Di-neutron correlation and two-neutron decay of nuclei beyond the neutron drip line

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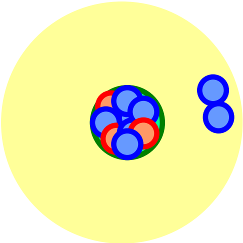
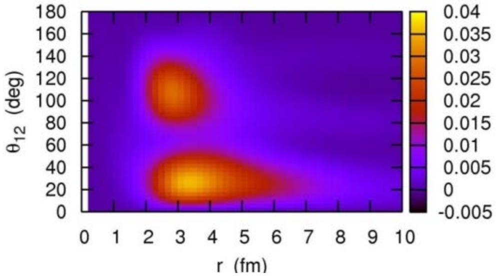




1. *Introduction: Di-neutron correlation*
2. *Coulomb breakup of Borromean nuclei*
3. *Two-neutron decay of unbound nucleus ^{26}O*
4. *Summary*

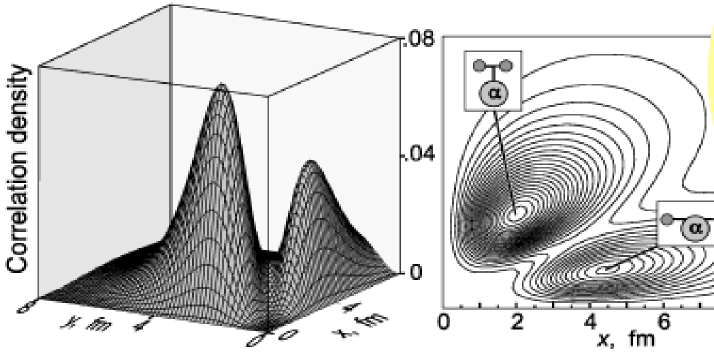
Borromean nuclei and Di-neutron correlation

Borromean nuclei: unique three-body systems

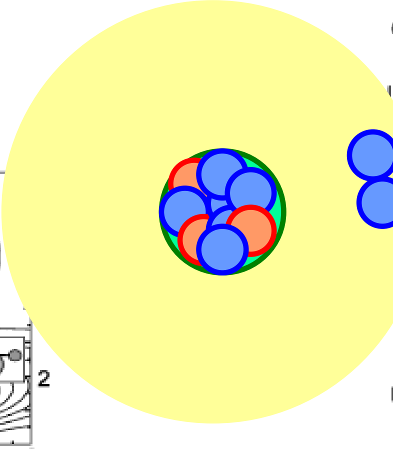
Three-body model calculations:

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

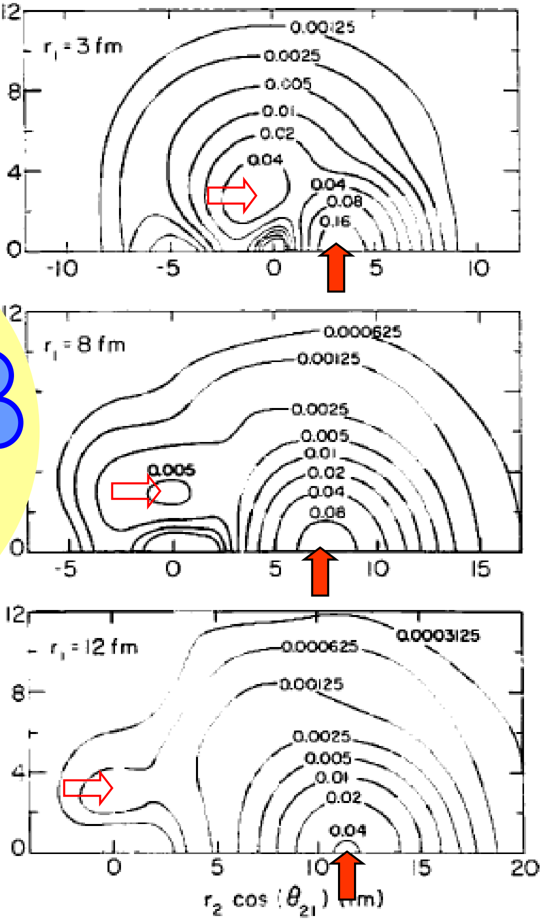
$x^2y^2\,\rho_2(x,y)$ for ^{6}He



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

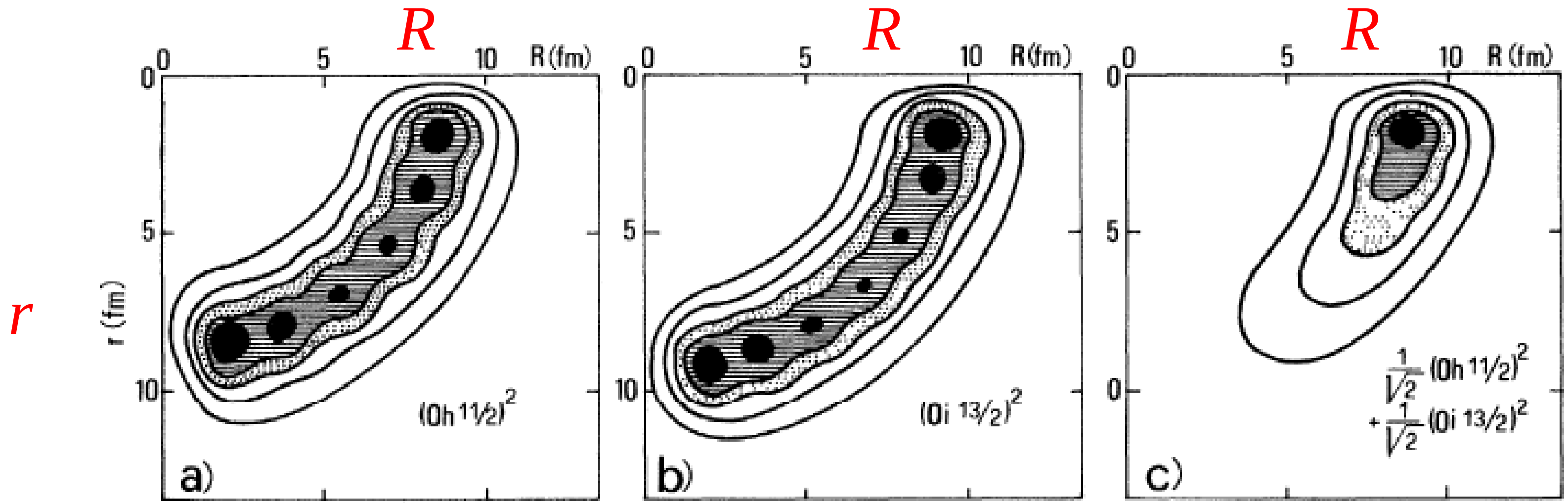


G.F. Bertsch, H. Esbensen,
Ann. of Phys., 209('91)327

cf. earlier works

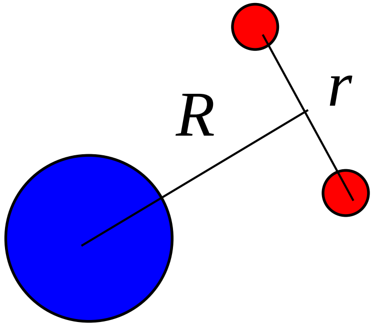
- ✓ A.B. Migdal ('73)
- ✓ P.G. Hansen and B. Jonson ('87)

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

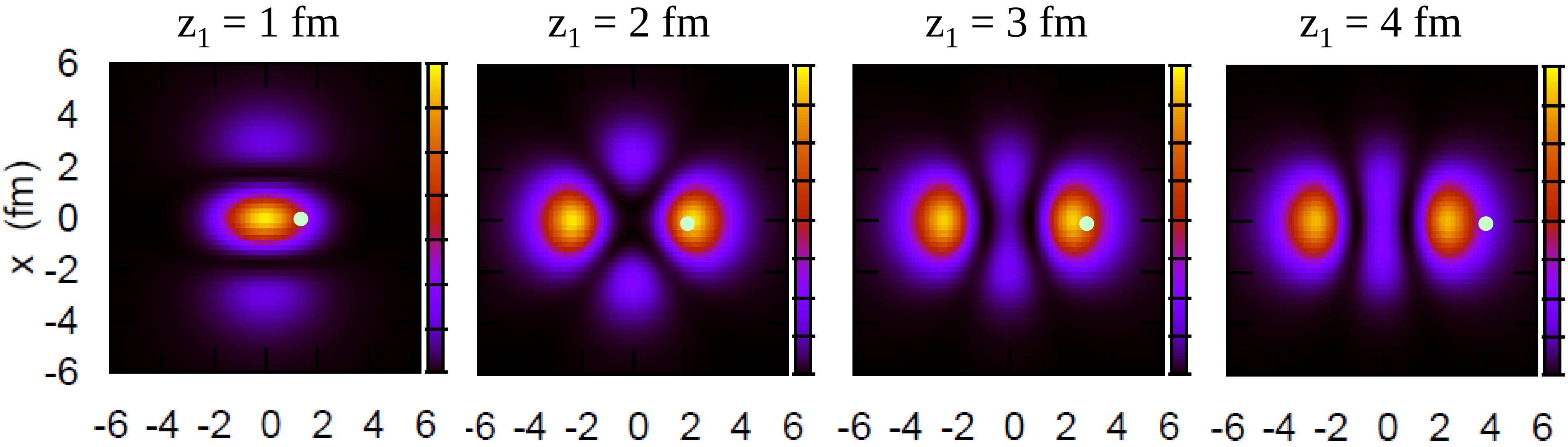


interference of even and odd partial waves

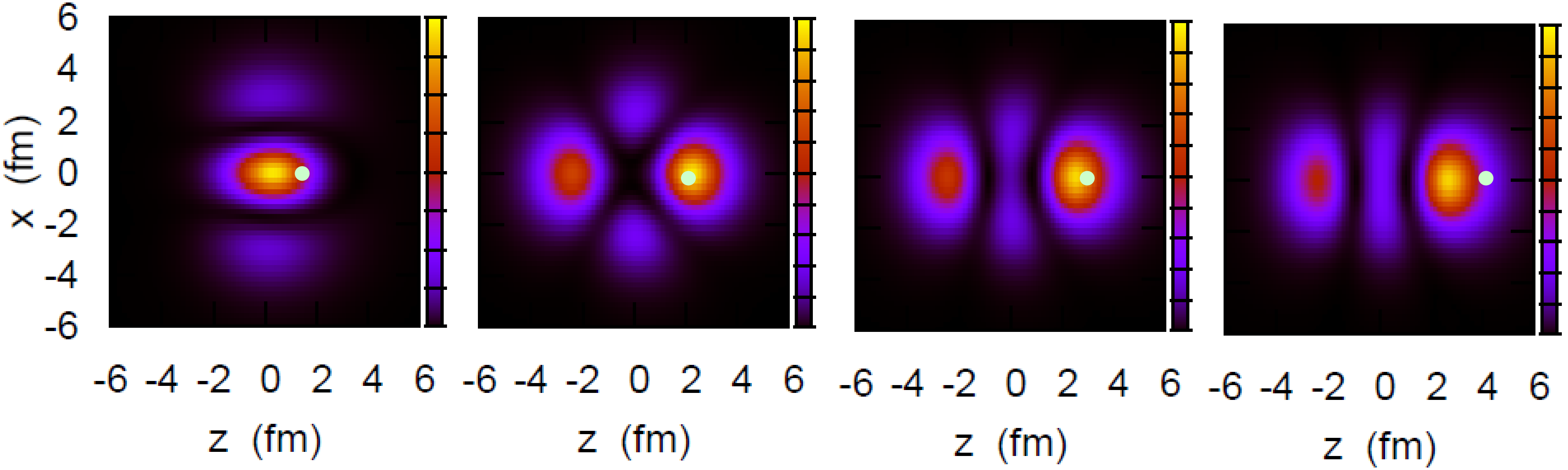
$$\rho_2(x_1,x_2) = |\Psi_{ee}(x_1,x_2)|^2 + |\Psi_{oo}(x_1,x_2)|^2 + \boxed{2\Psi_{ee}(x_1,x_2)\Psi_{oo}(x_1,x_2)}$$

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

i) even parity only

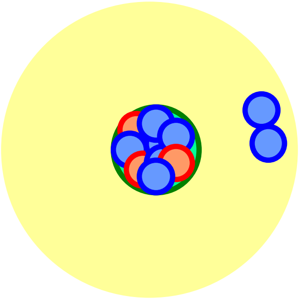


ii) both even and odd parities



Dineutron correlation in the momentum space

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

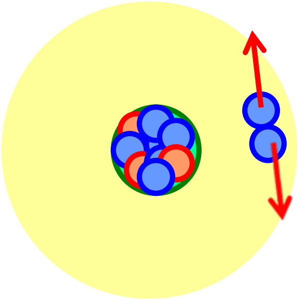


⟶ Fourier transform

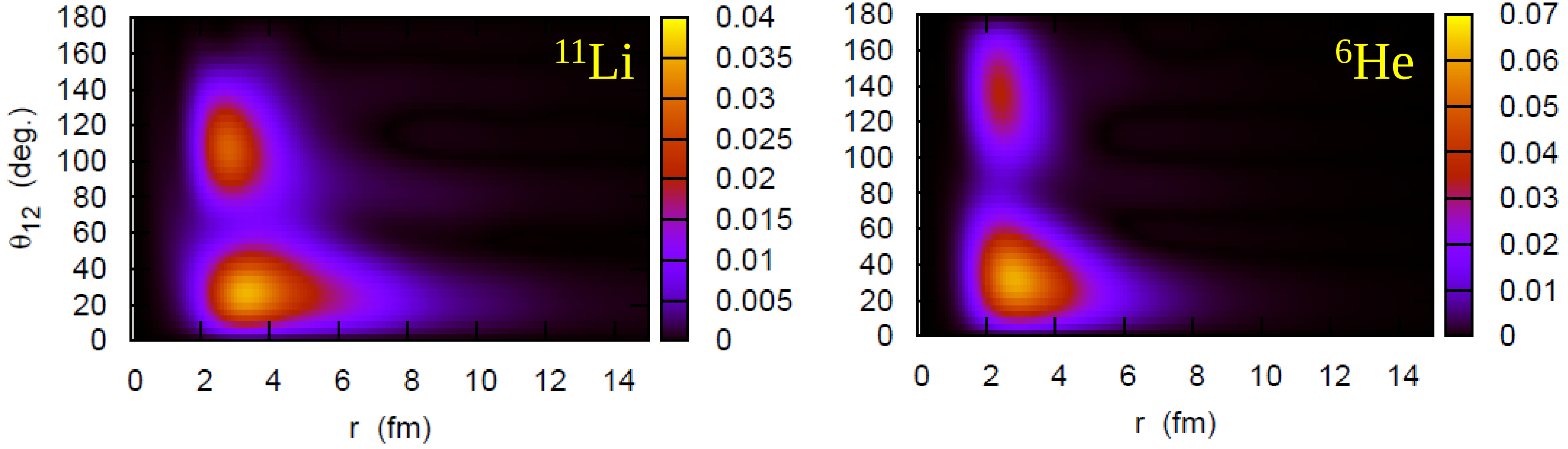
$$\tilde{\Psi}(\boldsymbol{k},\boldsymbol{k}') = \int e^{i\boldsymbol{k}\cdot\boldsymbol{r}} e^{i\boldsymbol{k}'\cdot\boldsymbol{r}'} \Psi(\boldsymbol{r},\boldsymbol{r}')\,d\boldsymbol{r}\,d\boldsymbol{r}'$$

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

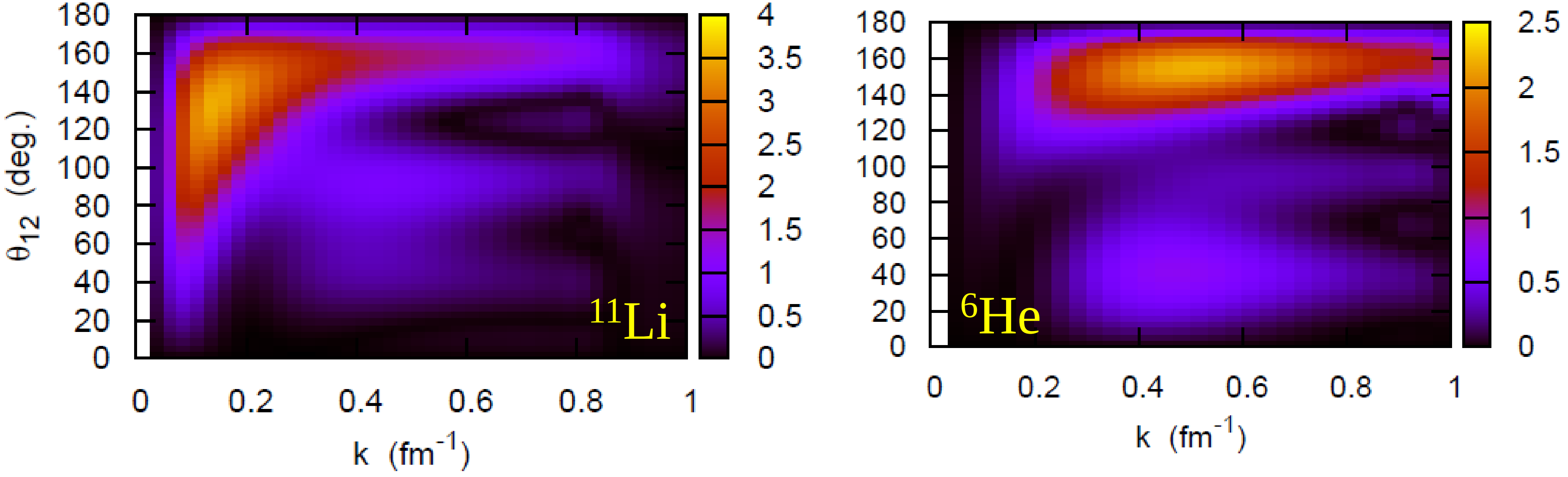
$$\boxed{\tilde{\Psi}(\boldsymbol{k},\boldsymbol{k}') = \alpha\,\tilde{\Psi}_{s^2}(\boldsymbol{k},\boldsymbol{k}') - \beta\,\tilde{\Psi}_{p^2}(\boldsymbol{k},\boldsymbol{k}')} \longrightarrow \theta_k = \pi\text{: enhanced}$$



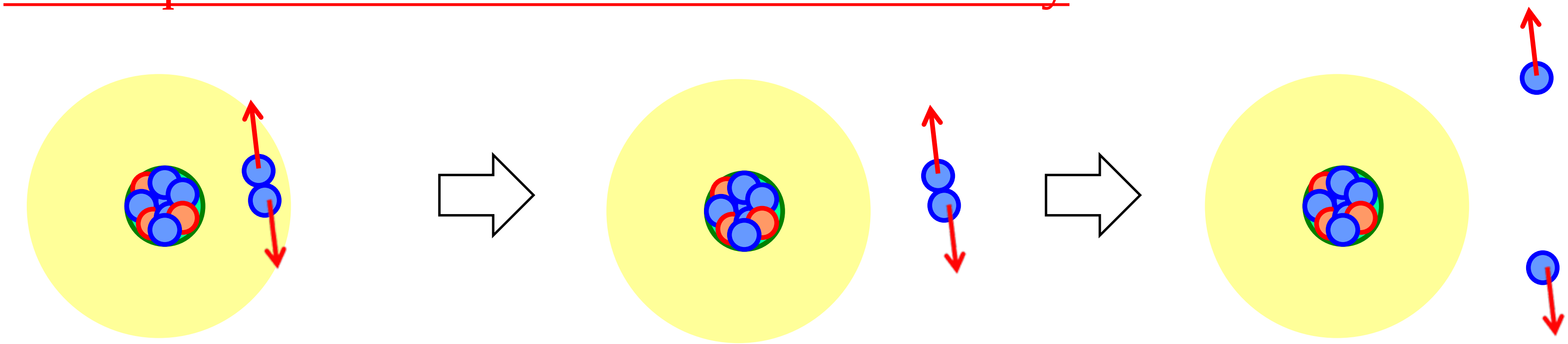
Two-particle density in the *r* space: $8\pi^2 r^4 \sin\theta \cdot \rho(r,r,\theta)$



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

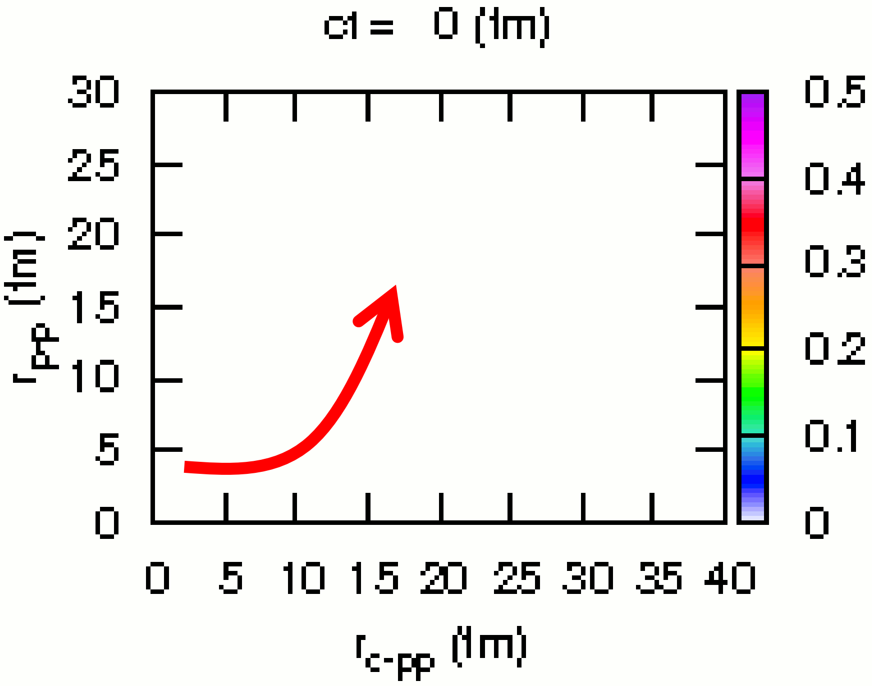


Consequence to a two-nucleon emission decay



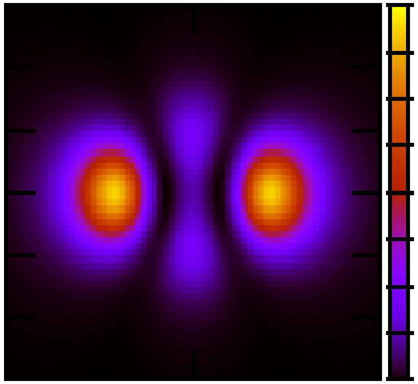
2p decay of ^{6}Be

: time-dependent calculations

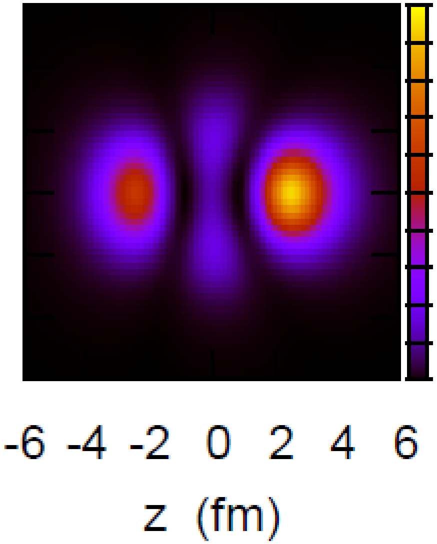


T. Oishi (Tohoku → Jyvaskyla),
K.H., H. Sagawa,
PRC90 ('14) 034303

Di-neutron correlation in weakly-bound exotic nuclei (WBEN)



parity mixing



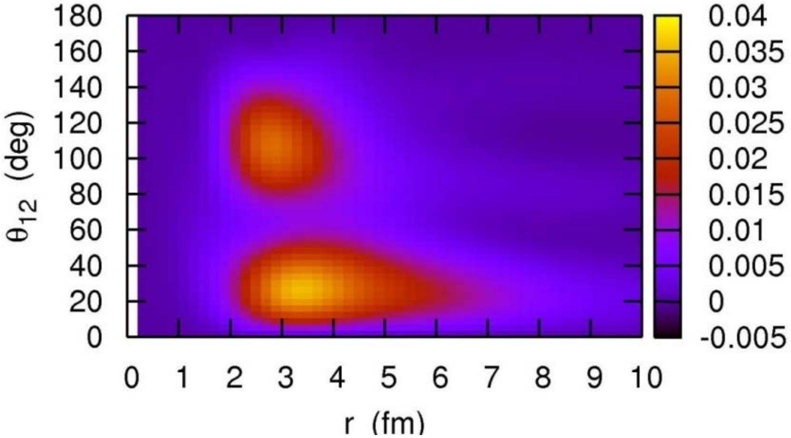
spatial localization of two neutrons
(dineutron correlation)

weakly bound systems

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

⟶ dineutron correlation: enhanced

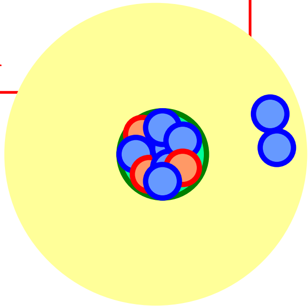
cf. - Bertsch, Esbensen, Ann. of Phys. 209('91)327
- M. Matsuo, K. Mizuyama, Y. Serizawa,
PRC71('05)064326



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

Di-neutron correlations in neutron-rich nuclei

Strong di-neutron correlations 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)

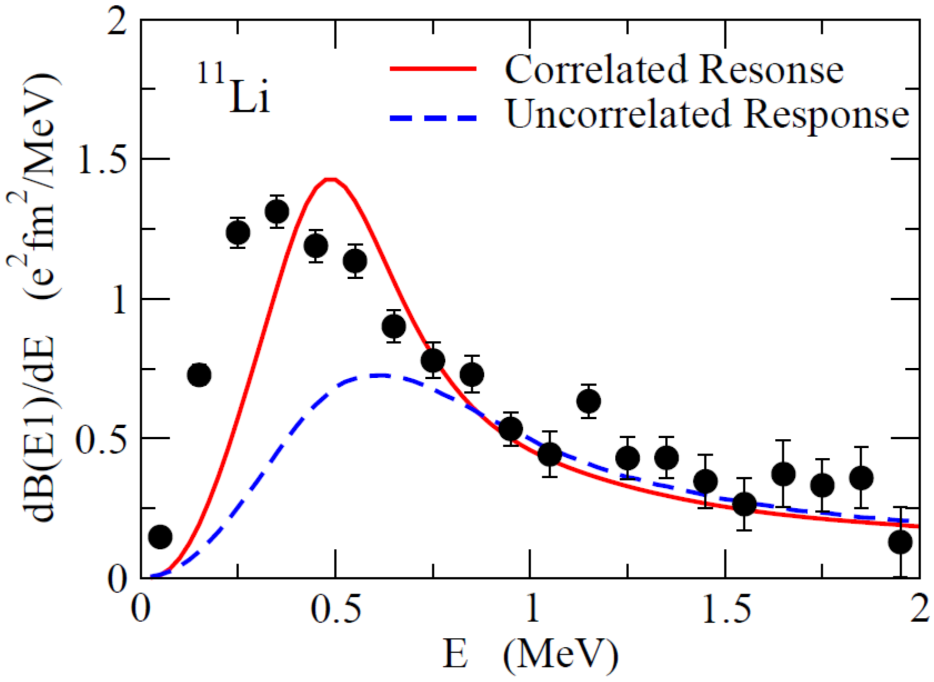
How to probe it?

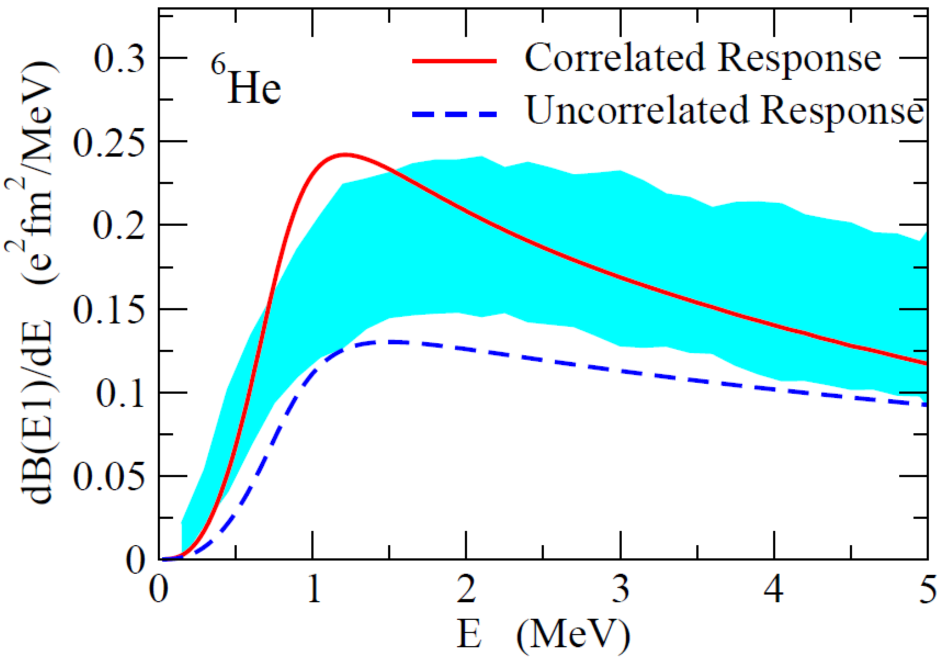
- Coulomb breakup
  T. Nakamura et al.
  cluster sum rule
  (mean value of θ_{nn})
- pair transfer reactions
- two-proton decays
  Coulomb 3-body problem

- 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? ⟶ Coulomb breakup





Experiments:

T. Nakamura et al., PRL96(’06)252502

T. Aumann et al., PRC59(‘99)1252

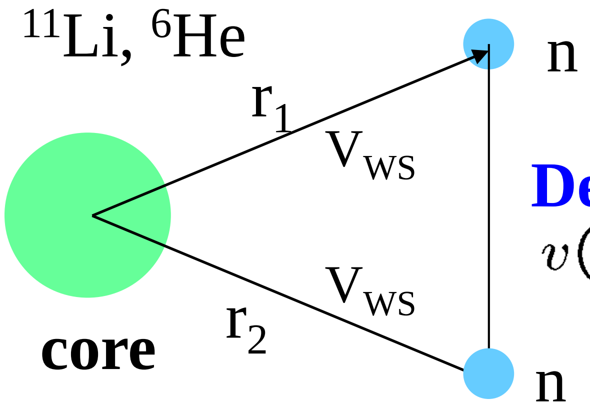
3-body model calculations:

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

cf. Y. Kikuchi et al., PRC87(‘13)034606 ⟵ structure of the core nucleus (^{9}Li)

also for ^{22}C, ^{14}Be, ^{19}B etc. (T. Nakamura et al.)

3-body model calculation for Borromean nuclei



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

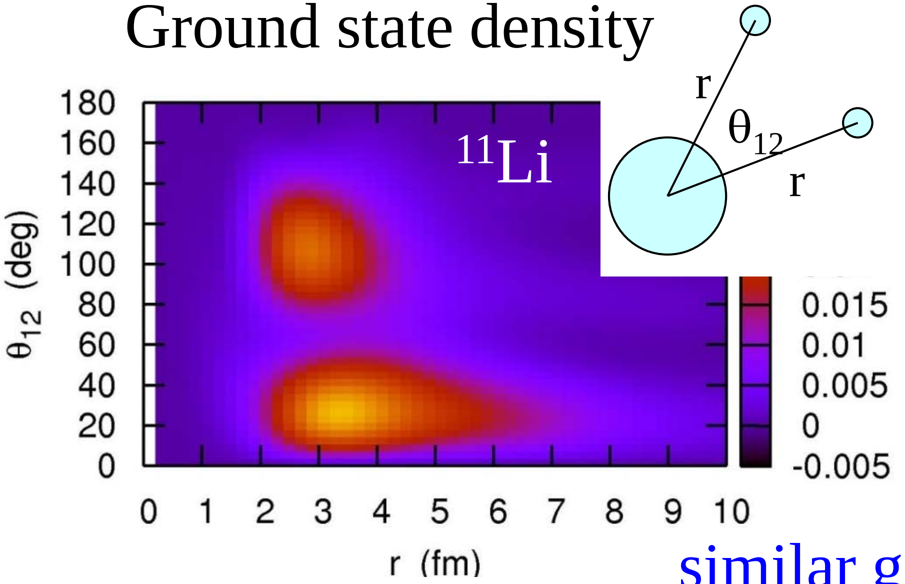
Density-dependent delta-force

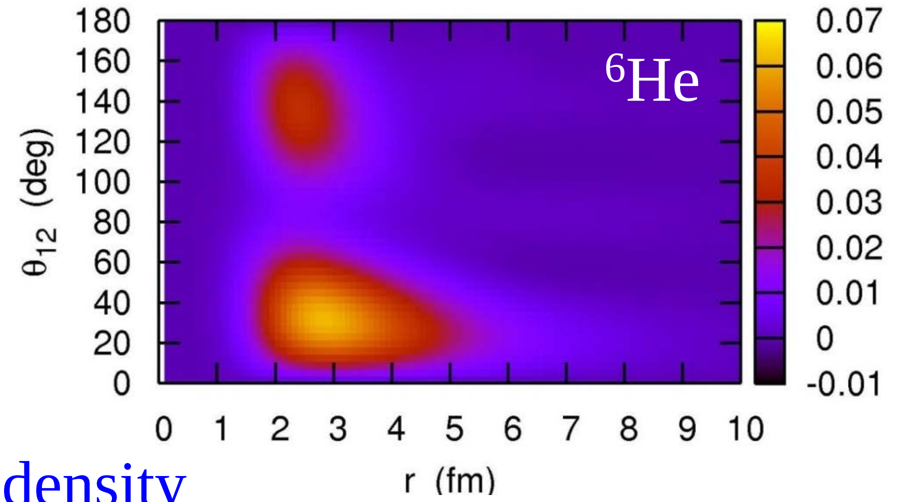
$$v(\boldsymbol{r}_1,\boldsymbol{r}_2) = v_0(1+\alpha\rho(r)) \times\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)$$

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

Ground state density

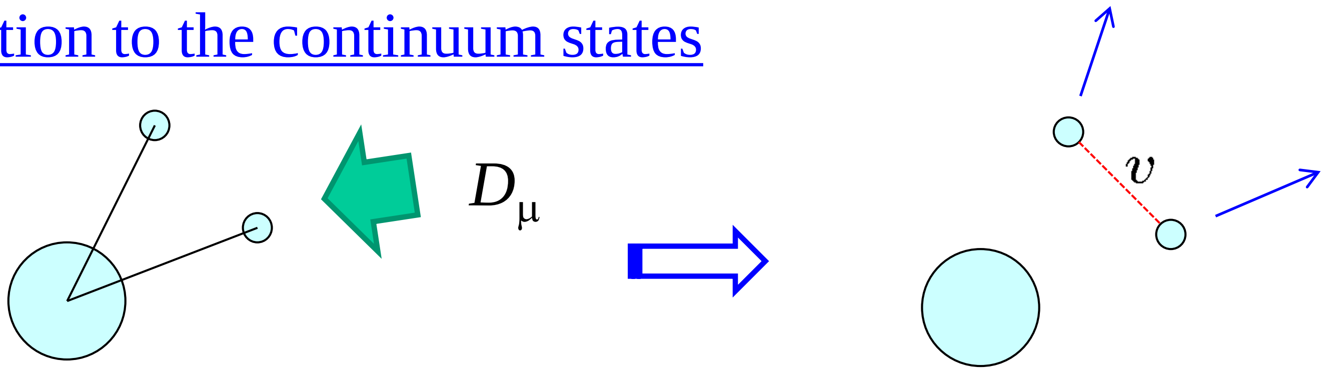
K.H. and H. Sagawa, PRC72('05)044321





similar g.s. density

E1 excitation to the continuum states



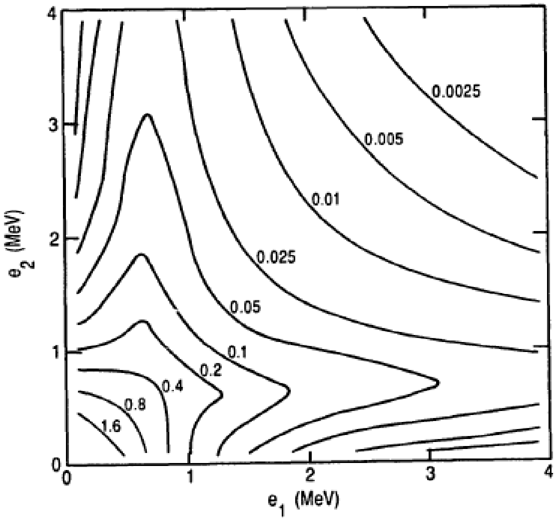
$$\begin{aligned} M(E1) &= \langle (j_1 j_2)^1_\mu | (1 - vG_0 + vG_0 vG_0 - \cdots) D_\mu | \Psi_{gs} \rangle \\ &= \langle (j_1 j_2)^1_\mu | \underbrace{(1 + vG_0)^{-1}}_{\text{FSI}} D_\mu | \Psi_{gs} \rangle \end{aligned}$$

dipole operator

unperturbed continuum wf

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

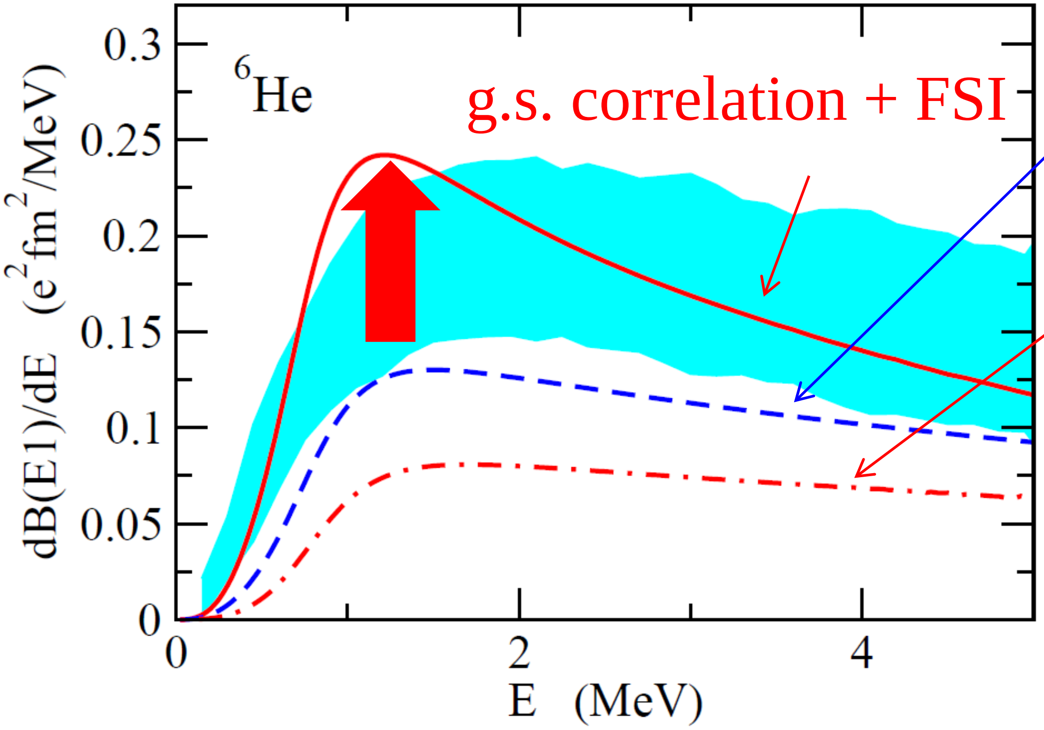
$$\boxed{\frac{d^2 B(E1)}{de_1 de_2} = 3 \sum_{l_1 j_2 l_2 j_2} |M(E1)|^2 \frac{dk_1}{de_1} \frac{dk_2}{de_2}}$$



H. Esbensen and G.F. Bertsch, NPA542('92)310

g.s. correlation? or correlation in excited states?

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



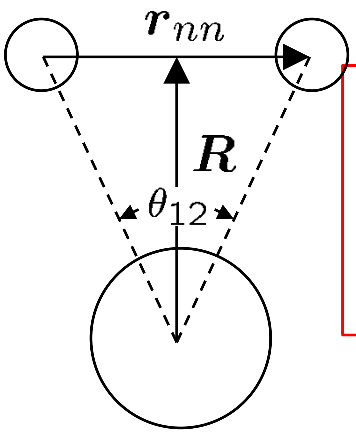
g.s. correlation + FSI

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

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

✓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

“experimental data” for opening angle

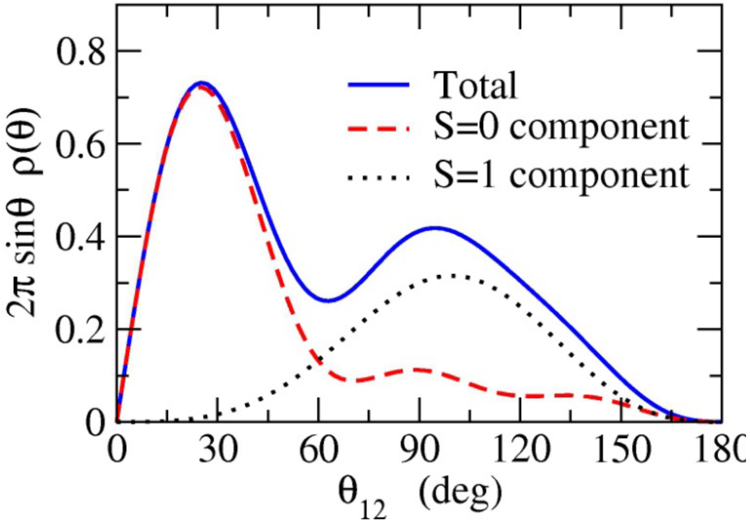
$\sqrt{\langle R^2\rangle} \longleftarrow$ $B_{\rm tot}$(E1)

$\sqrt{\langle r^2_{\rm nn}\rangle} \longleftarrow$ 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

3-body model calculations



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

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

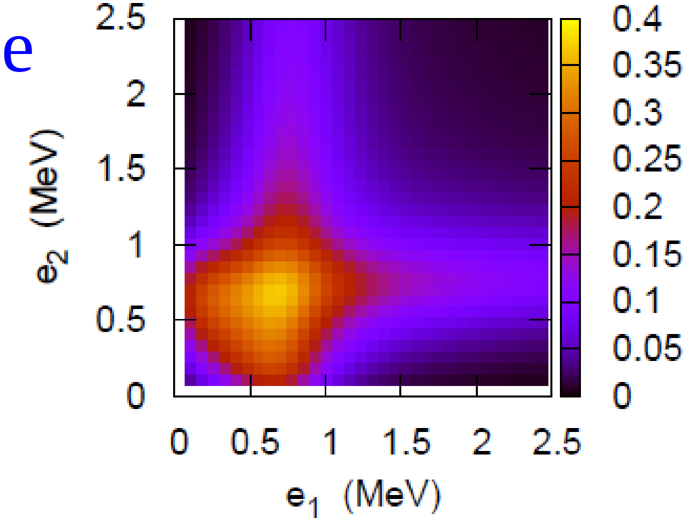
suggests dineutron corr.

(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

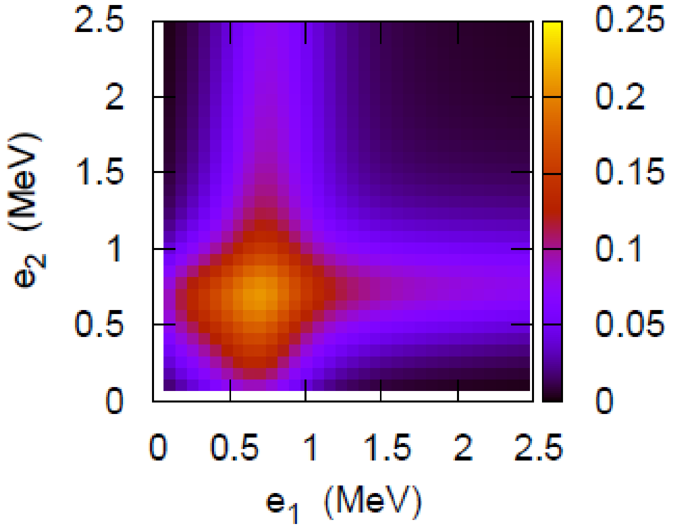
Energy distribution of emitted neutrons

^{6}He

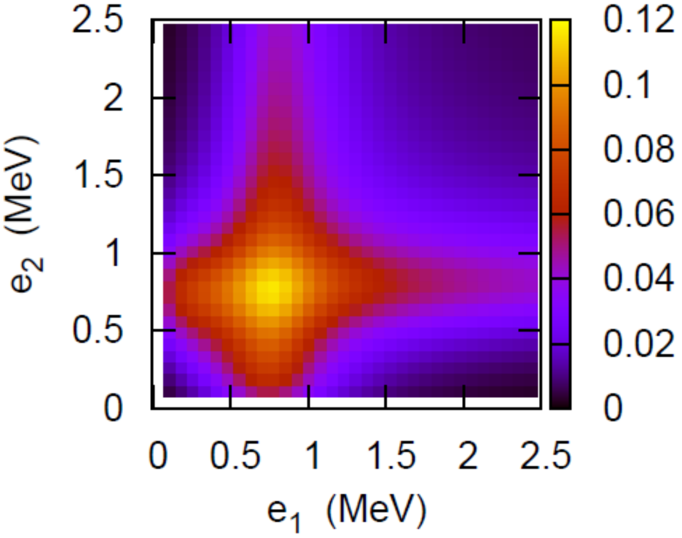


- ✓shape of distribution: insensitive to the nn-interaction (except for the absolute value)
- ✓strong sensitivity to V_{nC}
- ✓similar situation in between ^{11}Li and ^{6}He

$v_{nn} = 0$

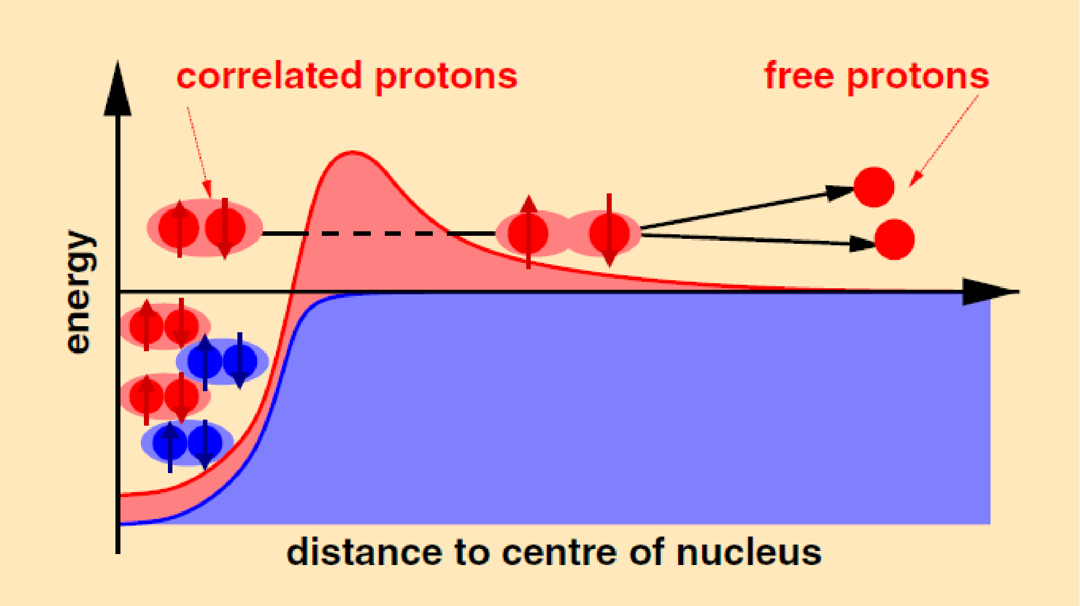


no di-neutron corr. in the g.s.
(odd-*l* only)



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

2-proton radio activity



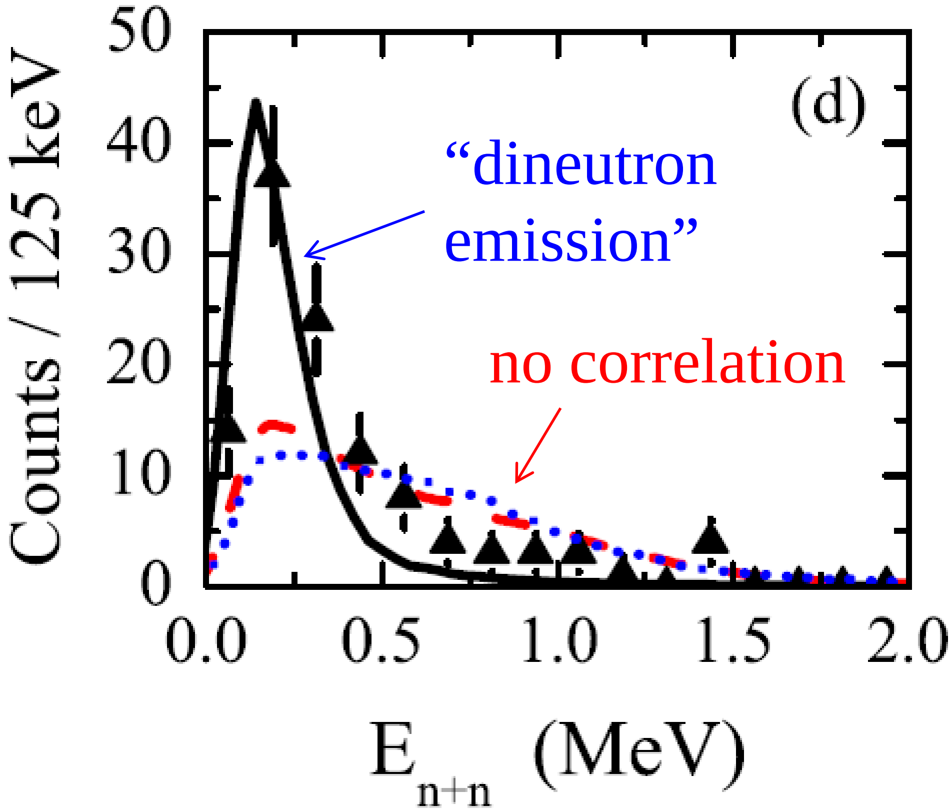
B. Blank and M. Ploszajczak, Rep. Prog. Phys. 71('08)046301

- ✓ 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?

⟶ diproton correlation: unclear in many systems
(theoretical calculations: not many)

2-neutron decay（MoNA@MSU）

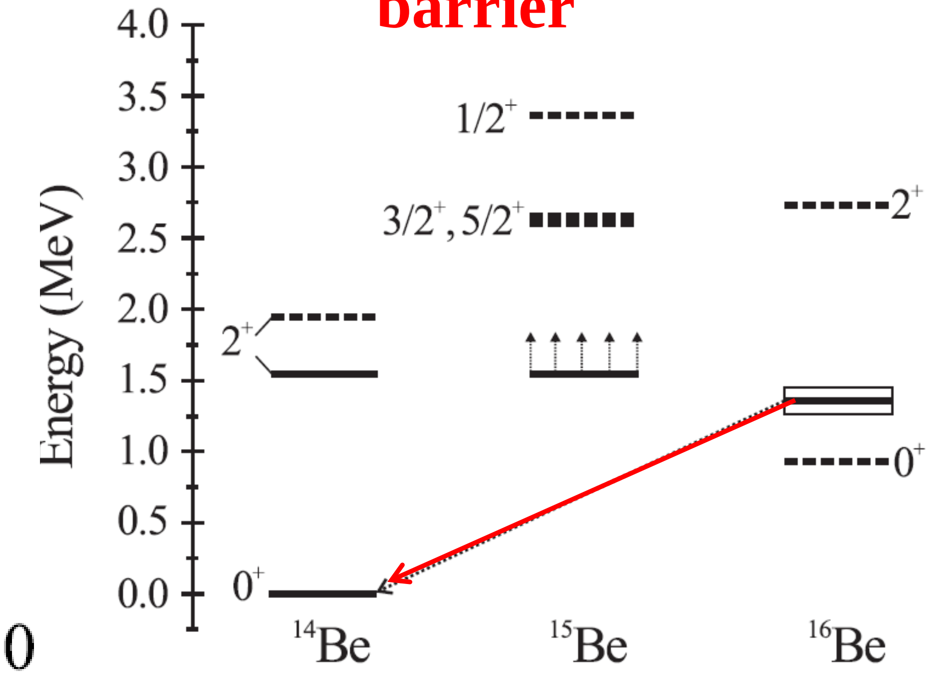
$^{17}B \rightarrow {}^{16}Be \rightarrow {}^{14}Be + n + n$



"dineutron emission"

no correlation

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

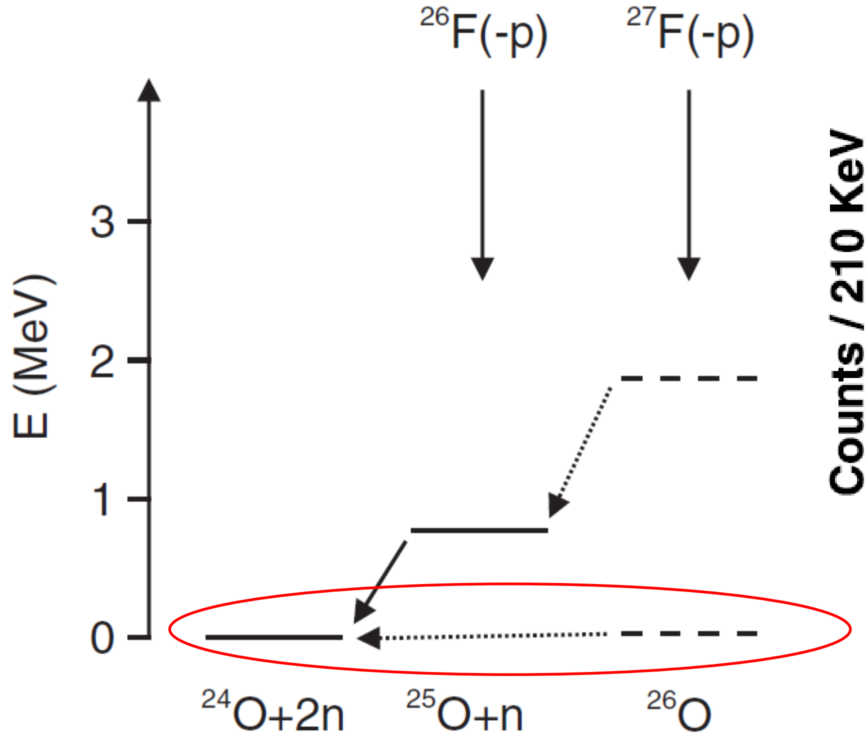
Two-neutron decay of ^{26}O

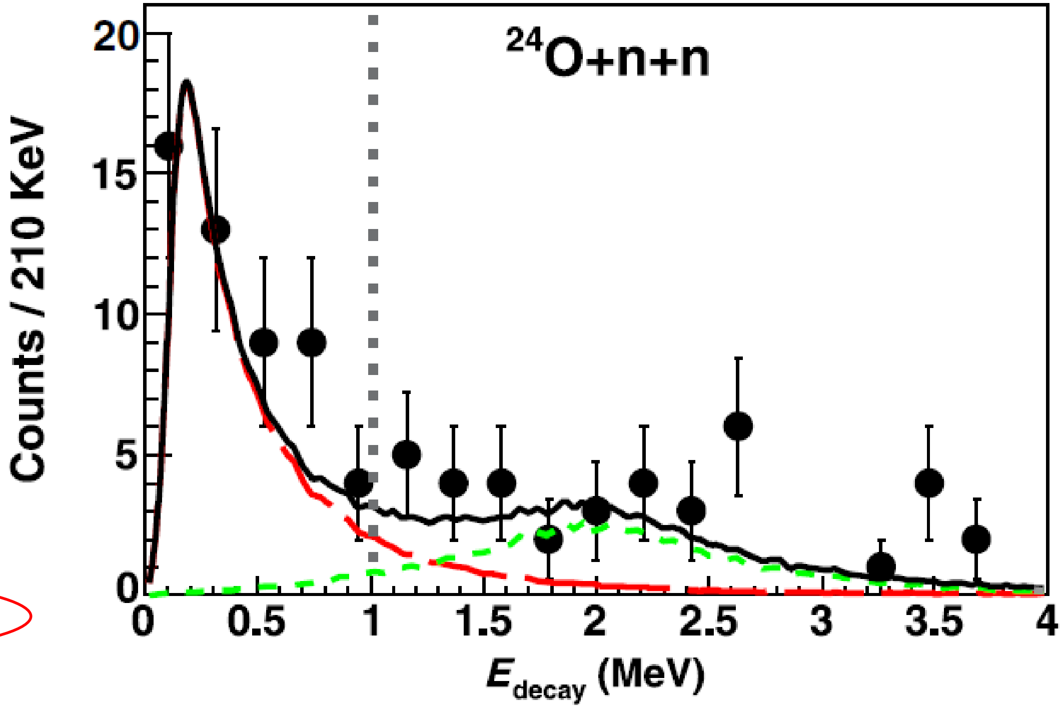
- the simplest among ^{16}Be, ^{13}Li, ^{26}O (MSU)
  ^{16}Be: deformation, ^{13}Li: treatment of ^{11}Li core

Experiment:

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

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





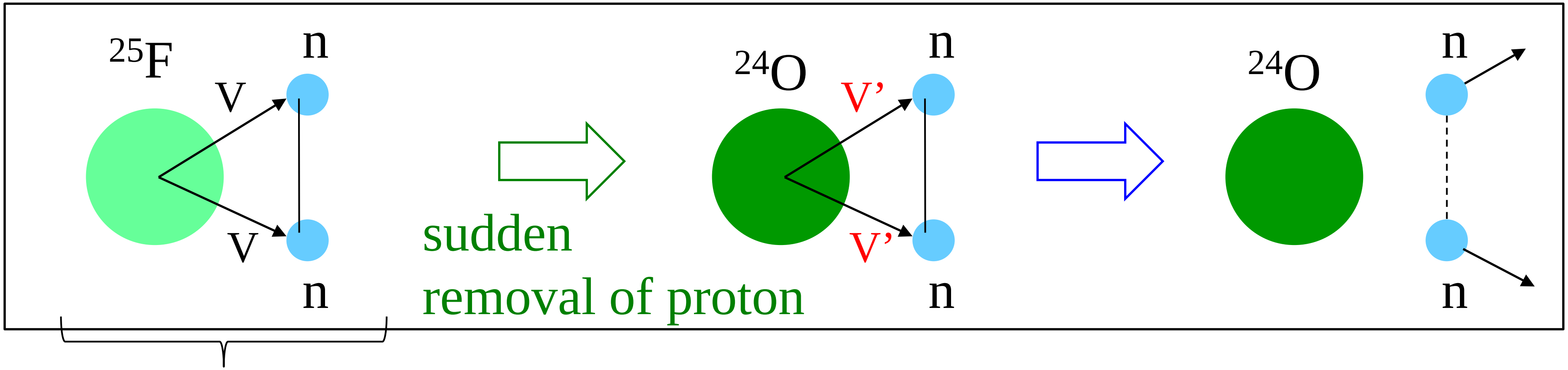
cf. C. Caesar et al., PRC88 (‘13) 034313 (GSI exp.)
Y. Kondo et al., (SAMURAI)

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



sudden
removal of proton

spontaneous decay

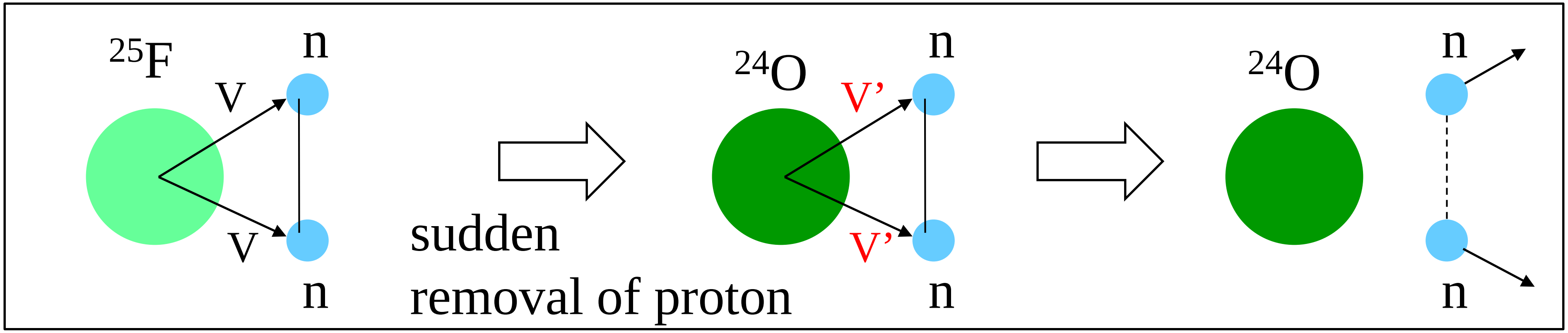
g.s. of ^{27}F (bound)

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

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

FSI ⟶ Green’s function method ⬅ continuum effects

$$\begin{aligned} M_{fi} &= \langle (j_1j_2)^{J=0}|(1 - vG_0 + vG_0vG_0 - \cdots)|\Psi_i\rangle \\ &= \langle (j_1j_2)^{J=0}|(1 + vG_0)^{-1}|\Psi_i\rangle \end{aligned}$$



- ^{24}O + n potential

Woods-Saxon potential

C.R. Hoffman et al.,
PRL100(‘08)152502

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

$e_{1d3/2} = +\ 770^{+20}_{-10}$ keV, $\Gamma_{1d3/2}$ = 172(30) keV

- ^{25}F + n potential

(^{24}O + n) potential + δV_{ls} ← pn tensor interaction

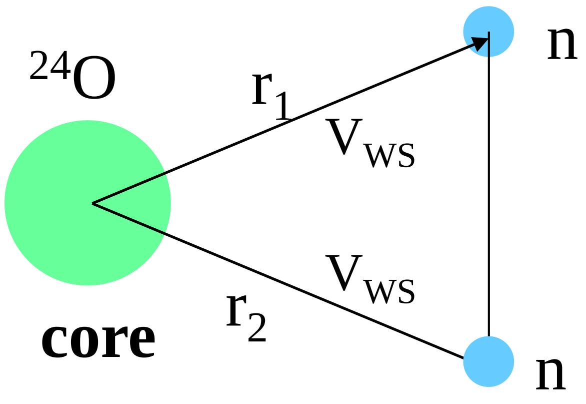
T. Otsuka et al., PRL95(‘05)232502

$e_{1d3/2}$ (^{26}F) = - 0.811 MeV

- nn interaction (density-dependent zero-range interaction)

← E_{exp} (^{27}F) = -2.80(18) MeV

i) 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

$$\boxed{\frac{dP_I}{dE} = \sum_k |\langle\Psi_k^{(I)}|\Phi_{\rm ref}^{(I)}\rangle|^2\,\delta(E-E_k)}$$

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

overlap with a ref. state ⟵ 2n config. with ^{25}F + n + n

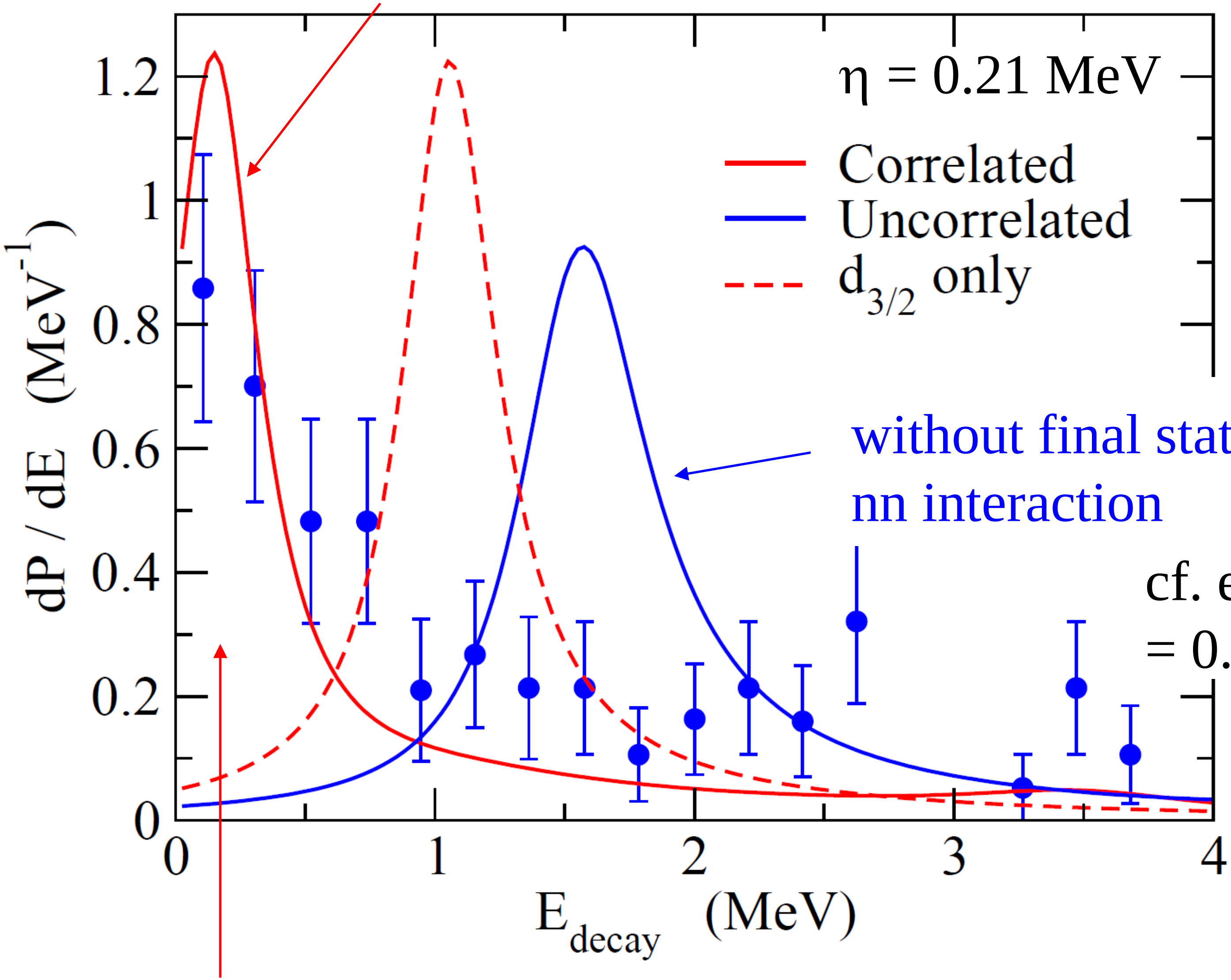
$$\boxed{G^{(I)}(E) = G_0^{(I)}(E) - G_0^{(I)}(E)v(1+G_0^{(I)}(E)v)^{-1}G_0^{(I)}(E)}$$

⟵ continuum effects

i) Decay energy spectrum

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

with final state nn interaction



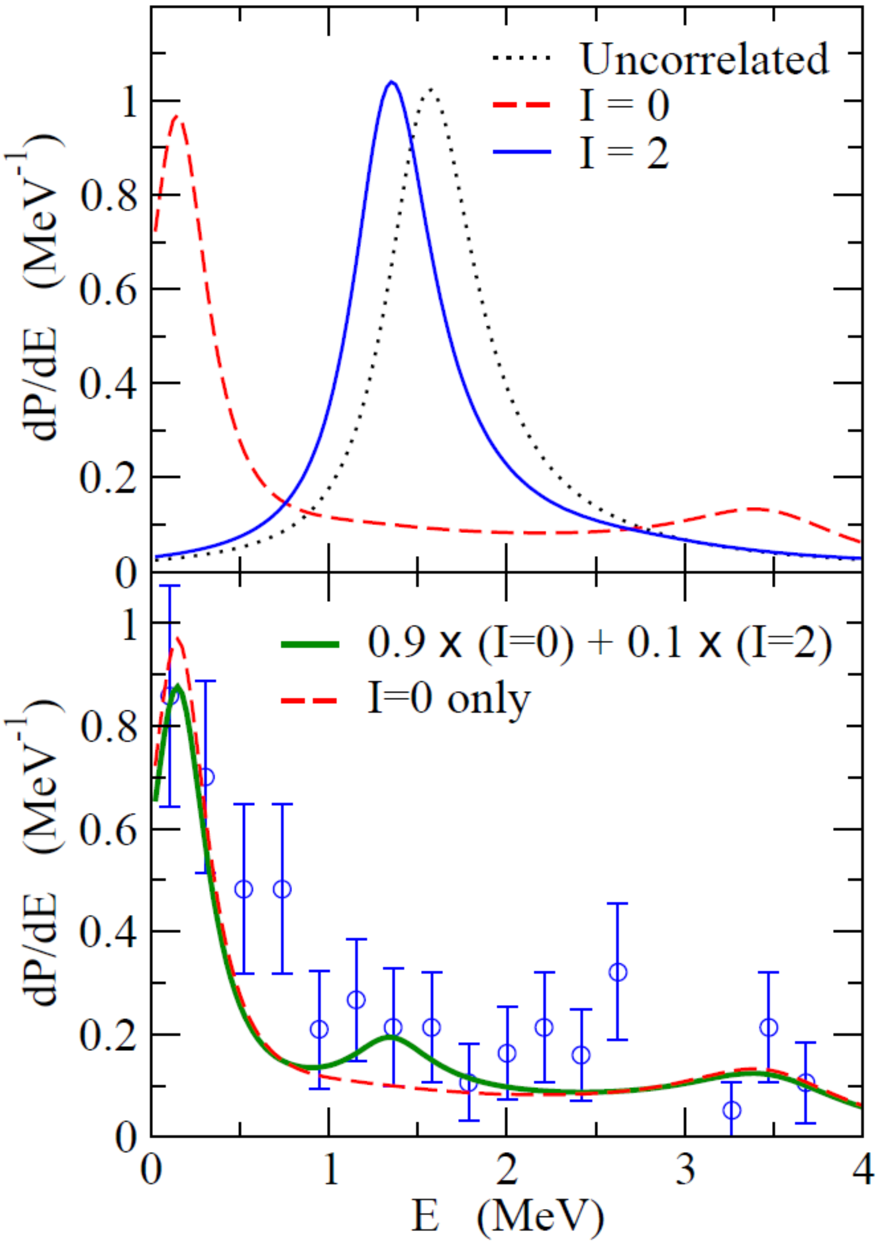
without final state
nn interaction

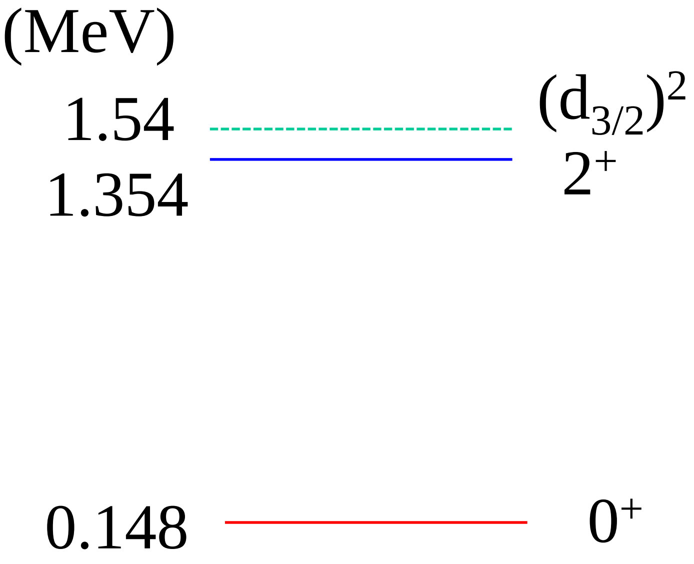
cf. $e_{1d3/2}(^{25}O)$
= 0.770 MeV

very narrow three-body resonance state (Γ_{exp} ~ 10^{-10} MeV)

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

2^+ state of ^{26}O Kondo et al. : a prominent second peak at $E \sim 1.3$ MeV



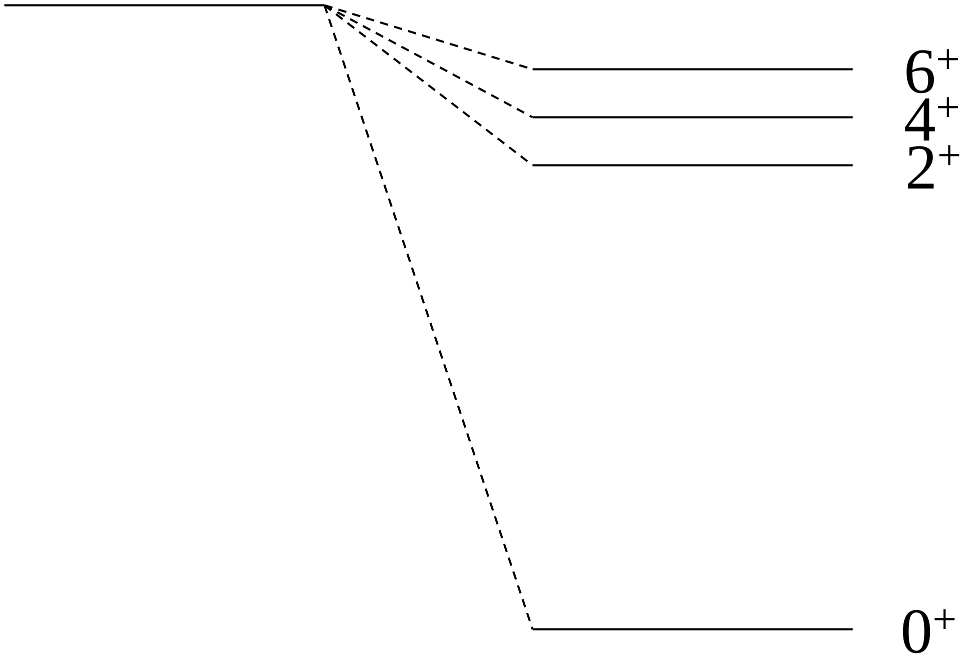


a textbook example
of pairing interaction!

cf. another set of parameters:
$E(0^+) = 5$ keV
$E(2^+) = 1.338$ MeV

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

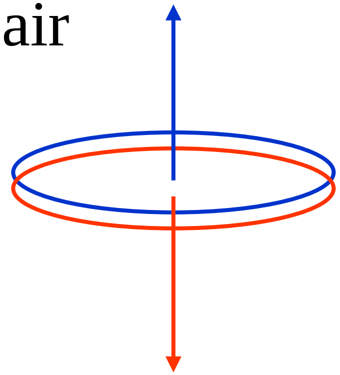
$[jj]^{(I)} = 0^+, 2^+, 4^+, 6^+, \ldots..$



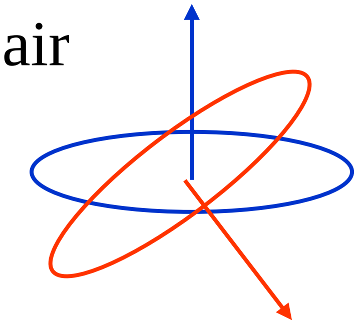
without residual interaction

with residual interaction

I=0 pair

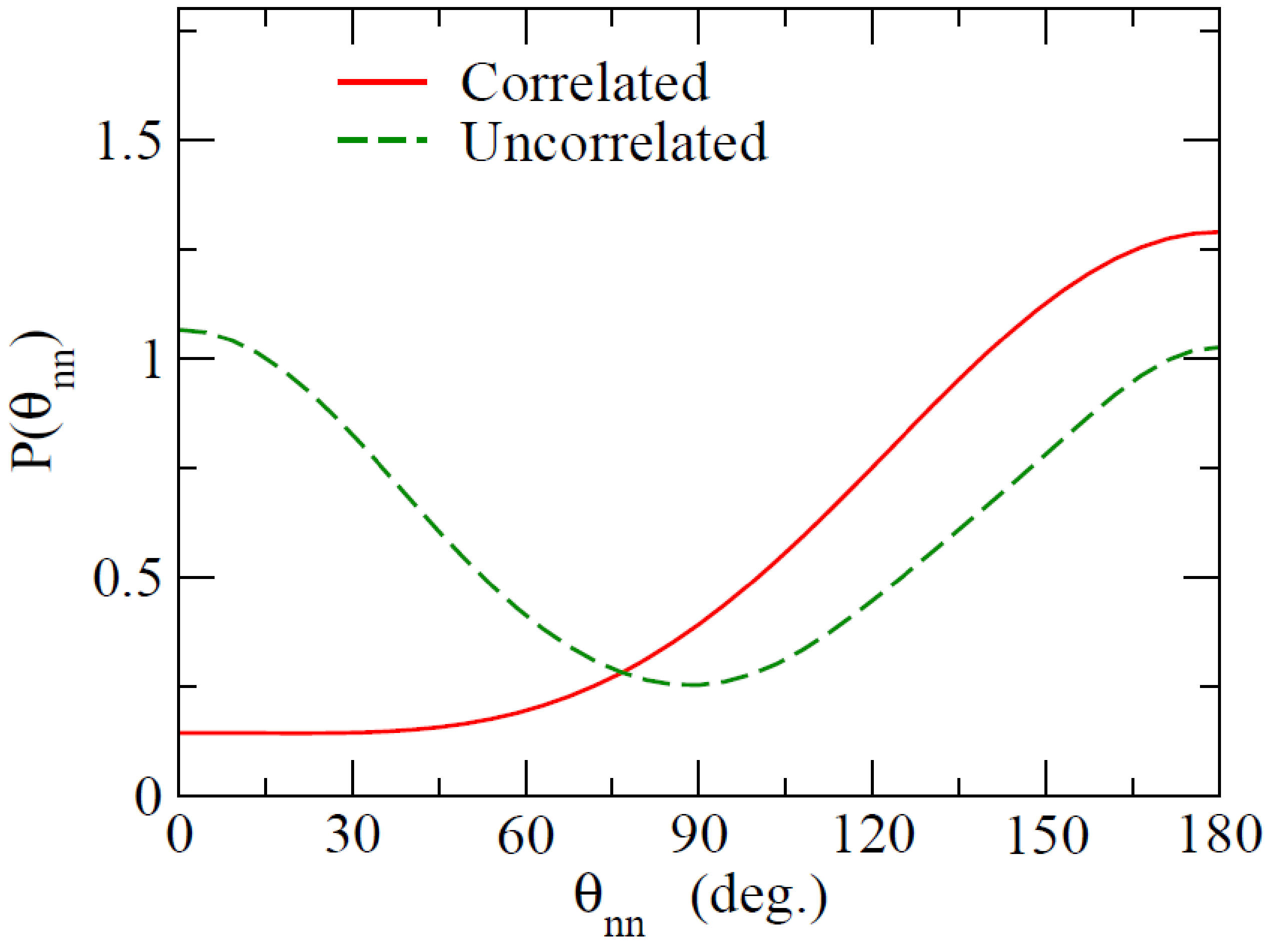


$I \neq 0$ pair



ii) angular correlations of the emitted neutrons

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

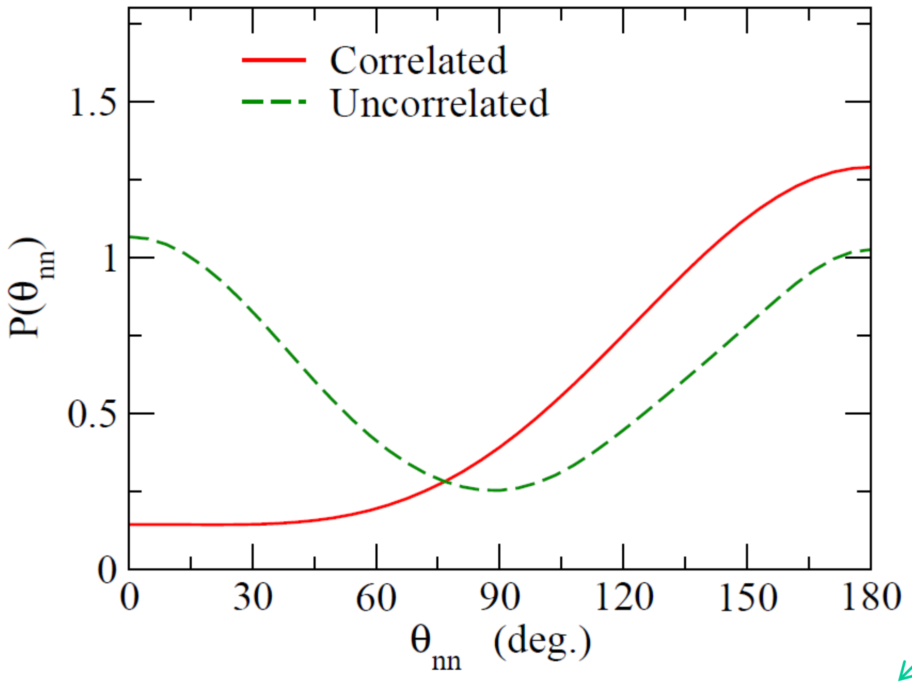


$$\langle \theta_{nn} \rangle = 115.3^\circ$$

correlation → enhancement of back-to-back emissions

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

ii) distribution of opening angle for two-emitted neutrons

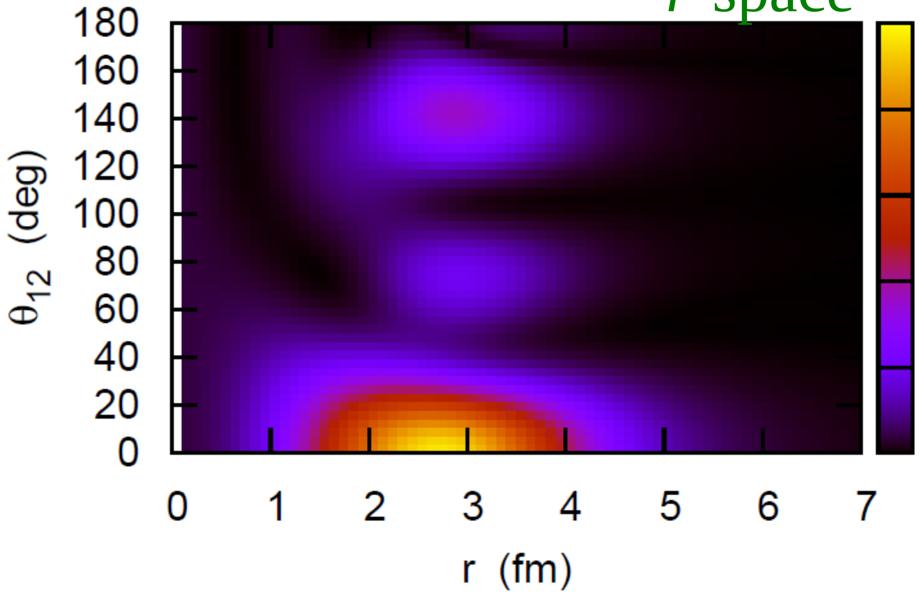


density of the resonance state (with the box b.c.)

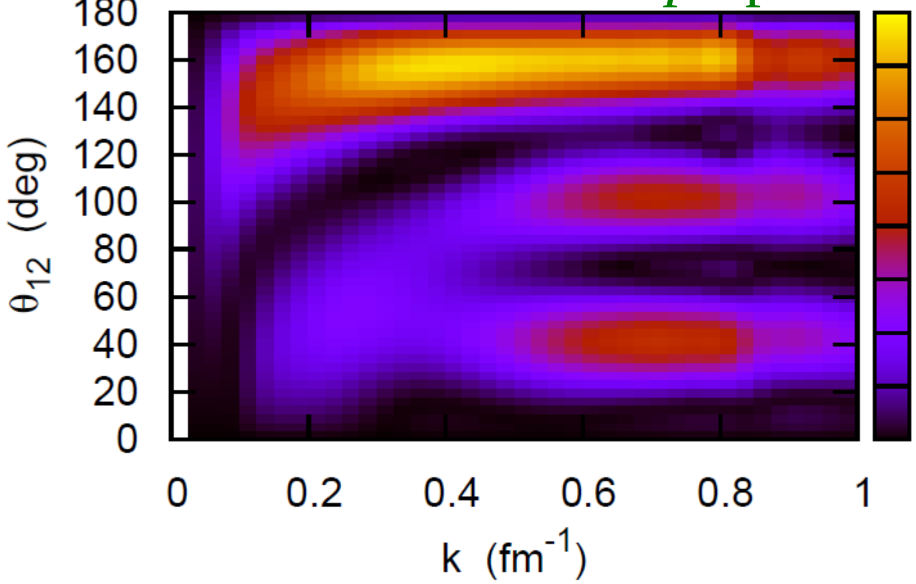
$$\rho(r, r, \theta)$$

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

r-space

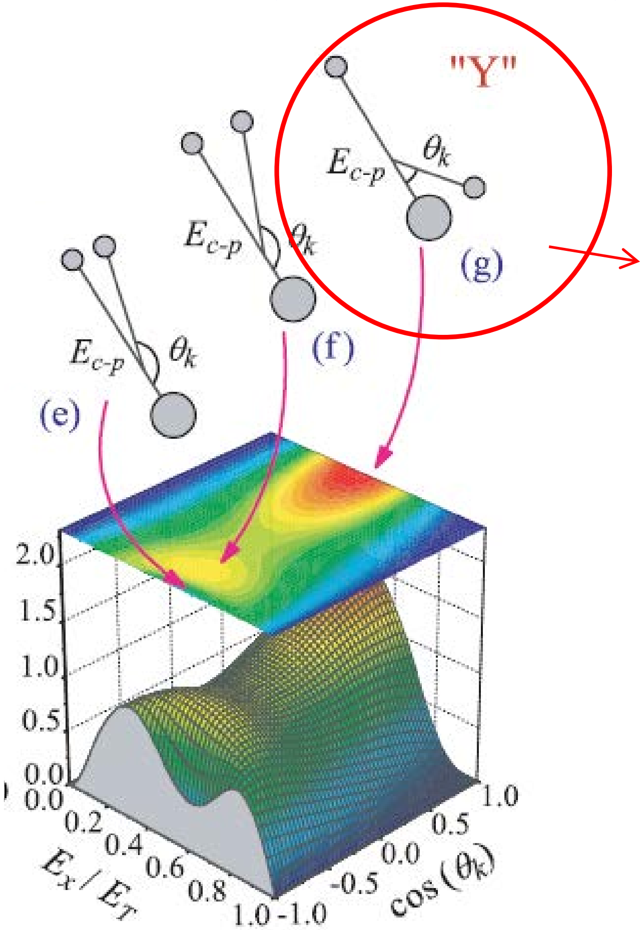


p-space



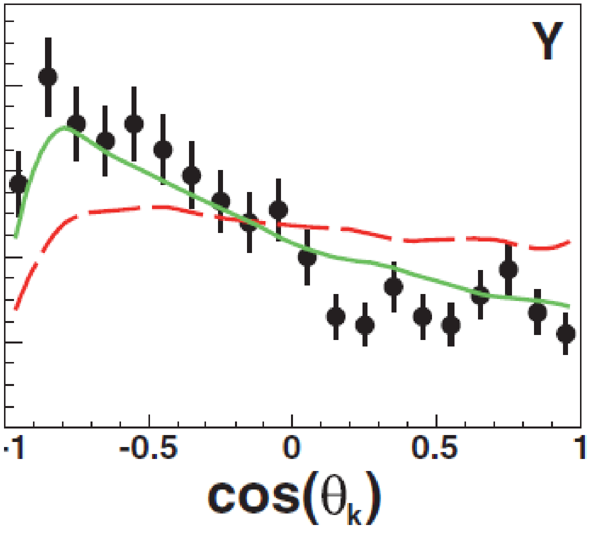
➢Discussions: back-to-back? or forward angles?

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



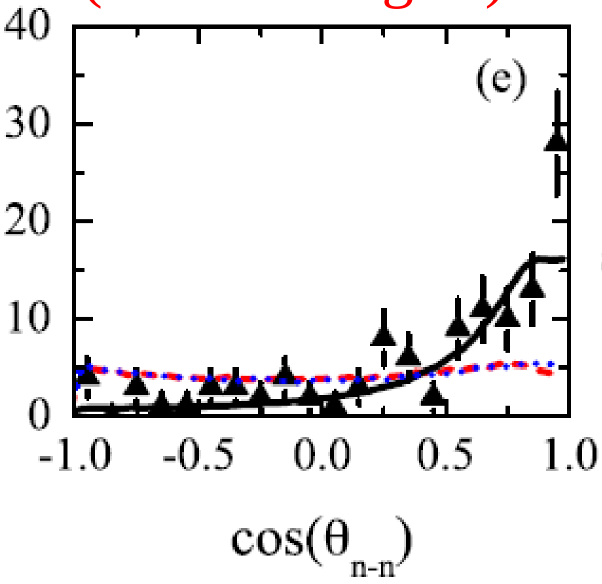
L.V. Grigorenko et al.,
PRC80 (‘09) 034602

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



Z. Kohley et al.,
PRC87(‘13)011304(R)

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



A. Spyrou et al.,
PRL108(‘12) 102501

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

↑

open problem

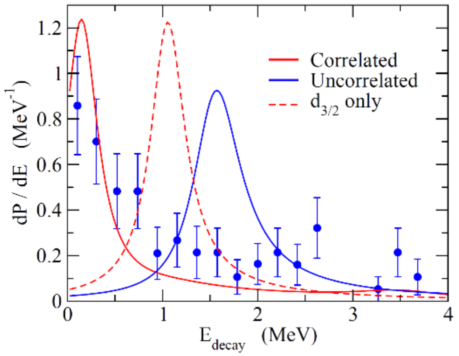
Summary

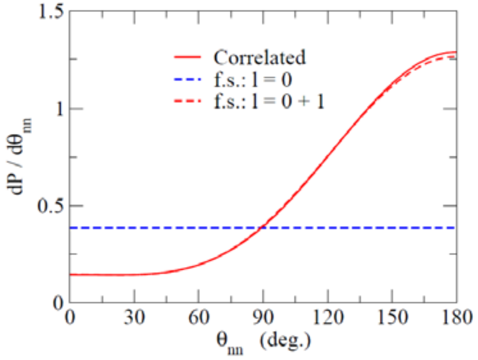
three-body model with
density-dependent zero-range interaction:
continuum calculations: relatively easy

➤ Coulomb breakup of Borromean nuclei
➤ 2n emission decay of ^{26}O

- ✓ Decay energy spectrum: strong low-energy peak
- ✓ 2^+ energy
- ✓ Angular distributions: enhanced back-to-back emission

↔ dineutron emission





☐ open problems

- ✓ Analyses for ^{16}Be, ^{13}Li (especially angular distributions)
- ✓ Decay width?