Di-neutron correlation and two-neutron decay of the ^{26}O nucleus

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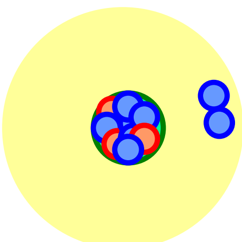
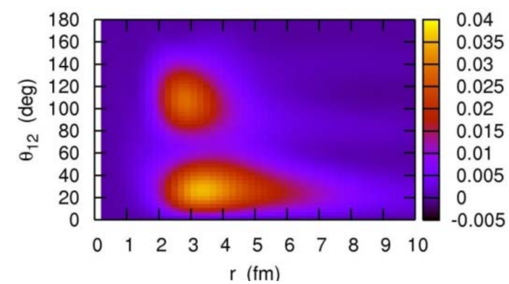
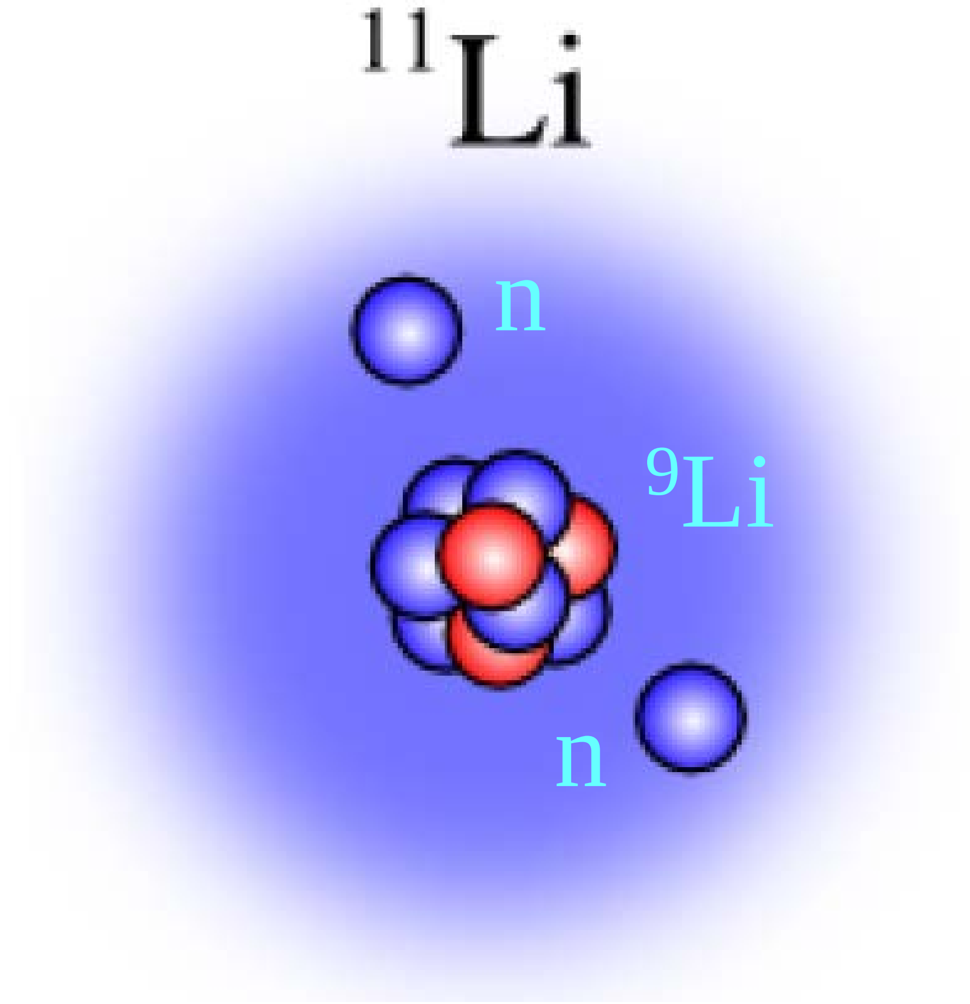




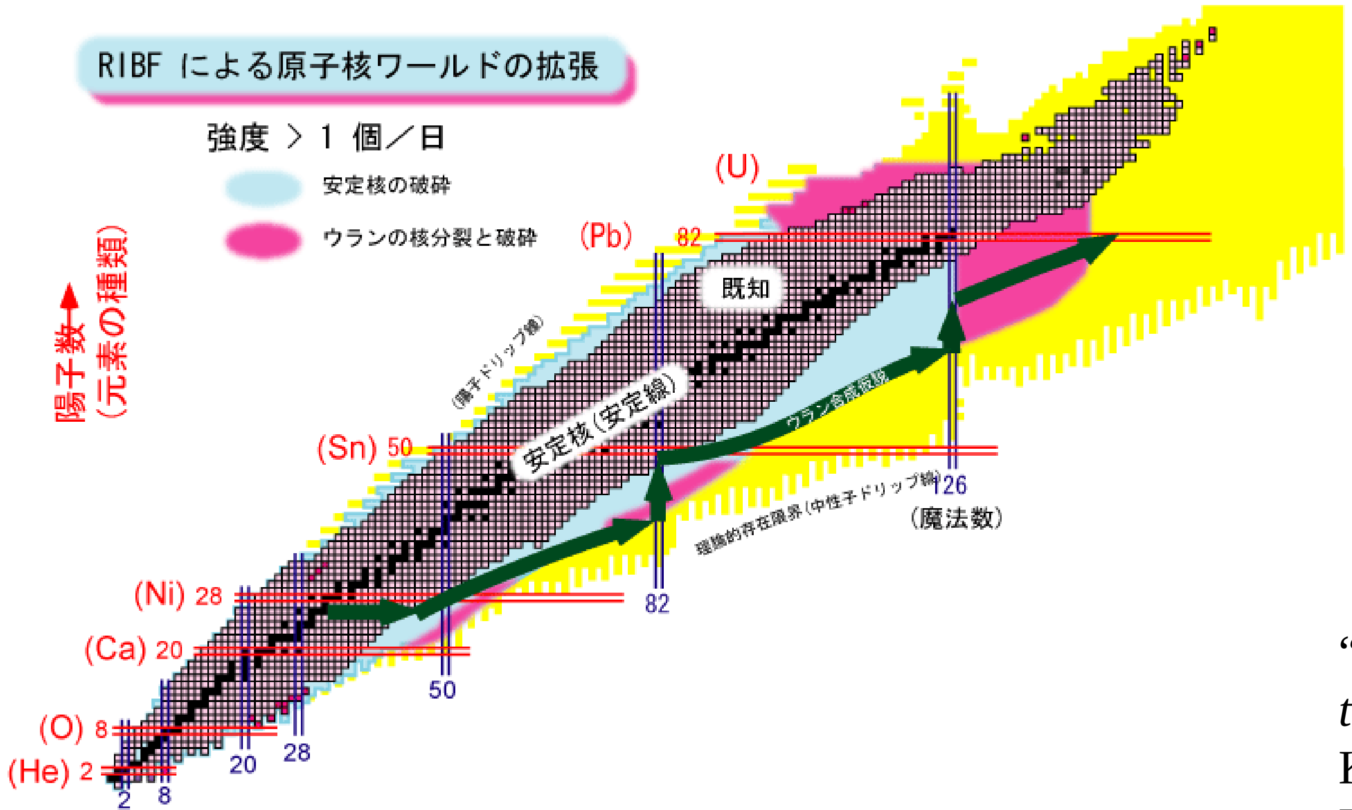
1. *Di-neutron correlation: what is it?*
2. *Two-neutron decay of unbound nucleus ^{26}O*
3. *Summary*

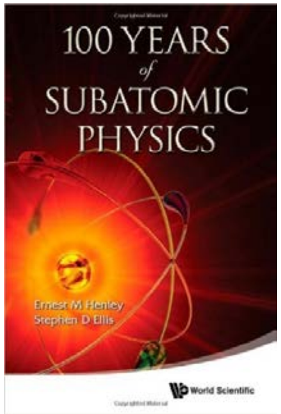


Is this picture correct?

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)

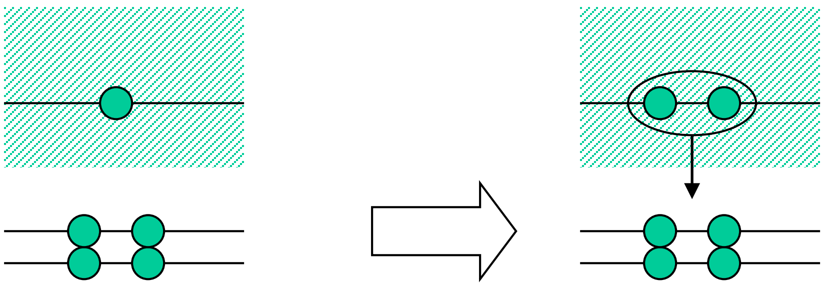
"*Exotic nuclei far from the stability line*"
K.H., I. Tanihata, and H. Sagawa

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

Borromean nuclei

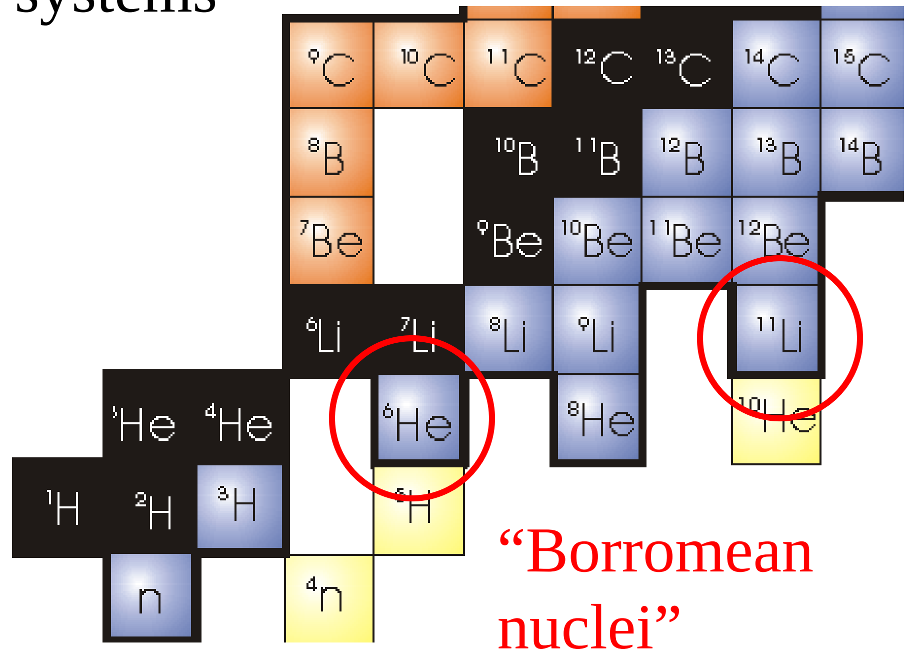
Borromean nuclei: unique three-body systems

residual interaction → attractive



^{5}He
particle unstable

^{6}He
particle stable



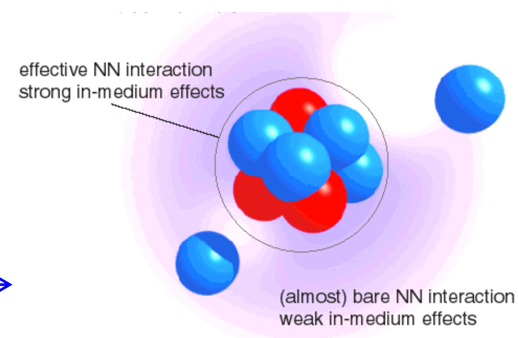
"Borromean nuclei"

^{11}Li = ^{9}Li + n + n

^{6}He = ^{4}He + n + n

<u>Structure of Borromean nuclei</u>

- What is the spatial structure of the valence neutrons?
- To what extent is this picture correct? →

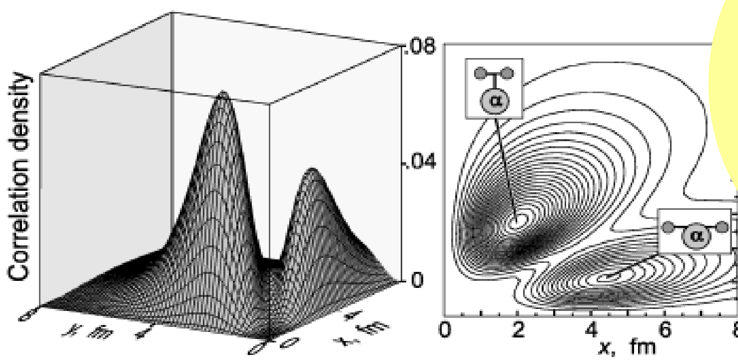


Borromean nuclei and Di-neutron correlation

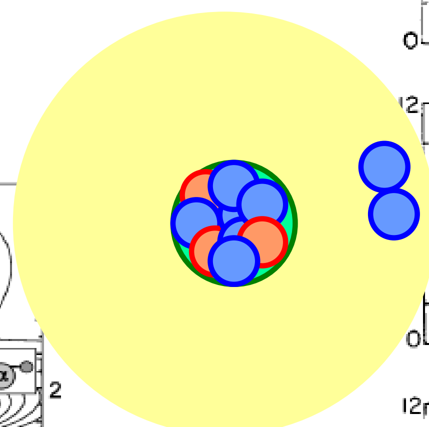
Three-body model calculations:

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

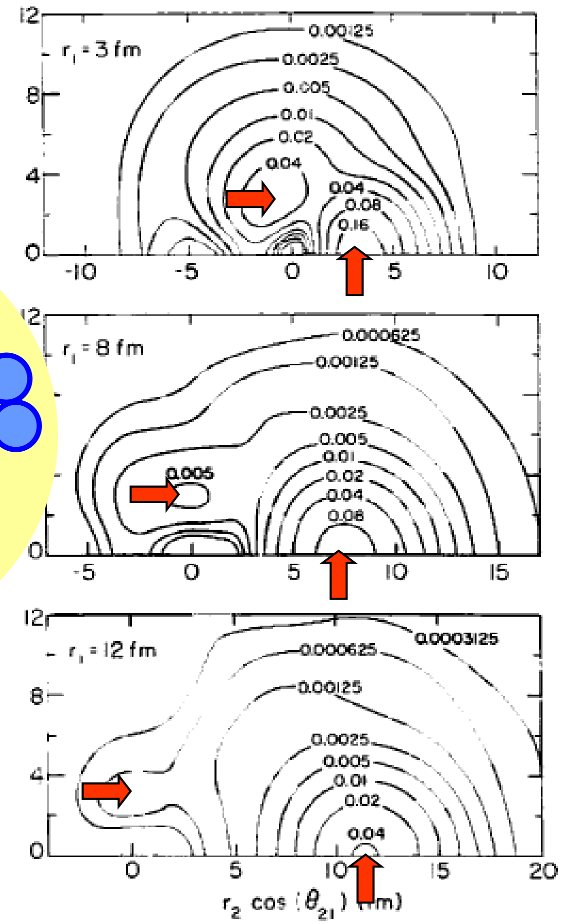
$x^2 y^2 \rho_2(x,y)$ for ^{6}He



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



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



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

cf. earlier works

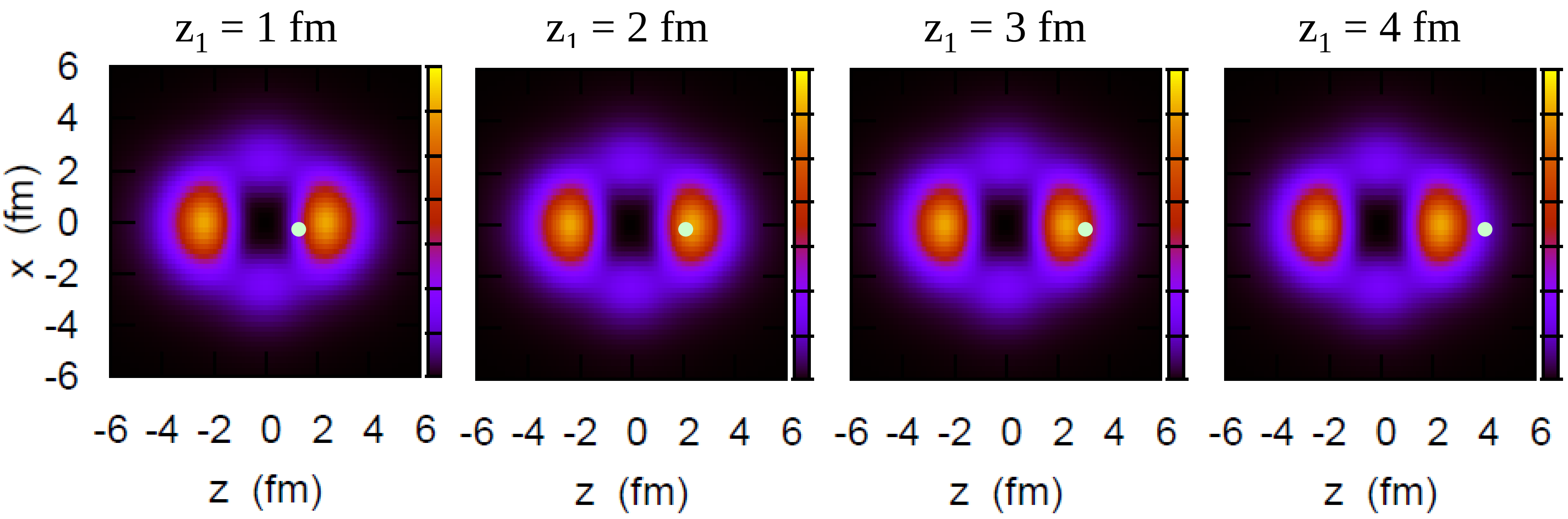
- ✓ A.B. Migdal ('73)
- ✓ P.G. Hansen and B. Jonson ('87)

What is Di-neutron correlation?

Example: $^{18}O = {}^{16}O + n + n$

i) Without nn interaction: $|nn\rangle = |(1d_{5/2})^2\rangle$

Distribution of the 2nd neutron when the 1st neutron is at z_1 :



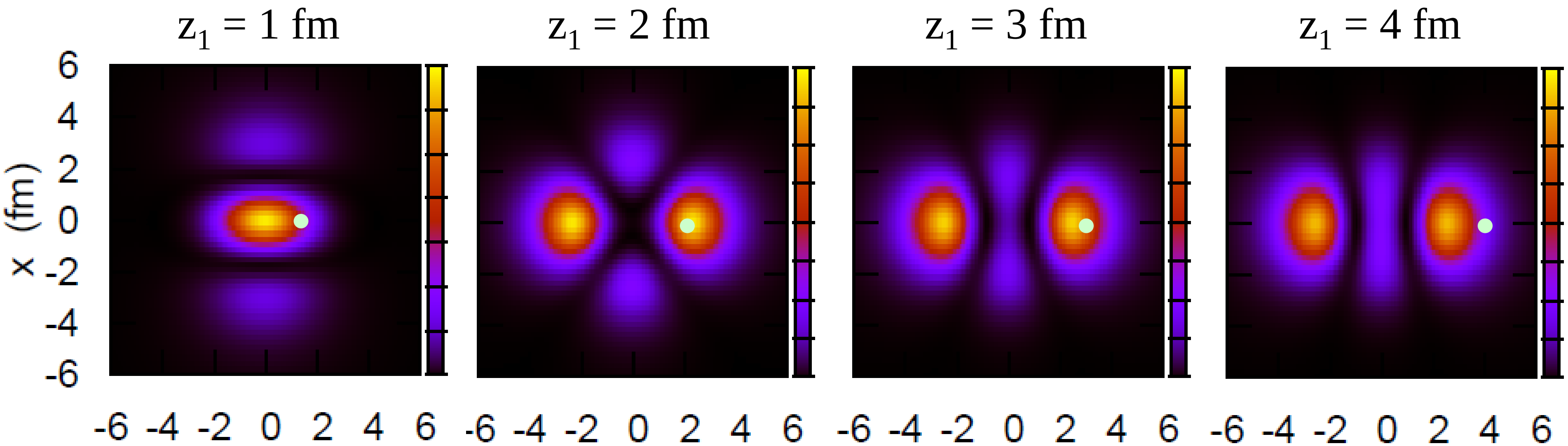
✓Two neutrons move independently

✓No influence of the 2nd neutron from the 1st neutron

⟶ need correlations to form a "pair"

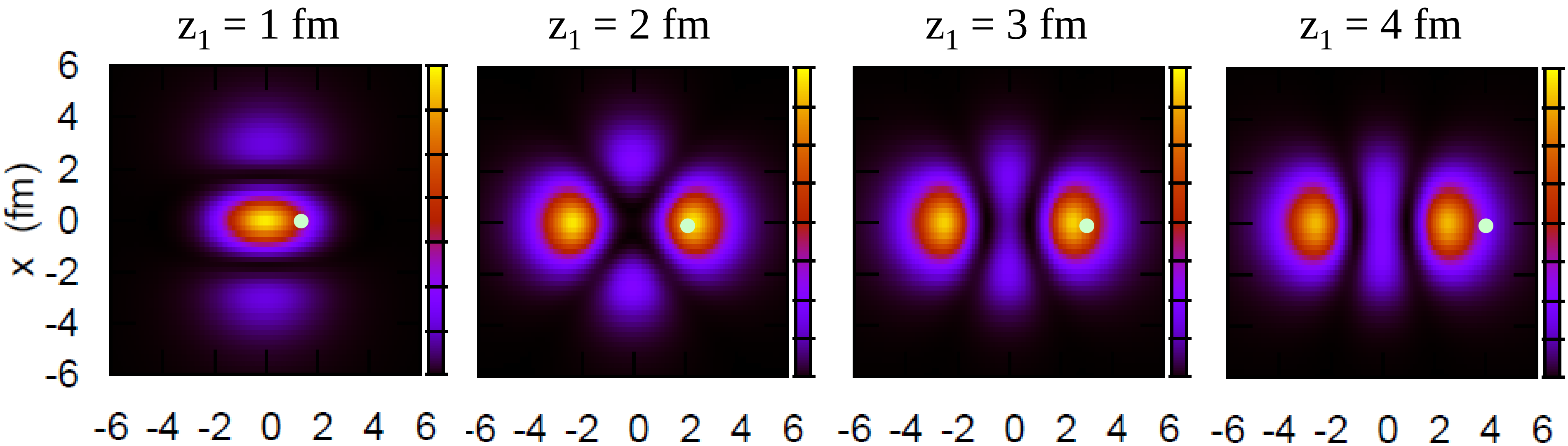
Example: $^{18}O = {}^{16}O + n + n$ cf. ^{17}O : 3 bound states ($1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$)

i) even parity only ⟶ insufficient

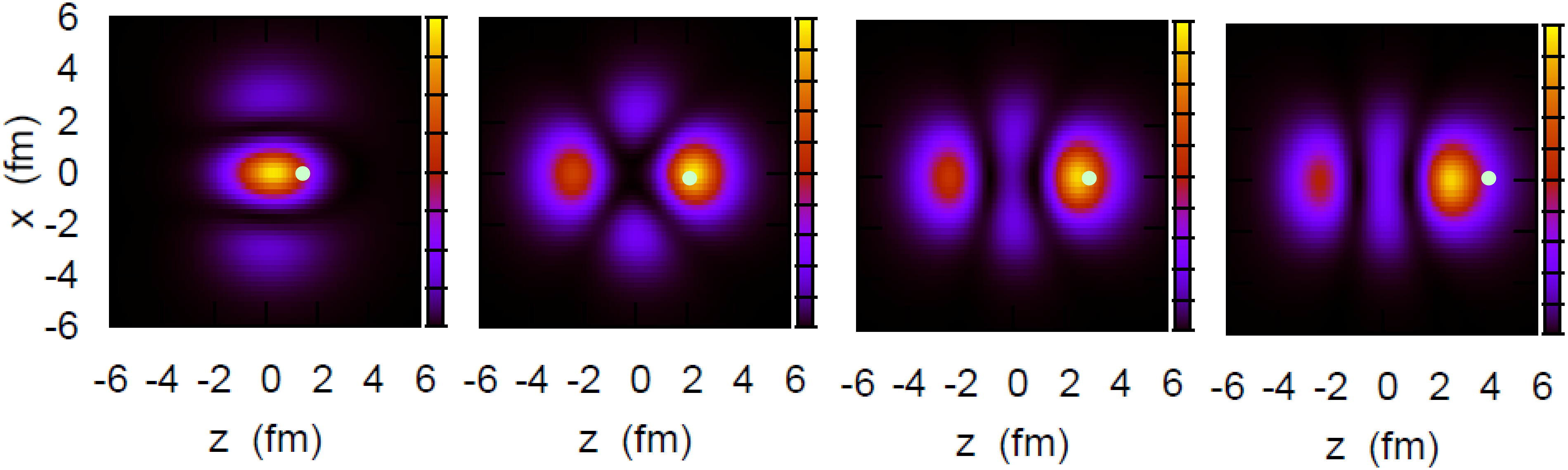


Example: $^{18}O = {}^{16}O + n + n$ cf. ^{17}O : 3 bound states ($1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$)

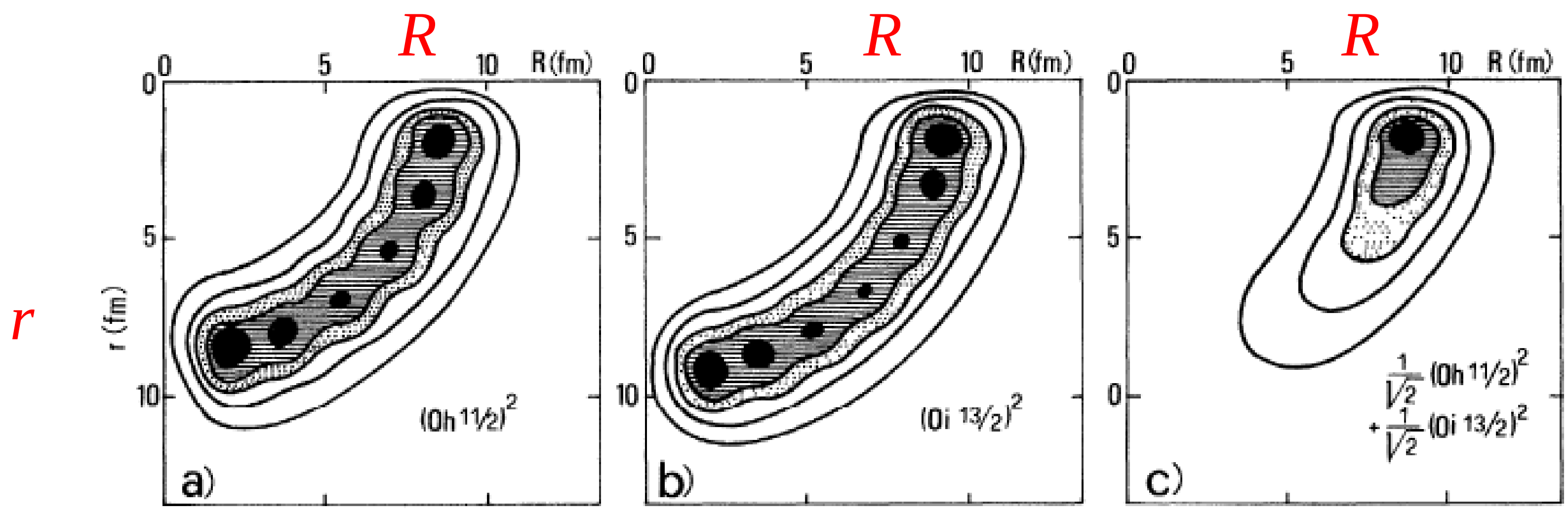
i) even parity only ⟶ insufficient



ii) both even and odd parities (bound + continuum states)

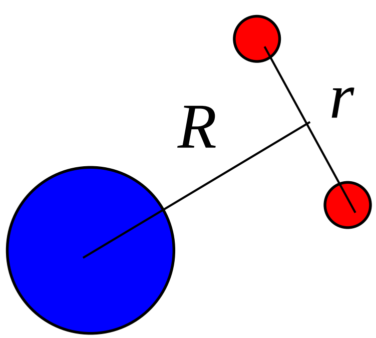


dineutron correlation: caused by the admixture of different parity states



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

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



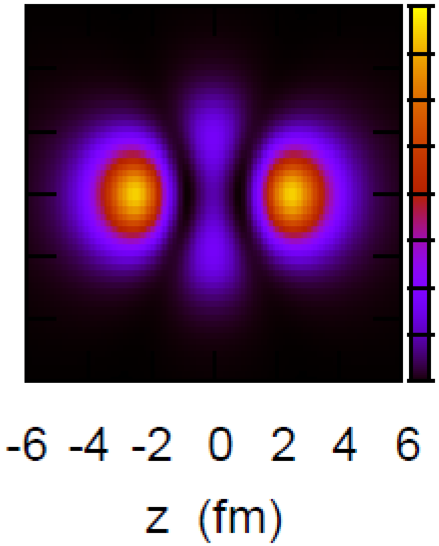
interference of even and odd partial waves

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

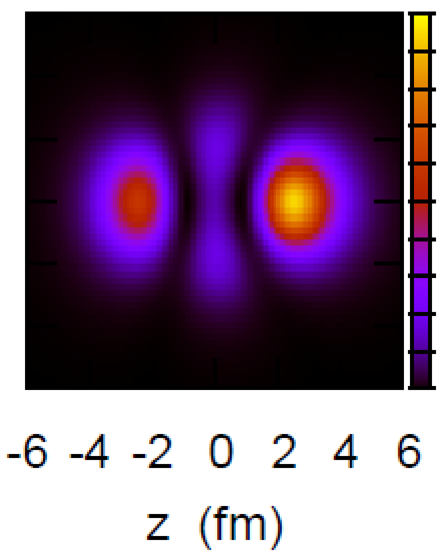
spatial localization of two neutrons

(dineutron correlation)

cf. Migdal, Soviet J. of Nucl. Phys. 16 (‘73) 238
Bertsch, Broglia, Riedel, NPA91(‘67)123



parity mixing

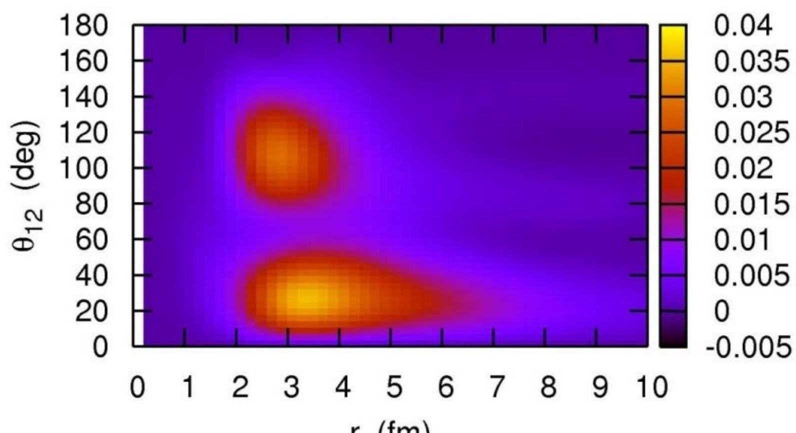


weakly bound systems

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

⟶ dineutron correlation: enhanced

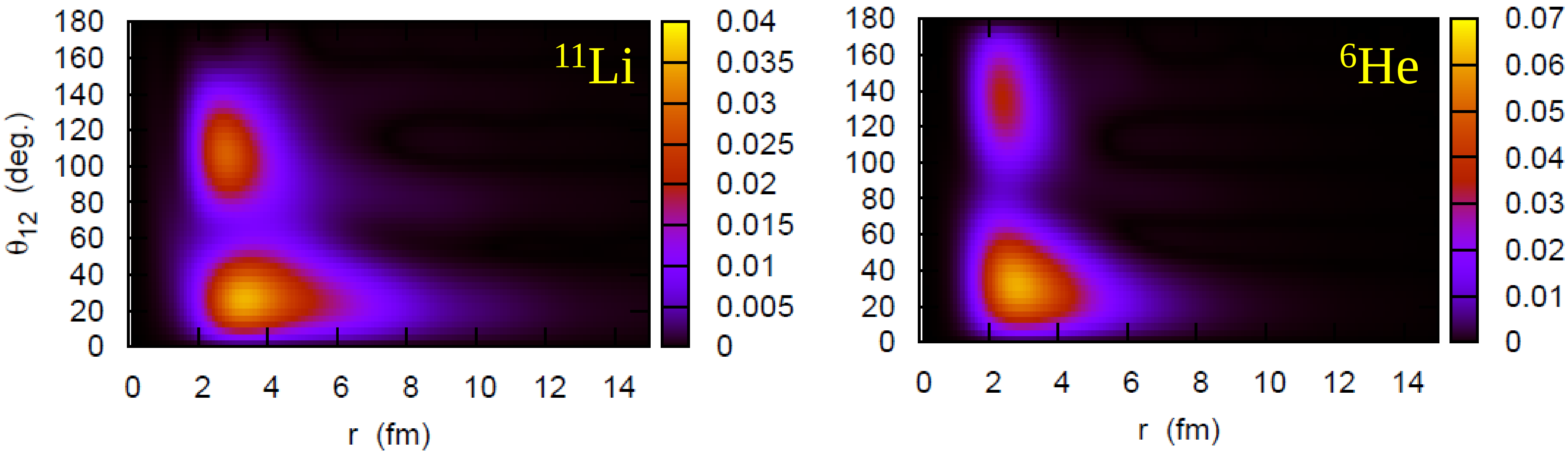
cf. - Bertsch, Esbensen, Ann. of Phys. 209(’91)327
- M. Matsuo, K. Mizuyama, Y. Serizawa, PRC71(‘05)064326



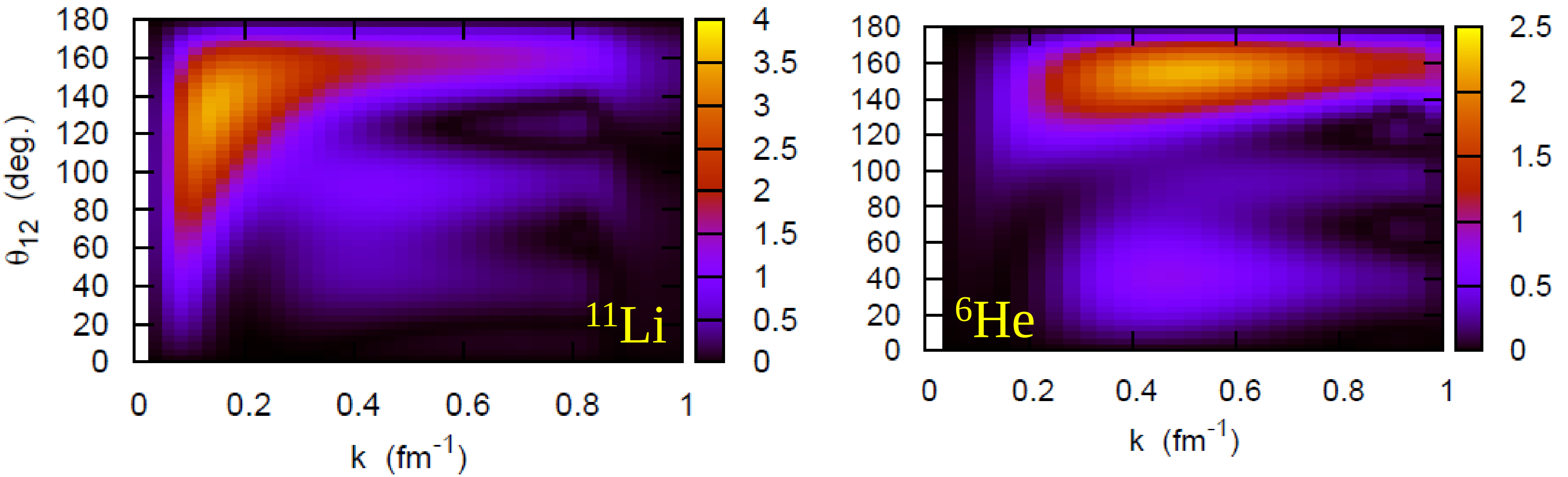
K.H. and H. Sagawa, PRC72(’05)044321

Dineutron correlation in the momentum space

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

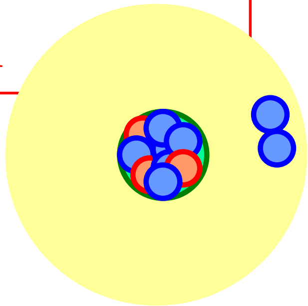


Two-particle density in the *p* space: $8\pi^2 k^4 \sin\theta \cdot \rho(k, k, \theta)$



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)

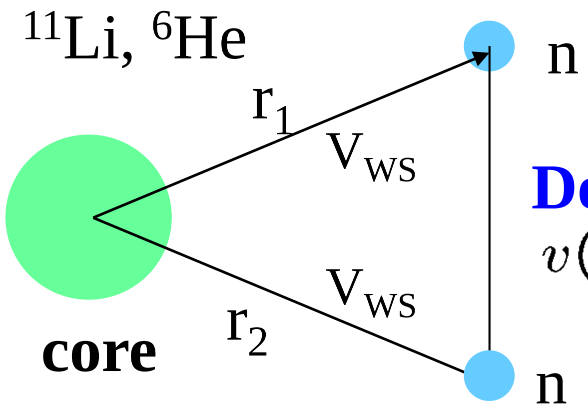
✓ Heavier nuclei (HFB calc.)
- Matsuo et al. (‘05)
- Pillet-Sandulescu-Schuck (‘07)

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

- 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

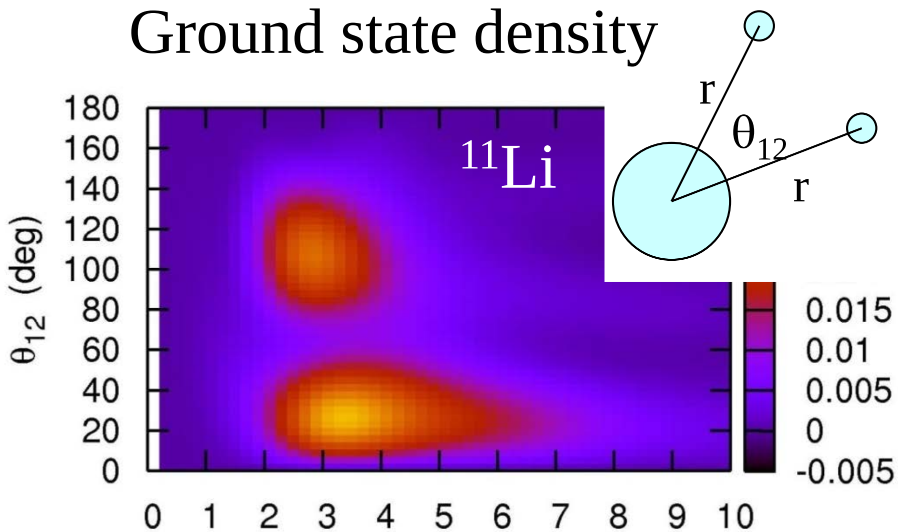
Density-dependent delta-force

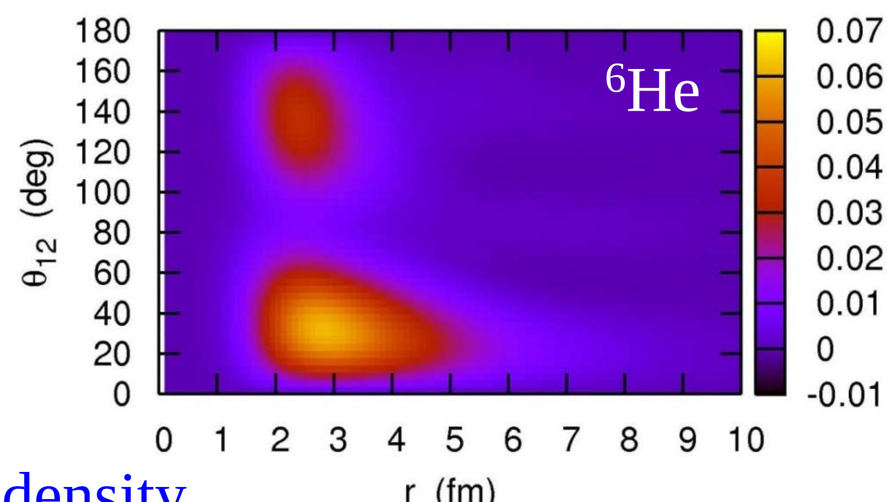
$$v(\boldsymbol{r}_1, \boldsymbol{r}_2) = v_0(1 + \alpha\rho(r)) \times \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)$$

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

Ground state density

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



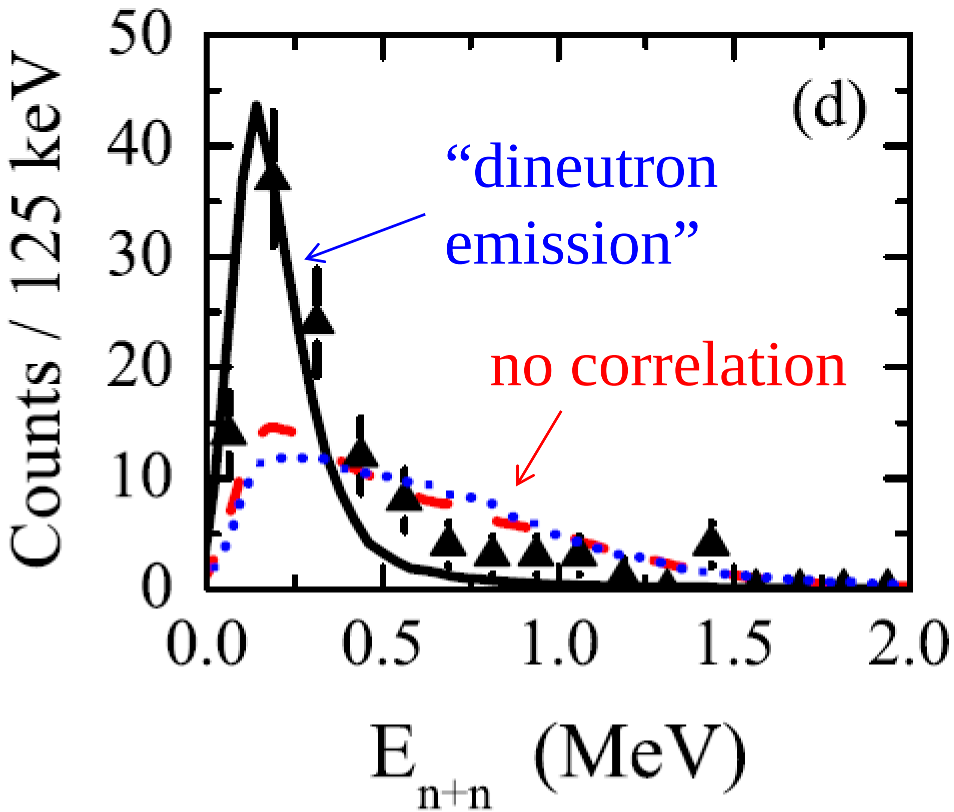


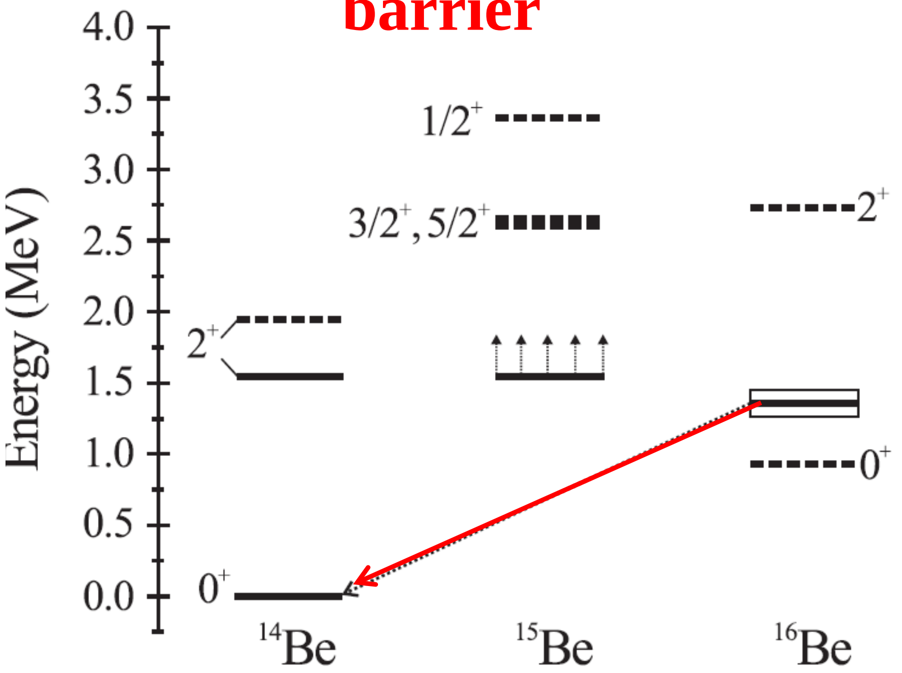
similar g.s. density

2-neutron decay（MoNA@MSU）

$^{17}B \rightarrow {}^{16}Be \rightarrow {}^{14}Be + n + n$

3-body resonance due to the **centrifugal barrier**





A. Spyrou et al., PRL108('12) 102501

Other data:

^{13}Li (Z. Kohley et al., PRC87('13)011304(R)) $^{14}Be \rightarrow {}^{13}Li \rightarrow {}^{11}Li + 2n$

^{26}O (E. Lunderbert et al., PRL108('12)142503) $^{27}F \rightarrow {}^{26}O \rightarrow {}^{24}O + 2n$

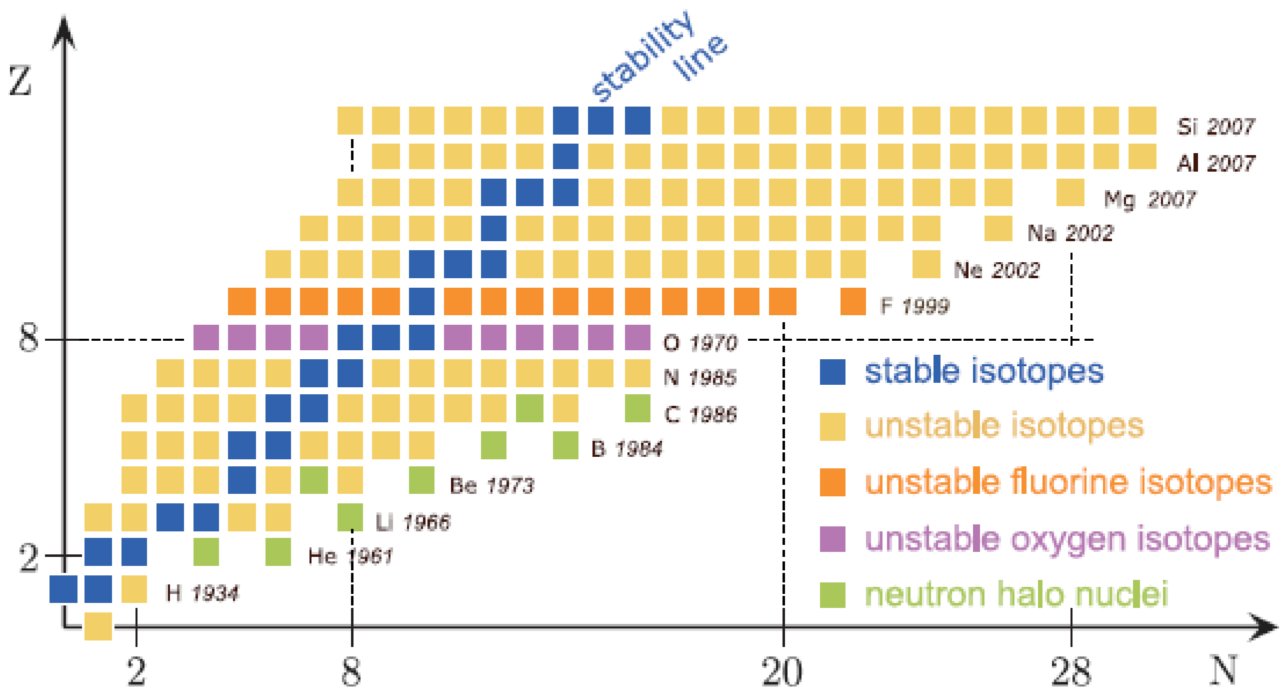
3-body model calculation with nn correlation: required

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 effects

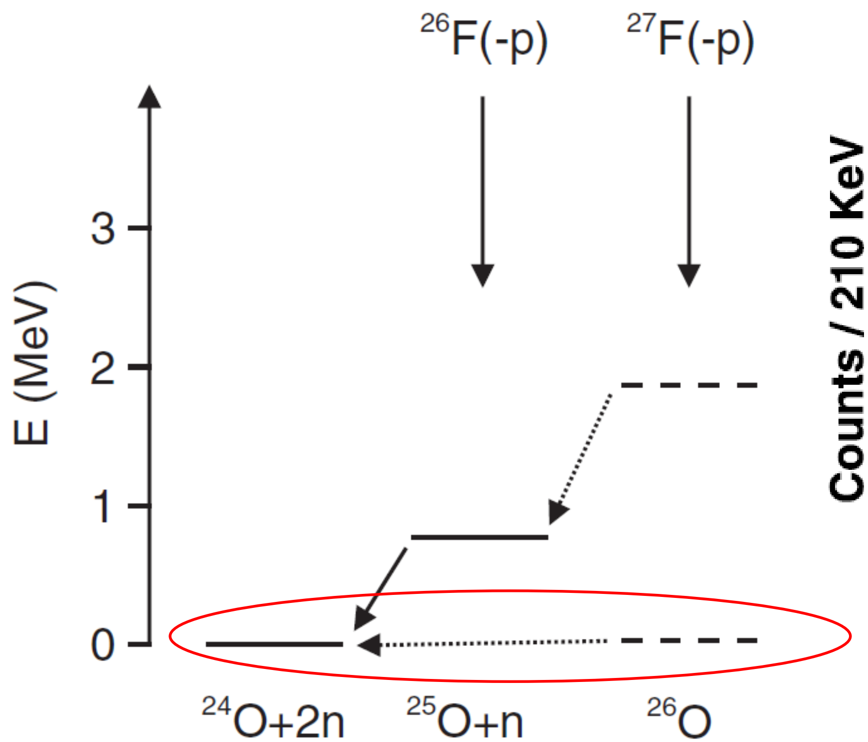
Two-neutron decay of ^{26}O

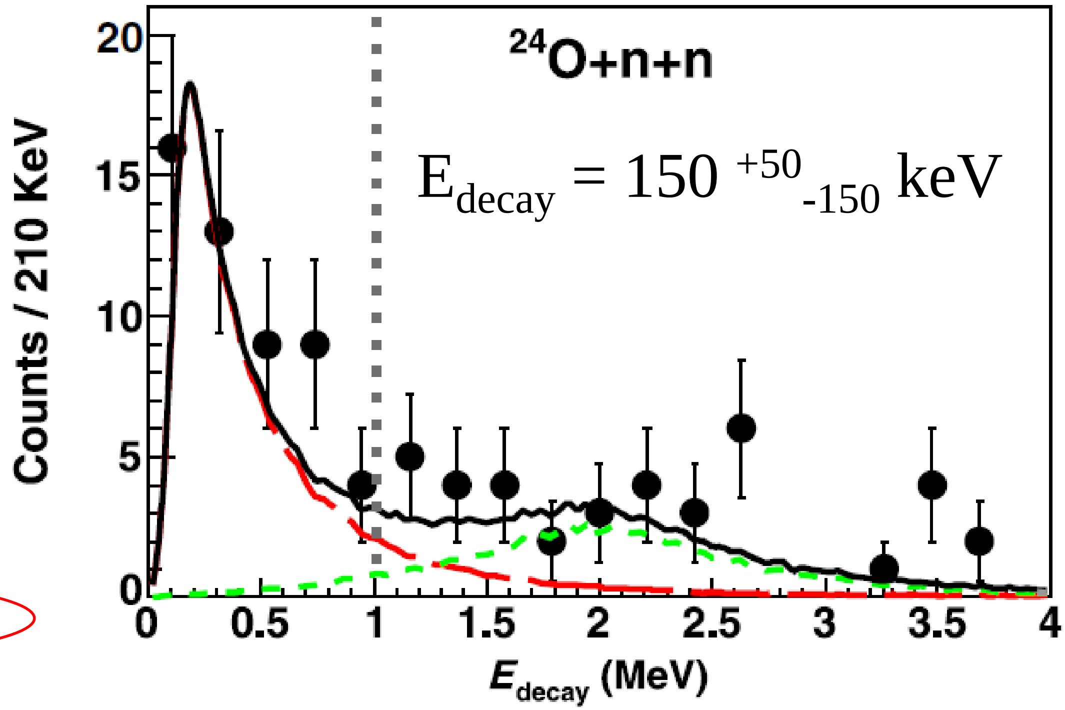
- the simplest among ^{16}Be, ^{13}Li, ^{26}O (MSU)
  ^{16}Be: deformation, ^{13}Li: treatment of ^{11}Li core

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

Experiment:

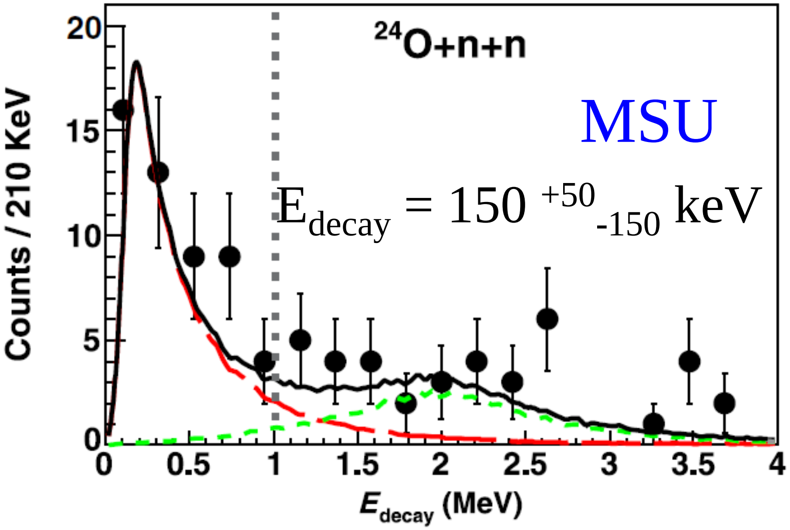
^{27}F (82 MeV/u) + ^{9}Be → ^{26}O → ^{24}O + n + n



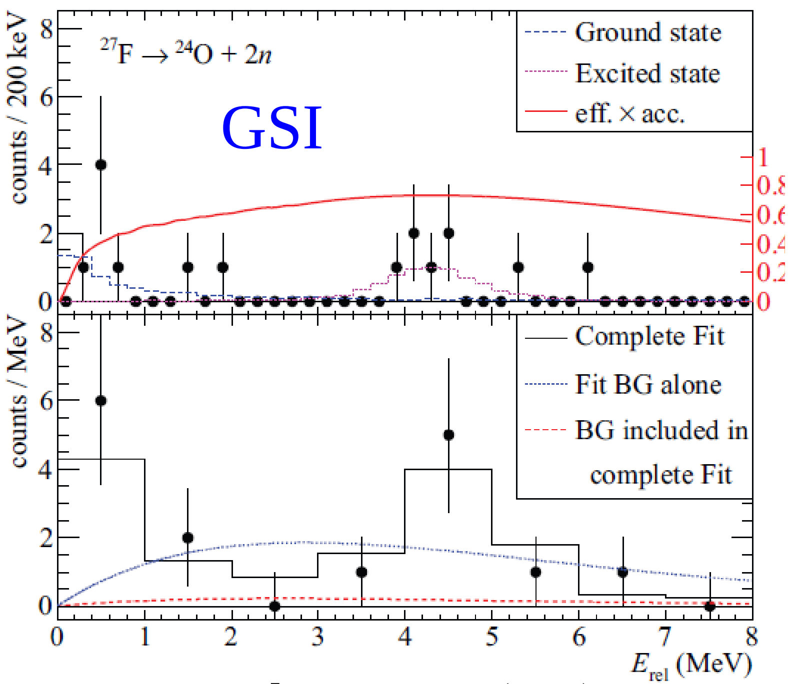


E_{decay} = 150 $^{+50}_{-150}$ keV

cf. C. Caesar et al., PRC88 (‘13) 034313 (GSI exp.) ⟶ E_{decay} < 120 keV

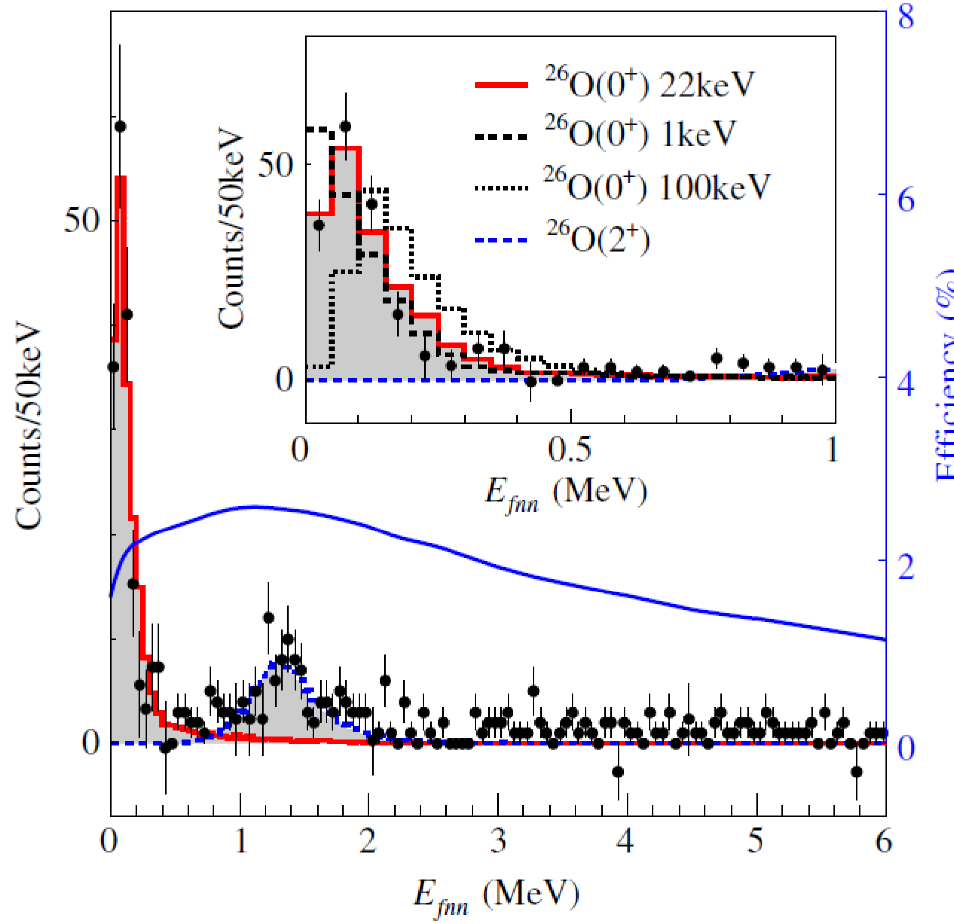


E. Lunderberg et al.,
PRL108 ('12) 142503



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

New RIKEN data

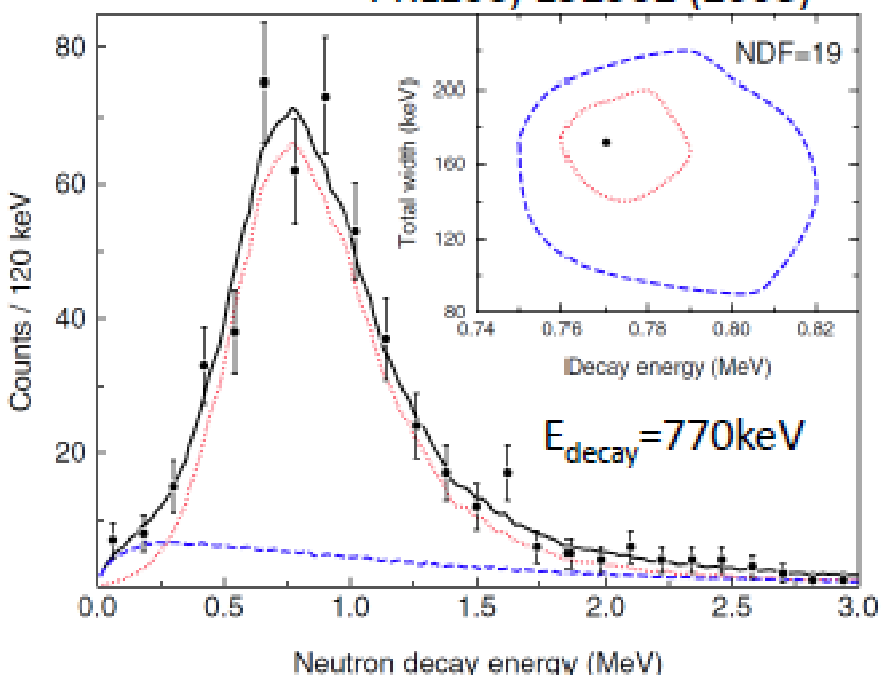


Y. Kondo et al., PRL116('16)102503

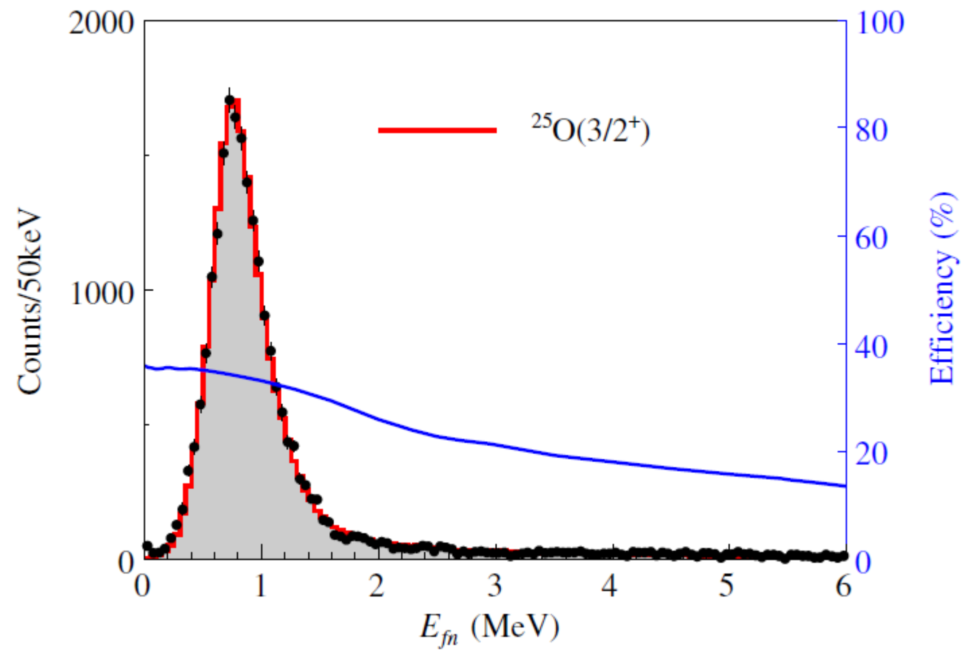
E_{decay} = 18 +/- 3 +/- 4 keV

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
$\Gamma = 172(30)$ keV

⇨

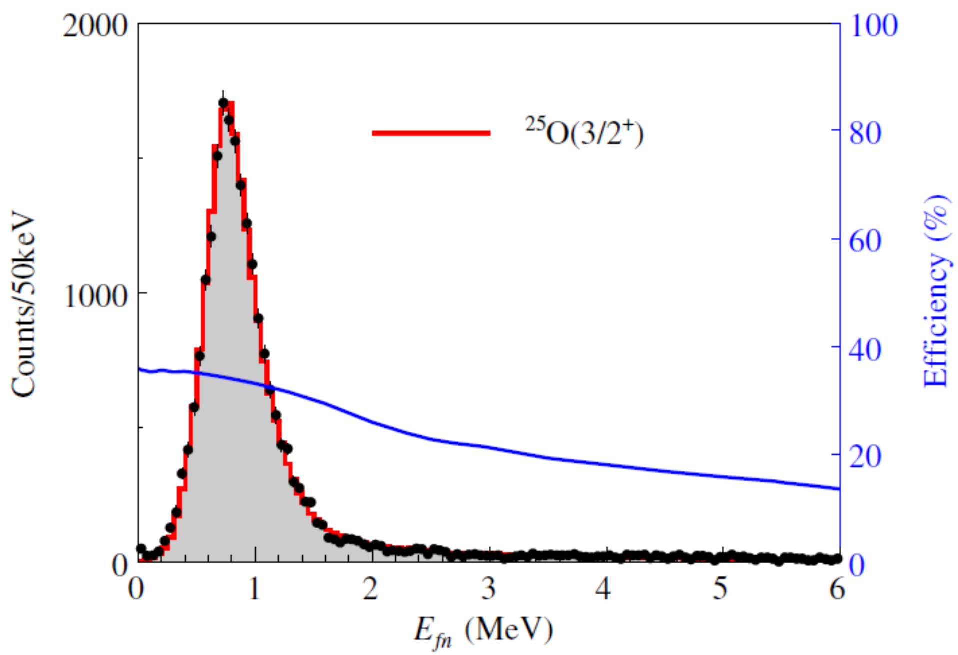
$E = +\ 749(10)$ keV
$\Gamma = 88(6)$ keV

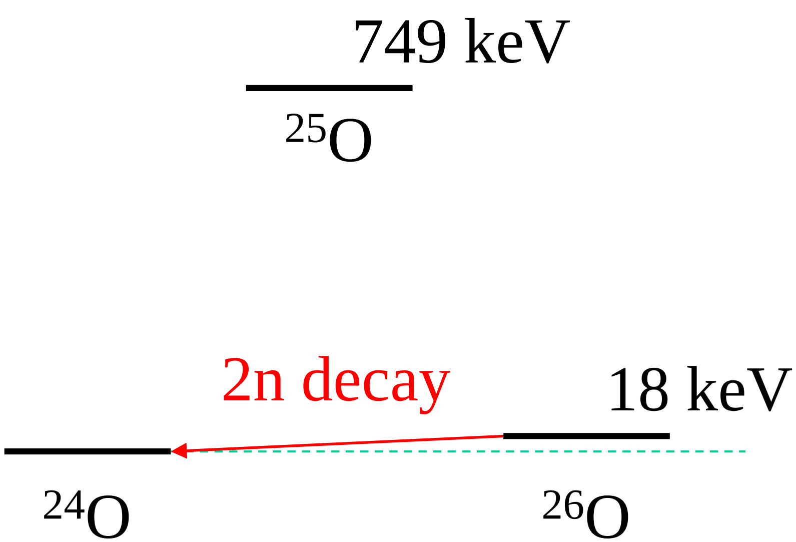
PRL 116, 102503 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

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]

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

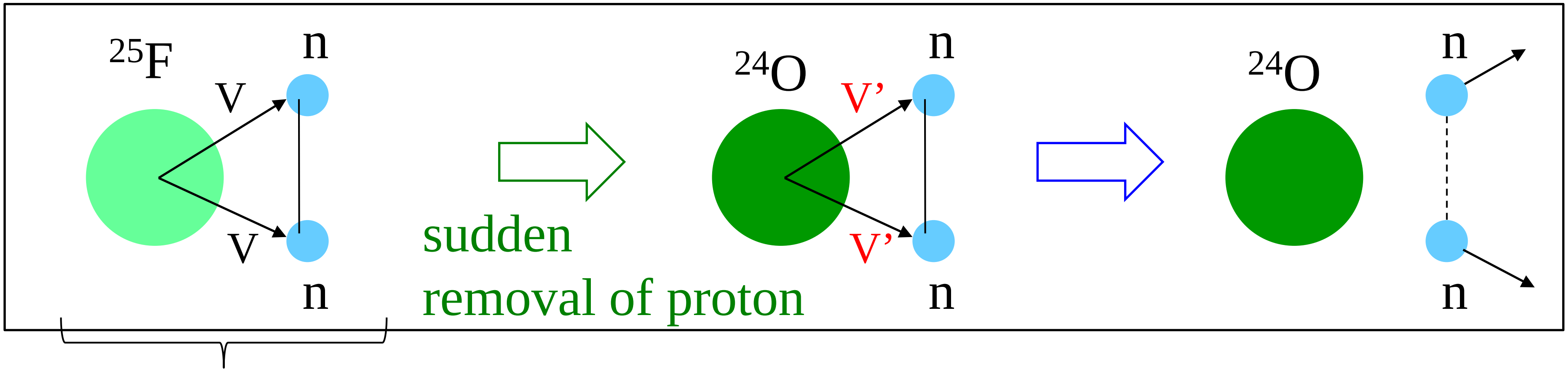




3-body model analysis for ^{26}O decay

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)

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

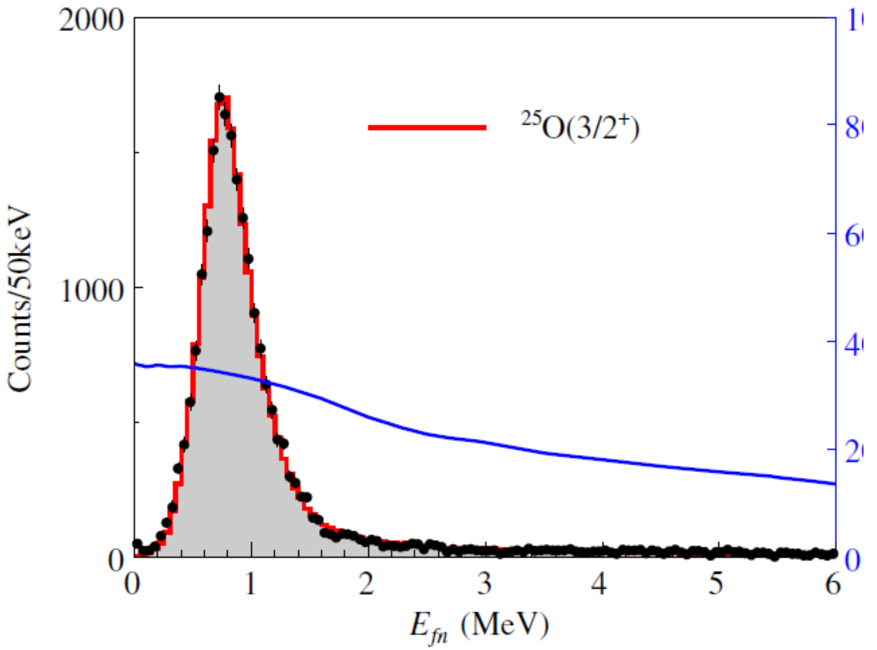
→ the same config. (the reference state)

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

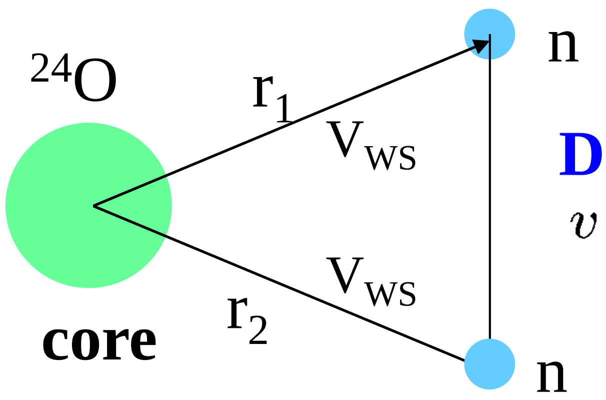


Gamow states (outgoing boundary condition)

$d_{3/2}$: 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

Two-neutron decay of ^{26}O : i) Decay energy spectrum



Density-dependent delta-force

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

v_0 : free nn interaction

α : $E_{gs}(^{26}\text{O})$

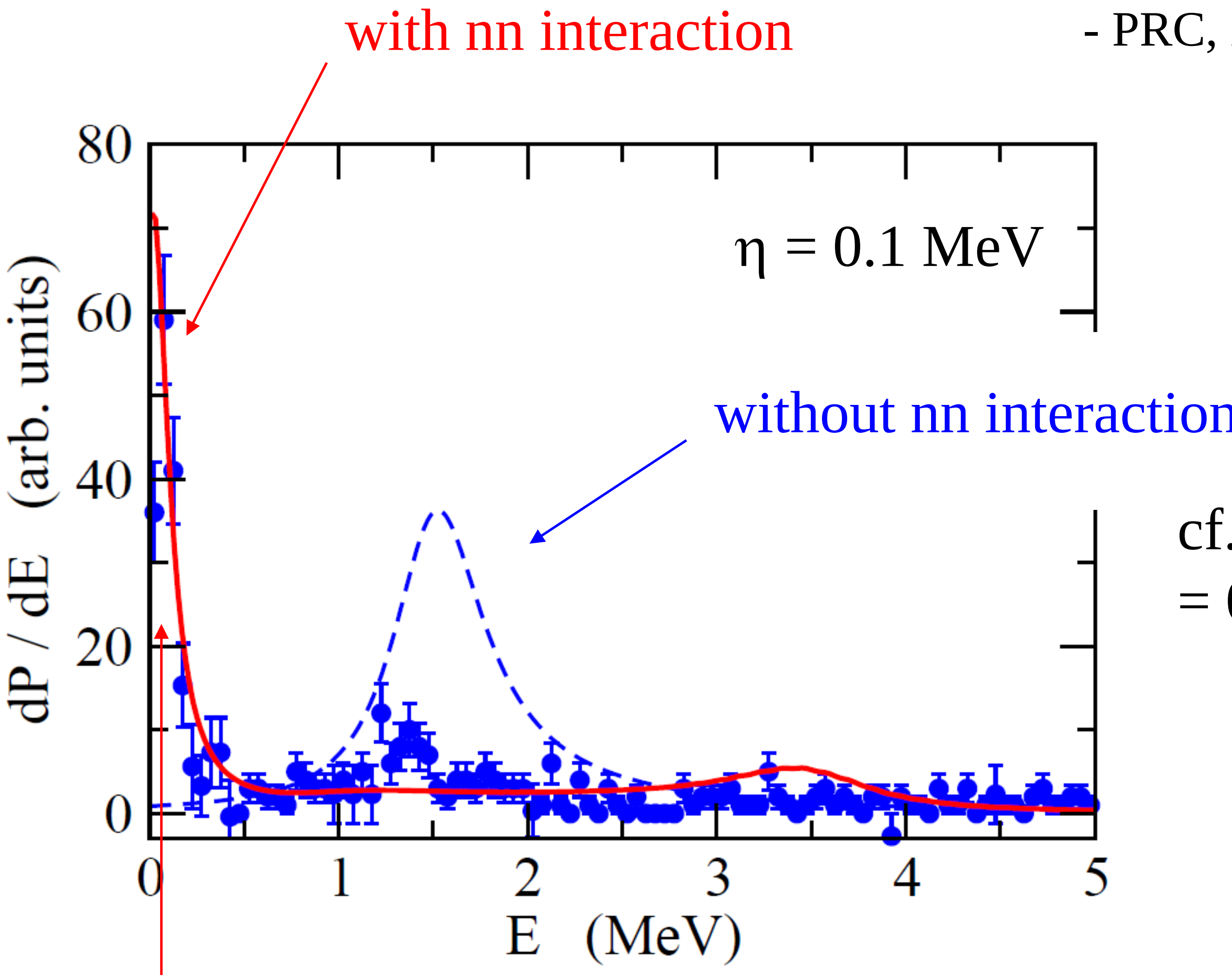
$$H = T_1 + V_1 + T_2 + V_2 + v_{nn}$$

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

Reference (initial) state: $(d_{3/2})^2$ in ^{27}F

i) Decay energy spectrum

K.H. and H. Sagawa,
- PRC89 ('14) 014331
- PRC, in press ('16)



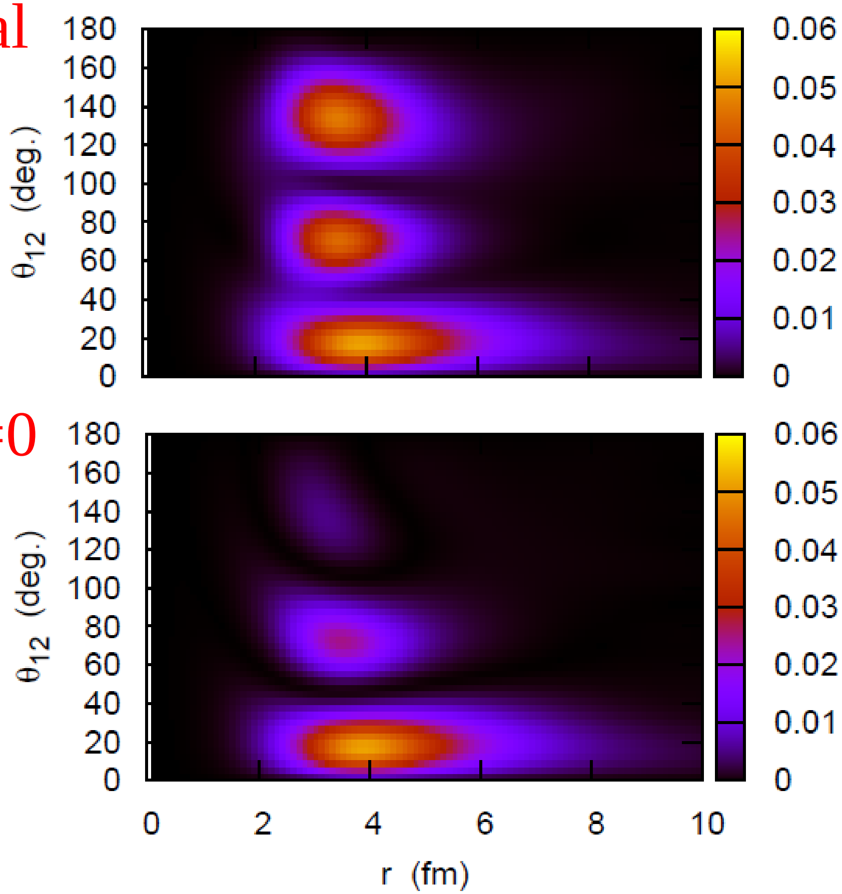
cf. $e_{1d3/2}(^{25}O)$
= 0.749 MeV

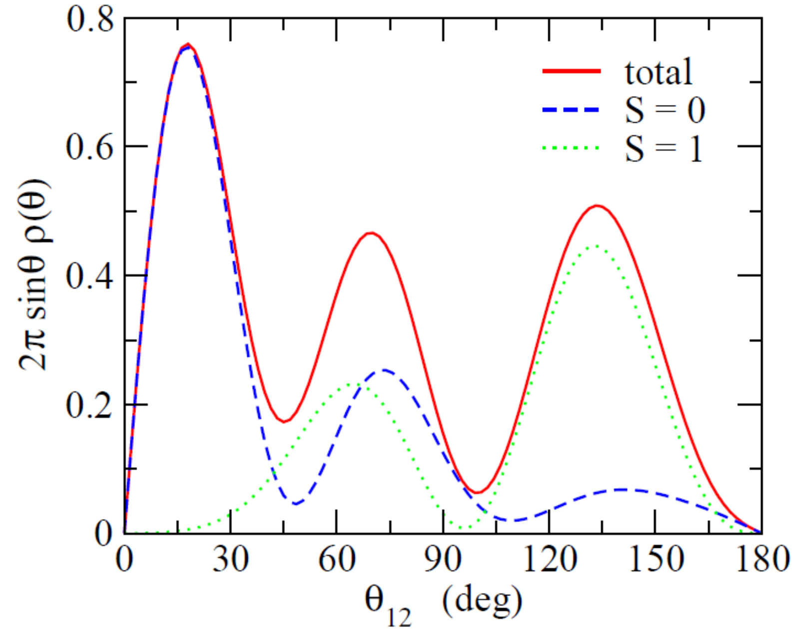
E_{peak} = 18 keV (input)

Two-particle density in the bound state approximation

total

S=0





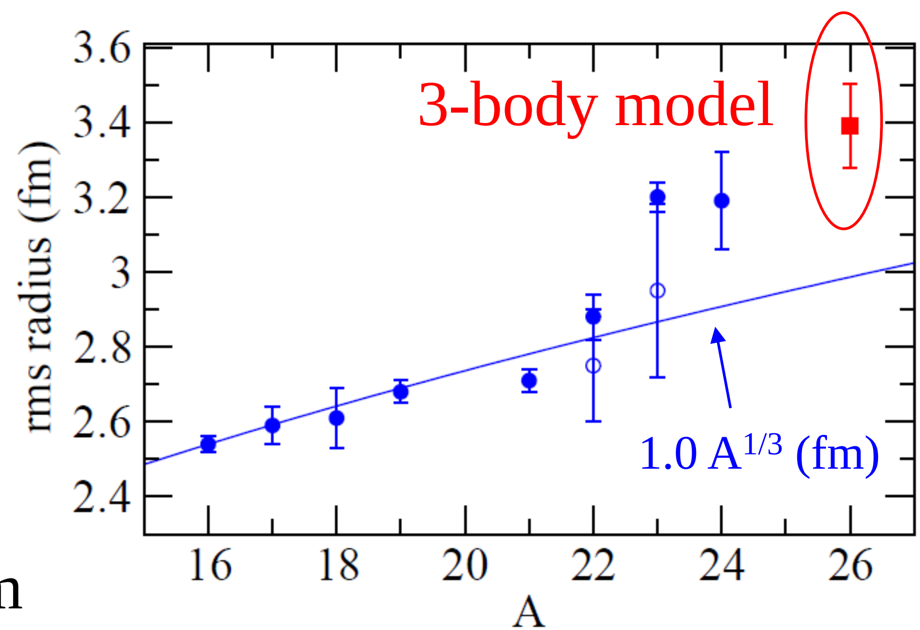
$(d_{3/2})^2$: 66.1%

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

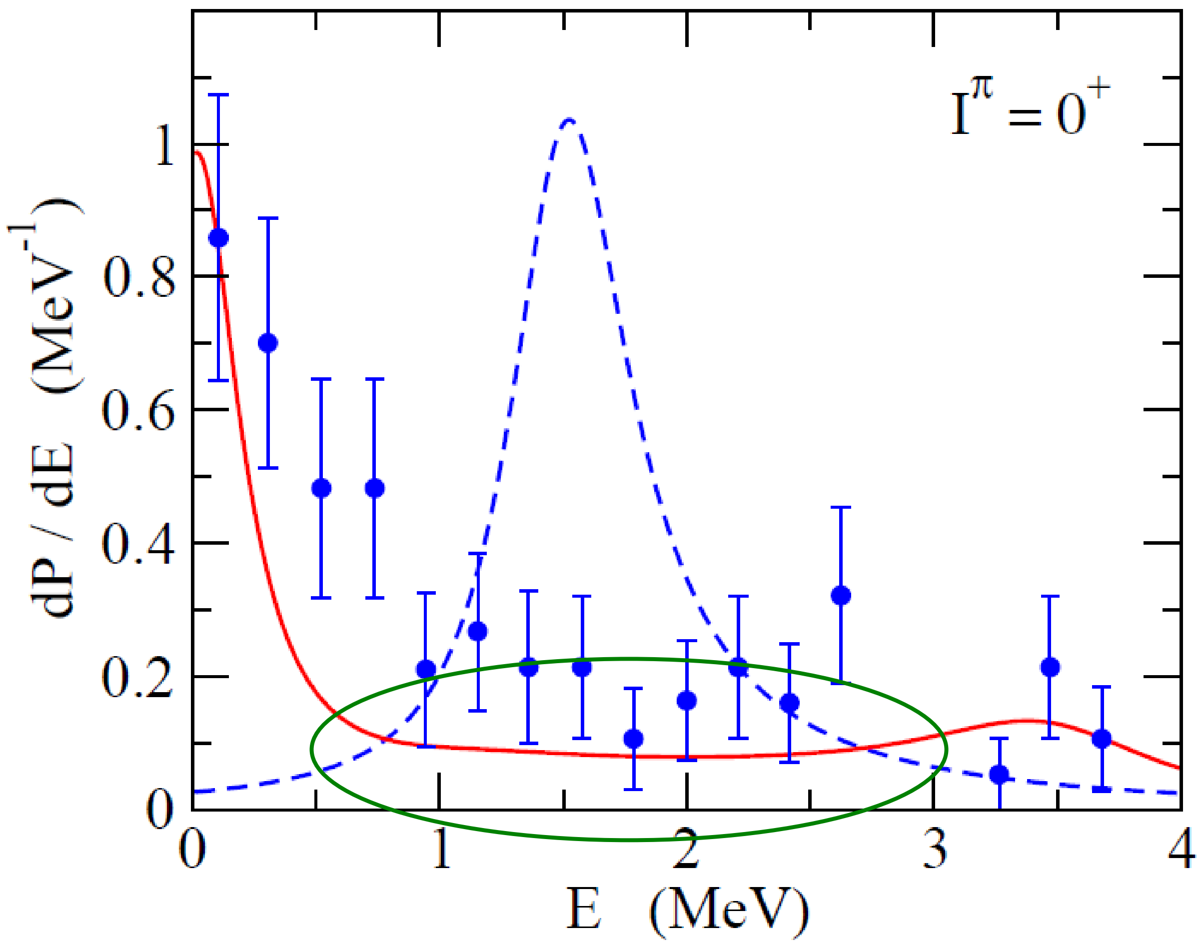
$(p_{3/2})^2$: 10.5%

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

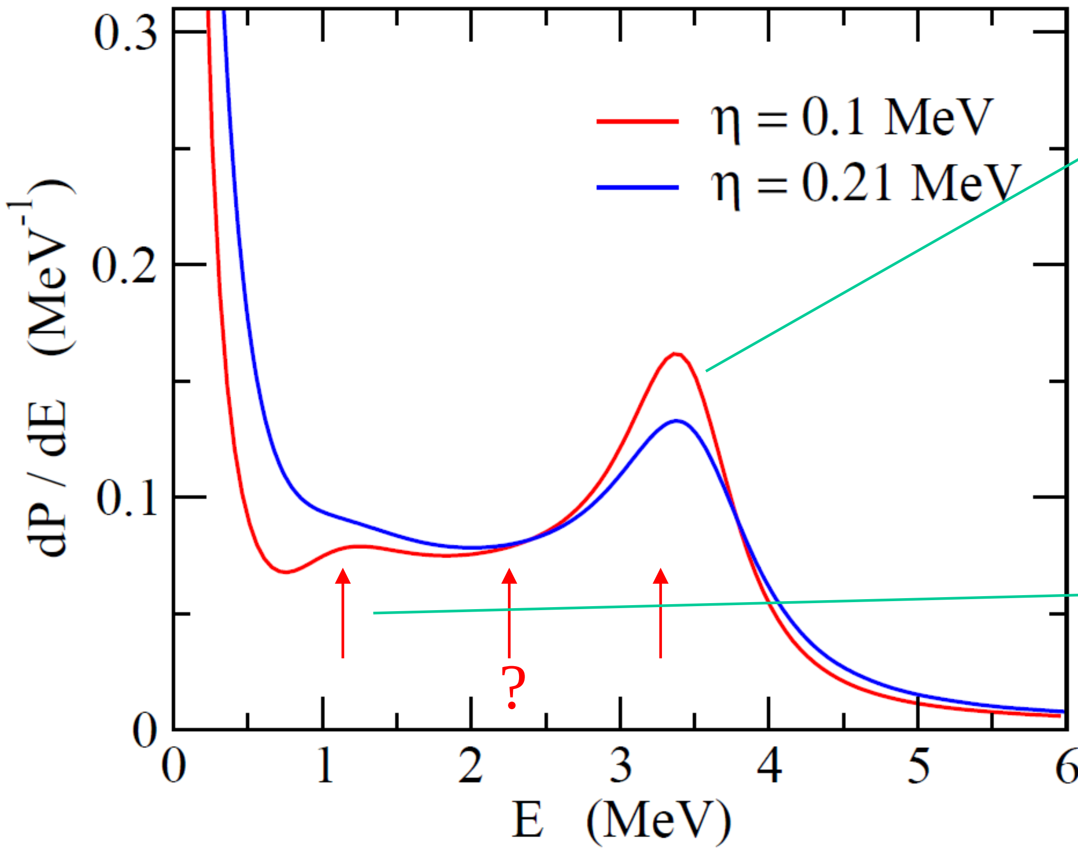
rms radius = 3.39 +/- 0.11 fm



Excited 0^+ states



Excited 0^+ states



$$\langle \Psi_E | (jj)^{(0)} \rangle$$
$$\propto \langle \Phi_{\text{ref}} | G(E) | (jj)^{(0)} \rangle$$

E = 3.379 MeV
Γ = 0.737 MeV

$(f_{7/2})^2$: 62.1%
$(d_{3/2})^2$: 24.9%
$(p_{3/2})^2$: 10.4%

E = 1.215 MeV

$(p_{3/2})^2$: 60.3%
$(d_{3/2})^2$: 26.8%
$(f_{7/2})^2$: 2.02%

cf. Grigorenko et al. (PRC91 (‘15) 064617)

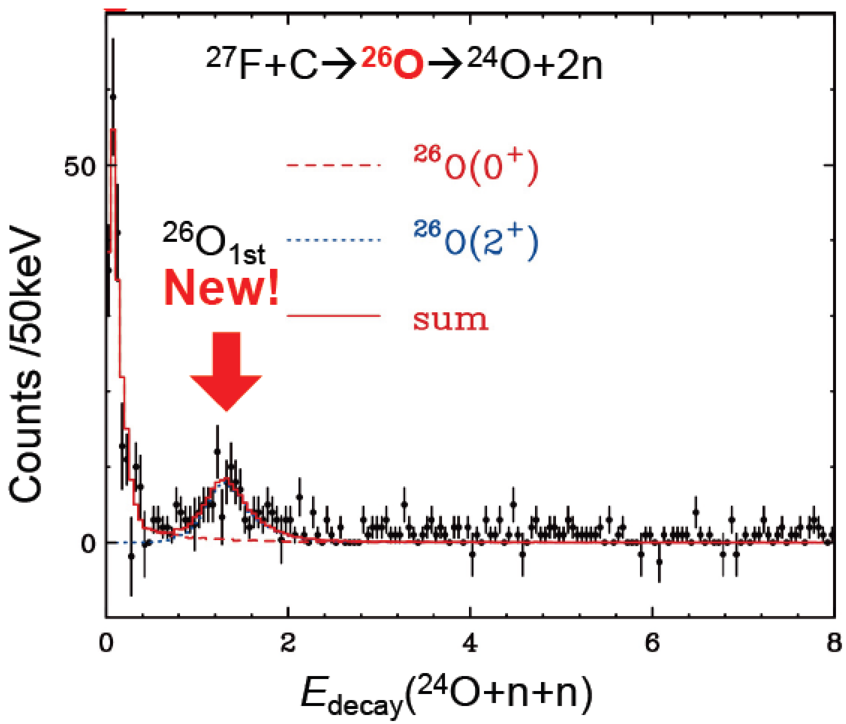
E = 0.01 MeV [$(d_{3/2})^2$: 79 %]
E = 1.7 MeV [$(d_{3/2})^2$: 80 %]
E = 2.6 MeV [$(d_{3/2})^2$: 86 %]

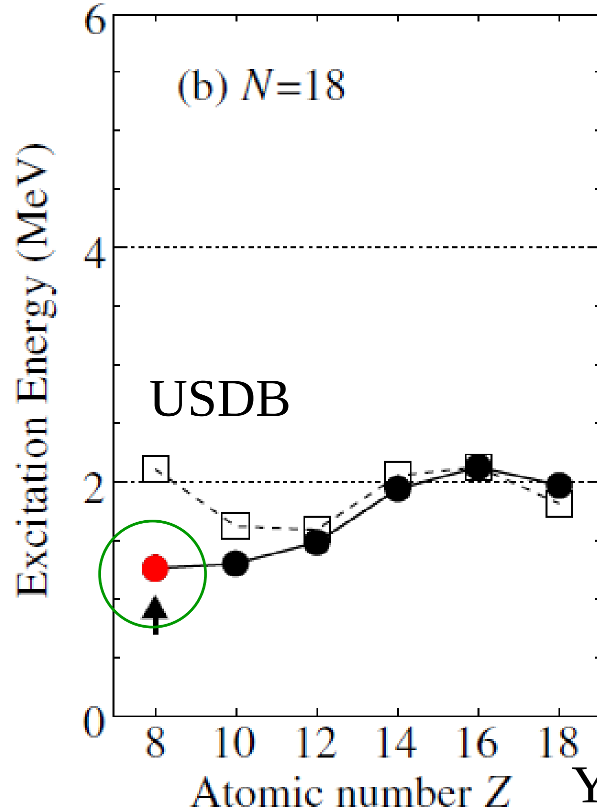
cf. s.p. resonances (MeV)

$d_{3/2}$: E = 0.75, Γ = 0.087
$f_{7/2}$: E = 2.44, Γ = 0.21
$p_{3/2}$: E = 0.58, Γ = 1.63

2^+ state in ^{26}O

New RIKEN data : a prominent second peak at $E = 1.28\ ^{+0.11}_{-0.08}$ MeV





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

cf. ab-initio calc. with chiral NN+3N: E_{2+} = 1.6 MeV

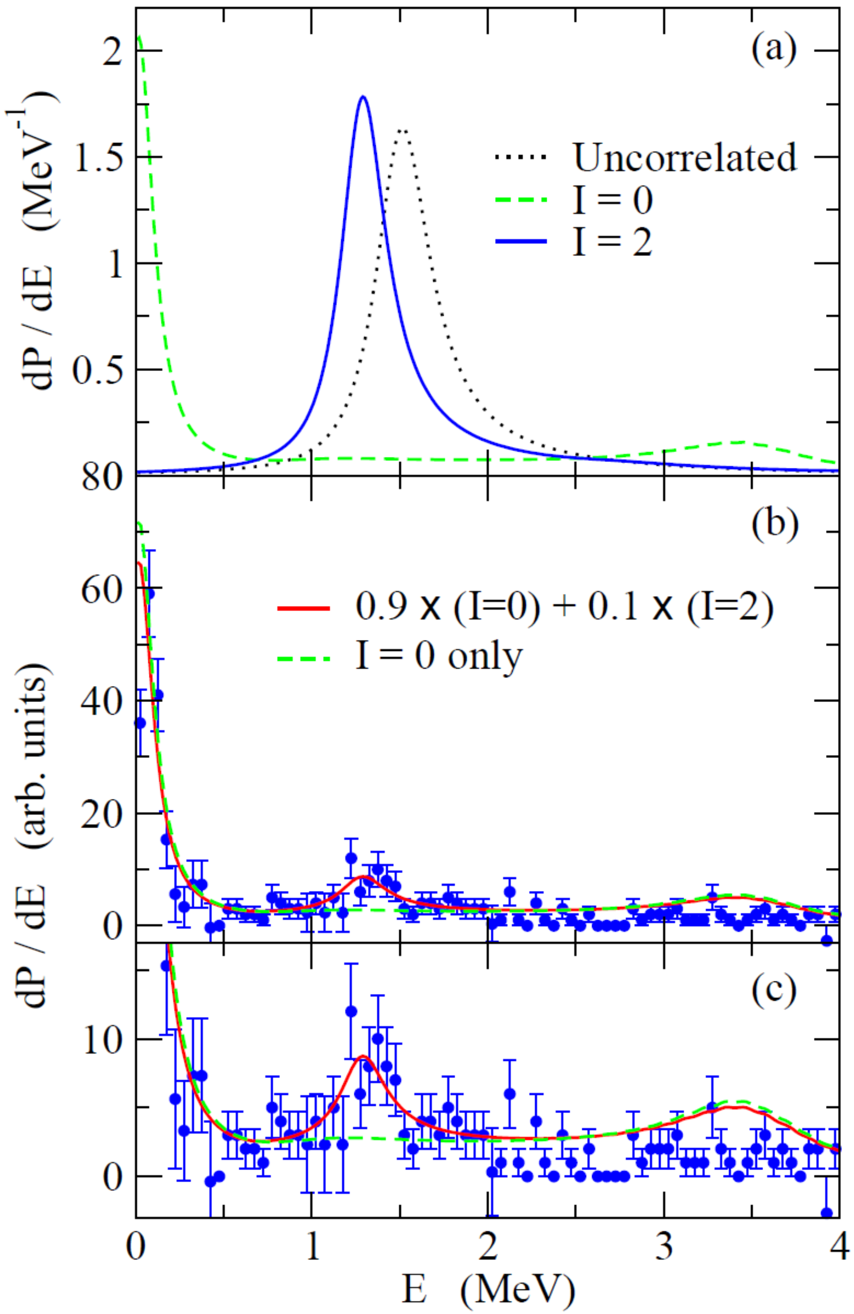
(C. Caesar et al., PRC88('13)034313)

continuum shell model: E_{2+} = 1.8 MeV

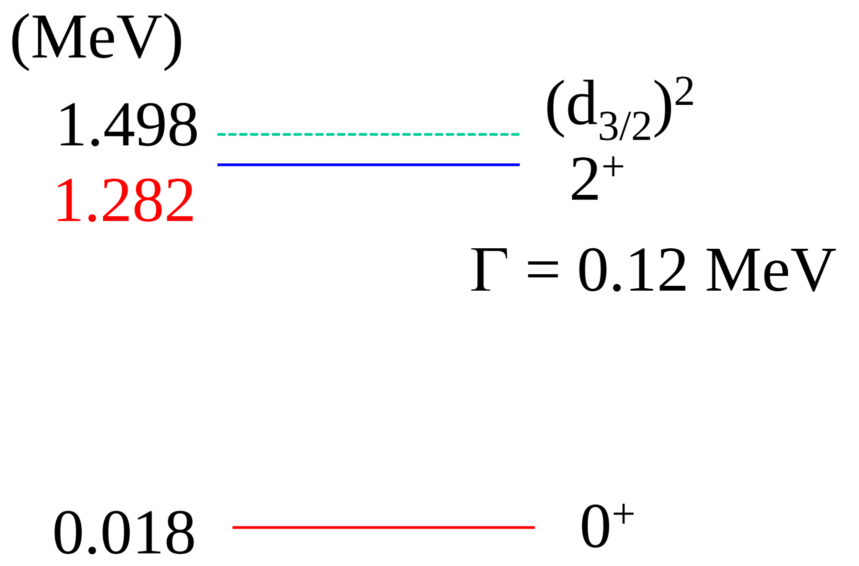
(A. Volya and V. Zelvinsky, PRC74 ('14) 064314)

2^+ state of ^{26}O

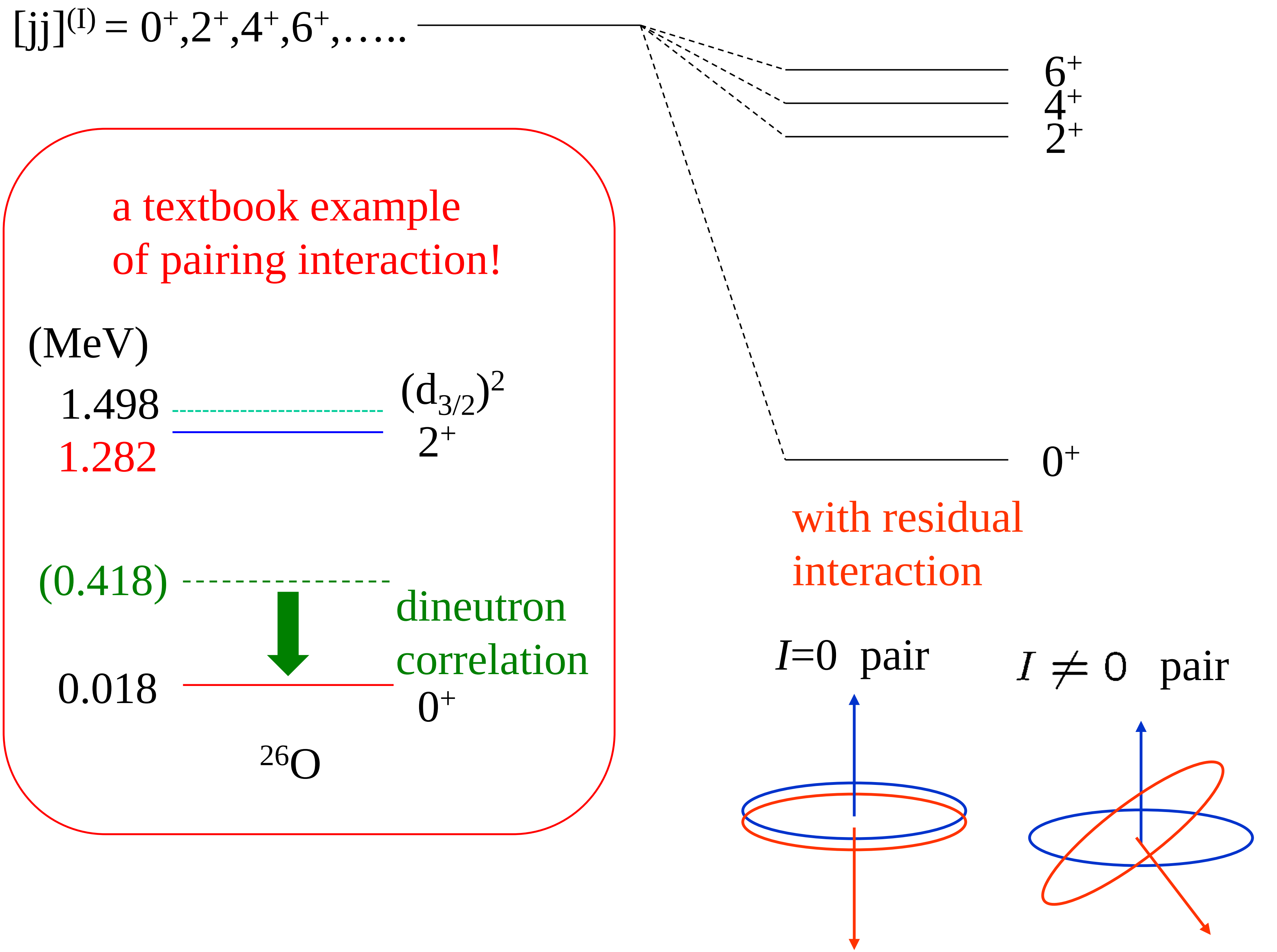
Kondo et al. : a prominent second peak at $E \sim 1.28^{+0.11}_{-0.08}$ MeV



three-body model calculation:



K.H. and H. Sagawa,
PRC90('14)027303; PRC, in press ('16).

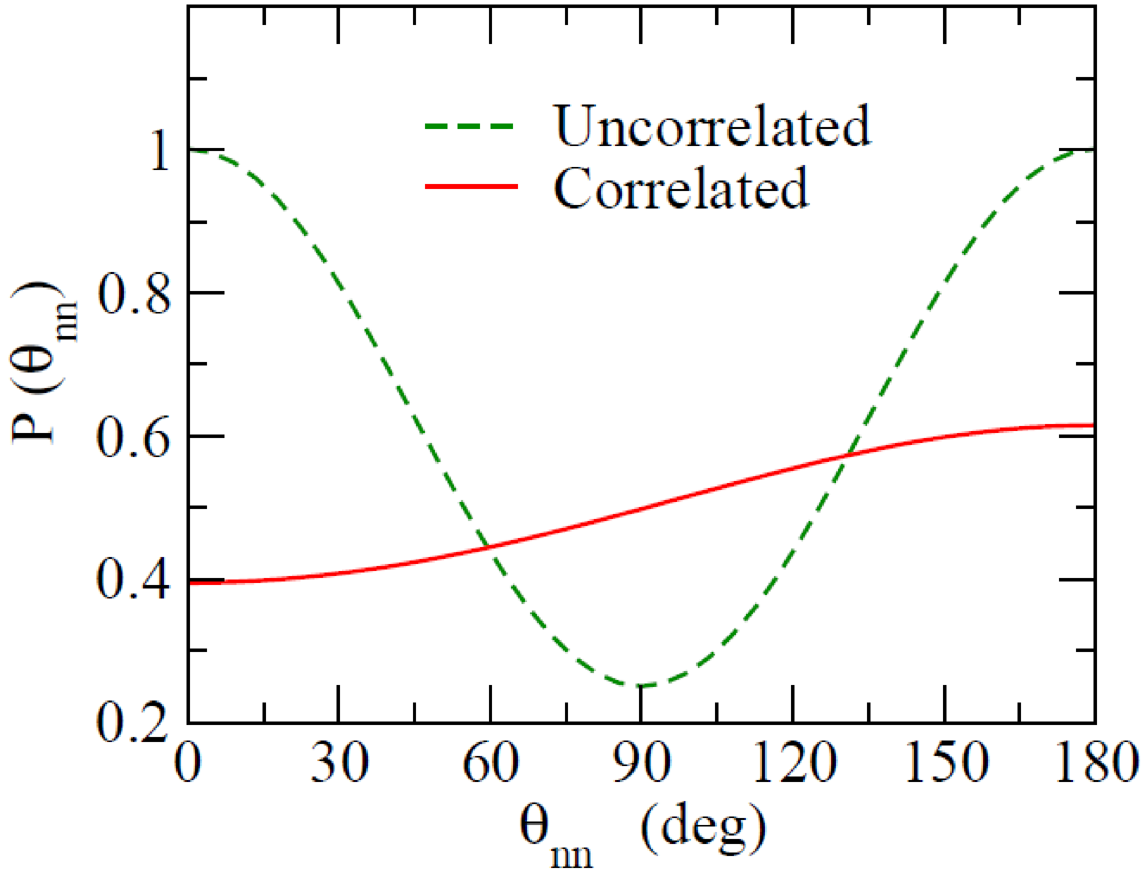


[jj]^(I) = 0+,2+,4+,6+,…..
6+
4+
2+
0+
with residual interaction
a textbook example of pairing interaction!
(MeV)
1.498
1.282
(d3/2)^2
2+
(0.418)
dineutron correlation
0.018
0+
26O
I=0 pair
I ≠ 0 pair

Angular correlations

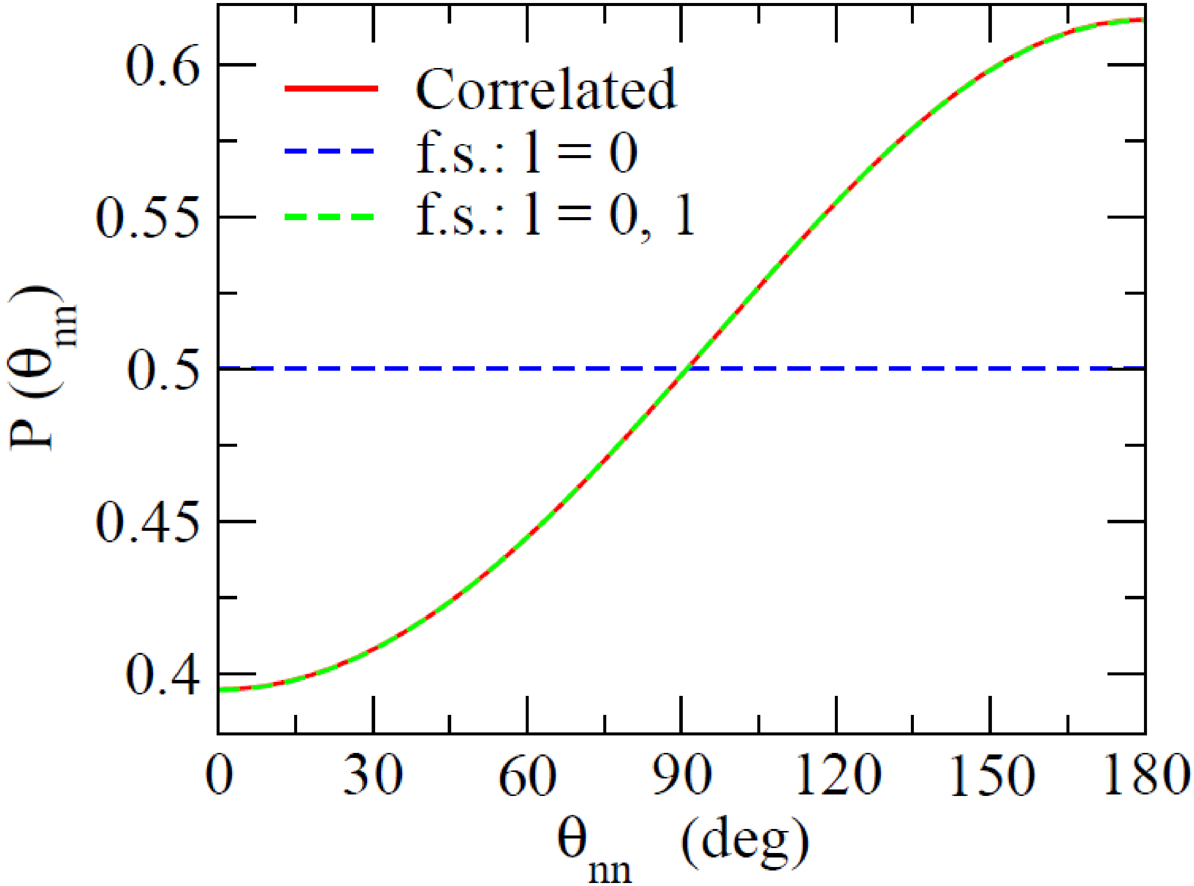
K.H. and H. Sagawa,
PRC89 (‘14) 014331;
PRC, in press (‘16).

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



correlation → enhancement of back-to-back emissions

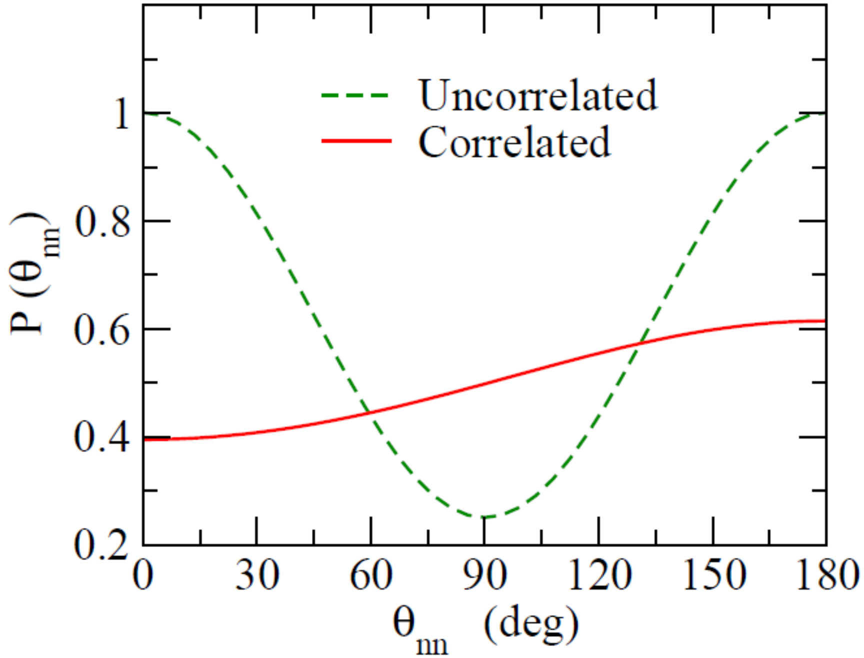
cf. Similar conclusion: L.V. Grigorenko, I.G. Mukha, and M.V. Zhukov, PRL 111 (2013) 042501



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} ~ 18 keV, e_1 ~ e_2 ~ 9 keV)

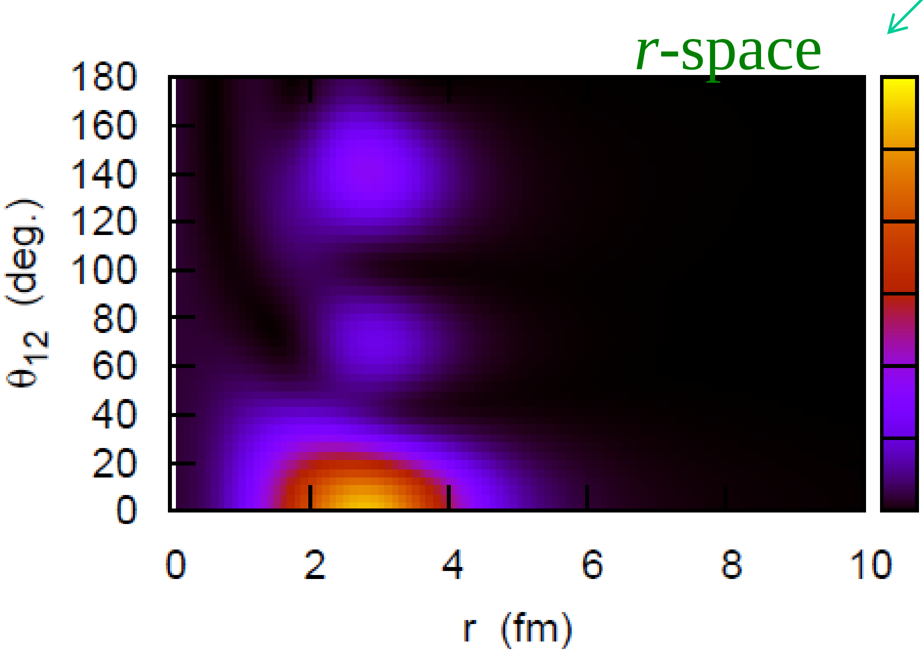
ii) distribution of opening angle for two-emitted neutrons

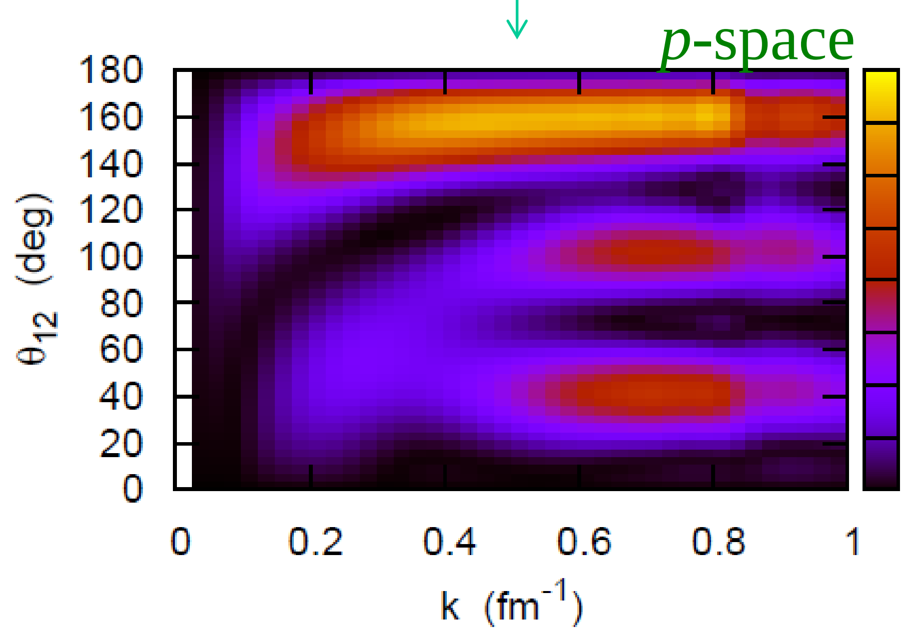


density of the resonance state (with the box b.c.)

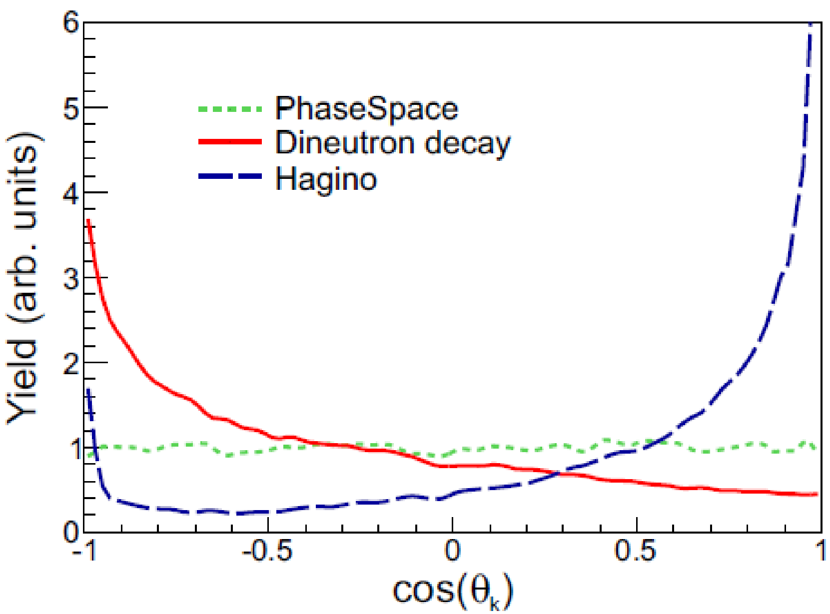
$\rho(r, r, \theta)$

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

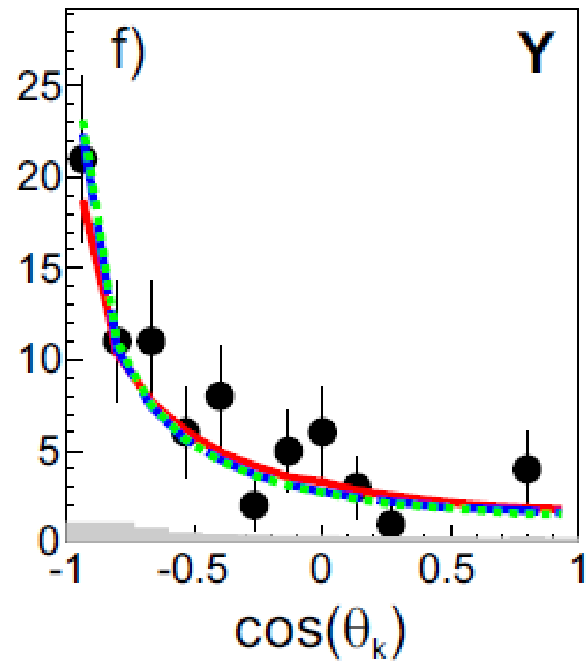


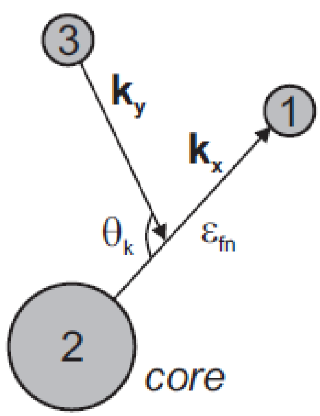


Recent measurements and simulations at MONA



simulation





Y system

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

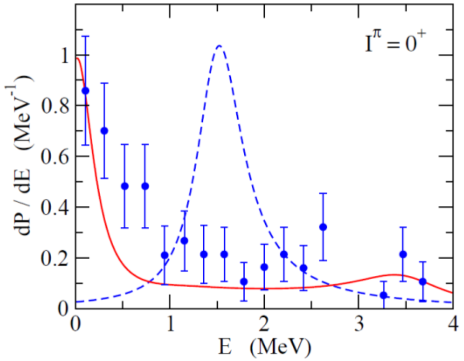
Z. Kohley et al., PRC91 ('15) 034323

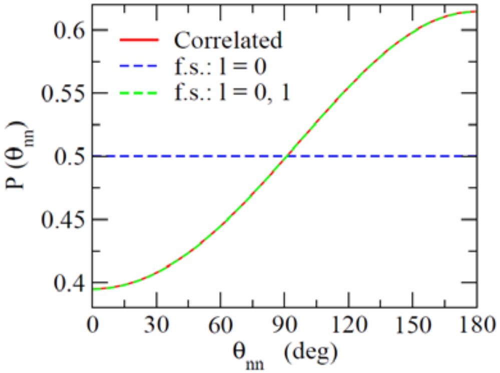
Summary

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