Dineutron correlations in neutron-rich nuclei

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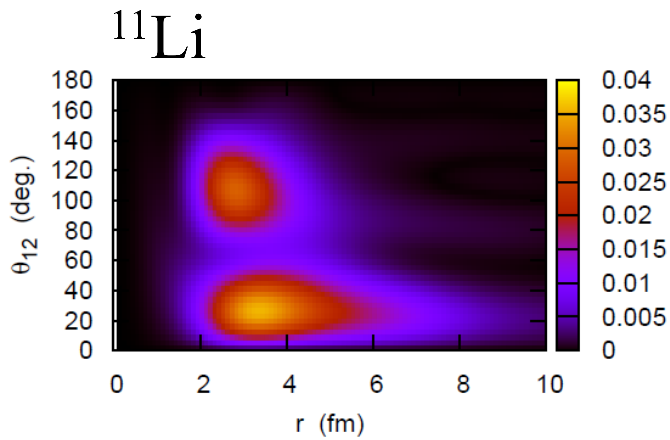
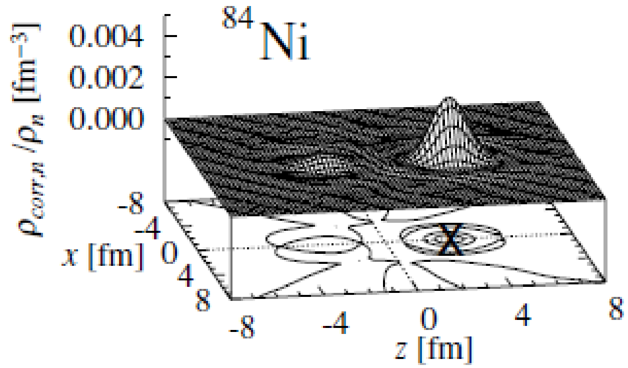
1. Introduction: dineutron correlations
2. Correlations with a replusive interaction
3. A measure of the dineutron correlation
4. Future perspectives
5. Summary

Physics of RI: Recent progress and perspectives, RIKEN, May 30 – Jun 1, 2022

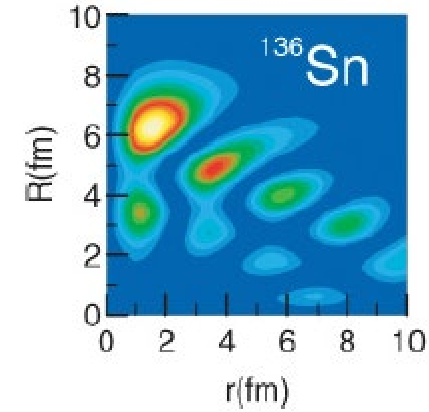
Di-neutron correlation



Bertsch-Esbensen, Ann. Phys. ('91)
Zhukov et al., Phys. Rep. ('93)
Hagino-Sagawa, PRC72 ('05)



Matsuo et al.,
PRC71 ('05)



Pillet et al.,
PRC76 ('07)

cf. coherence length in the BCS approximation:

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

→ much larger than nuclei

Experiments:

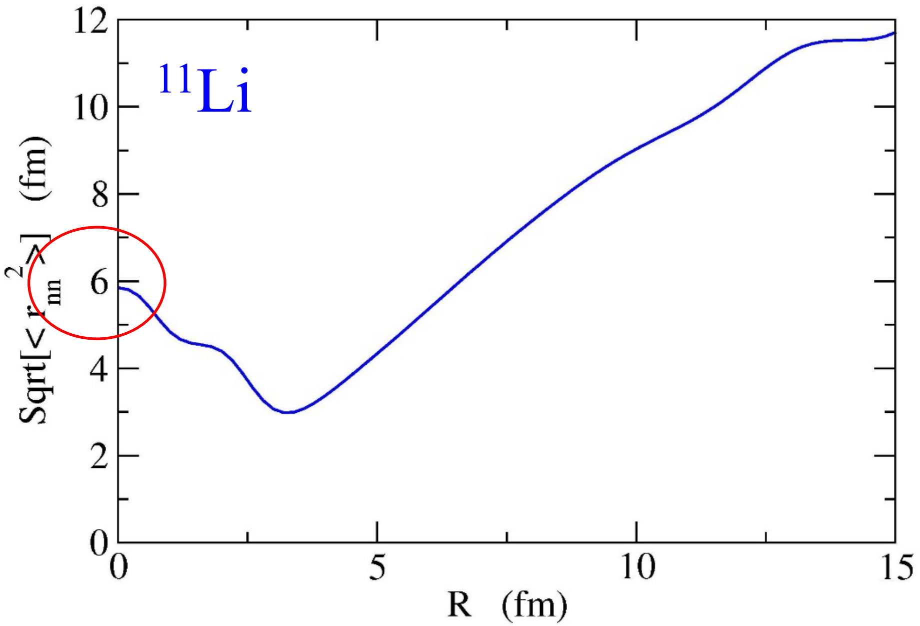
- Coul.-ex. (^{11}Li, ^{19}B, etc.)

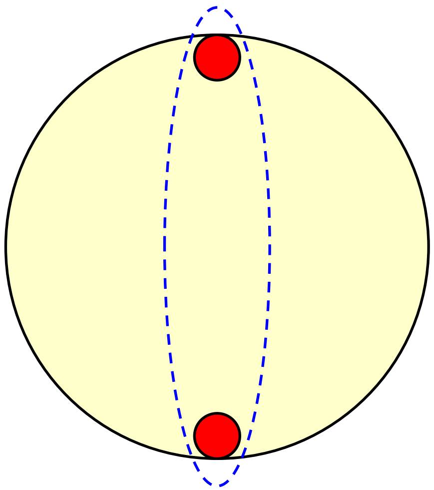
  K.J. Cook et al.,
  PRL124 ('20) 212503

- knockout (^{11}Li) ^{11}Li(p,pn) ^{10}Li

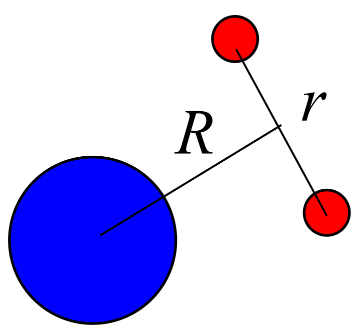
  Y. Kubota et al.,
  PRL 125 ('20) 252501

Surface dineutron correlations

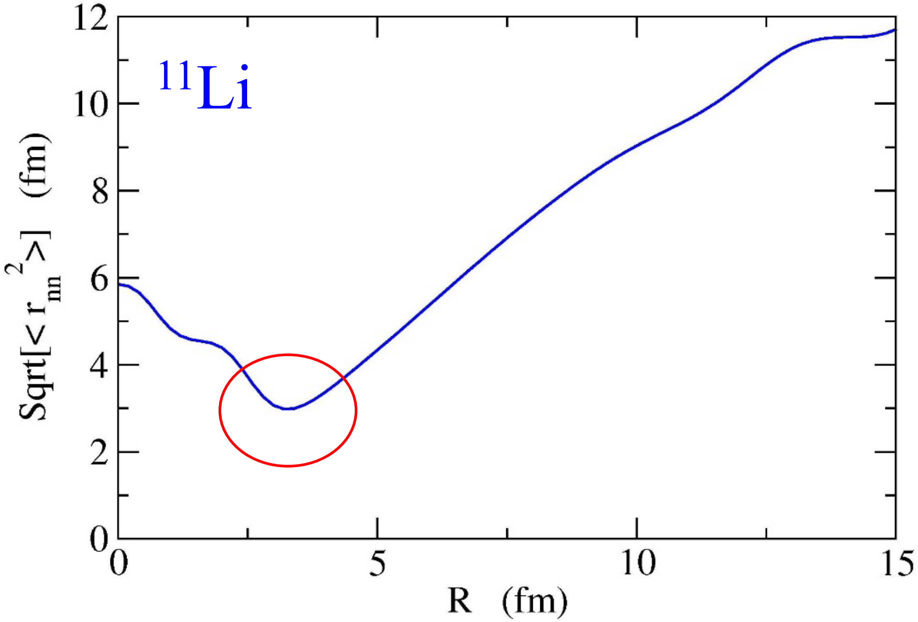




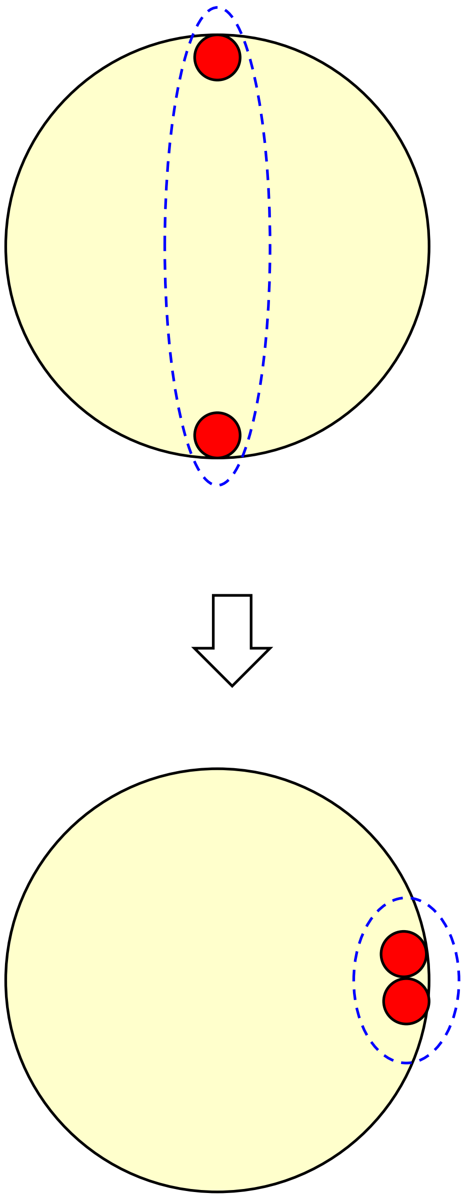
K.H., H. Sagawa, J. Carbonell, and P. Schuck,
PRL99('07)022506

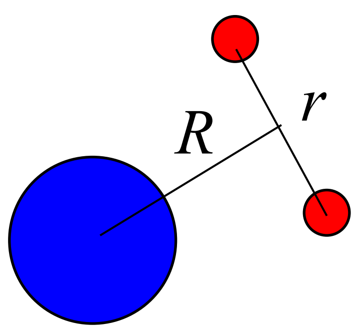


Surface dineutron correlations



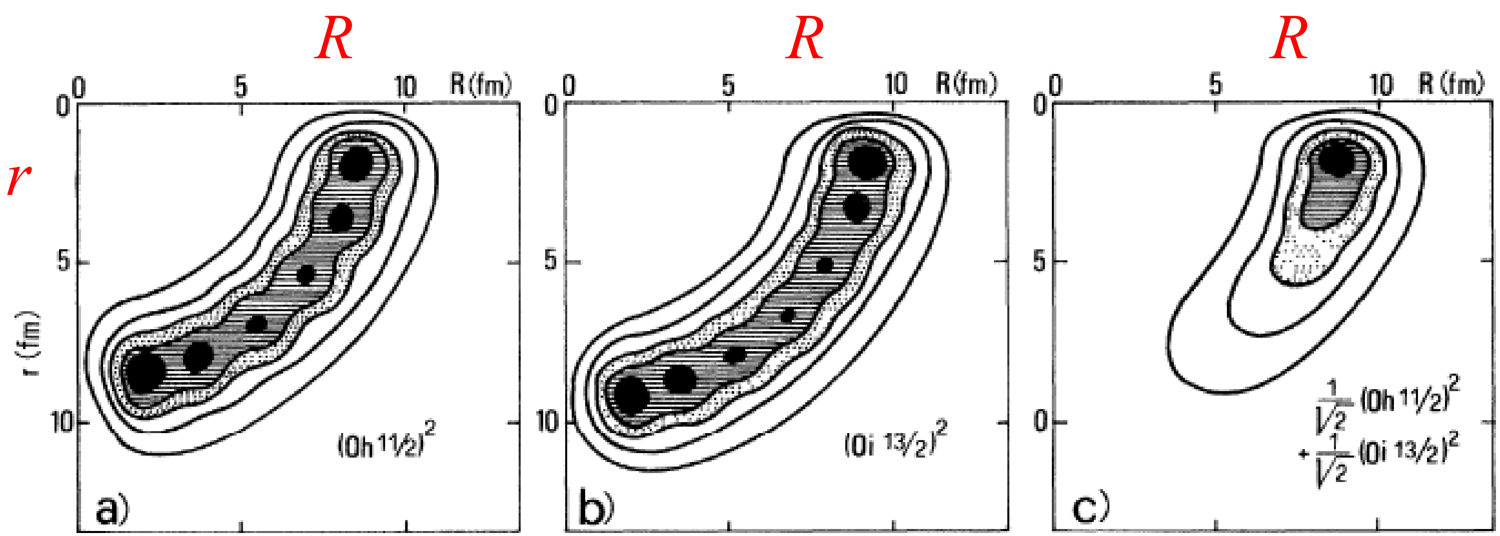
K.H., H. Sagawa, J. Carbonell, and P. Schuck, PRL99('07)022506

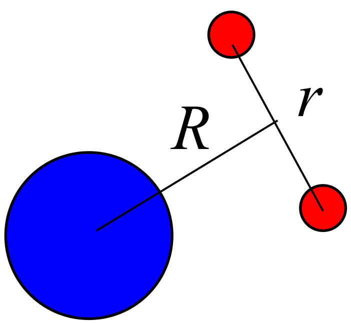




the origin of dineutron correlation: a mixing of $[jl]^2$ with different parities

$$|\Psi\rangle = \sum_{j,l} C_{jl} |[jl]^2\rangle$$





$(0h_{11/2})^2$ $\quad$ $(0i_{13/2})^2$ $\quad$ $\frac{1}{\sqrt{2}}(0h_{11/2})^2 + \frac{1}{\sqrt{2}}(0i_{13/2})^2$

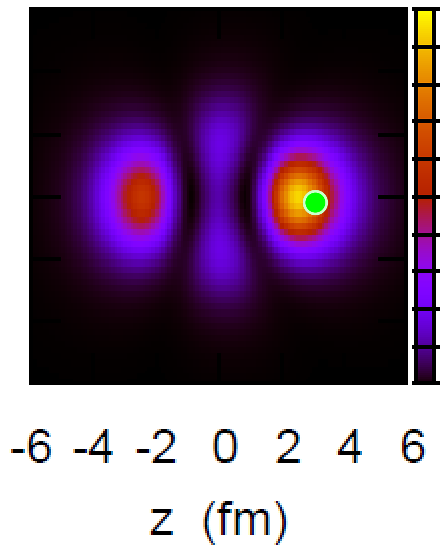
$l = 5$ $\quad$ $l = 6$

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

cf. the phase of C_{jl}

Two-nucleon correlation with a repulsive interaction

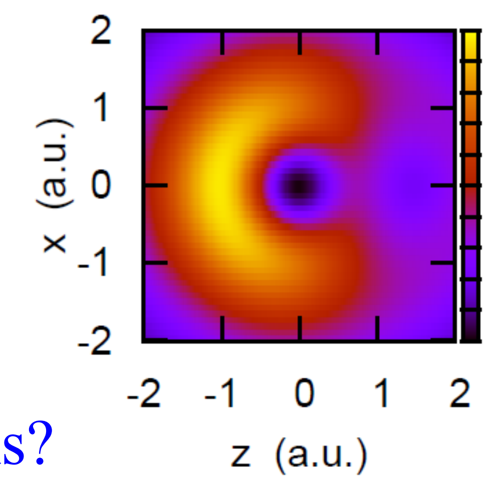
$$|\Psi\rangle = \sum_{j,l} C_{jl}|[jl]^2\rangle$$

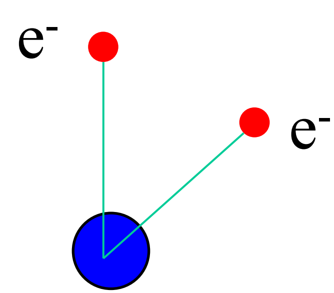


nuclear attractive interaction
→ dineutron correlation

What happens when the interaction is repulsive?

cf. A Coulomb hole in
He atoms



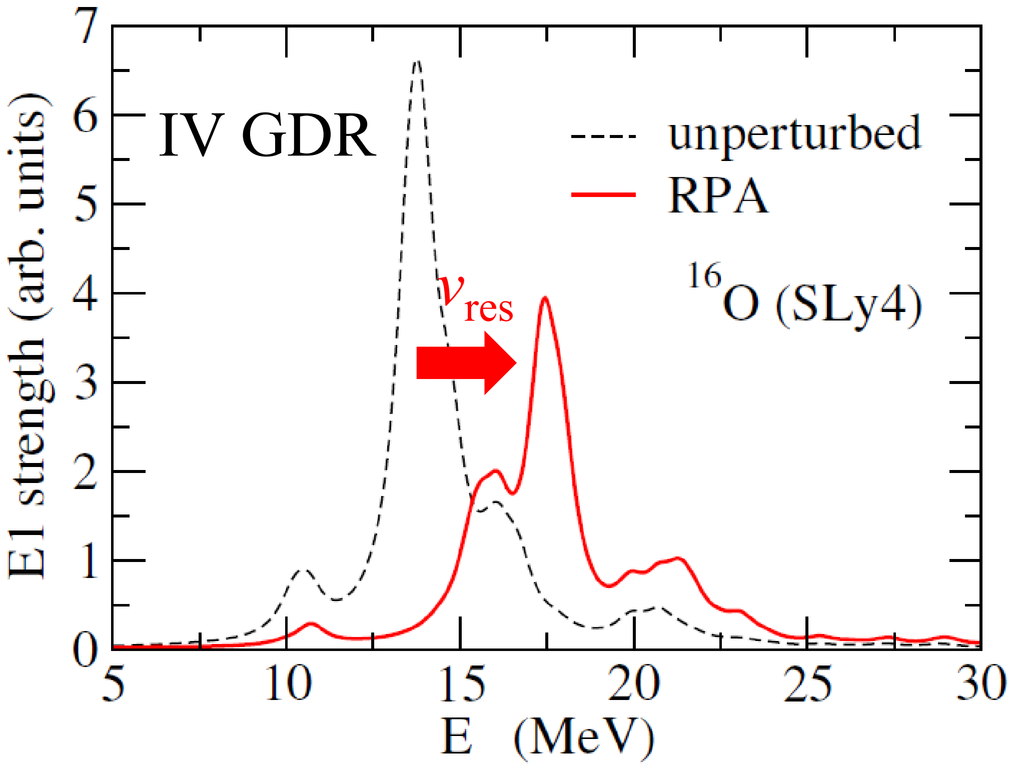


how about nuclear systems?

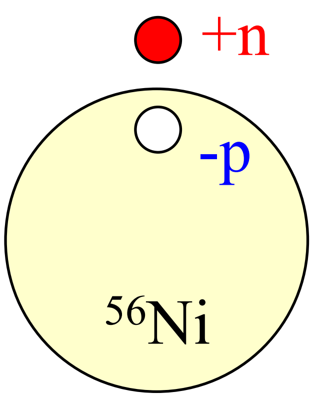
Two-nucleon correlation with a repulsive interaction

What happens when the interaction is repulsive?

IV(T=1) particle-hole interaction: repulsive



$^{56}Co = ^{56}Ni + n - p$



→ the particle-hole density?

IV ph configurations

Tamm-Dancoff approximation with a Skyrme interaction

$^{56}\mathrm{Co} = {}^{56}\mathrm{Ni} + \mathrm{n} - \mathrm{p}$

$$|^{56}\mathrm{Co}\rangle = \sum_{p,h} C_{ph}\, a^{\dagger}_{\nu p} a_{\pi h}\, |^{56}\mathrm{Ni}\rangle$$

diagonalize H_{Sk} Skyrme HF

$2p_{3/2}$

28 e_F

$1f_{7/2}$

$(2p_{3/2})_n(1f_{7/2})_p^{-1}$

$^{56}\mathrm{Ni}(0^+)$

	expt.	TDA (SIII)
2^+	-0.65	-1.10
4^+	-1.62	-1.75

IV ph configurations

$^{56}\mathrm{Co} = {}^{56}\mathrm{Ni} + \mathrm{n} - \mathrm{p}$

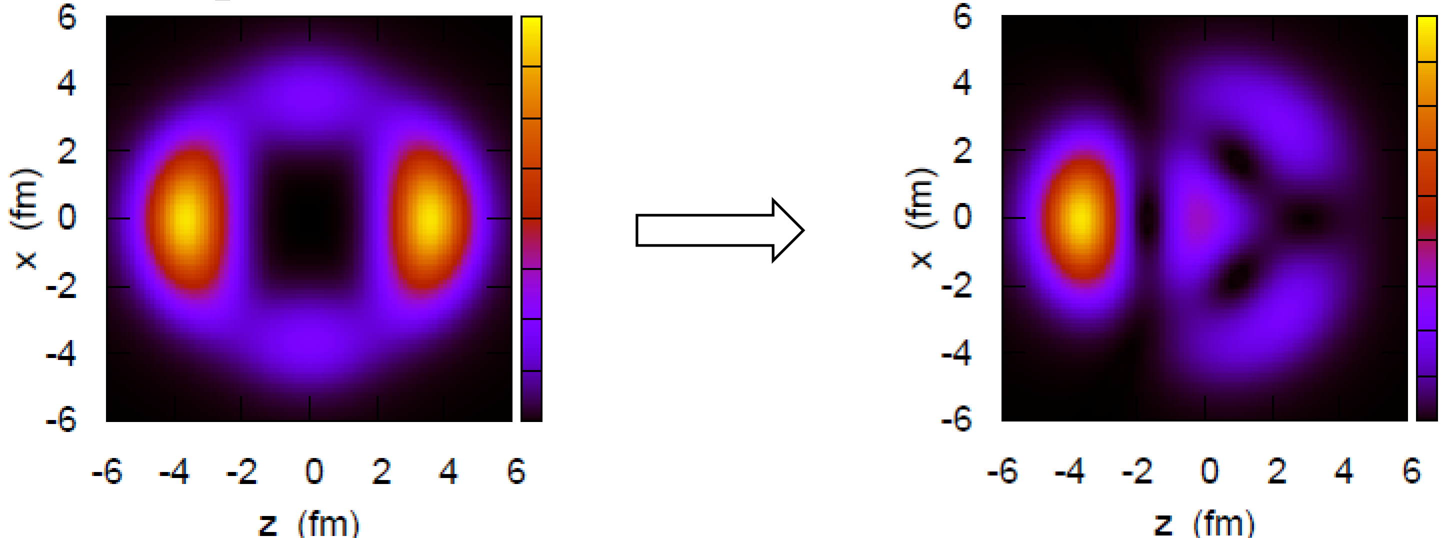
$$|^{56}\mathrm{Co}\rangle = \sum_{p,h} C_{ph}\, a^{\dagger}_{\nu p} a_{\pi h}\, |^{56}\mathrm{Ni}\rangle$$

the spatial distribution of a hole configuration :
the 4^{+} state of ^{56}Co (M=0)

a neutron at 3.4 fm

unperturbed

Skyrme TDA (SLy4)



$(2p_{3/2})_n (1f_{7/2})_p^{-1}$

IV ph configurations

Tamm-Dancoff approximation with a Skyrme interaction

^{56}Co = ^{56}Ni + n - p

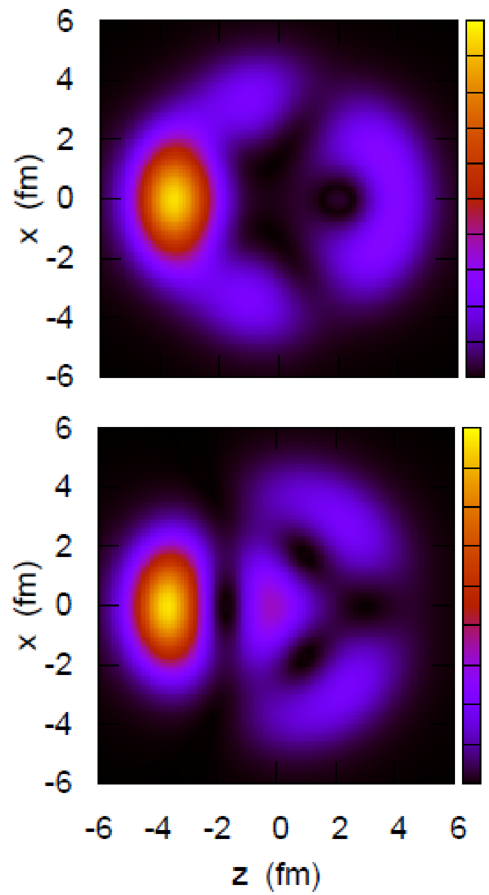
$$|^{56}\mathrm{Co}\rangle = \sum_{p,h} C_{ph}\, a^\dagger_{\nu p} a_{\pi h}\, |^{56}\mathrm{Ni}\rangle$$

^{56}Ni(0^+)

2^+ —— -1.97

4^+ —— -2.54

TDA (SLy4)



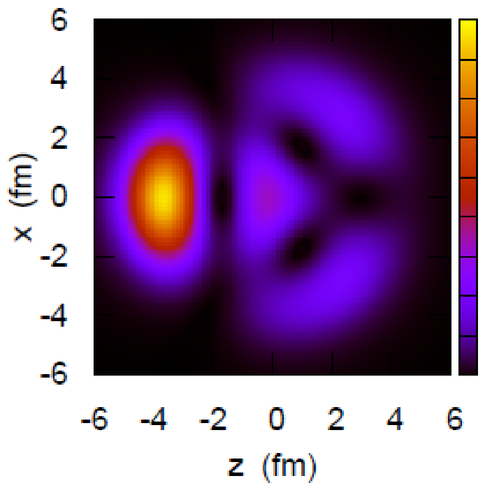
cf.
effects on
d-transfer?

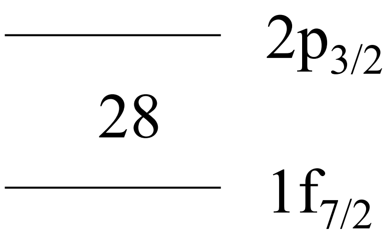
K.H. and H. Sagawa, in preparation

IV ph configurations

^{56}Co = ^{56}Ni + n - p

$$|^{56}\mathrm{Co}\rangle = \sum_{p,h} C_{ph}\, a^\dagger_{\nu p} a_{\pi h}\, |^{56}\mathrm{Ni}\rangle$$





$(2p_{3/2})_n(1f_{7/2})_p^{-1}$: 97.7%

$(\mathrm{even})_n(\mathrm{even})_p^{-1}$: 0.10%

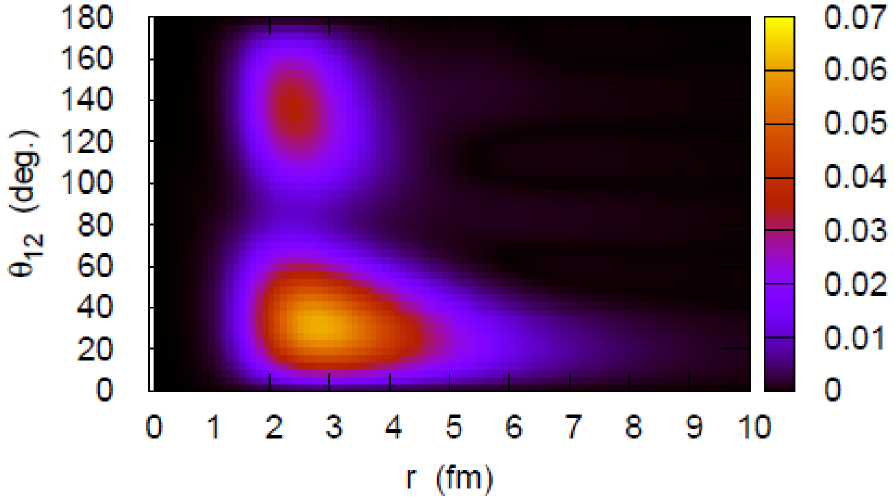
$(\mathrm{odd})_n(\mathrm{odd})_p^{-1}$: 99.9%

the origin of dineutron correlation: a mixing of $[jl]^2$ with different parities

$$|\Psi\rangle = \sum_{j,l} C_{jl} |[jl]^2\rangle$$

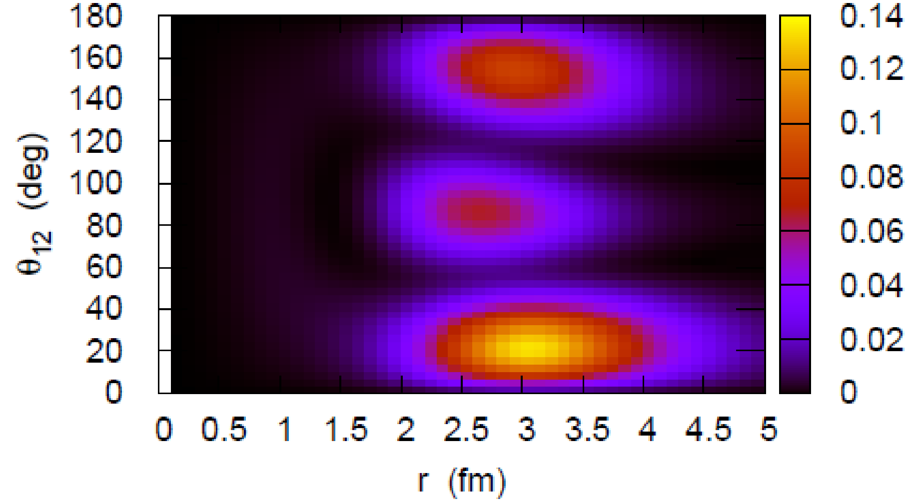
How large should the mixing be? What is a measure of the correlation?

^{6}He (S_{2n} = 0.978 MeV)



odd^2: 89.1 % [$(p_{3/2})^2$=83%]
even^2: 10.9%

^{18}O (S_{2n} = 12.2 MeV)



odd^2: 3.37 %
even^2: 96.6% [sd shell=94.8%]

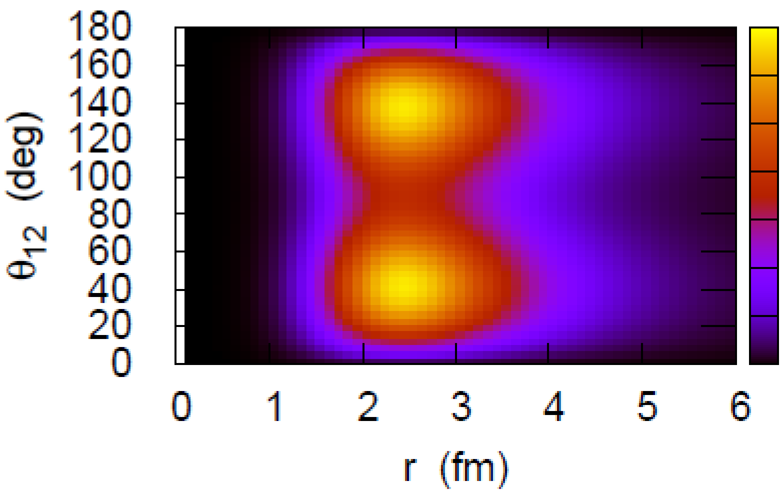
even a small mixing leads to an asymmetric distribution

2 configuration model

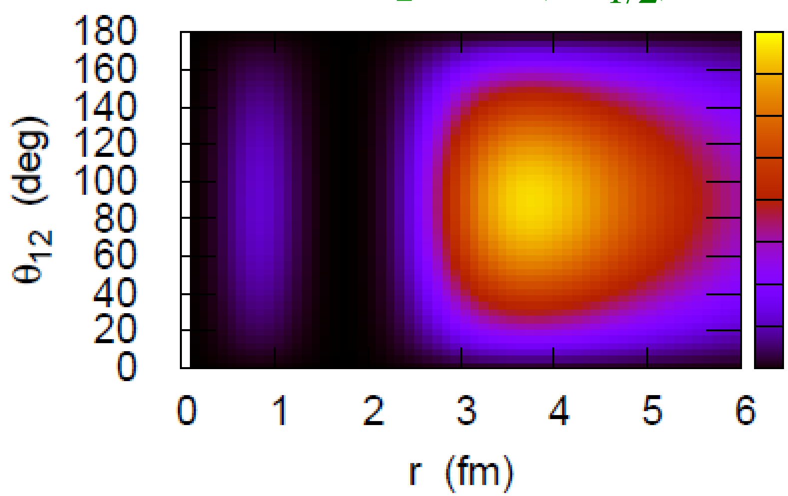
$$|\Psi\rangle = \sqrt{\alpha^2}\,|(1p_{3/2})^2\rangle + \sqrt{1-\alpha^2}\,|(2s_{1/2})^2\rangle$$

✓ wave functions of $1p_{3/2}$, $2s_{1/2}$ states ←a Woods-Saxon potential
✓ the depth of WS pot.: e_{sp} = -0.5 MeV for each state

$\alpha = 1$: pure $(1p_{3/2})^2$

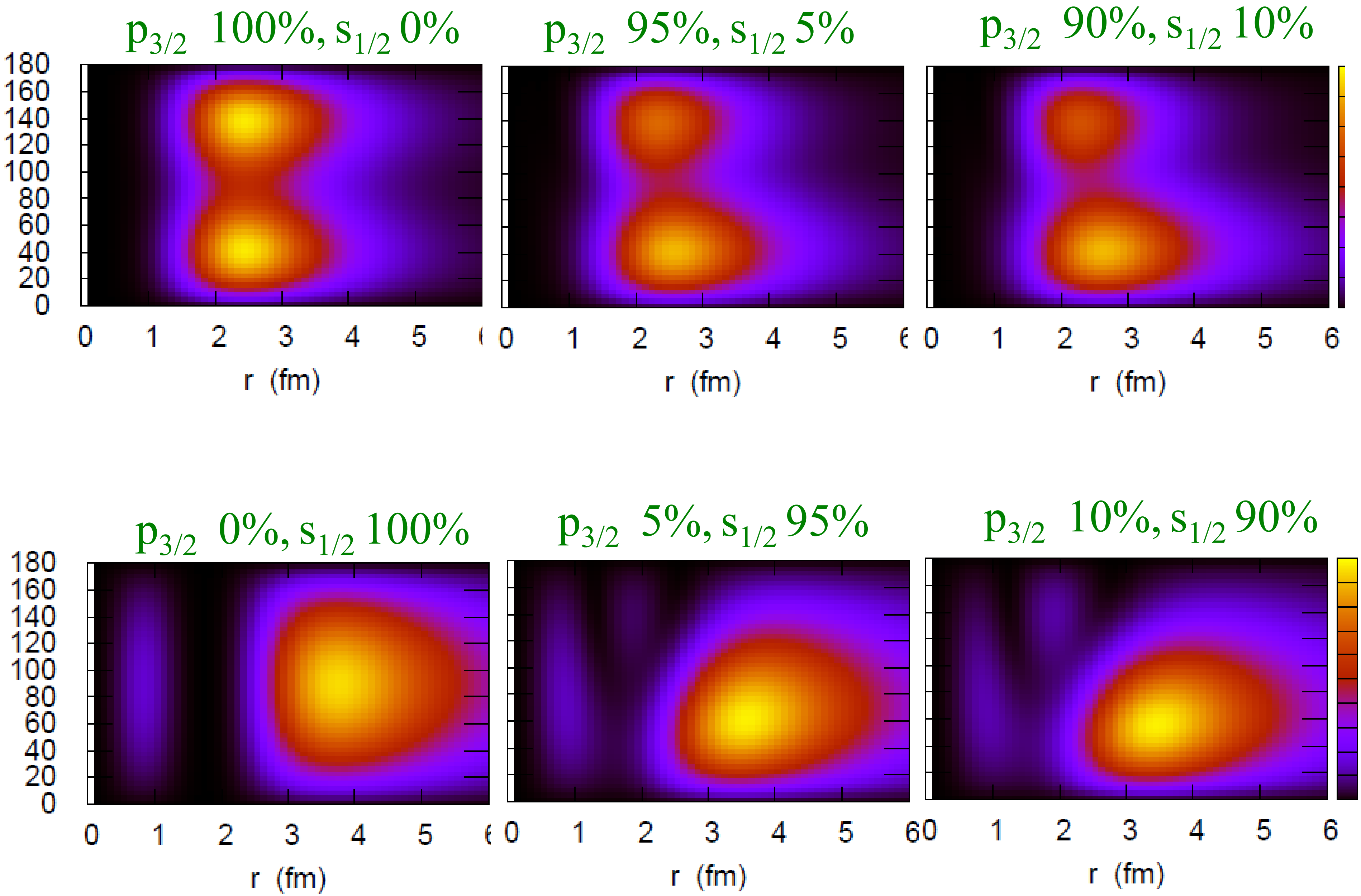


$\alpha = 0$: pure $(2s_{1/2})^2$



2 config. model

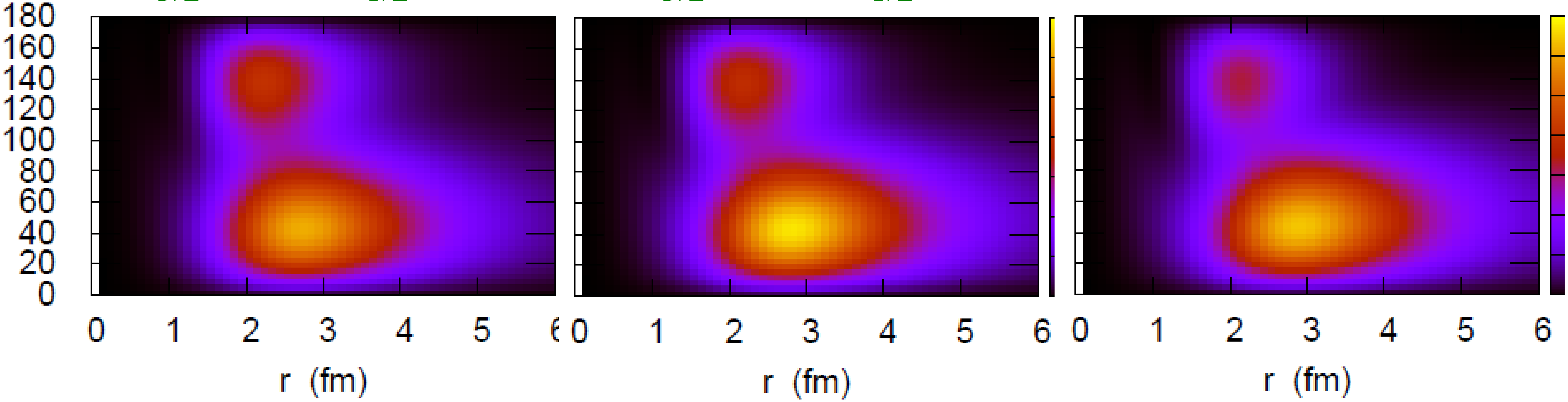
$$|\Psi\rangle = \sqrt{\alpha^2}\,|(1p_{3/2})^2\rangle + \sqrt{1-\alpha^2}\,|(2s_{1/2})^2\rangle$$



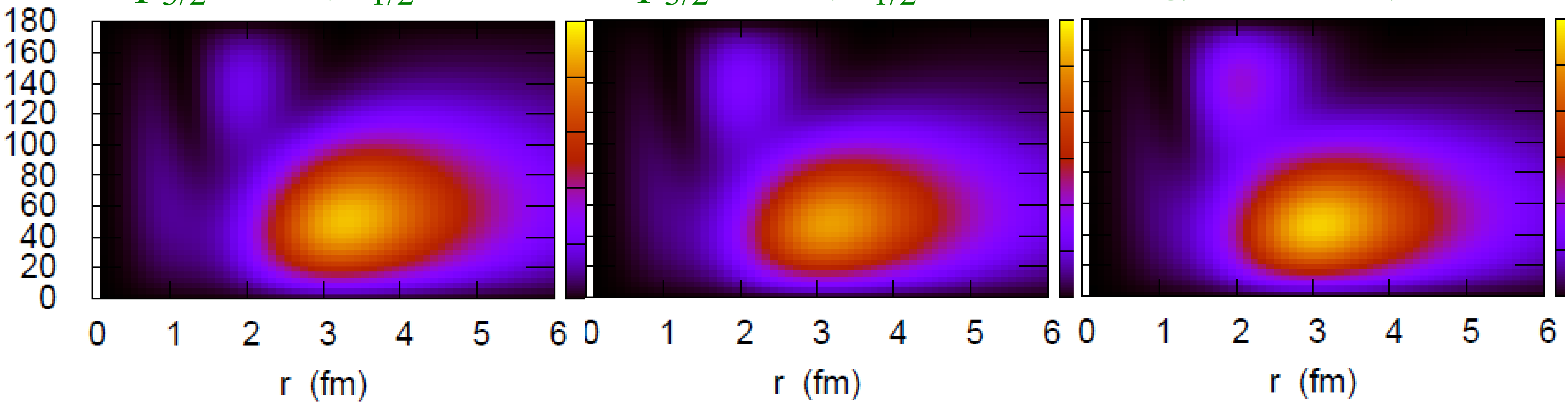
2 configuration model

$$|\Psi\rangle = \sqrt{\alpha^2}\,|(1p_{3/2})^2\rangle + \sqrt{1-\alpha^2}\,|(2s_{1/2})^2\rangle$$

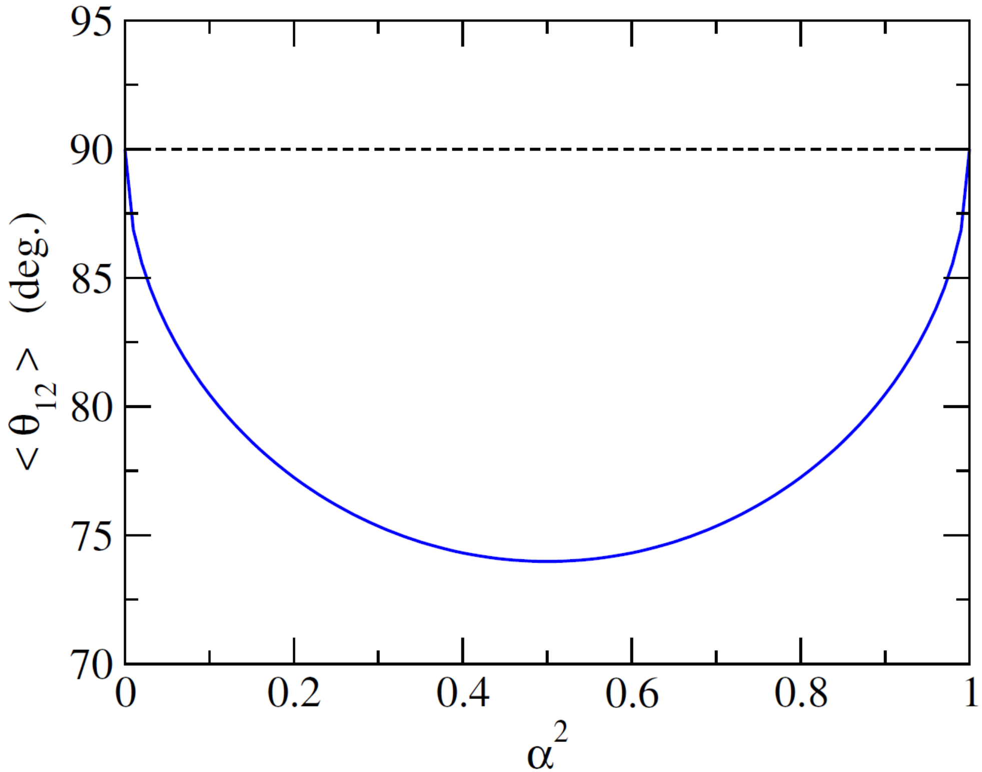
$p_{3/2}$ 80%, $s_{1/2}$ 20% | $p_{3/2}$ 70%, $s_{1/2}$ 30% | $p_{3/2}$ 60%, $s_{1/2}$ 40%



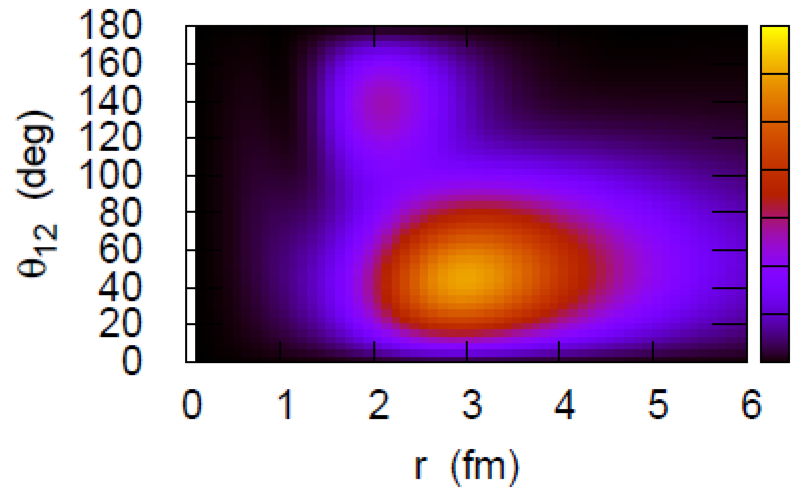
$p_{3/2}$ 20%, $s_{1/2}$ 80% | $p_{3/2}$ 30%, $s_{1/2}$ 70% | $p_{3/2}$ 40%, $s_{1/2}$ 60%



2 configuration model $|\Psi\rangle = \sqrt{\alpha^2}\,|(1p_{3/2})^2\rangle + \sqrt{1-\alpha^2}\,|(2s_{1/2})^2\rangle$



$p_{3/2}$ 50%, $s_{1/2}$ 50%



✓ symmetric at α^2=0.5→ the correlation does not matter whether the main configuration is $s_{1/2}$ or not

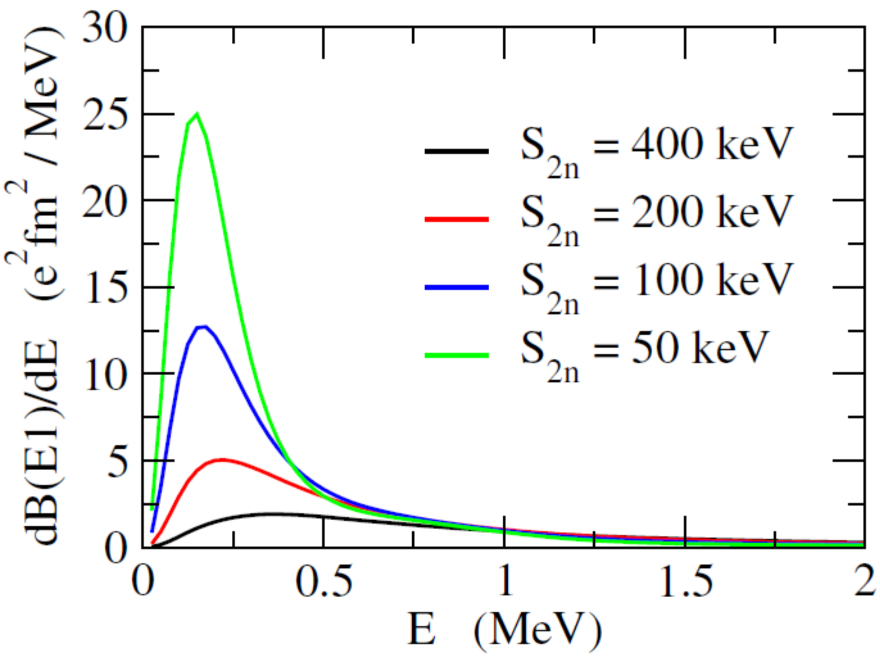
✓ even a small admixture → large asymmetry in density

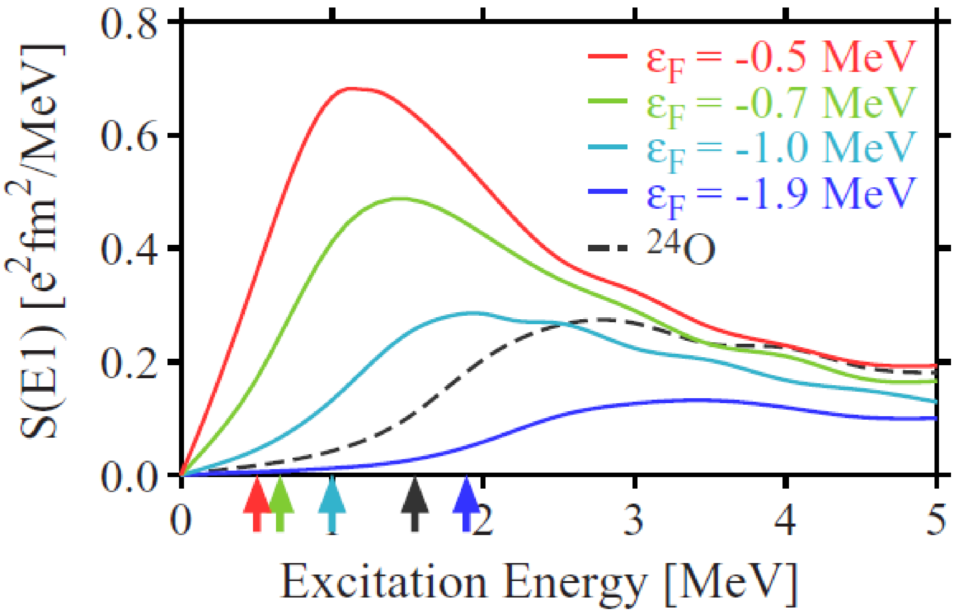
What is a good measure of the degree of correlations?
(an open question)

Future perspectives of theoretical studies

- spherical core + 2n → deformed core + 2n

Coul. b.u. of ^{22}C





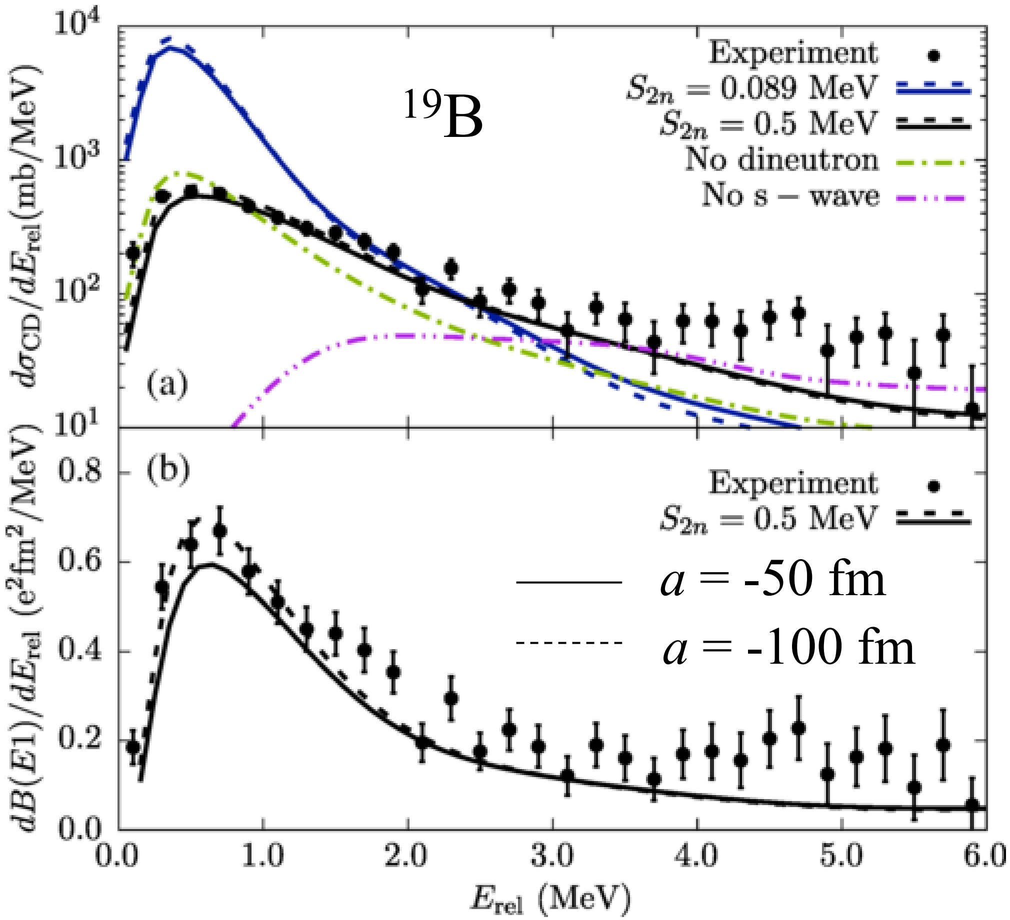
Skyrme HF+RPA
→ suggested deformation effects
(but, no pairing correlation)
T. Inakura et al., PRC89 ('14) 064316

Exp. data (Nakamura et al.):
a peak at around 1 MeV

cf. another 3-body model calc. by Zhukov
S.N. Ershov, J.S. Vaagen, and M.V. Zhukov, PRC86 ('12) 034331

Future perspectives of theoretical studies

- spherical core + 2n → deformed core + 2n



3-body model calculation with
^{19}B = ^{17}B (spherical) + n + n

^{15}B, ^{16}B, ^{17}B, ^{18}B, ^{19}B, ^{20}B

unbound

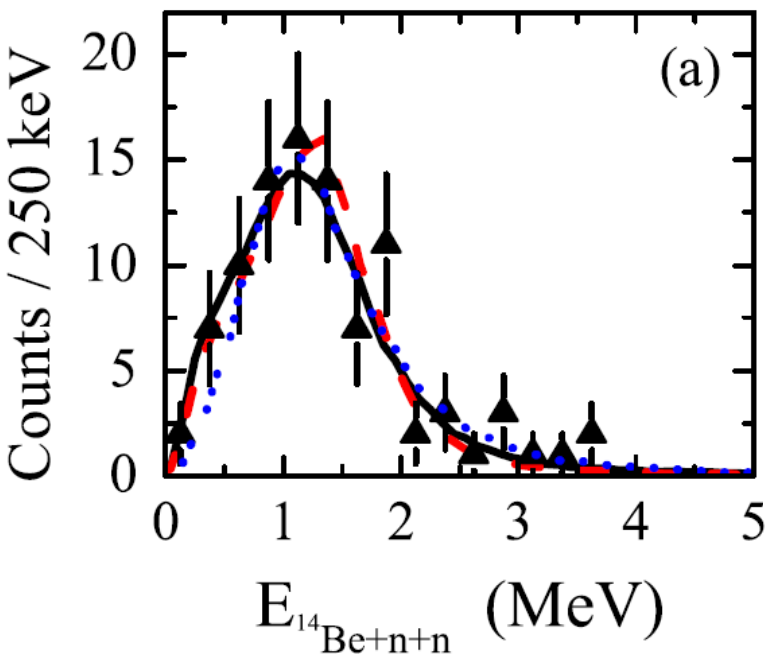
→deformation effects?

K.J. Cook et al., PRL124, 212503 (2020)

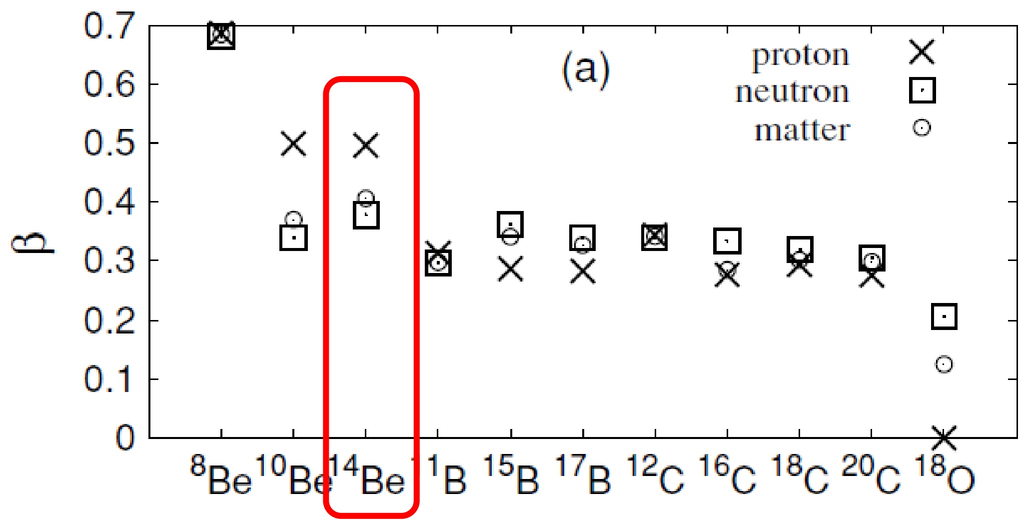
Future perspectives of theoretical studies

- spherical core + 2n → deformed core + 2n

2n emission decay of ^{16}Be



AMD calculations



Y. Kanada-En'yo and M. Kimura, PRC72 ('05) 064301

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

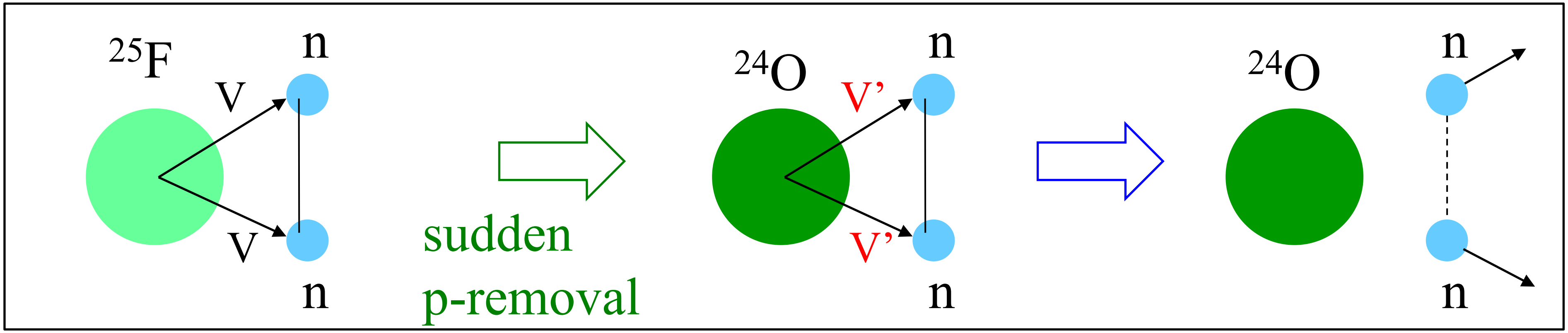
theory (3-body) : A.E. Lovell, F.M. Nunes, and I.J. Thompson, PRC95 ('17) 034605

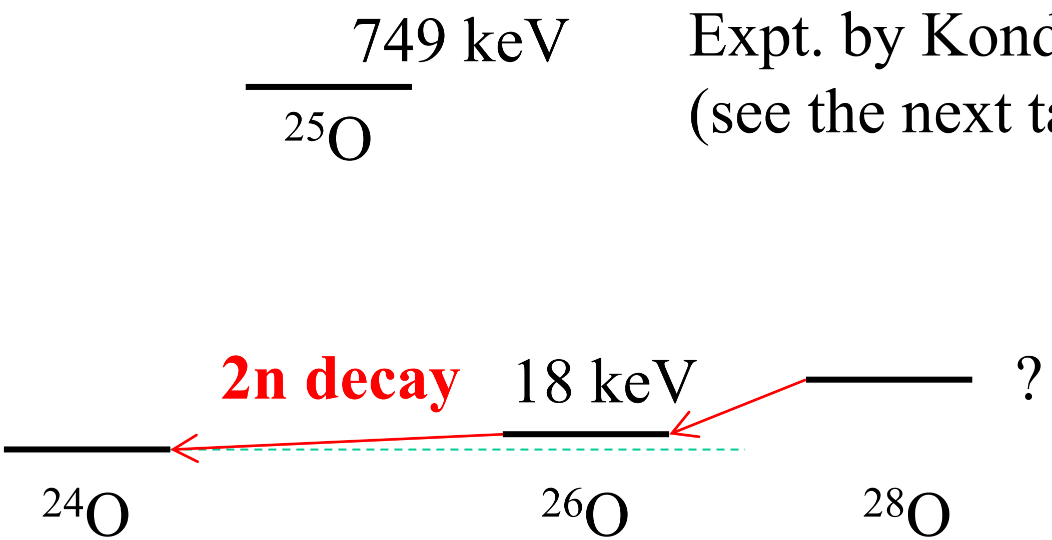
Future perspectives of theoretical studies

- 3-body → 5-body model

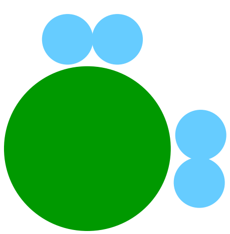
K.H. and H. Sagawa, PRC89 ('14) 014331; PRC93 ('16) 034330

2n emission decay of ^{26}O



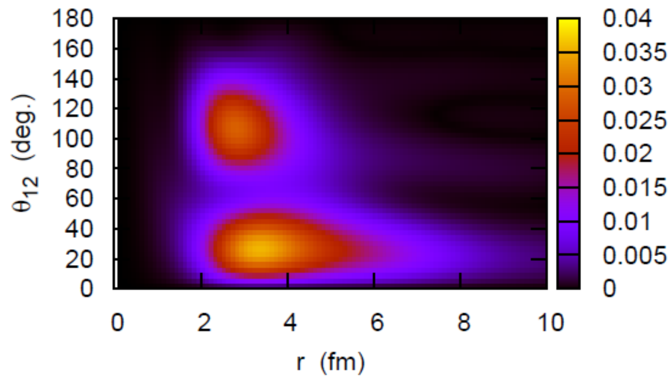


Expt. by Kondo-san (TIT) (see the next talk)



double dineutrons?

Summary



- Dineutron correlations ← mixing of config. consisted of opposite parity states
  - an attractive pairing interaction → dineutron

    even a small mixing → a large asymmetry in density
  - anti-correlation if the interaction is repulsive
    - ✓ T=1 particle-hole interaction
- Future theoretical perspectives
  - An extension of 3-body model with core deformation
  - An extention to a 5-body mode: double dineutrons? ← ^{28}O
  - two-nucleon transfer