Di-neutron correlation in neutron-rich nuclei

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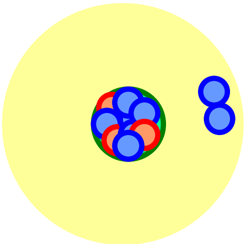
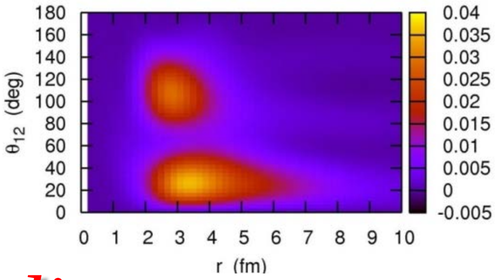
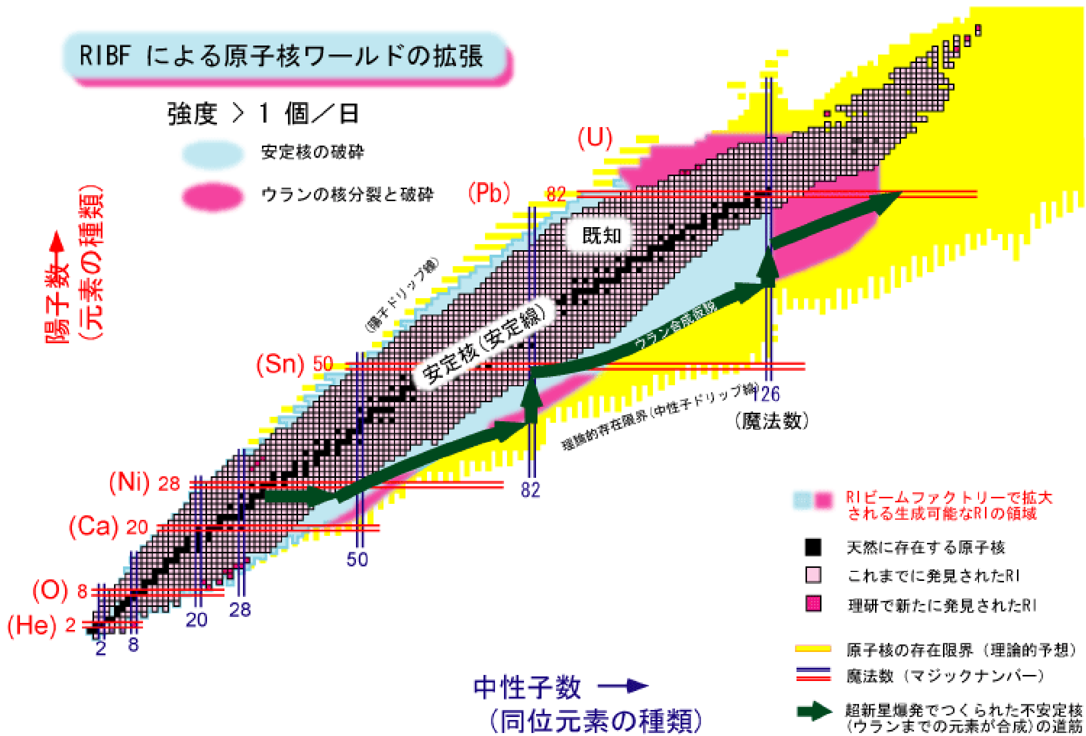




1. *Borromean nuclei and di-neutron correlation*
2. *Three-body model approach*
3. *Coulomb breakup*
4. *Two-neutron decay of unbound nucleus ^{26}O*
5. *Summary*

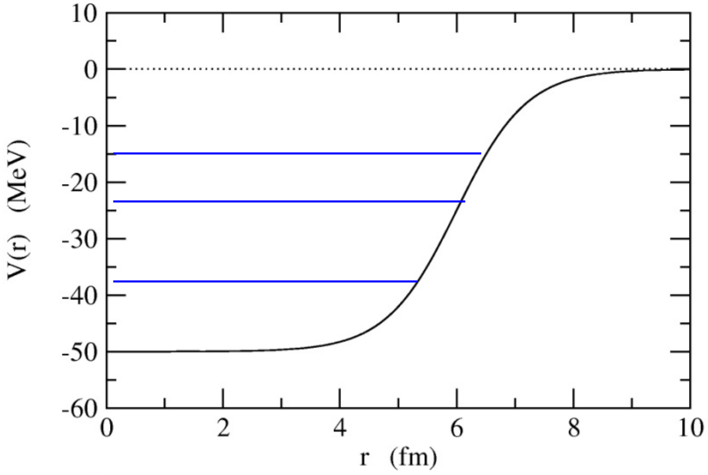
Introduction: neutron-rich nuclei

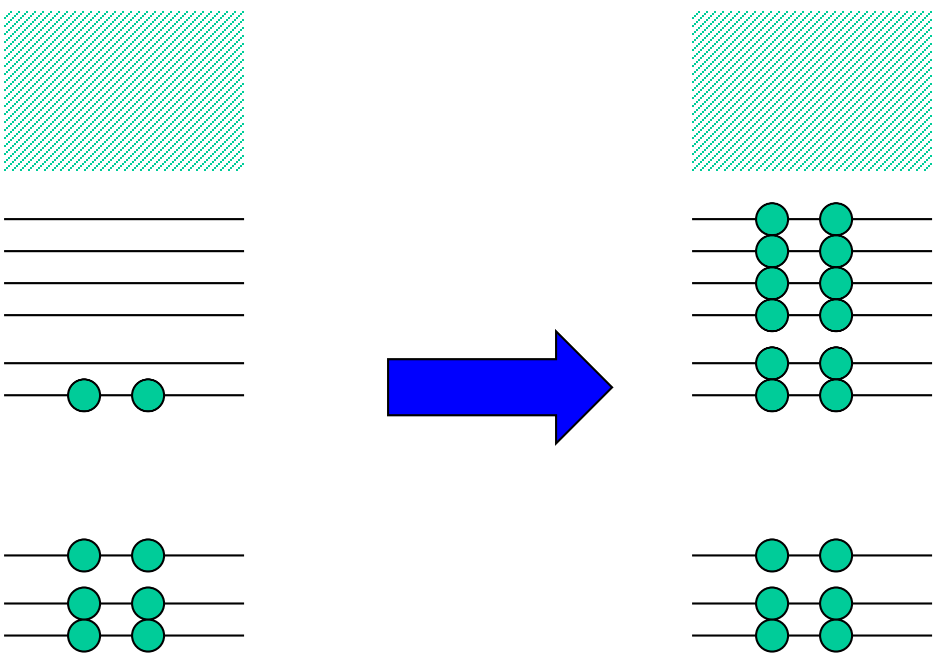
Next generation RI beam facilities : e.g., RIBF (RIKEN, Japan)



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

Mean-field approximation

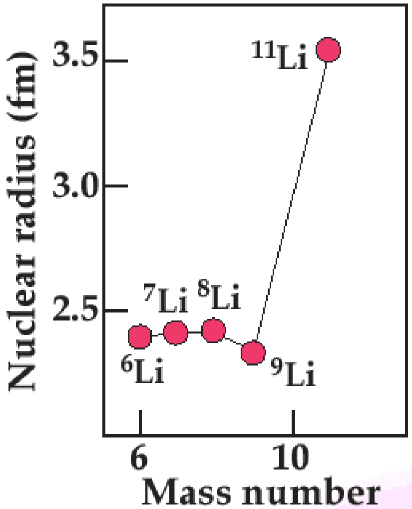




stable nuclei

neutron-rich nuclei

weakly bound
systems !!



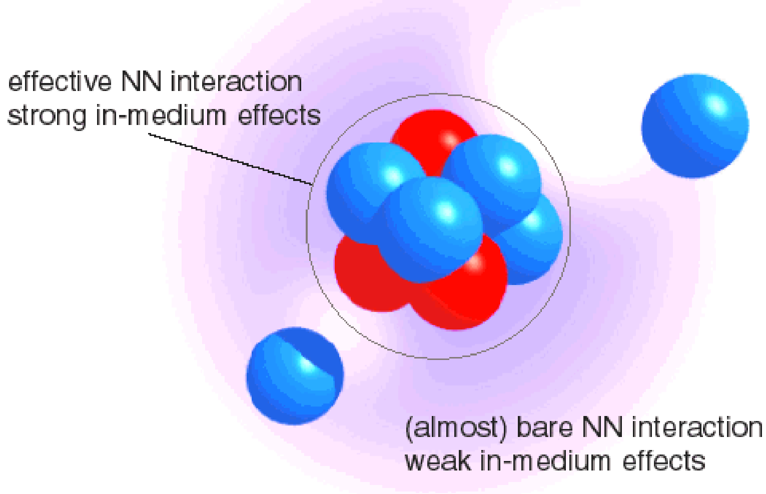
I. Tanihata et al.
Phys. Rev. Lett. 55, 2676 (1985)

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

^{11}Li

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

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



weakly bound systems

↓

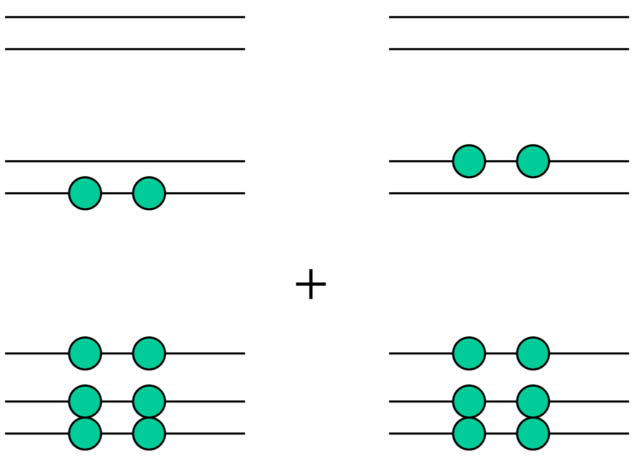
large extension of density

halo nucleus

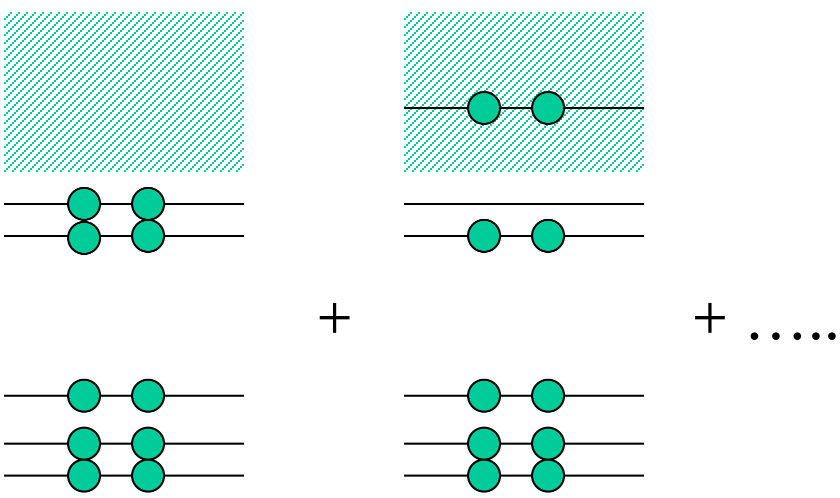
Role of redidual interaction

$$H = \sum_i T_i + \sum_{i<j} v_{ij} \rightarrow H = \sum_i (T_i + V_i) + \underbrace{\sum_{i<j} v_{ij} - \sum_i V_i}_{\text{residual interaction (pairing)}}$$

residual interaction
(pairing)



open shell nuclei



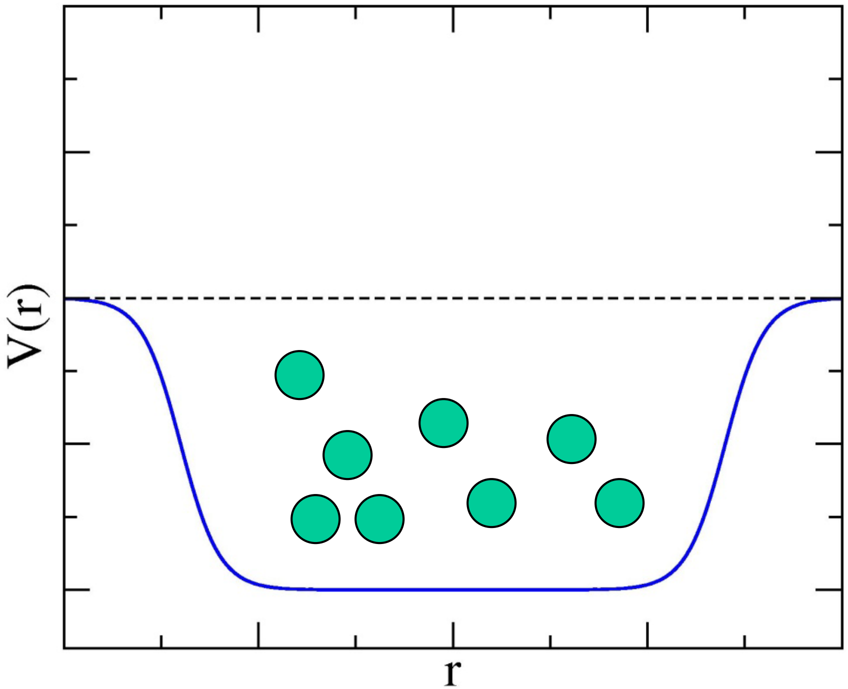
weakly bound nuclei

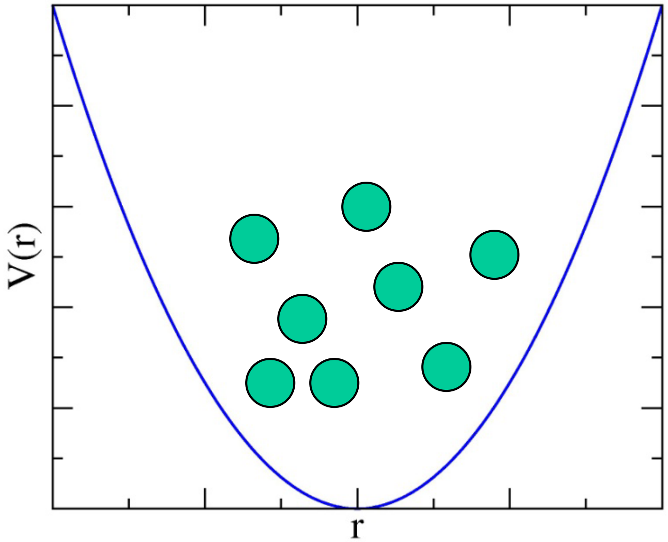
Neutron-rich nuclei:

- weakly bound systems: low neutron density
- residual interaction (pairing interaction)
- many-body correlations

← laboratory for NS matter at low densities

many-particles in a confining potential





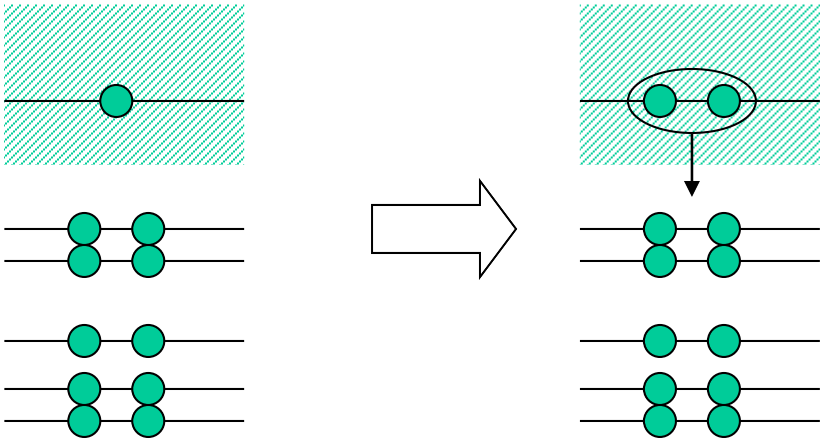
cf. a harmonic trap

- finite-well confining potential
- self-consistent potential

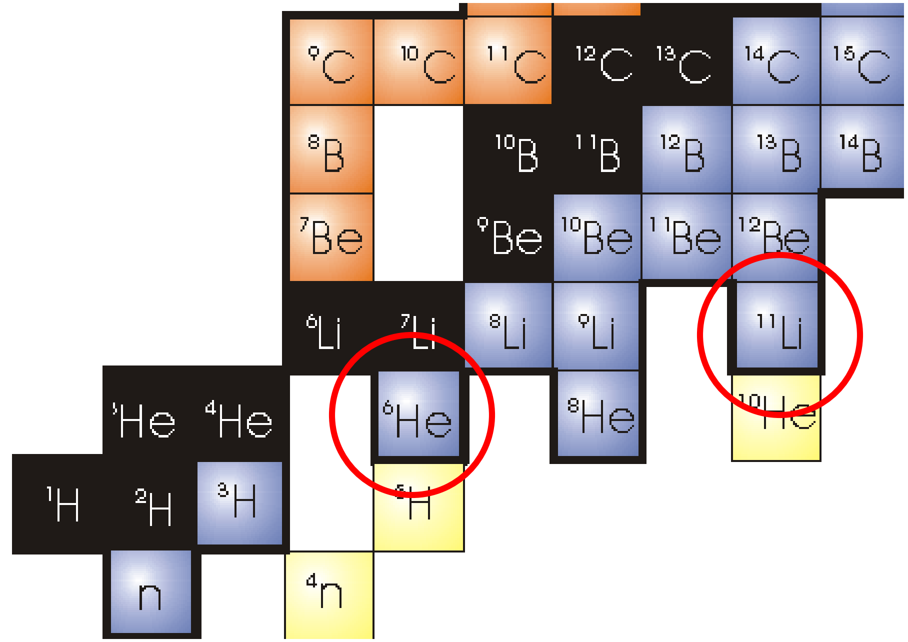
➡ a challenging problem

Borromean nucleus

residual interaction → attractive



particle unstable　　　　particle stable

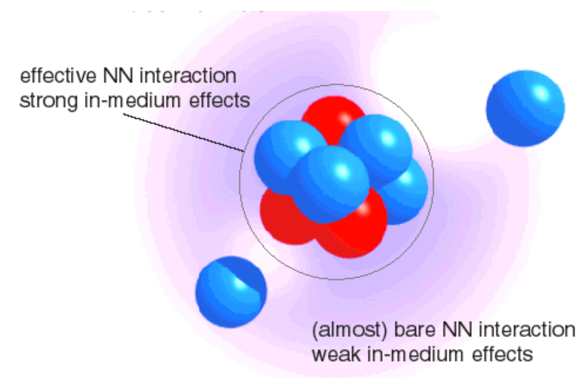


"Borromean nuclei"

Remaining problems

- *What is the spatial structure of the valence neutrons?*

  (To what extent is this picture correct?)
- *E1 excitations?*
- *Influence to nuclear reactions?*



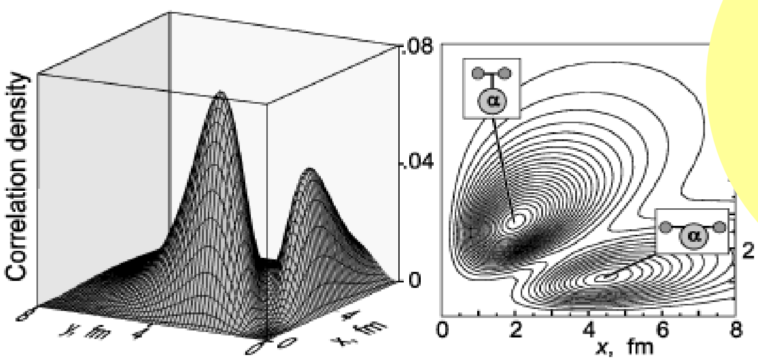
Borromean nuclei and Di-neutron correlation

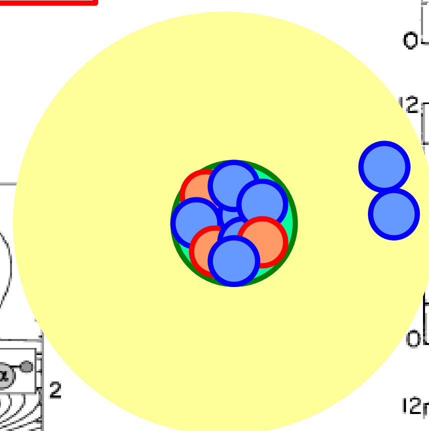
Borromean nuclei: unique three-body systems

Three-body model calculations:

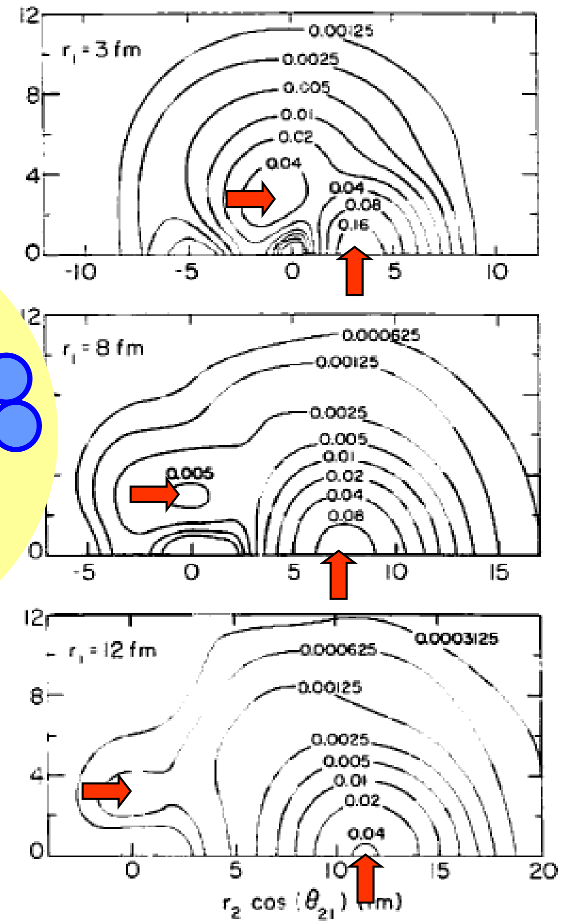
strong di-neutron correlation
in ^{11}Li and ^{6}He

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





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



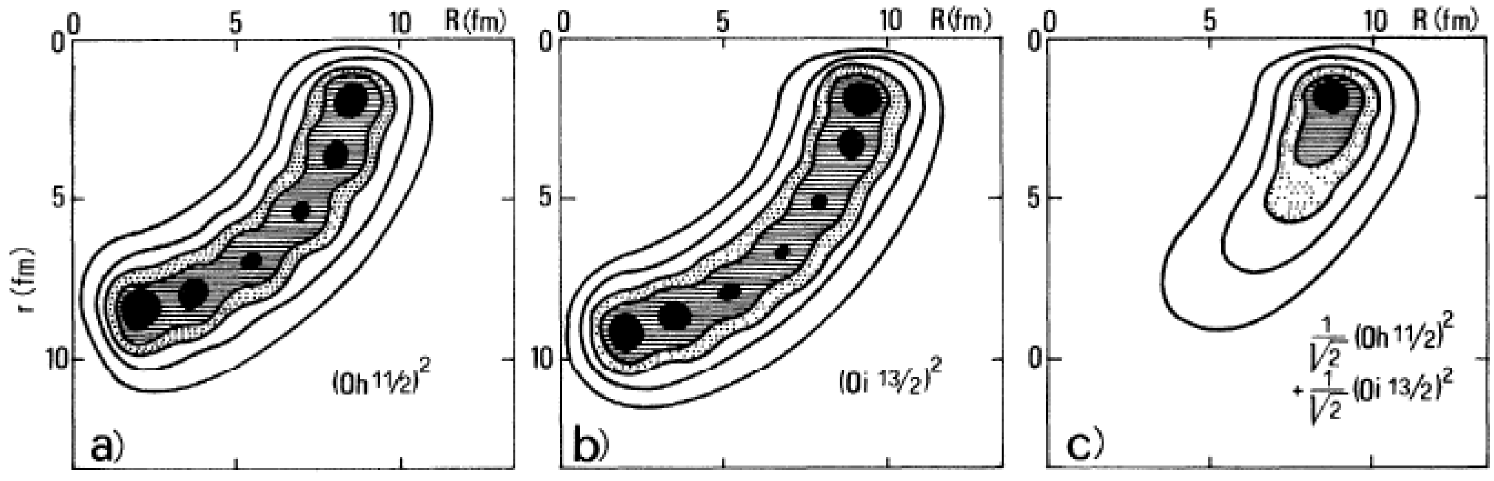
Yu.Ts. Oganessian et al., *PRL82('99)4996*
M.V. Zhukov et al., *Phys. Rep. 231('93)151*

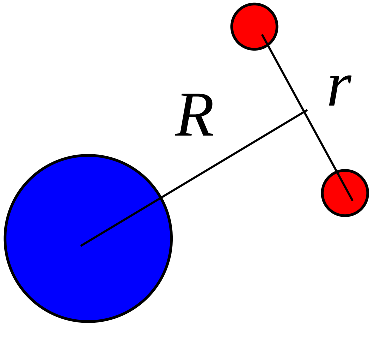
G.F. Bertsch, H. Esbensen,
Ann. of Phys., 209('91)327

cf. earlier works

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

dineutron correlation: caused by the admixture of different parity states





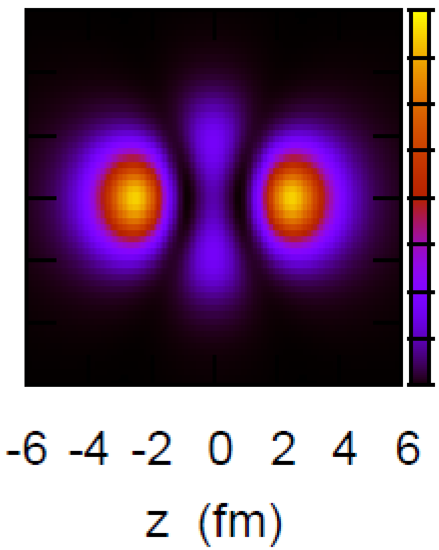
F. Catara, A. Insolia, E. Maglione, and A. Vitturi, PRC29('84)1091 spatial localization of two neutrons

(dineutron correlation)

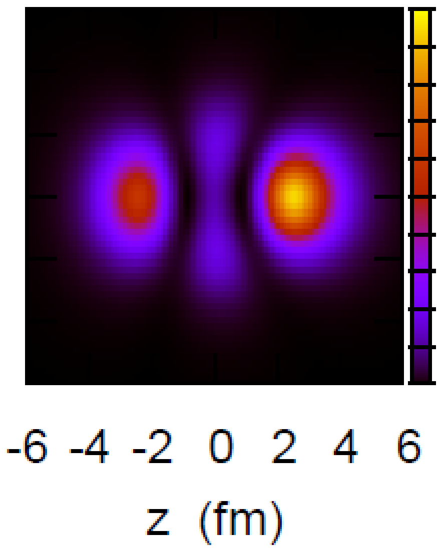
cf. Migdal, Soviet J. of Nucl. Phys. 16 ('73) 238
Bertsch, Broglia, Riedel, NPA91('67)123

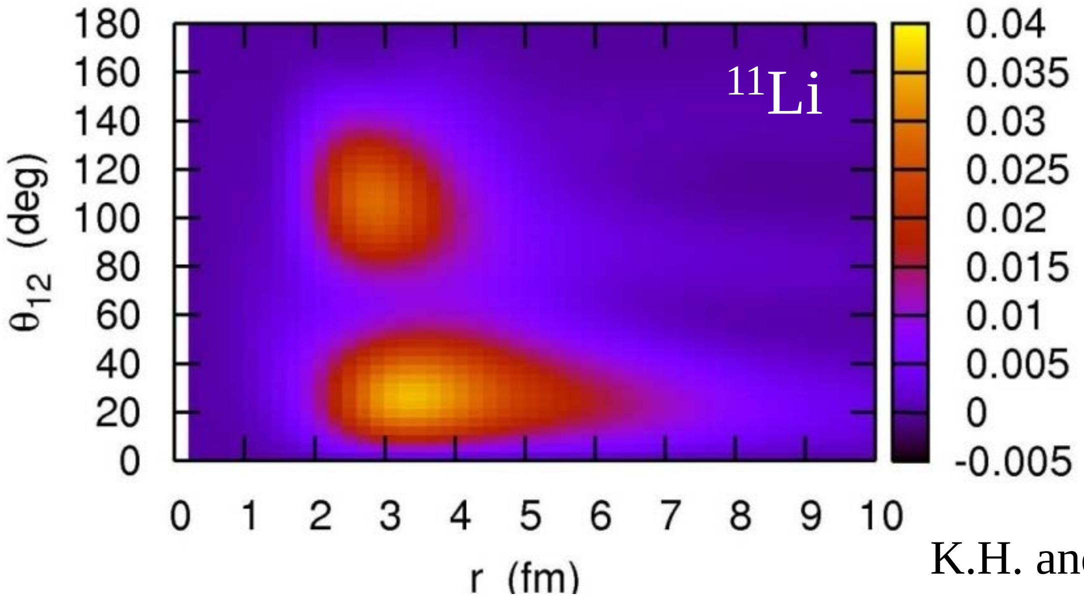
weakly bound systems

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



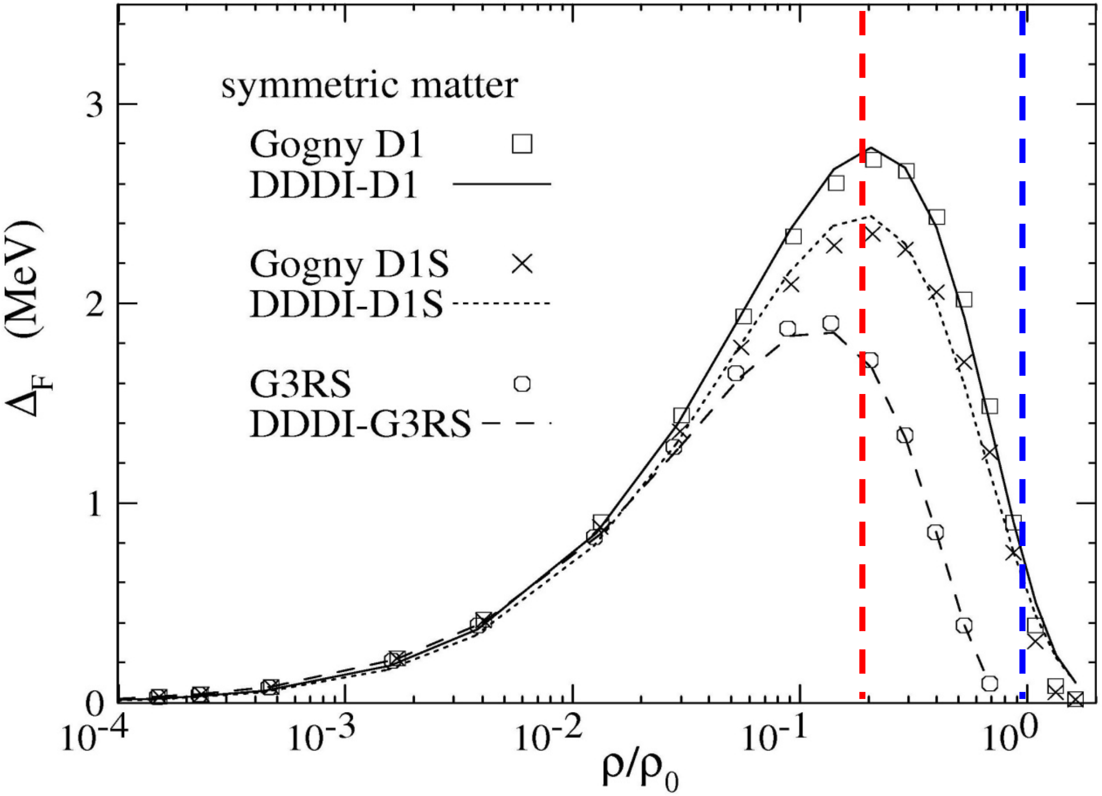
parity mixing





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

pairing gap in infinite nuclear matter

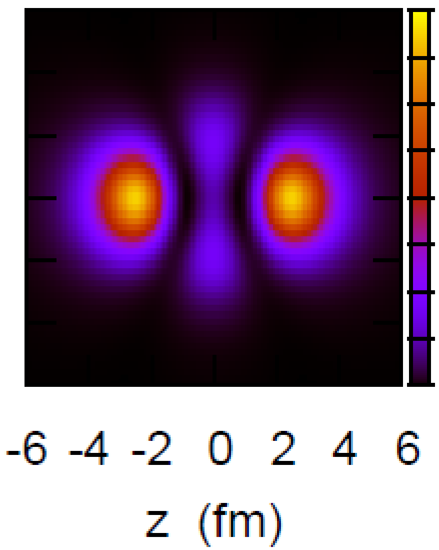


M. Matsuo, PRC73('06)044309

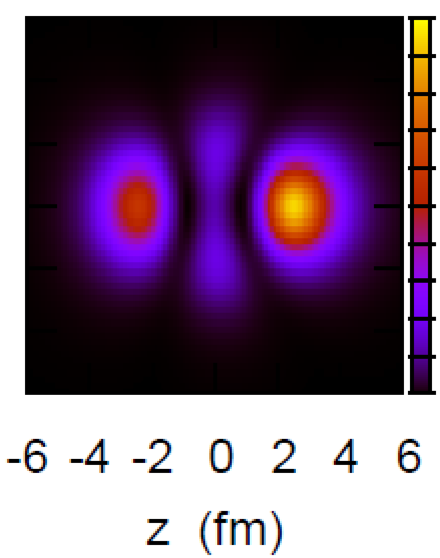
spatial localization of two neutrons

(dineutron correlation)

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



parity mixing



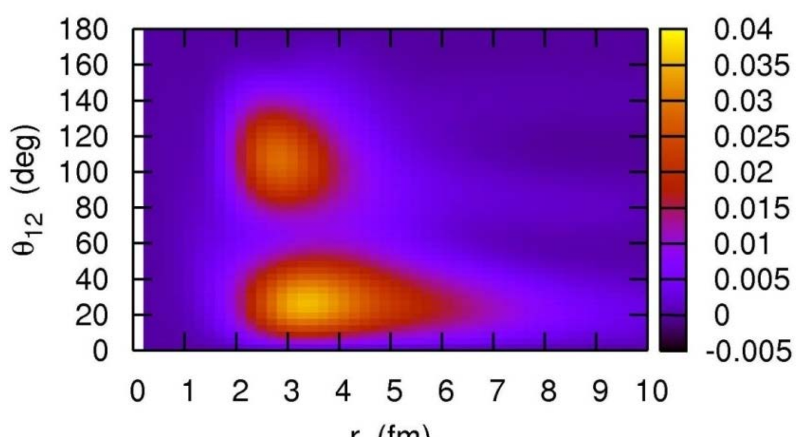
weakly bound systems

→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



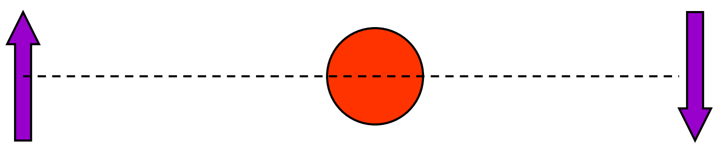
K.H. and H. Sagawa, PRC72(’05)044321

Pairing correlations in atomic nuclei

Spatial structure of a Cooper pair?

Coherence length of a Cooper pair:

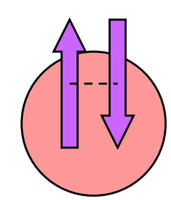
$$\xi = \frac{\hbar^2 k_F}{m\Delta}$$



→ much larger than the nuclear size

⇕ ?

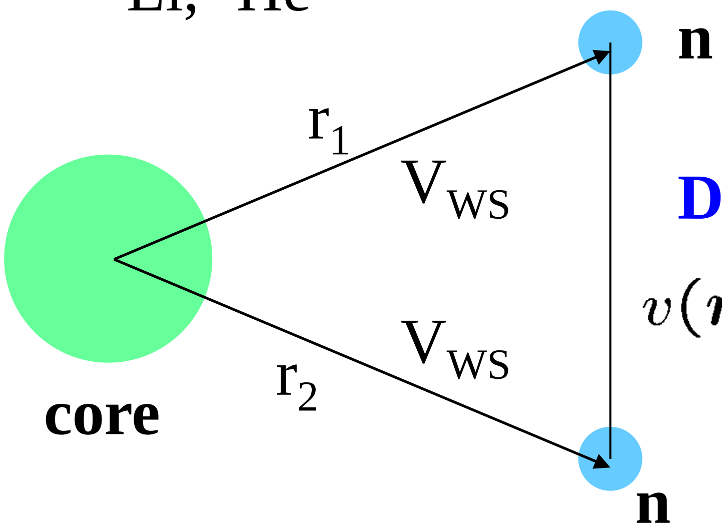
Di-neutron correlations in neutron-rich nuclei



Three-body model with density-dependent delta force

G.F. Bertsch and H. Esbensen,
Ann. of Phys. 209('91)327
H. Esbensen, G.F. Bertsch, K. Hencken,
Phys. Rev. C56('99)3054
K.H. and H. Sagawa, *PRC72('05)044321*

^{11}Li, ^{6}He

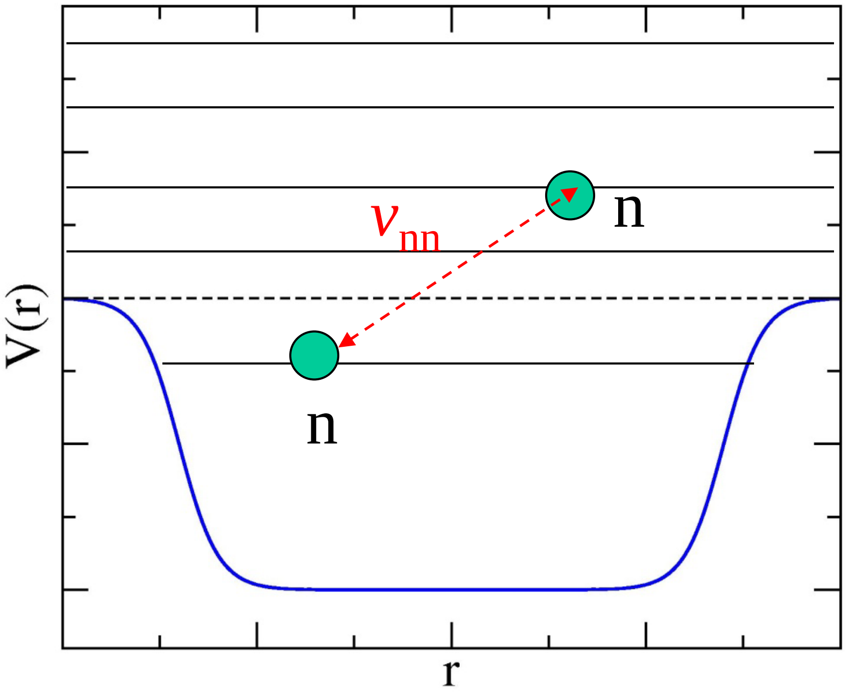


Density-dependent delta-force

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

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

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



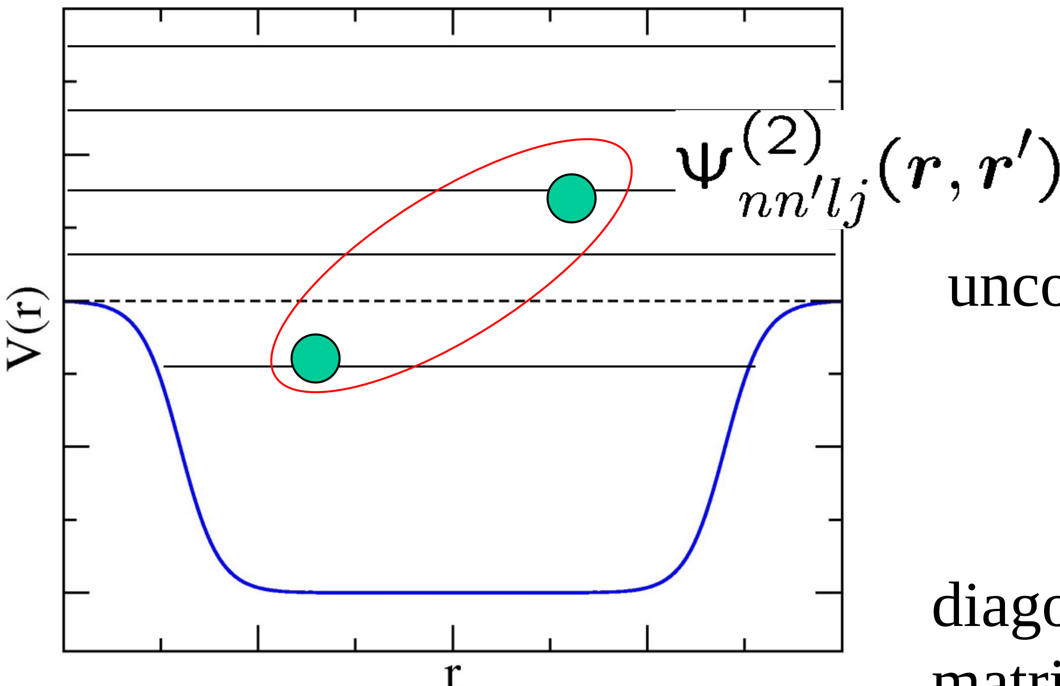
continuum states:
discretized in a large box

$$V_{nn}(\boldsymbol{r}_1, \boldsymbol{r}_2) = \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)\left(v_0 + \frac{v_\rho}{1 + \exp[(r_1 - R_\rho)/a_\rho]}\right)$$

- ✓ contact interaction
- ✓ v_0: free n-n ← scattering length
- ✓ density dependent term: medium many-body effects

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

$$\Psi_{gs}(\boldsymbol{r}, \boldsymbol{r}') = \mathcal{A} \sum_{nn'lj} \alpha_{nn'lj} \, \Psi^{(2)}_{nn'lj}(\boldsymbol{r}, \boldsymbol{r}')$$



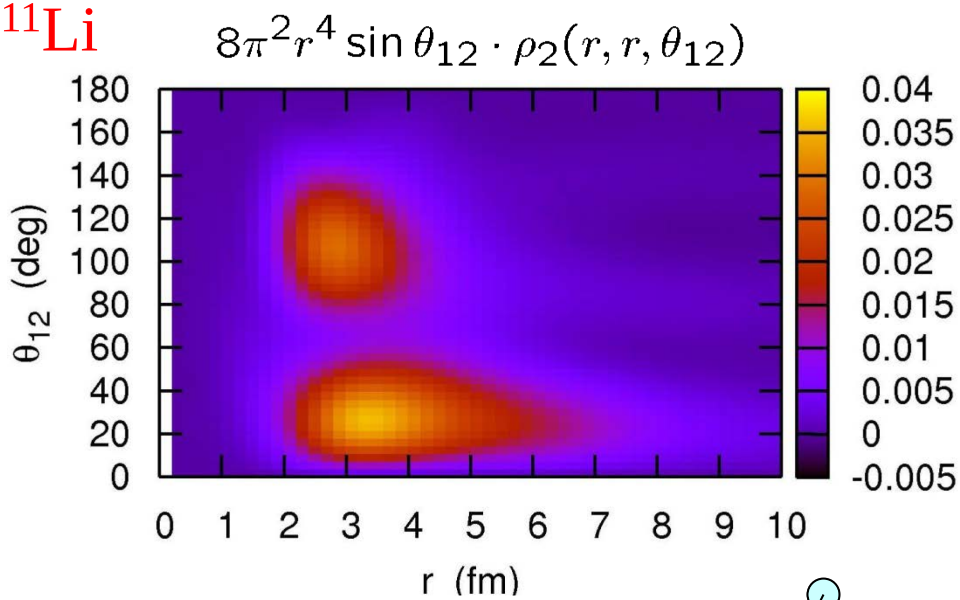
uncorrelated basis

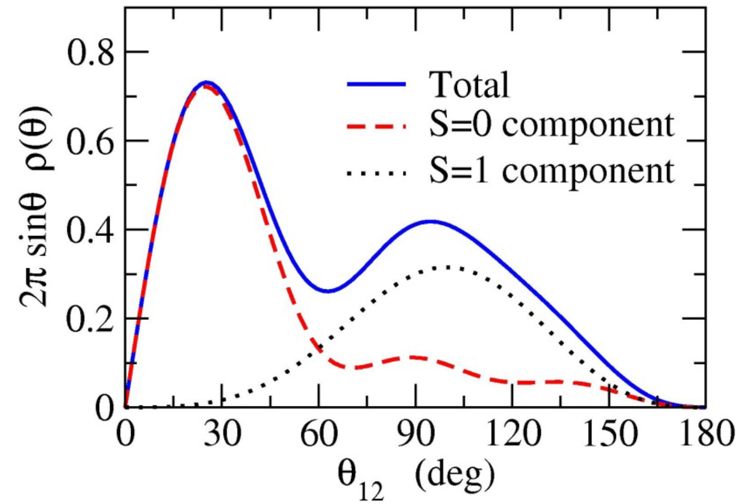
↓

diagonalization of Hamiltonian matrix
(~ 1500 dimensions)

Two-particle density for the ground state → strong di-neutron correlation

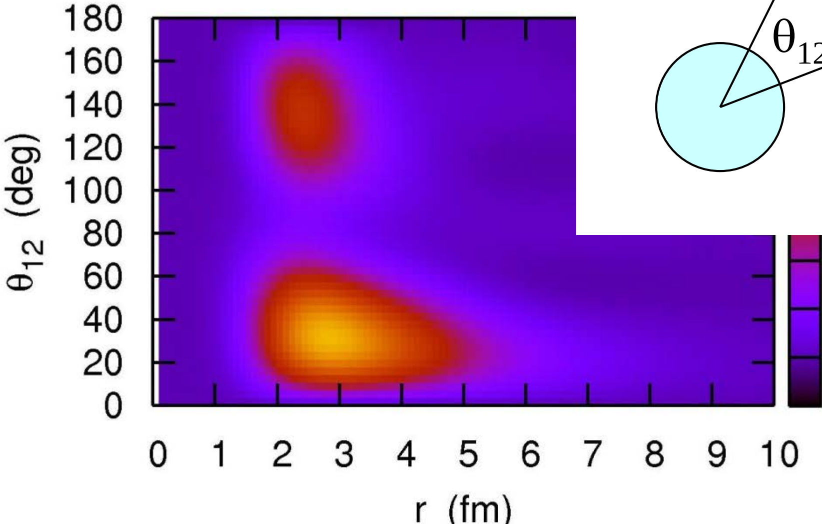
^{11}Li

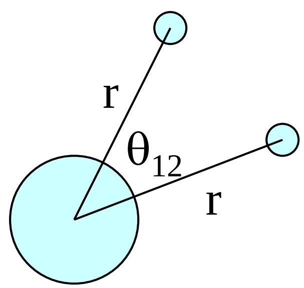


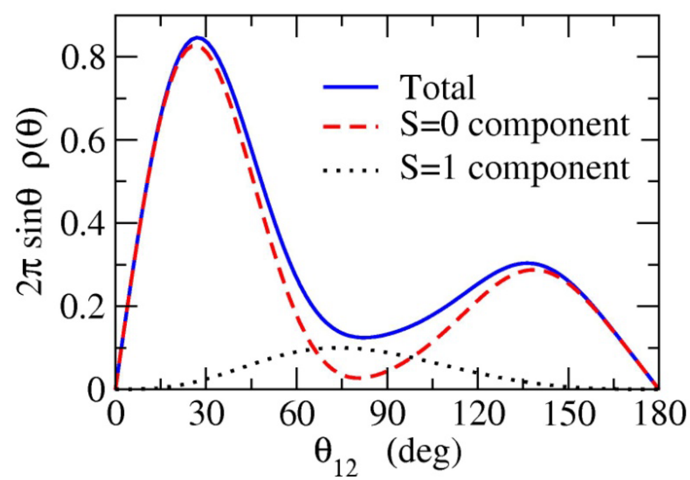


$\to \langle\theta_{12}\rangle = 65.29$ deg.

^{6}He







$\to \langle\theta_{12}\rangle = 66.33$ deg.

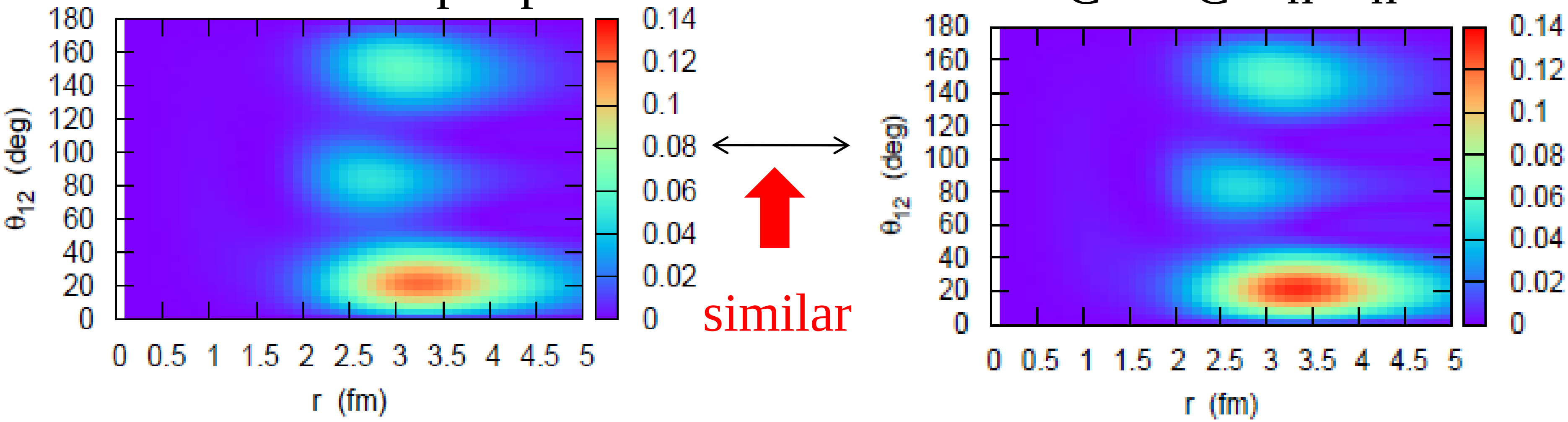
K.H. and H. Sagawa, PRC72('05)044321

cf. “di-proton” correlation

^{17}Ne = ^{15}O + p + p   (S_{2p} = 0.944 MeV)

v_{pp} = density-dep. contact interaction + Coulomb

^{17}Ne = ^{15}O + p + p ^{16}C = ^{14}C + n + n



$$\langle v_{pp}^{(\mathrm{nucl})}\rangle = -3.26 \quad \mathrm{MeV}$$

$$\langle v_{pp}^{(\mathrm{Coul})}\rangle = 0.448 \quad \mathrm{MeV}$$

← about 15% contribution

cf. two-proton decays of proto-rich nuclei beyond the proton drip-line

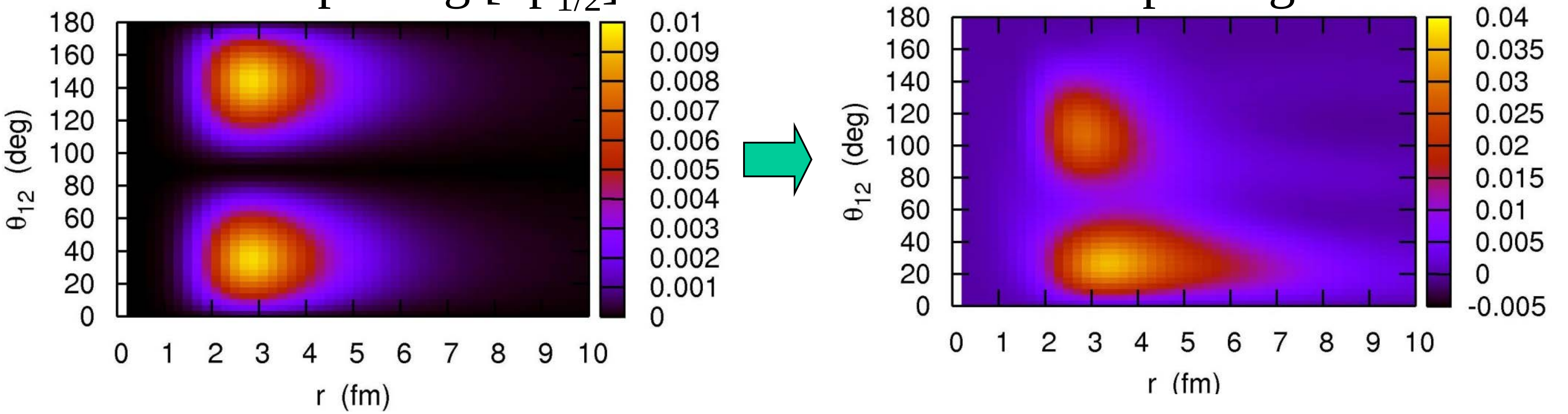
T. Oishi, K. Hagino, and H. Sagawa, PRC82(‘10)024315; PRC90(‘14)034303

✧ Role of pairing correlation

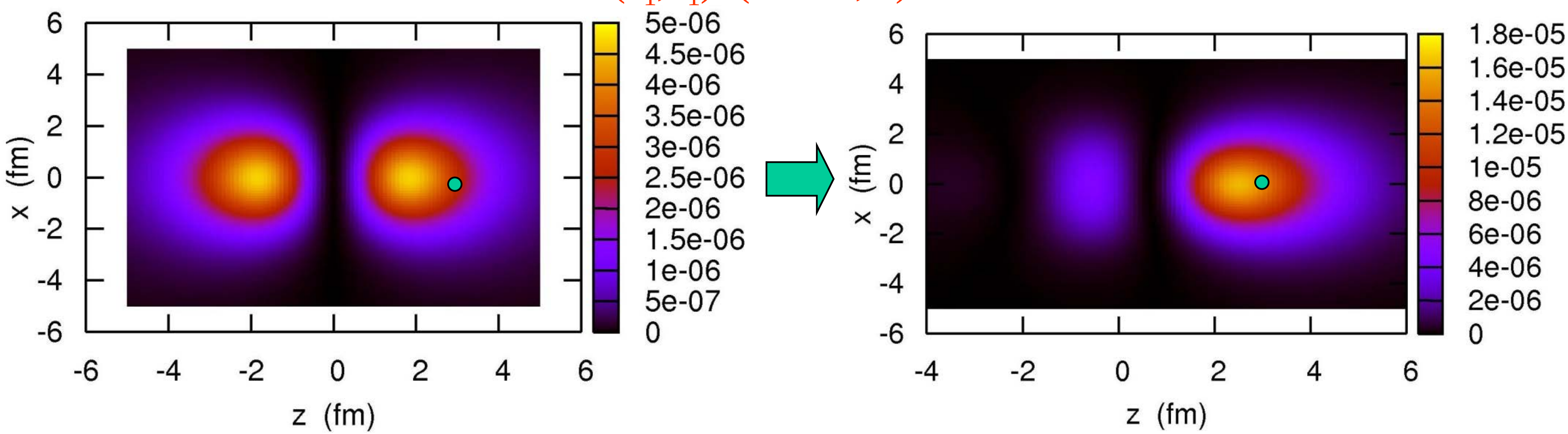
⟶ configuration mixing of different parity states

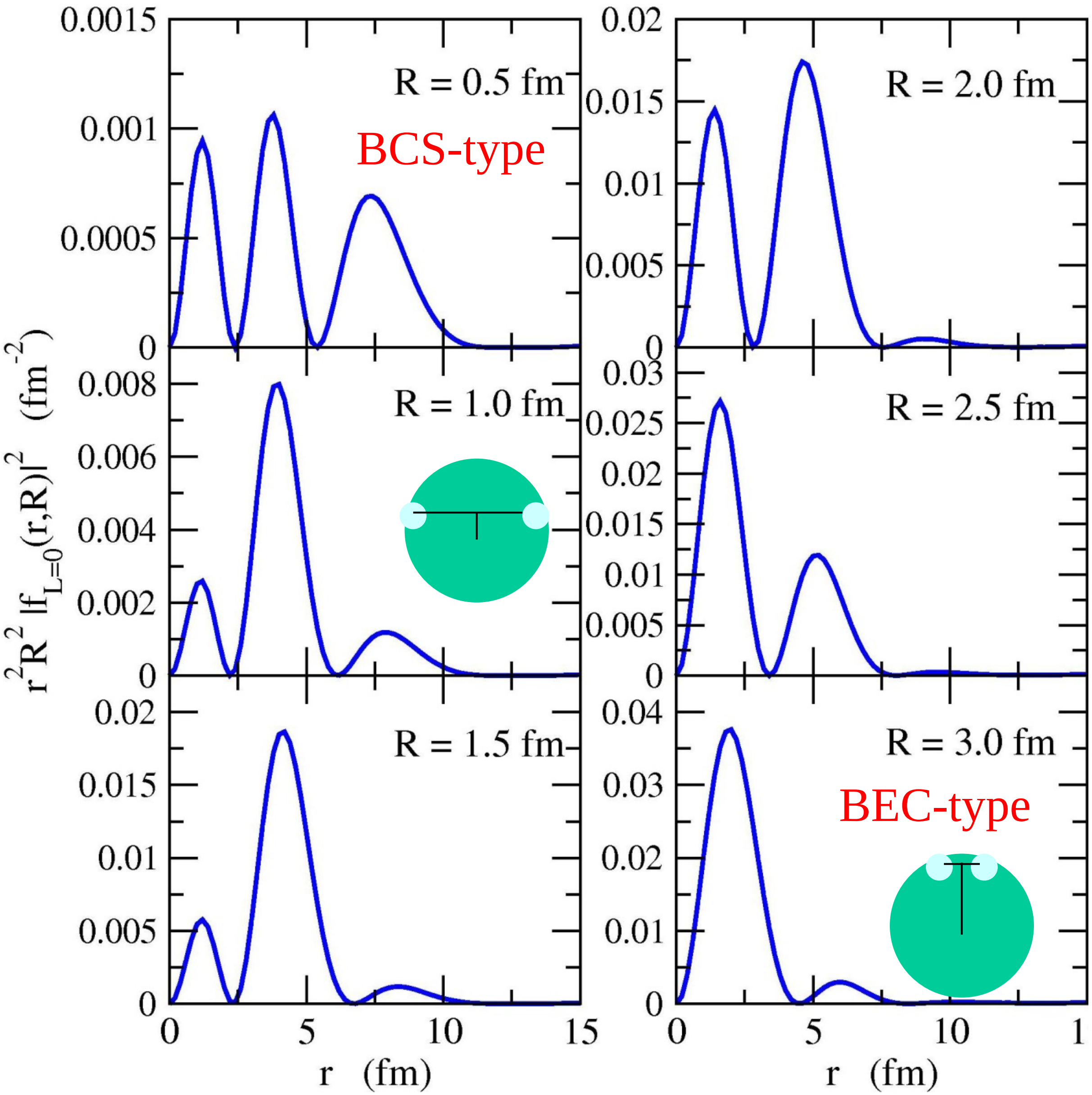
^{11}Li

without pairing $[1p_{1/2}]^2$ — with pairing

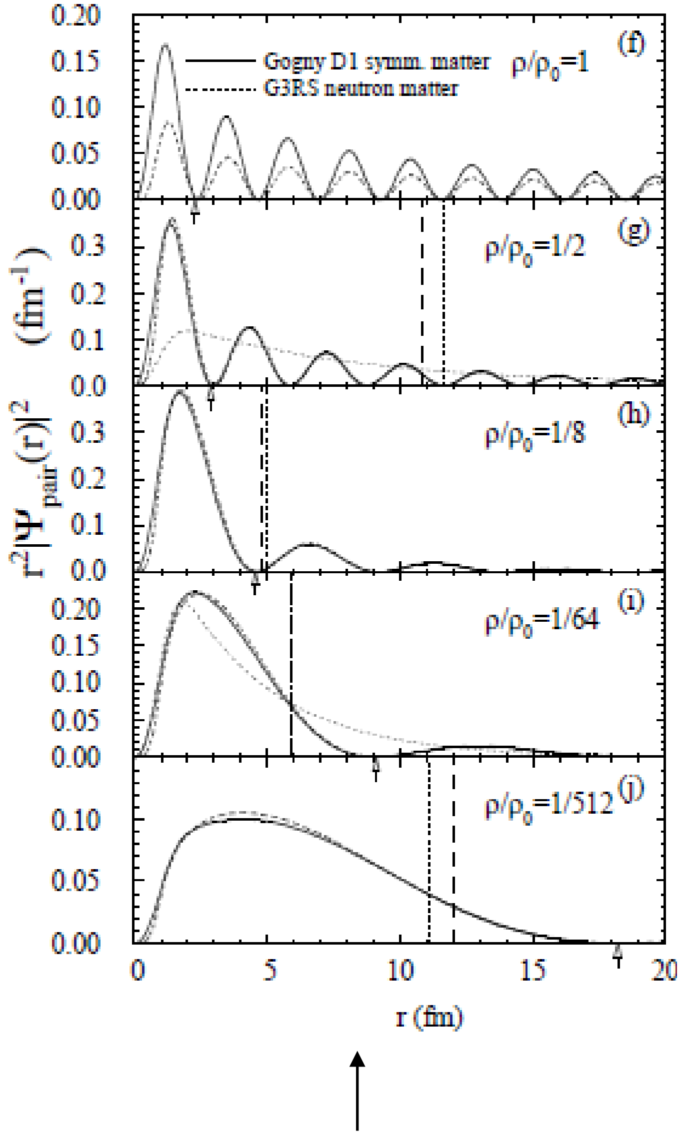


$(z_1,x_1)=(3.4\text{ fm}, 0)$





K.Hagino, H. Sagawa, J. Carbonell, and P. Schuck, PRL99('07)022506

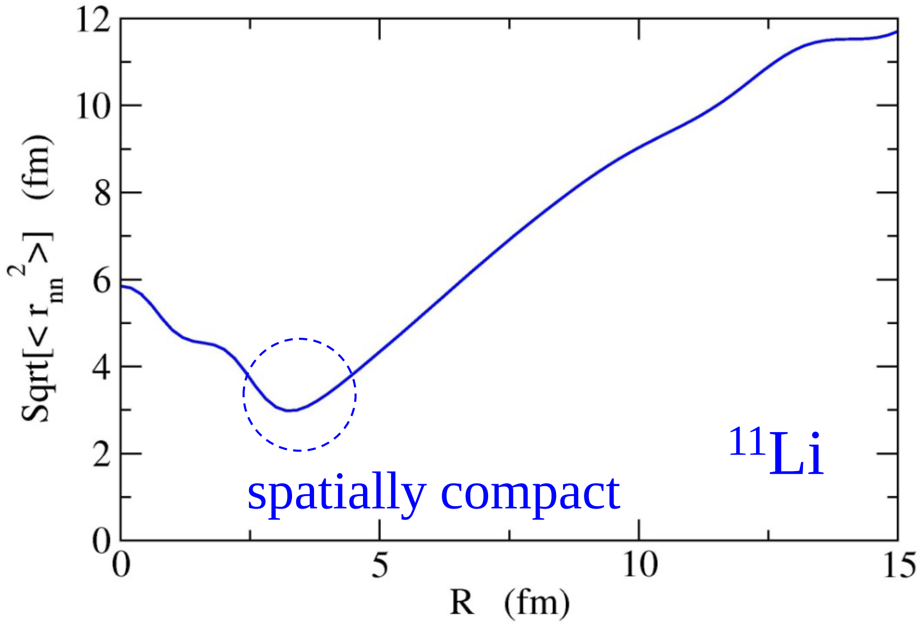


infinite neutron matter

M. Matsuo, PRC73('06)044309

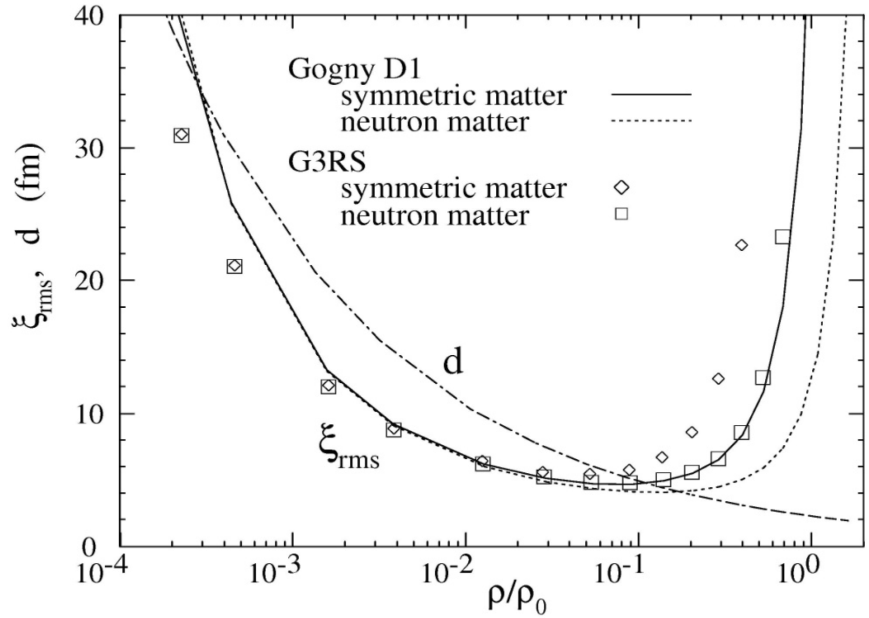
2n-rms distance

$$\sqrt{\langle r_{nn}^2 \rangle}(R) = \sqrt{\frac{\int r^4 dr\, |f_{L=0}(r,R)|^2}{\int r^2 dr\, |f_{L=0}(r,R)|^2}}$$

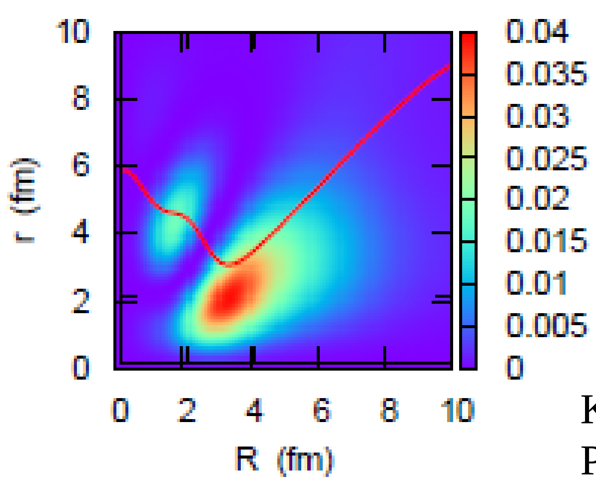


K.Hagino, H. Sagawa, J. Carbonell, and P. Schuck, PRL99('07)022506

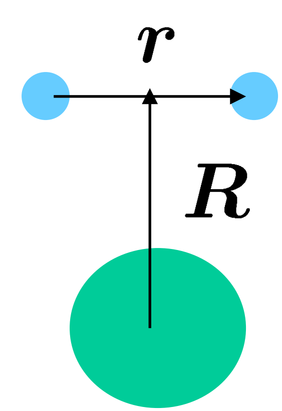
Matter Calculation



M. Matsuo, PRC73('06)044309

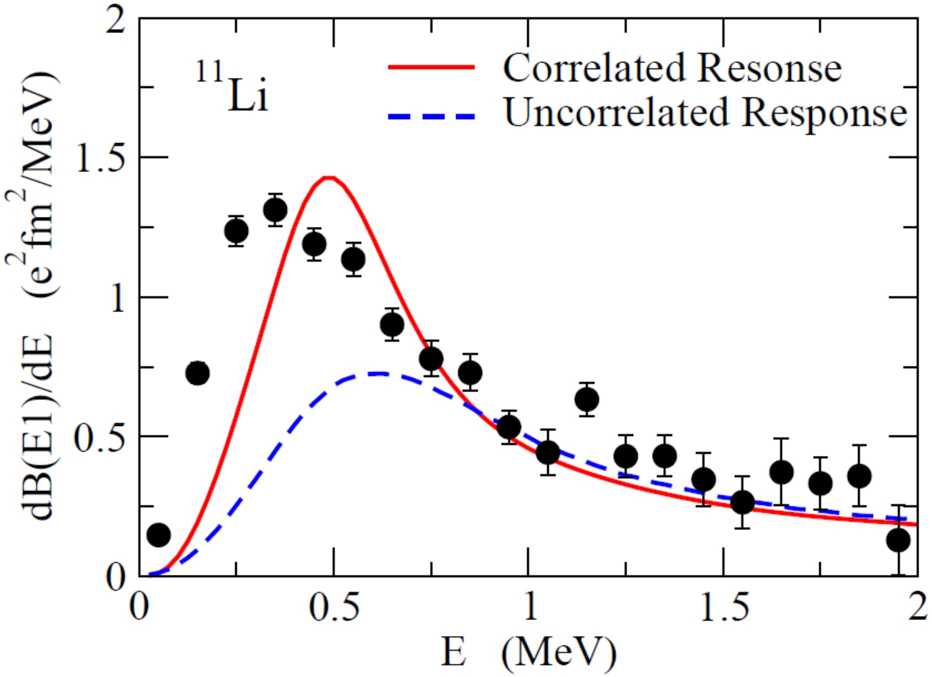


K.H., H. Sagawa, and
P. Schuck, J. of Phys. G37('10)064040

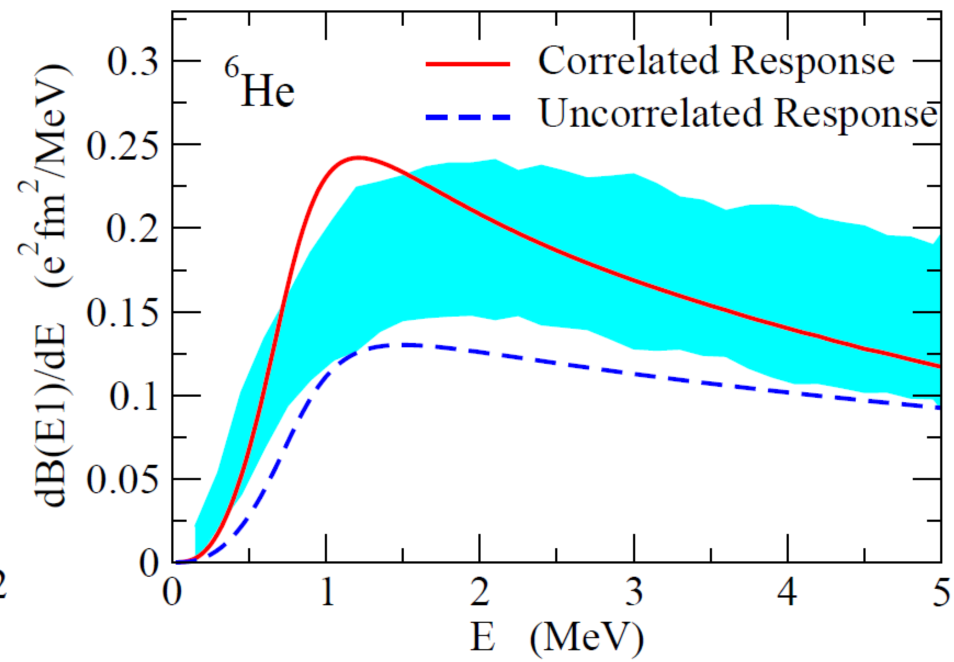


Coulomb breakup of 2-neutron halo nuclei

How to probe the dineutron correlation? ⟶ Coulomb breakup



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.)

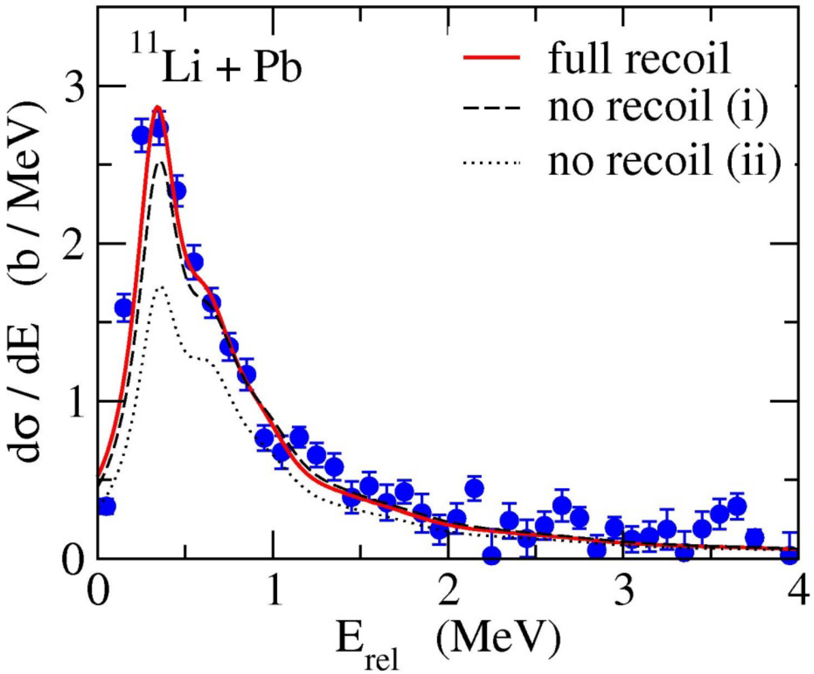
Dipole excitations

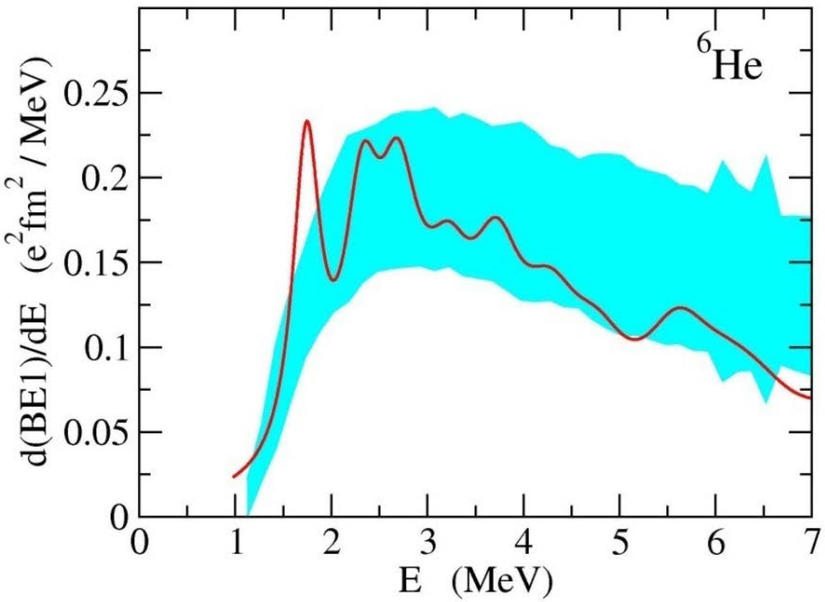
Response to the dipole field:

$$B_k(E1) = 3|\langle \Psi^k_{1^-}|\hat{D}_0|\Psi_{gs}\rangle|^2$$

$$\hat{D} = -\frac{Ze}{A}(r_1 + r_2)$$

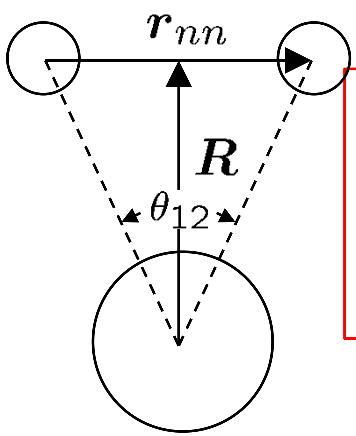
excited states ground state





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

Geometry of Borromean nuclei

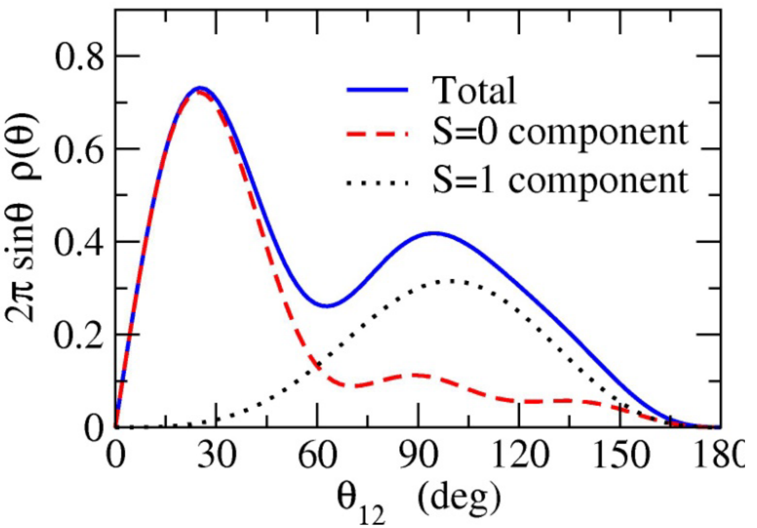


Cluster sum rule

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

reflects the g.s. correlation

3-body model calculations



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

"experimental data" for opening angle

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

$\sqrt{\langle r_{nn}^2 \rangle}$ ← 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.

↓

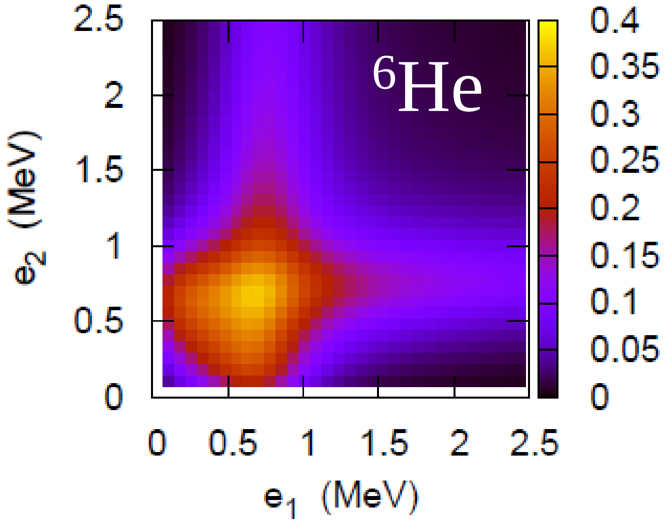
suggests dineutron corr.

(but, an average of small and large angles)

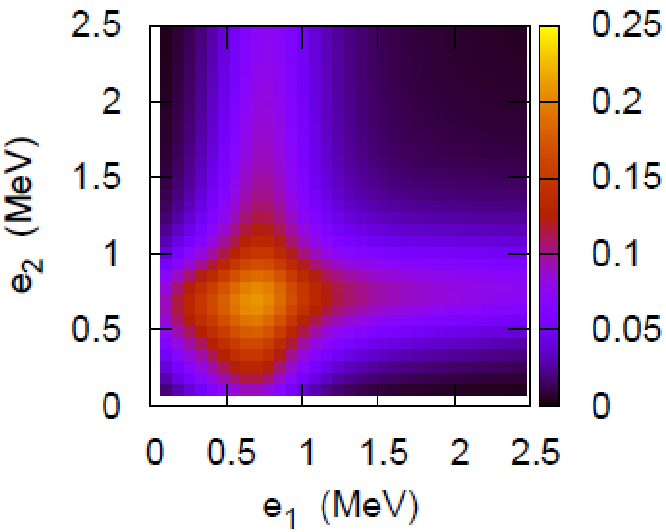
cf. T. Nakamura et al., PRL96('06)252502

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

•Coulomb excitations ⟶ A problem: an external field is too weak



$v_{nn} = 0$



Energy distribution of emitted neutrons

✓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

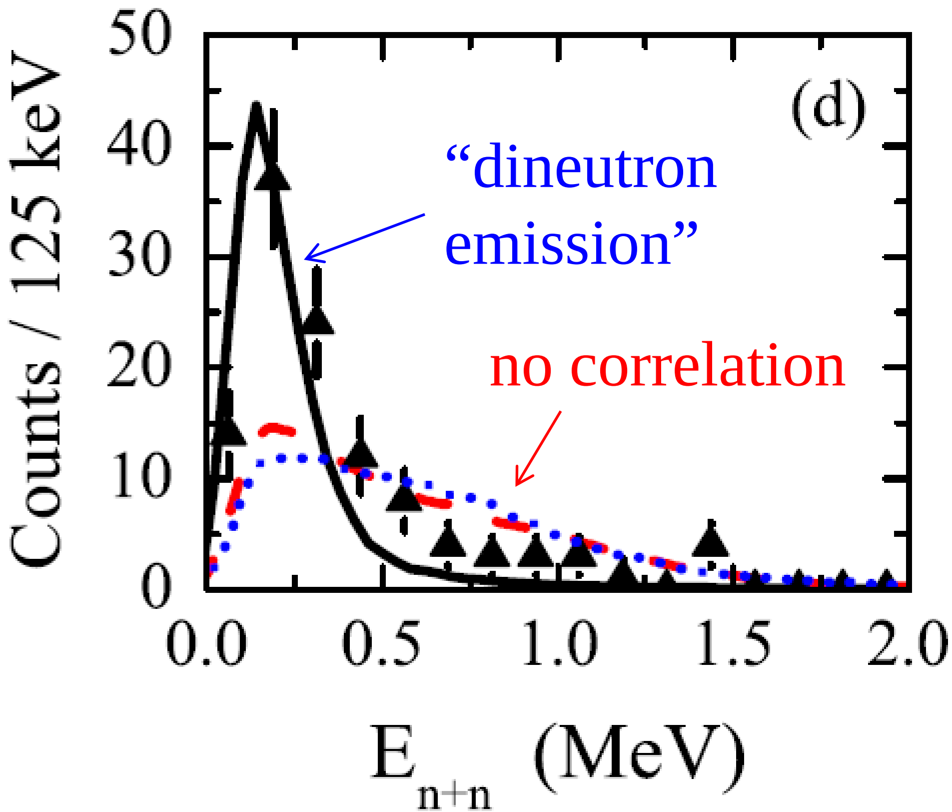
other probes?

- ➢ two-neutron transfer reactions
- ➢ two-nucleon emission

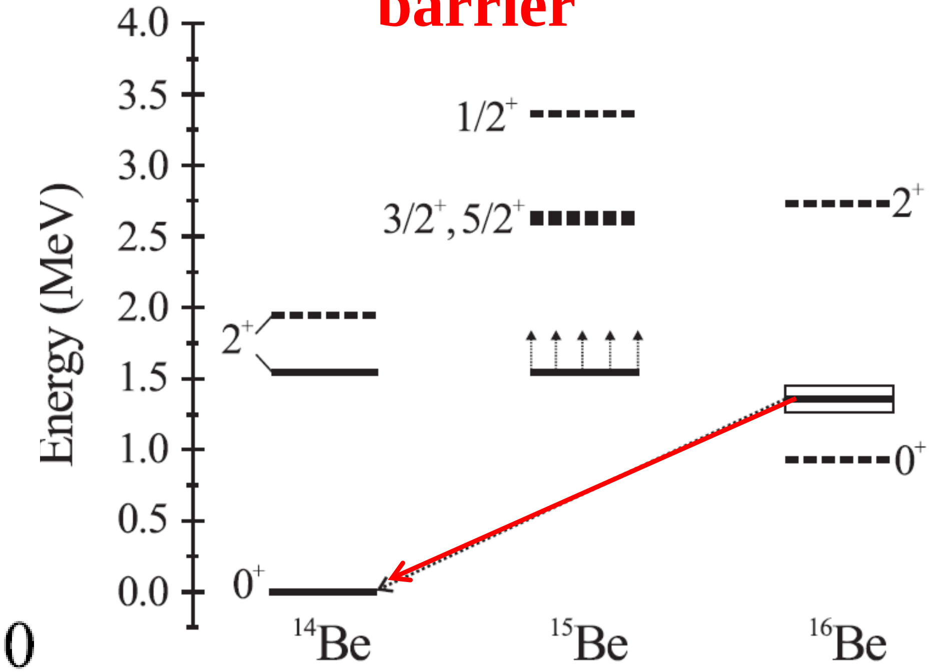
K.H., H. Sagawa, T. Nakamura, S. Shimoura, PRC80('09)031301(R)

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:

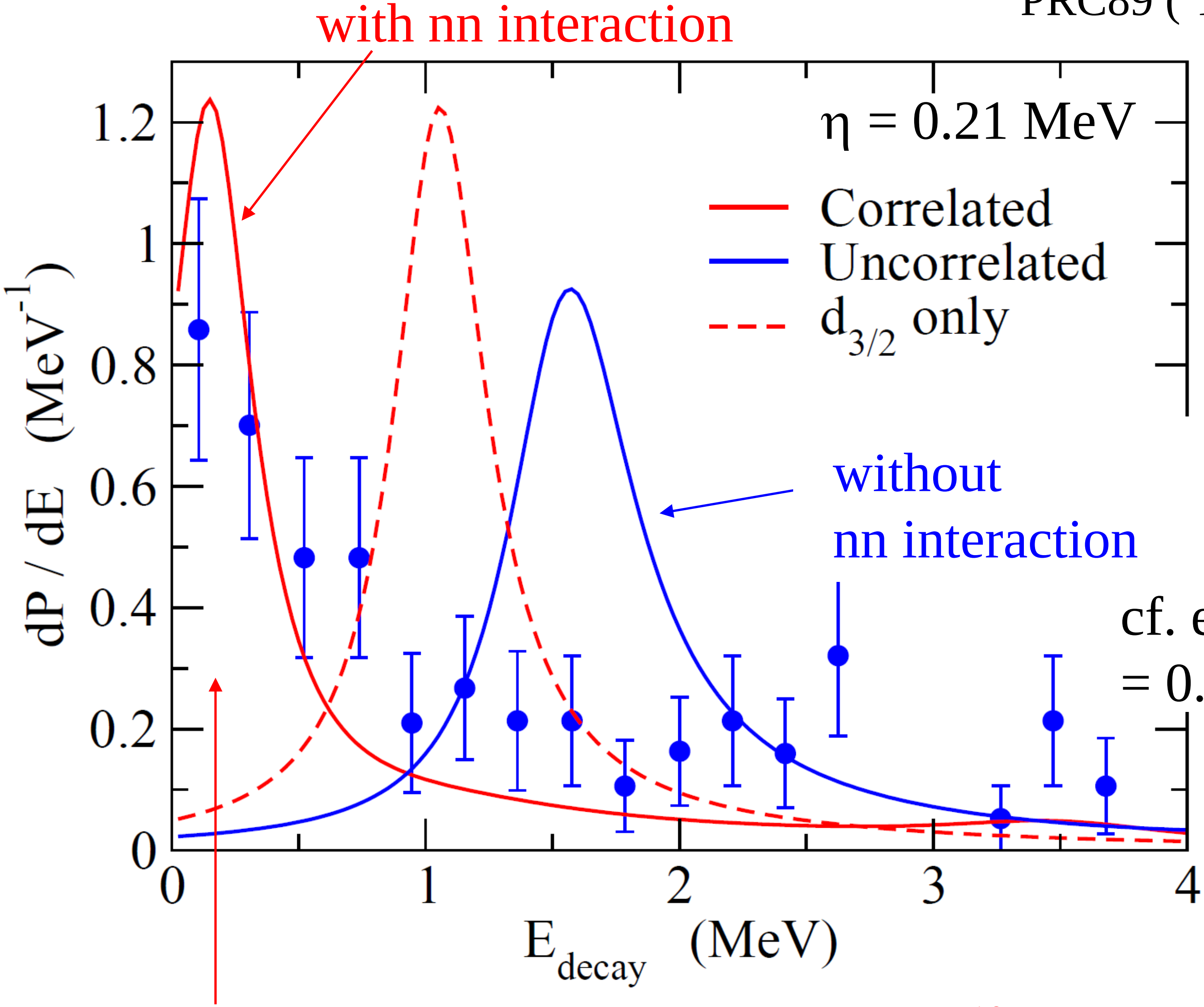
^{13}Li (Z. Kohley et al., PRC87(‘13)011304(R)) $^{14}Be \rightarrow {}^{13}Li \rightarrow {}^{11}Li + 2n$

^{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: application to ^{26}O decay

i) Decay energy spectrum for ^{26}O decay

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



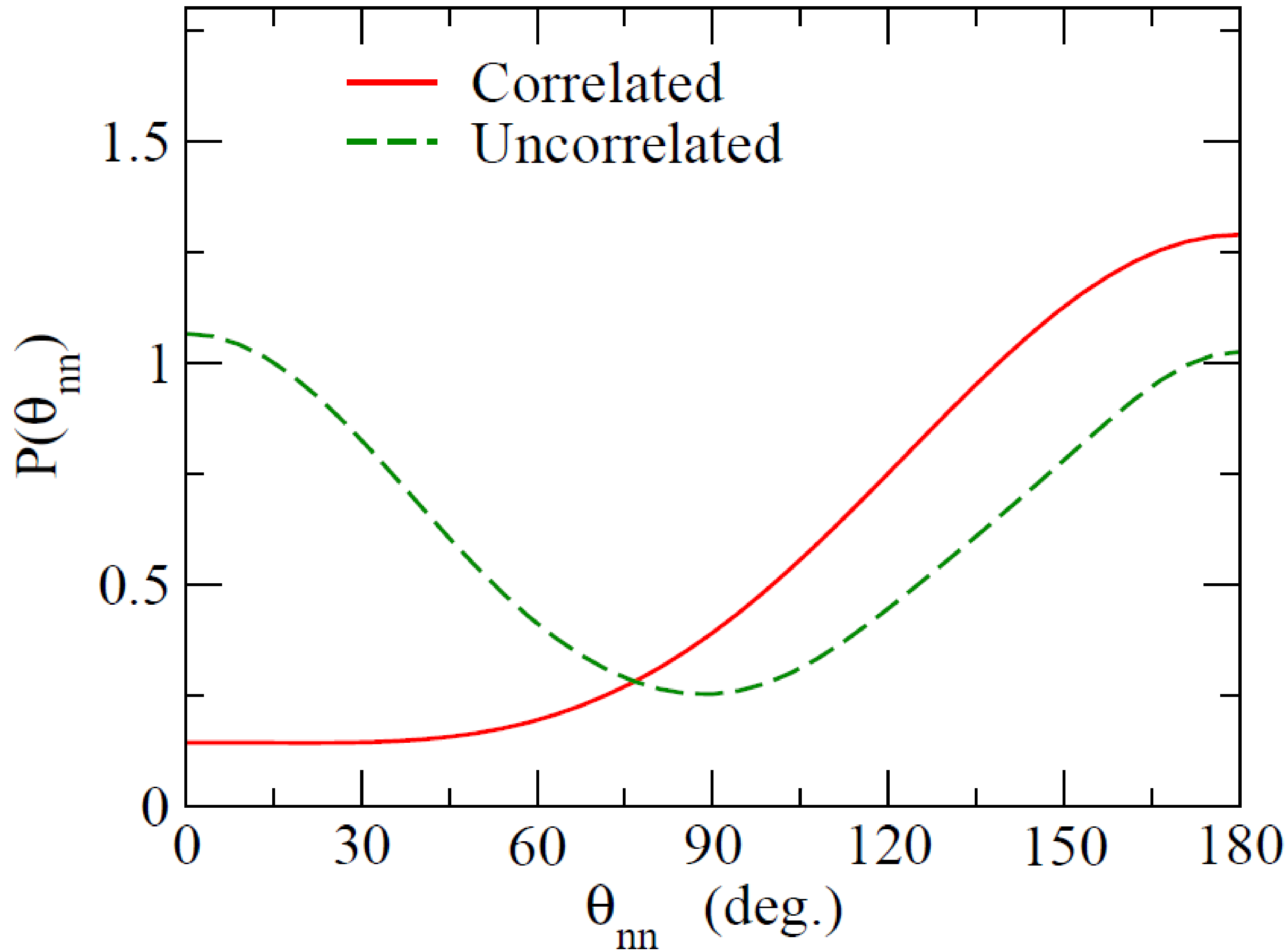
cf. $e_{1d3/2}(^{25}O)$ = 0.770 MeV

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

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

ii) angular correlations of the emitted neutrons

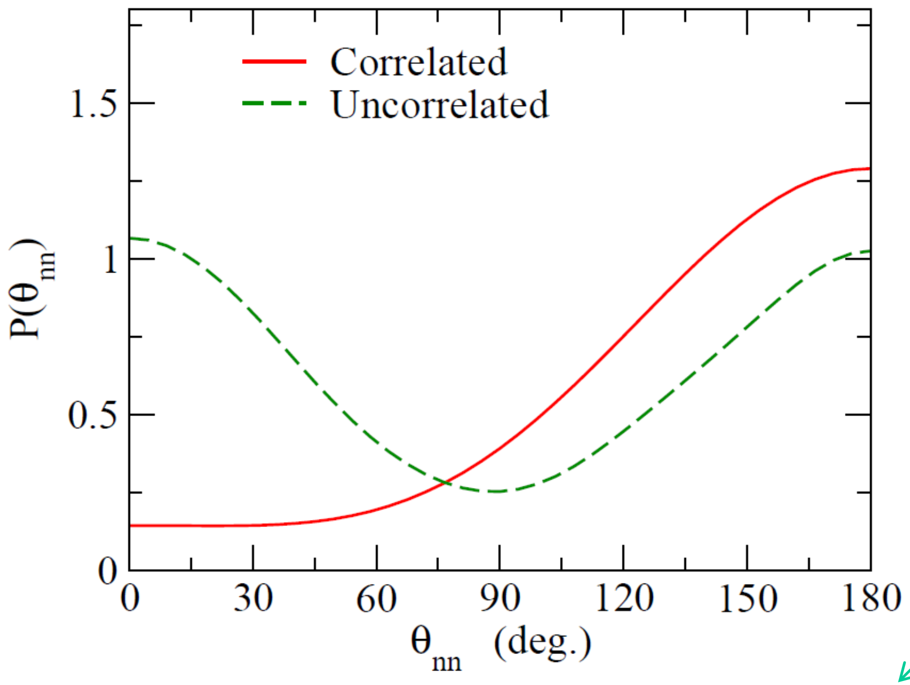
K.H. and H. Sagawa,
PRC89 ('14) 014331



correlation → enhancement of back-to-back emissions

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

ii) distribution of opening angle for two-emitted neutrons

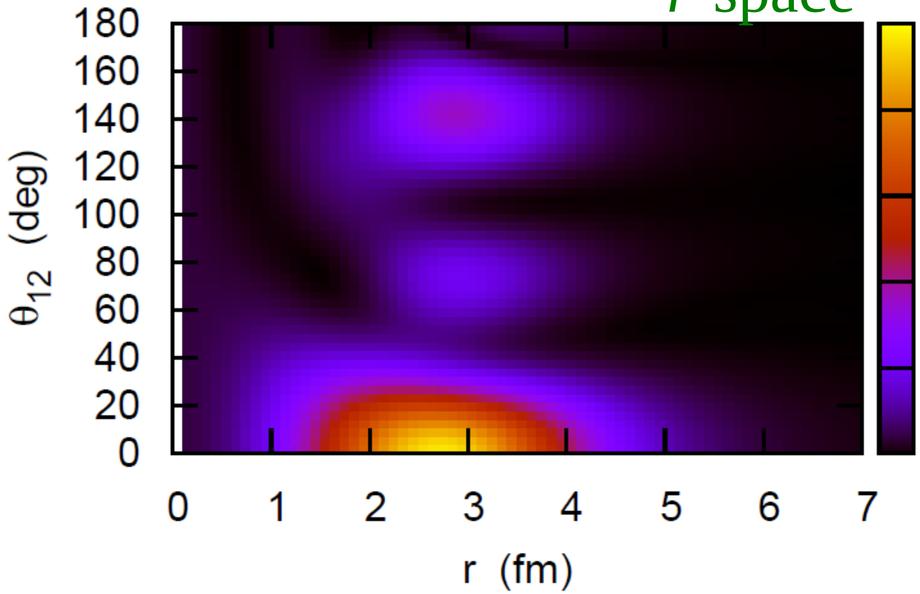


density of the resonance state (with the box b.c.)

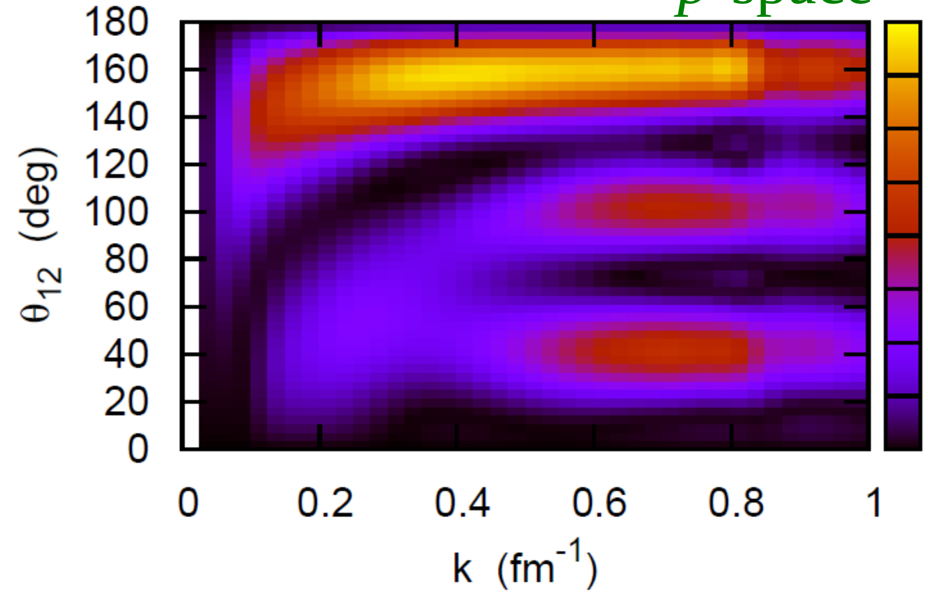
$$\rho(r, r, \theta)$$

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

r-space



p-space



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

⟷ dineutron correlation