Two-neutron decay of the ^{26}O nucleus and nn-correlations

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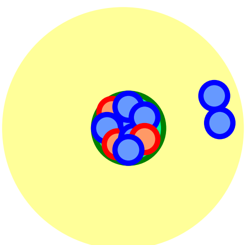

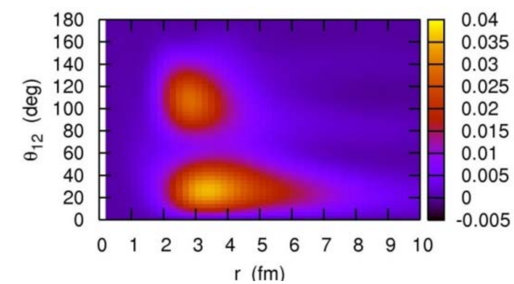

1. *Di-neutron correlation in neutron-rich nuclei*
2. *Two-neutron decay of unbound nucleus ^{26}O*
3. *Summary*

One-day workshop on “NN and quartet correlations in nuclei”, YITP, June 27, 2016

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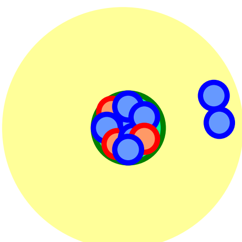
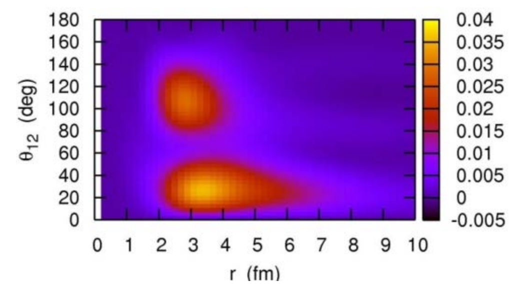




1. Di-neut ... on-rich nuclei
2. Two-neu ... ucleus ^{26}O
3. Summar

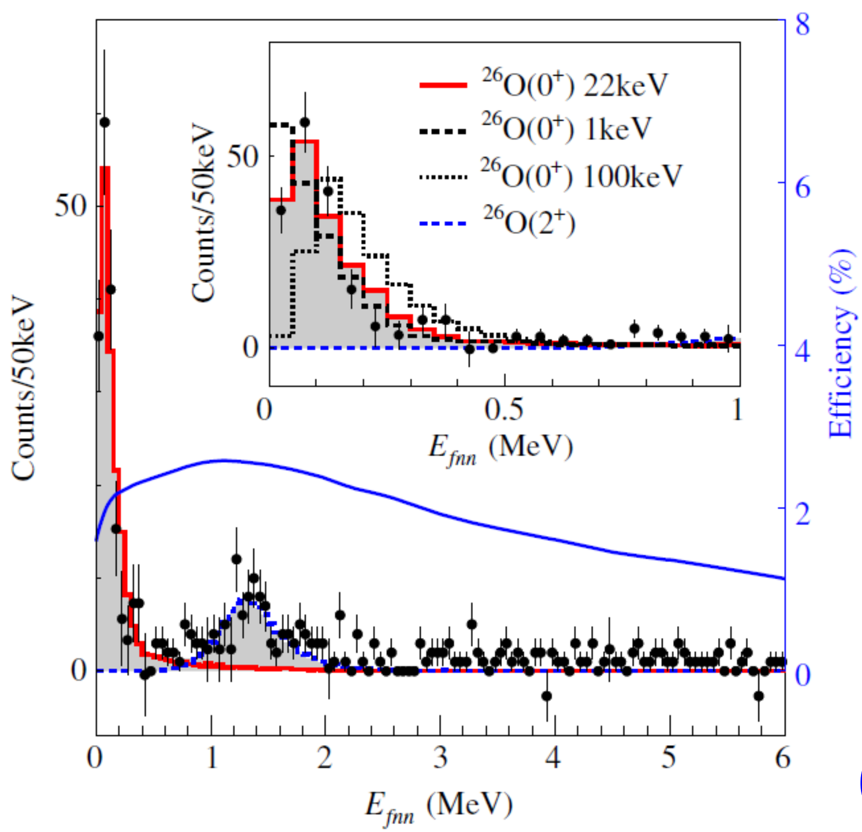
One-day workshop on "NN and quartet correlations in nuclei", YITP, June 27, 2016

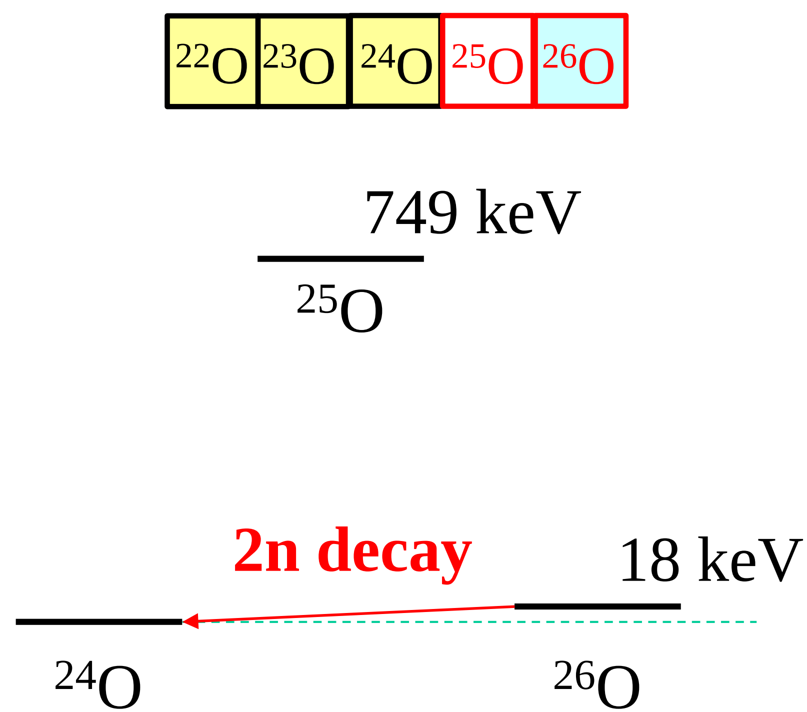
Two-neutron decay of ^{26}O

PRL **116,** 102503 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

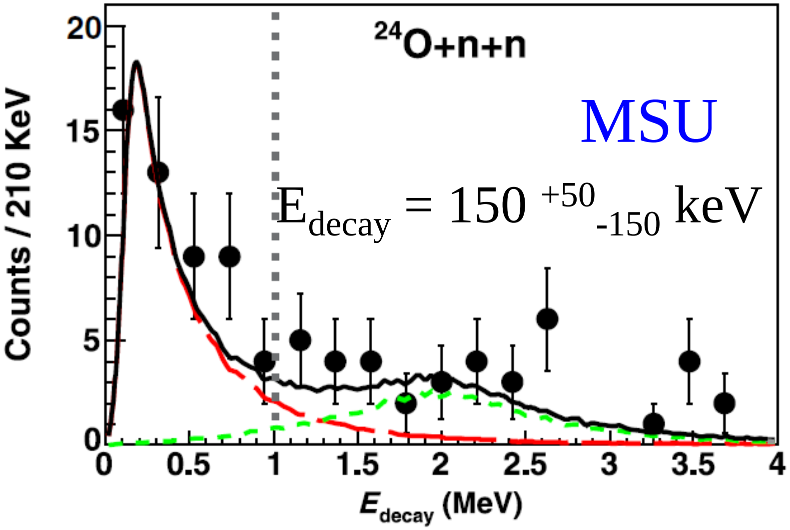
Nucleus ^{26}O: A Barely Unbound System beyond the Drip Line

Y. Kondo,[1] T. Nakamura,[1] R. Tanaka,[1] R. Minakata,[1] S. Ogoshi,[1] N. A. Orr,[2] N. L. Achouri,[2] T. Aumann,[3,4] H. Baba,[5] F. Delaunay,[2] P. Doornenbal,[5] N. Fukuda,[5] J. Gibelin,[2] J. W. Hwang,[6] N. Inabe,[5] T. Isobe,[5] D. Kameda,[5] D. Kanno,[1] S. Kim,[6] N. Kobayashi,[1] T. Kobayashi,[7] T. Kubo,[5] S. Leblond,[2] J. Lee,[5] F. M. Marqués,[2] T. Motobayashi,[5] D. Murai,[8] T. Murakami,[9] K. Muto,[7] T. Nakashima,[1] N. Nakatsuka,[9] A. Navin,[10] S. Nishi,[1] H. Otsu,[5] H. Sato,[5] Y. Satou,[6] Y. Shimizu,[5] H. Suzuki,[5] K. Takahashi,[7] H. Takeda,[5] S. Takeuchi,[5] Y. Togano,[4,1] A. G. Tuff,[11] M. Vandebrouck,[12] and K. Yoneda[5]

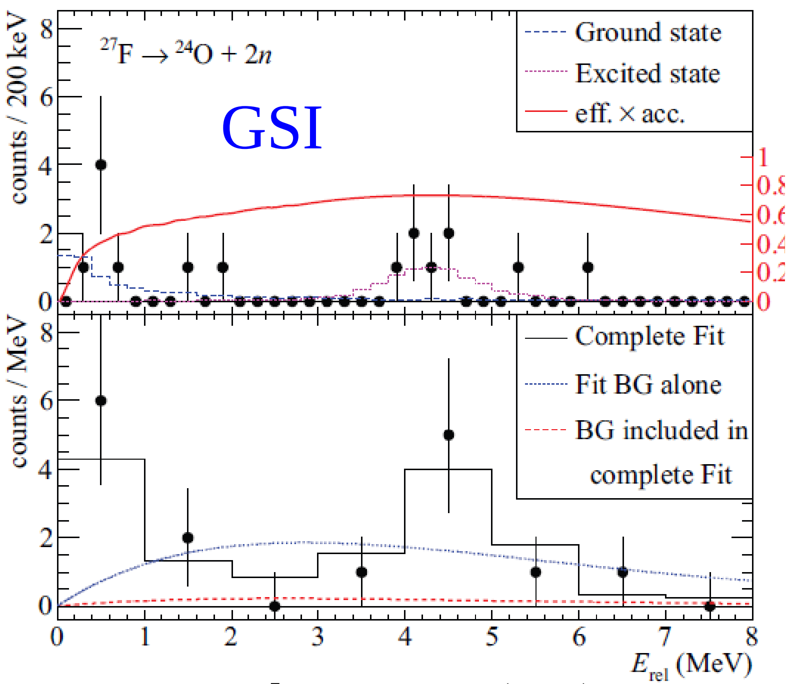




(neutron drip line)

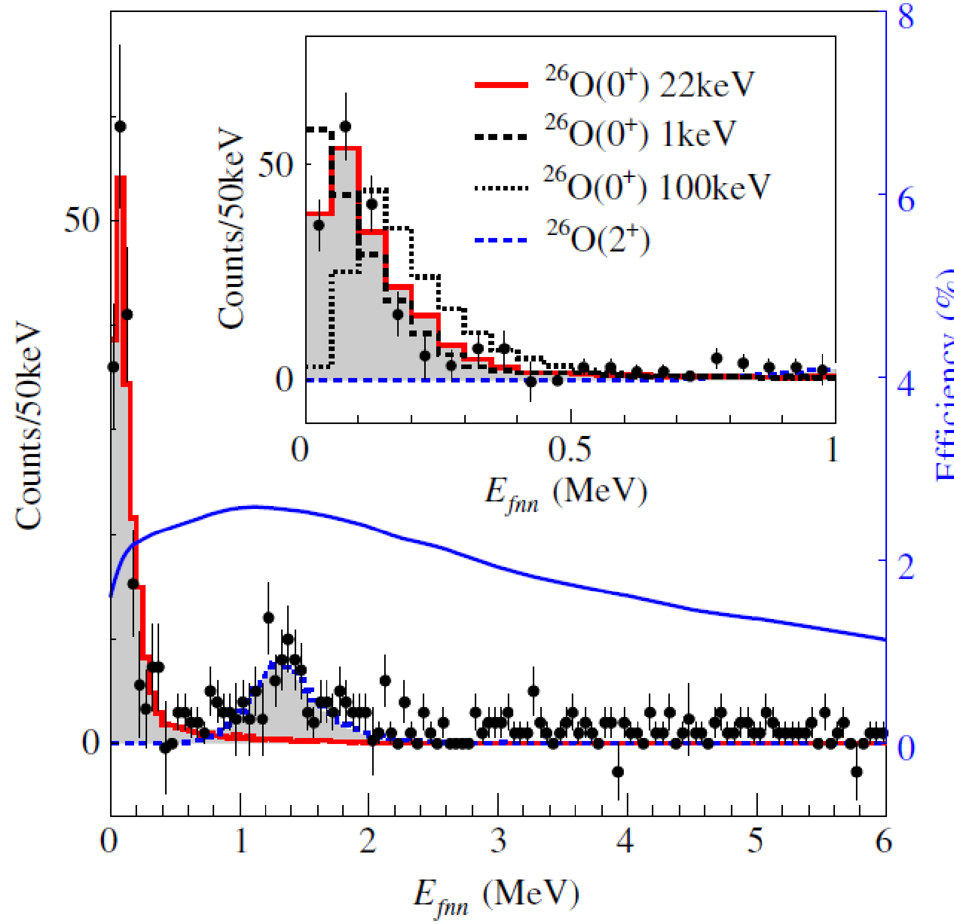


E. Lunderberg et al.,
PRL108 (‘12) 142503



C. Caesar et al., PRC88 (‘13) 034313

New RIKEN data

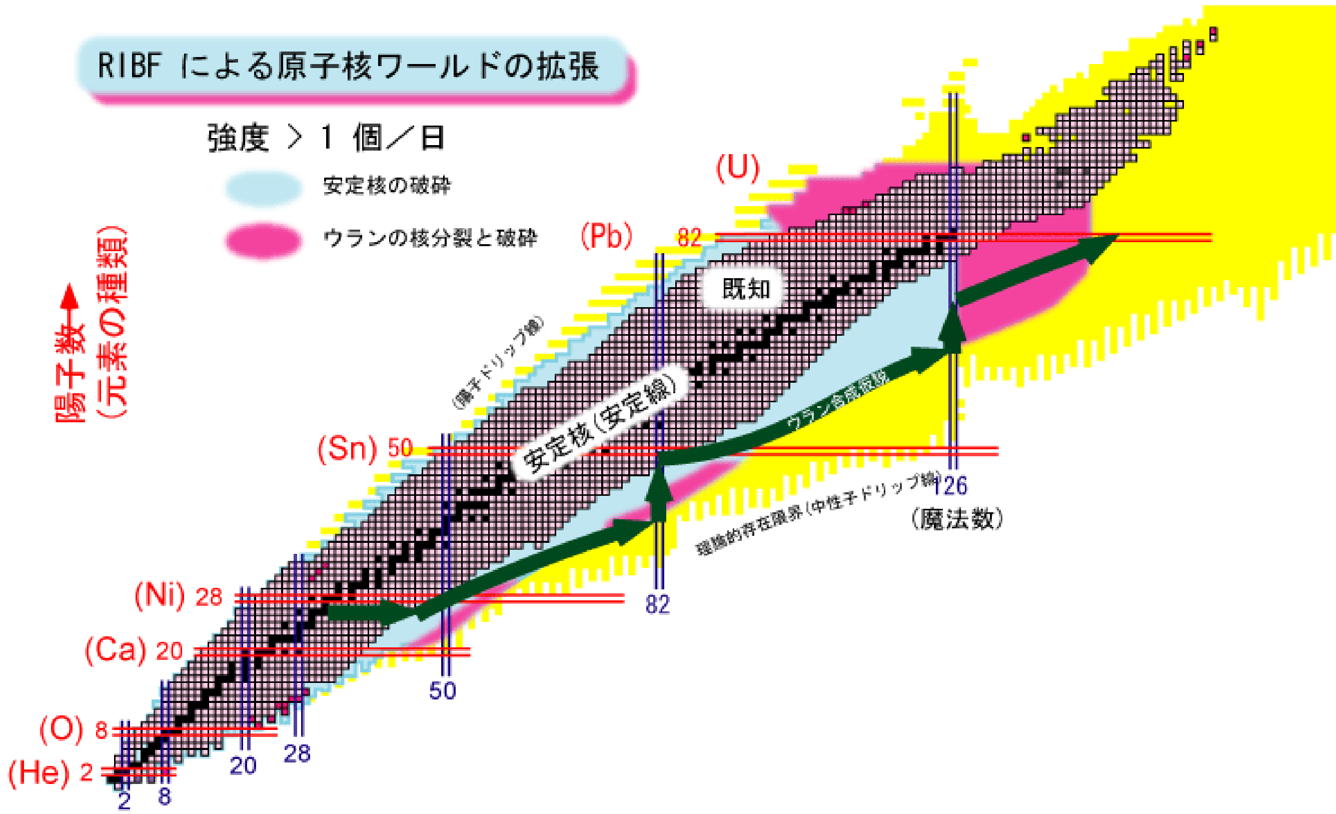


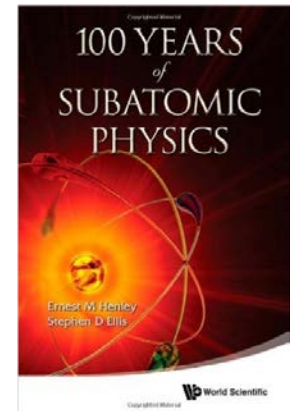
Y. Kondo et al., PRL116(’16)102503

E_{decay} = 18 +/- 3 +/- 4 keV

Introduction: neutron-rich nuclei

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





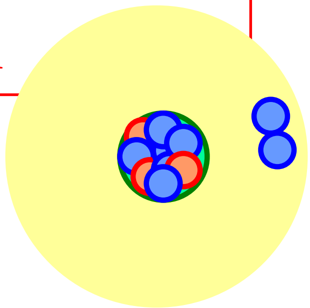
ed. by E.M. Henley and S.D. Ellis (2013)

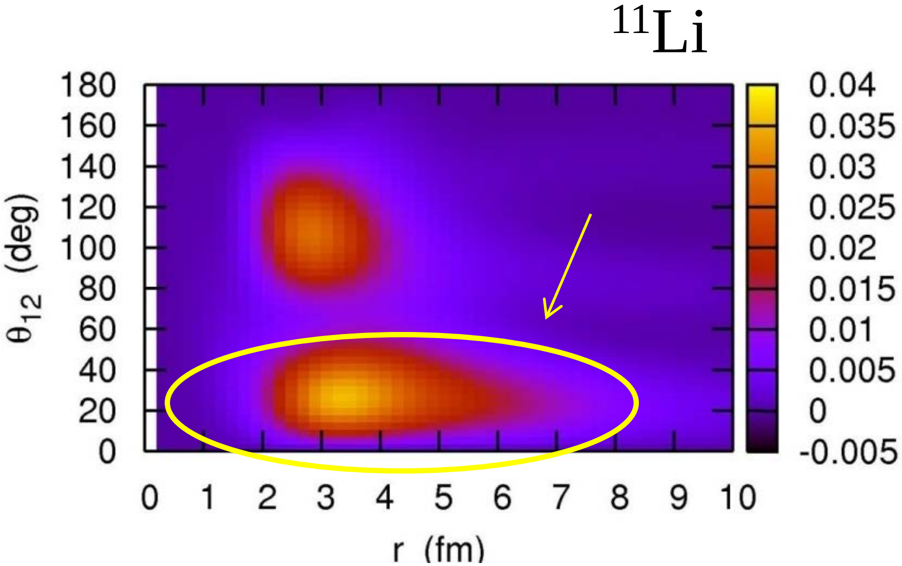
"*Exotic nuclei far from the stability line*"
K.H., I. Tanihata, and H. Sagawa

- ●halo/skin structure
- ●Borromean nuclei
- ●large E1 strength
- ●Dineutron correlations
- ●shell evolution
- ●………….

Di-neutron correlations in neutron-rich nuclei

Strong di-neutron correlations
in neutron-rich nuclei

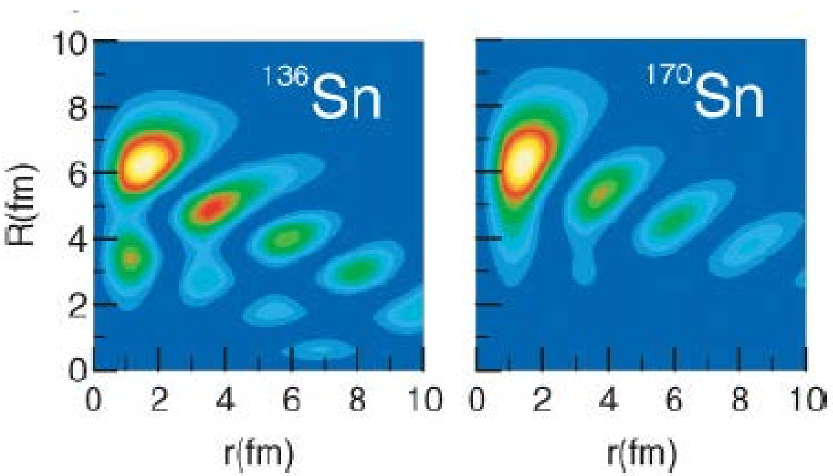




K.H. and H. Sagawa,
PRC72('05)044321

- ✓ Borromean nuclei (3body calc.)
  - Bertsch-Esbensen ('91)
  - Zhukov et al. ('93)
  - Hagino-Sagawa ('05)
  - Kikuchi-Kato-Myo ('10)

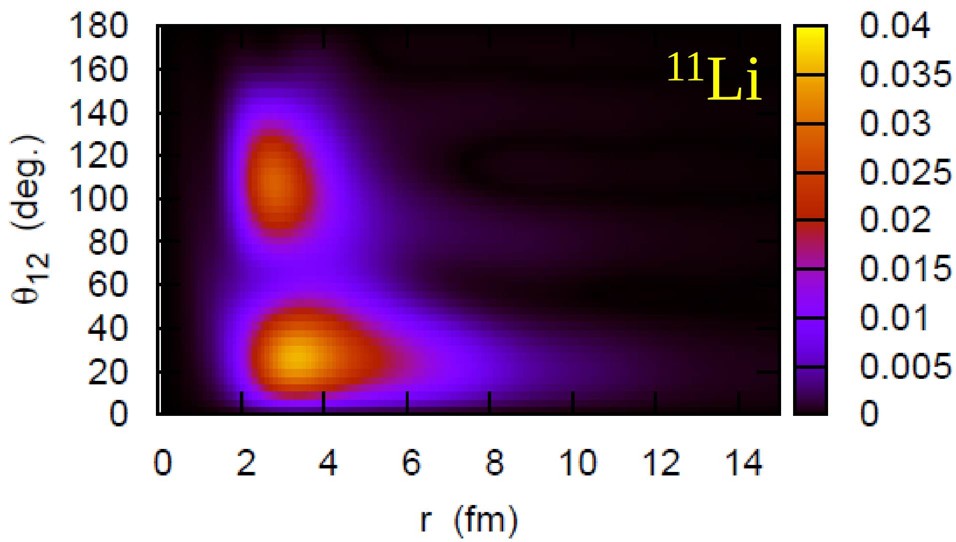
- ✓ Heavier nuclei (HFB calc.)
  - Matsuo et al. ('05)
  - Pillet-Sandulescu-Schuck ('07)

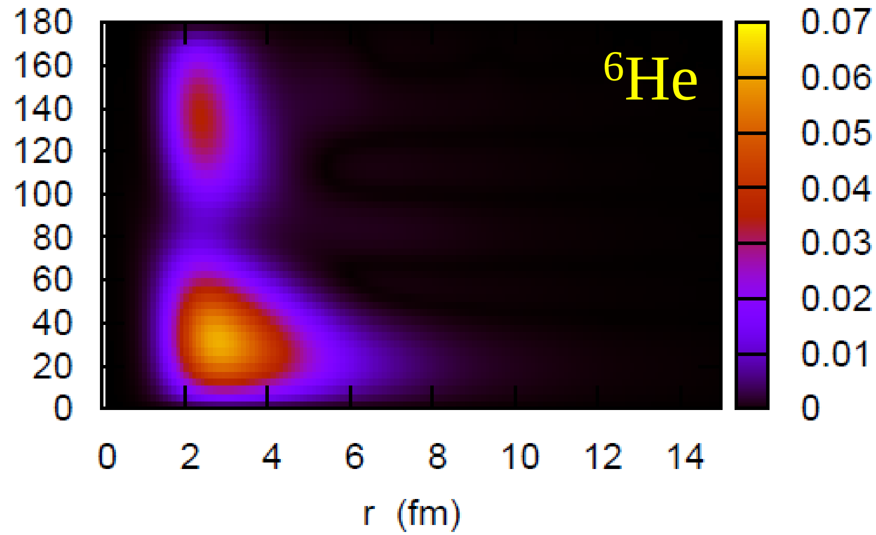


N. Pillet, N. Sandulescu, and P. Schuck,
PRC76('07)024310

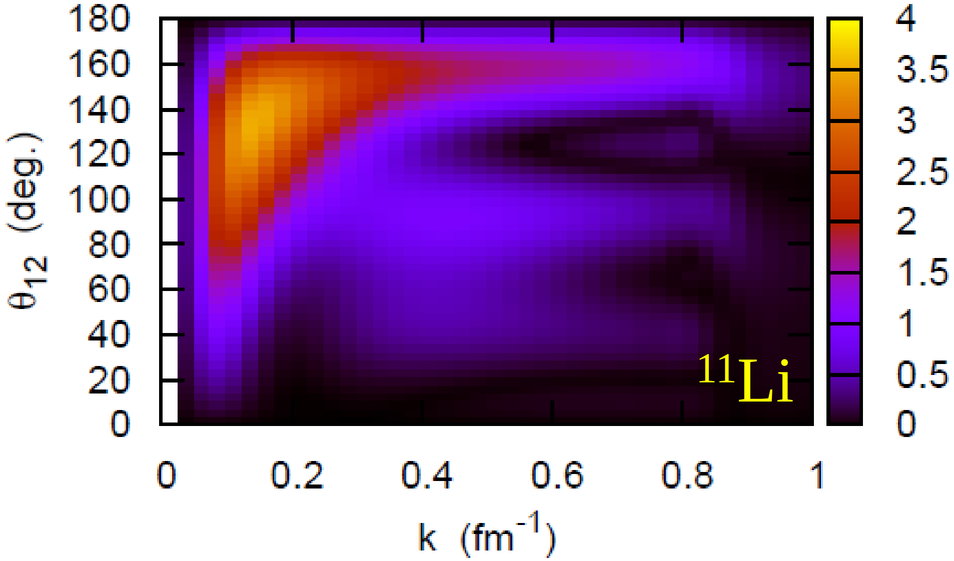
Dineutron correlation in the momentum space

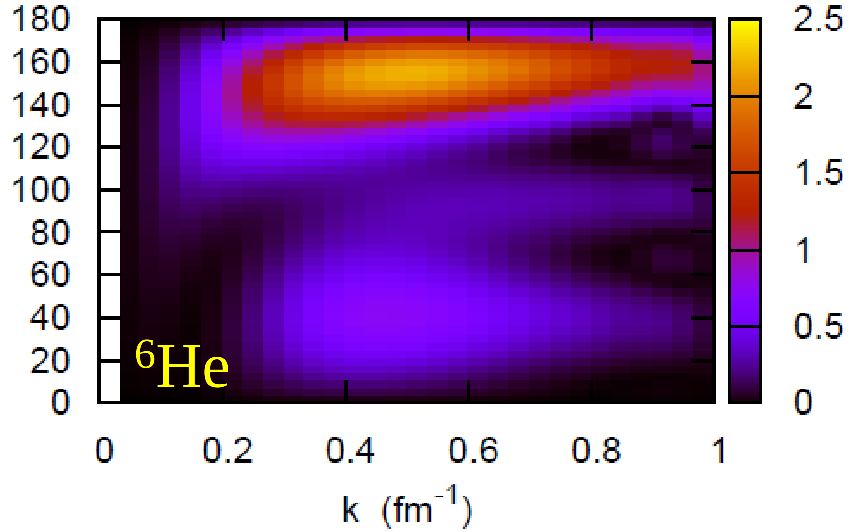
Two-particle density in the *r* space: $8\pi^2 r^4 \sin\theta \cdot \rho(r,r,\theta)$

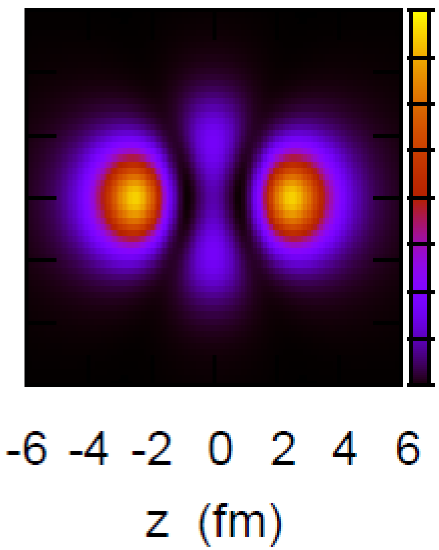




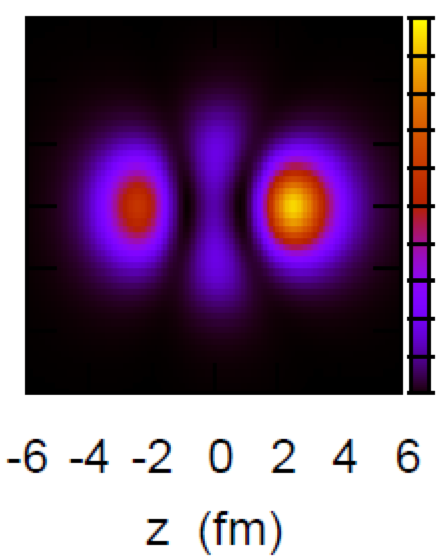
Two-particle density in the *p* space: $8\pi^2 k^4 \sin\theta \cdot \rho(k,k,\theta)$







parity mixing



spatial localization of two neutrons
(dineutron correlation) ← parity mixing

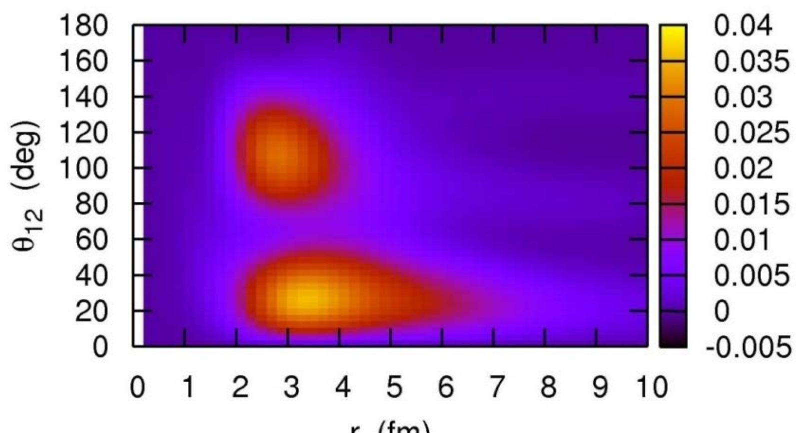
cf. F. Catara, A. Insolia, E. Maglione, and A. Vitturi, PRC29('84)1091

weakly bound systems

→easy to mix different parity states due to the continuum couplings
+ enhancement of pairing on the surface

→ dineutron correlation: enhanced

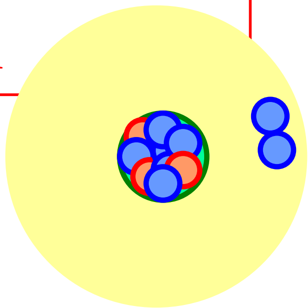
cf. - Bertsch, Esbensen, Ann. of Phys. 209('91)327
- M. Matsuo, K. Mizuyama, Y. Serizawa, PRC71('05)064326



K.H. and H. Sagawa, PRC72('05)044321

Di-neutron correlation in neutron-rich nuclei

Strong di-neutron correlation
in neutron-rich nuclei



✓ Borromean nuclei (3body calc.)
 Bertsch-Esbensen (‘91)
 Zhukov et al. (‘93)
 Hagino-Sagawa (‘05)
 Kikuchi-Kato-Myo (‘10)

✓ Heavier nuclei (HFB calc.)
 Matsuo et al. (‘05)
 Pillet-Sandulescu-Schuck (‘07)

How to probe it?

- Coulomb breakup
  T. Nakamura et al.
  cluster sum rule
  (mean value of θ_{nn})
- pair transfer reactions
- two-proton decays
  Coulomb 3-body problem

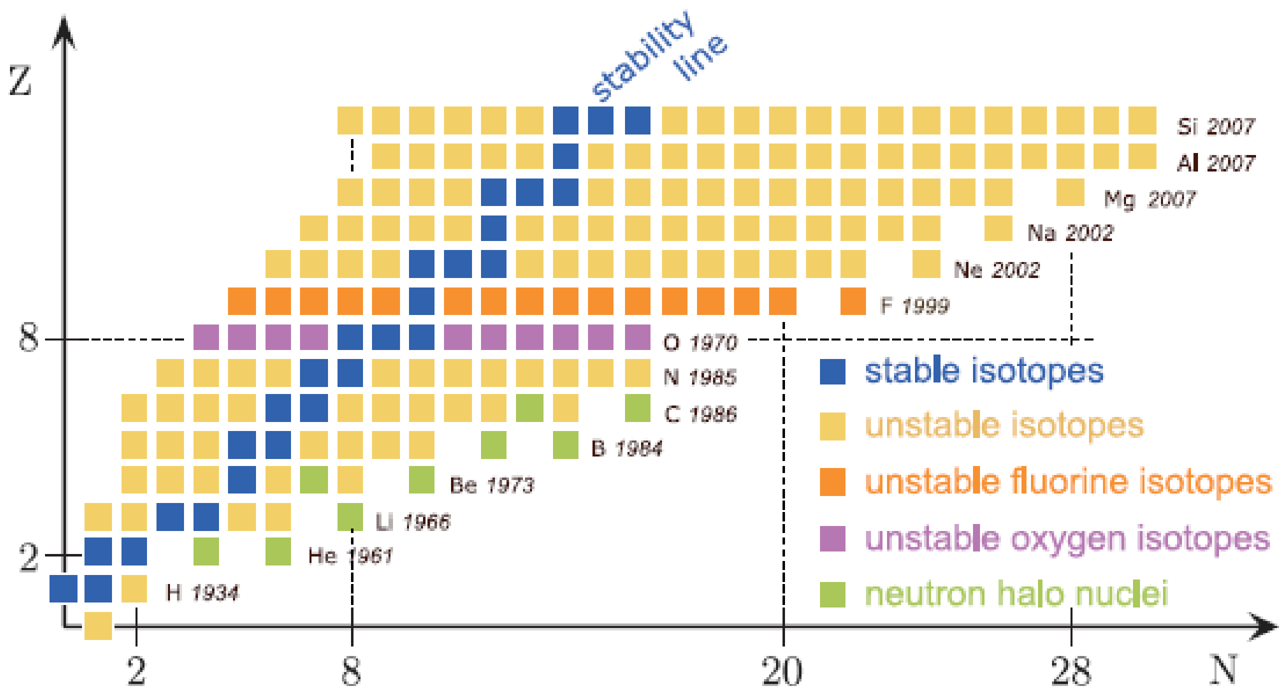
- <u>two-neutron decays</u>
  3-body resonance due to a centrifugal barrier
  MoNA (^{16}Be, ^{13}Li, ^{26}O)
  SAMURAI (^{26}O)
  GSI (^{26}O)

Two-neutron decay of ^{26}O

- the simplest among ^{16}Be, ^{13}Li, ^{26}O (MSU)
  ^{16}Be: deformation, ^{13}Li: treatment of ^{11}Li core

E. Lunderberg et al., PRL108 (‘12) 142503
Z. Kohley et al., PRL 110 (‘13)152501

- anomaly of the neutron drip line in O isotopes



^{31}F: bound

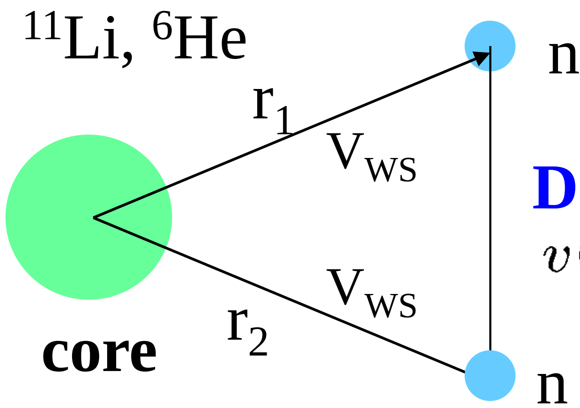
H. Sakurai et al., PLB448 (‘99) 180

^{24}O: the last bound

T. Otsuka et al., PRL105(‘10)032501

✓ three-body force
✓ tensor interaction

3-body model calculation for Borromean nuclei



G.F. Bertsch and H. Esbensen,
Ann. of Phys. 209('91)327; PRC56('99)3054

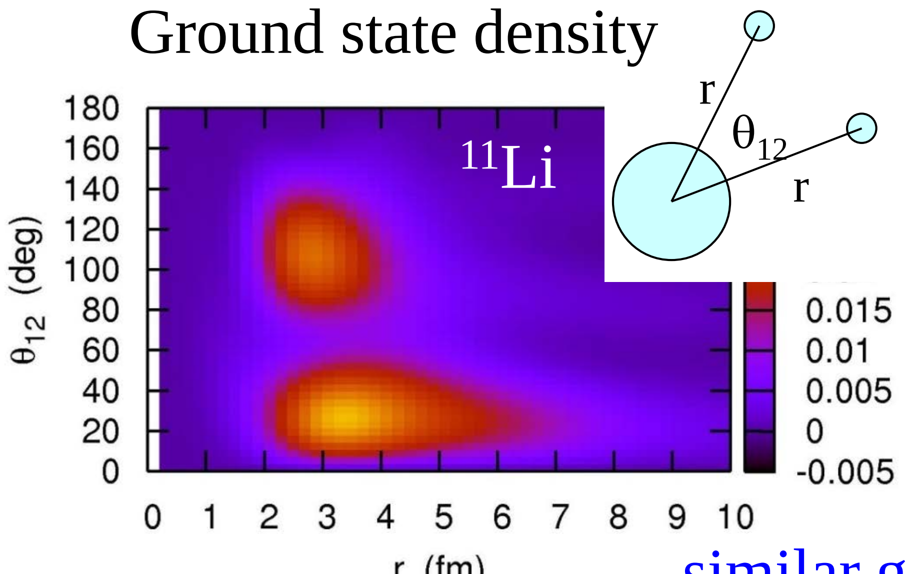
Density-dependent delta-force

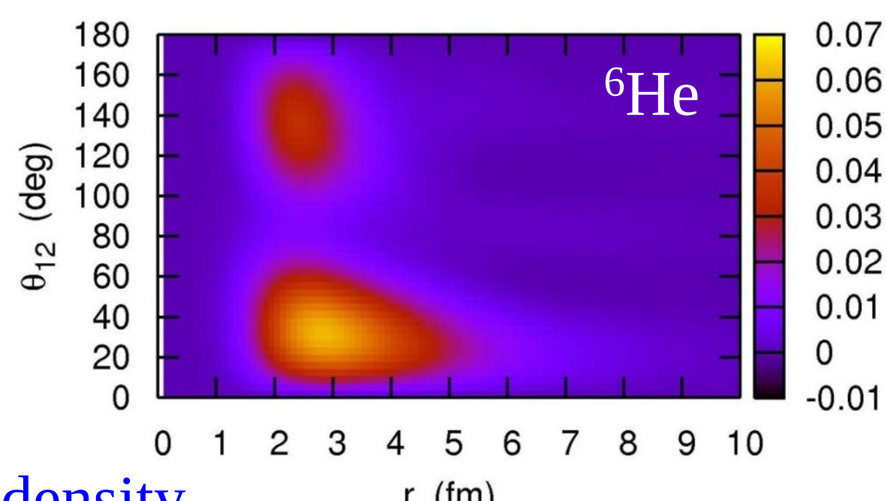
$$v(\boldsymbol{r}_1, \boldsymbol{r}_2) = v_0(1 + \alpha\rho(r)) \times \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)$$

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

Ground state density

K.H. and H. Sagawa, PRC72('05)044321



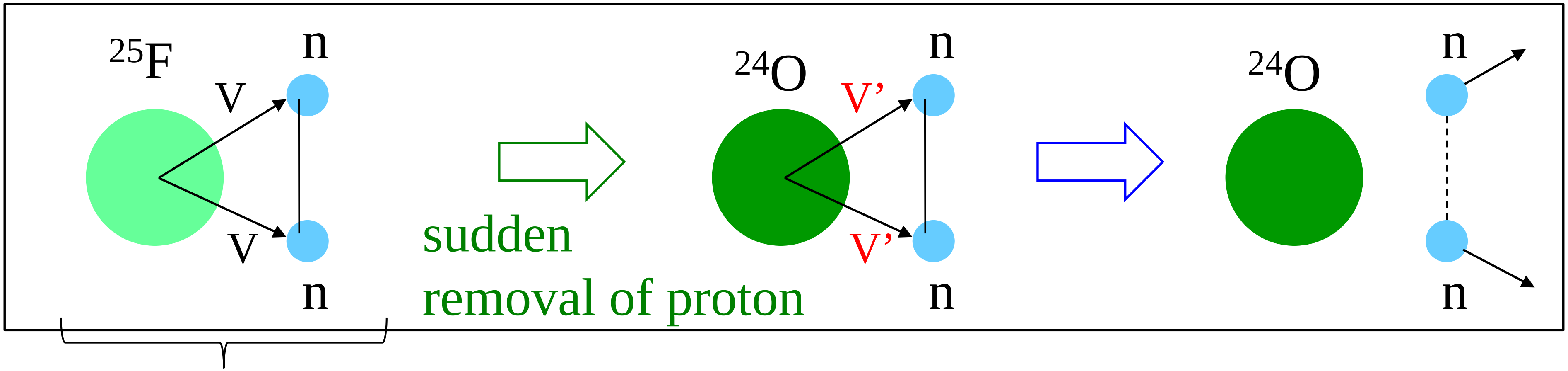


similar g.s. density

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

K.H. and H. Sagawa,
PRC89 ('14) 014331

cf. Expt. : ^{27}F (201 MeV/u) + ^{9}Be → ^{26}O → ^{24}O + n + n



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

$$\Psi_{nn} \otimes |^{25}\mathrm{F}\rangle \;\Rightarrow\; \Psi_{nn} \otimes |^{24}\mathrm{O}\rangle \;\Rightarrow$$ spontaneous decay

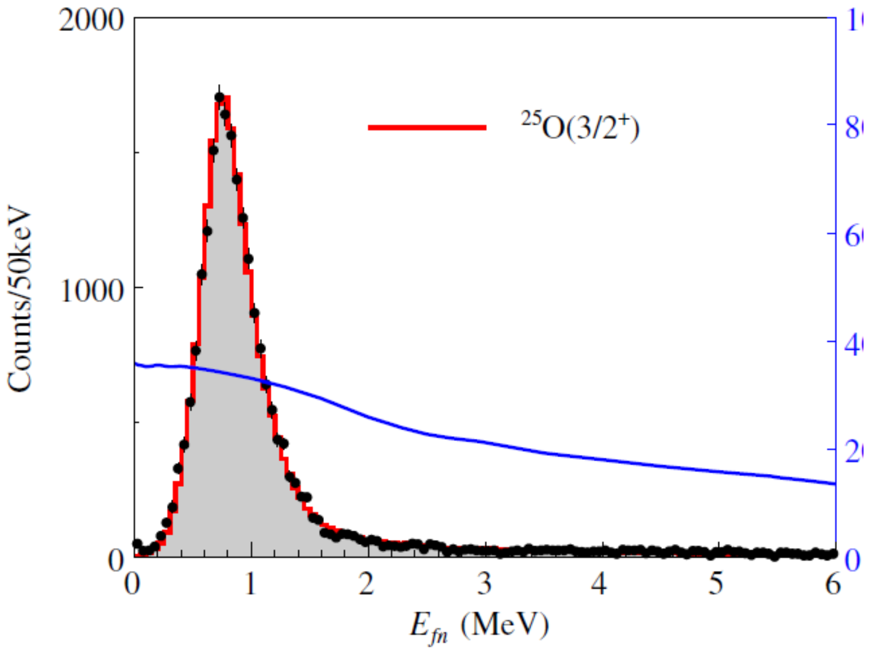
→ the same config. (the reference state)

FSI → Green's function method ⬅ continuum effects

^{25}O : calibration of the n-^{24}O potential

n-^{24}O Woods-Saxon potential

$$\left\{\begin{array}{l} a = 0.72 \text{ fm (fixed)} \\ r_0 = 1.25 \text{ fm (fixed)} \\ V_0 \longleftarrow e_{2s1/2} = -4.09\ (13) \text{ MeV} \\ V_{ls} \longleftarrow e_{d3/2} = 0.749(10) \text{ MeV} \end{array}\right.$$



Gamow states (outgoing boundary condition)

$d_{3/2}$: E = 0.749 MeV (input), Γ = 87.2 keV   cf. Γ_{exp} = 86 (6) keV

$f_{7/2}$: E = 2.44 MeV, Γ = 0.21 MeV

$p_{3/2}$: E = 0.577 MeV, Γ = 1.63 MeV

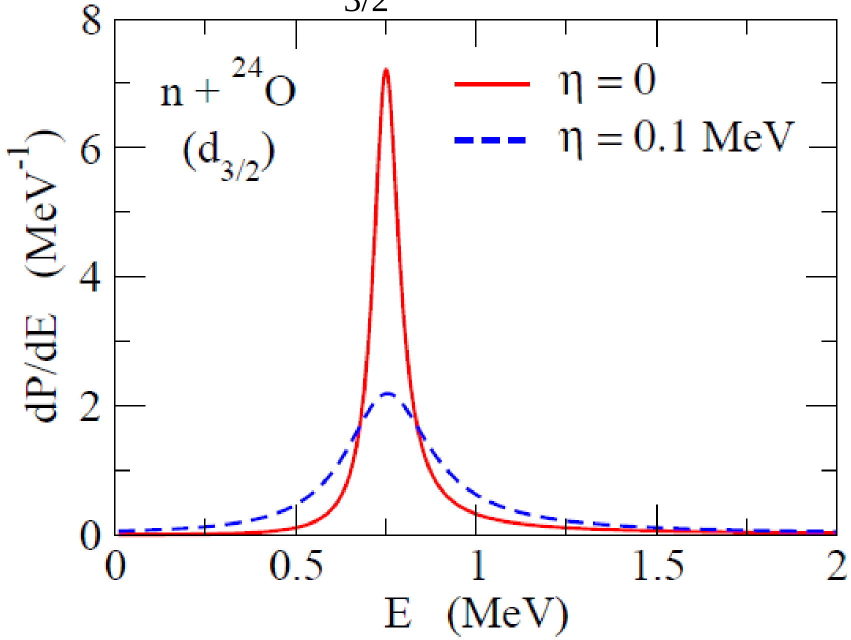
n-^{24}O decay spectrum

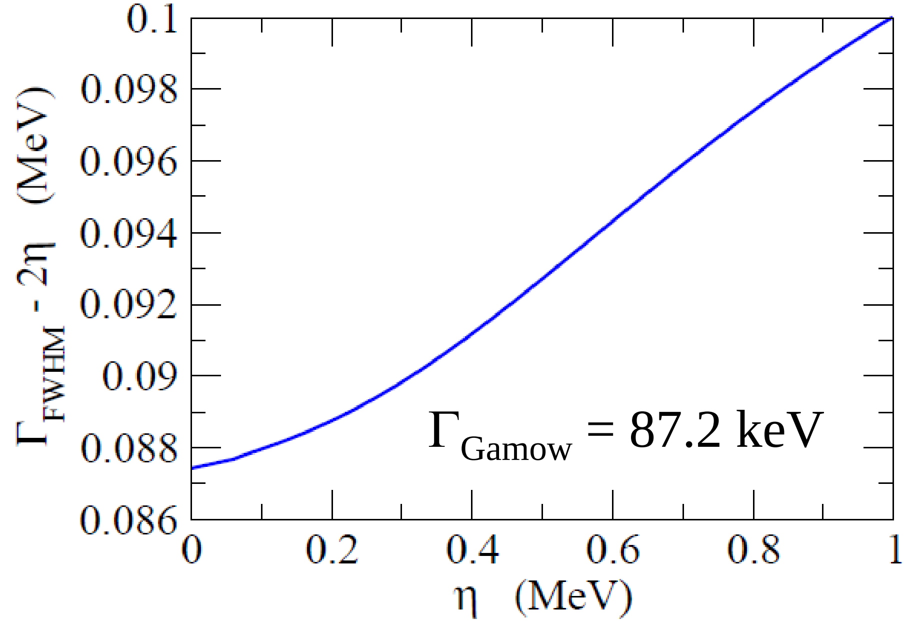
$$\frac{dP}{dE} = |\langle \Phi_{\rm ref} | \Psi_E \rangle|^2 = \int dE' \, |\langle \Phi_{\rm ref} | \Psi_{E'} \rangle|^2 \delta(E - E')$$

$$\to \frac{1}{\pi} Im \int dE' \, |\langle \Phi_{\rm ref} | \Psi_{E'} \rangle|^2 \frac{1}{E' - E - i\eta}$$

$= 1 / (H - E - i\eta) = G(E)$

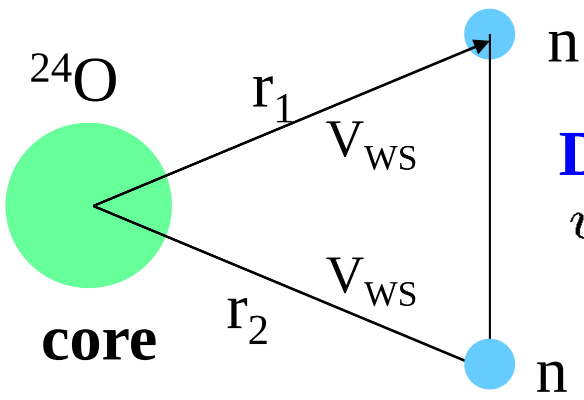
Reference state:
bound 1d$_{3/2}$ state in ^{26}F





→ apply a similar method to ^{24}O + n + n

Decay energy spectrum



Density-dependent delta-force

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

$$\frac{dP}{dE} = \int dE' |\langle \Psi_{E'} | \Phi_{\rm ref} \rangle|^2 \, \delta(E - E') = \frac{1}{\pi} \Im \langle \Phi_{\rm ref} | \frac{1}{H - E - i\eta} | \Phi_{\rm ref} \rangle$$

correlated Green's function:

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

← continuum effects

uncorrelated Green's function

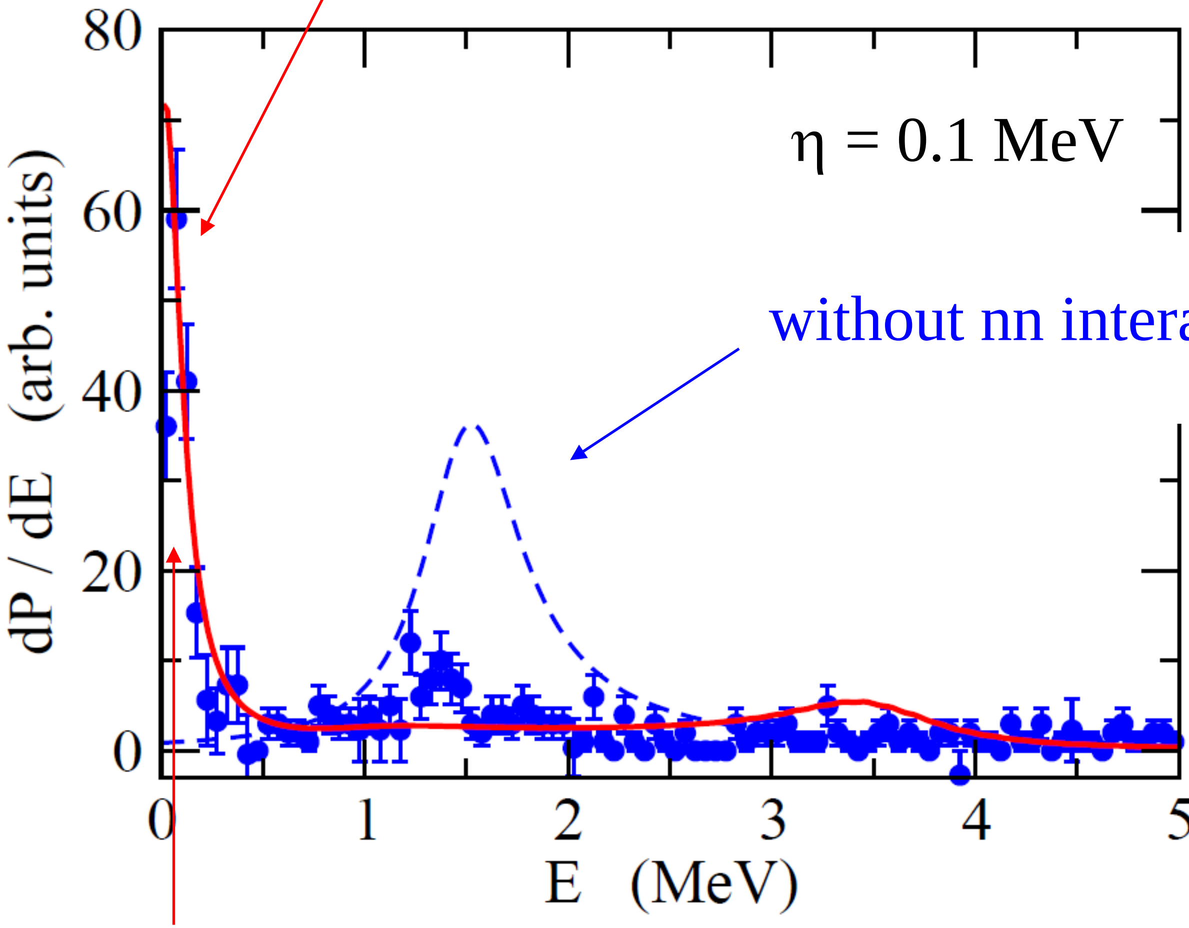
$$G_0(E) = \sum_{j_1, l_1} \sum_{j_2, l_2} \int de_1 de_2 \frac{|\psi_1 \psi_2\rangle \langle \psi_1 \psi_2|}{e_1 + e_2 - E - i\eta}$$

← small, finite η

i) Decay energy spectrum

K.H. and H. Sagawa,
- PRC89 ('14) 014331
- PRC93('16)034330

with nn interaction



without nn interaction

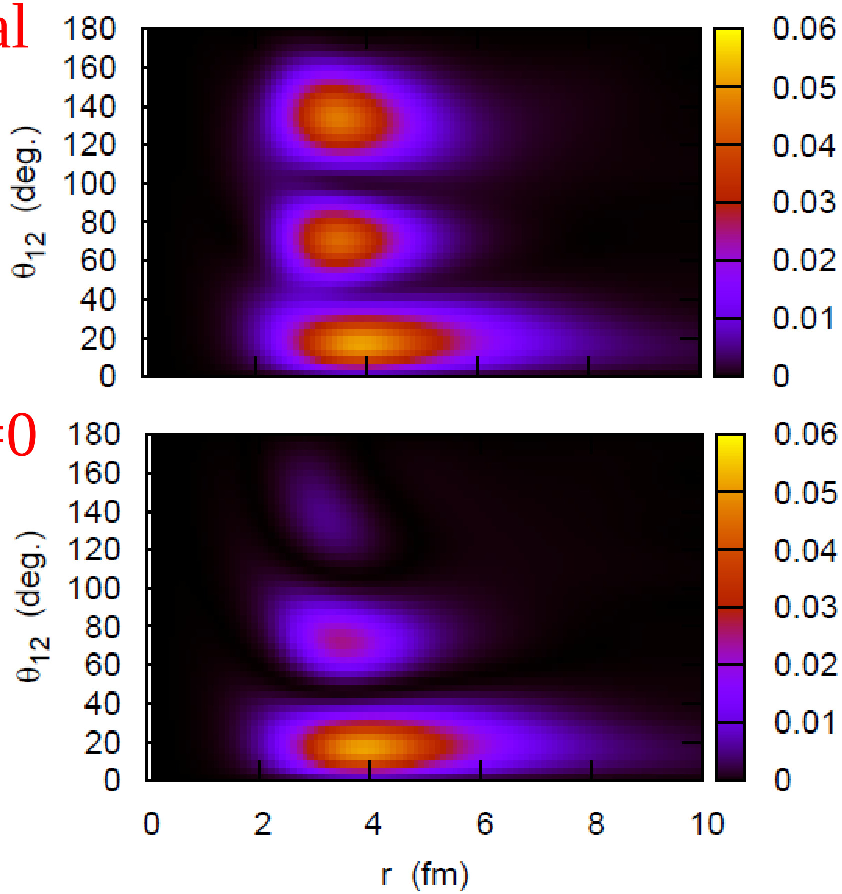
cf. $e_{1d3/2}(^{25}O)$
= 0.749 MeV

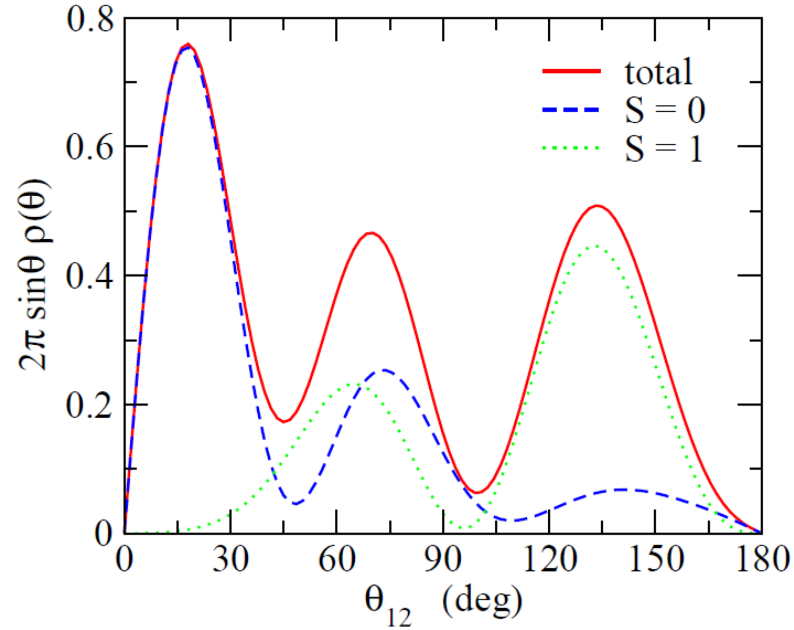
E_{peak} = 18 keV (input)

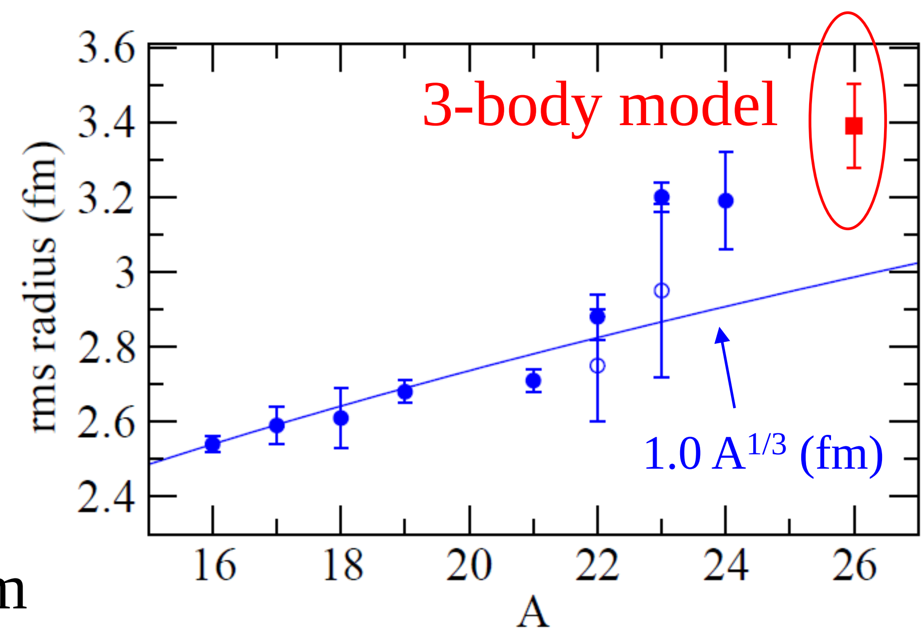
Two-particle density in the bound state approximation

total

S=0







$(d_{3/2})^2$: 66.1%

$(f_{7/2})^2$: 18.3%

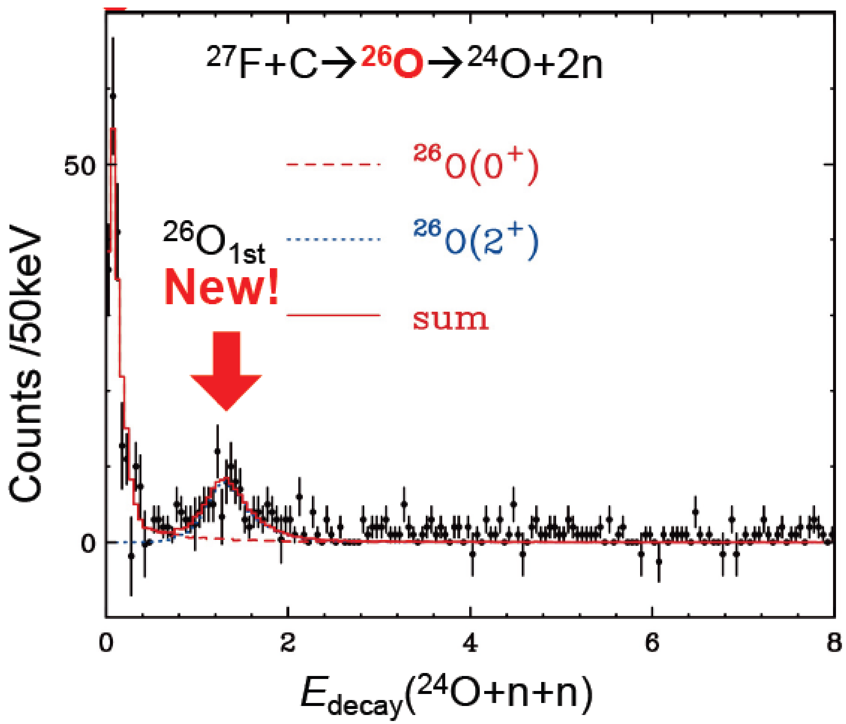
$(p_{3/2})^2$: 10.5%

$(s_{1/2})^2$: 0.59%

rms radius = 3.39 +/- 0.11 fm

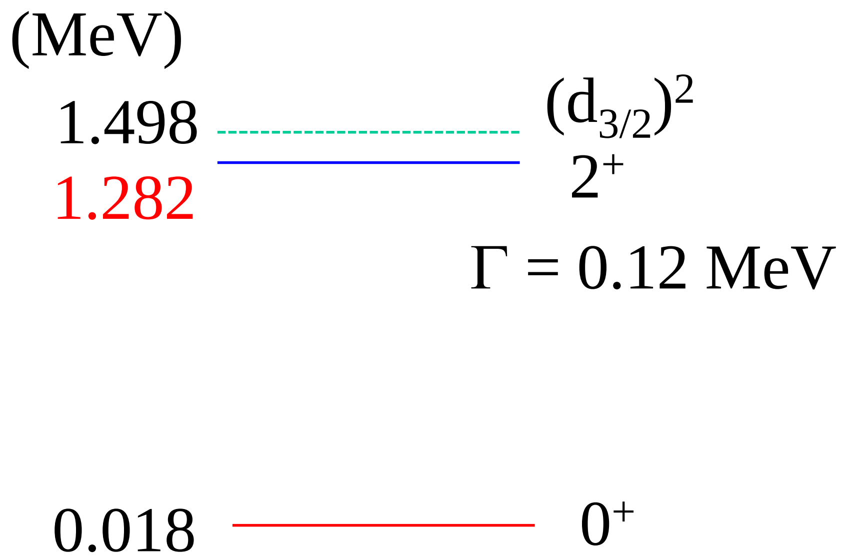
2^+ state in ^{26}O

a prominent second peak
at $E = 1.28^{+0.11}_{-0.08}$ MeV



Y. Kondo et al.,
PRL116('16)102503

three-body model calculation:



K.H. and H. Sagawa,
PRC90('14)027303; PRC93('16)034330.

2^+ state in ^{26}O

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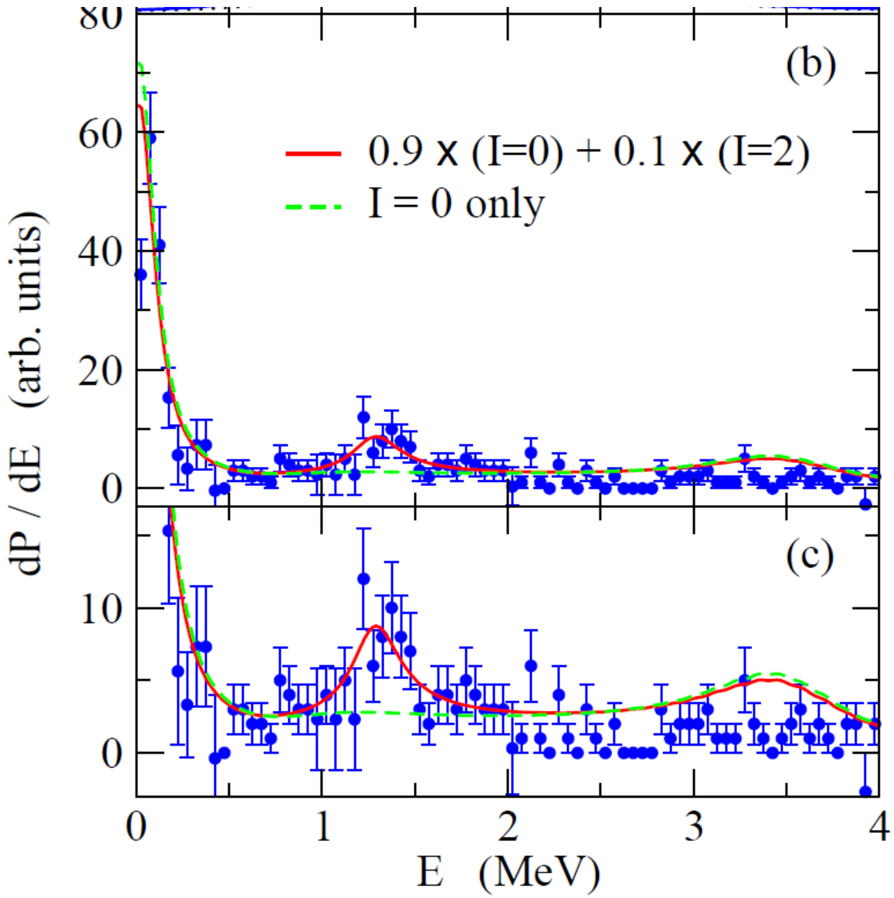

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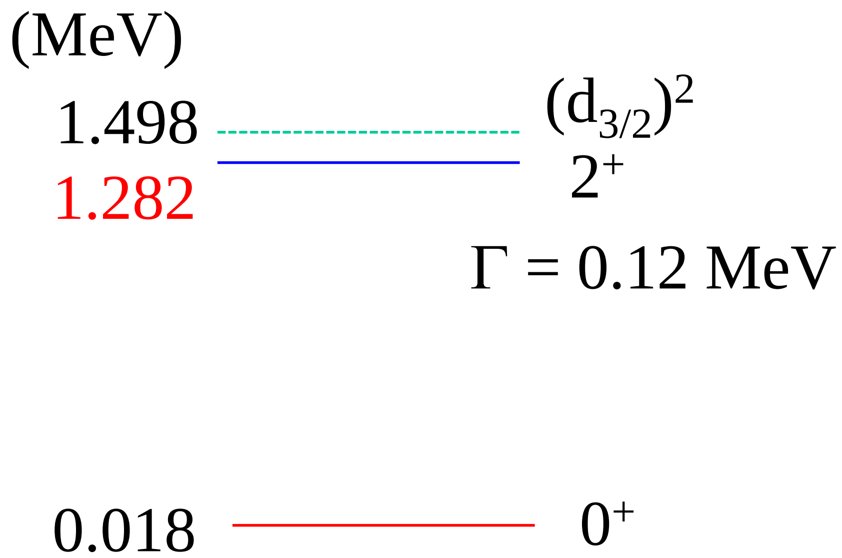
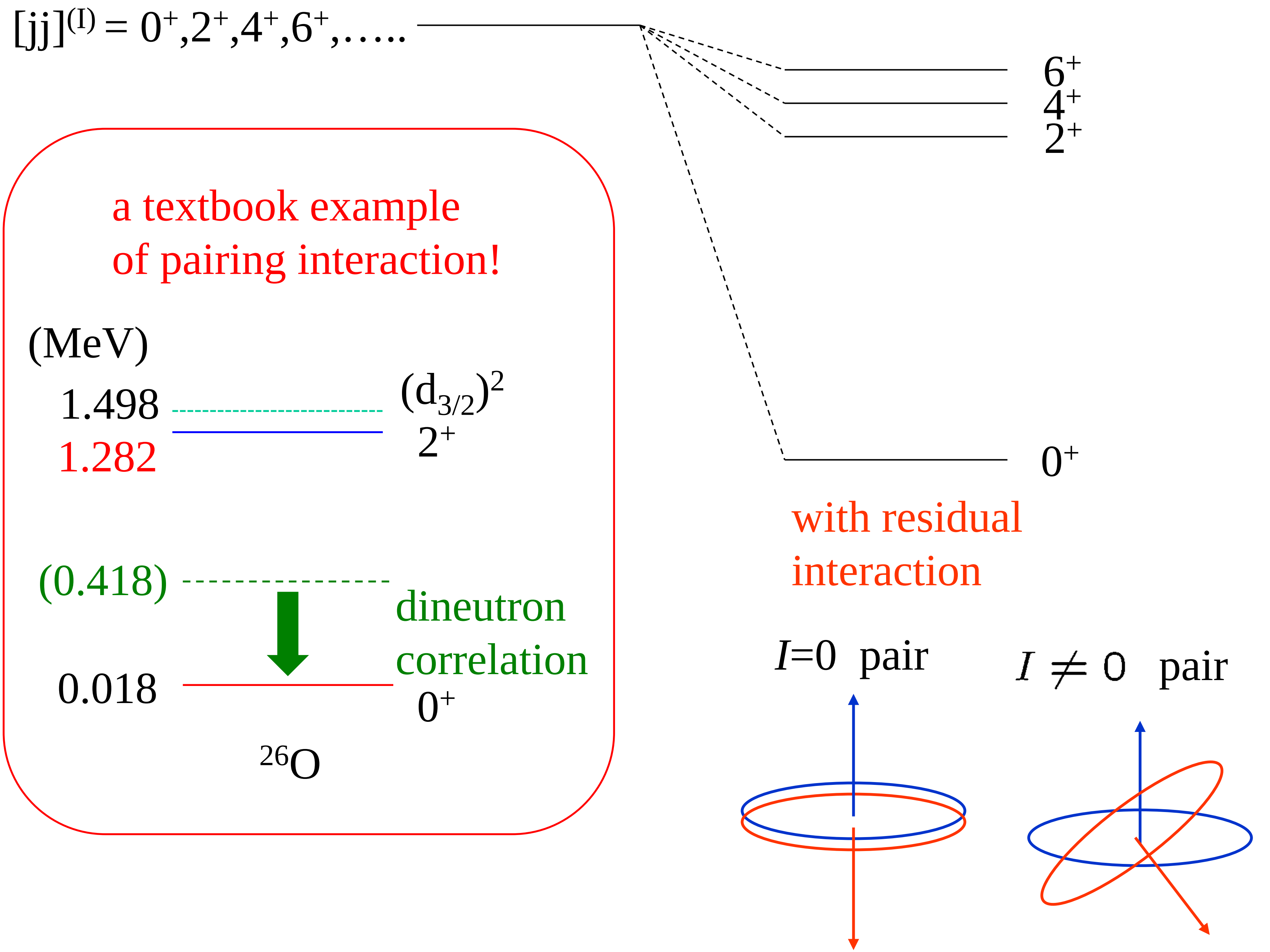
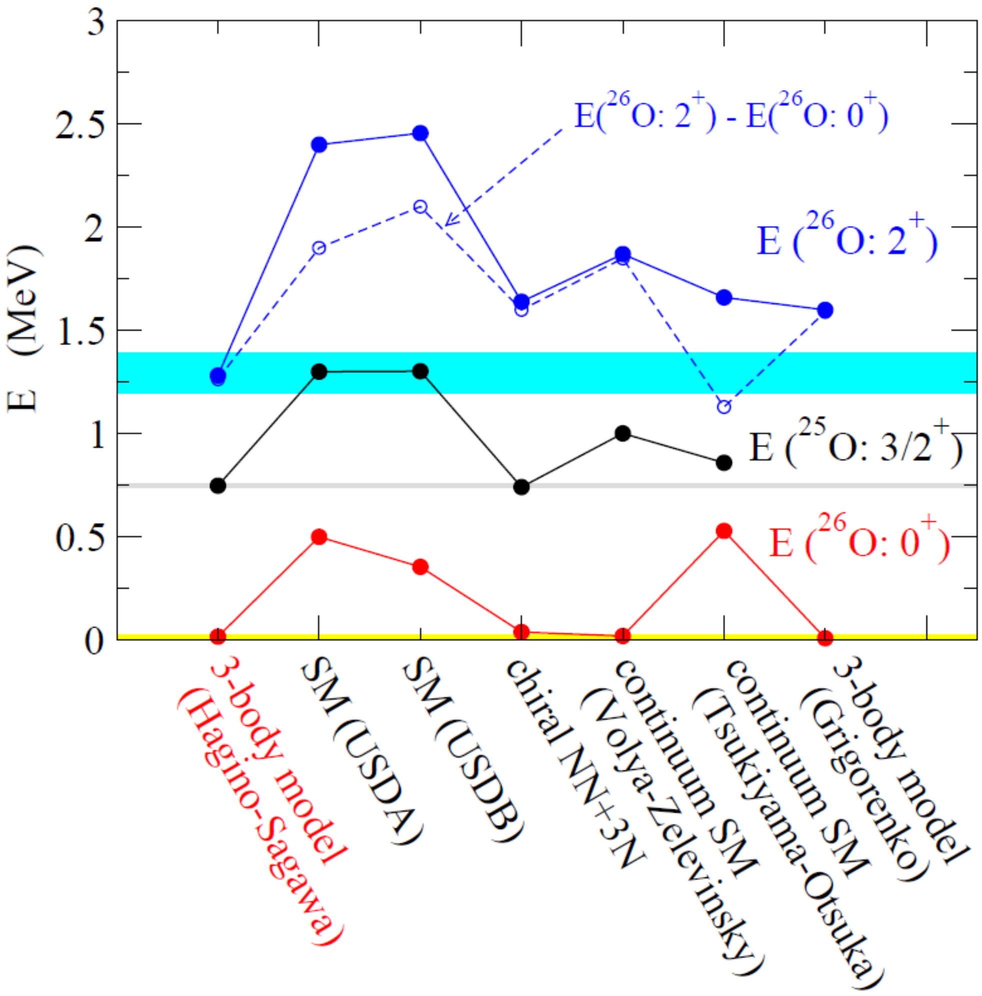


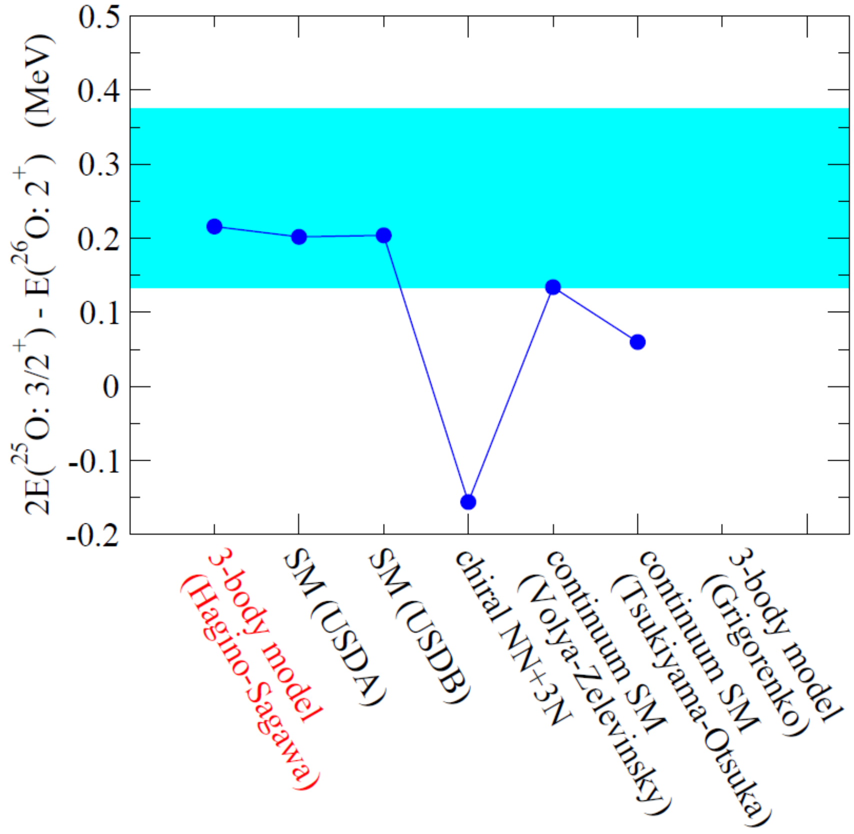
K.H. and H. Sagawa,
PRC90('14)027303; PRC93('16)034330.



$[jj]^{(I)} = 0^+, 2^+, 4^+, 6^+, \ldots..$
6^+
4^+
2^+
0^+
with residual interaction
a textbook example of pairing interaction!
(MeV)
1.498
1.282
$(d_{3/2})^2$
2^+
(0.418)
dineutron correlation
0.018
0^+
^{26}O
I=0 pair
$I \neq 0$ pair



E_{corr} for the 2^+ state of ^{26}O

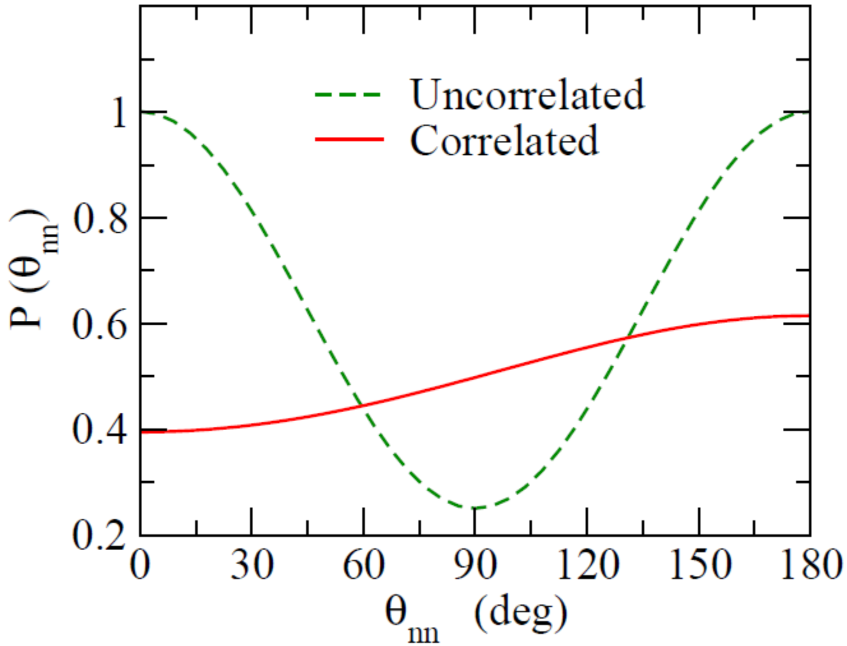


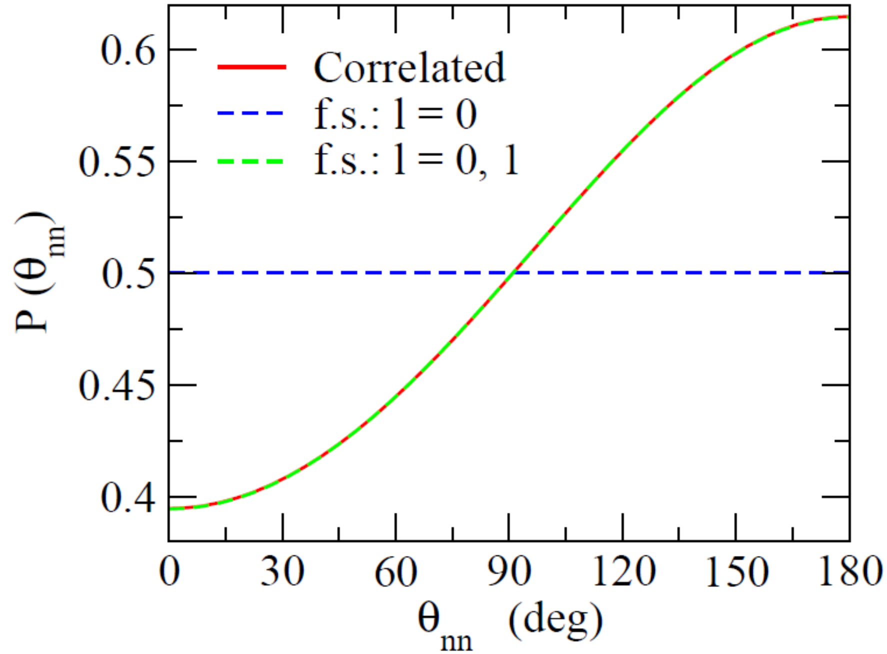
role of 3N interation?

Angular correlations

K.H. and H. Sagawa,
- PRC89 (‘14) 014331
- PRC93(‘16)034330

$$P(\theta) \sim |\langle \boldsymbol{k}_1 \boldsymbol{k}_2 | \Psi_{\rm 3bd}(E)\rangle|^2$$





correlation → enhancement of back-to-back emissions

cf. dineutron correlation in momentum space

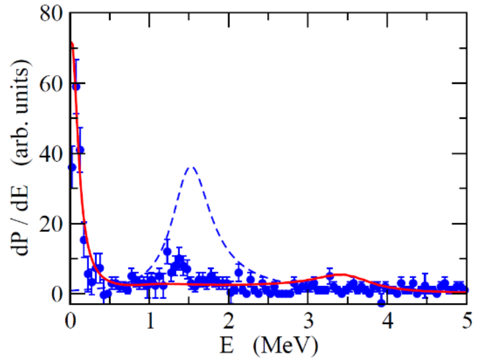
cf. Similar conclusion: L.V. Grigorenko, I.G. Mukha, and M.V. Zhukov, PRL 111 (2013) 042501

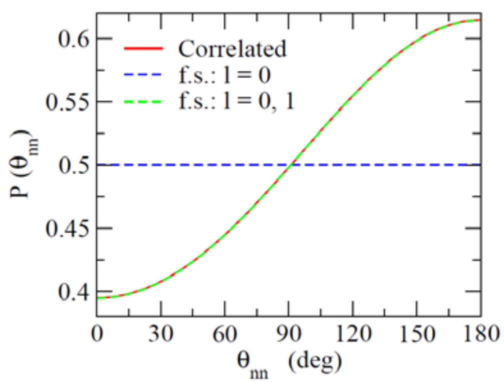
Summary

2n emission decay of ^{26}O ⟵ three-body model with density-dependent zero-range interaction: continuum calculations: relatively easy

- ✓ Decay energy spectrum: strong low-energy peak
- ✓ 2^+ energy: excellent agreement with the data
- ✓ Angular distributions: enhanced back-to-back emission

⟷ dineutron emission





□ open problems

- ✓ Analyses for ^{16}Be and ^{13}Li
- ✓ Decay width?
- ✓ Extension to 4n decay c.f. ^{28}O