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

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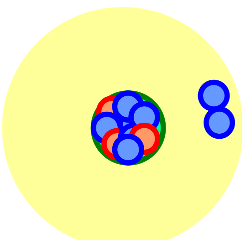
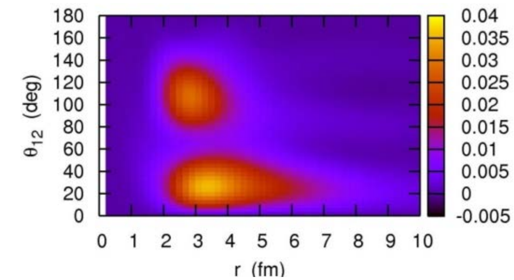
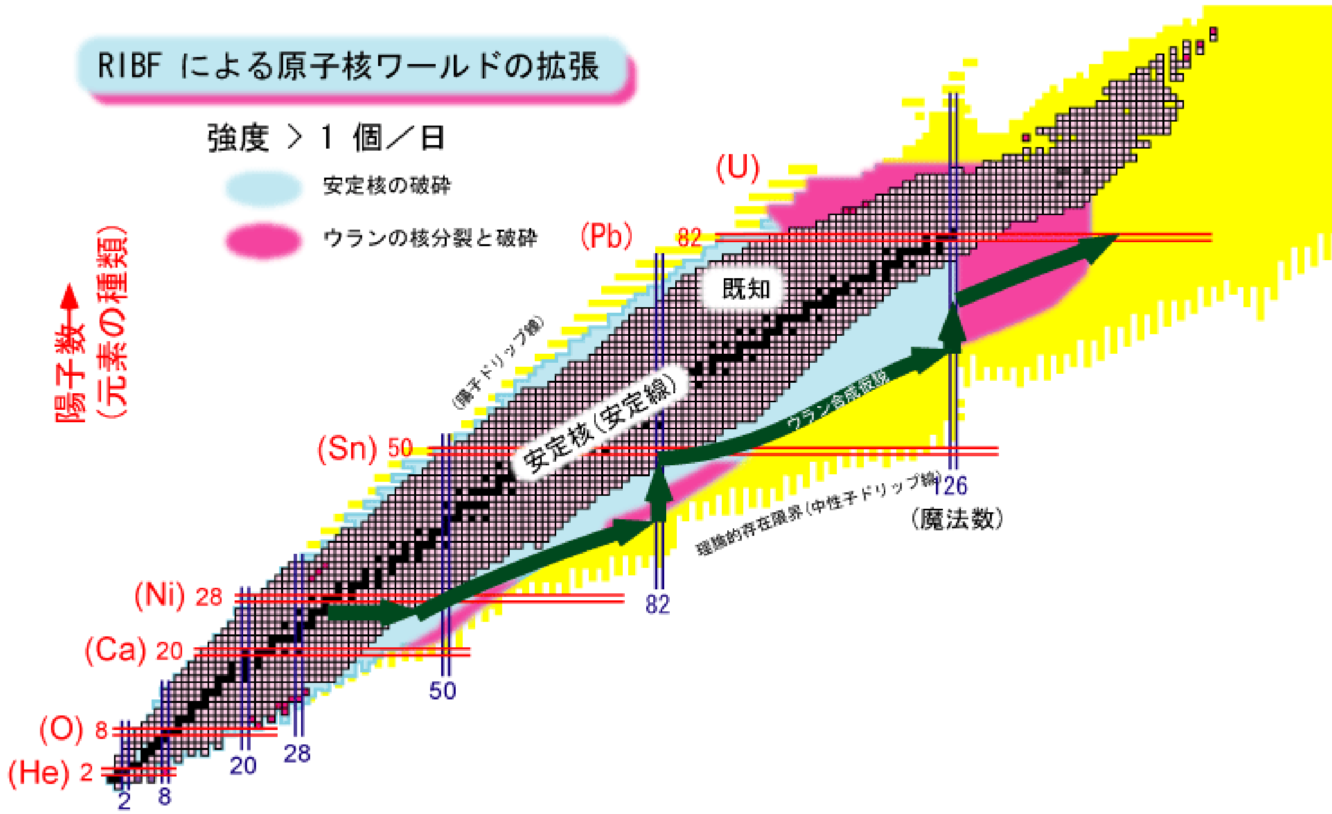


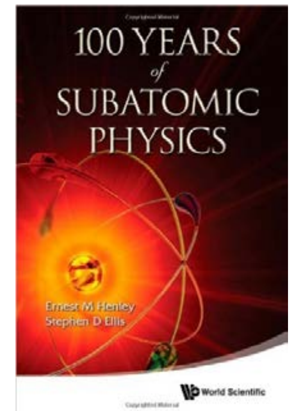


1. *Di-neutron correlation: what is it?*
2. *Coulomb breakup*
3. *Two-neutron decay of unbound nucleus ^{26}O*
4. *Summary*

Introduction: neutron-rich nuclei

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





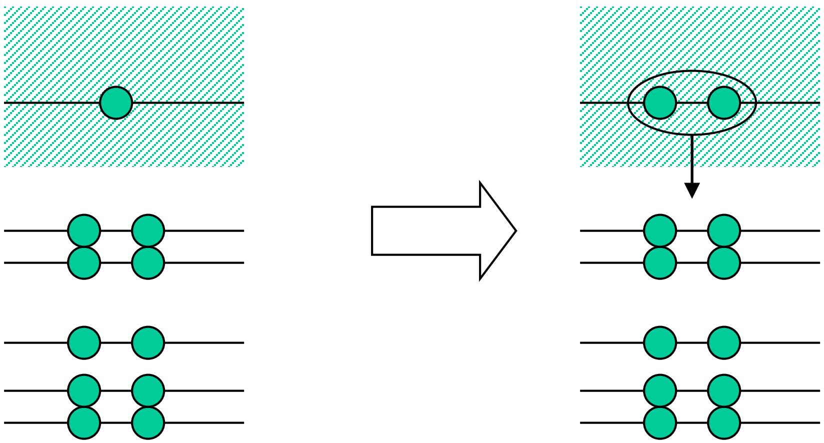
ed. by E.M. Henley and S.D. Ellis

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

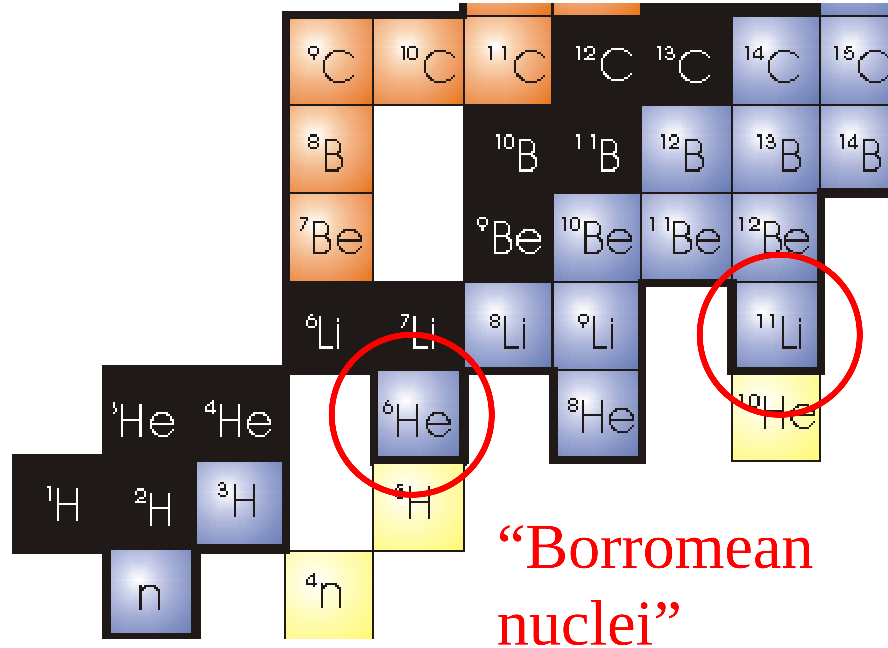
- halo/skin structure
- Borromean nuclei
- large E1 strength
- shell evolution
- ....

Borromean nuclei

residual interaction → attractive



particle unstable particle stable



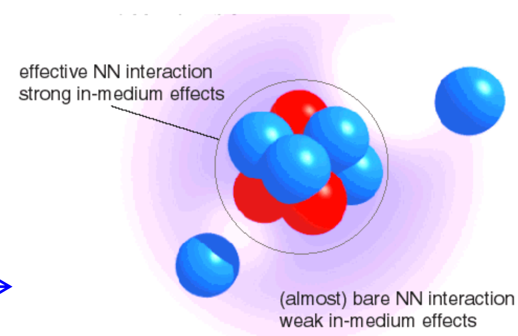
“Borromean nuclei”

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

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

Structure of Borromean nuclei

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



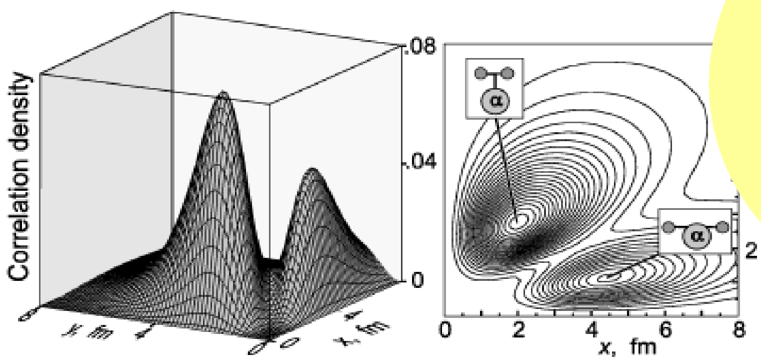
Borromean nuclei and Di-neutron correlation

Borromean nuclei: unique three-body systems

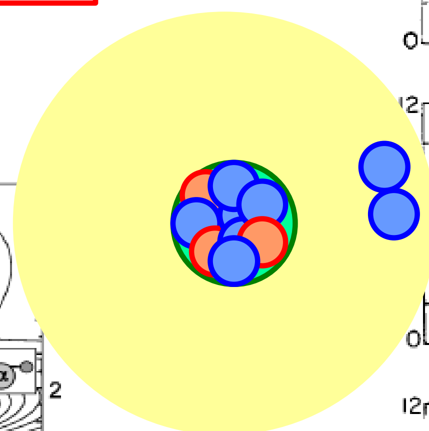
Three-body model calculations:

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

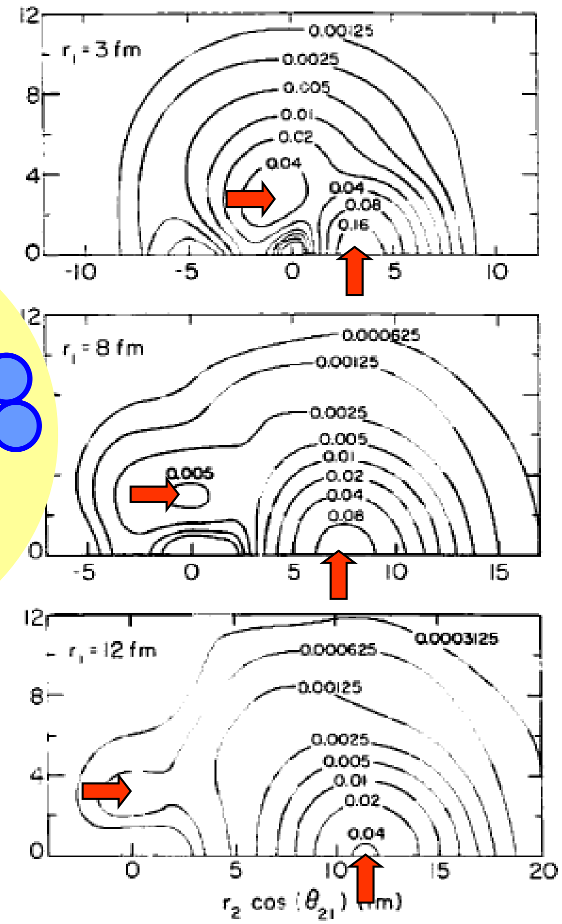
$x^2y^2\rho_2(x,y)$ for ^{6}He



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

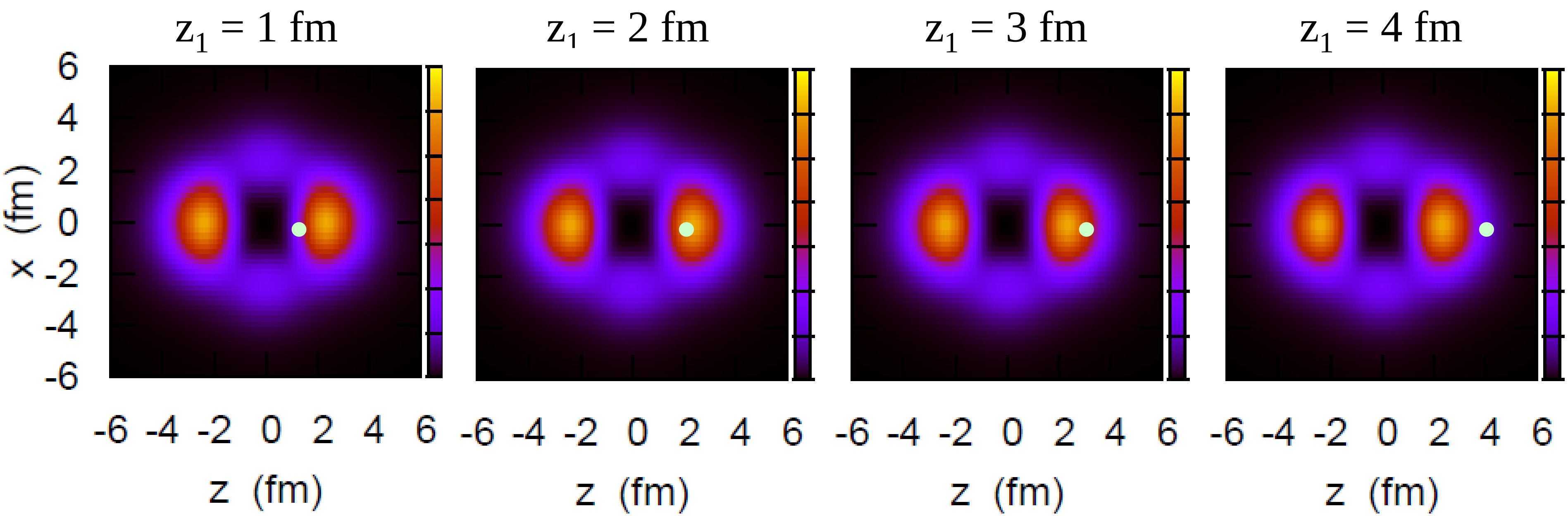
- ✓ A.B. Migdal ('73)
- ✓ P.G. Hansen and B. Jonson ('87)

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 2^{nd} neutron when the 1^{st} neutron is at z_1 :



✓Two neutrons move independently

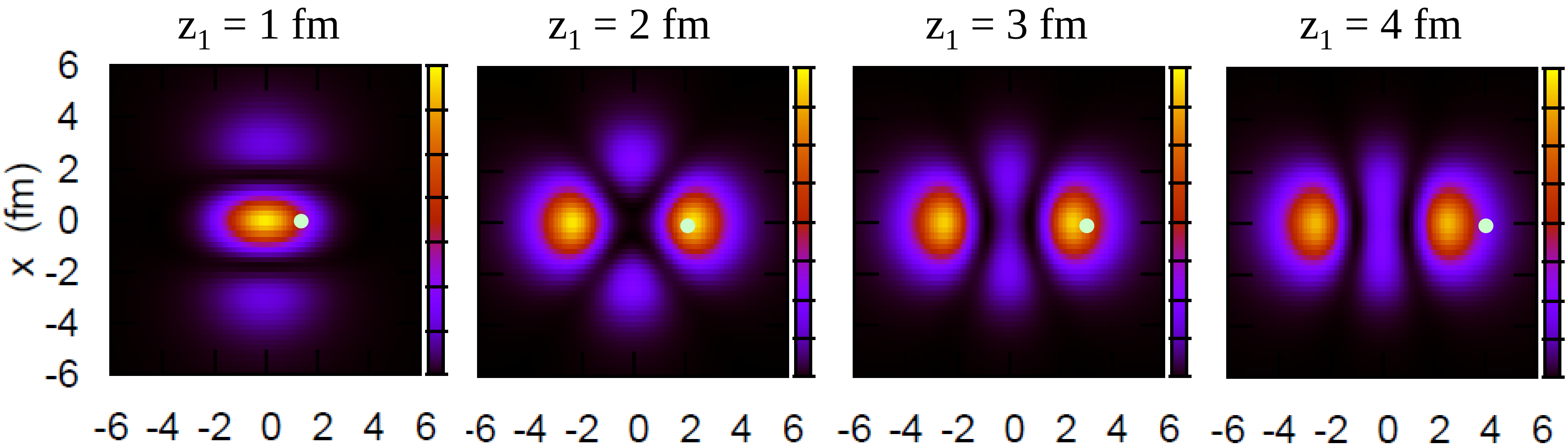
✓No influence of the 2^{nd} neutron from the 1^{st} neutron

⟶ need correlations to form a “pair”

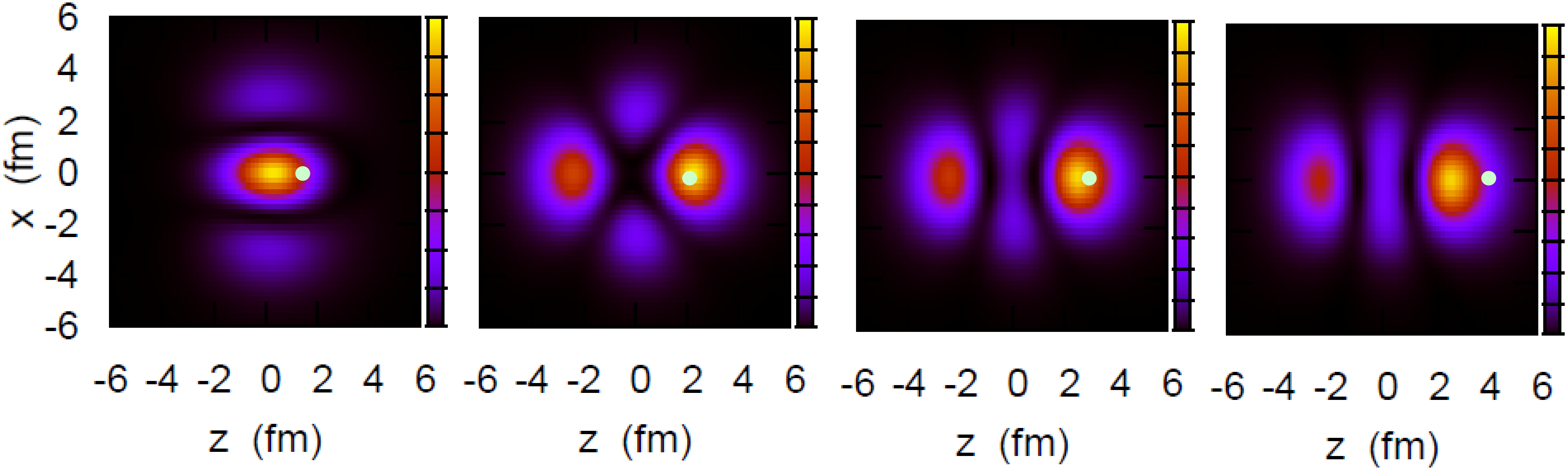
Example: $^{18}O = {}^{16}O + n + n$

cf. ^{17}O : 3 bound states ($1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$)

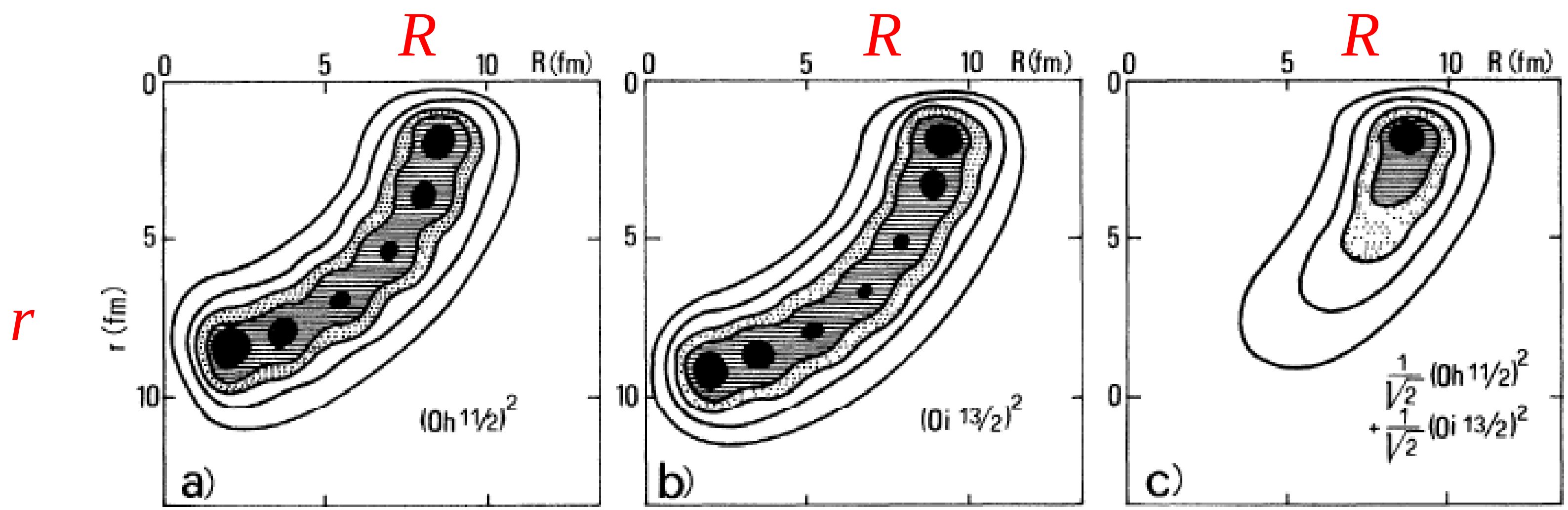
i) even parity only $\longrightarrow$ insufficient



ii) both even and odd parities

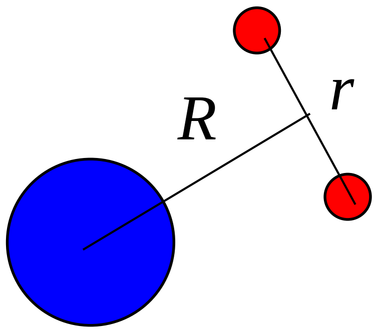


dineutron correlation: caused by the admixture of different parity states



$(0h_{11/2})^2$ $(0i_{13/2})^2$ $(0h_{11/2})^2 + (0i_{13/2})^2$

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

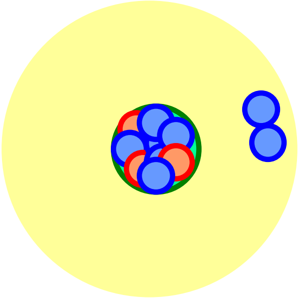


interference of even and odd partial waves

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

Dineutron correlation in the momentum space

$$\boxed{\Psi(\boldsymbol{r},\boldsymbol{r}') = \alpha\,\Psi_{s^2}(\boldsymbol{r},\boldsymbol{r}') + \beta\,\Psi_{p^2}(\boldsymbol{r},\boldsymbol{r}')} \longrightarrow \theta_r = 0\text{: enhanced}$$

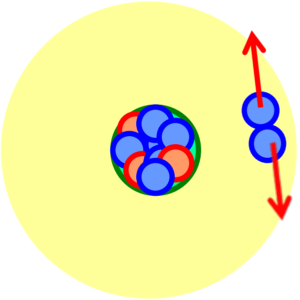


$\longrightarrow$ Fourier transform

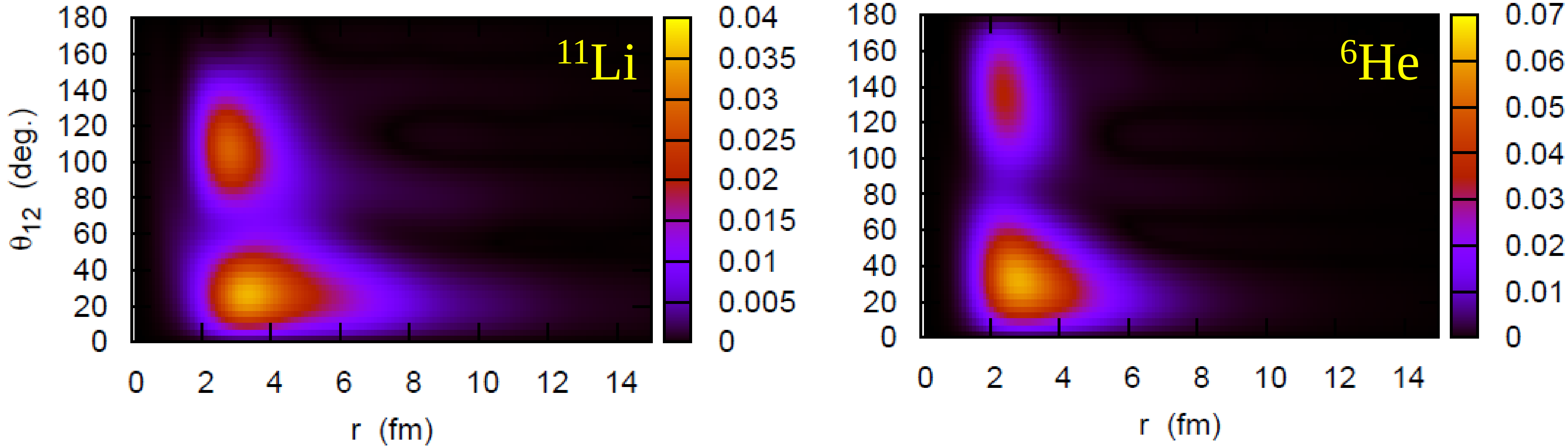
$$\tilde{\Psi}(\boldsymbol{k},\boldsymbol{k}') = \int e^{i\boldsymbol{k}\cdot\boldsymbol{r}} e^{i\boldsymbol{k}'\cdot\boldsymbol{r}'} \Psi(\boldsymbol{r},\boldsymbol{r}') d\boldsymbol{r} d\boldsymbol{r}'$$

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

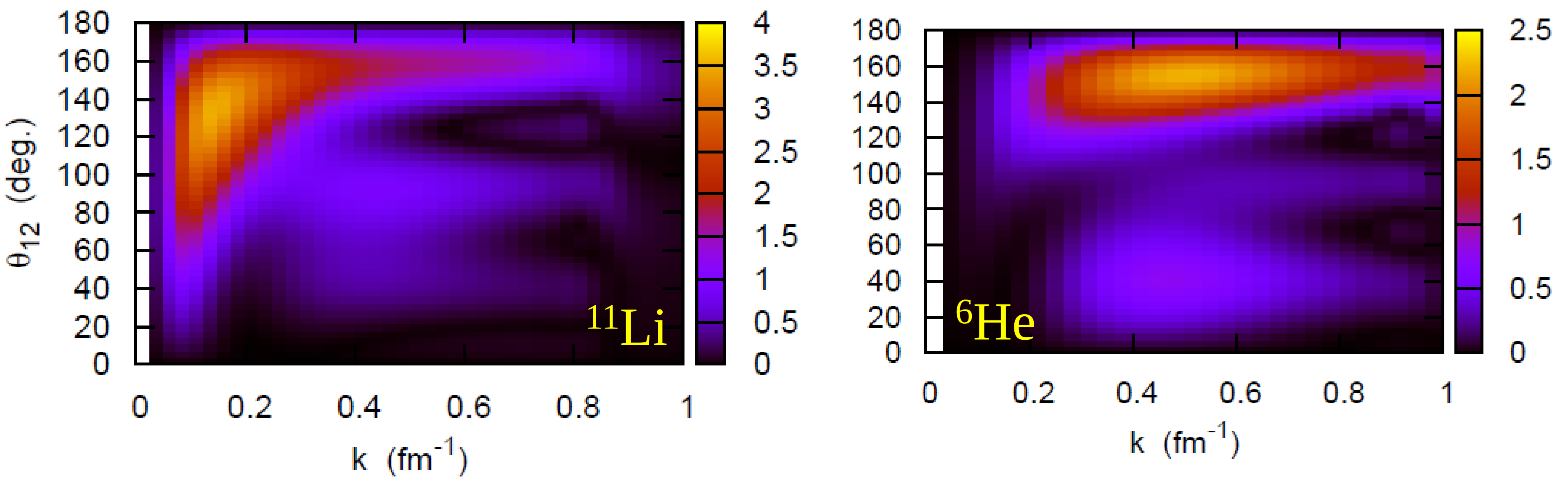
$$\boxed{\tilde{\Psi}(\boldsymbol{k},\boldsymbol{k}') = \alpha\,\tilde{\Psi}_{s^2}(\boldsymbol{k},\boldsymbol{k}') - \beta\,\tilde{\Psi}_{p^2}(\boldsymbol{k},\boldsymbol{k}')} \longrightarrow \theta_k = \pi\text{: enhanced}$$



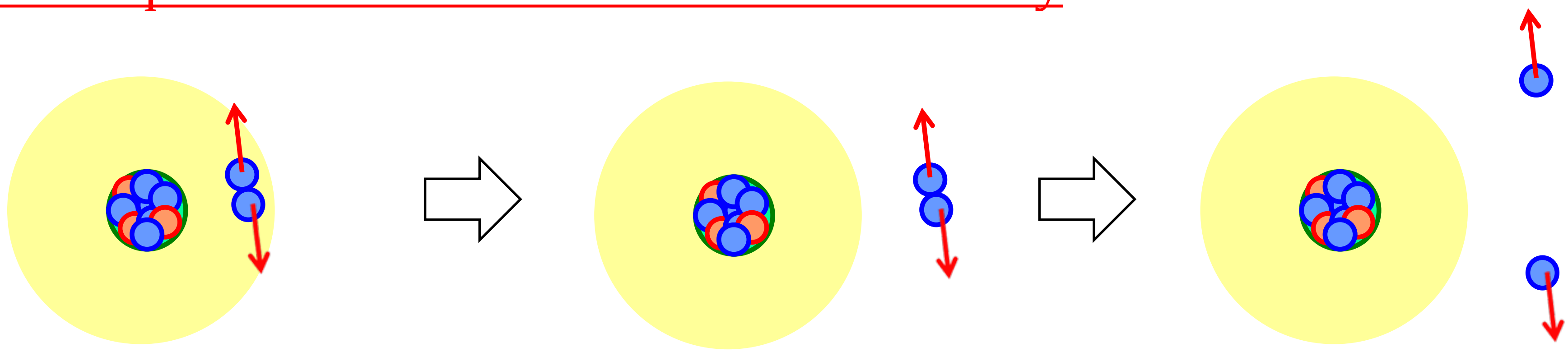
Two-particle density in the *r* space: $8\pi^2 r^4 \sin\theta \cdot \rho(r,r,\theta)$



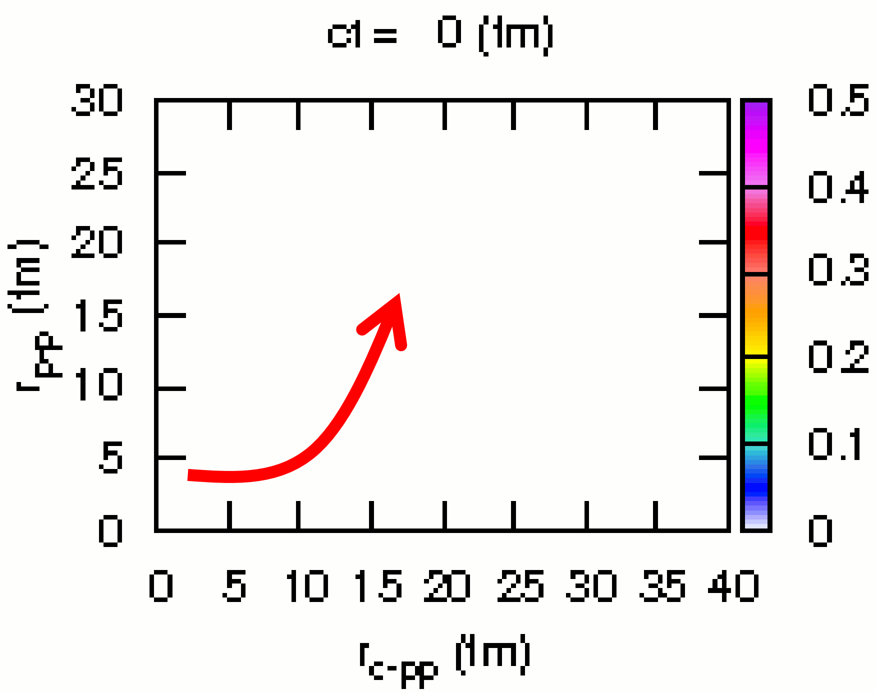
Two-particle density in the *p* space: $8\pi^2 k^4 \sin\theta \cdot \rho(k,k,\theta)$



Consequence to a two-nucleon emission decay

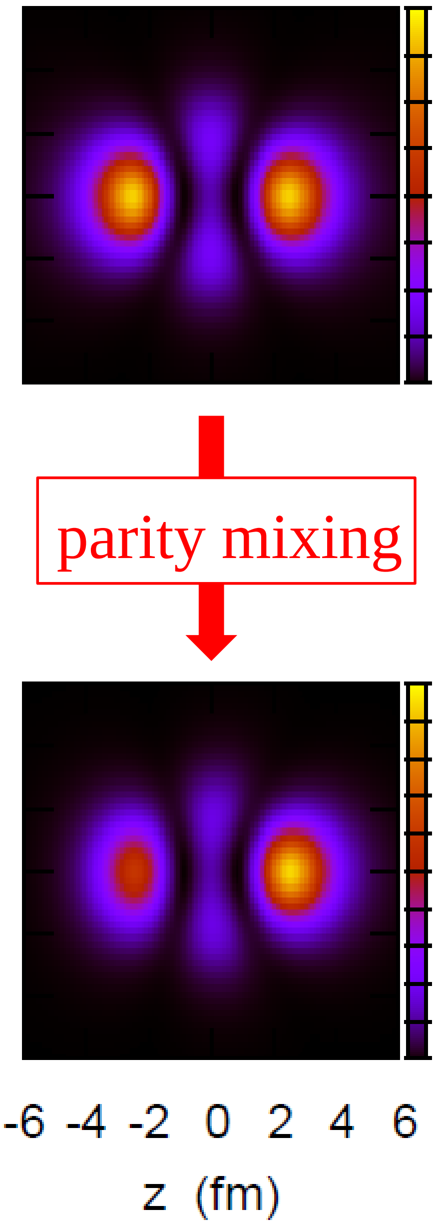


2p decay of ^{6}Be
: time-dependent calculations



T. Oishi (Tohoku → Jyvaskyla),
K.H., H. Sagawa,
PRC90 ('14) 034303

Di-neutron correlation in weakly-bound exotic nuclei



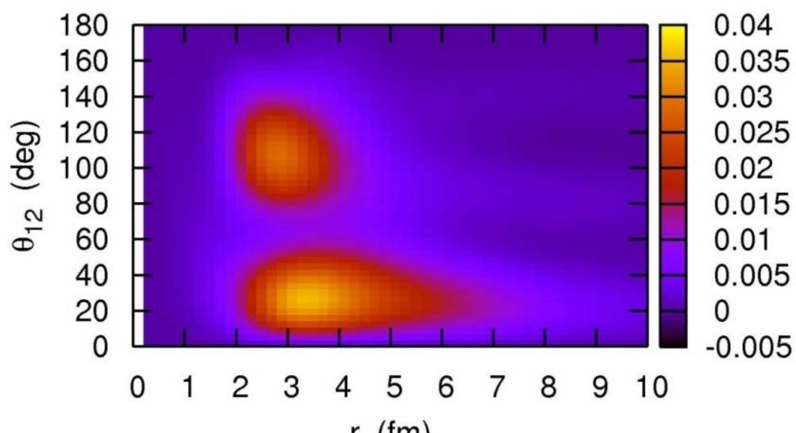
spatial localization of two neutrons
(dineutron correlation)

weakly bound systems

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

⟶ dineutron correlation: enhanced

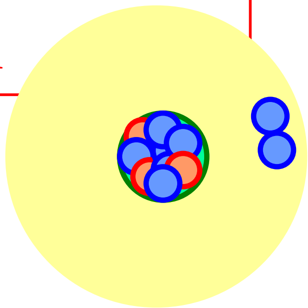
cf. - Bertsch, Esbensen, Ann. of Phys. 209('91)327
- M. Matsuo, K. Mizuyama, Y. Serizawa, PRC71('05)064326



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)

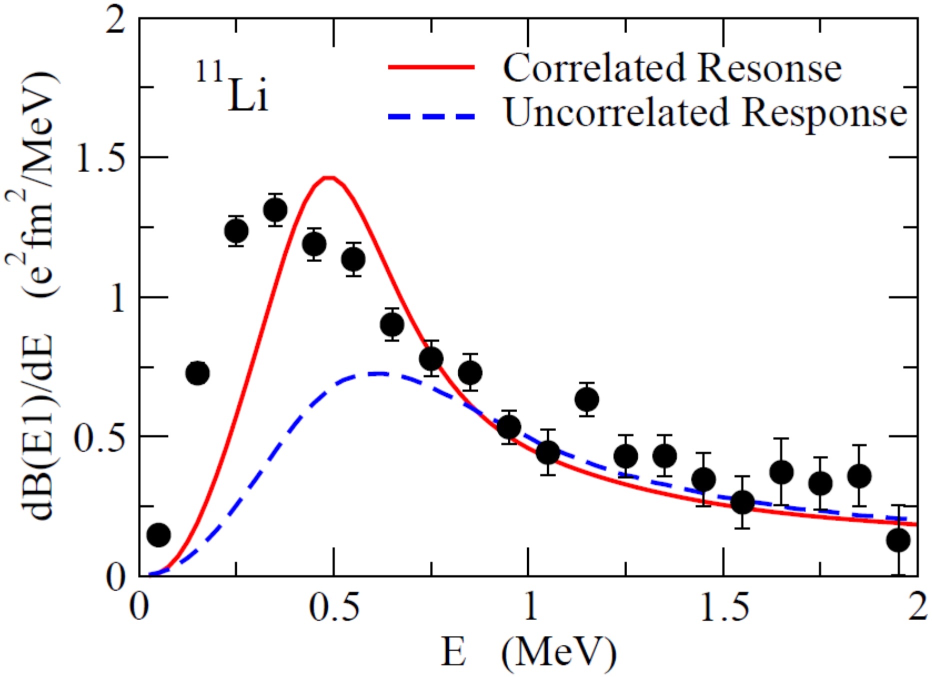
How to probe it?

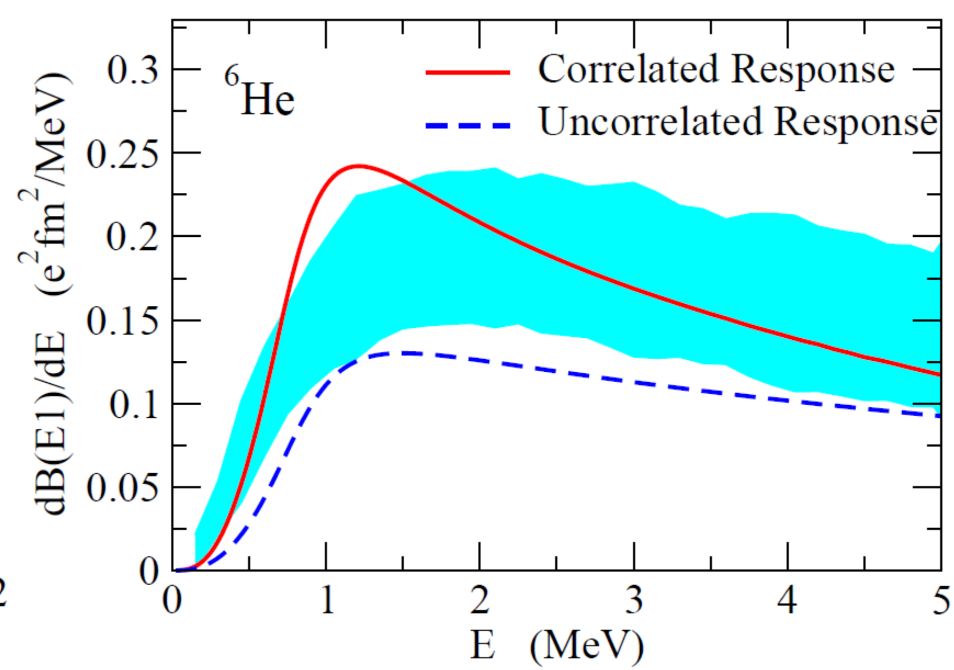
- Coulomb breakup
  T. Nakamura et al.
  cluster sum rule
  (mean value of θ_{nn})
- pair transfer reactions
- two-proton decays
  Coulomb 3-body problem

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

Coulomb breakup of 2-neutron halo nuclei

How to probe the dineutron correlation? $\longrightarrow$ Coulomb breakup





Experiments:

T. Nakamura et al., PRL96('06)252502

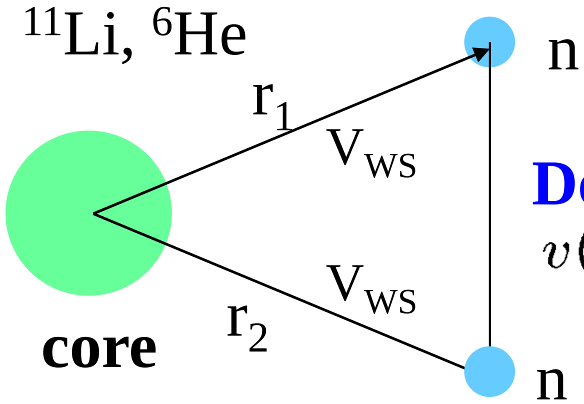
T. Aumann et al., PRC59('99)1252

3-body model calculations:

K.H., H. Sagawa, T. Nakamura, S. Shimoura, PRC80('09)031301(R)

cf. Y. Kikuchi et al., PRC87('13)034606 $\longleftarrow$ structure of the core nucleus (^{9}Li)

3-body model calculation for Borromean nuclei



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

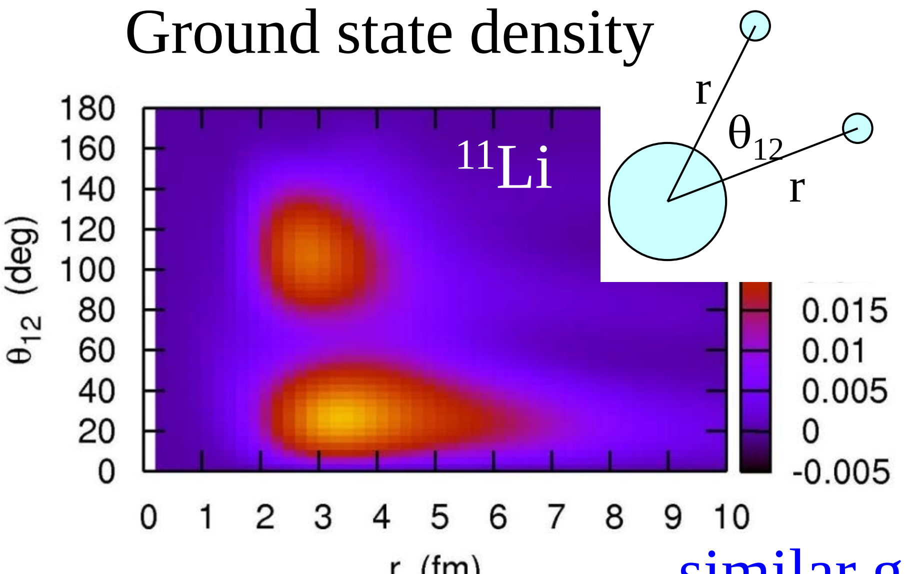
Density-dependent delta-force

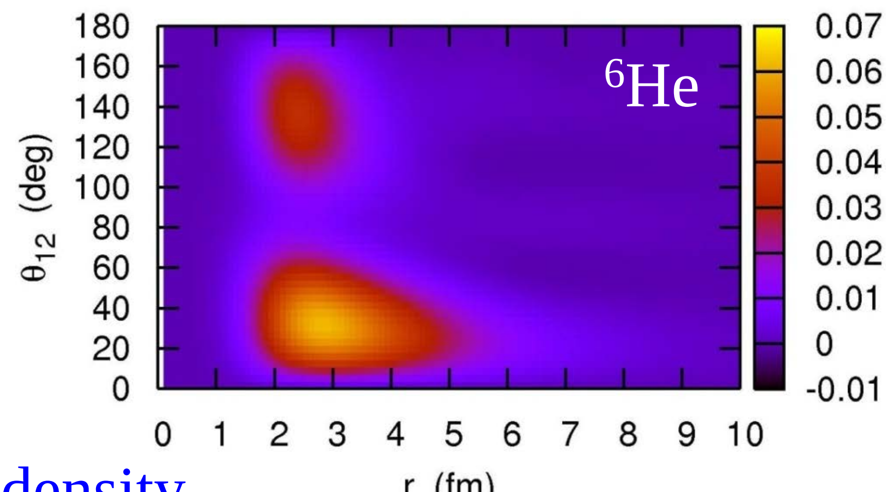
$$v(\boldsymbol{r}_1, \boldsymbol{r}_2) = v_0(1 + \alpha\rho(r)) \times \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)$$

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

Ground state density

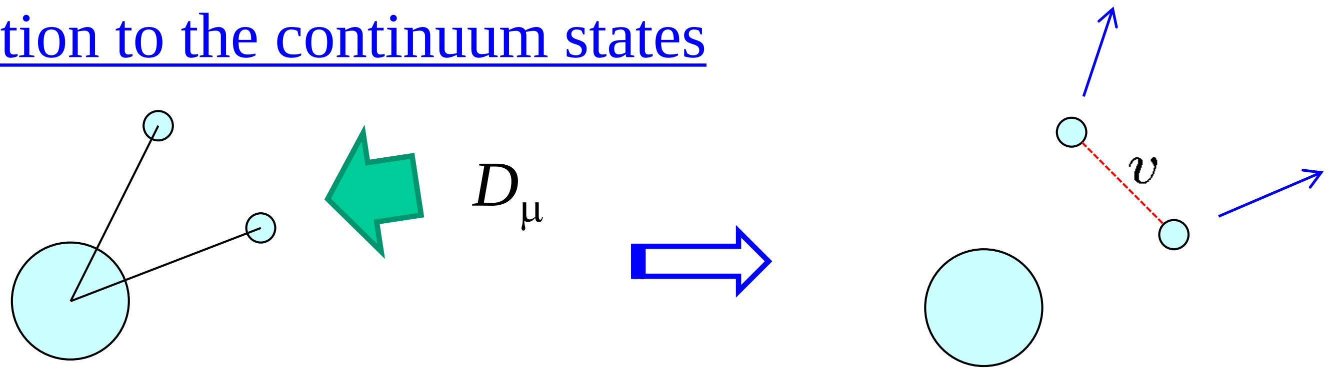
K.H. and H. Sagawa, PRC72('05)044321





similar g.s. density

E1 excitation to the continuum states



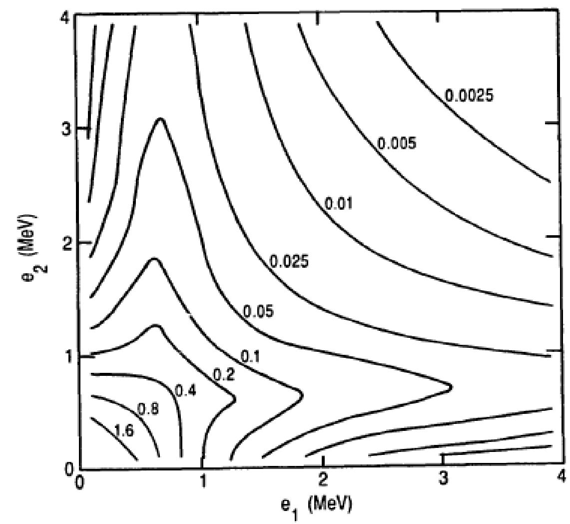
$$
\begin{aligned}
M(E1) &= \langle (j_1 j_2)^1_\mu | (1 - vG_0 + vG_0 vG_0 - \cdots) D_\mu | \Psi_{gs} \rangle \\
&= \langle (j_1 j_2)^1_\mu | \underbrace{(1 + vG_0)^{-1}}_{\text{FSI}} D_\mu | \Psi_{gs} \rangle
\end{aligned}
$$

dipole operator

unperturbed continuum wf

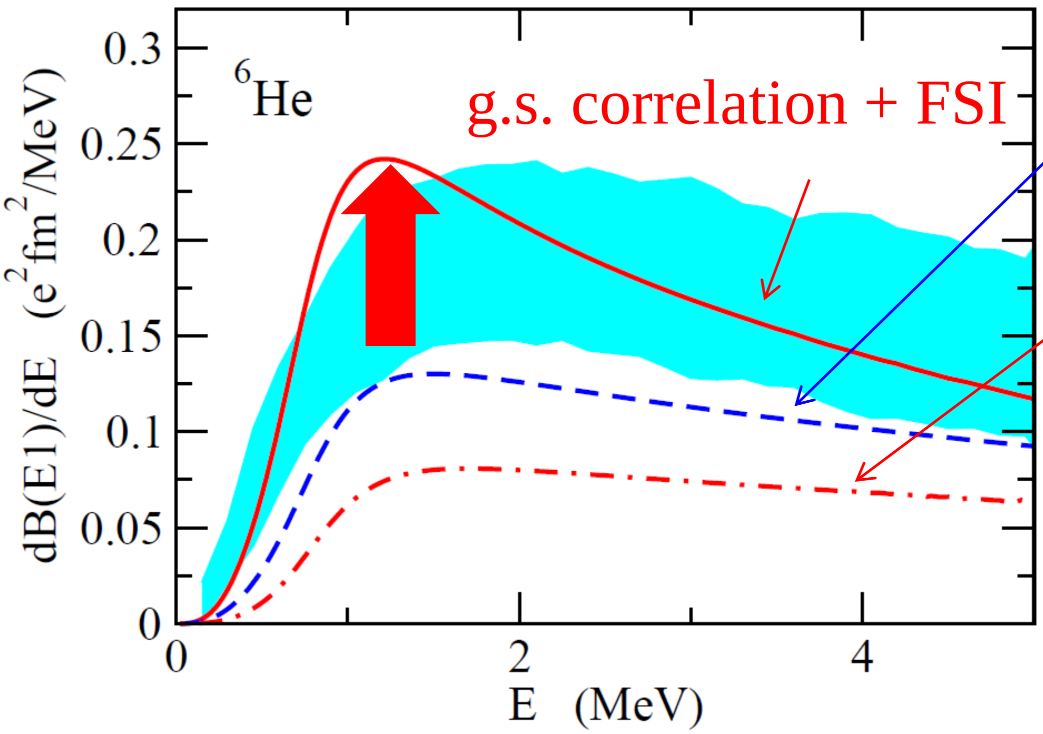
$$
G_0(E) = \sum_{\mu, f.st.} \frac{\left| (j_1 j_2)^1_\mu \right\rangle \left\langle (j_1 j_2)^1_\mu \right|}{e_1 + e_2 - E - i\eta}
$$

$$
\boxed{\frac{d^2 B(E1)}{de_1 de_2} = 3 \sum_{l_1 j_2 l_2 j_2} |M(E1)|^2 \frac{dk_1}{de_1} \frac{dk_2}{de_2}}
$$



H. Esbensen and G.F. Bertsch, NPA542('92)310 g.s. correlation? or correlation in excited states?

$^{6}He(0^{+}) \rightarrow {}^{6}He(1^{-}) \rightarrow \alpha + n + n$



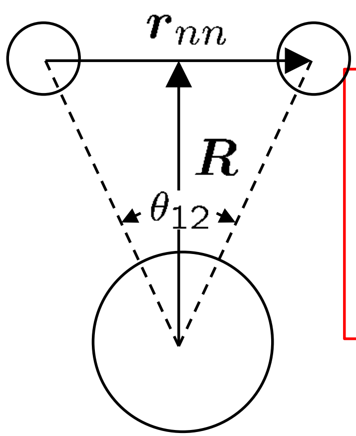
g.s. correlation only
(no nn interaction in
the final state)

g.s. : odd-l only
(no dineutron correlation)
+FSI

K.H., H. Sagawa, T. Nakamura,
S. Shimoura,
PRC80('09)031301(R)

✓Both FSI and dineutron correlations: important role in E1 strength

Geometry of Borromean nuclei

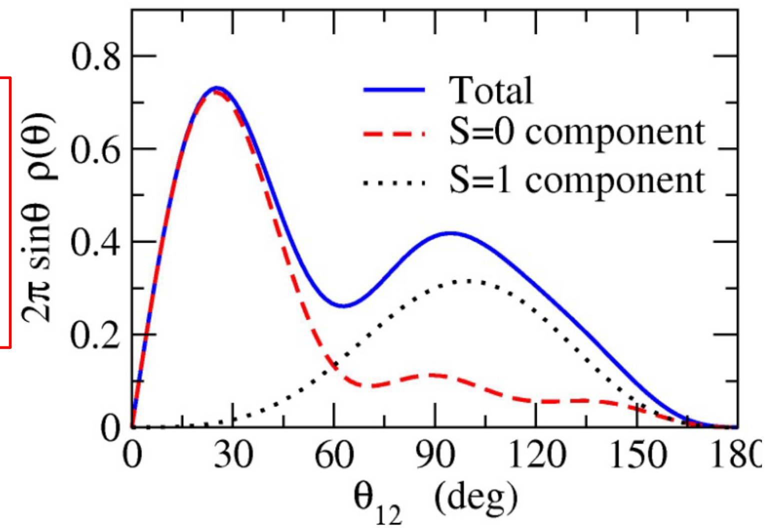


Cluster sum rule

$$B_{\rm tot}(E1) = \sum_f |\langle \Psi_f | \hat{T}_{\rm E1} | \Psi_0 \rangle|^2 \sim \frac{3}{\pi}\left(\frac{Z_c e}{A_c + 2}\right)^2 \langle R^2 \rangle$$

reflects the g.s. correlation

3-body model calculations



$$\langle \theta_{12} \rangle = 65.29 \quad \text{deg.}$$

“experimental data” for opening angle

$\sqrt{\langle R^2 \rangle} \longleftarrow B_{\rm tot}(E1)$

$\sqrt{\langle r_{\rm nn}^2 \rangle} \longleftarrow$ matter radius or HBT

$$\begin{aligned} \langle \theta_{12} \rangle &= 65.2 \pm 12.2 \ \ (^{11}\text{Li}) \\ &= 74.5 \pm 12.1 \ \ (^{6}\text{He}) \end{aligned}$$

K.H. and H. Sagawa,PRC76(’07)047302

$\langle \theta_{12} \rangle$: significantly smaller than 90 deg.

↓

suggests dineutron corr.

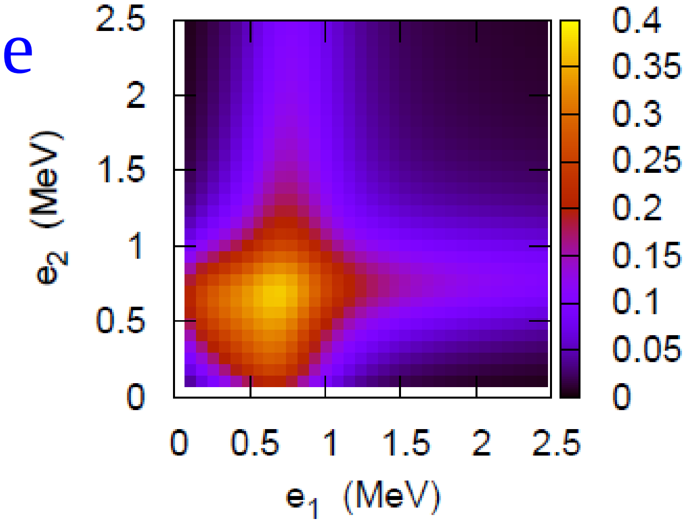
(but, an average of small and large angles)

cf. T. Nakamura et al., PRL96(’06)252502

C.A. Bertulani and M.S. Hussein, PRC76(’07)051602

Energy distribution of emitted neutrons

^{6}He

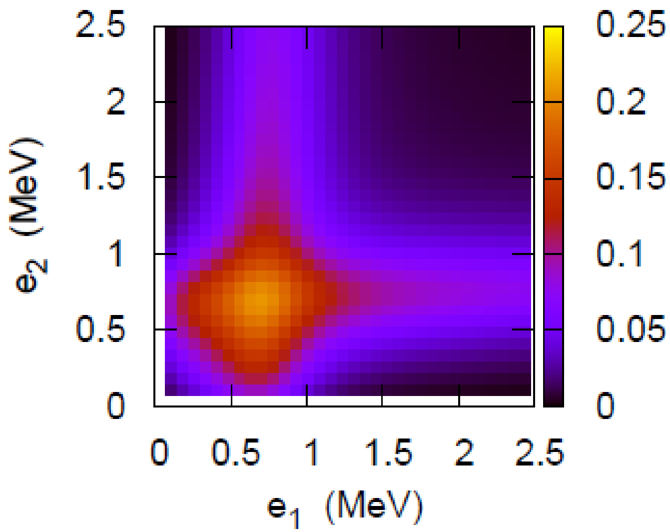


✓shape of distribution: insensitive to the nn-interaction (except for the absolute value)

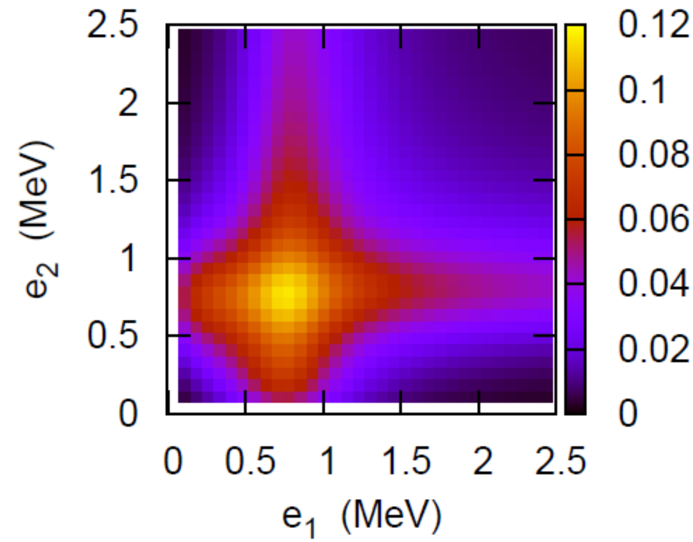
✓strong sensitivity to V_{nC}

✓similar situation in between ^{11}Li and ^{6}He

$$v_{nn} = 0$$

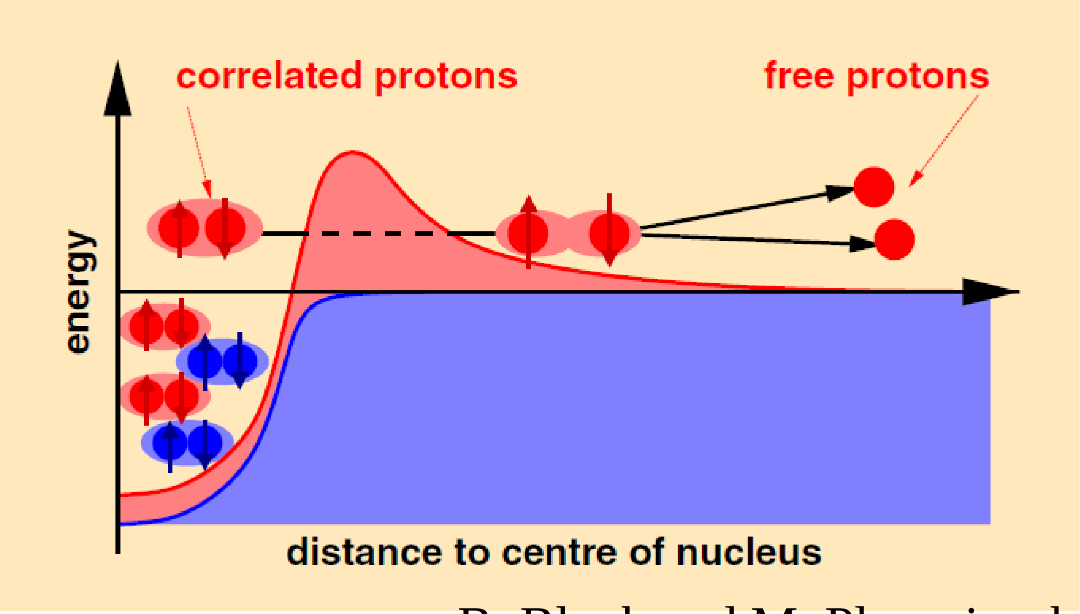


no di-neutron corr. in the g.s. (odd-*l* only)



K.H., H. Sagawa, T. Nakamura, S. Shimoura, PRC80(‘09)031301(R)

2-proton radio activity



B. Blank and M. Ploszajczak, Rep. Prog. Phys. 71(‘08)046301

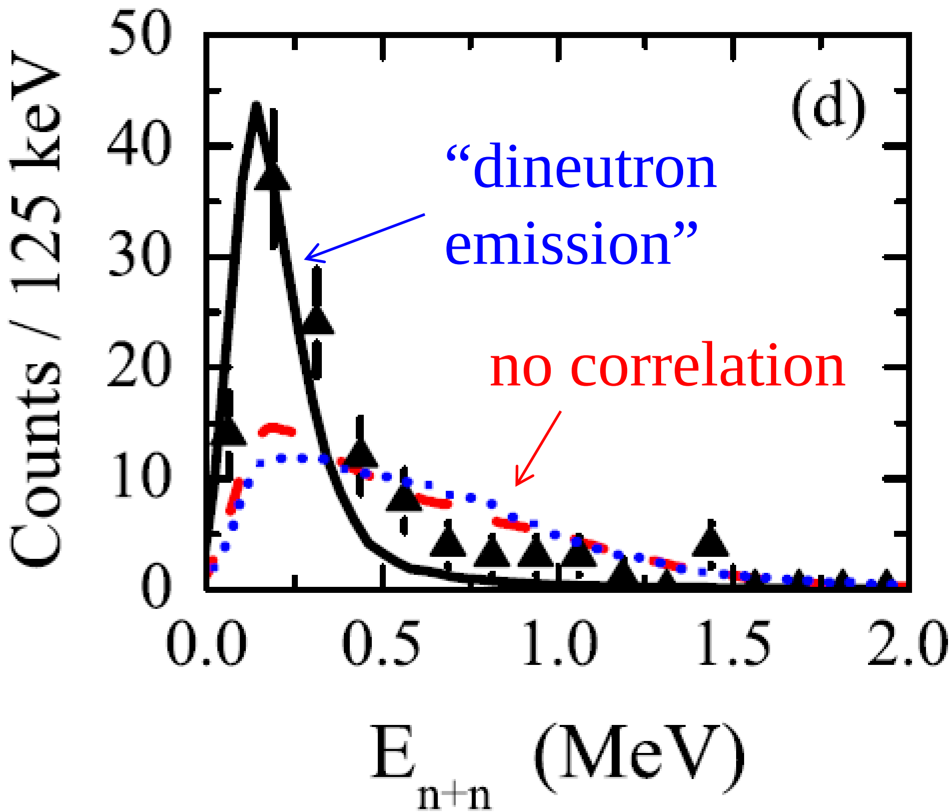
- ✓ probing correlations from energy and angle distributions of two emitted protons?
- ✓ Coulomb 3-body system
  - Theoretical treatment: difficult
  - how does FSI disturb the g.s. correlation?

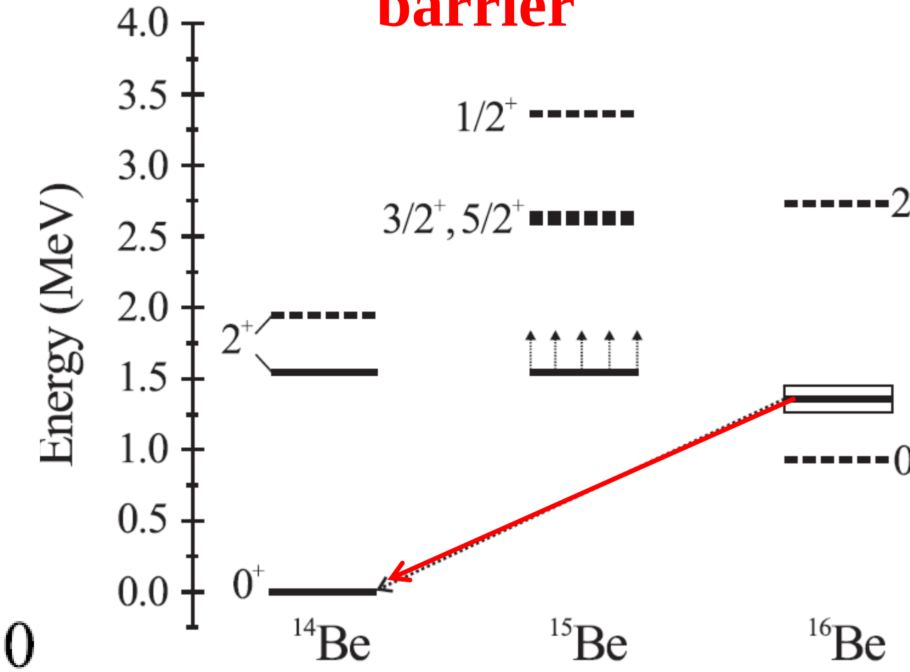
$\longrightarrow$ diproton correlation: unclear in many systems (theoretical calculations: not many)

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

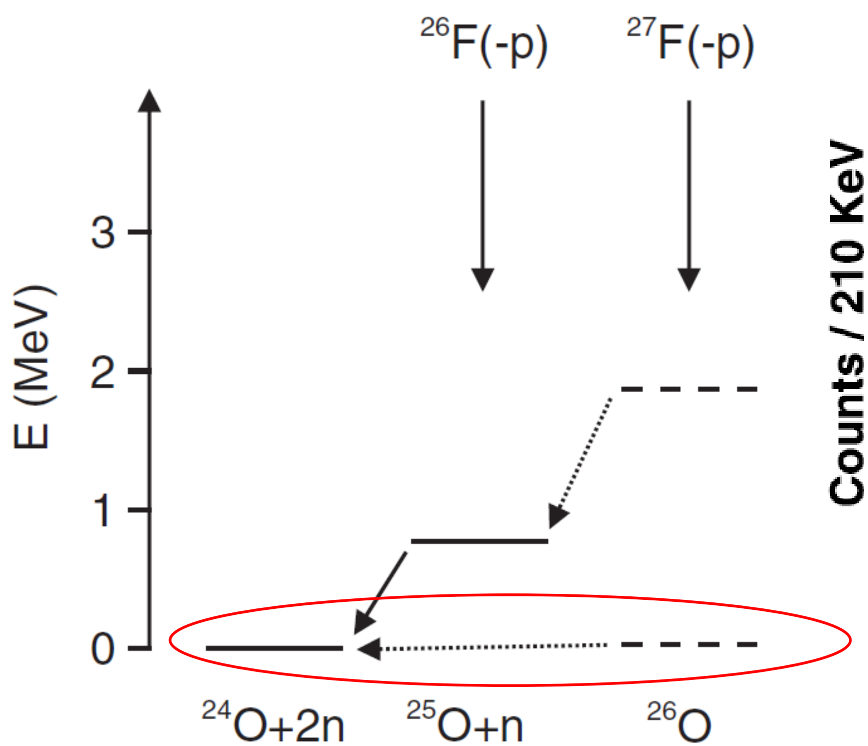
Two-neutron decay of ^{26}O

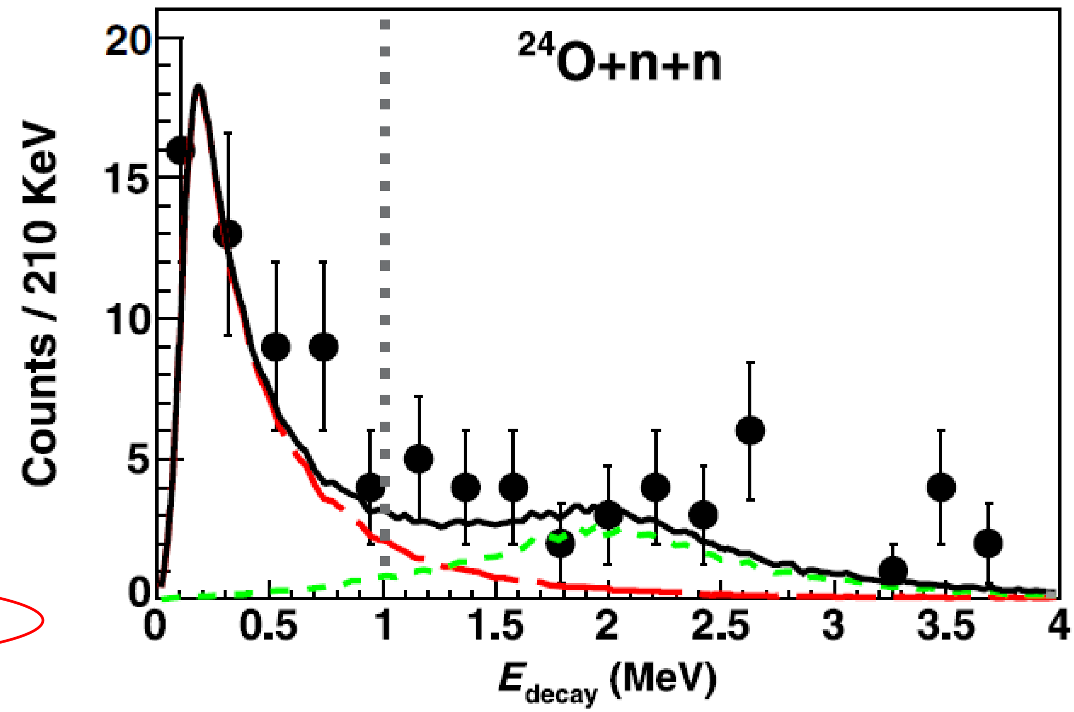
- the simplest among ^{16}Be, ^{13}Li, ^{26}O (MSU)
  ^{16}Be: deformation, ^{13}Li: treatment of ^{11}Li core

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

Experiment:

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





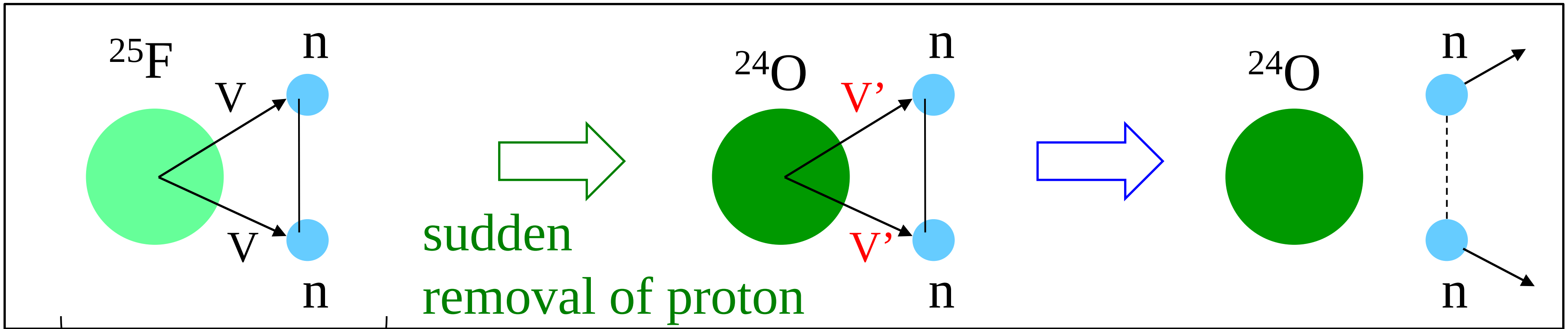
cf. C. Caesar et al., PRC88 ('13) 034313 (GSI exp.)
Y. Kondo et al., (SAMURAI)

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

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

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

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



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

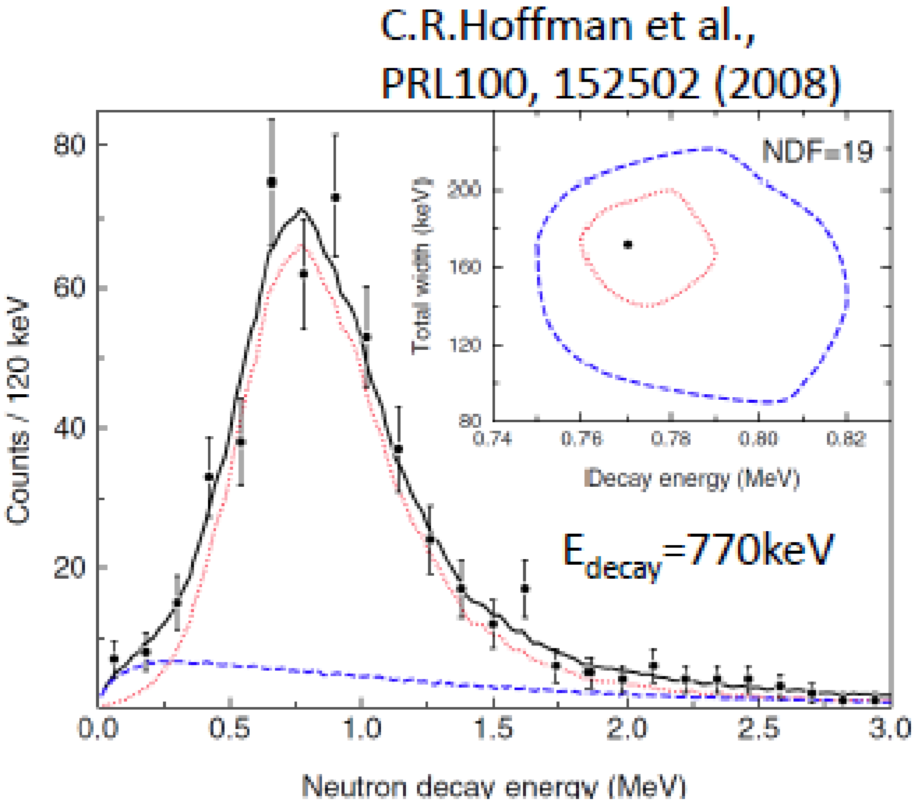
$$\Psi_{nn} \otimes |^{25}\mathrm{F}\rangle \quad \Rightarrow \quad \Psi_{nn} \otimes |^{24}\mathrm{O}\rangle \quad \Rightarrow$$

spontaneous decay

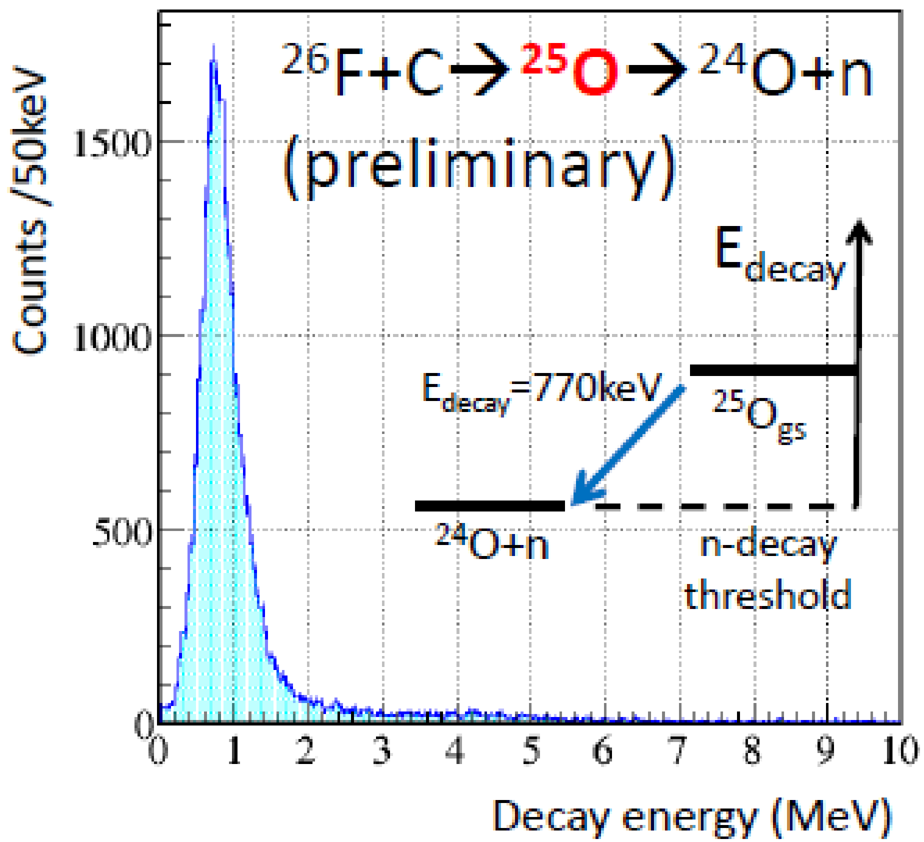
the same config. (non-eigenstate of ^{24}O+n+n)

FSI → Green's function method ⇐ continuum effects

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



Y. Kondo et al. (2015)



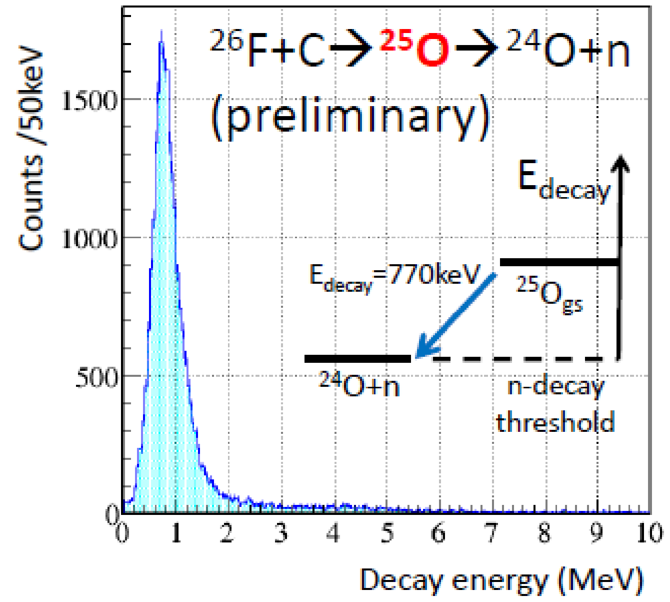
$E = +\,770^{+20}_{-10}$ keV
$\Gamma = 172(30)$ keV

⇨

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

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

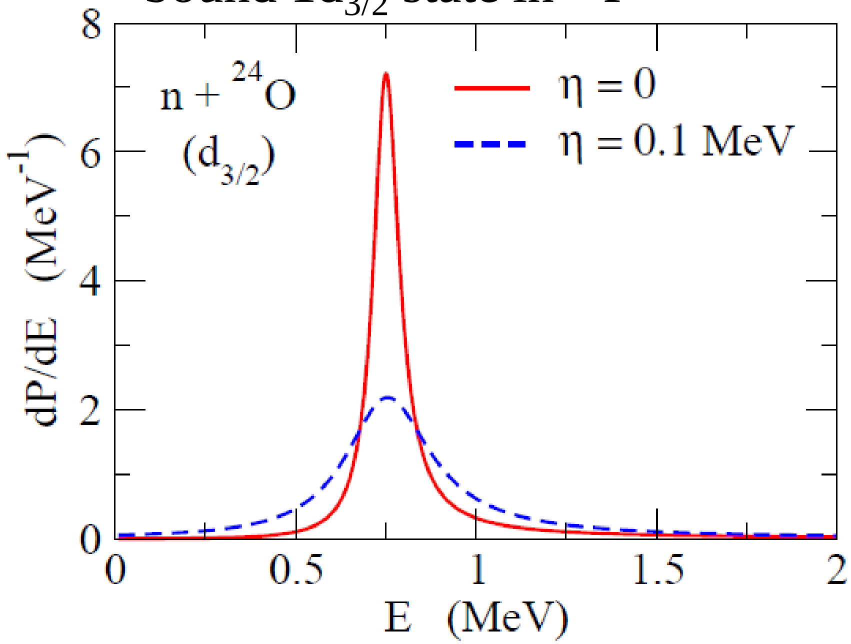
$p_{3/2}$: E = 0.577 MeV, Γ = 1.63 MeV

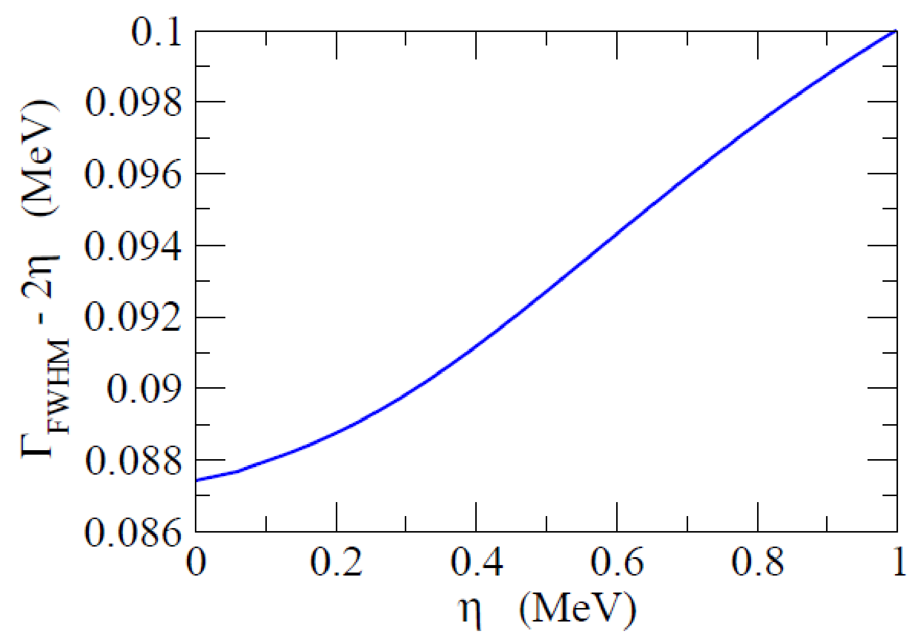
n-^{24}O decay spectrum

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

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

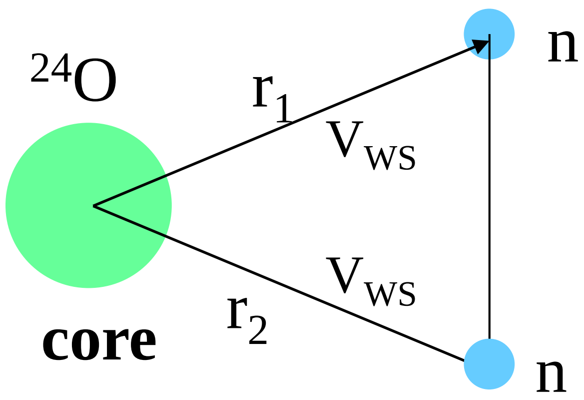
Reference state:
bound $1d_{3/2}$ state in ^{26}F





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

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



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

correlated Green's function:

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

$\longleftarrow$ continuum effects

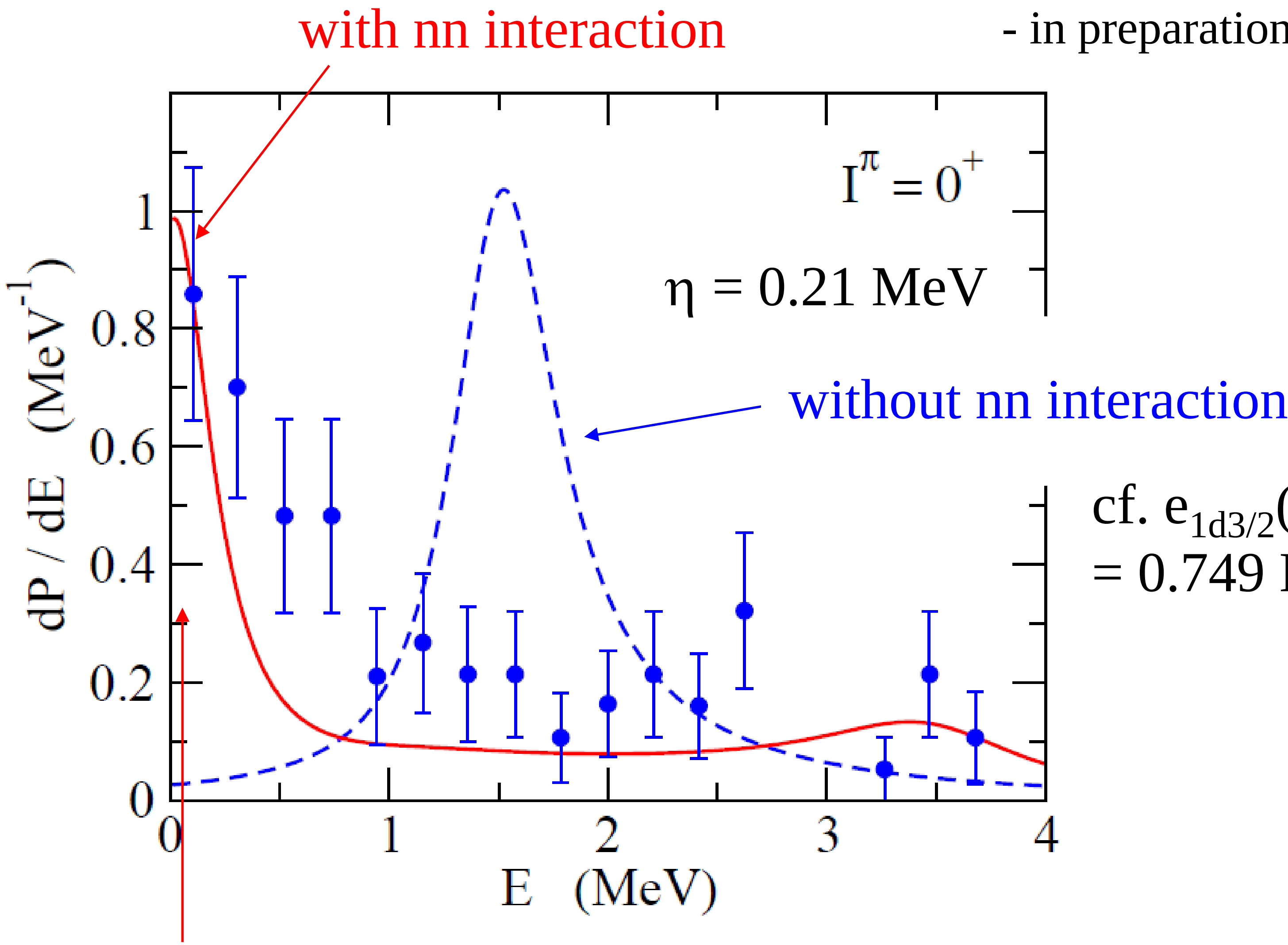
uncorrelated Green's function

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

$\longleftarrow$ small, finite η

i) Decay energy spectrum

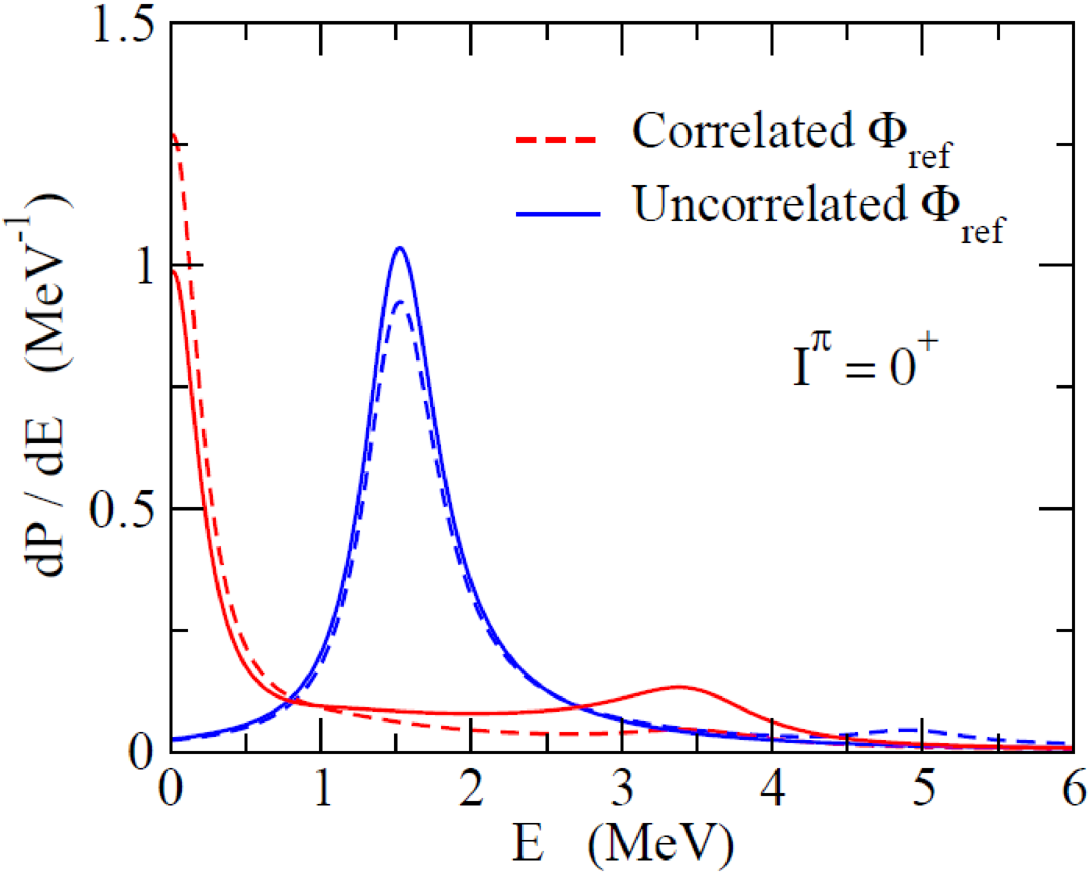
K.H. and H. Sagawa,
- PRC89 ('14) 014331
- in preparation



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

E_{peak} = 18 keV (input)

Sensitivity to the reference state



not sensitive to how ^{26}O is formed

dP/dE: properties of ^{26}O 3-body wf

$$\frac{dP}{dE} = |\langle \Psi_E | \Phi_{\rm ref} \rangle|^2$$

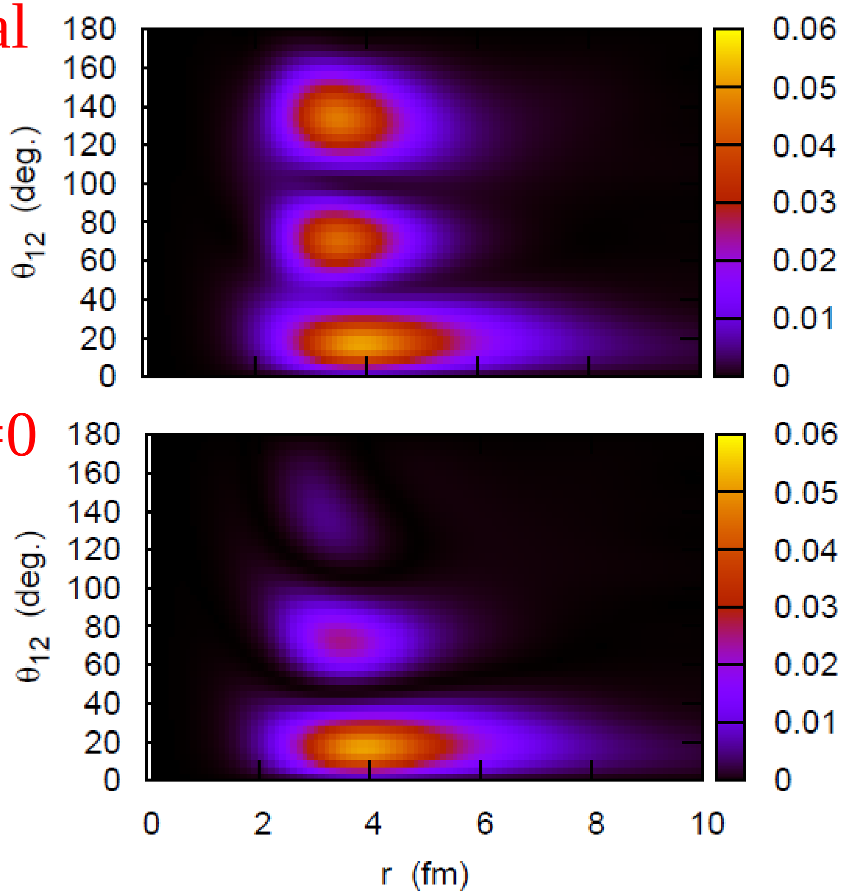
$$= -\frac{1}{\pi}\Im\langle \Phi_{\rm ref} | \underbrace{G_0 - G_0 v (1 + G_0 v)^{-1} G_0}_{\text{FSI in the nuclear reaction terminology}} | \Phi_{\rm ref} \rangle$$

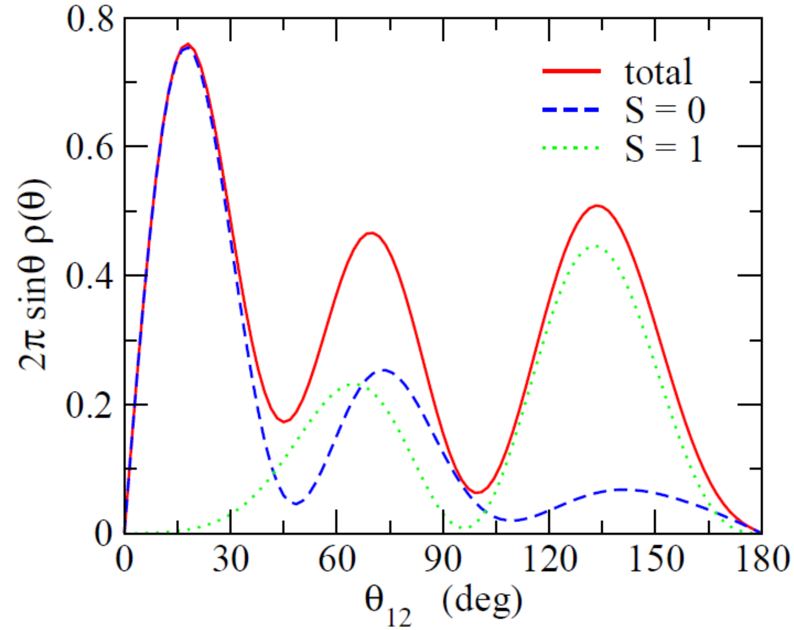
FSI in the nuclear reaction terminology

Two-particle density in the bound state approximation

total

S=0





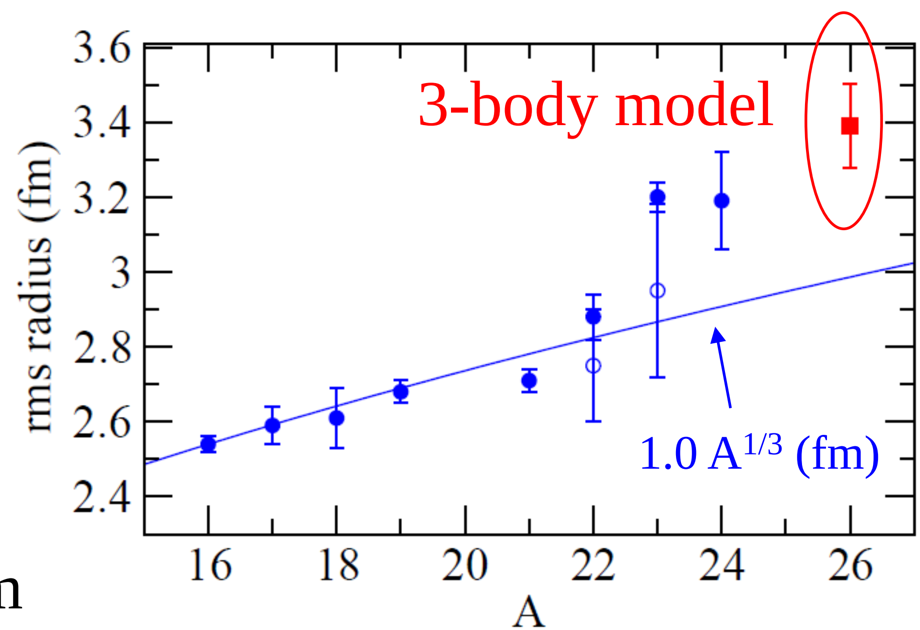
$(d_{3/2})^2$: 66.1%

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

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

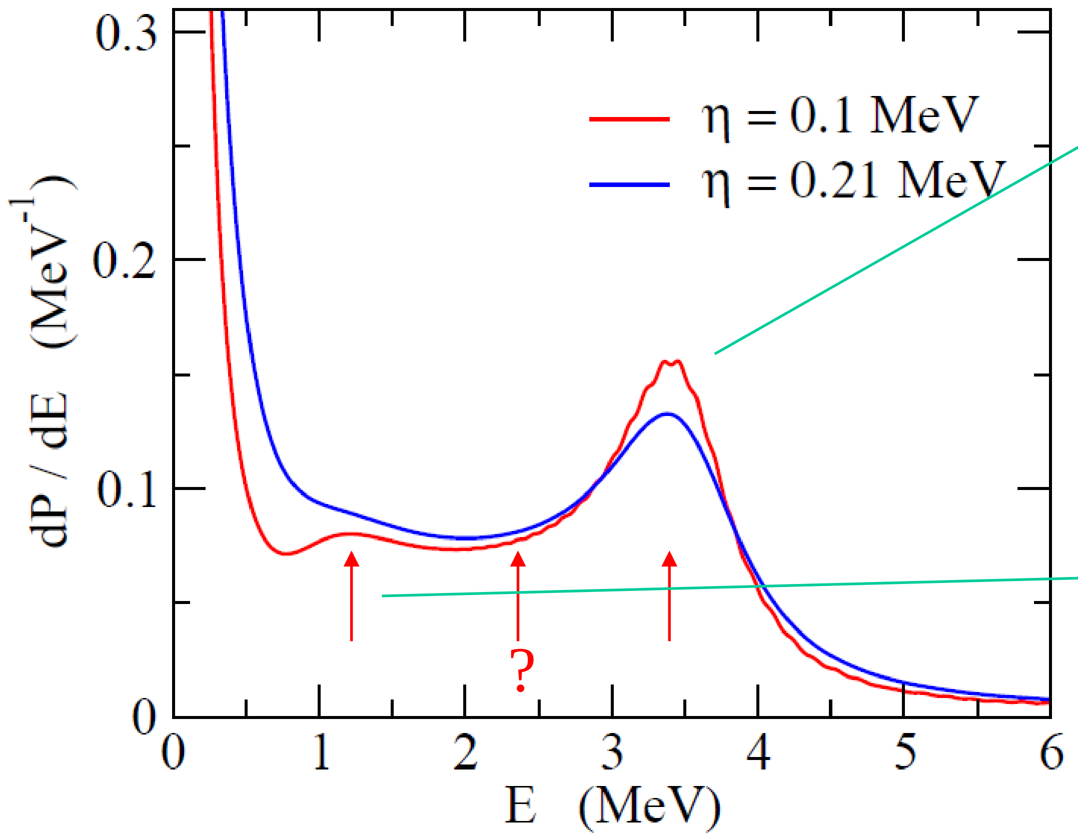
$(s_{1/2})^2$: 0.59%

rms radius = 3.39 +/- 0.11 fm



Excited 0^+ states

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



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)

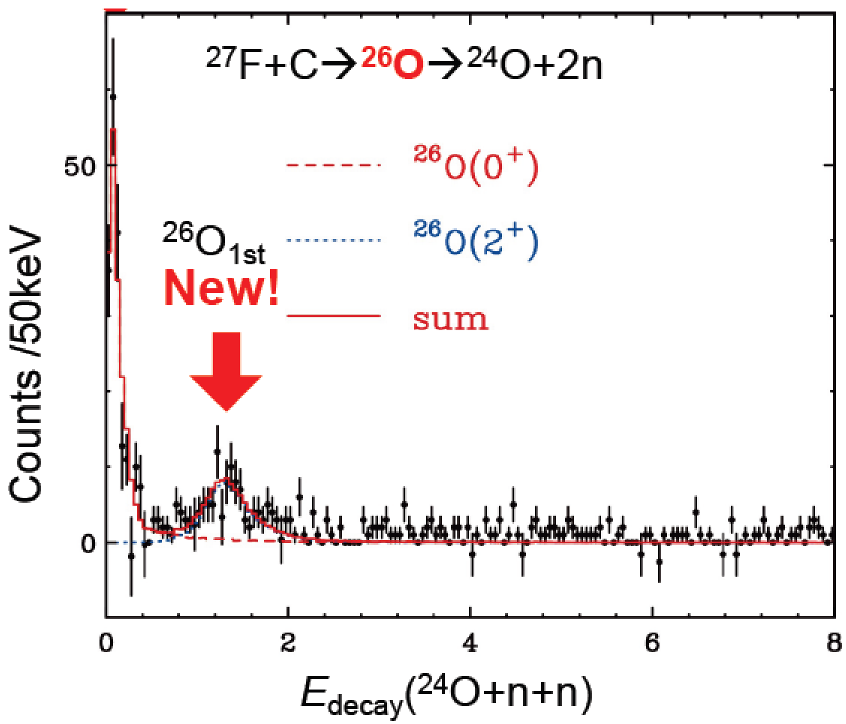
$d_{3/2}$: E = 0.75, Γ = 0.087

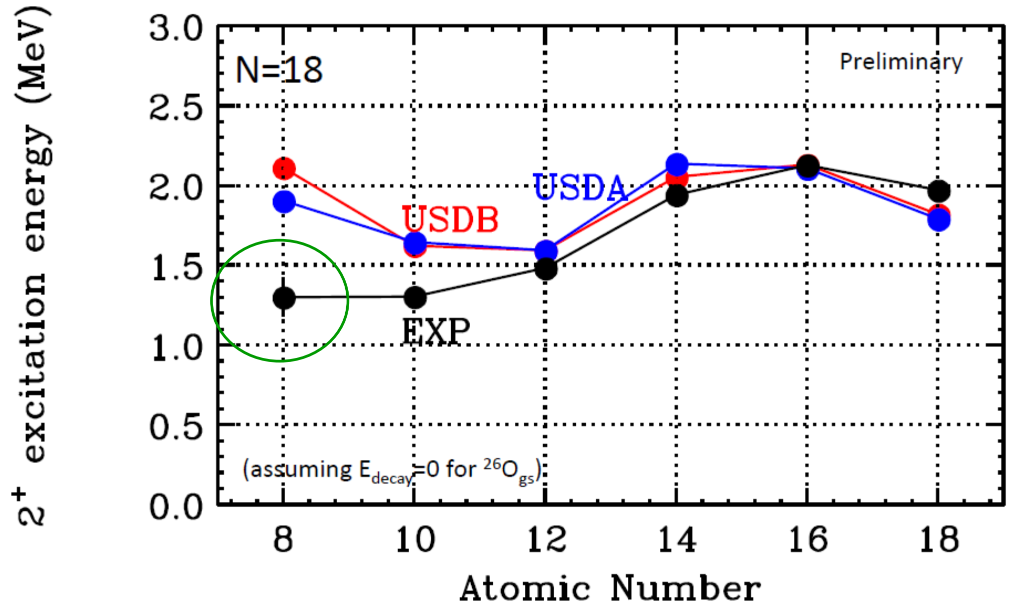
$f_{7/2}$: E = 2.44, Γ = 0.21

$p_{3/2}$: 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





Courtesy: Y. Kondo

cf. sdpf-m: E_{2+} = 2.62 MeV (Y. Utsuno)

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

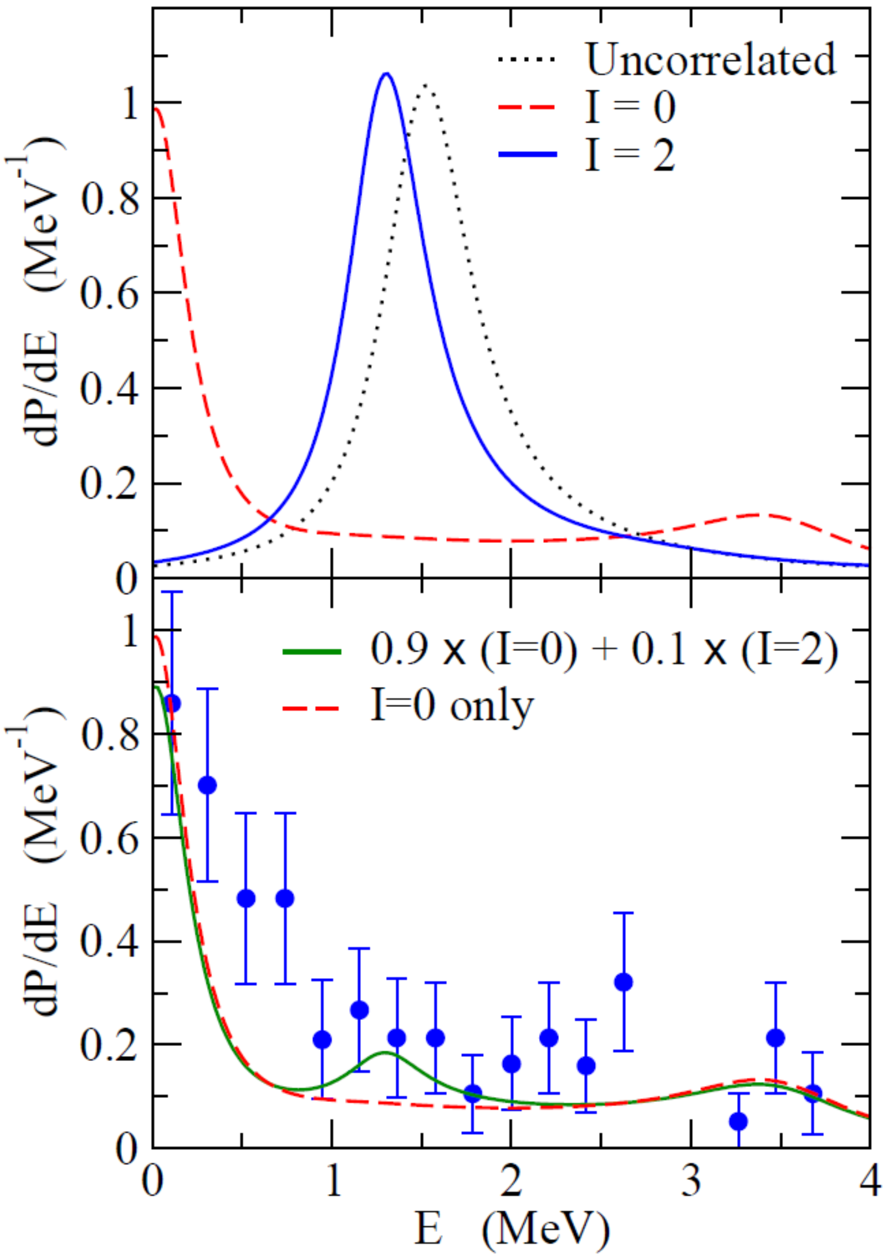
(C. Caesar et al., PRC88('13)034313)

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 ~ 1.28$^{+0.11}_{-0.08}$ MeV



(MeV)

1.498 $(d_{3/2})^2$

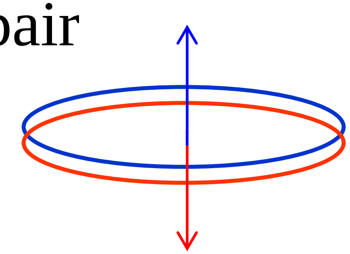
1.282 2^+

Γ = 0.12 MeV

0.018 0^+

a textbook example
of pairing interaction!

I=0 pair

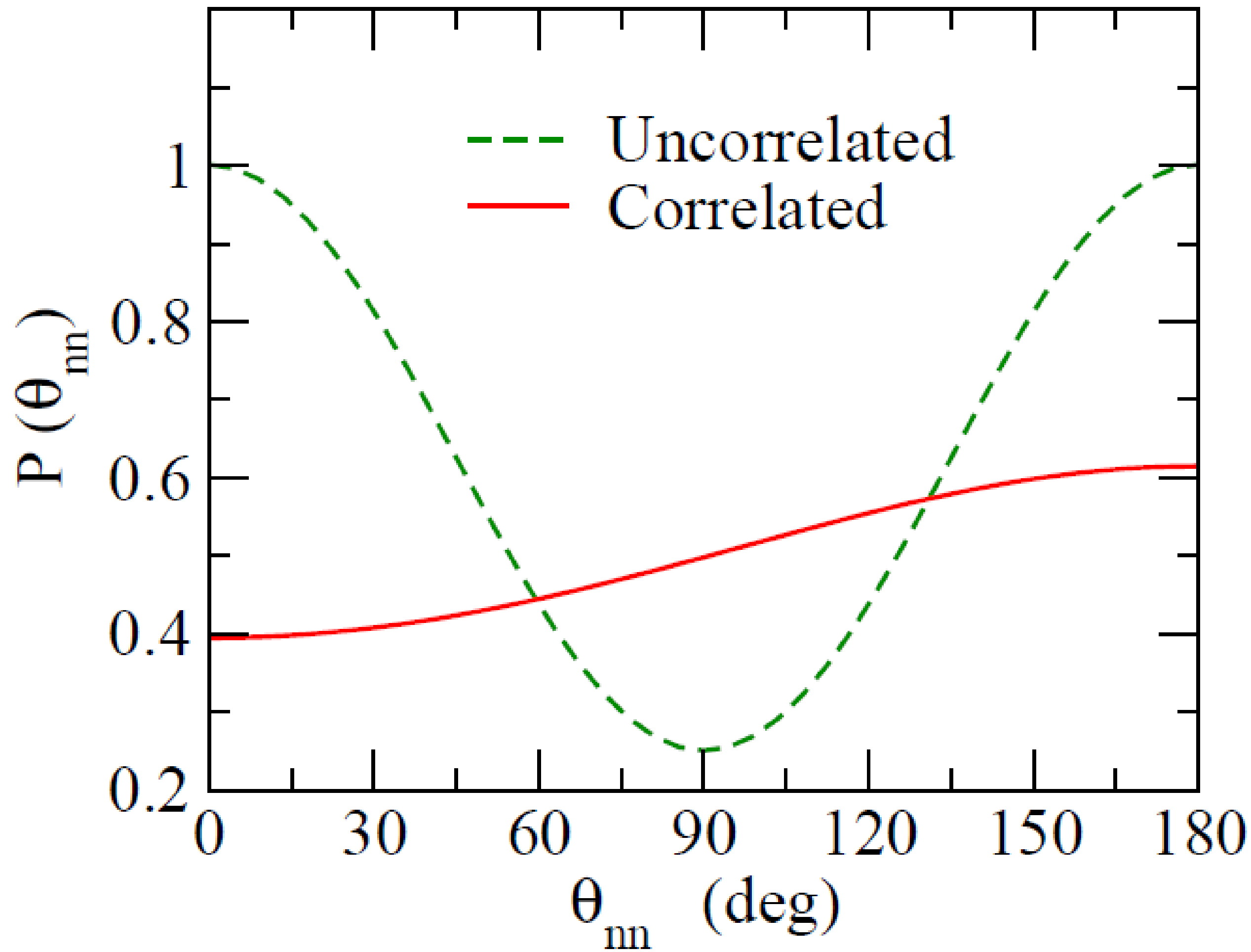


K.H. and H. Sagawa,
PRC90('14)027303; in preparation.

	^{25}O (3/2$^+$)	^{26}O (2$^+$)
Experiment	+ 749 (10) keV	$1.28^{+0.11}_{-0.08}$ MeV
USDA	1301 keV	1.9 MeV
USDB	1303 keV	2.1 MeV
sdpf-m (Utsuno)	?	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)	749 keV (input)	1.282 MeV

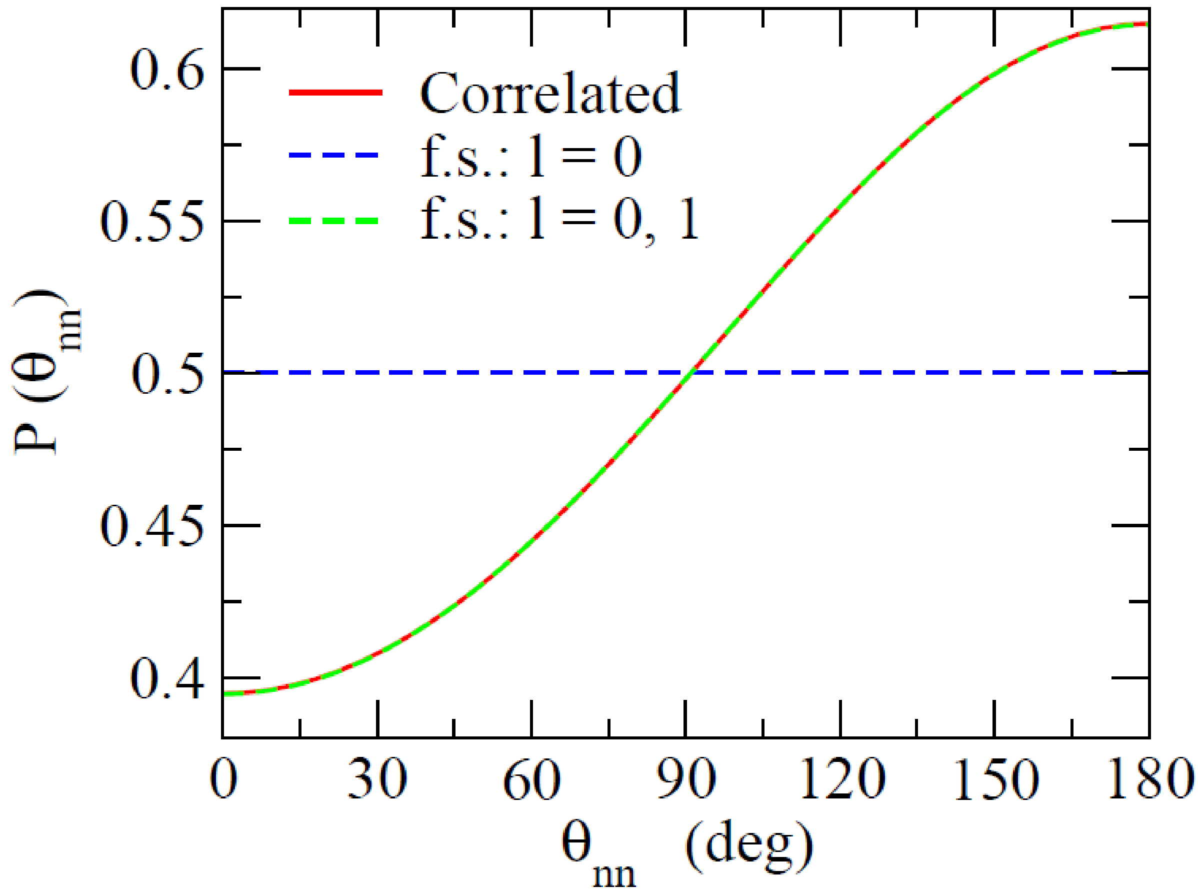
angular correlations

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



correlation → enhancement of back-to-back emissions

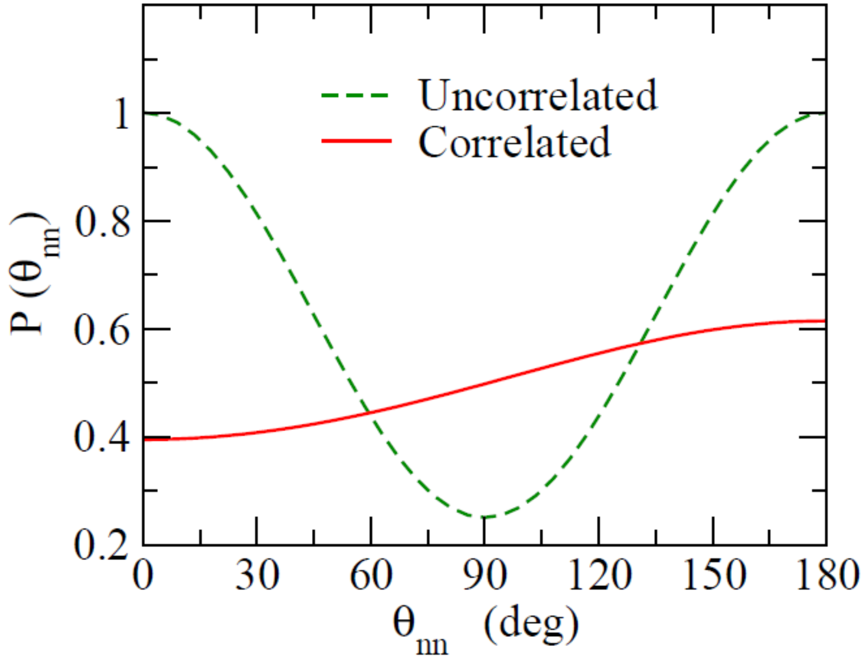
cf. Similar conclusion: L.V. Grigorenko, I.G. Mukha, and M.V. Zhukov, PRL 111 (2013) 042501



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, $e_1 \sim e_2 \sim 9$ keV)

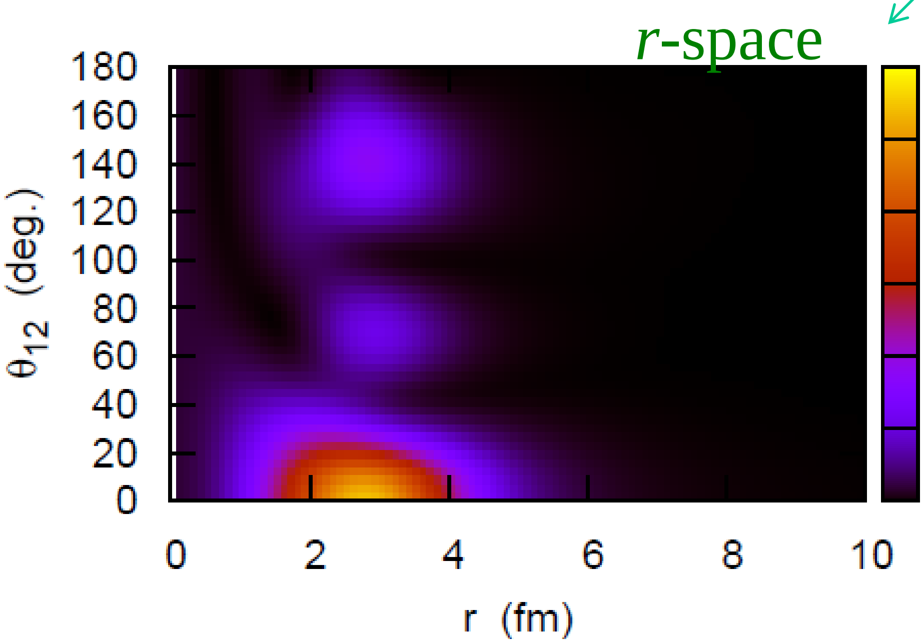
ii) distribution of opening angle for two-emitted neutrons

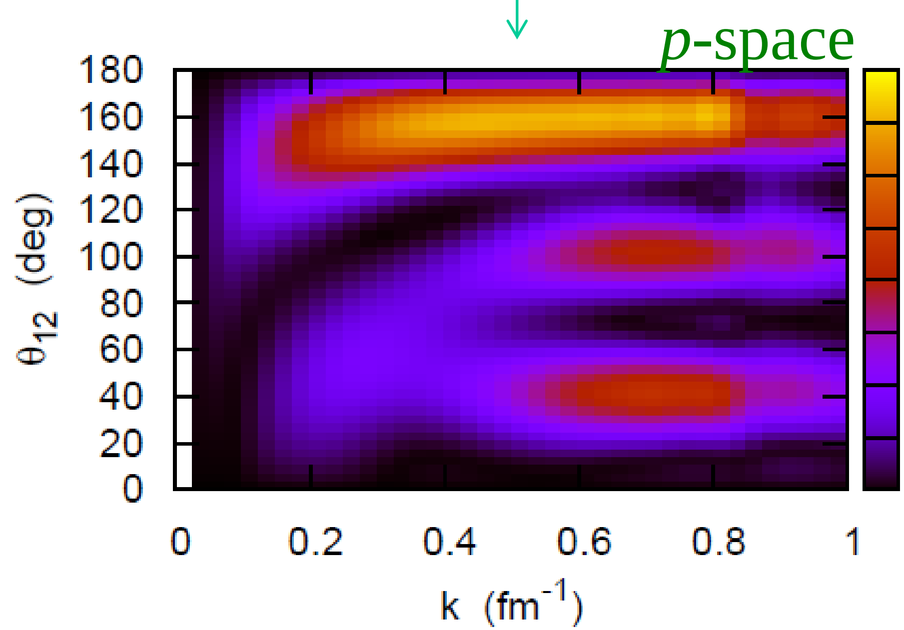


density of the resonance state (with the box b.c.)

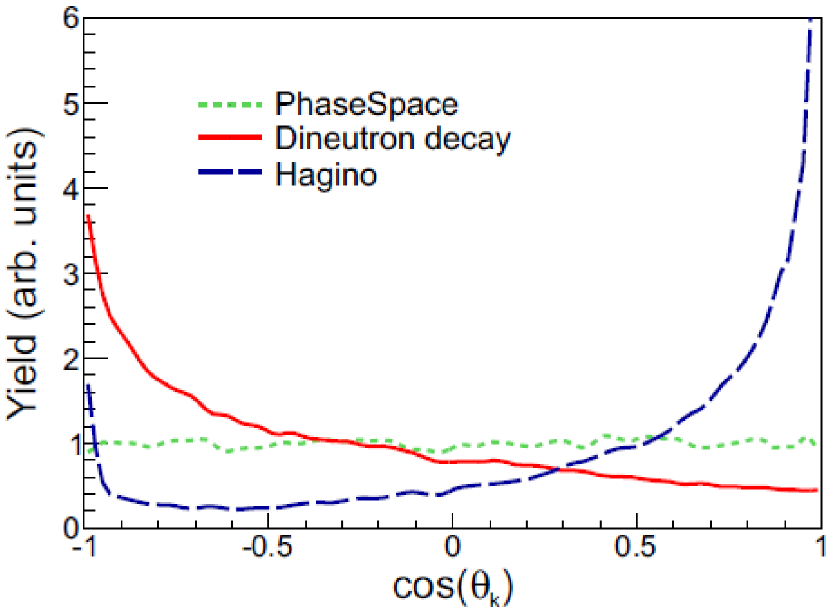
$$\rho(r, r, \theta)$$

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

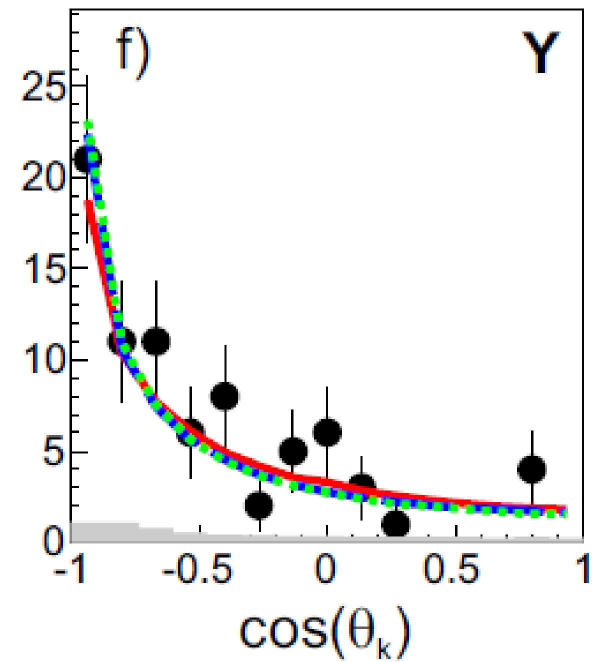


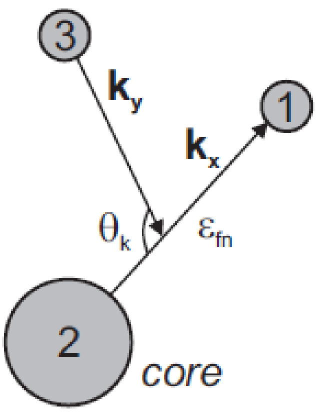


Recent measurements and simulations at MONA



simulation





Y system

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

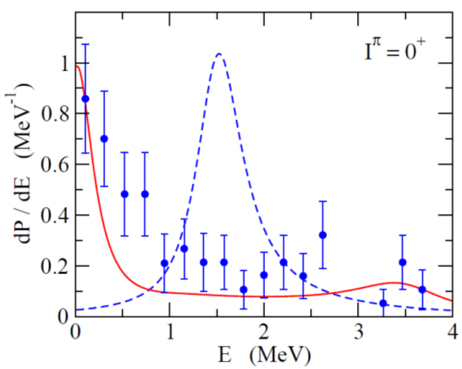
Z. Kohley et al., PRC91 (‘15) 034323

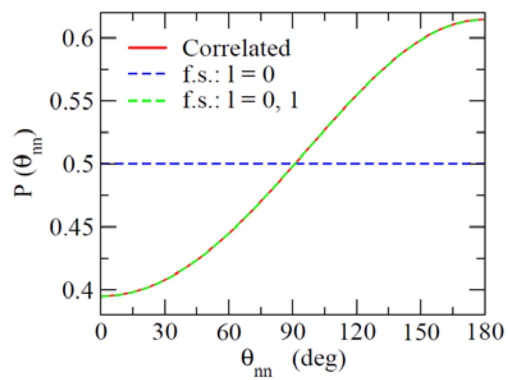
Summary

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
- ✓ Energy distribution of 2 neutrons: three-body resonance
- ✓ 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?