Study of medium-mass nuclei by large-scale shell model calculations

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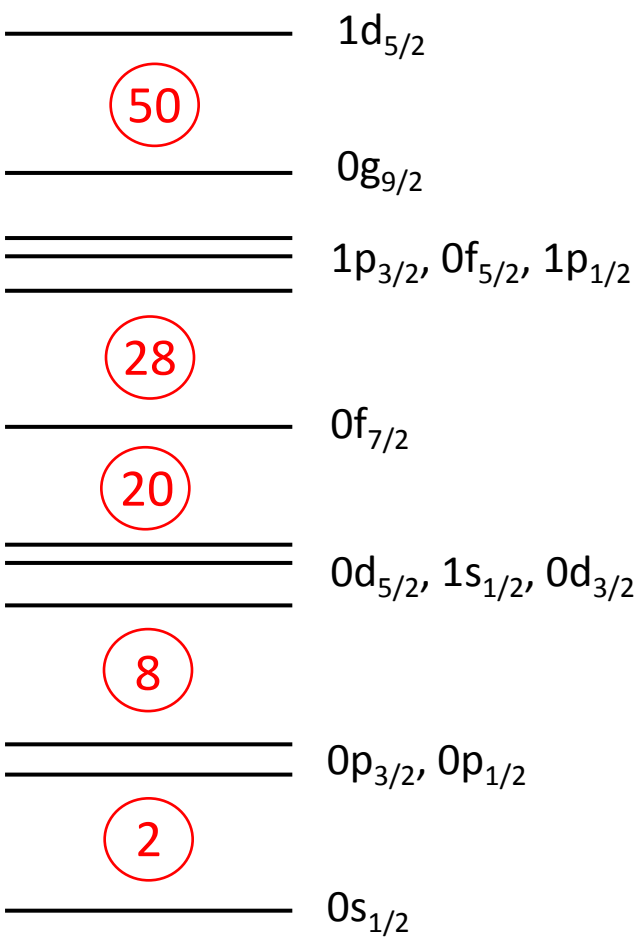
Motivation

Shell structure
in stable nuclei (Z∼N)



Different structure
in exotic nuclei (Z≪N, Z≫N)

Some magic numbers disappear
New magic numbers appear

Magic number nucleus: closed shell
Ground state has spherical shape
Excited states are higher

open shell nucleus:
Nucleus can have deformed shape
Excited states are lower

Motivation

Phenomena in exotic nuclei ($Z \ll N$, $Z \gg N$)

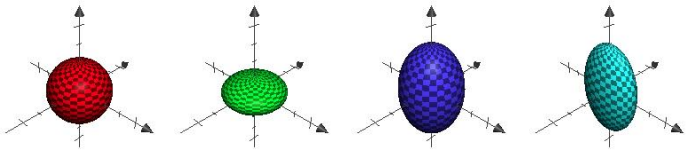
Evolution of shell structure

Size of shell gaps changes

Magicity becomes strong/weak

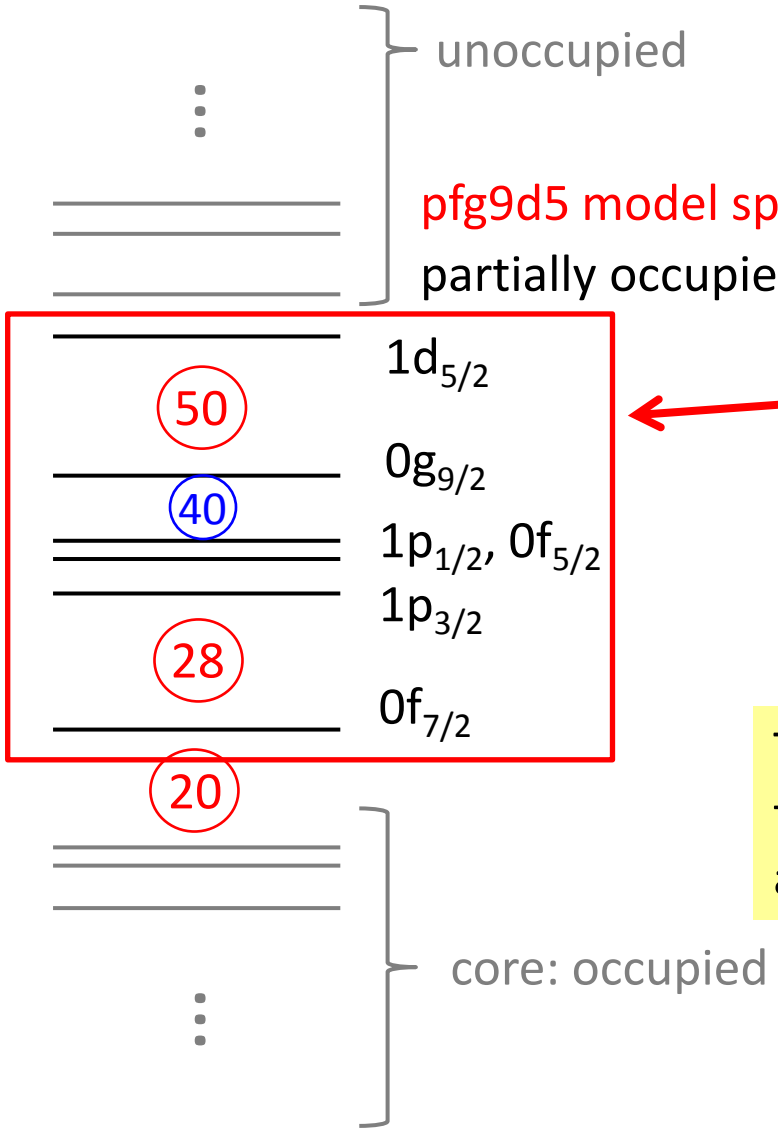
Shape coexistence

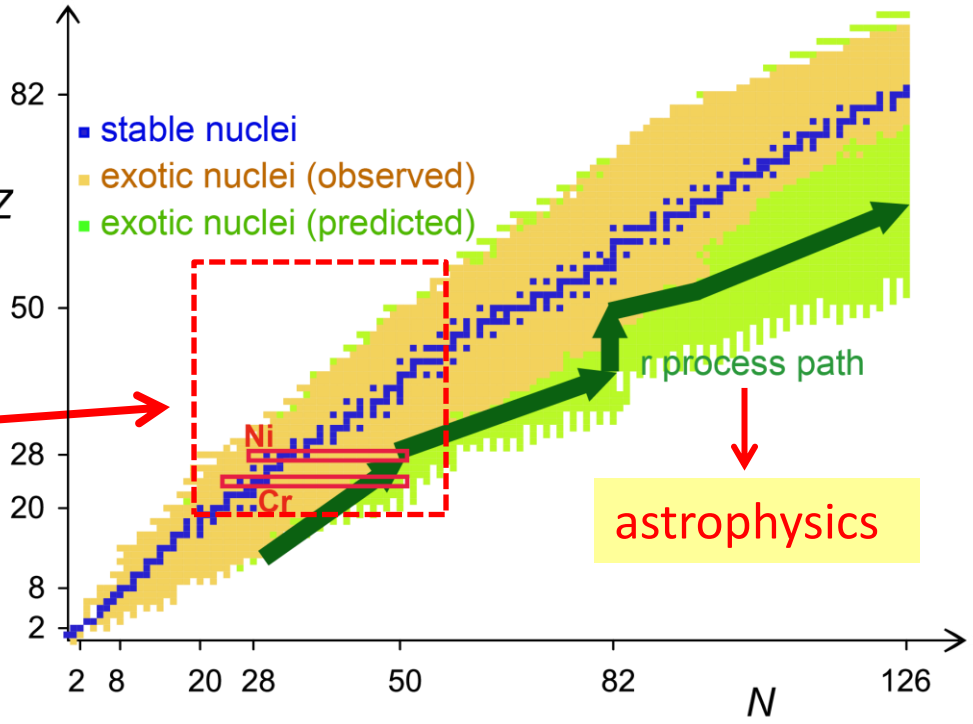
States of different shape coexist



Necessity of large-scale calculations in large model space

Shell model calculation



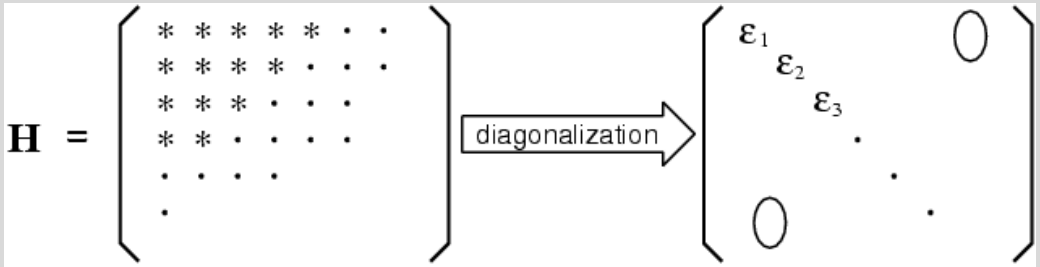


This model space is wide enough
to discuss how magic numbers 28, 50
and semi-magic number 40 are retained/broken

Our effective interaction consists of
microscopic and empirical interactions

Monte Carlo shell model (MCSM)

More than 10^{15} (in our model space)

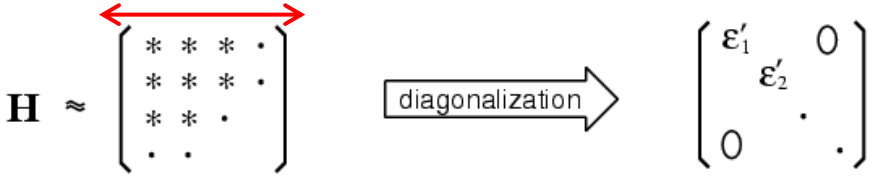


Conventional Shell Model

all Slater determinants

Direct diagonalization is impossible in large model space

about 100



Monte Carlo Shell Model

bases important for a specific eigenstate

In MCSM, we diagonalize small Hamiltonian matrix constructed from MCSM bases

T. Otsuka *et al.* PPNP47, 319 (2001)

$$|\Psi_N\rangle = \sum_{n=1}^{N} \sum_{K=-J}^{J} f_{n,K}^{(N)} P_{MK}^{J\pi} |\psi_n\rangle$$

Generated to minimize eigenenergies using quantum MC + variational method

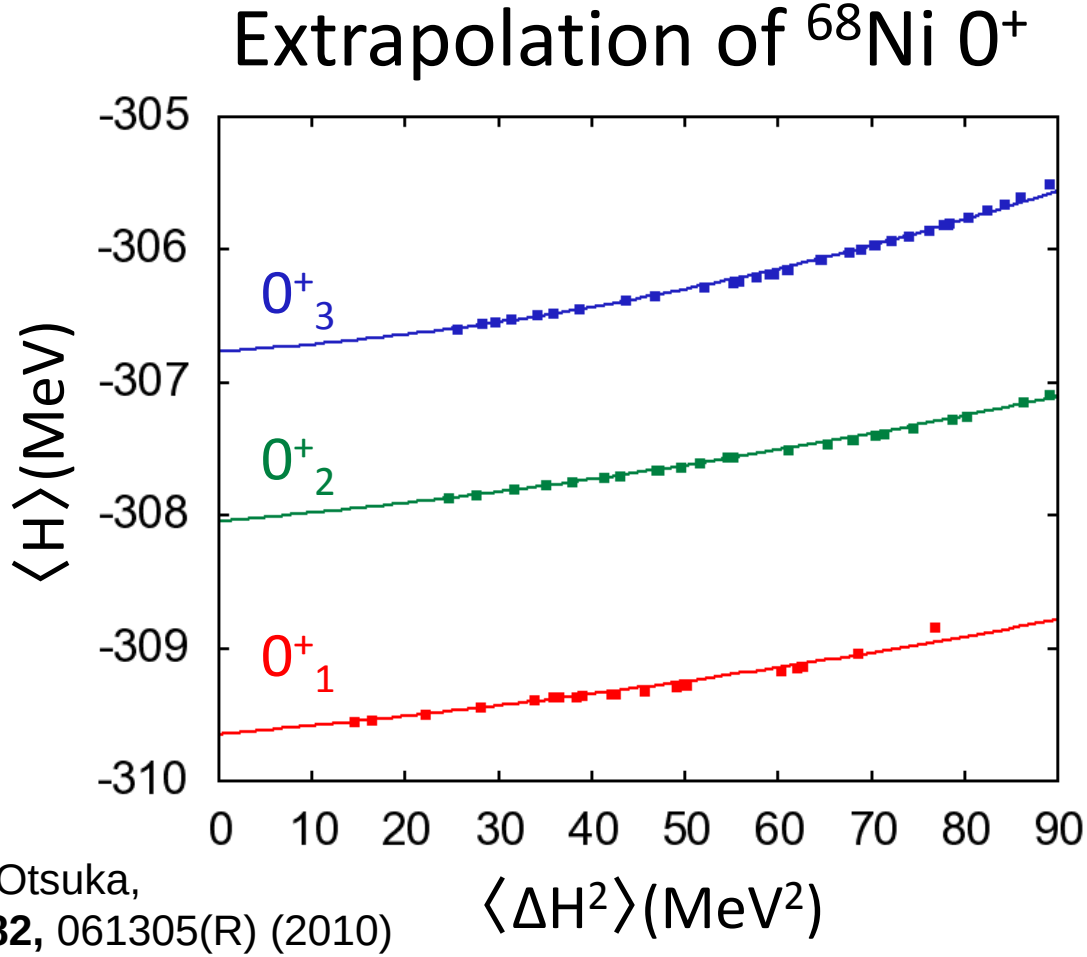
eigenstate

angular-momentum, parity projection

Slater determinant

Energy-variance extrapolation

- Second-order extrapolation using energy variance $\langle \Delta H^2 \rangle = \langle H^2 \rangle - \langle H \rangle^2$
- Points are calculated with each number of bases



N. Shimizu, Y. Utsuno, T. Mizusaki, T. Otsuka, T. Abe, and M. Honma, Phys. Rev. C **82,** 061305(R) (2010)

Based on T. Mizusaki and M. Imada, Phys. Rev. C **65,** 064319 (2002); **67,** 041301(R) (2003)

Parallel calculation

- Calculational bottleneck is integration over 3D rotations to restore the angular momentum
  ⇒ # of total mesh points ～ 50,000
- Calculated parallelly for each mesh point
- Calculated on K computer (AICS), FX10 (U. Tokyo), and T2K Open Supercomputer (U. Tokyo, U. Tsukuba)

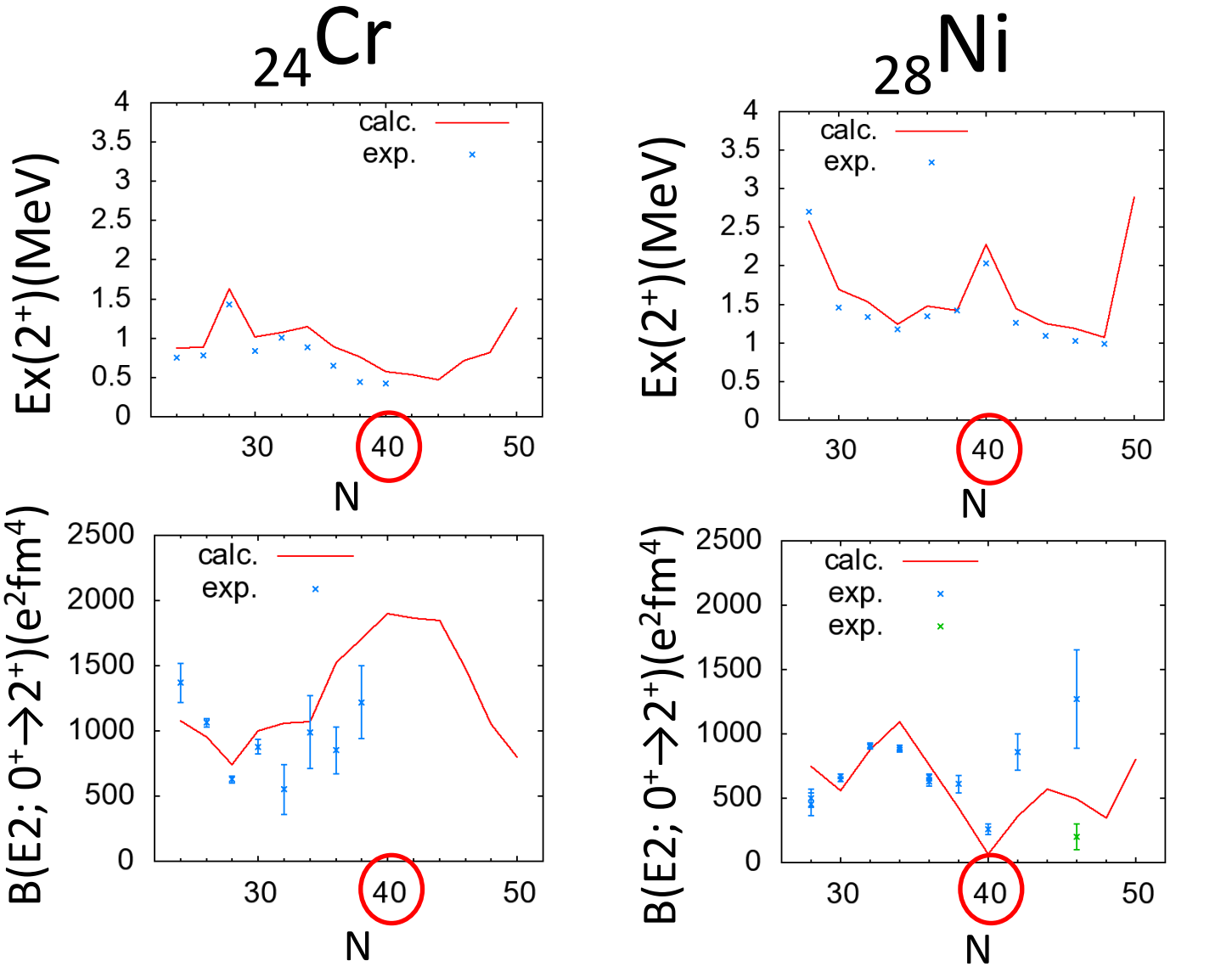
K computer

- 14 hours, 7680 CPU cores for $^{68}Ni\ 8^{+}$ (K computer)

Results of Cr and Ni

2^+ ex. energy

B(E2; $0^+ \rightarrow 2^+$):
reduced transition probability



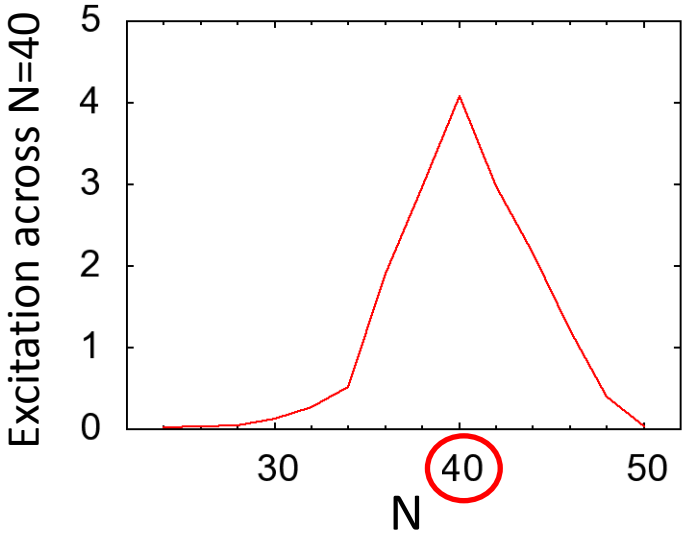
× B. Pritychenko, et al., arXiv:1102.3365v2 (2011)

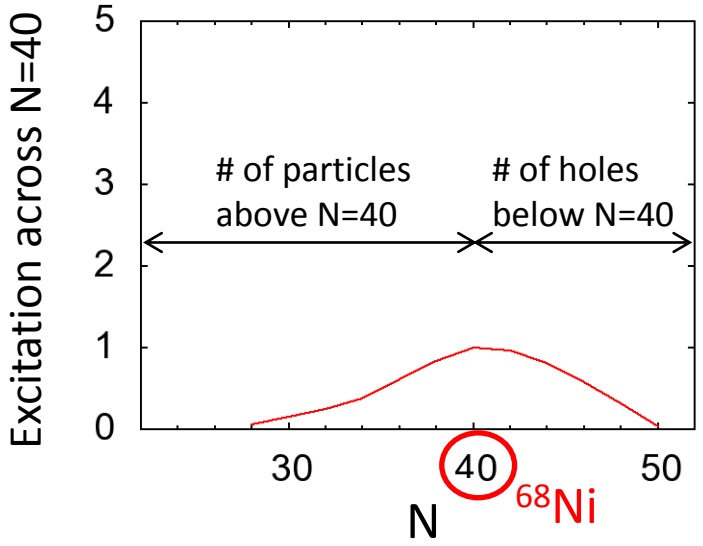
× de Angelis, private communication

Neutron excitation across N=40 gap

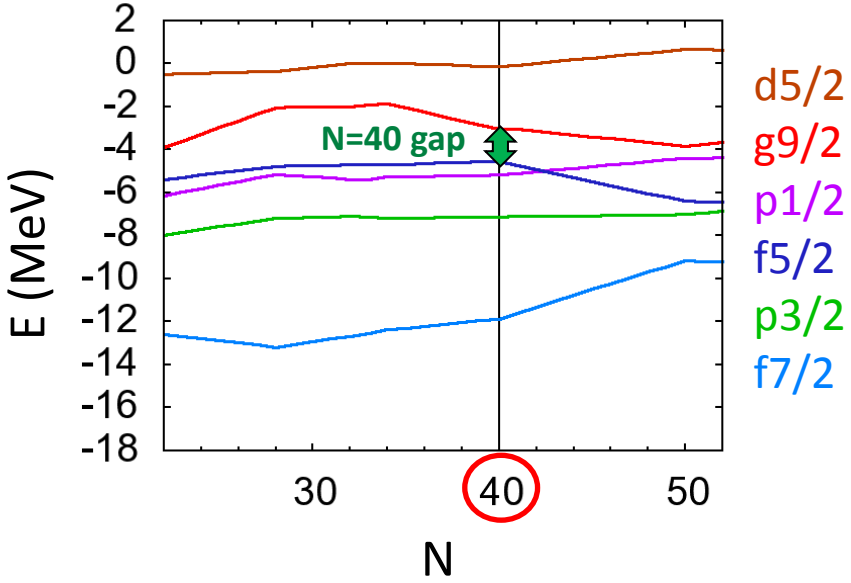
$_{24}$Cr ⟵ Change of N=40 magicity ⟶ $_{28}$Ni

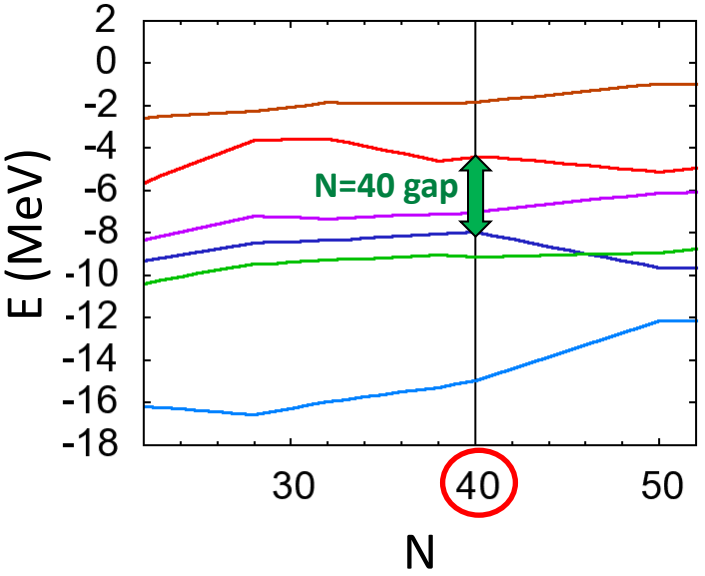
# of neutrons excited across N=40 (0^+_1)





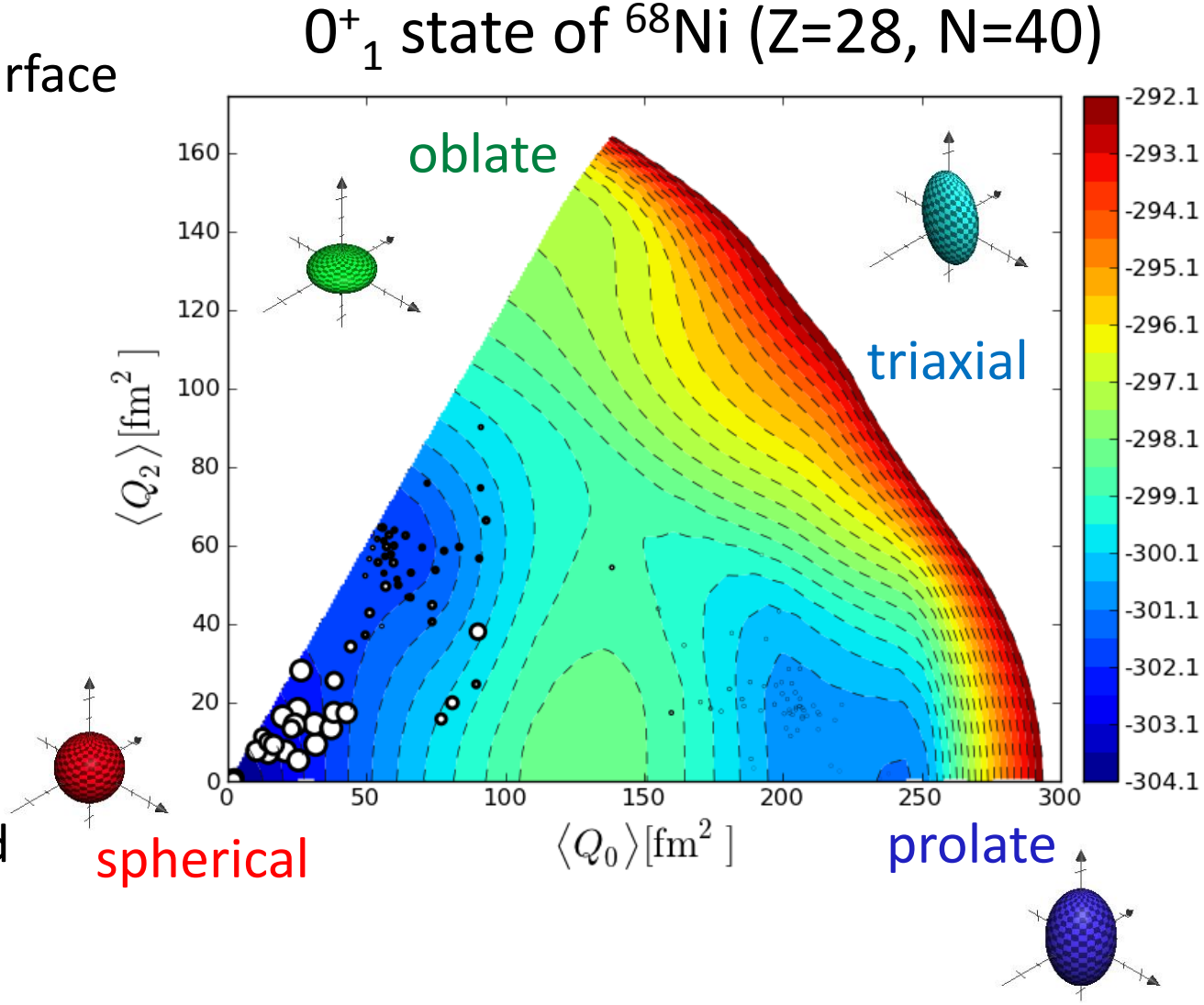
Neutron effective single-particle energy





PES (energy contour plot of various shapes)

- Potential energy surface (PES) is calculated by Constrained HF
- Location of circle: quadrupole deformation of unprojected MCSM basis
- Area of circle: overlap probability between each projected basis and wave function

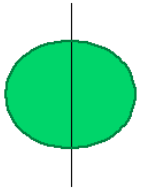


^{68}Ni 0^+ states ⇔ different shapes

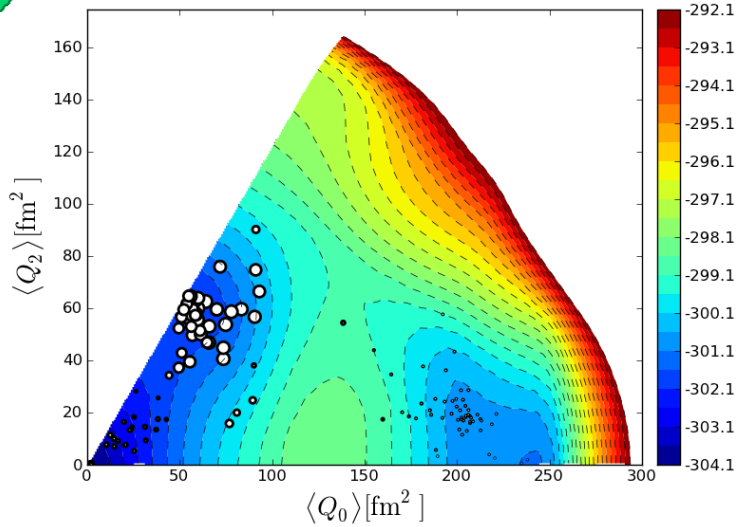
We diagonalize
the quadrupole moment
to get principal axes

β: deformation parameter
β>0: prolate
β=0: spherical
β<0: oblate

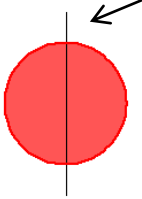
Shape coexistence



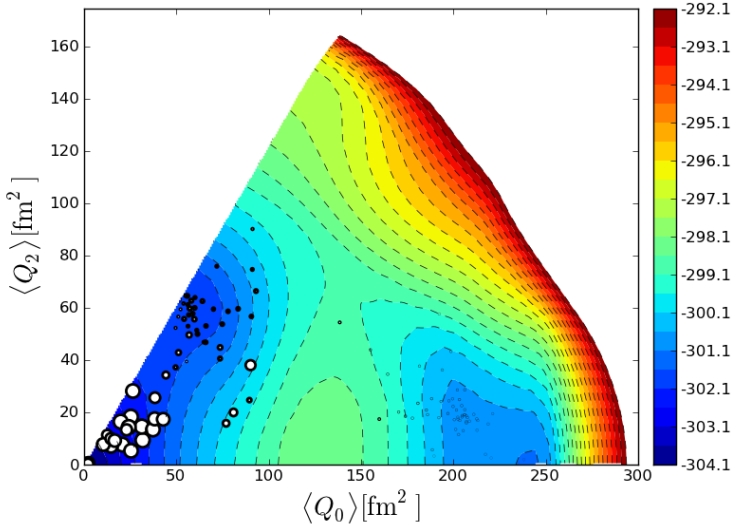
0^+_2 : oblate β ∼ -0.2

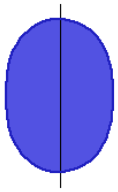


symmetry axis

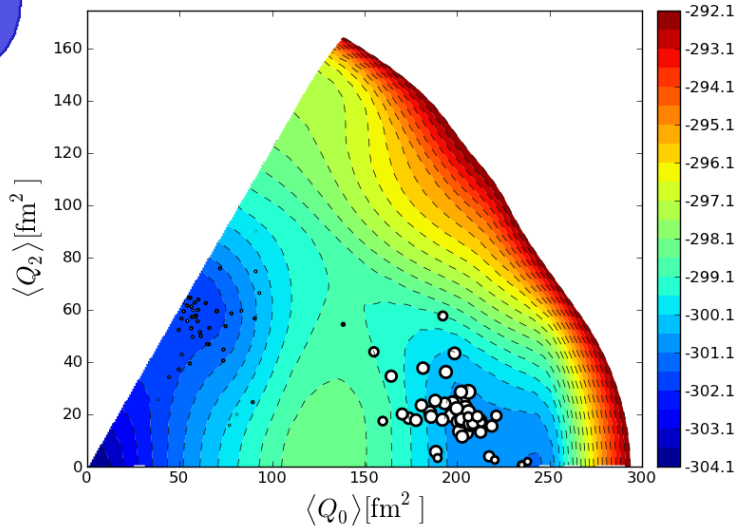


0^+_1 : spherical β ∼ 0

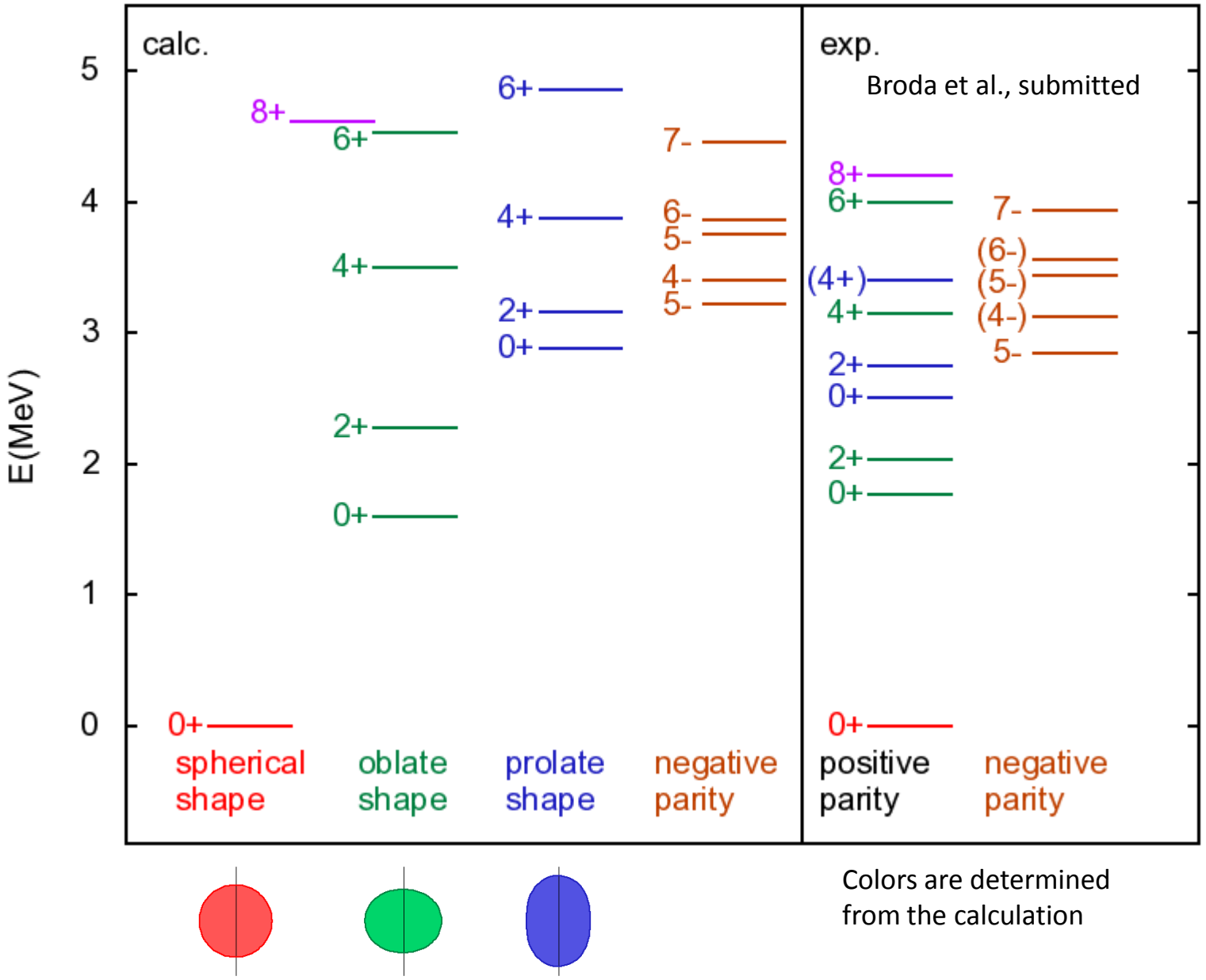




0^+_3 : prolate β ∼ +0.4



Level scheme of ^{68}Ni



Summary

- MCSM calculations for Cr, Ni nuclei in pfg9d5-shell
- Analysis of nuclear shape by using overlap and deformation of MCSM bases

- N=40 magicity changes between Cr and Ni
- Three 0^+ states of ^{68}Ni ⇔ three different shapes within 3 MeV (shape coexistence)
- Calculated excitation energies of ^{68}Ni agree with experiments

↳ Unified description by using the same Hamiltonian due to large-scale calculation