"Appearance of Shape Isomerism in the Ni isotopic chain"

S. Leoni[1], F. Crespi, S. Fracassetti, C. Porzio, G. Benzoni, S. Bottoni, A. Bracco, …
B. Fornal[2], N. Cieplicka-Orynczak, L. Iskra, …
M. Sferrazza[3],
N. Mărginean[4], C. Mihai, M. Boromiza, C. Costache, A. Ionescu, R. Mărginean, R.E. Mihai, A. Mitu, C.R. Niță, A. Olăcel, S. Pascu, P. Petkov, L. Stan, A. Turturică, S. Ujeniuc, C.A. Ur

and **T. Otsuka[5], Y. Tsunoda[5]**

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9th international workshop: Quantum Phase Transitions in Nuclei and Many-body Systems

22-25 May 2018 *Padova*
Europe/Rome timezone

Outline

- **Introduction**

  Shape coexistence and shape isomers

- **Nuclear fission (shape) isomers**

- **The unique case of ^{66}Ni**

  Interplay between experiment and theory

- **Our systematic investigation of shape coexistence in Ni isotopes**

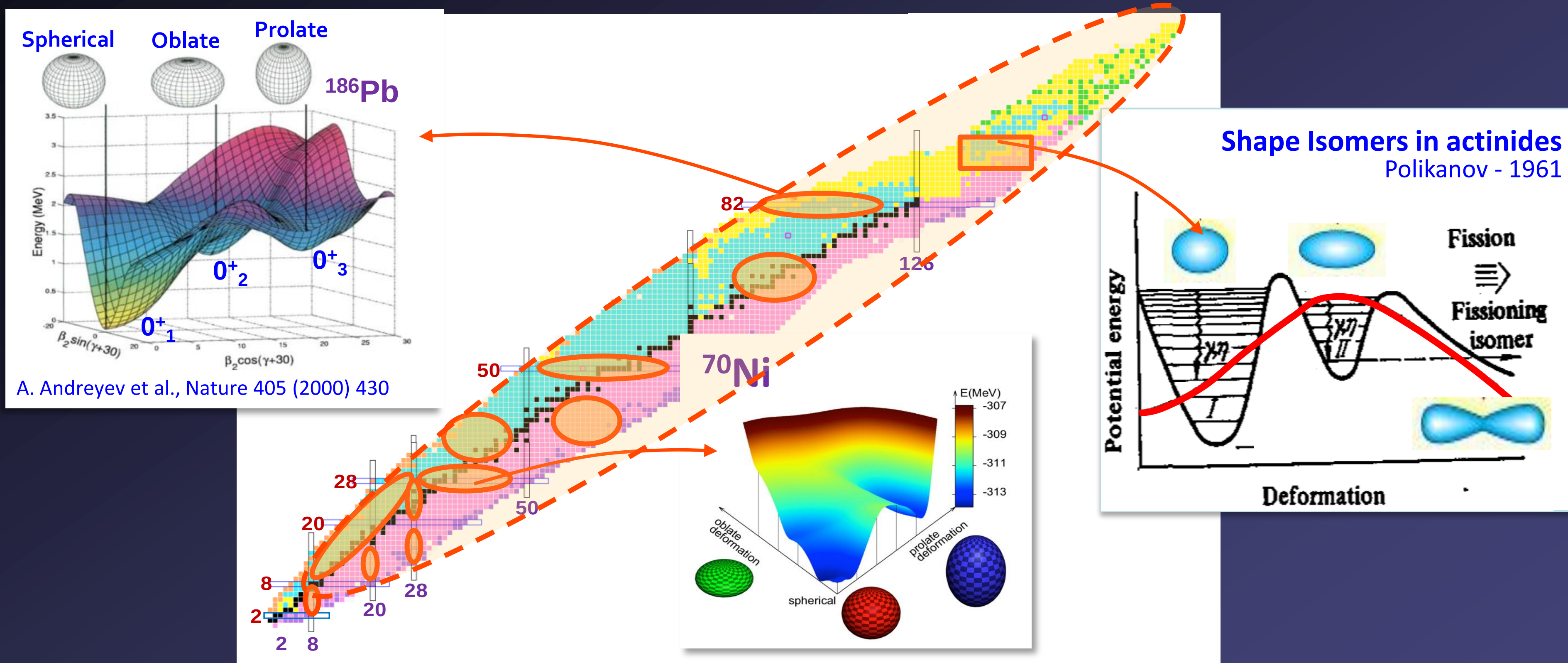
  From ^{62}Ni to ^{66}Ni, considering also the odd case of ^{65}Ni

- **Probing the state wave fuction with different reactions**

SHAPE Coexistence in Atomic Nuclei

Appearence of states with different shapes at low excitation energy

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

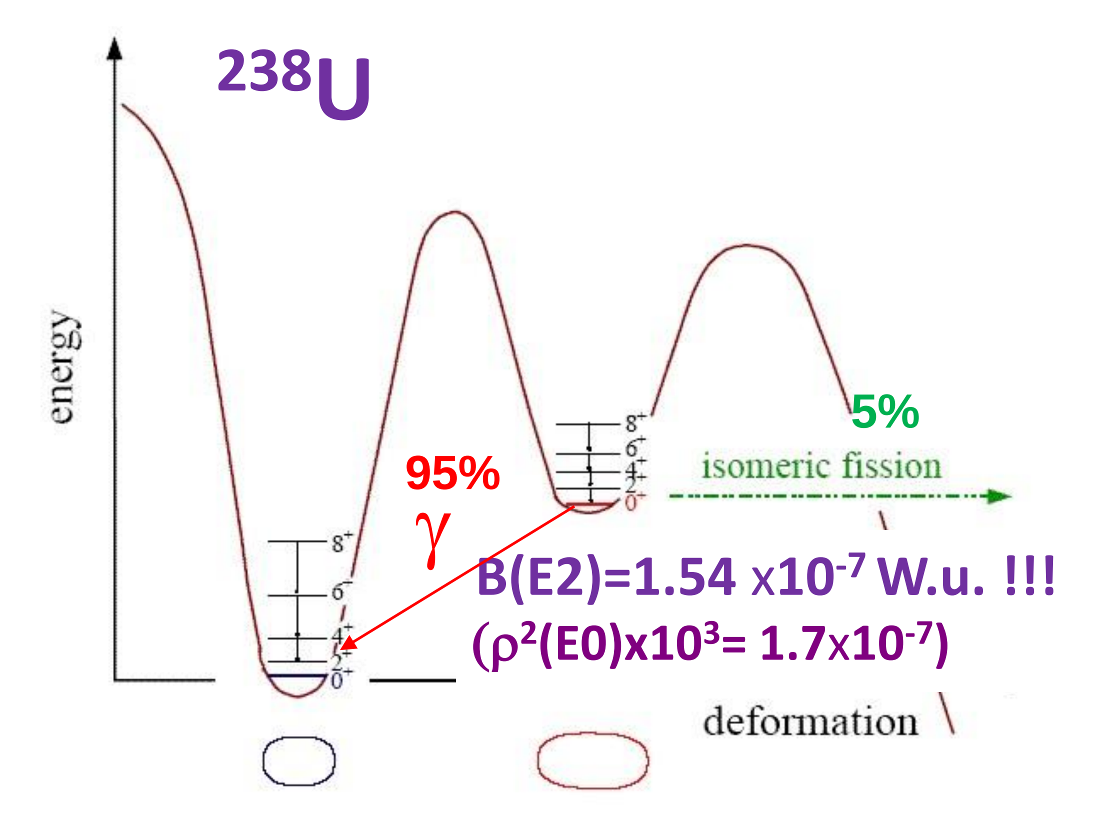


Through the last 50 years of experimental activities, the concept has evolved:

1) exotic rarity (1970')
2) islands of occurrence (1990')
3) <u>current believe</u>: occurrence in all (but the lightest) nuclei

SHAPE ISOMERS - very peculiar metastable states

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

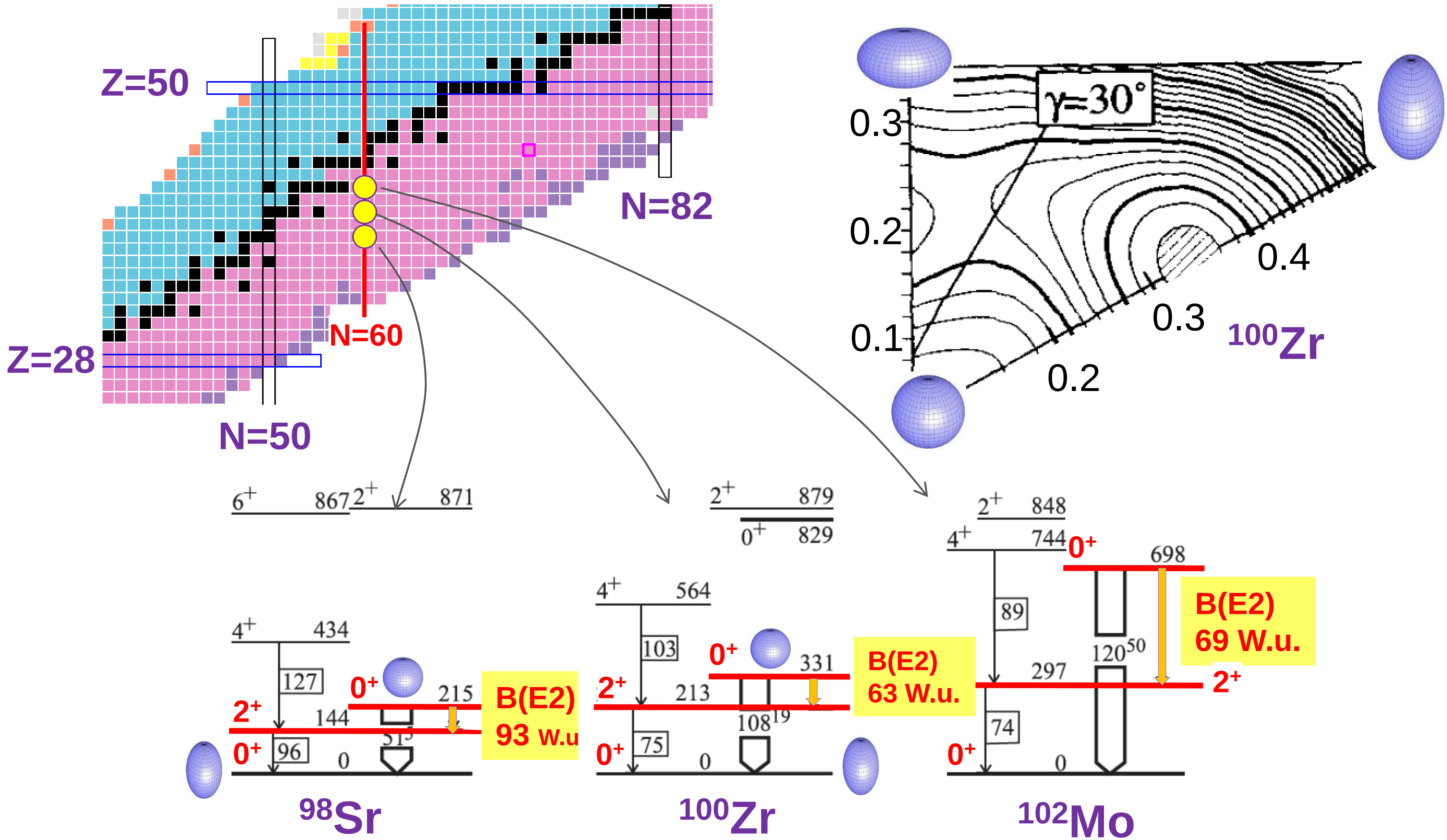


Structures living in "separate worlds"

MAIN FINGER PRINT: hindrance of deexciting transitions

Can OTHER (lighter) nuclei exhibit a **retarded E2 decay from a 0^+ state** ?

(most clear signature of a high barrier, no angular momentum involved !)



<u>No retardation in γ decay from 0⁺ states is observed !!!!</u>

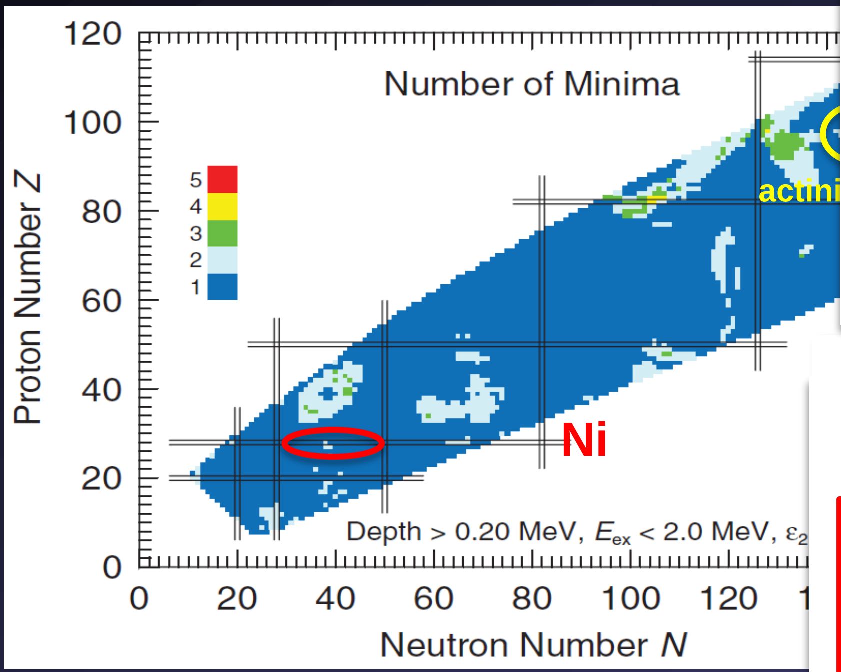
Potential barrier **NOT sizable** enough to prevent fast shape changes

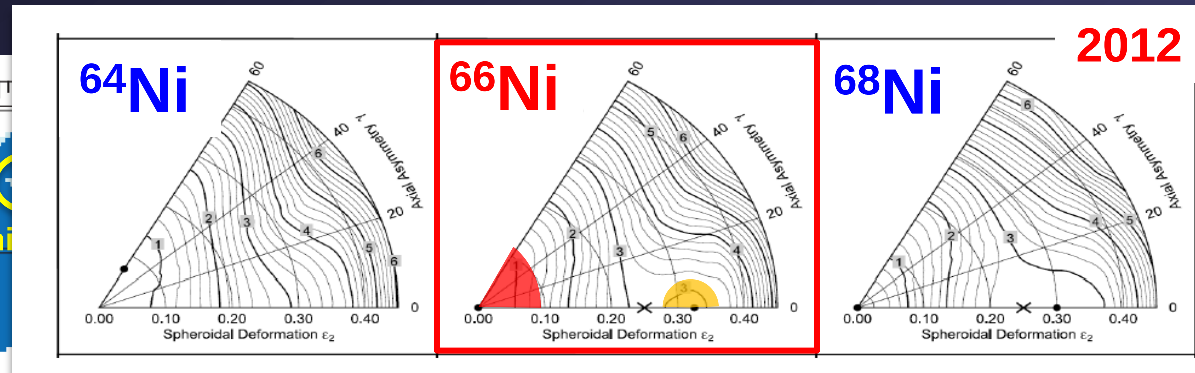
Predictions for SHAPE ISOMERS/COEXISTENCE - Mean Field Based

Macro-Microscopic Model (2012 - P. Moeller, A.J. Sierk, R. Bengtsson, H. Sagawa, T. Ichikawa)

Global Calculation Searching for Nuclear Shape Isomers

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



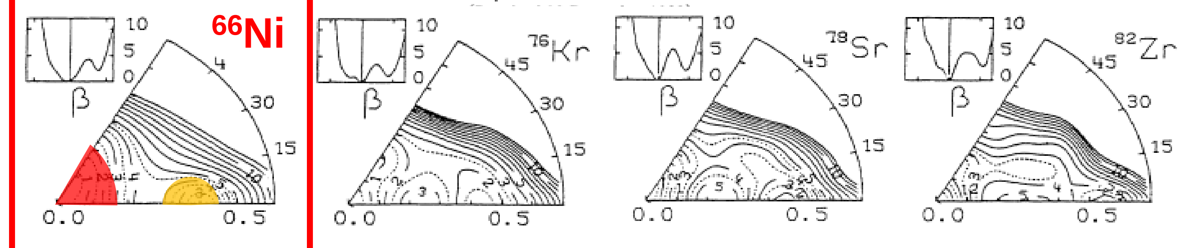


VOLUME 62, NUMBER 21 PHYSICAL REVIEW LETTERS 22 MAY 1989

Hartree-Fock-Bogoliubov Predictions for Shape Isomerism in Nonfissile Even-Even Nuclei 1989

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*

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Department of Physics, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
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Division de Physique Théorique[3], Institut de Physique Nucléaire, F-91406 Orsay Cedex, France
P.-H. HEENEN[4]
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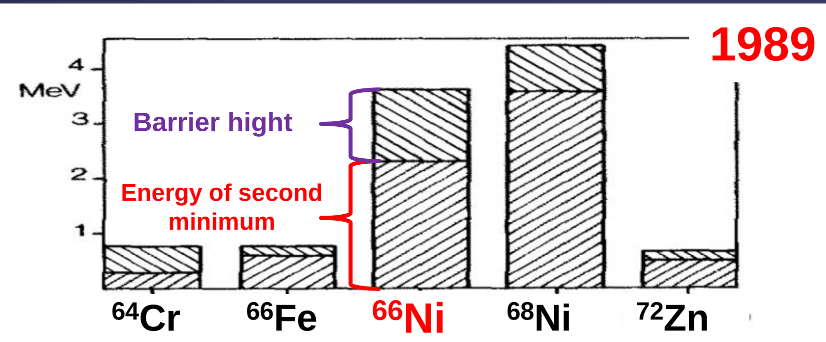
Received 7 March 1989



Predictions for SHAPE ISOMERS/COEXISTENCE - SHELL Model Based

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

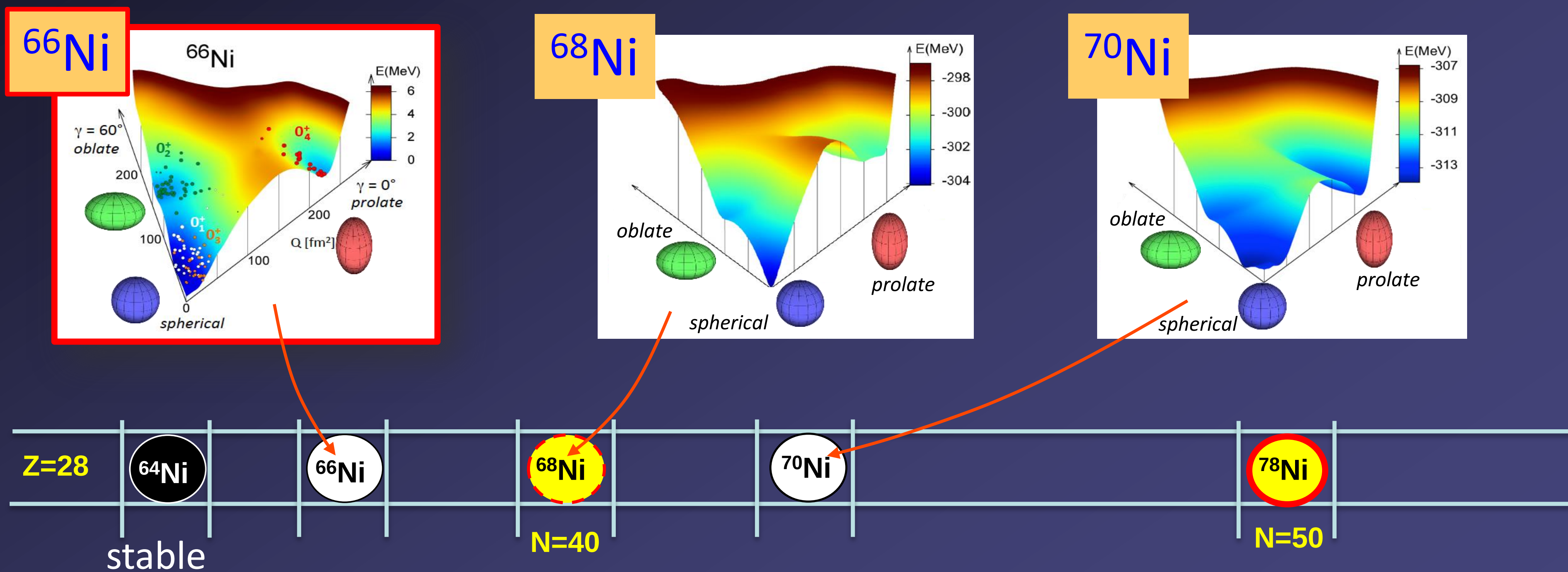
SHELL Model with very extended configuration space

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)

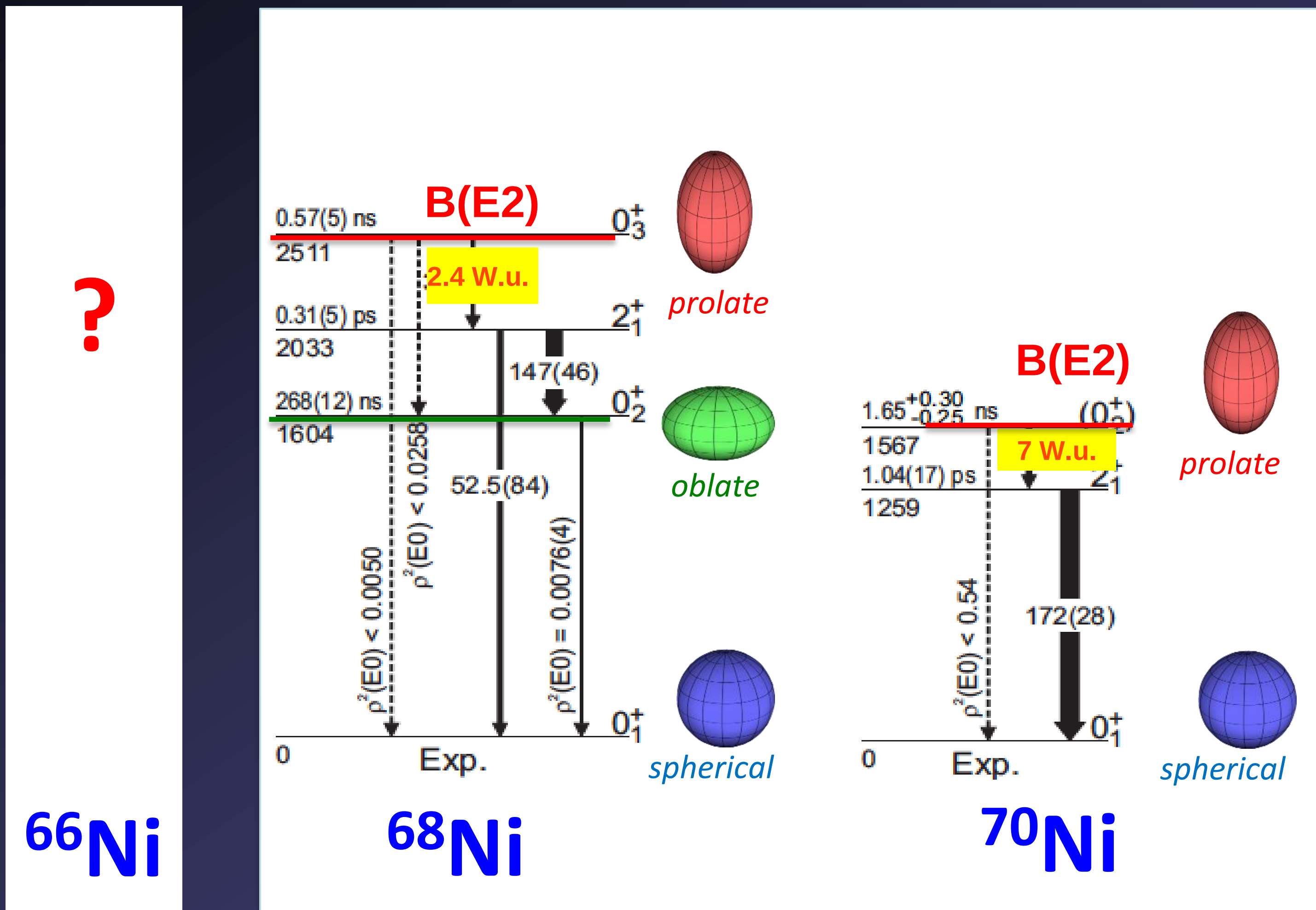
^{64}Ni – ^{78}Ni: FULL pf + $g_{9/2}$ + $d_{5/2}$ for both neutrons and protons



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

Experimental status in 2016 … before our search …

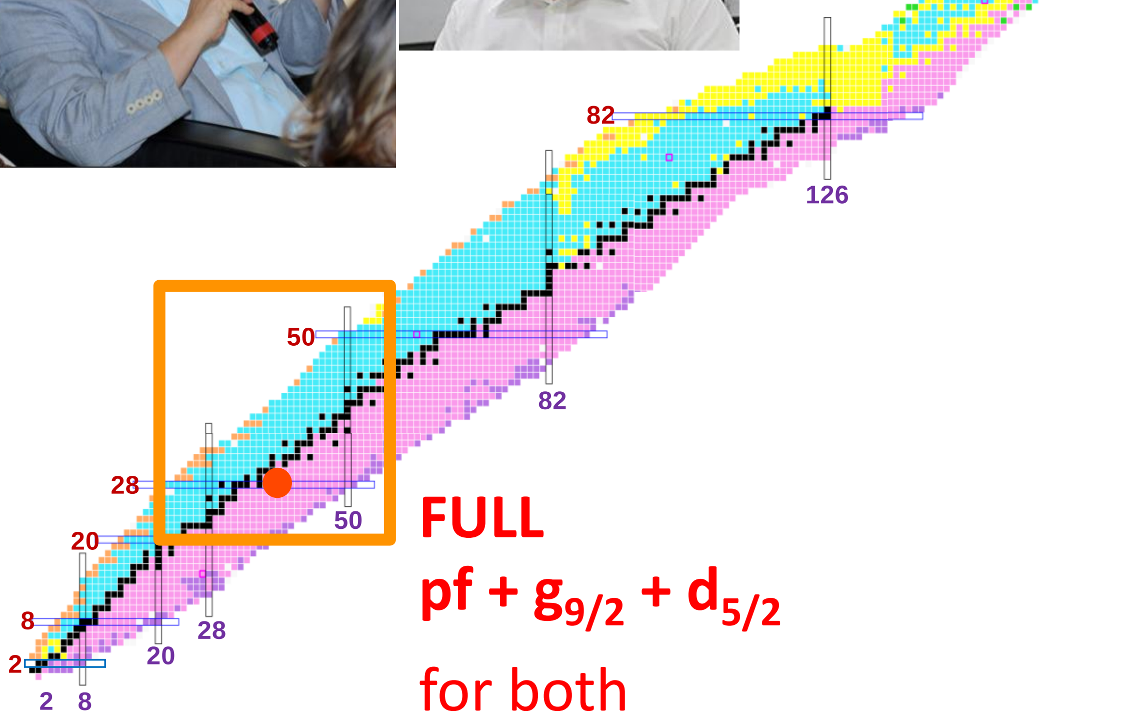
No retardation observed in ^{68}Ni and ^{70}Ni



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

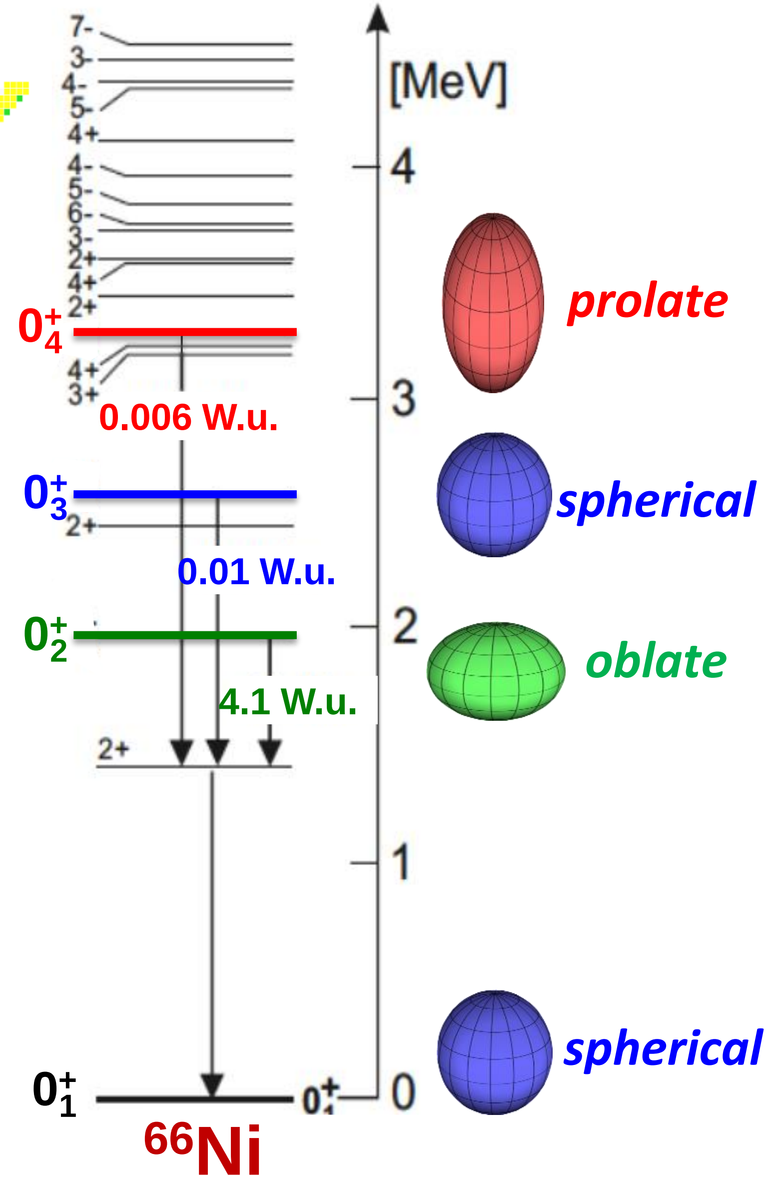
MONTE CARLO SHELL MODEL Calculations

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



FULL
$pf + g_{9/2} + d_{5/2}$

for both neutrons and protons



MONTE CARLO SHELL MODEL Calculations

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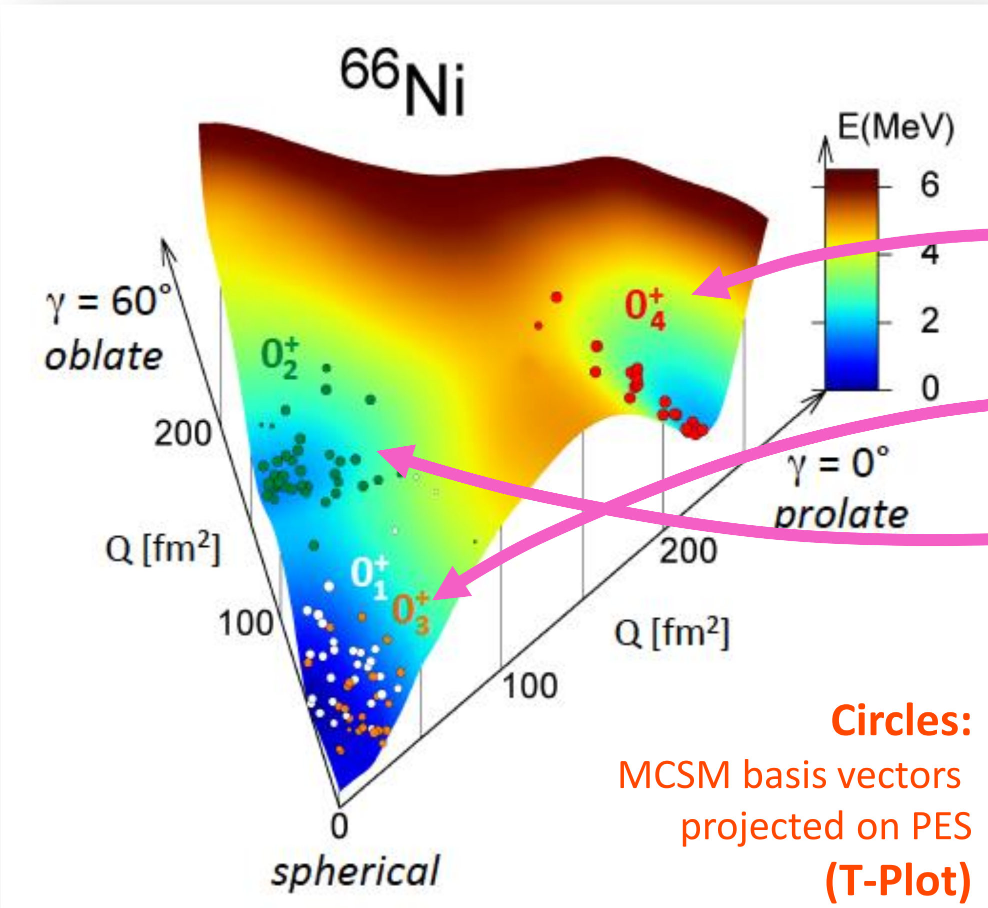
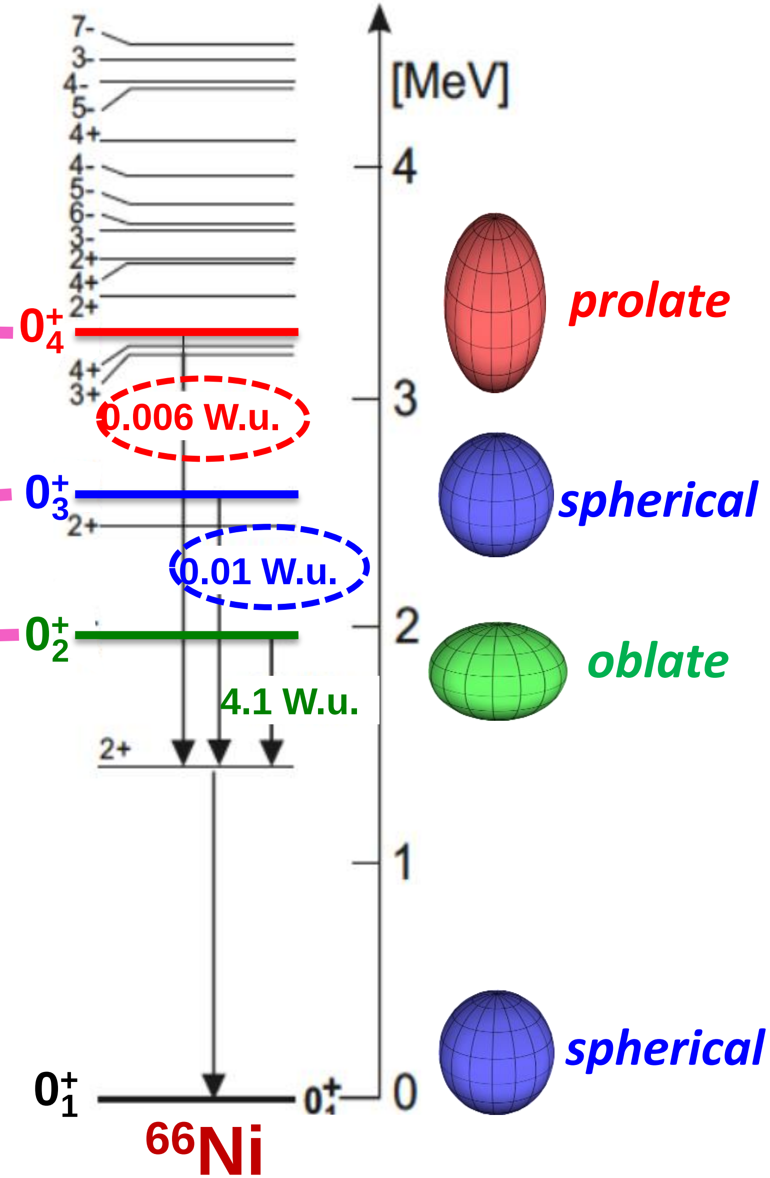
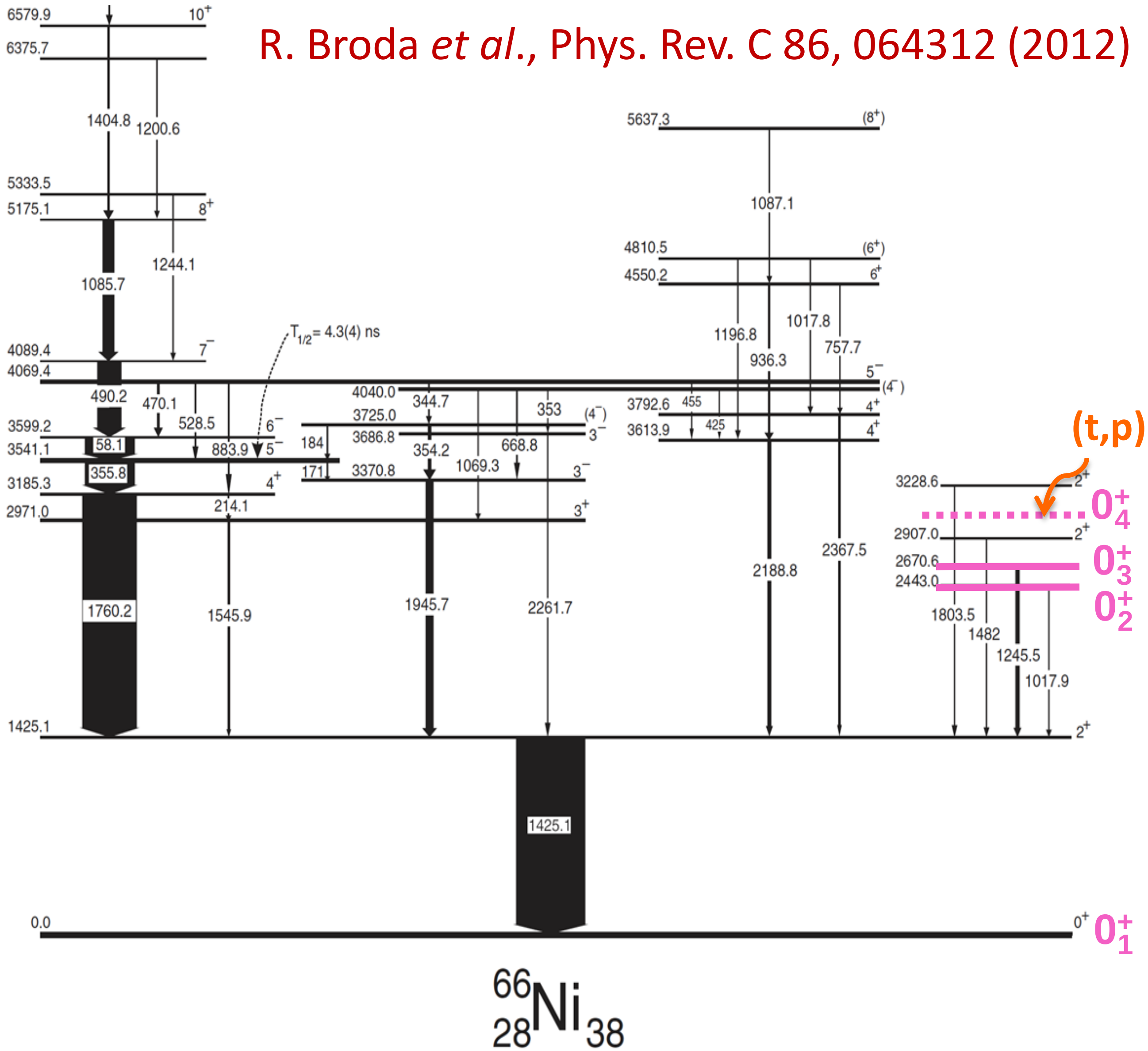




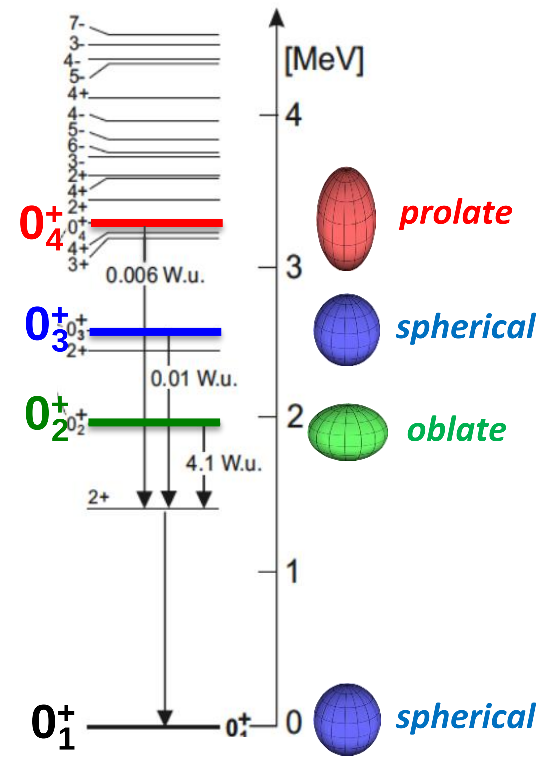
A quadruplet of 0^+ states !!!!

Decay Scheme of ^{66}Ni

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



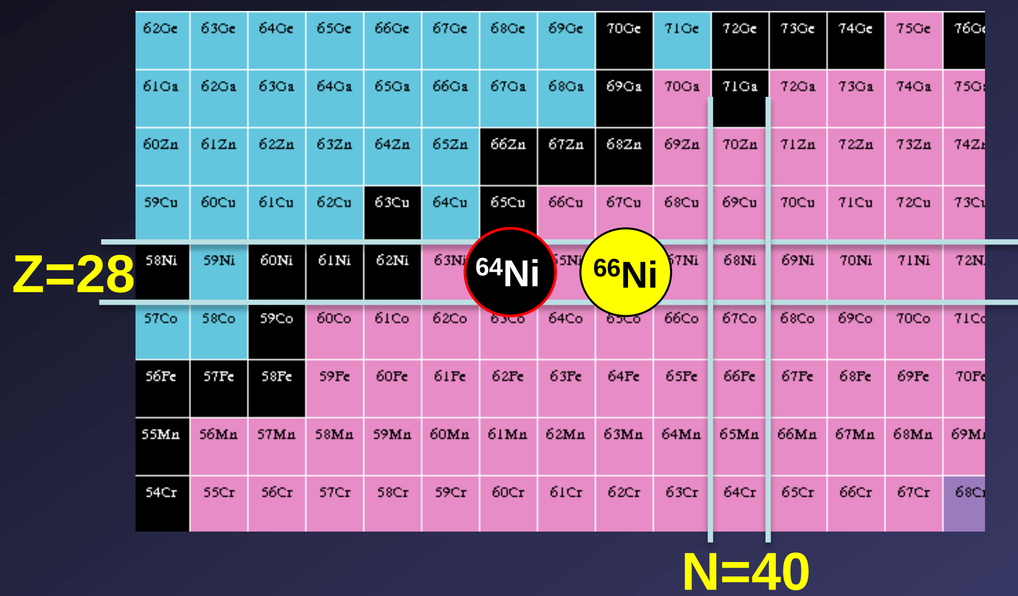
Monte Carlo SHELL Model



Excited states energies … One-to-one correspondence (**<u>including 0⁺ states</u>** !)

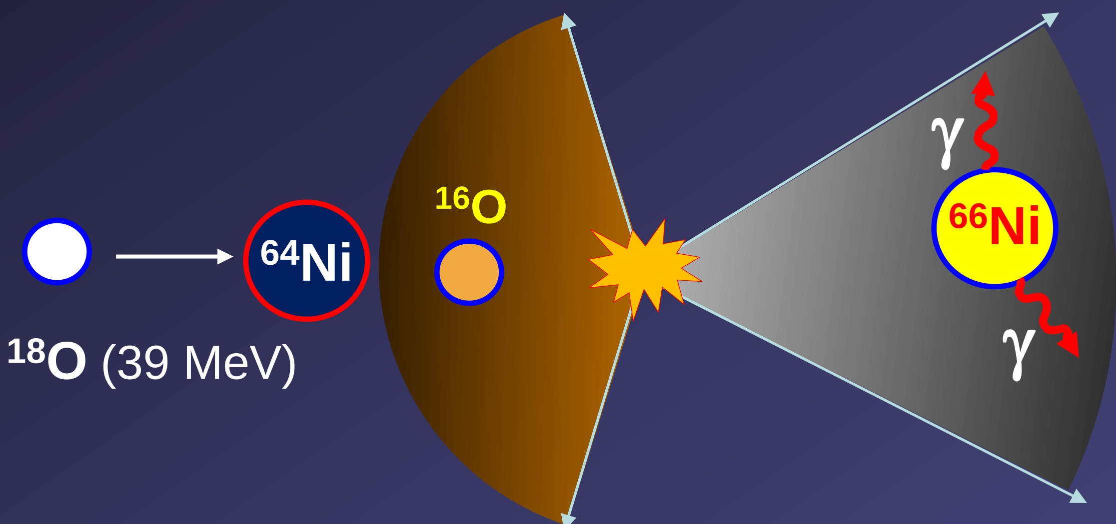
$^{18}O + ^{64}Ni \rightarrow ^{16}O + ^{66}Ni$ - Bucharest (IFIN HH), July 2016

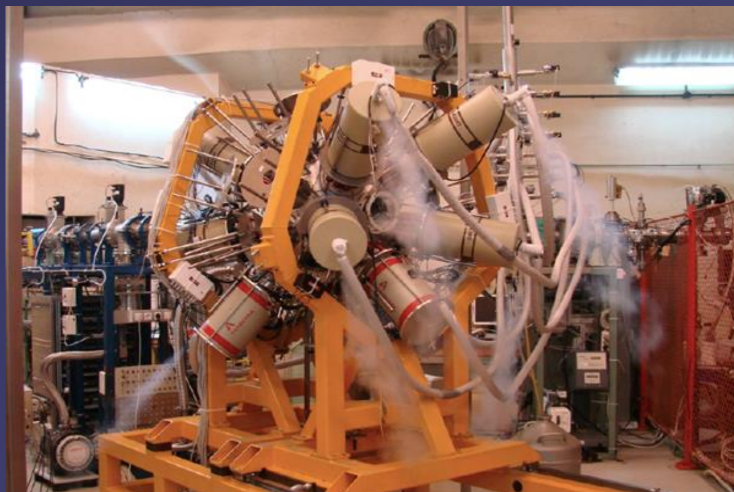
SUB BARRIER TRANSFER (2n Transfer - 1 MeV below Coulomb Barrier)



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

FUSION
strongly suppressed





ROSPHERE
14 HPGe - 1.1% eff
11 $LaBr_3$(Ce) - 1.75% eff

> 1.5 month

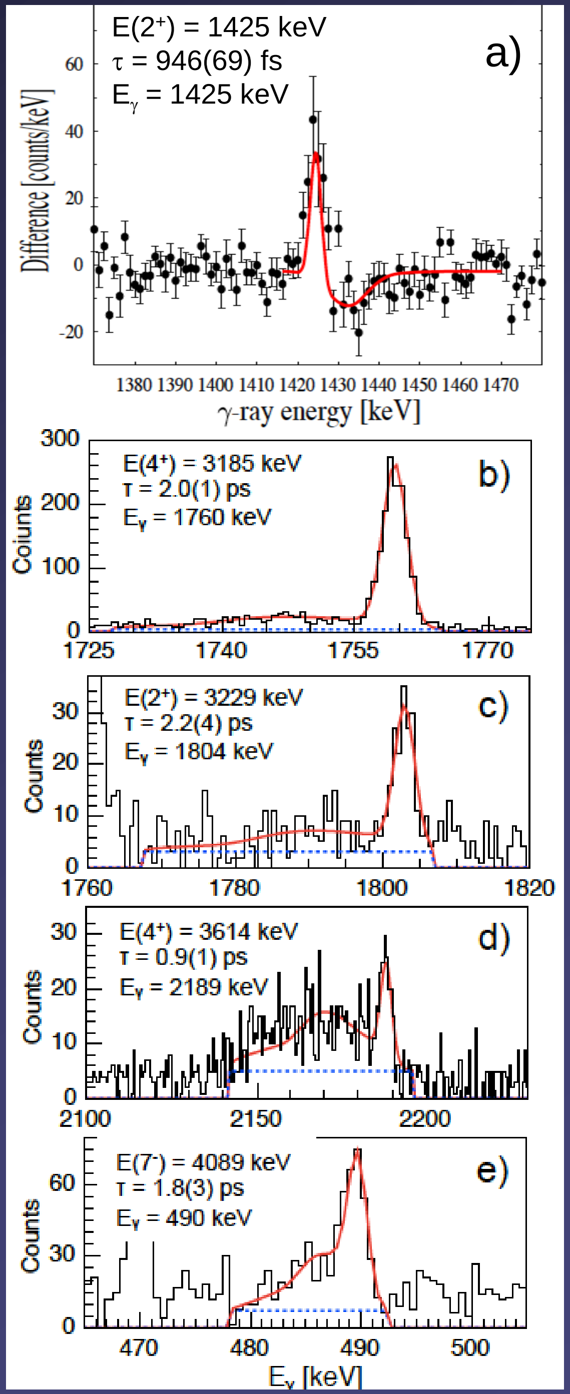
30 pnA beam current

○ **SHORT lived states** (1-2 ps)

Doppler Shift Attenuation Method

Thick target 5 mg/cm^2

E [keV]	$T_{1/2}$ [ps]	Eγ [keV]	$I_i \rightarrow I_f$ (E/Mλ)	B(E/Mλ)$_{exp.}$ [W.u.]	B(E/Mλ)$_{Th.}$ [W.u.]
1425	0.656(42)	1425	$2^+ \rightarrow 0^+$ (E2)	9.3(6)	5.1
2971	0.9(1)	1546	$3^+ \rightarrow 2^+$ (M1)	$6.3(7)\times10^{-3}$	2.8×10^{-3}
3185	1.4(1)	1760	$4^+ \rightarrow 2^+$ (E2)	1.5(1)	5.9
3229	1.5(2)	1804	$2^+ \rightarrow 2^+$ (M1)	$2.5(4)\times10^{-3}$	2.4×10^{-3}
3614	0.6(1)	2189	$4^+ \rightarrow 2^+$ (E2)	1.1(1)	0.74
3371	1.4(1)	1946	$3^- \rightarrow 2^+$ (E1)	< 10	-
3687	0.9(1)	2262	$3^- \rightarrow 2^+$ (E1)	$3.9(5)\times10^{-5}$	-
4089	1.3(2)	490	$7^- \rightarrow 6^-$ (M1)	0.15(2)	0.073



Strong predictive power of MCSM !!!

F. Crespi et al., in preparation

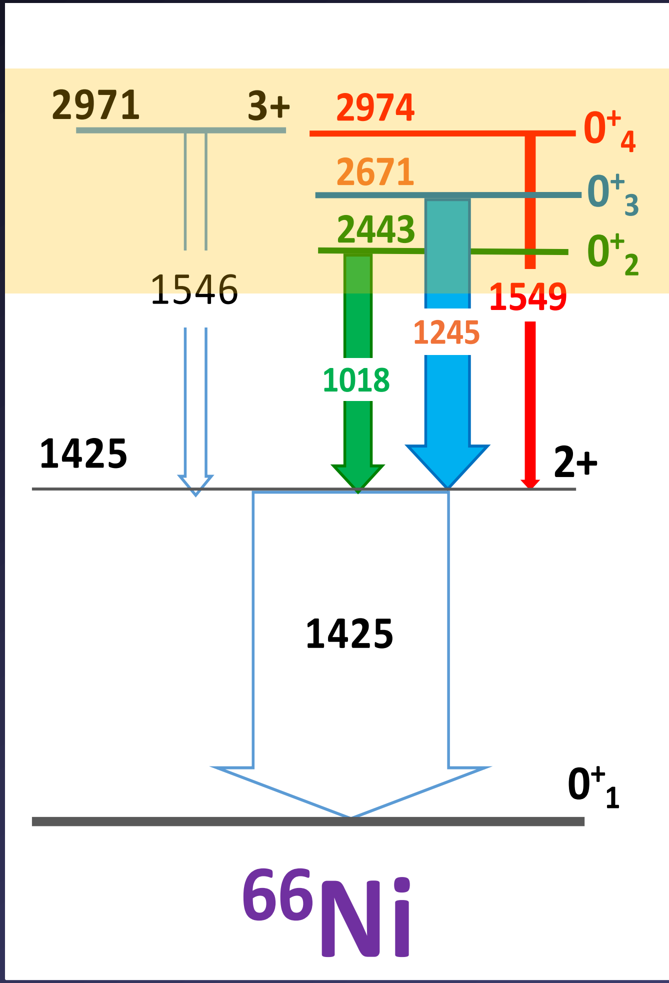
○ LONGER lived states (> 5 ps)

PLUNGER

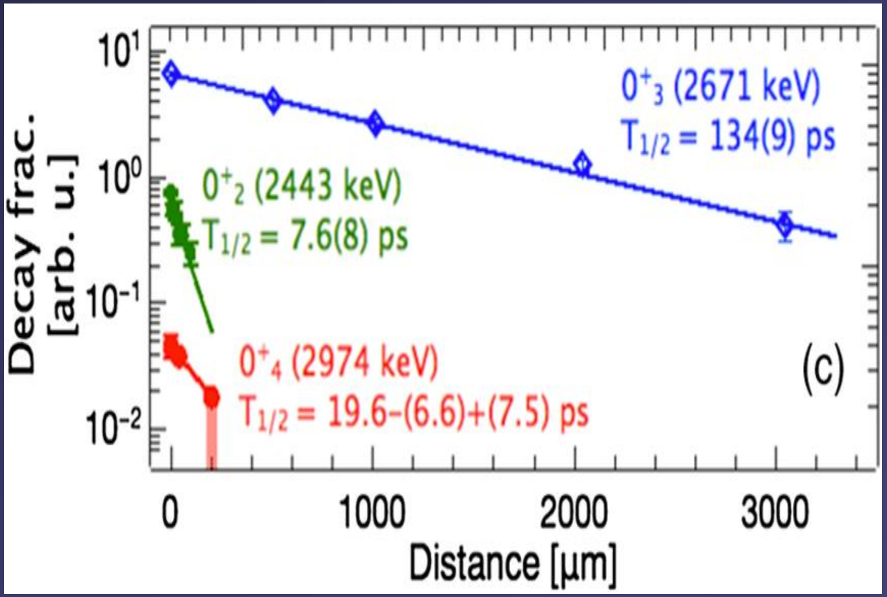
12 distances from 10 to 3000 μm

v/c ≈ 2.2 %

TOF of 155 ps in 1 mm



20(7) ps
134(9) ps
7.6(8) ps



Lifetimes of all three 0^+ states

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

○ LONGER lived states (> 5 ps)

PLUNGER

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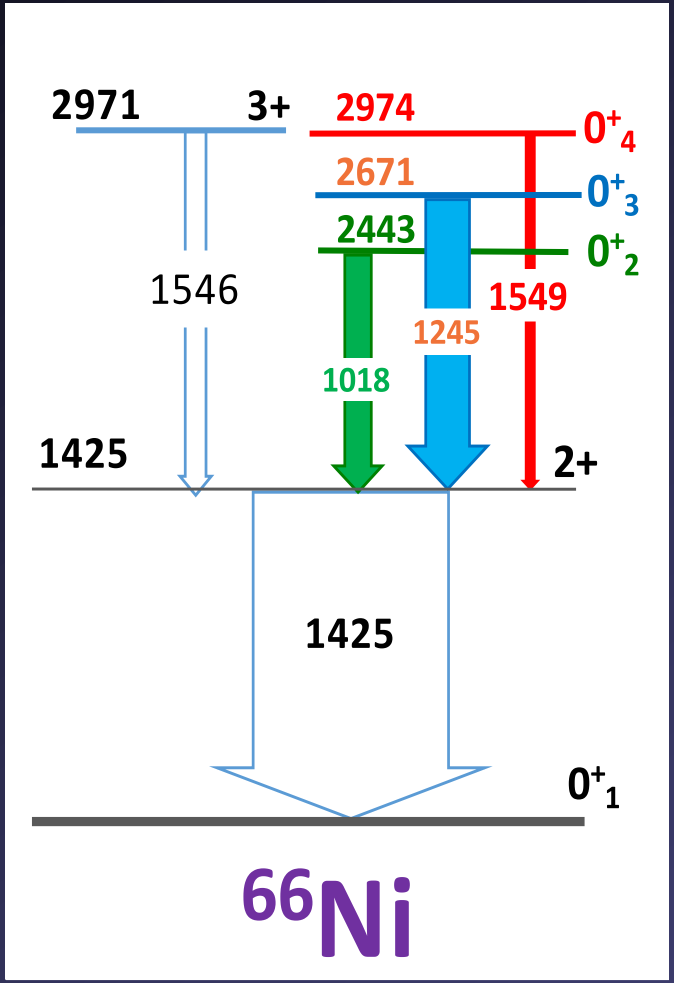
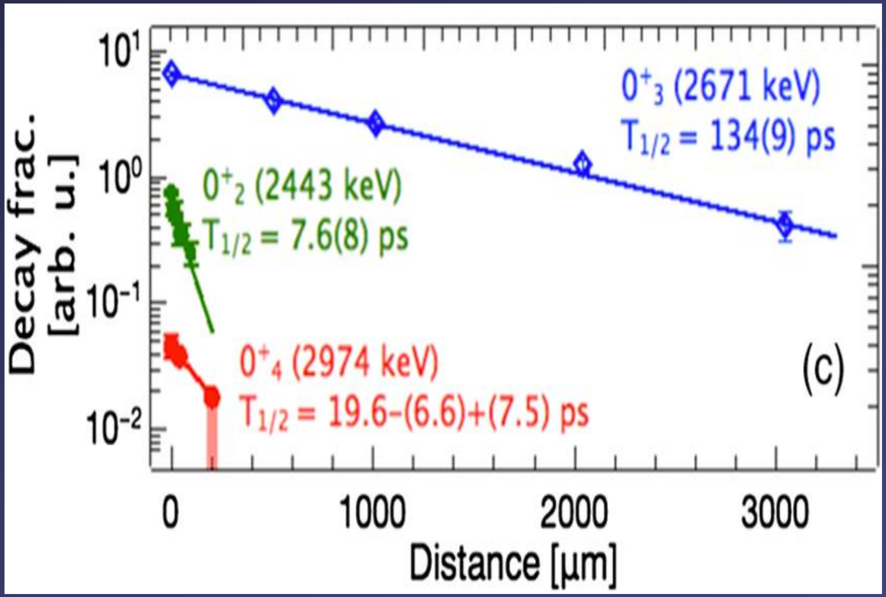


B(E2)~0.2 Wu

B(E2)=0.1 Wu

B(E2)=4.3 Wu

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



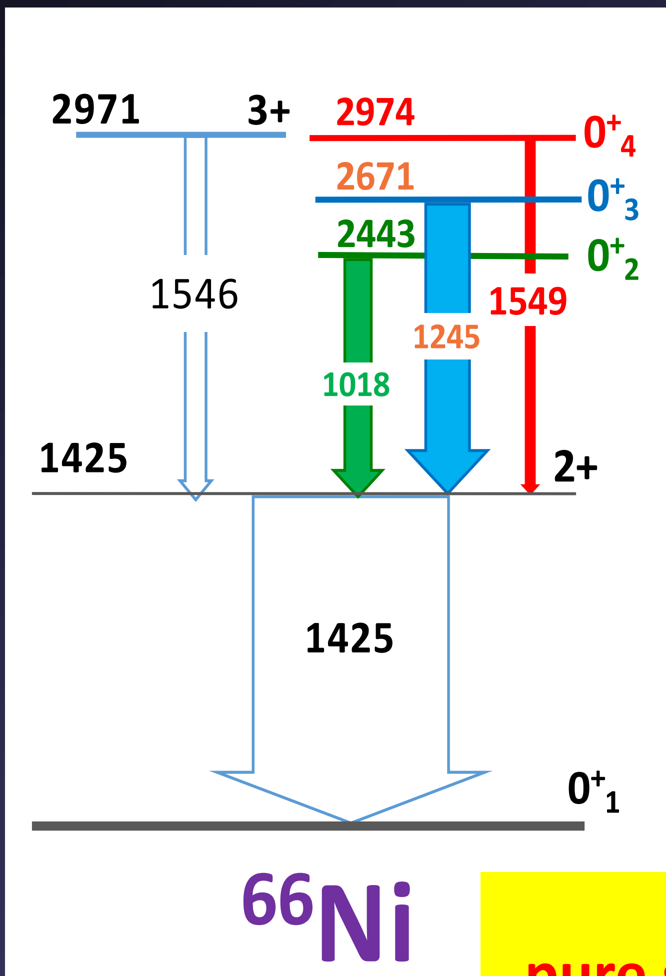
Lifetimes of all three 0^+ states

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

^{66}Ni:

lightest and unique example of SHAPE ISOMER !!!

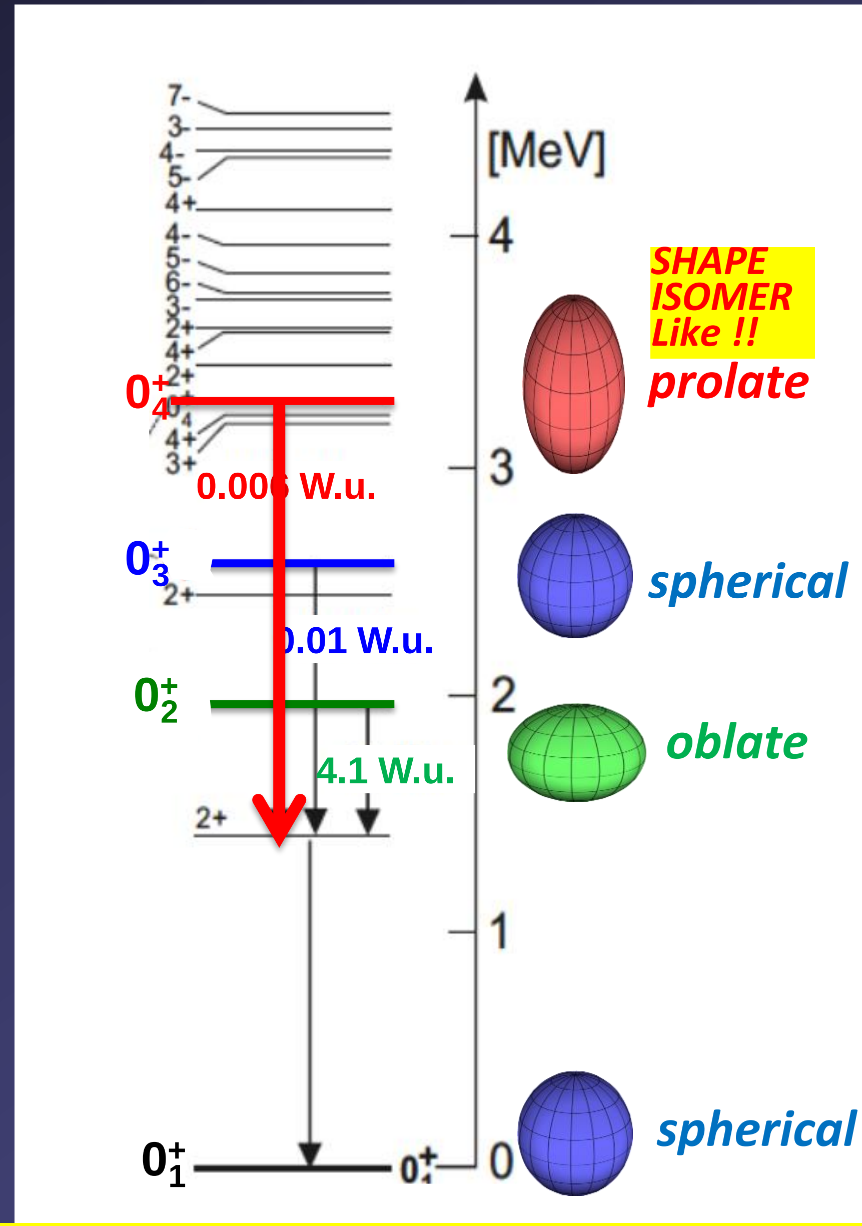
apart from the actinides (Polikanov 1973)



B(E2)~0.2 Wu
B(E2)=0.1 Wu
B(E2)=4.3 Wu

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

As predicted by MCSM

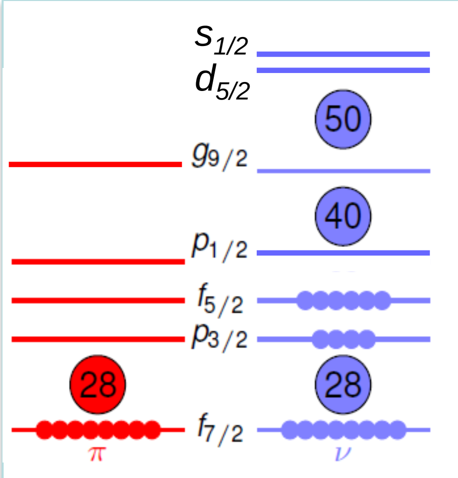


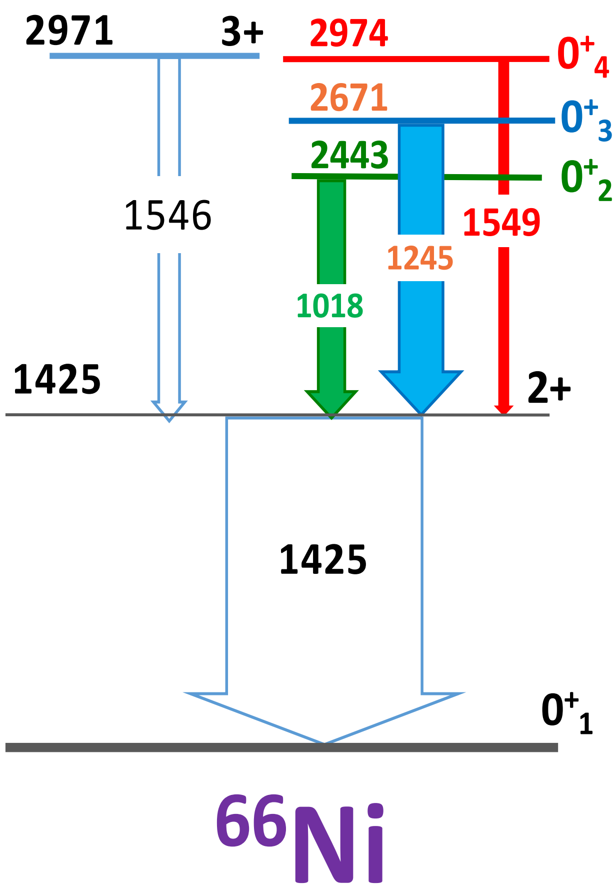
$0^+_4 \rightarrow 2^+_1$: HINDRANCE due to pure shape change through high potential barrier !!!!

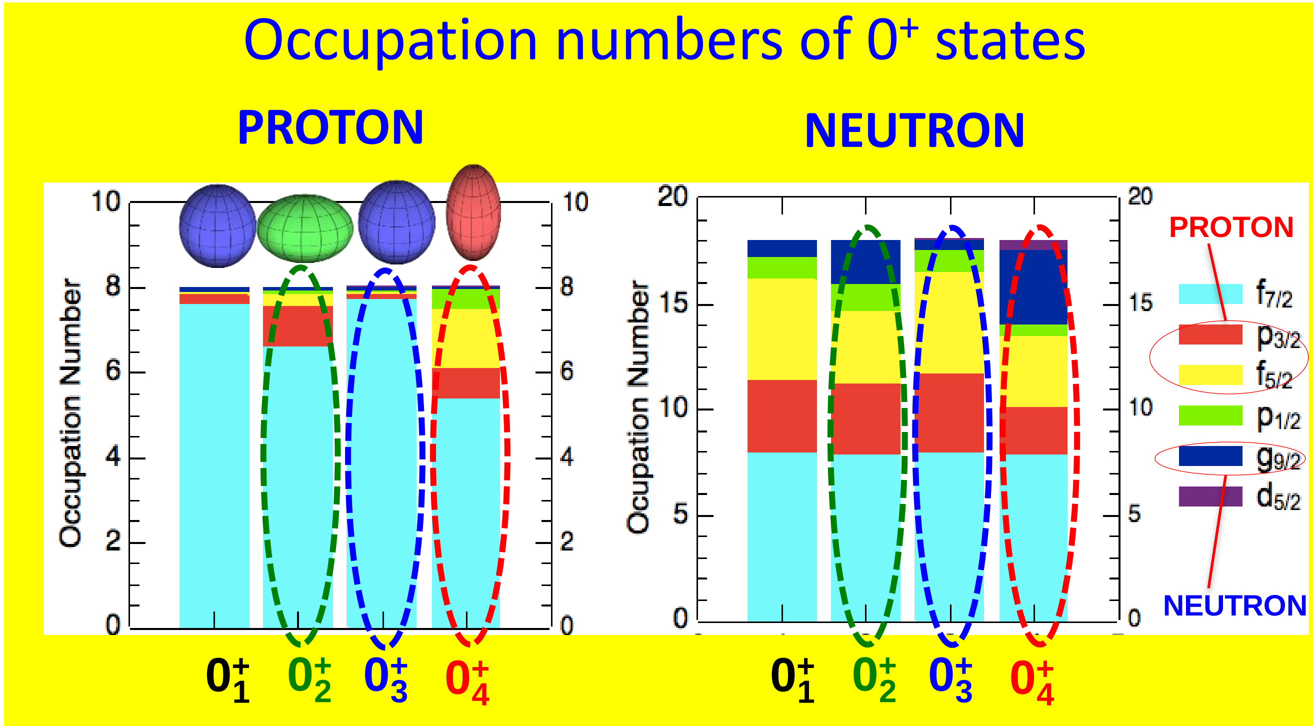
MICROSCOPIC INTERPRETATION (MCSM)

rearrengement of nucleons in orbitals causes emergence of deformation

(TYPE II SHELL evolution – tensor force)







0^+_1 and 0^+_3 are spherical (very similar)

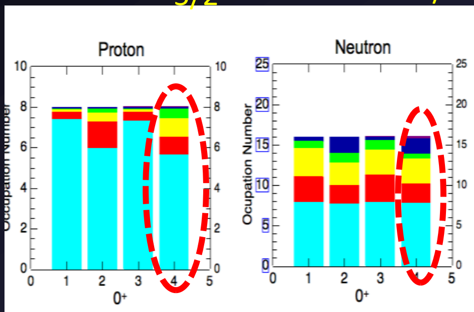
0^+_2 is oblate (<u>sizable</u> $\pi\ p_{3/2}$; $\nu\ g_{9/2}$)

0^+_4 is prolate (<u>sizable</u> $\pi\ p_{3/2}$, $\pi\ f_{5/2}$; $\nu\ g_{9/2}$)

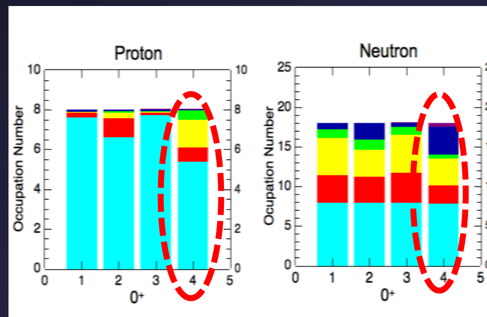
Same features of PROLATE 0^+ states along the Ni chain

sizable occupation of neutron $g_{9/2}$ and proton $p_{3/2}$, $f_{5/2}$ orbitals

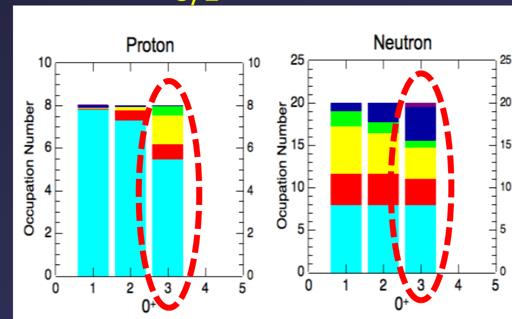
$\pi\, p_{3/2}$, $\pi\, f_{5/2}$ $\nu\, g_{9/2}$



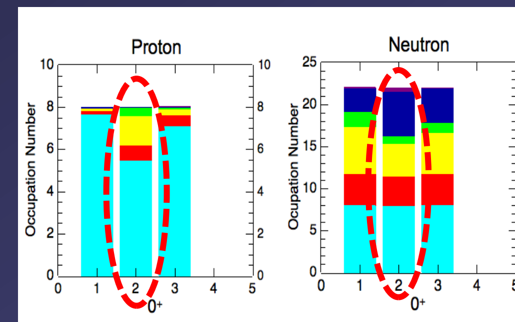
$\pi\, p_{3/2}$, $\pi\, f_{5/2}$ $\nu\, g_{9/2}$

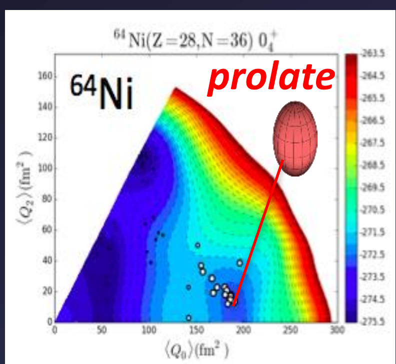


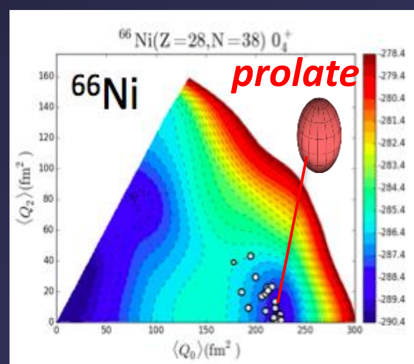
$\pi\, p_{3/2}$, $\pi\, f_{5/2}$ $\nu\, g_{9/2}$

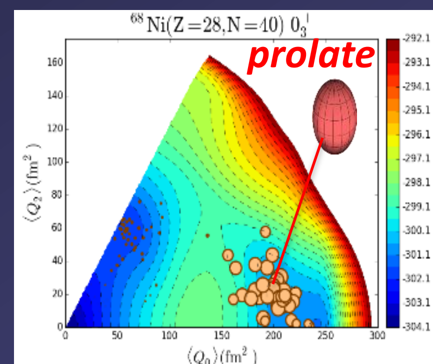


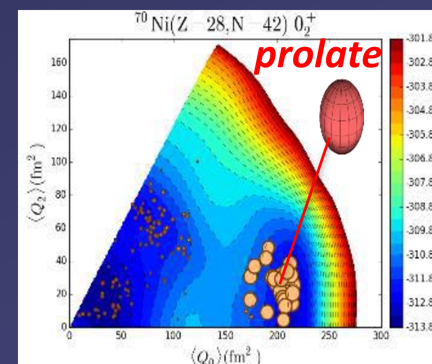
$\pi\, p_{3/2}$, $\pi\, f_{5/2}$ $\nu\, g_{9/2}$









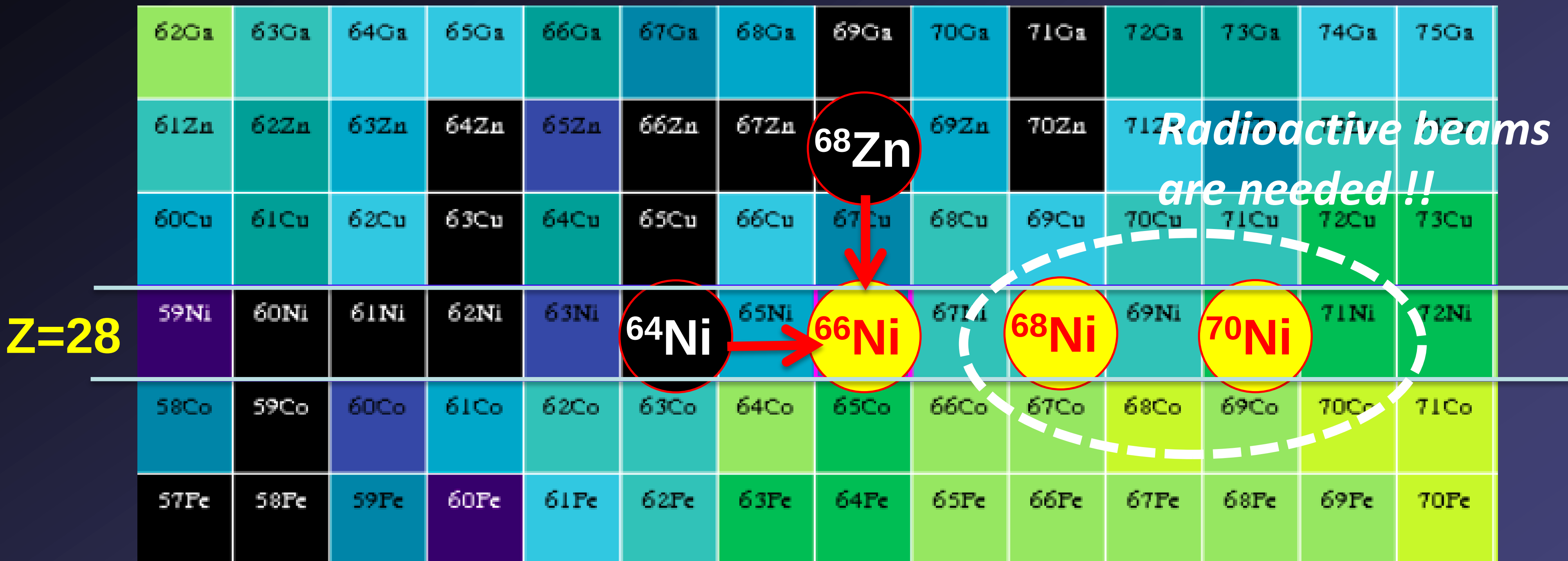


^{64}Ni ^{66}Ni ^{68}Ni ^{70}Ni

How can we probe ***- experimentally -*** the wave function composition ?

(proton component in 0^+_2 and 0^+_4 ...)

Probing the wave functions composition by proton and neutron transfer reactions



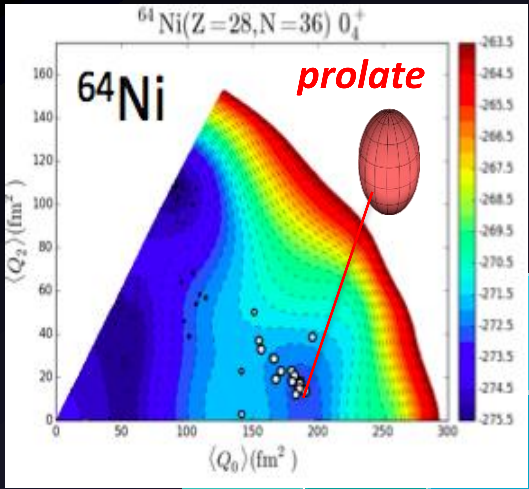
^{66}Ni

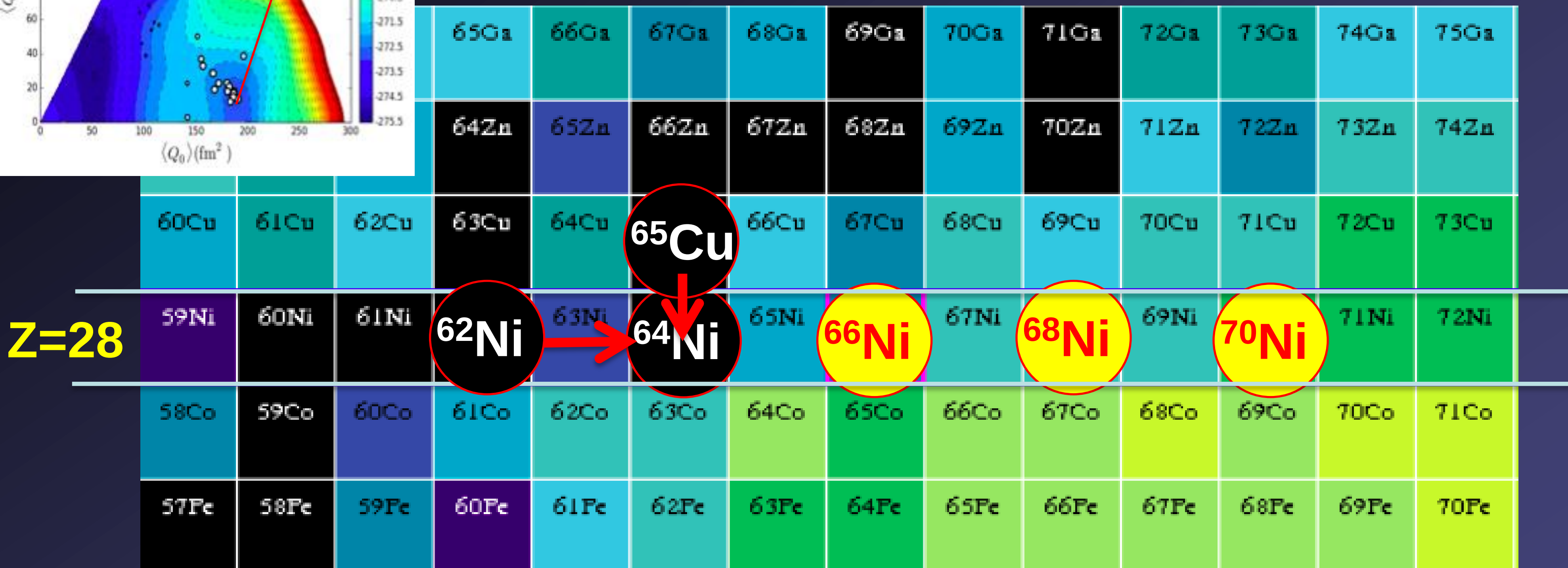
2n : ^{16}O + ^{64}Ni → ^{12}C + ^{66}Ni, neutron excitations enhanced (spherical/oblate)

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

NOT feasible in terms of Q-values

Probing the wave function composition by neutron and proton transfer reactions





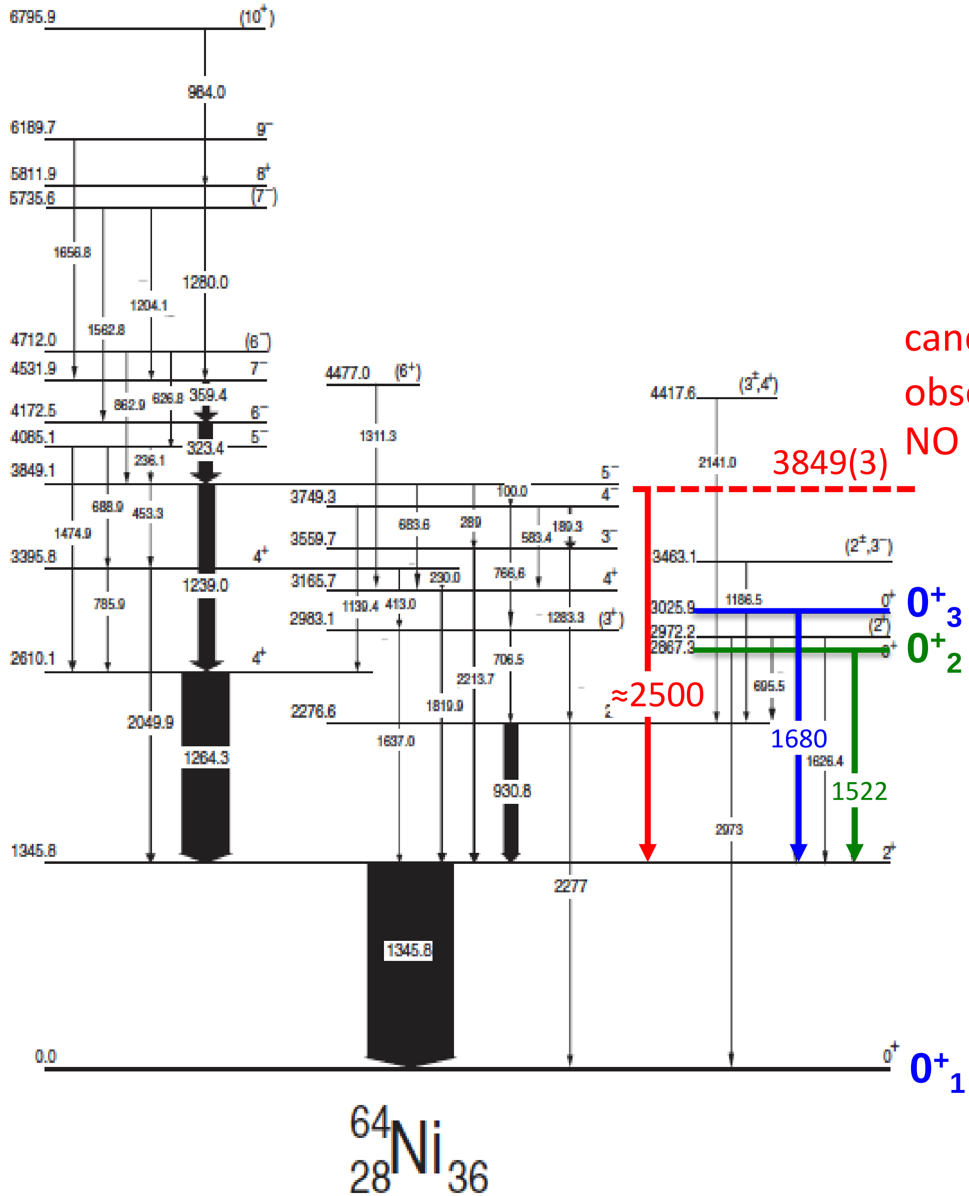
^{64}Ni Both reactions are feasible !!!!

2n : $^{16}O + ^{62}Ni \rightarrow ^{12}C + ^{64}Ni$, **neutron** excitations enhanced **(spherical/oblate)**

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

Experiments made in Bucharest (IFIN HH), July 2017 and January 2018

^{64}Ni level scheme from studies of R. Broda et al.

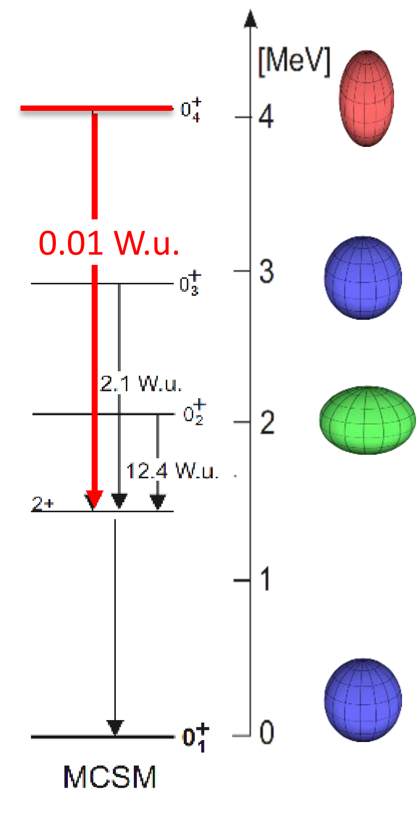


candidate
observed in (t,p) study
NO spin assignment

0^+_4 ?

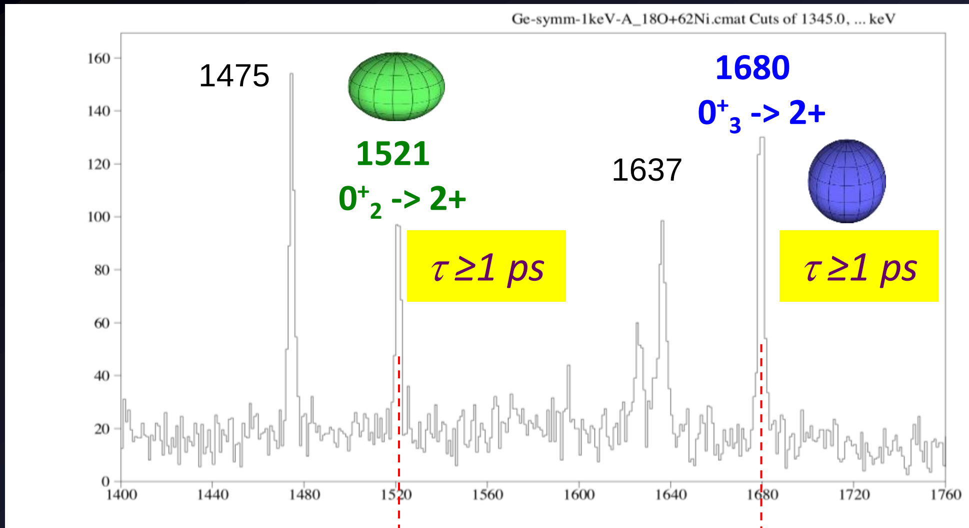
sizable **proton component** is expected

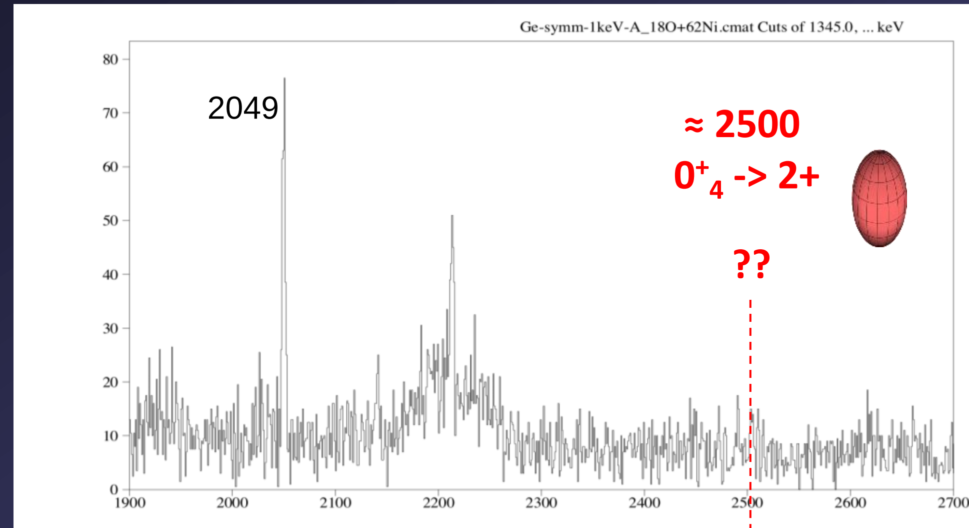
a third excited 0^+ state (prolate) is expected by MCSM at around 4 MeV



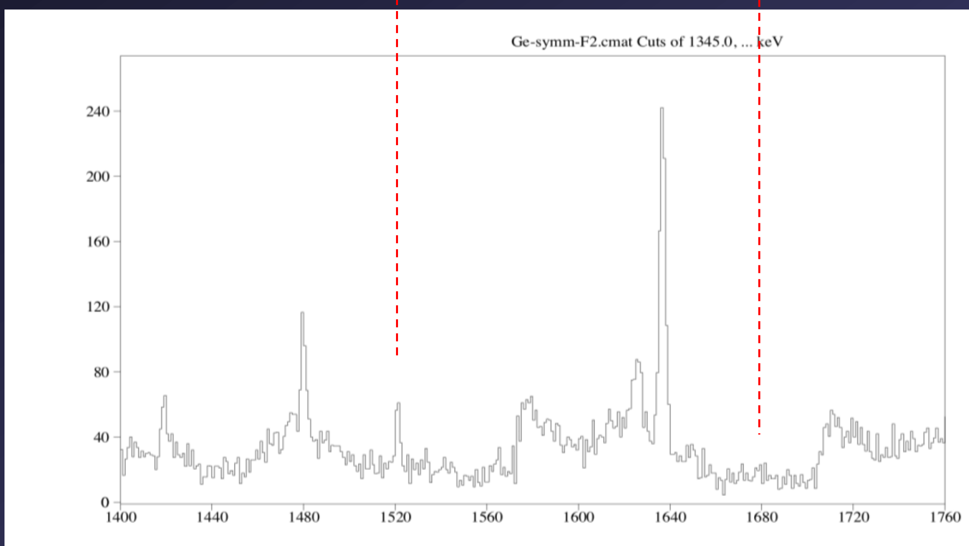
R. Broda et al., Phys. Rev. C 86, 064312 (2012)

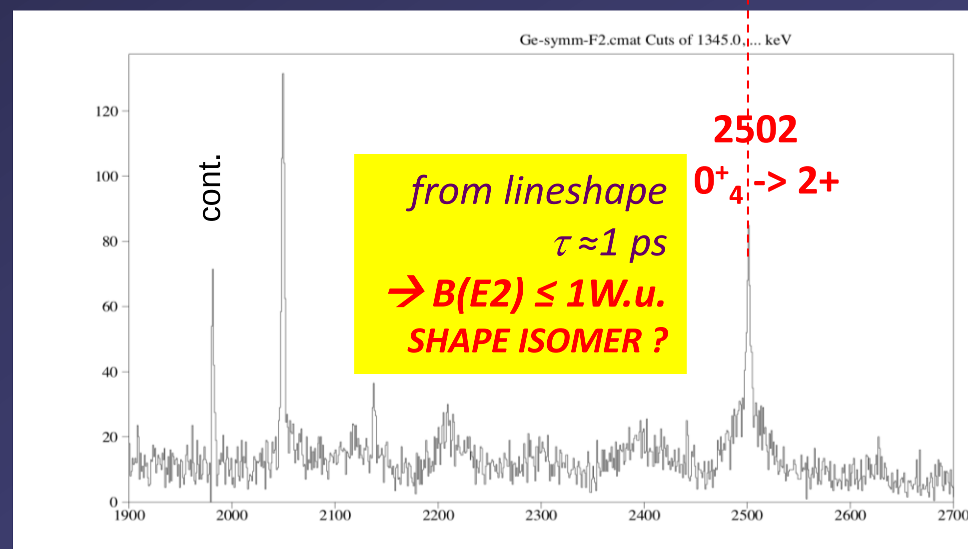
2n transfer: $^{62}Ni(^{18}O,^{16}O)^{64}Ni$ E_b = 39 MeV, neutron excitations favoured (spherical/oblate)





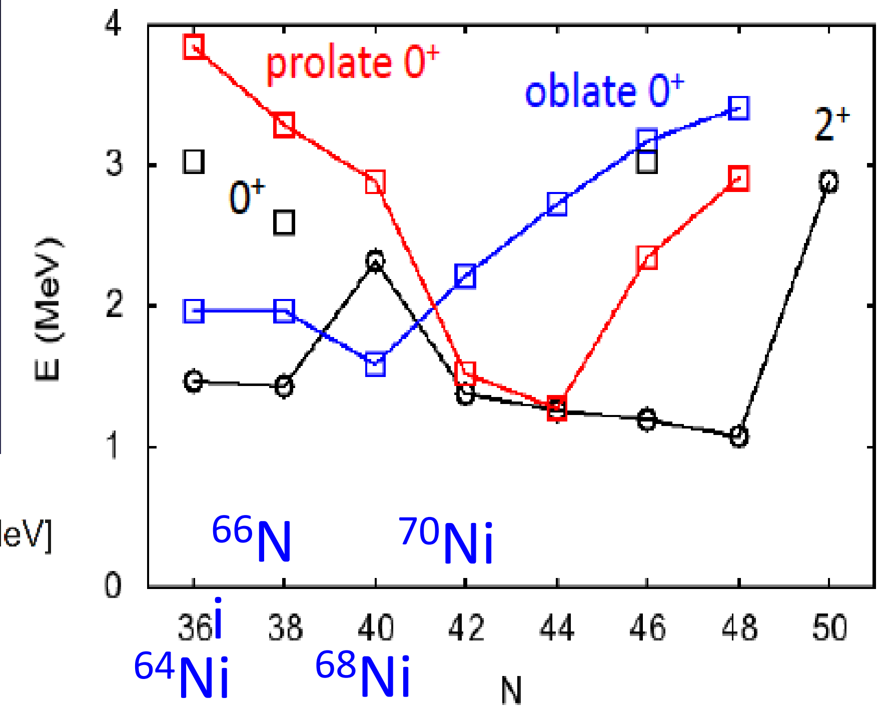
1p transfer: $^{65}Cu(^{11}B,^{12}C)^{64}Ni$ E_b = 26 MeV, proton excitations favoured (prolate)

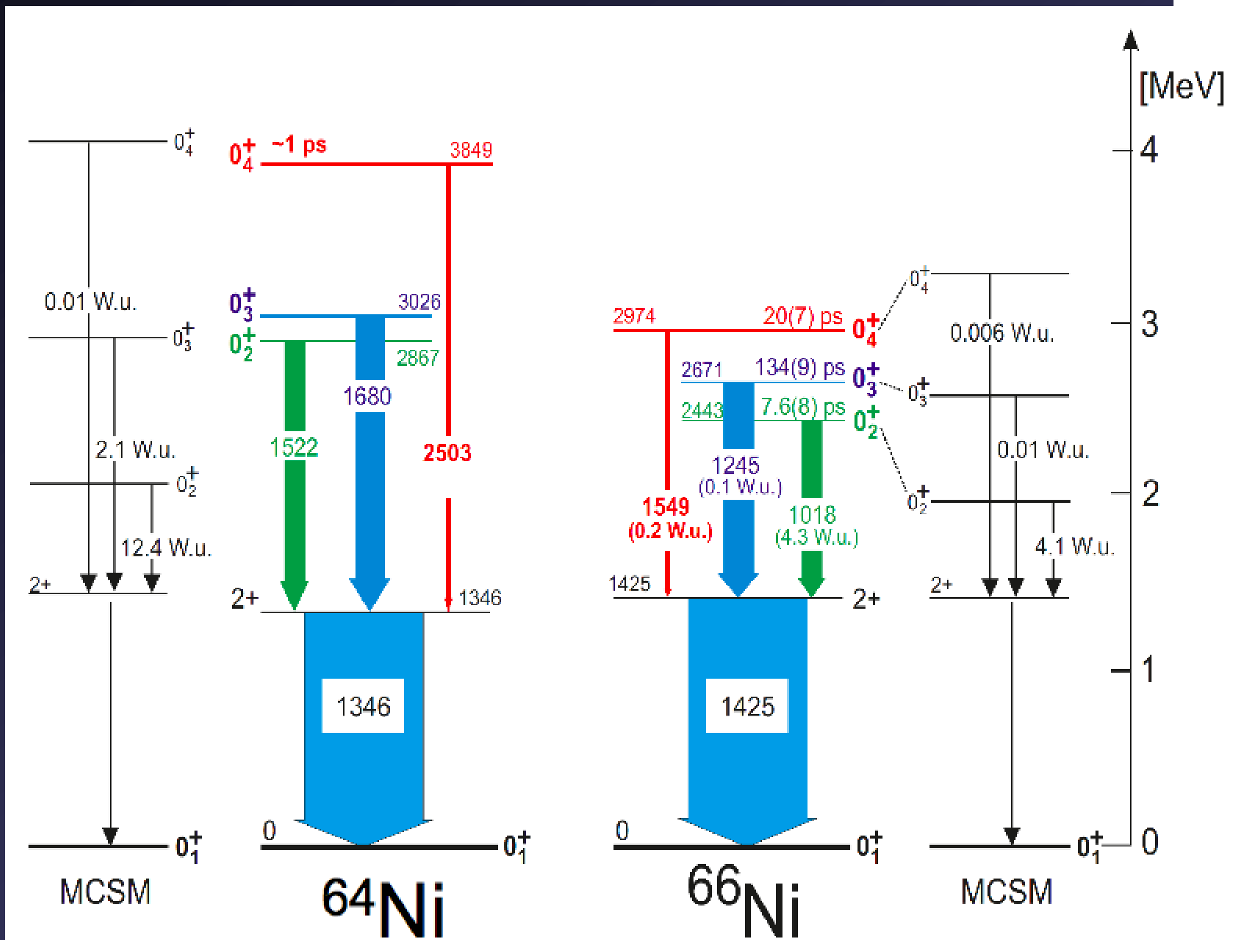




<u>WORK in PROGRESS</u>: angular distribution of (0^+_4) and lifetimes of all 0^+ states

The prolate 0^+ state rises in excitation energy for N < 40 (in ^{62}Ni … ?)

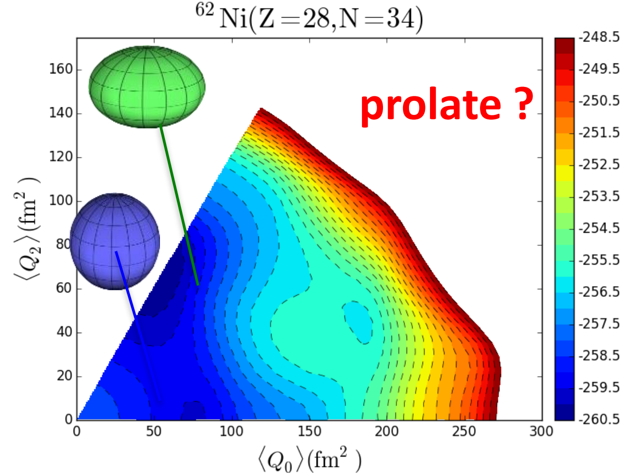


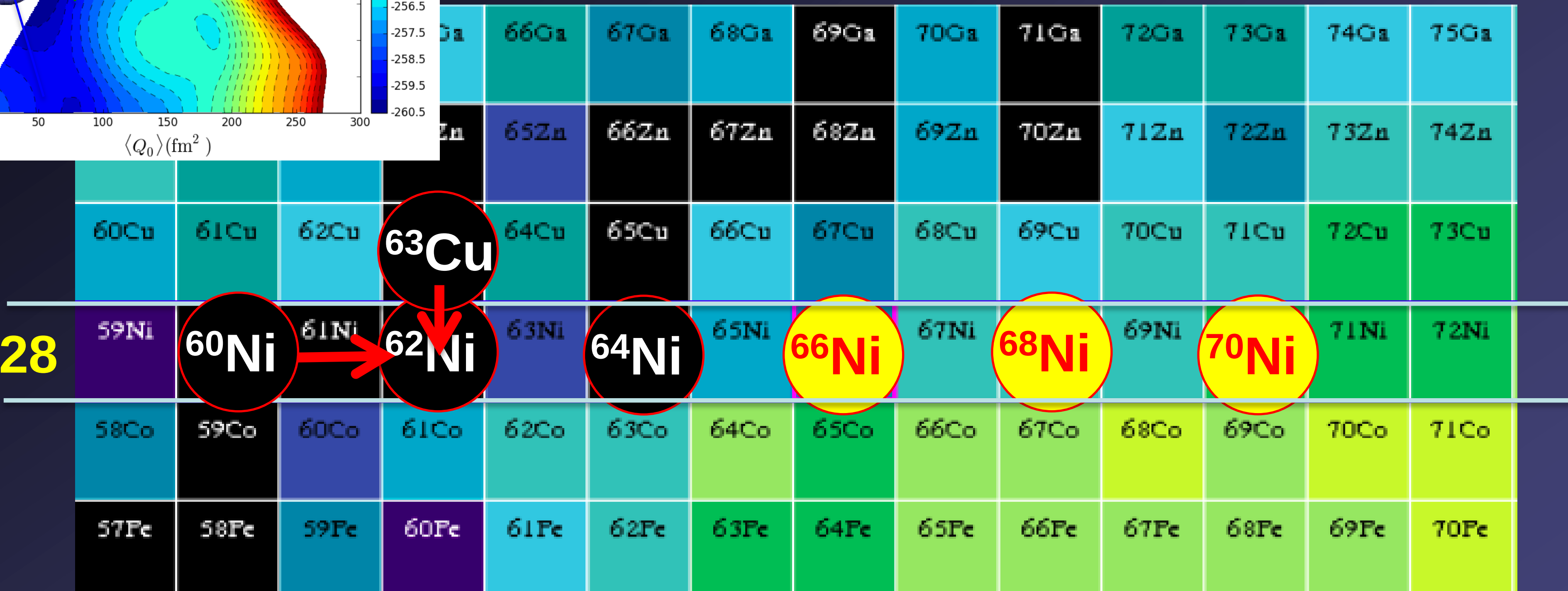


MCSM predictions

Similar studies for ^{62}Ni

neutron and proton transfer reactions





^{62}Ni **Both reactions are feasible !!!!**

2n : $^{16}O + ^{60}Ni \rightarrow ^{12}C + ^{62}Ni$, **neutron** excitations are enhanced **(spherical/oblate)**

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

A new measurement is coming …

^{65}Ni

Probing the wave functions composition by neutron transfer and neutron capture reactions

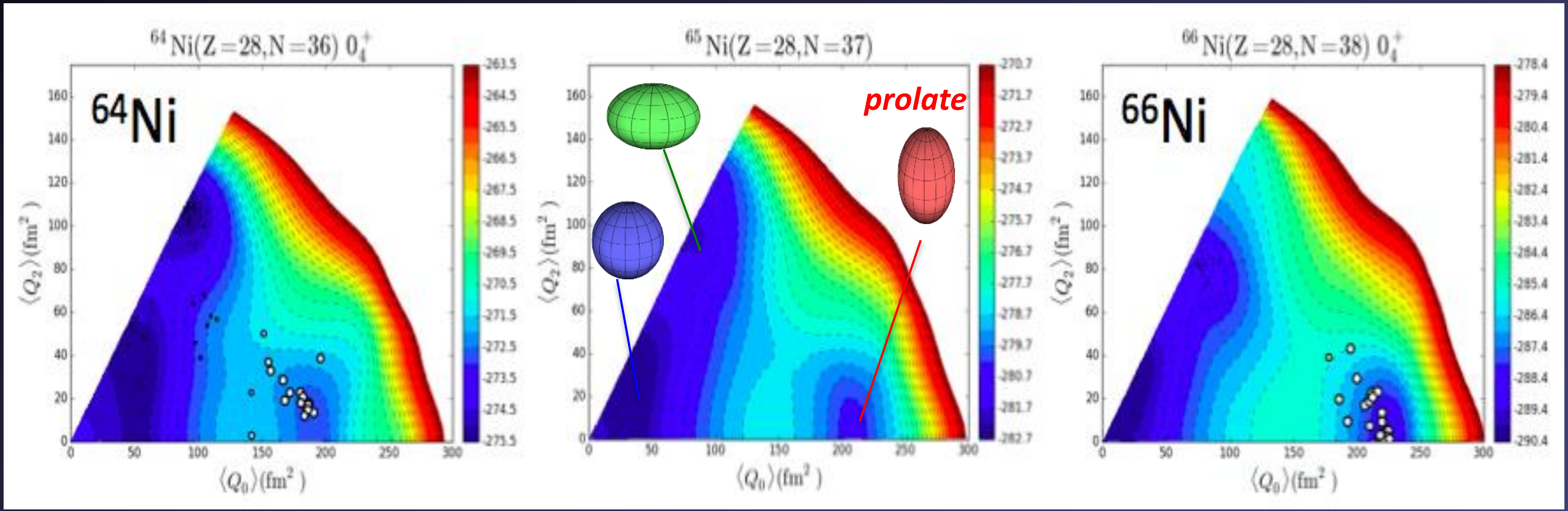
The ^{65}Ni odd system

1n : ^{13}C + ^{64}Ni → ^{12}C + ^{65}Ni, **low and higher spins** (spherical/oblate/prolate ?)

n capture : n + ^{64}Ni → ^{65}Ni, **low spin γ decay from n capture state** (only spherical ?)

Experiments made in Bucharest (IFIN HH) and ILL Spring 2018

^{64}Ni ^{65}Ni ^{66}Ni



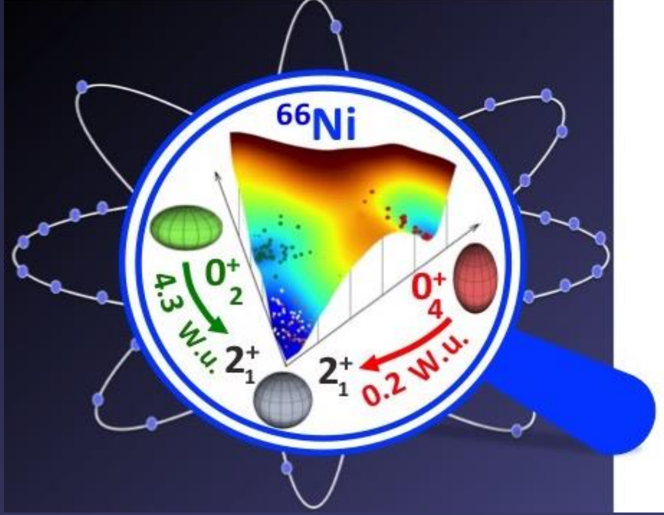
MCSM calculations predict for <u>^{65}Ni strong similarities with ^{66}Ni</u>

Less pronounced barrier, spherical/oblate/prolate shapes

<u>Possibility of shape isomerism</u>:

$3/2^+_1$ (3.39 MeV) , $5/2^+_2$ (3.47 MeV), $9/2^+_3$ (3.76 MeV)

Conclusions



- We have located a 0^+ state in **^{66}Ni** with a **photon decay** **hindered by a nuclear shape change**

It is a unique example of a **shape-isomerlike** structure in a light nucleus

This was possible due to a close and iterative connection between Experiment and Theory (Taka Otsuka group ...)

- This work has started a **detailed and systematic investigation of Ni isotopes** moving towards the stability line (!!!): **^{62}Ni, ^{64}Ni, ^{65}Ni, ...**

- **p, n transfer and n capture reactions can be used to probe the state wavefunctions**

THANK YOU !