Revealing microscopic origins of shape coexistence in the Ni isotopic chain

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
- **C. Michelagnoli** et al., ILL, Grenoble, France
- **M. Sferrazza** et al., Universite libre de Bruxelles, Belgium
- **T. Otsuka, Y. Tsunoda** et al., University of Tokyo, Japan

Venezia 13-17 May 2019

Nuclear Structure and Dynamics NSD 2019

Outline

- **Introduction**

  Nuclear Shapes and Shape coexistence

- **The extreme case of Shape Isomer**

  Unique examples: $^{236,238}U$ and ^{66}Ni

- **Our systematic investigation of shape coexistence along the Ni isotopic chain**

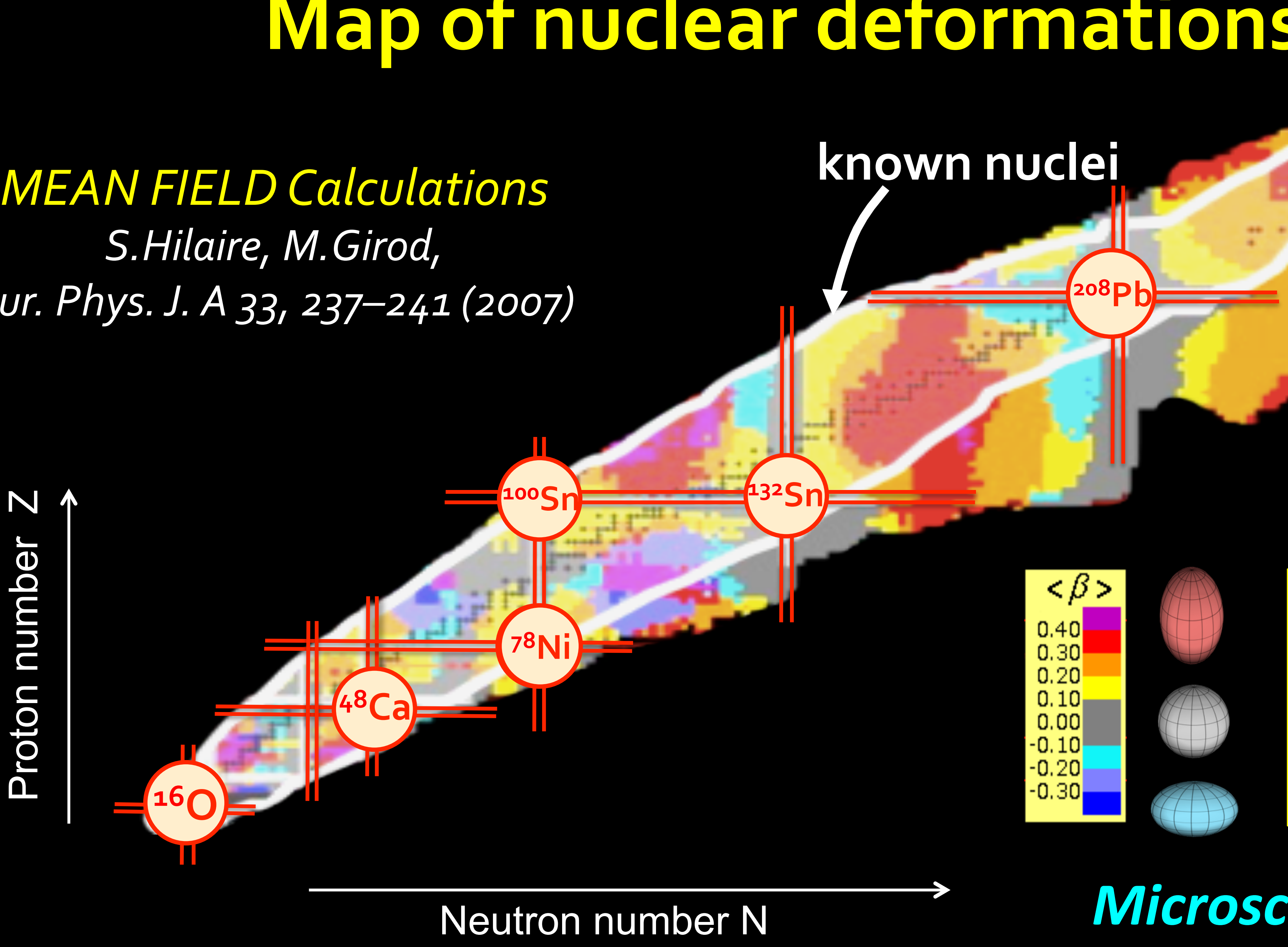
  ^{62}Ni , ^{64}Ni, ^{65}Ni and ^{66}Ni
  Probing state wave functions with different reactions

Map of nuclear deformations

MEAN FIELD Calculations

S.Hilaire, M.Girod,

Eur. Phys. J. A 33, 237–241 (2007)



VERY COMPACT OBJECT

up to ~ 250 nucleons

SIZE ~ 10^{-45} m^3

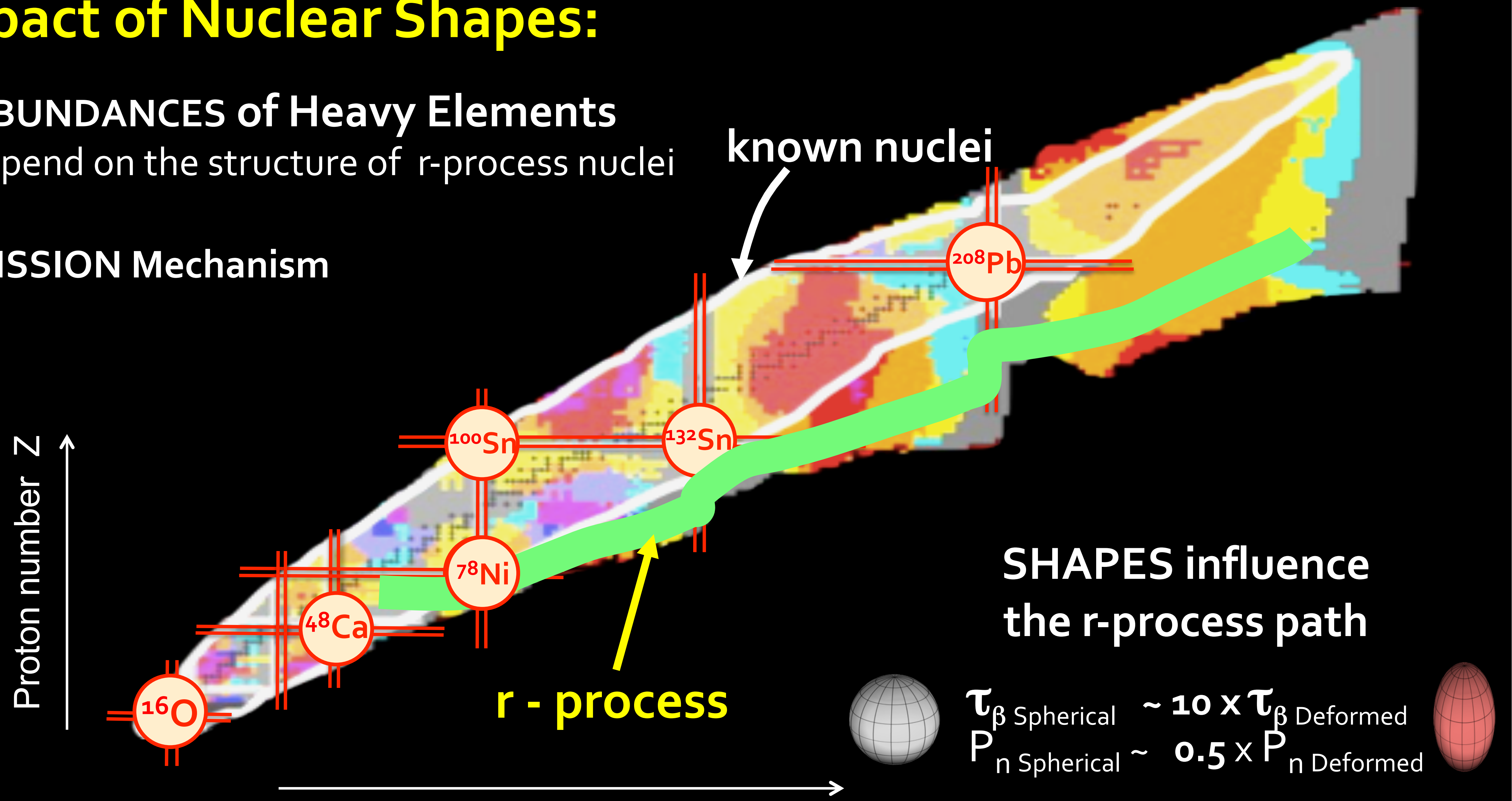
DENSITY ~ 10^{17} kg/m^3

Microscopic origin ?

Impact of Nuclear Shapes:

- **ABUNDANCES of Heavy Elements**
  depend on the structure of r-process nuclei

- **FISSION Mechanism**



SHAPES influence the r-process path

$\tau_{\beta\ \mathrm{Spherical}} \sim 10 \times \tau_{\beta\ \mathrm{Deformed}}$

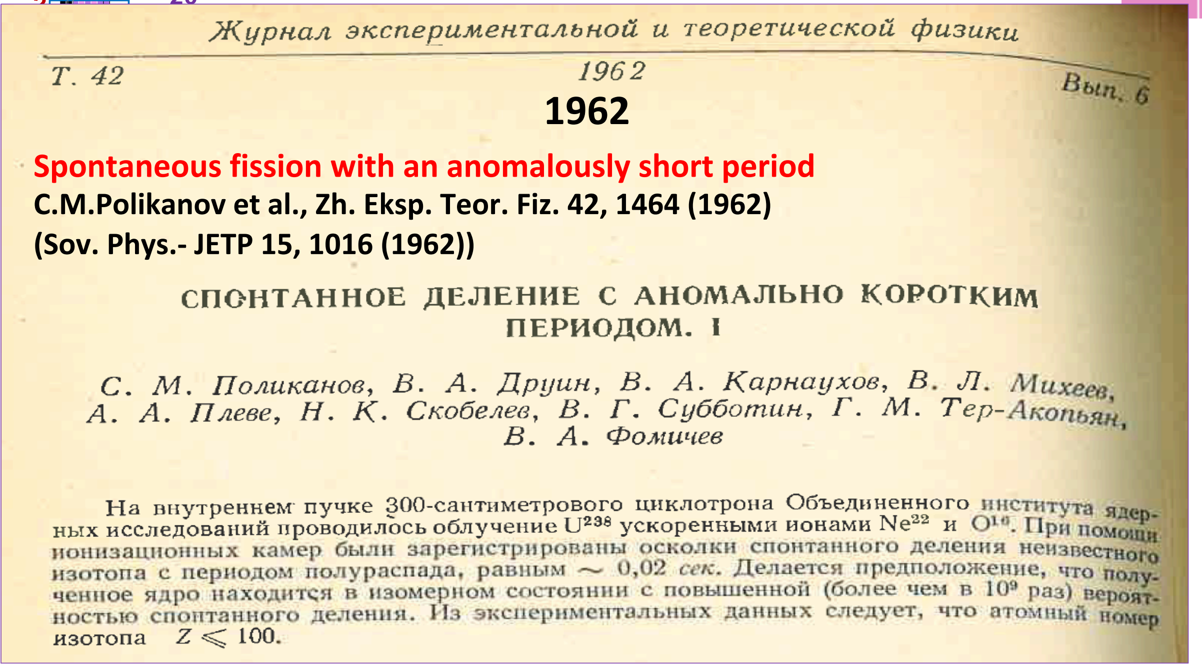
$P_{n\ \mathrm{Spherical}} \sim 0.5 \times P_{n\ \mathrm{Deformed}}$

Discovery of the first spontaneously fissioning isomer – Dubna 1961

S.M. Polikanov et al.

Reaction $^{16}O + ^{238}U$;
formation of nuclei near ^{238}U

Observation of fissioning isomer with a half-life 14 msec



Журнал экспериментальной и теоретической физики

Т. 42 | 1962 | Вып. 6

1962

Spontaneous fission with an anomalously short period

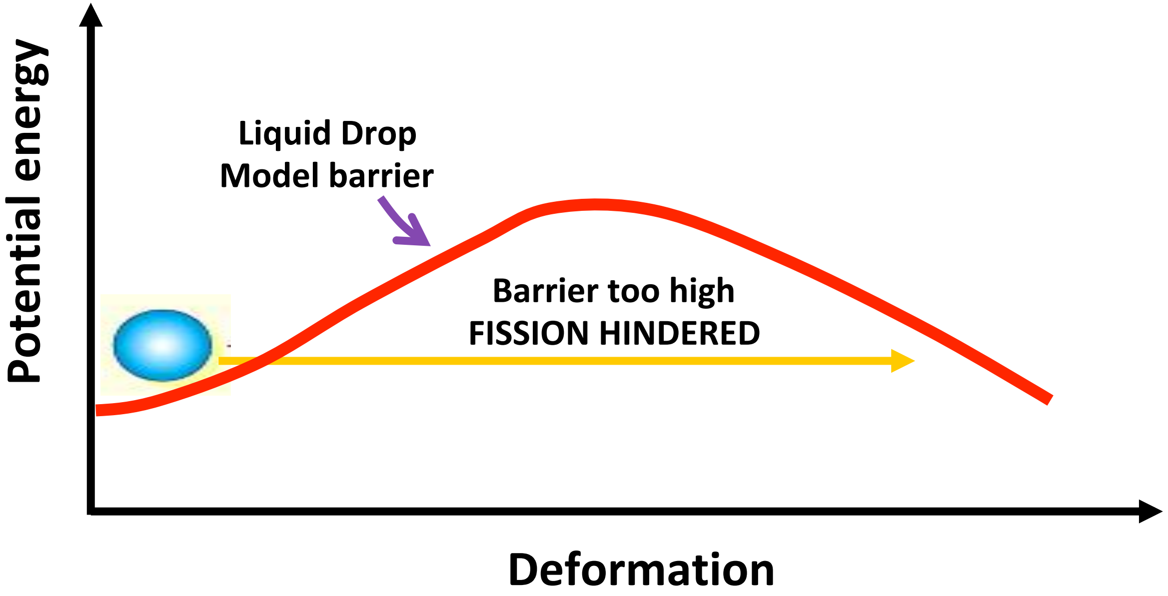
C.M.Polikanov et al., Zh. Eksp. Teor. Fiz. 42, 1464 (1962)

(Sov. Phys.- JETP 15, 1016 (1962))

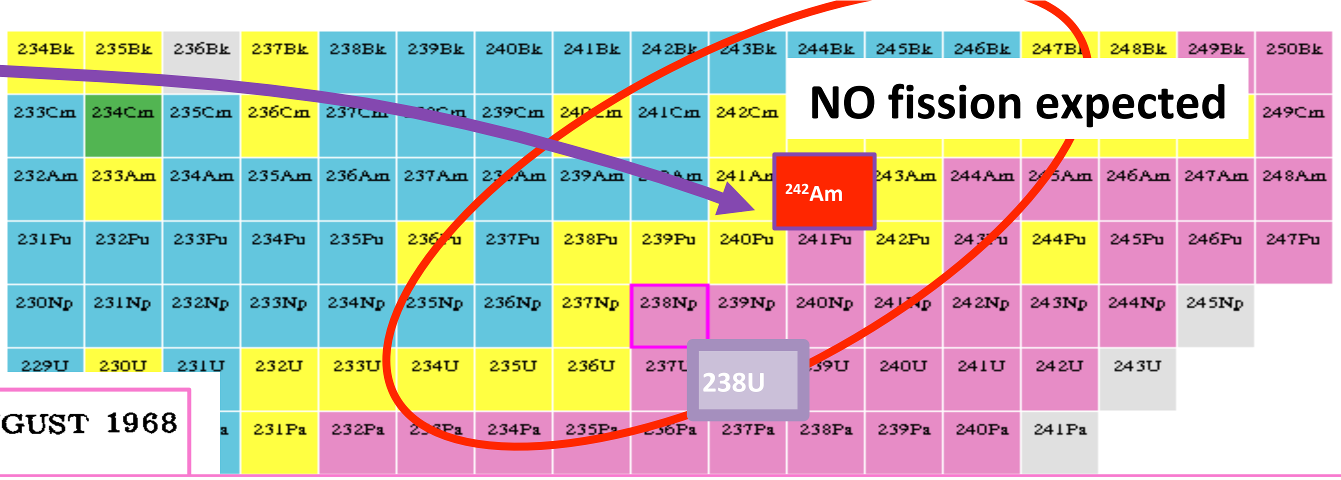
СПОНТАННОЕ ДЕЛЕНИЕ С АНОМАЛЬНО КОРОТКИМ ПЕРИОДОМ. I

С. М. Поликанов, В. А. Друин, В. А. Карнаухов, В. Л. Михеев, А. А. Плеве, Н. К. Скобелев, В. Г. Субботин, Г. М. Тер-Акопьян, В. А. Фомичев

На внутреннем пучке 300-сантиметрового циклотрона Объединенного института ядерных исследований проводилось облучение U^{238} ускоренными ионами Ne^{22} и O^{16}. При помощи ионизационных камер были зарегистрированы осколки спонтанного деления неизвестного изотопа с периодом полураспада, равным $\sim 0{,}02$ *сек*. Делается предположение, что полученное ядро находится в изомерном состоянии с повышенной (более чем в 10^9 раз) вероятностью спонтанного деления. Из экспериментальных данных следует, что атомный номер изотопа $Z \leqslant 100$.



Observation of fissioning isomer with a half-life 14 msec



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

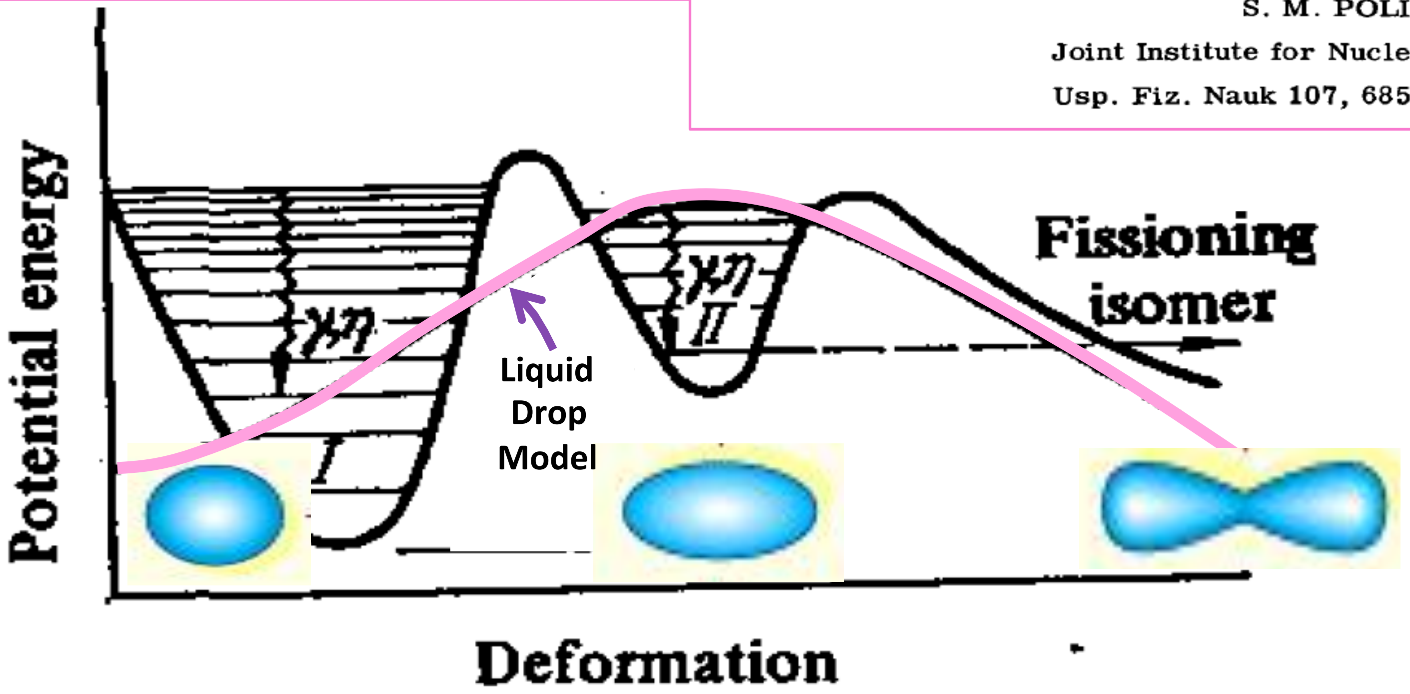
Physics of Our Days

NUCLEAR SHAPE ISOMERS

S. M. POLIKANOV

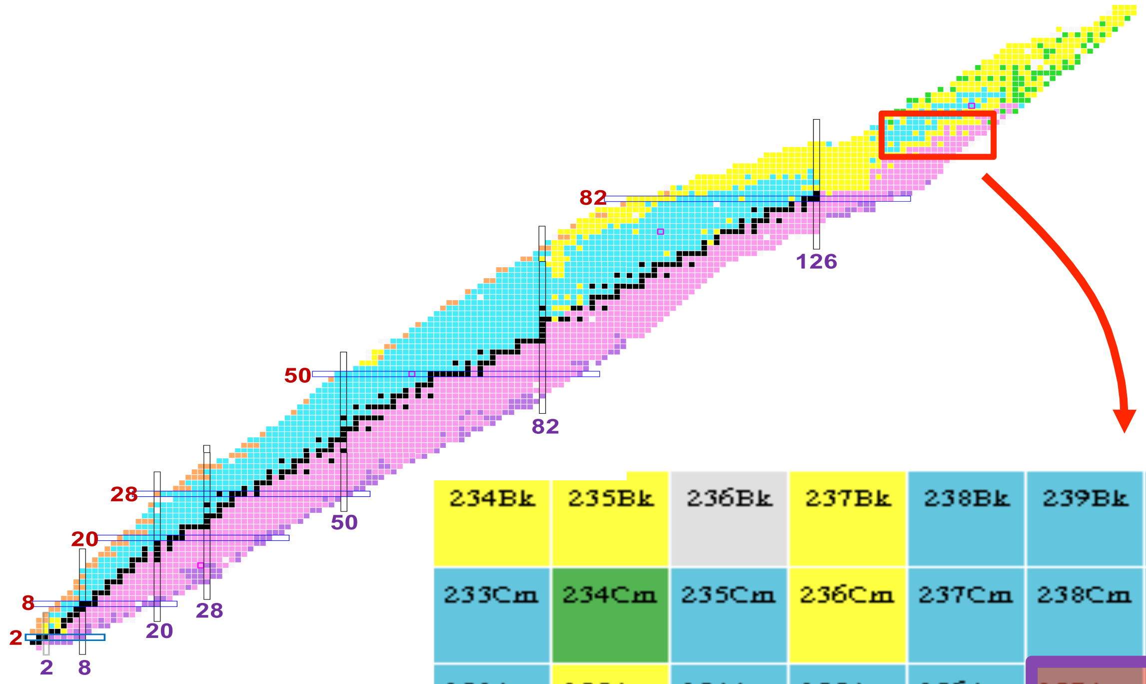
Joint Institute for Nuclear Research, Dubna

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



Shape isomers in actinides

- Nucleus trapped In the second minimum
- Spontaneous fission from the second minimum



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					

Shape isomers in actinides

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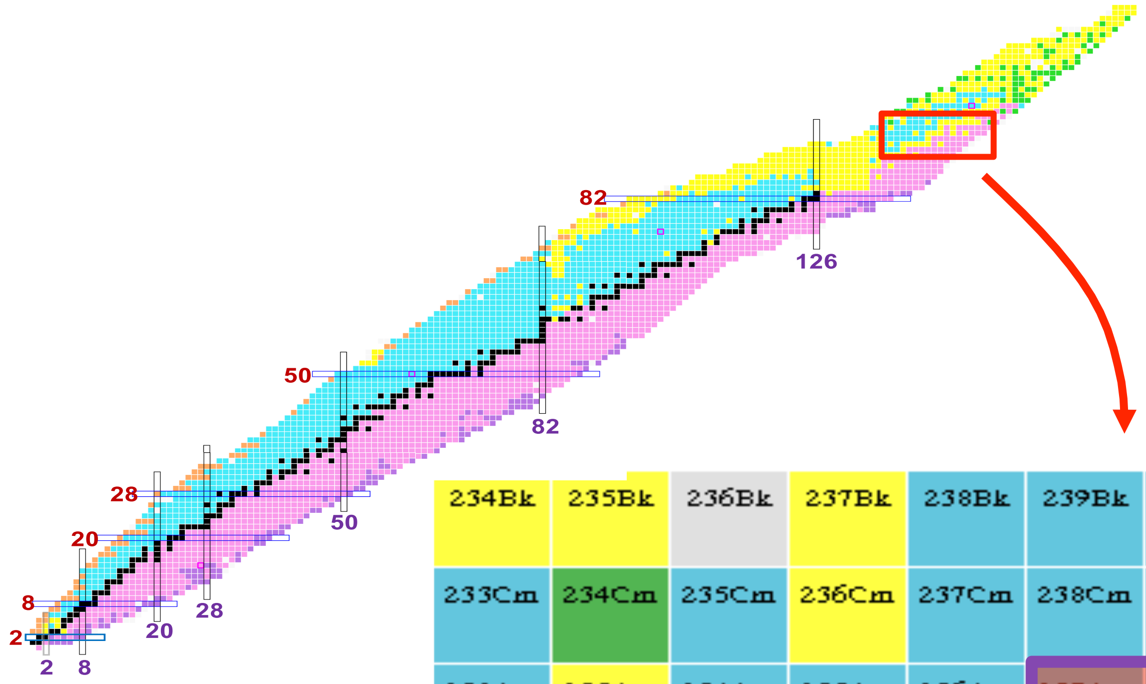
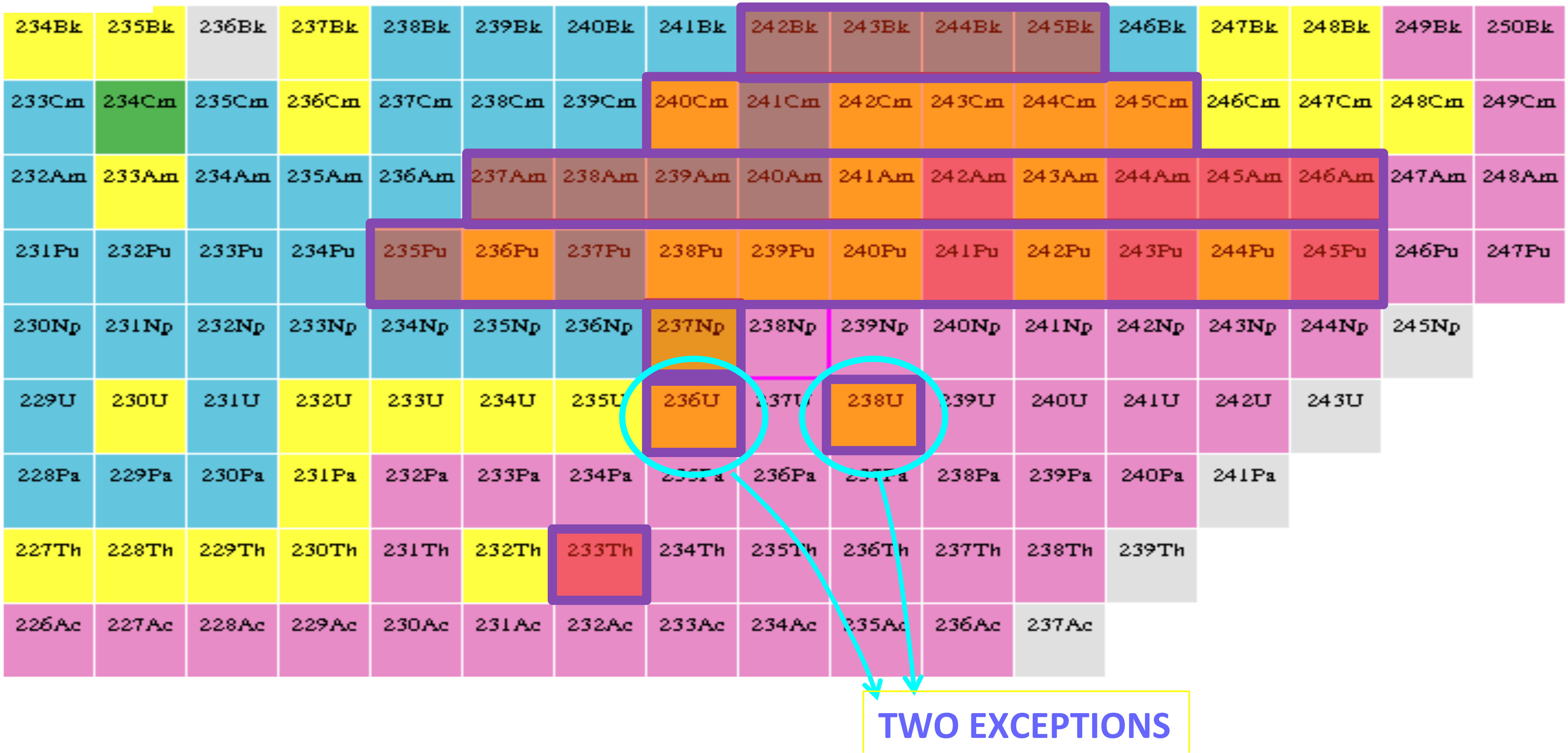
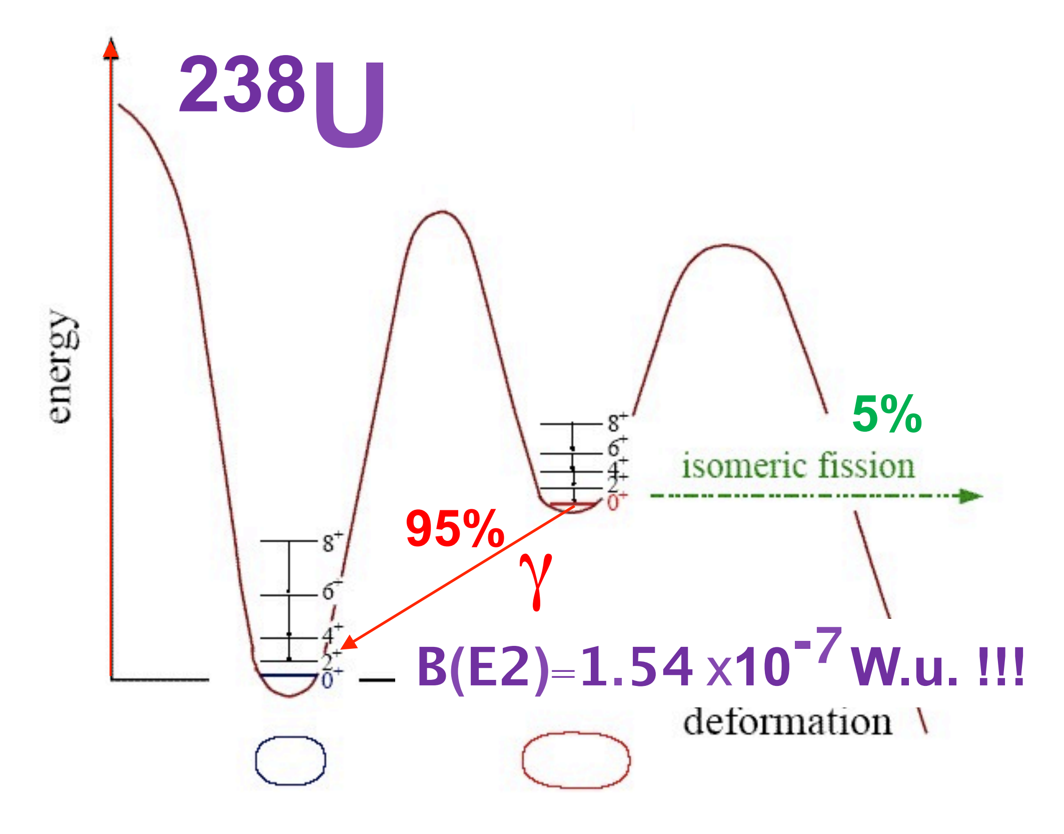




SHAPE ISOMER in ^{238}U:

very retarded photon decay (***10^7 hindrance***)

TWO SEPARATED WORLDS …



B(E2)– reduced E2 transition probability

(for almost all known E2 transitions B(E2) > 1 W.u.)

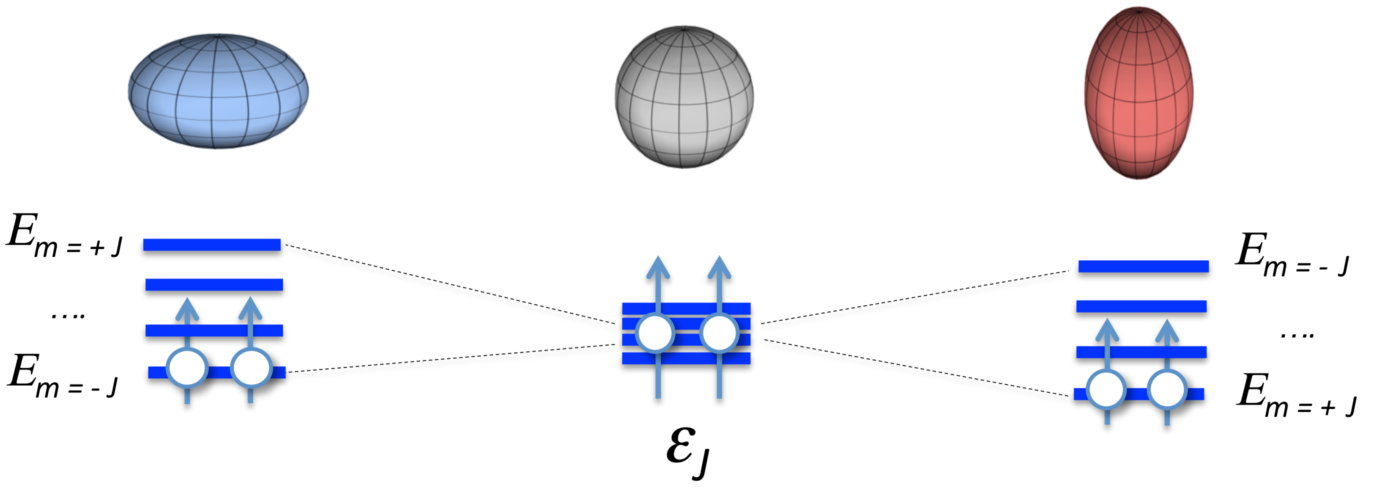
Can OTHER (lighter) nuclei exhibit these features?

We think of hindered decay from $J^{\pi}=0^{+}$ states!

LIGHTER SYSTEMS accessible by state-of-the-art **SHELL MODEL** calculations could be used to probe the **MICROPIC ORIGIN** of nuclear deformation

ORIGIN of the existence of different SHAPES in atomic nuclei

SPONTANEOUS SPHERICAL SYMMETRY-BREAKING
(single-particle states are degenerate and strongly coupled to a collective mode)



NUCLEAR JAHN-TELLER EFFECT

✔ Transition to deformed shapes as a nuclear Jahn-Teller effect
P.-G. Reinhard and E.W. Otten
Nuclear Physics A420 (1984) 173-192

✔ Microscopic Origin of Nuclear Deformations
W. Nazarewicz
Nuclear Physics A574 (1994) 27c-49c

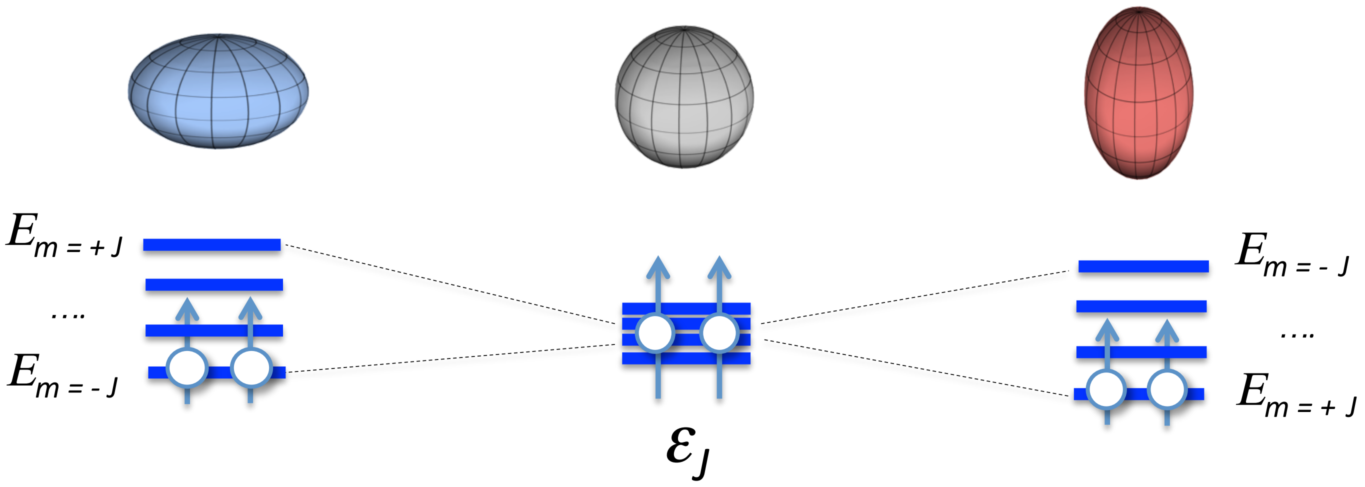
✔ Nuclear deformations as a spontaneous symmetry breaking
W. Nazarewicz
Int. Journal of Modern Physics E Vol. 2 (1993) 51

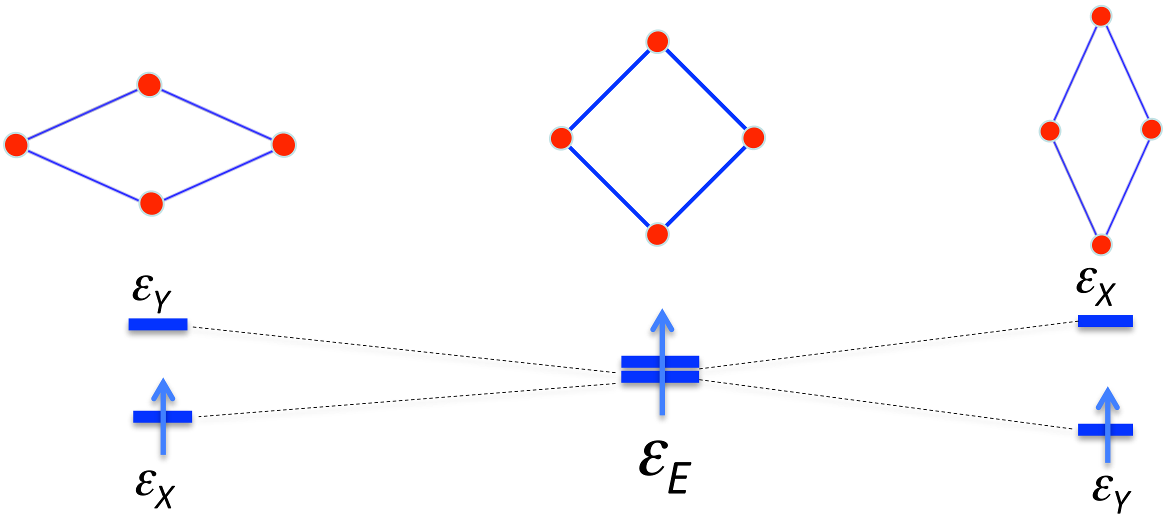
appearence of deformation
in the **ground state**
or in **excited states**
(SHAPE coexistence)

STRONG COUPLING between PARTICLES and COLLECTIVE degrees of freedom

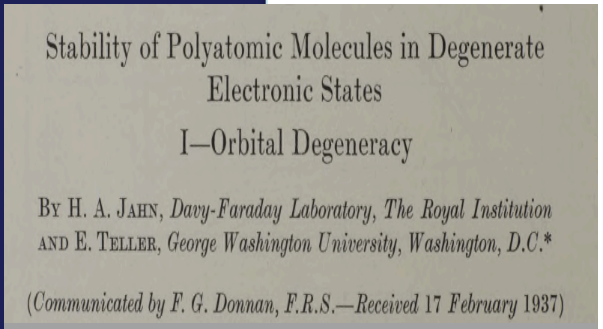
NUCLEAR JAHN-TELLER EFFECT

SPONTANEOUS SPHERICAL SYMMETRY-BREAKING
(single-particle states are degenerate and strongly coupled to a collective mode)





NON-LINEAR MOLECULES with **SPATIALLY DEGENERATE** electronic ground states undergo a **GEOMETRICAL DISTORTION** that removes that degeneracy


Stability of Polyatomic Molecules in Degenerate Electronic States

I—Orbital Degeneracy

By H. A. Jahn, *Davy-Faraday Laboratory, The Royal Institution* and E. Teller, *George Washington University, Washington, D.C.**

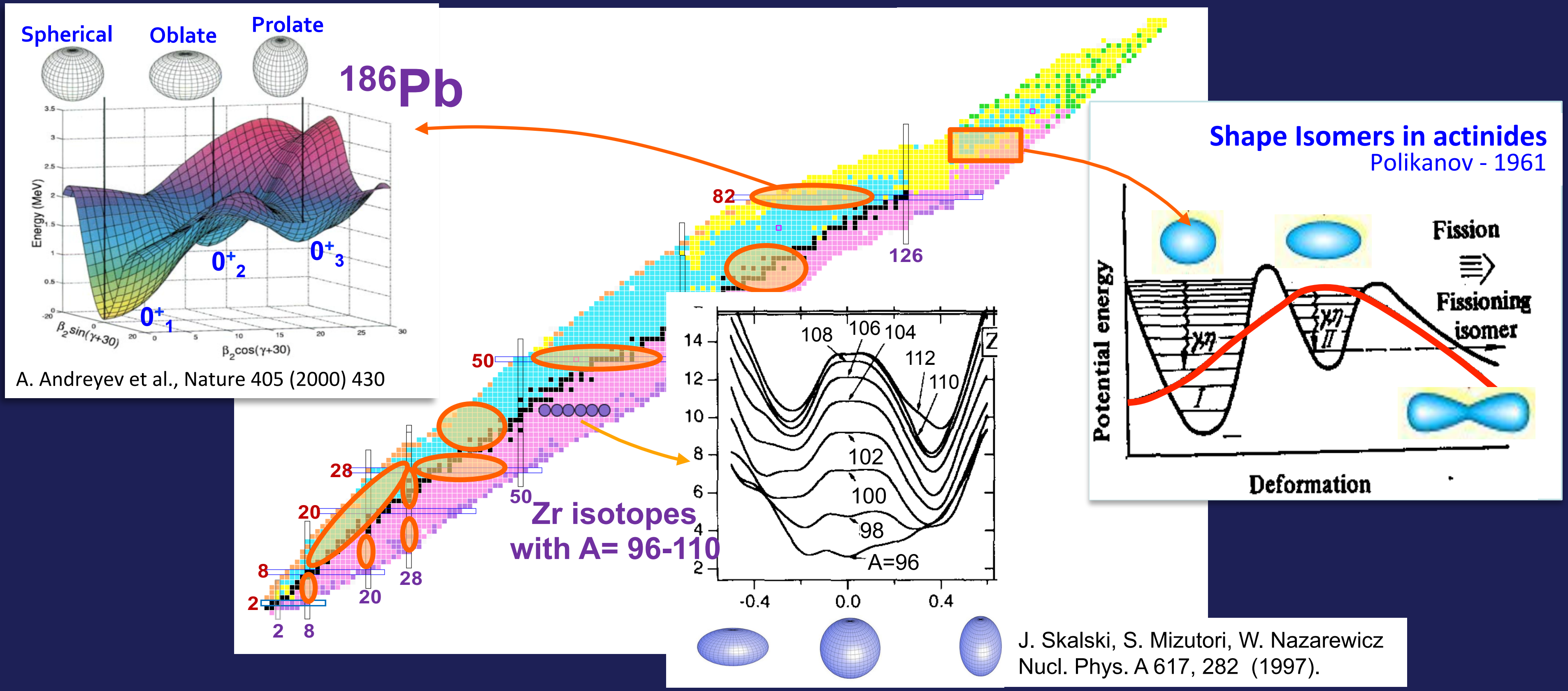
(*Communicated by F. G. Donnan, F.R.S.—Received 17 February 1937*)

H.A. Jahn and E. Teller,
Proc. Roy. Soc. A161 (1937) 220

SHAPE Coexistence in Atomic Nuclei

Appearence of states with different shapes at comparable (and low) excitation energies

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



Through the last 50 years of experimental activities, the concept has evolved:

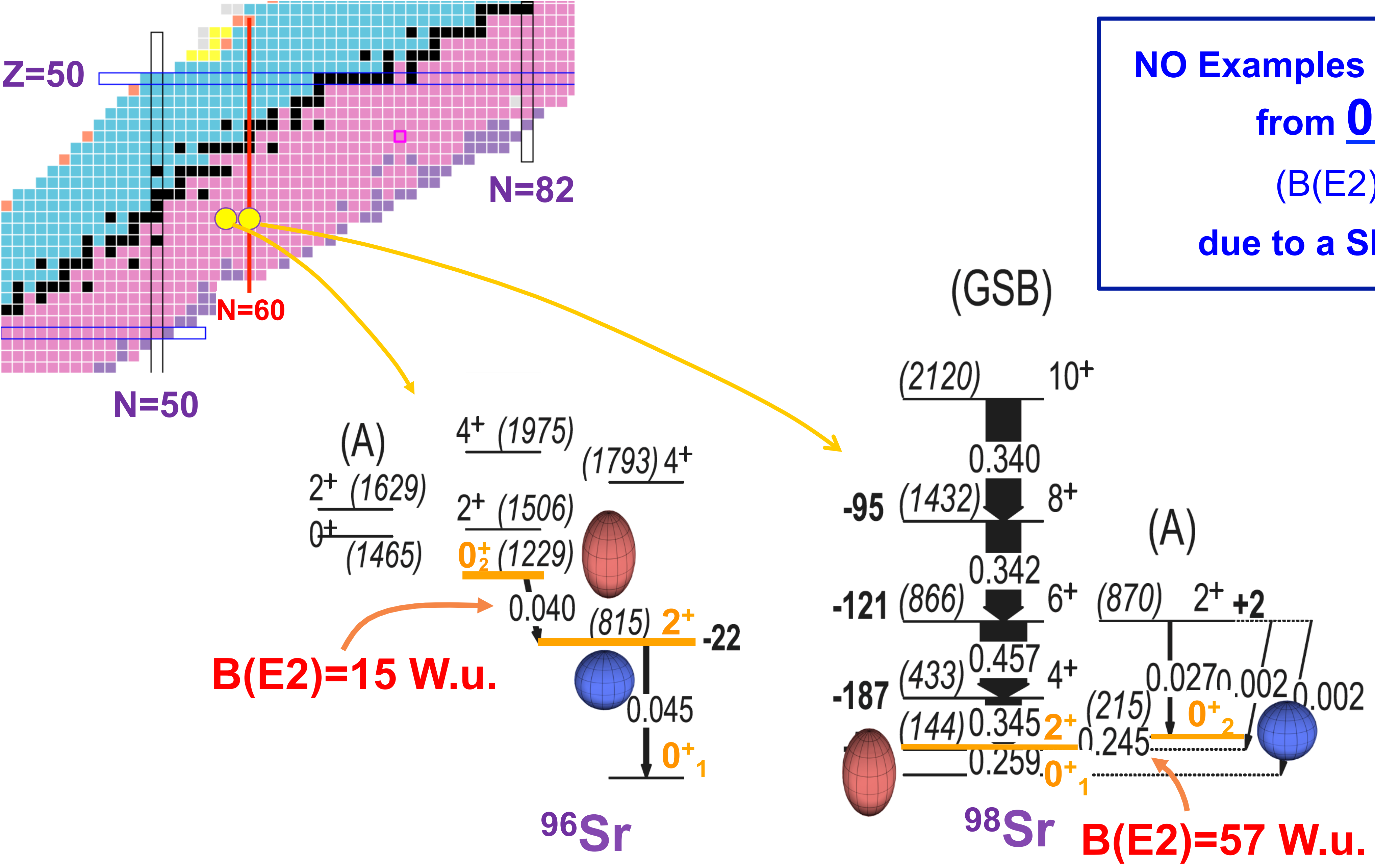
- exotic rarity (1970')
- islands of occurrence (1990')

<u>Several Talks on Shape Coexistence at NSD19</u>
V. Werner, N. Marchini – Zr
L. Iskra, E. Sahin, …

NO Examples of retarded decay from <u>0^+ states</u>

($B(E2) < 1$ W.u.)

due to a SHAPE Change



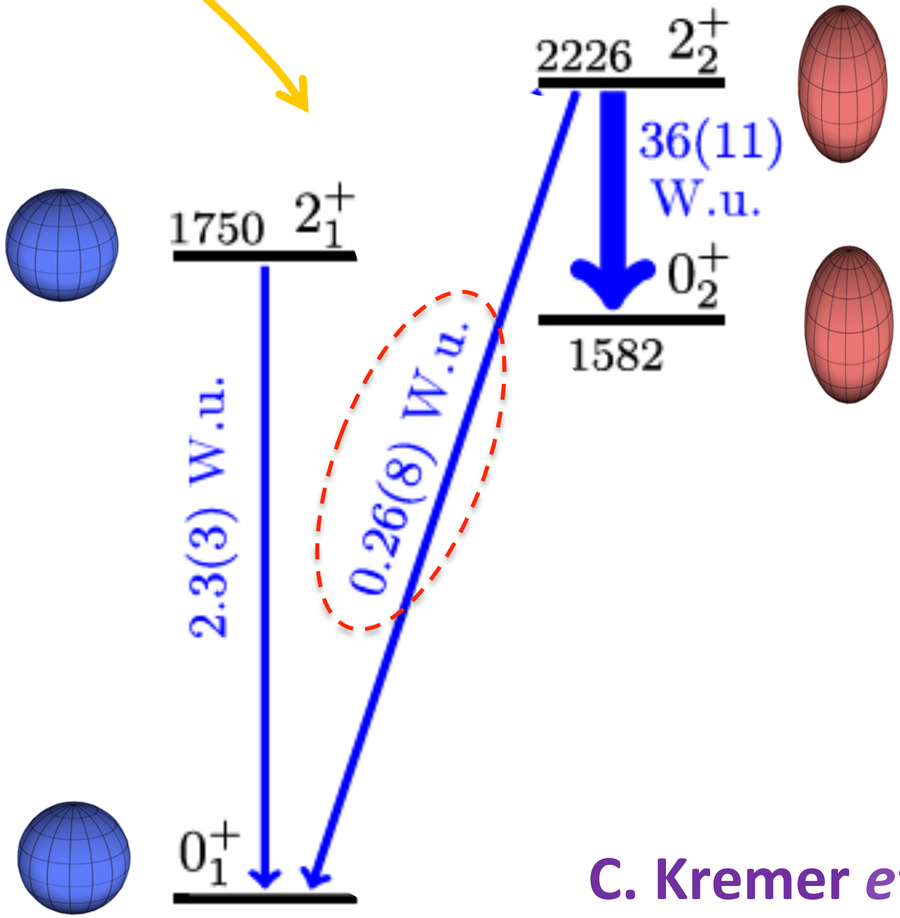
E. Clément *et al.*, Phys.Rev. Lett. 116, 022701 (2016)

94Mo	95Mo	96Mo	97Mo	98Mo	99Mo	100Mo	101Mo	102Mo	103Mo	104Mo	105Mo	106Mo
93Nb	94Nb	95Nb	96Nb	97Nb	98Nb	99Nb	100Nb	101Nb	102Nb	103Nb	104Nb	105Nb
92Zr	93Zr	94Zr	95Zr	96Zr	97Zr	98Zr	99Zr	100Zr	101Zr	102Zr	103Zr	104Zr
91Y	92Y	93Y	94Y	95Y	96Y	97Y	98Y	99Y	100Y	101Y	102Y	103Y

Only example of retarded decay from deformed <u>2^+ state</u>

($B(E2) < 1$ W.u.)

due to a SHAPE Change



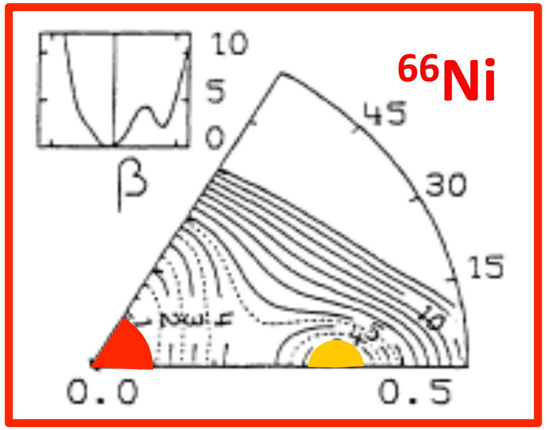
^{96}Zr

See V. Werner's Talk

C. Kremer *et al.*, Phys. Rev. Lett. 117, 172503 (2016)

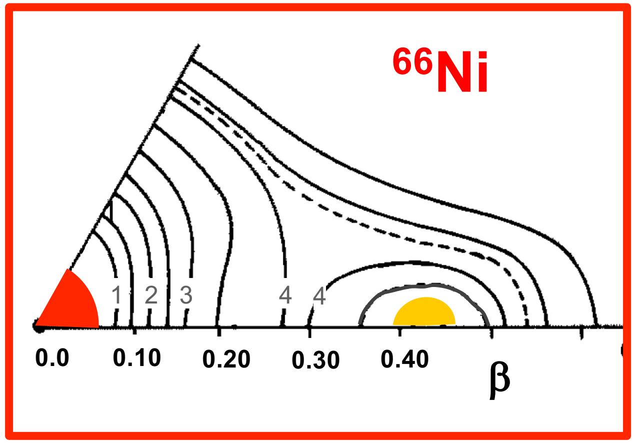
The Ni chain: one of the best "grounds" for testing coexistence of nuclear SHAPES

✓ Since 1980's Mean Field Models



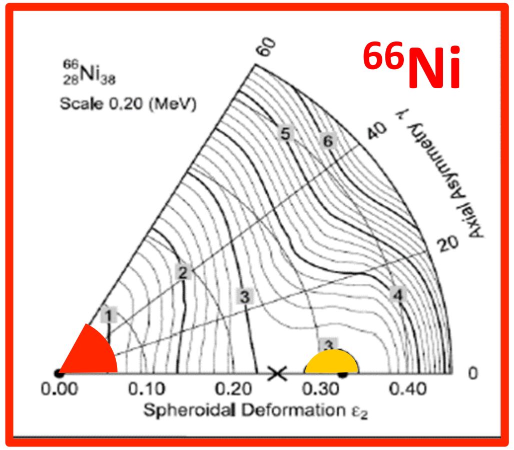
Microscopic Hartree-Fock-Bogoliubov

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



Microscopic Hartree-Fock plus BCS

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



Macro-Microscospic Model

P. Möller, A.J. Sierk, R. Bengtsson, H. Sagawa, T. Ichikawa At. Data and Nuc. Data Tables 98(2012)149

The Ni chain: one of the best "grounds" for testing coexistence of nuclear SHAPES

- ✓ **Since 1980's Mean Field Models**
- ✓ **Recently: LARGE SHELL MODEL Calculations**

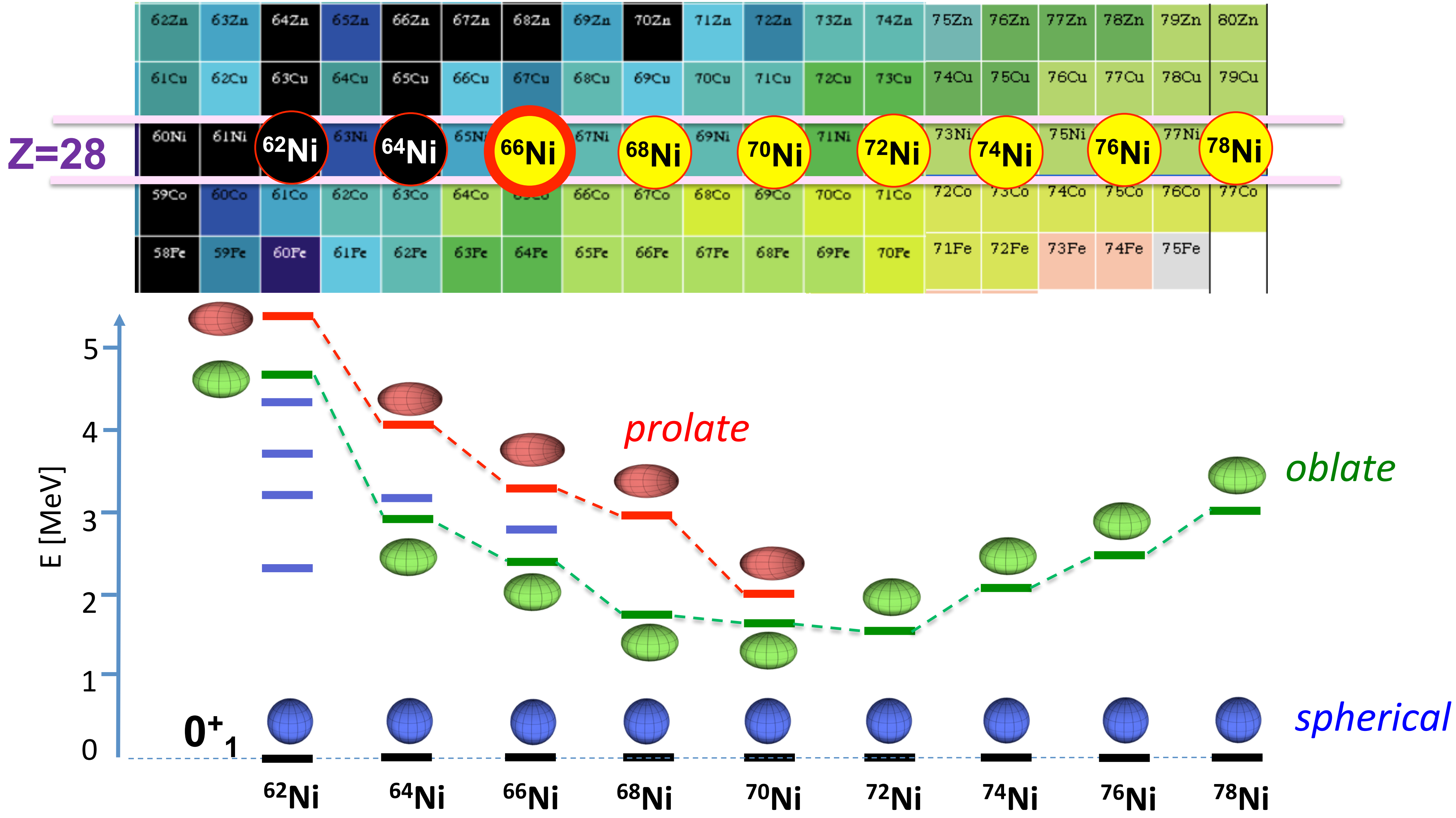
F. Nowacki, S. Lenzi, A. Poves
T. Otsuka

Monte Carlo Shell Model
Y. Tsunoda, T. Otsuka (Univ. of Tokyo)

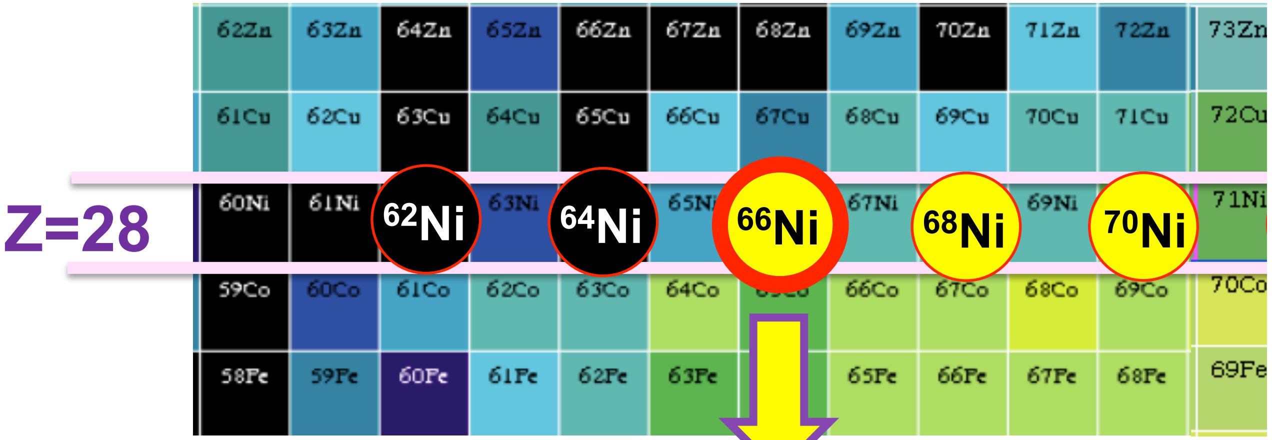
- Configuration space: $f_{7/2}$, $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$, $d_{5/2}$, $g_{7/2}$
- Number of configurations **10^{20}**
- New calculation schemes
- Very powerful computing systems with **1 000 000 parallel processors** *K-Computer in Tokyo*

MICROSCOPIC UNDERSTANDING: Wave Functions, B(Eλ/Mλ), …

The 0^+ states in Ni isotopes from MCSM calculations



Microscopic interpretation of deformation appearance in ^{66}Ni within the Monte Carlo Shell Model approach



PROLATE: significant components

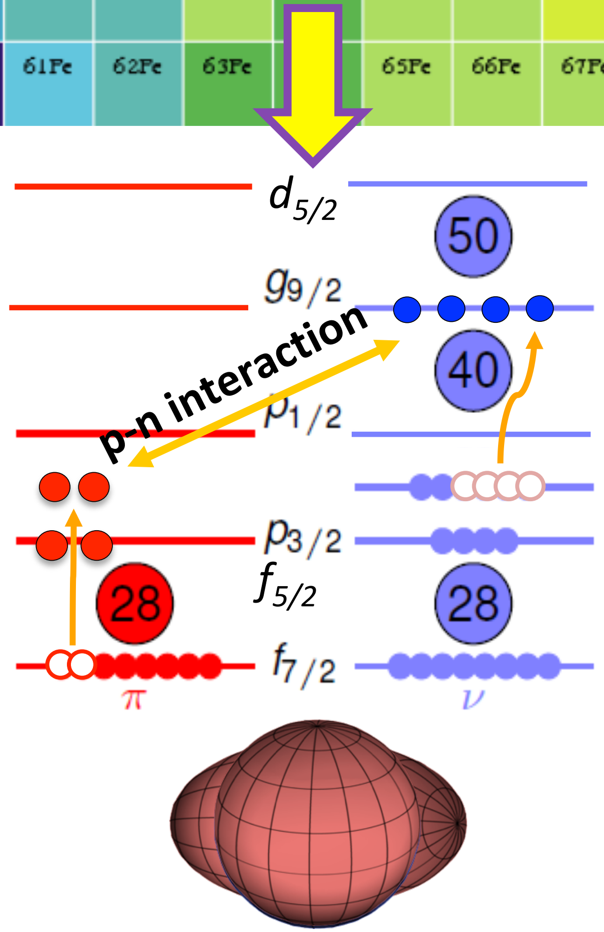
neutron $g_{9/2}$

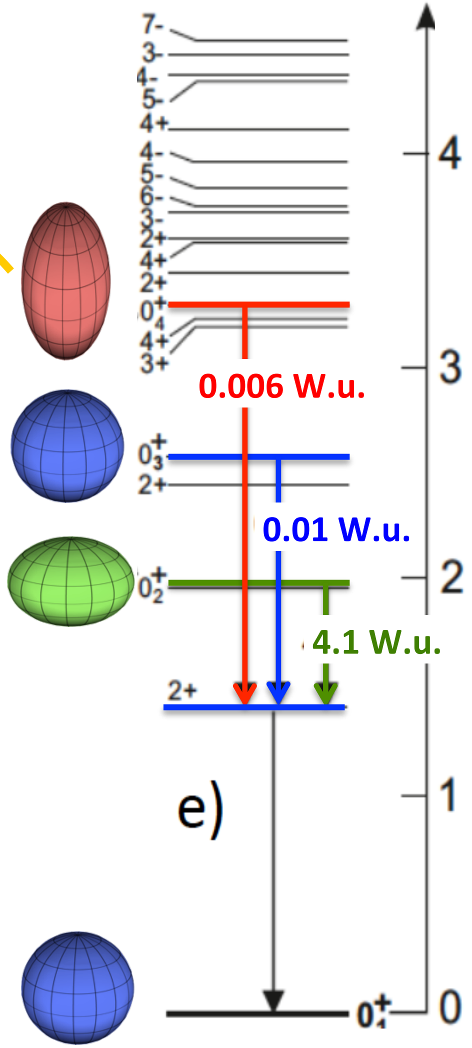
proton $p_{3/2}$, $f_{5/2}$

Hindered Decay

B(E2) < 1 W.u.

"SHAPE ISOMER-like"





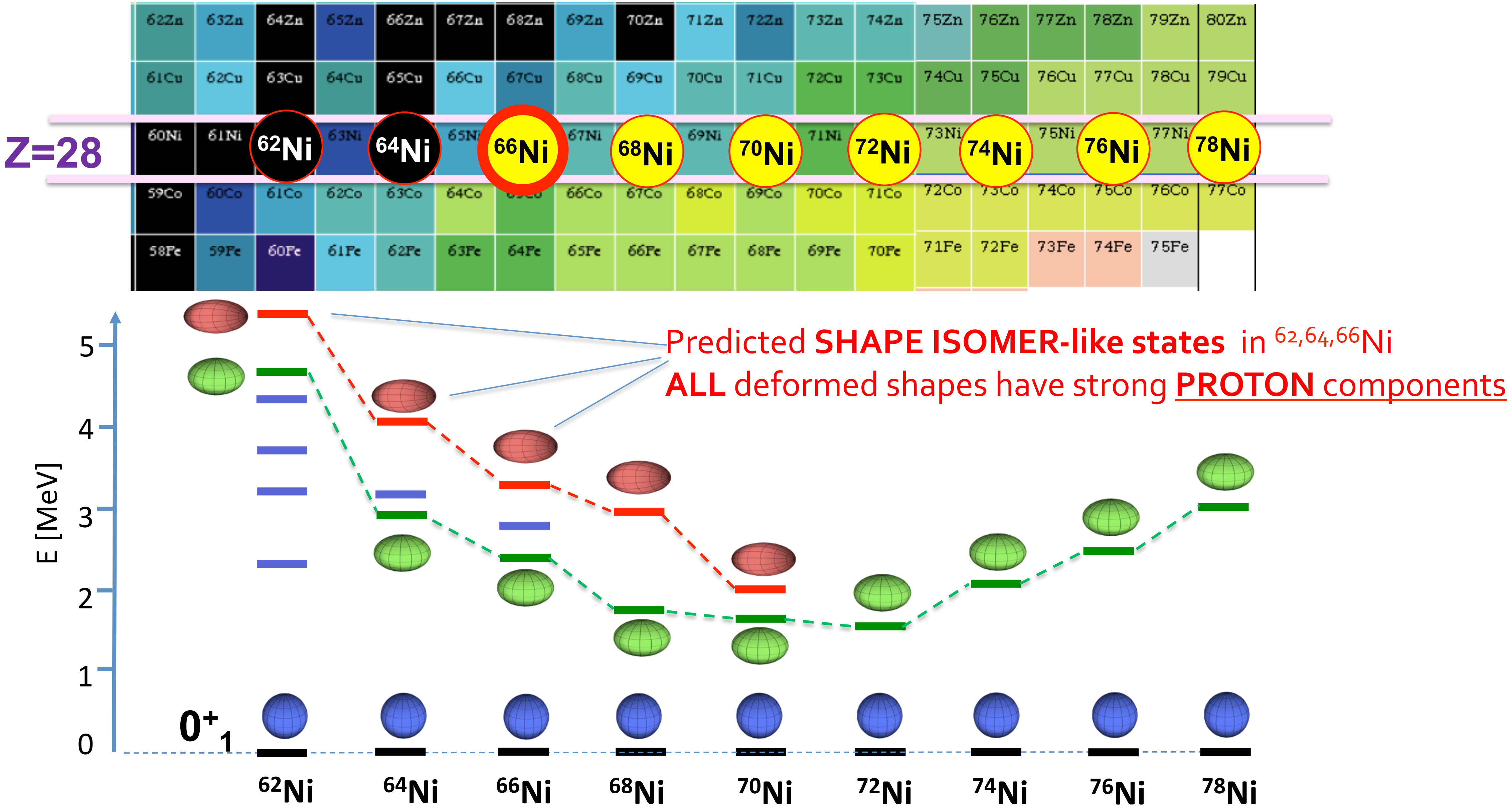
^{66}Ni - MCSM

Tensor-Force-Driven JAHN-TELLER effect

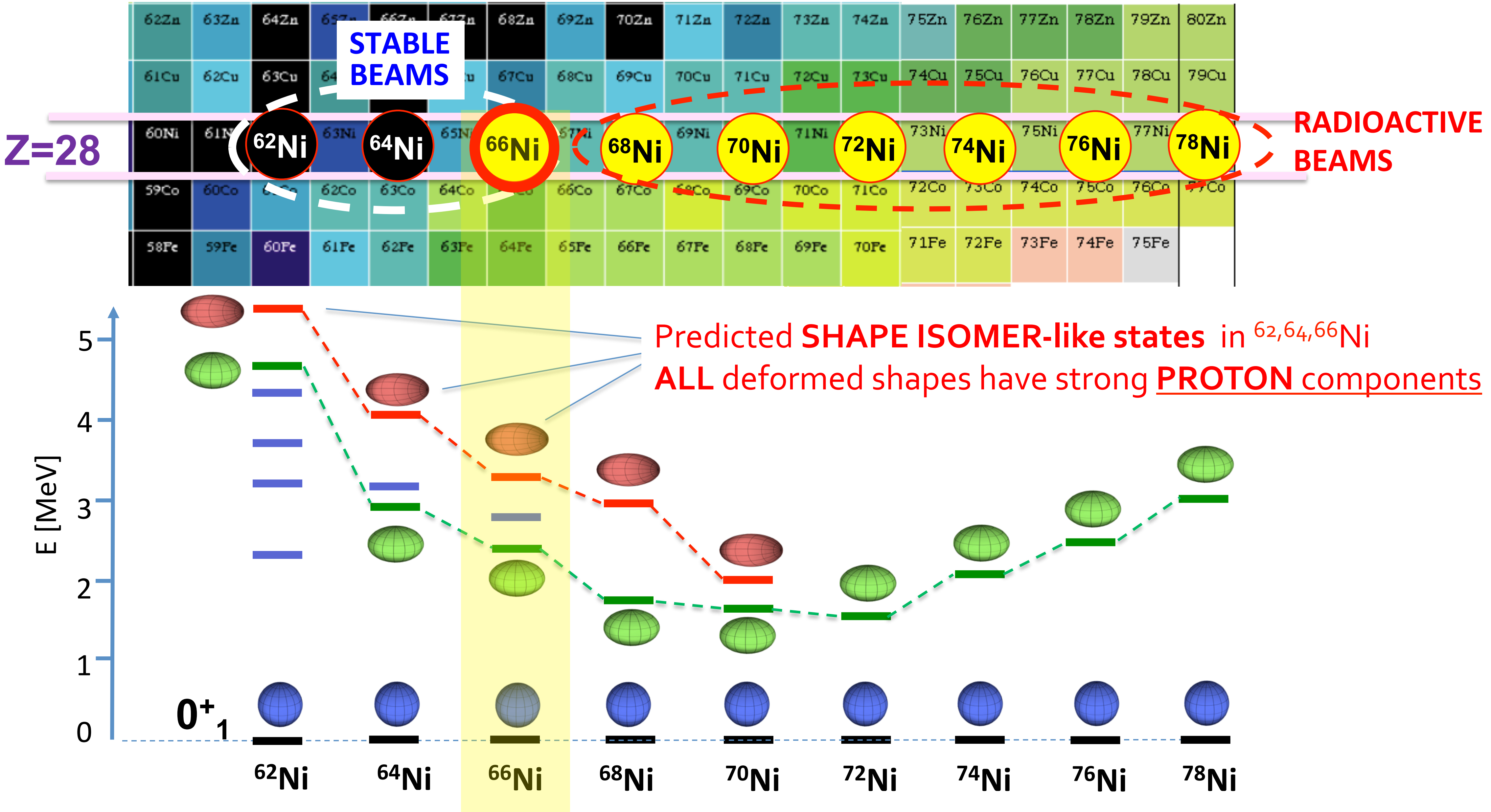
(spontaneus symmetry breaking)

Shape transition occurs WITHIN the SAME nucleus Type-II Shell Evolution

Microscopic interpretation of deformation appearance in ^{66}Ni within the Monte Carlo Shell Model approach



Joint experimental program at IFIN-HH, ILL, Orsay:
search for SHAPE isomers in Ni and probe the wave function component



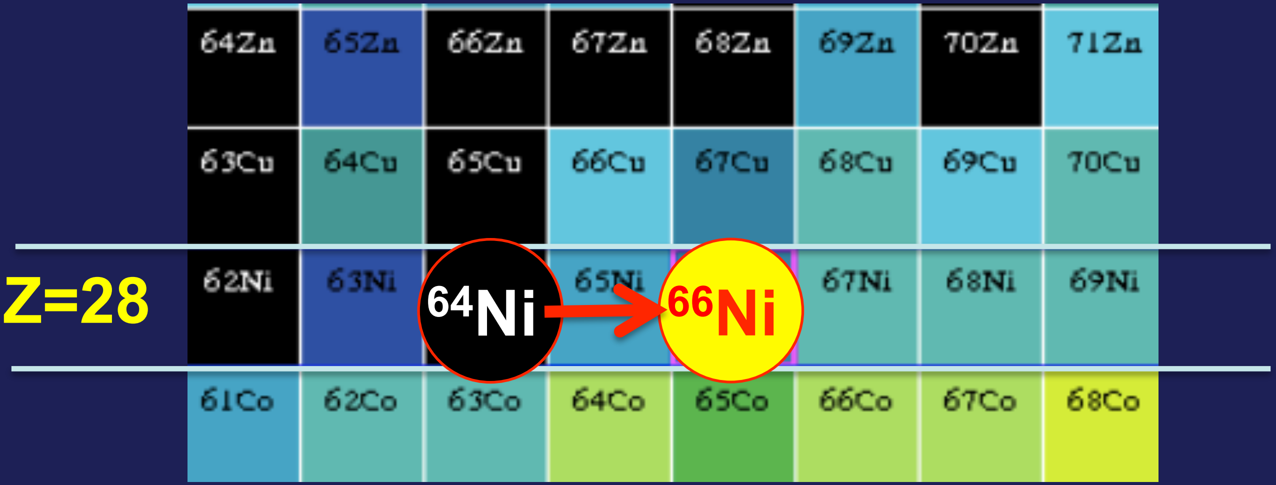
^{66}Ni experiment at IFIN-HH in Bucharest (July 2016)

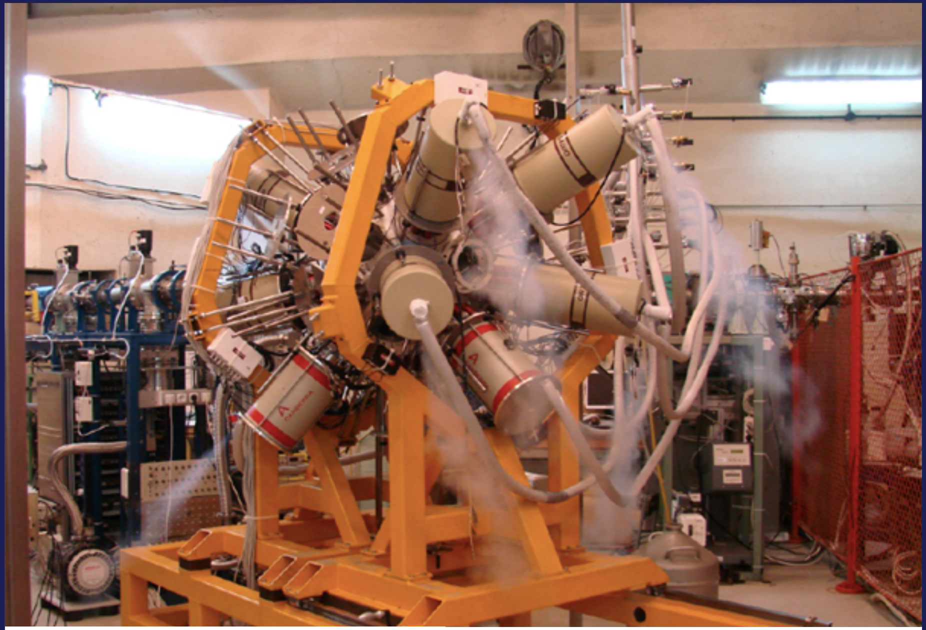
Sub-Barrier Transfer induced by ^{18}O

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

$\sigma(^{66}Ni) \approx$ few mb

FUSION strongly suppressed





ROSPHERE

14 HPGe - 1.1% eff

11 $LaBr_3(Ce)$ - 1.75% eff

- **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

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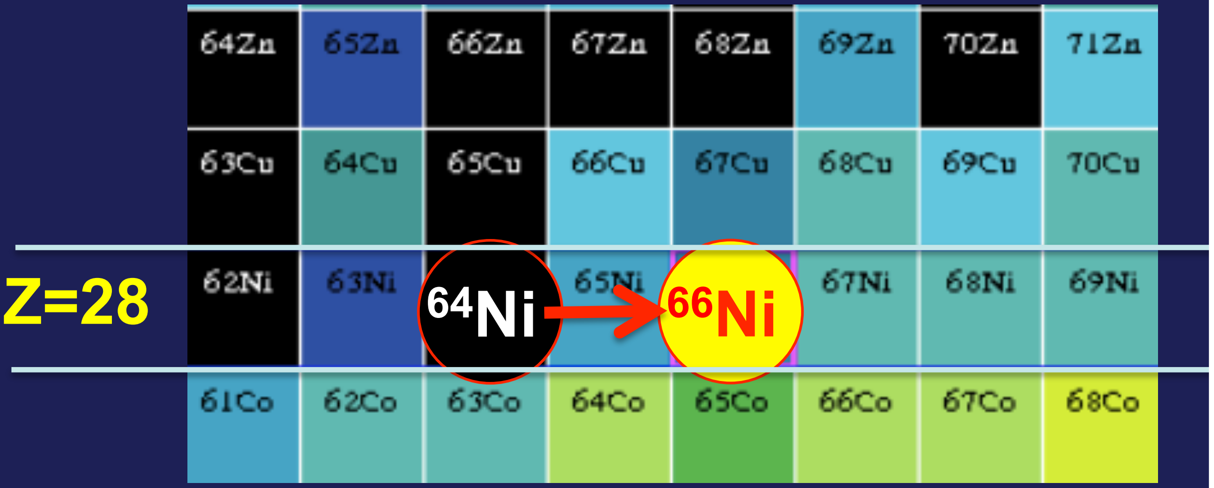
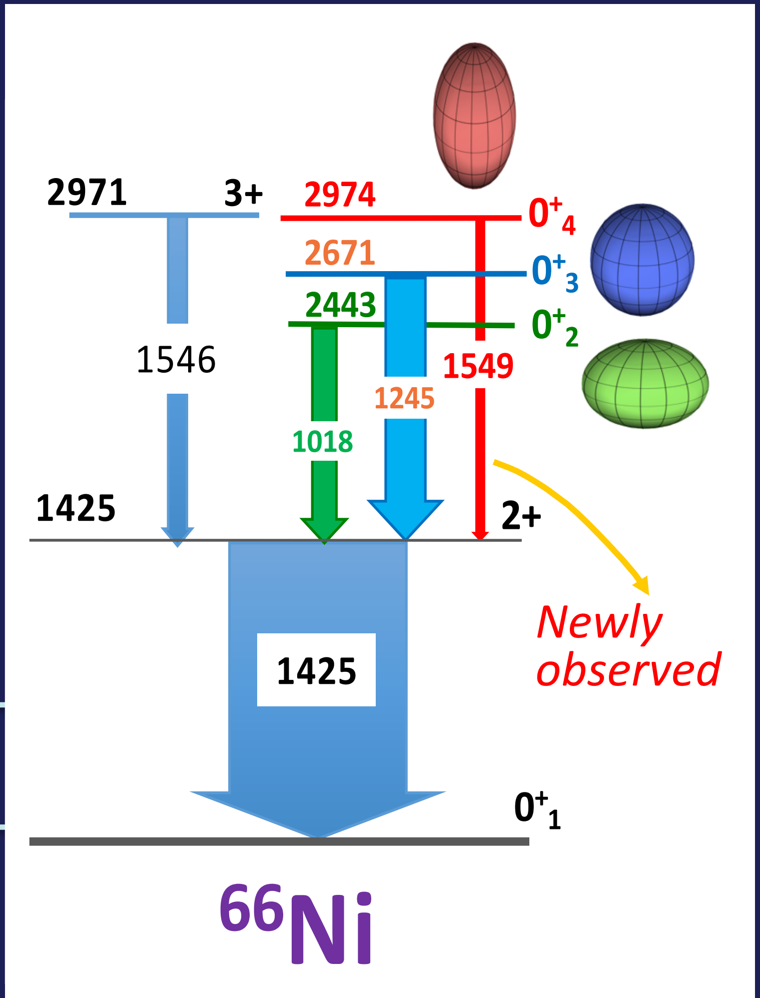




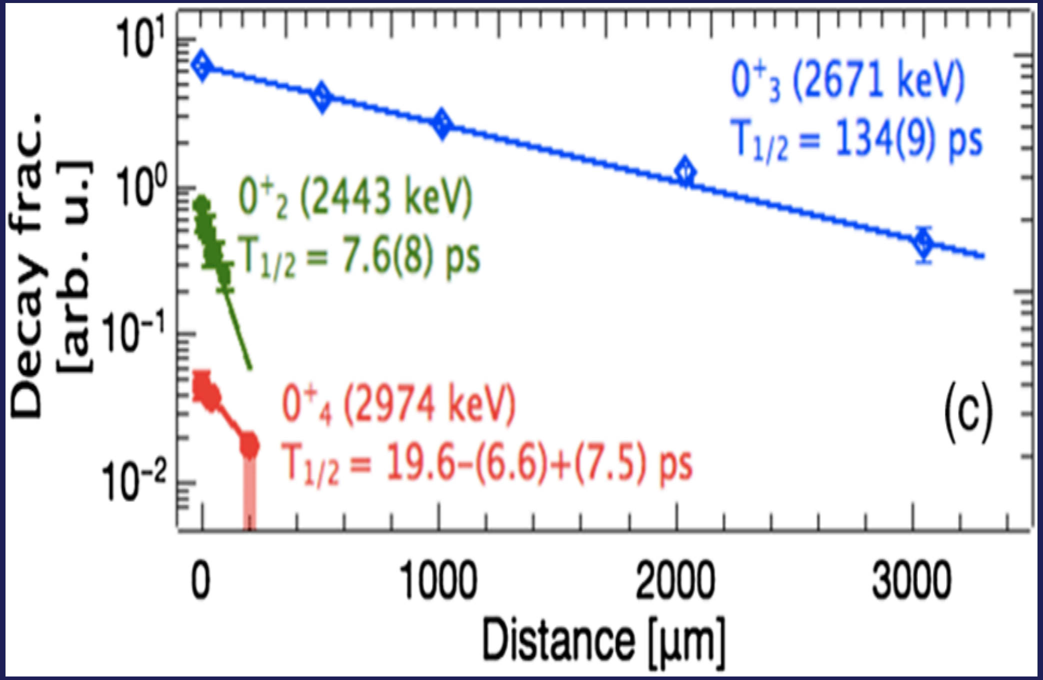
Powerful Reaction mechanism for direct population of 0^+ states

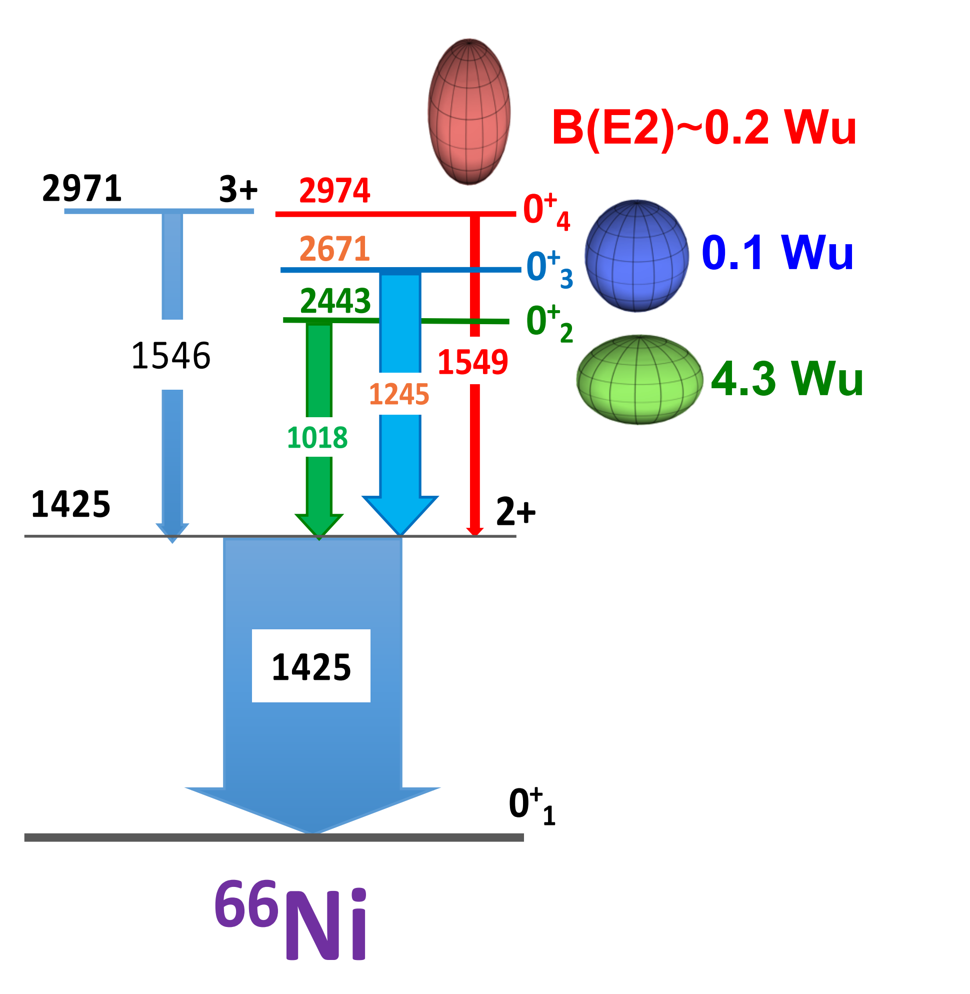
^{66}Ni experiment at IFIN-HH in Bucharest (July 2016)

Sub-Barrier Transfer induced by ^{18}O

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

Lifetimes of all three 0^+ states





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

0^+_3 lifetime independently measured by B. Olaizola, et al., *PRC95, 061303(R) (2017)*

^{66}Ni experiment at IFIN-HH in Bucharest (July 2016)

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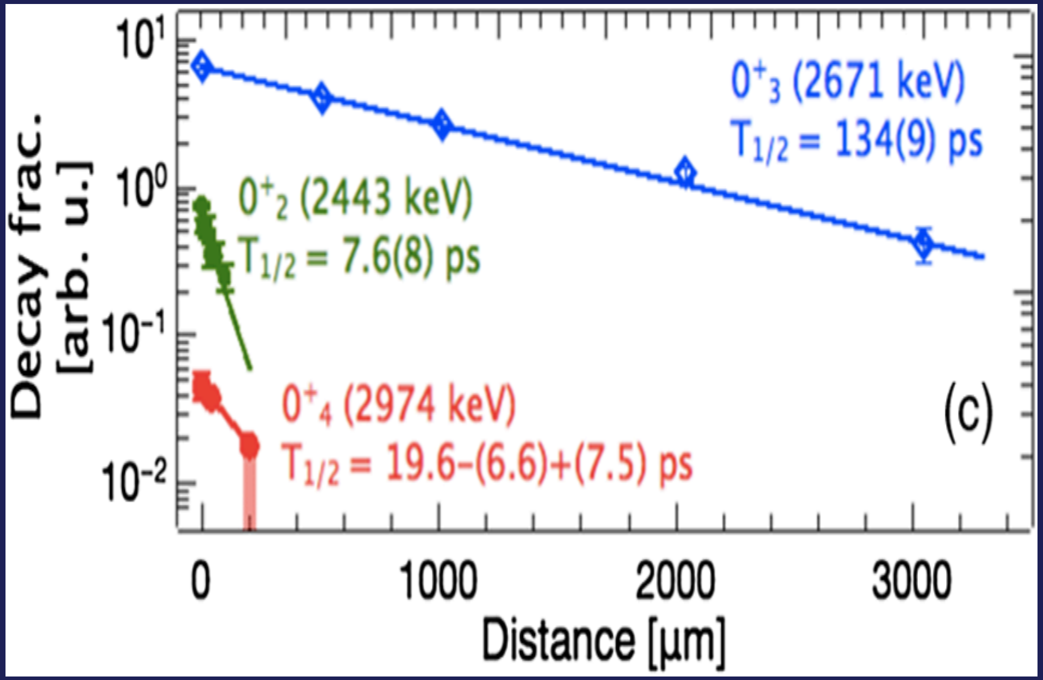
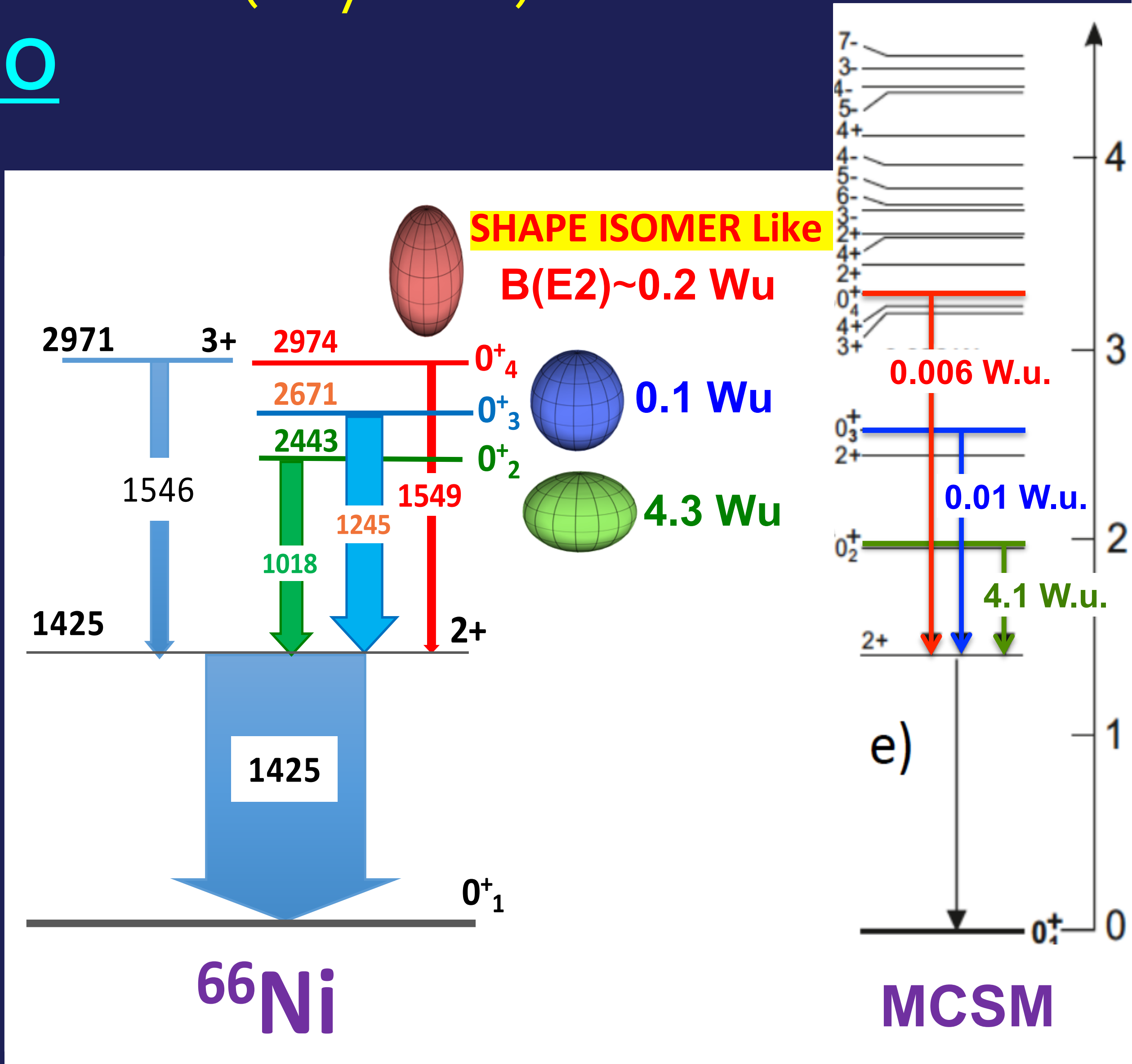
Lifetimes of all three 0^+ states





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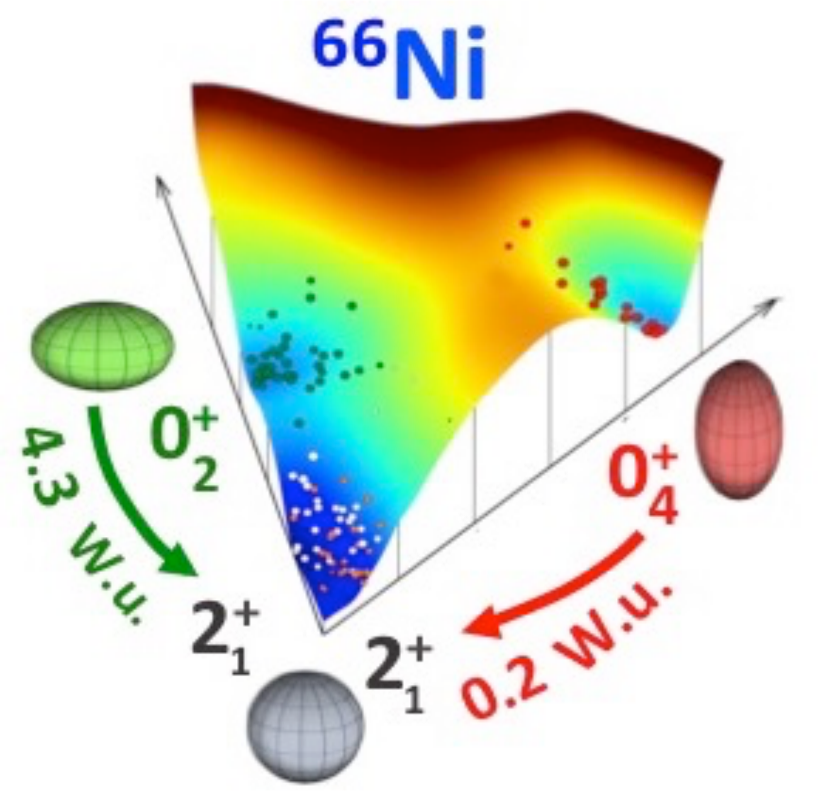

^{66}Ni: lightest and unique example

- apart from the actinides –

of 0^+ deformed state deexciting via HINDERED γ transition

a SHAPE-ISOMER-like structure !

It is a probe of Monte Carlo Shell Model predictive power:

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

S. Leoni,[1,2,*] B. Fornal,[3] N. Mărginean,[4] M. Sferrazza,[5] Y. Tsunoda,[6] T. Otsuka,[6,7,8,9] G. Bocchi,[1,2] F. C. L. Crespi,[1,2] A. Bracco,[1,2] S. Aydin,[10] M. Boromiza,[4,11] D. Bucurescu,[4] N. Cieplicka-Oryǹczak,[2,3] C. Costache,[4] S. Călinescu,[4] N. Florea,[4] D. G. Ghiţă,[4] T. Glodariu,[4] A. Ionescu,[4,11] Ł.W. Iskra,[3] M. Krzysiek,[3] R. Mărginean,[4] C. Mihai,[4] R. E. Mihai,[4] A. Mitu,[4] A. Negreţ,[4] C. R. Niţă,[4] A. Olăcel,[4] A. Oprea,[4] S. Pascu,[4] P. Petkov,[4] C. Petrone,[4] G. Porzio,[1,2] A. Şerban,[4,11] C. Sotty,[4] L. Stan,[4] I. Ştiru,[4] L. Stroe,[4] R. Şuvăilă,[4] S. Toma,[4] A. Turturică,[4] S. Ujeniuc,[4] and C. A. Ur[12]
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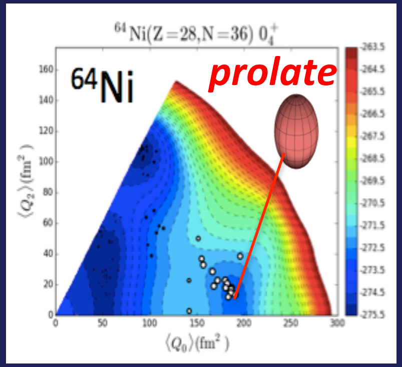
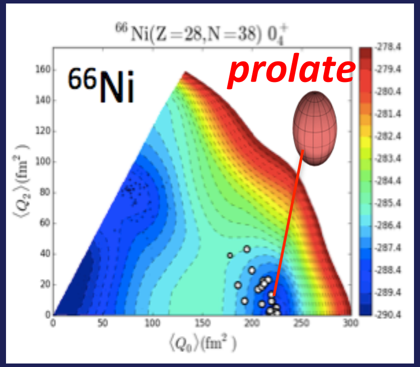
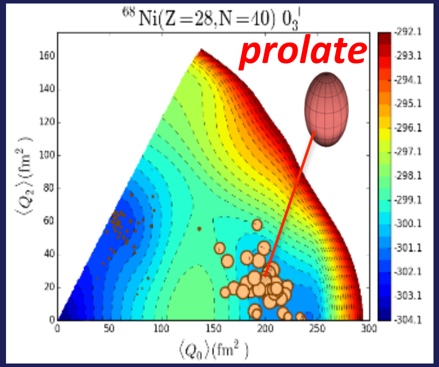
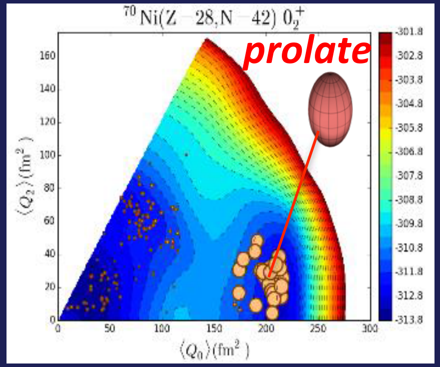
Same features of PROLATE 0^+ states along the Ni chain:

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

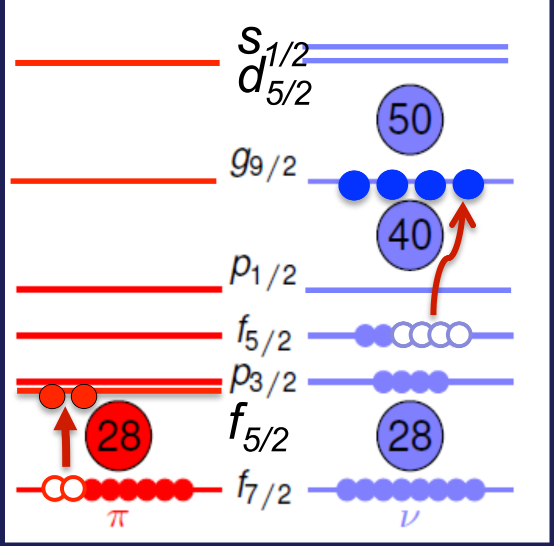








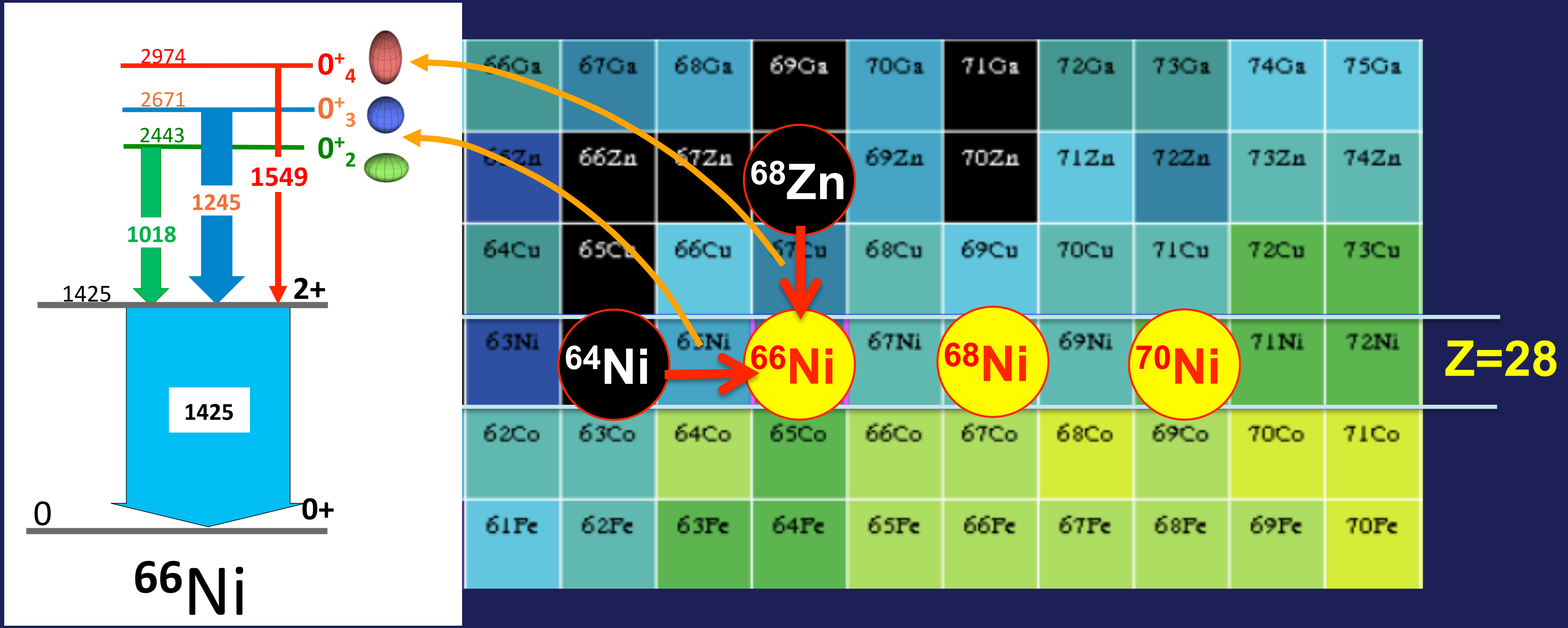
$B(E2, 0^+_{prolate} \rightarrow 2^+_{spher.}) = 0.2$ W.u. 2.3 W.u. 3.4 W.u.



Sizable occupation of <u>neutron</u> $g_{9/2}$ and <u>proton</u> $p_{3/2}$, $f_{5/2}$ orbitals

Can we enhance the population of prolate 0^+ state ?

Probing the wave functions composition by proton and neutron transfer reactions

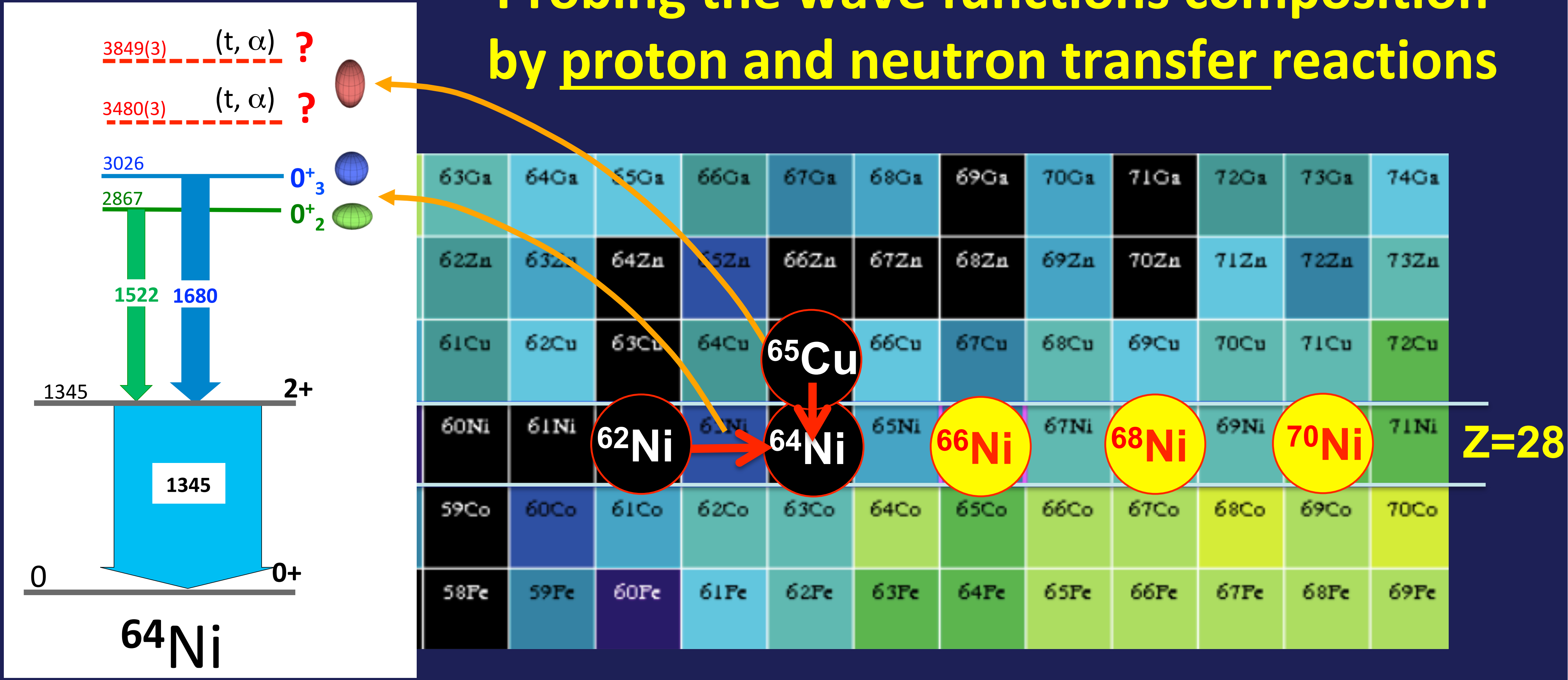


2n : $^{18}O + ^{64}Ni \rightarrow ^{16}O + ^{66}Ni$, neutron excitations enhanced (spherical/oblate)

~~2p : $^{14}C + ^{68}Zn \rightarrow ^{16}O + ^{66}Ni$,~~ proton excitations enhanced (prolate)

NOT FEASIBLE at SUB-BARRIER ENERGIES – checked experimentally !!!

Probing the wave functions composition by proton and neutron transfer reactions



Both reactions are feasible !!!!

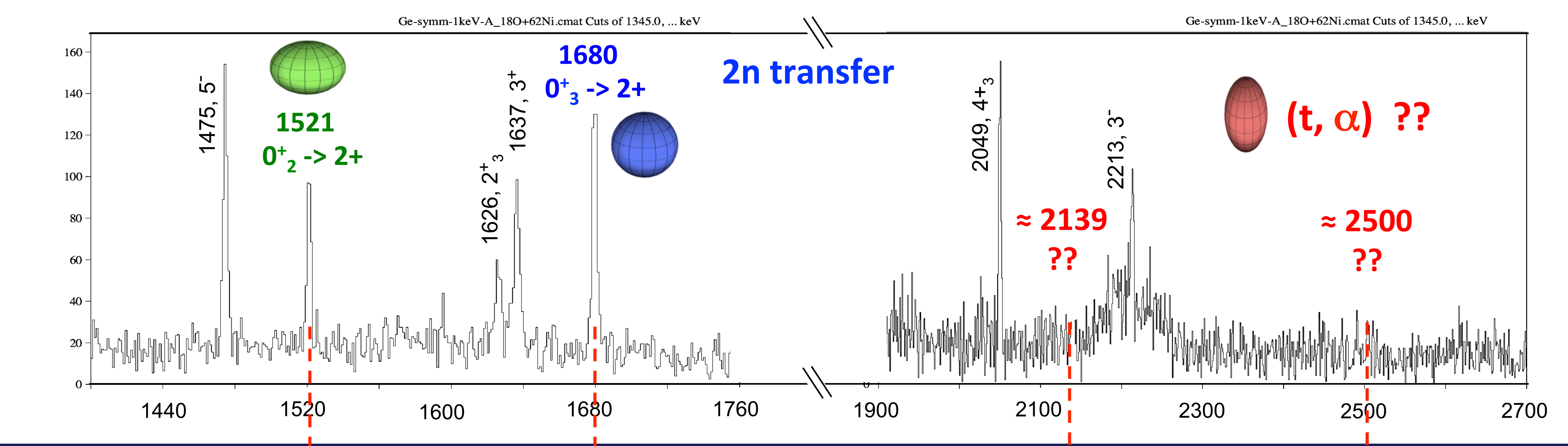
2n : $^{18}O + ^{62}Ni \rightarrow ^{16}O + ^{64}Ni$, **neutron** excitations enhanced **(spherical/oblate)**

1p : $^{11}B + ^{65}Cu \rightarrow ^{12}C + ^{64}Ni$, **proton** excitations are enhanced **(prolate)**

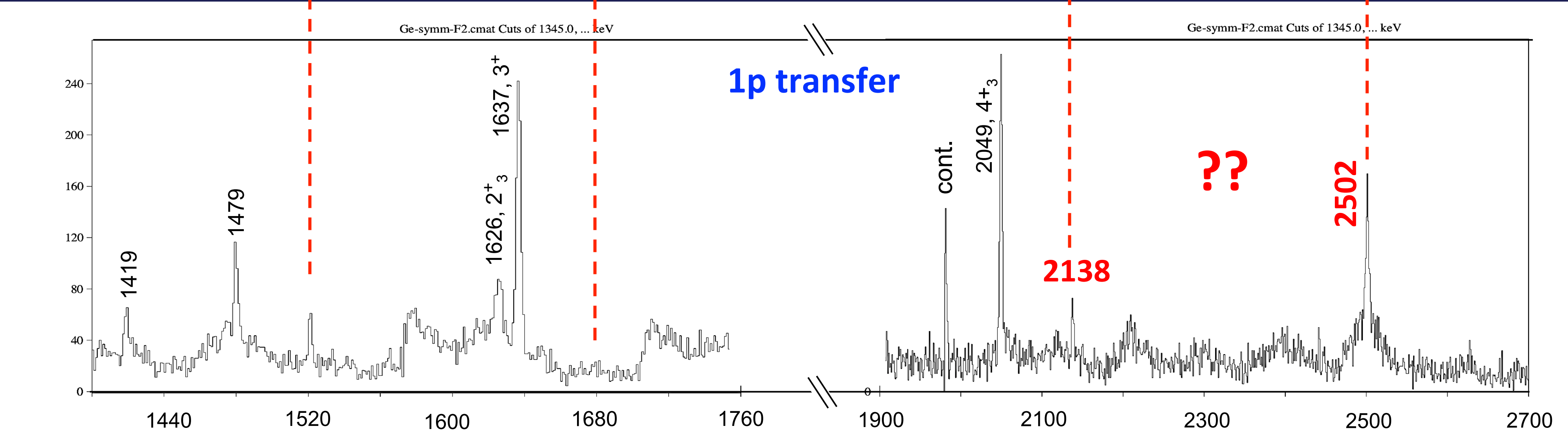
Experiments done in Bucharest (IFIN HH), March and July 2018, March 2019

2n transfer: $^{62}Ni(^{18}O,^{16}O)^{64}Ni$ E_b = 39 MeV, neutron excitations favoured (spherical/oblate)

^{64}Ni



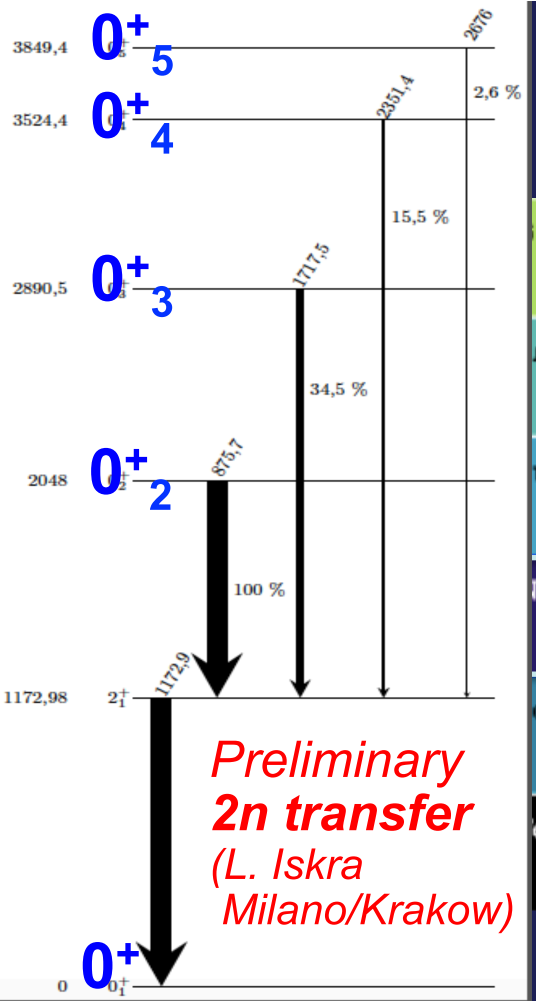
1p transfer: $^{65}Cu(^{11}B,^{12}C)^{64}Ni$ E_b = 26 MeV, proton excitations favoured (prolate)



→ *STRONG SELECTIVITY to STATE population*

Similar Study in ^{62}Ni

^{62}Ni



2n : ^{10}O + ^{60}Ni → ^{16}O + ^{62}Ni, **neutron** excitations are enhanced **(spherical/oblate)**

NU-Ball
at ALTO (June 18)

1p : ^{11}B + ^{63}Cu → ^{12}C + ^{62}Ni, **proton** excitations are enhanced **(prolate)**

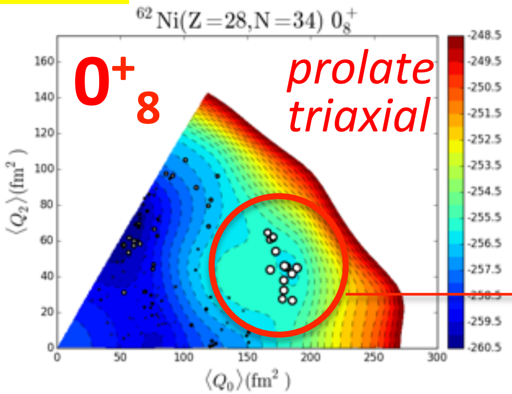
at IFIN-HH (May 2019)

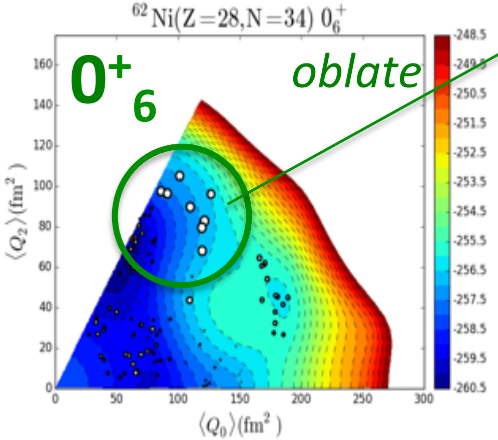
n capture : n + ^{62}Ni → ^{62}Ni, *complete low spins spectroscopy* **(ILL Approved exp.)**

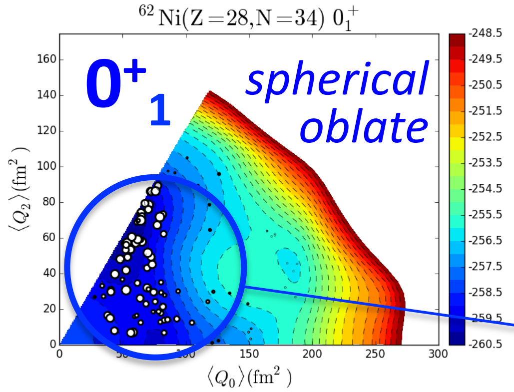
^{62}Ni

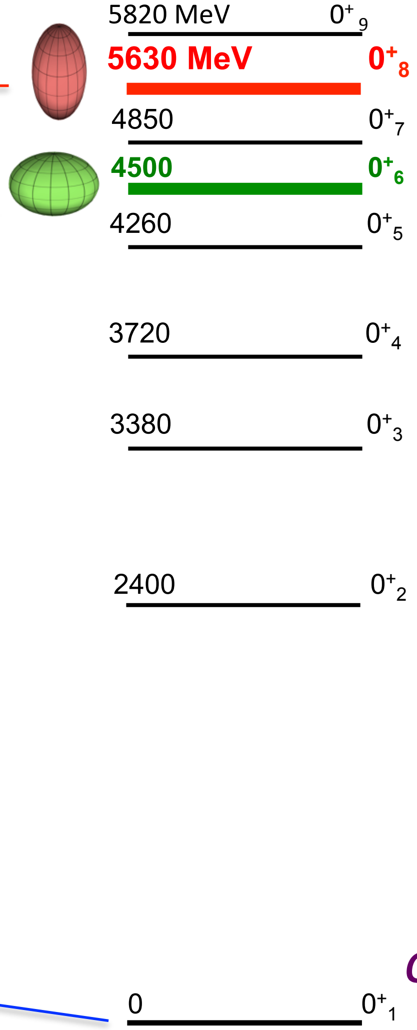
^{62}Ni – MCSM

nine 0^+ states



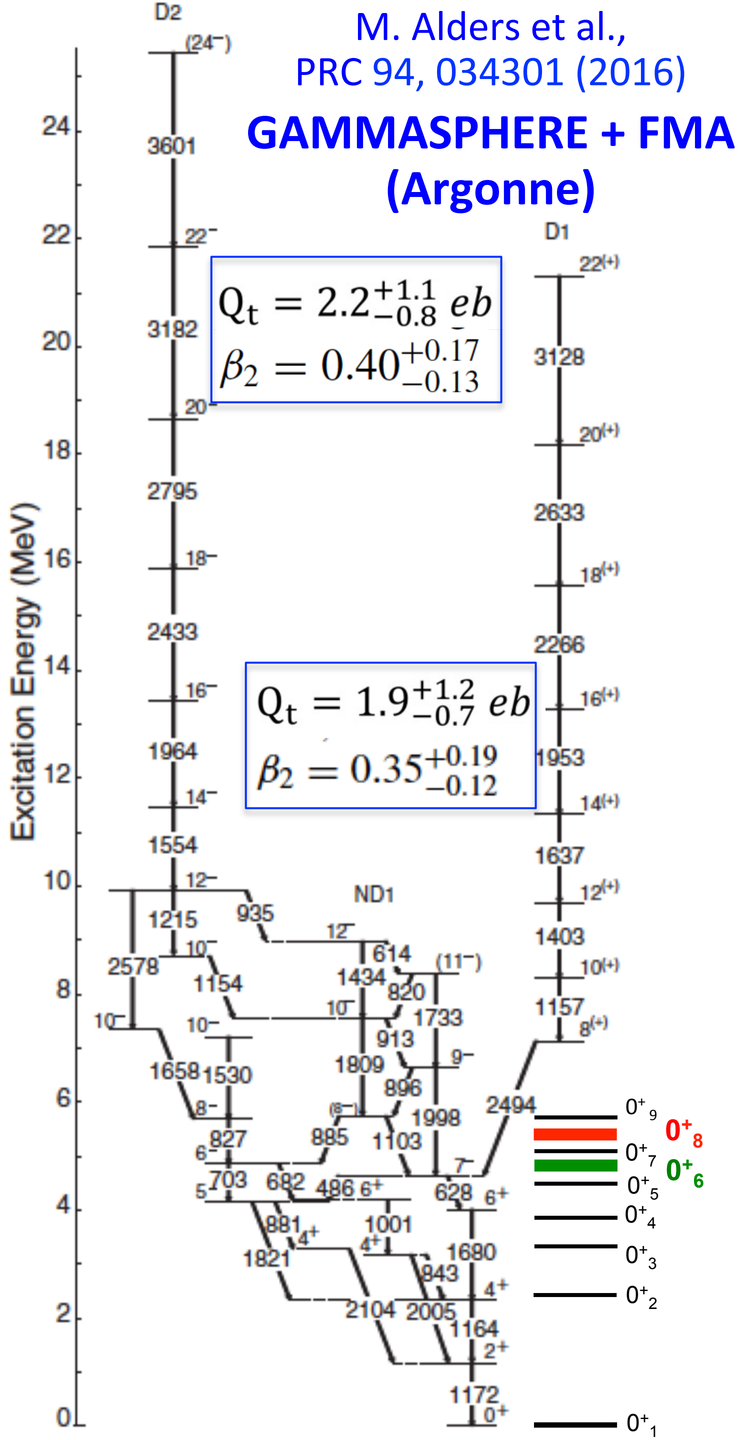






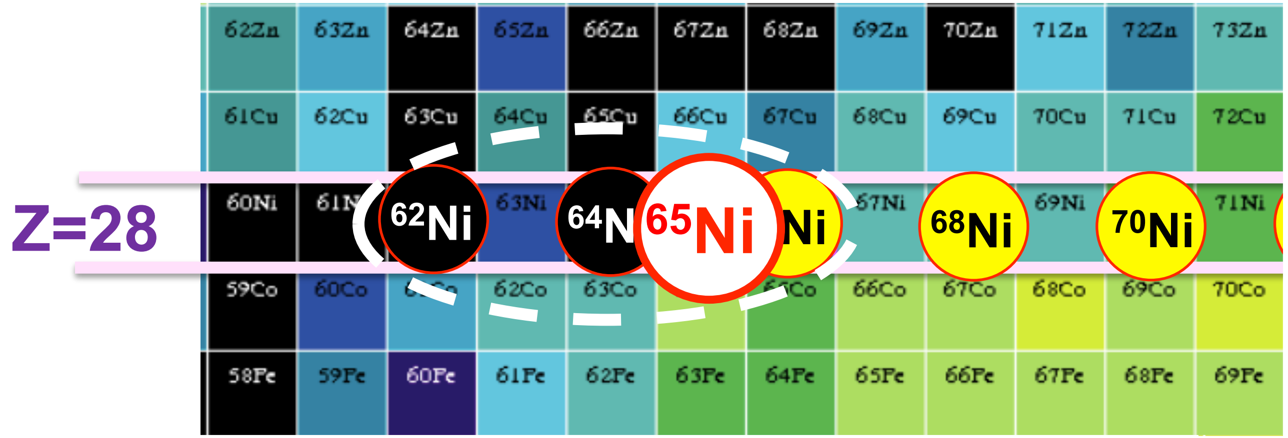
M. Alders et al.,
PRC 94, 034301 (2016)

GAMMASPHERE + FMA (Argonne)



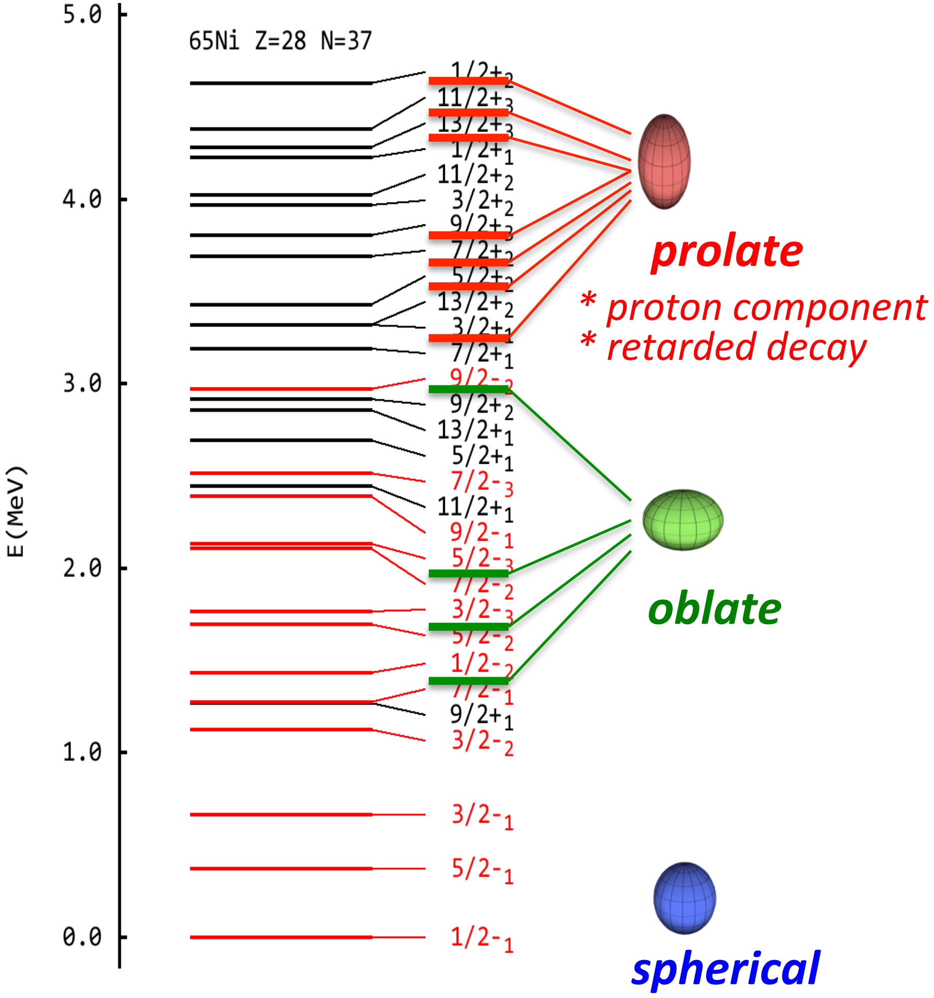
Isomeric 0^+ states could be the ***BANDHEADS*** *of rotational structures observed at higher spins*

Joint experimental program at IFIN-HH, ILL, Orsay:
search for SHAPE Isomers in Ni and probe the wave function component



- ✓ First ODD system studied – very challenging !!!

- ✓ MONTE CARLO SHELL MODEL
  Calculations predict for ^{65}Ni
  strong similarities with ^{66}Ni
  (T. Otsuka, Univ. of Tokyo)



1n transfer : ^{13}C + ^{64}Ni → ^{12}C + ^{65}Ni, *medium spins* **(IFIN-HH, January 2018)**

n capture : n + ^{64}Ni → ^{65}Ni, *low spins from capture state* **(ILL, March 2018)**

CONCLUSIONS

✓ We have an extended Experimental Program aiming at **"Understanding the Microscopic origin of nuclear deformation"** → Ni isotopes

One of the most fondamental issue in Modern Nuclear Structure

✓ HIGH Precision γ-spectroscopy measurements are performed with **DIFFERENT REACTION MECHANISMS**

Opportunity for reaching unprecedented sensitivity to the state wave-function composition

Key aspect: understanding of REACTION properties
Collaboration with L. Fortunato and A. Vitturi (Padua Univ.)

→ *Bormio 2020*

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V^th Topical Workshop on Modern Aspects in Nuclear Structure

The Many Facets of Nuclear Structure

BORMIO 4 - 9 February 2020

Università degli Studi di Milano and ***Istituto Nazionale di Fisica Nucleare*** (sez. Milano) are pleased to announce the ***Fourth Edition*** of this new series of ***Topical Workshops on Modern Aspects of Nuclear Structure.*** The meetings are organized every second year in the month of February in Bormio, focusing on specific topics which are relevant for the nuclear physics community and related areas. Within the workshop, ***experimental*** and ***theoretical*** collaborations will have the opportunity to present and discuss their latest development on physics and more technical issues (Link to Previous Edition Bormio 2018).

The Workshop is preceded on **February 3rd** by a
Satellite Meeting on " Beta-decay studies: present and future campaigns"
(Organizer Giovanna Benzoni - Giovanna.Benzoni@mi.infn.it)

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