DREB2016
Halifax
July 11 (11-15), 2016

Shell evolution and spectroscopic factors

Takaharu Otsuka
University of Tokyo / MSU / KU Leuven

Shell evolution

→ Type I :
magic number
  magic index
  (*prob. that the ground state is a closed shell.*)

Type II :
shape coexistence
quantum phase transition
  (abrupt shape change)

They are related to spectroscopic factors

"MAGIC IS MIGHT"

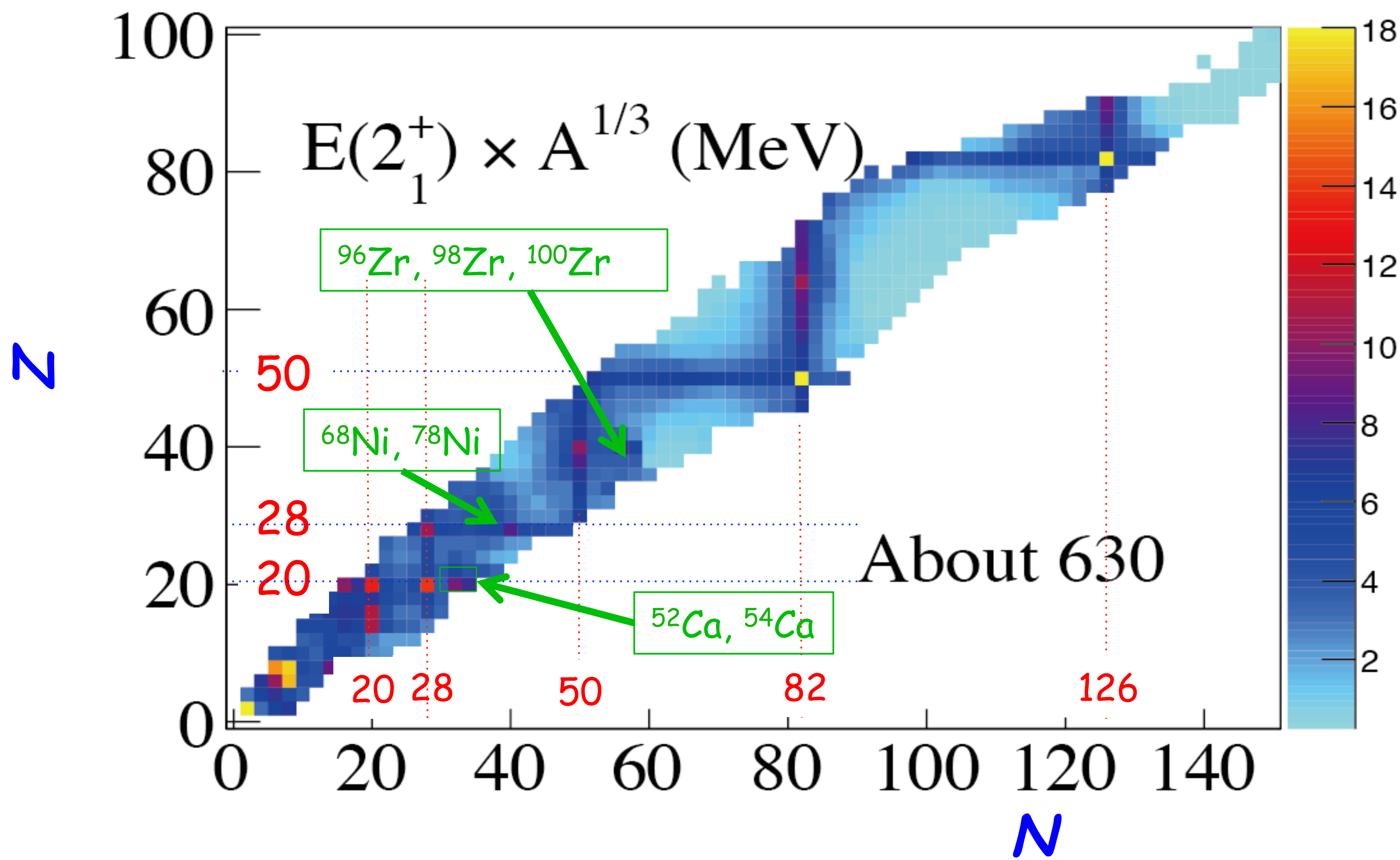
The ministry of magic
London, U.K.

Background picture courtesy from Pieter Doornenbal

2^+ levels $\times A^{1/3}$

Z, *N* even numbers only

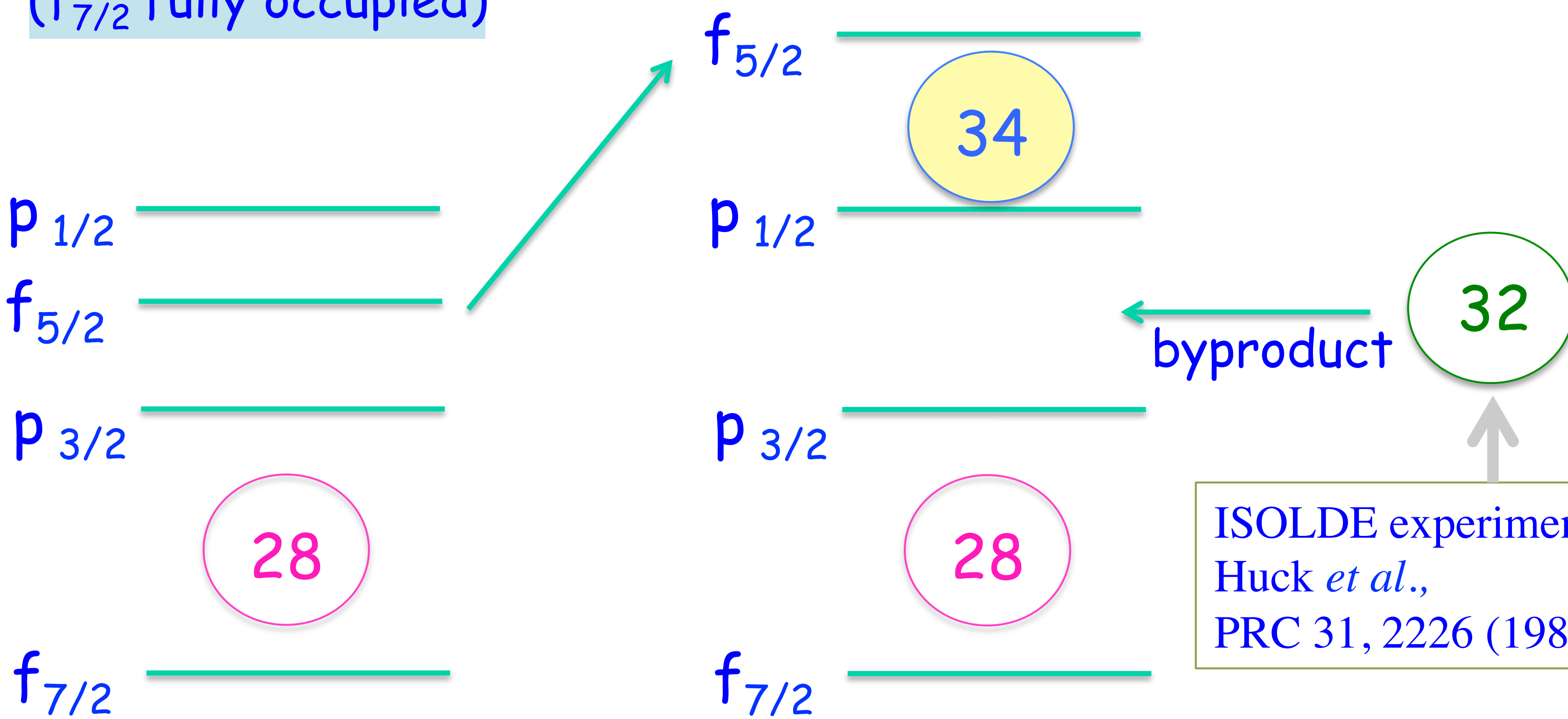
Red numbers : Conventional magic numbers



Appearance of N= 32 and 34 magic structures

shell structure
for neutrons
in Ni isotopes
($f_{7/2}$ fully occupied)

N=34 magic number may appear
if proton $f_{7/2}$ becomes vacant (Ca)
($f_{5/2}$ becomes less bound)

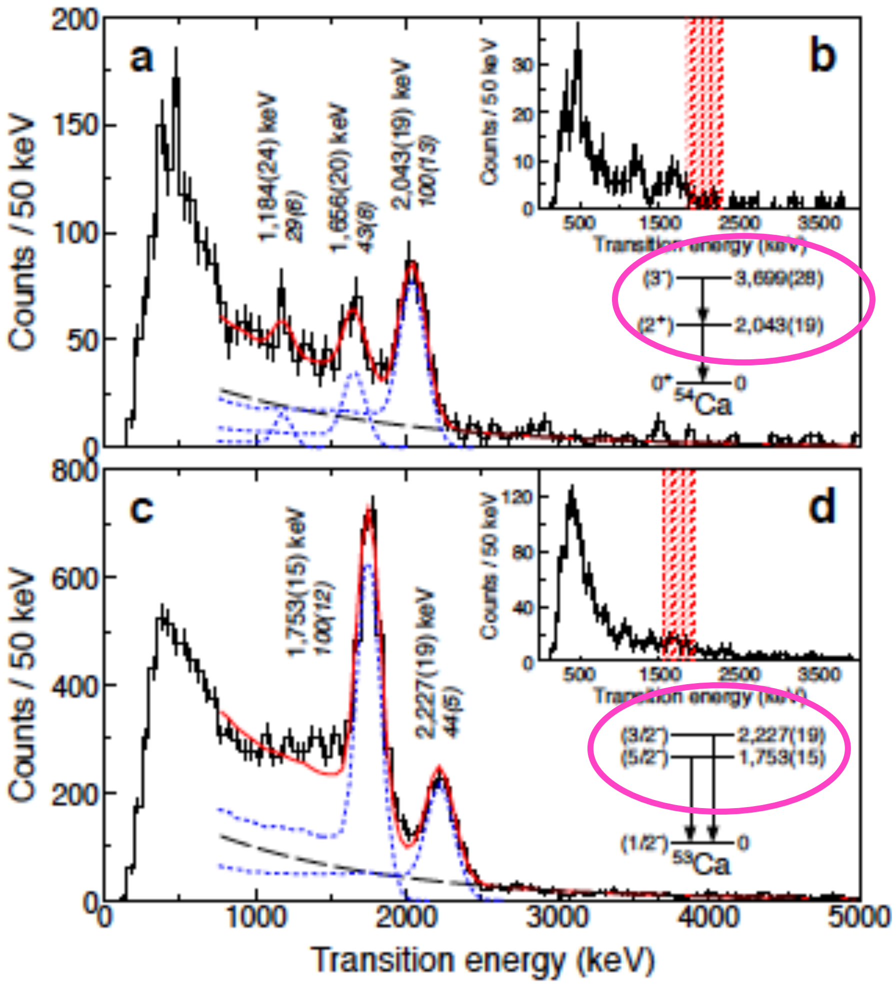


ISOLDE experiment
Huck *et al.*,
PRC 31, 2226 (1985).

Mayer-Jensen, 1949

Predicted by TO *et al*,
PRL 87, 082502 (2001)

Experiment @ RIBF → Finally confirmed



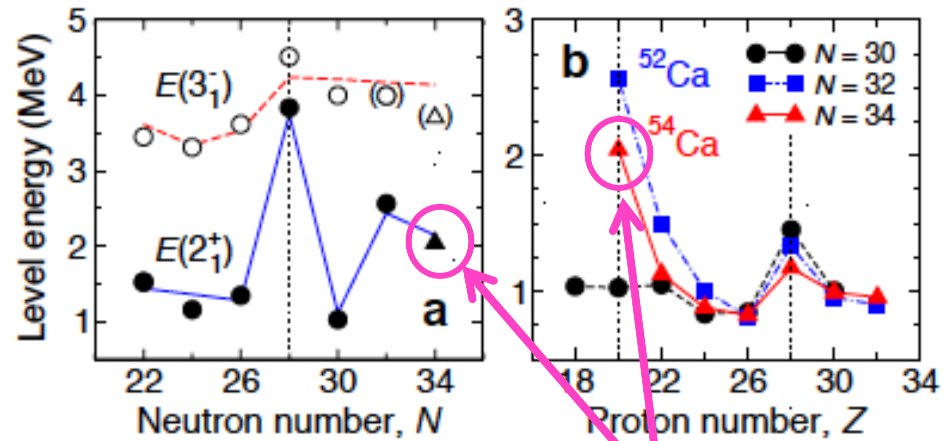


FIG. 4: **Systematics of excited-state e[...] even-even Ca isotopes and neighbouring n[...]** [...]ergies of first 2^+ (closed symbols) and 3^- (open [...]ls for even-even $^{42-54}$Ca isotopes [28]. The res[...]resent study are indicated by triangular marke[...]l and dashed lines are shell-model predictions of [...](3_1^-), respectively (see text for details). Tentat[...]ty assignments are enclosed by parentheses. **b,** $E(2_1^+)$ along the $N = 30$, 32 and 34 isotonic chains. The solid and dashed lines are intended to guide the eye. Vertical dotted lines represent the traditional magic numbers in both plots.

new RIBF data

er-corrected γ-ray energy spectra. De-excitation γ rays measured in coinci-

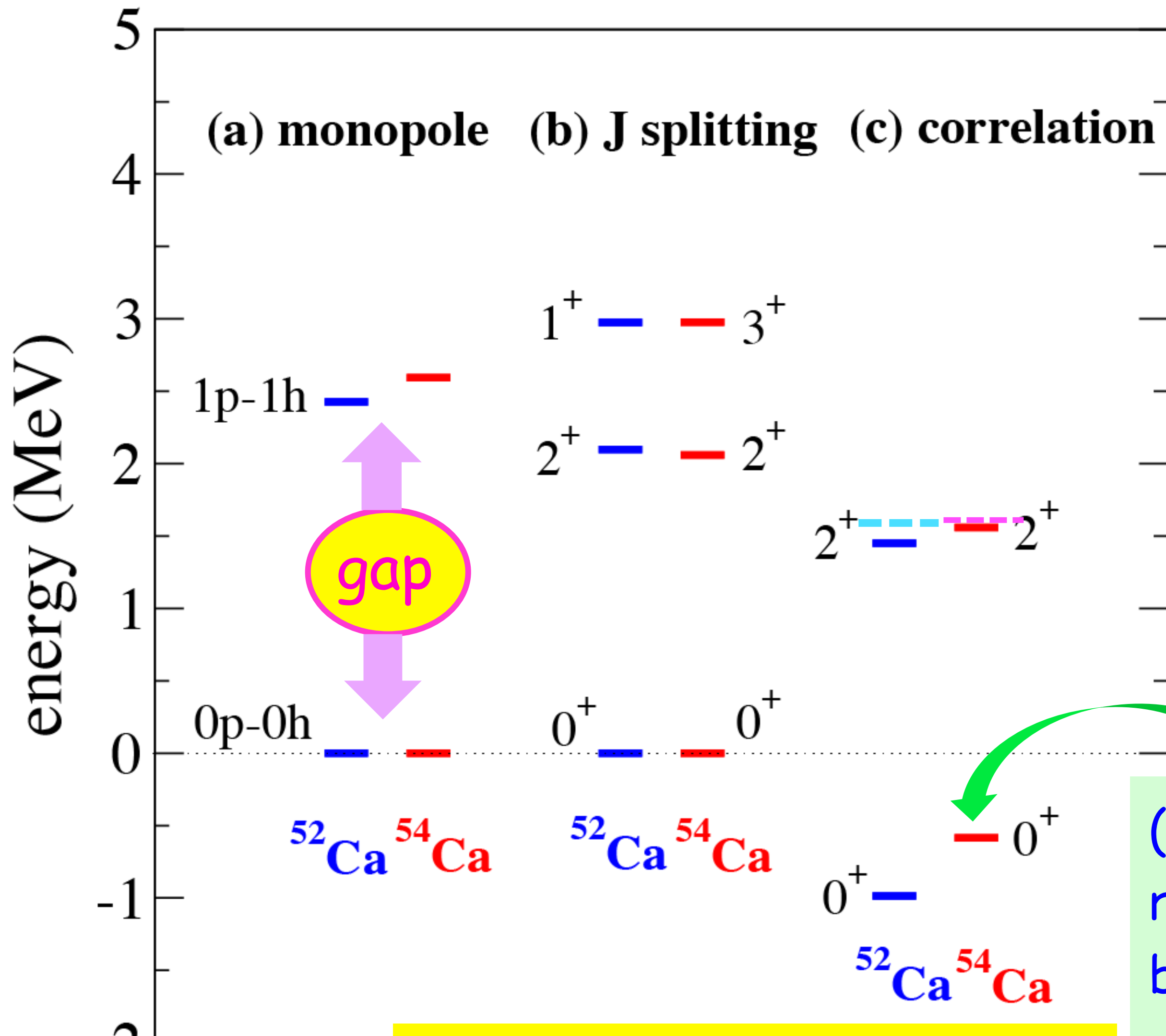
^{54}Ca and **c,** ^{53}Ca reaction products. Peaks a

ive intensities are indicated by italic fonts. The short-blue and long-black dashed

Steppenbeck *et al.* Nature, 502, 207 (2013)

2^+ energy level v.s. shell gap

Calculation by GXPF1Br interaction



Exp.

For ^{54}Ca,
2^+ excitation energy
< gap energy

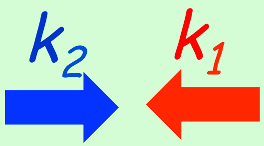
$(p_{1/2})^2$ pairing repulsive (+0.5 MeV) by tensor force, weakening total pairing

Magic index : 86% 89%
(proton part not considered)

One-dimensional collision model - summary-

TO, Suzuki *et al*. PRL 95, 232502 (2005)
TO, Phys. Scr. T152, 014007 (2013)

At collision point: $\Psi \propto e^{ik_1x_1}e^{ik_2x_2} + e^{ik_2x_1}e^{ik_1x_2} = 2\,e^{iKX}\cos(kx)$

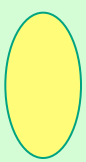


large relative momentum k

⇩

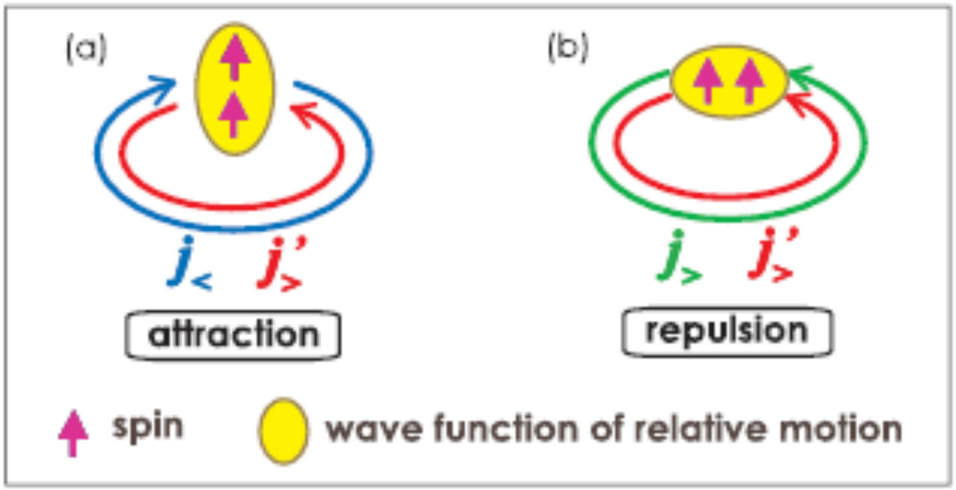
strong damping

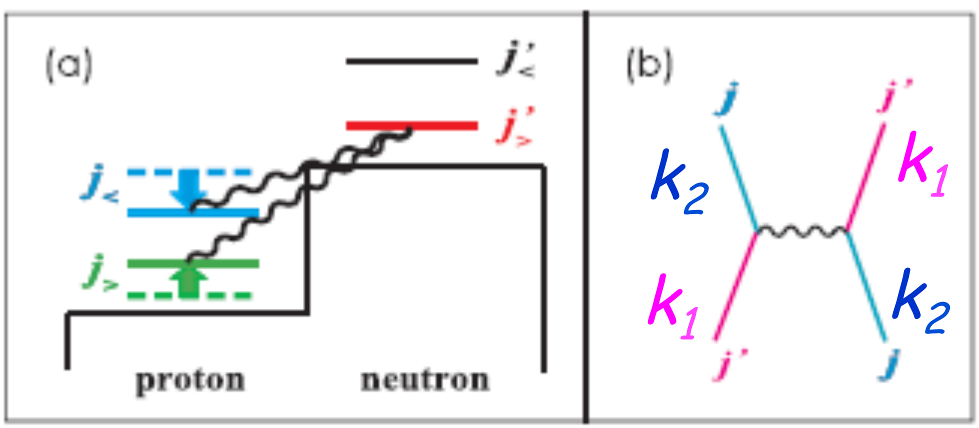
⇩

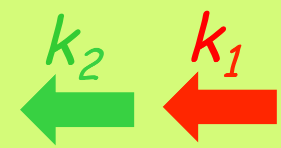


wave function of relative coordinate

$k = k_1 - k_2\,,\quad K = k_1 + k_2$





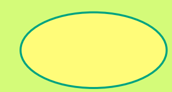


small relative momentum k

⇩

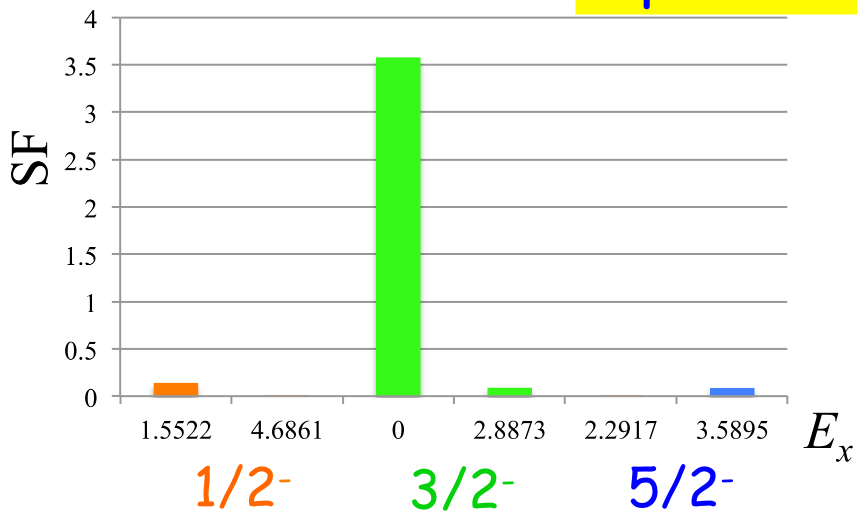
loose damping

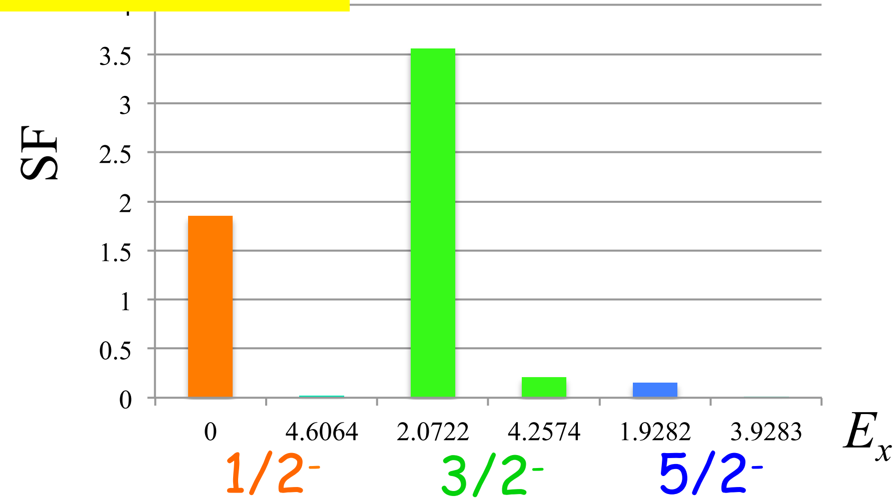
⇩



wave function of relative coordinate

Spectroscopic Factors





-1n (^{51}Ca)

-1n (^{53}Ca)

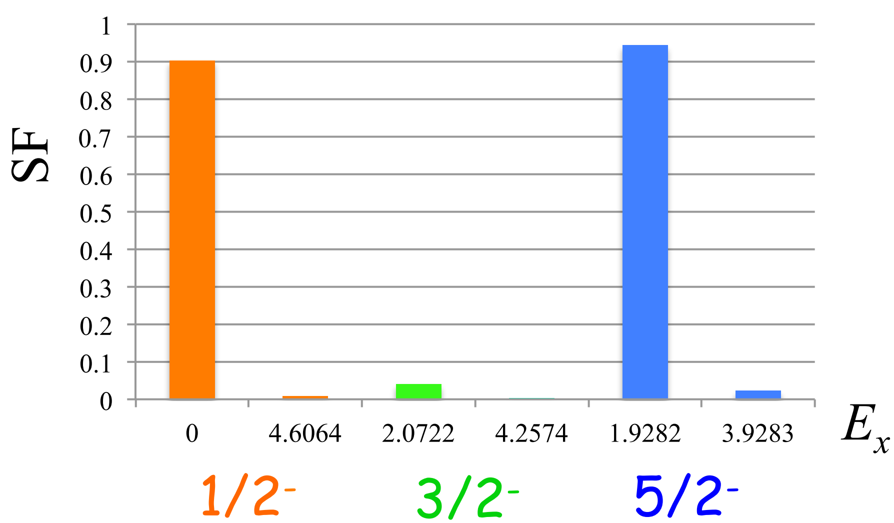
^{52}Ca

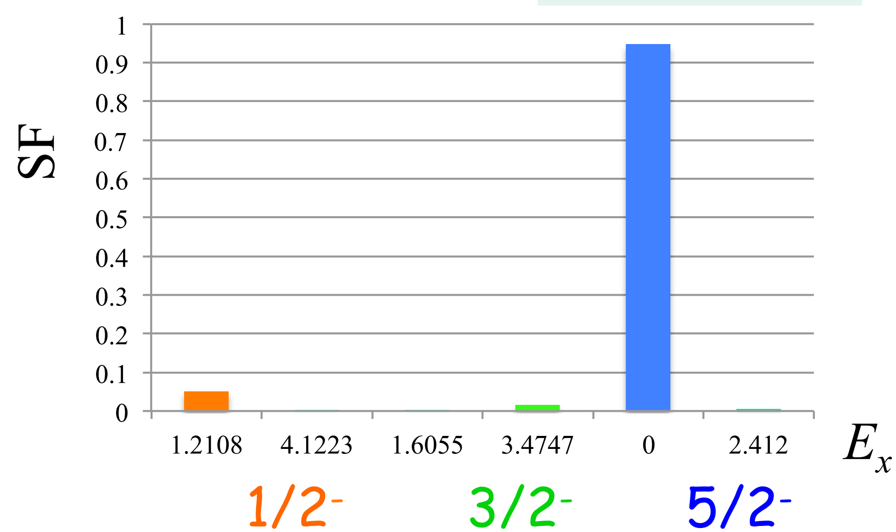
equally magic

^{54}Ca

+1n (^{53}Ca)

+1n (^{55}Ca)





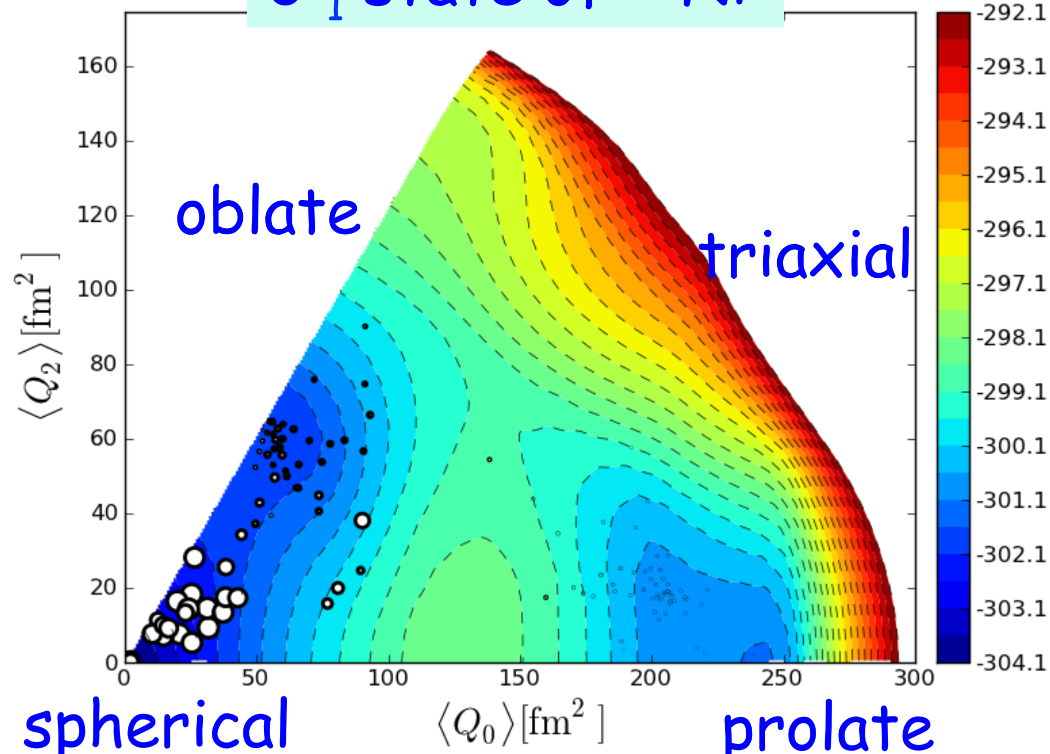
MCSM basis vectors on Potential Energy Surface

eigenstate $\Psi = \sum_i c_i P[J^\pi] \Phi_i$

Slater determinant → intrinsic shape

- PES is calculated by CHF for the shell-model Hamiltonian
- Location of circle : quadrupole deformation of unprojected MCSM basis vectors
- Area of circle : overlap probability between each projected basis and eigen wave function

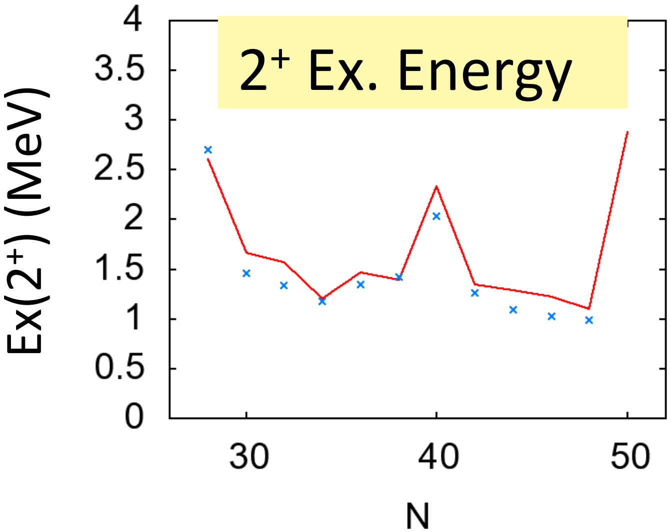
0^+_1 state of ^{68}Ni

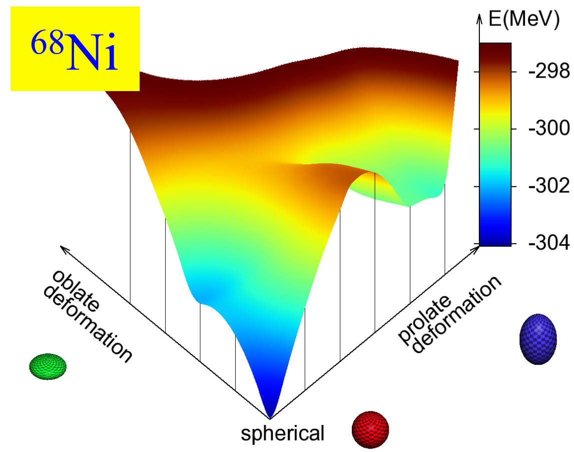


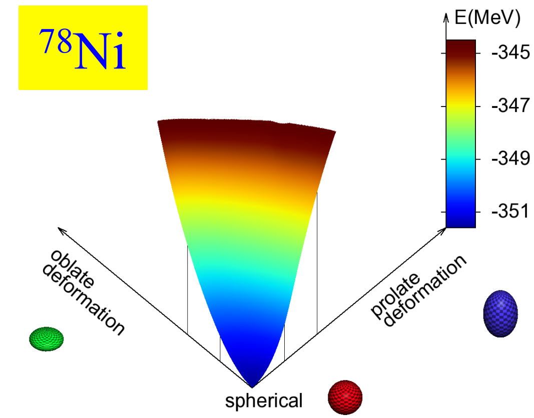
Called *T-plot* in reference to

Y. Tsunoda, TO, Shimizu, Honma and Utsuno, PRC 89, 031301 (R) (2014)

Different appearance of Double Magicity of $^{56,68,78}Ni$







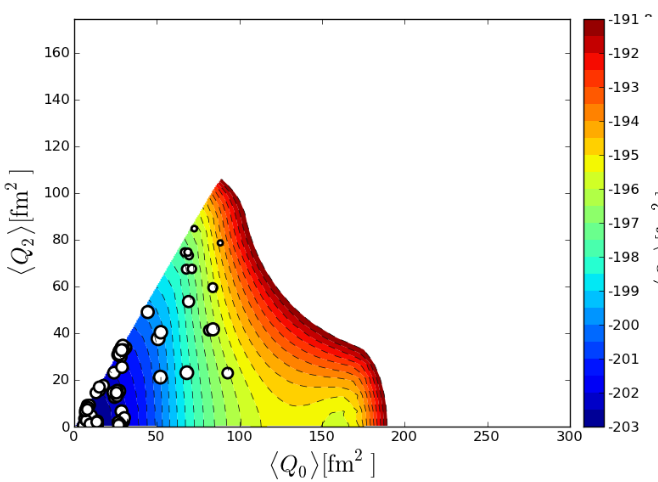
sharper minimum

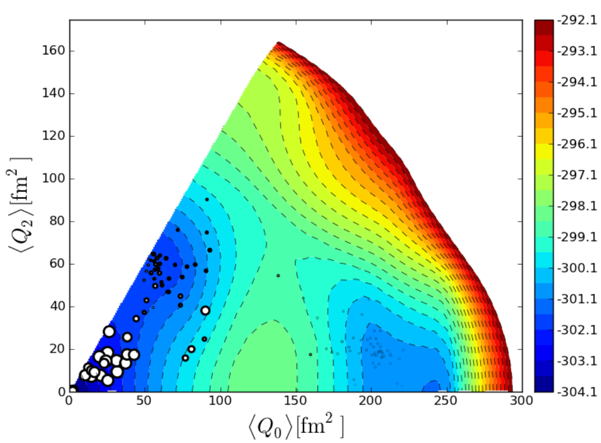
0^+_1 state of ^{56}Ni

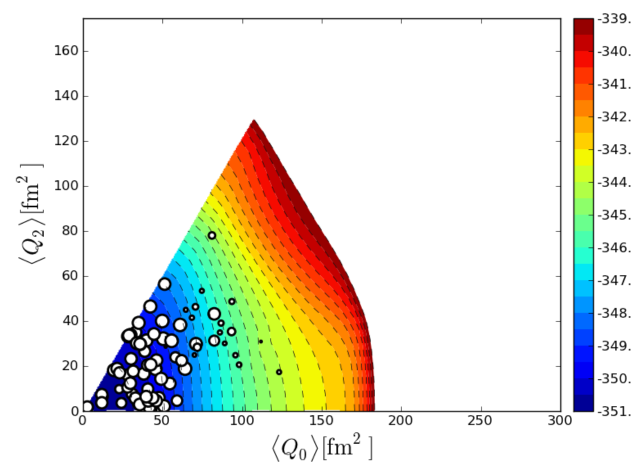
0^+_1 state of ^{68}Ni

0^+_1 state of ^{78}Ni

Magic index 60% 53% 75%







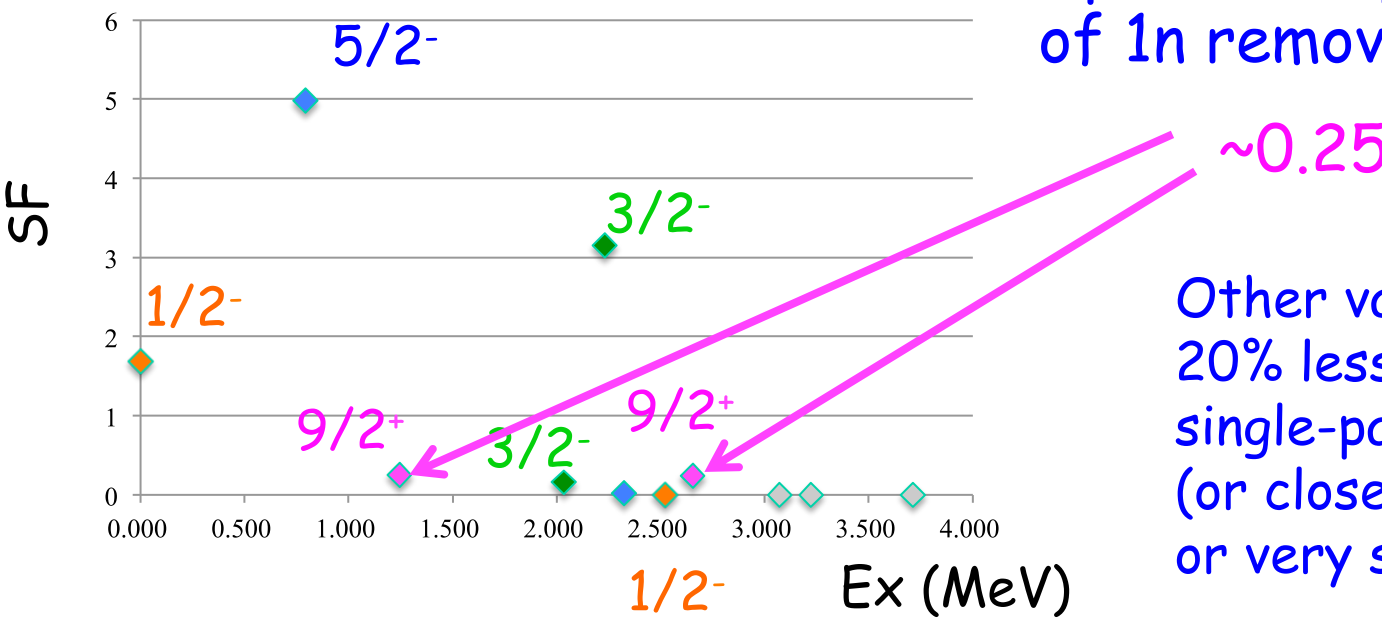
Why 53% for ^{68}Ni ?

The ground state of ^{68}Ni contains about 1 neutron in the $g_{9/2}$+$d_{5/2}$ orbits.

=> ~50% 0p0h and ~50% 2p2h configurations.

The state is largely spherical because the mixing is mainly due to the $J=0^+$ pairing.

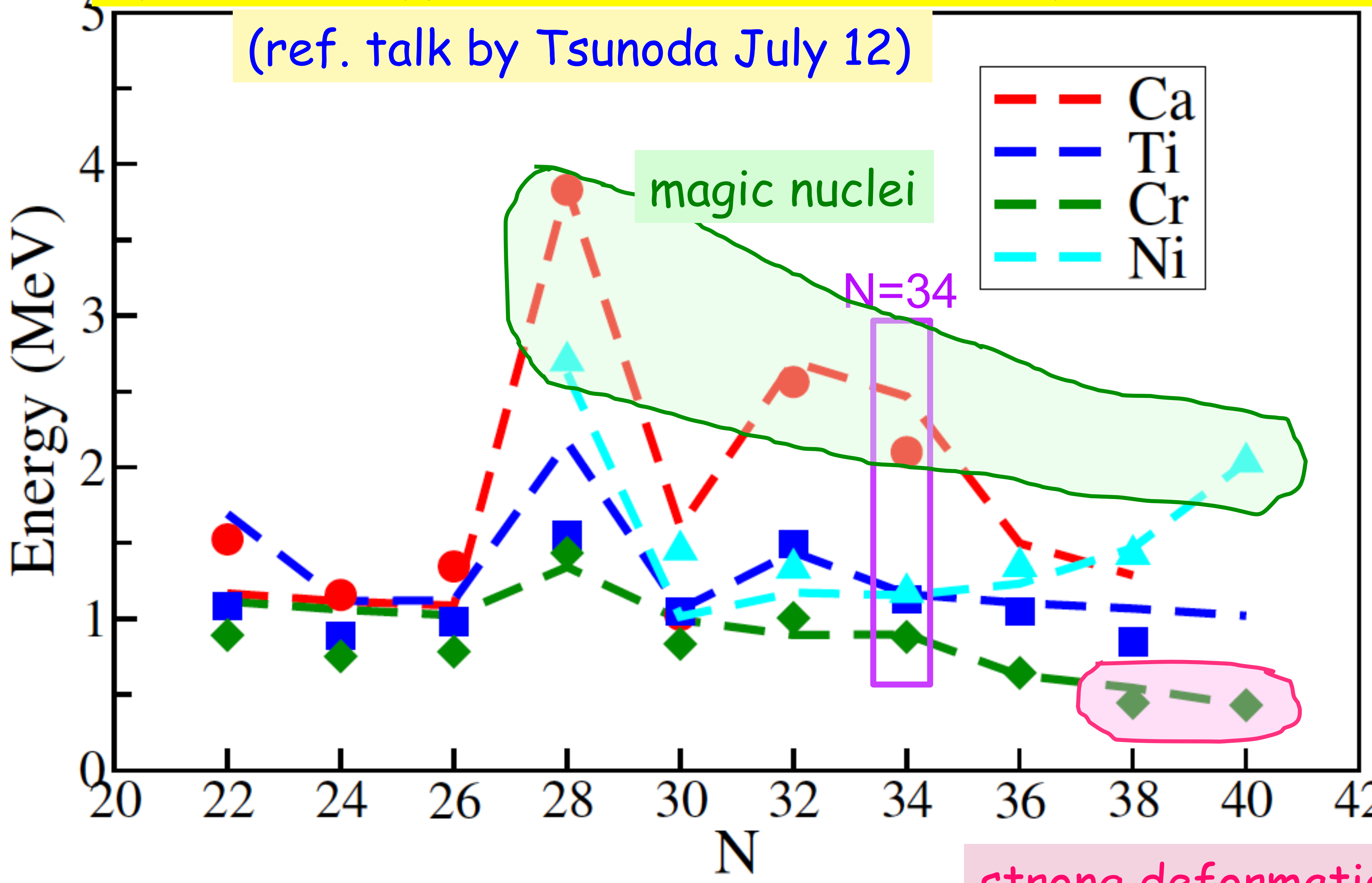
Spectroscopic factors of 1n removal from ^{68}Ni



Other values : about 20% less than the single-particle limit (or closed-shell value) or very small.

Proton Z=28 shell is broken only by 0.2 protons excited, with SF ($7/2^-_1$) ~ 7.3.

2$^+$ level systematics of Ca, Ti, Cr and Ni isotopes by ab-initio type shell-model interaction by EKK method



strong deformation

Quantum Phase Transition in Zr isotopes caused by type II shell evolution

Togashi, Tsunoda, Otsuka *et al.* 1606.09056v1 [nucl-th]

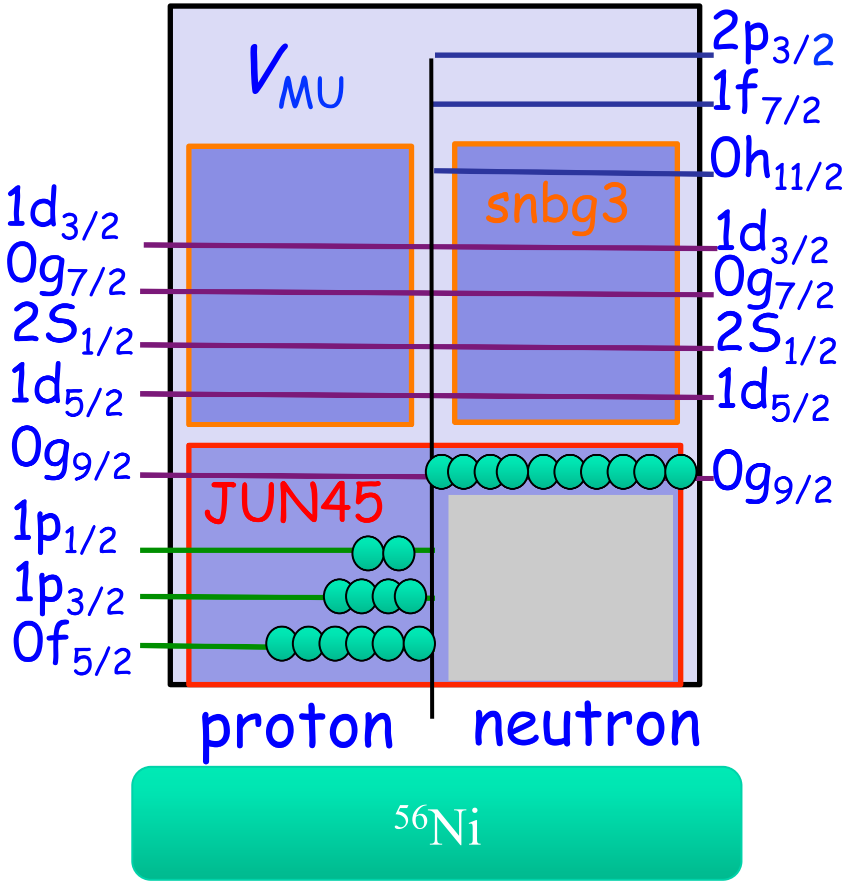
Model space and Effective interaction

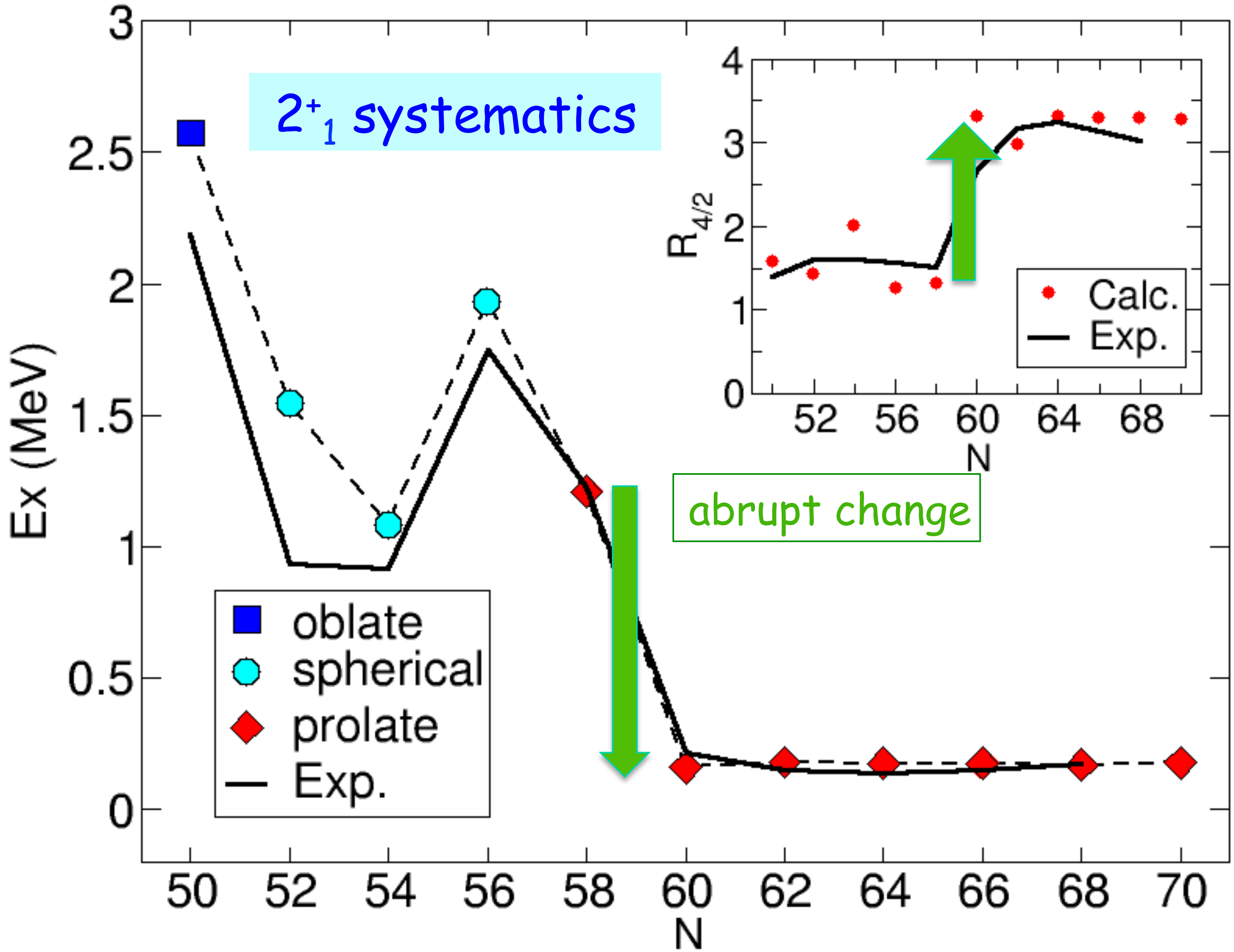
- Effective interaction:
  JUN45 + snbg3 + V_{MU}

  known effective interactions

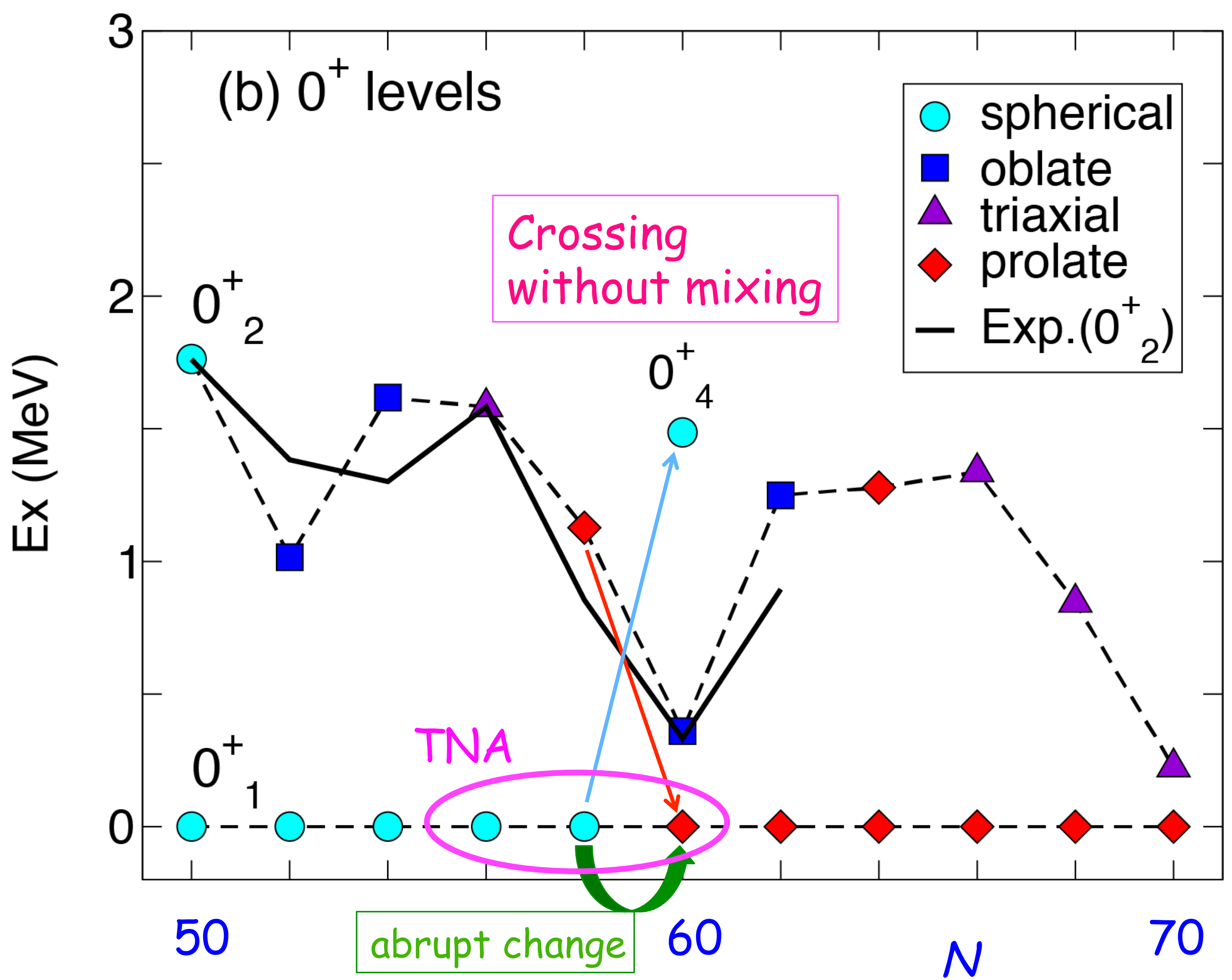
  + minor fit for a part of T=1 TBME's

Nucleons are excited fully within this model space (no truncation)





2+1 systematics
abrupt change
Ex (MeV)
N
3
2.5
2
1.5
1
0.5
0
50
52
54
56
58
60
62
64
66
68
70
oblate
spherical
prolate
Exp.
R4/2
Calc.
Exp.



(b) 0+ levels
Ex (MeV)
3
2
1
0
spherical
oblate
triaxial
prolate
Exp.(0+2)
Crossing
without mixing
0+2
0+4
0+1
TNA
abrupt change
50
60
70
N

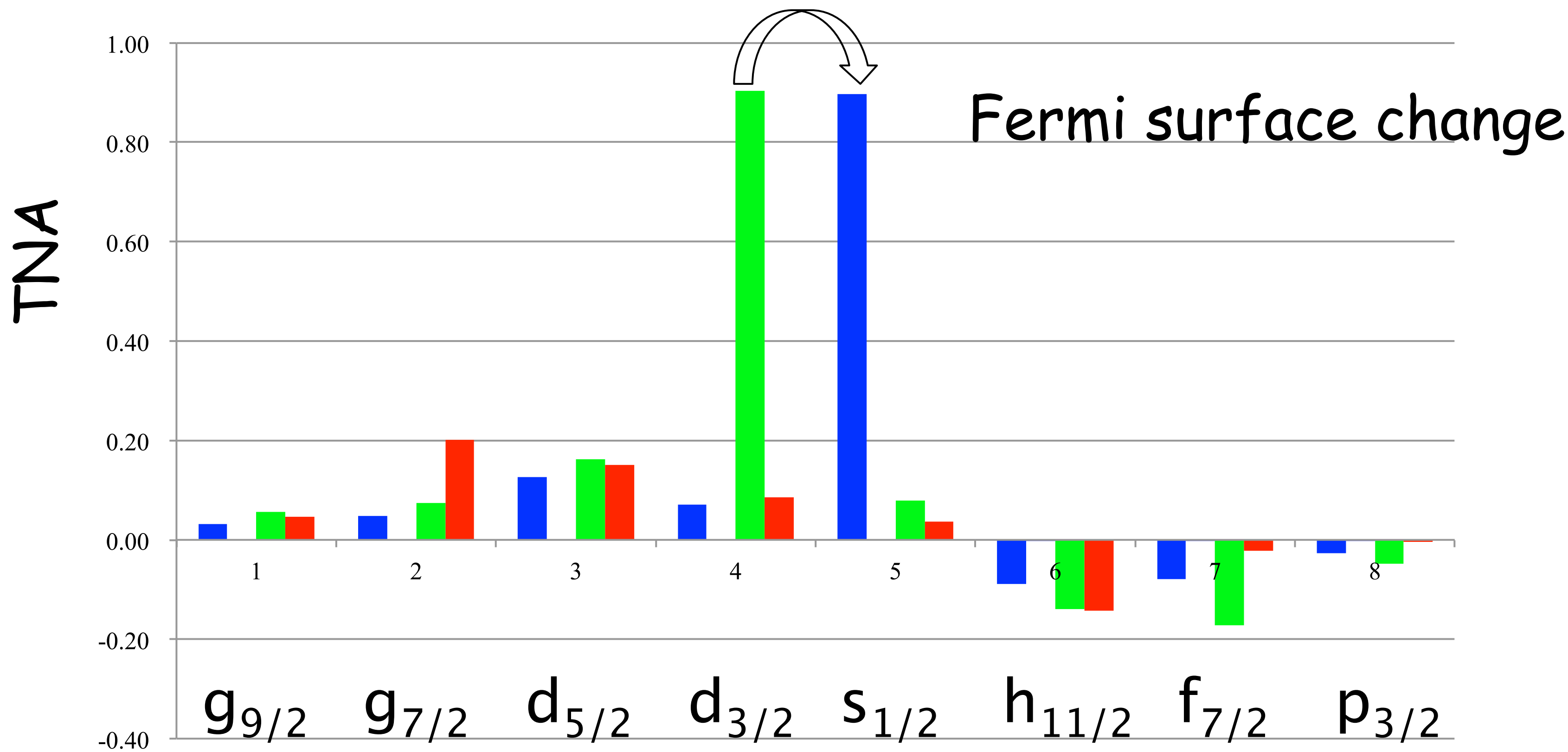
TNA (two-nucleon amplitude)

$^{96}Zr\ (0^+_1) \rightarrow\ ^{98}Zr\ (0^+_1)$
sph sph

$^{98}Zr\ (0^+_1) \rightarrow\ ^{100}Zr\ (0^+_1)$
sph def

$^{98}Zr\ (0^+_1) \rightarrow\ ^{100}Zr\ (0^+_4)$
sph sph

$^{98}Zr\ (0^+_2) \rightarrow\ ^{100}Zr\ (0^+_1)$
def def



Summary

1. Magic structure can be studied further (better) from the viewpoint of wave functions by the help of spectroscopic factors.

2. For example, ^{52}Ca and ^{54}Ca are equally magic, although the 2^+ level is lower in the latter. (An exercise of the tensor force.)

3. ^{68}Ni is more spherical than ^{78}Ni, whereas ^{78}Ni shows higher magic index than ^{68}Ni.

4. TNA can be very interesting in ^{96}Zr-^{98}Zr-^{100}Zr, because of the abrupt change, i.e., the quantum phase transition.

Collaborators

- Yusuke Tsunoda (CNS, Tokyo)
- Tomoaki Togashi (CNS, Tokyo)
- Naofumi Tsunoda (CNS, Tokyo)
- Noritaka Shimuzu (CNS, Tokyo)
- Yutaka Utsuno (JAEA)
- Kazuo Takayanagi (Sophia Univ.)
- Toshio Suzuki (Nihon Univ.)
- Morten Hjorth-Jensen (MSU/Oslo)