Role of nn-correlations in the two-neutron decay of the ^{26}O nucleus

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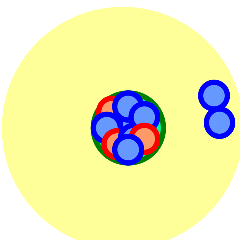
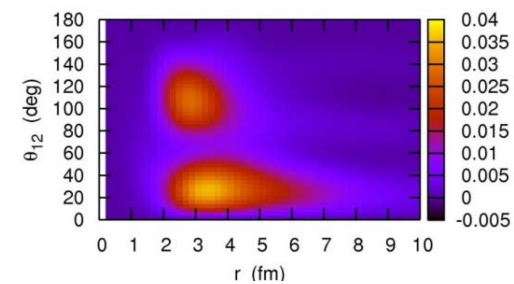




1. *Di-neutron correlation in neutron-rich nuclei*
2. *Two-neutron decay of unbound nucleus ^{26}O*
3. *Summary*

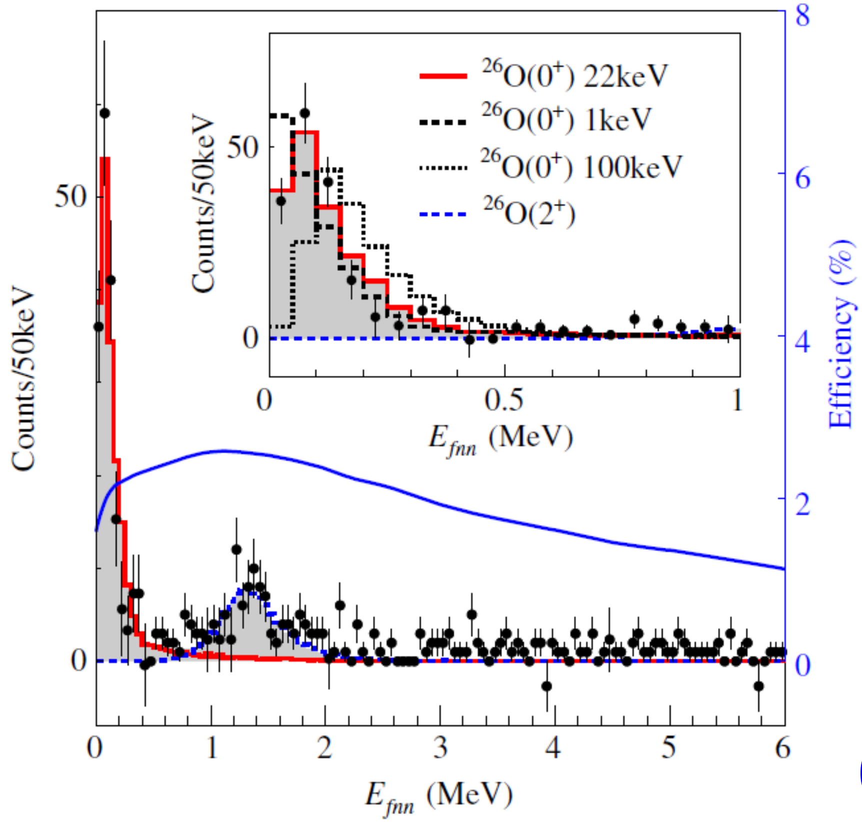
ECT* workshop “Physics beyond the limits of stability: exploring the continuum” Oct. 17-21, 2016

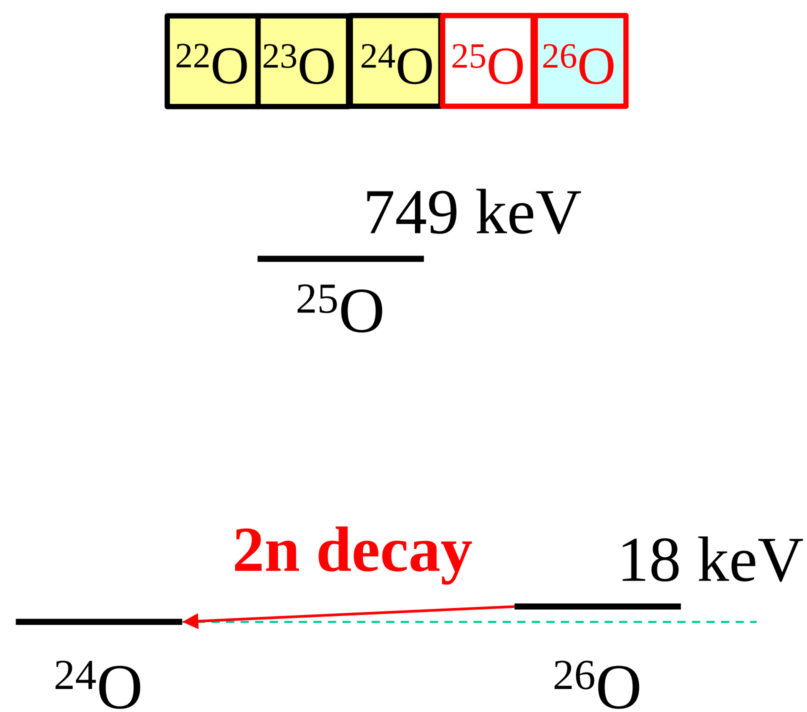
Two-neutron decay of ^{26}O

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

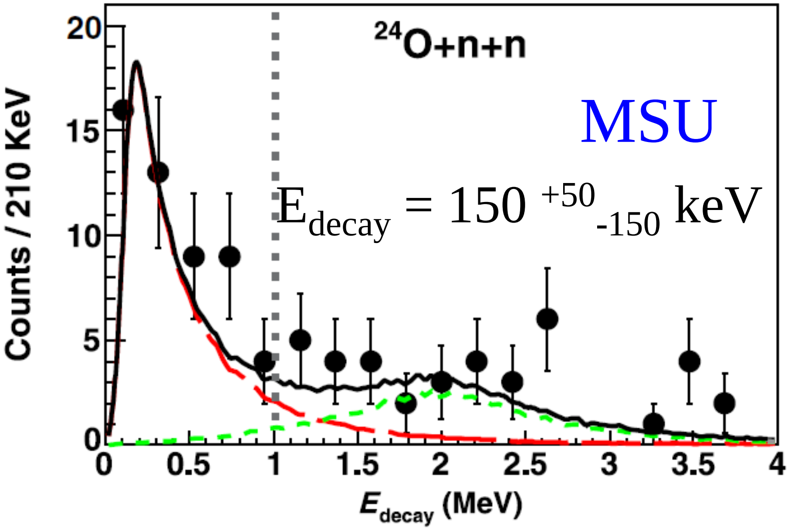
Nucleus ^{26}O: A Barely Unbound System beyond the Drip Line

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]

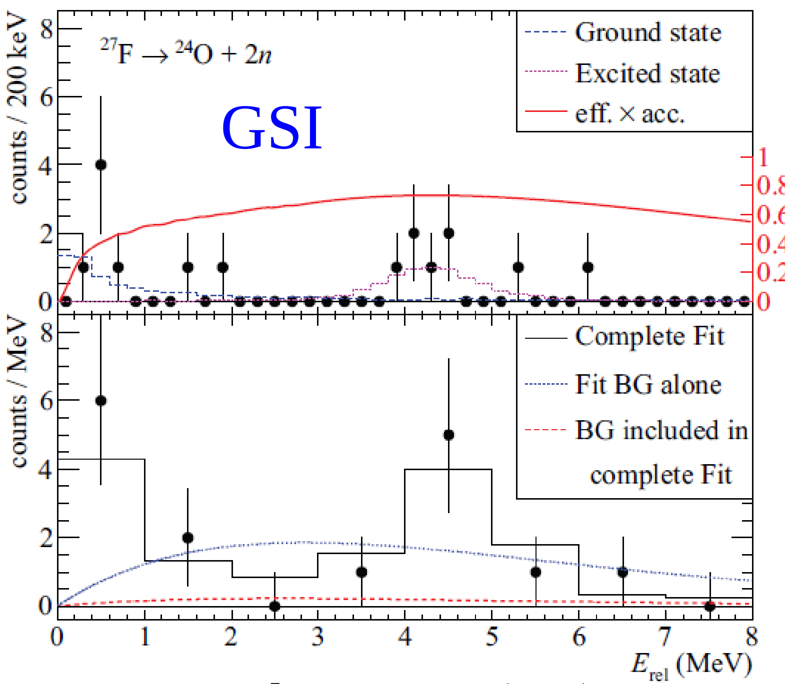




(neutron drip line)

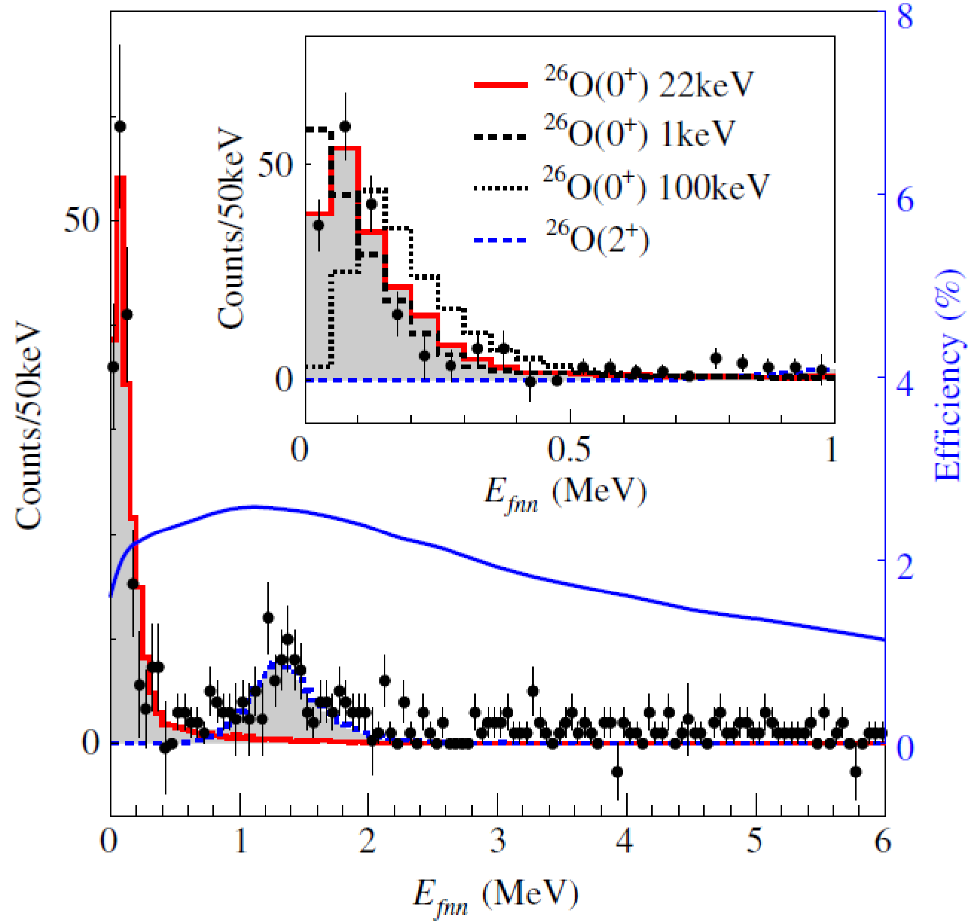


E. Lunderberg et al.,
PRL108 ('12) 142503



C. Caesar et al., PRC88 ('13) 034313

New RIKEN data

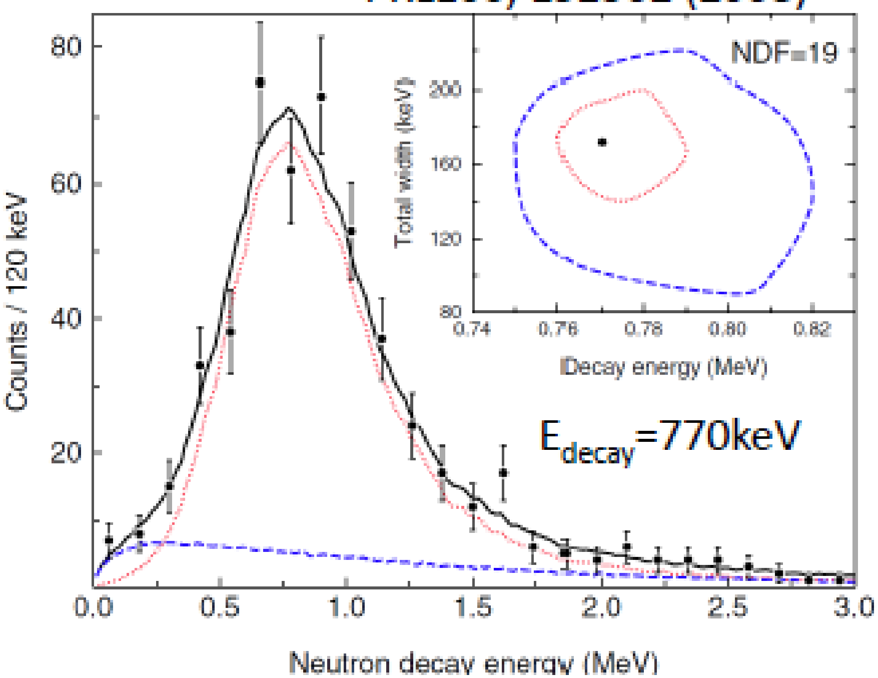


Y. Kondo et al., PRL116('16)102503

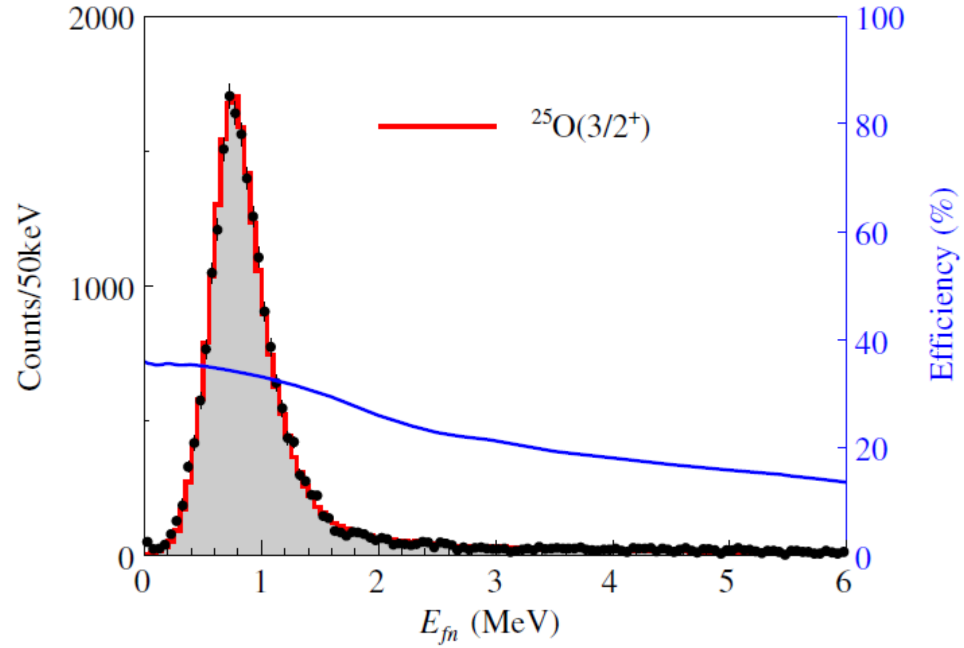
E_{decay} = 18 +/- 3 +/- 4 keV

Spectrum for the two-body subsystem: ^{25}O

C.R.Hoffman et al.,
PRL100, 152502 (2008)



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



$E = +\ 770^{+20}_{-10}$ keV
Γ = 172(30) keV

⇒

E = + 749(10) keV
Γ = 88(6) keV

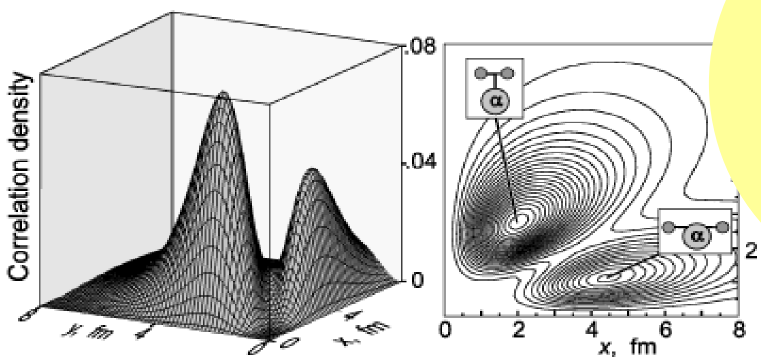
c.f. $\Gamma_{sp} \sim 87$ keV

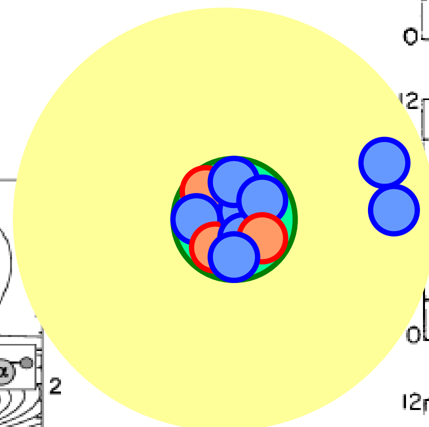
Borromean nuclei and Di-neutron correlation

Three-body model calculations:

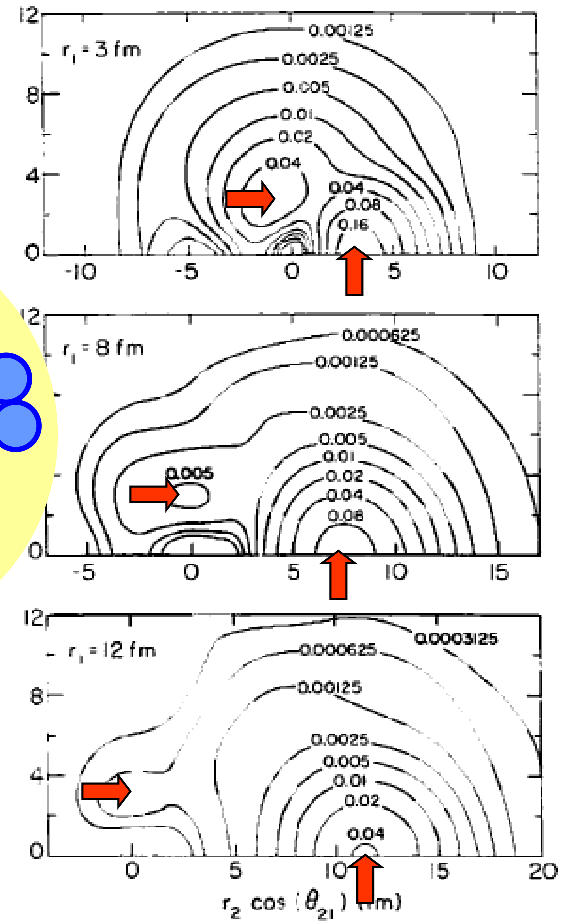
strong di-neutron correlation
in ^{11}Li and ^{6}He

$x^2 y^2 \rho_2(x, y)$ for ^{6}He





$\rho_2(r_1, r_2, \theta_{12})$ for ^{11}Li



Yu.Ts. Oganessian et al., *PRL82('99)4996*
M.V. Zhukov et al., *Phys. Rep. 231('93)151*

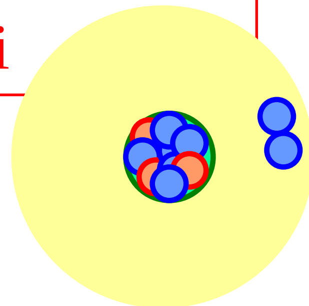
G.F. Bertsch, H. Esbensen,
Ann. of Phys., 209('91)327

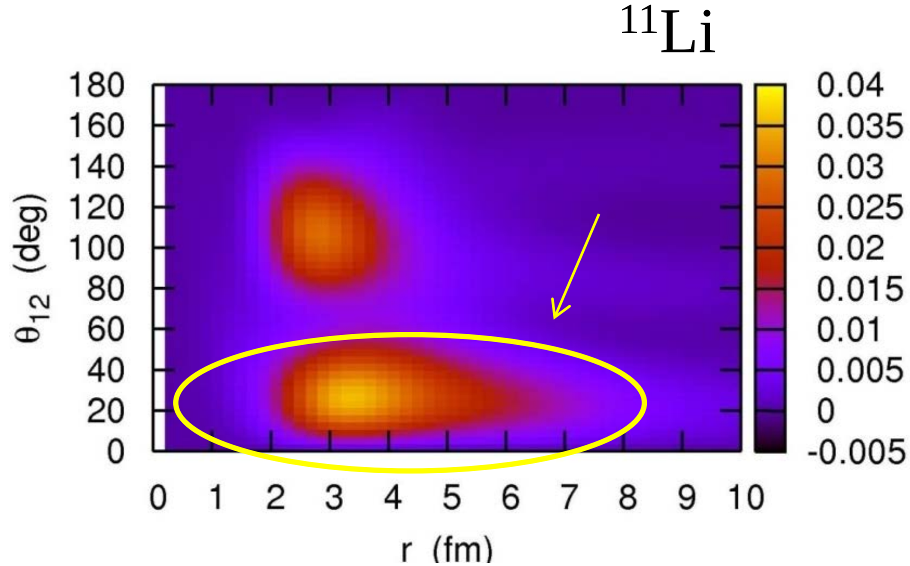
cf. earlier works

- ✓ A.B. Migdal ('73)
- ✓ P.G. Hansen and B. Jonson ('87)

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)
  - Barranco et al. ('01)
  - Hagino-Sagawa ('05)
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- ✓ Heavier nuclei (HFB calc.)
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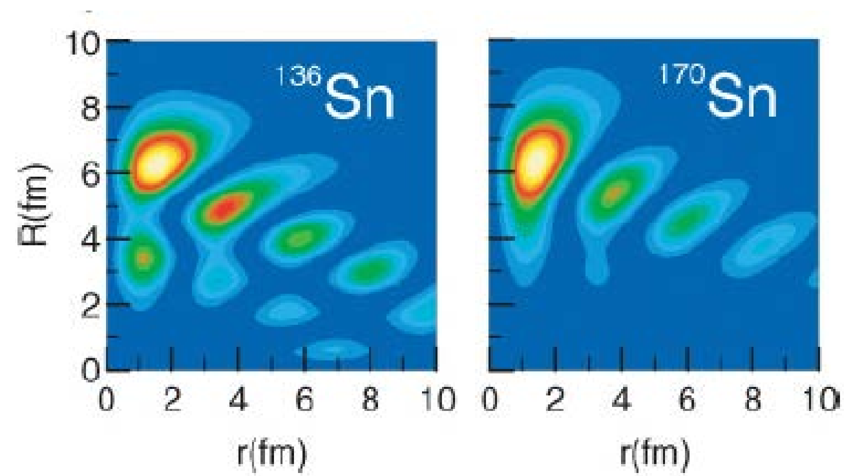
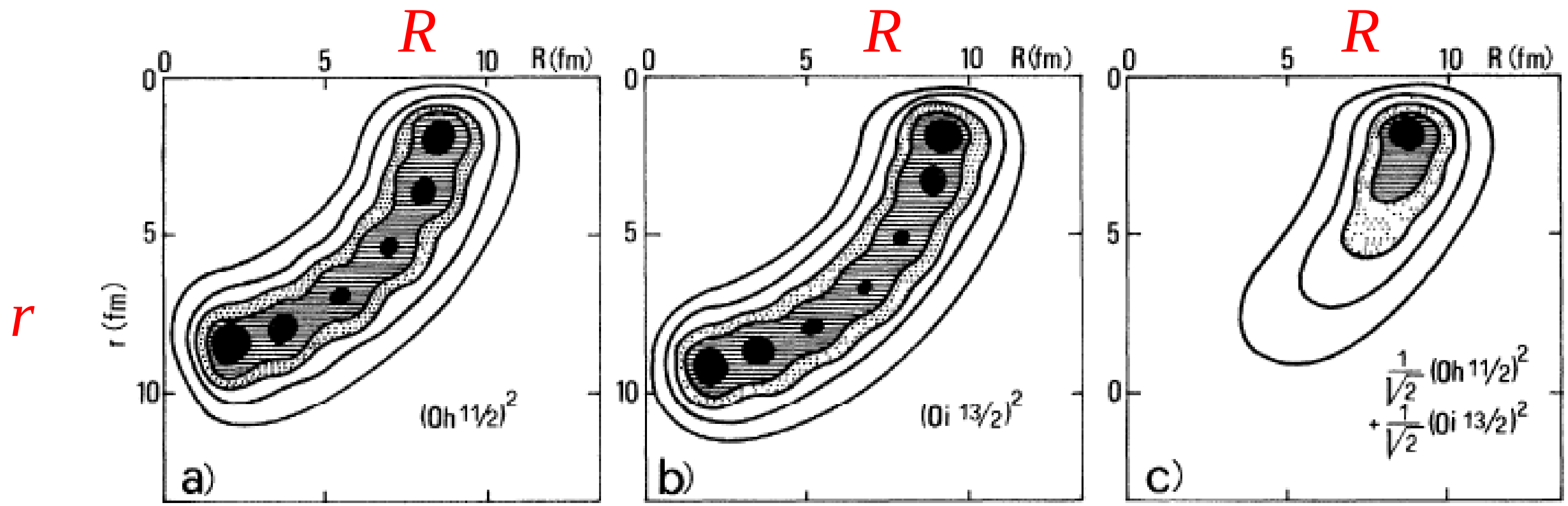


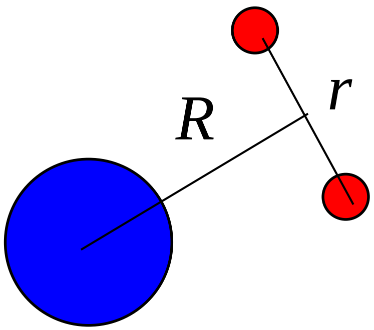
N. Pillet, N. Sandulescu, and P. Schuck, PRC76('07)024310

dineutron correlation: caused by the admixture of different parity states



$(0h_{11/2})^2$ $(0i_{13/2})^2$ $\frac{1}{\sqrt{2}}(0h_{11/2})^2 + \frac{1}{\sqrt{2}}(0i_{13/2})^2$

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

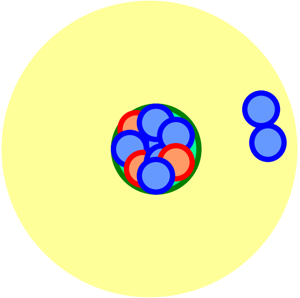


interference of even and odd partial waves

$$\rho_2(x_1,x_2) = |\Psi_{ee}(x_1,x_2)|^2 + |\Psi_{oo}(x_1,x_2)|^2 + \boxed{2\Psi_{ee}(x_1,x_2)\Psi_{oo}(x_1,x_2)}$$

Dineutron correlation in the momentum space

$$\Psi(\boldsymbol{r},\boldsymbol{r}') = \alpha\,\Psi_{ee}(\boldsymbol{r},\boldsymbol{r}') + \beta\,\Psi_{oo}(\boldsymbol{r},\boldsymbol{r}')$$ → $\theta_r = 0$: enhanced

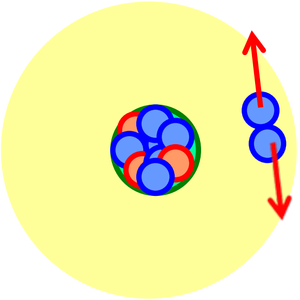


→ Fourier transform

$$\tilde{\Psi}(\boldsymbol{k},\boldsymbol{k}') = \int e^{i\boldsymbol{k}\cdot\boldsymbol{r}} e^{i\boldsymbol{k}'\cdot\boldsymbol{r}'} \Psi(\boldsymbol{r},\boldsymbol{r}')d\boldsymbol{r}d\boldsymbol{r}'$$

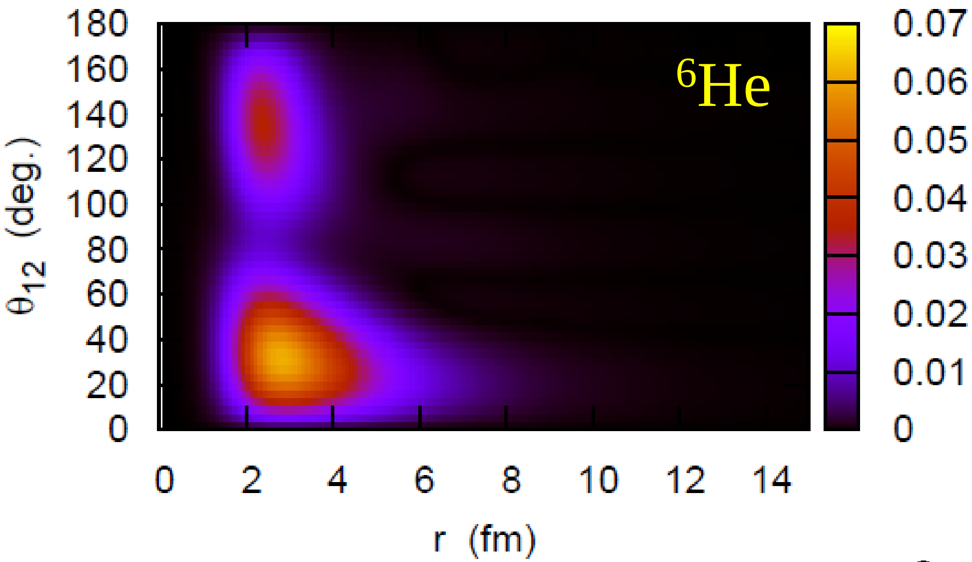
$$e^{i\boldsymbol{k}\cdot\boldsymbol{r}} = \sum_l (2l+1) i^l \ldots\ldots \longrightarrow \underset{r}{i^l} \cdot \underset{r'}{i^l} = i^{2l} = (-)^l$$

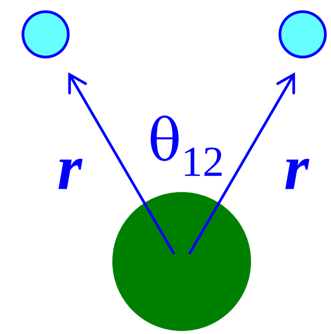
$$\tilde{\Psi}(\boldsymbol{k},\boldsymbol{k}') = \alpha\,\tilde{\Psi}_{ee}(\boldsymbol{k},\boldsymbol{k}') - \beta\,\tilde{\Psi}_{oo}(\boldsymbol{k},\boldsymbol{k}')$$ → $\theta_k = \pi$: enhanced



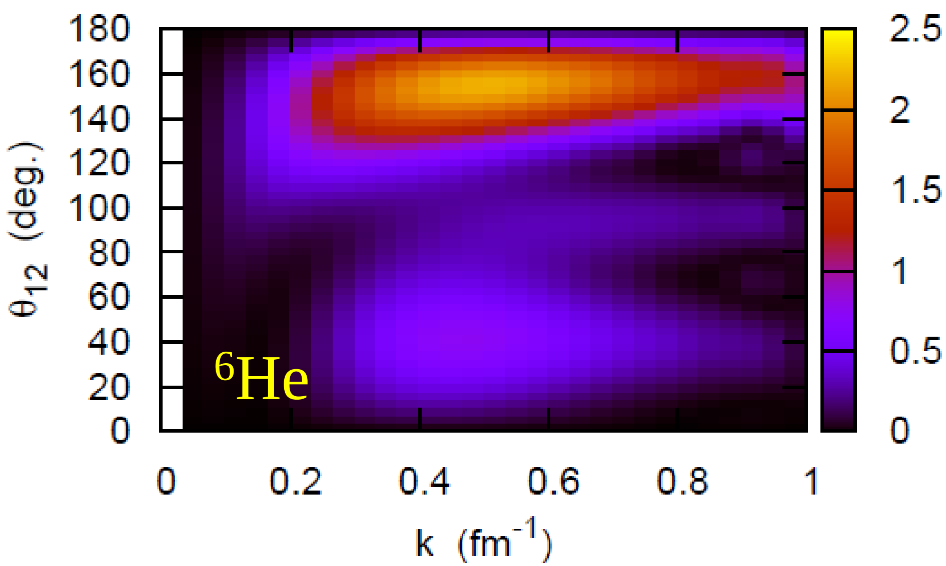
Dineutron correlation in the momentum space

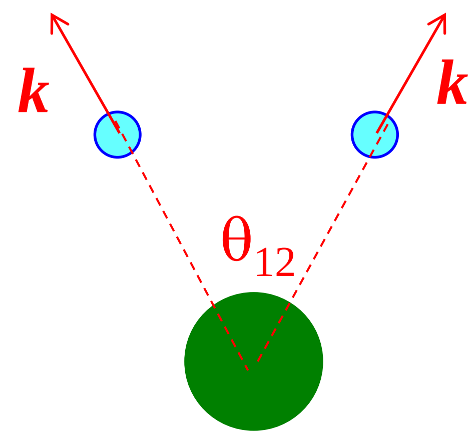
Two-particle density in **the *r* space**: $8\pi^2 r^4 \sin\theta \cdot \rho(r,r,\theta)$





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





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

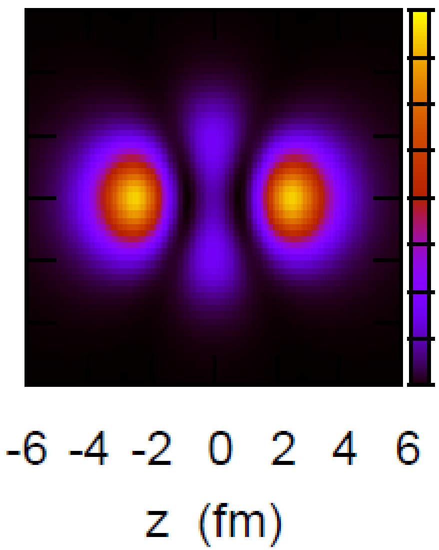
cf. F. Catara, A. Insolia, E. Maglione, and A. Vitturi, PRC29('84)1091

weakly bound systems

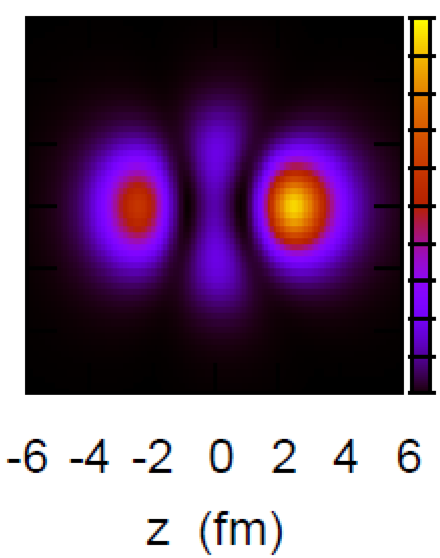
→easy to mix different parity states due to the continuum couplings
+ enhancement of pairing on the surface

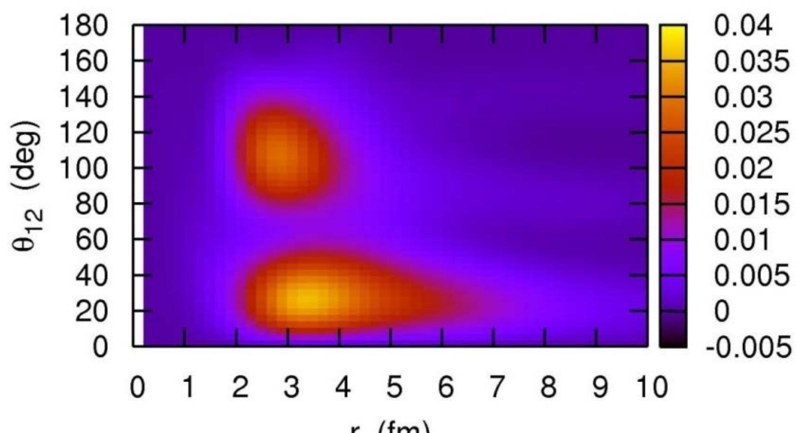
→ dineutron correlation: enhanced

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



parity mixing

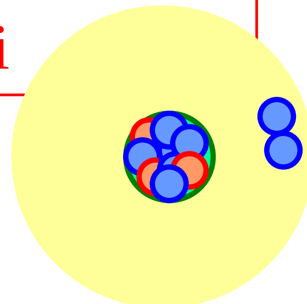




K.H. and H. Sagawa, PRC72('05)044321

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)
- Barranco et al. ('01)
- Hagino-Sagawa ('05)
- Kikuchi-Kato-Myo ('10)

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

How to probe it?

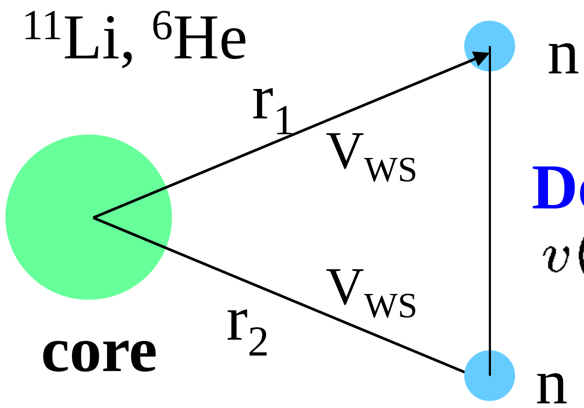
➢ Coulomb breakup
T. Nakamura et al.
cluster sum rule
(mean value of θ_{nn})

➢ pair transfer reactions

➢ two-proton decays
Coulomb 3-body problem

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

3-body model calculation for Borromean nuclei



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

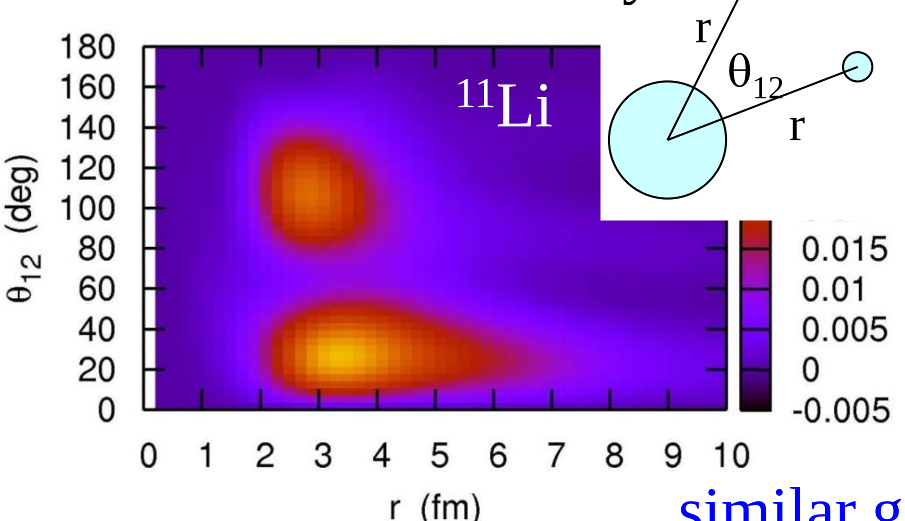
Density-dependent delta-force

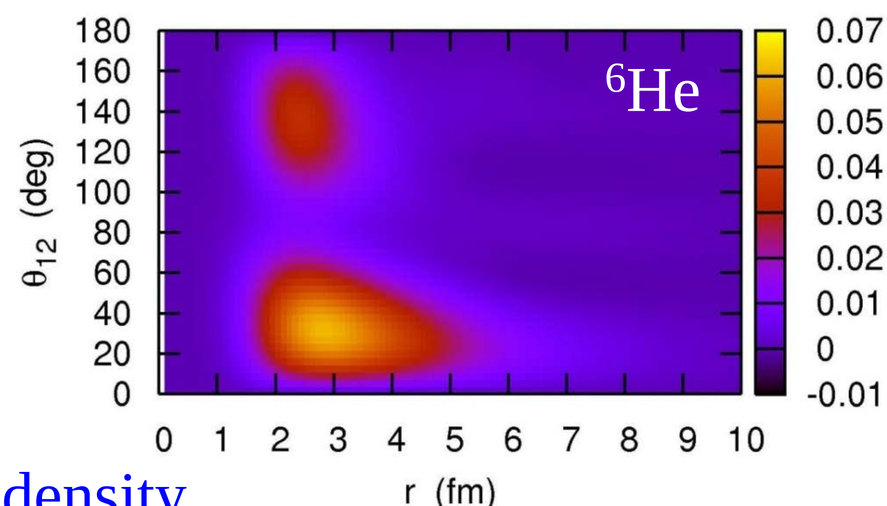
$$v(\boldsymbol{r}_1, \boldsymbol{r}_2) = v_0(1 + \alpha\rho(r)) \times \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)$$

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

Ground state density

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



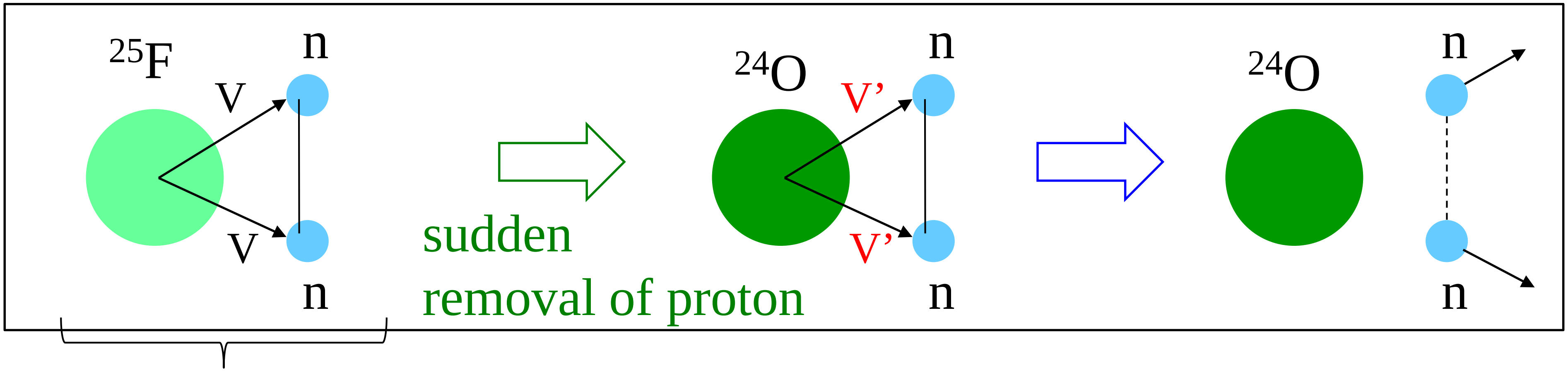


similar g.s. density

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)

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

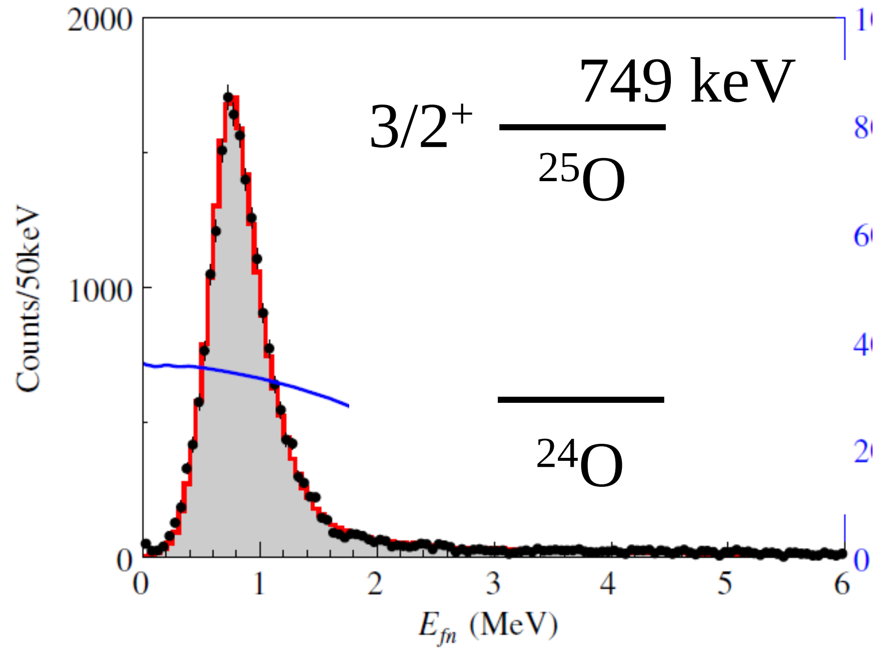
→ the same config. (the reference state)

FSI → Green's function method ⟸ continuum effects

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

n-^{24}O Woods-Saxon potential

- a = 0.72 fm (fixed)
- r_0 = 1.25 fm (fixed)
- $V_0 \longleftarrow e_{2s1/2}$ = -4.09 (13) MeV
- $V_{ls} \longleftarrow e_{d3/2}$ = 0.749(10) MeV



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

Gamow states (outgoing boundary condition)

$d_{3/2}$: E = 0.749 MeV (input), Γ = 87.2 keV

cf. Γ_{exp} = 88 (6) keV

$f_{7/2}$: E = 2.44 MeV, Γ = 0.21 MeV

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

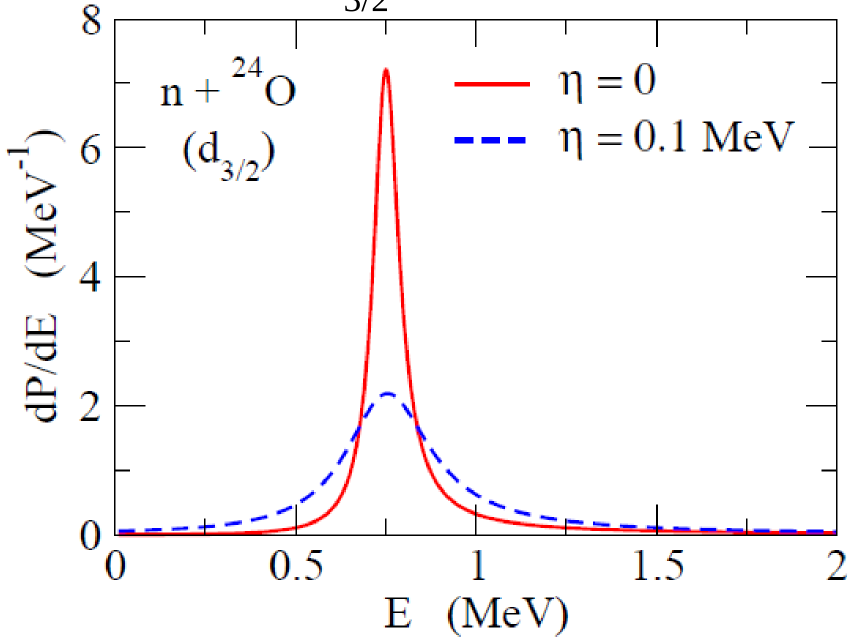
n-^{24}O decay spectrum: an *alternative* way

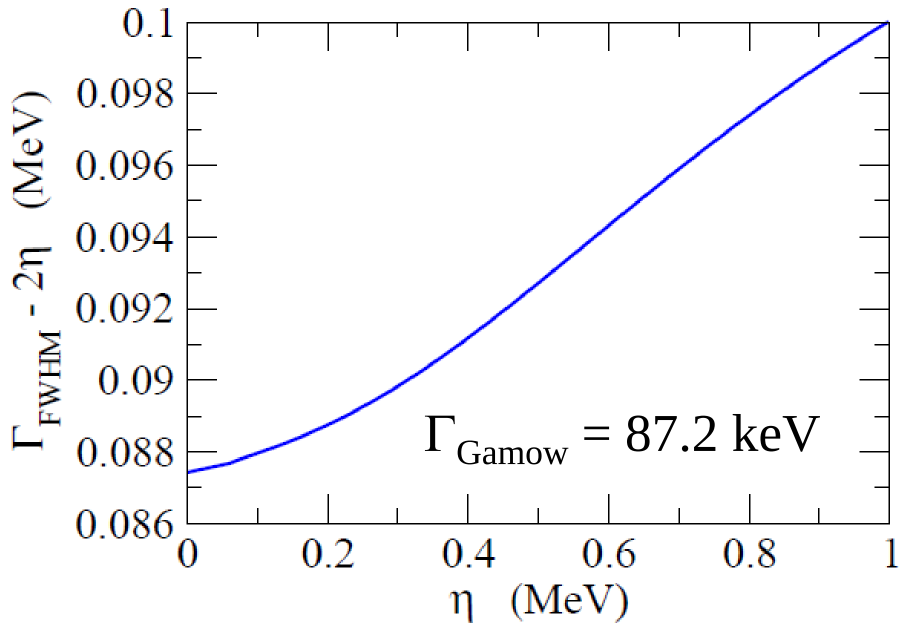
$$\frac{dP}{dE} = |\langle \Phi_{\rm ref} | \Psi_E \rangle|^2 = \int dE' \, |\langle \Phi_{\rm ref} | \Psi_{E'} \rangle|^2 \delta(E - E')$$

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

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

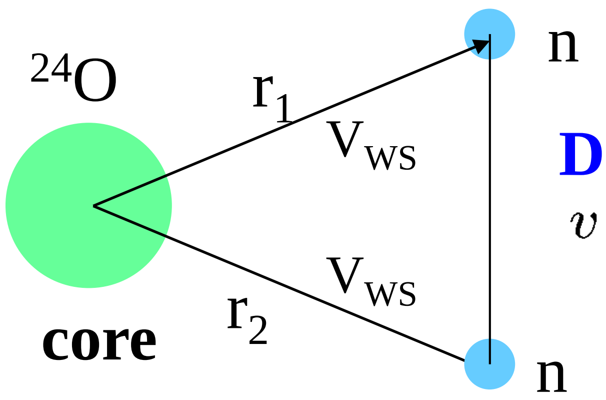
Reference state:
bound $1d_{3/2}$ state in ^{26}F





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

Decay energy spectrum



Density-dependent delta-force

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

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

$= G(E)$

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

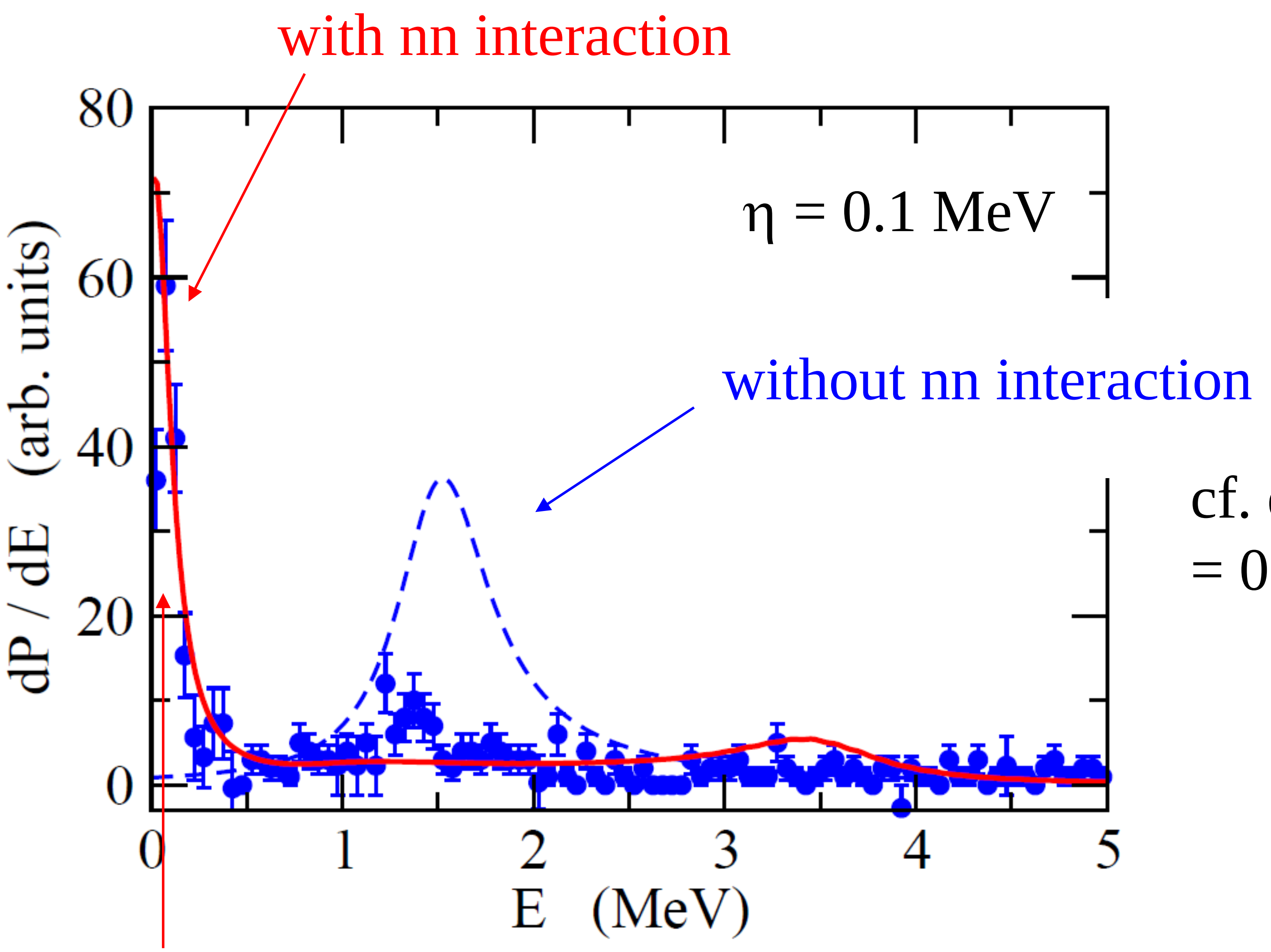
$$G_0(E) = \sum_{j_1, l_1} \sum_{j_2, l_2} \int de_1 de_2 \frac{|\psi_1\psi_2\rangle\langle\psi_1\psi_2|}{e_1 + e_2 - E - i\eta}$$

← small, finite η

i) Decay energy spectrum

$|\Phi_{ref}\rangle = |[1d_{3/2}]^2\rangle$ in ^{27}F

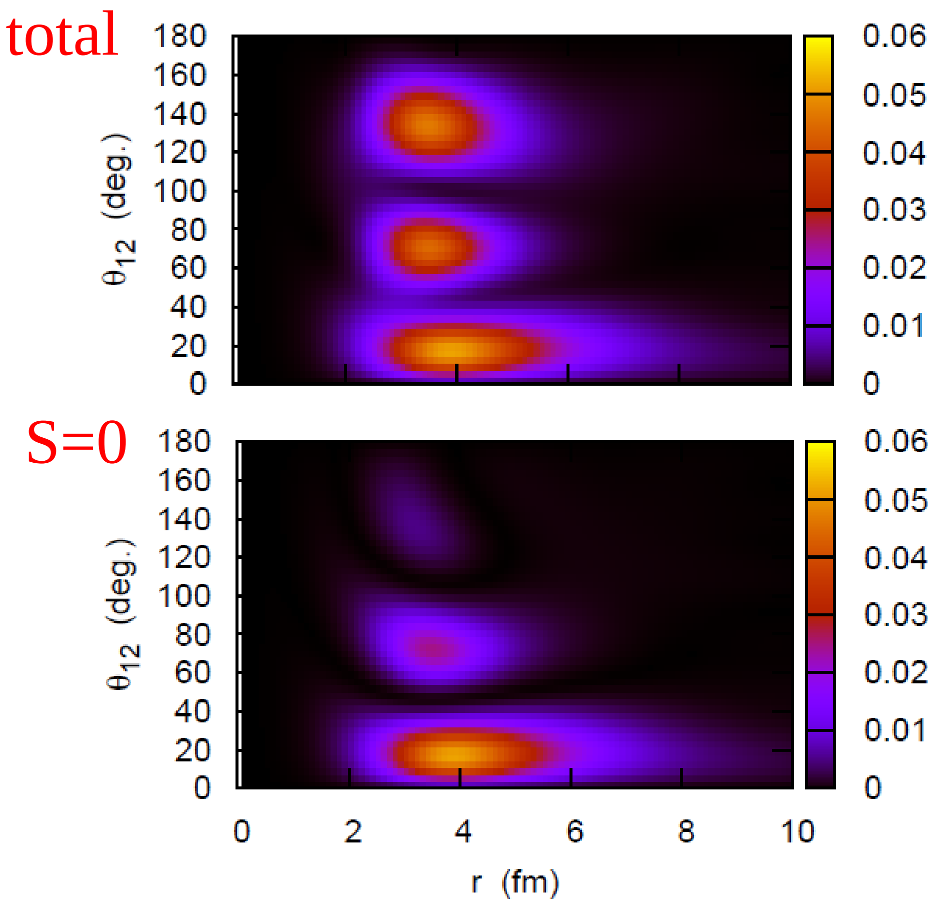
K.H. and H. Sagawa,
- PRC89 ('14) 014331
- PRC93('16)034330

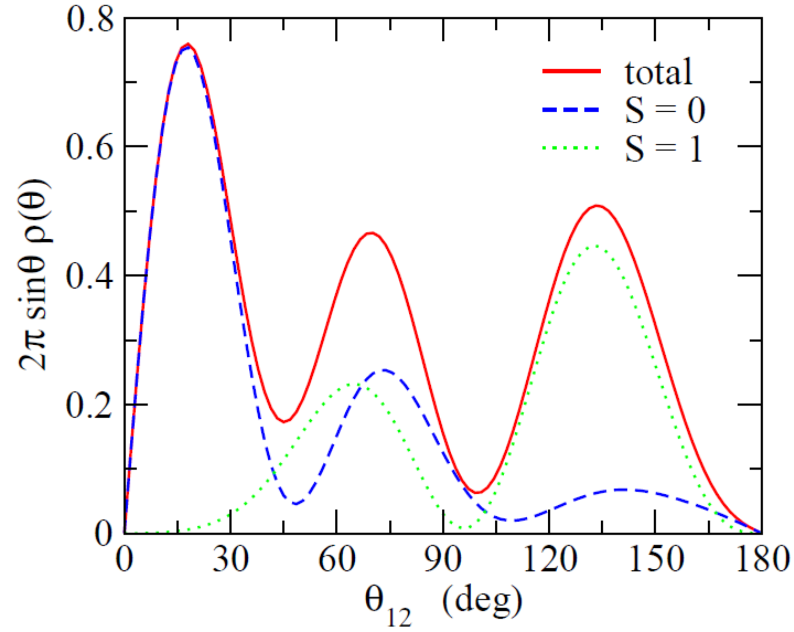


cf. $e_{1d3/2}(^{25}O)$
= 0.749 MeV

E_{peak} = 18 keV (input)

Two-particle density in the bound state approximation





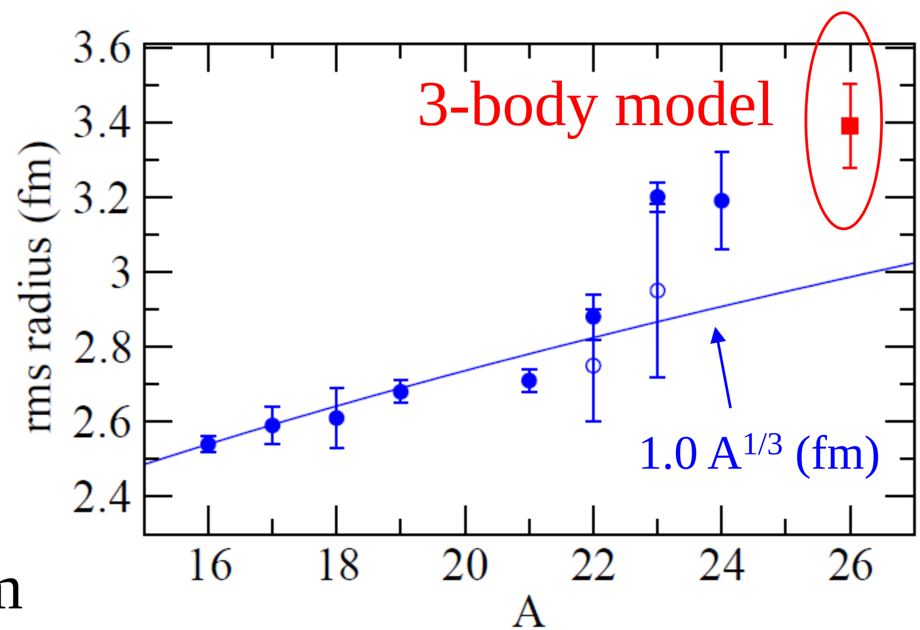
$(d_{3/2})^2$: 66.1%

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

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

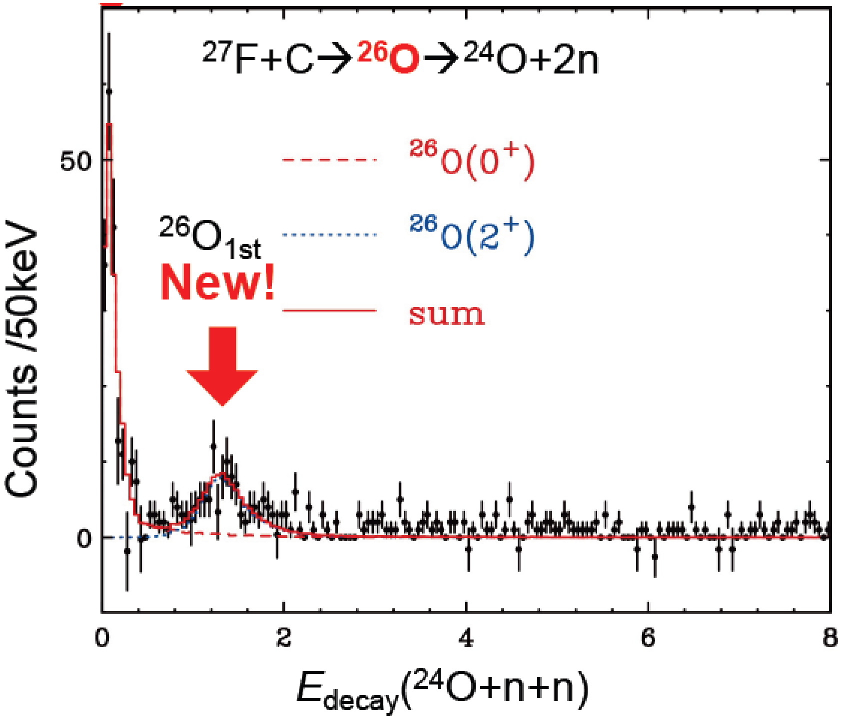
$(s_{1/2})^2$: 0.59%

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

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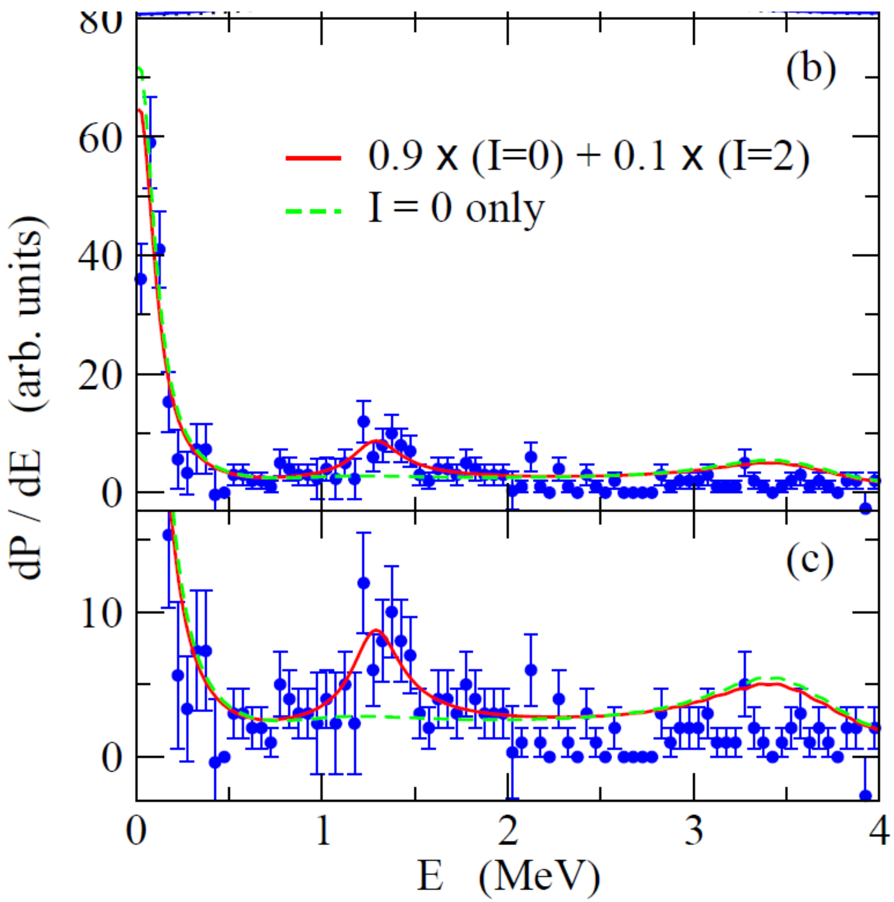
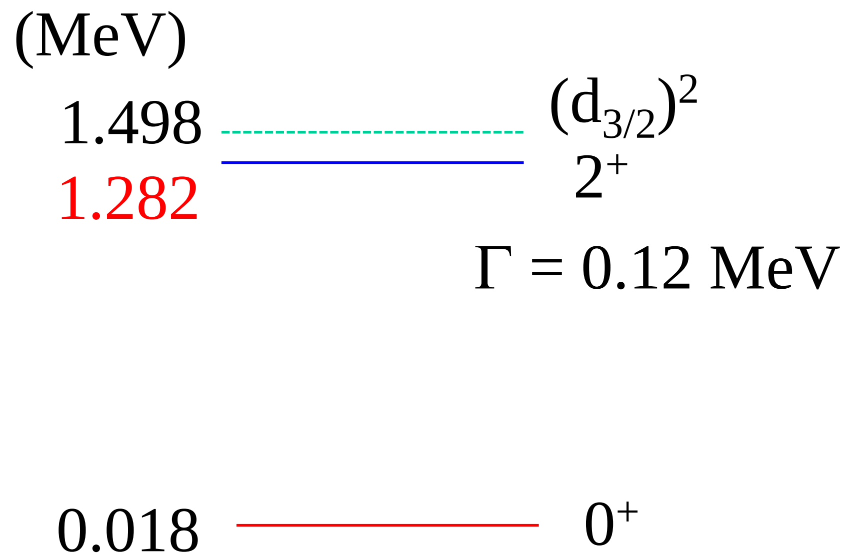
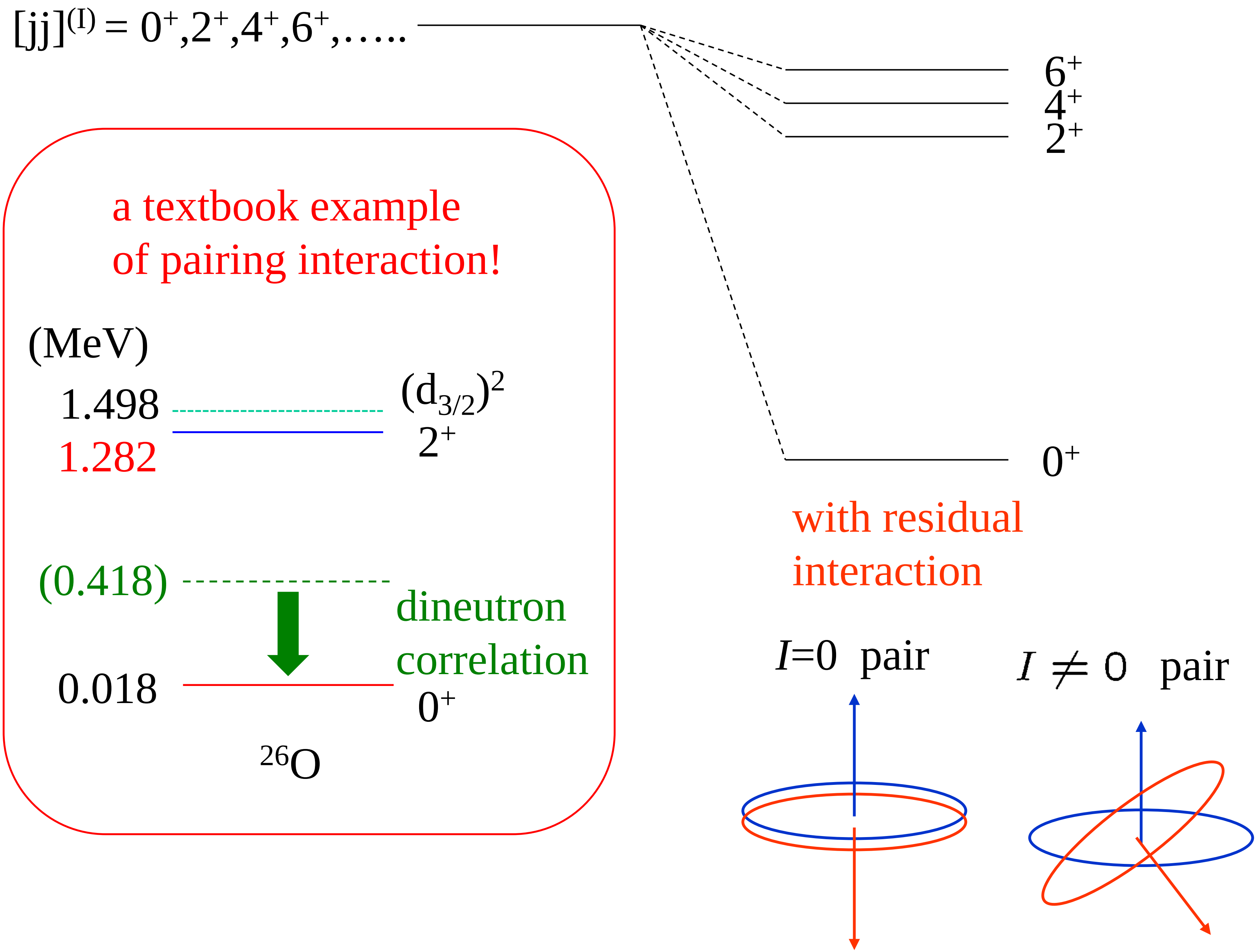


three-body model calculation:

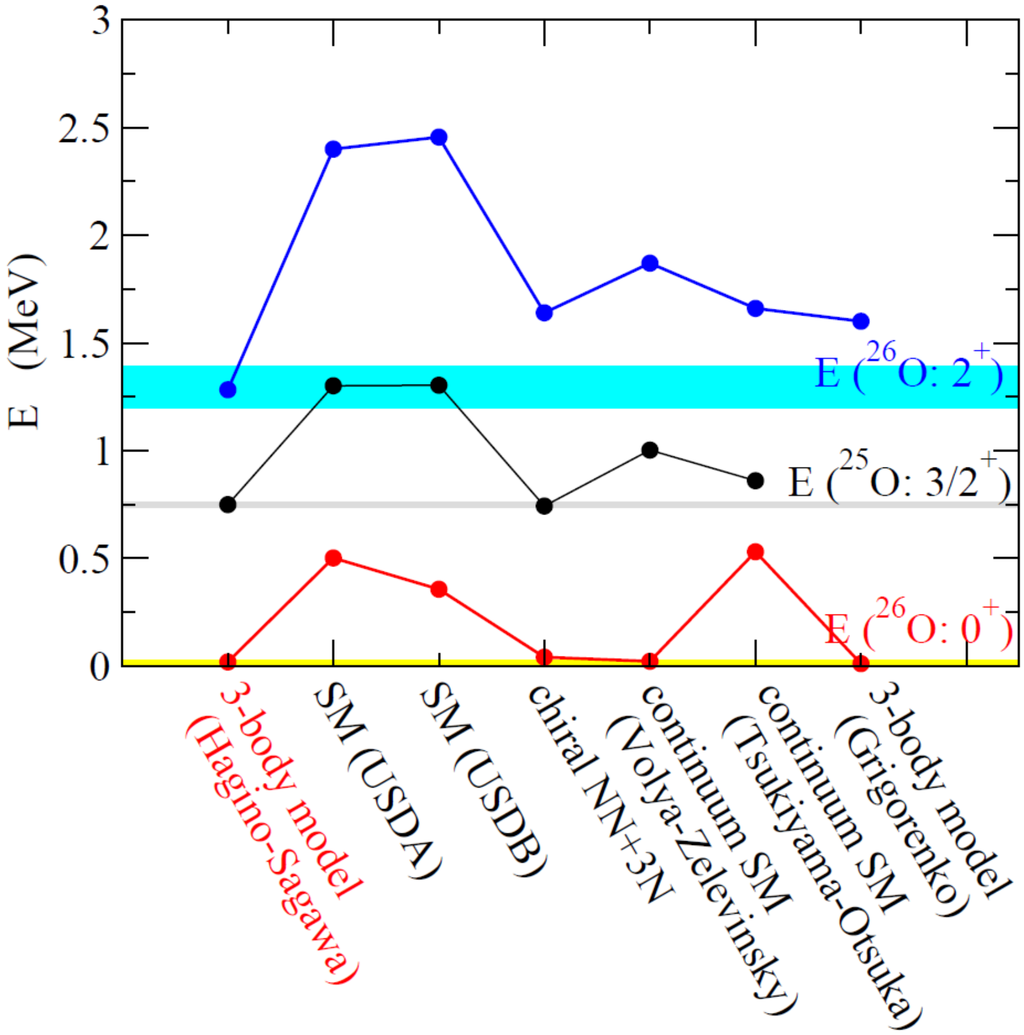


K.H. and H. Sagawa,
PRC90('14)027303; PRC93('16)034330.

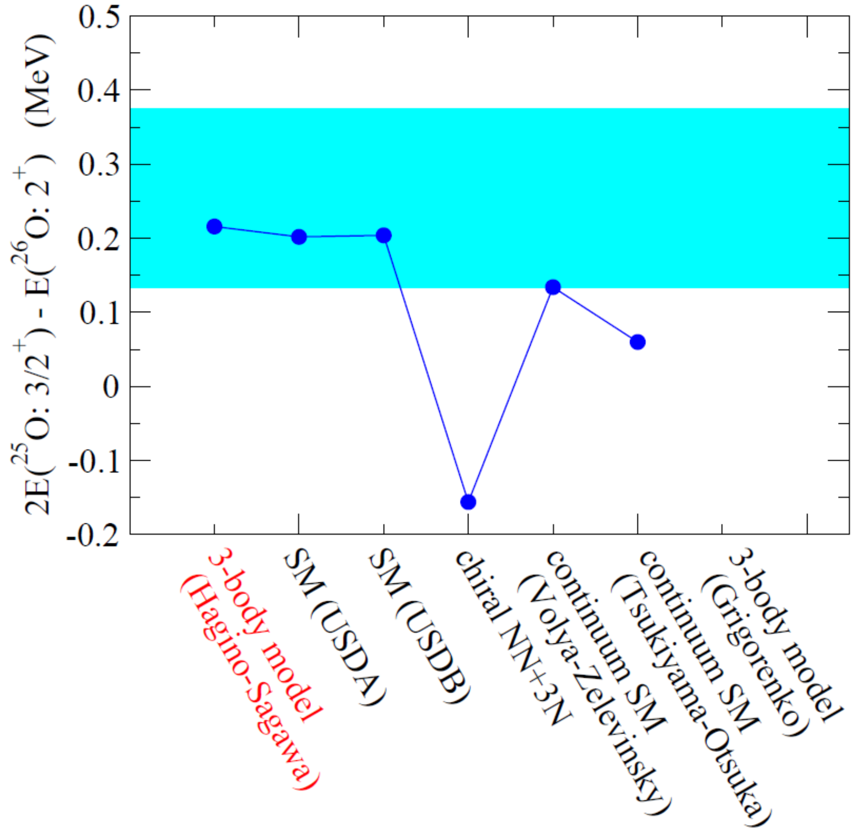


$[jj]^{(I)} = 0^+, 2^+, 4^+, 6^+, \ldots\ldots$
6^+
4^+
2^+
0^+
with residual interaction
a textbook example of pairing interaction!
(MeV)
1.498
$(d_{3/2})^2$
1.282
2^+
(0.418)
dineutron correlation
0.018
0^+
^{26}O
$I=0$ pair
$I \neq 0$ pair

comparison to other calculations



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

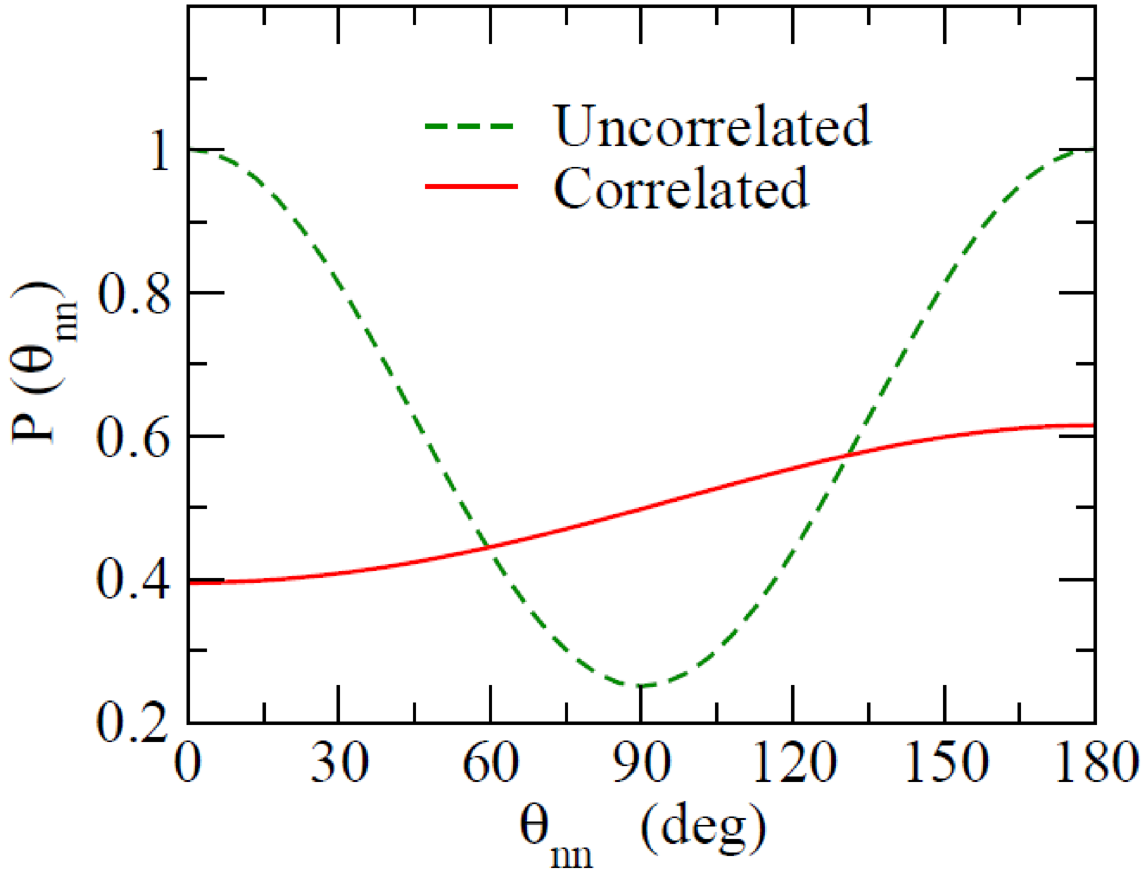


role of 3N interation?

Angular correlations

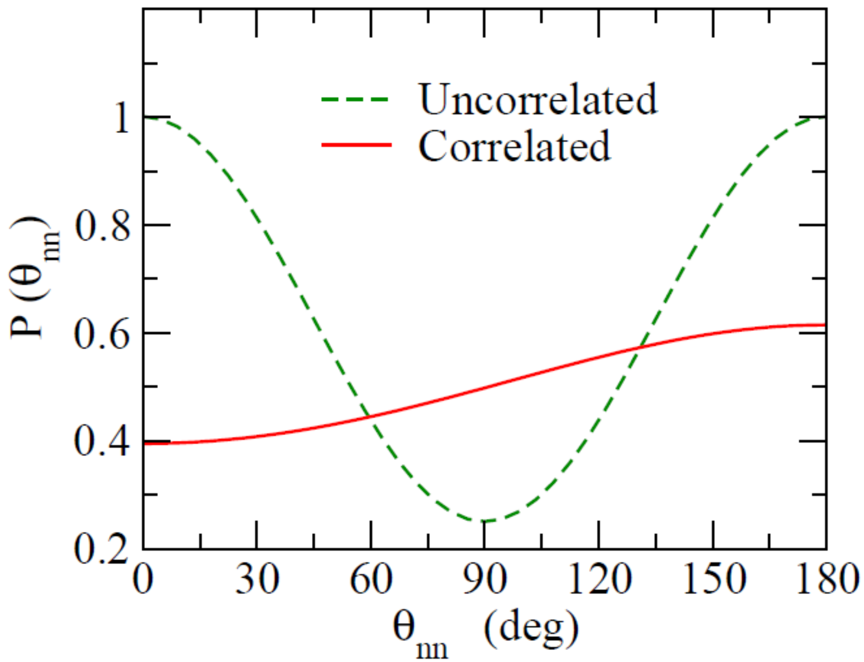
K.H. and H. Sagawa,
PRC89 ('14) 014331;
PRC93 ('16) 034330

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



correlation → enhancement of back-to-back emissions

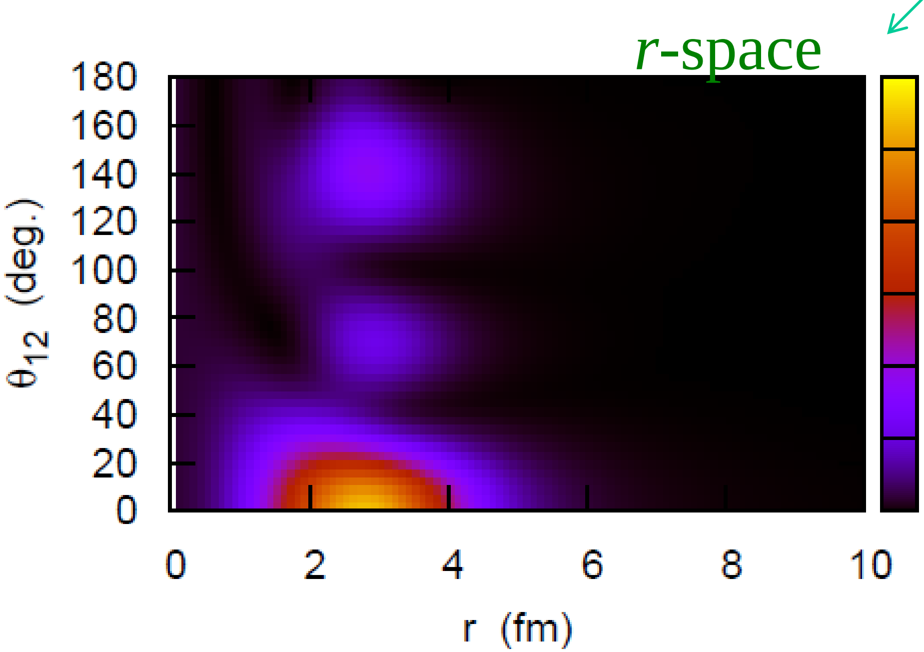
cf. Similar conclusion: L.V. Grigorenko, I.G. Mukha, and M.V. Zhukov, PRL 111 (2013) 042501

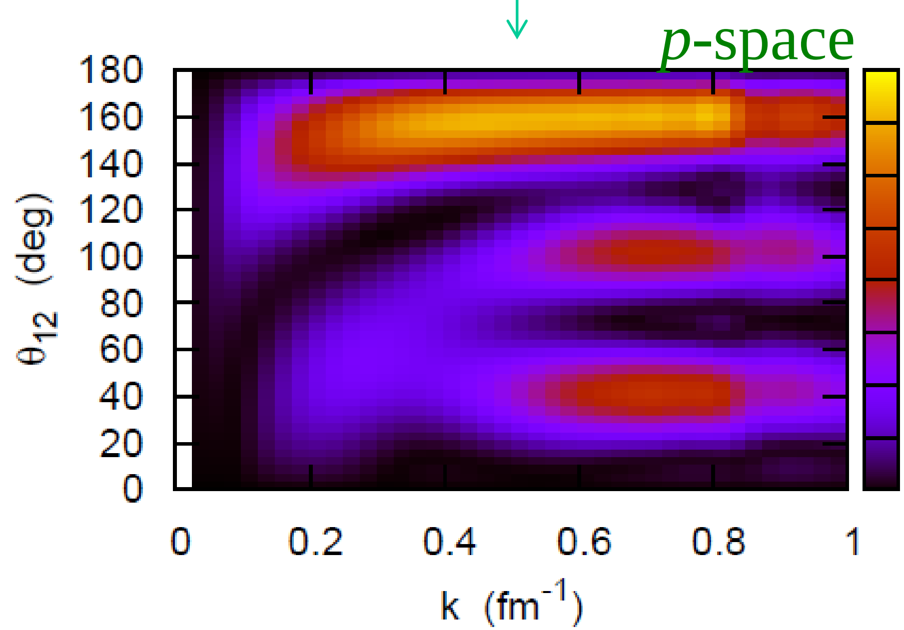


density of the resonance state (with the box b.c.)

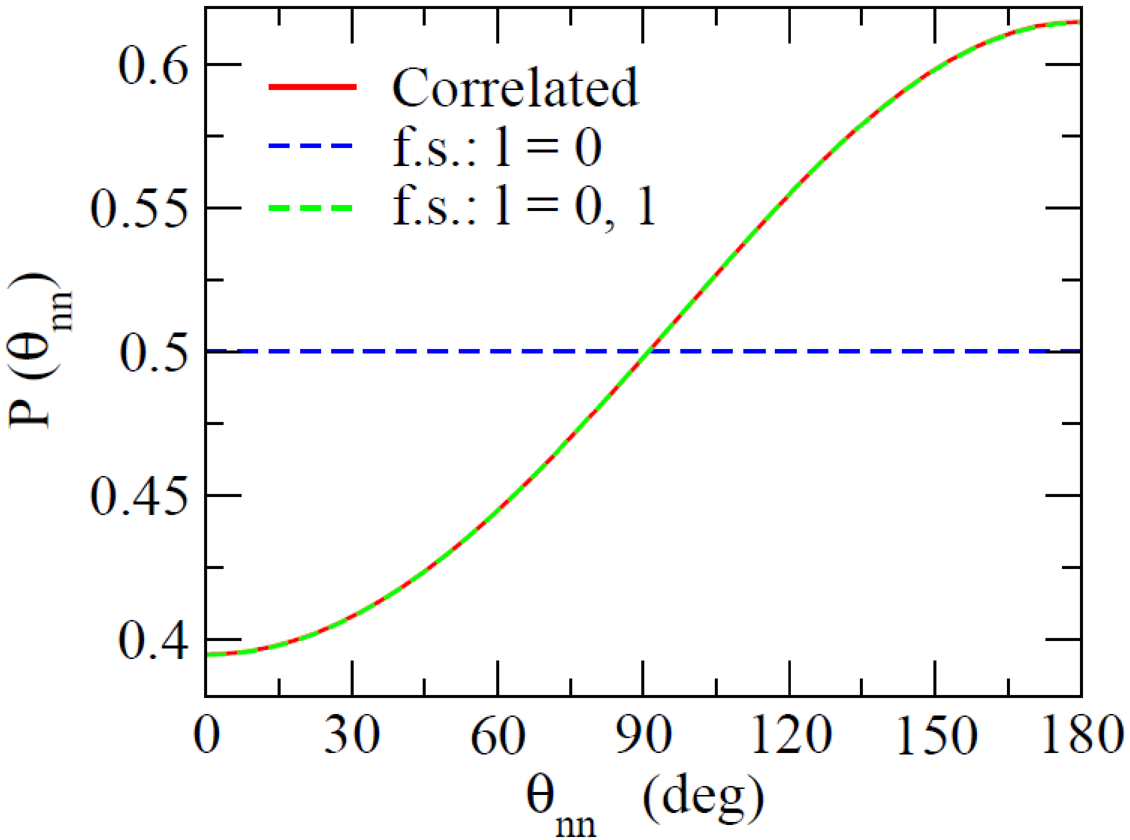
$$\rho(r, r, \theta)$$

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





$$M_{fi} = \langle (jj)^{J=0} | (1 - vG_0 + vG_0vG_0 - \cdots) | \Psi_i \rangle$$

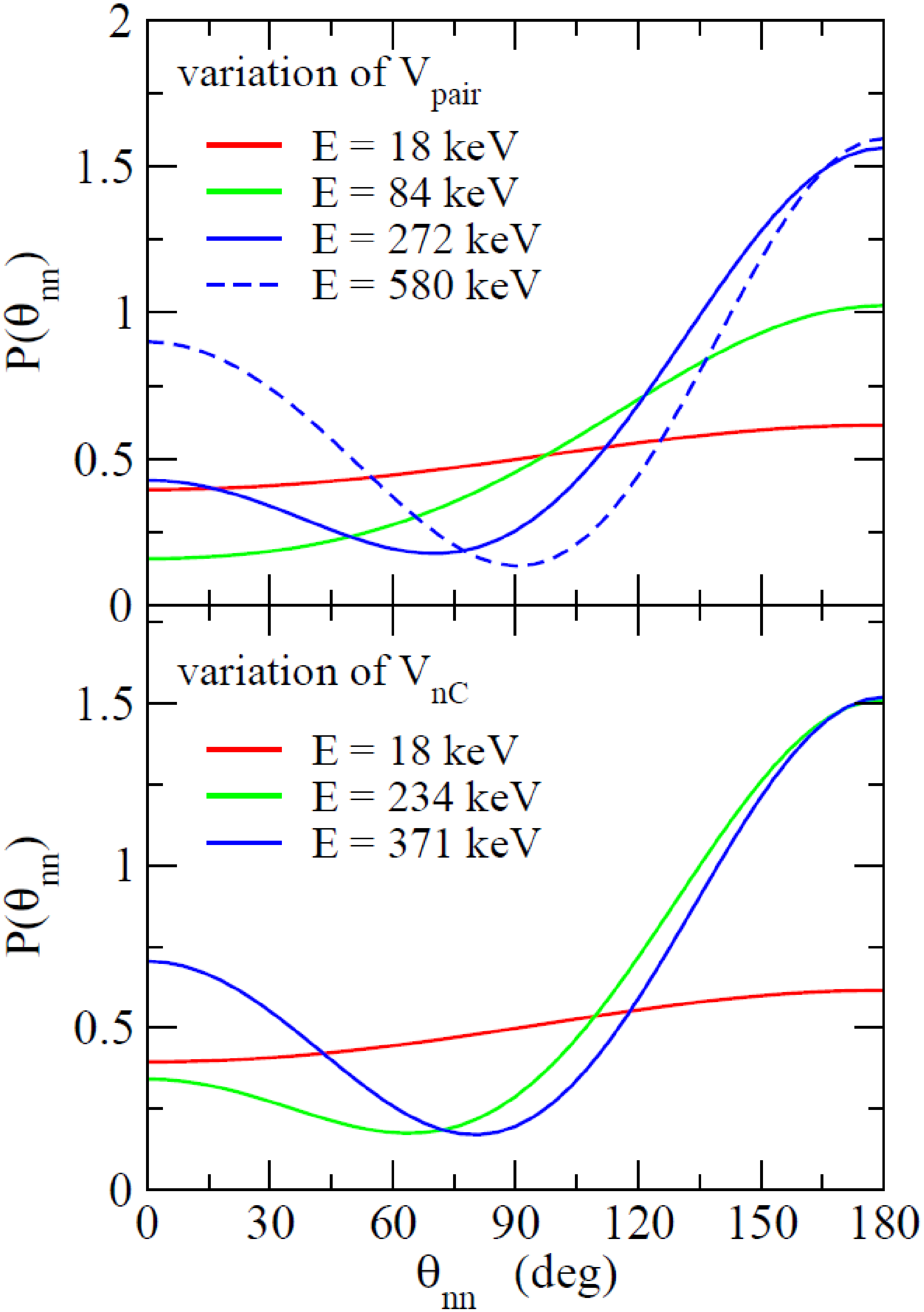


$(s_{1/2})^2$: 99.37%
$(p_{3/2})^2$: 0.56%
$(p_{1/2})^2$:0.07%

main process: initial state $(d_{3/2})^2 \longrightarrow (s_{1/2})^2$ or $(p_{3/2})^2$,$(p_{1/2})^2$

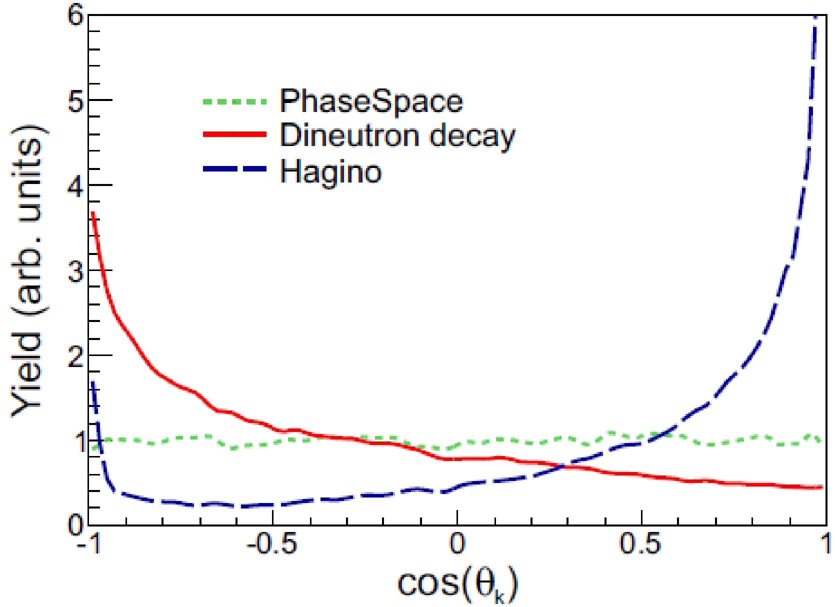
rescattering due to pairing interaction

*higher *l* components: largely suppressed due to the centrifugal pot.
(E_{decay} ~ 18 keV, e_1 ~ e_2 ~ 9 keV)

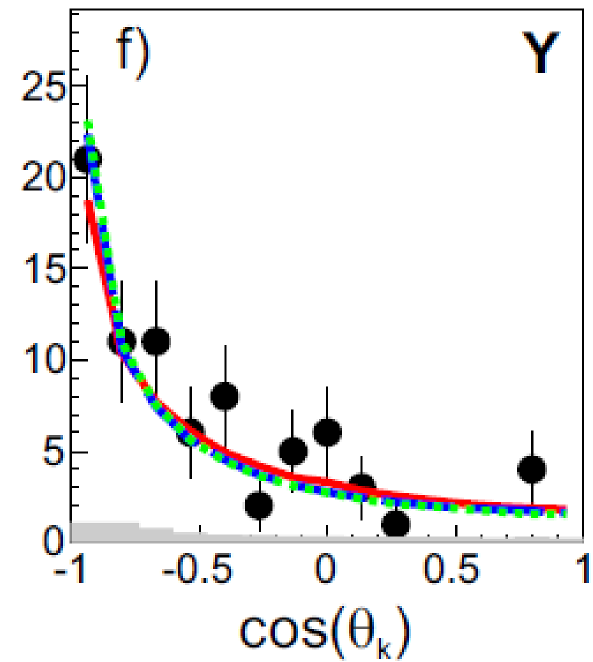


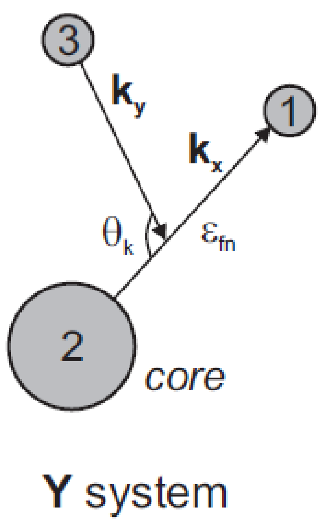
variation of V_{pair}
E = 18 keV
E = 84 keV
E = 272 keV
E = 580 keV
variation of V_{nC}
E = 18 keV
E = 234 keV
E = 371 keV
$P(\theta_{nn})$
θ_{nn} (deg)
0
30
60
90
120
150
180
0
0.5
1
1.5
2

Recent measurements and simulations at MONA



simulation





insensitive to the models due to the uncertainty in the momentum of ^{24}O

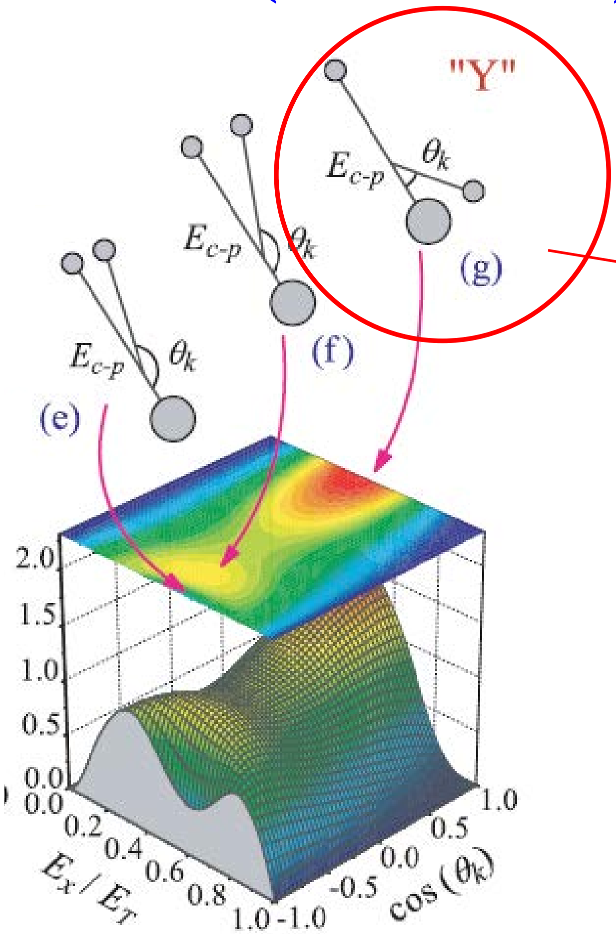
Z. Kohley et al., PRC91 (‘15) 034323

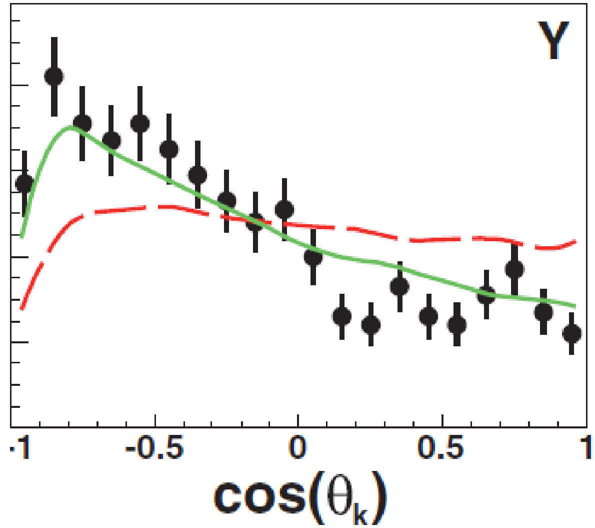
➢Discussions: back-to-back? or forward angles?

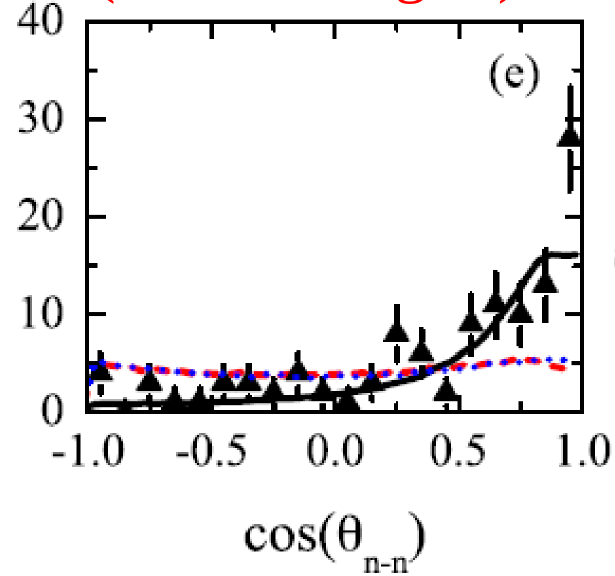
two-proton decay from ^{6}Be (back-to-back)

2n decay of ^{13}Li (forward angles)

2n decay of ^{16}Be (forward angles)







L.V. Grigorenko et al., PRC80 (‘09) 034602

Z. Kohley et al., PRC87(‘13)011304(R)

A. Spyrou et al., PRL108(‘12) 102501

✓Q-value effect? (cf. nuclear phase shifts)

✓core excitations?

↑

open problem

Summary

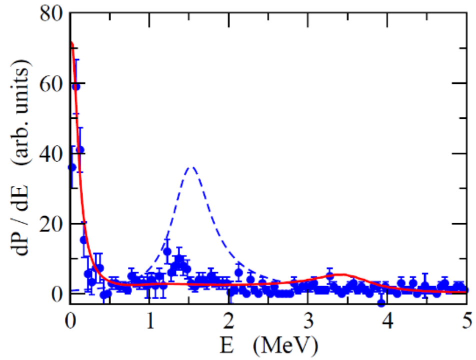
2n emission decay of ^{26}O ⟵ three-body model with
density-dependent zero-range interaction:
continuum calculations: relatively easy

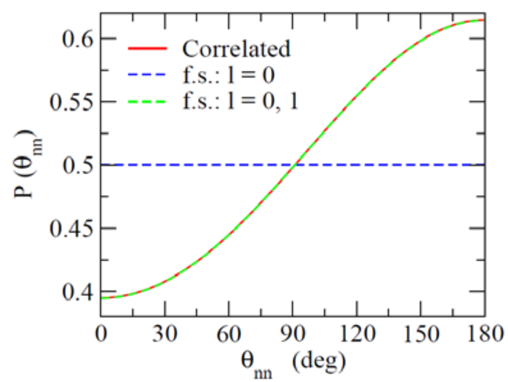
✓ Decay energy spectrum: strong low-energy peak

✓ 2^+ energy: excellent agreement with the data

✓ Angular distributions: enhanced back-to-back emission

⟷ dineutron emission





☐ an open issue

✓ Angular distribution of 2n and 2p emitters?