Resonance workshop, RIFP
Kyoto, Japan
December 13 (12-13), 2012

Low-lying continuum states of drip-line Oxygen isotopes

Takaharu Otsuka
University of Tokyo / MSU

Koshiroh Tsukiyama, Rintaro Fujimoto
University of Tokyo

東京大学
THE UNIVERSITY OF TOKYO

Motivation

Emission from doorway-state

A bound state is shifted to continuum suddenly through a nuclear reaction

V.S.

Emission from single-particle resonance

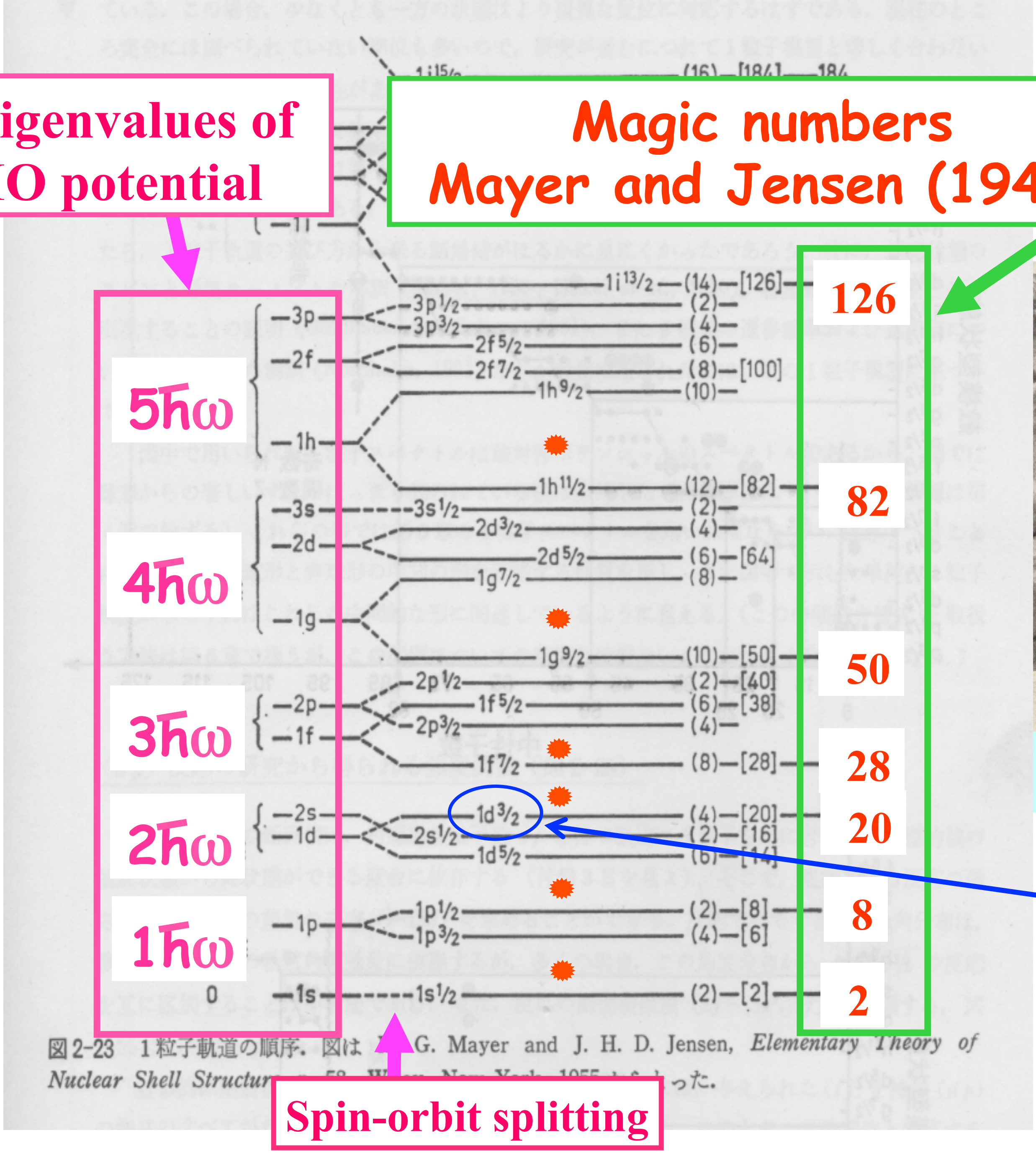


図2-23 1粒子軌道の順序．図は G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structur* … った．

Eigenvalues of HO potential

$5\hbar\omega$

$4\hbar\omega$

$3\hbar\omega$

$2\hbar\omega$

$1\hbar\omega$

Spin-orbit splitting

Magic numbers
Mayer and Jensen (1949)

126

82

50

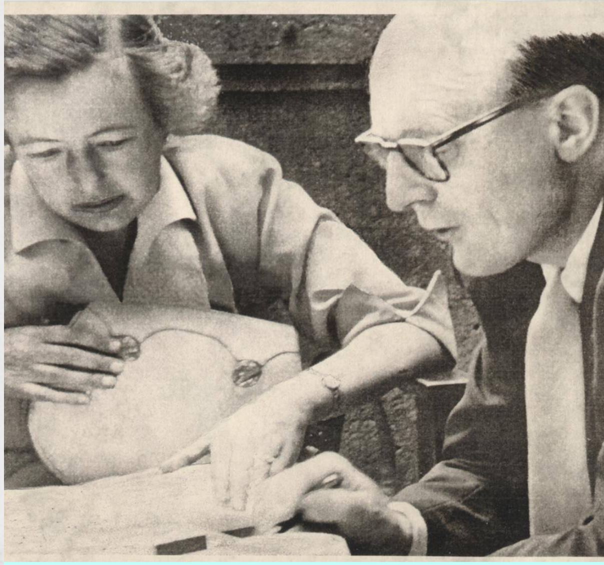
28

20

8

2

$d_{3/2}$



Mayer & Jensen

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

solid line : full (central + tensor)

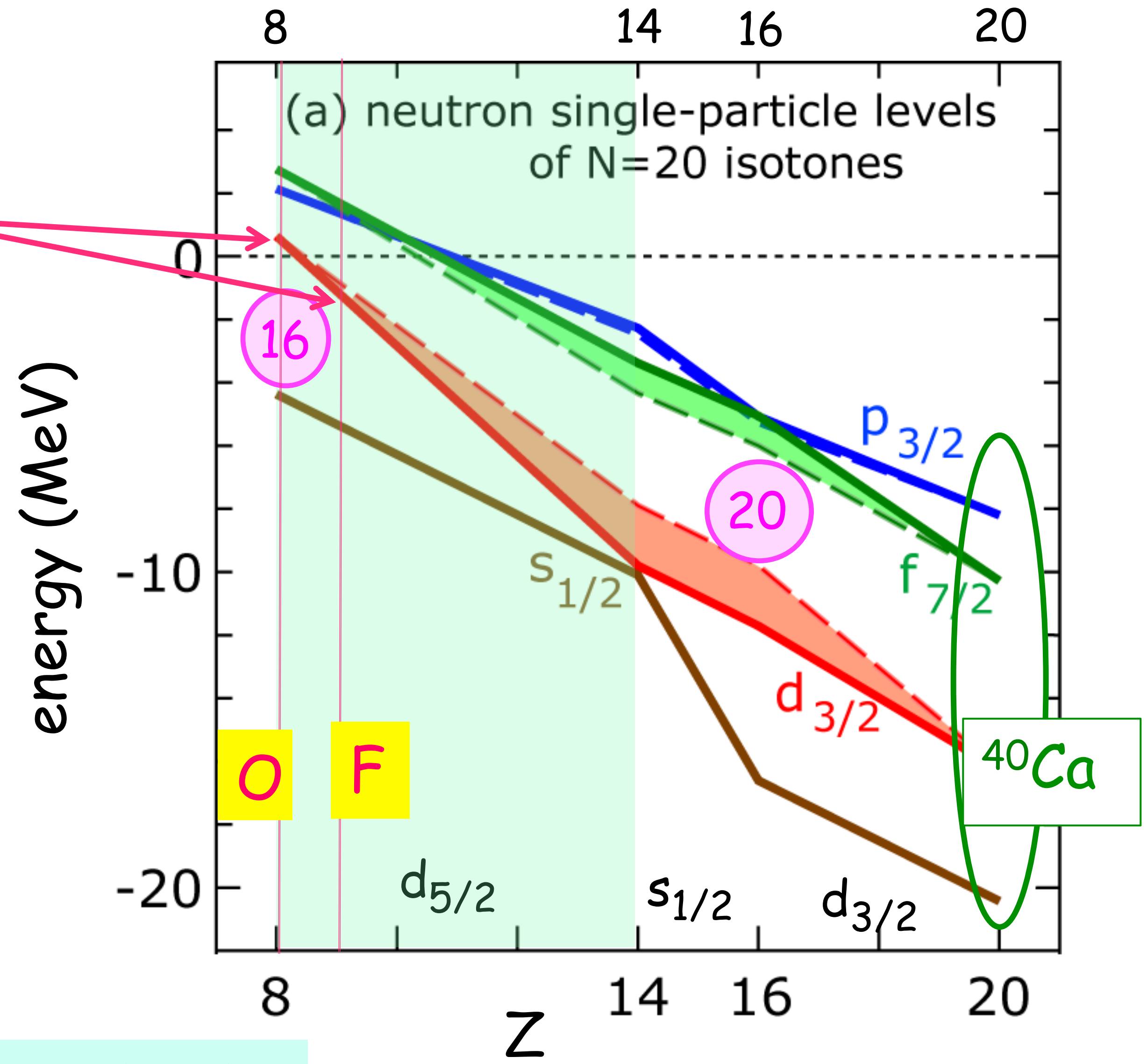
dashed line : central only

$d_{3/2}$

bound in F

unbound in O

due to interplay between tensor and three-body forces

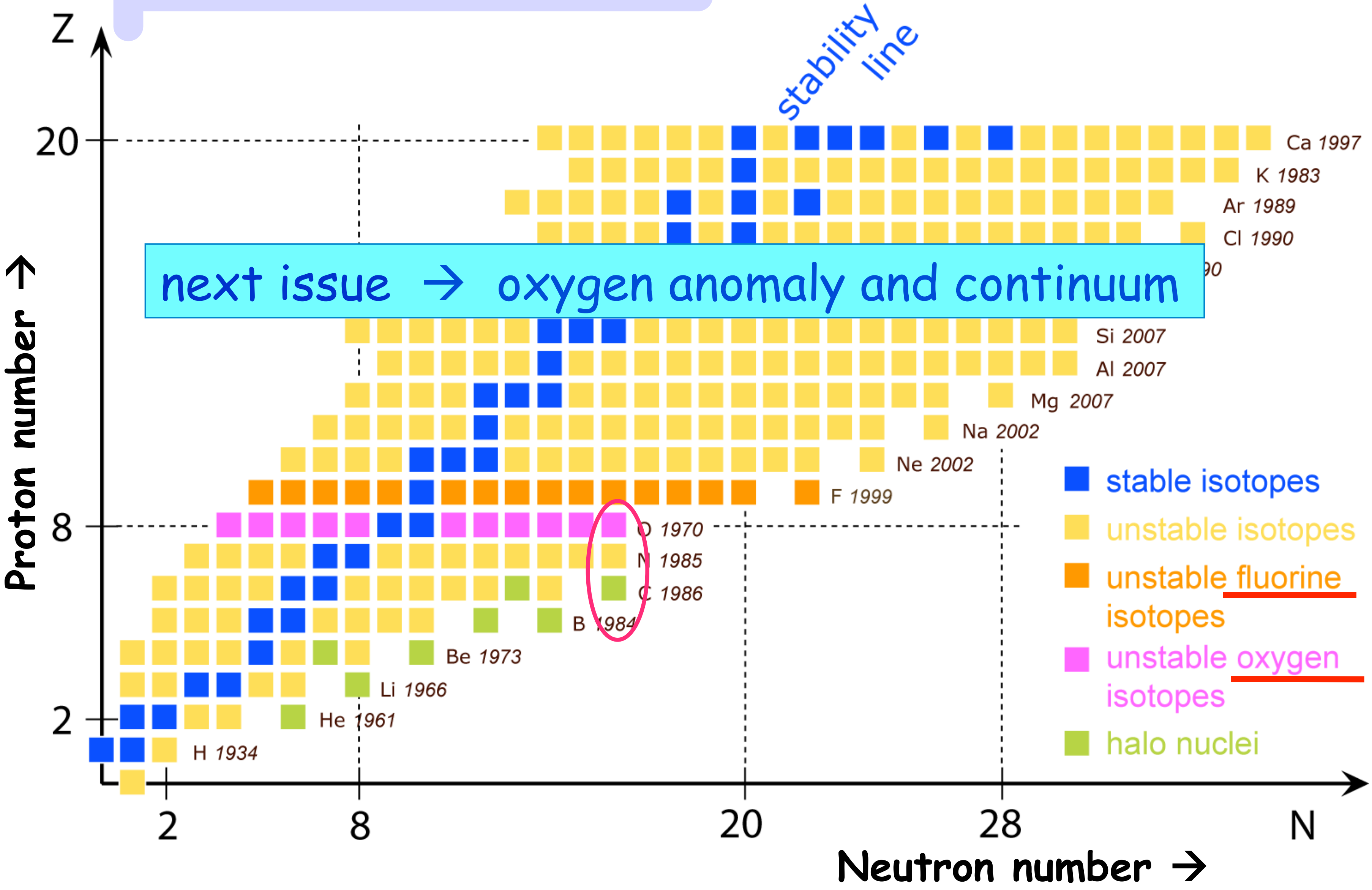


TO, et al. PRL 104, 012501 (2010)

One of the Backgrounds

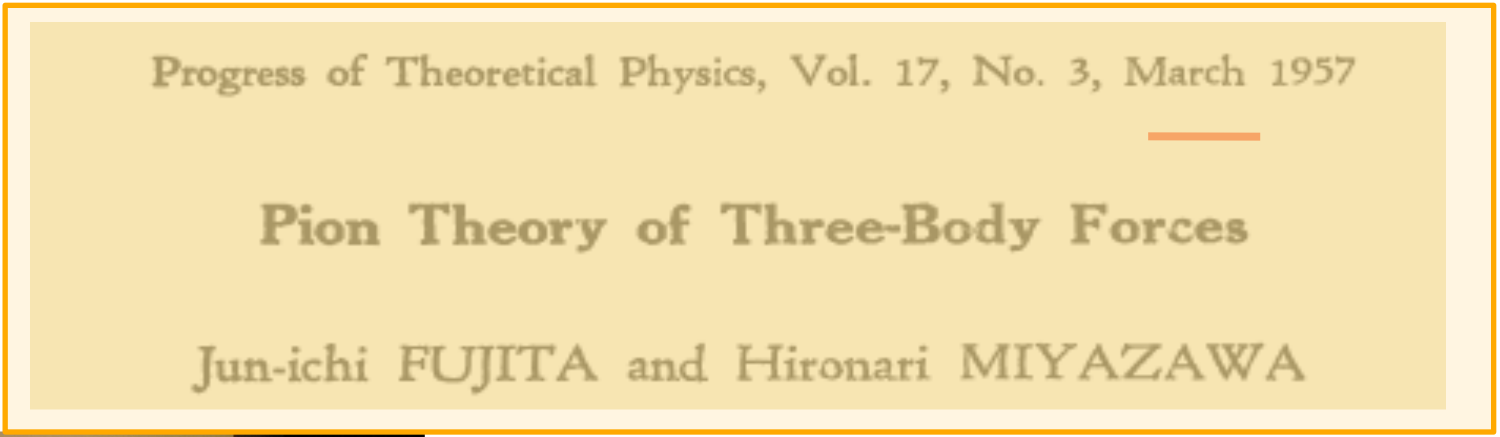
Nuclear Chart
- Left Lower Part -

Why is the drip line of Oxygen so near ?



next issue → oxygen anomaly and continuum

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



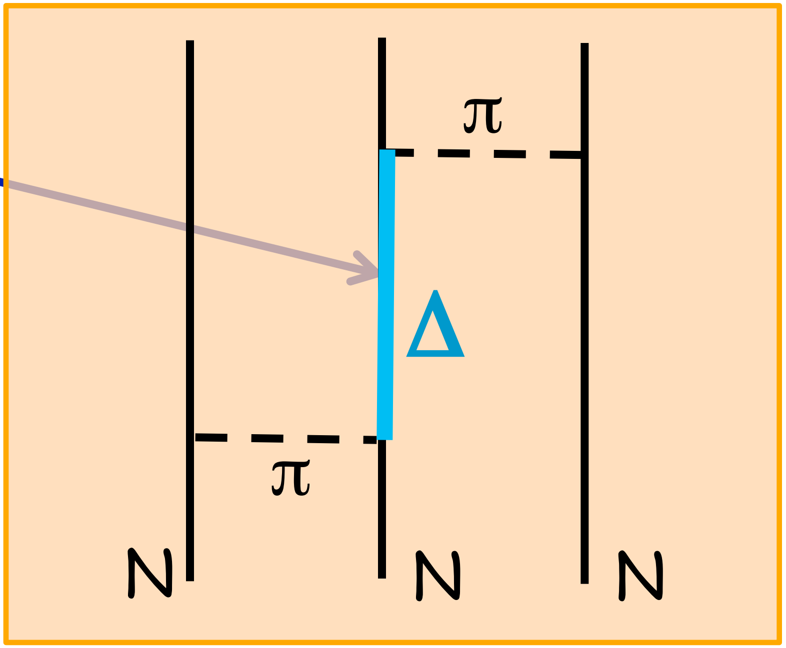
Progress of Theoretical Physics, Vol. 17, No. 3, March 1957

Pion Theory of Three-Body Forces

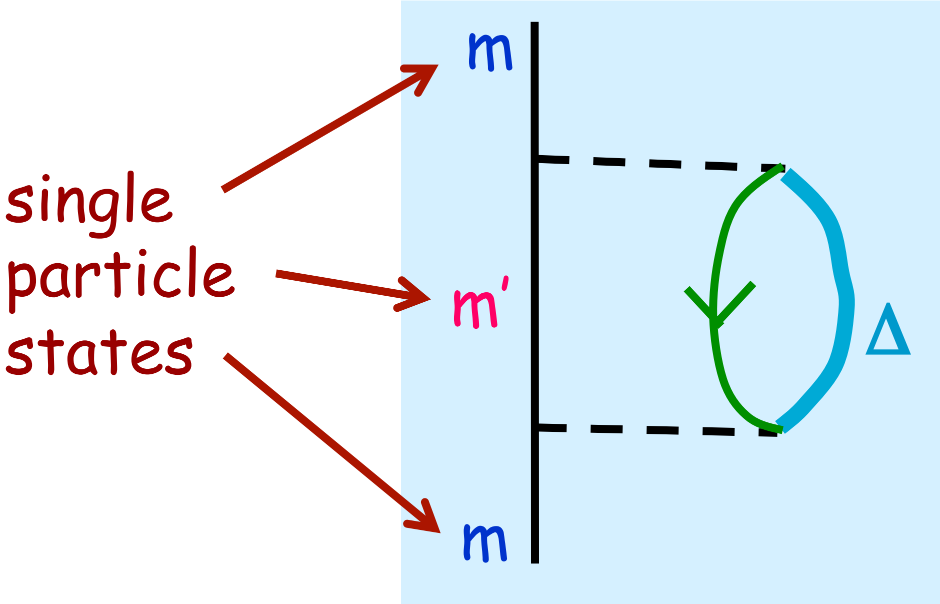
Jun-ichi FUJITA and Hironari MIYAZAWA

Miyazawa, 2007

Δ particle
m=1232 MeV
S=3/2, I=3/2

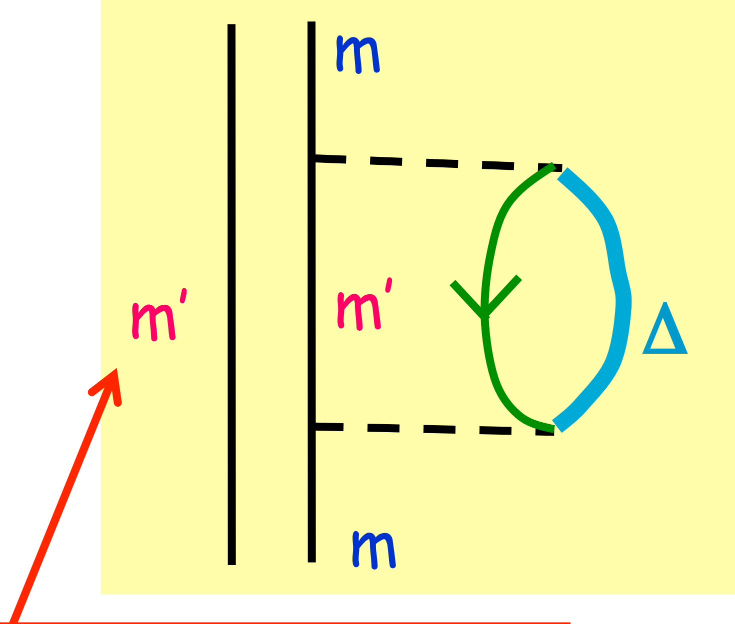


Pauli blocking effect on the renormalization of single-particle energy



single particle states

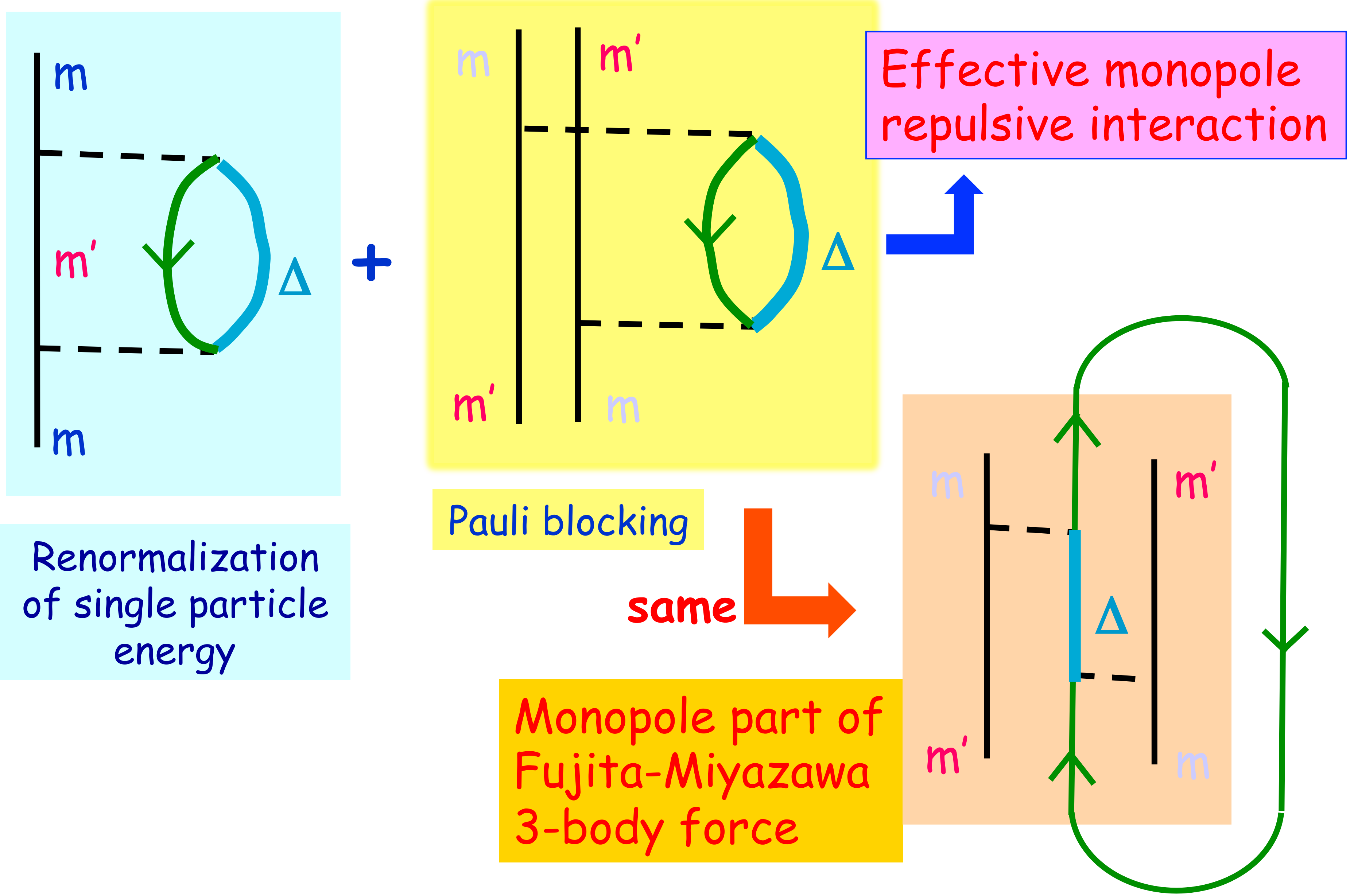
Renormalization of single particle energy due to Δ-hole excitation → more binding (attractive)



Another valence particle in state m′

Pauli Forbidden
→ *The effect is suppressed*

Most important message with Fujita-Miyazawa 3NF



Renormalization of single particle energy

Pauli blocking

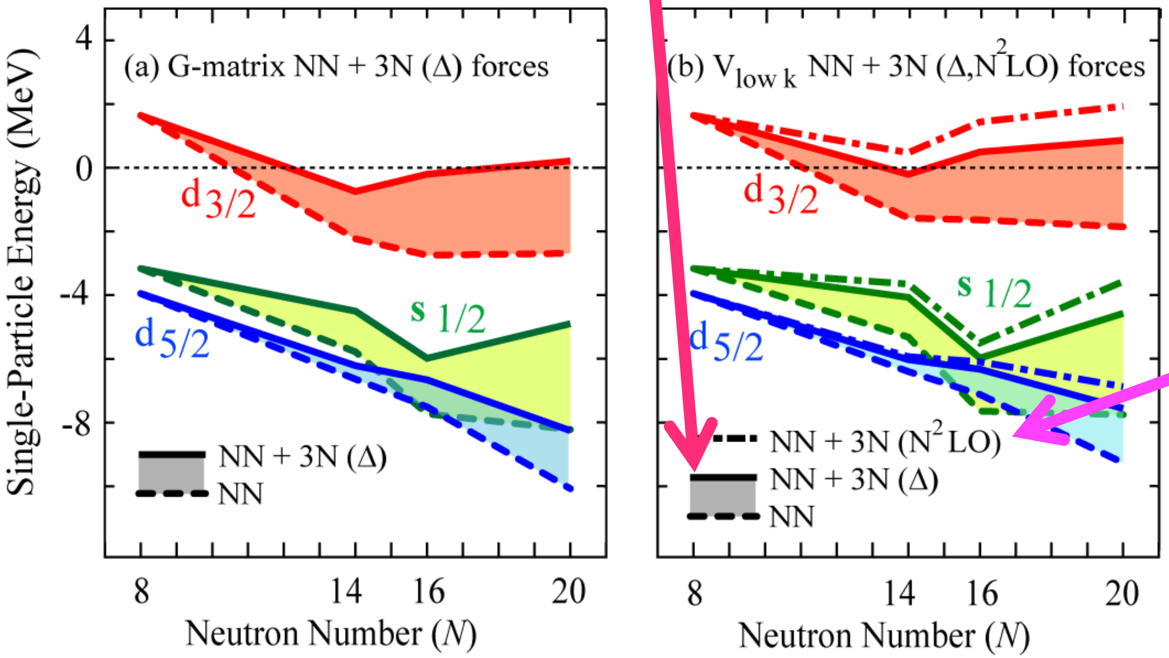
Effective monopole repulsive interaction

same

Monopole part of Fujita-Miyazawa 3-body force

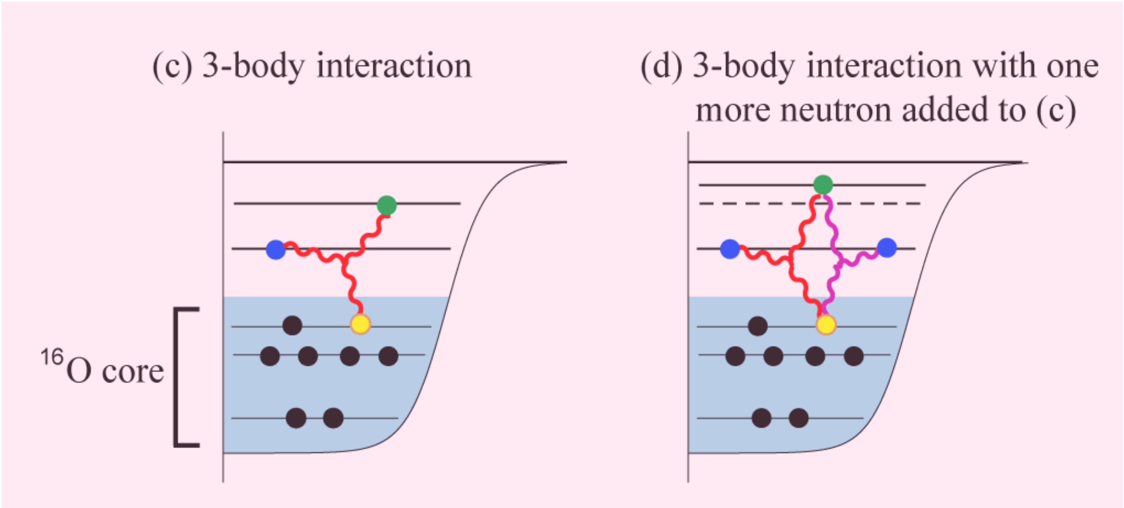
(i) Δ-hole excitation in a conventional way

(ii) EFT with Δ



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

Δ-hole dominant role in determining oxygen drip line

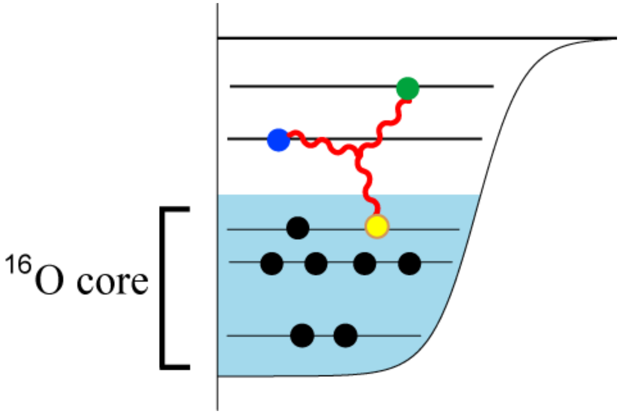


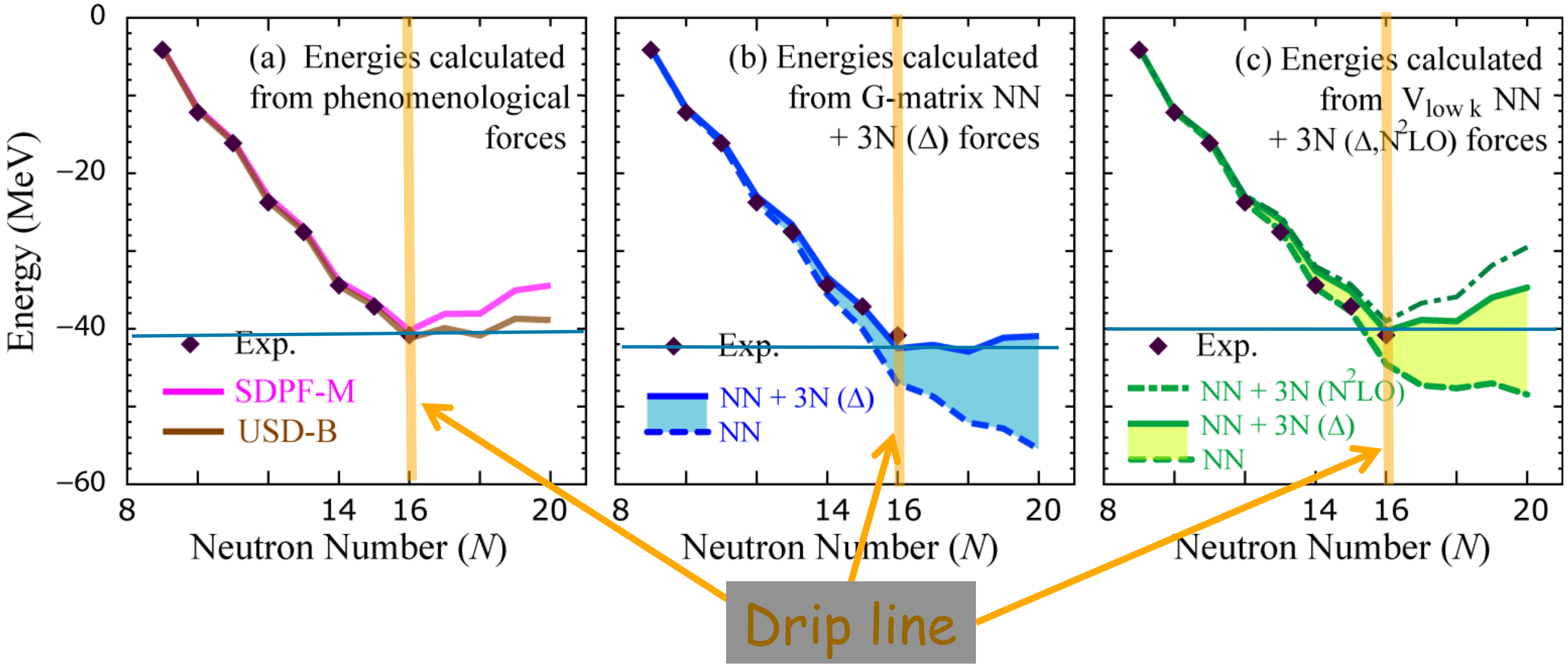
O, Suzuki, Holt, Schwenk, Akaishi, PRL 105 (2010)

Ground-state energies of oxygen isotopes

NN force + *3N*-induced *NN* force

(Fujita-Miyazawa force)

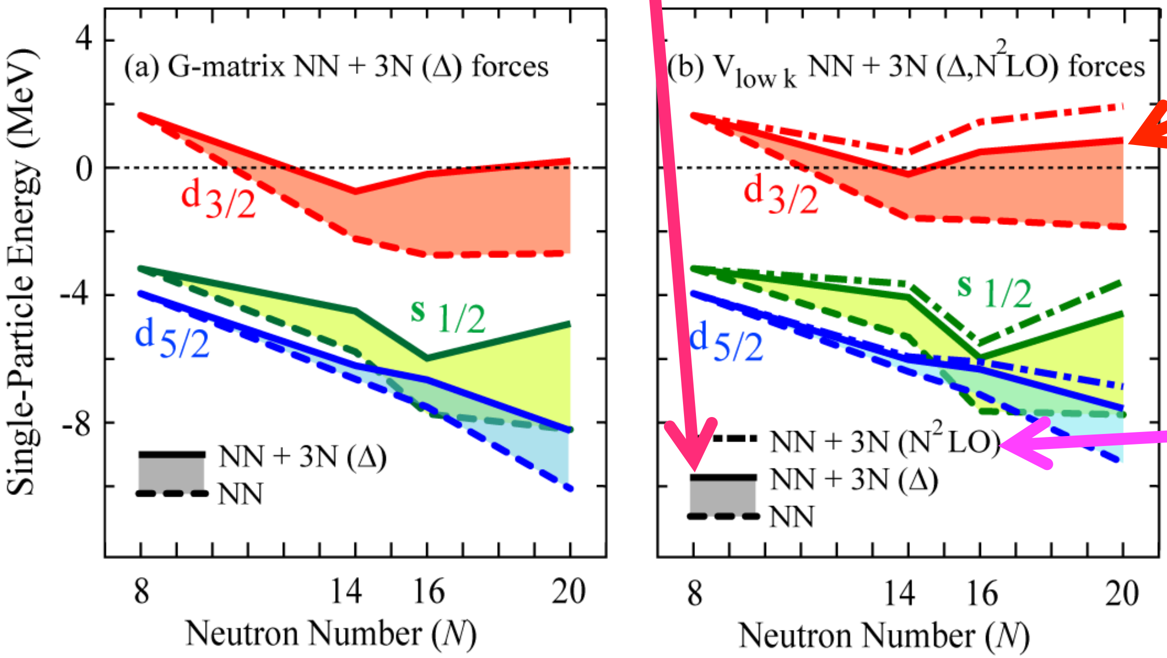




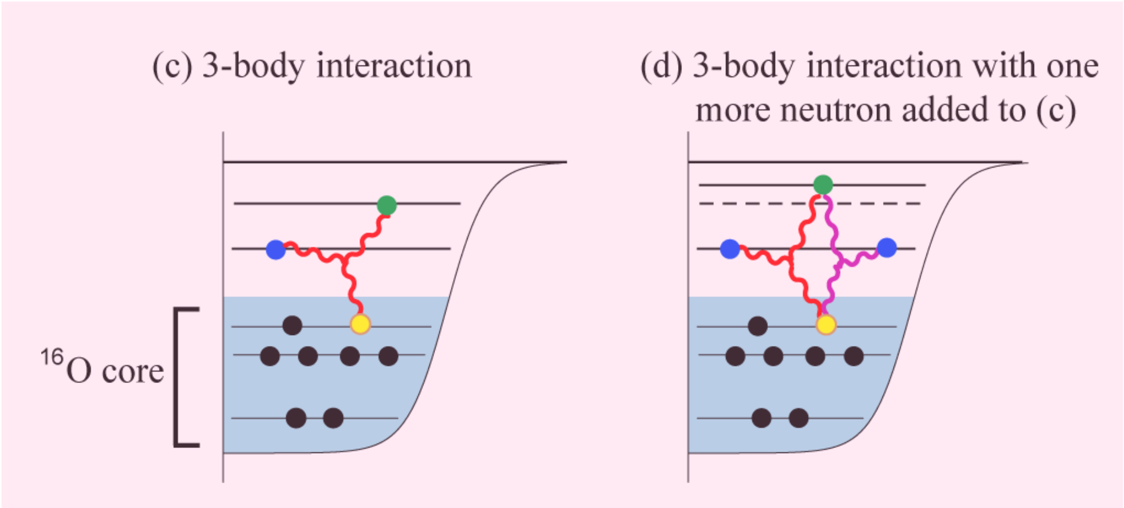
(i) Δ-hole excitation in a conventional way

(ii) EFT with Δ

in continuum,
but calculated
as a bound state
⇒ to be discussed
now



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


(c) 3-body interaction

(d) 3-body interaction with one more neutron added to (c)

Δ-hole dominant role in determining oxygen drip line

Continuum-coupled shell model (CCSM)

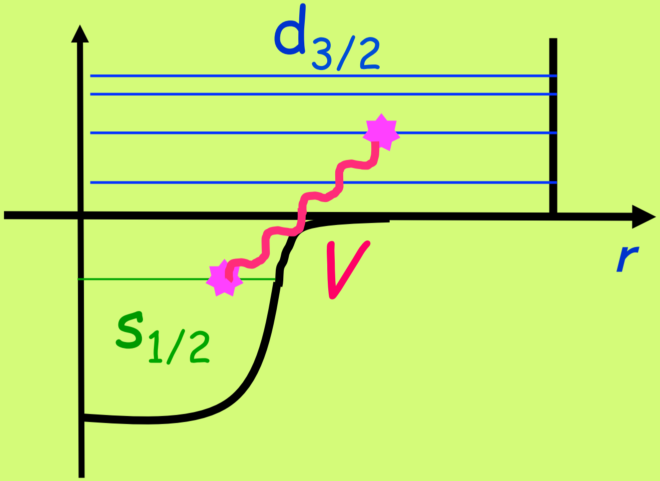
Hamiltonian : $H = H_0 + \hat{V} = \sum_j \tilde{\epsilon}_j n_j + \hat{V}$

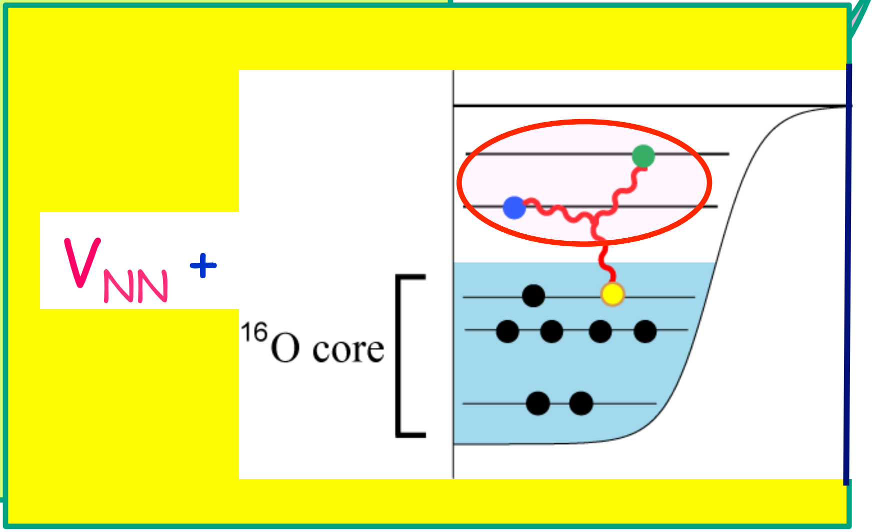
$$H_0 = T + U_{WS} + V_{\rm wall} = \sum_j \tilde{\epsilon}_j n_j$$

approximated by Gaussian

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

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



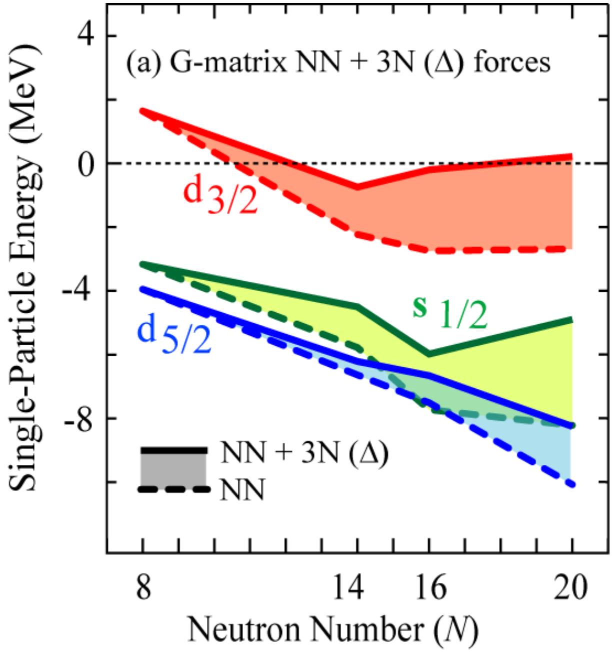


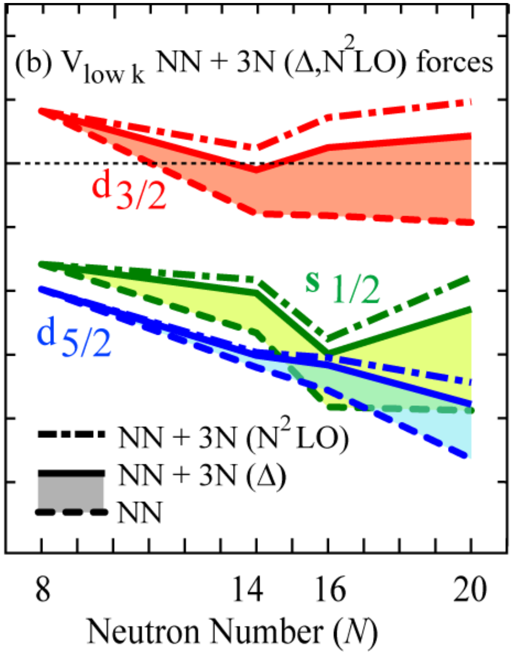
included

(i) Δ-hole excitation in a conventional way

(ii) EFT with Δ

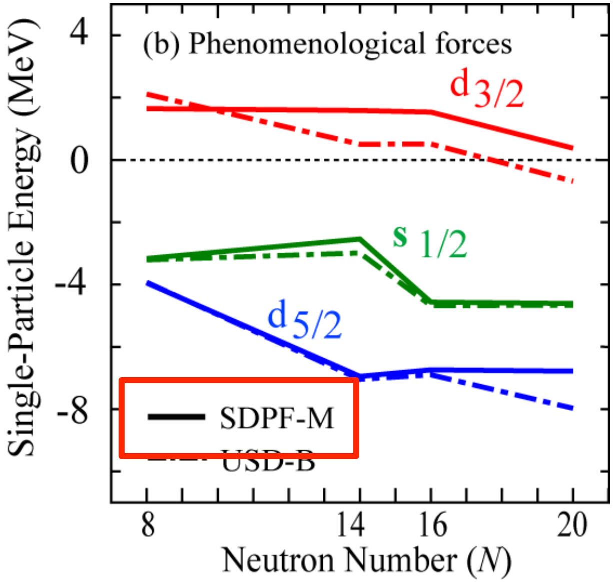
O, Suzuki, Holt, Schwenk, Akaishi, PRL 105 (2010)



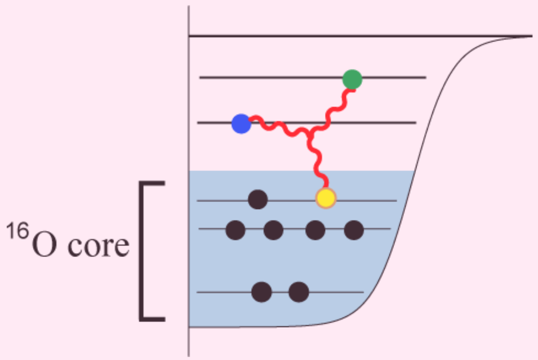


Δ-hole dominant role in determining oxygen drip line

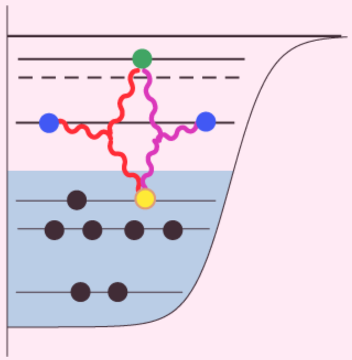
phenomenological shell model



(c) 3-body interaction



(d) 3-body interaction with one more neutron added to (c)



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

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

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^+ :

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

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

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

diagonalize H

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

Reaction mechanism

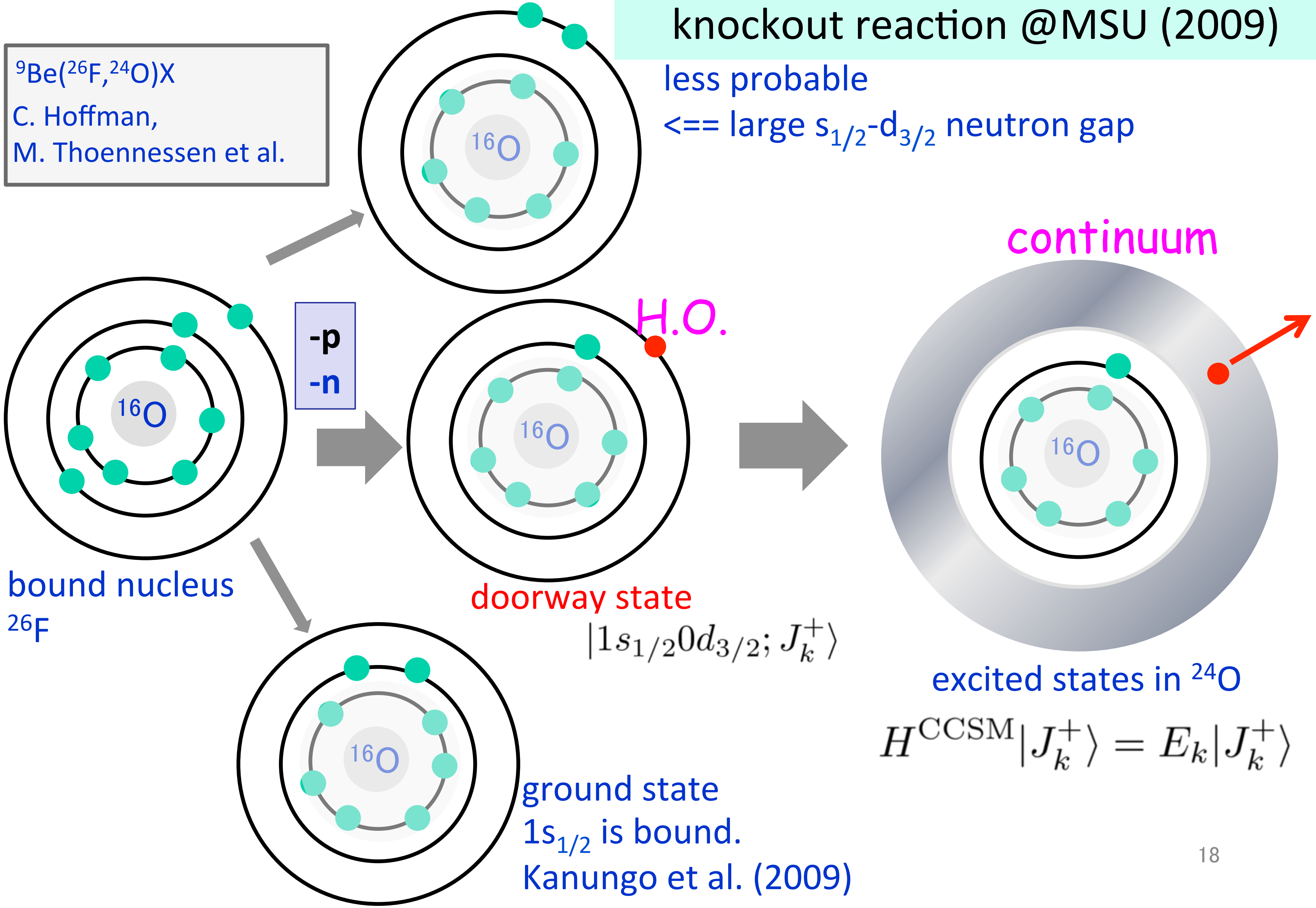
-> Doorway state

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

^{9}Be(^{26}F,^{24}O)X
C. Hoffman,
M. Thoennessen et al.

knockout reaction @MSU (2009)

less probable
<== large $s_{1/2}$-$d_{3/2}$ neutron gap



bound nucleus
^{26}F

doorway state

$$|1s_{1/2}0d_{3/2}; J_k^+\rangle$$

excited states in ^{24}O

$$H^{\mathrm{CCSM}}|J_k^+\rangle = E_k|J_k^+\rangle$$

ground state
$1s_{1/2}$ is bound.
Kanungo et al. (2009)

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

solid line : full (central + tensor)

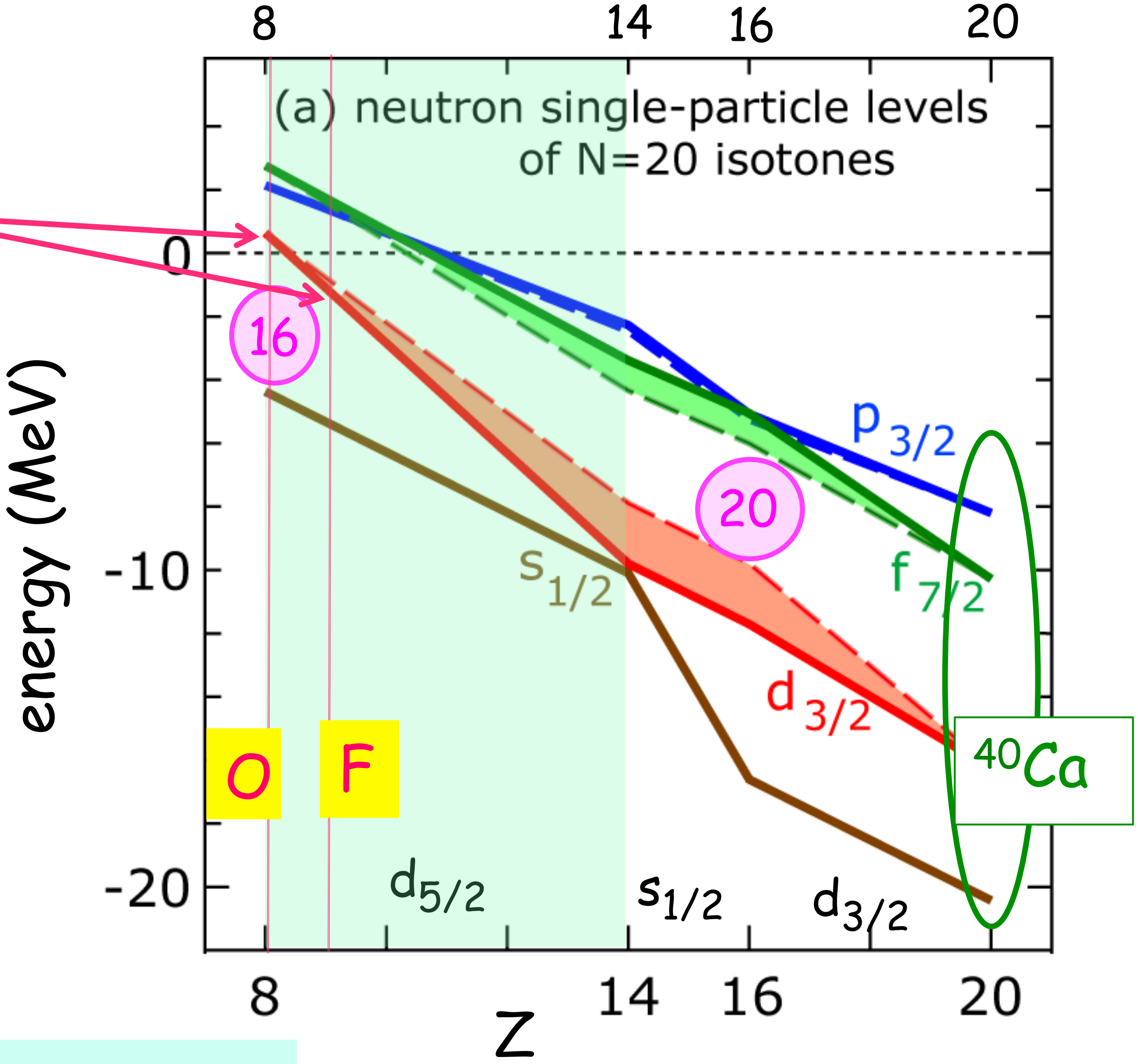
dashed line : central only

$d_{3/2}$

bound in F

unbound in O

due to interplay between tensor and three-body forces



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

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

Before the removal, neutron $d_{3/2}$ is well-bound in ^{26}F and can be described by a HO wave function.

Sudden removal -> doorway state with HO $d_{3/2}$

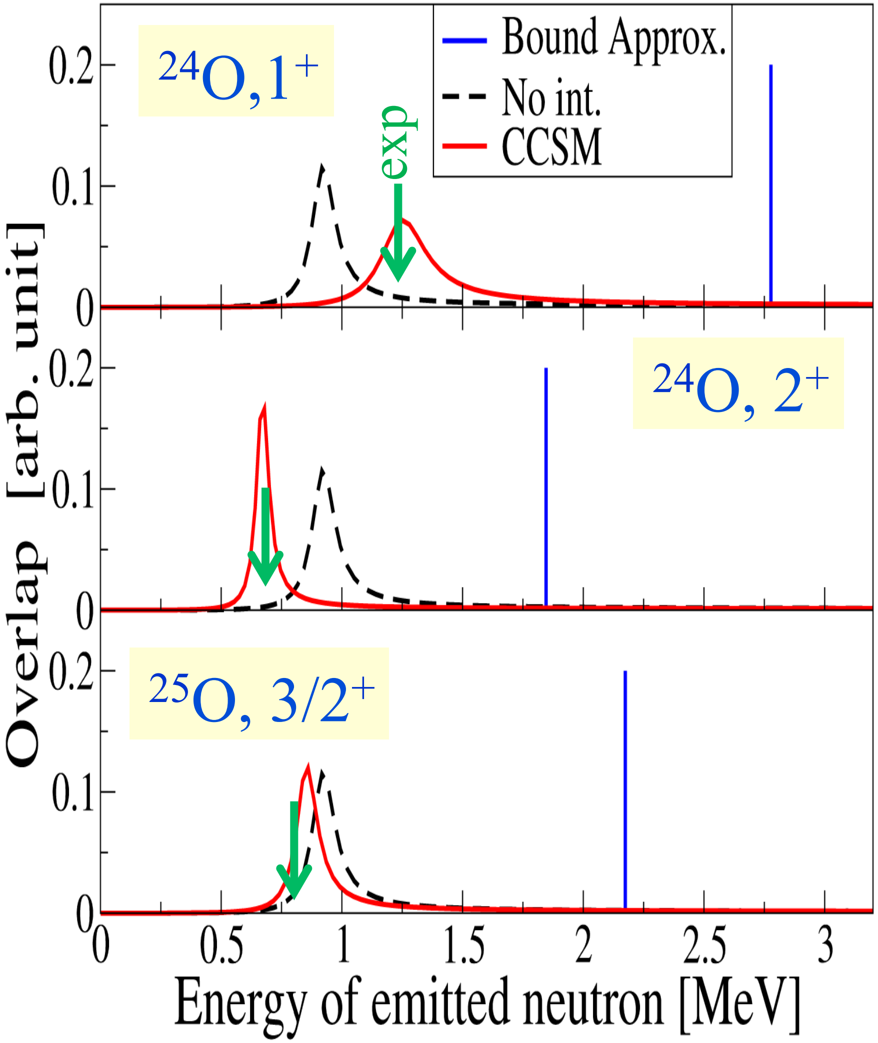
Decay of neutron from this $d_{3/2}$

through overlap with continuum states :

$$\zeta_k^{(J)} \equiv \langle J_k^+ | 1s_{1/2} 0d_{3/2}; J^+ \rangle = \sum_i c_i^{(J,k)} \langle i d_{3/2} | 0d_{3/2} \rangle$$

$p_k^{(J)} \equiv |\zeta_k^{(J)}|^2$ ➡ Spectrum of emitted neutron

Low-lying Continuum Spectra in ^{24}O



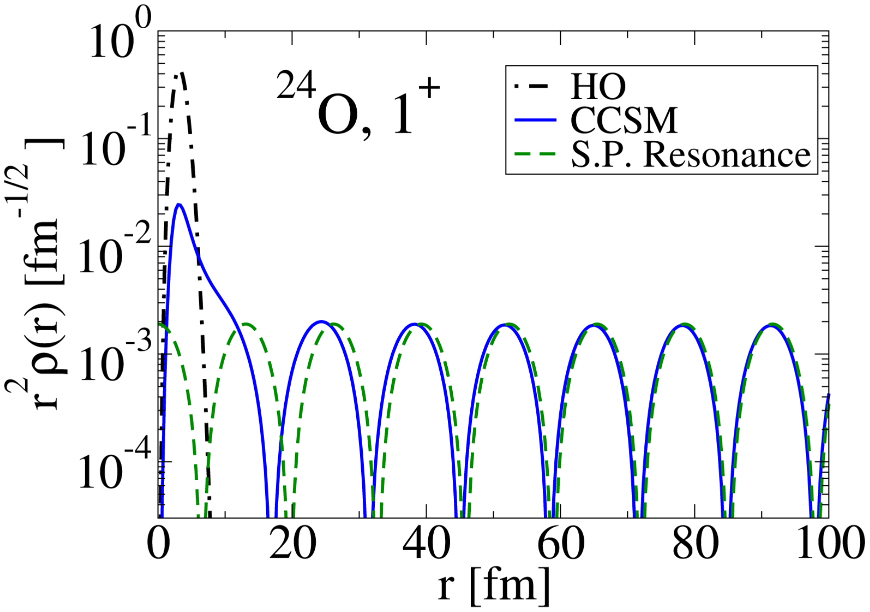
Doorway state ==> continuum states in ^{24}O

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

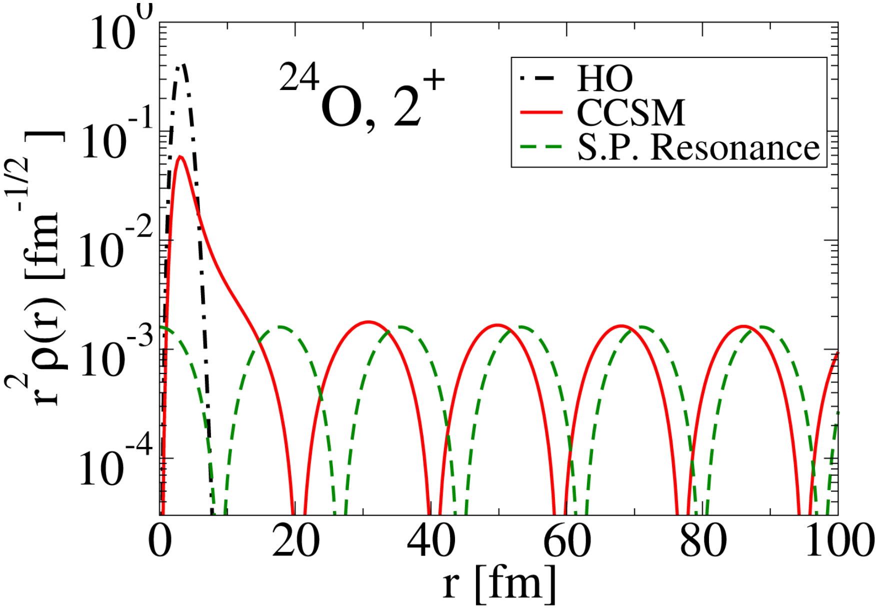
- **bound approx**imation:
  Normal shell model with the same Hamiltonian : NO continuum effect
- **CCSM** : With continuum effect
  incl. residual interaction
- **no int.** : With continuum effect but
  no residual interaction.

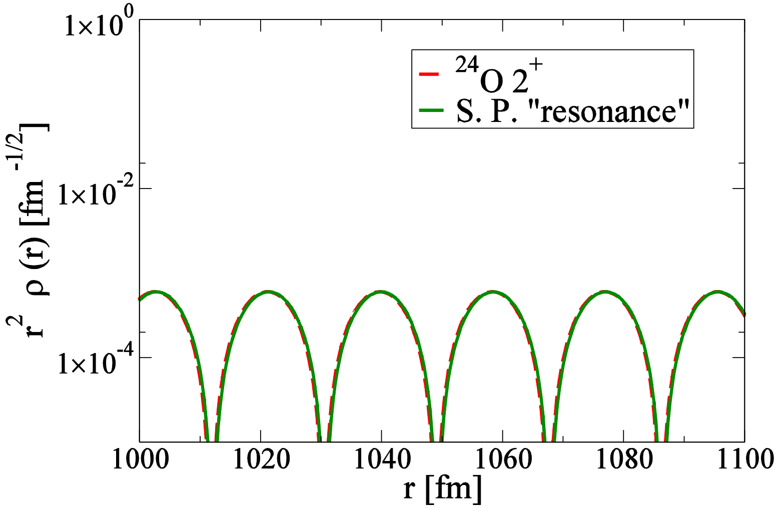
- Continuum effect is about 1 MeV
- No bound excited state.
- 1^+-2^+ splitting by 2-body interaction
- 1^+-2^+ splitting is in good agreement with experiments.

Radial density (w.f.) of continuum states in ^{24}O

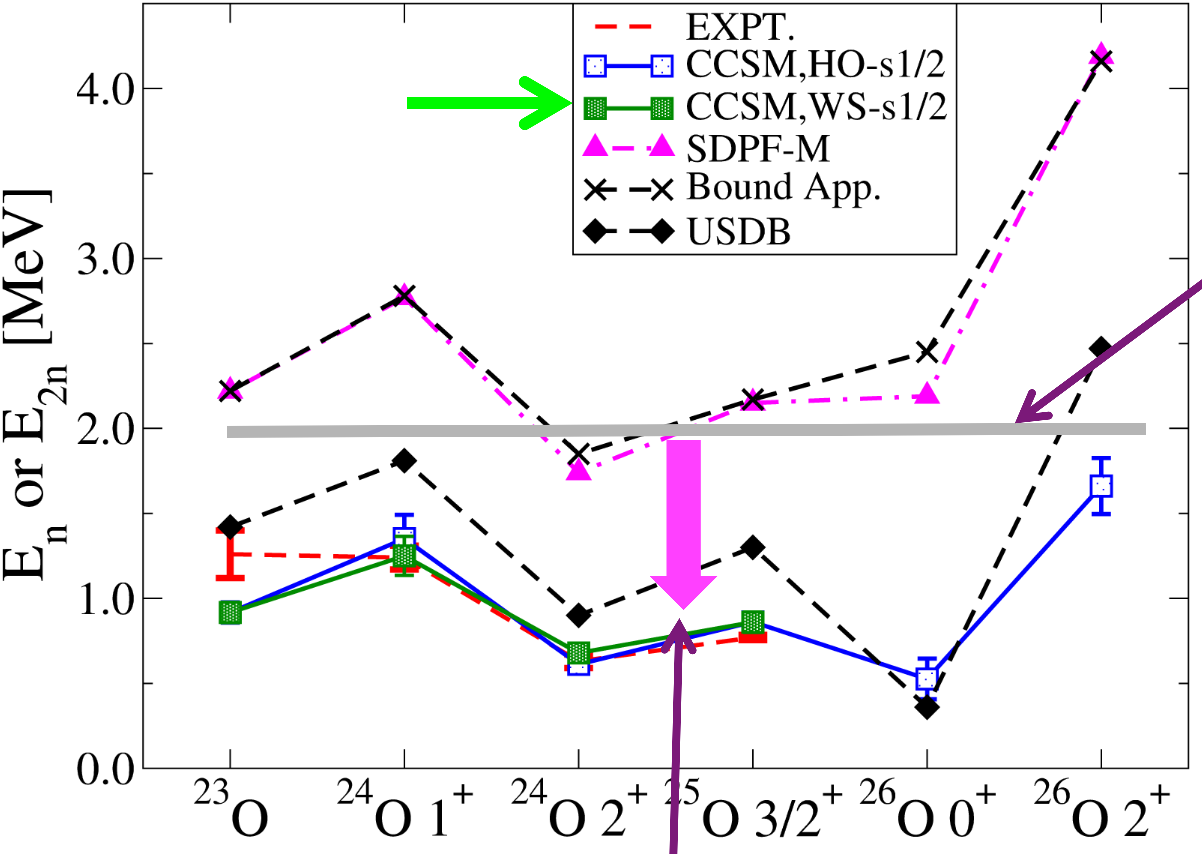


- Notable difference between 1^+ and 2^+ stares.
- The peak states in CCSM reproduce the behavior of "resonance wave" at far distance (phase shift of $\pi/2$).



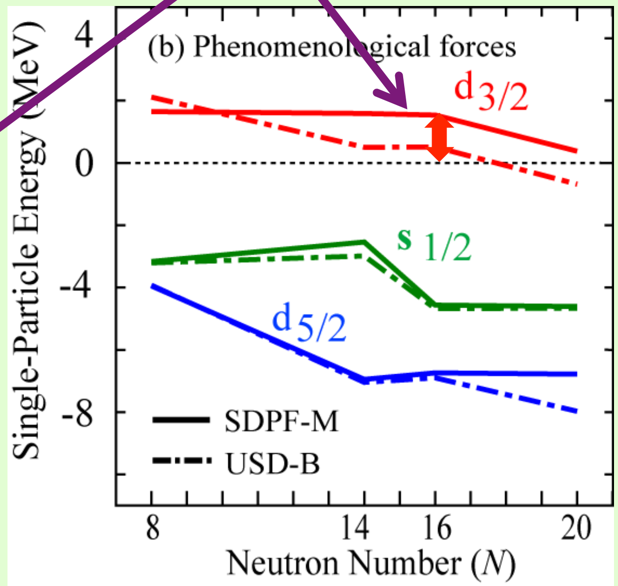


Peak Energies of neutron emission



SPE as bound state

2 MeV

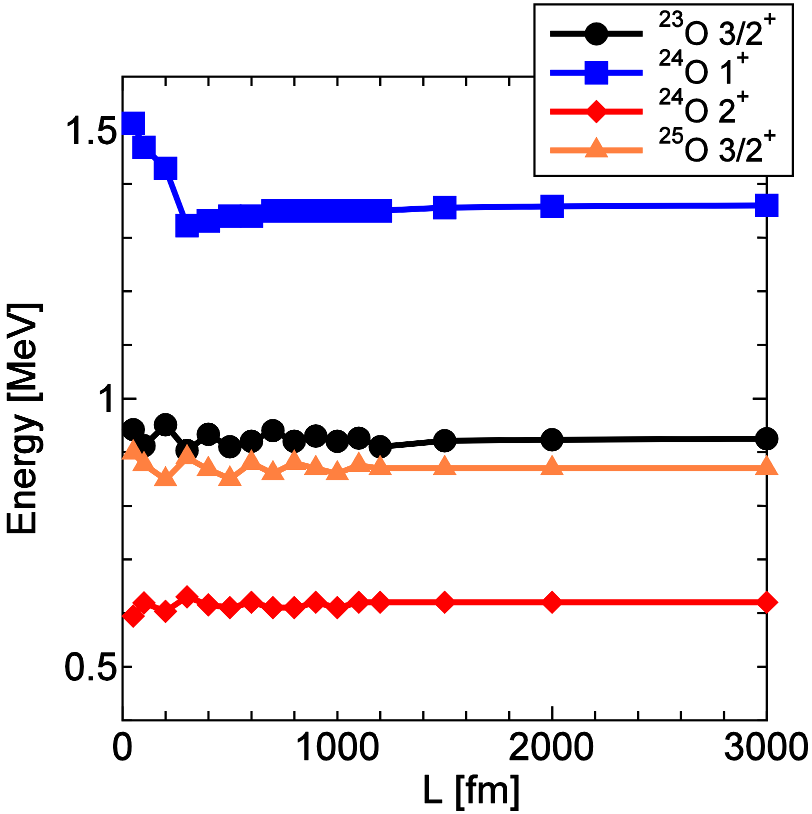


Exp. : MSU (Hoffman et al),
RIKEN (Elekes et al)

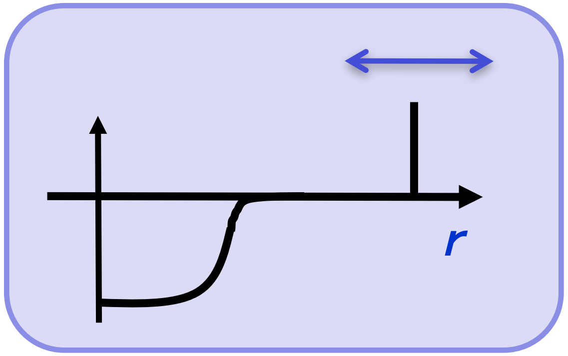
Lowering due to continuum effect

Continuum spectra are consistent with the shell evolution

Convergence with respect to boundary condition



The peak energies as a function of L.



- The results do not change so much if L is taken to be sufficiently large.
- Even usual values of L~50 fm are not stable.

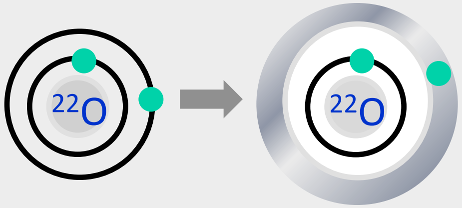
Comparison to

single-particle resonance

Effective phase shift and one-body reduction

Can many-body resonance be described by effective one-body problem?

CCSM



CCSM: continuum spectra are obtained by taking the overlap between the doorway state and CCSM eigenstates in continuum.

Effective phase shift

We define effective phase shift by introducing 1-body reduction of CCSM wave function.

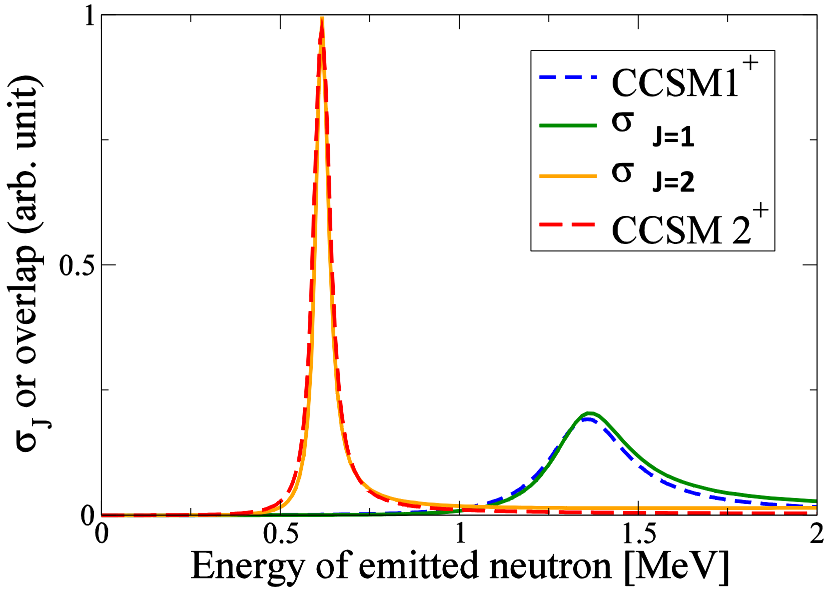
$$
\begin{aligned}
|J_k^+\rangle &= \sum_i c_i^{(J,k)} |1s_{1/2} \otimes i d_{3/2}; J\rangle \\
&=: |1s_{1/2} \otimes \tilde{d}_{3/2;J,k}; J\rangle
\end{aligned}
$$

$$\boxed{|\tilde{d}_{3/2;J,k}; J\rangle = \sum_i c_i^{(J,k)} |i d_{3/2}\rangle}$$

One can then obtain phase shift, and can use it for calculating the cross section.

$$\sigma_J = \frac{4\pi}{k^2}(2l+1)\sin^2\delta_J$$

Effective phase shift and one-body reduction

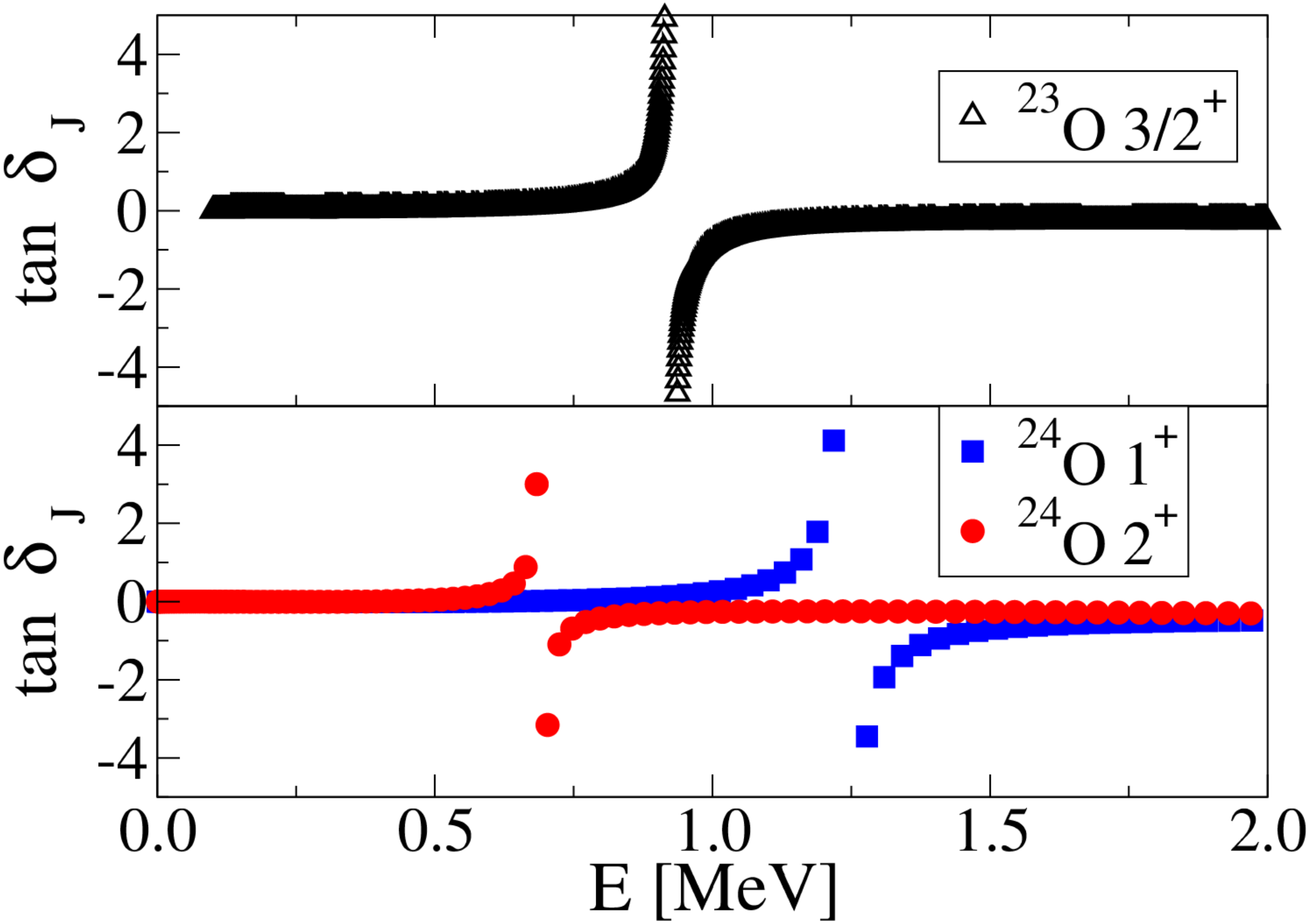


- CCSM(doorway state approach) and effective phase shift approach give very similar results for for peak positions.
- Notable difference appears for the width of 2^+ in ^{24}O.
  - Doorway state decays faster. -

Unit : MeV	**^{23}O**	**^{24}O**	
states	3/2+	1+	2+
CCSM E	0.92	1.35	0.61
CCSM Γ	0.11	0.28	**0.06**
Phase shift E	0.92	1.36	0.61
Phase shiftΓ	0.11	0.28	**0.04**

50 % longer life time

Phase shift


tan δ_J
4
2
0
-2
-4
△ ^{23}O $3/2^+$
tan δ_J
4
2
0
-2
-4
■ ^{24}O 1^+
● ^{24}O 2^+
0.0
0.5
1.0
1.5
2.0
E [MeV]

Although resonance state and doorway state are different, continuum spectra are similar.

What is the meaning of single-particle resonance states in complex dynamical processes such as multi-nucleon transfer heavy-ion reactions ???

Time scale of the heavy-ion reaction may be shorter than the resonance life time.

Coupling to continuum lowers the (peak) energies by more than 1 MeV for oxygen isotopes.

spectroscopy in continuum