Three-body model study of unbound nucleus ^{26}O

--- NN2015 ---

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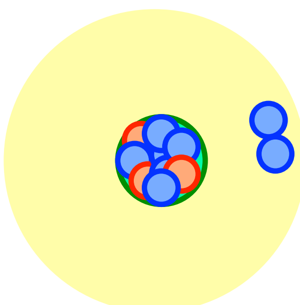
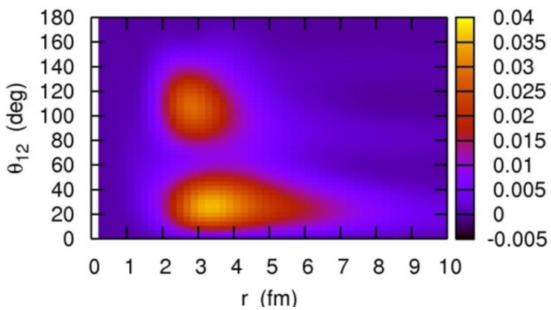




1.di-neutron correlation and three-body model approach

2. Nuclei beyond drip line and 2n-decay

3. Summary and future perspectives

Exotic structure close to drip lines

- Halo, Giant halo/skin structure
- shell evolution
- di-neutron and di-proton correlations
- Shape evolution, shape coexistence
- Anti-halo effect

Exotic Nuclei Far from the Stability Line

K. Hagino[1], I. Tanihata[2,3] and H. Sagawa[4]

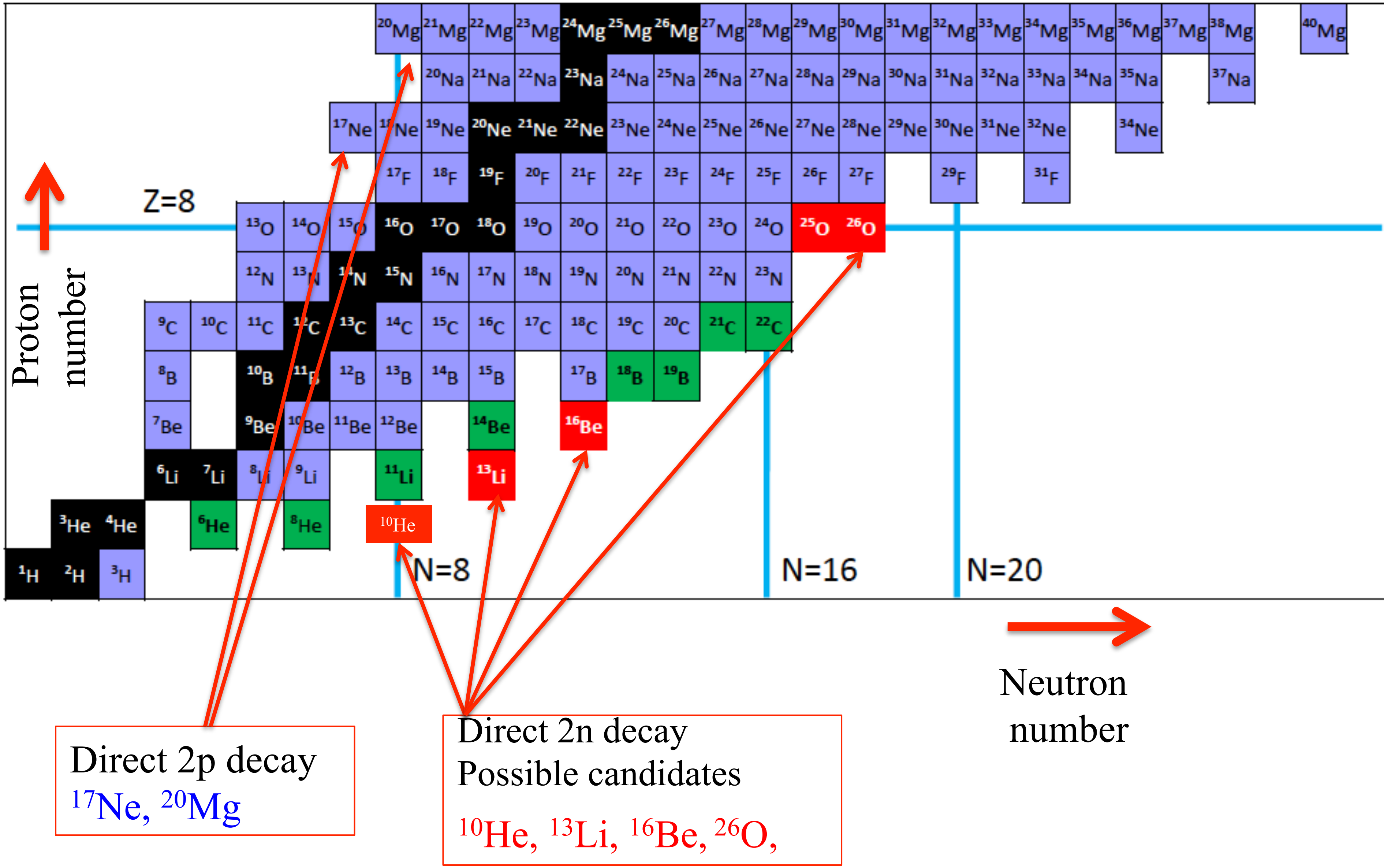
"100 years of subatomic physics"
(Edited by E.M. Henley and S. D. Ellis)
pp. 231-273 (World Scientific, 2013)

How to probe these exotic structures ?

Nuclear reactions

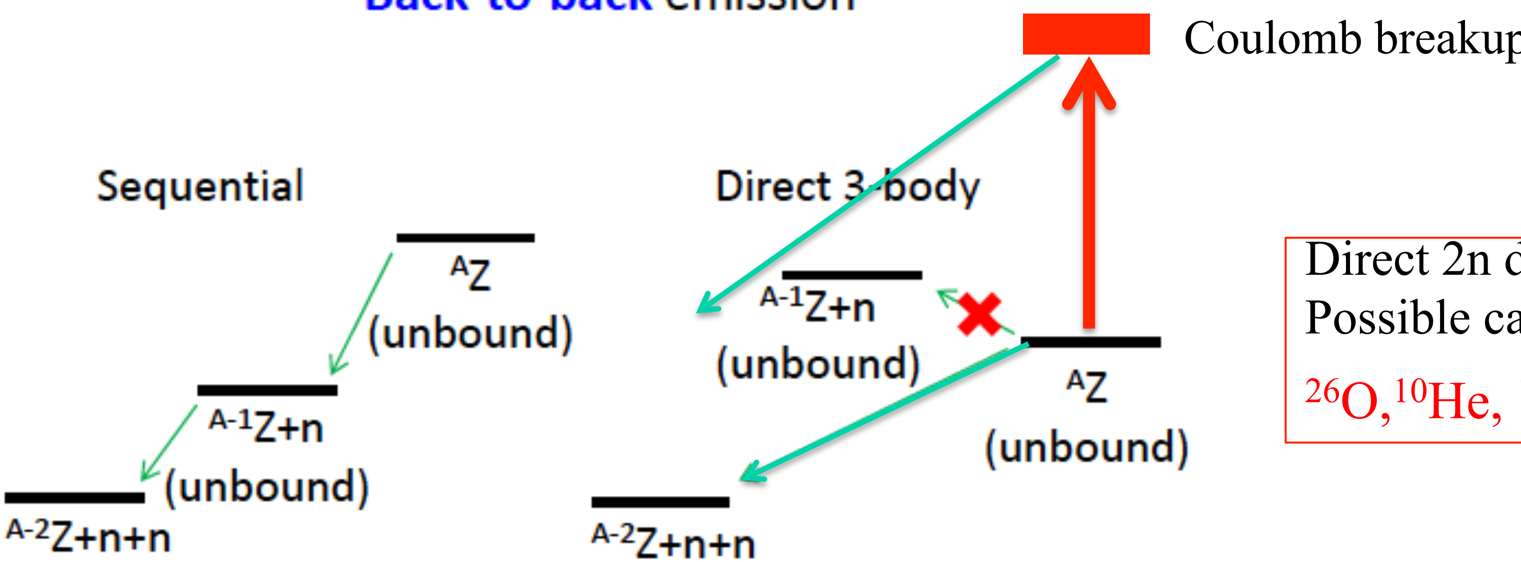
- Coulomb breakup reactions
- Nuclear breakup reactions
- Nucleon transfer reactions
- Direct two-nucleon decays
- Sequential two-nucleon decays
- n-n correlation measurements
- Charge exchange reactions

Next generation RI beam facilities : e.g., RIBF (RIKEN, Japan)



Nuclei beyond drip lines
---- direct two neutron decays -------

- Decay of 3-body unbound system
  - **Sequential** decay via core + n resonance
  - Direct 3-body decay
    - **Democratic** decay (phase space decay)
    - **Di-neutron** emission
    - **Back-to-back** emission

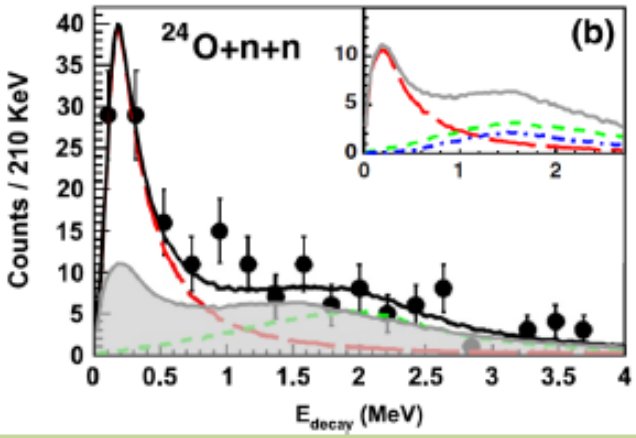


Direct 2n decay
Possible candidates
^{26}O, ^{10}He, ^{13}Li, ^{16}Be

$^{27}F \rightarrow ^{26}O \rightarrow ^{24}O + 2n$

2n radioactivity of ^{26}O?

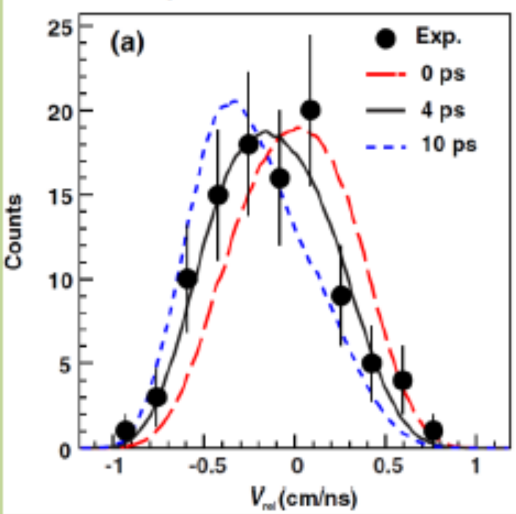
E. Lunderberg et al.PRL108, 142503 (2012)



Er < 200keV

2-neutron decay （MoNA@MSU）

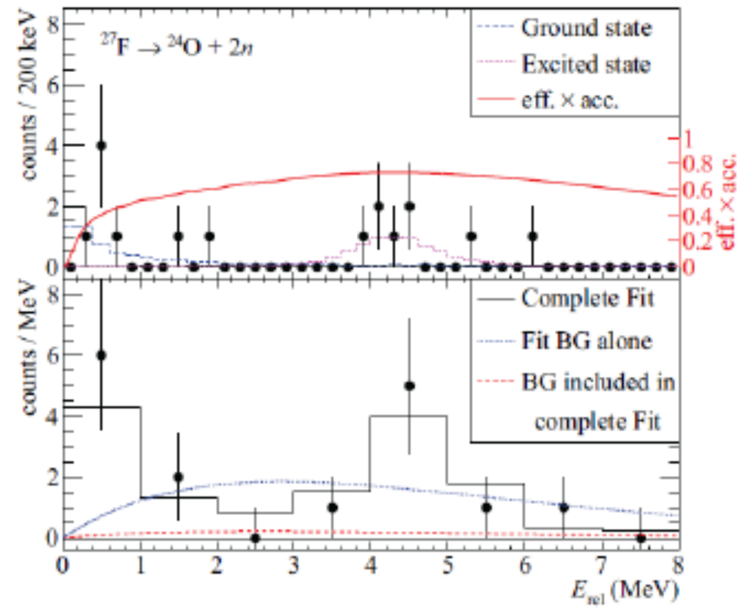
Z. Kohley et al,PRL110,152501 (2013)



$T_{1/2}=4.5^{+1.1}_{-1.5}$ps
(3ps systematic error)

→2n radioactivity?

C. Caesar et al.PRC88, 034313 (2013)



Er < 120keV (95% CL)

τ < 5.7ns

Excite state at 4.2MeV?

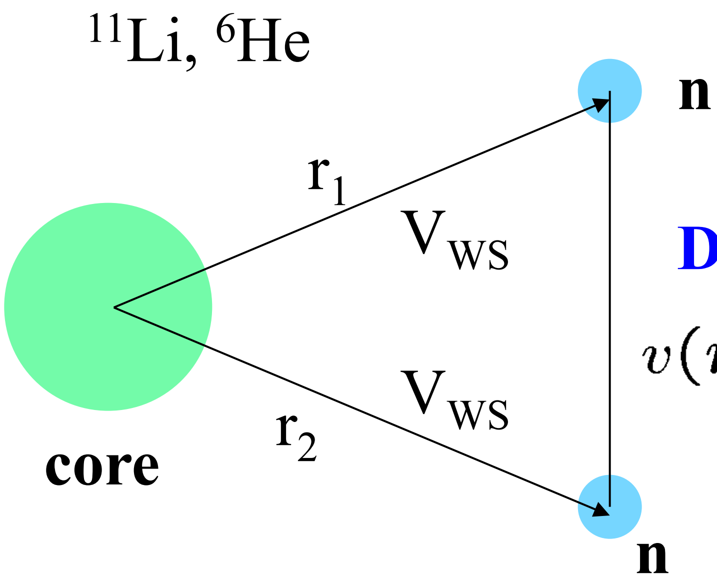
R3B-LAND at GSI

Large uncertainty of experimental study

- Only upper limit is given for the ground state energy
- Large systematic error in the lifetime measurement

Di-neutron correlations and three-body model

G.F. Bertsch and H. Esbensen, *Ann. of Phys. 209('91)327*
H. Esbensen, G.F. Bertsch, K. Hencken, *Phys. Rev. C56('99)3054*
K.Hagino and H. S., *PRC72('05)044321*
H. S. and K. Hagino, *EPJA review (2015)*



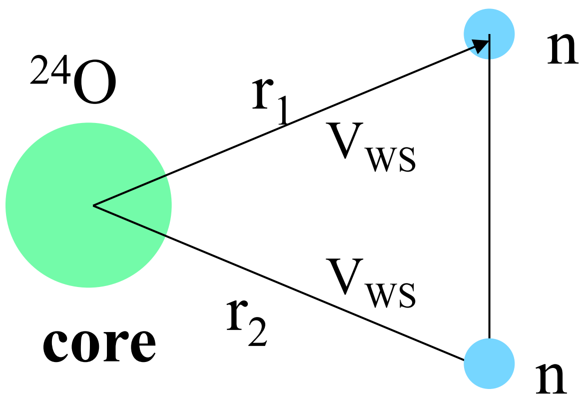
Density-dependent delta-force

$$v(\boldsymbol{r}_1, \boldsymbol{r}_2) = v_0(1 + \alpha\rho(r)) \times\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)$$

$$H = \frac{\boldsymbol{p}_1^2}{2m} + \frac{\boldsymbol{p}_2^2}{2m} + V_{nC}(r_1) + V_{nC}(r_2) + V_{nn} + \frac{(\boldsymbol{p}_1 + \boldsymbol{p}_2)^2}{2A_c m}$$

All parameters are determined empirically to fit the s.p. energies of neighboring nuclei and n-n scattering lengths.

Decay energy spectrum



➢ ^{24}O + n potential

Woods-Saxon potential to reproduce

$e_{2s1/2}$ = -4.09 (13) MeV,

$e_{1d3/2} = +\ 770^{+20}_{-10}$ keV,

$\Gamma_{1d3/2}$ = 172(30) keV

➢ nn interaction

density-dep. contact interaction

E (^{27}F) = -2.69 MeV

$$\frac{dP_I}{dE} = \sum_k |\langle\Psi_k^{(I)}|\Phi_{\rm ref}^{(I)}\rangle|^2\,\delta(E-E_k) = -\frac{1}{\pi}\Im\sum_k \langle\Phi_i^{(I)}|\Psi_k^{(I)}\rangle\frac{1}{E_k - E - i\eta}\langle\Psi_k^{(I)}|\Phi_i^{(I)}\rangle$$

$$= -\frac{1}{\pi}\Im\langle\Phi_{\rm ref}^{(I)}|G^{(I)}(E)|\Phi_{\rm ref}^{(I)}\rangle,$$

$$G^{(I)}(E) = G_0^{(I)}(E) - G_0^{(I)}(E)v(1+G_0^{(I)}(E)v)^{-1}G_0^{(I)}(E)$$

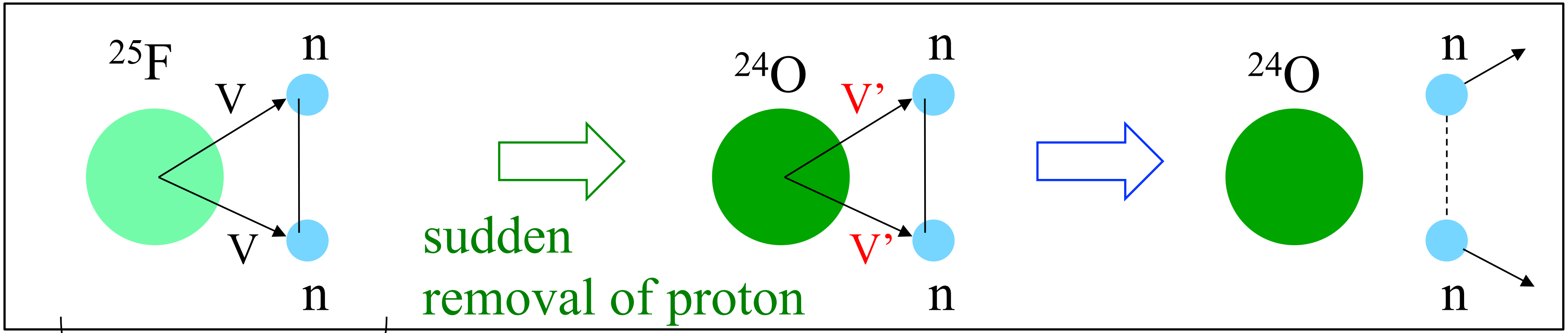
$$G_0^{(I)}(E) = \sum_{1,2}\frac{|(j_1j_2)^{(I)}\rangle\langle(j_1j_2)^{(I)}|}{\varepsilon_1+\varepsilon_2-E-i\eta}$$

← continuum effects

3-body model analysis for ^{26}O decay

K.Hagino and H. S., PRC89 ('14) 014331

cf. Expt. : ^{27}F (82 MeV/u) + ^{9}Be → ^{26}O → ^{24}O + n + n



g.s. of ^{27}F (bound)

spontaneous decay

$$\Psi_{nn} \otimes |^{25}\mathrm{F}\rangle \qquad \Psi_{nn} \otimes |^{24}\mathrm{O}\rangle$$

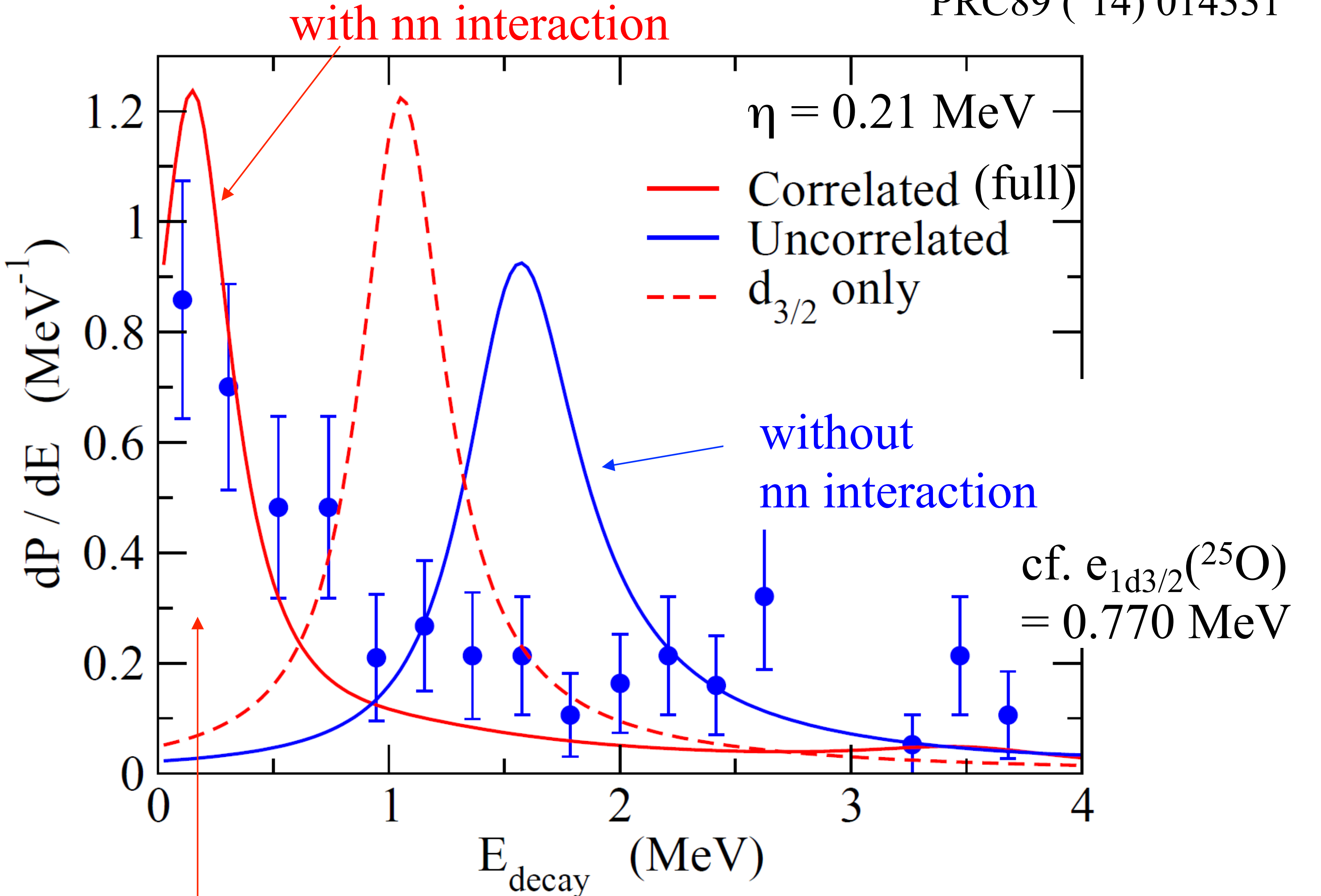
→ the same config. (non-eigenstate of ^{24}O+n+n)

FSI → Di-neutron correlations

$$G^{(I)}(E) = G_0^{(I)}(E) - G_0^{(I)}(E)v(1 + G_0^{(I)}(E)v)^{-1}G_0^{(I)}(E)$$

i) Decay energy spectrum for ^{26}O decay

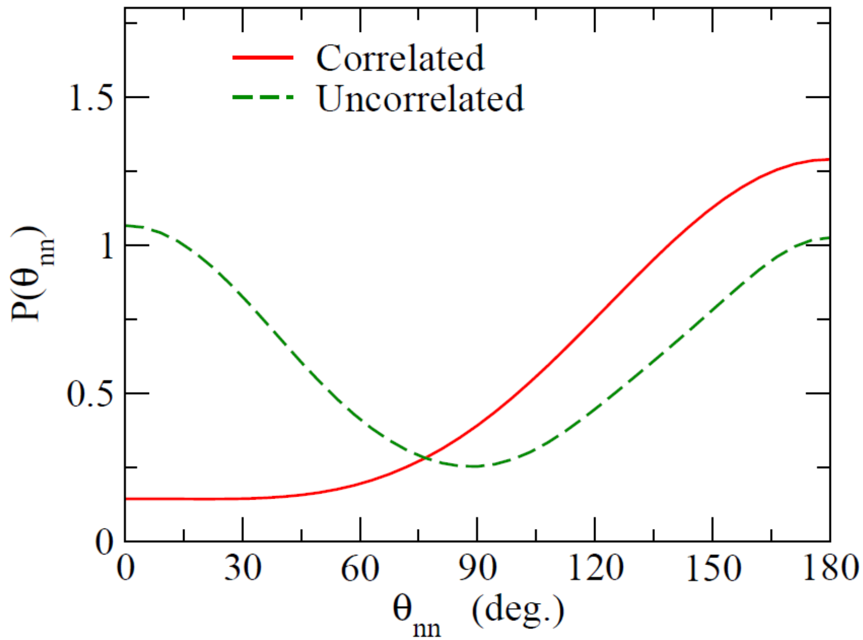
K.Hagino and H. S., PRC89 ('14) 014331



very narrow three-body resonance state ($\Gamma_{exp} \sim 10^{-10}$ MeV)

E_{peak} = 0.14 MeV with this setup for the Hamiltonian

ii) distribution of opening angle for two-emitted neutrons



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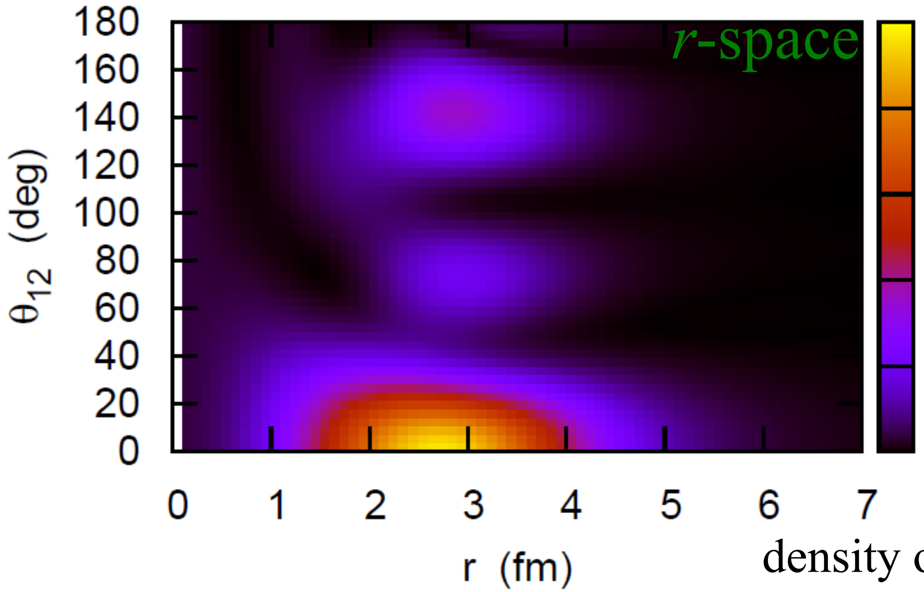
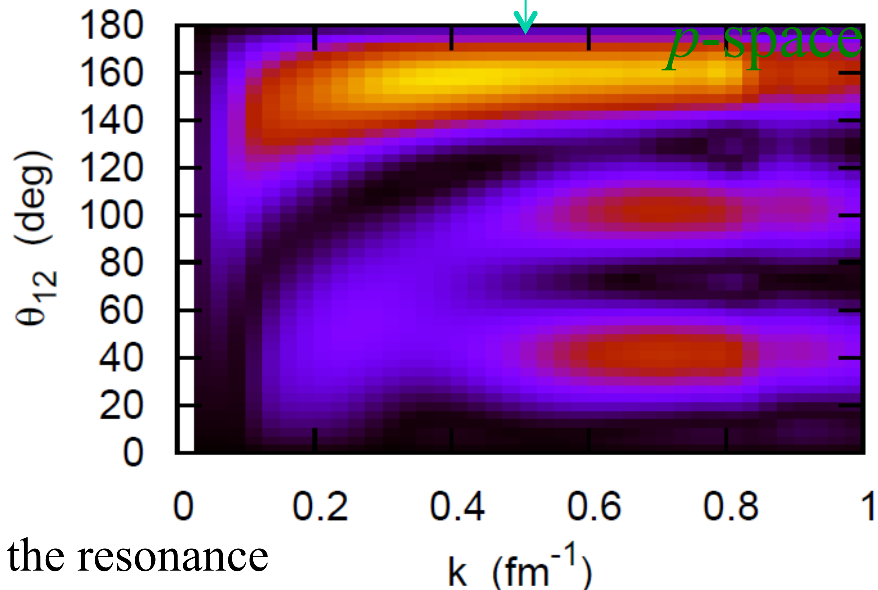
Heisenberg uncertainty principle between r and p

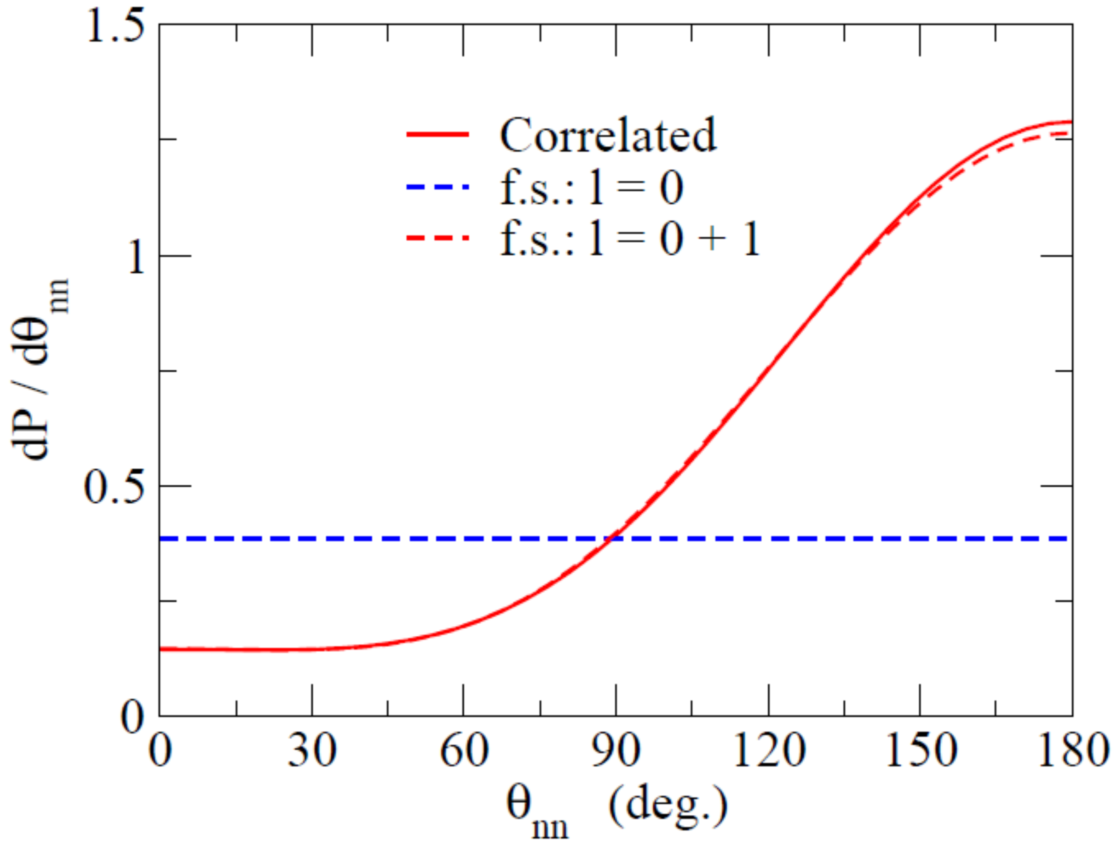
$$\rho(r,r,\theta)$$

$$8\pi^2 k^4 \sin\theta \cdot \rho(k,k,\theta)$$





density of the resonance state (with the box b.c.)

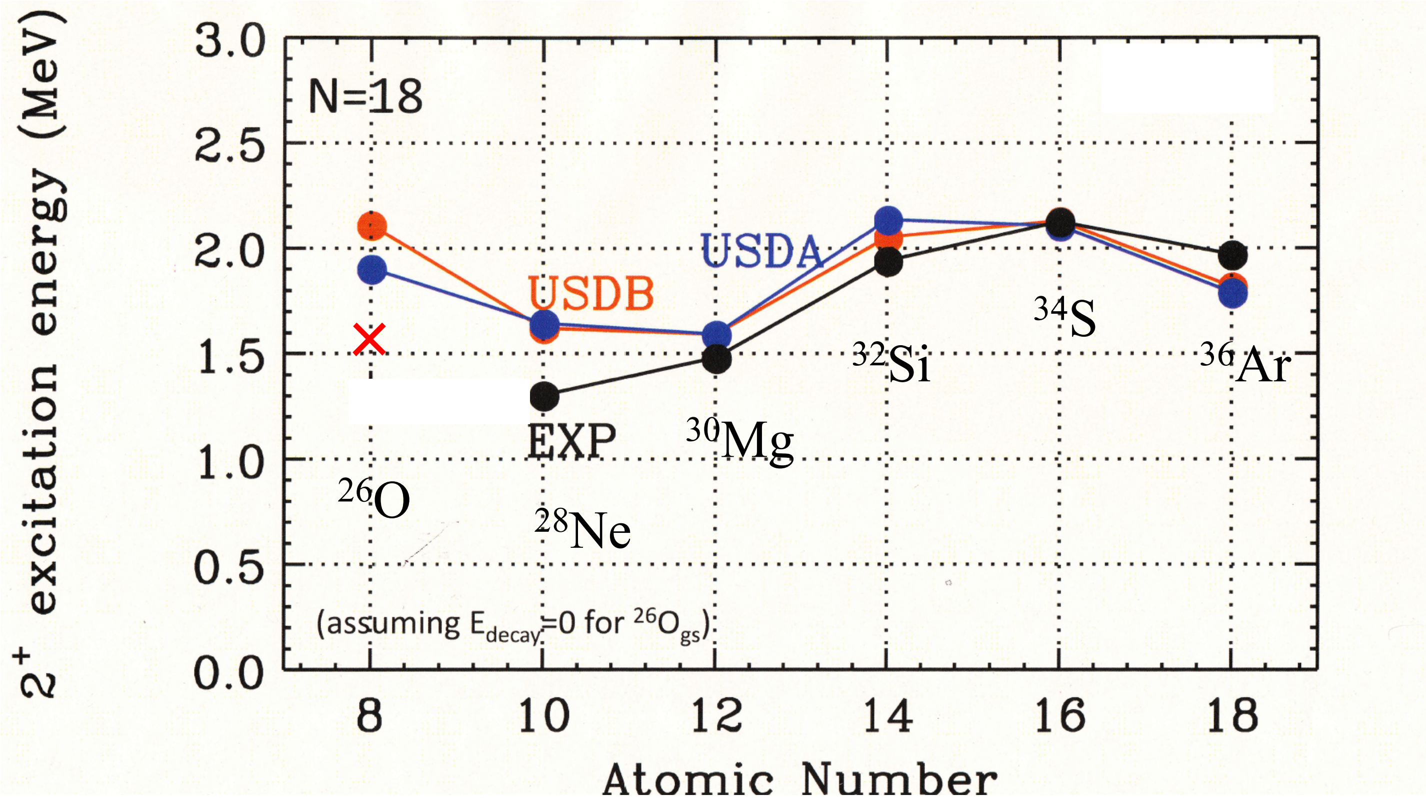


main contributions: *s*- and *p*-waves in three-body wave function
(no or low centrifugal barrier)

*higher *l* components: largely suppressed due to the centrifugal pot.
(E_{decay} ~ 0.14 MeV, e_1 ~ e_2 ~ 0.07 MeV)

Excited 2^+ state in ^{26}O

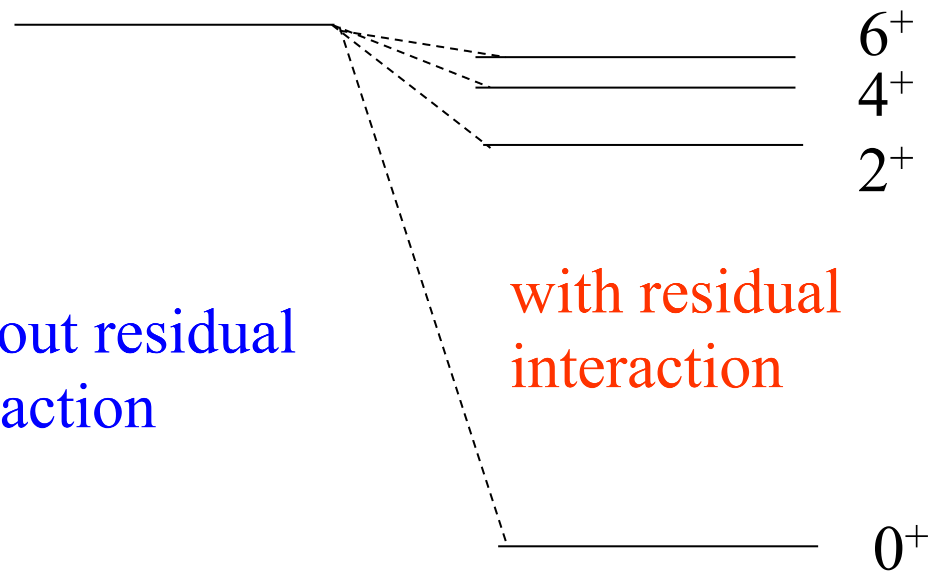
× Ab initio shell model with three-body interaction

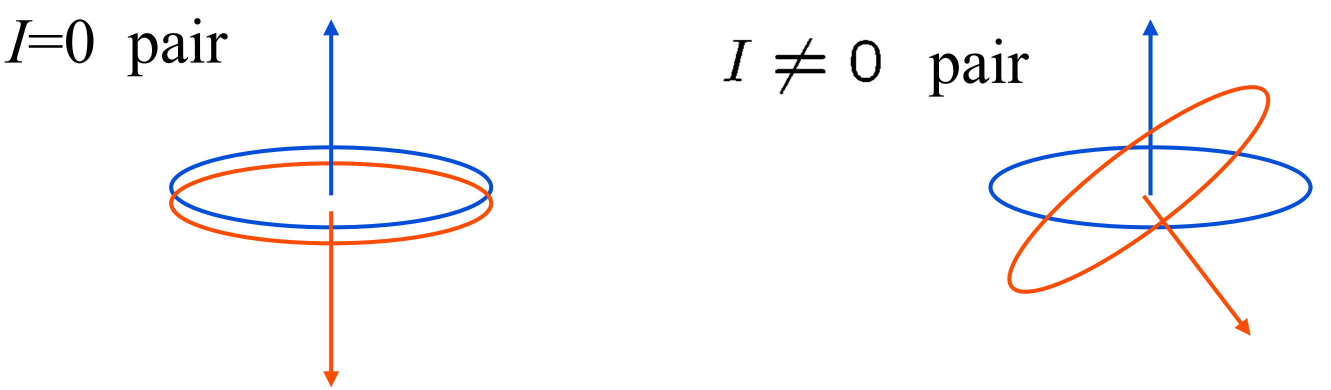


Energy spectrum of contact interaction

$$v(\boldsymbol{r}_1,\boldsymbol{r}_2)=\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\left\{v_0+\frac{v_\rho}{1+\exp[(r_1-R_\rho)/a_\rho]}\right\},$$

$[jj]^{(I)} = 0^+, 2^+, 4^+, 6^+, \ldots\ldots$

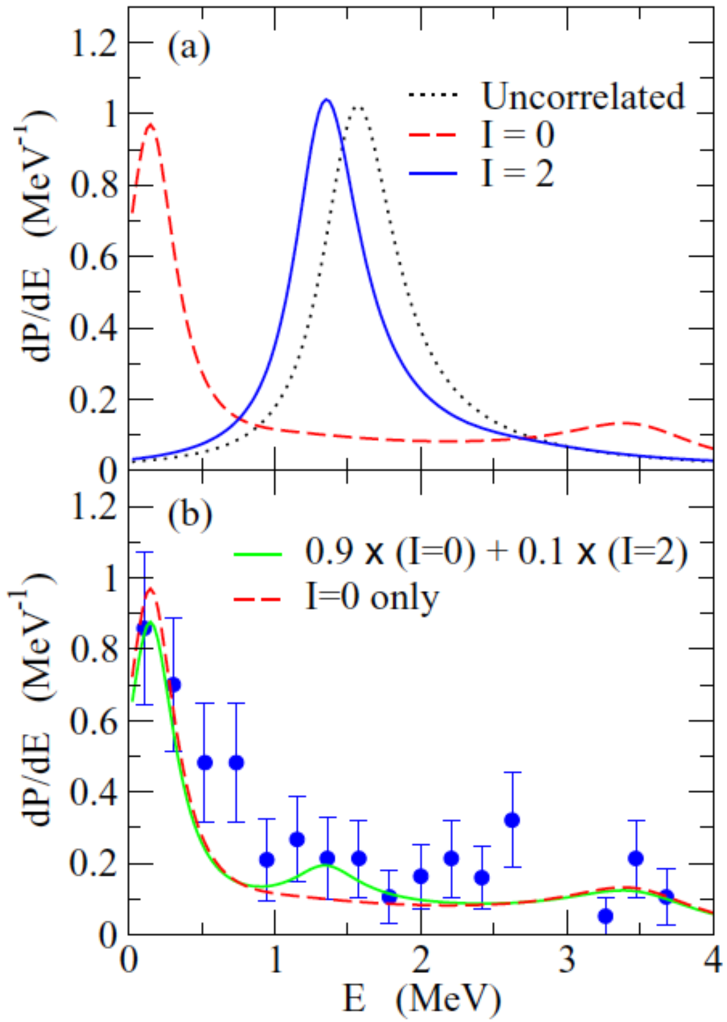




PHYSICAL REVIEW C **90**, 027303 (2014)

Three-body model calculation of the 2^+ state in ^{26}O

K. Hagino[1,2] and H. Sagawa[3,4]



$E(0^+)=5.0$ keV

$E(2^+)=1.338$MeV

^{25}O resonance of d3/2 state e(d3/2)=0.77MeV

2^+ with a simple configuration $(d3/2)^2$:
Ex=1.54MeV (unperturbed)

FIG. 1. (Color online) (Top) The decay energy spectrum for the two-neutron emission decay of ^{26}O. The dashed and the solid lines are for the 0^+ and 2^+ states, respectively. The dotted line shows the uncorrelated spectrum obtained by ignoring the interaction between the valence neutrons. (Bottom) The decay energy spectrum obtained by superposing the $I = 0$ and $I = 2$ components. The dashed line is the same as the one in the top panel, that is, the decay energy spectrum for the pure $I = 0$ configuration. The experimental data, normalized to the unit area, are taken from Ref. [5].

	^{25}O (3/2$^+$)	^{26}O (2$^+$)
Experiment	+ 770^{+20}_{-10} keV	~ 1.3 MeV
USDA	1301 keV	1.9 MeV
USDB	1303 keV	2.1 MeV
sdpf-m	2.15MeV	2.6 MeV
chiral NN+3N	742 keV	1.6 MeV
continuum SM (Volya-Zelevinsky)	1002 keV	1.8 MeV
3-body model (Hagino-Sagawa)	770 keV (input)	1.35 MeV

Summary

Di-neutron correlation : spatial localization of two neutrons

✓Theroy: large model space (parity mixing)
✓ scattering to the continuum states
enhancement of pairing on the surface

how to probe it?

•Direct two-neutron emission decay (^{26}O, ^{14}Be)

✓ decay energy spectrum
✓ Final state interaction=di-neutron correlations
✓ opening angle of two emitted neutrons (back-to-back)

^{26}O

ground state: very small width ($\Gamma \sim 10^{-10}$MeV)
very small resonance energy (Ex<140keV)

2^+ :The three-body model with a contact pairing interaction gives E_x=1.3MeV. ab initio and USD shell model calculations give higher energy than E_x>1.6MeV.