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

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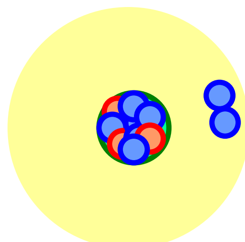
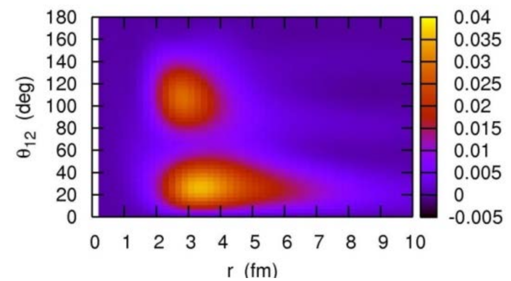




1. Di-neutron correlation: what is it?

2. Coulomb breakup

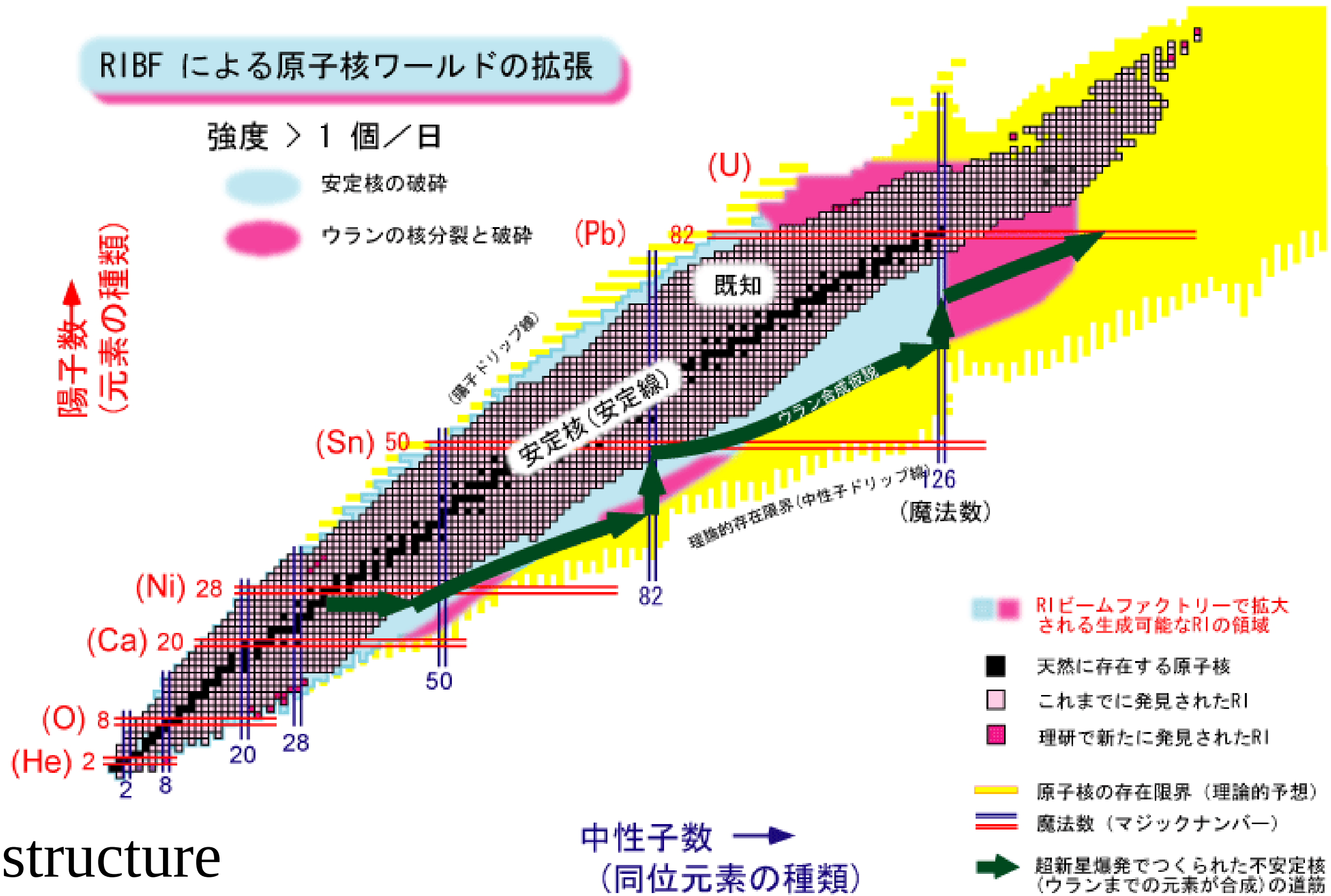
3. Other probes

4. Two-neutron decay of unbound nucleus ^{26}O

5. Summary

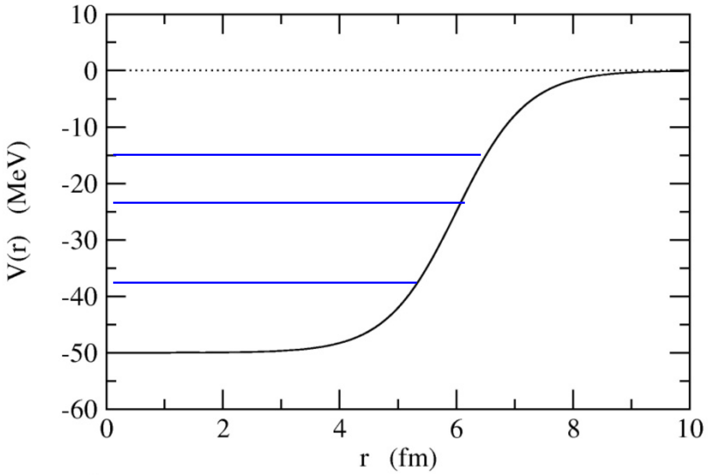
Introduction: neutron-rich nuclei

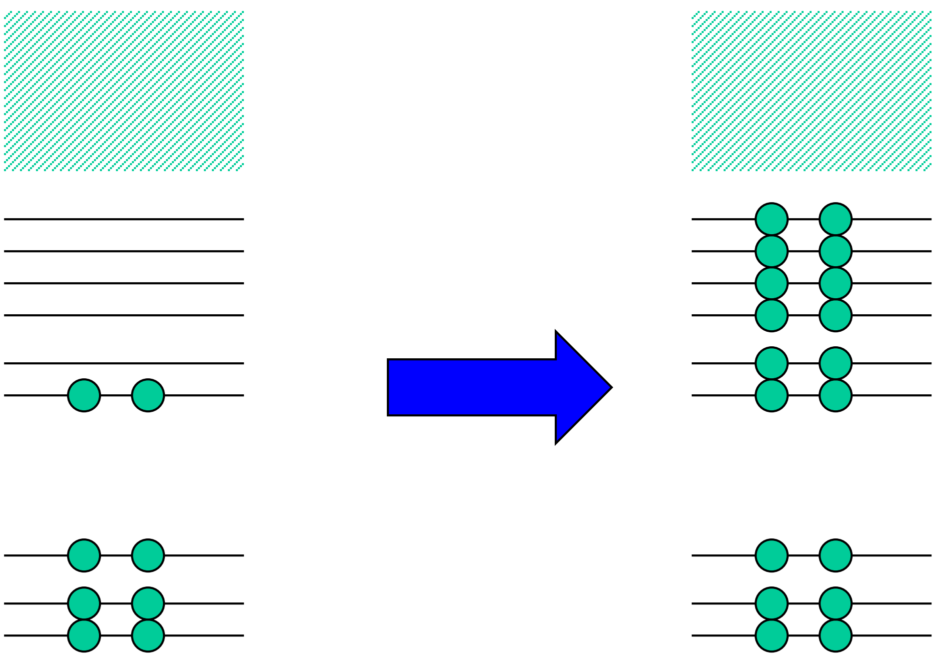
Next generation RI beam facilities： e.g. RIBF (RIKEN, Japan)



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

Mean-field approximation

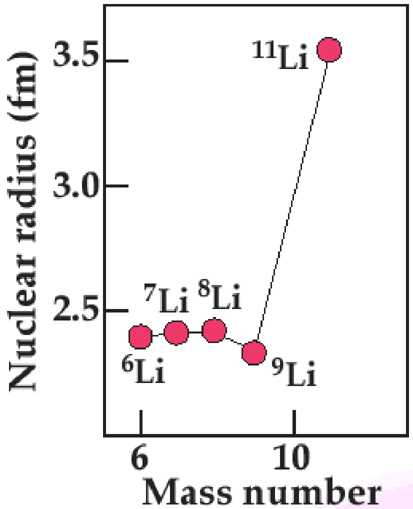




weakly bound systems !!

stable nuclei

neutron-rich nuclei



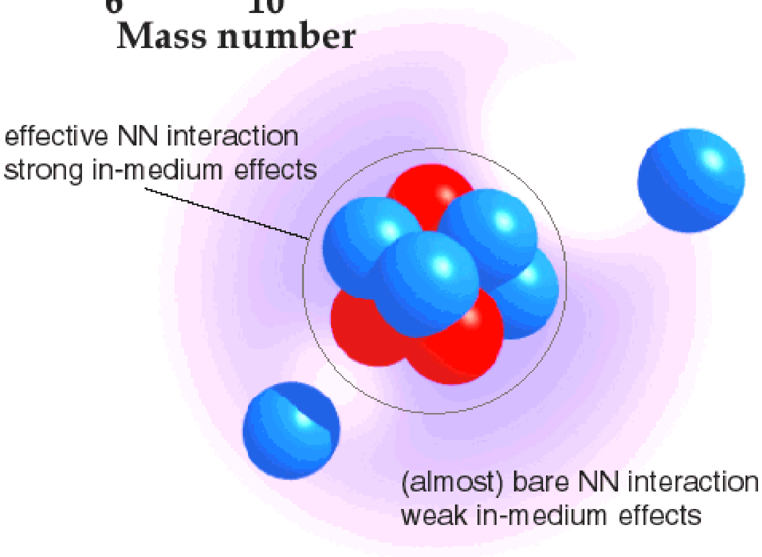
I. Tanihata et al.
Phys. Rev. Lett. 55, 2676 (1985)

Interaction cross section
measurements at Bevalac
(790 MeV/u)

^{11}Li

$$\psi(r) \sim \exp(-\kappa r)$$

$$\kappa = \sqrt{2m|\epsilon|/\hbar^2}$$



halo nucleus

weakly bound systems

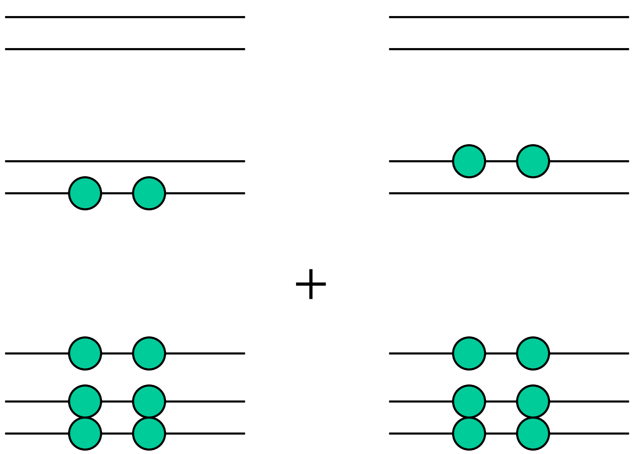
↓

large extension of density

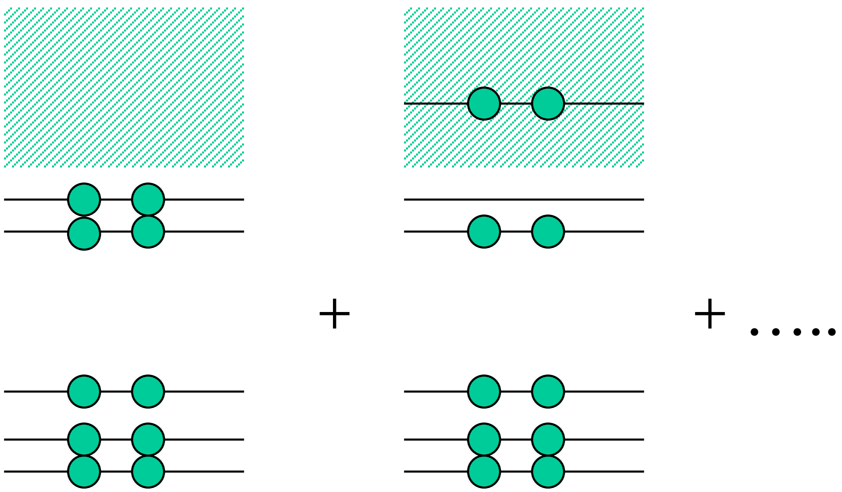
Role of redidual interaction

$$H=\sum_i T_i+\sum_{i<j} v_{ij} \rightarrow H=\sum_i (T_i+V_i)+\sum_{i<j} v_{ij}-\sum_i V_i$$

residual interaction
(pairing)



open shell nuclei

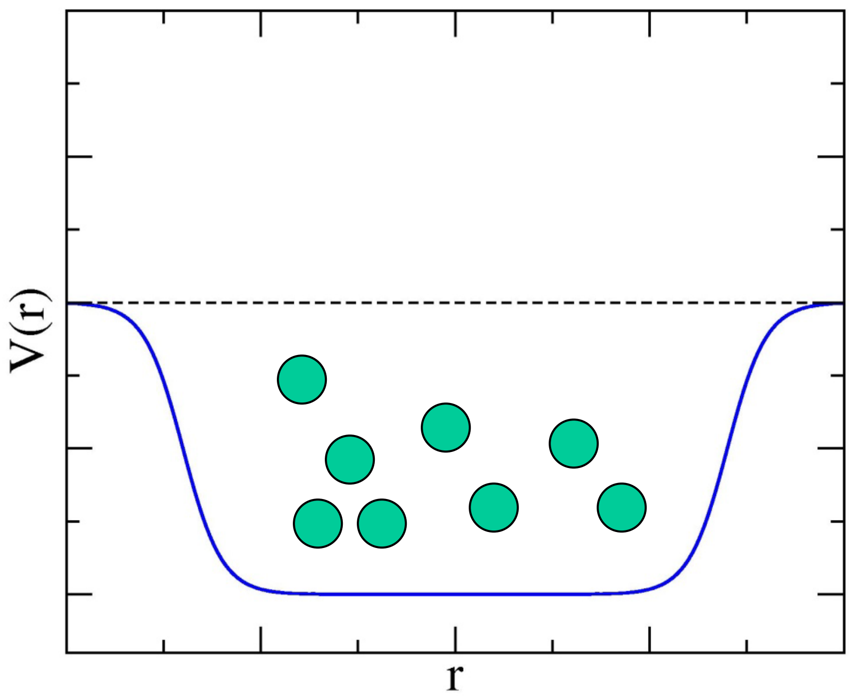


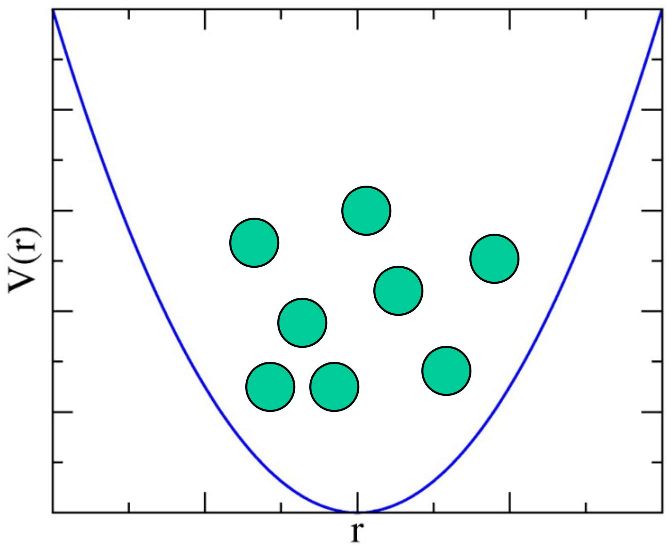
weakly bound nuclei

Neutron-rich nuclei:

- weakly bound systems
- residual interaction (pairing interaction)
- couplings to continuum

many-particles in a confining potential





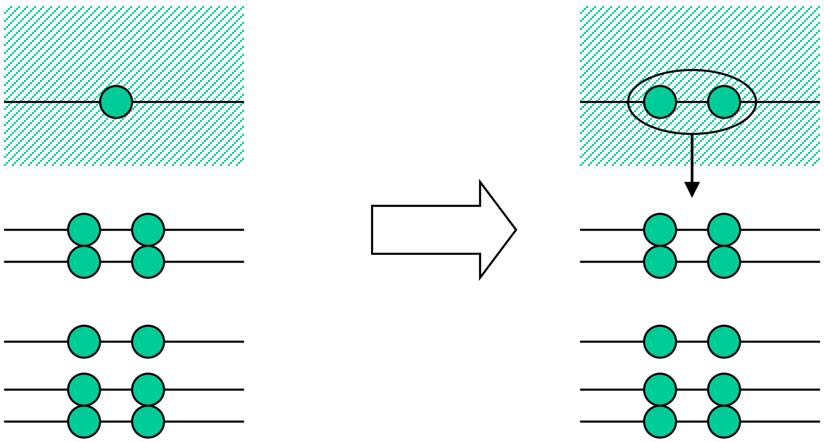
cf. a harmonic trap

- finite-well confining potential
- self-consistent potential

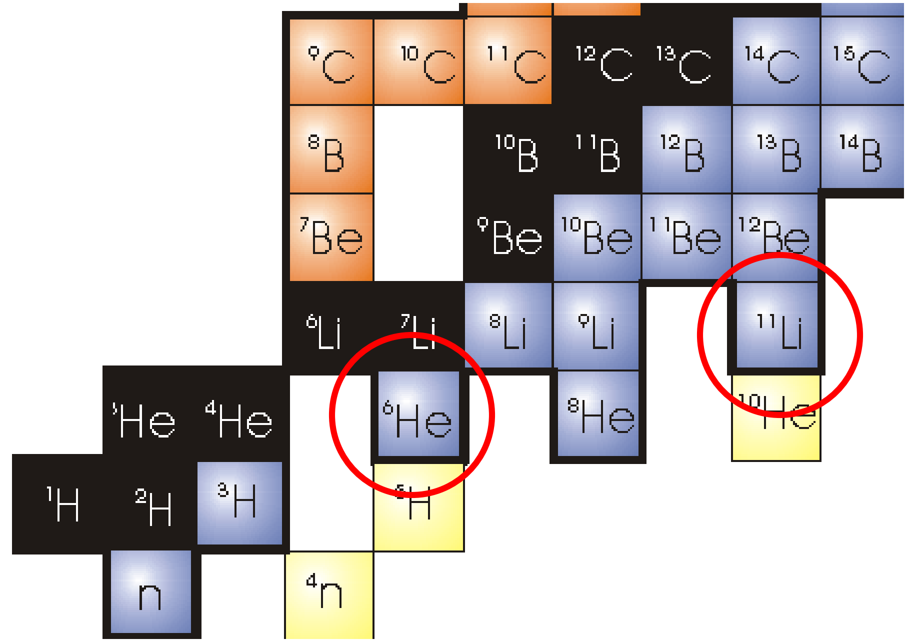
⇒ a challenging problem

Borromean nucleus

residual interaction → attractive



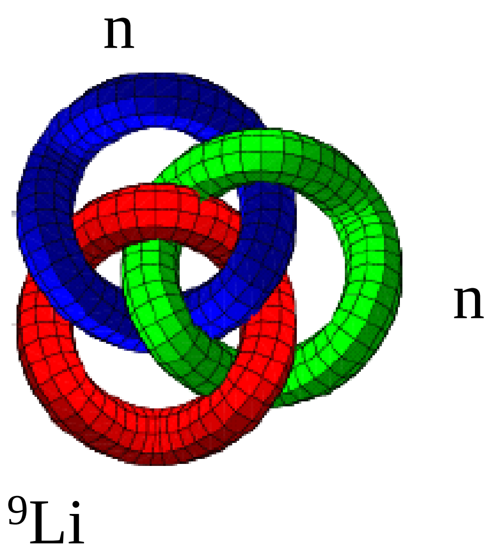
particle unstable　　　　particle stable



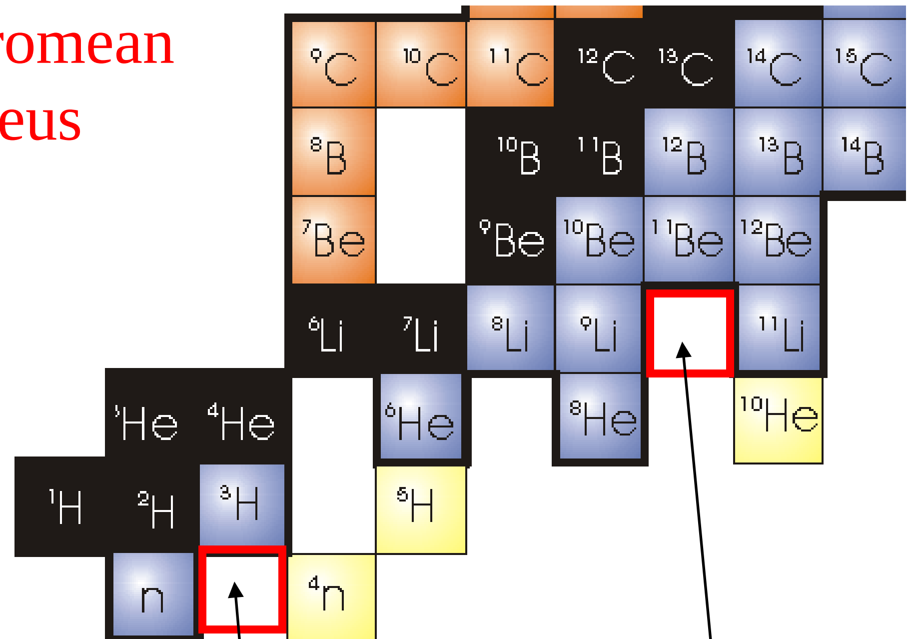
"Borromean nuclei"

Structure of Borromean nuclei

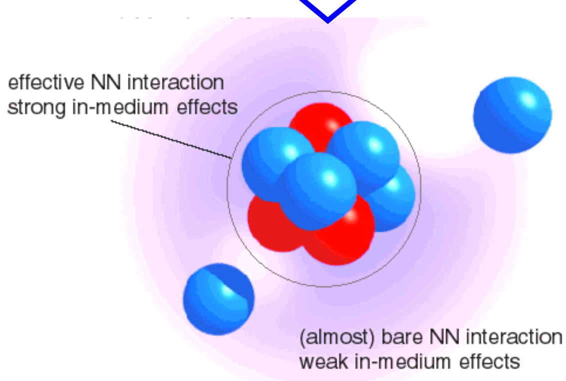
✓non-trivial because of many-body correlations
✓has attracted many interests



Borromean nucleus



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



^{10}Li (^{9}Li+n) does not exist

^{2}n (n+n) does not exist

What is Di-neutron correlation?

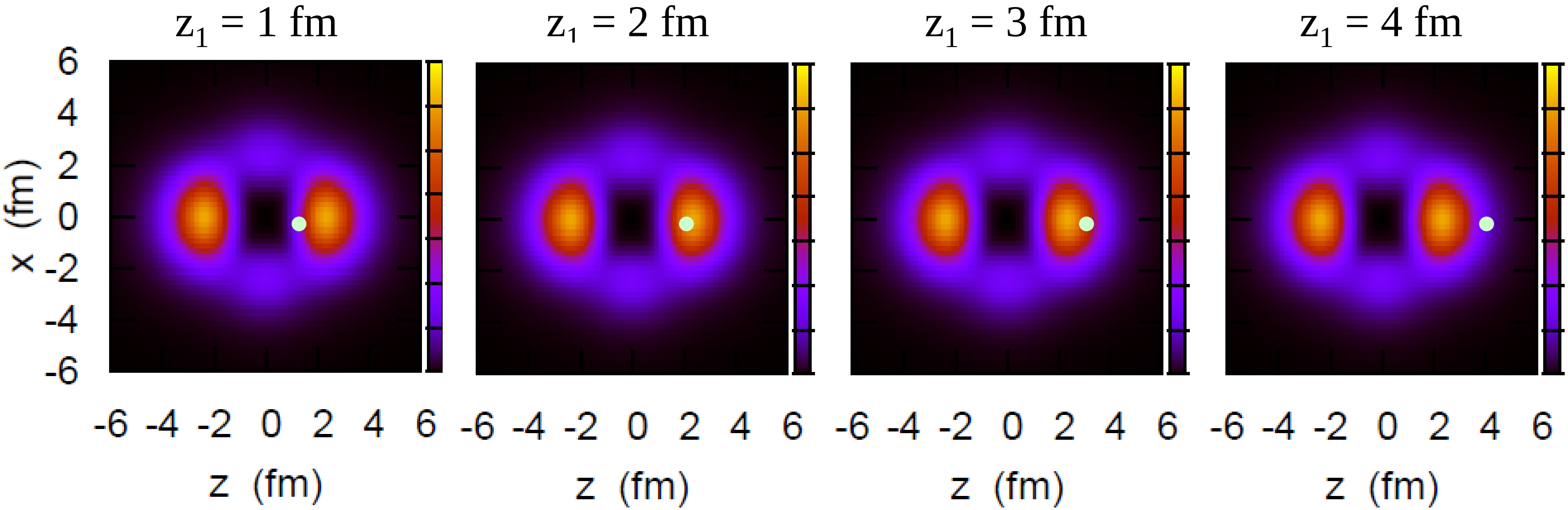
Correlation : $\langle AB \rangle \neq \langle A \rangle \langle B \rangle$

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

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

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

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



✓Two neutrons move independently

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

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

What is Di-neutron correlation?

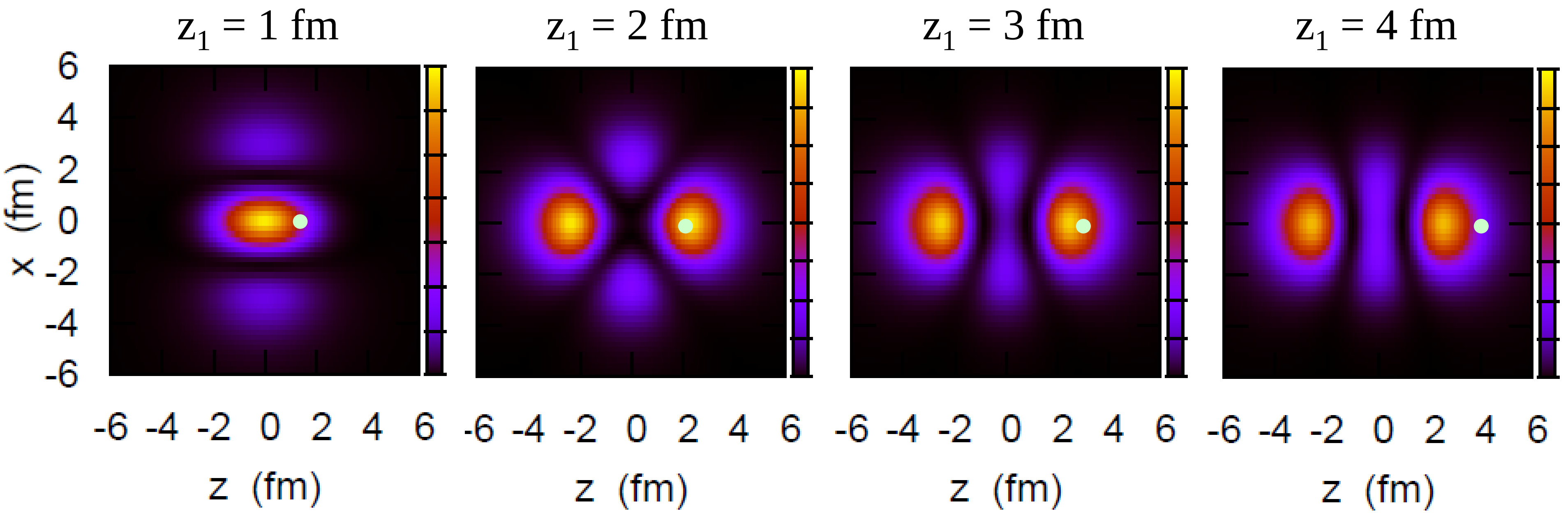
Correlation : $\langle AB \rangle \neq \langle A \rangle \langle B \rangle$

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

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



✓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?

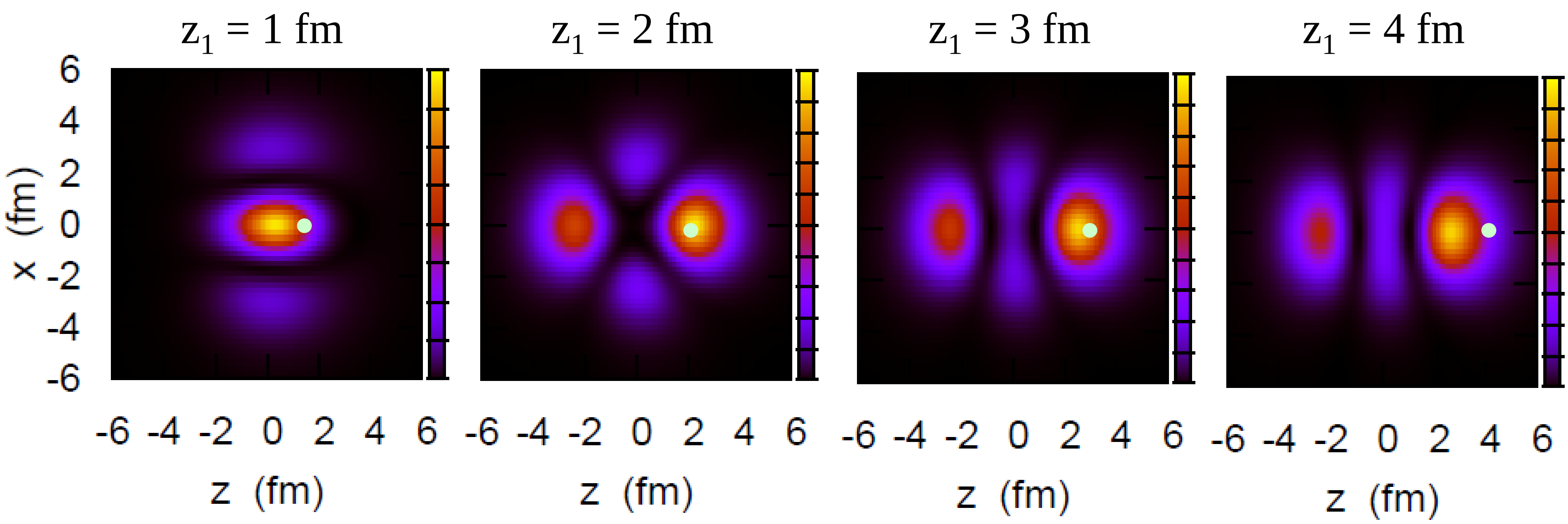
Correlation: $\langle AB \rangle \neq \langle A \rangle \langle B \rangle$

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

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

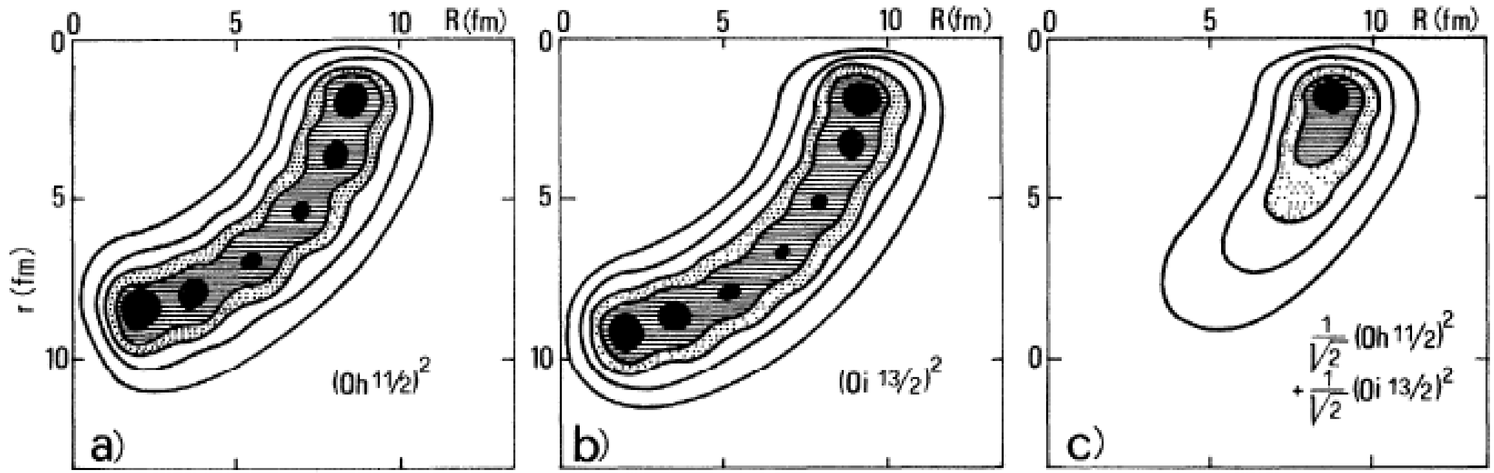


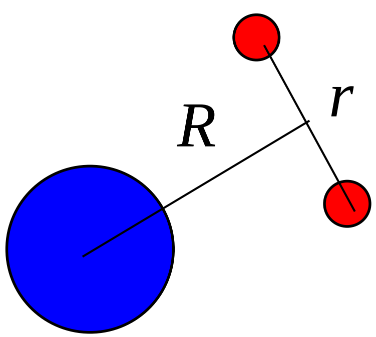
✓spatial correlation: the density of the 2^{nd} neutron localized close to the 1^{st} neutron (dineutron correlation)

✓parity mixing: essential role

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

dineutron correlation: caused by the admixture of different parity states





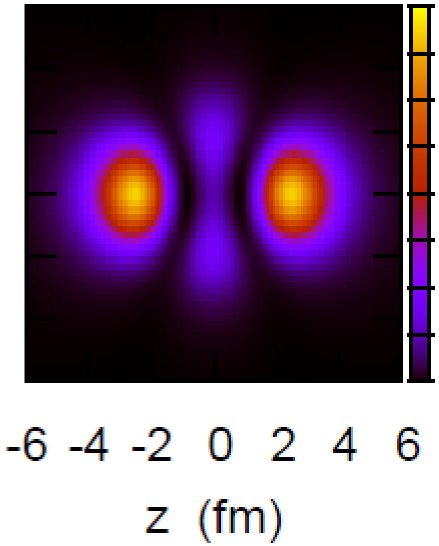
F. Catara, A. Insolia, E. Maglione, and A. Vitturi, PRC29('84)1091

spatial localization of two neutrons
(dineutron correlation)

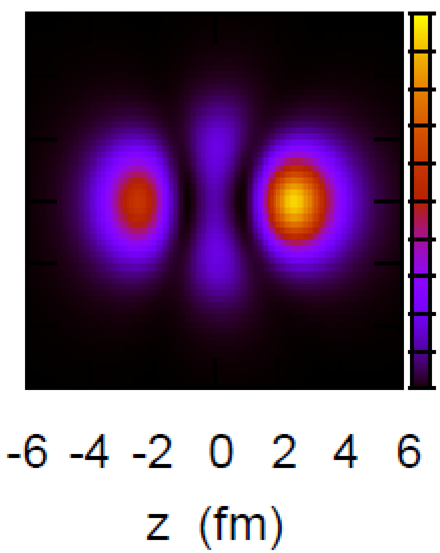
cf. Migdal, Soviet J. of Nucl. Phys. 16 (‘73) 238
Bertsch, Broglia, Riedel, NPA91(‘67)123

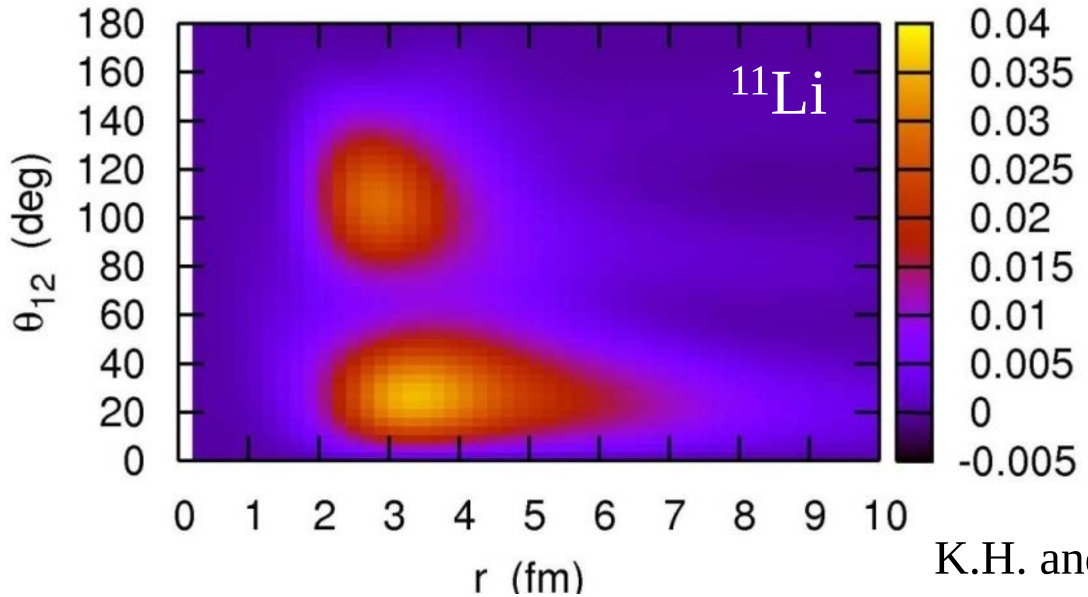
weakly bound systems

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



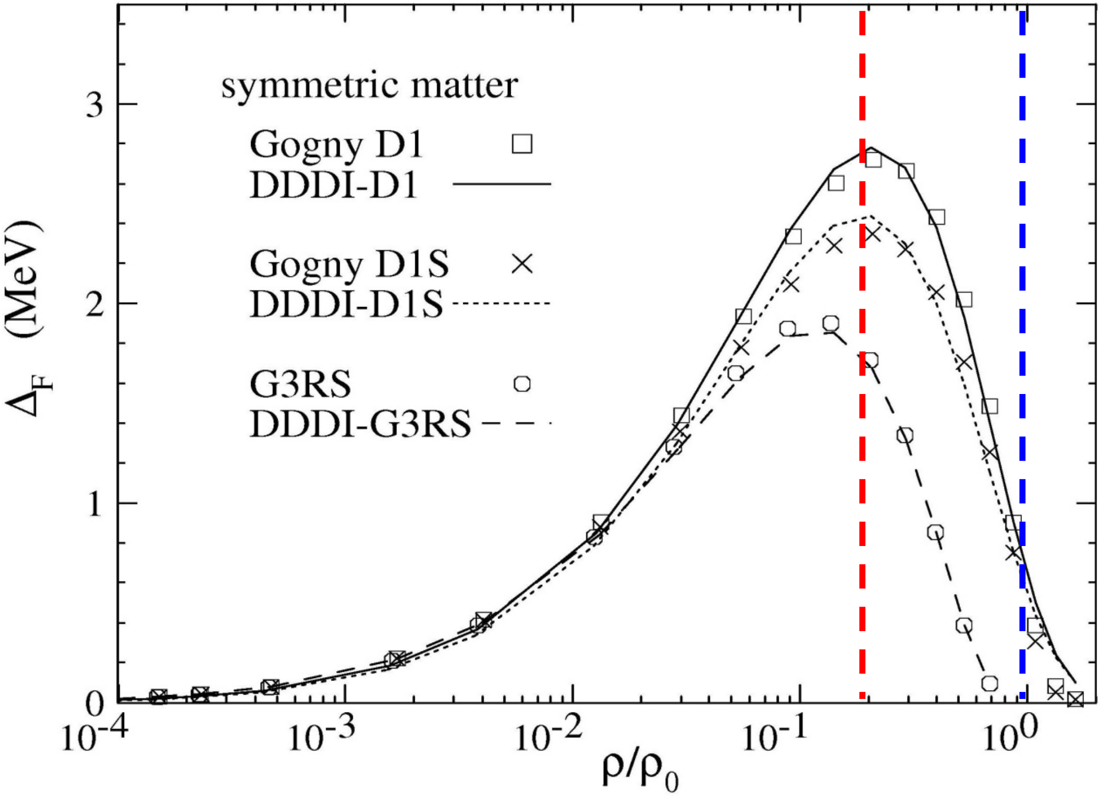
parity mixing





K.H. and H. Sagawa, PRC72(’05)044321

pairing gap in infinite nuclear matter

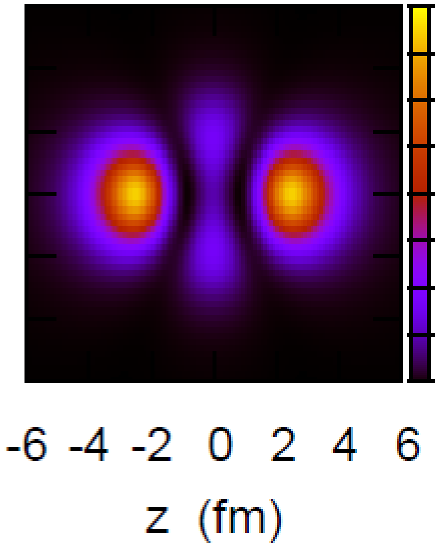


M. Matsuo, PRC73('06)044309

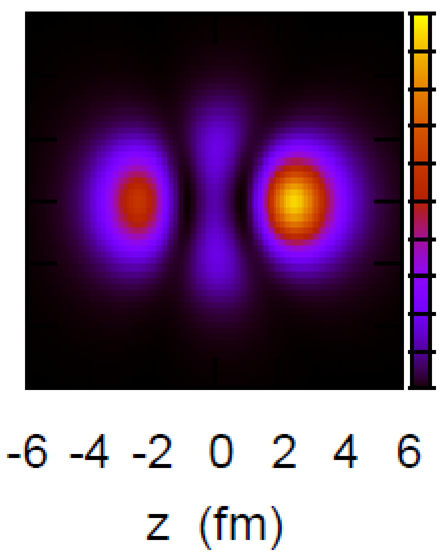
spatial localization of two neutrons

(dineutron correlation)

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



parity mixing

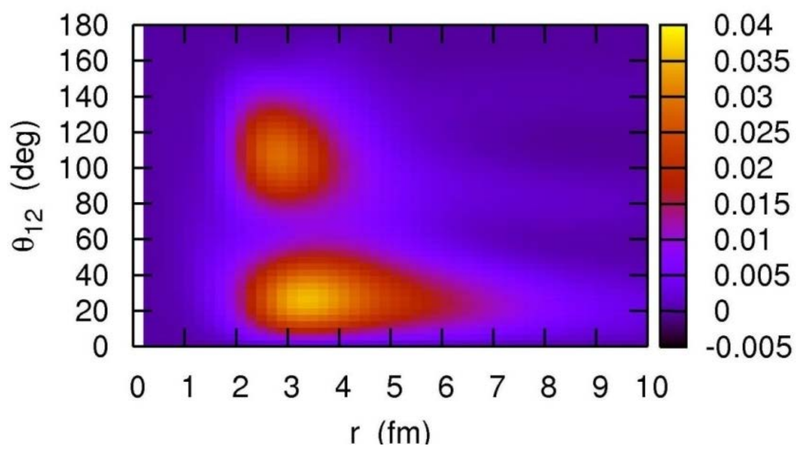


weakly bound systems

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

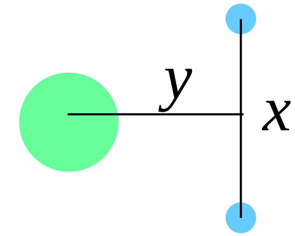
⟶ dineutron correlation: enhanced

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

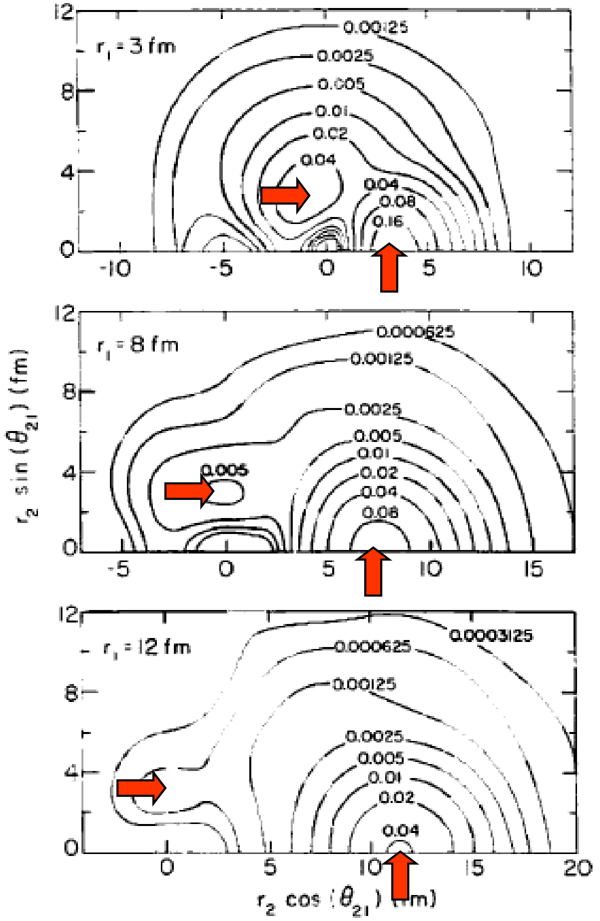


K.H. and H. Sagawa, PRC72(’05)044321

dineutron correlation in Borromean nuclei



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



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

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

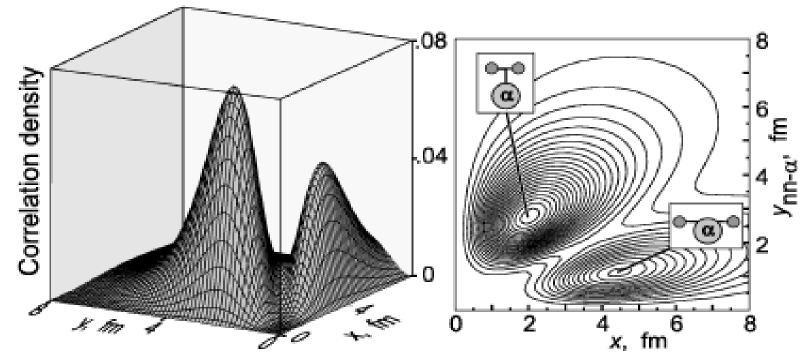
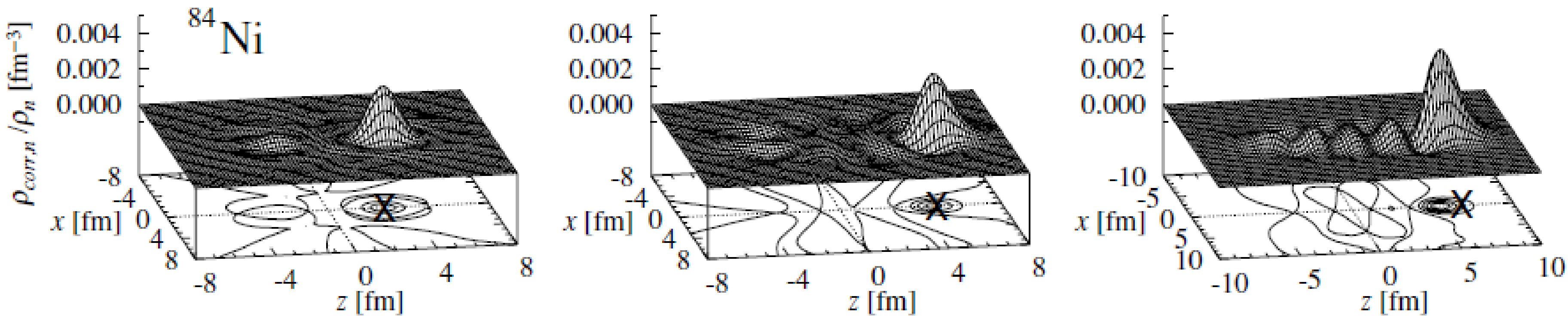


FIG. 1. Spatial correlation density plot for the 0^+ ground state of ^{6}He. Two components—di-neutron and cigarlike—are shown schematically.

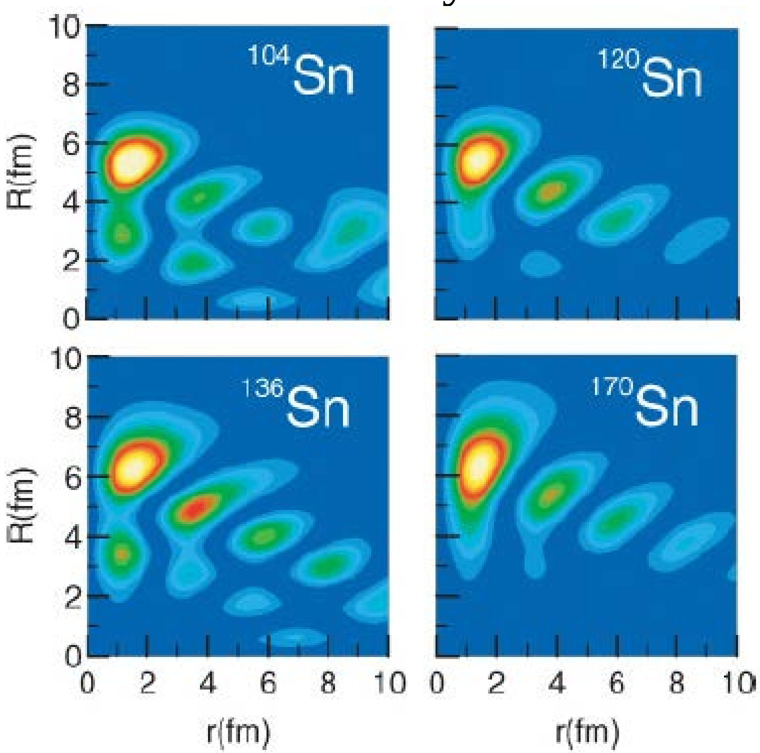
Yu.Ts. Oganessian, V.I. Zagrebaev,
and J.S. Vaagen, *PRL82('99)4996*
M.V. Zhukov et al., *Phys. Rep. 231('93)151*

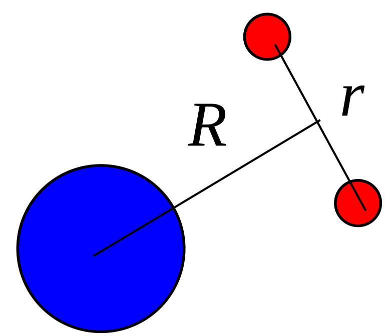
"di-neutron" and *"cigar-like"* configurations

dineutron correlation in heavy neutron-rich nuclei



M. Matsuo, K. Mizuyama, and Y. Serizawa, PRC71(‘05)064326
Skyrme HFB

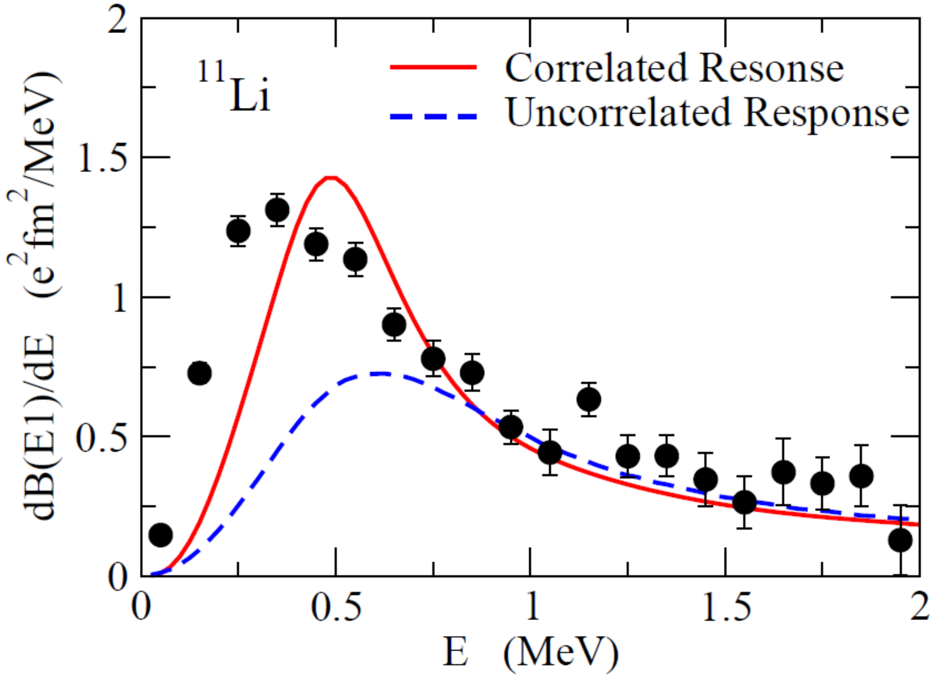


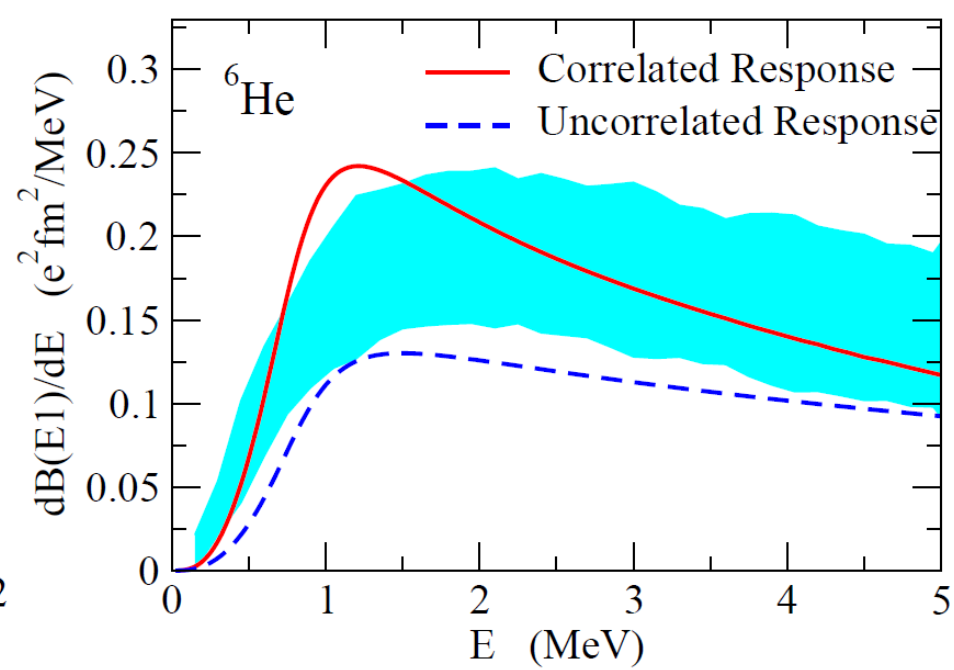


N. Pillet, N. Sandulescu, and P. Schuck,
PRC76(‘07)024310
Gogny HFB

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

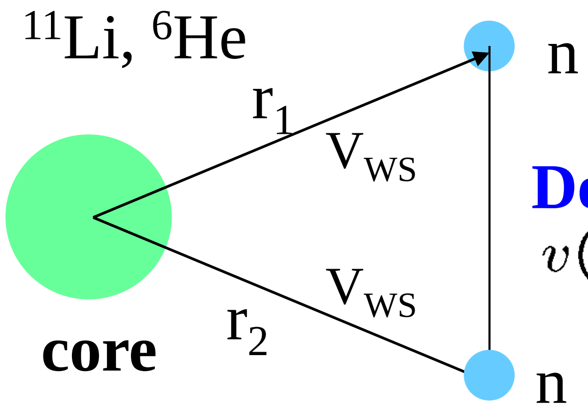
3-body model calculations:

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

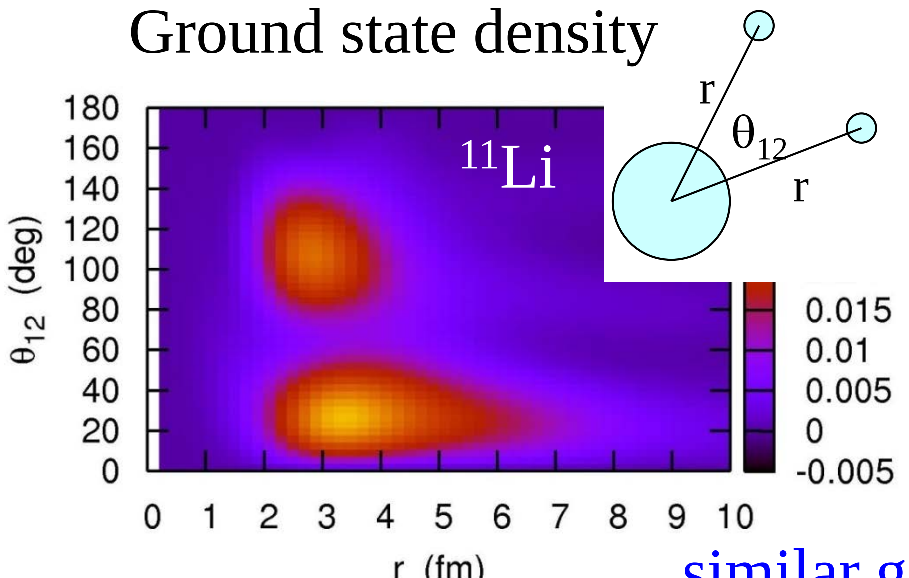
Density-dependent delta-force

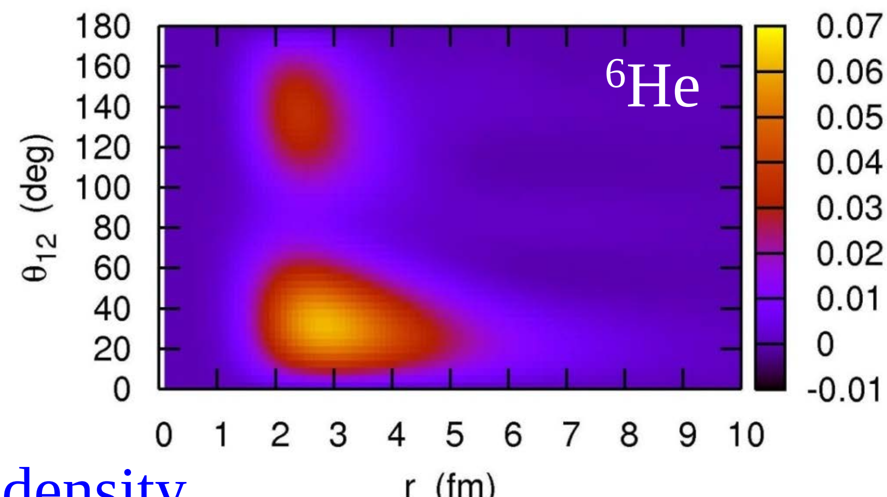
$$v(\boldsymbol{r}_1, \boldsymbol{r}_2) = v_0(1 + \alpha\rho(r)) \times\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)$$

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

Ground state density

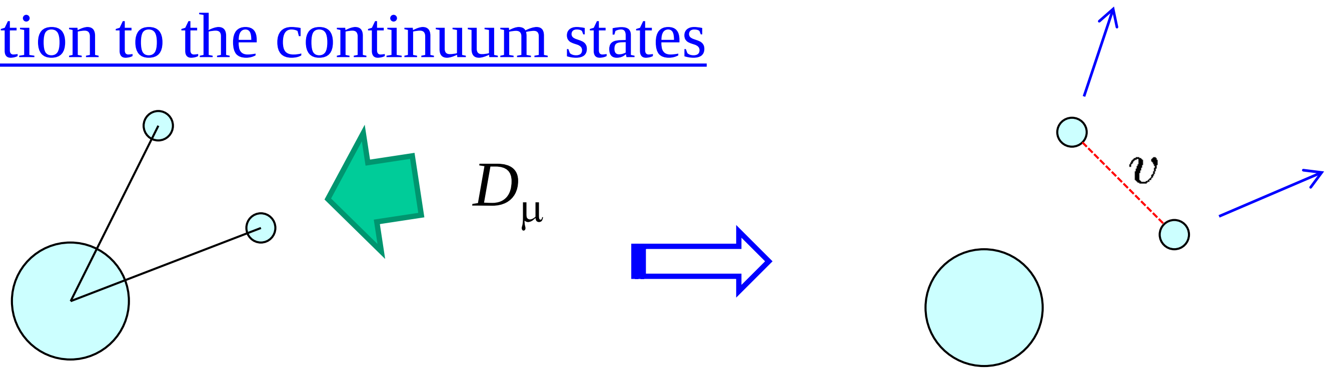
K.H. and H. Sagawa, PRC72('05)044321





similar g.s. density

E1 excitation to the continuum states



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

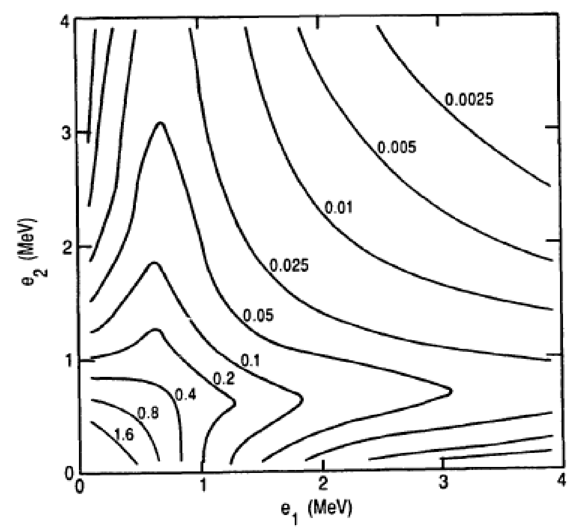
FSI

dipole operator

unperturbed continuum wf

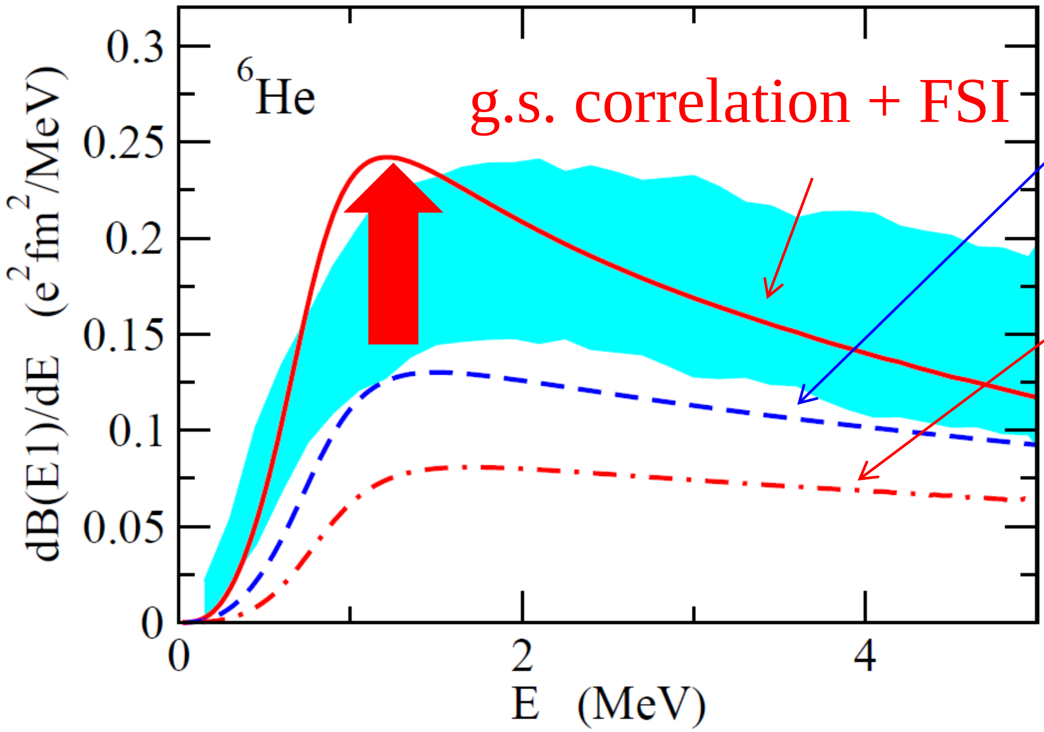
$$G_0(E) = \sum_{\mu, f.st.} \frac{\left| (j_1 j_2)^1_\mu \right\rangle \left\langle (j_1 j_2)^1_\mu \right|}{e_1 + e_2 - E - i\eta}$$

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



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

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

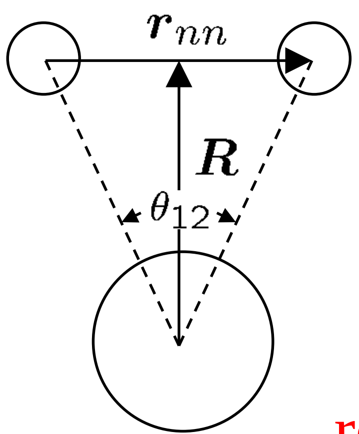


g.s. correlation only
(no nn interaction in
the final state)

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

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

Geometry of Borromean nuclei

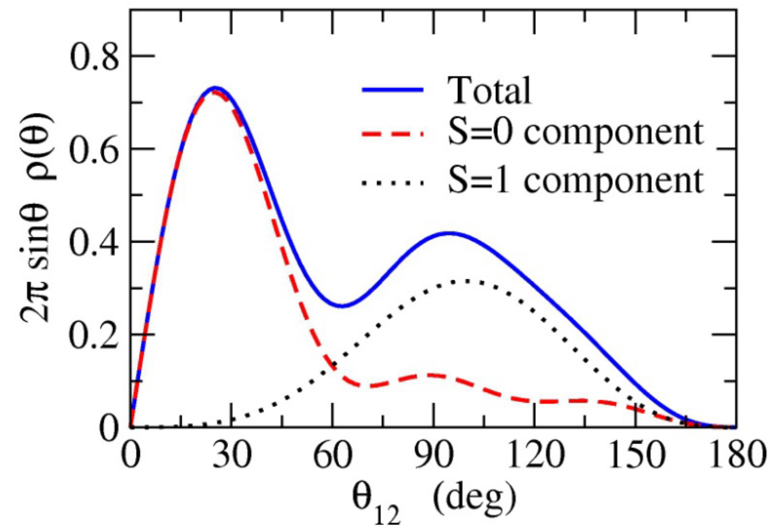


Cluster sum rule

$$B_{\rm tot}(E1) \sim \frac{3}{\pi}\left(\frac{Z_c e}{A_c+2}\right)^2 \langle R^2\rangle$$

reflects the g.s. correlation

3-body model calculations



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

"experimental data" for opening angle

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

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

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

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

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

↓

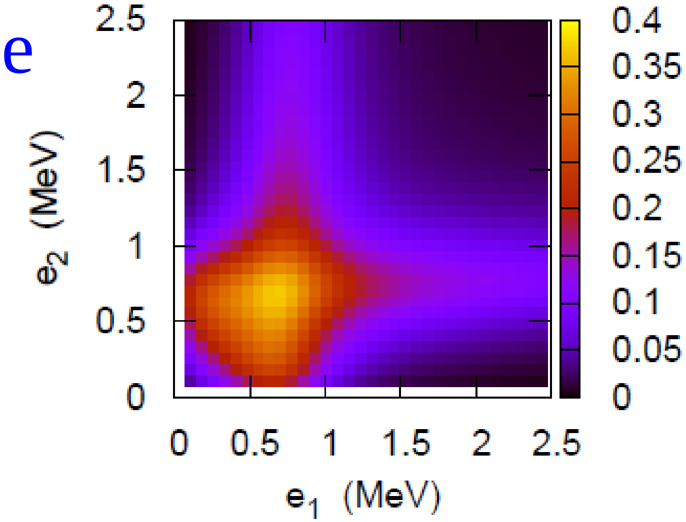
suggests dineutron corr.

(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

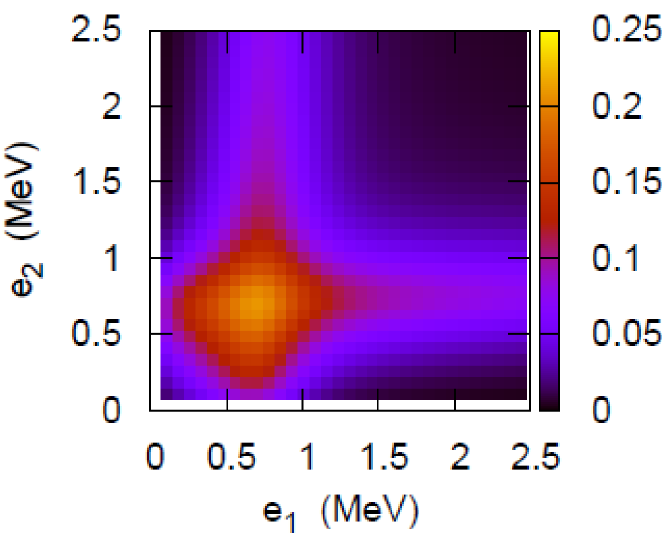


✓shape of distribution: insensitive to the nn-interaction (except for the absolute value)

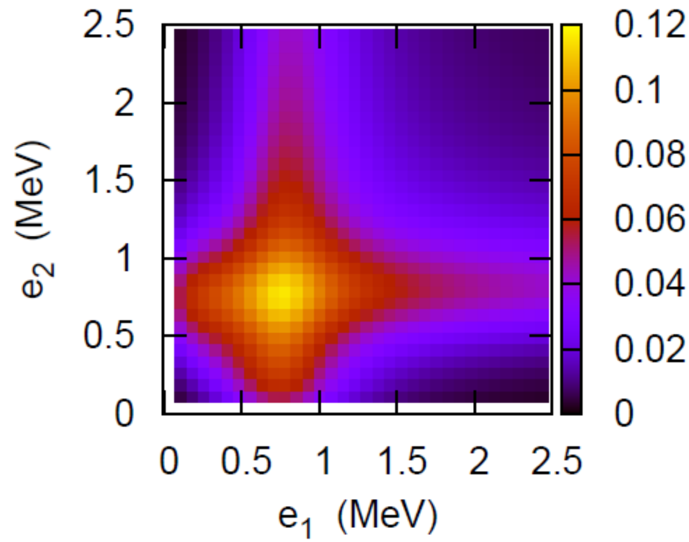
✓strong sensitivity to V_{nC}

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

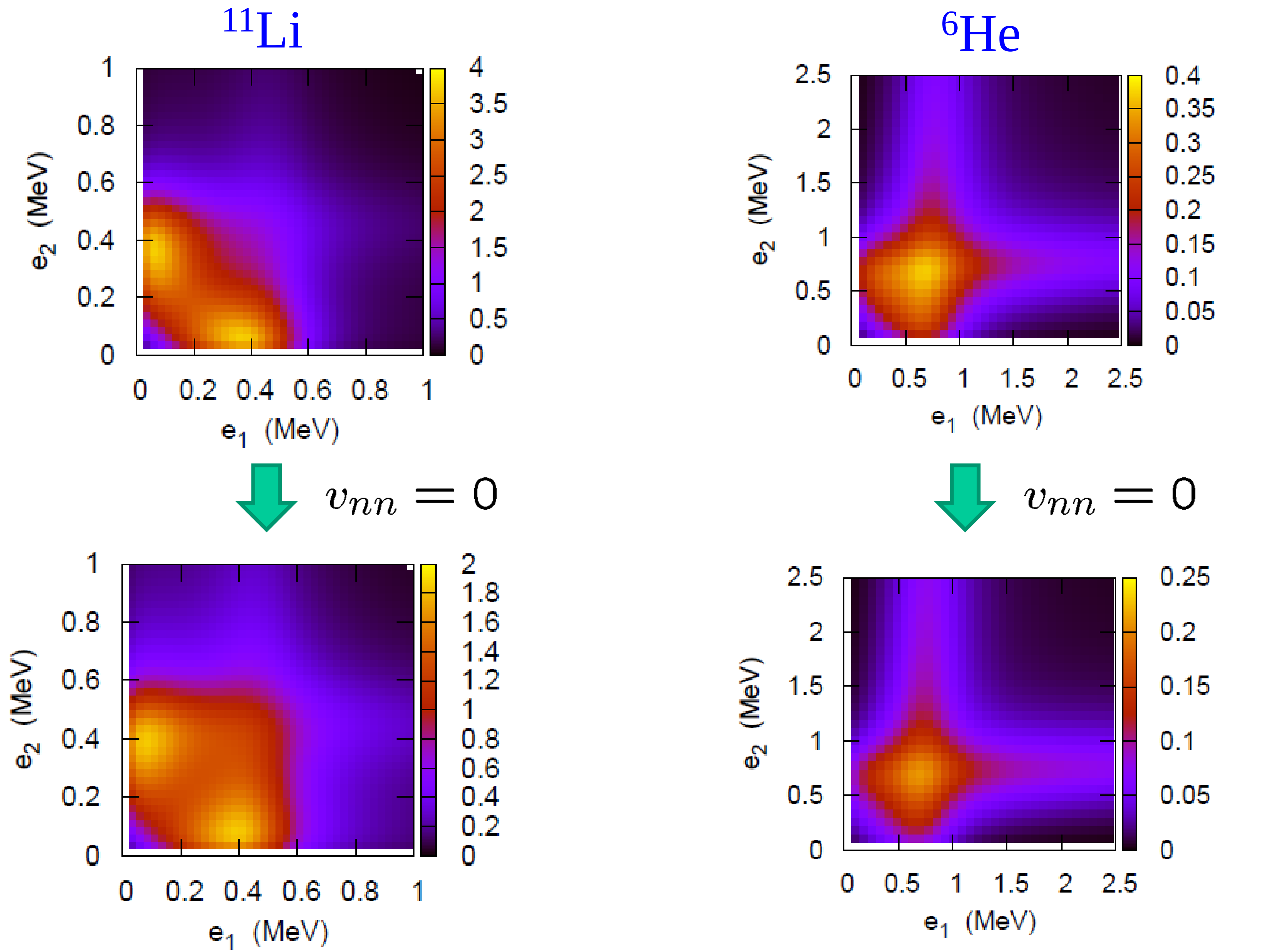
$$v_{nn} = 0$$



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



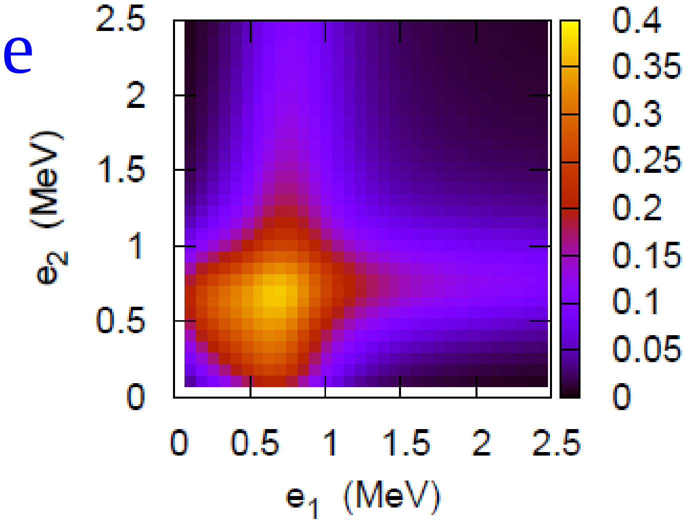
K.H., H. Sagawa, T. Nakamura, S. Shimoura, PRC80('09)031301(R)



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

Energy distribution of emitted neutrons

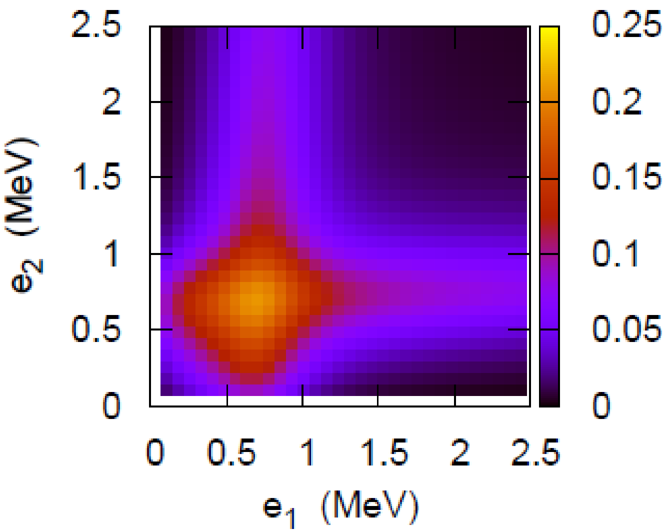
^{6}He



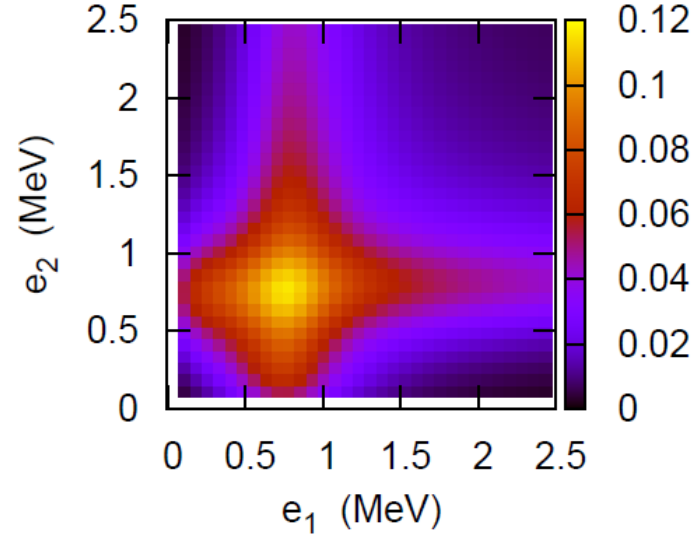
- ✓shape of distribution: insensitive to the nn-interaction (except for the absolute value)
- ✓strong sensitivity to V_{nC}
- ✓similar situation in between ^{11}Li and ^{6}He

⟶ Coul. b.u.: 2-step process

$v_{nn} = 0$

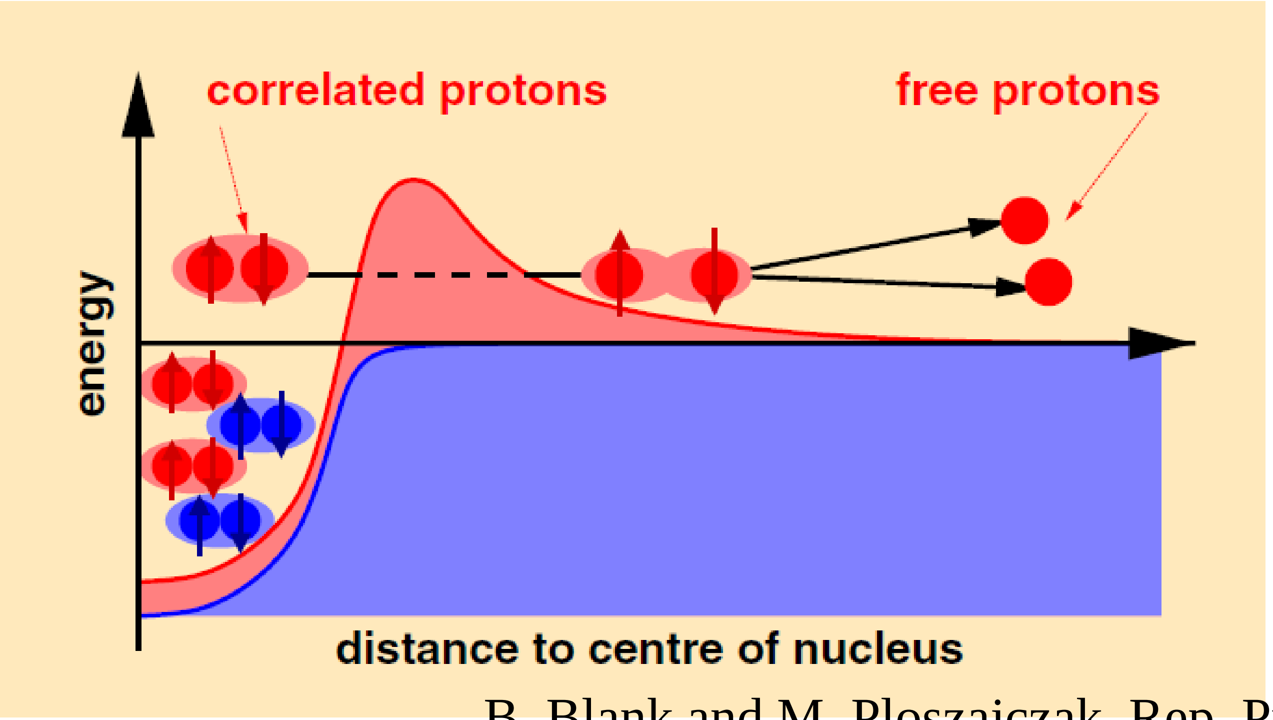


no di-neutron corr. in the g.s.



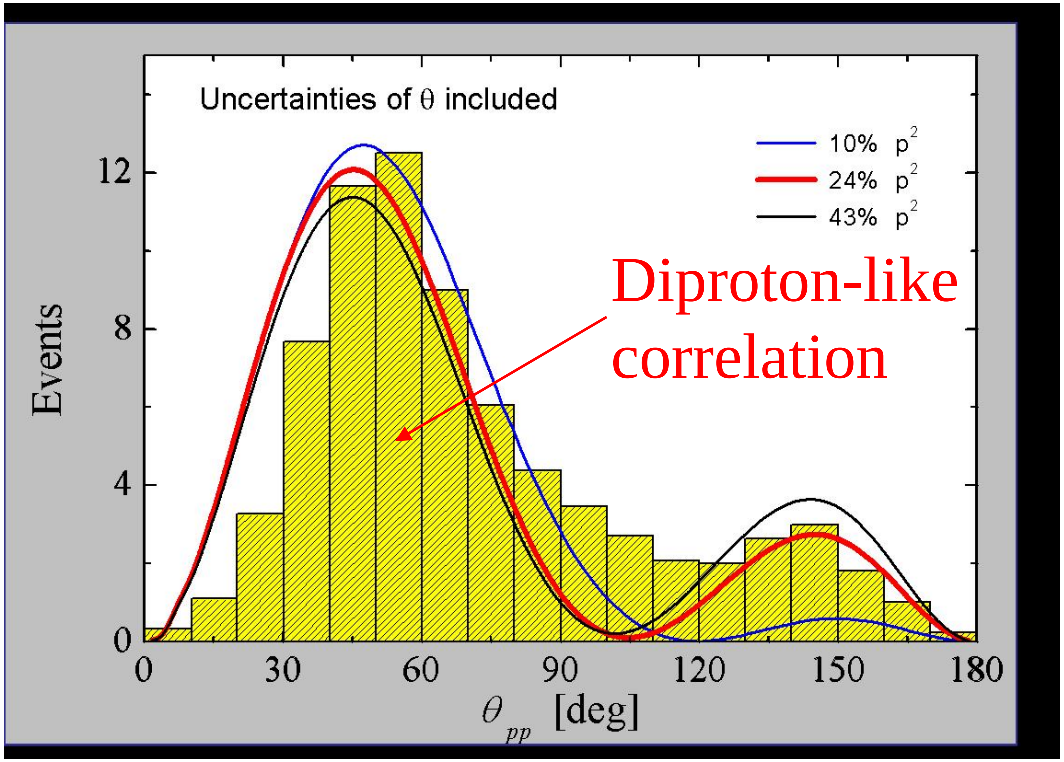
K.H., H. Sagawa, T. Nakamura, S. Shimoura, PRC80('09)031301(R)

2-proton 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?

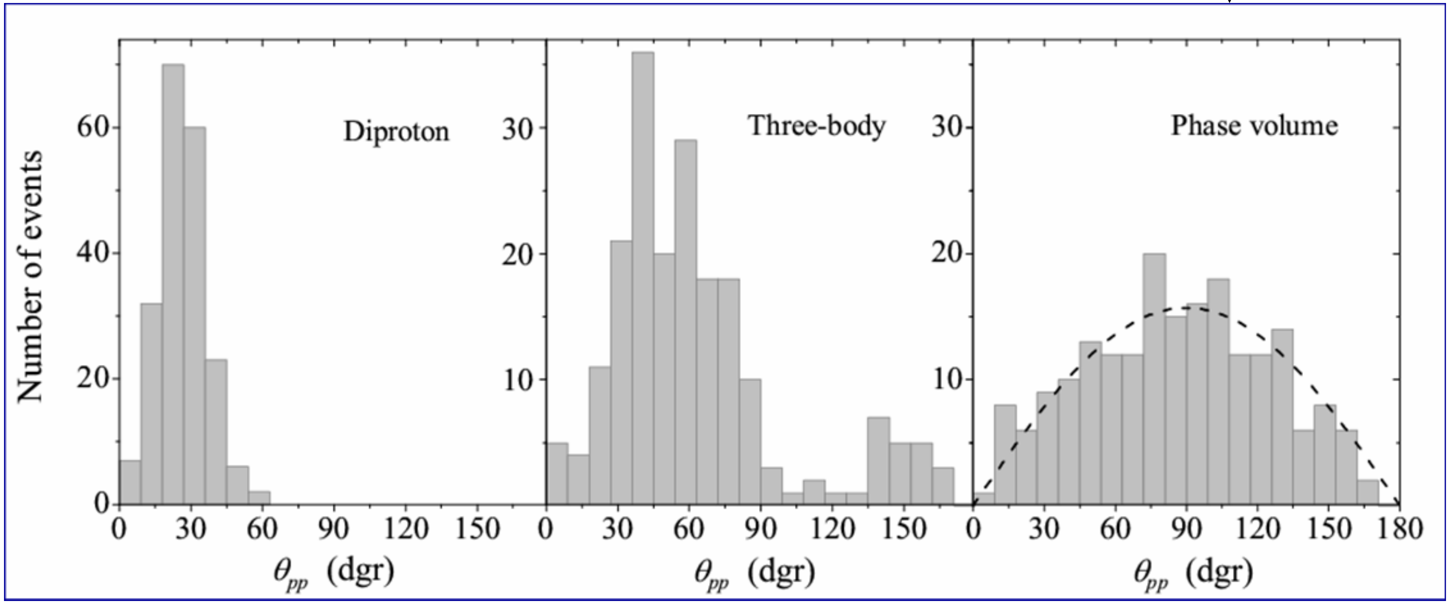


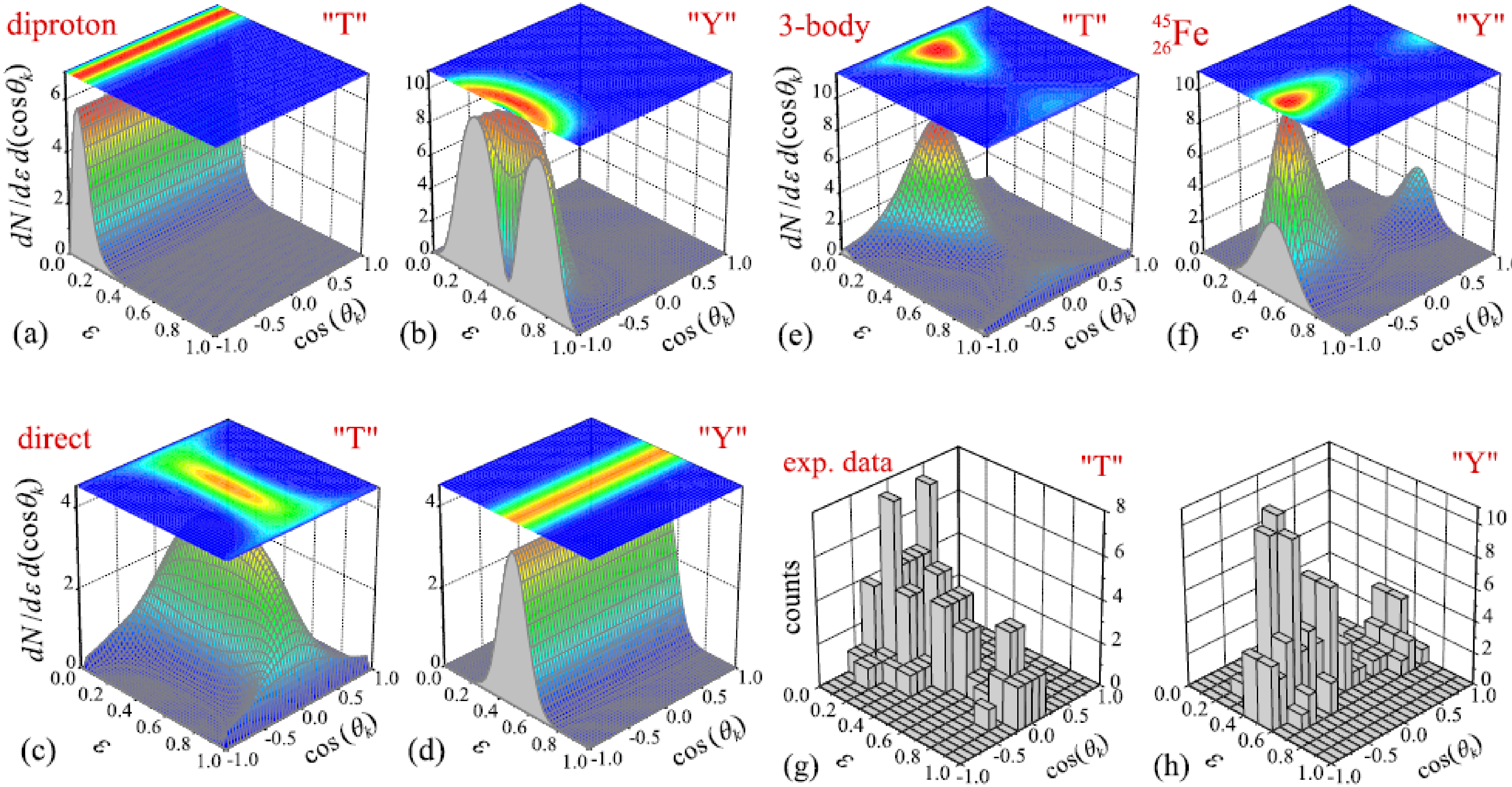
2-proton decay of ^{45}Fe

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

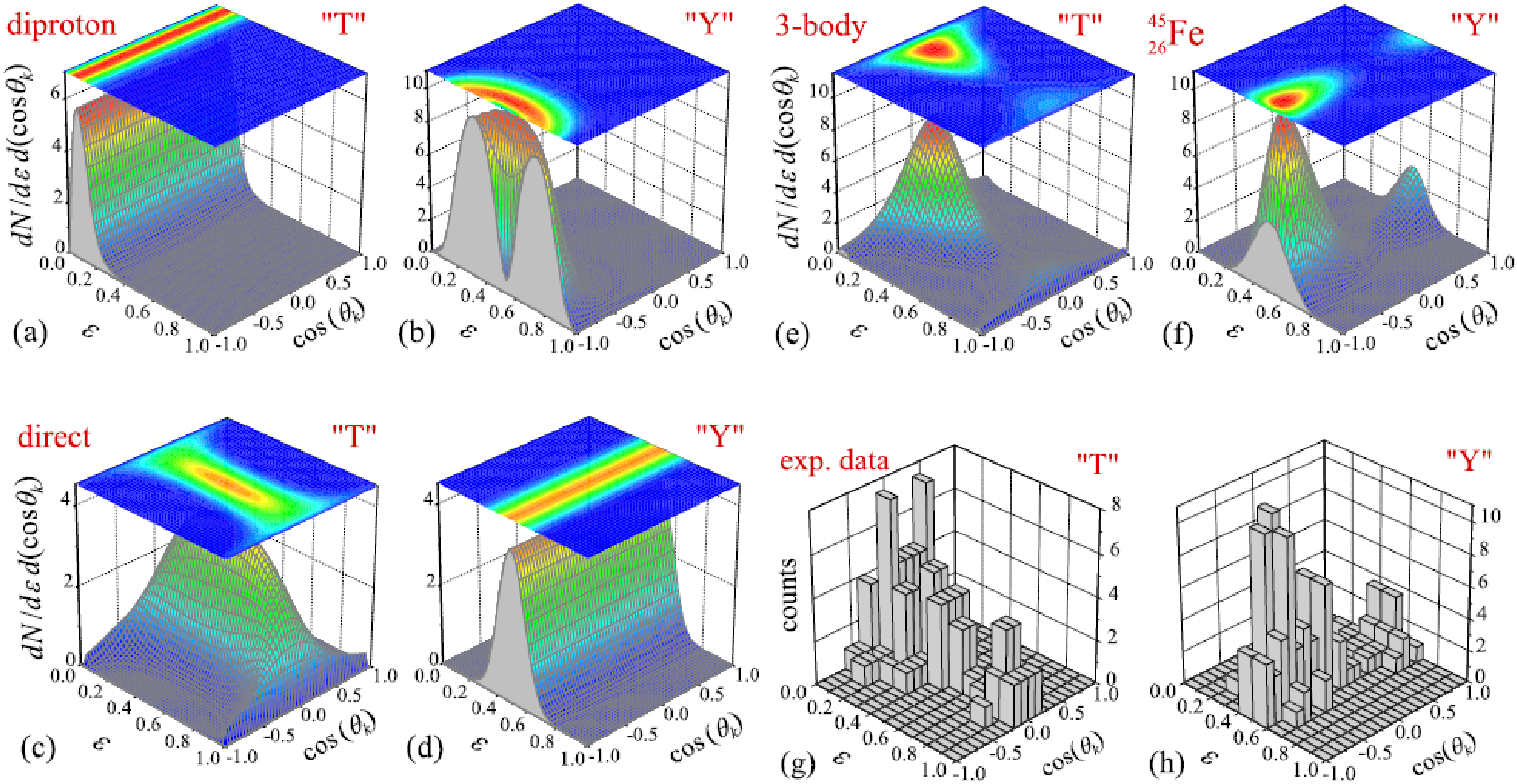
← experimental data

calculations (Grigorenko)





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

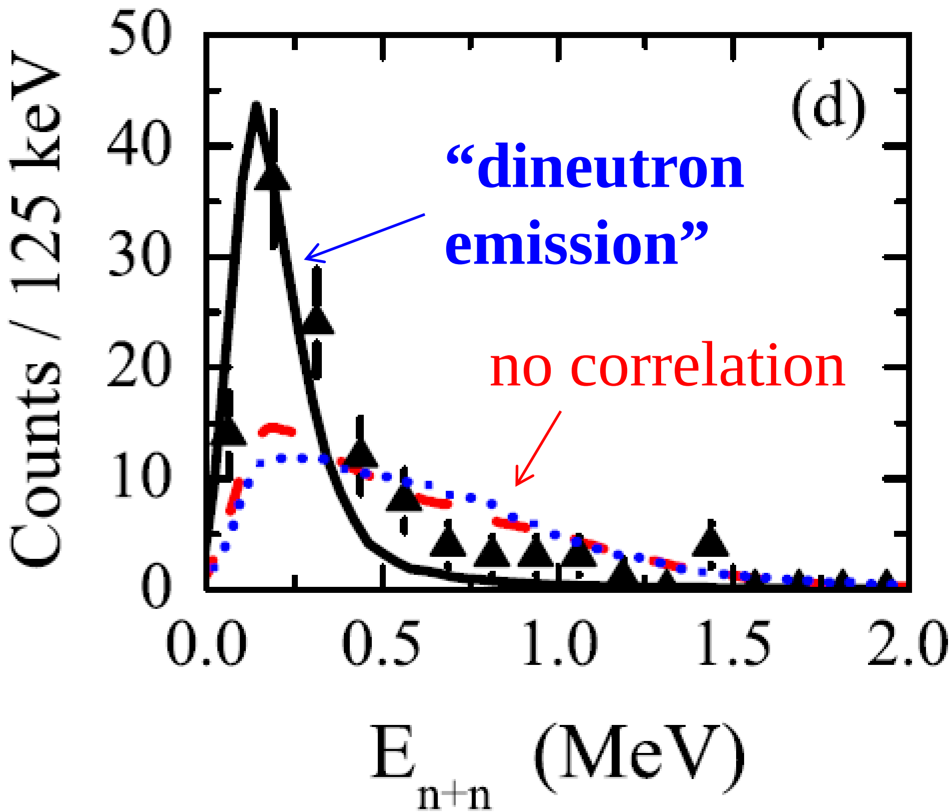


M. Pfutzner, M. Karny, L.V. Grigorenko, K. Riisager, Rev. Mod. Phys. 84 ('12) 567

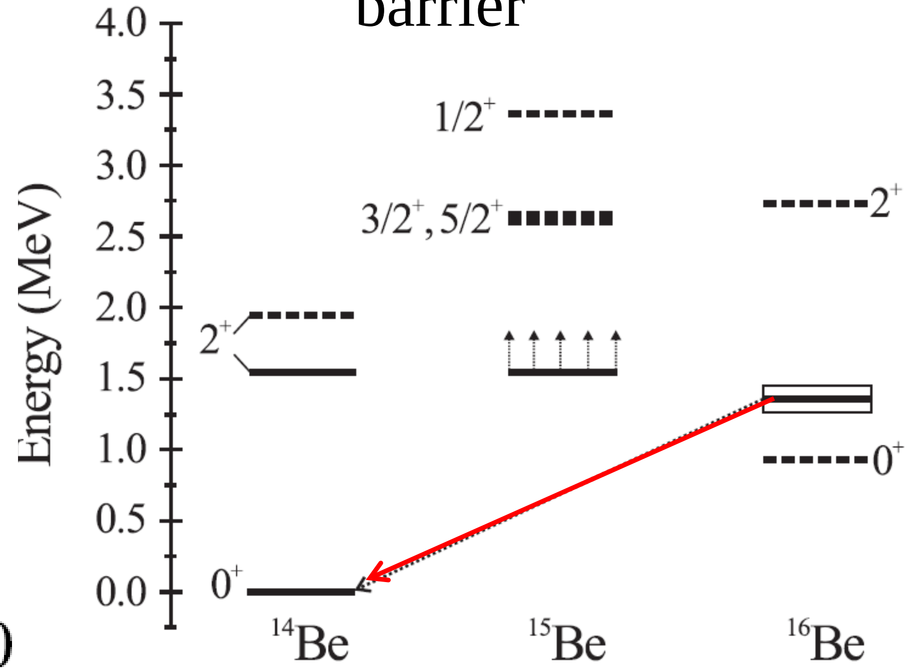
→ diproton correlation: unclear in many other systems (theoretical calculations: not many)

2-neutron decay（MoNA@MSU）

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



3-body resonance due to the centrifugal barrier



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

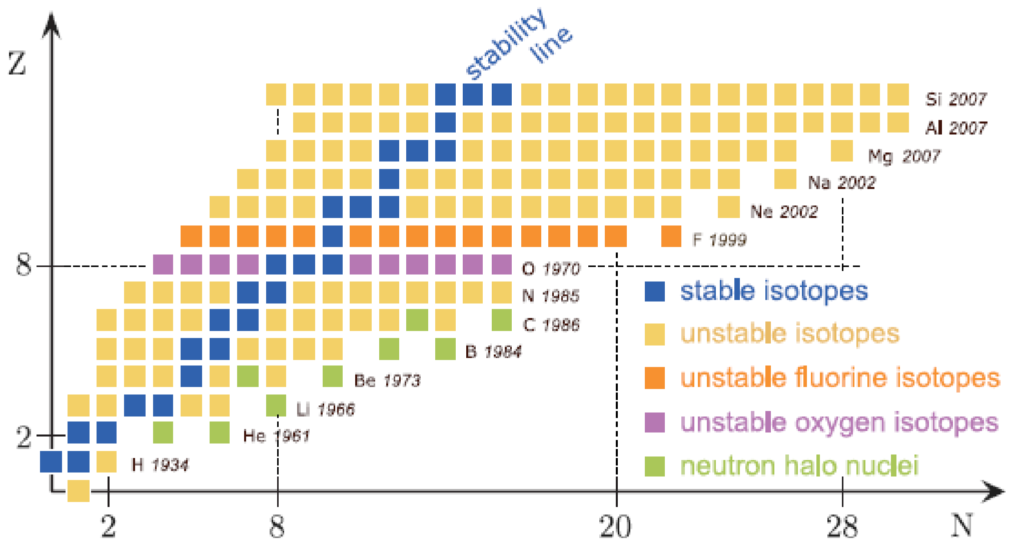
3-body model calculation with nn correlation: urgently needed

3-body model calculations for ^{26}O

K.H. and H. Sagawa, arXiv: 1307.5502

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

- Neutron-rich O and F



H. Sakurai et al.,
PLB448 (‘99) 180
(stability of ^{31}F and unboundness of ^{28}O)

T. Otsuka et al.,
PRL105(‘10)032501

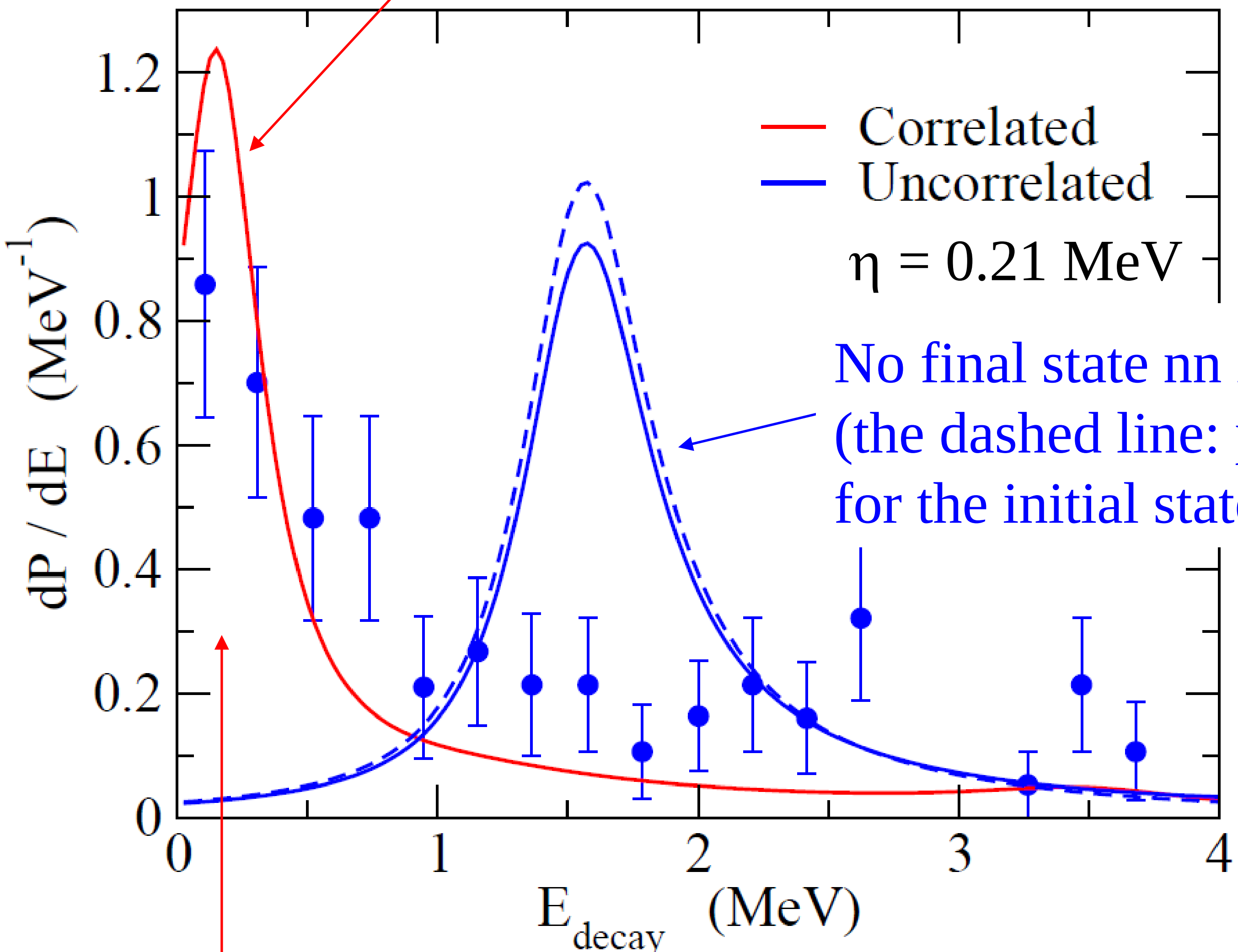
✓ 3-body interaction

- New experiment at SAMURAI (RIBF)

  Y. Kondo et al.

i) Decay energy spectrum

with final state nn interaction



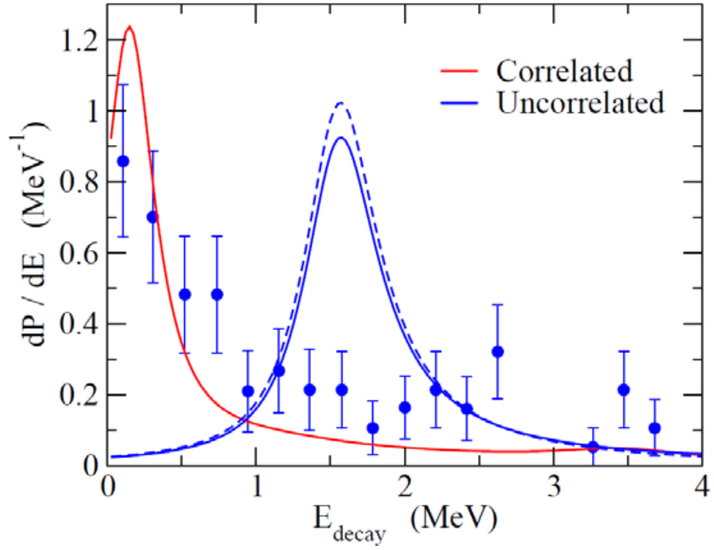
η = 0.21 MeV

No final state nn interaction
(the dashed line: pure $(1d_{3/2})^2$
for the initial state)

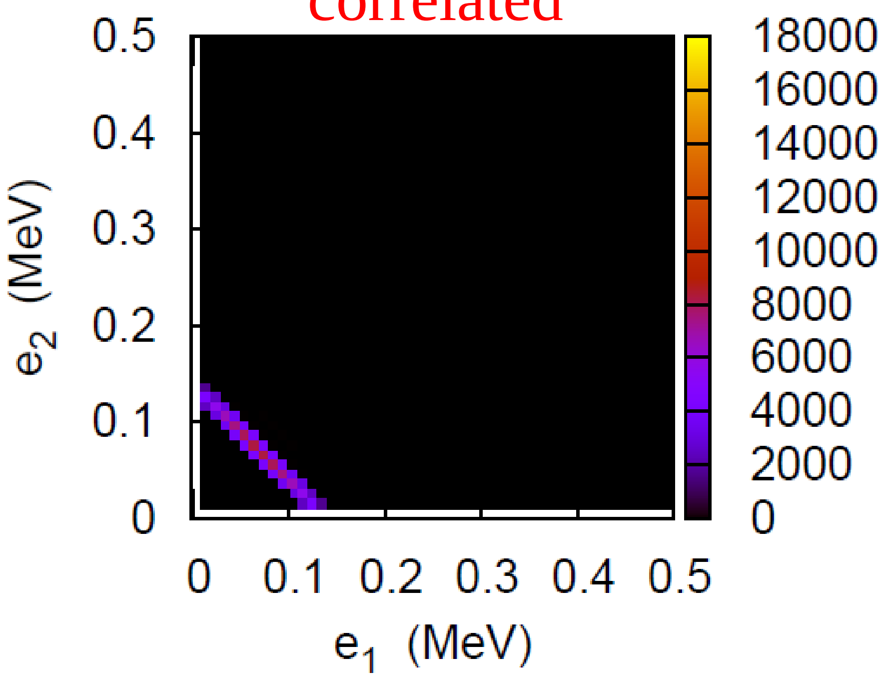
cf. $e_{1d3/2}(^{25}O)$ = 0.770 MeV

Very narrow (Γ_{exp} ~ 10^{-10} MeV) 3-body resonance state

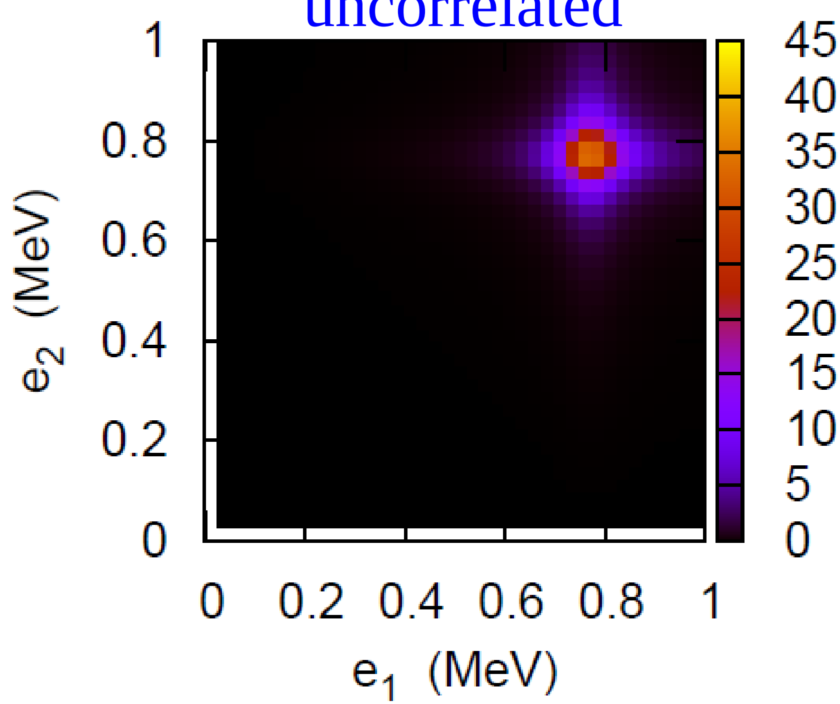
ii) energy spectrum for 2-emitted neutrons



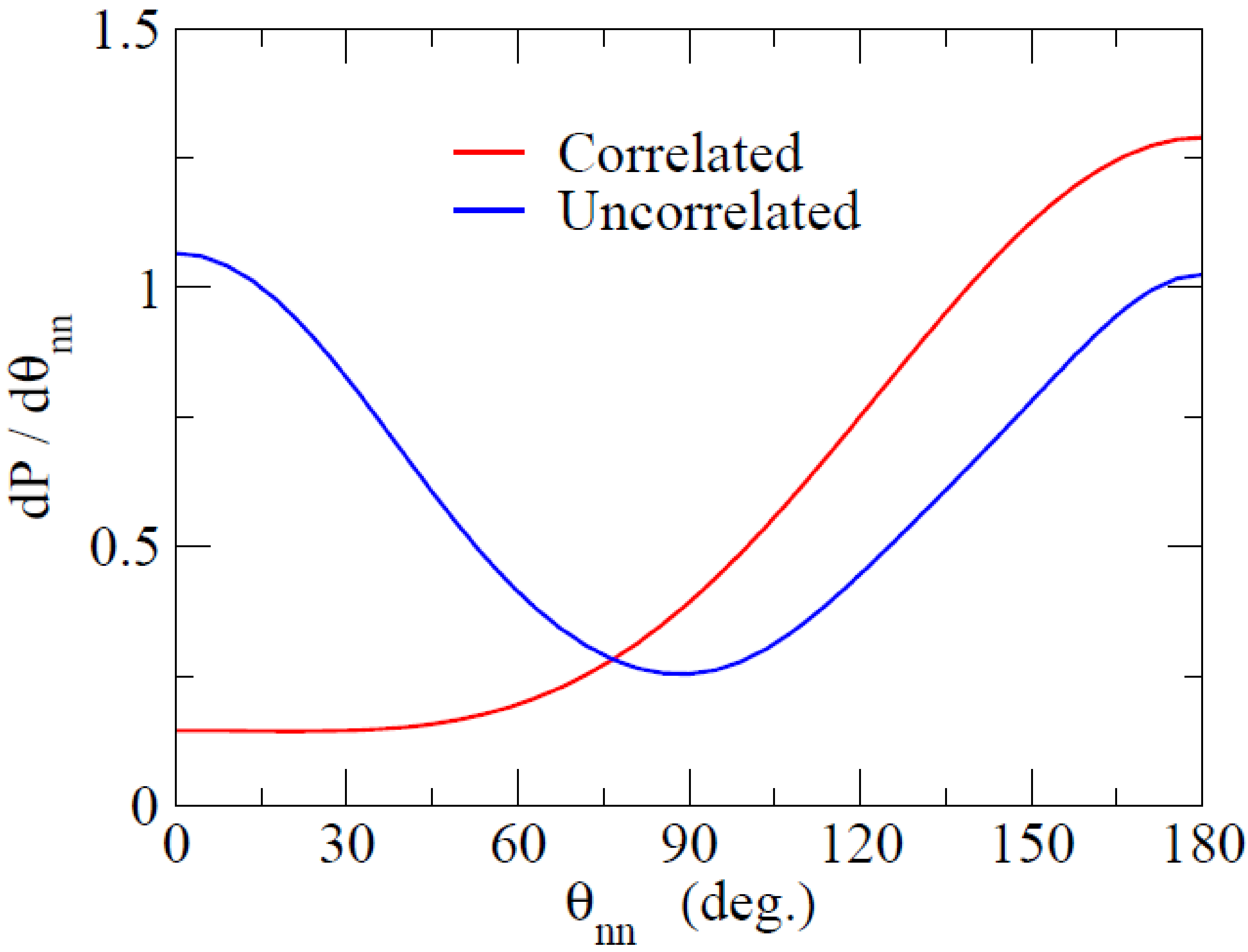
correlated



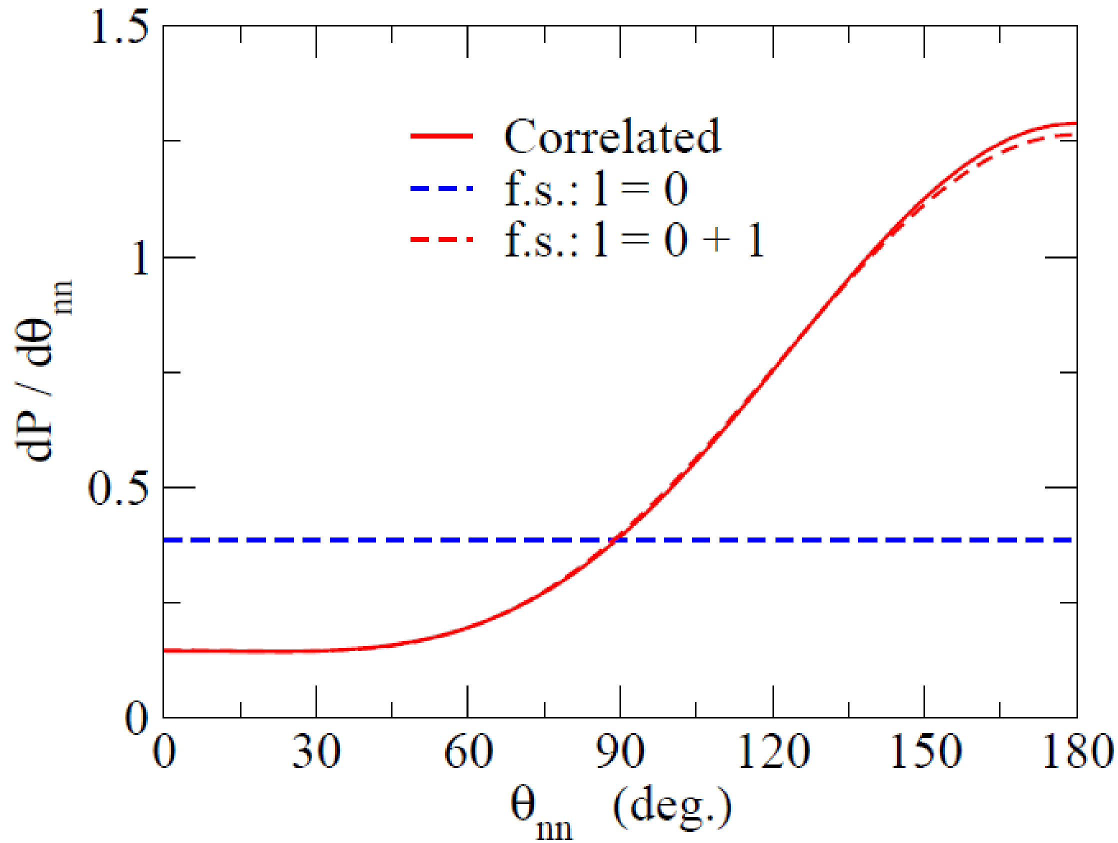
uncorrelated



iii) distribution of opening angle for two-emitted neutrons



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



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

rescattering due to the pairing interaction

*other l components: largely suppressed due to V_{cent}
$(E_{decay} \sim 0.14$ MeV, $e_1 \sim e_2 \sim 0.07$ MeV)

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