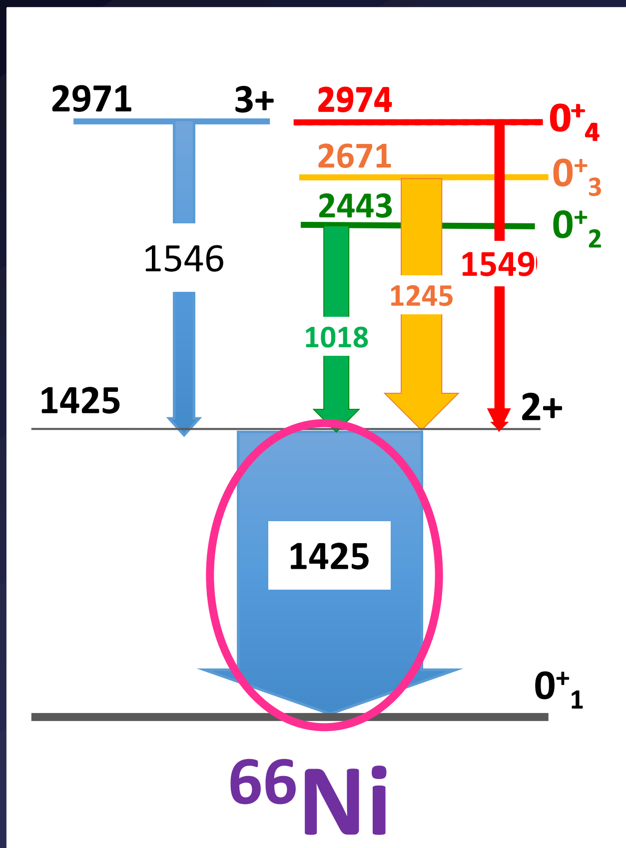


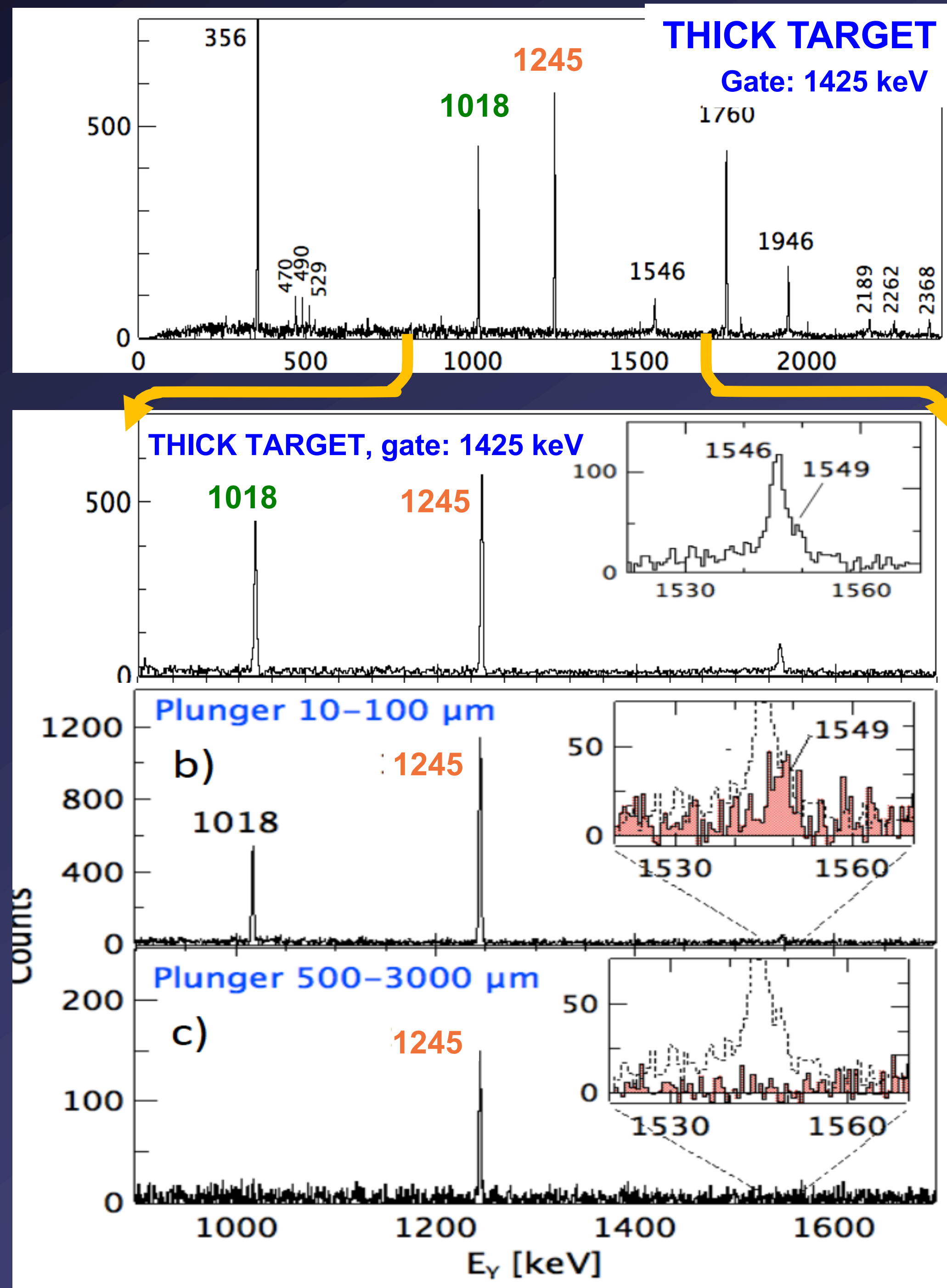
$^{18}O+^{64}Ni \rightarrow ^{16}O+^{66}Ni$

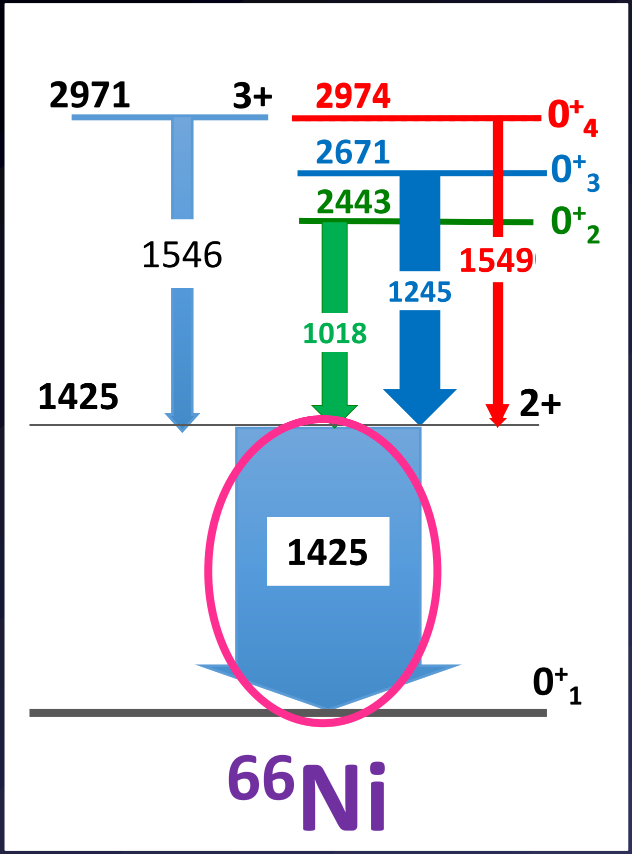
E_{beam} = 39 MeV

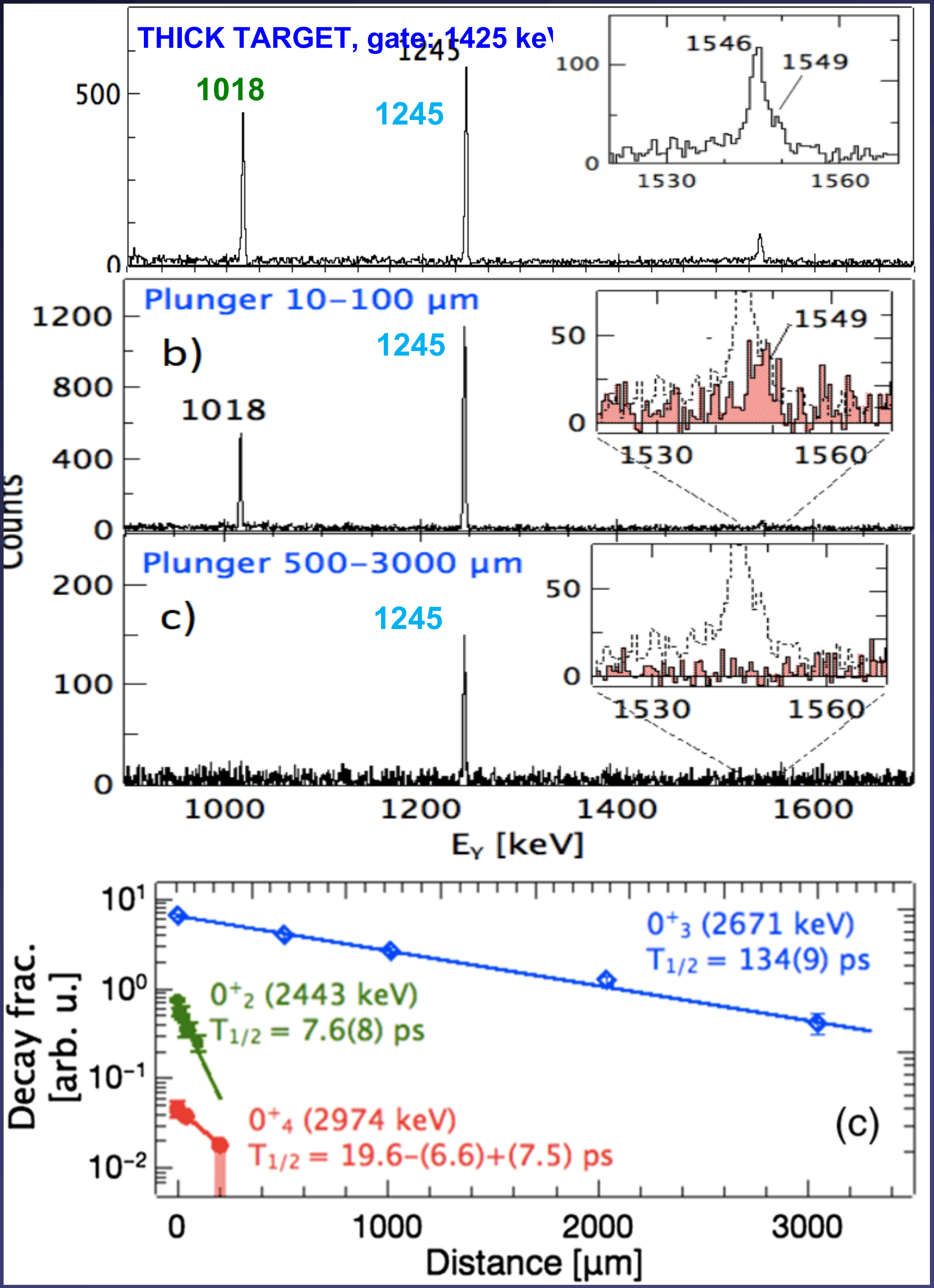
2n transfer below Coulomb Barrier

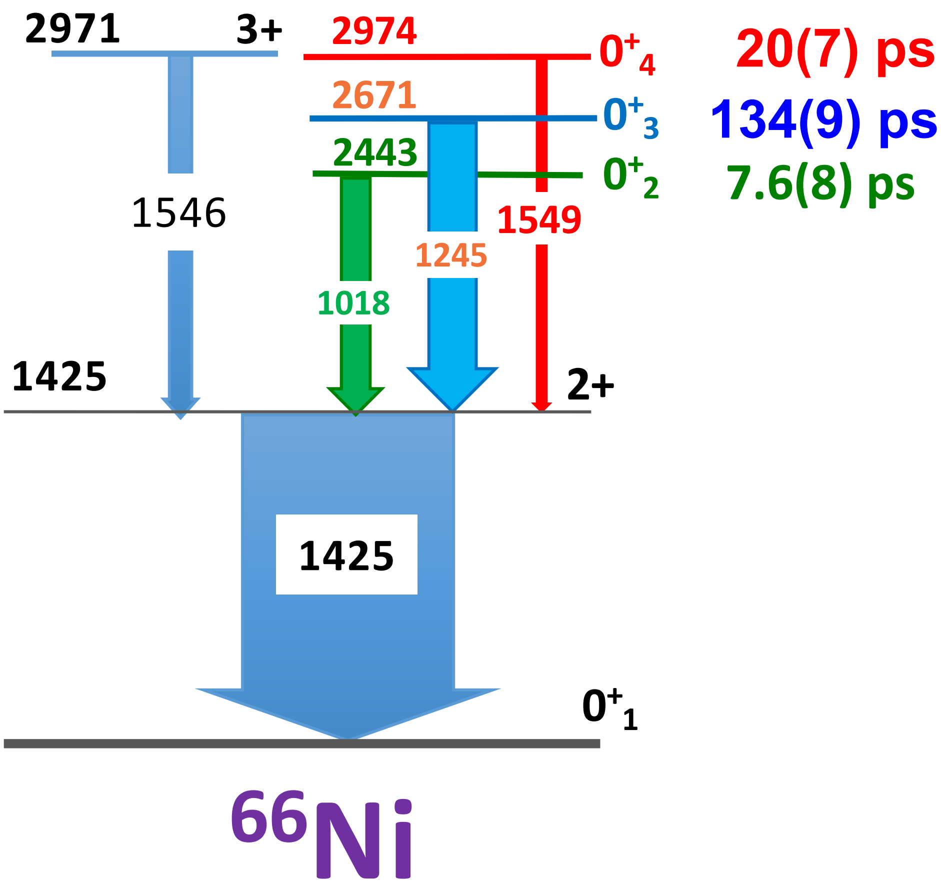
at IFIN HH Bucarest

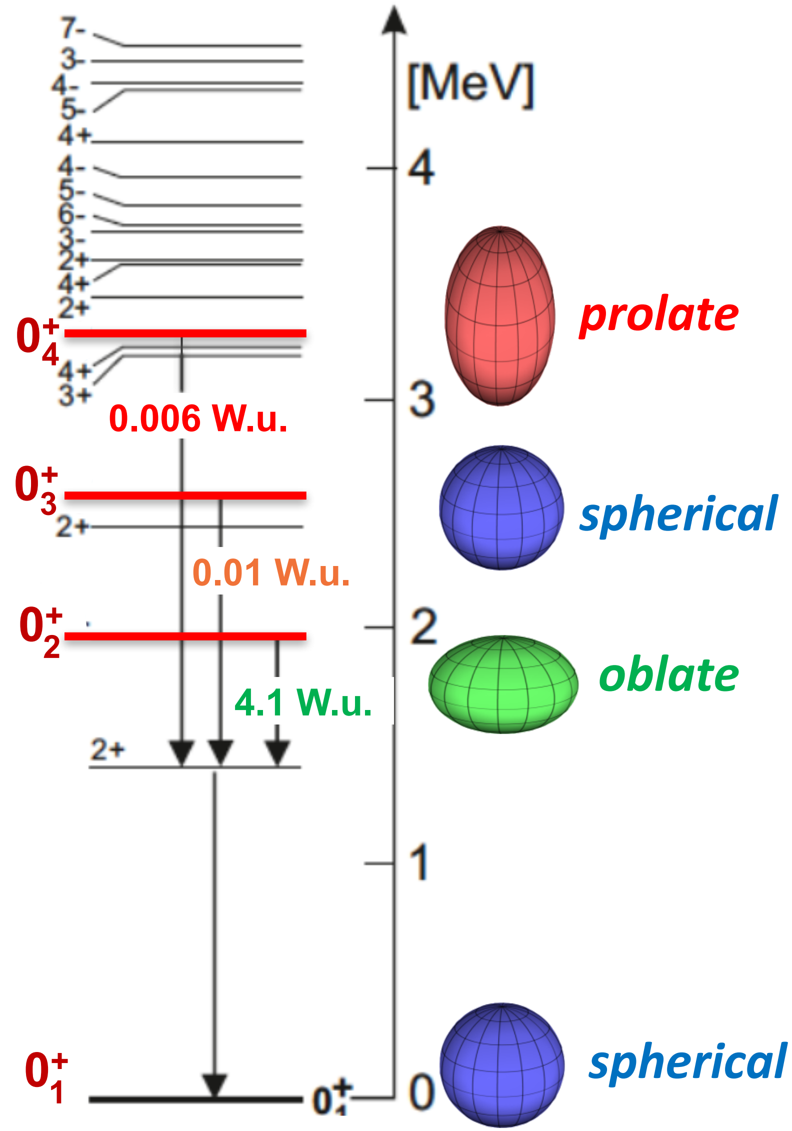


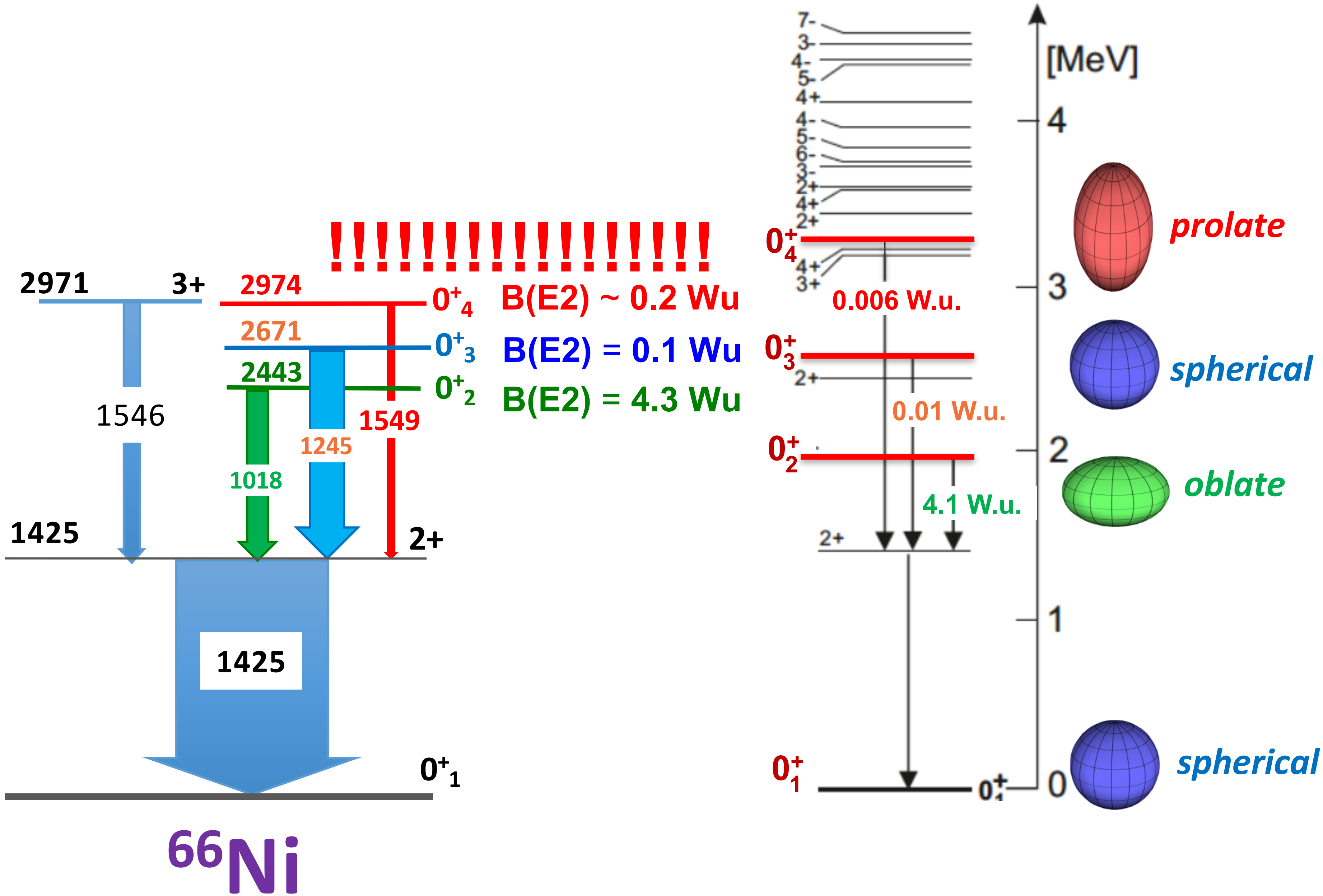



2971
3+
2974
0+4
2671
0+3
2443
0+2
1546
1549
1245
1018
1425
2+
1425
0+1
66Ni

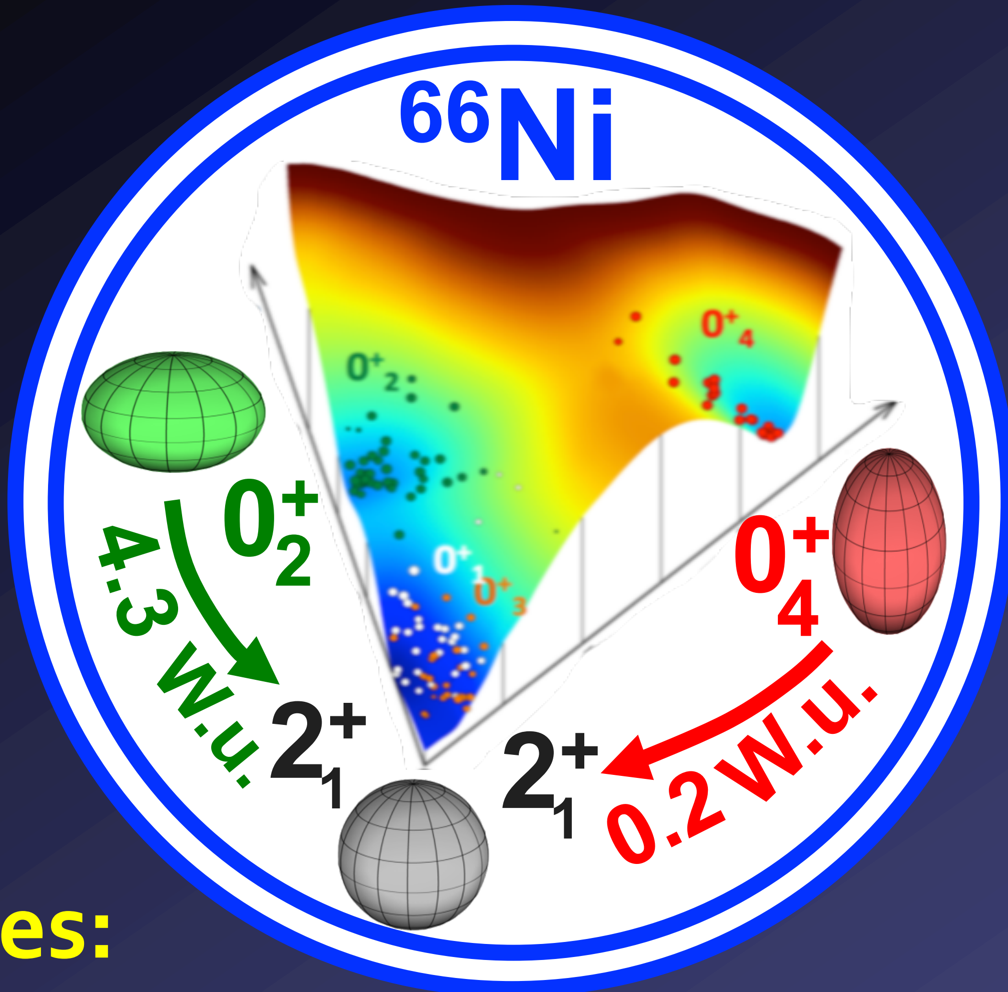

THICK TARGET, gate: 1425 keV
1018
1245
1546
1549
1530
1560
Plunger 10–100 μm
b)
1245
1018
1549
1530
1560
Plunger 500–3000 μm
c)
1245
1530
1560
Counts
Eγ [keV]
1000
1200
1400
1600
0+3 (2671 keV)
T1/2 = 134(9) ps
0+2 (2443 keV)
T1/2 = 7.6(8) ps
0+4 (2974 keV)
T1/2 = 19.6–(6.6)+(7.5) ps
(c)
Decay frac. [arb. u.]
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
66Ni


[MeV]
4
3
2
1
0
0+4
0.006 W.u.
0+3
0.01 W.u.
0+2
4.1 W.u.
2+
0+1
prolate
spherical
oblate
spherical



!!!!!!!!!!!!!!!!!!
2971
3+
2974
0^+_4
B(E2) ~ 0.2 Wu
2671
0^+_3
B(E2) = 0.1 Wu
2443
0^+_2
B(E2) = 4.3 Wu
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
[MeV]
4
3
2
1
0
prolate
spherical
oblate
spherical



Perspectives:
precision measurements

- Coulomb Excitation
- Electric Monopole Transition Strength $0_+ \rightarrow 0_+$ – Electron Spectroscopy
- Search for Off Yrast Structures – gamma Spectroscopy
  e.g. CLUSTER Transfer, Multi-Nucleon Transfer, …

Summary

A shape-isomer-like state has been found in the ^{66}Ni nucleus.
It is the lightest, ever, atomic nucleus exhibiting a photon decay hindered by a nuclear shape change.

Our finding, caught through high resolution gamma-ray spectroscopy and a very selective nuclear reaction mechanism, shows that shape isomerism is characteristic not only for very heavy nuclei.
This will certainly be helpful for solving a puzzle on the origin of nuclear deformation.

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

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