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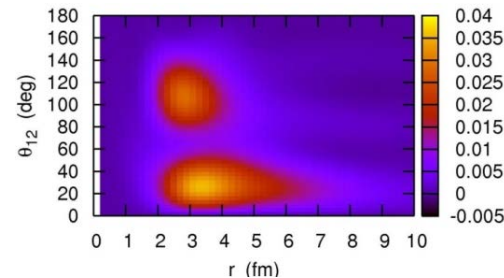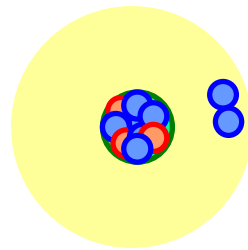
Kouichi Hagino

Tohoku University, Sendai, Japan

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

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

effective NN interaction
strong in-medium effects

(almost) bare NN interaction
weak in-medium effects

di-neutron correlations

Borromean
nuclei

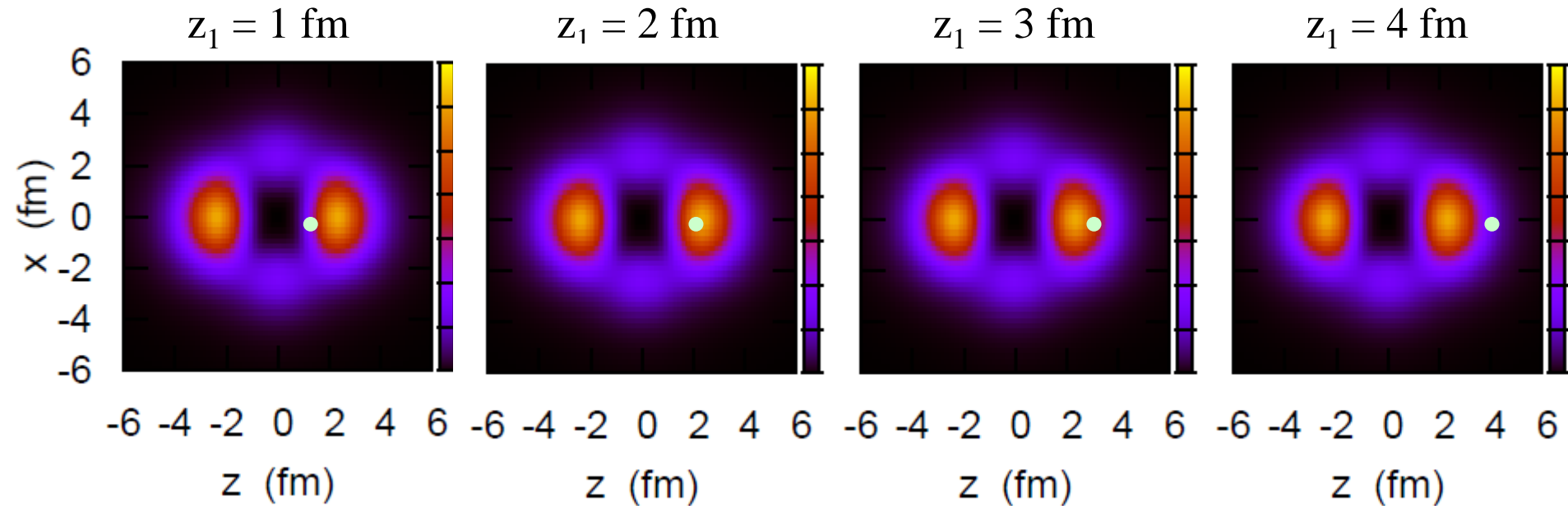Correlation: $\langle AB \rangle \neq \langle A \rangle \langle B \rangle$

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

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

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

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

$z_1 = 1$ fm $z_1 = 2$ fm $z_1 = 3$ fm $z_1 = 4$ fm

✓Two neutrons move independently
✓No influence of the 2nd neutron from the 1st neutron

$$\langle AB \rangle = \langle A \rangle \langle B \rangle$$

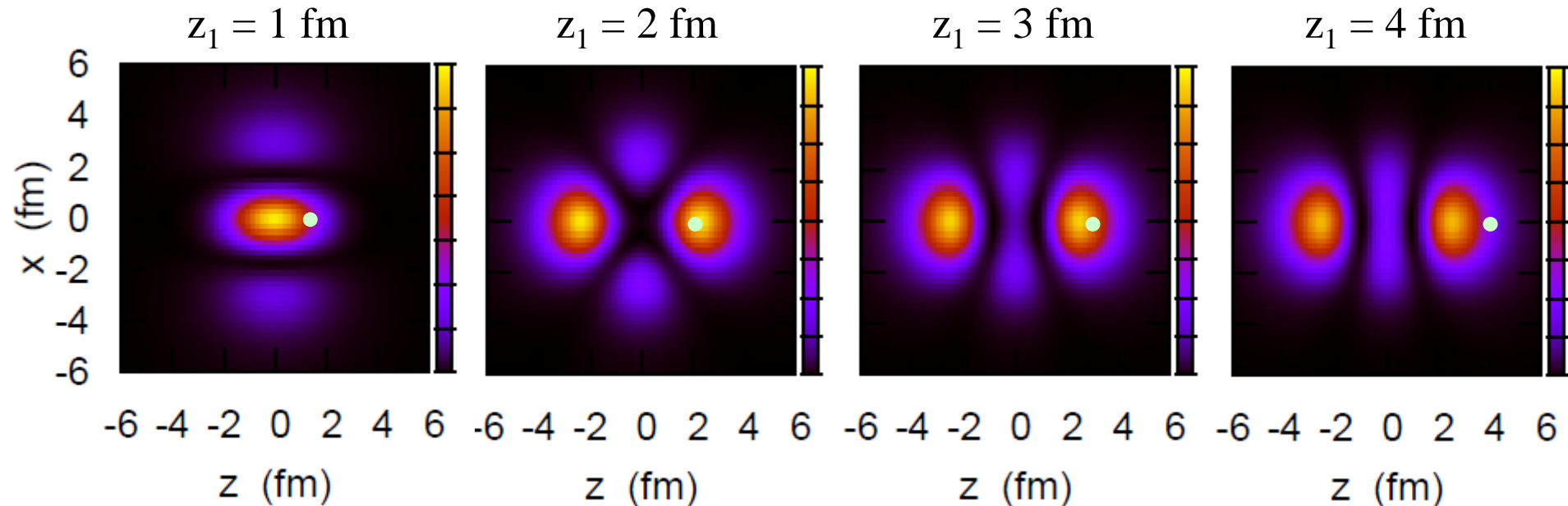# What is Di-neutron correlation?

Correlation: $\langle AB \rangle \neq \langle A \rangle \langle B \rangle$

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

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

ii) nn interaction: works only on the positive parity (bound) states

$$|nn\rangle = \alpha|(1d_{5/2})^2\rangle + \beta|(2s_{1/2})^2\rangle + \gamma|(1d_{3/2})^2\rangle$$

$z_1 = 1$ fm $z_1 = 2$ fm $z_1 = 3$ fm $z_1 = 4$ fm

✓ distribution changes according to the 1st neutron (nn correlation)
✓ but, the distribution of the 2nd neutron has peaks both at z_1 and $-z_1$
⟶ this is NOT called the di-neutron correlation
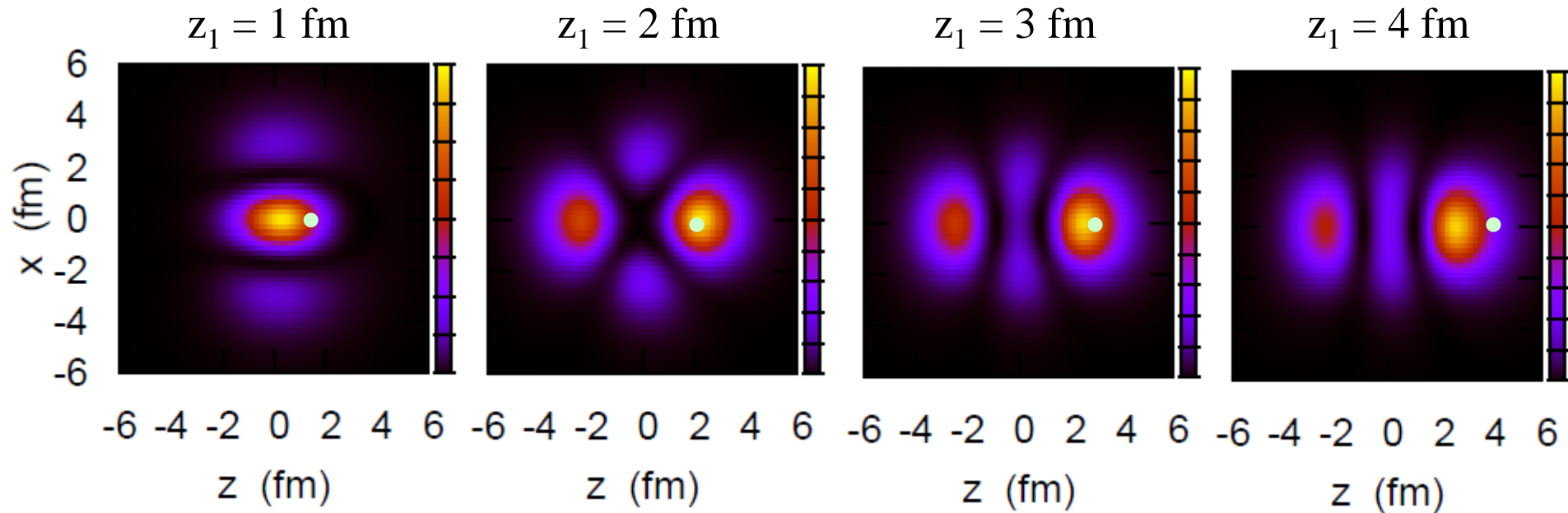
What is Di-neutron correlation?

Correlation : $\langle AB \rangle \neq \langle A \rangle \langle B \rangle$

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

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

iii) nn interaction: works also on the continuum states

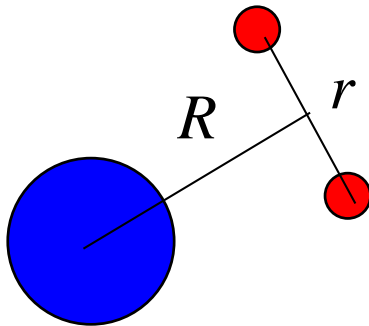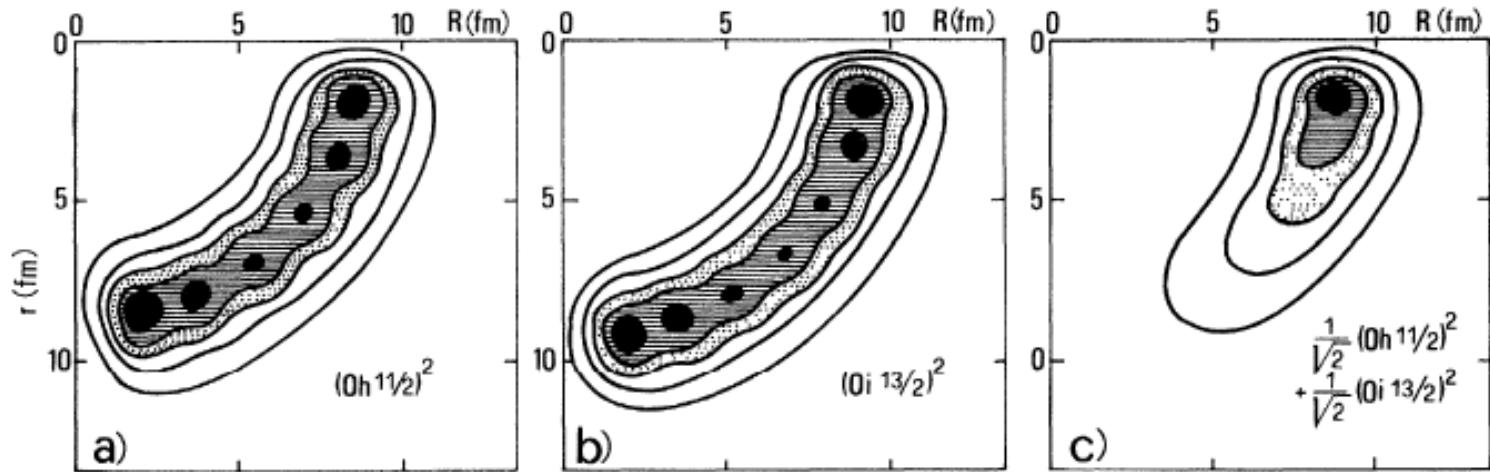$$|nn\rangle = \sum_{n,n',j,l} C_{nn'jl}|(nn'jl)^2\rangle$$

$z_1 = 1$ fm $z_1 = 2$ fm $z_1 = 3$ fm $z_1 = 4$ fm

✓ spatial correlation: the density of the 2nd neutron localized close
to the 1st neutron (dineutron correlation)

✓ parity mixing: essential role

cf. F. Catara et al., PRC29('84)1091

dineutron correlation: caused by the admixture of different parity states

F. Catara, A. Insolia, E. Maglione, and A. Vitturi, PRC29('84)1091
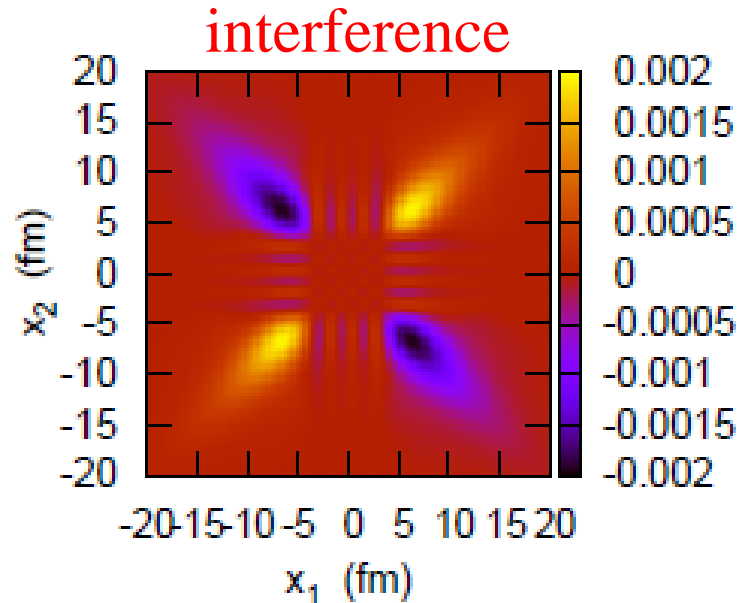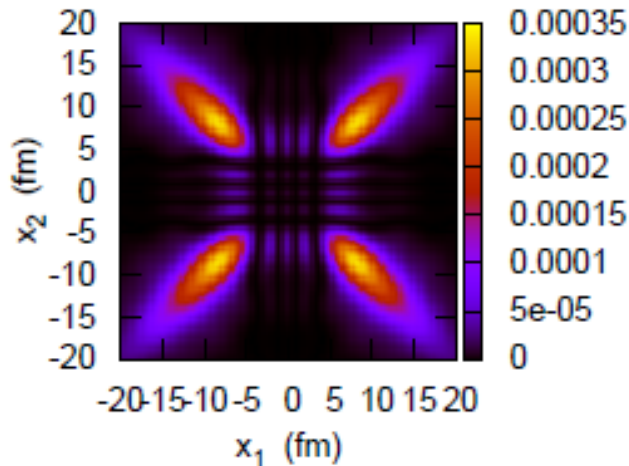
One dimensional 3-body model

$$\Psi_{\mathrm{gs}}(x_1, x_2) = \Psi_{\mathrm{ee}}(x_1, x_2) + \Psi_{\mathrm{oo}}(x_1, x_2)$$

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

$|\Psi_{\mathrm{ee}}(x_1, x_2)|^2$

$|\Psi_{\mathrm{oo}}(x_1, x_2)|^2$

interference

$$\Psi_{\mathrm{ee}}(x_1, x_2)\Psi_{\mathrm{oo}}(x_1, x_2)$$
$$= -\Psi_{\mathrm{ee}}(x_1, -x_2)\Psi_{\mathrm{oo}}(x_1, -x_2)$$

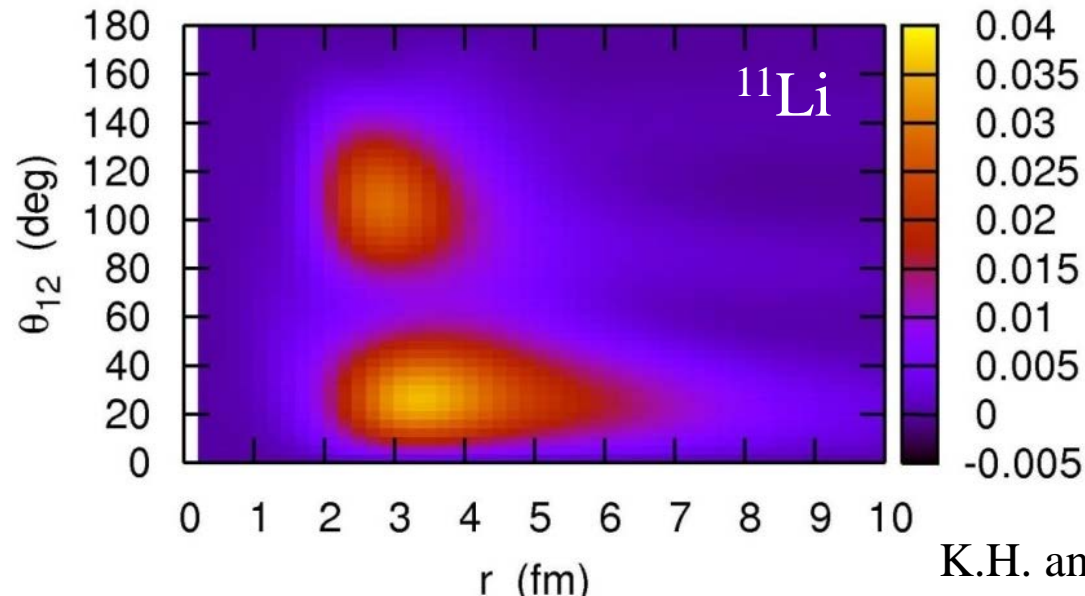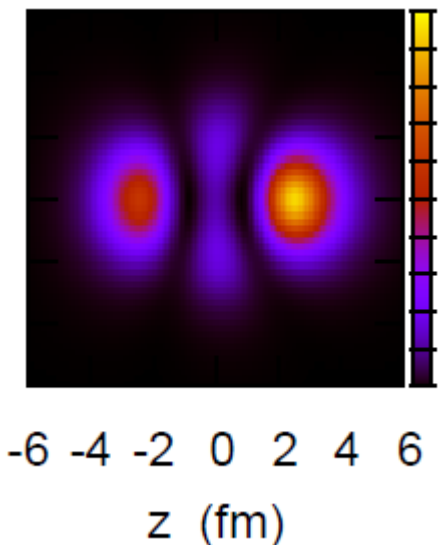spatial localization of two neutrons
(dineutron correlation)

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

weakly bound systems

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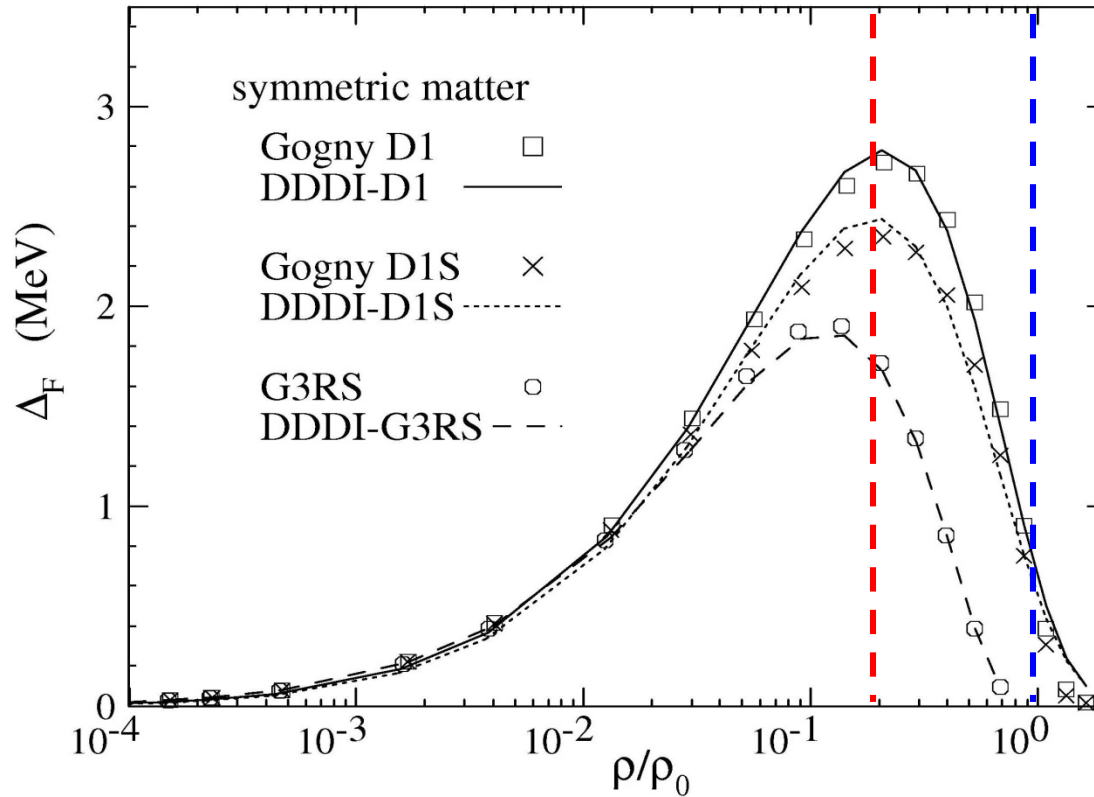+ enhancement of pairing on the surface

parity mixing

^{11}Li
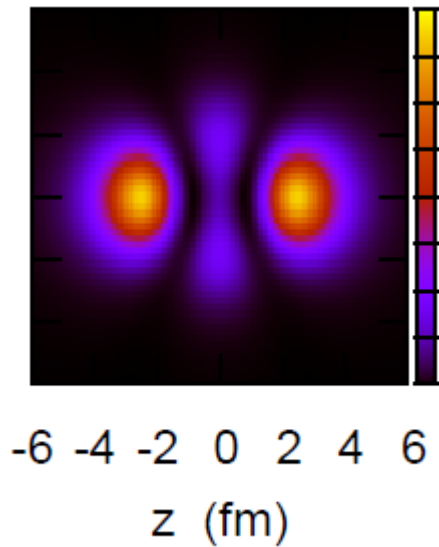
K.H. and H. Sagawa,
PRC72('05)044321

pairing gap in infinite nuclear matter

M. Matsuo, PRC73('06)044309

-6 -4 -2 0 2 4 6
z (fm)

parity mixing

-6 -4 -2 0 2 4 6
z (fm)

spatial localization of two neutrons
(dineutron correlation)

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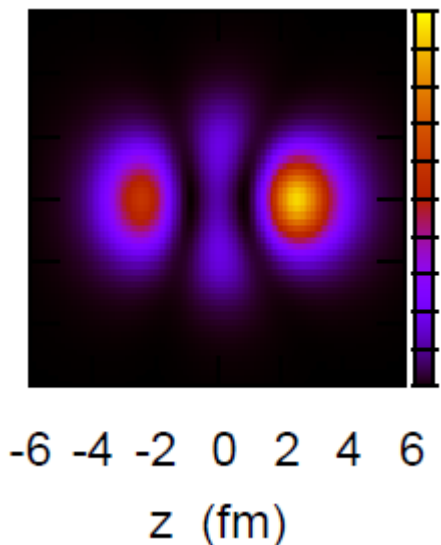Bertsch, Broglia, Riedel, NPA91('67)123

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
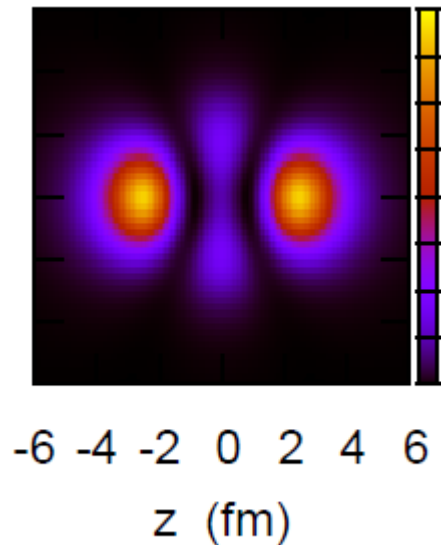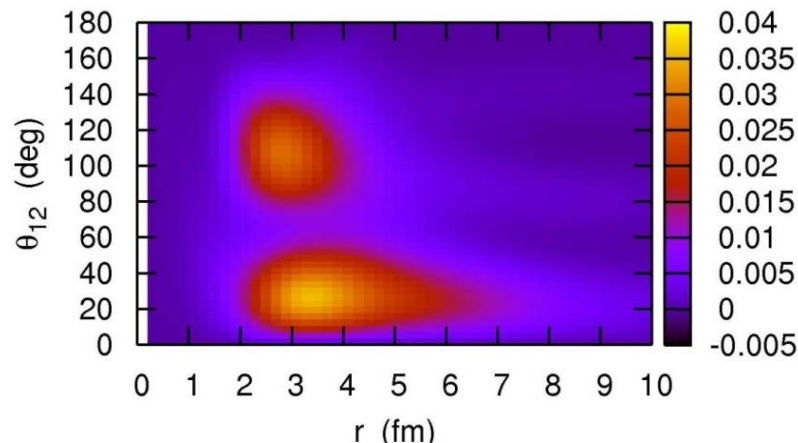
K.H. and H. Sagawa, PRC72('05)044321
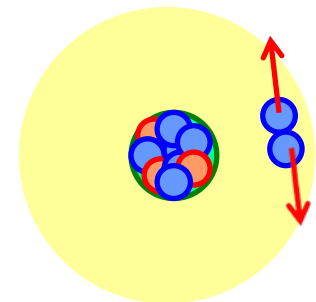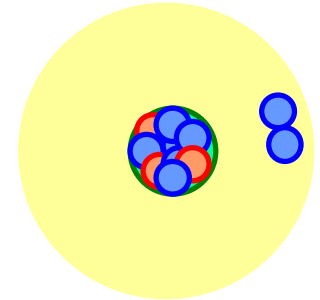
Dineutron correlation in the momentum space

$$\Psi(r, r') = \alpha \, \Psi_{s2}(r, r') + \beta \, \Psi_{p2}(r, r')$$

$\longrightarrow \theta_r = 0$: enhanced

$\longrightarrow$ Fourier transform

$$\tilde{\Psi}(k, k') = \int e^{ik \cdot r} e^{ik' \cdot r'} \Psi(r, r') dr dr'$$

$$e^{ik \cdot r} = \sum_l (2l+1) i^l \ldots \longrightarrow \quad i^l \cdot i^l = i^{2l} = (-)^l$$
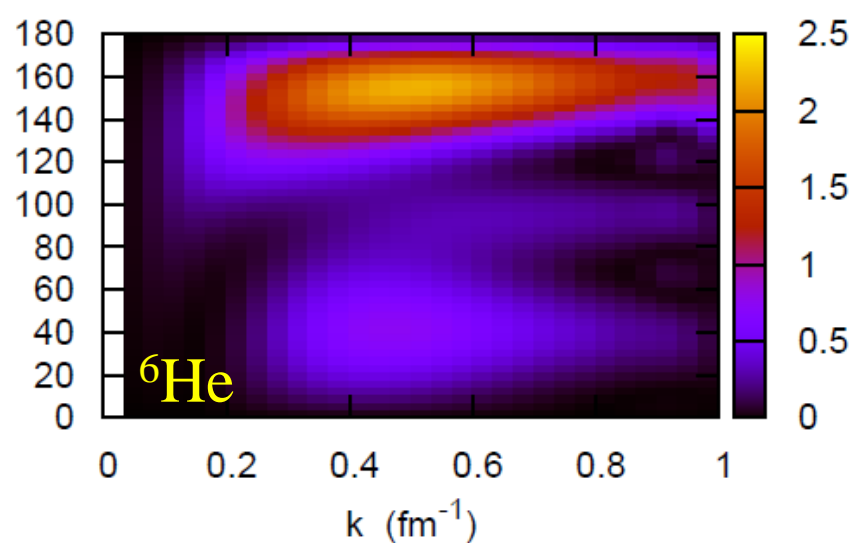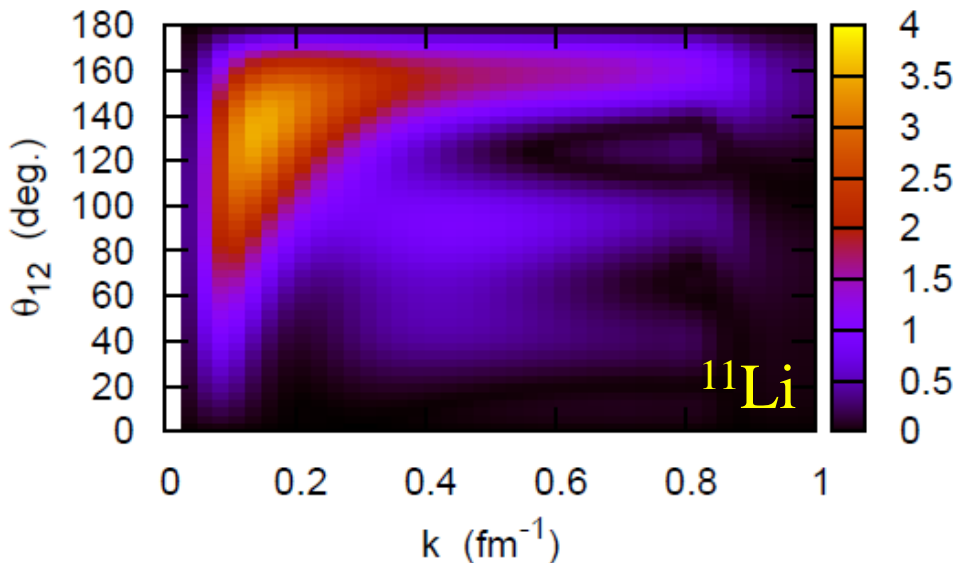
$$\uparrow \qquad \uparrow$$
$$r \qquad r'$$

$$\tilde{\Psi}(k, k') = \alpha \, \tilde{\Psi}_{s2}(k, k') - \beta \, \tilde{\Psi}_{p2}(k, k')$$

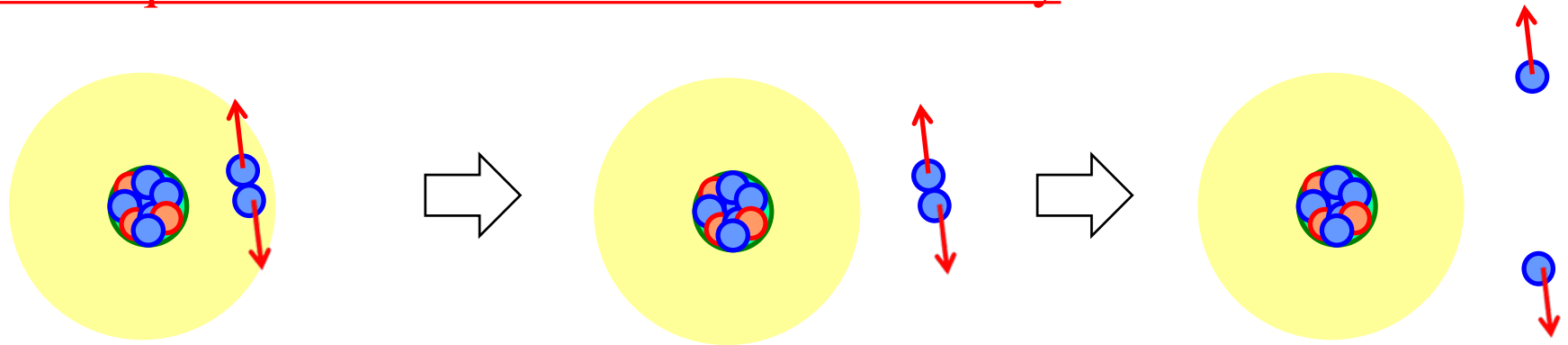$\longrightarrow \theta_k = \pi$: enhanced

Two-particle density in the r space: $8\pi^2 r^4 \sin\theta \cdot \rho(r,r,\theta)$
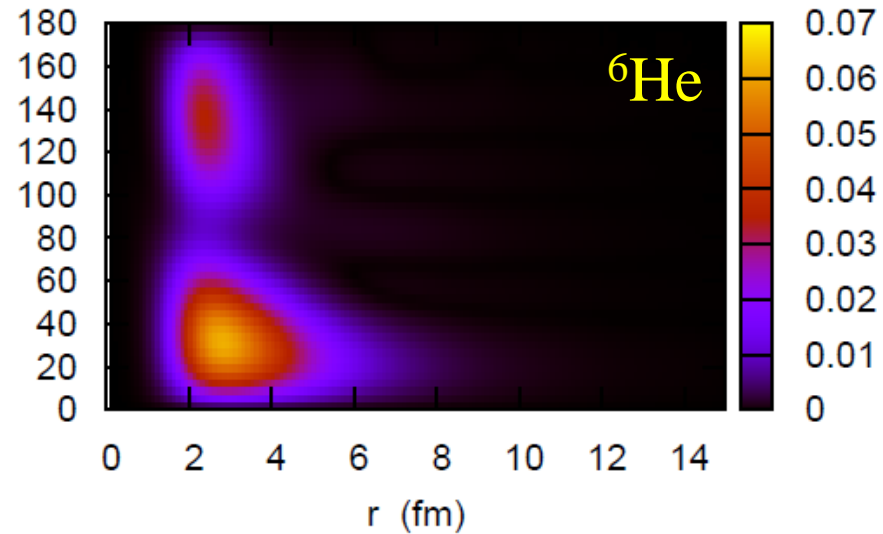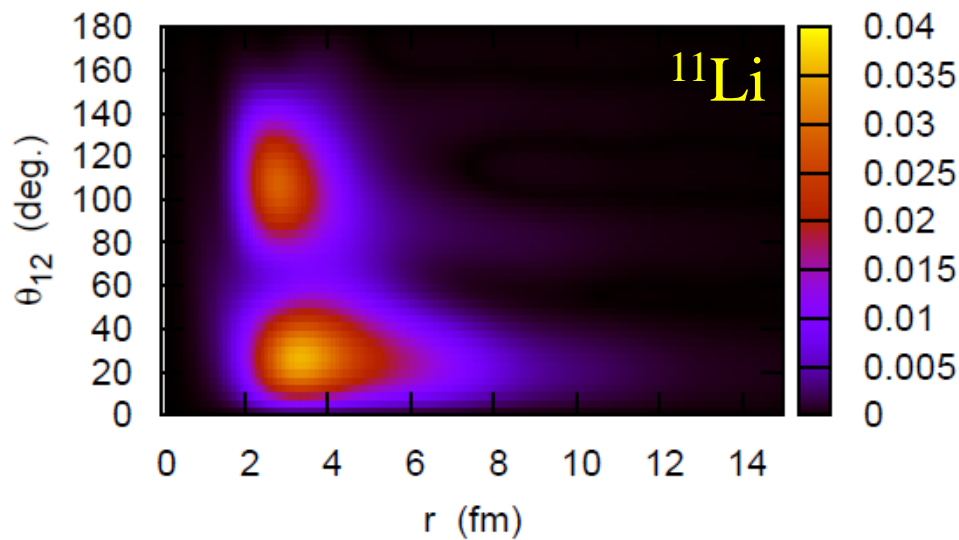
Two-particle density in the p space: $8\pi^2 k^4 \sin\theta \cdot \rho(k,k,\theta)$
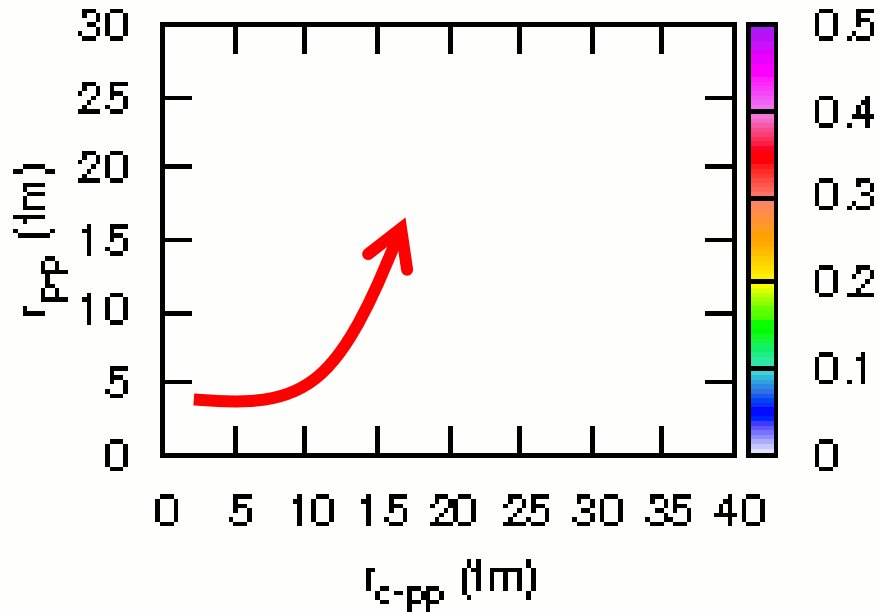
Consequence to a two-nucleon emission decay
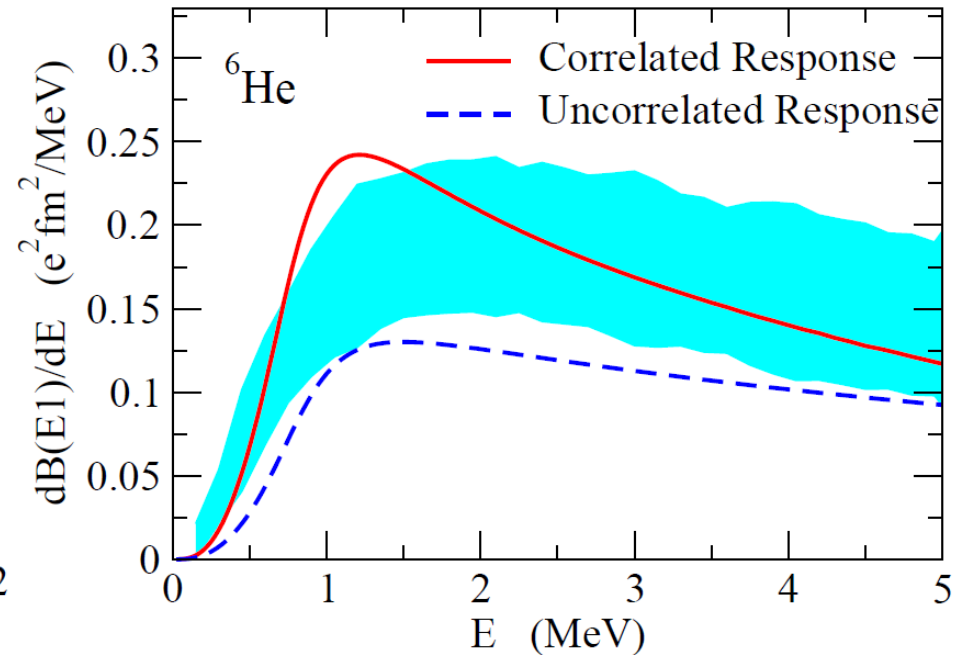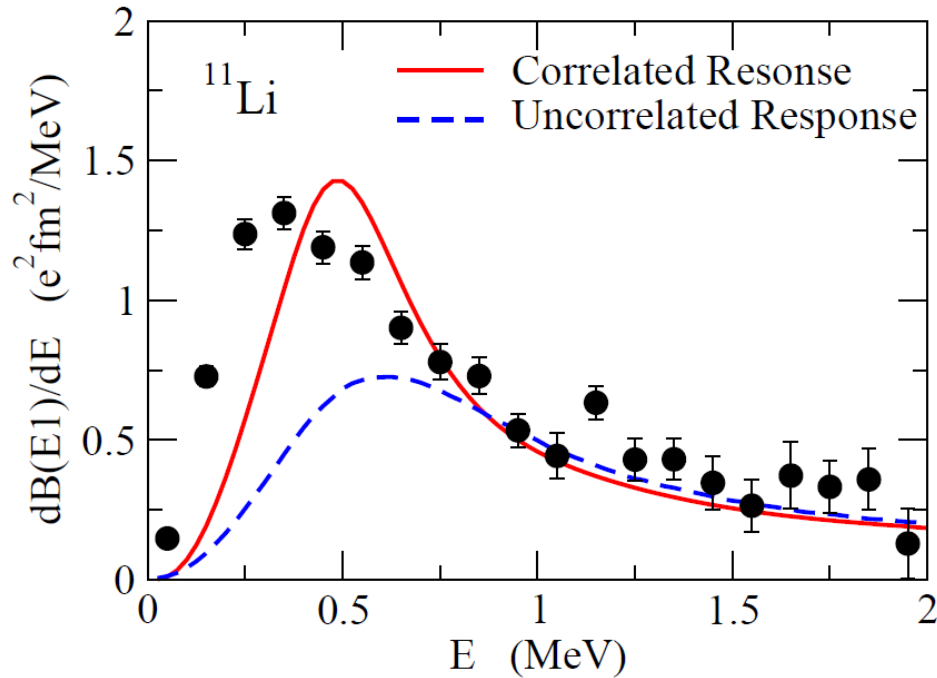

2p decay of ^{6}Be
: time-dependent calculations

ct = 0 (fm)

T. Oishi (Tohoku → Jyvaskyla),
K.H., H. Sagawa,
arXiv:1403.3019

Coulomb breakup of 2-neutron halo nuclei

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

Experiments:

T. Nakamura et al., PRL96('06)252502
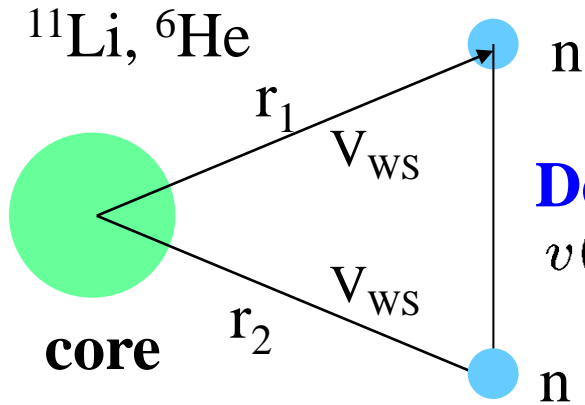
T. Aumann et al., PRC59('99)1252

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)

also for ^{22}C, ^{14}Be, ^{19}B etc. (T. Nakamura et al.)
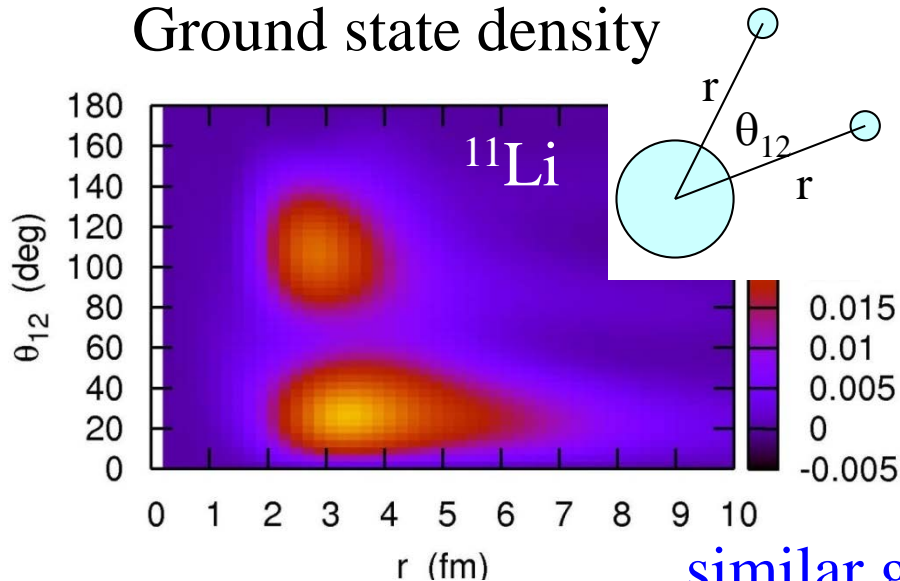
3-body model calculation for Borromean nuclei

^{11}Li, ^{6}He

r_1

V_{ws}

n

V_{ws}

r_2

core

n

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

^{11}Li

r
θ_{12}
r

^{6}He
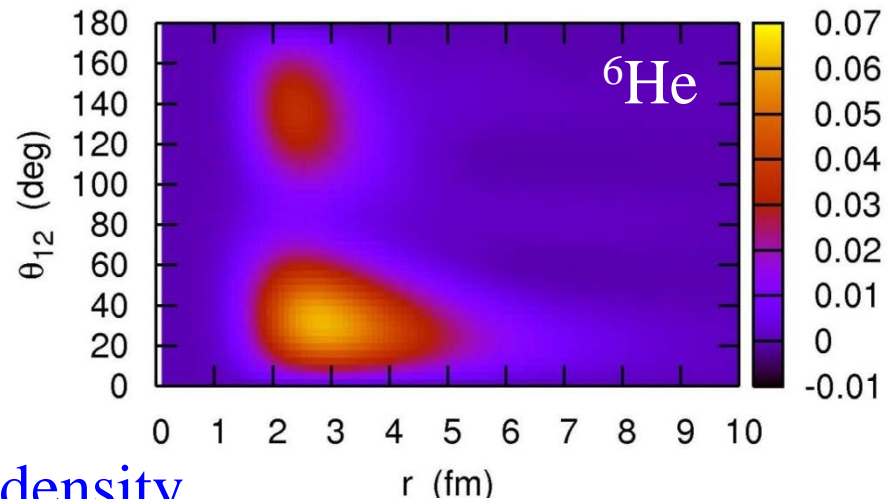
similar g.s. density

E1 excitation to the continuum states
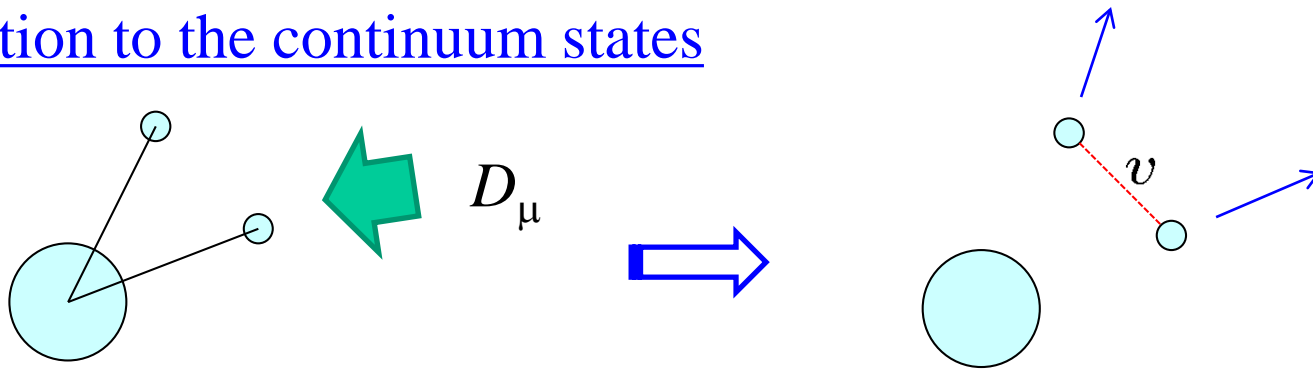
$$M(E1) = \langle (j_1 j_2)^1_\mu | (1 - vG_0 + vG_0vG_0 - \cdots)D_\mu|\Psi_{gs}\rangle$$
$$= \langle (j_1 j_2)^1_\mu | (1 + vG_0)^{-1}D_\mu|\Psi_{gs}\rangle$$

unperturbed continuum wf

FSI

dipole operator

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

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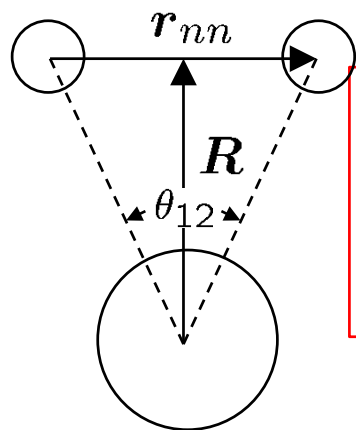

H. Esbensen and G.F. Bertsch, NPA542('92)310
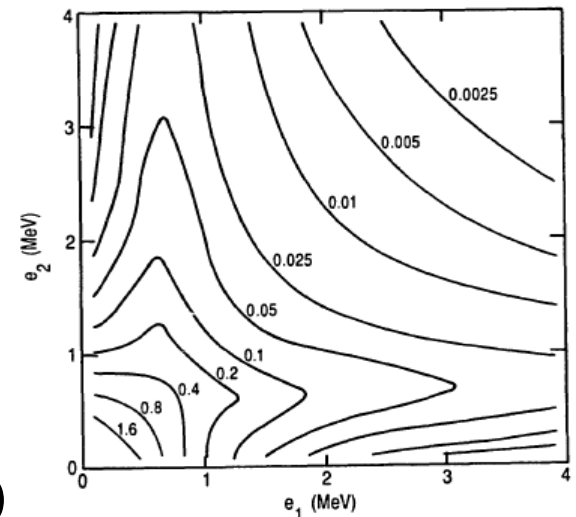
g.s. correlation? or correlation in excited states?

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

g.s. correlation + FSI

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

g.s. : odd-l only
(no dineutron correlation)
＋FSI
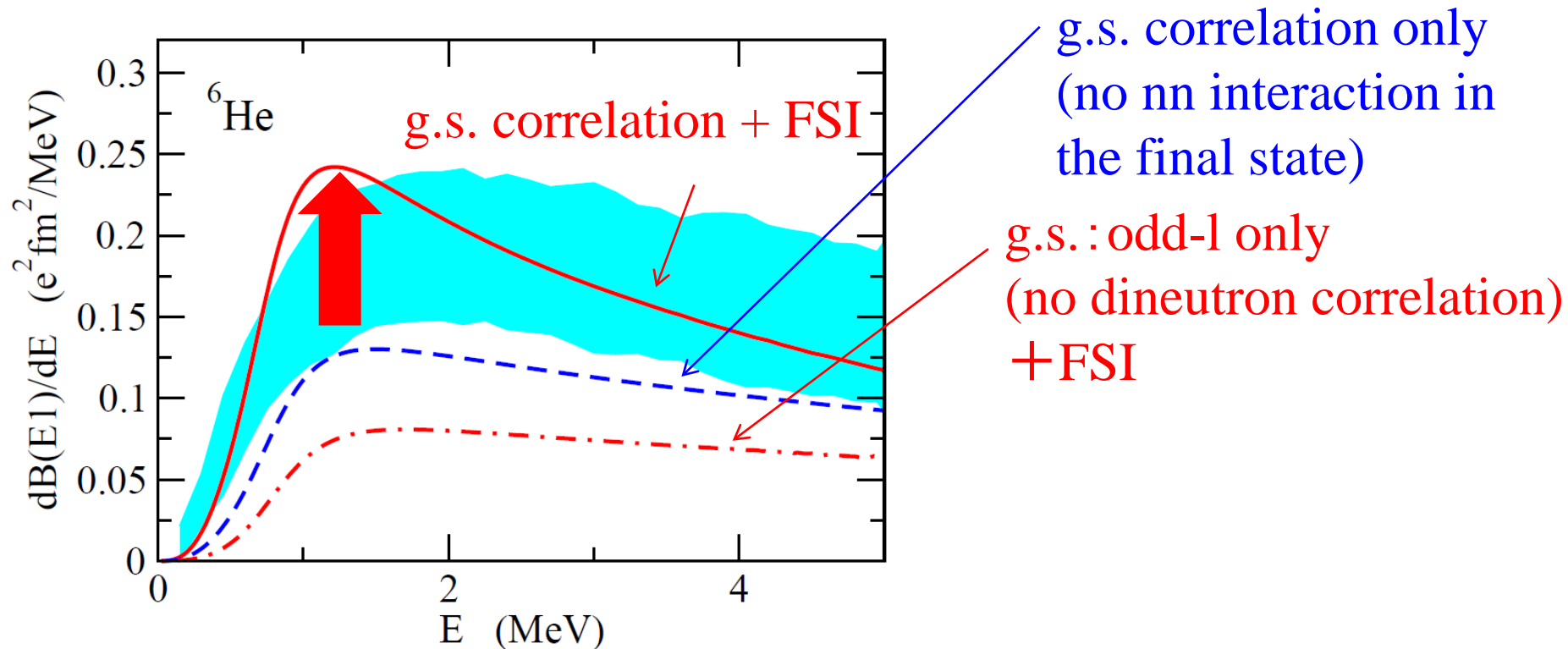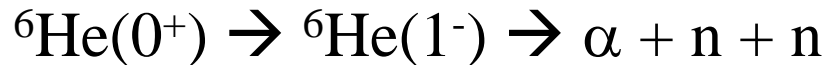
✓Both FSI and dineutron correlations: important role in E1 strength

Geometry of Borromean nuclei

r_{nn}

R

θ_{12}

Cluster sum rule

$$B_{\text{tot}}(E1) = \sum_f |\langle \Psi_f | \hat{T}_{E1} | \Psi_0 \rangle|^2$$

$$\sim \frac{3}{\pi} \left(\frac{Z_c e}{A_c + 2} \right)^2 \langle R^2 \rangle$$

reflects the g.s. correlation

3-body model calculations

- Total
- S=0 component
- S=1 component

$2\pi \sin\theta \, \rho(\theta)$ vs θ_{12} (deg)

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

"experimental data" for opening angle

$\sqrt{\langle R^2 \rangle}$ ⟵ $B_{\text{tot}}(E1)$

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

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

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

suggests dineutron corr.
(but, an average of small and large angles)

K.H. and H. Sagawa, PRC76('07)047302

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

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

^{6}He

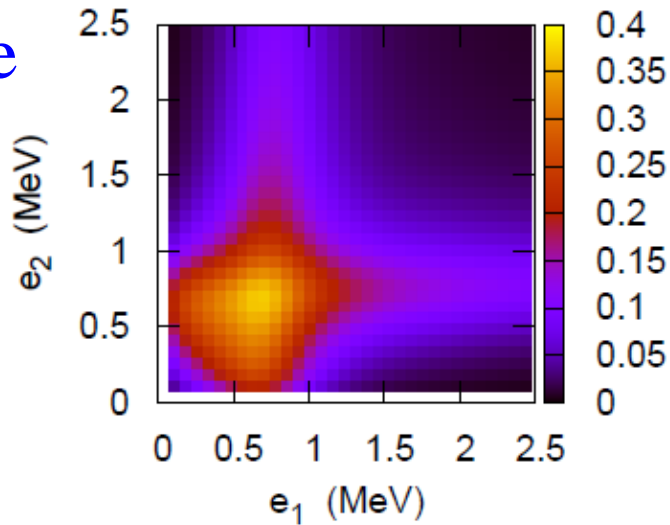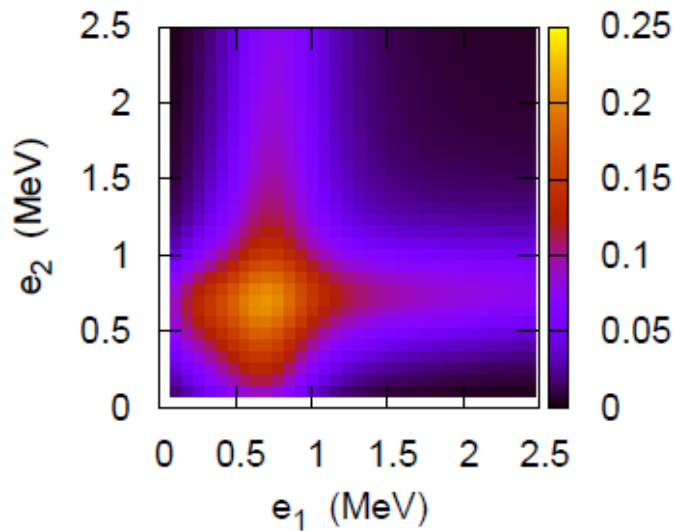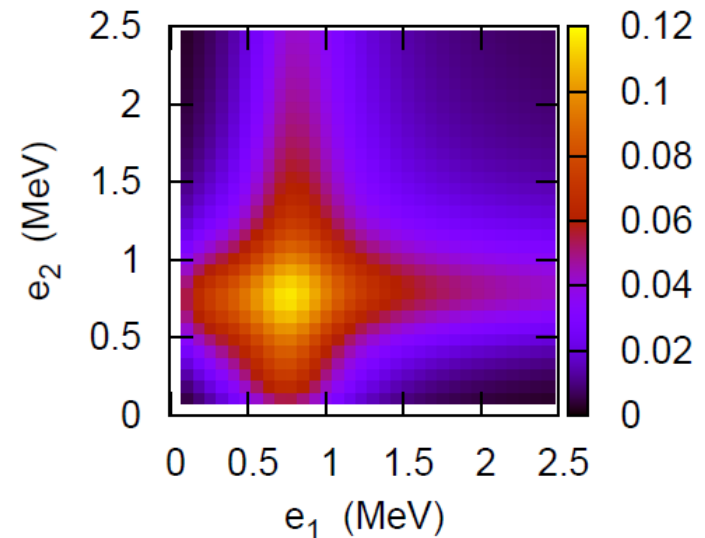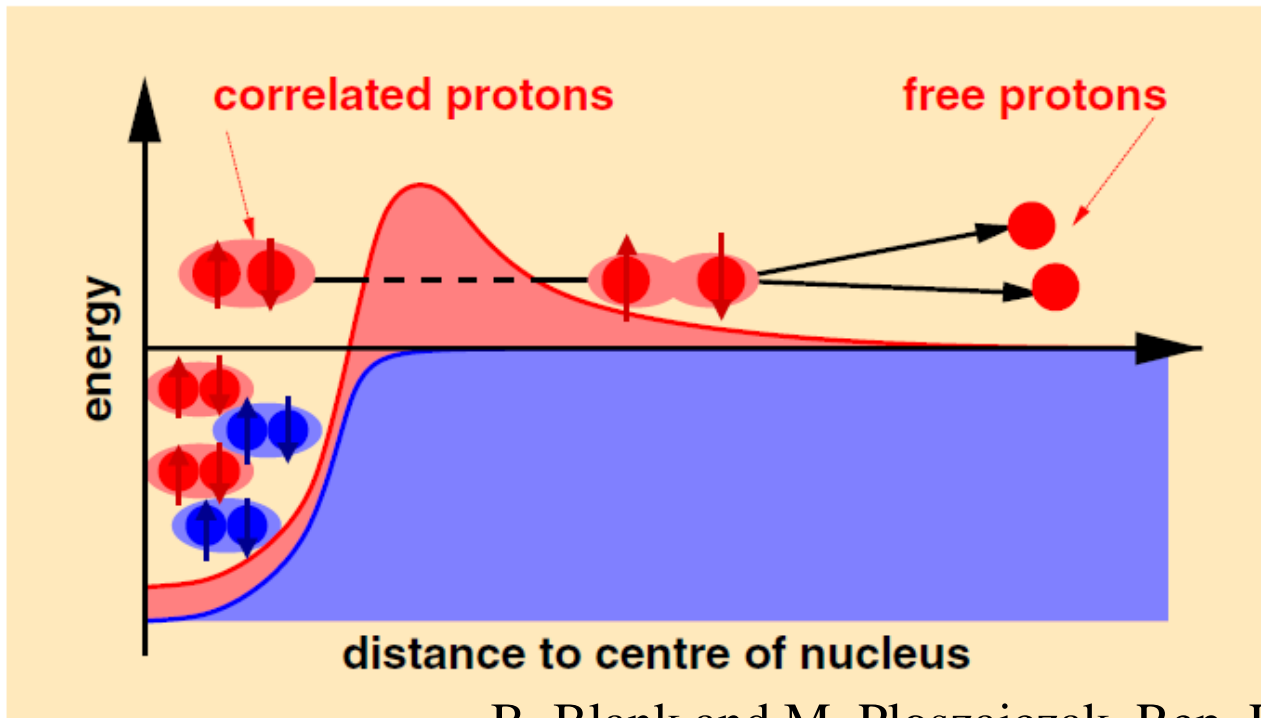✓shape of distribution: insensitive to the nn-interaction (except for the absolute value)
✓strong sensitivity to V_{nC}
✓similar situation in between ^{11}Li and ^{6}He

$v_{nn} = 0$

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
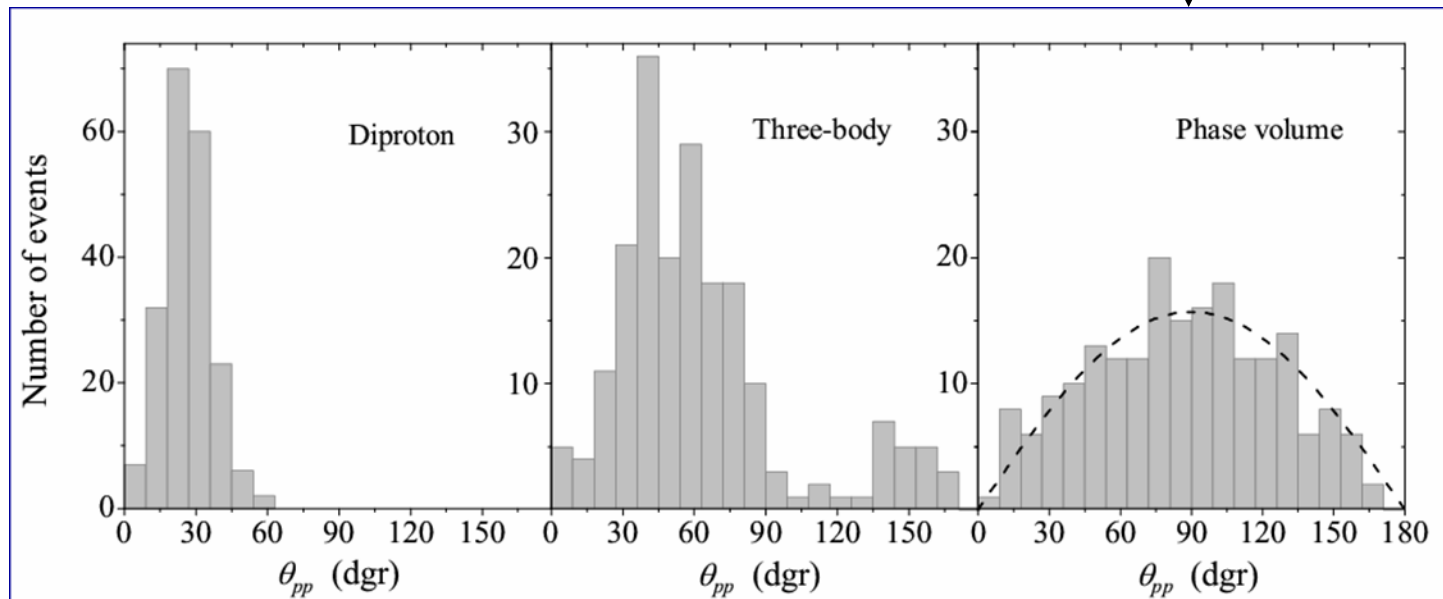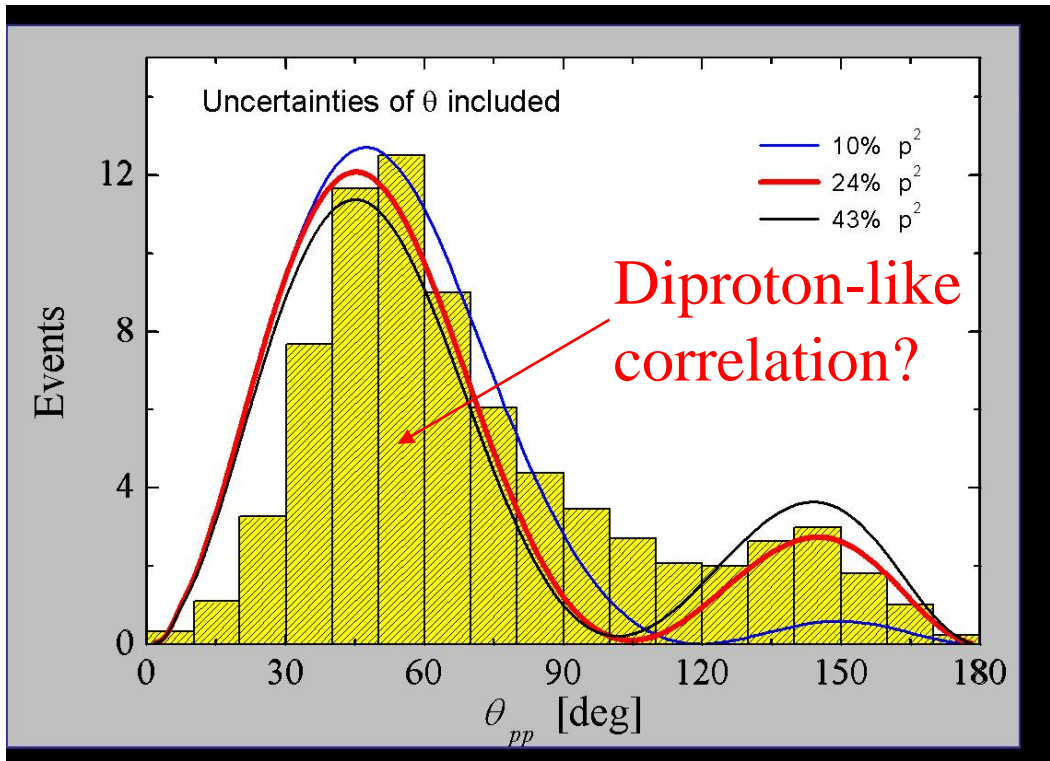- how does FSI disturb the g.s. correlation?
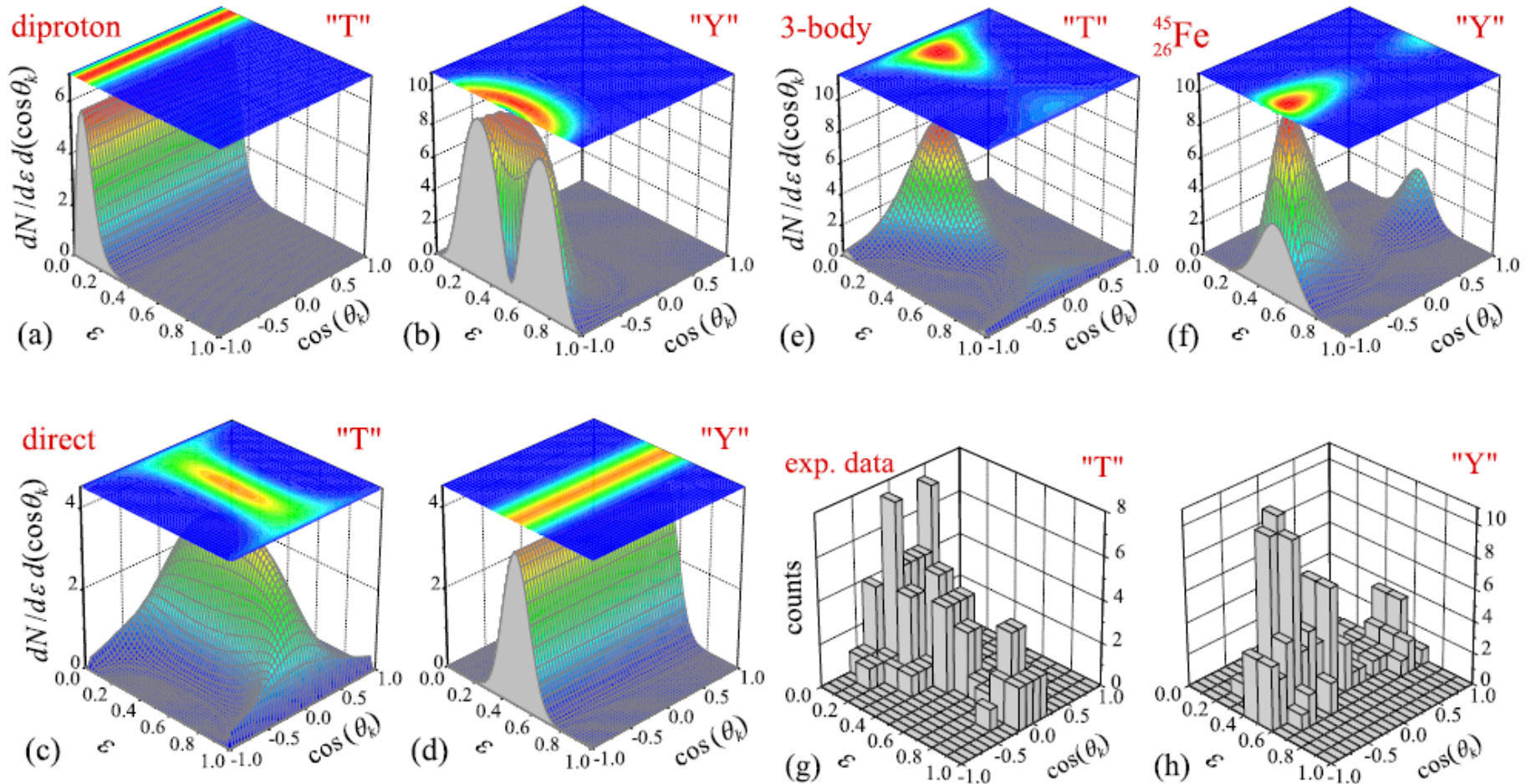
2-proton decay of ^{45}Fe

Uncertainties of θ included

10% p²
24% p²
43% p²

Diproton-like correlation?

K. Miernik et al.,
PRL99 ('07) 192501

← experimental data

calculations (Grigorenko)

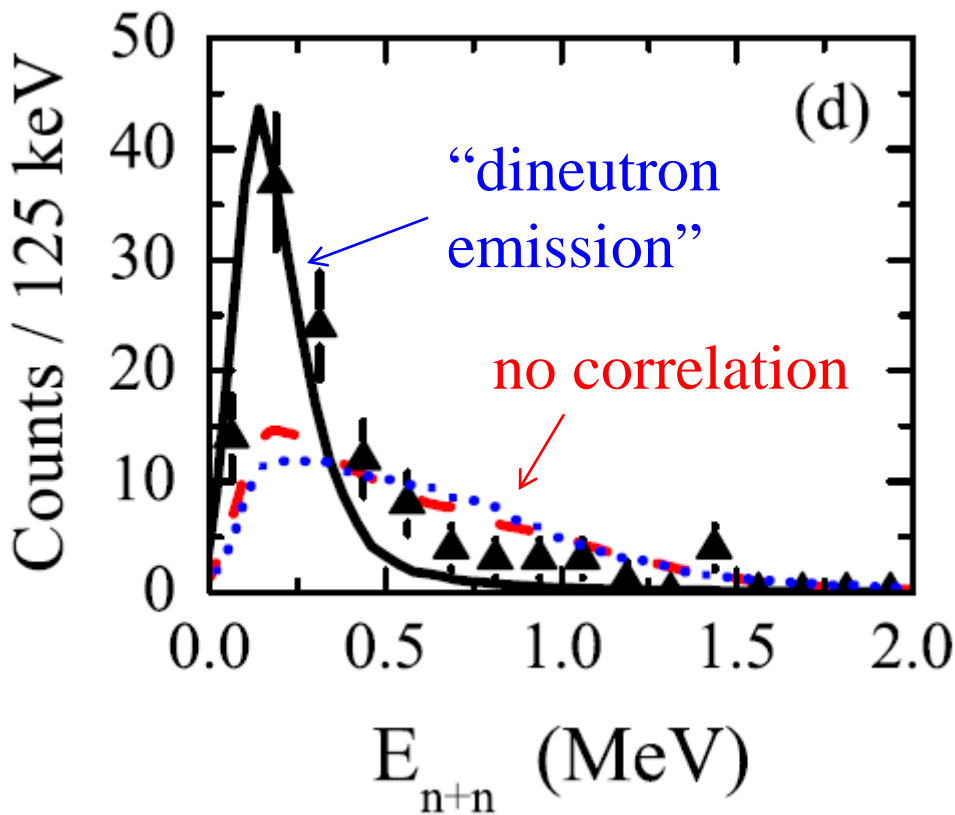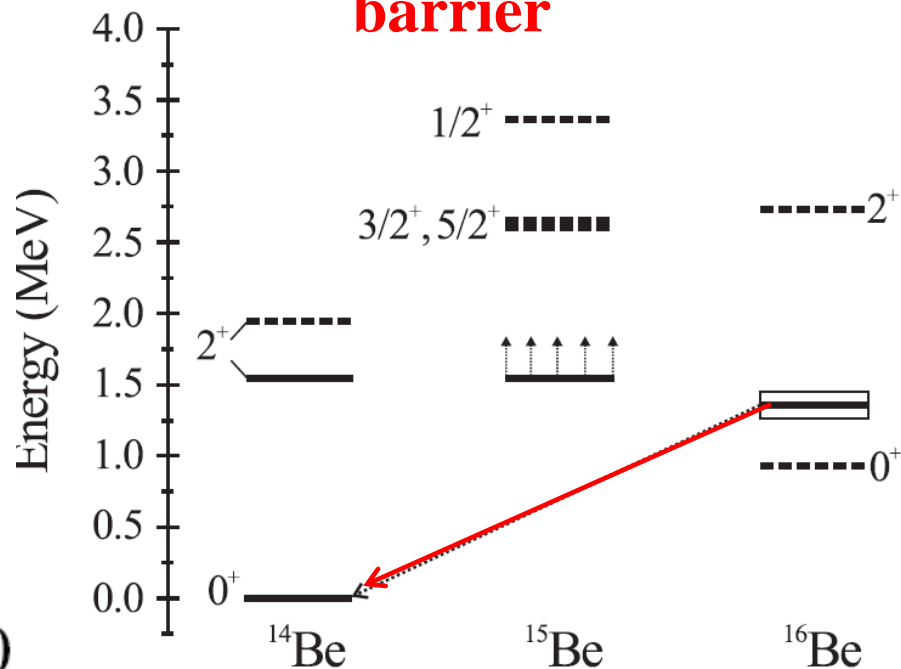RMP 84 ('12) 567

Diproton   Three-body   Phase volume

M. Pfutzner, M. Karny, L.V. Grigorenko, K. Riisager, Rev. Mod. Phys. 84 ('12) 567

⟶ diproton correlation: unclear in many other 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

"dineutron emission"

no correlation

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
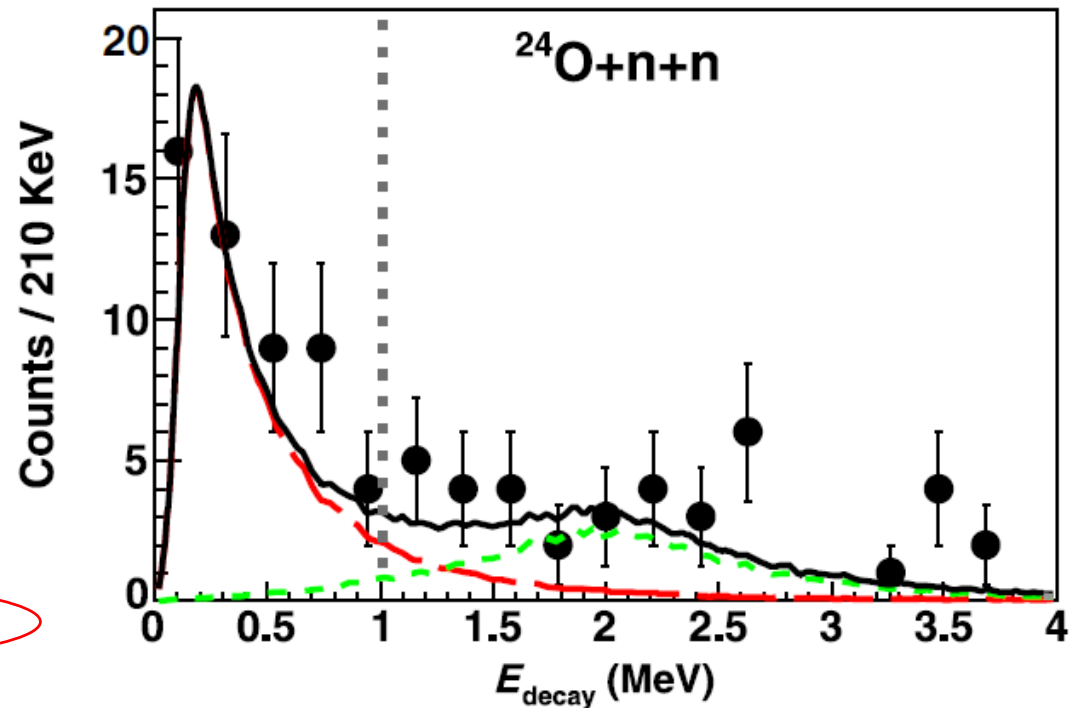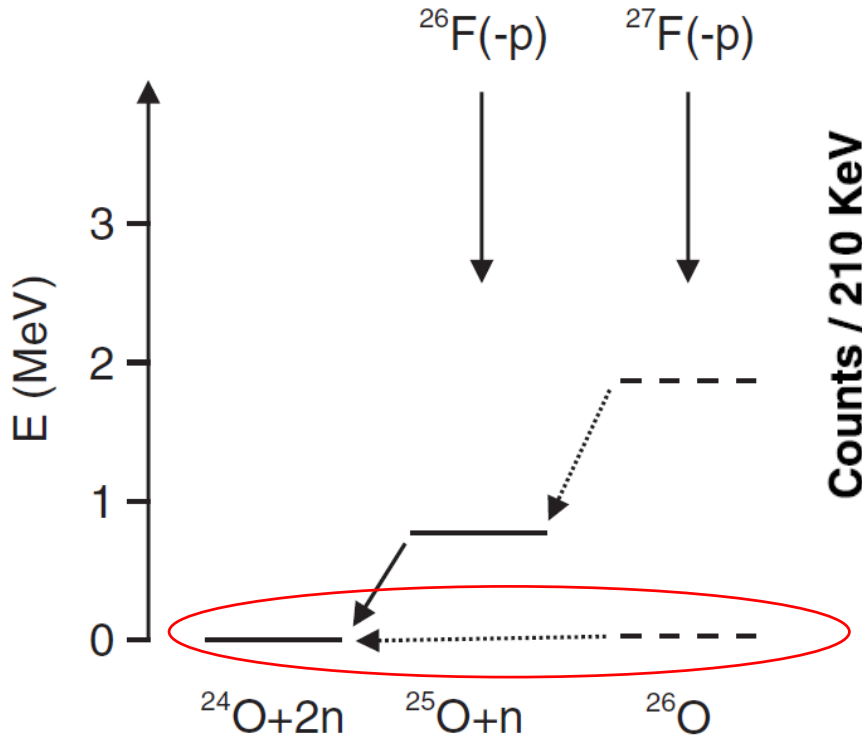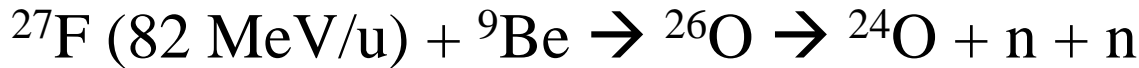
➤ the simplest among ^{16}Be, ^{13}Li, ^{26}O (MSU)

   ^{16}Be: deformation, ^{13}Li: treatment of ^{11}Li core

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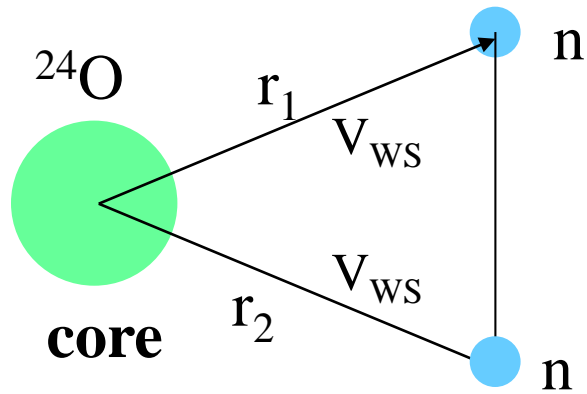
Z. Kohley et al., PRL 110 ('13)152501

^{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

i) Decay energy spectrum

^{24}O

r_1

v_{ws}

v_{ws}

r_2

core

n

n

➤ ^{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

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

$$= -\frac{1}{\pi} \Im \langle \Phi_{ref}^{(I)} | G^{(I)}(E) | \Phi_{ref}^{(I)} \rangle,$$
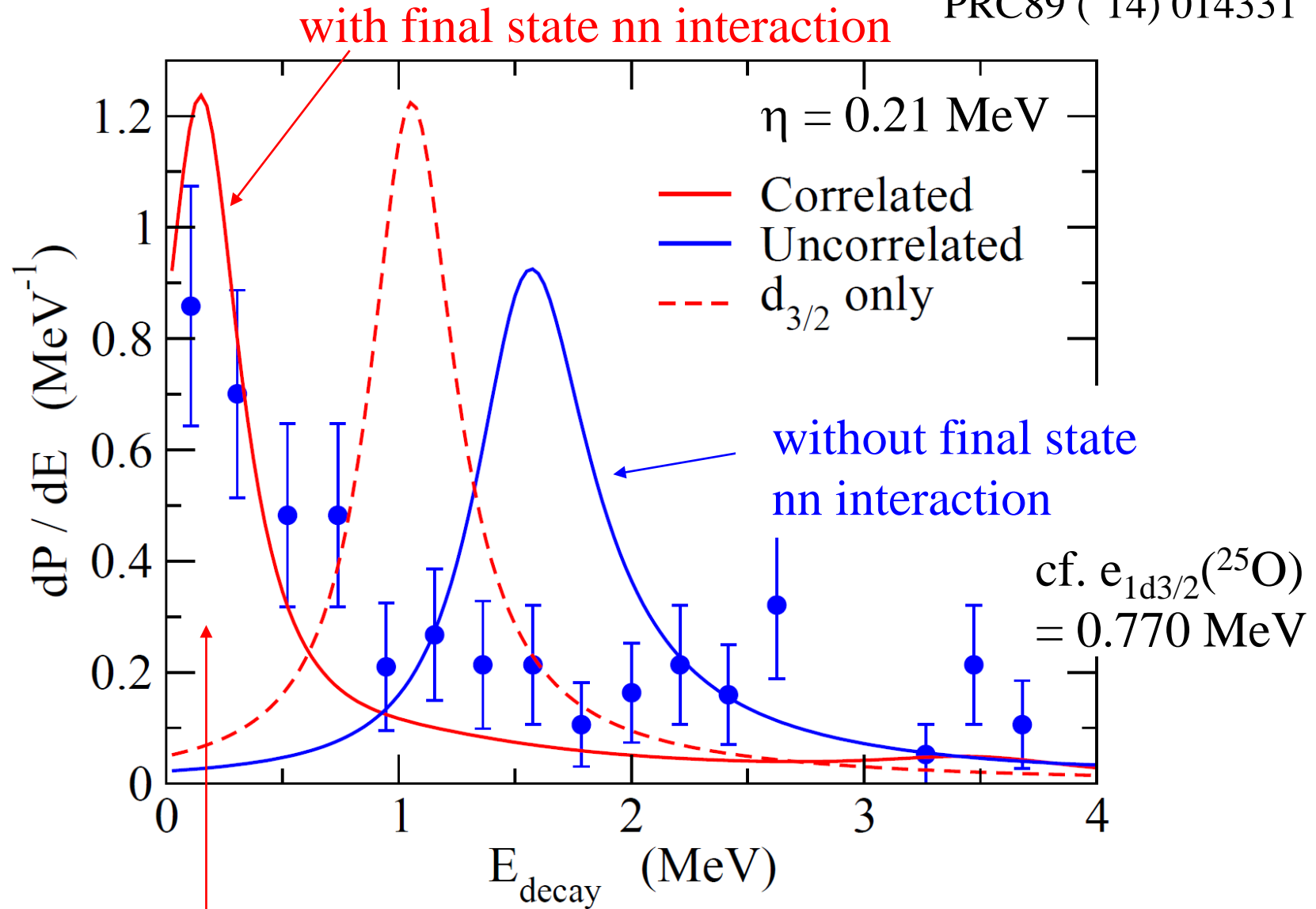
overlap with a ref.
state ⟵ 2n config. with
^{25}F + n + n

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

⟵ continuum effects

i) Decay energy spectrum

with final state nn interaction

$\eta = 0.21$ MeV

— Correlated
— Uncorrelated
-- $d_{3/2}$ only

without final state
nn interaction

cf. $e_{1d3/2}(^{25}O)$
= 0.770 MeV
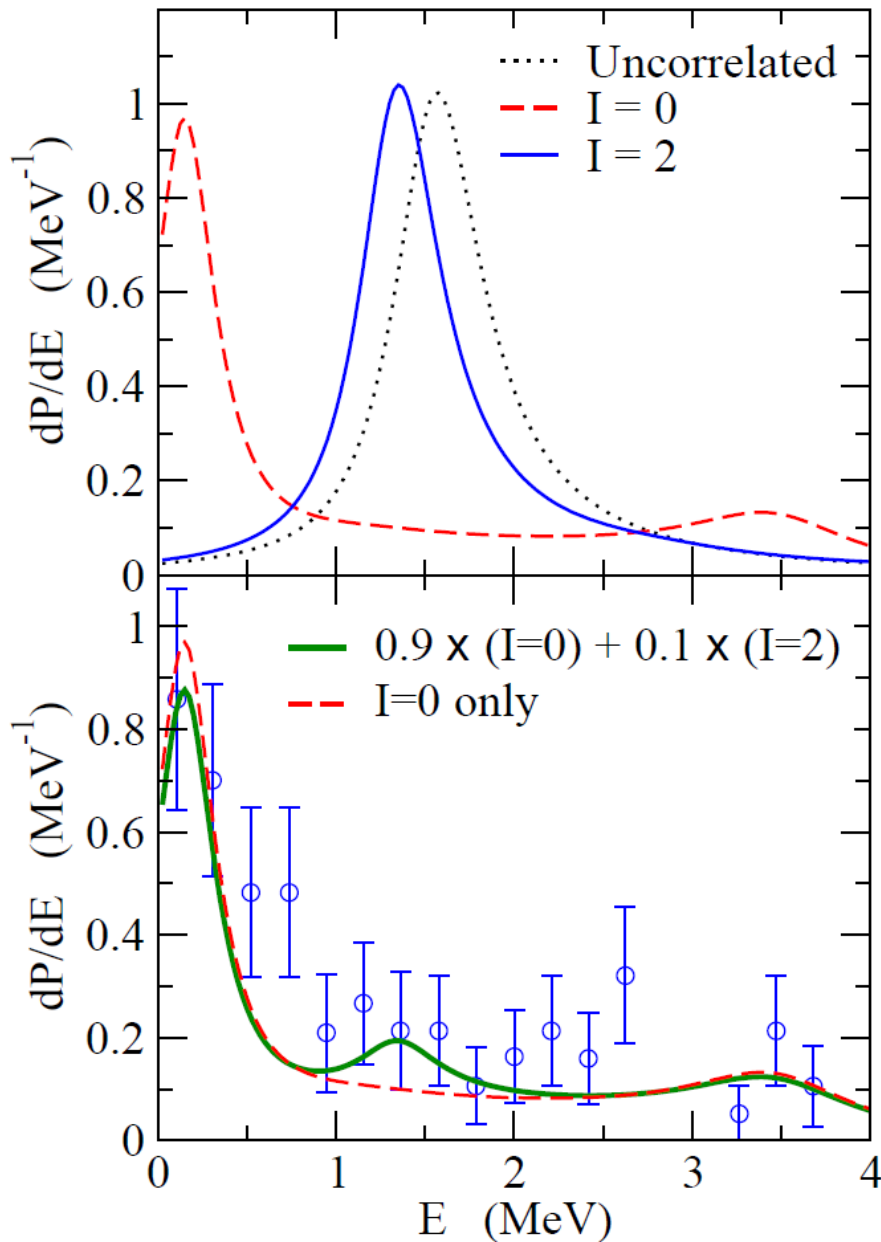
very narrow three-body resonance state ($\Gamma_{exp} \sim 10^{-10}$ MeV)

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

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

(MeV)

1.54 — $(d_{3/2})^2$

1.354 — 2^+

0.148 — 0^+
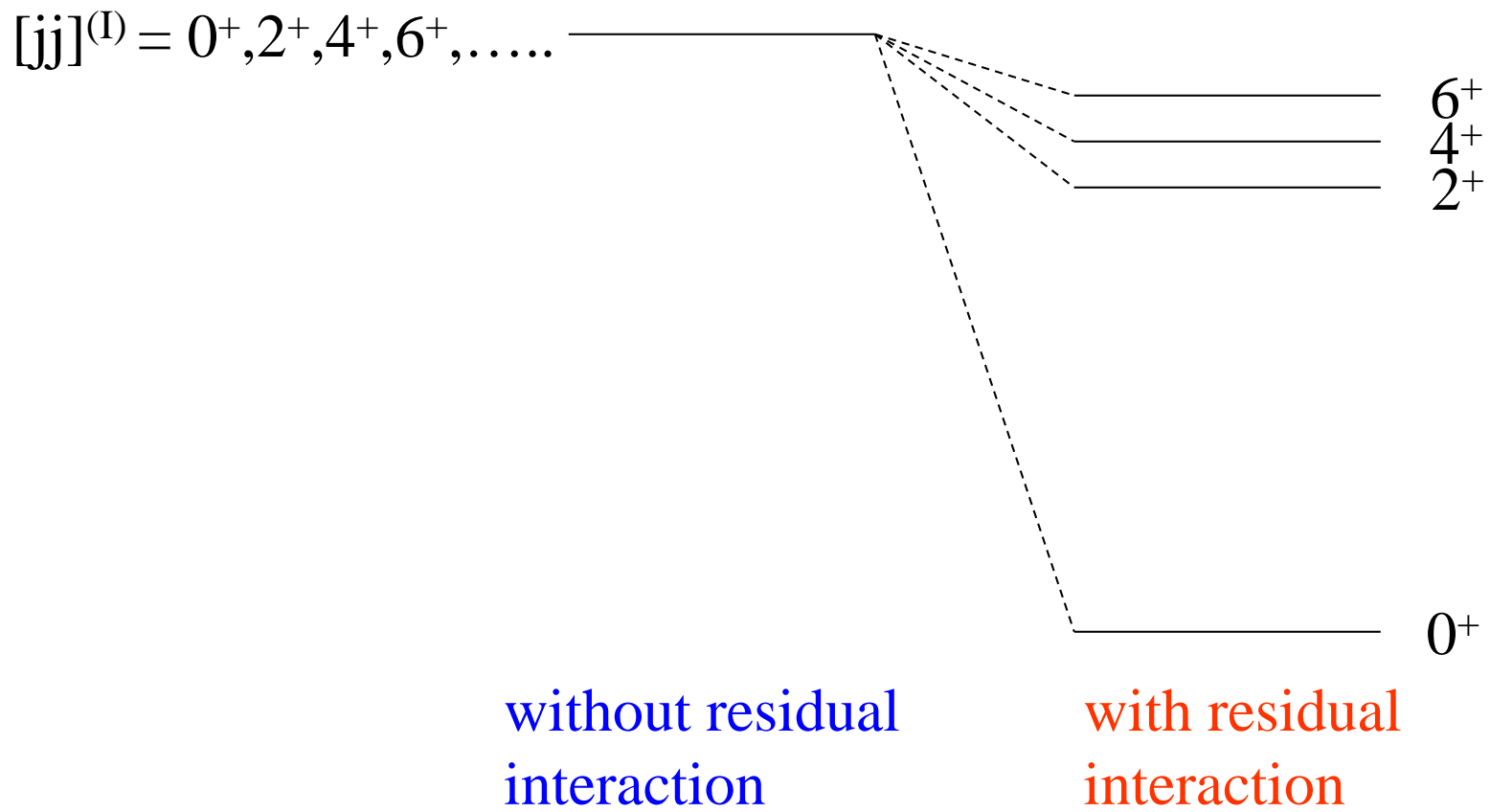
a textbook example
of pairing interaction!

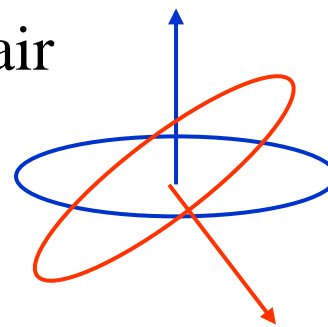cf. another set of parameters:
$E(0^+) = 5$ keV
$E(2^+) = 1.338$ MeV

K.H. and H. Sagawa, in preparation

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

6^+

4^+

2^+

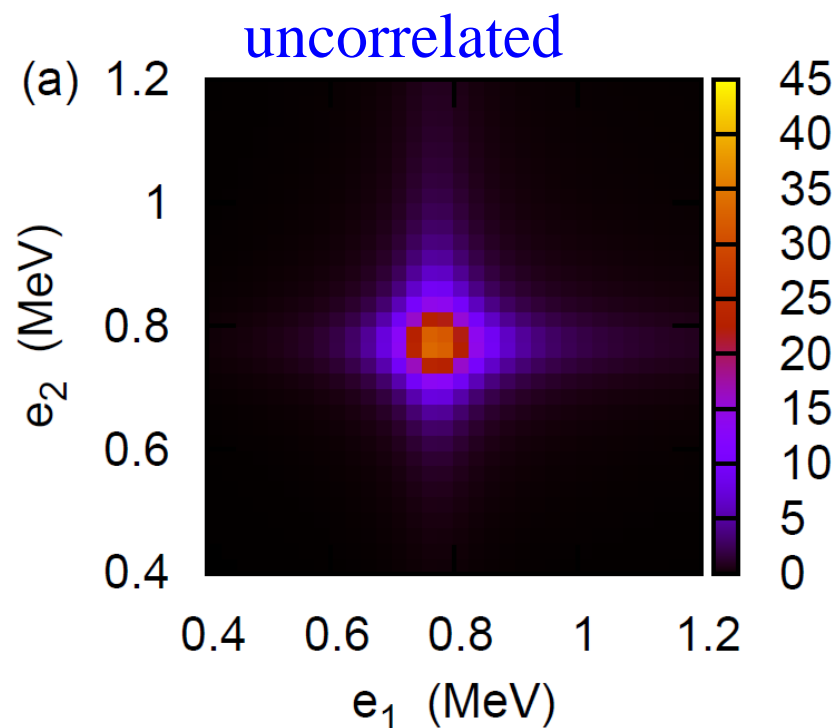0^+

without residual interaction

with residual interaction
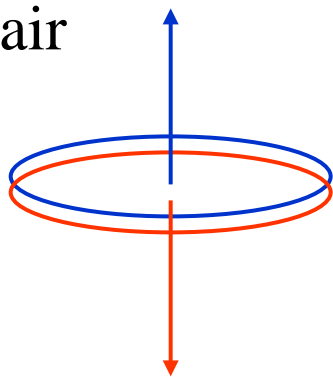
$I=0$ pair

$I \neq 0$ pair

ii) Energy spectrum of the emitted neutrons

correlated

uncorrelated
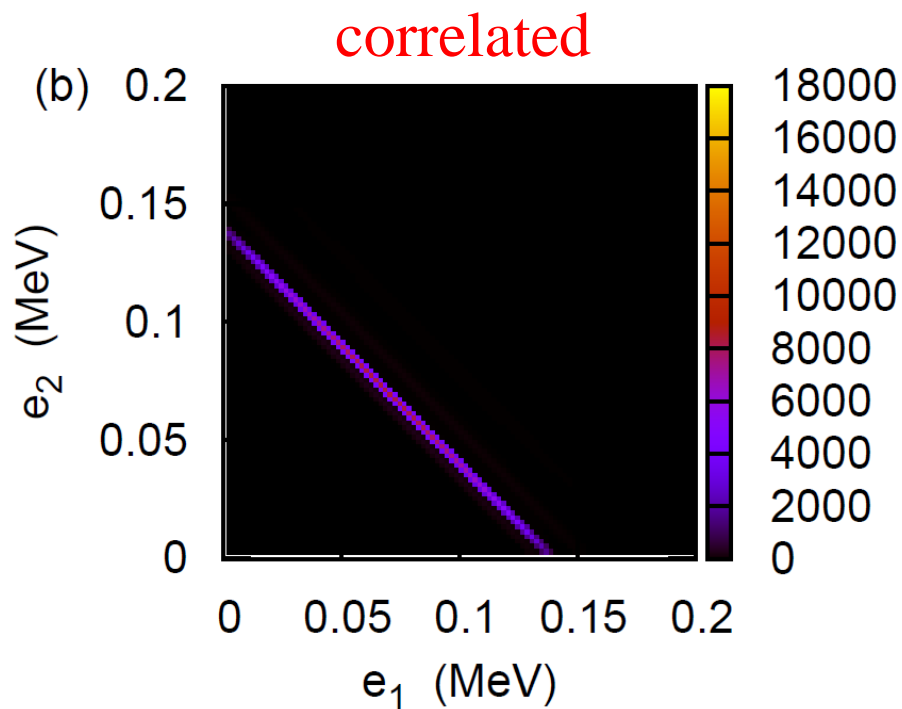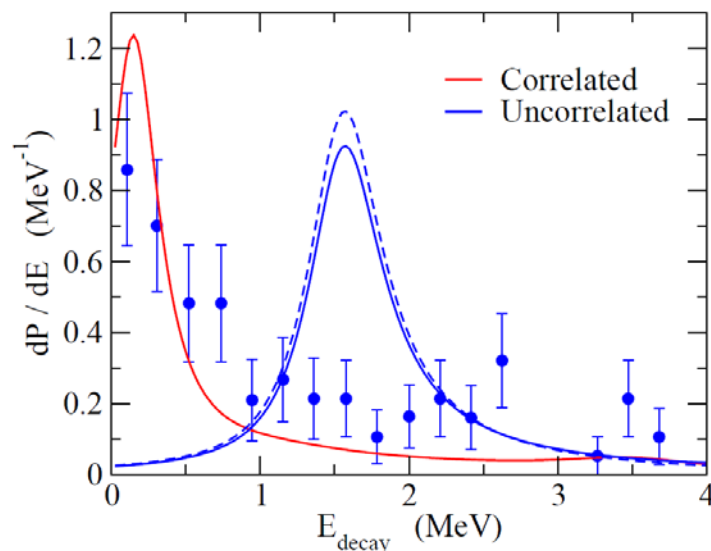
iii) angular correlations of the emitted neutrons
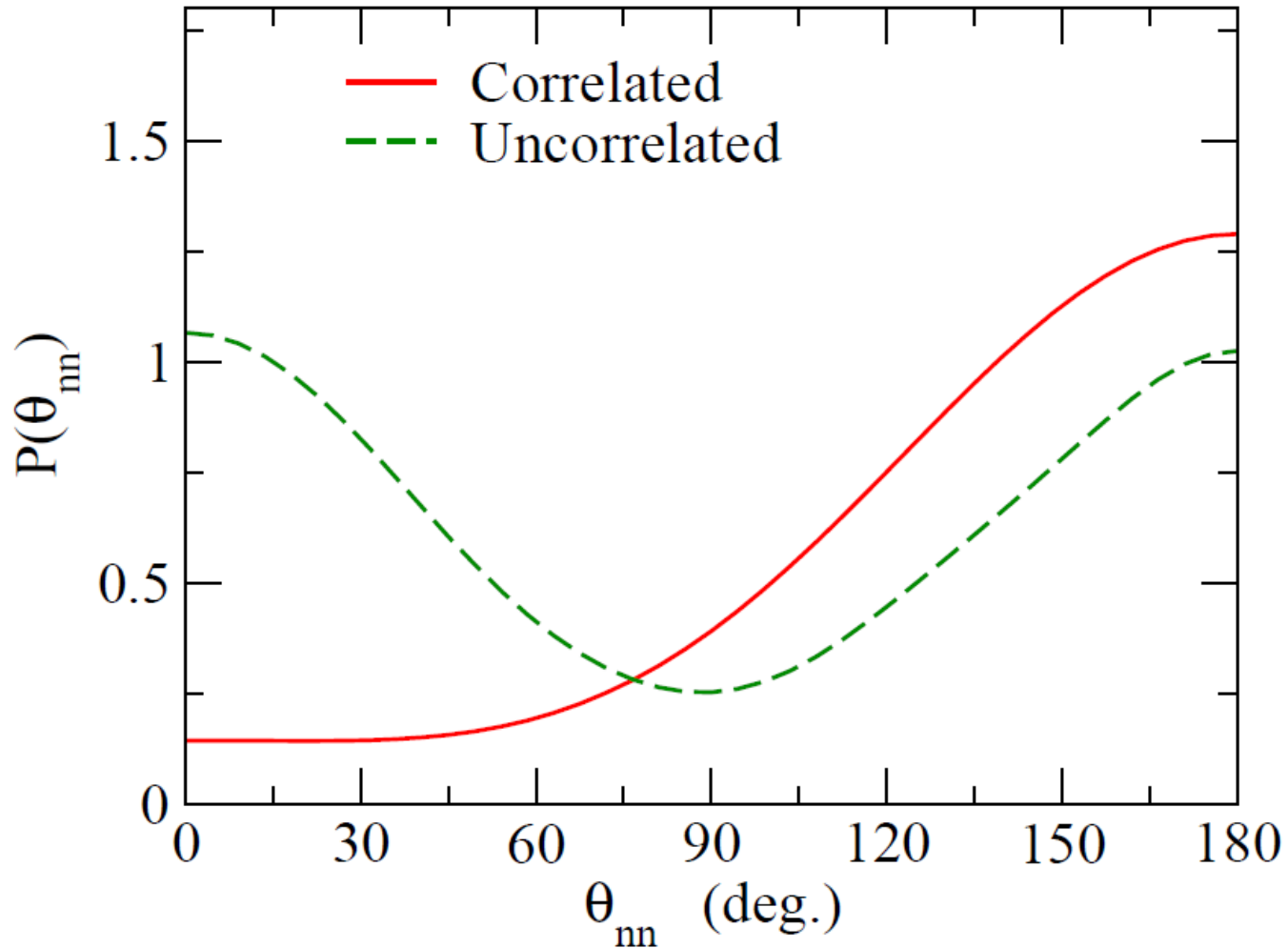
correlation → enhancement of back-to-back emissions

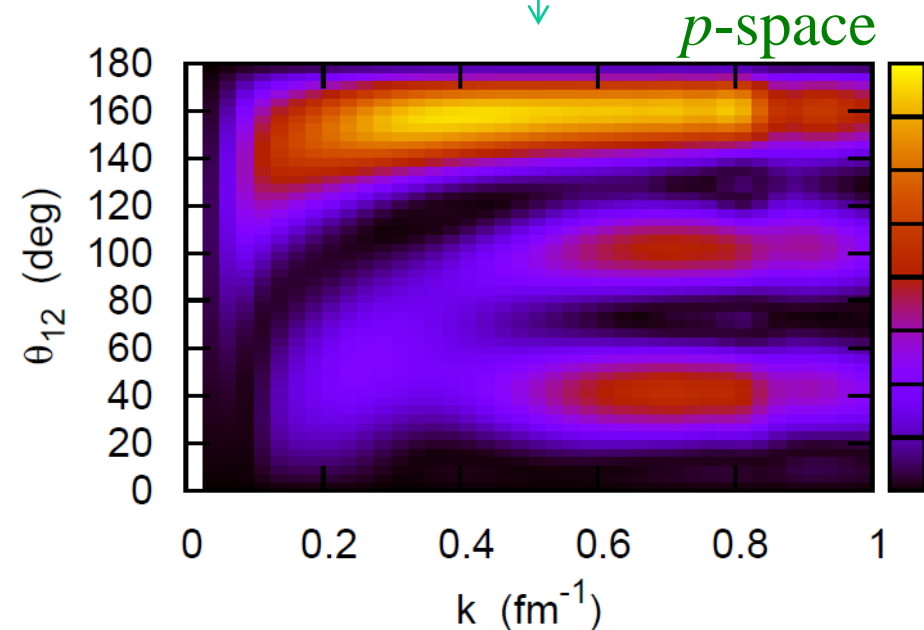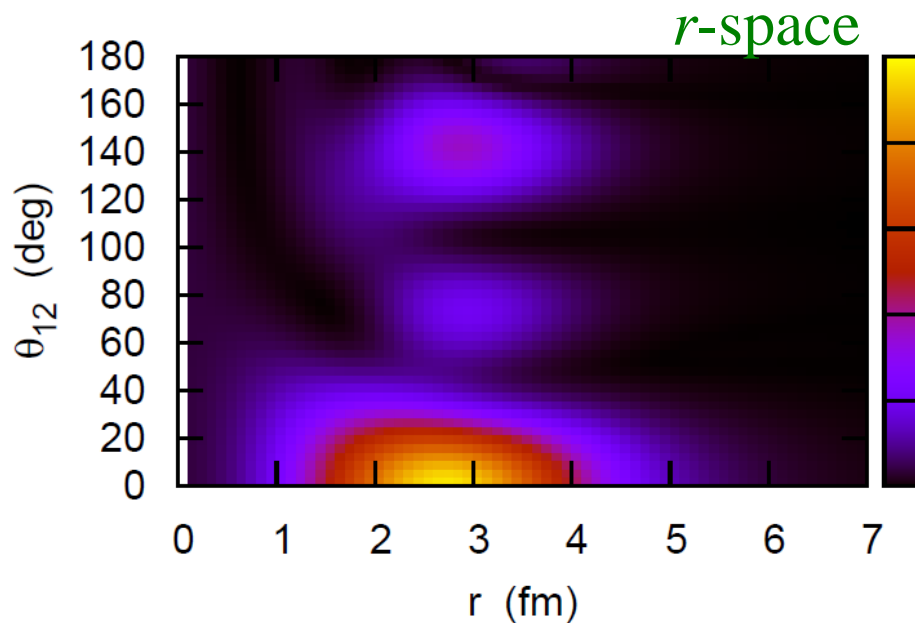$$\langle \theta_{nn} \rangle = 115.3°$$

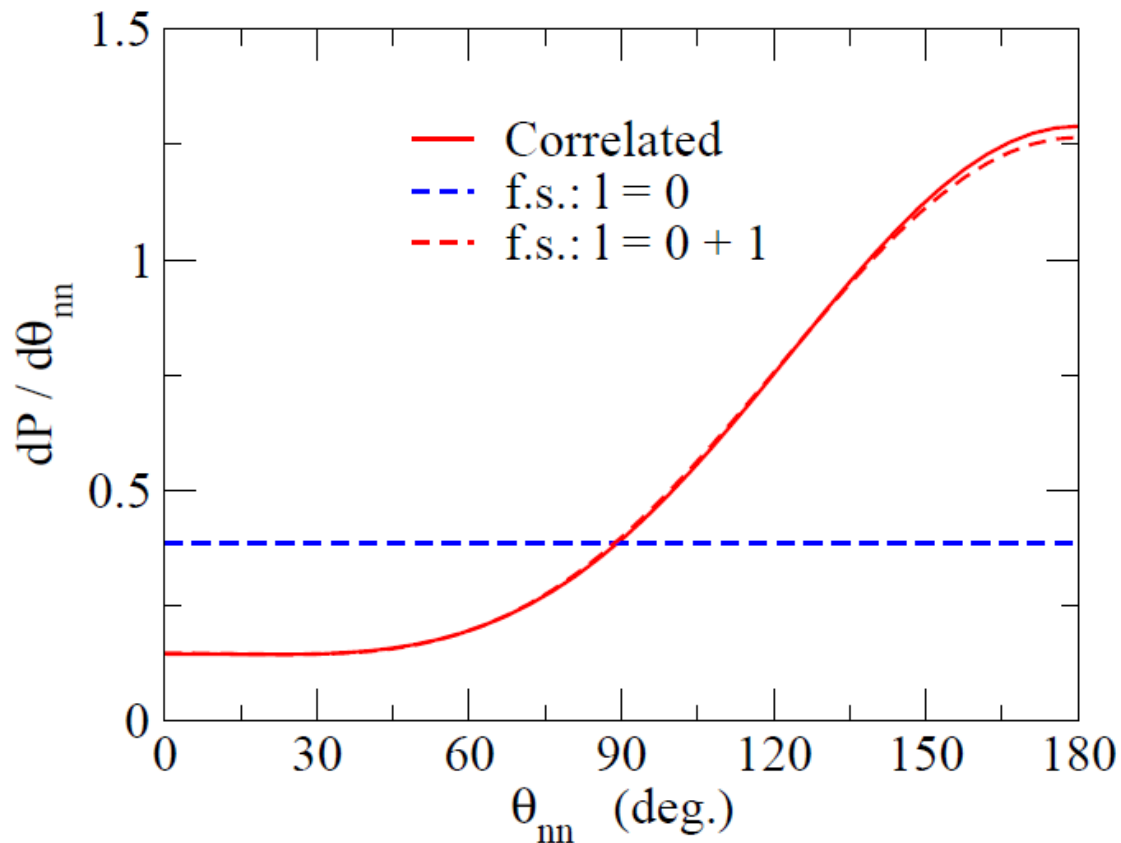# iii) distribution of opening angle for two-emitted neutrons
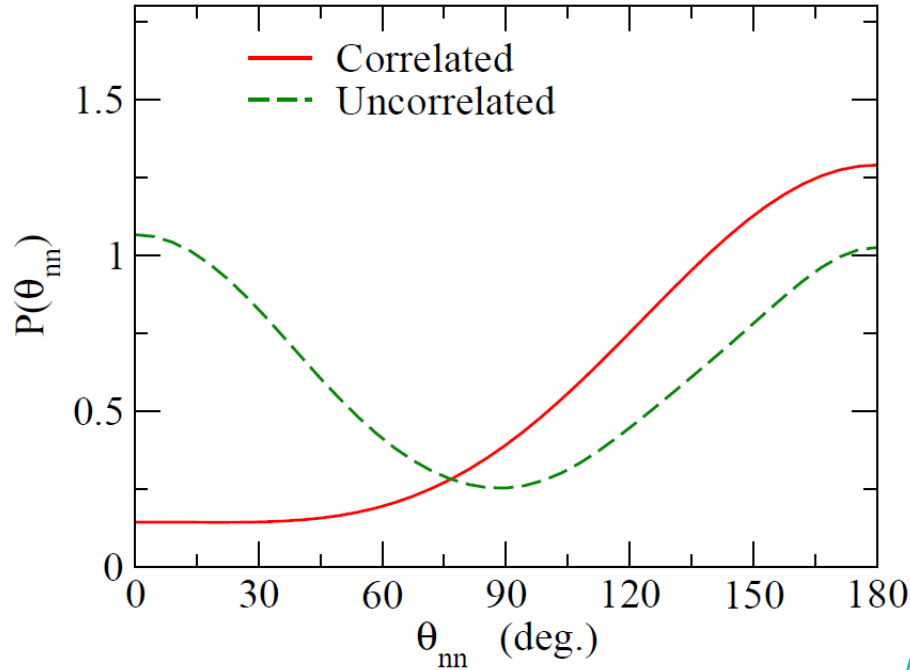
density of the resonance state (with the box b.c.)

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

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

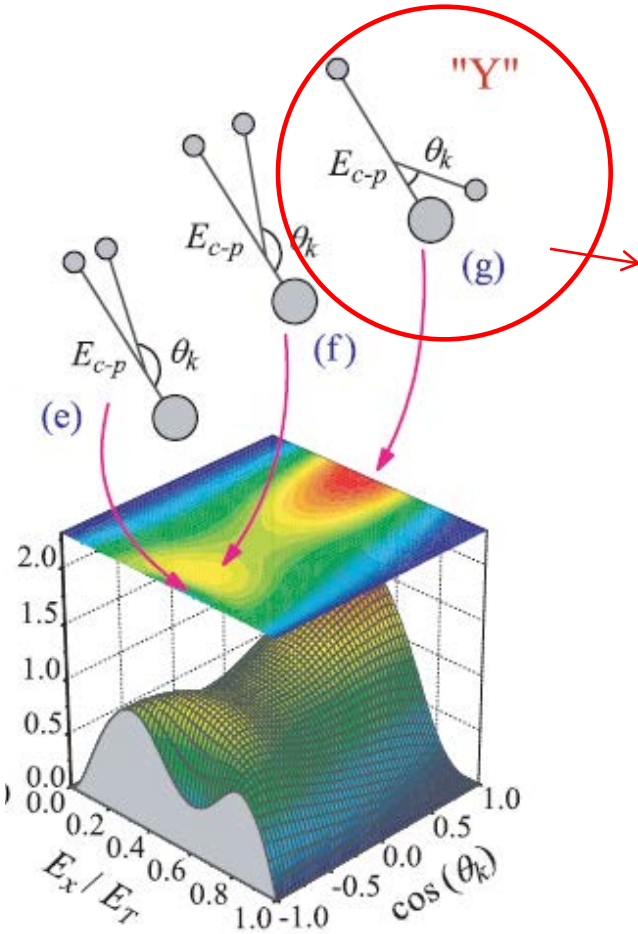r-space

p-space

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.
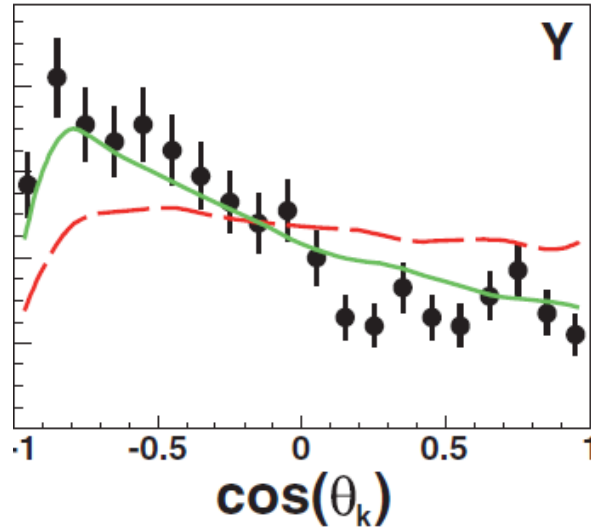($E_{decay} \sim 0.14$ MeV, $e_1 \sim e_2 \sim 0.07$ MeV)

➤ Discussions: back-to-back? or forward angles?
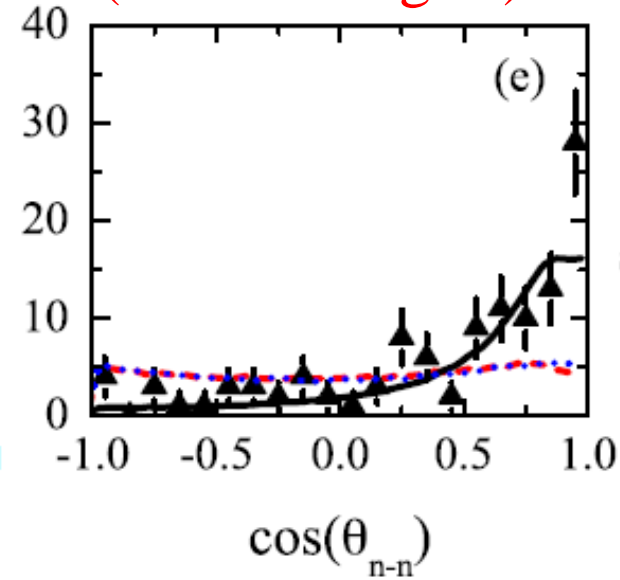
two-proton decay from ^{6}Be (back-to-back)

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

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

"Y"

E_{c-p} θ_k

(g)

E_{c-p} θ_k

(f)

E_{c-p} θ_k

(e)

Z. Kohley et al.,
PRC87('13)011304(R)

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

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

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

↑

open problem

Summary

di-neutron correlation：spatial localization of two neutrons

- ✓ parity mixing
- ✓ neutron-rich nuclei: scattering to the continuum states
  enhancement of pairing on the surface

how to probe it?

- • Coulomb breakup

  - ✓ enhancement of B(E1) due to the correlation
  - ✓ Cluster sum rule (only with the g.s. correlation)
  - ✓ opening angle of two neutrons

- • 2-neutron emission decay

  - ✓ decay energy spectrum
  - ✓ energy spectrum of two emitted neutrons
  - ✓ opening angle of two emitted neutrons (back-to-back)

    ⟵⟶   dineutron correlation