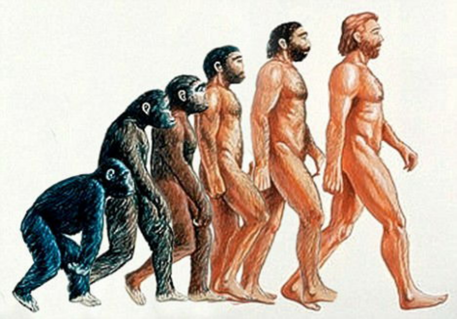
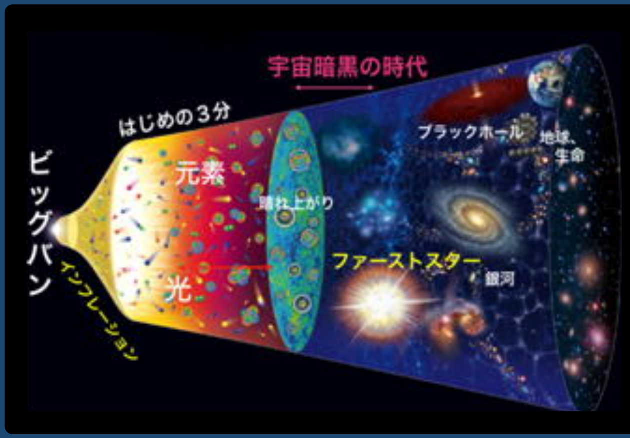


RIKEN 2koma plus seminar
Wako
July 1-2, 2015

Structure evolutions in exotic nuclei and nuclear forces - Day 2 -

Takaharu Otsuka
University of Tokyo / MSU / KU Leuven



東京大学
THE UNIVERSITY OF TOKYO

CENTER *for* NUCLEAR STUDY
THE UNIVERSITY *of* TOKYO

NSCL

KU LEUVEN

Addenda to Day 1

renormalization of tensor force
exotic silicon isotopes

Response to the renormalization of interactions

Renormalization processes
- short-range correlations
- in-medium corrections

bare interaction for free space

$$V = V_c + V_{LS} + V_T$$

effective interaction for a model space of low-momenta

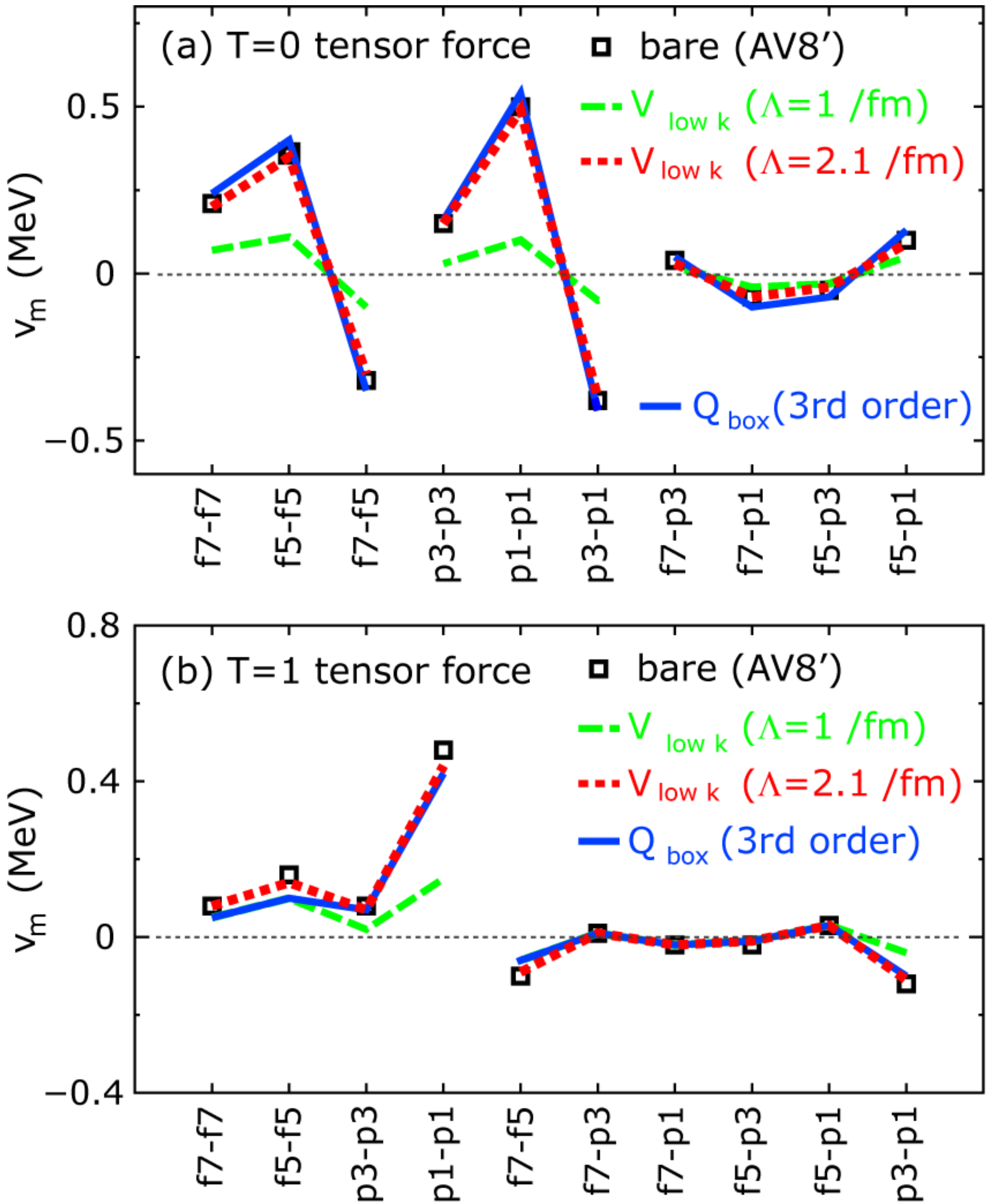
$$V' = V'_c + V'_{LS} + V'_T + V_{NNN} + \dots$$

In general, V'_x differs from V_x.

If $V_x = V'_x$, Renormalization Persistency holds.

- only good approx. at best, but it makes sense
- new approach to nuclear forces

Treatment of tensor force by $V_{low\,k}$ and Q box (3^{rd} order)



Monopole component of tensor interactions in *pf* shell

□ Bare (AV8′)

short-range correlation by $V_{low\,k}$

in-medium correction with intermediate states (> 10 hw, 3^{rd} order)

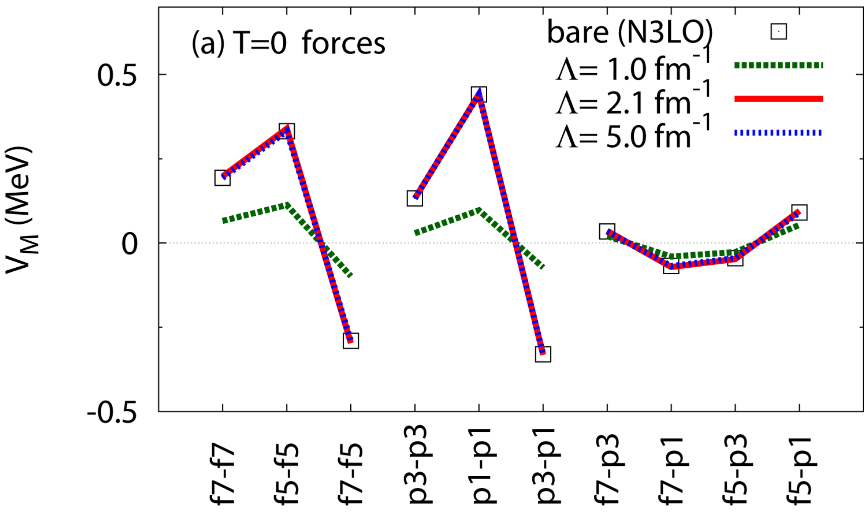
$V_{low\,k}$: Bogner, Kuo, Schwenk

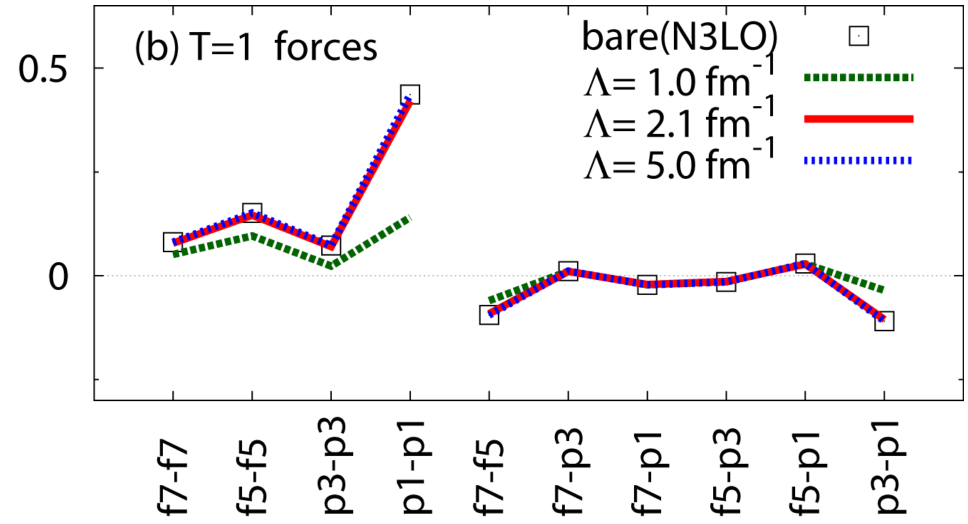
only for comparison

O, Suzuki, et al.
PRL 104, 012501 (2010)

N3LO (EFT of QCD) for pf-shell

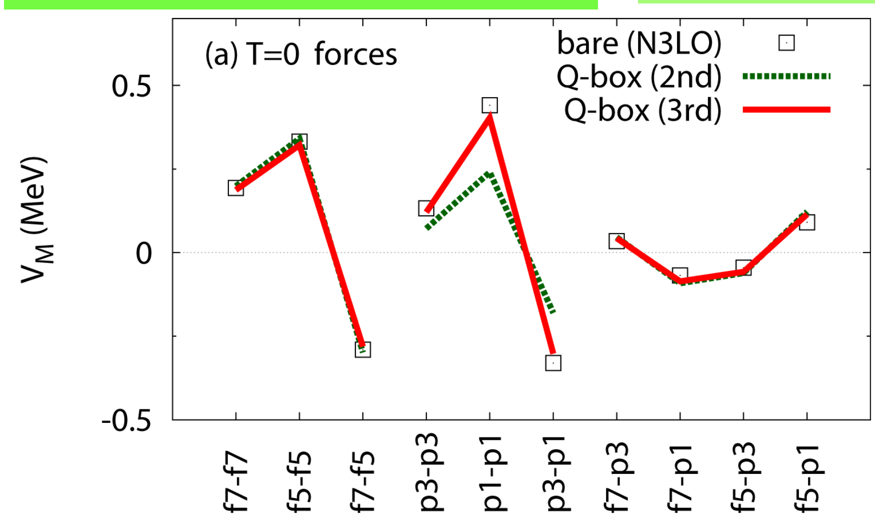
short-range correl.

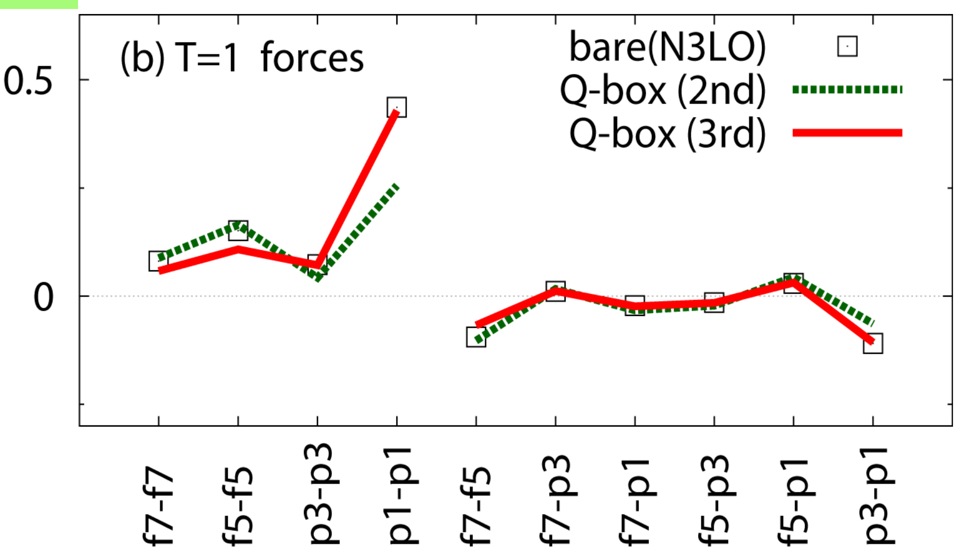




in-medium correc.

$\Lambda = 2.1\ \mathrm{fm}^{-1}$





PHYSICAL REVIEW C 84, 044322 (2011)

Renormalization persistency of the tensor force in nuclei

N.Tsunoda, T.O., K.Tsukiyama, M.H.-Jensen

Two steps of renormalization from full space to low-momentum space relevant to many-nucleon systems

1. Treatment of short range correlations

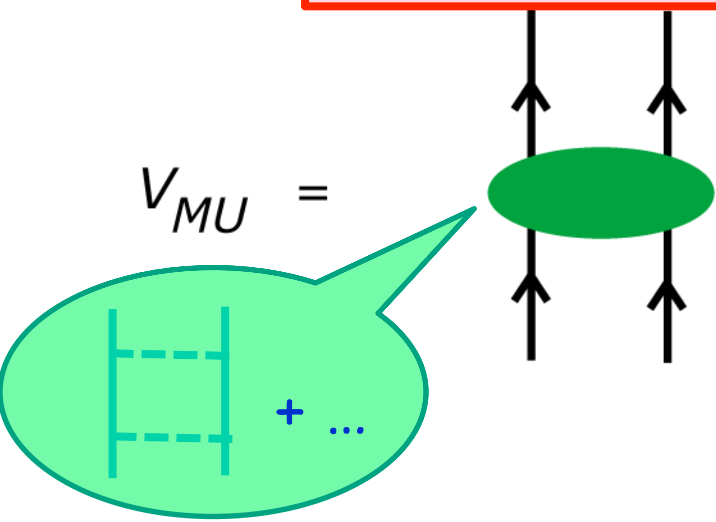
2. Inclusion of in-medium effects

Two major components in nuclear force

(a) central force :

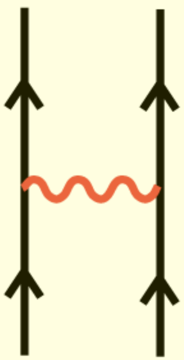
(strongly renormalized)

V_{MU} =



+

(b) tensor force :
π + ρ meson exchange



monopole component of tensor force **in nuclear medium**

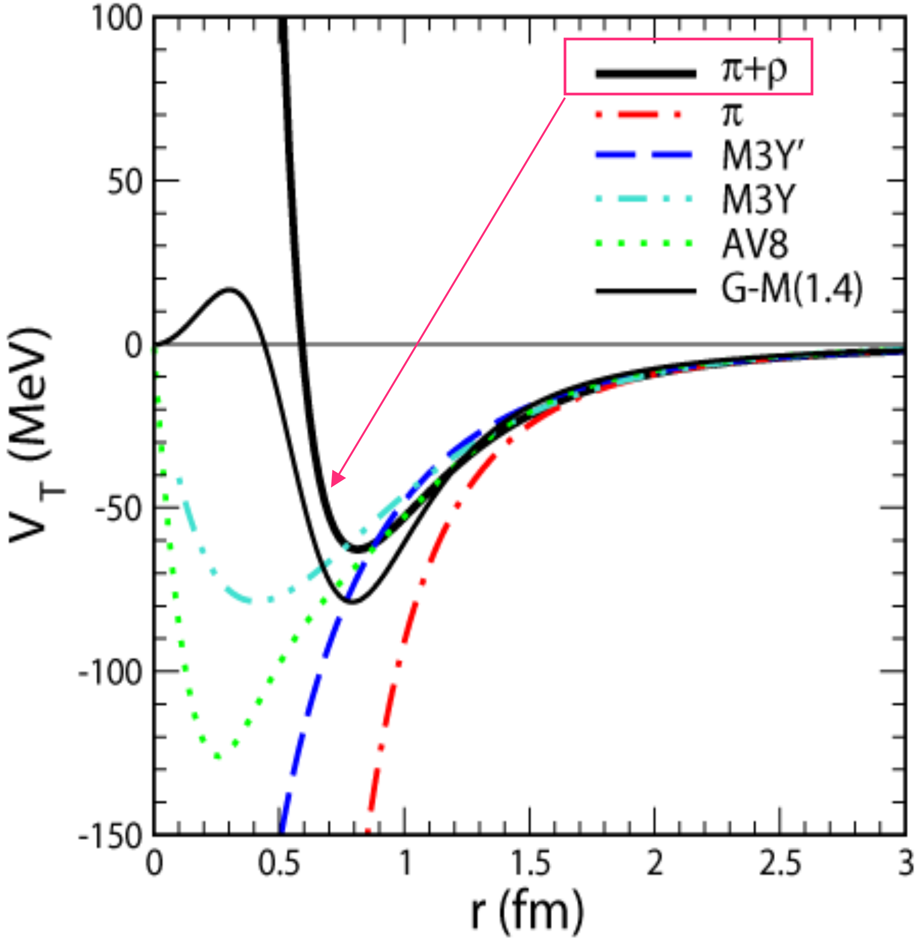
Renormalization Persistency

almost equal (no renormalization)

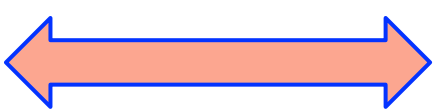
monopole component of tensor force **in free space**

N.Tsunoda, T.O., K.Tsukiyama, M.H.-Jensen, PRC84,044322 (2011)

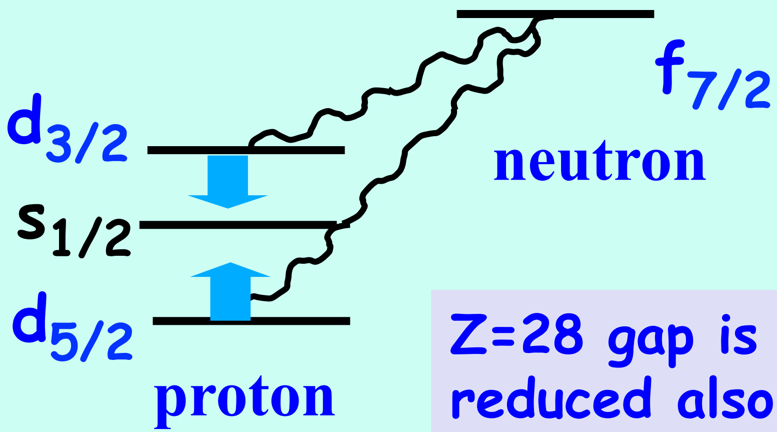
Tensor potentials



What is the *relevant part* of the tensor force to the present issue.

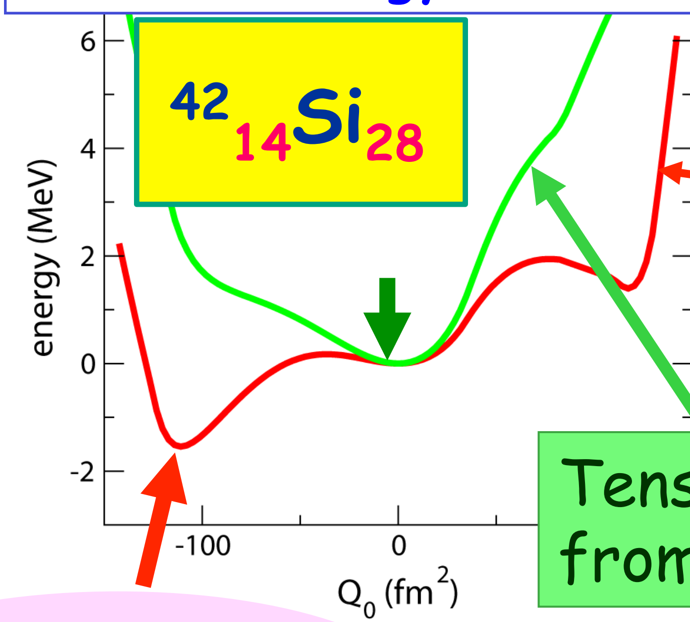


medium-long range



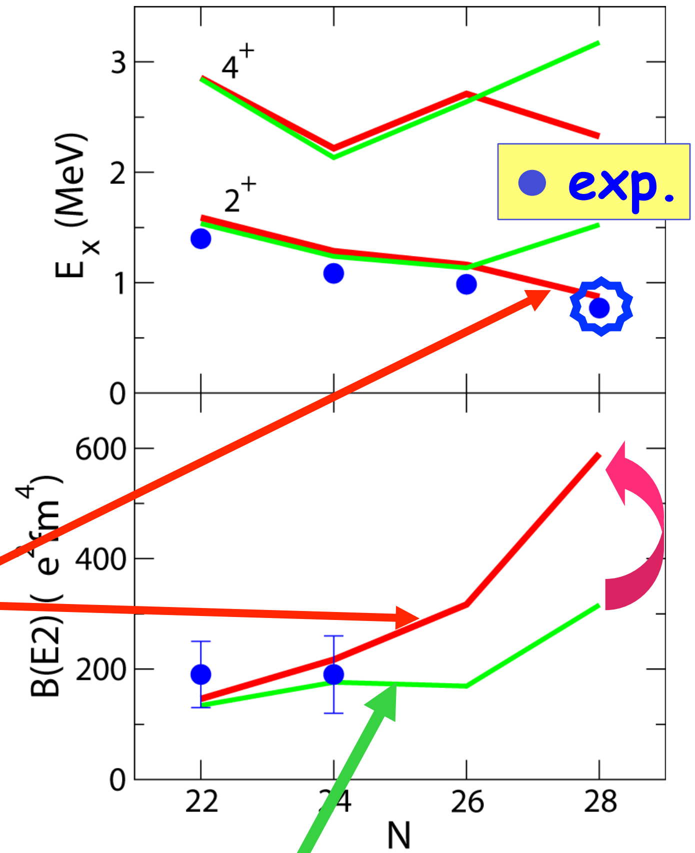
Z=28 gap is reduced also

Potential Energy Surface



$^{42}_{14}Si_{28}$

Si isotopes
SM calc. by Utsuno et al.



^{42}Si

full

Tensor force removed from cross-shell interaction

Strong oblate Deformation ?

Other calculations show a variety of shapes.

Otsuka, Suzuki and Utsuno, Nucl. Phys. A805, 127c (2008)

^{42}Si: *B. Bastin, S. Grévy et al., PRL 99 (2007) 022503*

Tensor force effects in exotic Si isotopes

PRL **109**, 182501 (2012) PHYSICAL REVIEW LETTERS

Well Developed Deformation in ^{42}Si

S. Takeuchi,[1,*] M. Matsushita,[1,2,†] N. Aoi,[1,‡] P. Doornenbal,[1] K. Li,[1,3] T. Motobayashi,[1] H. Scheit,
H. Wang,[1,3] H. Baba,[1] D. Bazin,[4] L. Càceres,[5] H. Crawford,[6] P. Fallon,[6] R. Gernhäuser,[7] J. Gibeli
C. Hinke,[7] C. R. Hoffman,[10] R. Hughes,[11] E. Ideguchi,[9,‡] D. Jenkins,[12] N. Kobayashi,[13] Y. Kon
T. Le Bleis,[14,15,¶] J. Lee,[1] G. Lee,[13] A. Matta,[16] S. Michimasa,[9] T. Nakamura,[13] S. Ota,[9] M. Petri,[6,§]
S. Shimoura,[9] K. Steiger,[7] K. Takahashi,[13] M. Takechi,[1,**] Y. Togano,[1,**] R. Winkler,[4,††]
[1]*RIKEN Nishina Center, Wako, Saitama 351-0198, Japan*

PRL **99**, 022503 (2007) PHYSICAL REVIEW LETTERS

Collapse of the $N = 28$ Shell Closure in ^{42}Si

B. Bastin,[2] S. Grévy,[1,*] D. Sohler,[3] O. Sorlin,[1,4] Zs. Dombrádi,[3] N. L. Achouri,[2] J. C. Angélique,
D. Baiborodin,[5] R. Borcea,[6] C. Bourgeois,[4] A. Buta,[6] A. Bürger,[7,8] R. Chapman,[9] J. C. Dalouzy,[1] Z. Dlou
Z. Elekes,[3] S. Franchoo,[4] S. Iacob,[6] B. Laurent,[2] M. Lazar,[6] X. Liang,[9] E. Liénard,[2] J. Mrazek,[5] L. Nalpas,
N. A. Orr,[2] Y. Penionzhkevich,[10] Zs. Podolyák,[11] F. Pougheon,[4] P. Roussel-Chomaz,[1]
M. G. Saint-Laurent,[1] M. Stanoiu,[4,6] and I. Stefan[1]
F. Nowacki[12] and A. Poves[13]

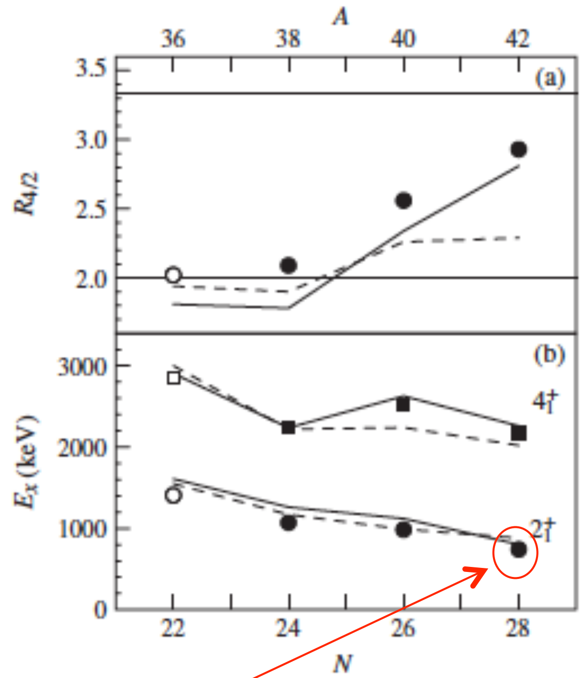


FIG. 3. (a) Ratio between the energies of the 2_1^+ and 4_1^+ states ($R_{4/2}$) for Si isotopes. The horizontal lines at 2.0 and 3.3 indicate the vibrational and rotational limits, respectively. (b) Excitation energies for 2_1^+ and 4_1^+ states, which are indicated by circles and squares, respectively. Filled symbols are results of the present study, and solid and dashed lines represent predictions of the SM with SDPF-MU [17] and SM with SDPF-U-MIX [33], respectively (see text for details). The 2^+ energies of the $N = 24$, 26, 28 Si isotopes have been measured in previous works [12,14,16].

The energies of the excited states in very neutron-rich ^{42}Si and ^{41,43}P have been measured using in-beam γ-ray spectroscopy from the fragmentation of secondary beams of ^{42,44}S at 39A MeV. The low 2^+ energy of ^{42}Si, 770(19) keV, together with the level schemes of ^{41,43}P, provides evidence for the disappearance of the $Z = 14$ and $N = 28$ spherical shell closures, which is ascribed mainly to the action of proton-neutron tensor forces. New shell model calculations indicate that ^{42}Si is best described as a well-deformed oblate rotor.

Tensor-force driven Jahn-Teller effect -> shape evolution

C 86, 051301(R) (2012).

PHYSICAL REVIEW C **86**, 051301(R) (2012)

Utsuno, TO, Brown, Honma, Mizusaki, Shimizu

RIBF data close to

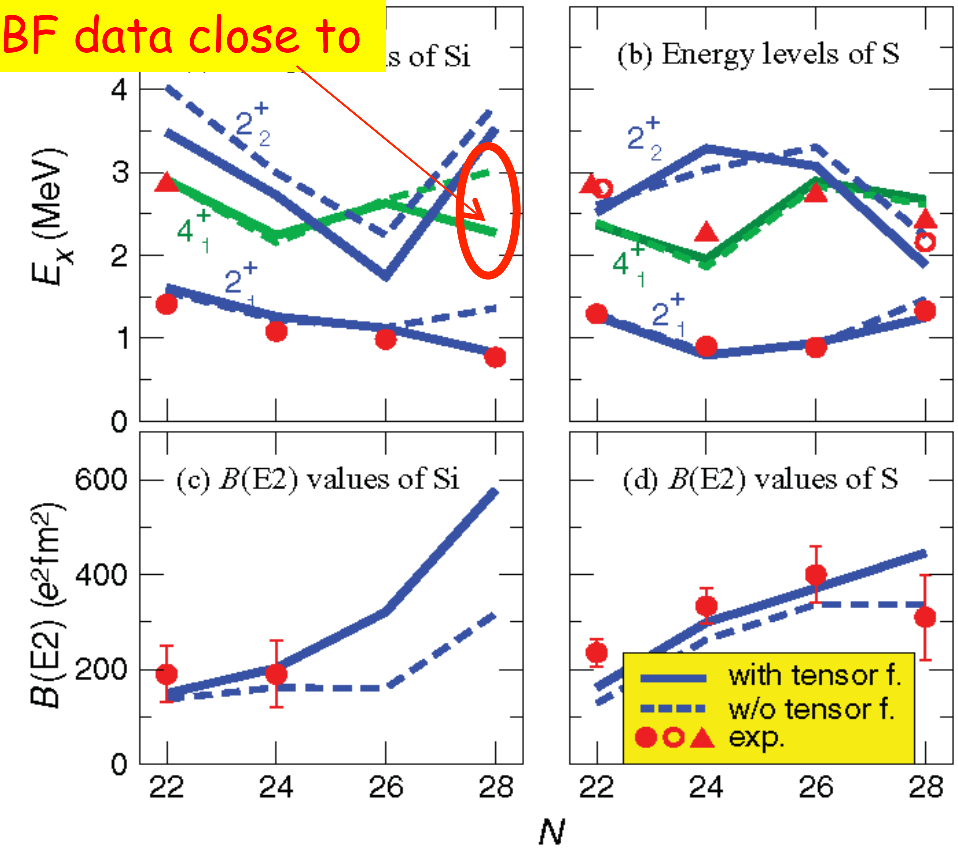
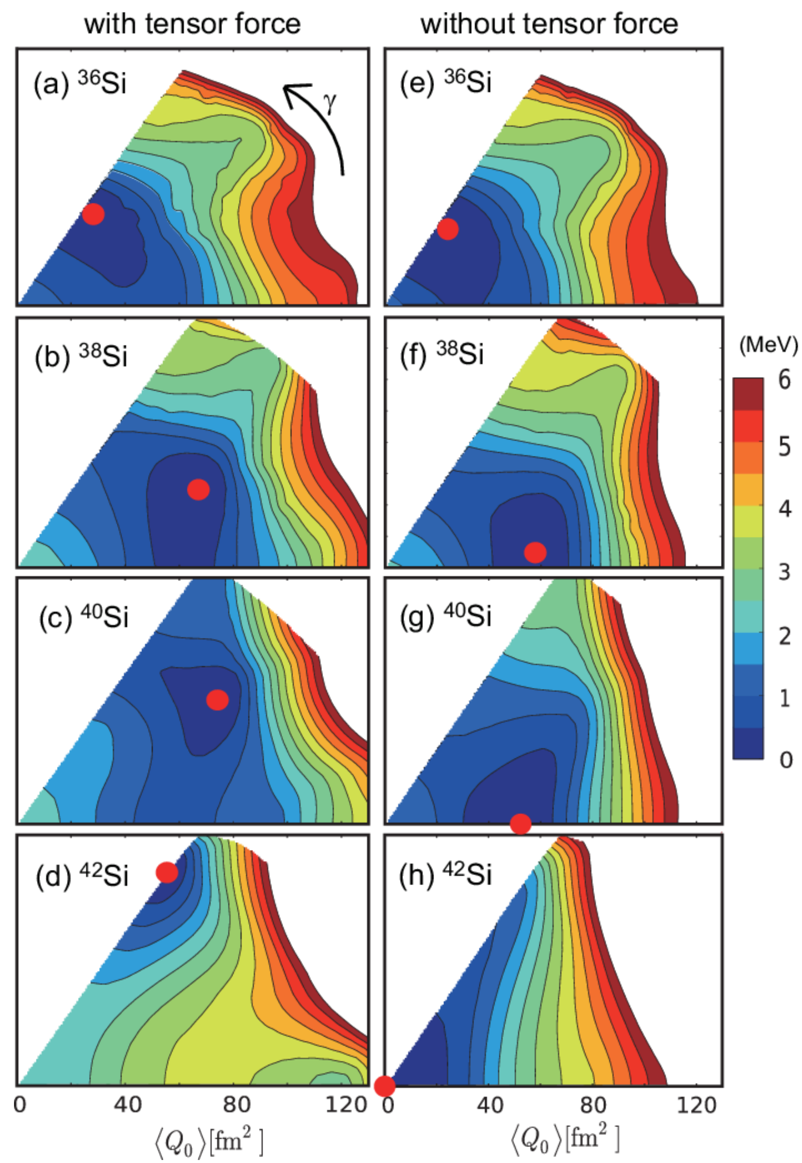
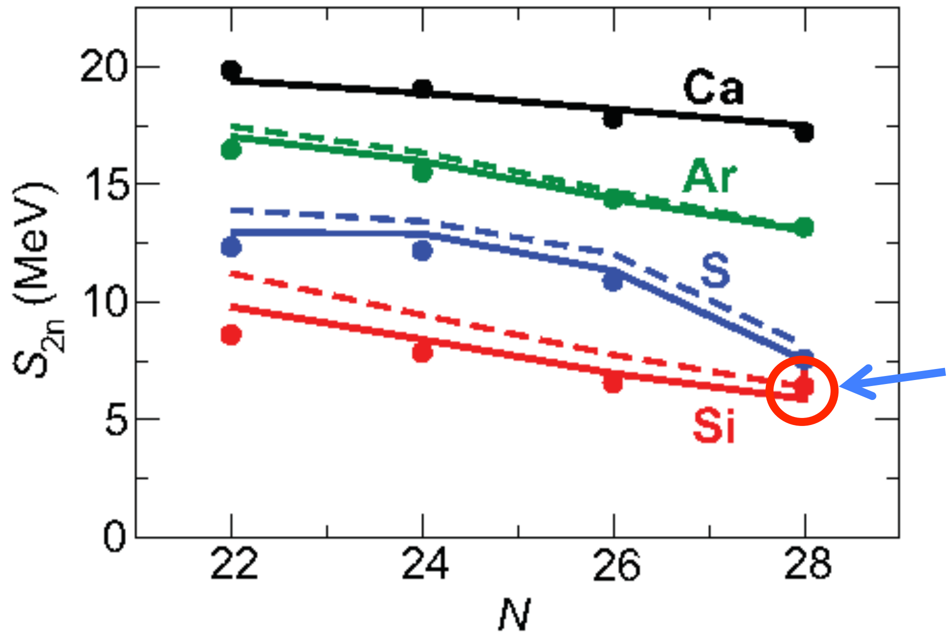


FIG. 3. (Color online) (a) and (b) $2^+_{1,2}$ (blue lines and red circles) and 4^+_1 (green lines and red triangles) energy levels and (c) and (d) $B(E2; 0^+_1 \to 2^+_1)$ values of Si and S isotopes for $N = 22$–28. Symbols are experimental data [13–19]. Solid (dashed) lines are calculations with (without) the cross-shell tensor force.



Tensor force effects
on binding energy (two-neutron separation energy)



Binding energy does not show tensor-force effect

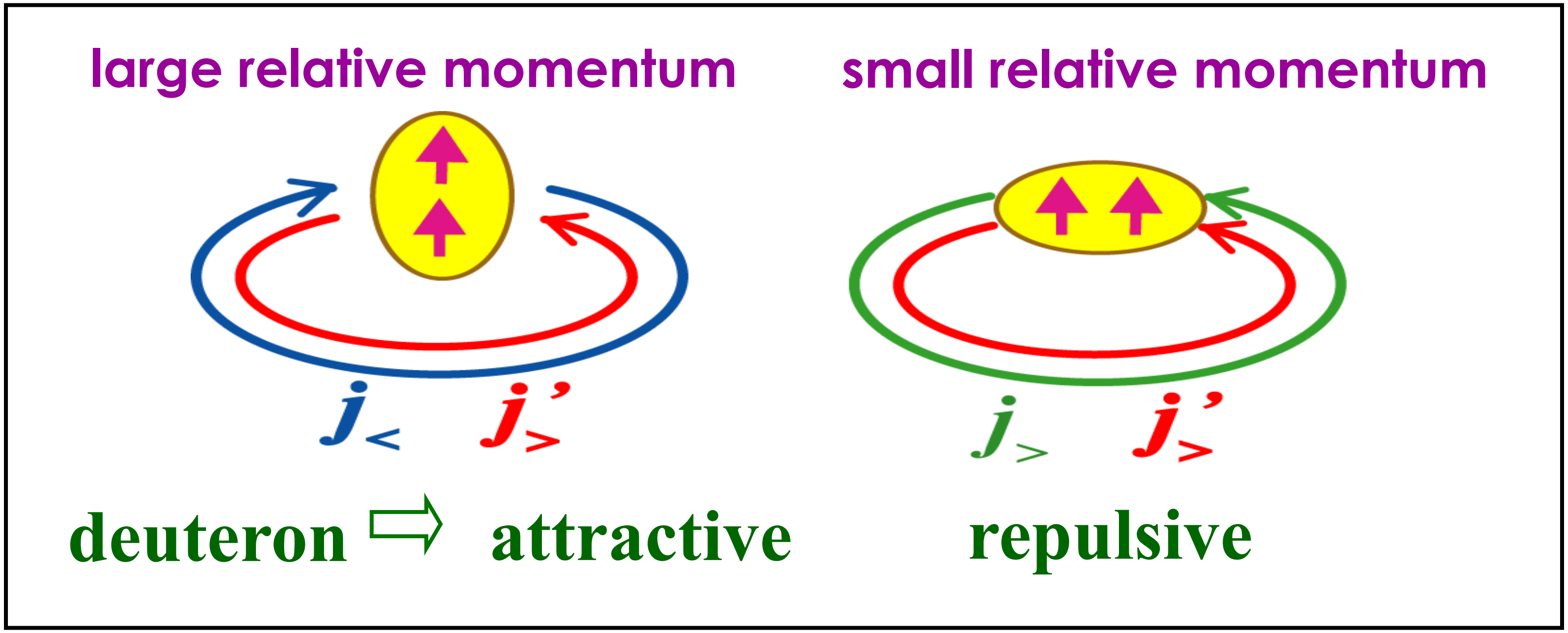
FIG. 6. (Color online) Two-neutron separation energies of Si and S isotopes from $N = 22$ to 28. Solid (dashed) lines are calculations with (without) the cross-shell tensor force. Points are experimental data [40,41].

Stancu, Brink and Flocard, Phys. Lett. 68B, 108 (1977)

Zero-range spin-momentum tensor coupling term

$$v_T = \tfrac{1}{2}T\{[(\sigma_1\cdot k')(\sigma_2\cdot k') - \tfrac{1}{3}(\sigma_1\cdot\sigma_2)k'^2]\delta(r_1 - r_2)$$
$$+\delta(r_1 - r_2)[(\sigma_1\cdot k)(\sigma_2\cdot k) - \tfrac{1}{3}(\sigma_1\cdot\sigma_2)k^2]\}$$
$$+U\{(\sigma_1\cdot k')\delta(r_1 - r_2)(\sigma_1\cdot k)$$
$$-\tfrac{1}{3}(\sigma_1\cdot\sigma_2)[k'\cdot\delta(r_1 - r_2)k]\}, \qquad (1)$$

This is not be a good approximation to the tensor force itself, but may simulate the monopole effect of the tensor shown below, picking up differences in relative momenta.

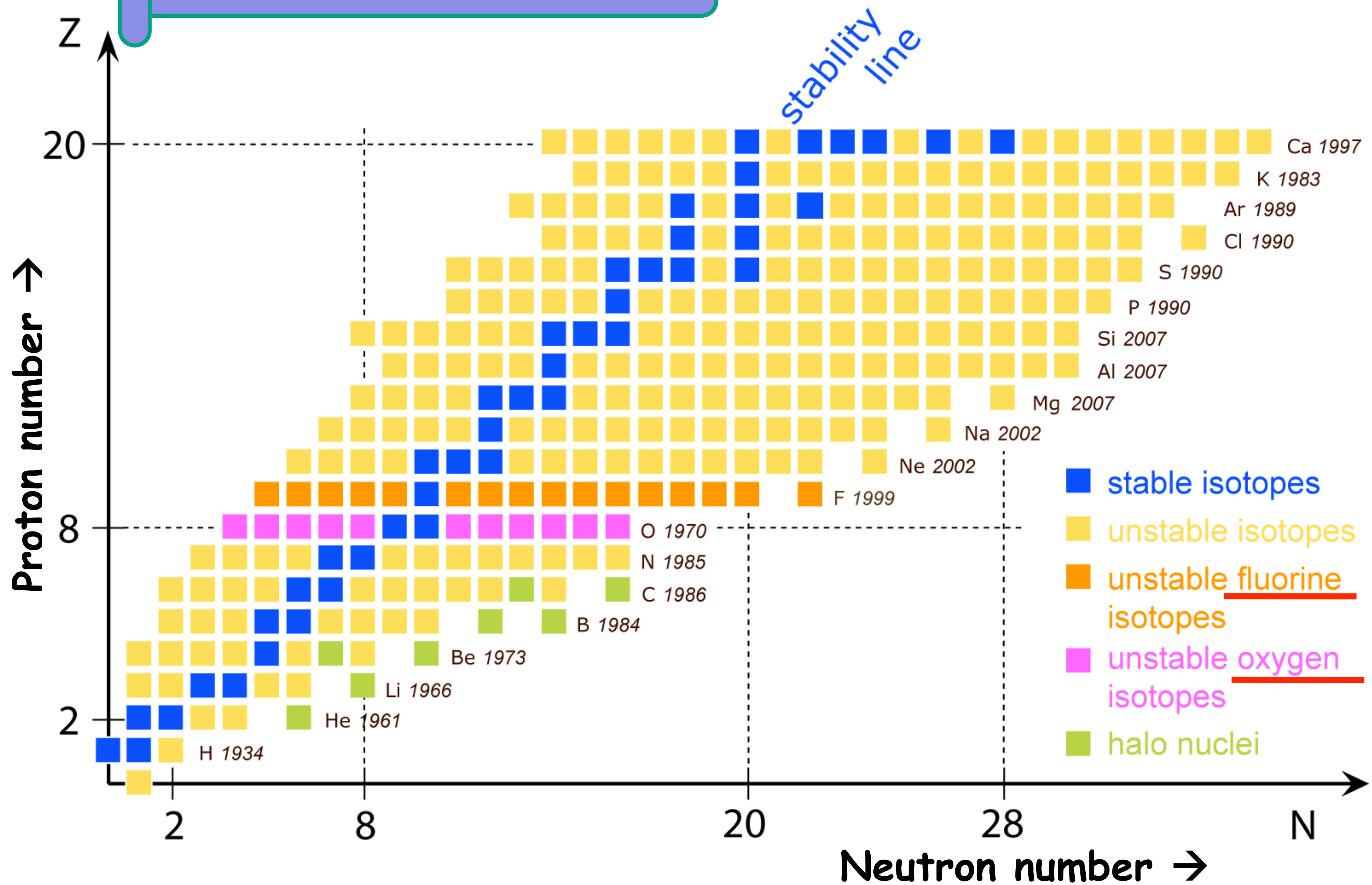


Outline

1. Introduction
2. Shell model and monopole interaction
3. Shell evolution and tensor force
4. Multiple quantum liquid in exotic nuclei
5. Shell evolution and three-nucleon force
6. Monte Carlo Shell Model
7. Summary

Nuclear Chart
- Left Lower Part -

Why is the drip line of Oxygen so near ?



Single-Particle Energy for Oxygen isotopes

by microscopic eff. int.

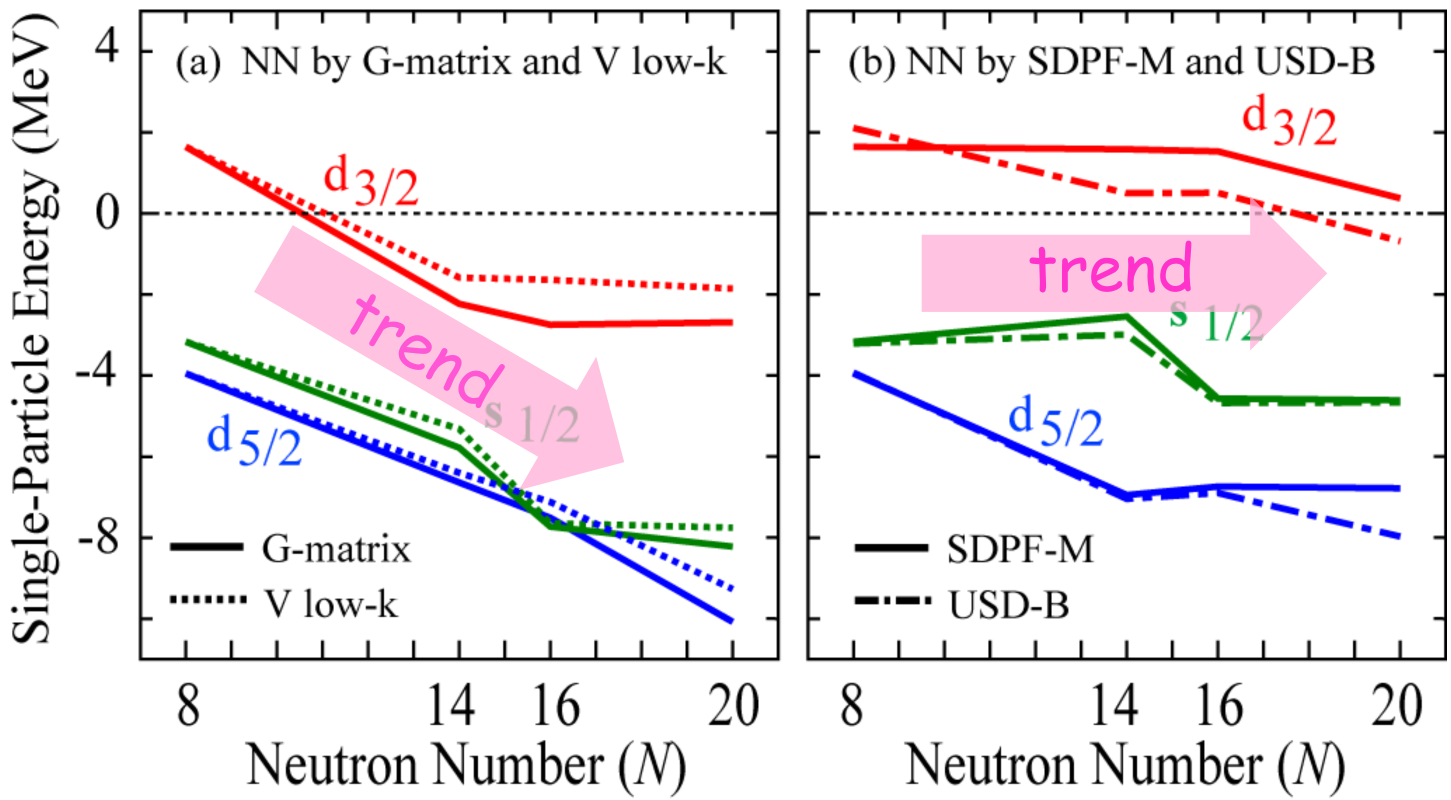
G-matrix+ core-pol. : Kuo, Brown

V_{low-k} : Bogner, Kuo, Schwenk

by phenomenological eff. int.
- G-matrix + fit -

SDPF-M — Utsuno, O., Mizusaki, Honma, Phys. Rev. C **60**, 054315 (1999)

USD-B — Brown and Richter, Phys. Rev. C **74**, 034315 (2006)



What is the origin of

the ***repulsive modification*** of

T=1 monopole matrix elements ?

The same puzzle as in the pf shell

A solution within *bare* 2-body interaction
is very unlikely
(considering efforts made so far)
Zuker, Phys. Rev. Lett. 90, 042502 (2003)

→ 3-body interaction

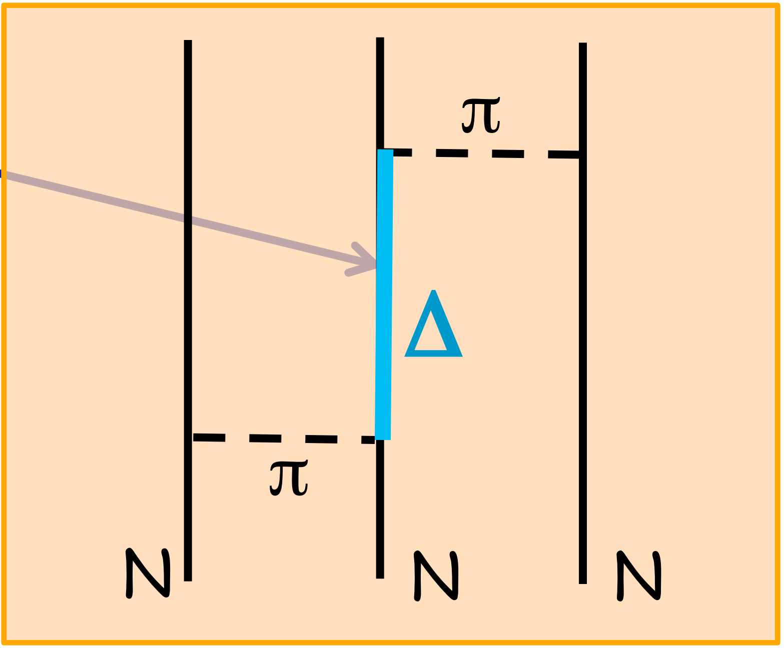
The clue : Fujita-Miyazawa 3N mechanism (Δ-hole excitation)

Progress of Theoretical Physics, Vol. 17, No. 3, March 1957

Pion Theory of Three-Body Forces

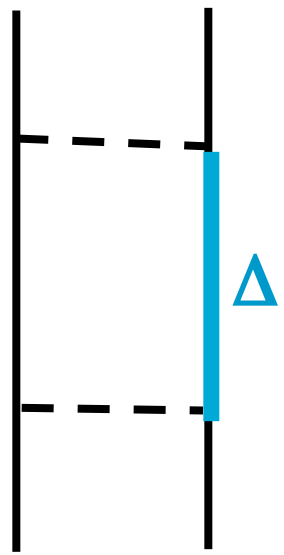
Jun-ichi FUJITA and Hironari MIYAZAWA

Δ particle
m=1232 MeV
S=3/2, I=3/2



Oset, Toki and Weise
Pionic modes of excitation
Phys. Rep. 83, 281 (1982)

Renormalization of *NN* interaction due to Δ **excitation** in the intermediate state



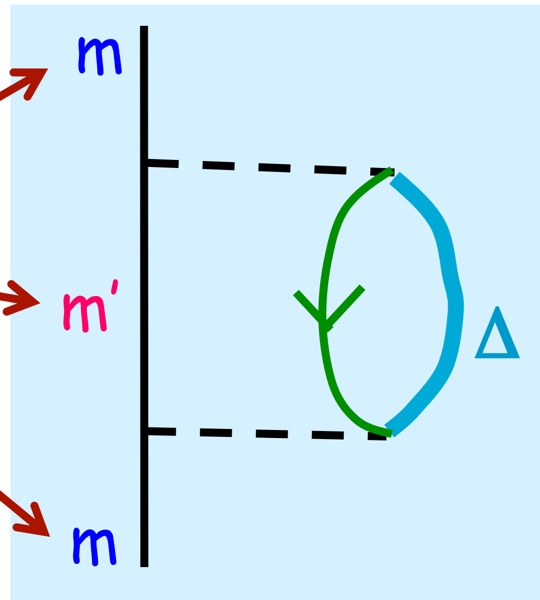
T=1
attraction
between *NN*
effectively

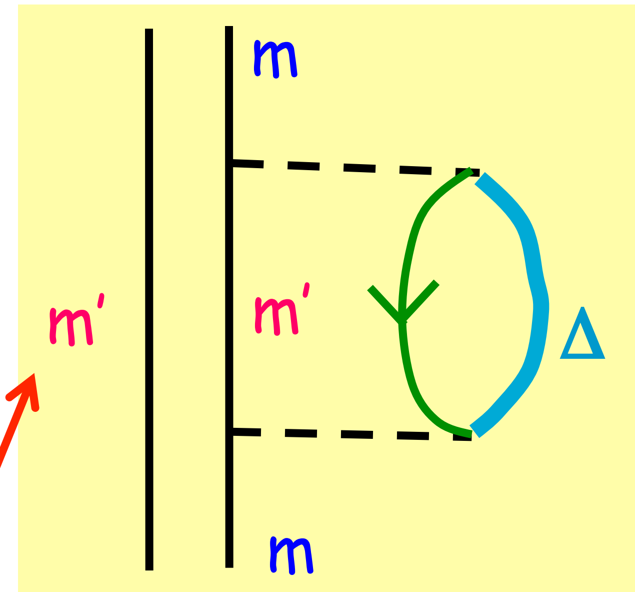
→

Modification to
bare *NN* interaction
(for *NN* scattering)

Pauli blocking effect on the renormalization of single-particle energy

single particle states



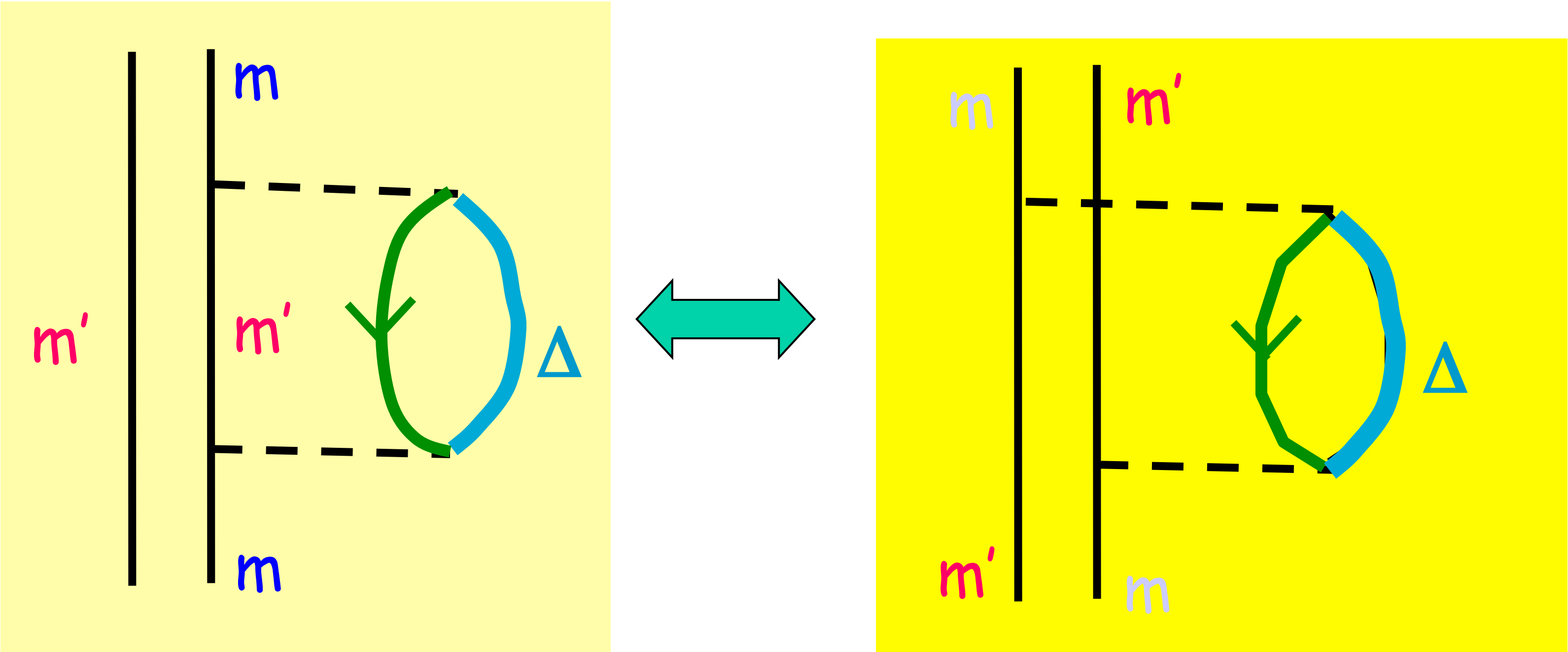


Renormalization of single particle energy due to Δ-hole excitation
→ more binding (attractive)

Another valence particle in state m′

Pauli Forbidden
→ *The effect is suppressed*

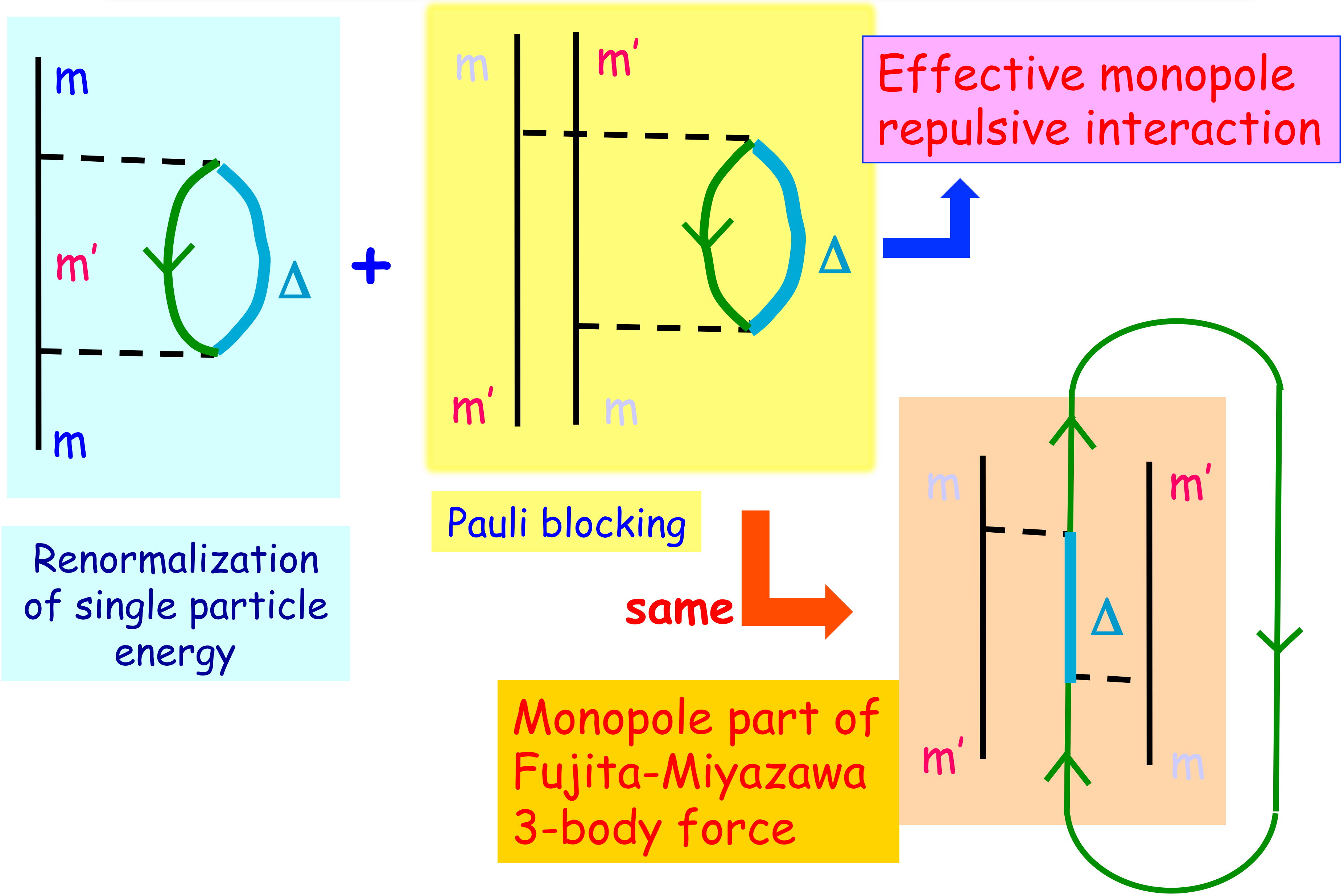
Inclusion of Pauli blocking



Pauli forbidden
(from previous page)

This Pauli effect is included automatically by the exchange term.

Most important message with Fujita-Miyazawa 3NF

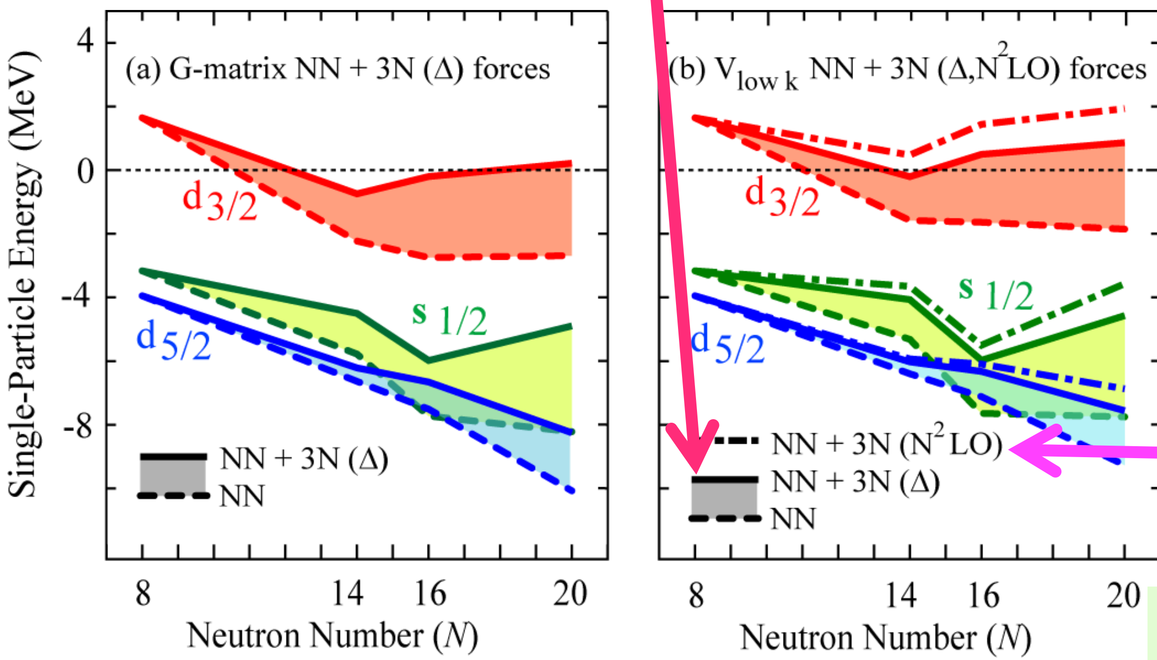


TO *et al.*, PRL 105, 032501 (2010)

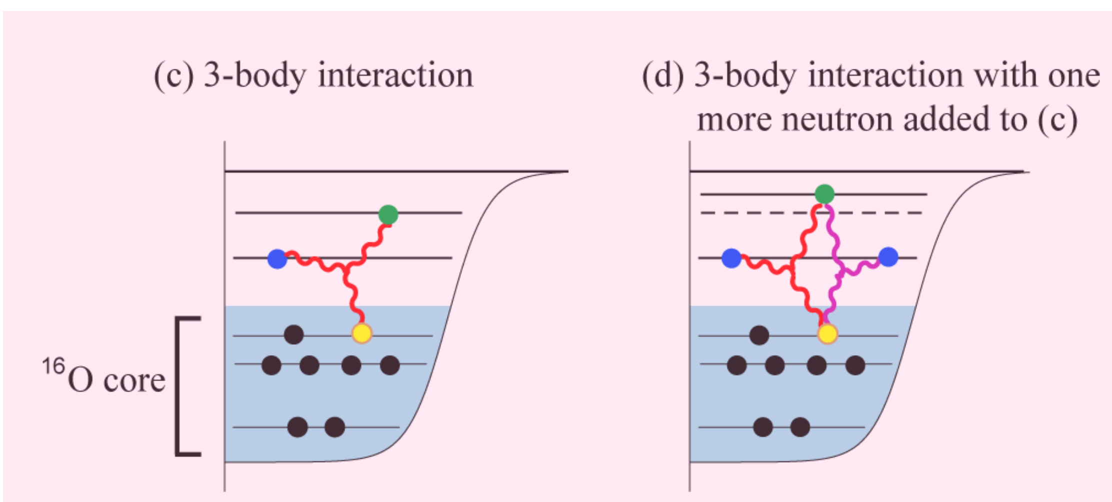
(i) Δ-hole excitation in a conventional way

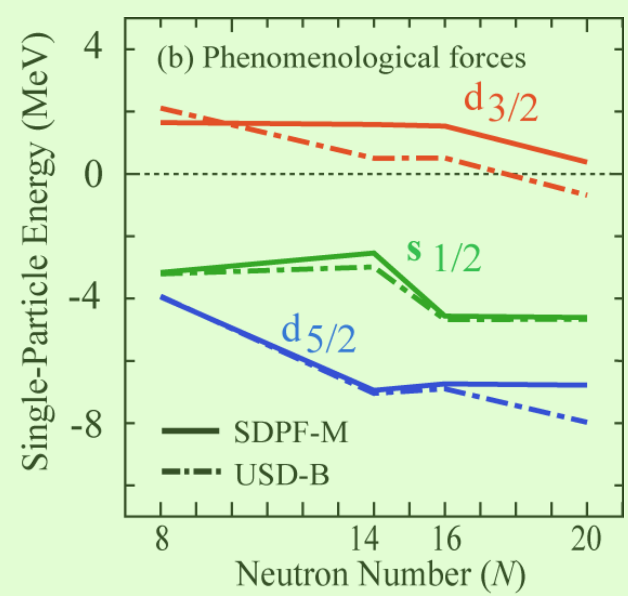
(ii) EFT with Δ

Δ-hole dominant role in determining oxygen drip line



(iii) EFT incl. contact terms (N^2LO)

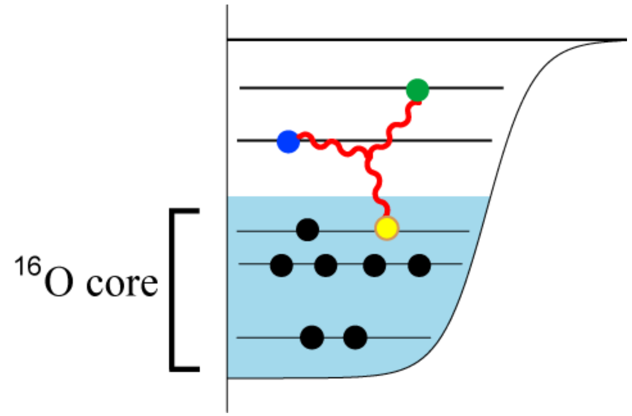


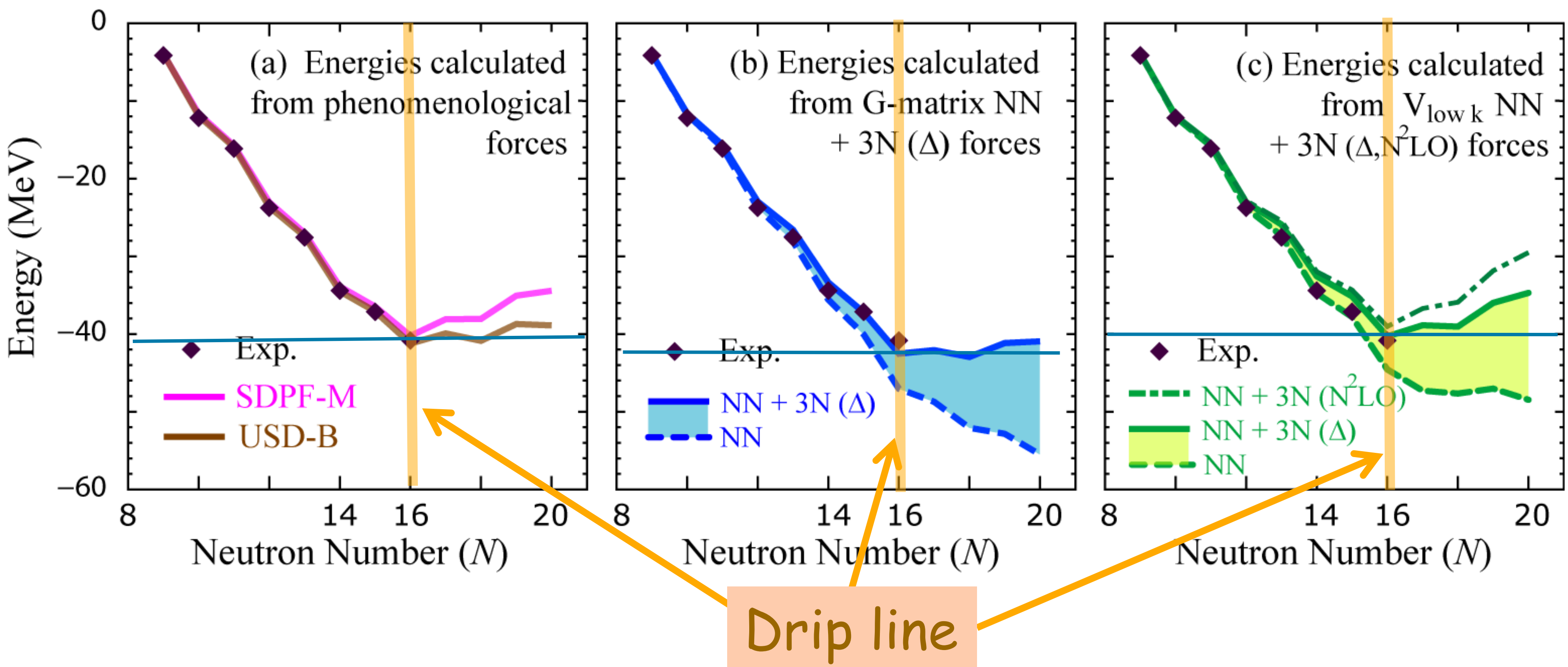


Ground-state energies of oxygen isotopes

TO *et al.*, PRL 105, 032501 (2010)

NN force + *3N*-induced *NN* force
(Fujita-Miyazawa force)





Conventional calculation with πNΔ coupling

π exchange with radial cut-off at 0.5 fm , ΔE =293 MeV

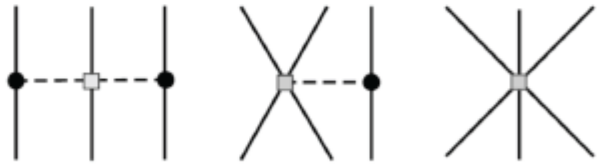
$f_{\pi N\Delta}/f_{\pi NN} = \sqrt{9/2}$

A.M. Green, Rep. Prog. Phys. 39, 1109 (1976)

Low-momentum 3N interactions

from leading N^2LO chiral EFT ~ $(Q/\Lambda)^3$ van Kolck (1994), Epelbaum et al. (2002)

long (2π) intermed. (π) short-range



c_1,c_3,c_4 terms D(Λ) term E(Λ) term

c_i from πN, consistent with NN $c_1 = -0.9^{+0.2}_{-0.5}$, $c_3 = -4.7^{+1.2}_{-1.0}$, $c_4 = 3.5^{+0.5}_{-0.2}$

Meissner (2007)

c_3,c_4 important for structure, large uncertainties at present

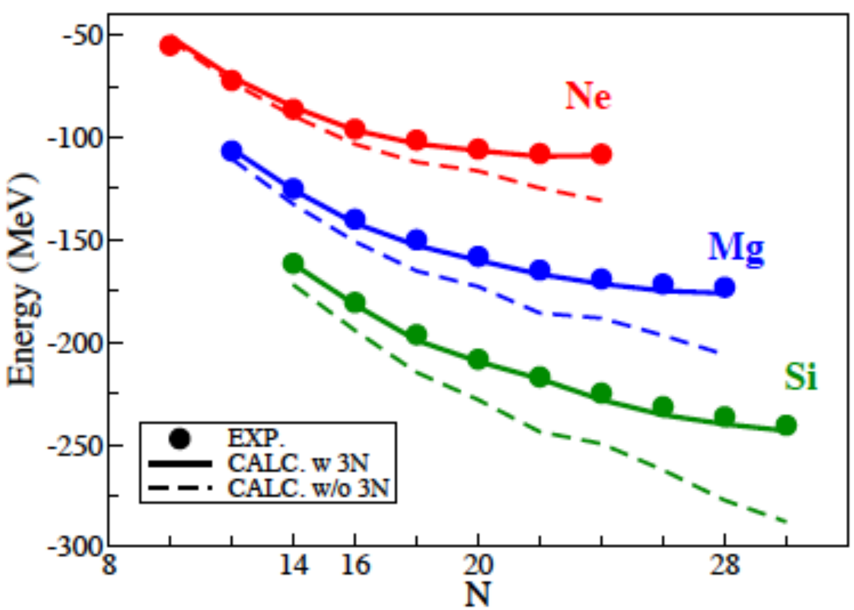
NN for smooth cutoff $V_{low\ k}$ (n_exp=4) from N^3LO(500)

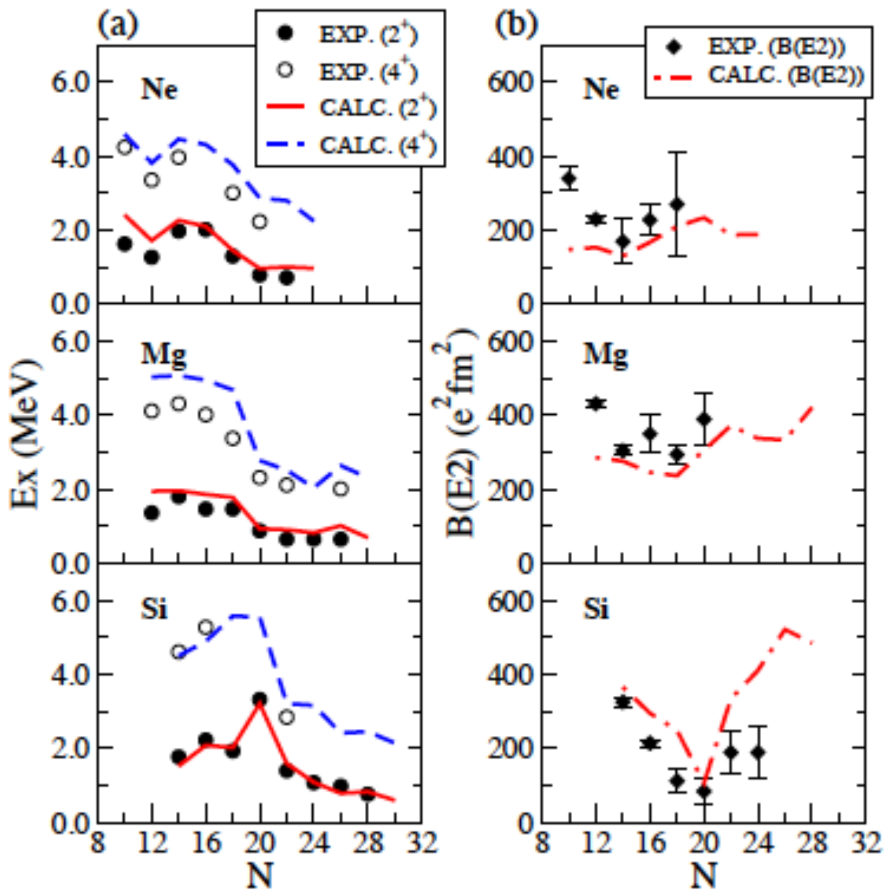
D, E terms fitted to E(3H) and radius(4He)

Ne-Mg-Si in the sd-pf shell
Prototype of future shell-model calculation

New & preliminary

Chiral N3LO NN interaction
+ EKK (Extended Kuo-Krenciglowa) method
+ three-body Fujita-Miyazawa force



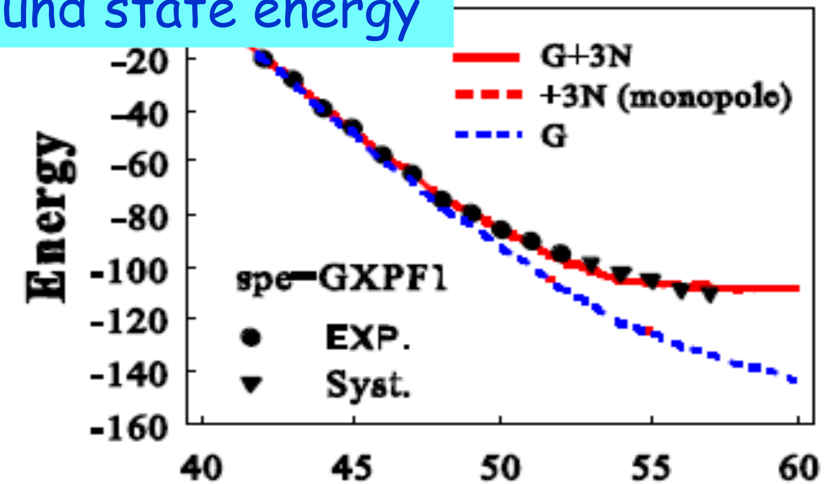


In preparation, Tsunoda, Shimizu, Otsuka, H.-Jensen, Takayanagi, and Suzuki

Ca isotopes

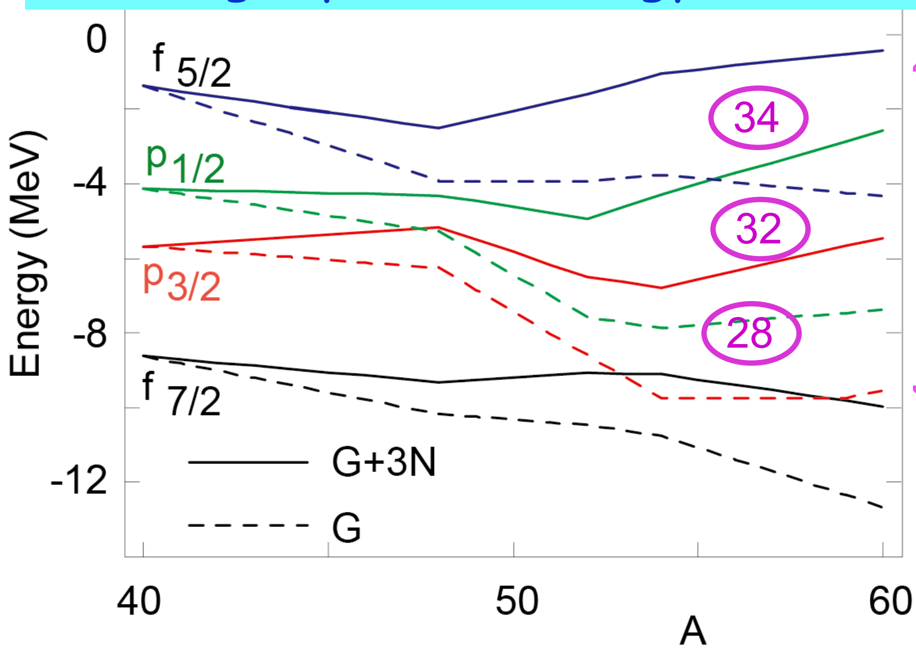
*Nuclear Structure and Dynamics 2012 Proceedings, **Suzuki**, Otsuka and Honma*

ground state energy



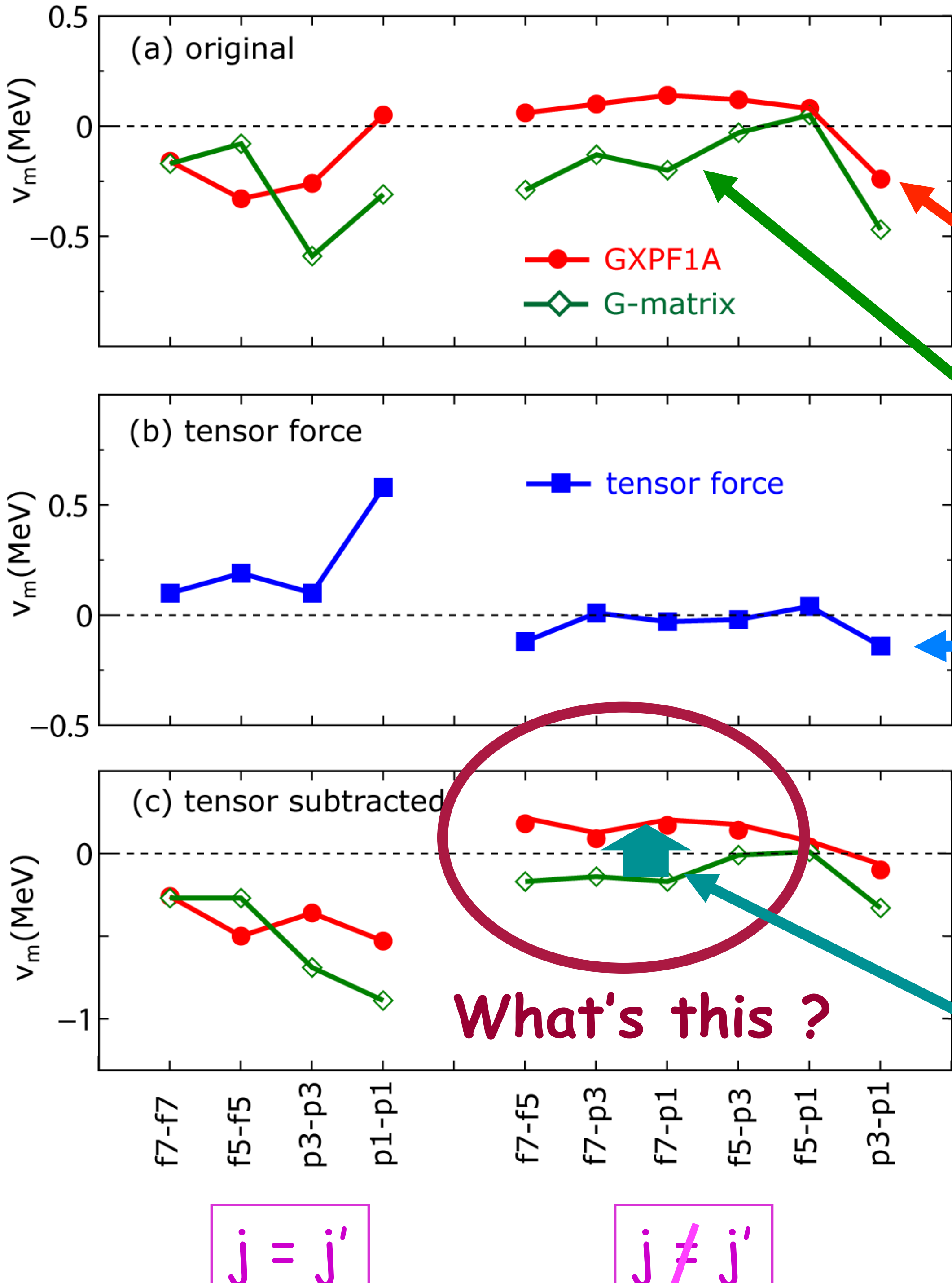
G-matrix (revised)
3rd order Q-box
24 hw int. states
3NF : Fujita-Miyazawa

eff. single-particle energy of neutrons



3-5 MeV rising of SPEs
=> ~40 MeV shift of B.E. of ^{60}Ca from 2NF result

2 MeV enlargement of full shell height (anti-quenching)



T=1 monopole interactions in the pf shell

GXPF1A

G-matrix (H.-Jensen)

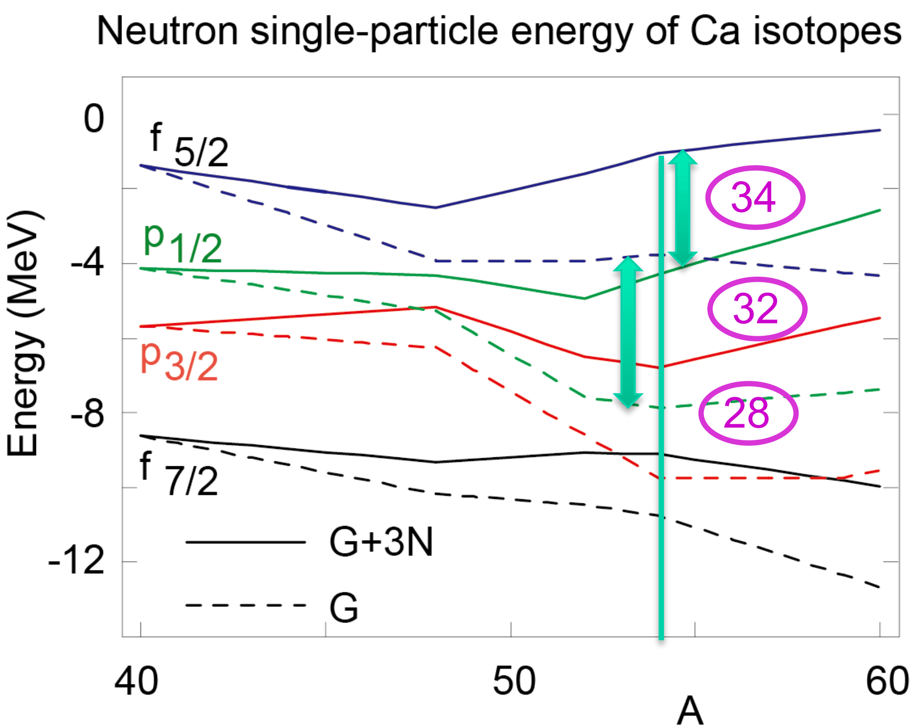
Tensor force ($\pi+\rho$ exchange)

Basic scale ~ 1/10 of T=0

Repulsive corrections to G-matrix

3-body forces does produce another shell evolution

Ca isotopes



Three-body force reduces $f_{5/2}$ - $p_{1/2}$ gap by pushing up $p_{1/2}$

G-matrix
3rd order Q-box
24 hw int. states
3NF : Fujita-Miyazawa

Nuclear Structure and Dynamics 2012 Proceedings, Suzuki, Otsuka and Honma

IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **39** (2012) 085111 (7pp) doi:10.1088/0954-3899/39/8/085111

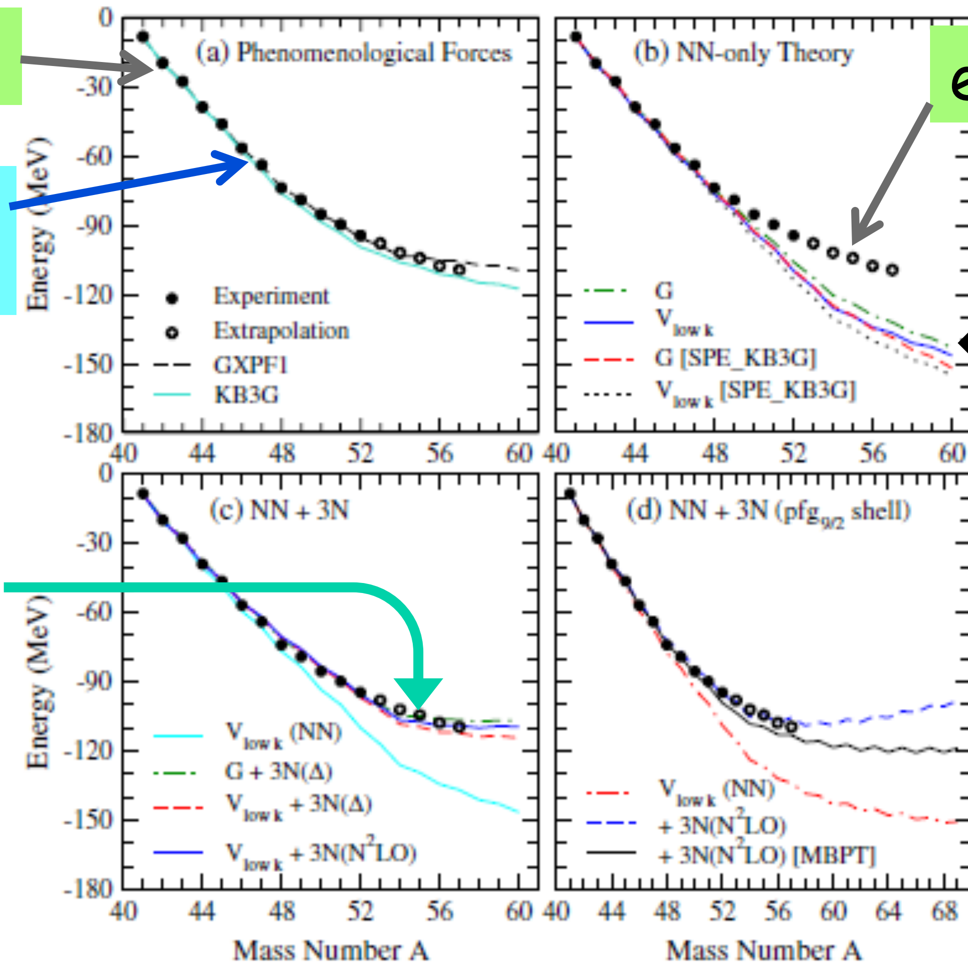
Three-body forces and shell structure in calcium isotopes

Jason D Holt[1,2], Takaharu Otsuka[3,4], Achim Schwenk[5,6] and Toshio Suzuki[7]

Ground-state energy of Ca isotopes

exp + extrap.

Phenomenological NN



exp + extrap.

Microscopic NN

Microscopic NN + 3NF

+ $g_{9/2}$

Continuum-coupled shell model (CCSM)

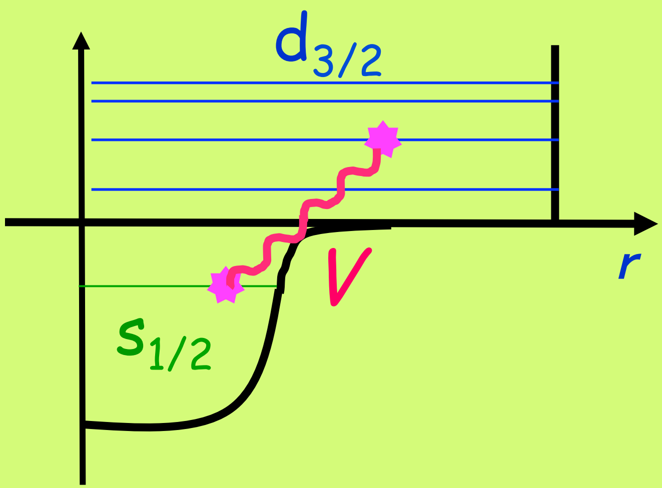
Hamiltonian : $H = H_0 + \hat{V} = \sum_j \tilde{\epsilon}_j n_j + \hat{V}$

$$H_0 = T + U_{WS} + V_{\rm wall} = \sum_j \tilde{\epsilon}_j n_j$$

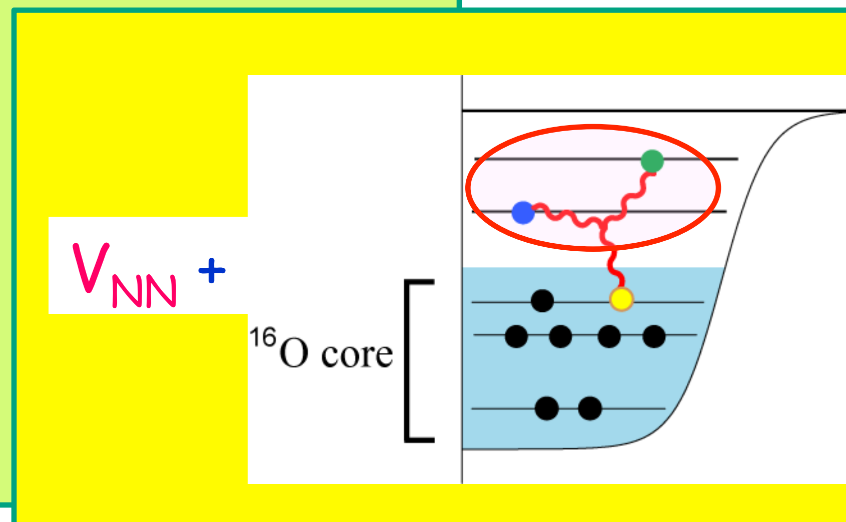
approximated by Gaussian

basis state-vector (denoted by j):
bound states + discretized continuum states

wall very far (3000 fm, ~3000 basis states)



included



$$\hat{V}(r) = \sum_{i=1,2} g_i(1 + a_i \sigma \cdot \sigma) e^{-r^2/d_i^2}$$

$d_{1,2}$=1.4, 0.7 fm

SDPF-M TBME = TBME of this $V(r)$
for HO wave functions

$$\langle 1s_{1/2} 0d_{3/2} | V | 1s_{1/2} 0d_{3/2} \rangle_{J=1,2}$$

$$\langle 0d_{3/2} 0d_{3/2} | V | 0d_{3/2} 0d_{3/2} \rangle_{J=0,2}$$

under the assumption that 3-body force effect
is included in SDPF-M interaction effectively

V (r) is fixed only by interaction

$^{24}O = ^{22}O + 2n$ in the space

ground state : 2n in $1s_{1/2}$

excited states of 1^+ and 2^+ :

$$|iJ^+\rangle = |1s_{1/2} \otimes id_{3/2}; J^+\rangle$$

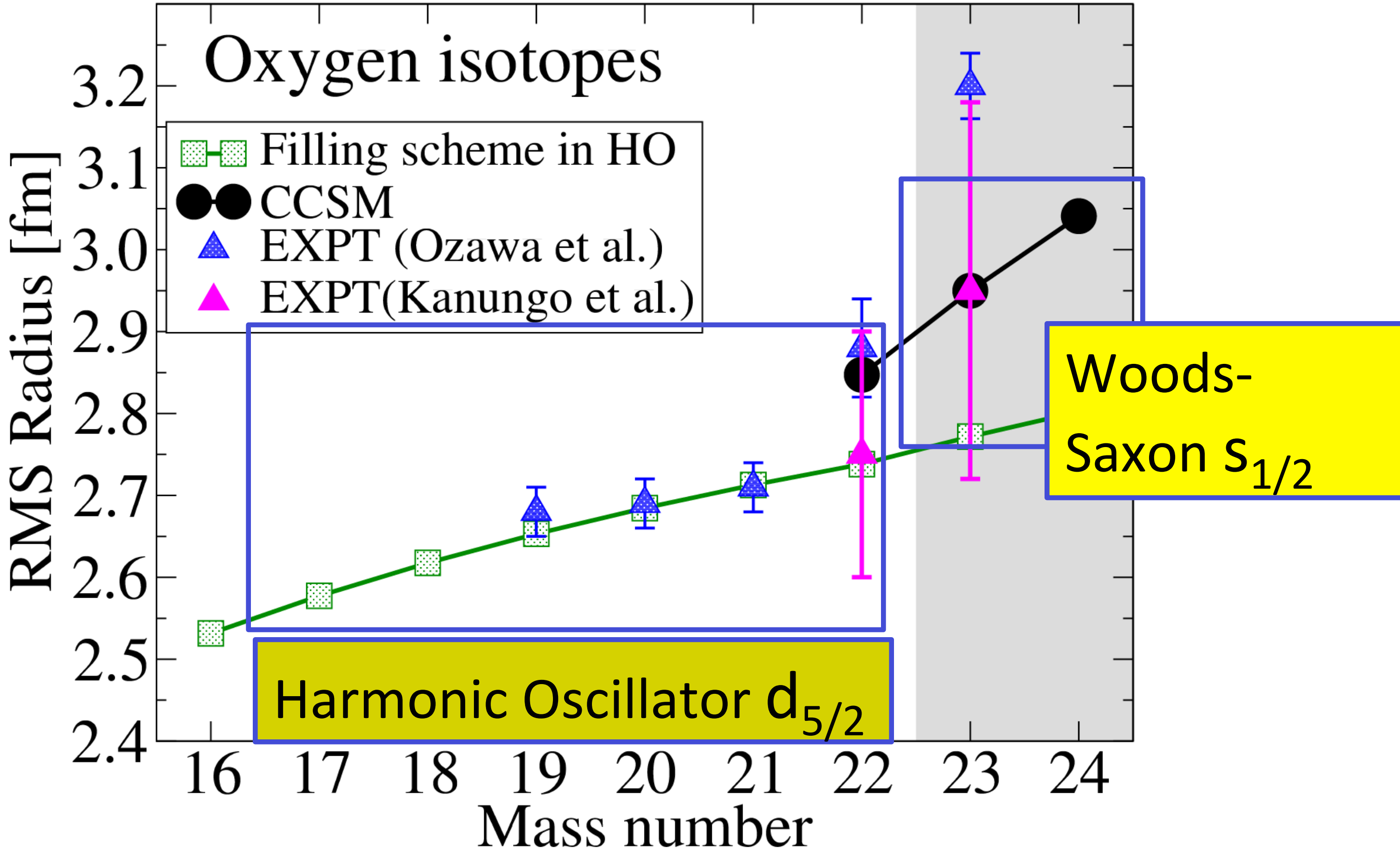
discretized continuum $id_{3/2}$ $(i = 1, 2, \ldots)$

$1s_{1/2}$: solution of Woods-Saxon potential with observed S_n

diagonalize H

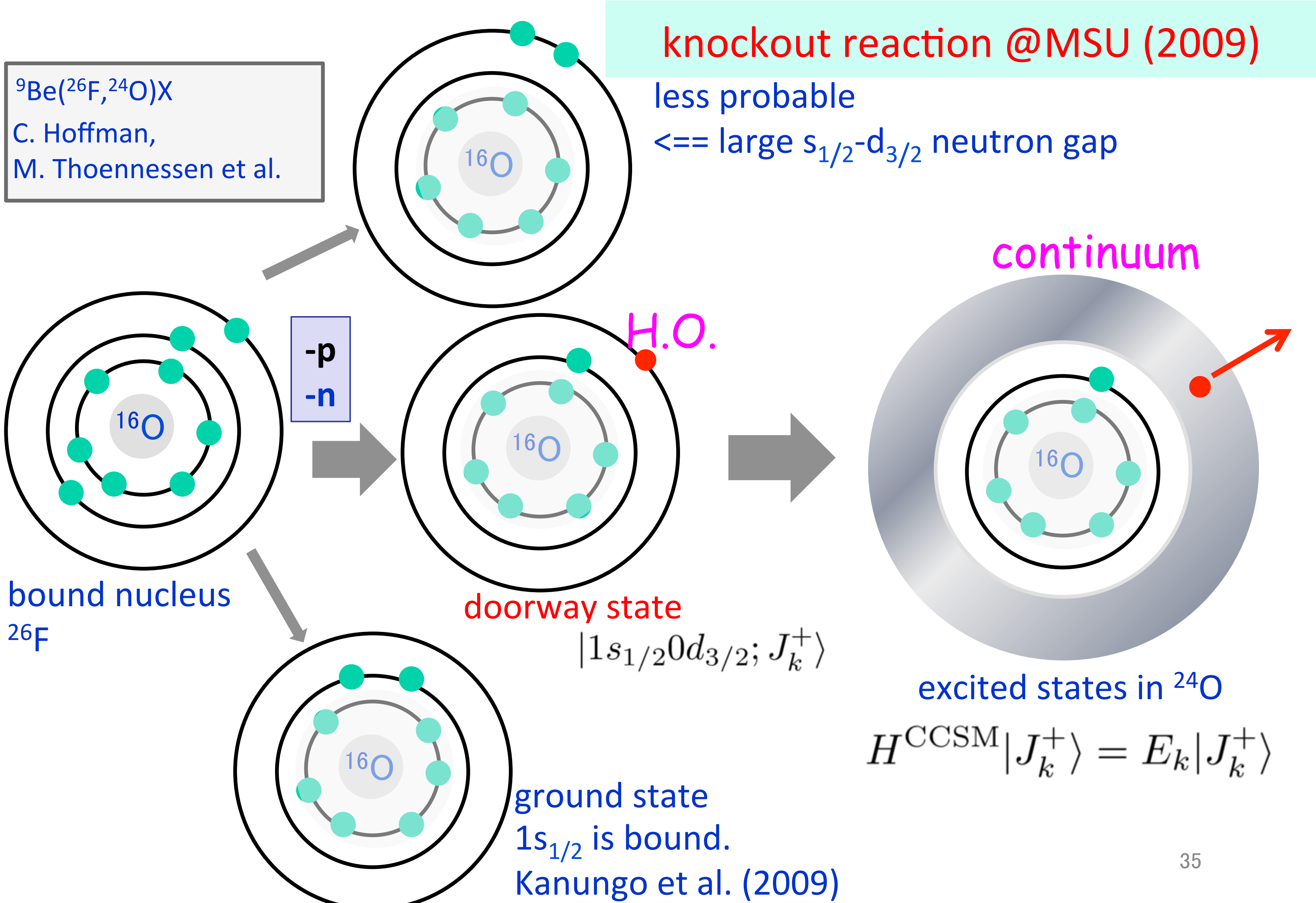
Eigenfunction : $|J_k^+\rangle = \sum_i c_i^{(J,k)} |iJ^+\rangle$

RMS Radius: $^{16-24}O$

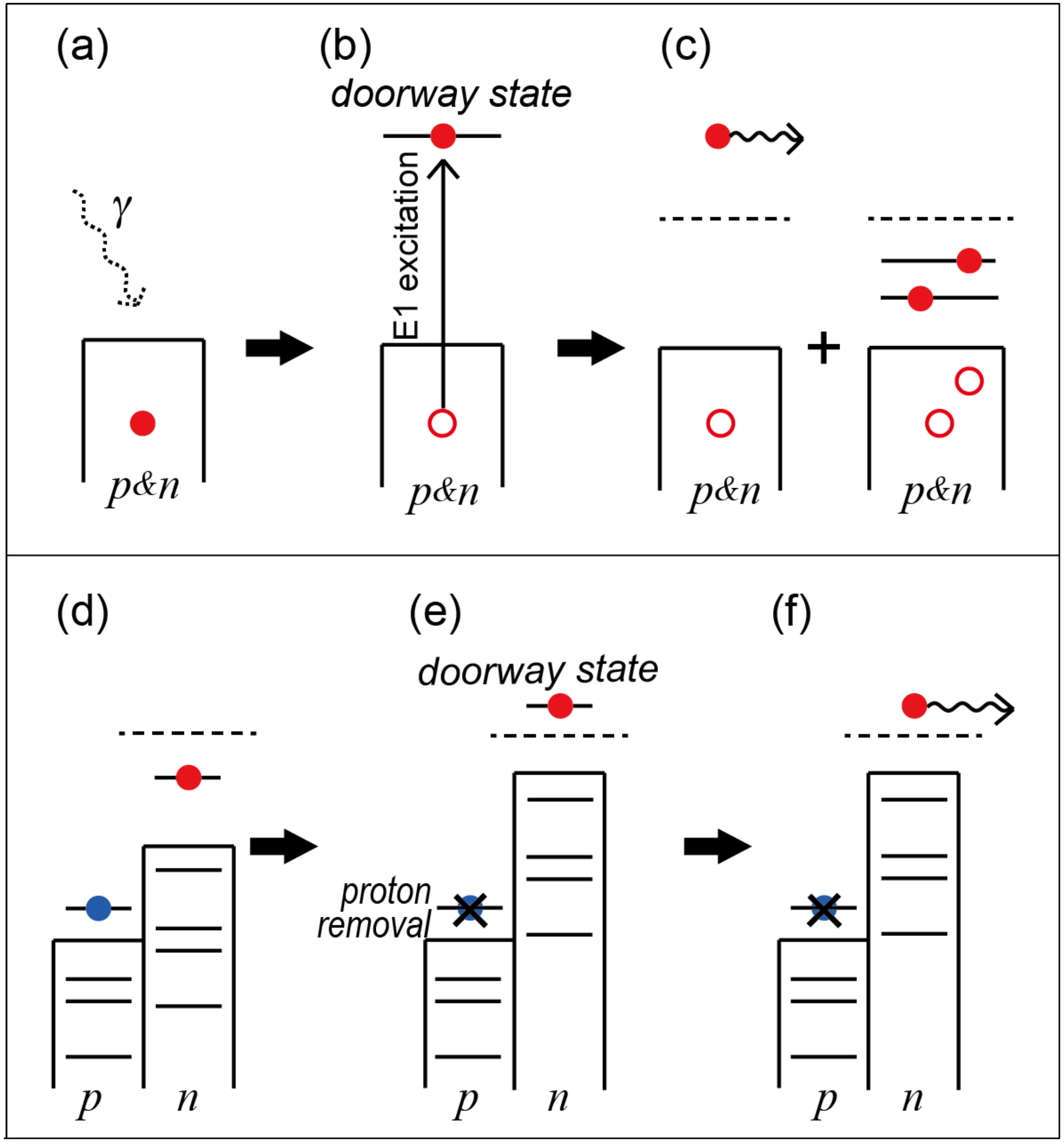


Exp: Ozawa et al., Nucl. Phys. A693, 32 (2001)
Kanungo et al., Phys. Rev. C84, 061304 (2011)

Removal of one proton and one neutron from ^{26}F



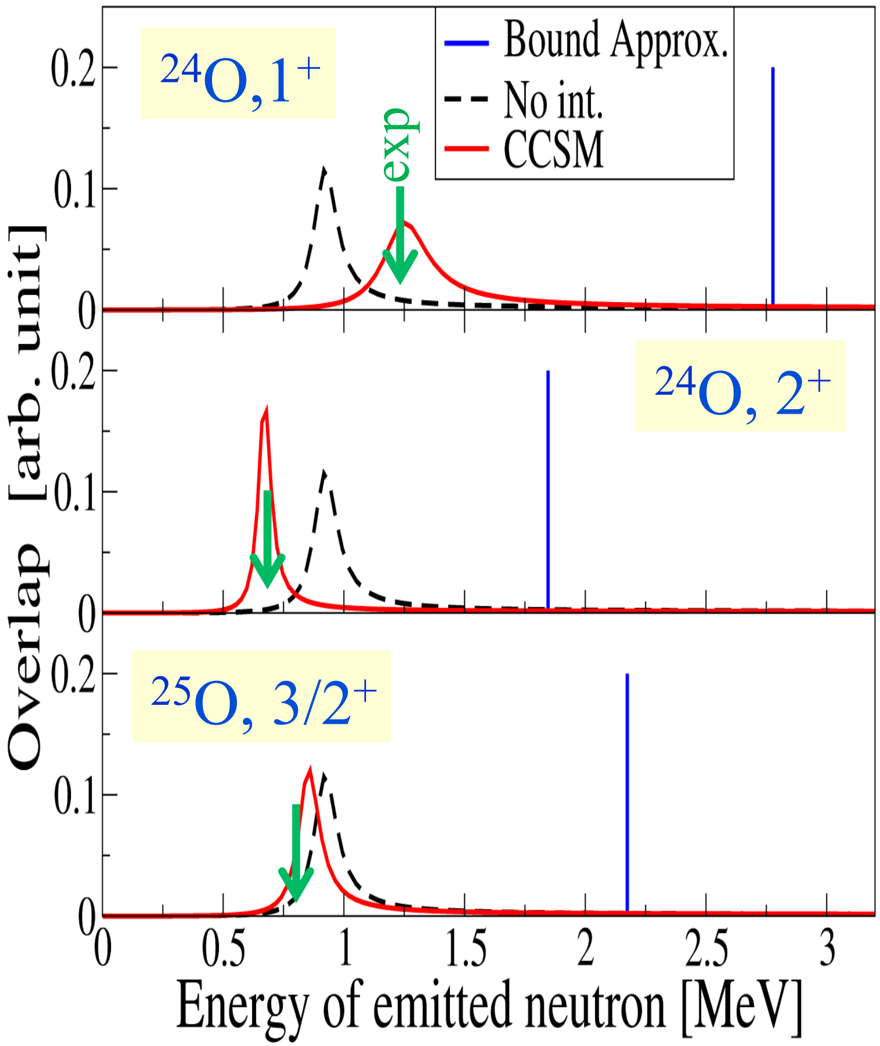
Doorway state -> doorway-state resonance



E1 excitation

nucleon transfer (proton removal)

Low-lying Continuum Spectra in ^{24,25}O



doorway-state resonance

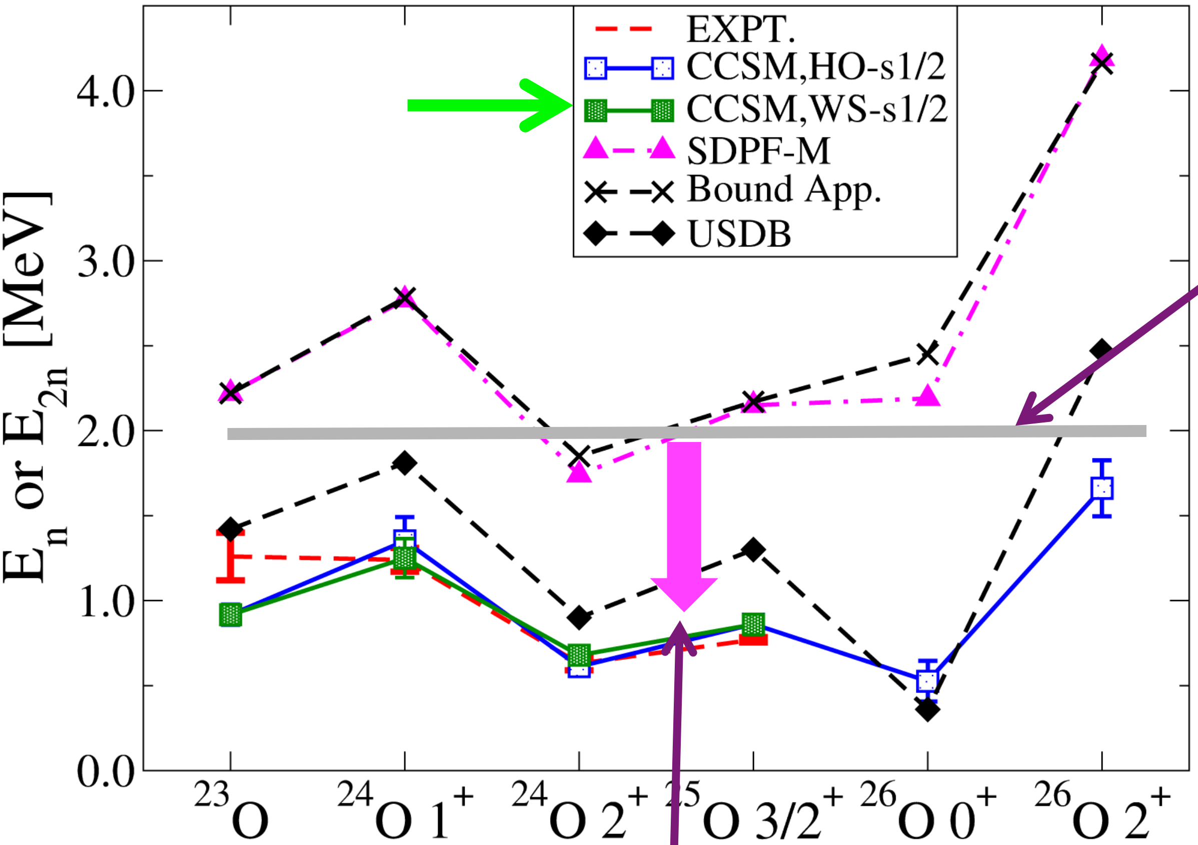
Doorway state ==> continuum states in ^{24}O

$$p_k^J = |\langle J_k^+|\Phi_{\text{doorway}}\rangle|^2 = |\sum_i C_i^{(k)}\langle id_{3/2}|0d_{3/2}\rangle|^2$$

- **bound approx**imation: Normal shell model with the same Hamiltonian : NO continuum effect
- **CCSM : With continuum effect** *incl. residual interaction*
- **no int.** : With continuum effect but *no residual interaction.*

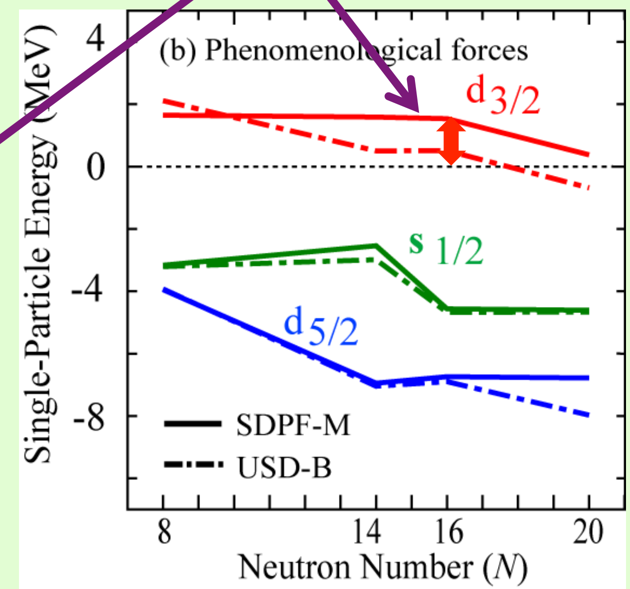
- Continuum effect is about 1 MeV
- No bound excited state.
- 1^+-2^+ splitting by 2-body interaction
- 1^+-2^+ splitting is in good agreement with experiments.

Peak Energies of neutron emission



SPE as bound state

2 MeV



Exp. : MSU (Hoffman et al), RIKEN (Elekes et al)

Lowering due to continuum effect

Continuum spectra are consistent with the shell evolution

Oxygen isotopes

↓

Fluorine isotopes

Neutron single-particle energies at N=20 for Z=8~20

solid line : full (central + tensor)

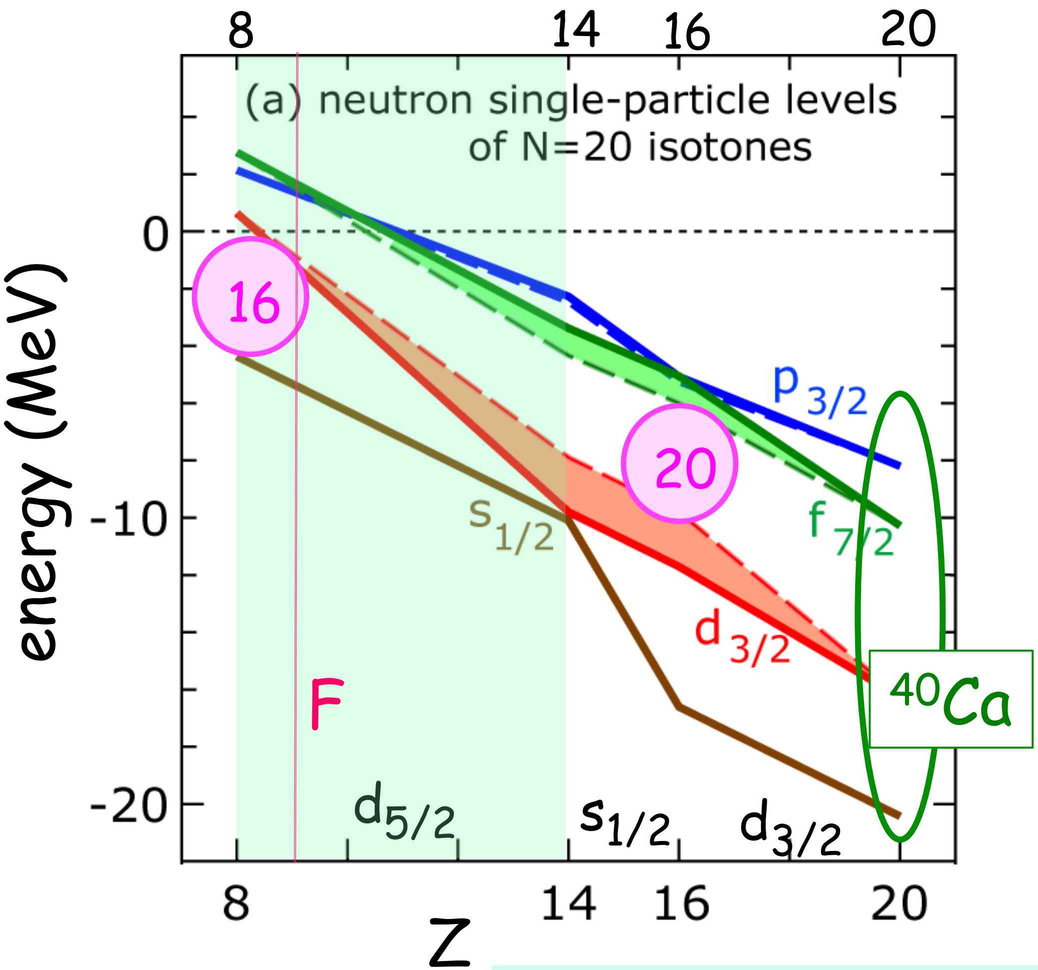
dashed line : central only

A proton in $d_{5/2}$ moves neutron orbits by

$d_{3/2}$	-2.0 MeV
$s_{1/2}$	-1.1 MeV
$d_{5/2}$	-1.6 MeV

^{29}F well bound already by s. p. e.

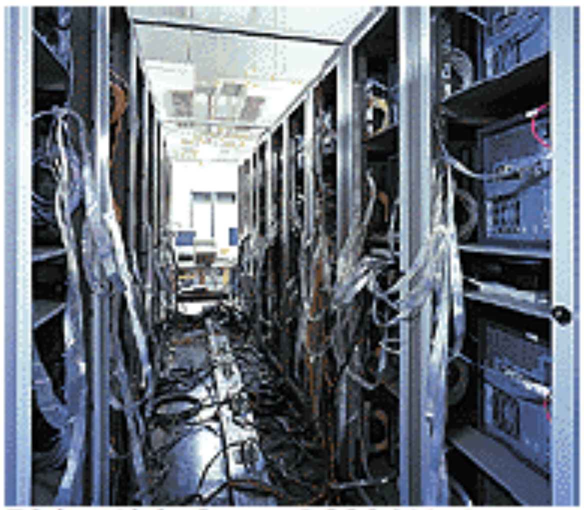
$^{31,...}$F bound through mixing with pf shell



TO, Suzuki, et al.
PRL 104, 012501 (2010)

Outline

1. Introduction
2. Shell model and monopole interaction
3. Shell evolution and tensor force
4. Multiple quantum liquid in exotic nuclei
5. Shell evolution and three-nucleon force
6. Monte Carlo Shell Model
7. Summary



70台のAlphaServer DS20をMyrinetで高速に並列結合し、最大のパラレル処理パフォーマンスを発揮するAlphleet

理化学研究所

RIKEN

クラスタ化した70台(140CPU)のAlphaServerとCompaq Tru64 UNIXが高い並列処理パフォーマンスを実現し、ビックバン以降の原子核の構造解明を推進

Major outcome

PHYSICAL REVIEW C, VOLUME 60, 054315

1999

Varying shell gap and deformation in $N\sim20$ unstable nuclei studied by the Monte Carlo shell model

Yutaka Utsuno,[1,2] Takaharu Otsuka,[1,2] Takahiro Mizusaki,[1] and Michio Honma[3]

Computations have been carried out partly by the Alphleet computer system of RIKEN.

Physics Letters B 346 (1995) 9–14

Large deformation of the very neutron-rich nucleus ^{32}Mg from intermediate-energy Coulomb excitation

T. Motobayashi[a,1], Y. Ikeda[a], Y. Ando[a], K. Ieki[a], M. Inoue[a], N. Iwasa[a], T. Kikuchi[a], M. Kurokawa[a], S. Moriya[a], S. Ogawa[a], H. Murakami[a], S. Shimoura[a], Y. Yanagisawa[a], T. Nakamura[b], Y. Watanabe[b], M. Ishihara[b,c], T. Teranishi[c], H. Okuno[c], R.F. Casten[d]

Present status

Advanced MCSM

PTEP

Prog. Theor. Exp. Phys. **2012**, 01A205 (27 pages)
DOI: 10.1093/ptep/pts012

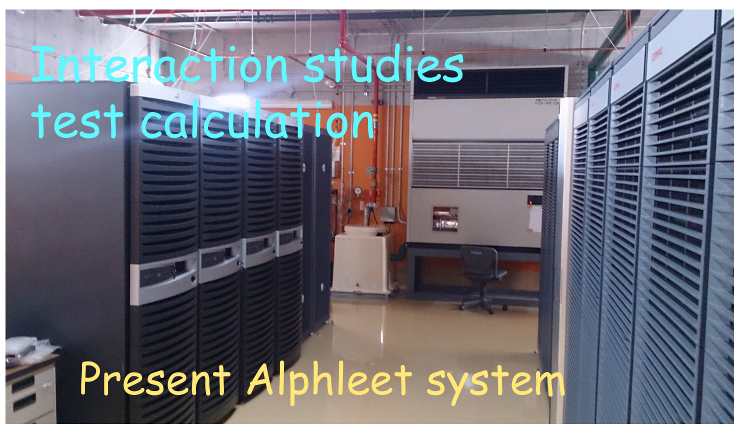
New-generation Monte Carlo shell model for the K computer era

Noritaka Shimizu,[1,*], Takashi Abe[1], Yusuke Tsunoda[2], Yutaka Utsuno[3], Tooru Yoshida[1], Takahiro Mizusaki[4], Michio Honma[5], and Takaharu Otsuka[1,2,6]

Project

HPCI Strategic Programs for Innovative Research (SPIRE)
Field 5 “The origin of matter and the universe”

Computer



Outline

- Methodology: advanced Monte Carlo shell model (MCSM)
  - intrinsic shape can be the objectives
  - ab initio (no core) MCSM and clustering in Be isotopes

- Shape coexistence and Quantum Liquid picture
  - exotic Ni isotopes (+ Co, Cu)

- Shape evolution (from seniority to rotor)
  - Xe and Ba isotopes

- Extension: Spectra to high-lying collective states
  - E1 excitation, GDR and PDR in Ca and Sr isotopes
  - Level density with shell model Hamiltonian

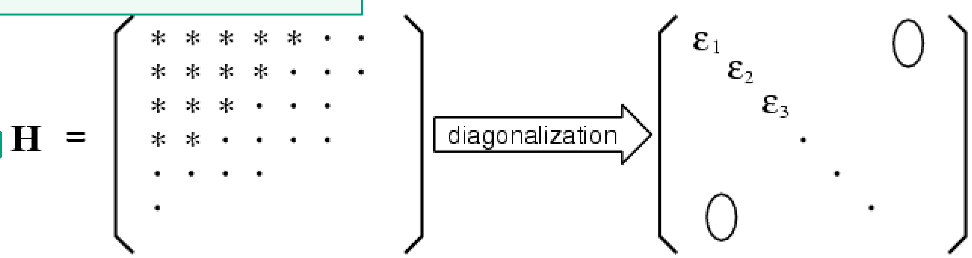
Advanced Monte Carlo shell model (MCSM)

Superposition of the projected Slater determinants
+ Extrapolation by energy variance

$$|\Psi\rangle = \sum_{k=1}^{N_{MCSM}} f_k P^{J,\pi} |\phi_k\rangle \qquad |\phi_k\rangle = \prod_{\alpha=1}^{N} \left(\sum_{i=1}^{N_{sp}} c_i^{\dagger} D_{i\alpha}^{(k)} \right) |-\rangle$$

MCSM basis, deformed Slater det.

$>10^{10}$ basis vectors



Conventional Shell Model
all Slater determinants

Monte Carlo Shell Model
bases important for a specific eigenstate

$\sim 10^2$ basis vectors

Step 1
- Select D stochastically from many candidates generated by the auxiliary-field Monte Carlo technique

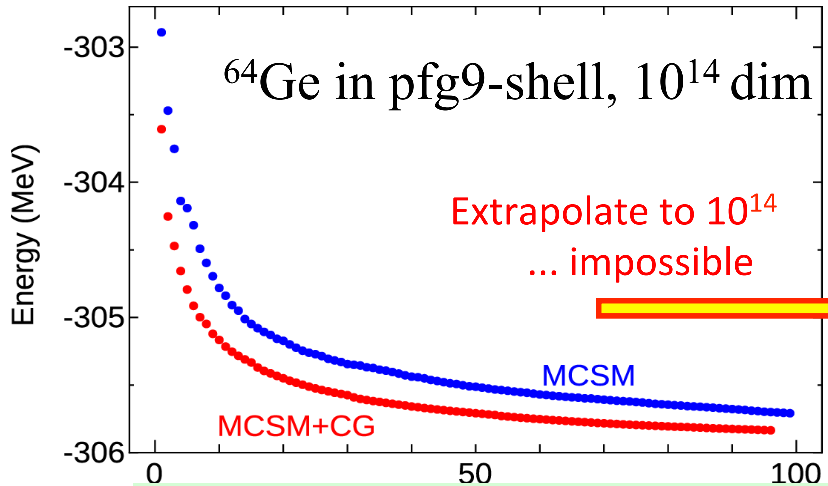
Step 2
- optimize D variationally by the conjugate gradient method so as to minimize the energy eigenvalue of this small matrix

Step 3 : Energy variance extrapolation

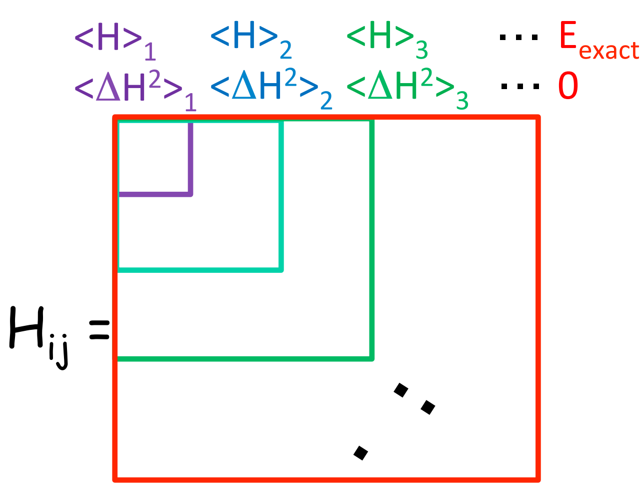
Energy variance : $\langle \Delta H^2 \rangle = \langle H^2 \rangle - \langle H \rangle^2$

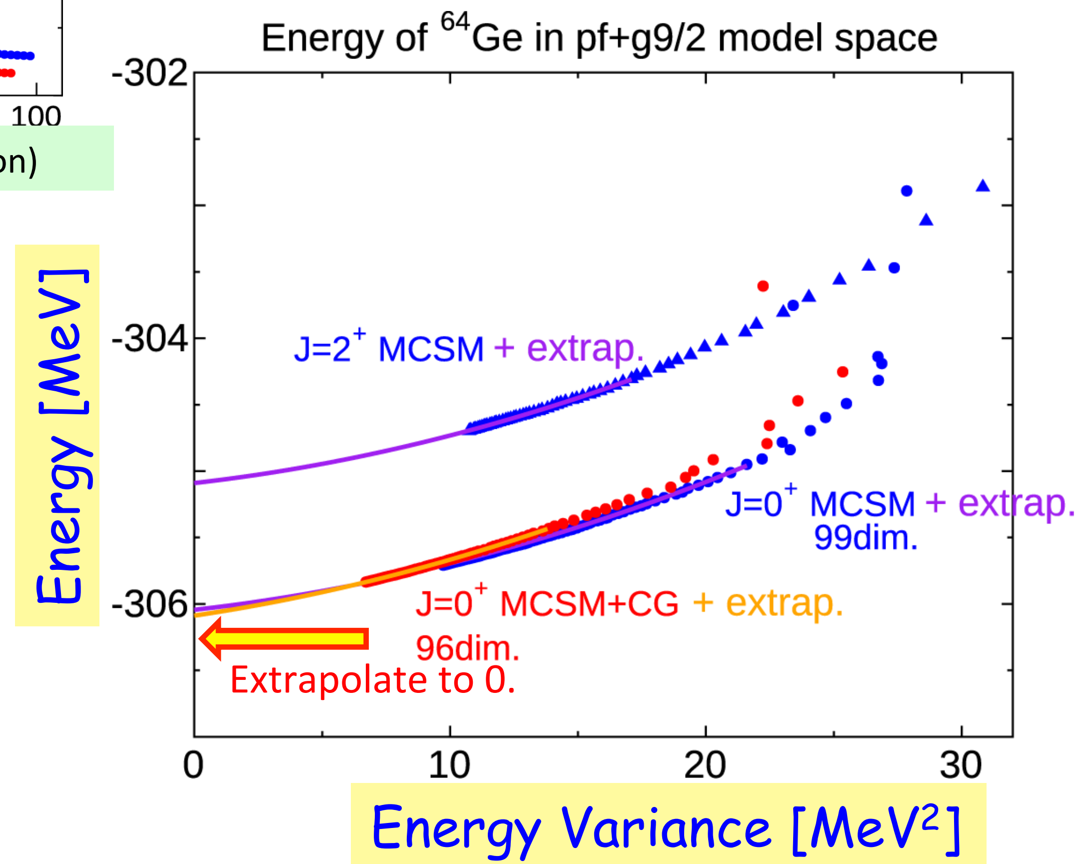
As the number of basis vectors increases, the approximated w.f. approaches the exact one and the energy variance approaches zero.

Extrapolate towards $\langle \Delta H^2 \rangle \to 0$



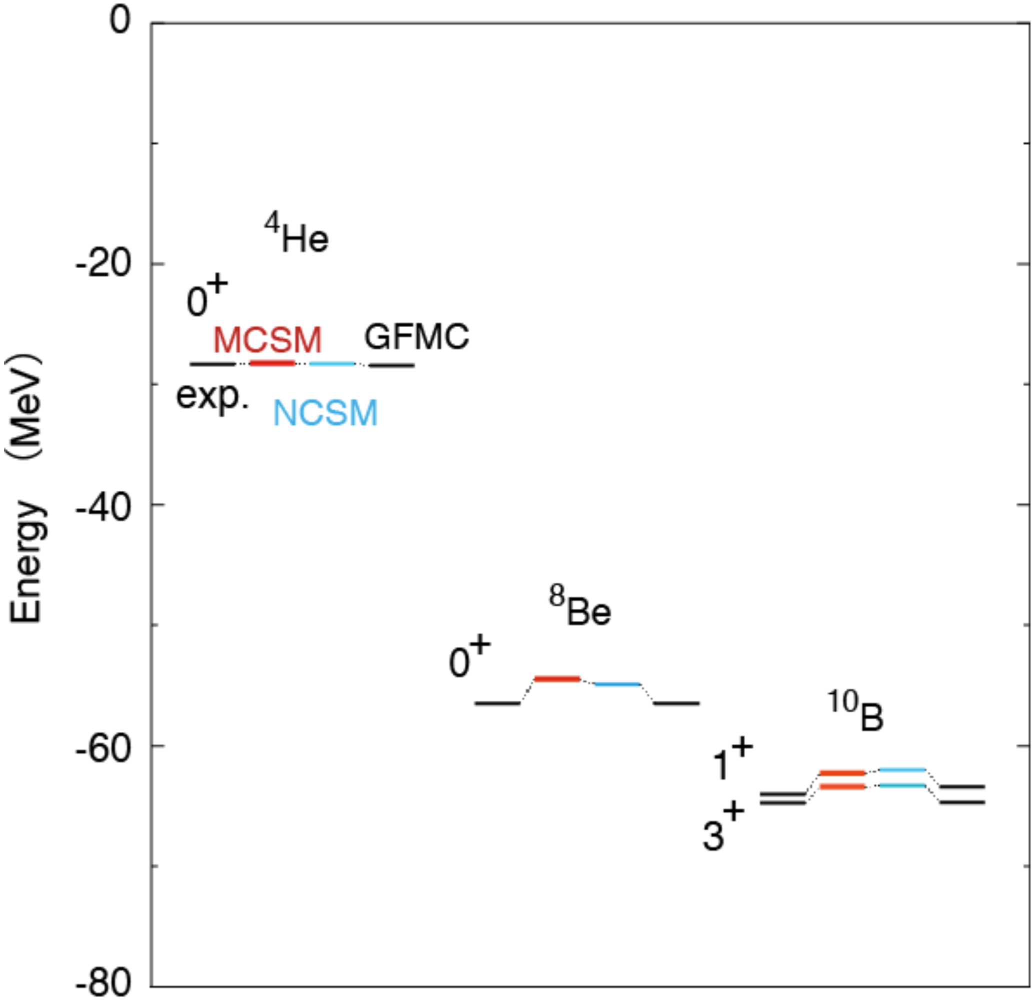
Number of MCSM basis states (dimension)





Systematic calculations in terms of *ab initio Monte Carlo Shell Model* with JISP-16 interaction

Extrapolation to infinite model space is included.



MCSM: same as present

NCSM:
No-core shell model with JISP-16
T. Abe, P. Maris, et al. PRC 86, 054301 (2012)

GFMC
AV18 + IL7
J. Carlson, et al., arXiv:1412.3081 (2014).

Ab initio (no-core) MCSM : Be isotopes

T. Yoshida, T. Abe *et al.*

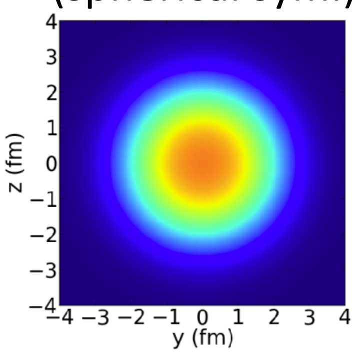
JISP-16 interaction used

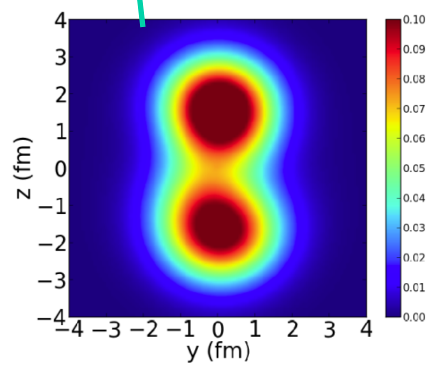
Matter density of the ground state $J^{\pi} = 0^{+}$ of ^{8}Be

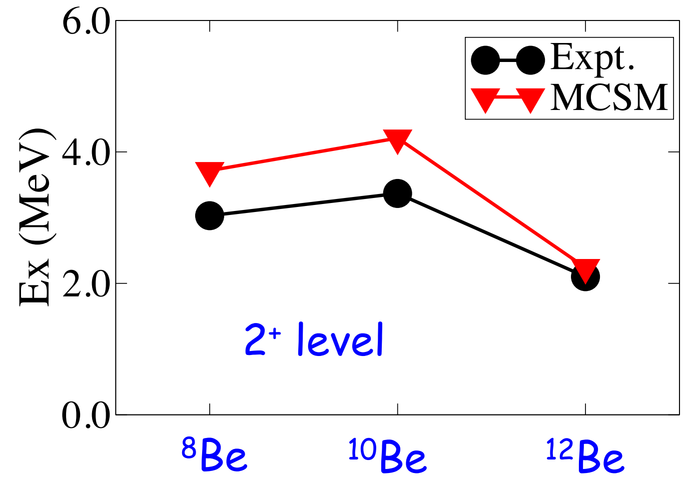
$$|\Psi\rangle = \sum_{k=1}^{N_{MCSM}} f_k P^{J,\pi} |\phi_k\rangle = P^{J,\pi} \left(\sum_{k=1}^{N_{MCSM}} f_k |\phi_k\rangle \right)$$

laboratory frame (spherical sym.)

Intrinsic frame

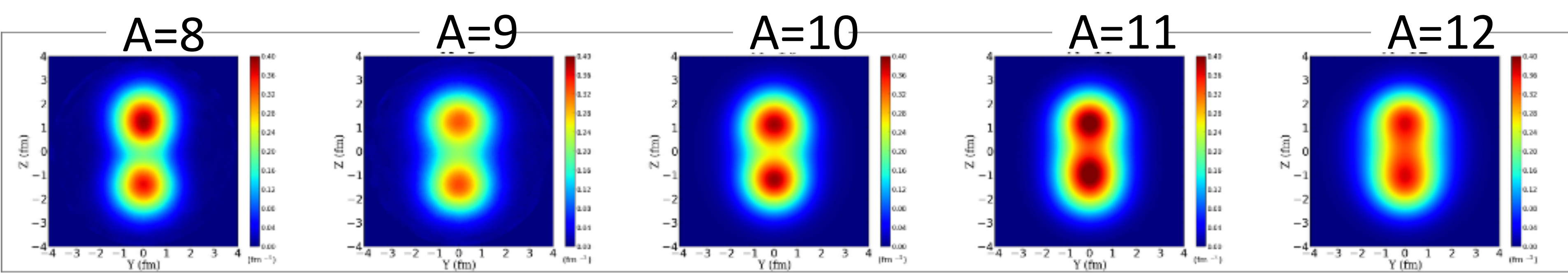






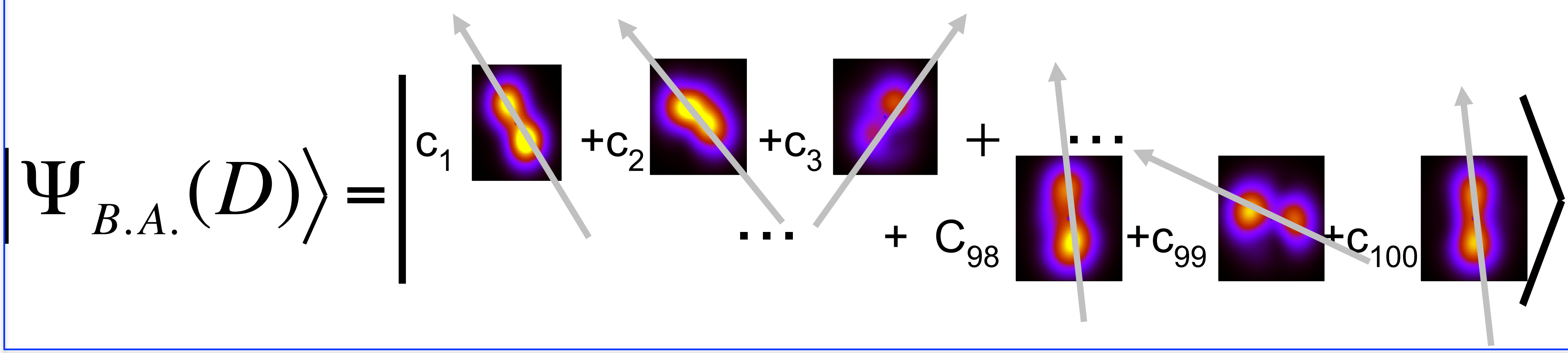
Cluster structure emerges spontaneously in ^{8}Be, and fades away as N increases

Matter density of Be isotopes

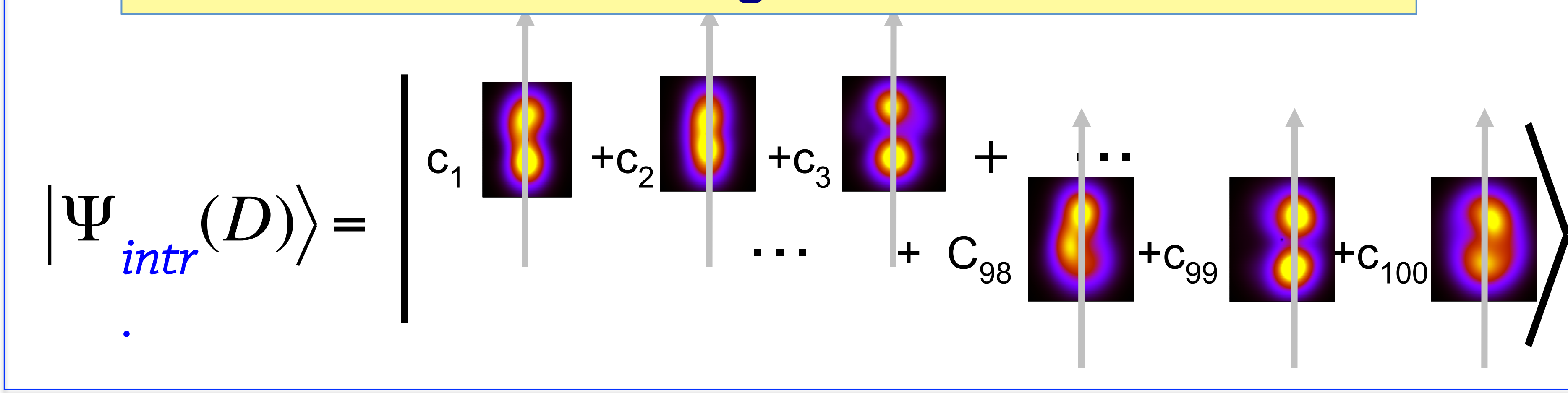


Alignment of each basis state (Slater determinant)

Before the alignment; orientations are random



All basis states are aligned → "intrinsic state"



Outline

- Methodology: advanced Monte Carlo shell model (MCSM)
  - intrinsic shape can be the objectives
  - ab initio (no core) MCSM and clustering in Be isotopes

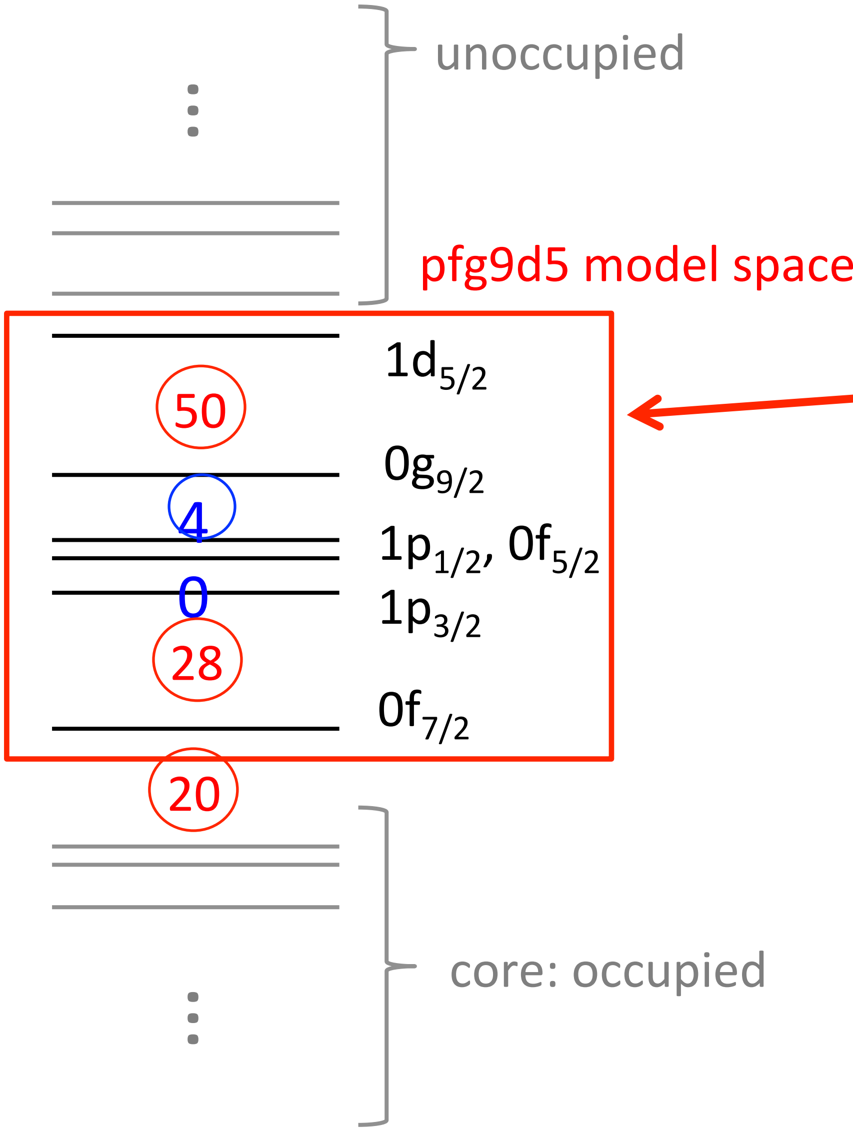
- Shape coexistence and Quantum Liquid picture
  - exotic Ni isotopes (+ Co, Cu)

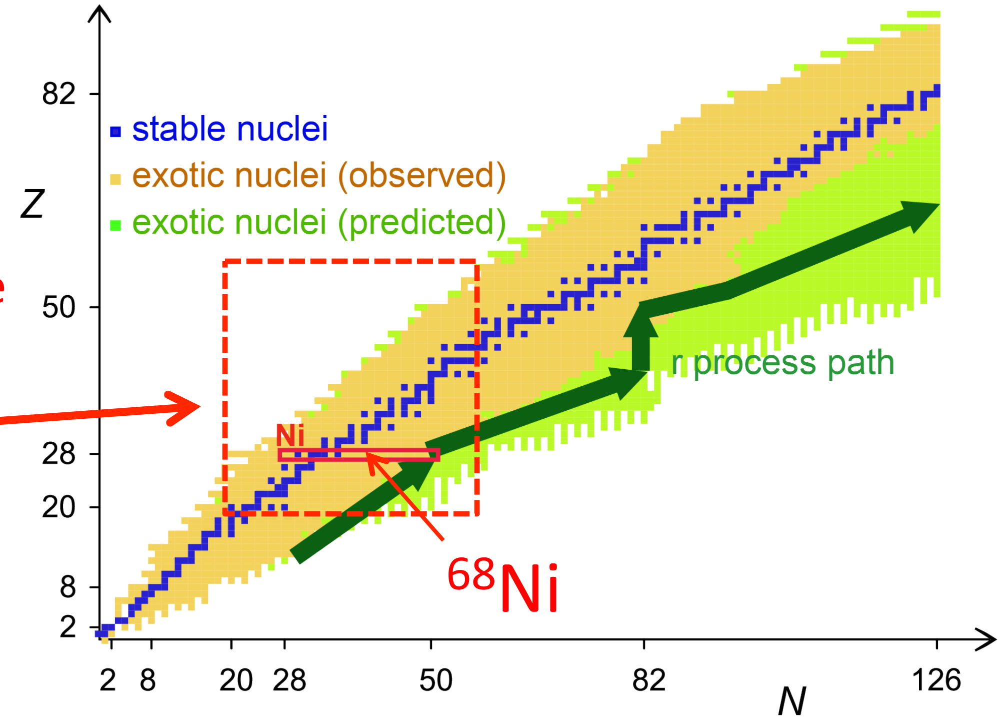
- Shape evolution (from seniority to rotor)
  - Xe and Ba isotopes

- Extension: Spectra to high-lying collective states
  - E1 excitation, GDR and PDR in Ca and Sr isotopes
  - Level density with shell model Hamiltonian

MCSM calculation on Ni isotopes

Y. Tsunoda et





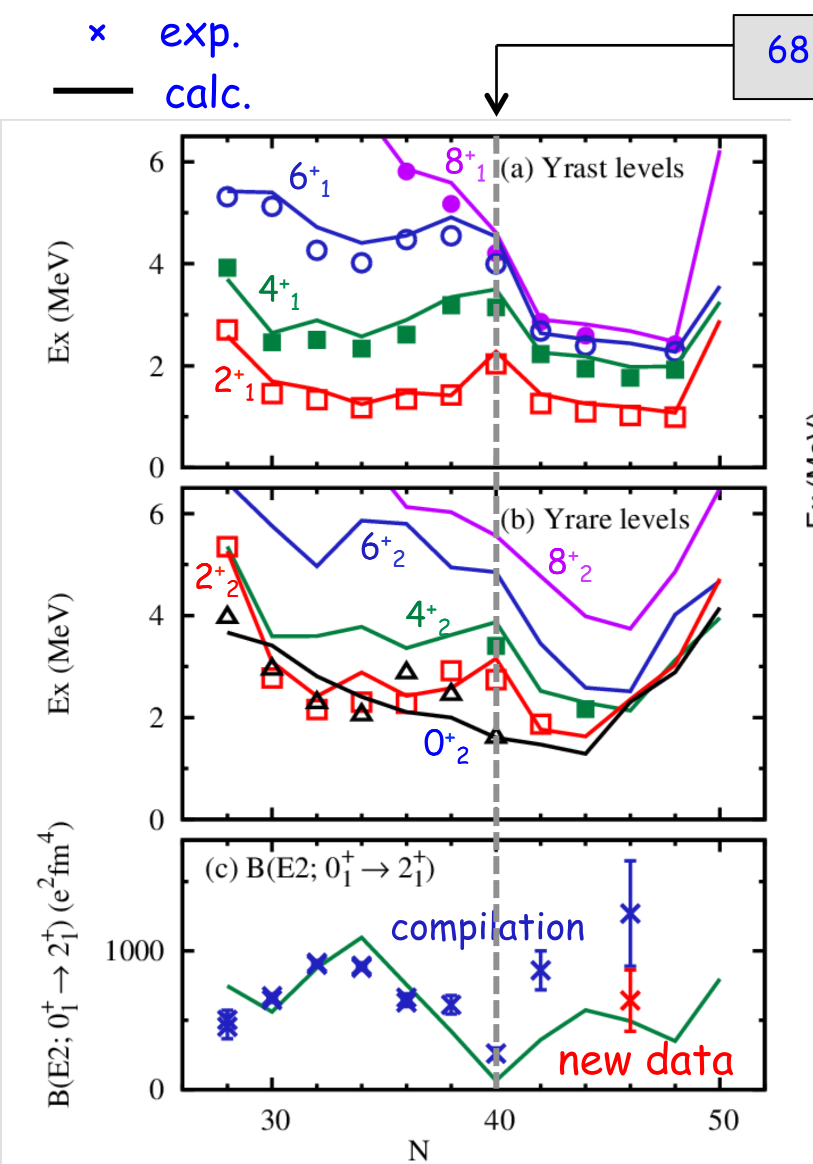
This model space is wide enough to discuss how magic numbers 28, 50 and semi-magic number 40 are visible or smeared out.

Interaction:
A3DA interaction is used with minor corrections

Energy levels and B(E2) values of Ni isotopes

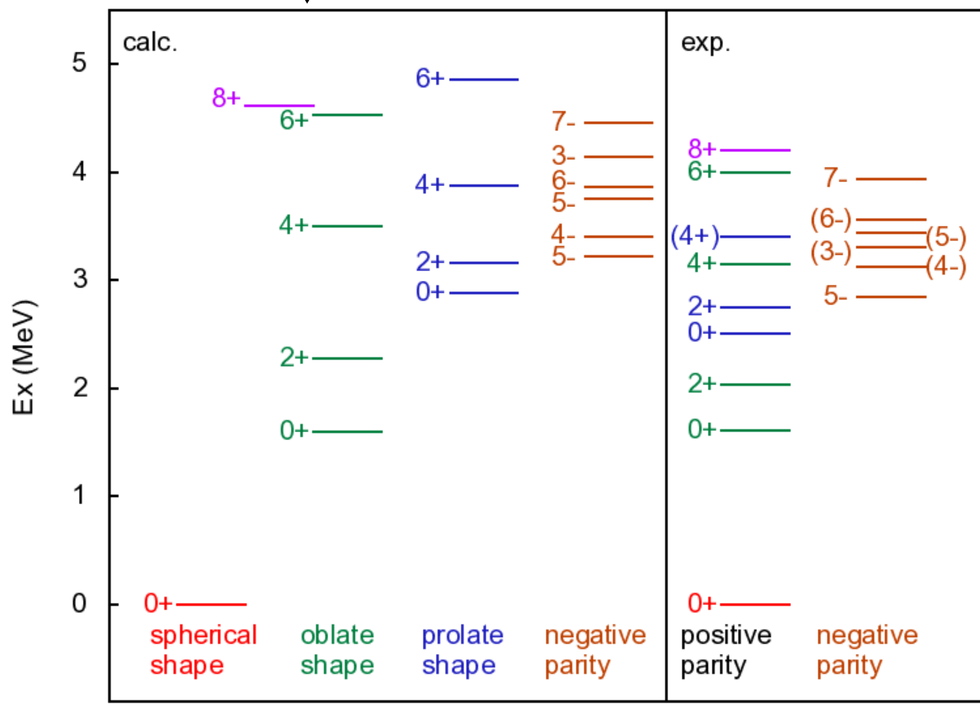
Description by the same Hamiltonian

Shape coexistence in ^{68}Ni



^{68}Ni

calc. exp.



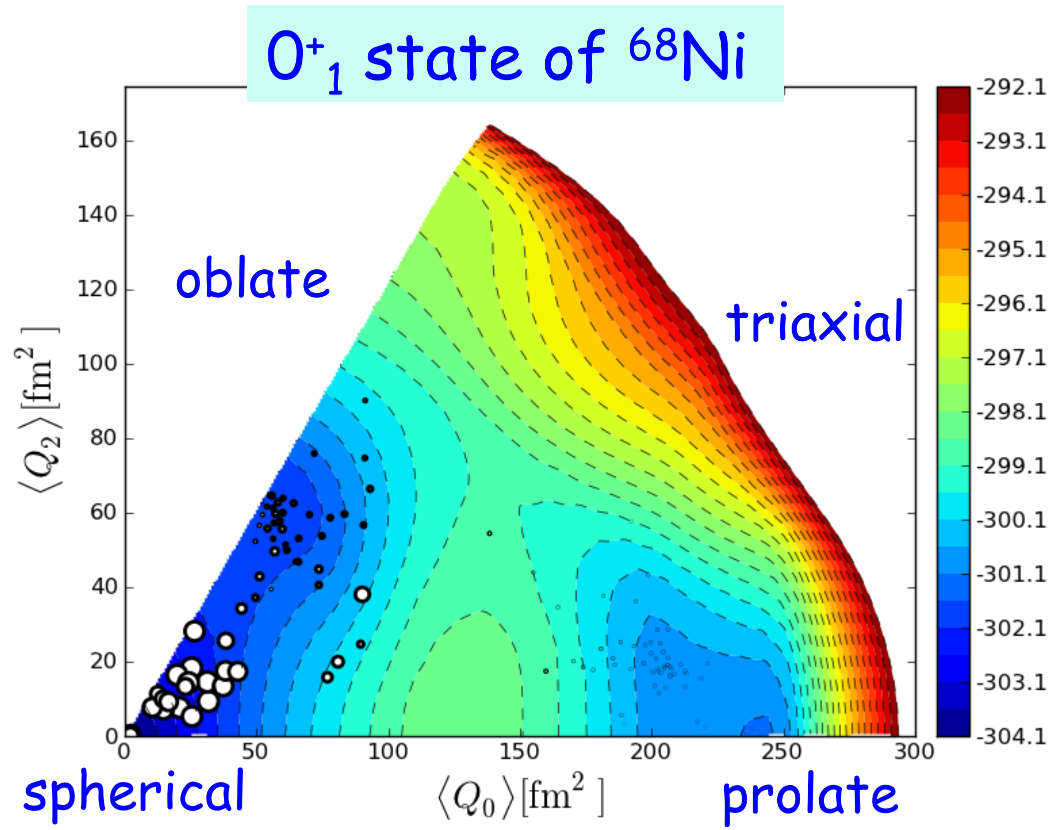
Y. Tsunoda, TO, Shimizu, Honma and Utsuno, PRC 89, 031301 (R) (2014)

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



Called *T-plot* in reference to

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

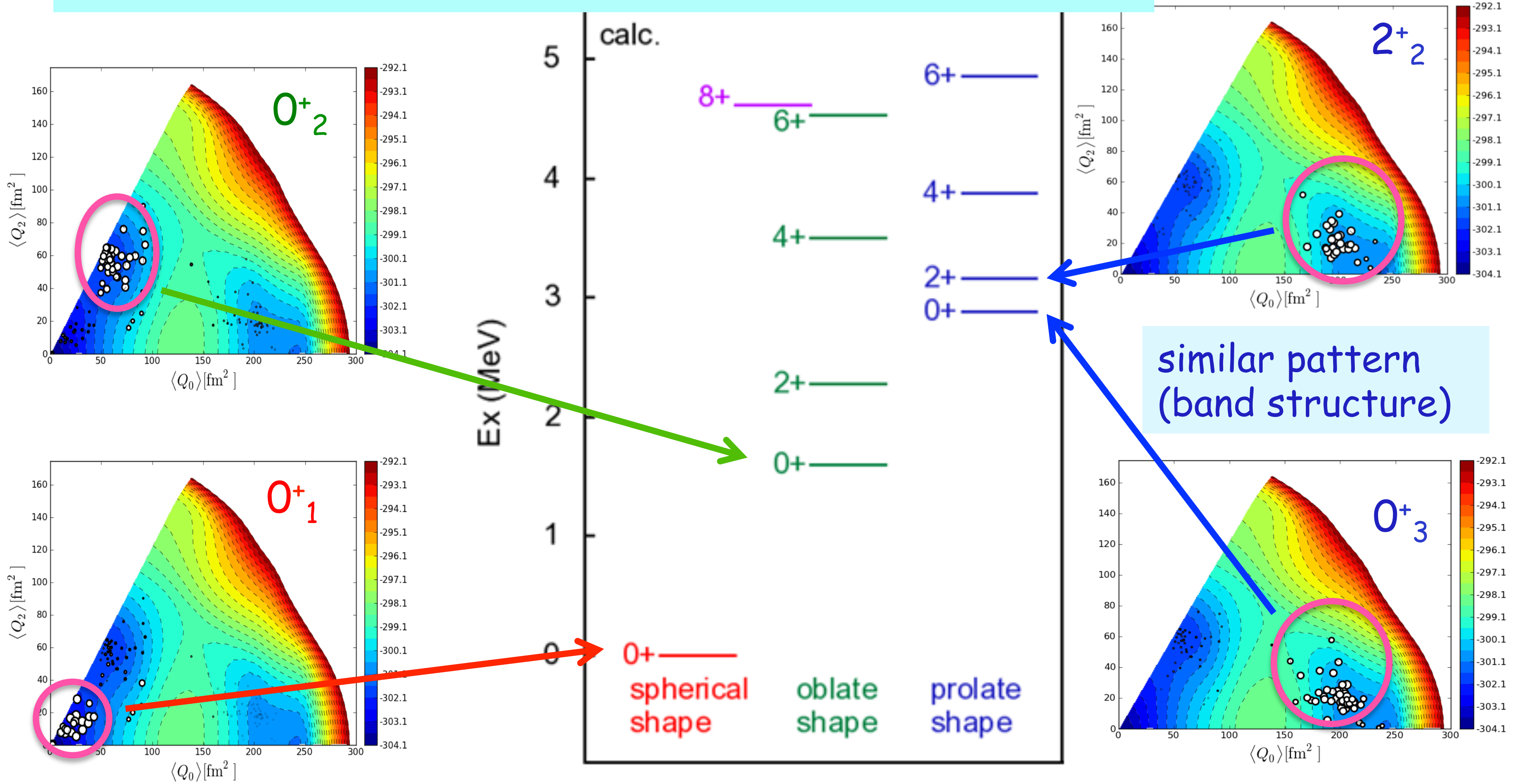
General properties of T-plot :

Certain number of large circles in a small region of PES

⇔ pairing correlations

Spreading beyond this can be due to shape fluctuation

Example : shape assignment to various 0^+ states of ^{68}Ni



^{68}Ni 0$^+$ states

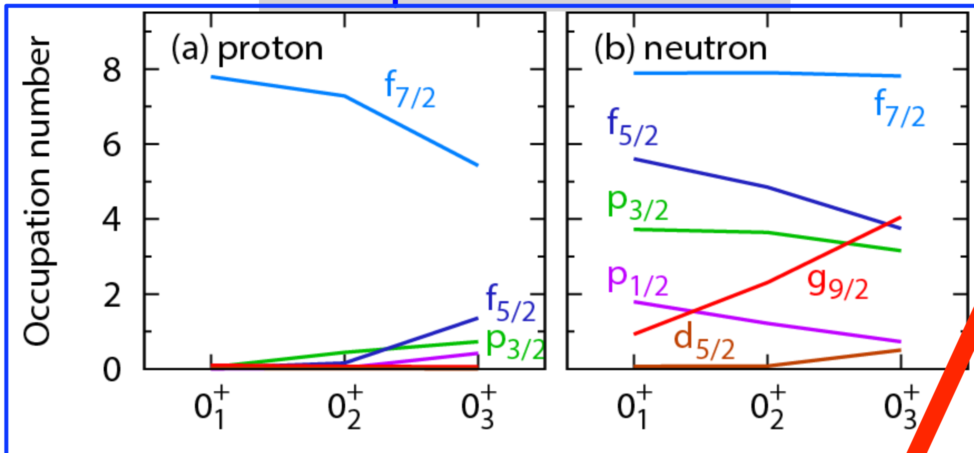
effective single-particle energies (ESPE) for correlated eigenstate

$$\epsilon_j = < \frac{\partial H_m}{\partial n_j} >$$

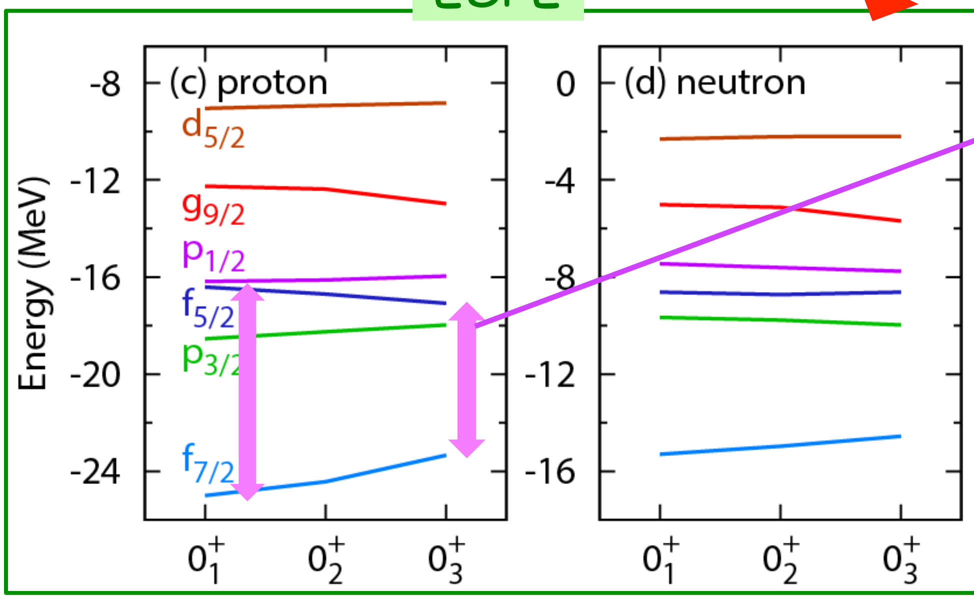
H_m monopole part of H

< > : by actual occup. numbers

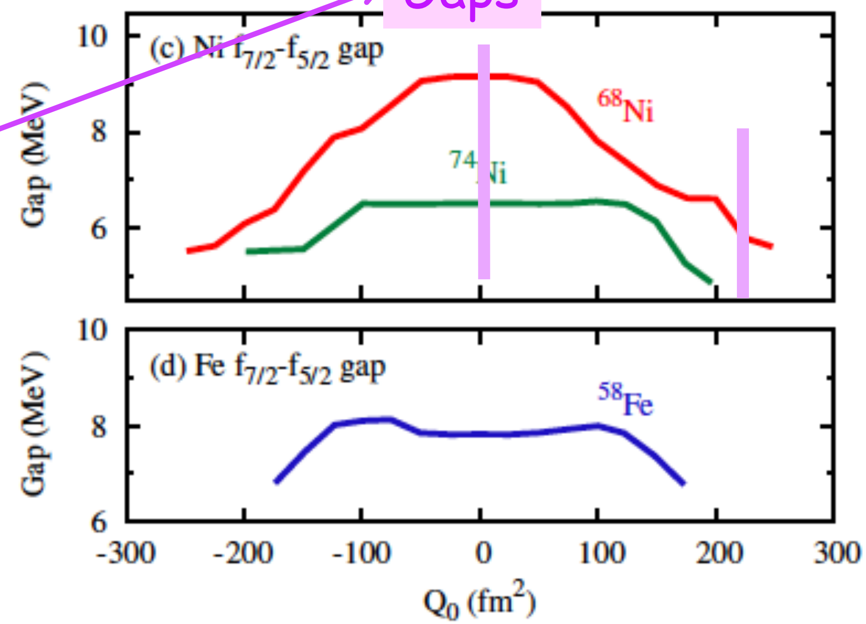
occupation numbers

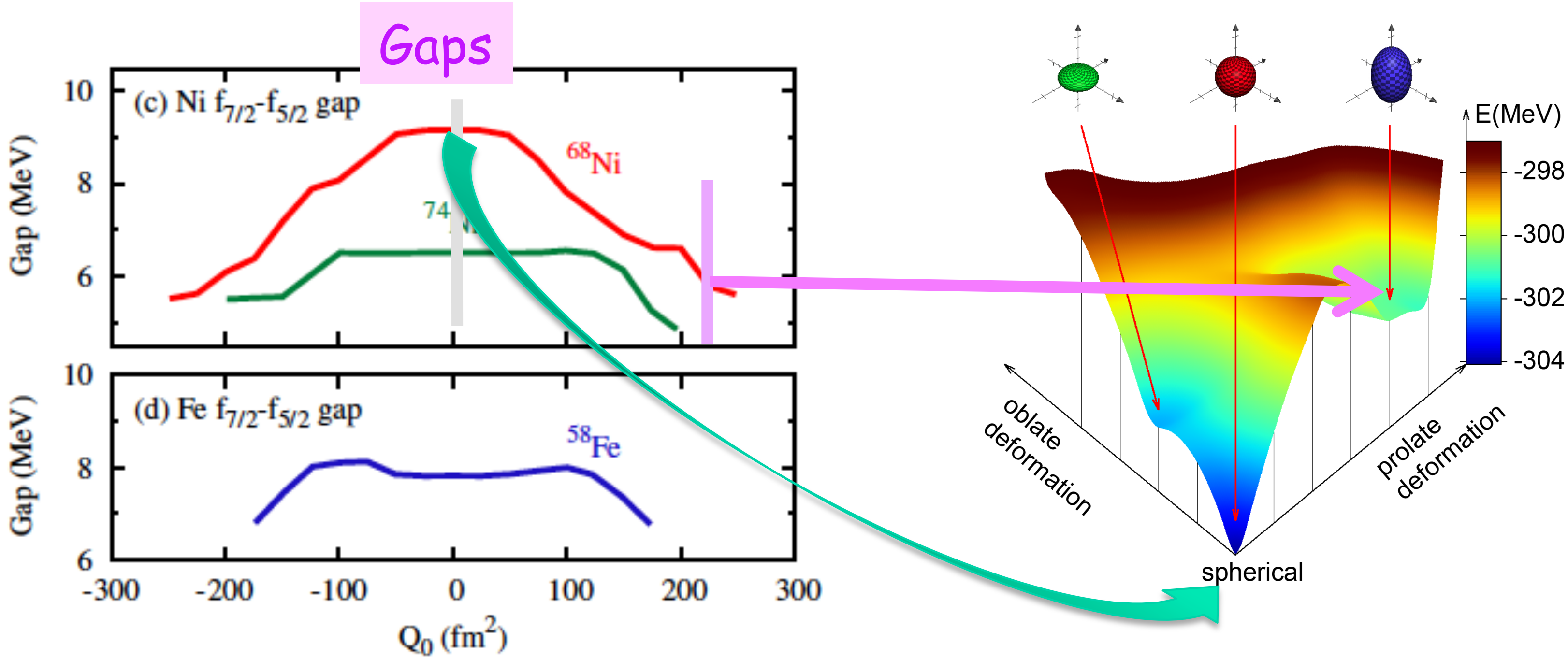


ESPE



Gaps





shell gap (spherical)

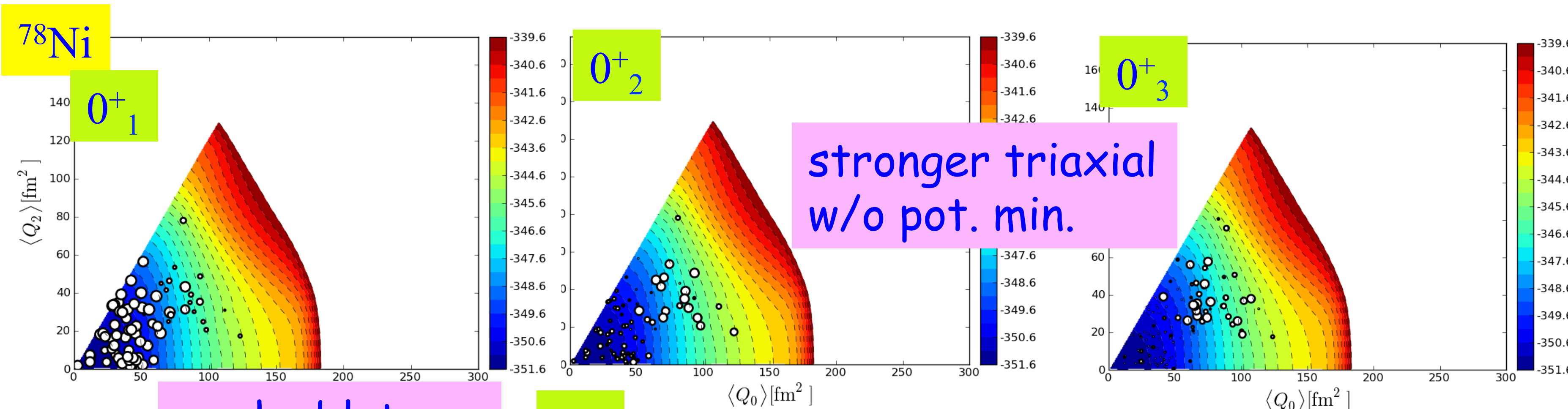
configurations = shapes

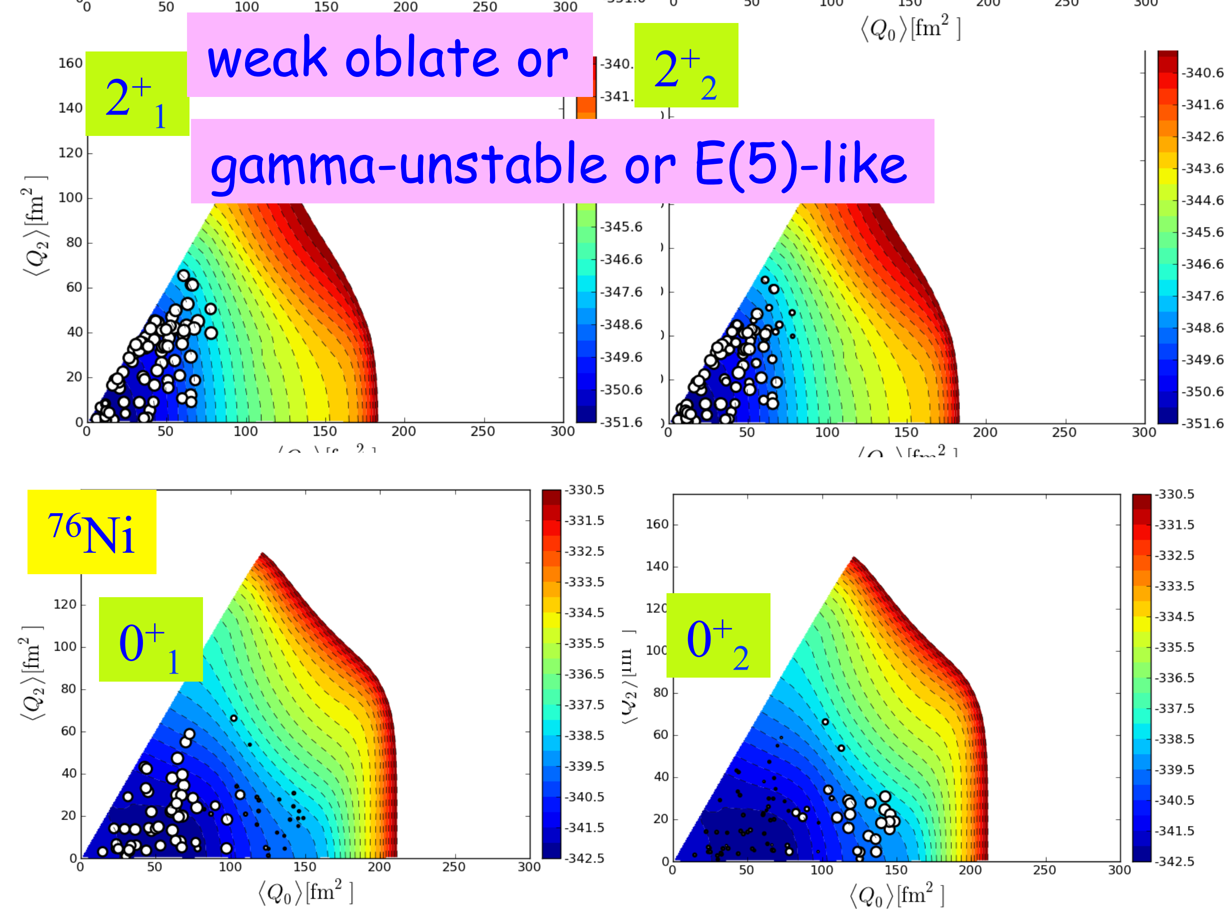
> determined self-consistently and non-linearly

Type II Shell Evolution

shell evolution within the same nucleus driven by the tensor force

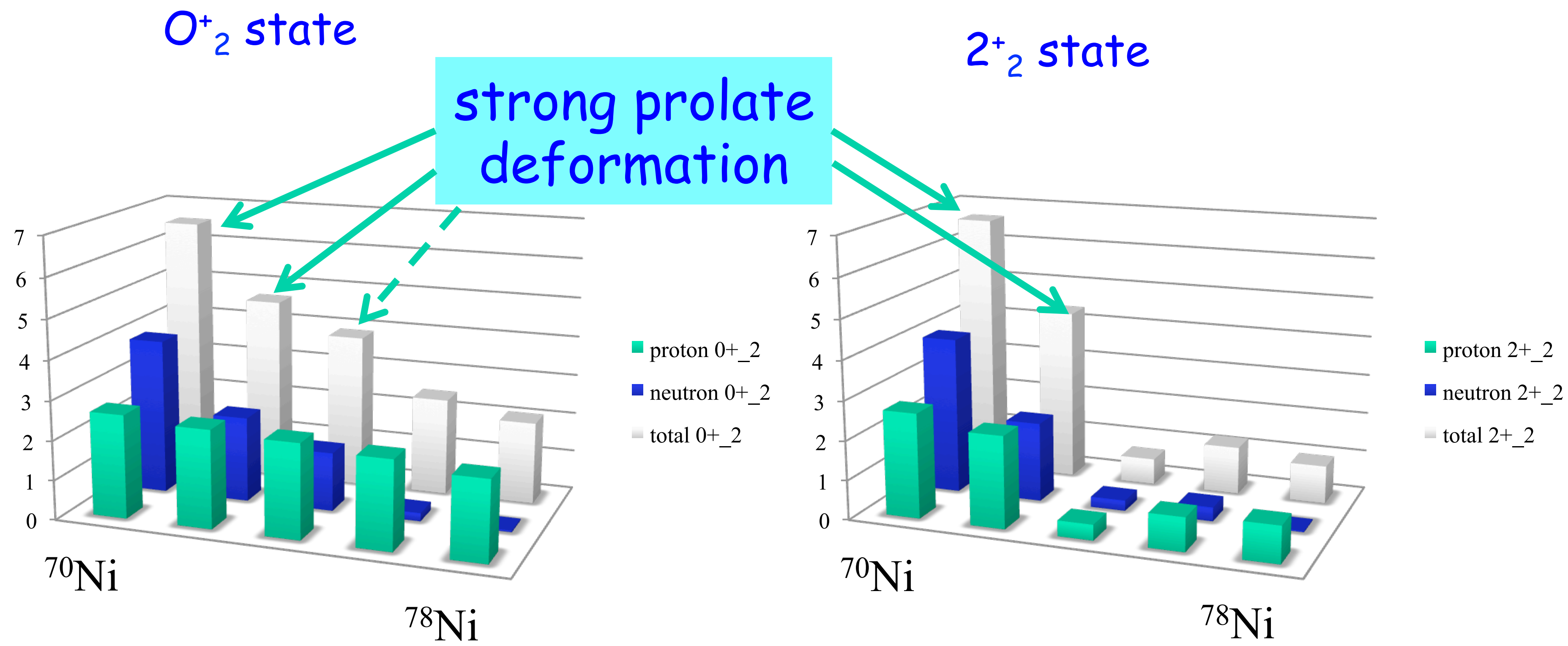
Spherical shell gap is not changed in Nilsson model





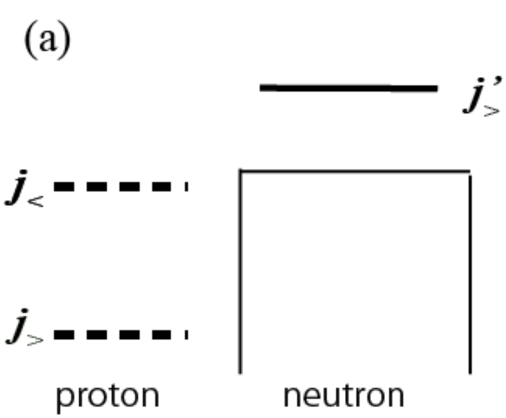
strong tendency towards
oblate,
triaxiality, or E(5)

Number of protons and neutrons excited across Z=28 or N=40 magic numbers

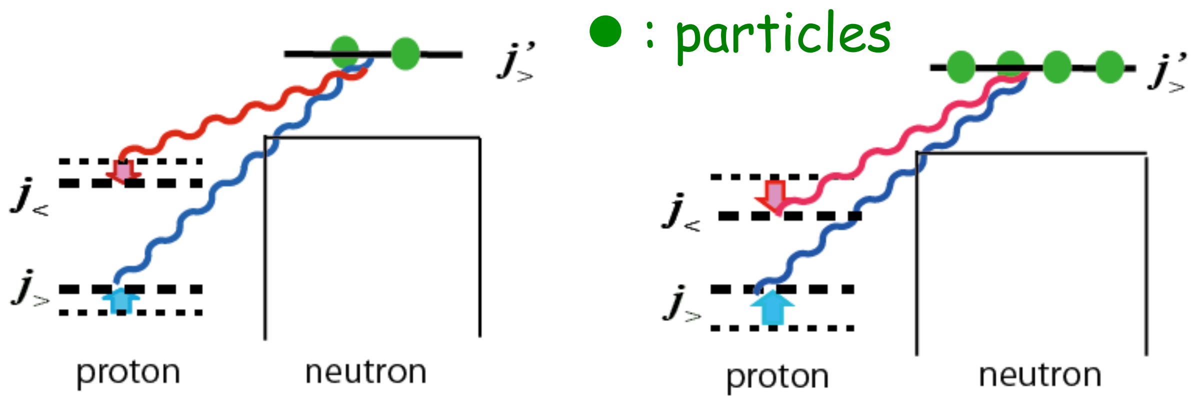


Underlying mechanism of the appearance of low-lying deformed states : Type II Shell Evolution

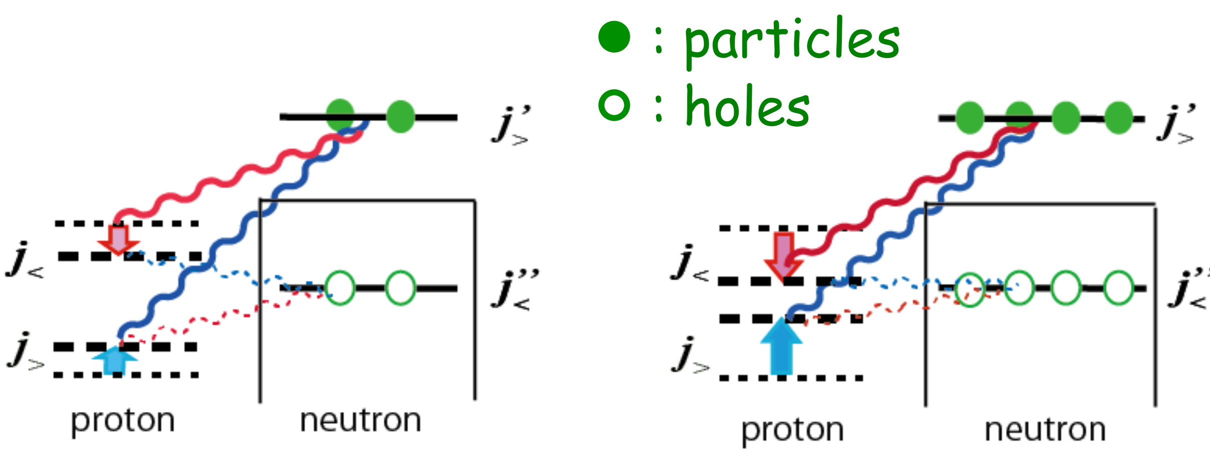
Monopole effects on the shell structure from the tensor interaction



Type I Shell Evolution : different isotopes

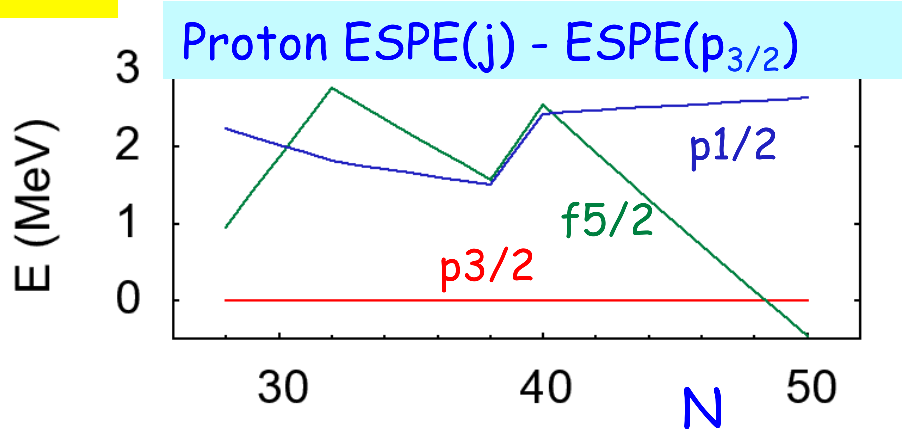


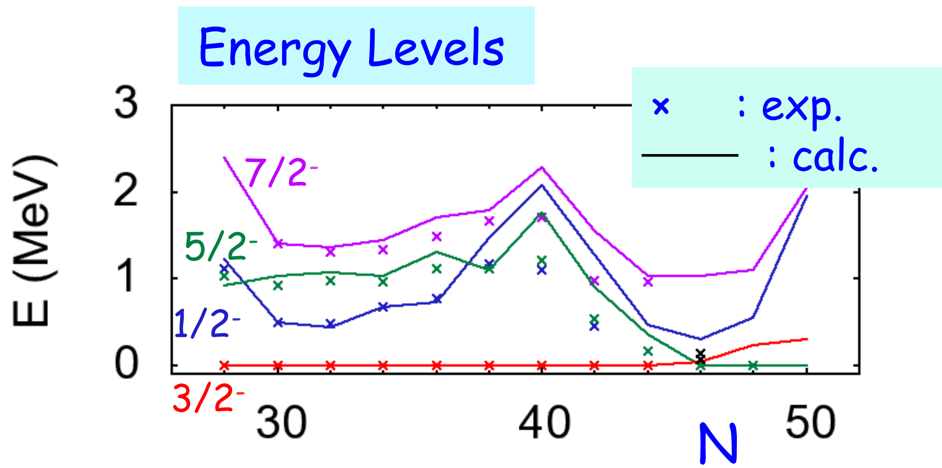
Type II Shell Evolution : within the same nucleus

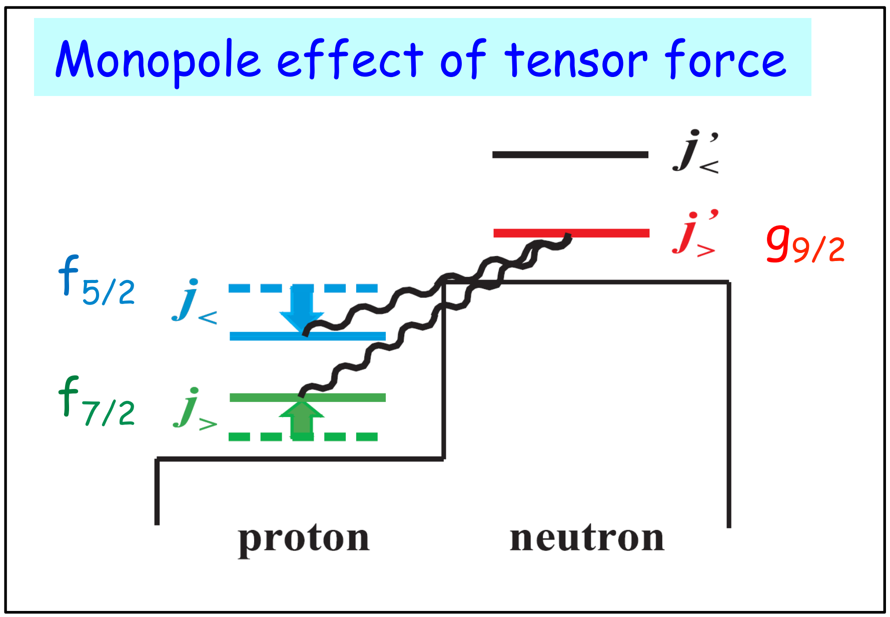


Cu isotopes

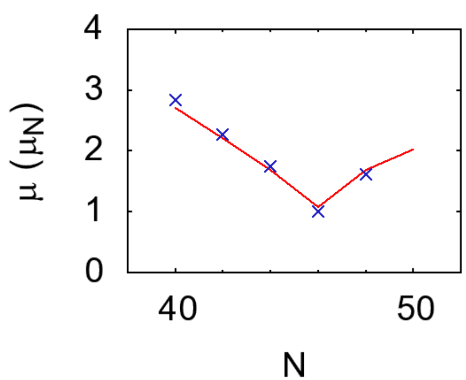
- proton $p_{3/2}$-$f_{5/2}$ level crossing from N = 40 to N = 50 (type I shell evolution)
- Calculated states show agreement with experiments, although they are not pure single-particle states.







magnetic moment of ground state



Shape coexistence of ^{70}Co (Z=27, N=43)

g.s. and an isomer in ^{70}Co are known experimentally (PRC **61**, 054308 (2000))

High-spin state (6^-,7^-)

$$\pi f_{7/2}^{-1} \nu g_{9/2}^{+3}$$

and Low-spin state (3^+)

$$\pi f_{7/2}^{-1} \nu p_{1/2}^{-1} \nu g_{9/2}^{+4}$$

were suggested

From our calculations,

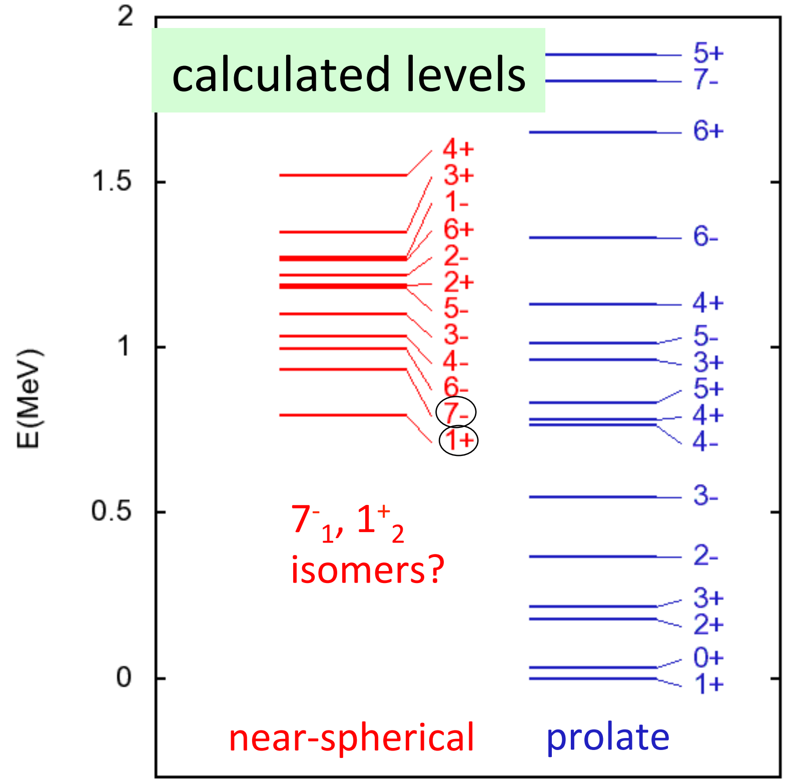
High-spin state (7^-) is near-spherical

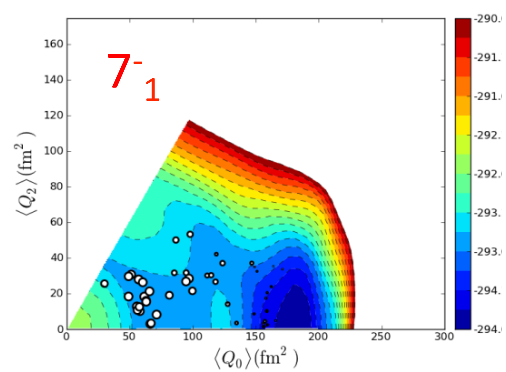
Low-spin state (1^+) is prolate deformed

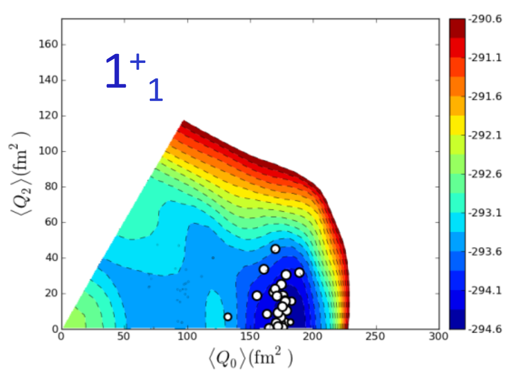
In the prolate state 1^+_1,
many nucleons are excited

~2.7 protons above Z=28 gap

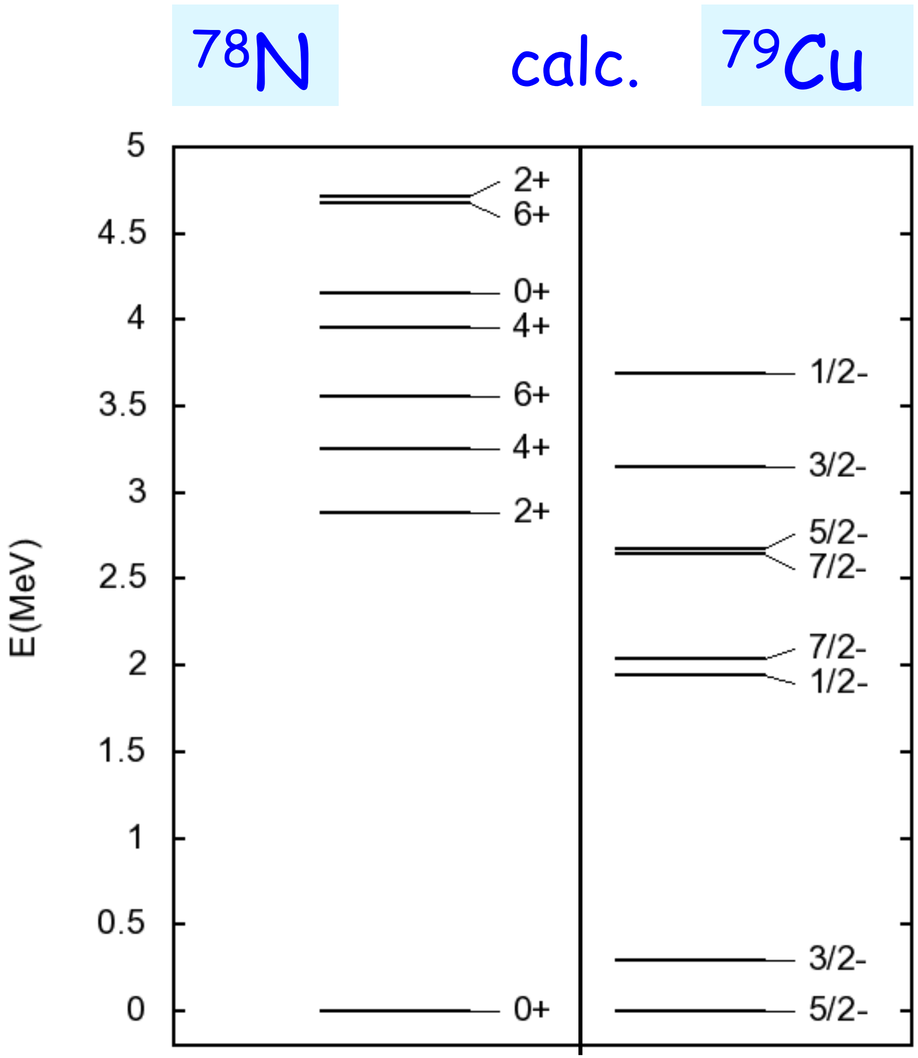
~3.1 neutron holes below N=40 gap



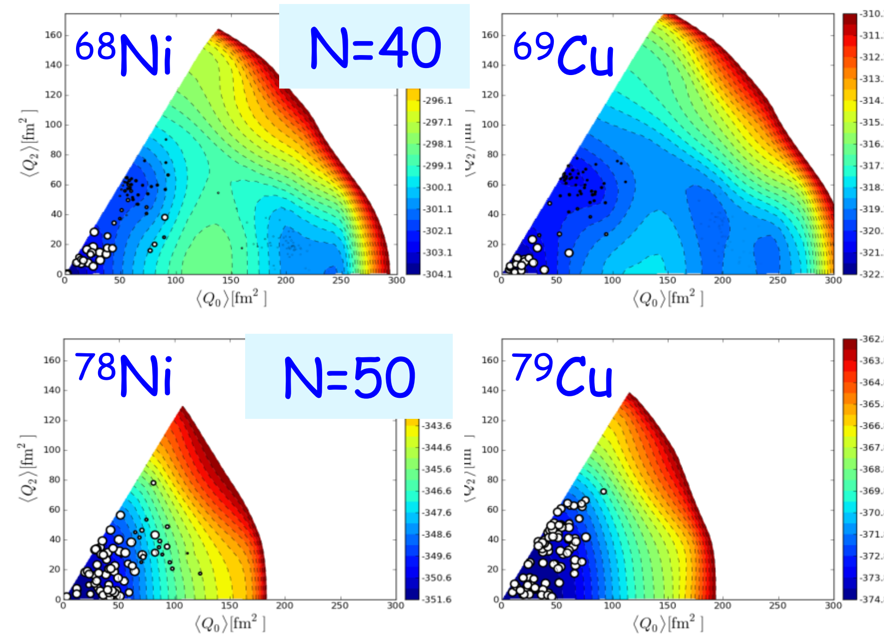




^{68}Ni - ^{69}Cu v.s. ^{78}Ni - ^{79}Cu



T-plot of ground state



- Similar distribution patterns between Ni and Cu, while Cu is somewhat more deformed
- Shape fluctuations are larger in N=50 isotones

Outline

- Methodology: advanced Monte Carlo shell model (MCSM)
  - intrinsic shape can be the objectives
  - ab initio (no core) MCSM and clustering in Be isotopes

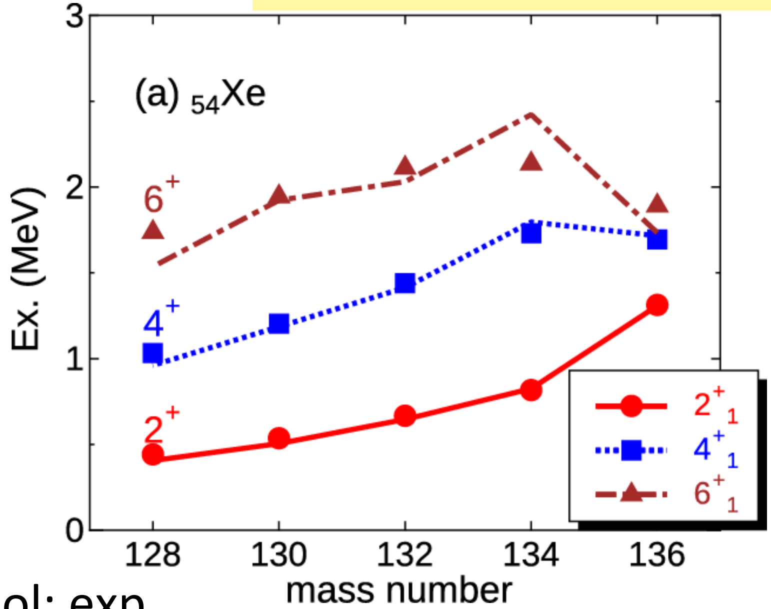
- Shape coexistence and Quantum Liquid picture
  - exotic Ni isotopes (+ Co, Cu)

- Shape evolution (from seniority to rotor)
  - Xe and Ba isotopes

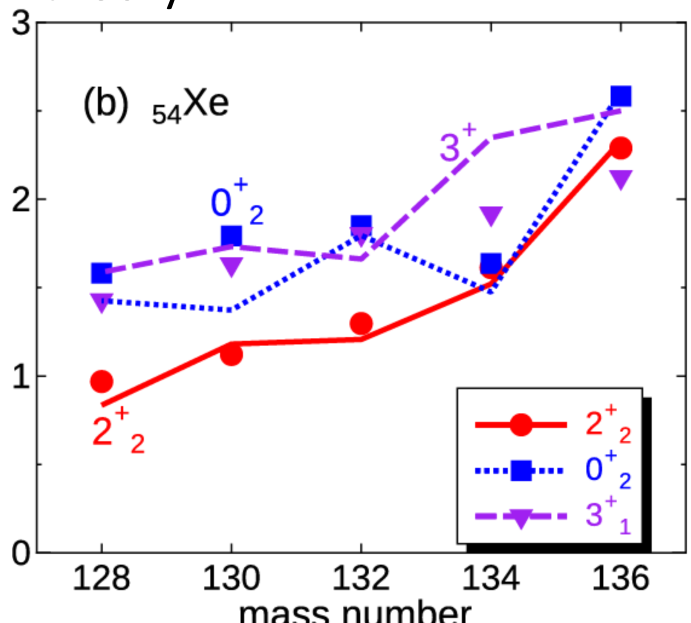
- Extension: Spectra to high-lying collective states
  - E1 excitation, GDR and PDR in Ca and Sr isotopes
  - Level density with shell model Hamiltonian

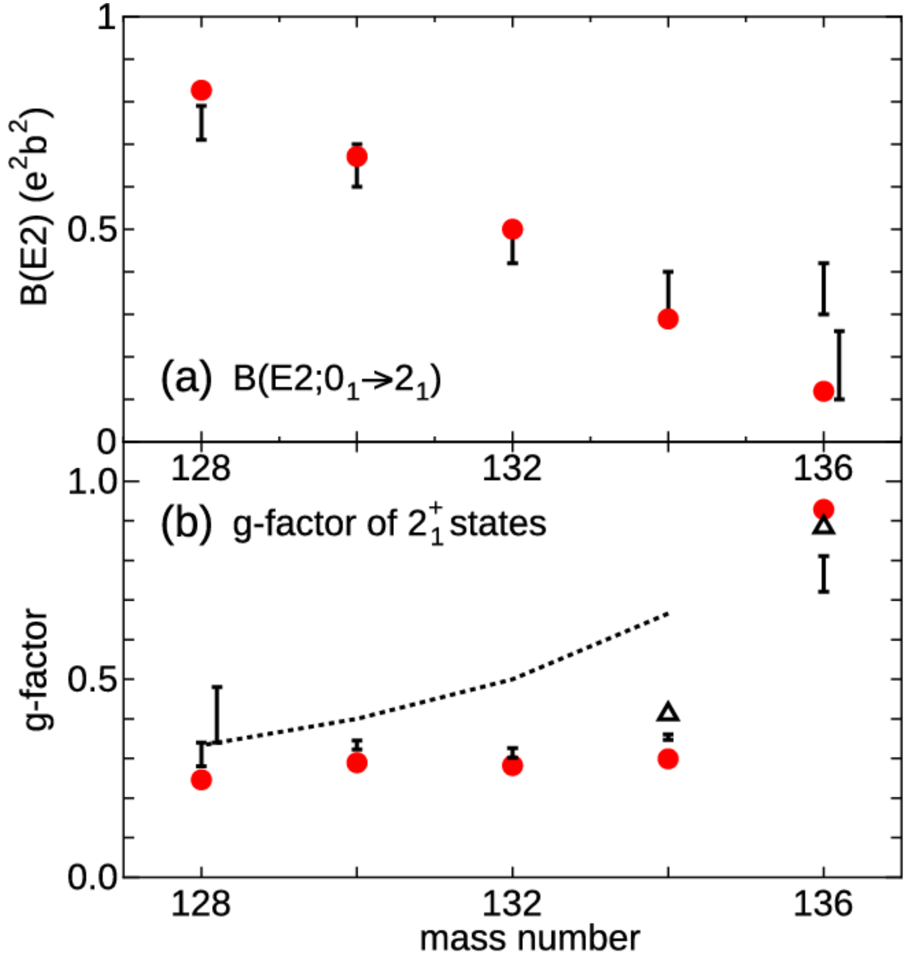
Shape evolution of Xe isotopes

P+QQ int.
model space: 50<N,Z<82



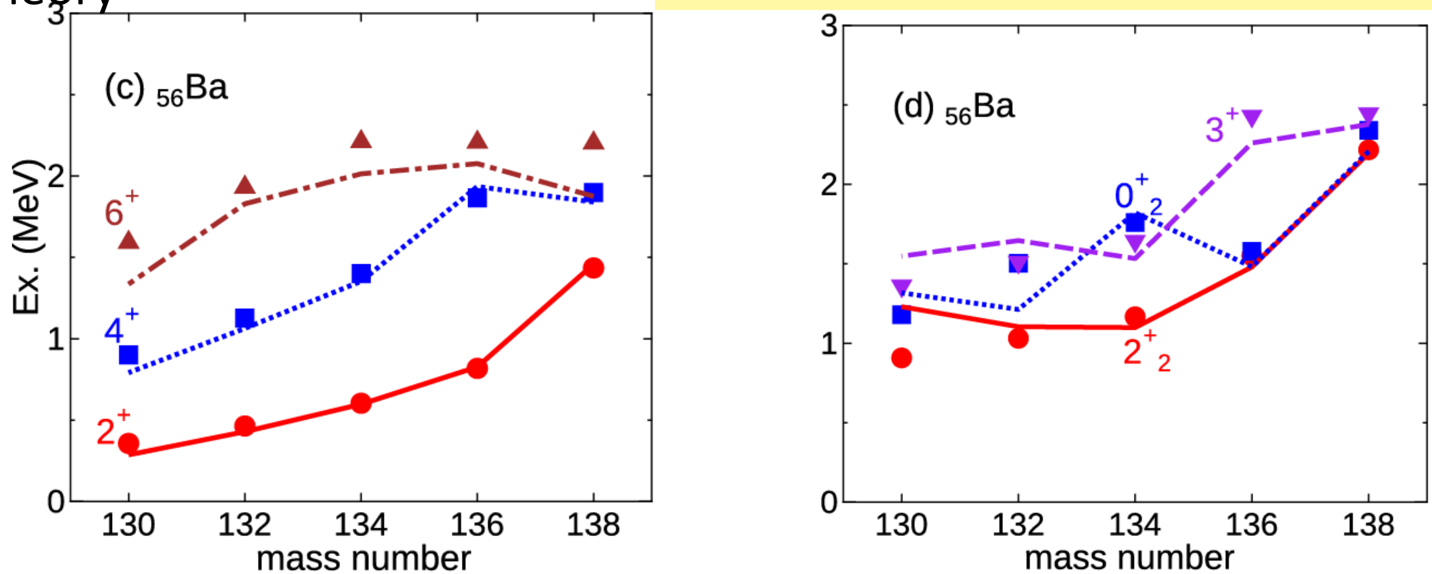
symbol: exp.
line : theory



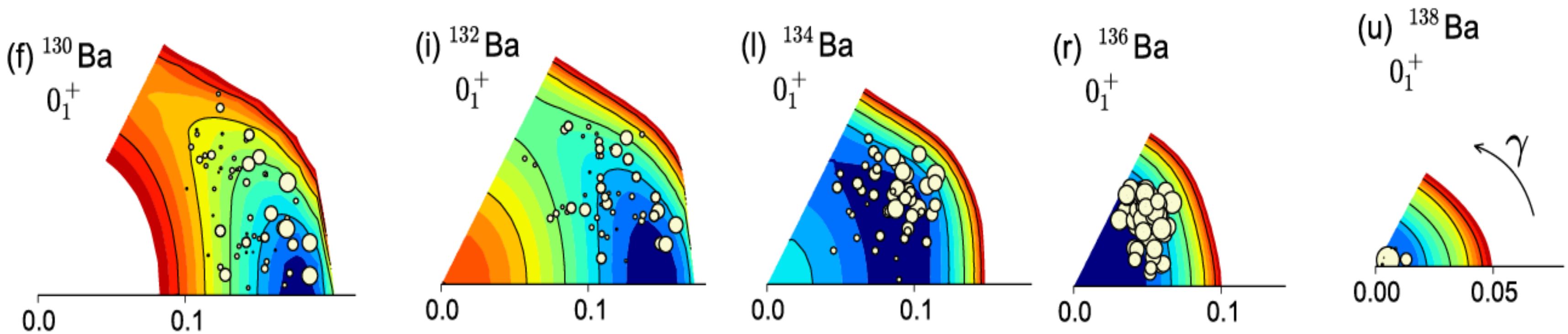


Shape evolution of Ba isotopes

symbol: exp.
line : theory



P+QQ int.
model space:
50<N,Z<82



MCSM w.f.

$$\left|\Psi\right\rangle = \sum_{k=1}^{N_{MCSM}\sim 100} f_k P^{J,\pi} \left|\phi_k\right\rangle$$

PES by Q-constraint HFB calc. for the SM Hamiltonian

Location of circle : quadrupole deformation of $|\phi_k>$

Area of circle : overlap probability with the eigenstate

Outline

- Methodology: advanced Monte Carlo shell model (MCSM)
  - intrinsic shape can be the objectives
  - ab initio (no core) MCSM and clustering in Be isotopes

- Shape coexistence and Quantum Liquid picture
  - exotic Ni isotopes (+ Co, Cu)

- Shape evolution (seniority to rotor)
  - Xe and Ba isotopes

- Extension: Spectra to high-lying collective states
  - E1 excitation, GDR and PDR in Ca and Sr isotopes

E1 excitation of Ca isotopes in (conventional) LSSM

NS, Y. Utsuno, S. Ebata, T. Otsuka, M. Honma and T. Mizusaki, in preparation

1hw/3hw sd-pf-sdg shell calculations
for negative-parity states of Ca isotopes

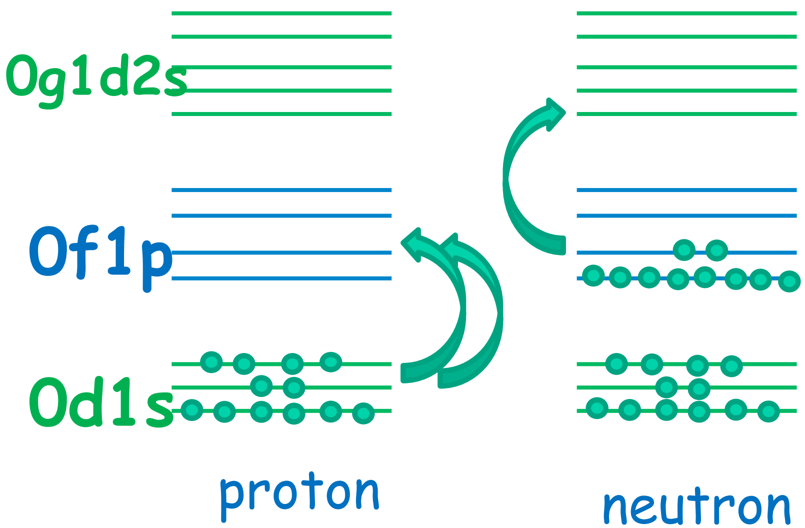
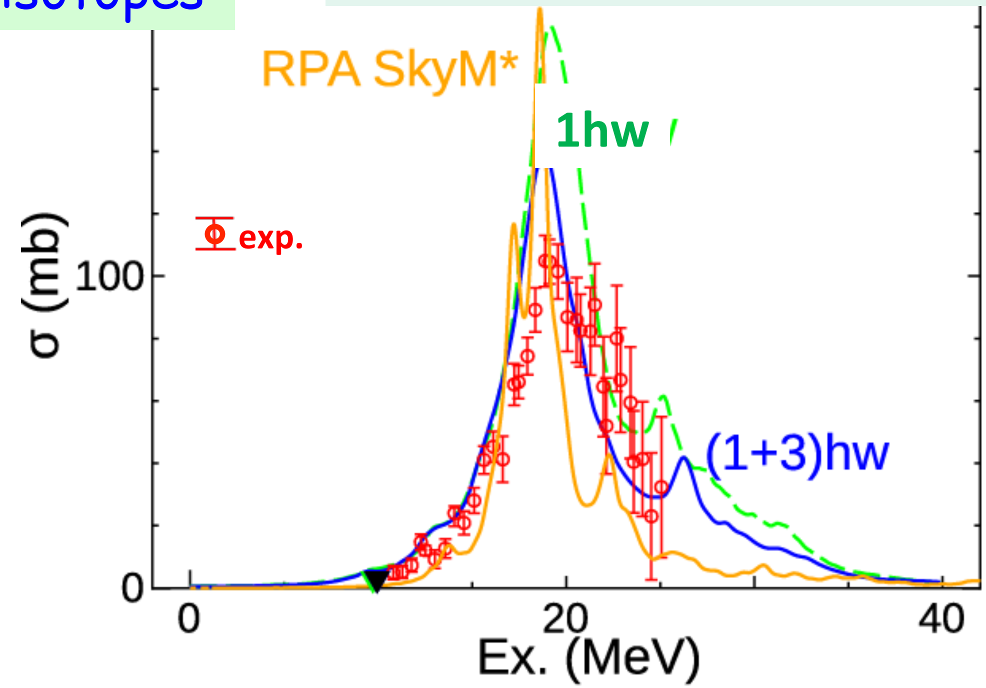


Photo-absorption cross section of ^{48}Ca



M-scheme shell-model code
"KSHELL"
by Lanczos method
on massive parallel computer

1hw : upto 1hw excitation in sd-pf-sdg shell
4.1×10^{6} M-scheme dim. at PC

(1+3)hw: up to 3hw excitation in sd-pf-sdg shell
1.2×10^{10} M-scheme dim. at supercomputer

B(E1) sum rule by Monte Carlo shell model N_{max} ħω configuration

E1 sum rule from fully correlated ground state wave function

- ^{48}Ca B(E1) sum rule (e^2fm^2)
  - 1ħω ... **16.5**
  - (1+3)ħω ... **13.6**
  - MCSM 50dim. ... **10.1**

-18%

-38%

- ^{51}V B(E1) sum rule (e^2fm^2)
  - 1ħω … **18.1**
  - (1+3)ħω … **NA**
  - MCSM 50dim … **12.4**

-32%

Many-body correlations reduces B(E1) sum rule

E1 excitation spectrum can be calculated by MCSM

Ground state:

$$|\Psi\rangle = \sum_{k=1}^{N_{MCSM}} f_k P^{J,\pi} |\varphi_k\rangle$$

Basis vector of the ground state

Basis vectors for *E1* spectrum (*a,b,c,d*, … : orbits)

$$\exp(i\varepsilon \cdot E1(a \to b))|\varphi_k\rangle,\ \exp(i\varepsilon \cdot E1(c \to d))|\varphi_k\rangle,\ \ldots (k = 1,2,\ldots)$$

These are still Slater determinants

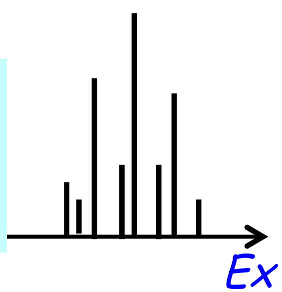
\+

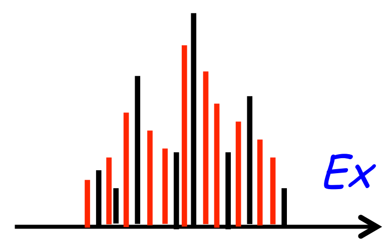
Additional bases for fine tuning :
variation for energy average by the conjugate gradient

$$|\varphi_k(E1(a \to b))^{Var}\rangle,\ \ |\varphi_k(E1(c \to d))^{Var}\rangle, \cdots$$

The global feature of excitation spectrum can be calculated.

Diagonalization with these basis vectors after projection to 1^-



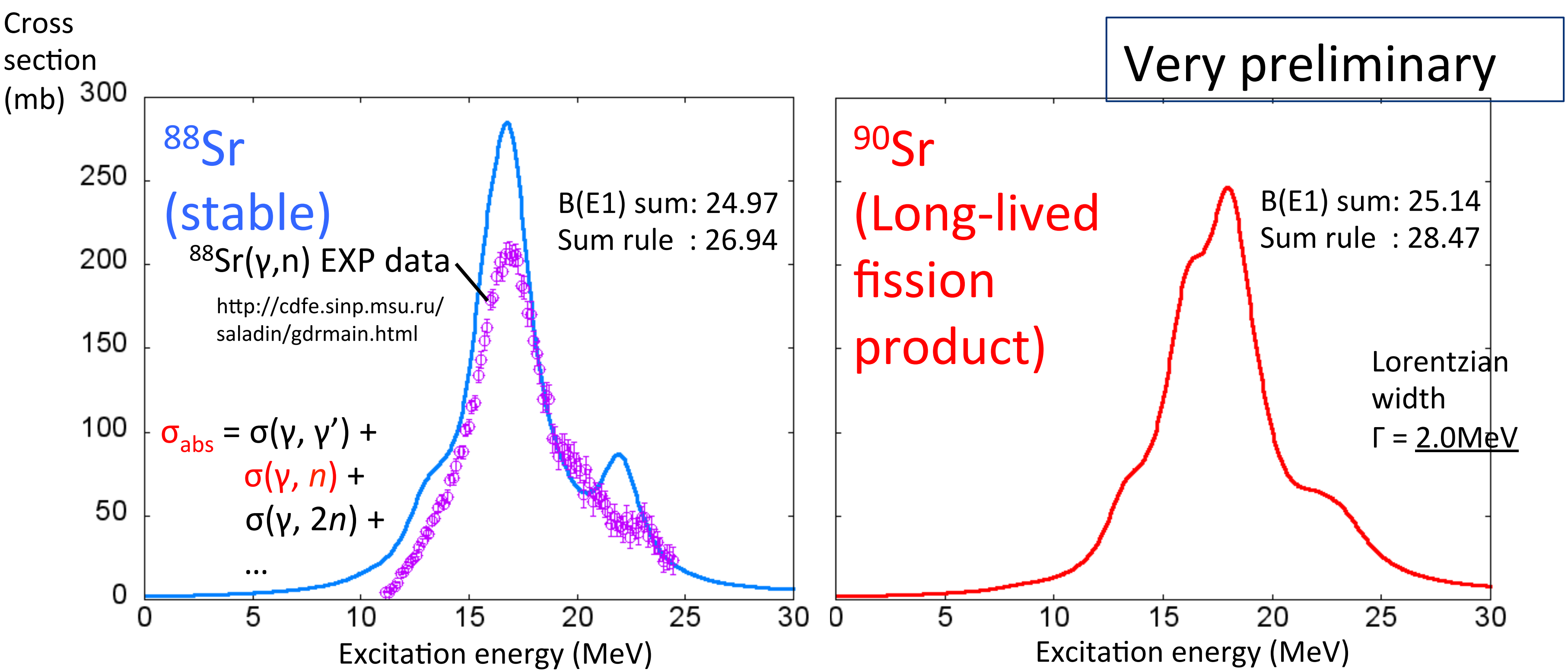


E1 spectrum with ~3000 levels connected somehow to the g.s. (confirmed by E1 sum rule)

E1 excitation spectrum by MCSM

T. Togashi, T. Otsuka *et al.*

Photoabsorption cross section of ^{88}Sr, ^{90}Sr



Application to the nuclear transmutation
for the purpose of nuclear waste processing (ex. ^{90}Sr LLFP)
as basic data for nuclear technology

Perspectives

1. Ab initio at the level of shell-model Hamiltonian based on EKK method (for multi-shells)
   tensor + 3NF inclusive

2. Variety of magic nuclei (magic index)

3. Quantum liquid - single or dual –
   implications ?

4. Shell evolution in continuum and doorway-state resonance - reminiscence of bound states -

5. Shapes and clusters by MCSM

6. Excitation spectrum by MCSM and their application to astrophysics, nuclear energy, etc.

Collaborators

HPCI project, Field 5

- Takashi Abe (Tokyo)
- Shuichiro Ebata (Hokkaido)
- Michio Honma (Aizu)
- Yoritaka Iwata (CNS, Tokyo)
- Takahiro Mizusaki (Senshu Univ.)
- Noritaka Shimuzu (CNS, Tokyo)
- Tomoaki Togashi (CNS, Tokyo)
- Naofumi Tsunoda (CNS, Tokyo)
- Yusuke Tsunoda (CNS, Tokyo)
- Yutaka Utsuno (JAEA)
- Tooru Yoshida (CNS, Tokyo)

- James Vary (Iowa)
- Pieter Maris (Iowa)

END

ご清聴ありがとうございました