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

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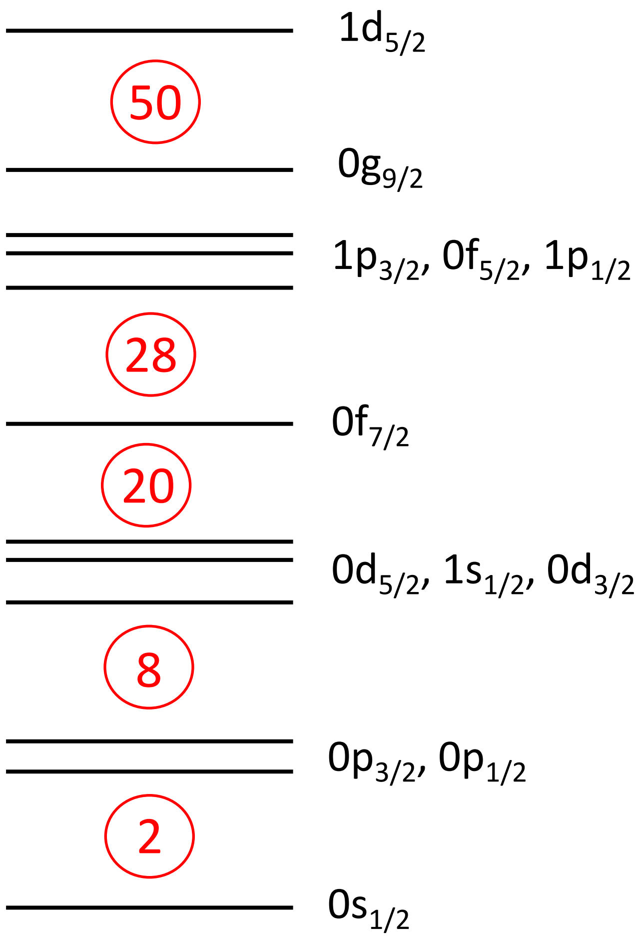
Motivation

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 ($Z \ll N$, $Z \gg N$)

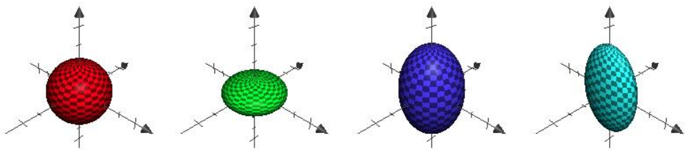
Evolution of shell structure

Size of shell gaps changes

Magicity becomes strong/weak

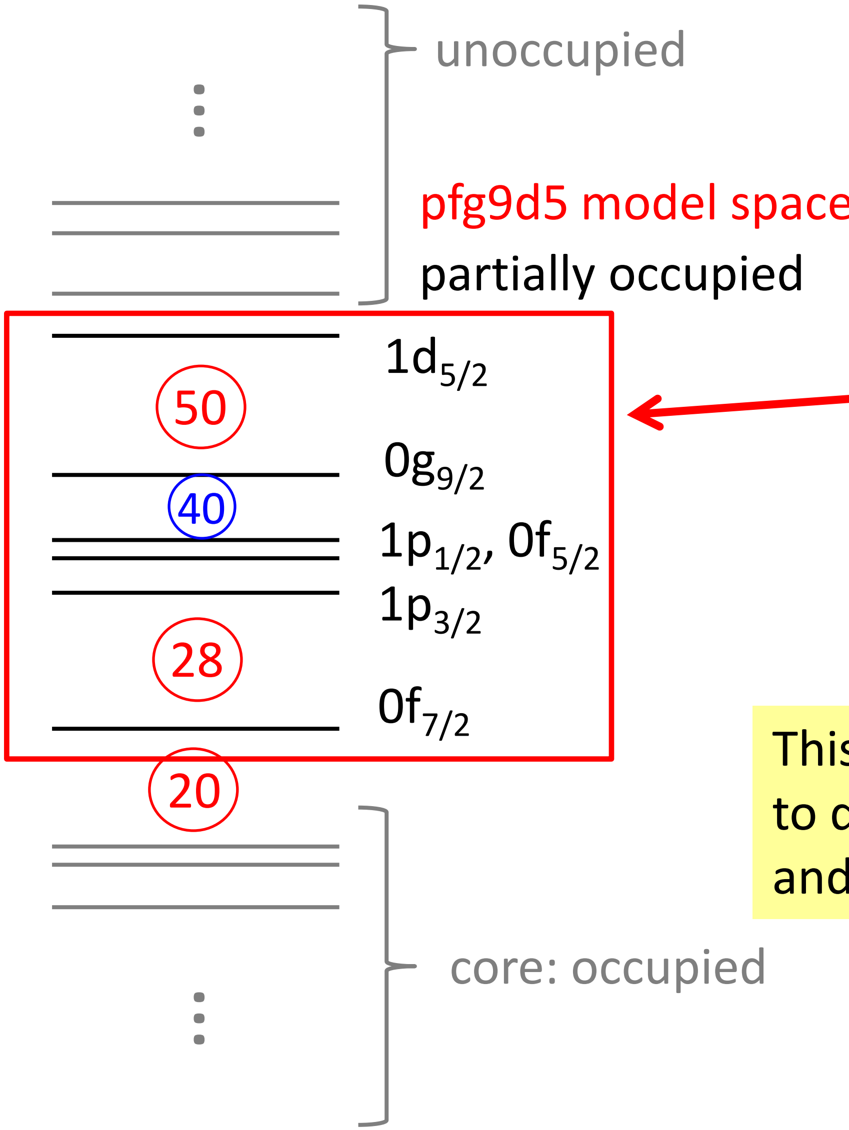
Shape coexistence

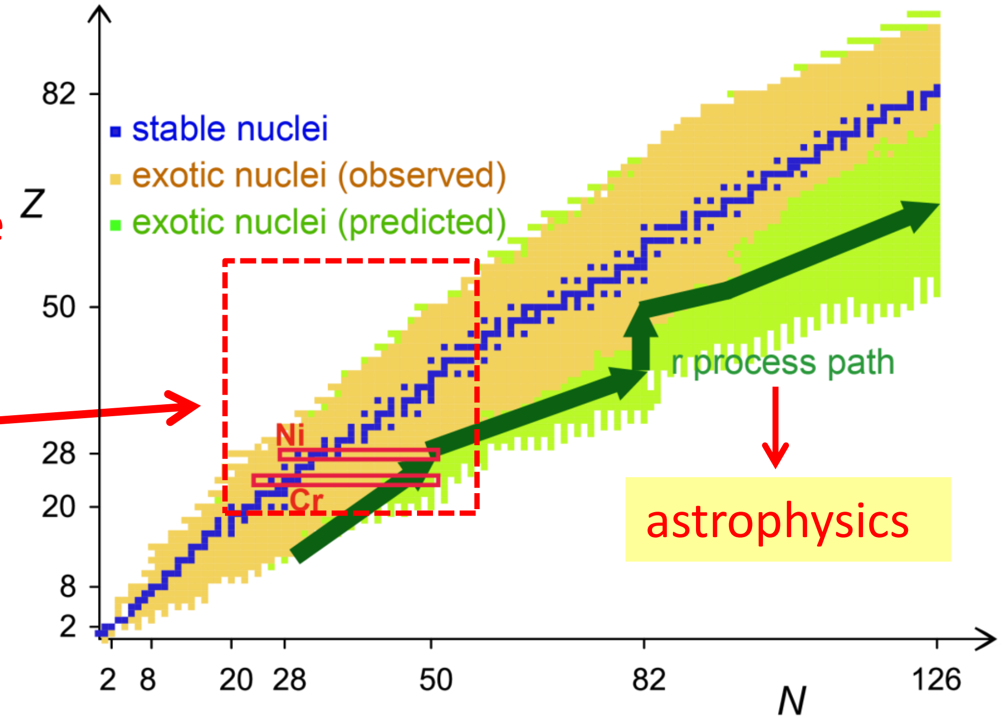
States of different shape coexist



Necessity of large-scale calculations in large model space

Shell model calculation



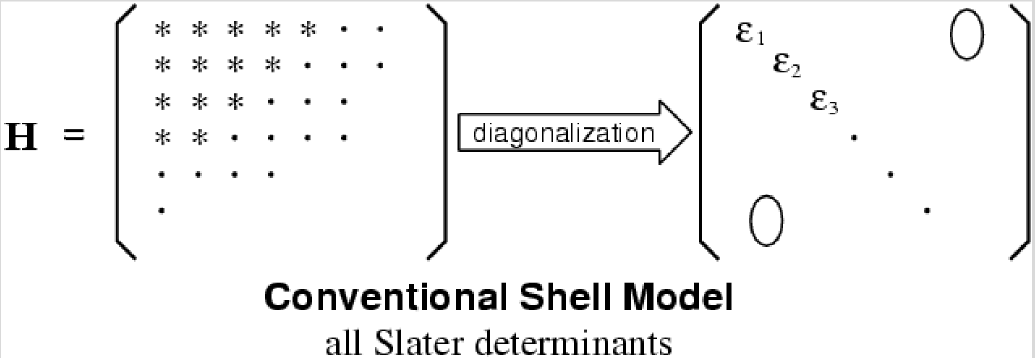


This model space is wide enough
to discuss how magic numbers 28, 50
and semi-magic number 40 are retained/broken

Our effective interaction consists of
microscopic and empirical interactions

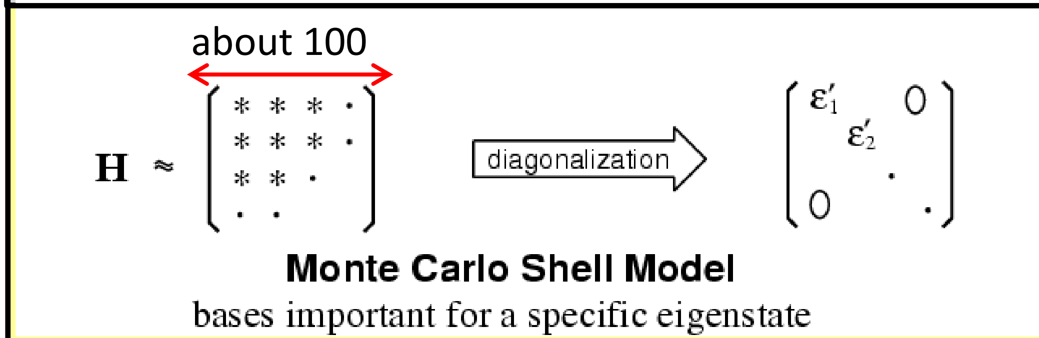
Monte Carlo shell model (MCSM)

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



Direct diagonalization is impossible in large model space

about 100



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

Generated to minimize eigenenergies
using quantum MC
+ variational method

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

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

eigenstate

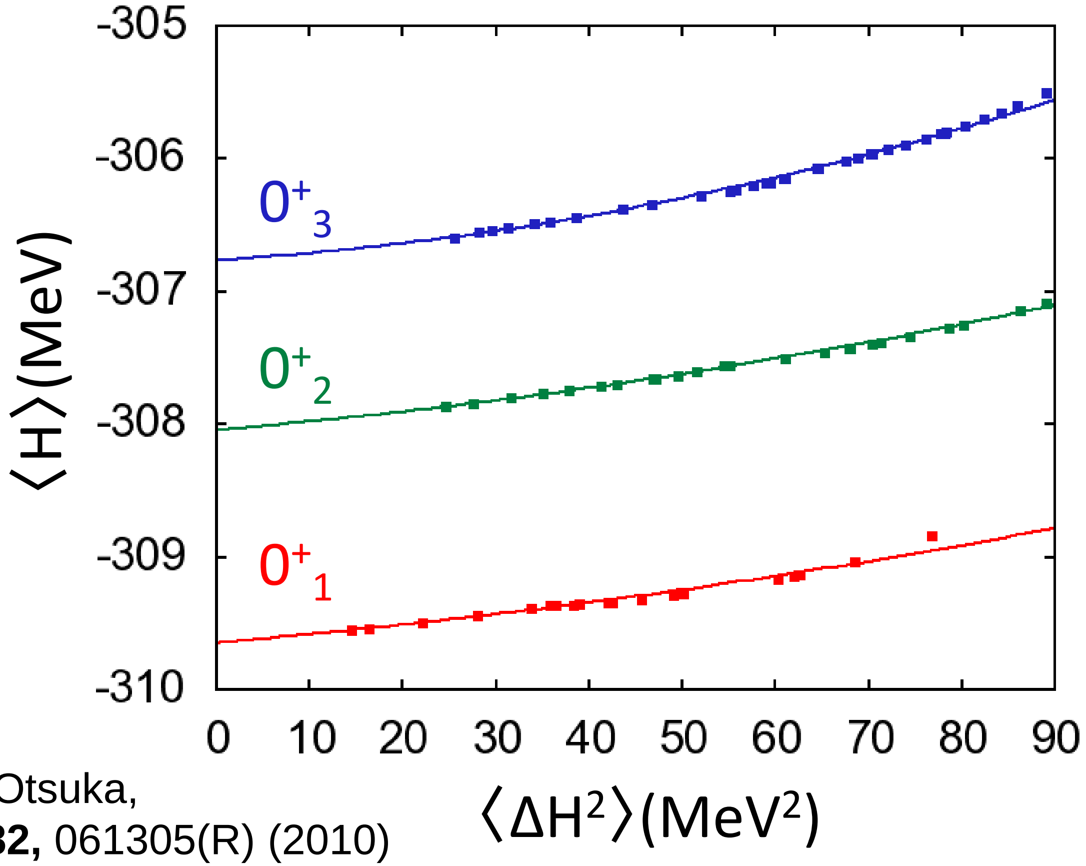
angular-momentum, parity projection

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

Extrapolation of ^{68}Ni 0^+



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
  $\Rightarrow$ # of total mesh points $\sim$ 50,000
- Calculated parallelly for each mesh point
- Calculated on K computer (AICS), FX10 (U. Tokyo), and T2K Open Supercomputer (U. Tokyo, U. Tsukuba)

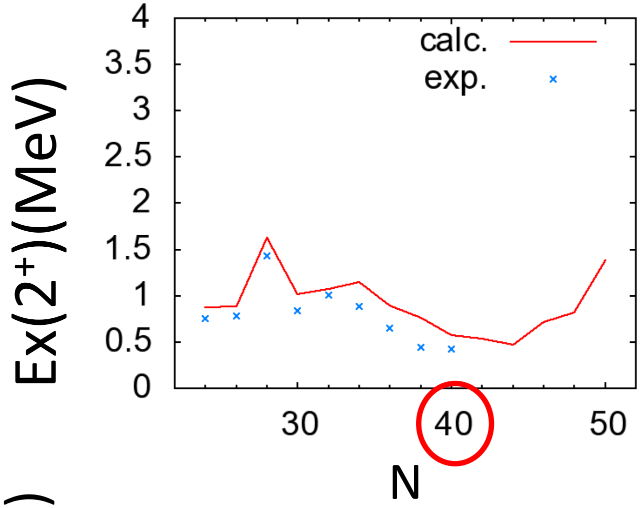
K computer

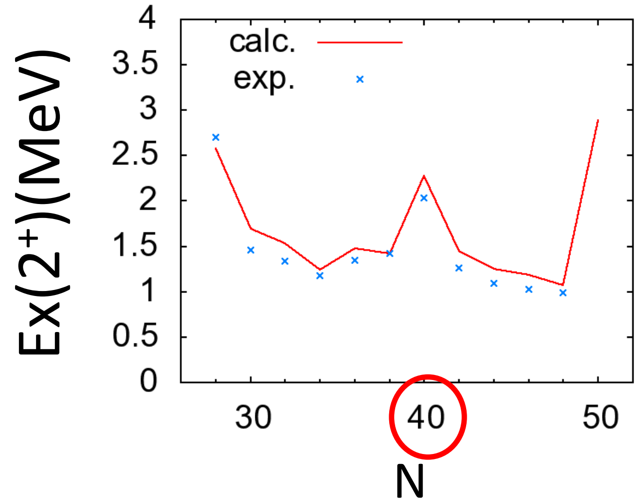
- 14 hours, 7680 CPU cores for ^{68}Ni 8^+ (K computer)

Results of Cr and Ni

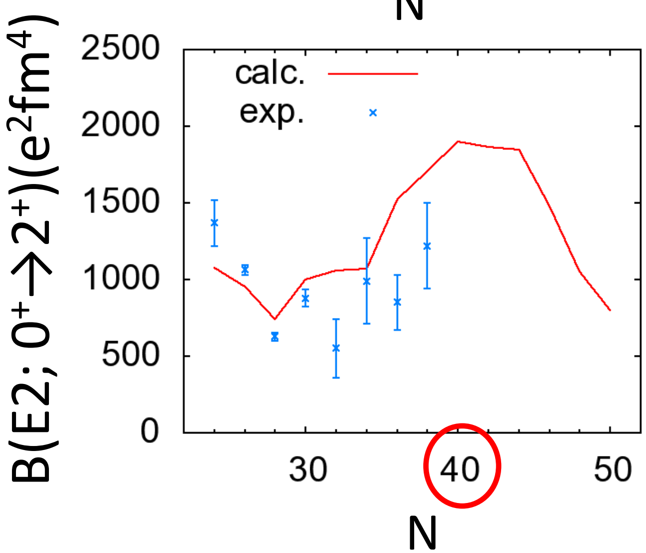
$_{24}$Cr　　　　　　$_{28}$Ni

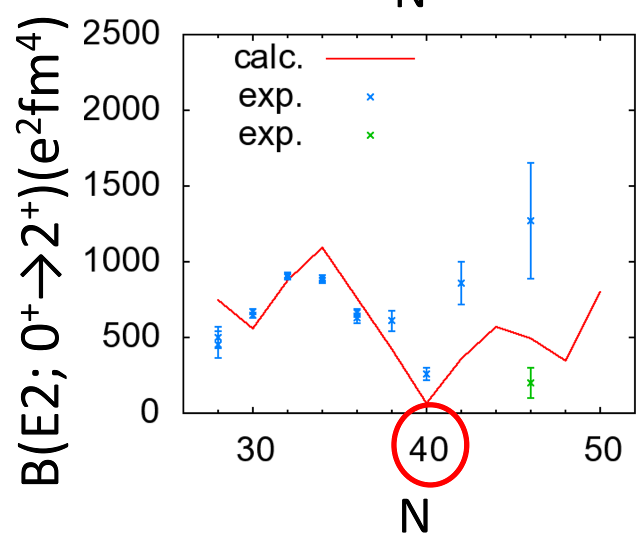
2^+ ex. energy





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

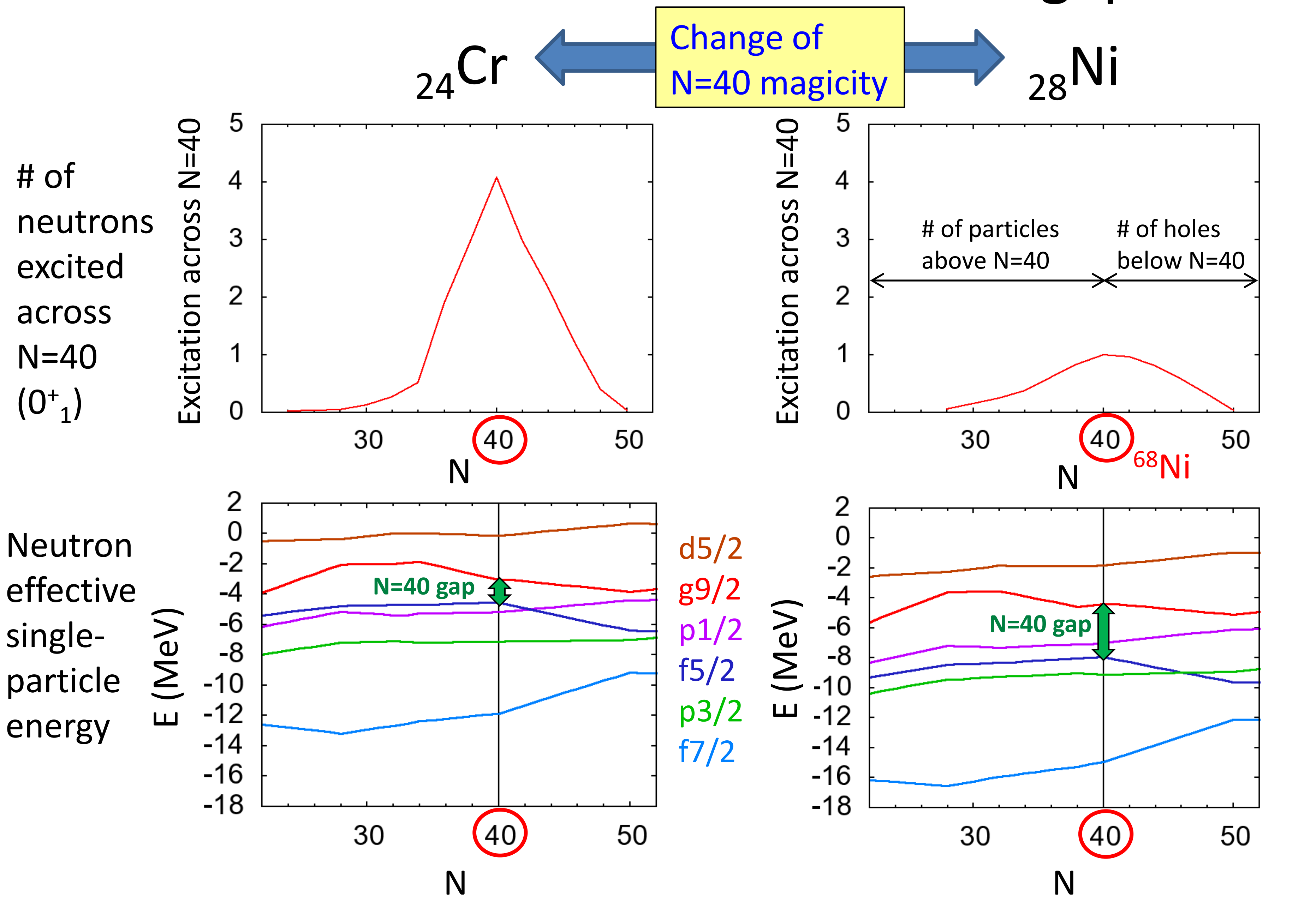




× B. Pritychenko, et al., arXiv:1102.3365v2 (2011)

× de Angelis, private communication

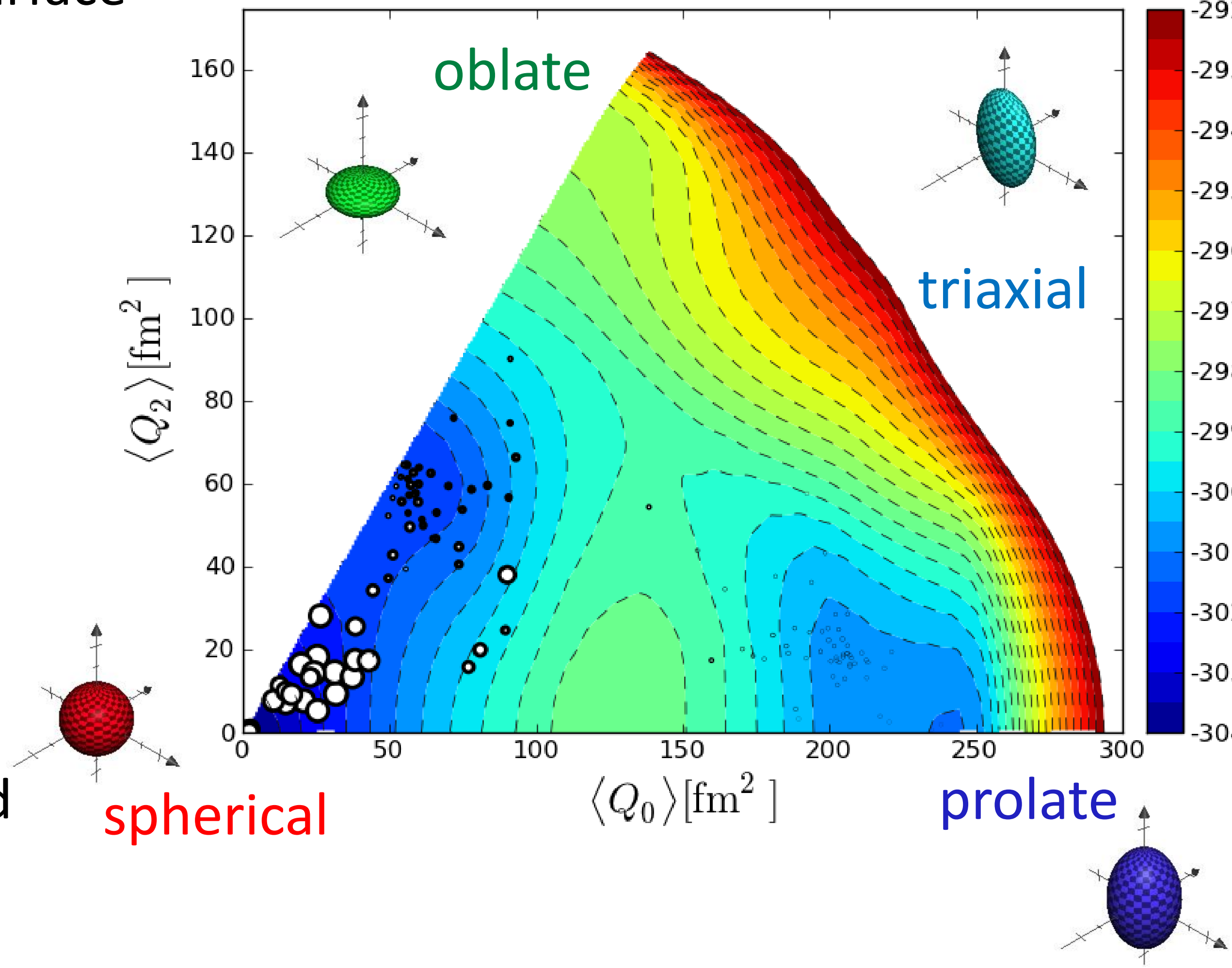
Neutron excitation across N=40 gap



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

0^+_1 state of ^{68}Ni (Z=28, N=40)

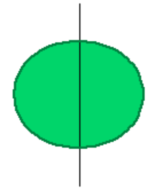


^{68}Ni 0^+ states ⇔ different shapes

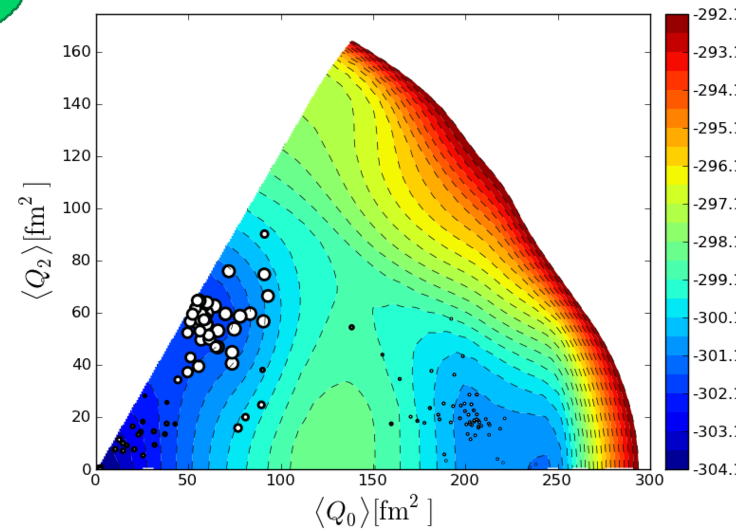
We diagonalize
the quadrupole moment
to get principal axes

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

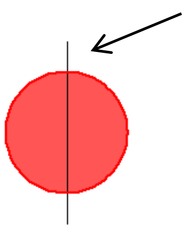
Shape coexistence



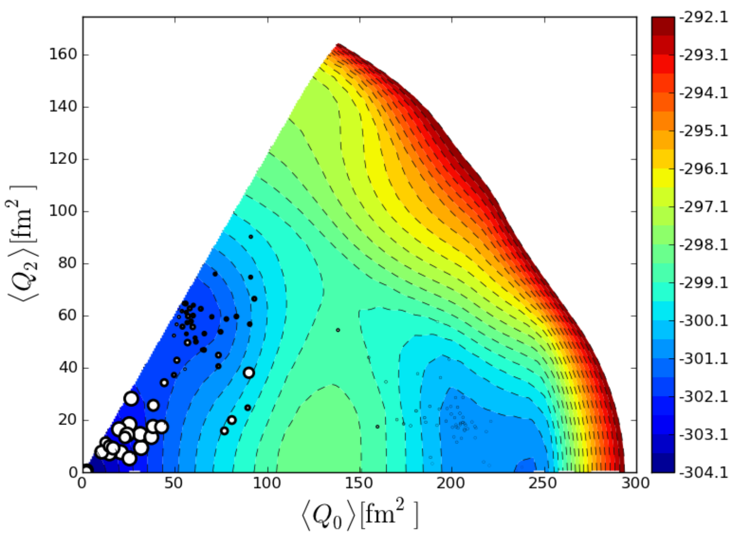
0^+_2 : oblate β ~ -0.2

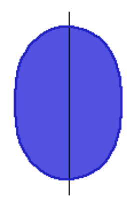


symmetry axis

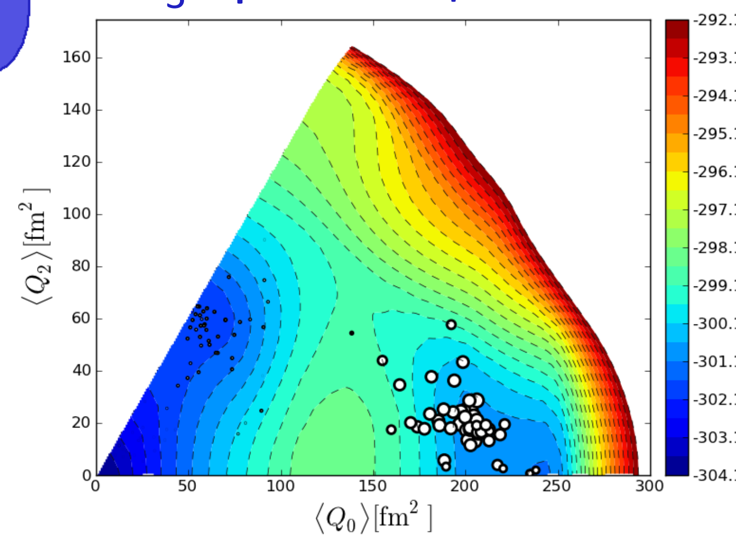


0^+_1 : spherical β ~ 0

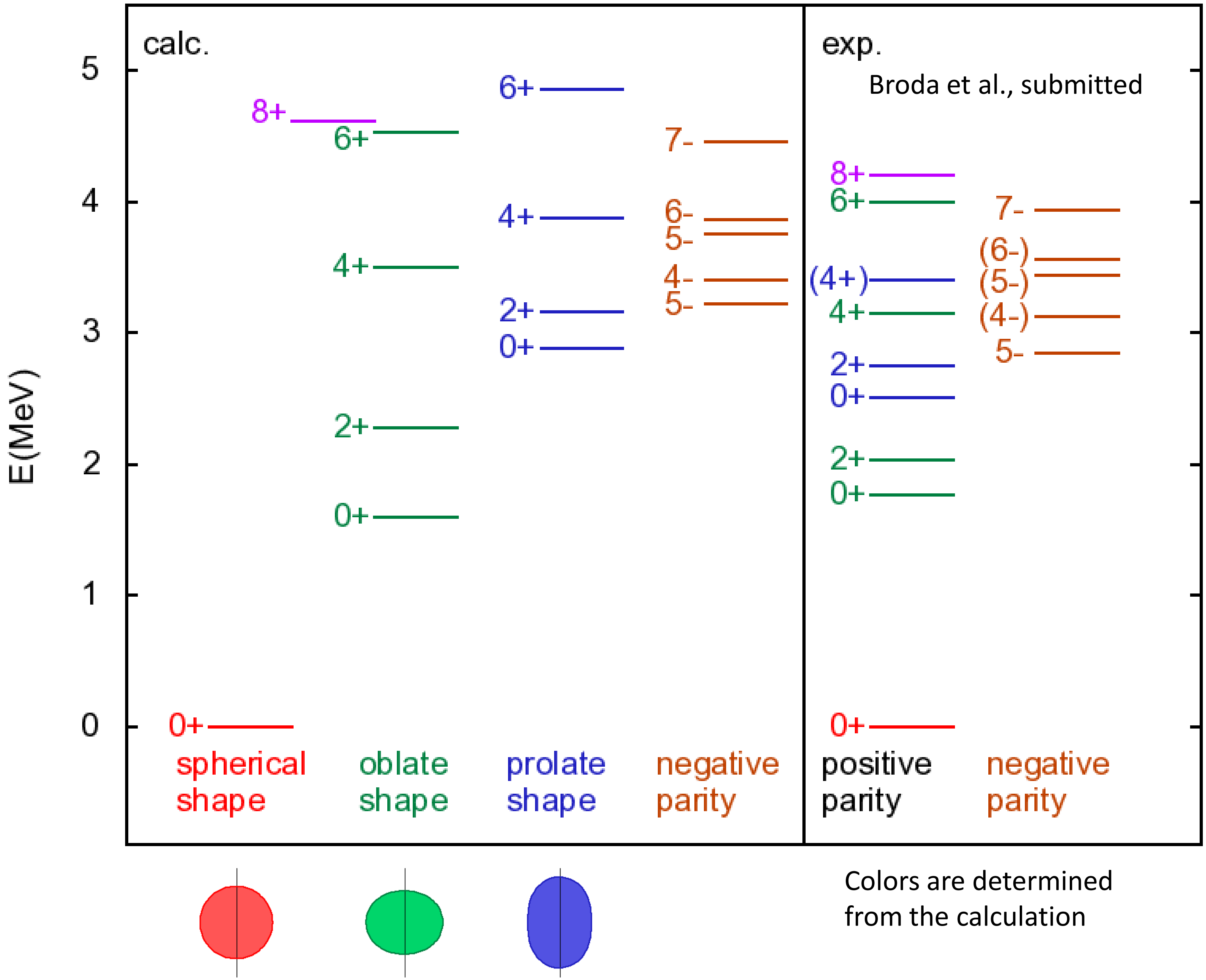




0^+_3 : prolate β ~ +0.4



Level scheme of ^{68}Ni



Colors are determined from the calculation

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