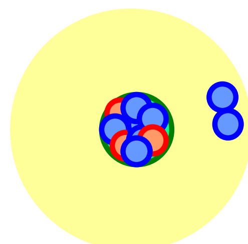
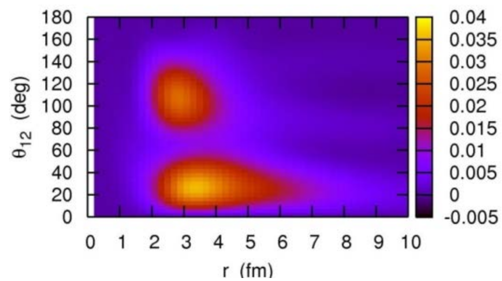
# Two-neutron decay of $^{26}$O and di-neutron correlation


Kouichi Hagino

*Tohoku University, Sendai, Japan*


TOHOKU UNIVERSITY






*1. Di-neutron correlation in neutron-rich nuclei*

*2. Coulomb breakup*

*3. Two-neutron decay of unbound nucleus $^{26}$O*

*4. Summary*

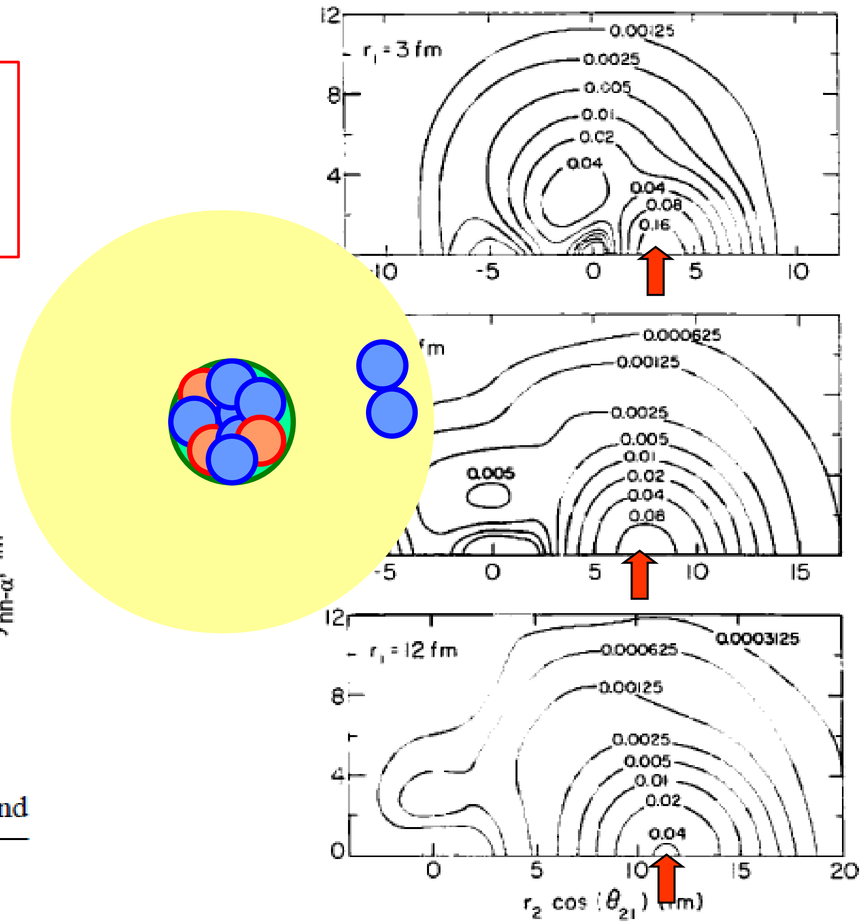
# Borromean nuclei and Di-neutron correlation

## Borromean nuclei: unique three-body systems

### Three-body model calculations:

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

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




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

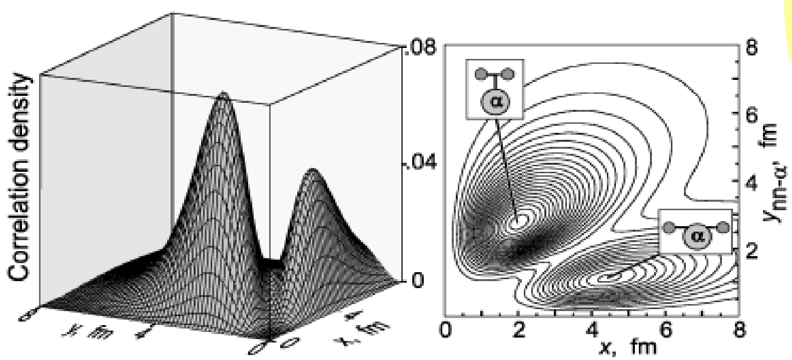



FIG. 1. Spatial correlation density plot for the $0^+$ ground state of $^6$He. Two components—di-neutron and cigarlike—are shown schematically.

Yu.Ts. Oganessian, V.I. Zagrebaev, and J.S. Vaagen, *PRL82('99)4996*

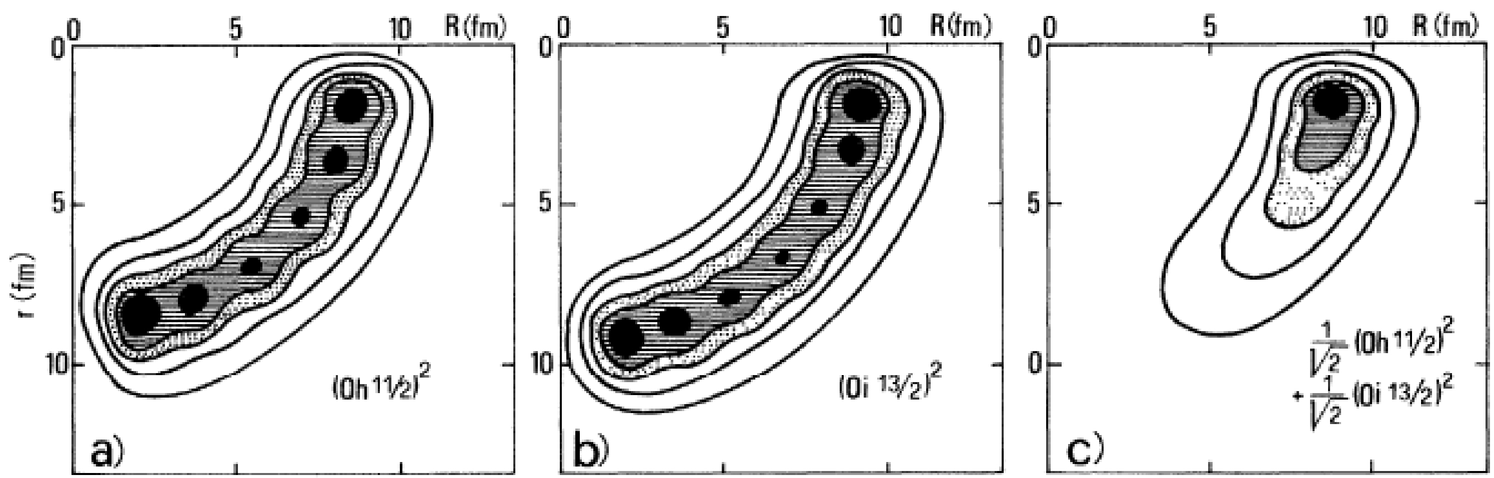
M.V. Zhukov et al., *Phys. Rep. 231('93)151*

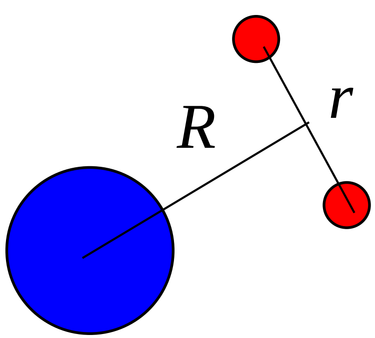
G.F. Bertsch, H. Esbensen, *Ann. of Phys., 209('91)327*

# spatial localization of two neutrons
(dineutron correlation)

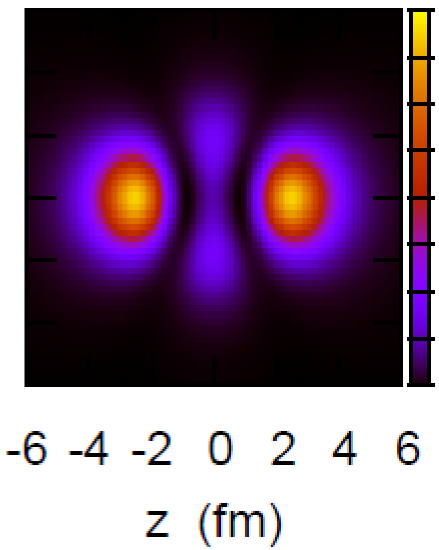
cf. Migdal, Soviet J. of Nucl. Phys. 16 (‘73) 238
Bertsch, Broglia, Riedel, NPA91(‘67)123

dineutron correlation: caused by the admixture of different parity states

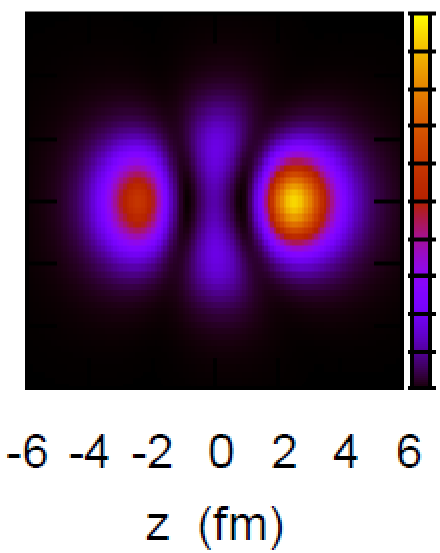



F. Catara, A. Insolia, E. Maglione, and A. Vitturi, PRC29(‘84)1091




parity mixing




spatial localization of two neutrons
(dineutron correlation)

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

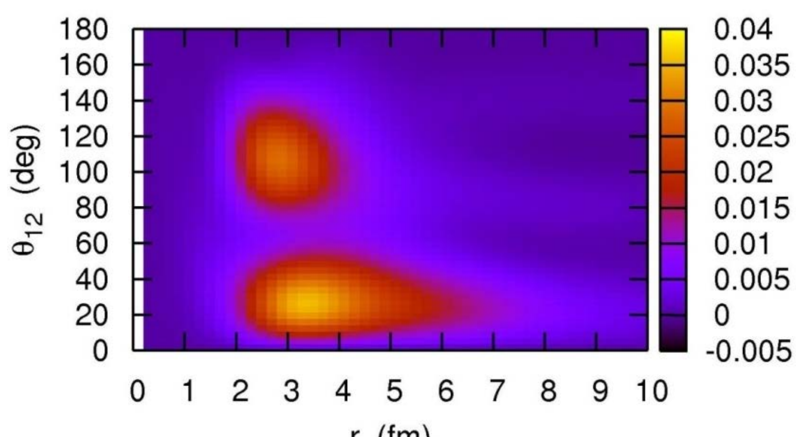
**weakly bound systems**

→ easy to mix different parity states due to the continuum couplings

\+ enhancement of pairing on the surface

⟶ dineutron correlation: enhanced

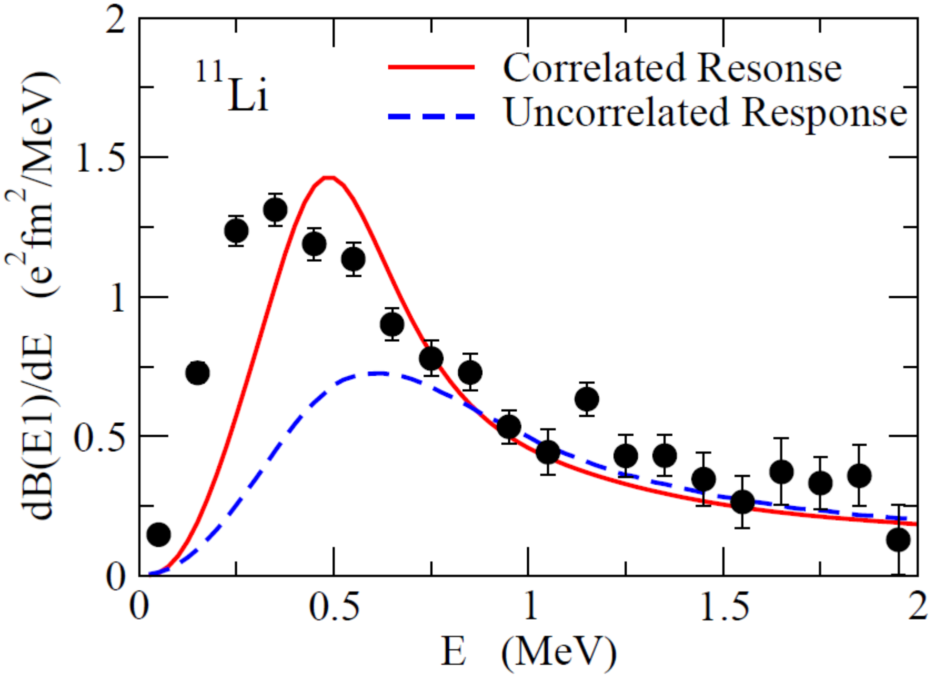
cf. - Bertsch, Esbensen, Ann. of Phys. 209('91)327
- M. Matsuo, K. Mizuyama, Y. Serizawa, PRC71('05)064326

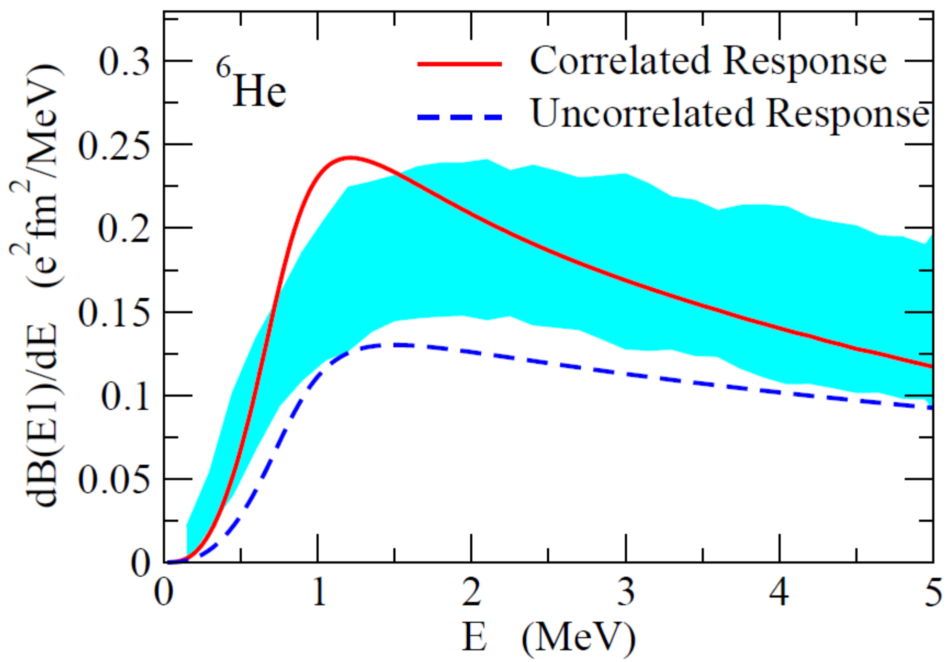



K.H. and H. Sagawa, PRC72('05)044321

# 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

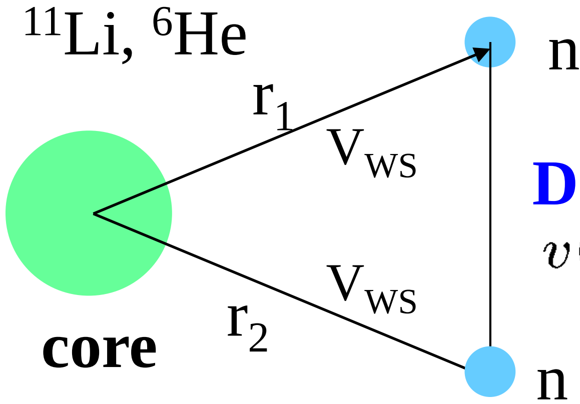
✓ 3-body model calculations:

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*

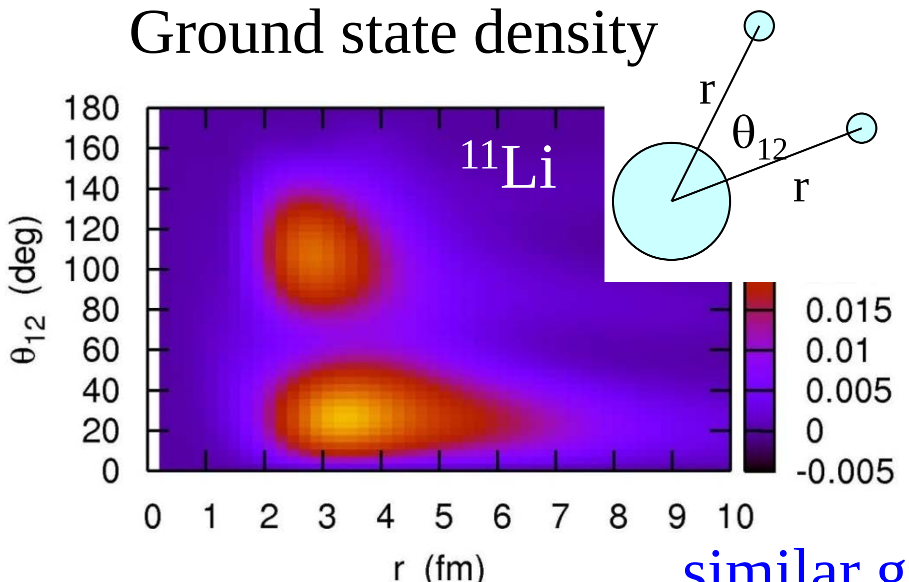
**Density-dependent delta-force**

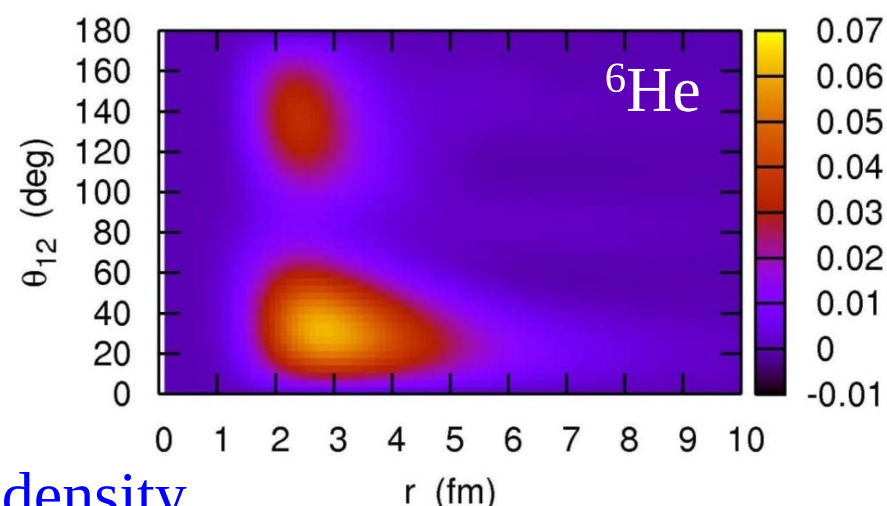
$$v(\boldsymbol{r}_1, \boldsymbol{r}_2) = v_0(1 + \alpha\rho(r)) \times \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)$$

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

Ground state density

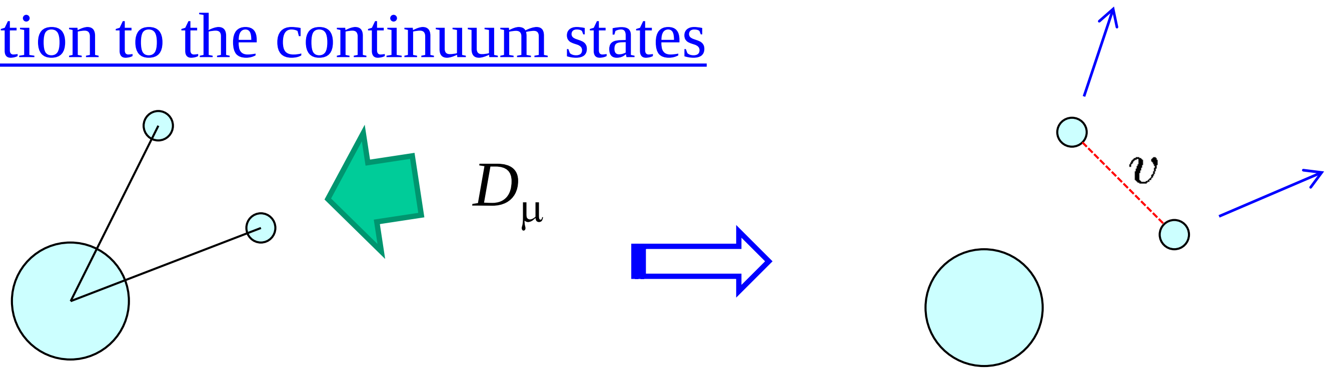
K.H. and H. Sagawa, PRC72('05)044321




similar g.s. density

# E1 excitation to the continuum states




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

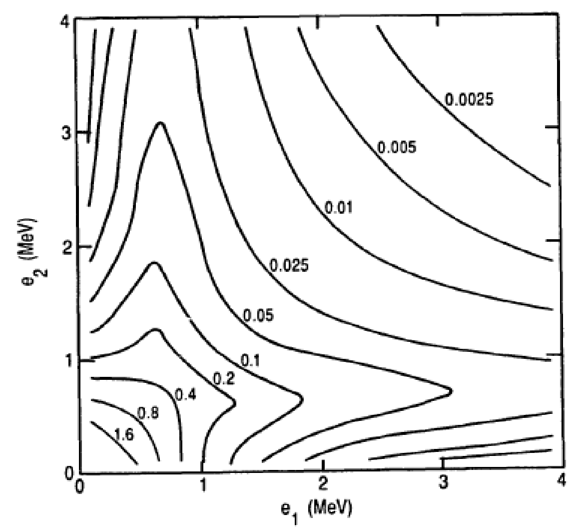
FSI

dipole operator

unperturbed continuum wf

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

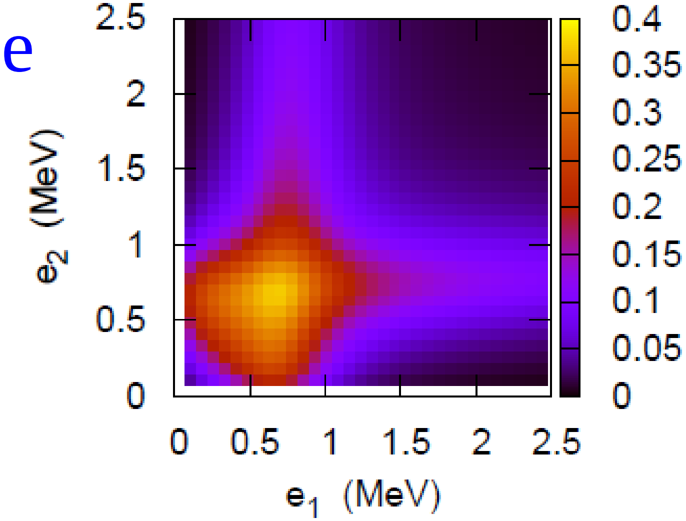
$$
\frac{d^2 B(E1)}{de_1 de_2} = 3 \sum_{l_1 j_2 l_2 j_2} |M(E1)|^2 \frac{dk_1}{de_1} \frac{dk_2}{de_2}
$$




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

# Energy distribution of emitted neutrons

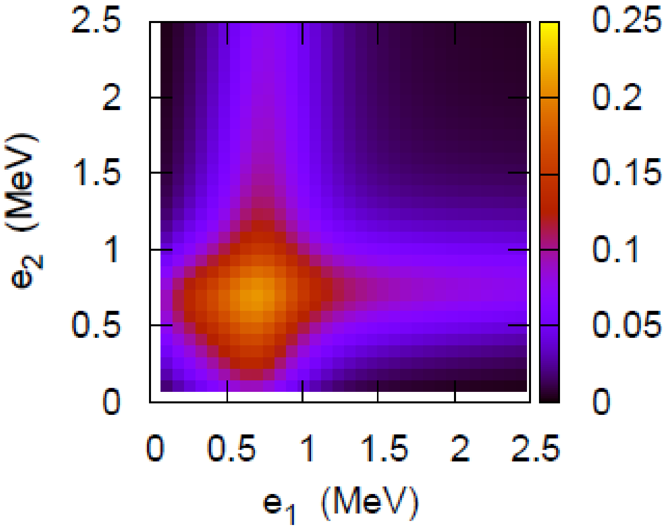
$^{6}$He



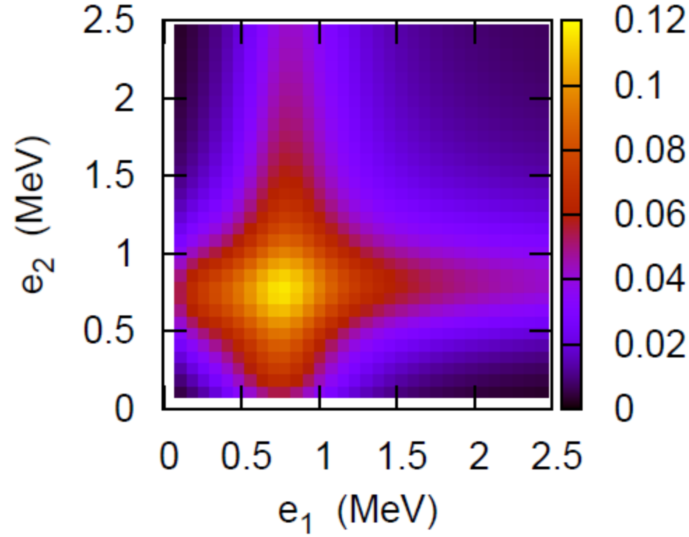

- ✓shape of distribution: insensitive to the nn-interaction (except for the absolute value)
- ✓strong sensitivity to $V_{nC}$
- ✓similar situation in between $^{11}$Li and $^{6}$He

→ Coul. b.u.: 2-step process

$v_{nn} = 0$

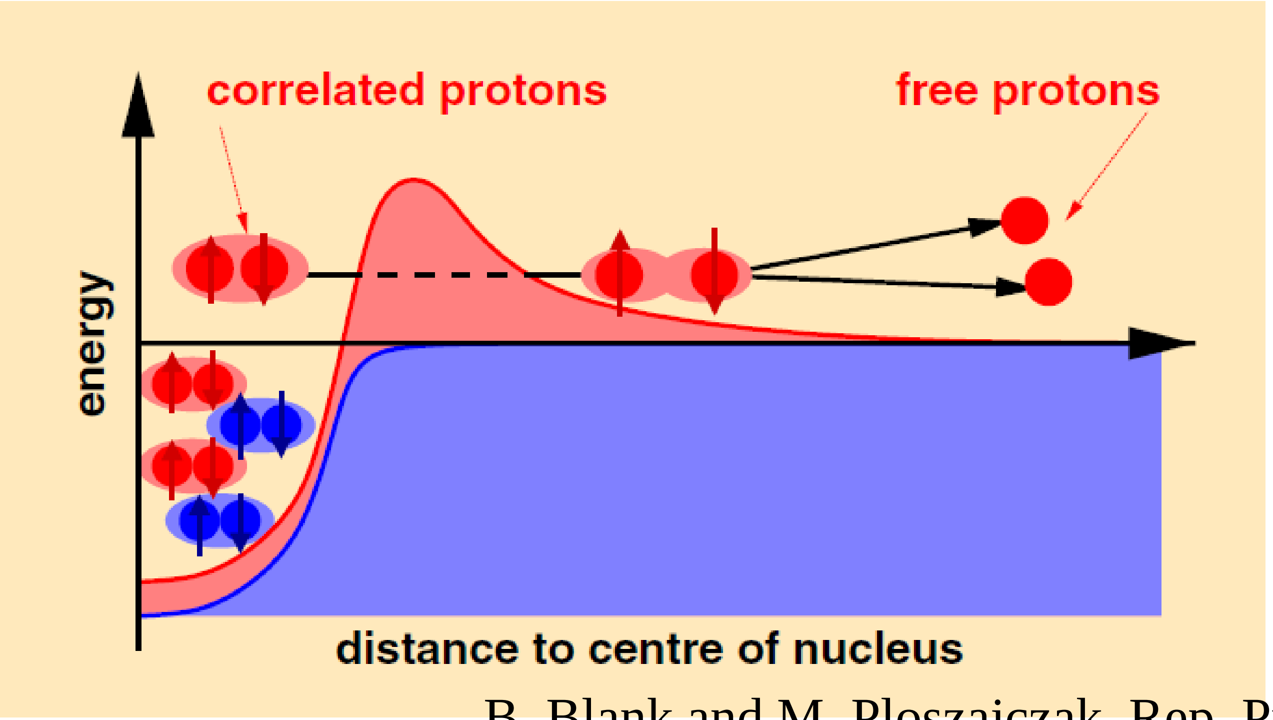



no di-neutron corr. in the g.s.




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

# 2-proton radioactivity



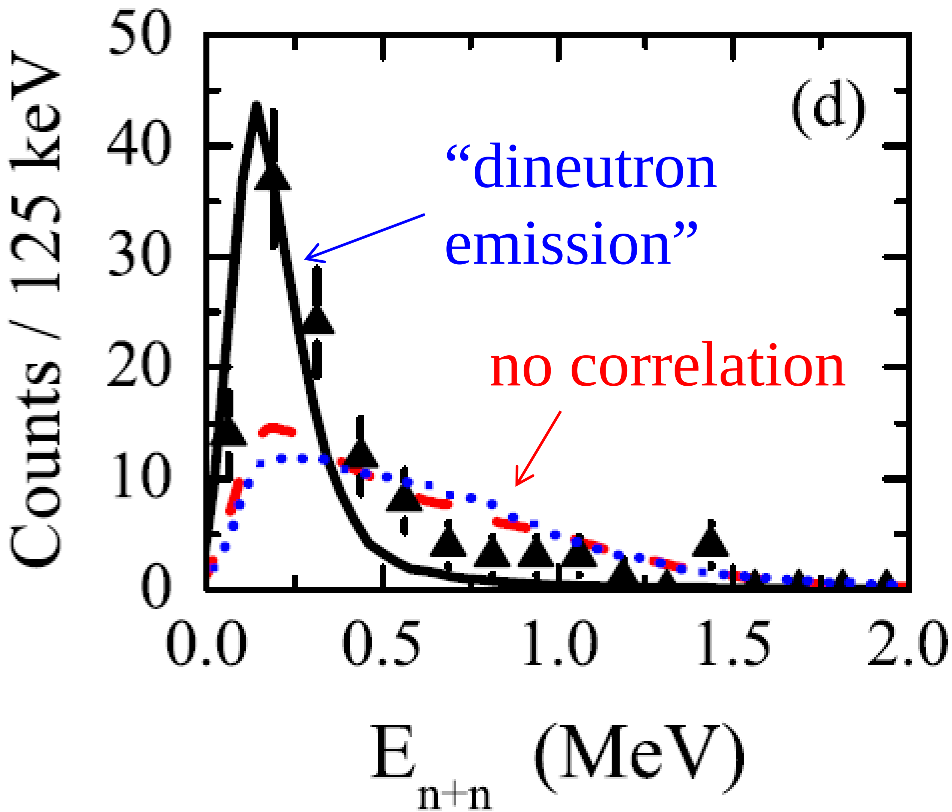

B. Blank and M. Ploszajczak, Rep. Prog. Phys. 71(‘08)046301

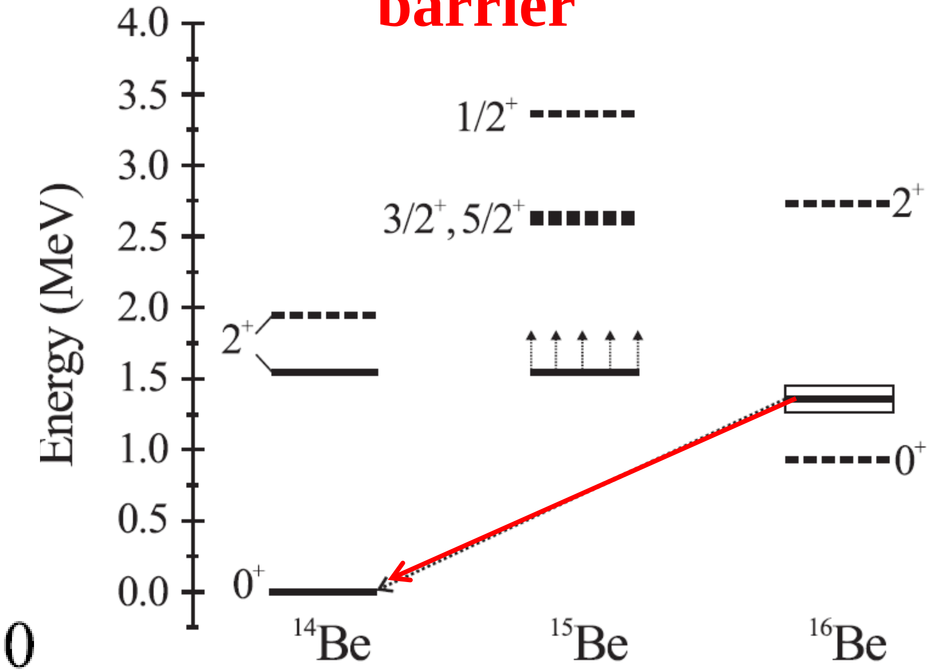
- ✓ probing correlations from energy and angle distributions of emitted two protons?
- ✓ Coulomb 3-body system
  - Theoretical treatment: difficult
  - how does FSI disturb the g.s. correlation?

# 2-neutron decay（MoNA@MSU）

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

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




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) $^{27}F \rightarrow {}^{26}O \rightarrow {}^{24}O + 2n$

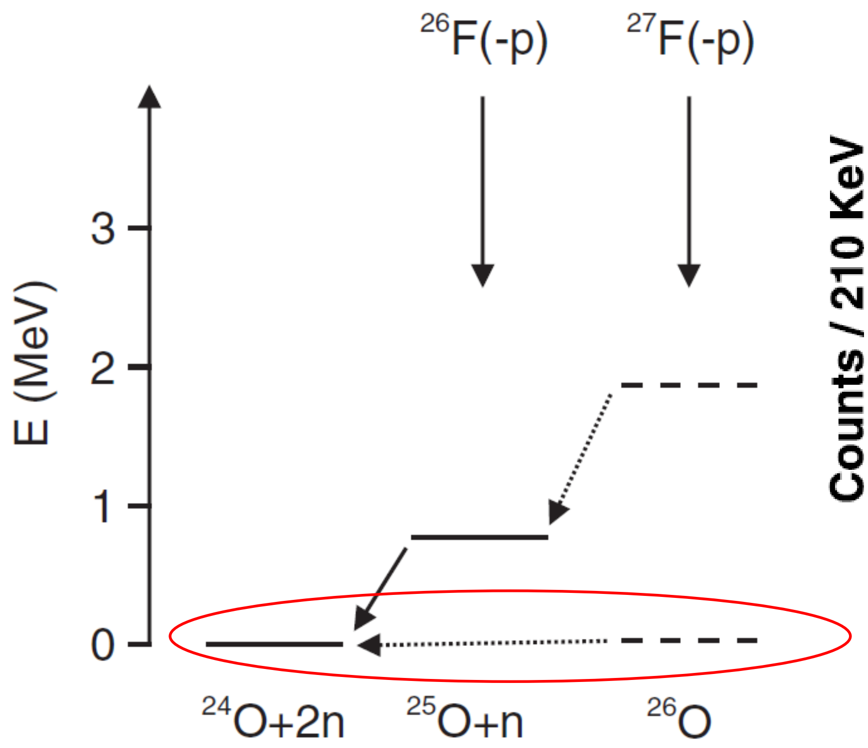
3-body model calculation with nn correlation: required

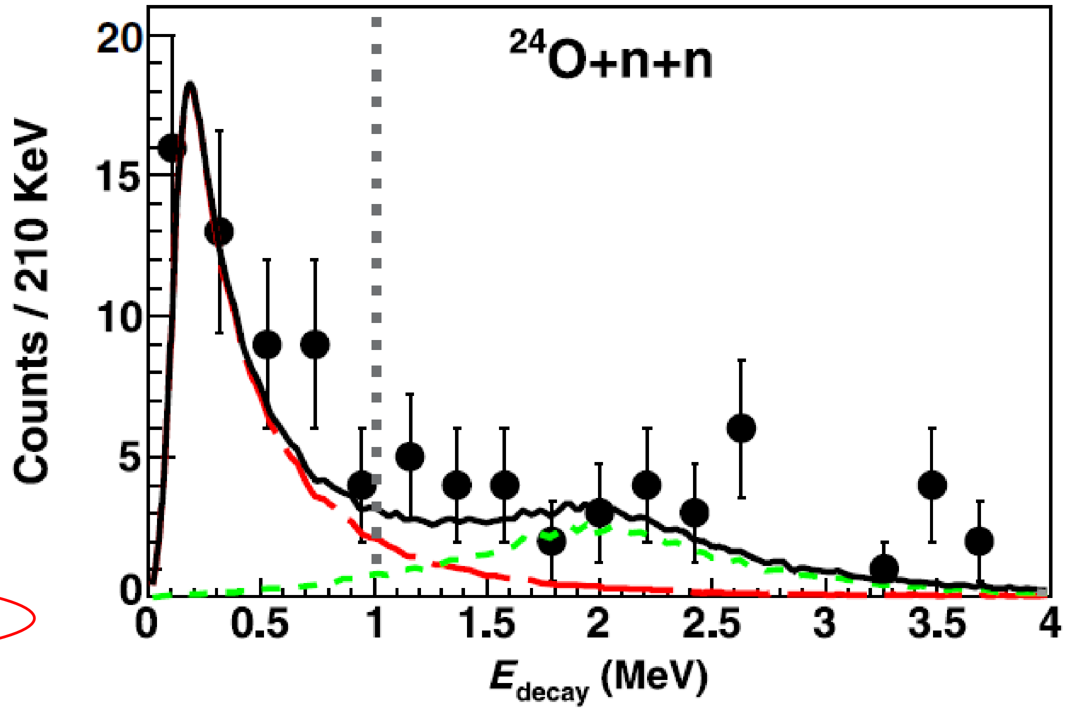
# Two-neutron decay of $^{26}$O

- 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



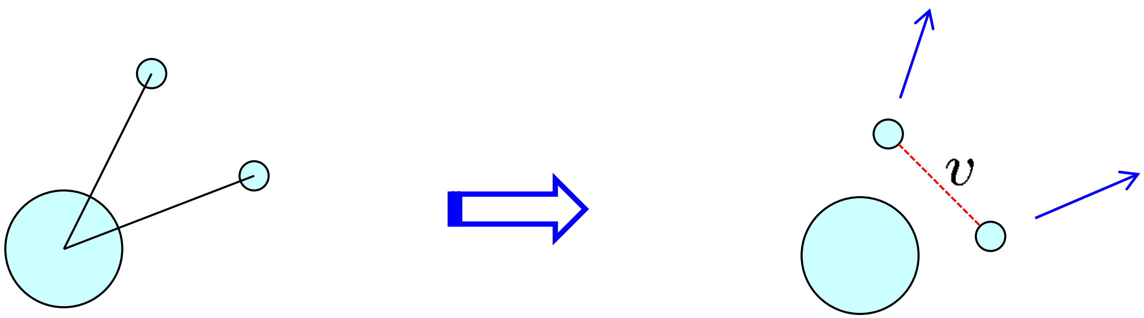




cf. C. Caesar et al., PRC88 ('13) 034313 (GSI exp.)

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

# Three-body model calculations: extension of continuum E1 for $^{11}$Li

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




initial
meta-stable state

$$M_{fi} = \langle (j_1 j_2)^{J=0} | (1 - vG_0 + vG_0 vG_0 - \cdots) | \Psi_i \rangle$$
$$= \langle (j_1 j_2)^{J=0} | (1 + vG_0)^{-1} | \Psi_i \rangle = \langle \Psi^{(J=0)}_{j_1 j_2} | \Psi_i \rangle$$

FSI

$$G_0(E) = \sum_{f.st.} \frac{\left|(j_1 j_2)^{J=0}\right\rangle \left\langle (j_1 j_2)^{J=0}\right|}{e_1 + e_2 - E - i\eta}$$

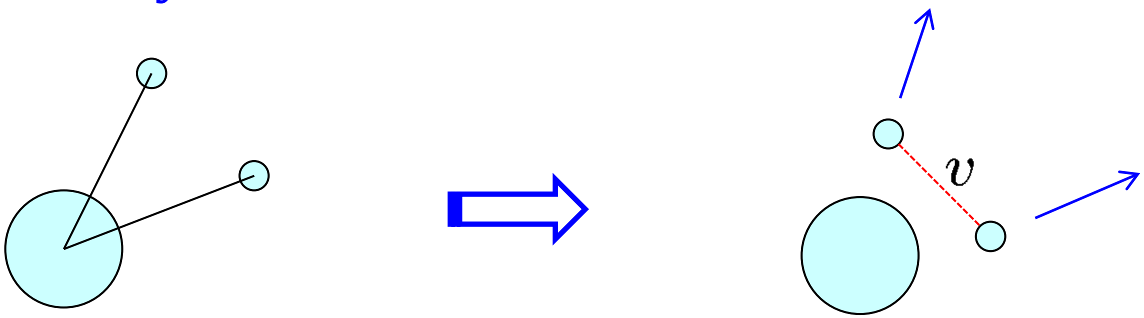
unperturbed continuum wf

## cf. Continuum E1 response:

E1 operator

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

# Three-body model calculations: extension of continuum E1 for $^{11}$Li




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

initial
meta-stable state

$$M_{fi} = \langle (j_1 j_2)^{J=0} | (1 - vG_0 + vG_0 vG_0 - \cdots) | \Psi_i \rangle$$

$$= \langle (j_1 j_2)^{J=0} | (1 + vG_0)^{-1} | \Psi_i \rangle = \langle \Psi_{j_1 j_2}^{(J=0)} | \Psi_i \rangle$$

FSI

unperturbed continuum wf

$$G_0(E) = \sum_{f.st.} \frac{\left| (j_1 j_2)^{J=0} \right\rangle \left\langle (j_1 j_2)^{J=0} \right|}{e_1 + e_2 - E - i\eta}$$

$$\frac{d^2P}{de_1 de_2} = \sum_{l_1 j_2 l_2 j_2} |M_{fi}|^2 \frac{dk_1}{de_1} \frac{dk_2}{de_2}$$

$$\frac{dP}{dE} = \int de_1 de_2 \frac{d^2P}{de_1 de_2} \delta(E - e_1 - e_2)$$

*Green function method:
 also for angular correlation

* approximate treatment
 for the recoil term

Initial state : the bound ground state for a 3-body model ($^{25}$F + n + n)

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

- $^{25}$F + n potential

($^{24}$O + n) potential + $\delta V_{ls}$

pn tensor interaction

T. Otsuka et al., PRL95('05)232502

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

cf. $e_{1d3/2}$ ($^{25}$O) = + $770^{+20}_{-10}$ keV

- pairing strength

→ E ($^{27}$F) = -2.69 MeV

cf. $E_{exp}$ ($^{27}$F) = -2.80(18) MeV

➡ sudden proton removal

(keep the nn configuration for $^{25}$F+n+n, and suddenly change the core from $^{25}$F to $^{24}$O)

$$M_{fi} = \langle (j_1 j_2)^{J=0} | (1 + vG_0)^{-1} | \Psi_i \rangle$$

Initial state : 3-body model ($^{25}$F + n + n)

⟶ sudden proton removal : $^{27}\mathrm{F} \rightarrow {}^{26}\mathrm{O}$

↳ spontaneous decay

cf. $\Psi_{nn}(^{27}\mathrm{F})$ : is not an eigenstate of $H_{nn}(^{26}\mathrm{O})$

Propagation & final uncorrelated state : 3-body model ($^{24}$O + n + n)

- $^{24}$O + n potential

Woods-Saxon potential to reproduce

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

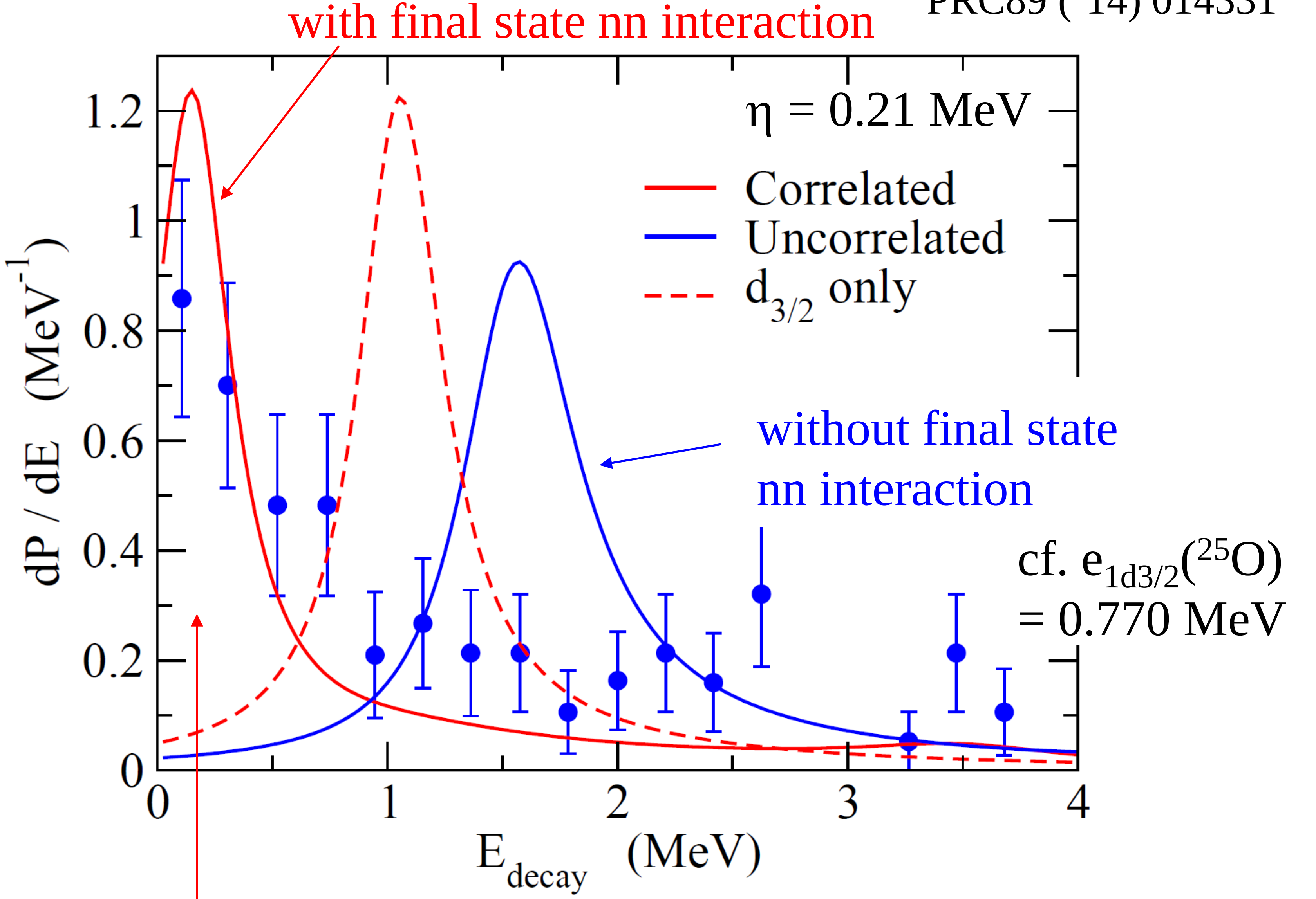
$e_{2s1/2}$ = -4.09 (13) MeV,

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

$a$ = 0.95 fm → $\Gamma_{1d3/2}$ = 141.7 keV

## i) Decay energy spectrum

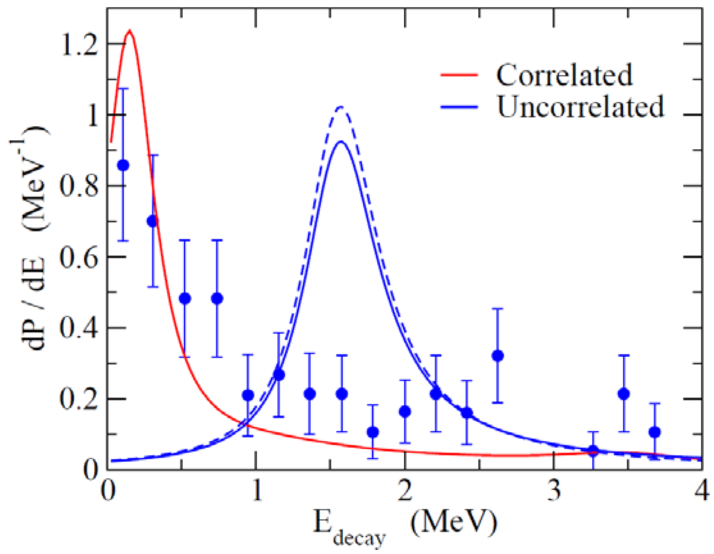
K.H. and H. Sagawa, PRC89 ('14) 014331

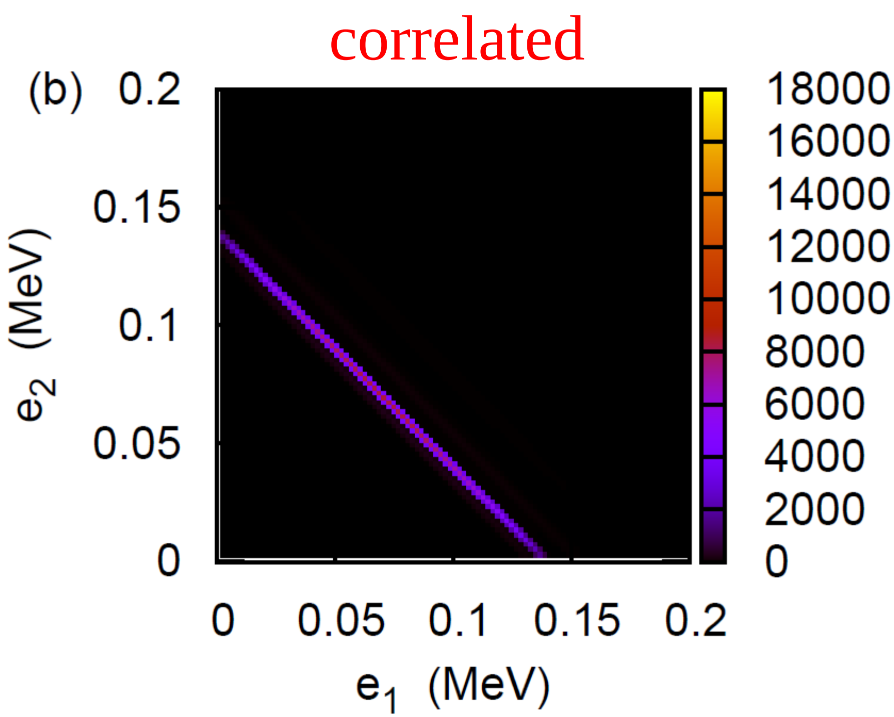


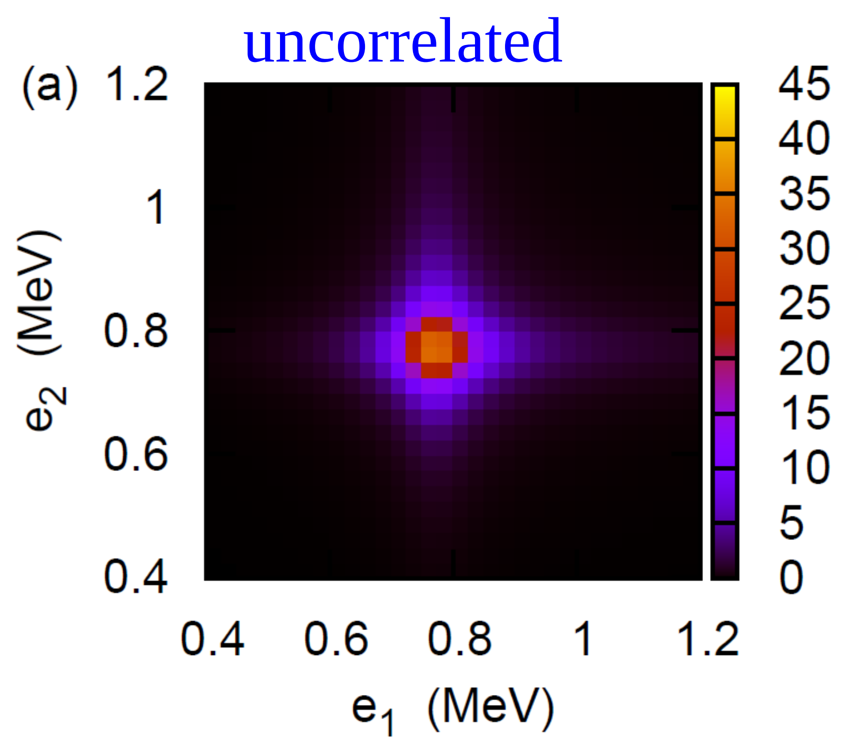

very narrow three-body resonance state ($\Gamma_{exp}$ ~ $10^{-10}$ MeV)

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

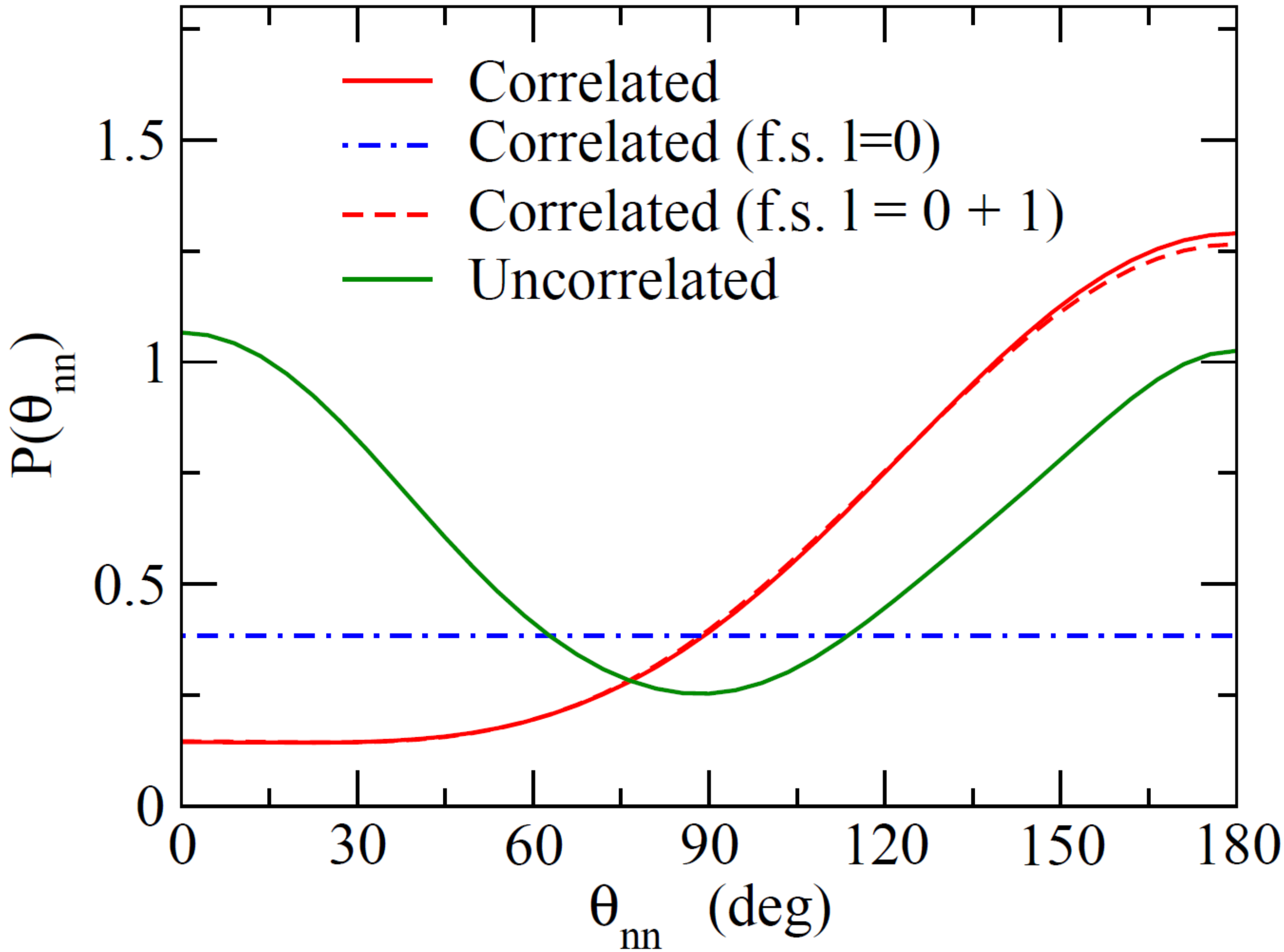
## ii) Energy spectrum of the emitted neutrons



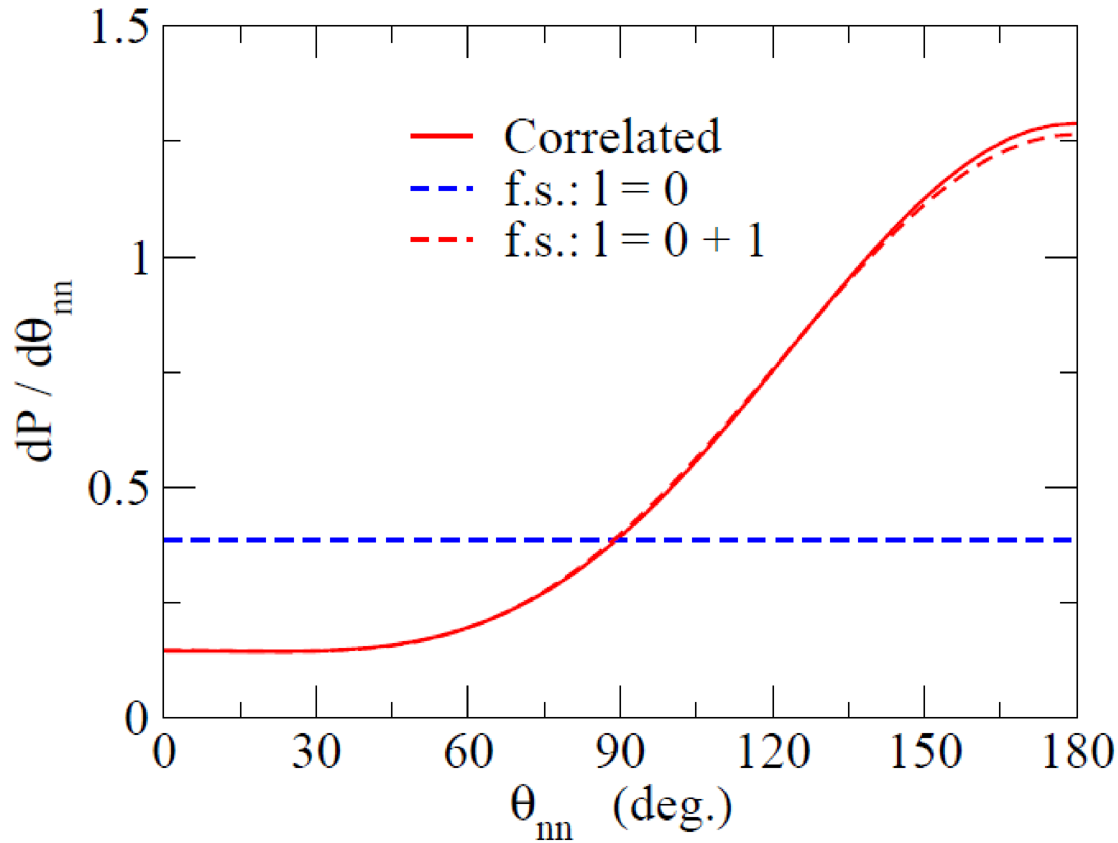
## iii) angular correlations of the emitted neutrons




correlation → enhancement of back-to-back emissions

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

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




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

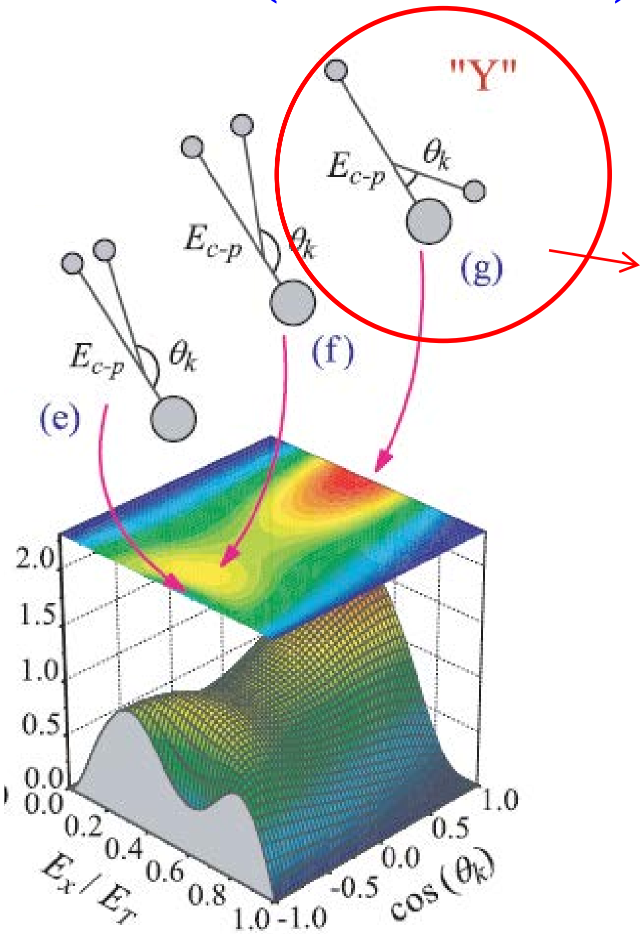
rescattering due to pairing interaction

*higher *l* components: largely suppressed due to the centrifugal pot.

($E_{decay}$ ~ 0.14 MeV, $e_1$ ~ $e_2$ ~ 0.07 MeV)

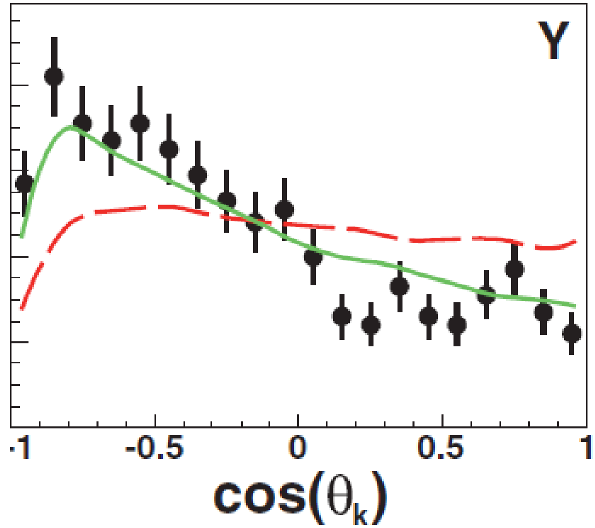
# ➢Discussions: back-to-back? or forward angles?

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



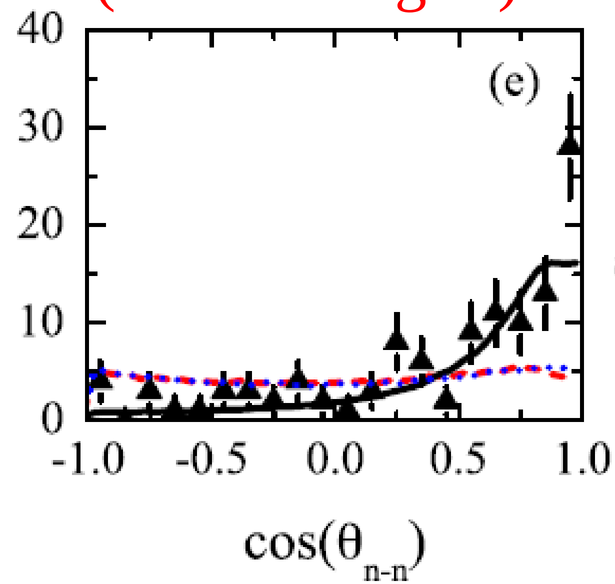

L.V. Grigorenko et al., PRC80 (‘09) 034602

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

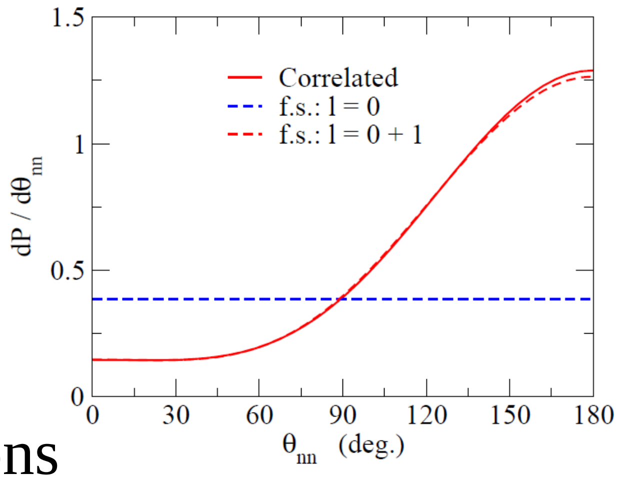
# Summary

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
- 2-neutron emission decay ($^{26}O$ nucleus)




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