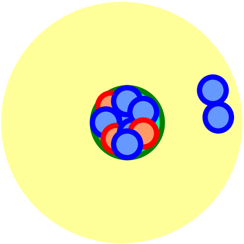
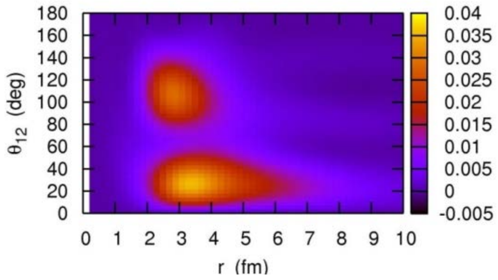
Unbound nucleus ^{26}O
Ground state decay and 2$^+$ state

Kouichi Hagino (Tohoku Univ.)
Hiroyuki Sagawa (Univ. of Aizu)

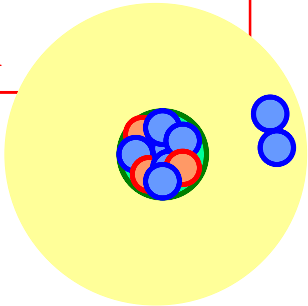




1. Di-neutron correlations in neutron-rich nuclei
2. Two-neutron decays of ^{26}O: three-body model
    - decay energy spectrum
    - angular distribution of two neutrons
3. Energy of the first 2$^+$ state in ^{26}O
4. Summary

Di-neutron correlations in neutron-rich nuclei

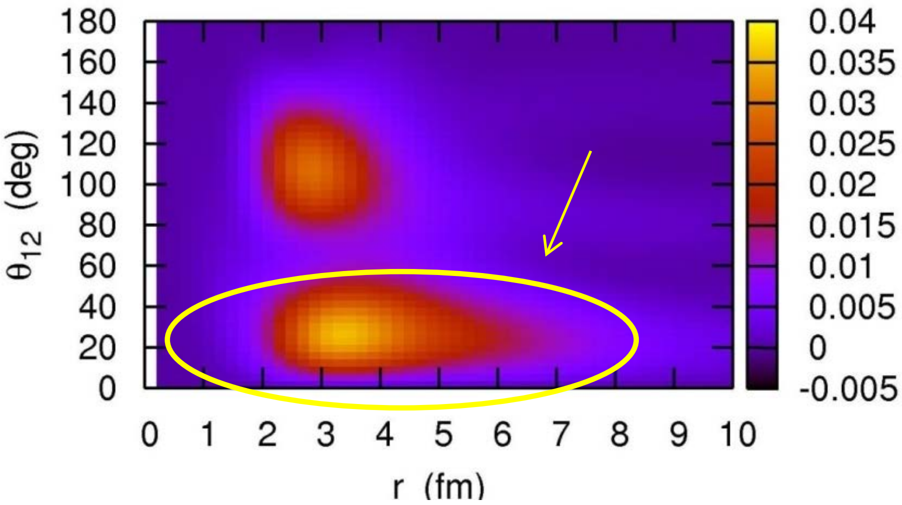
Strong di-neutron correlations
in neutron-rich nuclei



- ✓ Borromean nuclei (3body calc.)
  - Bertsch-Esbensen (‘91)
  - Zhukov et al. (‘93)
  - Hagino-Sagawa (‘05)
  - Kikuchi-Kato-Myo (‘10)

- ✓ Heavier nuclei (HFB calc.)
  - Matsuo et al. (‘05)
  - Pillet-Sandulescu-Schuck (‘07)

^{11}Li

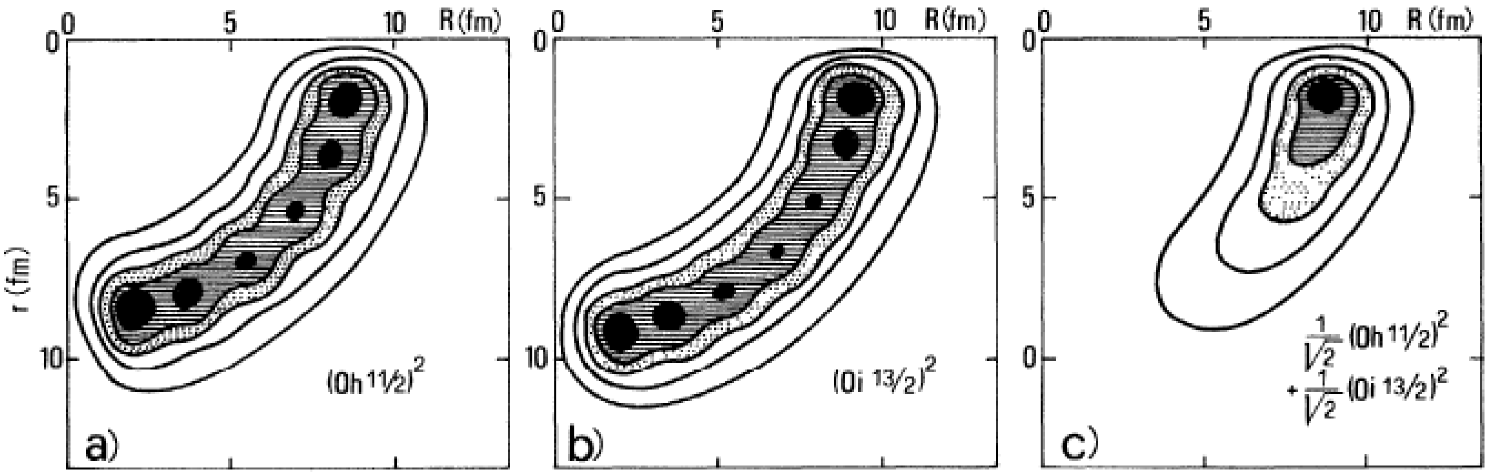


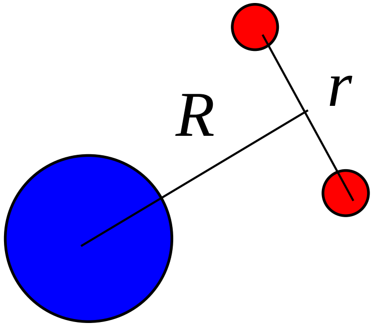
K.H. and H. Sagawa,
PRC72(’05)044321

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

spatial localization of two neutrons (dineutron correlation)

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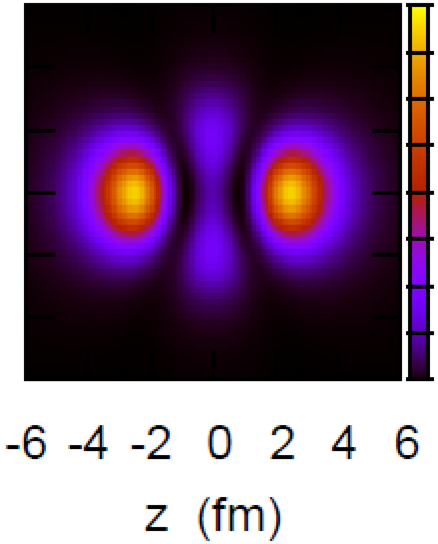
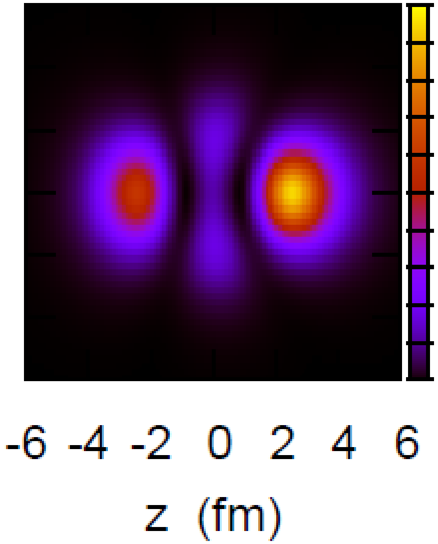


parity mixing



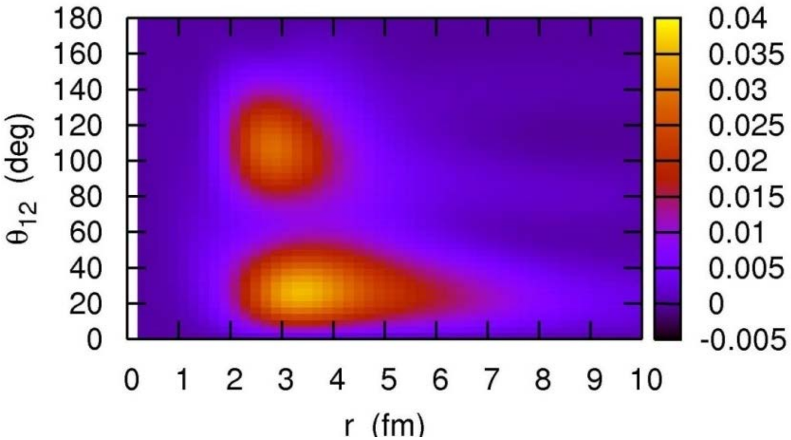
weakly bound systems

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

\+ enhancement of pairing on the surface

⟶ dineutron correlation: enhanced

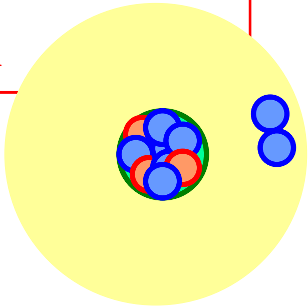
cf. - Bertsch, Esbensen, Ann. of Phys. 209('91)327
- M. Matsuo, K. Mizuyama, Y. Serizawa, PRC71('05)064326



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

Di-neutron correlations in neutron-rich nuclei

Strong di-neutron correlations
in neutron-rich nuclei



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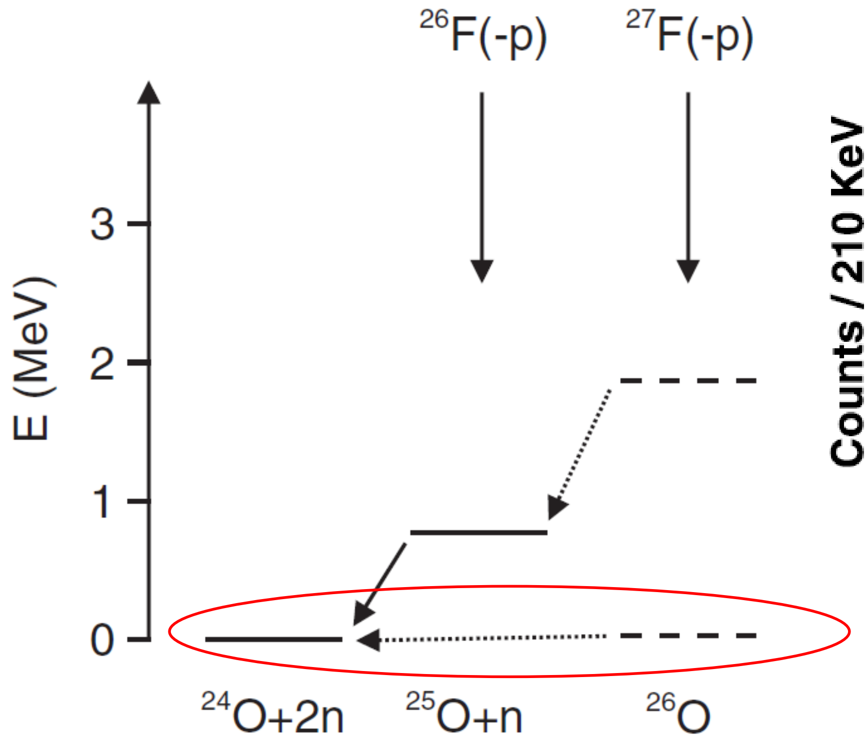
How to probe it?

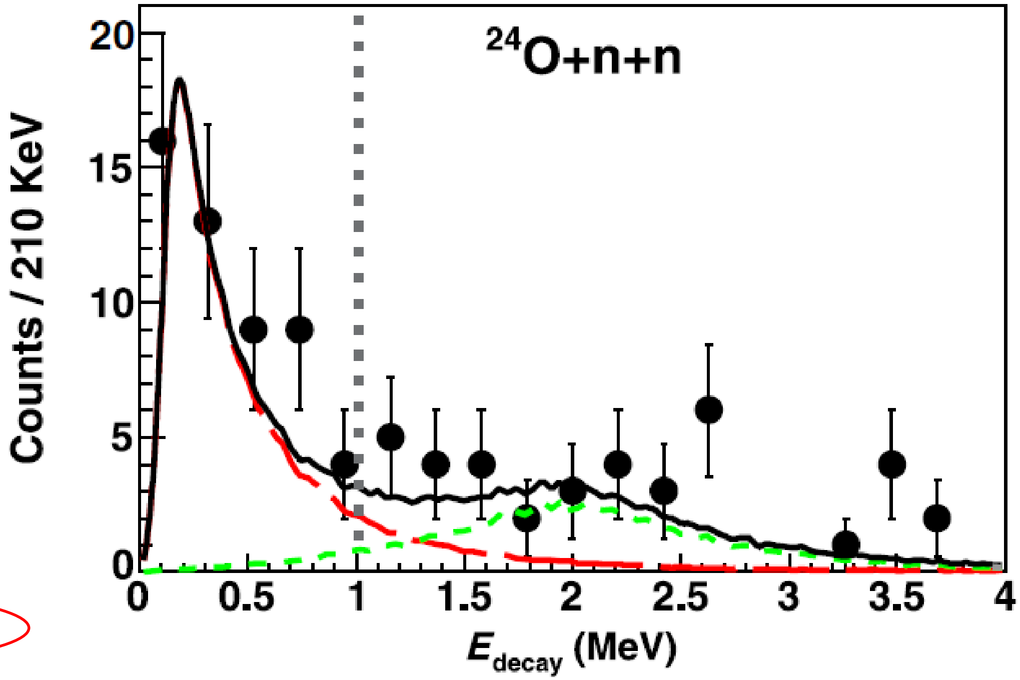
- ➢ Coulomb breakup
  - T. Nakamura et al.
  - cluster sum rule
  - (mean value of θ_{nn})
- ➢ pair transfer reactions
- ➢ two-proton decays
  - Coulomb 3-body problem
- ➢ <u>two-neutron decays</u>
  - 3-body resonance due to a centrifugal barrier
  - MoNA (^{16}Be, ^{13}Li, ^{26}O)
  - **SAMURAI (^{26}O)**
  - GSI (^{26}O)

Two-neutron emission decays of ^{26}O (MoNA@MSU)

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





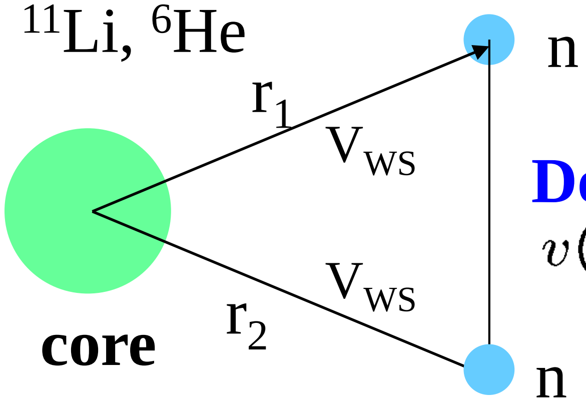
$E_{decay} = 150^{+50}_{-150}$ keV

$\Gamma_{exp} = 1.0^{+0.34}_{-0.25}$ +/- 0.68 x 10^{-10} MeV

cf. Y. Kondo et al., (SAMURAI)
C. Caesar et al., PRC88 (‘13) 034313 (GSI exp.)

3-body model calculation for Borromean nuclei

^{11}Li, ^{6}He



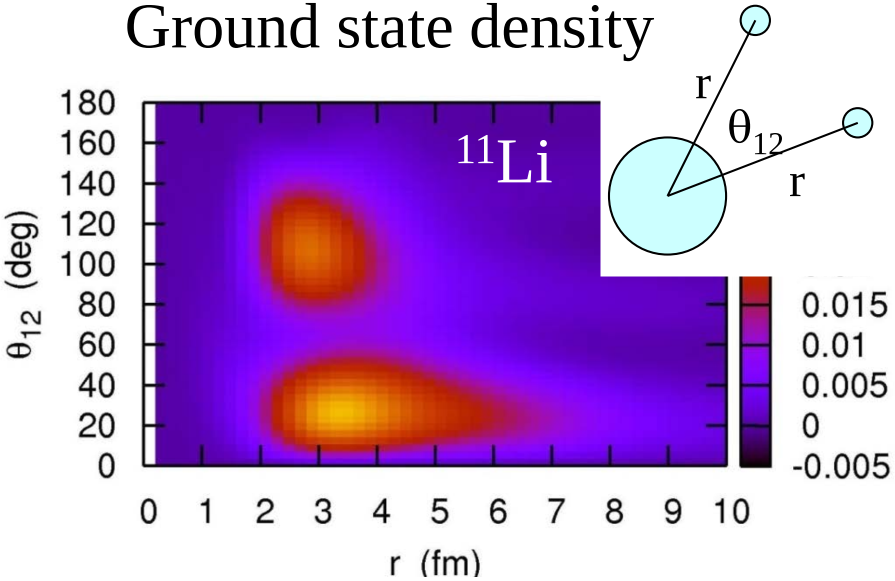
G.F. Bertsch and H. Esbensen,
Ann. of Phys. 209('91)327; PRC56('99)3054
K.H. and H. Sagawa, *PRC72('05)044321*

Density-dependent delta-force

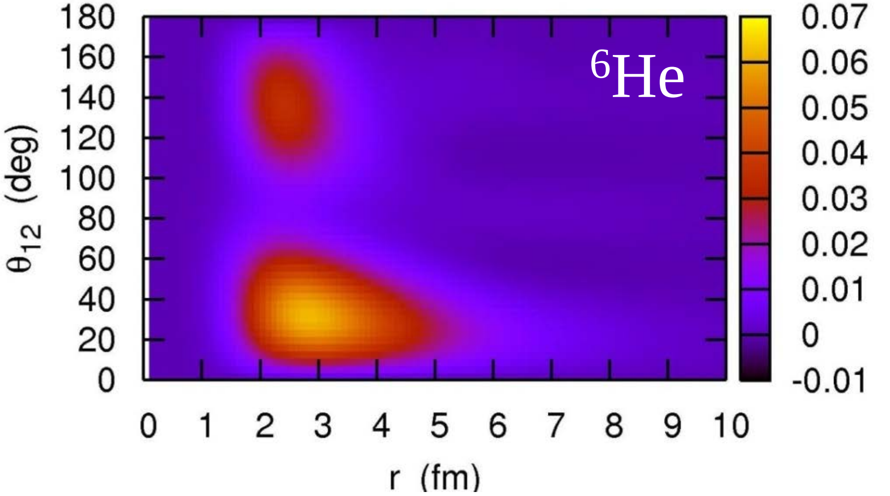
$$v(\boldsymbol{r}_1,\boldsymbol{r}_2) = v_0(1+\alpha\rho(r)) \times\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)$$

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

Ground state density



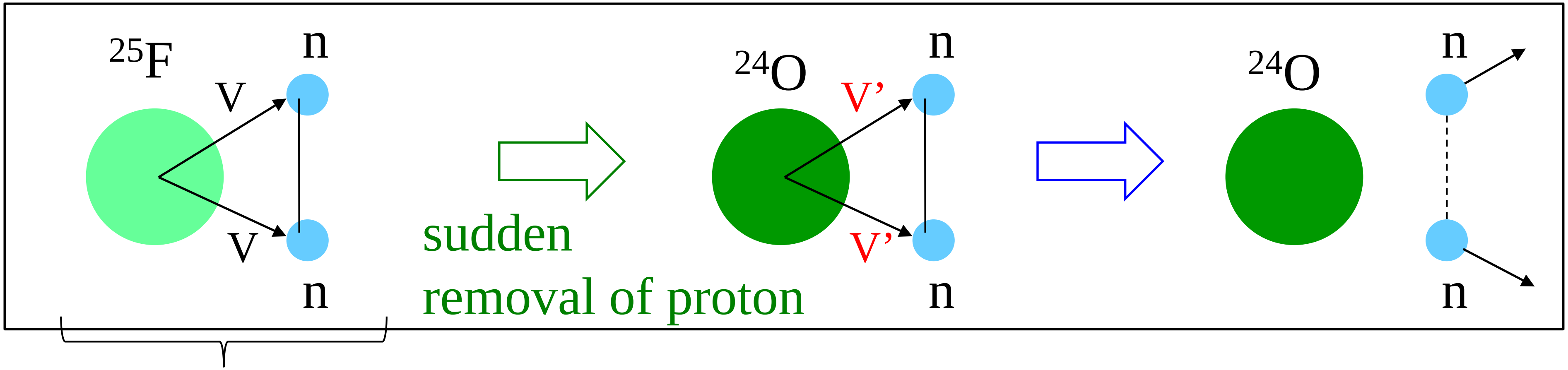
K.H. and H. Sagawa, PRC72('05)044321



3-body model analysis for ^{26}O decay

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

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



g.s. of ^{27}F (bound)

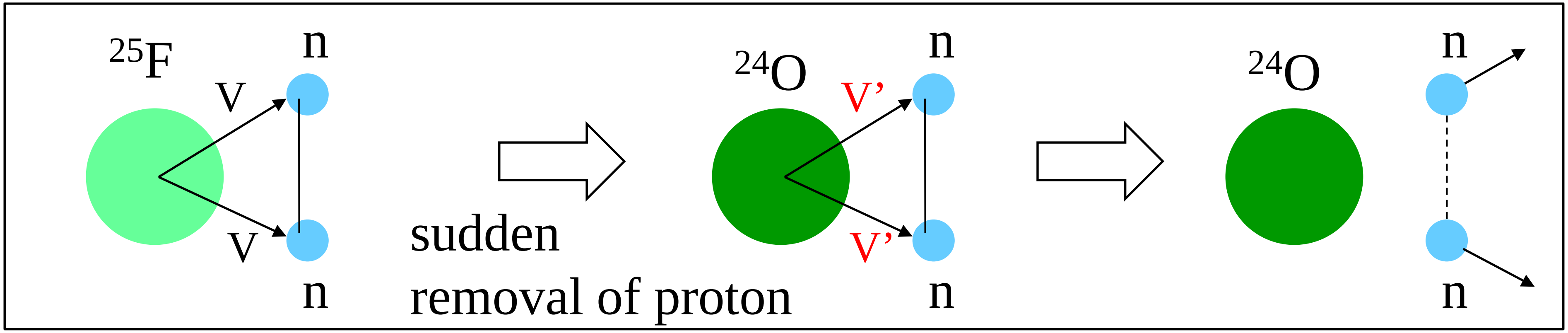
spontaneous decay

$$\underbrace{\Psi_{nn}}\otimes|^{25}\mathrm{F}\rangle \qquad \underbrace{\Psi_{nn}}\otimes|^{24}\mathrm{O}\rangle$$

→ the same config. (non-eigenstate of ^{24}O+n+n)

FSI ⟶ Green's function method ⬅ continuum effects

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



- ^{24}O + n potential

Woods-Saxon potential

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

- ^{25}F + n potential

(^{24}O + n) potential $\boxed{+\ \delta V_{ls}}$ ← pn tensor interaction

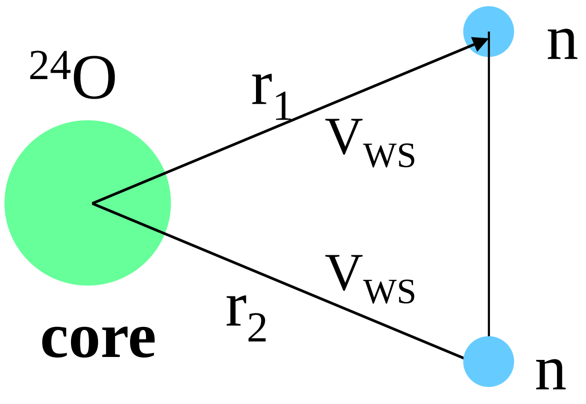
T. Otsuka et al., PRL95(‘05)232502

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

- nn interaction (density-dependent zero-range interaction)

← E_{exp} (^{27}F) = -2.80(18) MeV

Decay energy spectrum



- ^{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

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

$$= -\frac{1}{\pi}\Im\langle\Phi_{\rm ref}^{(I)}|G^{(I)}(E)|\Phi_{\rm ref}^{(I)}\rangle,$$

overlap with a ref.
state ⟵ 2n config. with
^{25}F + n + n

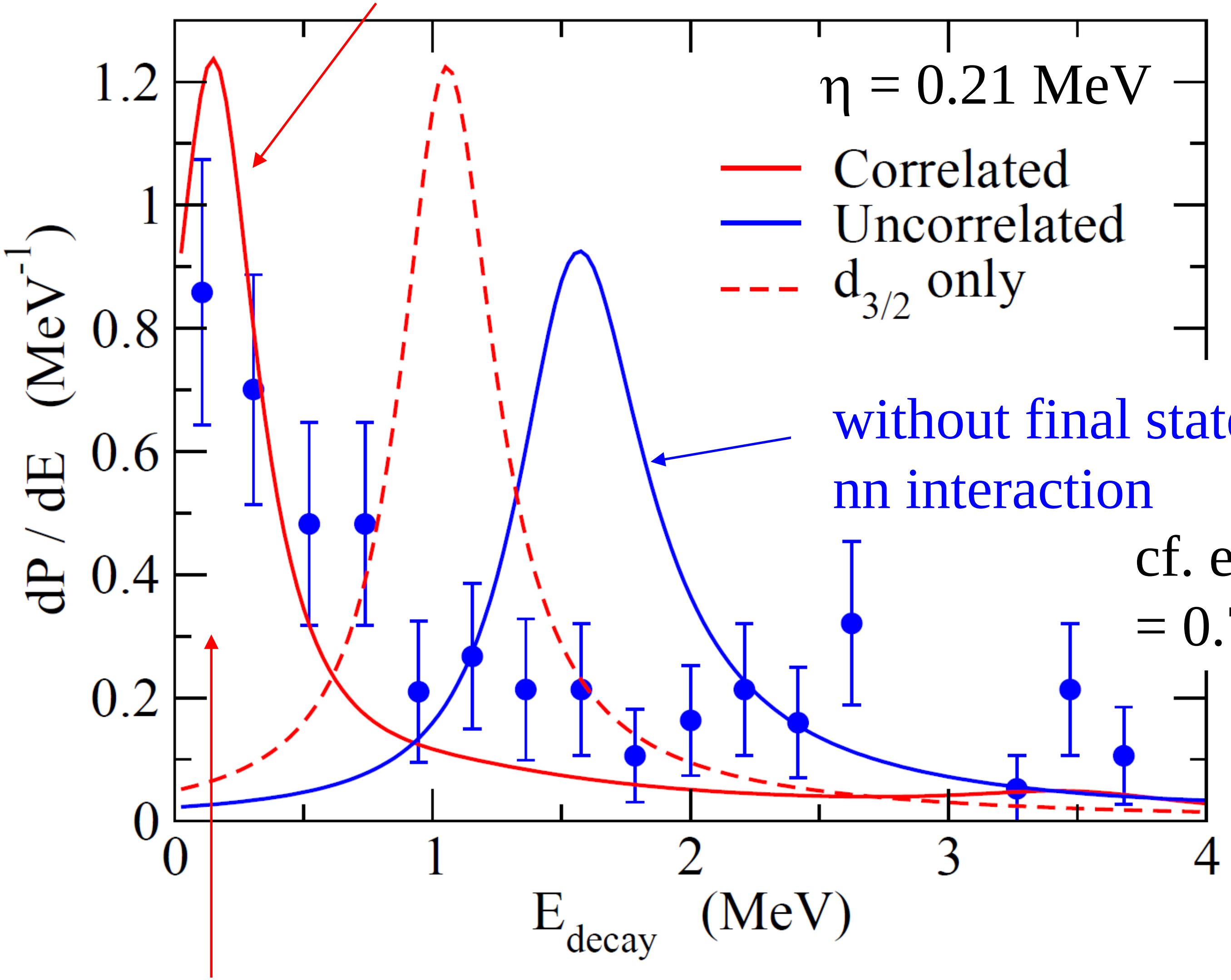
$$\boxed{G^{(I)}(E) = G_0^{(I)}(E) - G_0^{(I)}(E)v(1+G_0^{(I)}(E)v)^{-1}G_0^{(I)}(E)}$$

⟵ continuum effects

Decay energy spectrum

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

with final state nn interaction



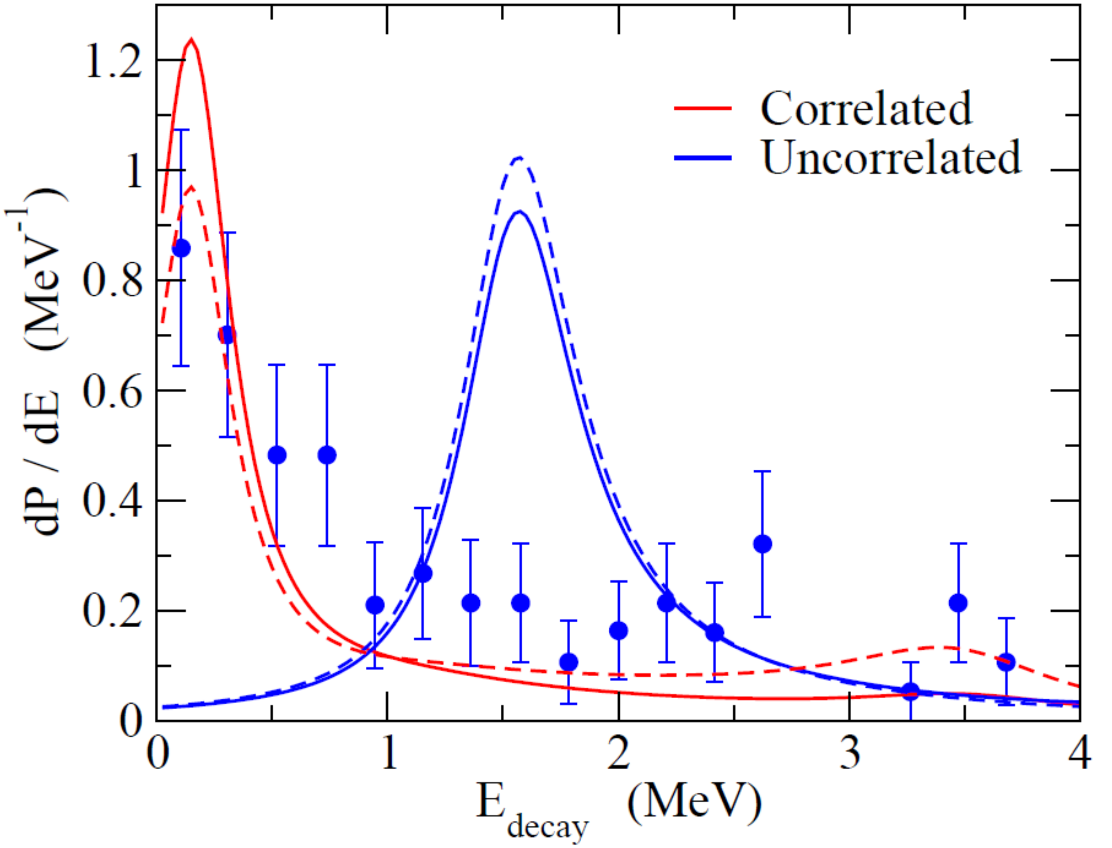
without final state nn interaction

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

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

E_{peak} = 0.14 MeV with this setup

Sensitivity to the initial wave function (how ^{26}O is formed)



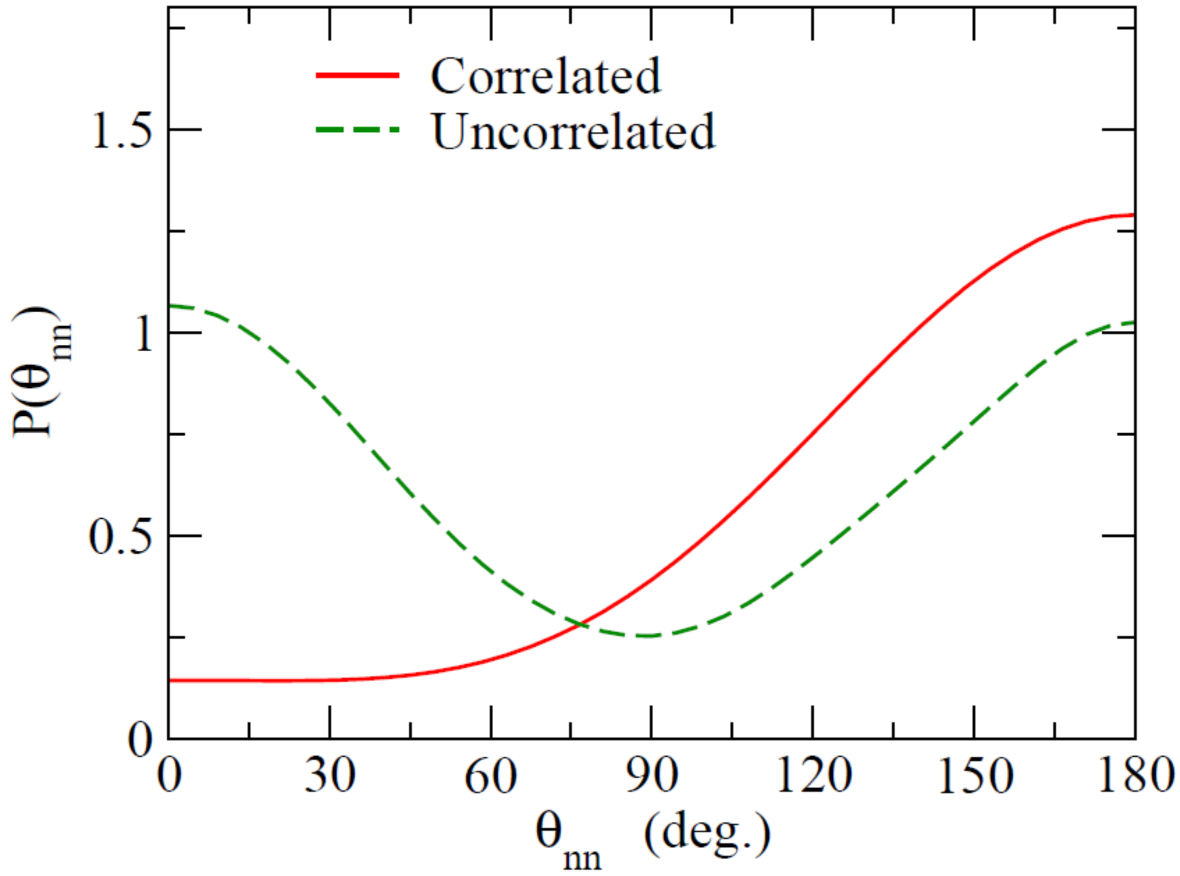
——— the g.s. of ^{25}F as the initial state

- - - - - - - pure $(1d_{3/2})^2$ for the initial state

$$\frac{dP}{dE} = \frac{1}{\pi}\mathrm{Im}\,\langle\Psi_i|G(E)|\Psi_i\rangle = \frac{1}{\pi}\mathrm{Im}\frac{\boxed{|\langle\Psi_{3\mathrm{b}}(E)|\Psi_i\rangle|^2}}{E_{3\mathrm{b}} - E - i\eta}$$

Angular correlation of the two emitted neutrons

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

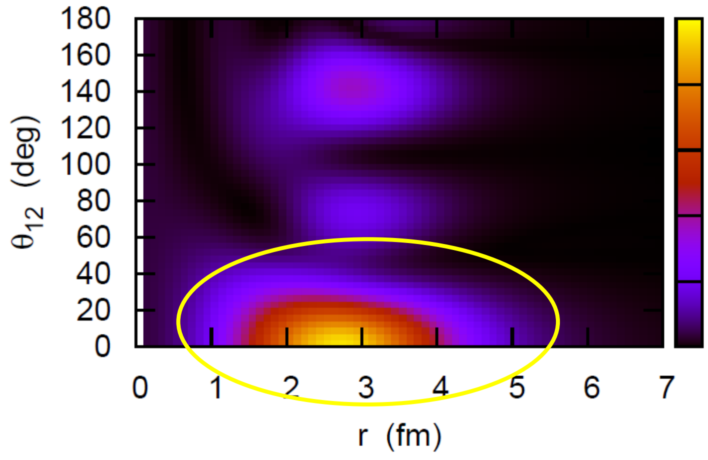


correlation → enhancement of back-to-back emissions

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

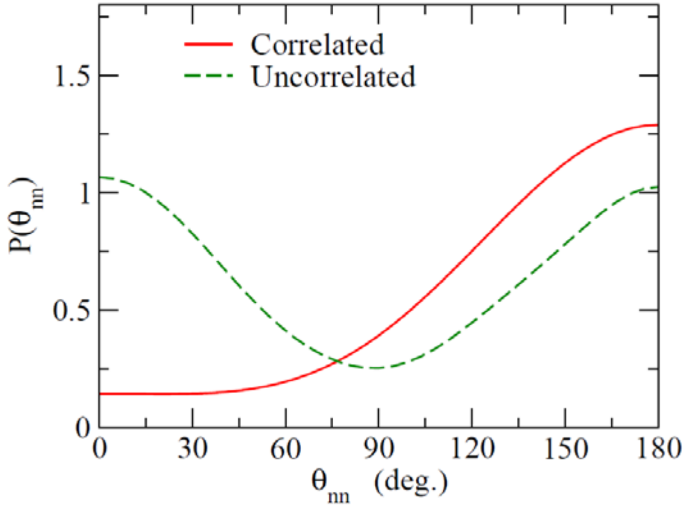
↔ dineutron correlation

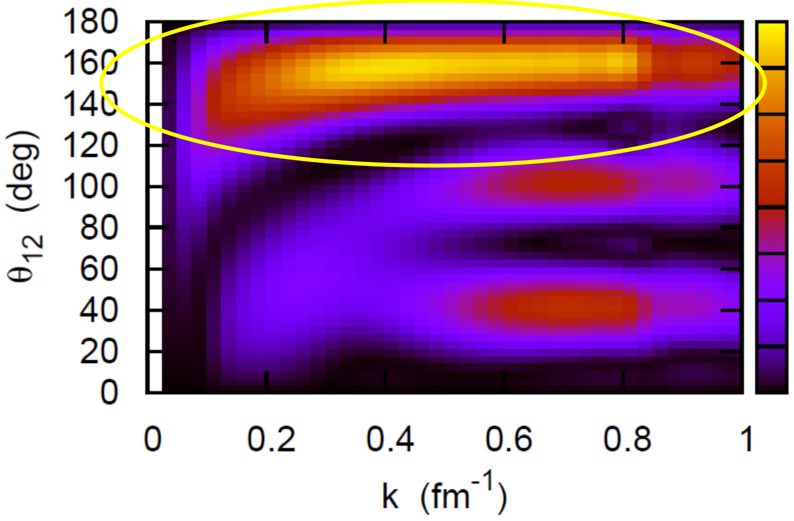
$$\Psi(\boldsymbol{r},\boldsymbol{r}') = \alpha\,\Psi_{s^2}(\boldsymbol{r},\boldsymbol{r}')\boxed{+\,\beta}\,\Psi_{p^2}(\boldsymbol{r},\boldsymbol{r}') \longrightarrow \theta_r = 0\text{: enhanced}$$

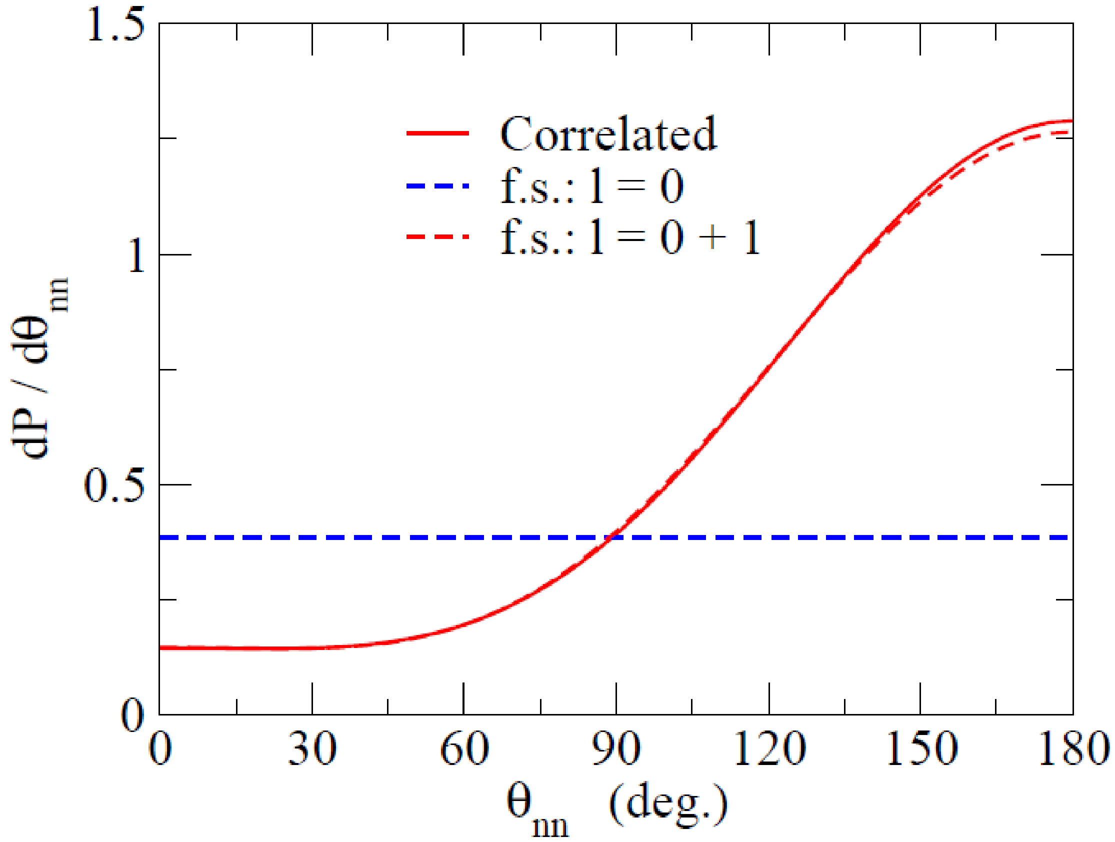


→ Fourier transform $e^{i\boldsymbol{k}\cdot\boldsymbol{r}} = \sum_l (2l+1)\, i^l \ldots.. \longrightarrow \underset{\overset{\uparrow}{r}}{i^l} \cdot \underset{\overset{\uparrow}{r'}}{i^l} = i^{2l} = (-)^l$

$$\tilde{\Psi}(\boldsymbol{k},\boldsymbol{k}') = \alpha\,\tilde{\Psi}_{s^2}(\boldsymbol{k},\boldsymbol{k}')\boxed{-\,\beta}\,\tilde{\Psi}_{p^2}(\boldsymbol{k},\boldsymbol{k}') \longrightarrow \theta_k = \pi\text{: enhanced}$$





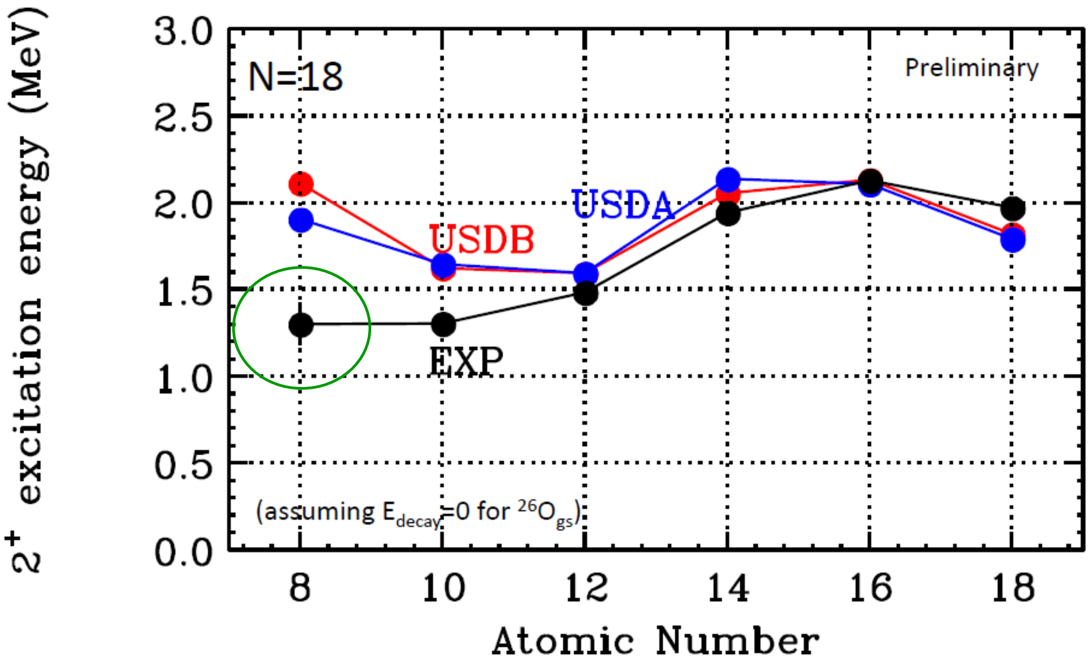


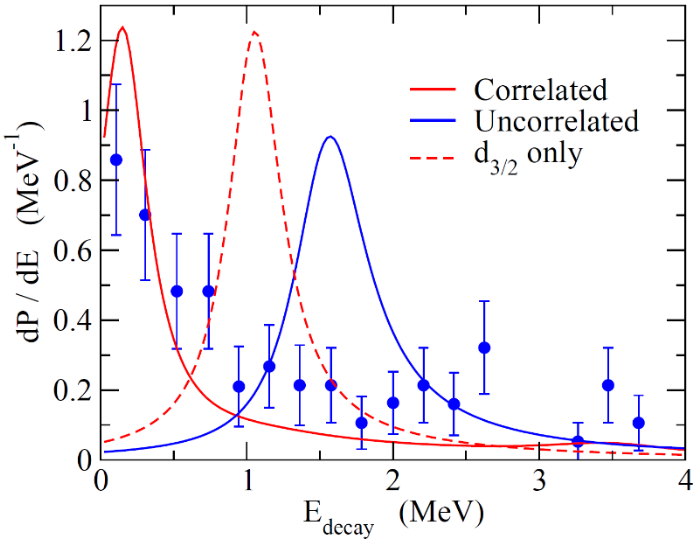
main contributions: *s*- and *p*-waves in three-body wave function (no or low centrifugal barrier)

*higher *l* components: largely suppressed due to the centrifugal pot. (E_{decay} ~ 0.14 MeV, e_1 ~ e_2 ~ 0.07 MeV)

2^+ state in ^{26}O

Kondo et al. : a prominent second peak at *E* ~ 1.3 MeV





cf. MSU data

Courtesy: Y. Kondo

cf. sdpf-m: E_{2+} = 2.62 MeV (Y. Utsuno) [according to Suzuki-san]

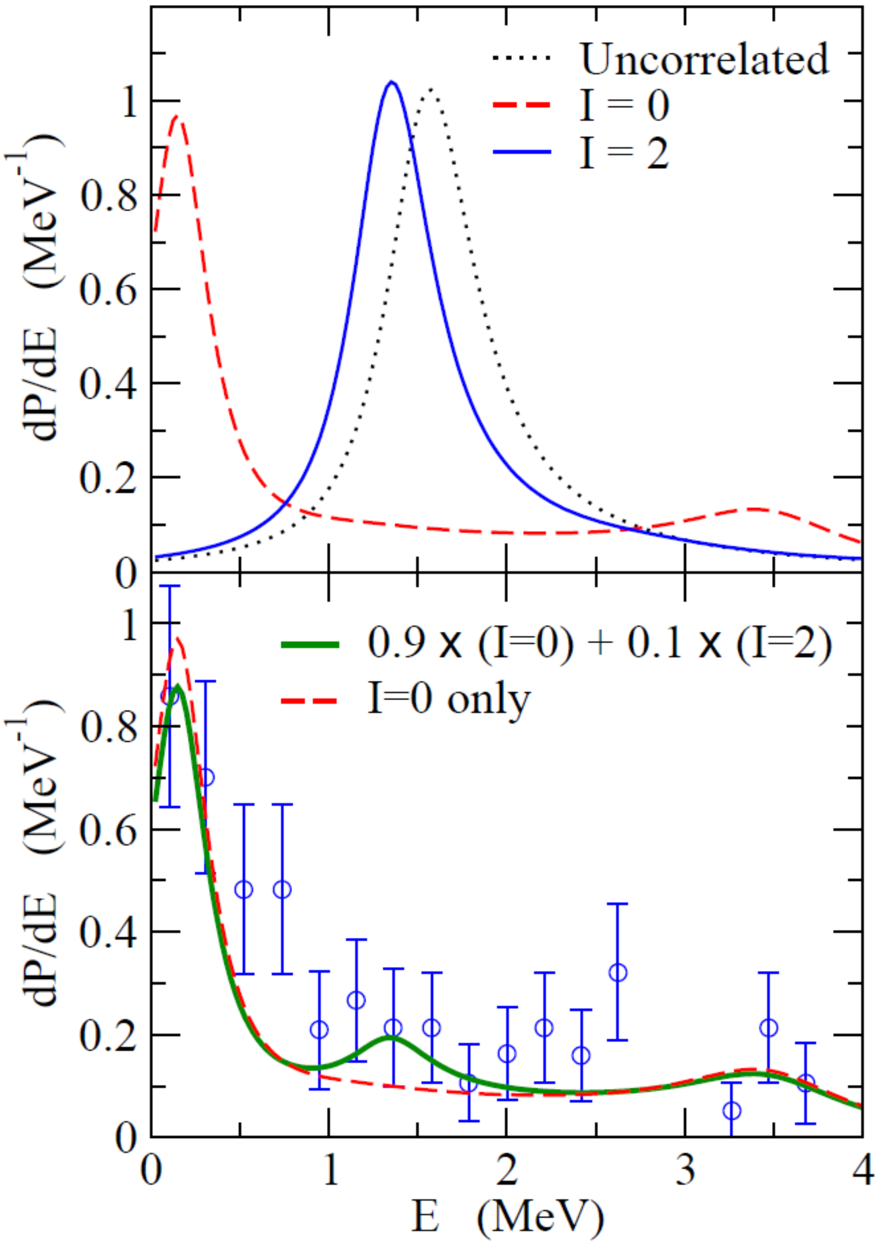
ab-initio calc. with chiral NN+3N: E_{2+} = 1.6 MeV

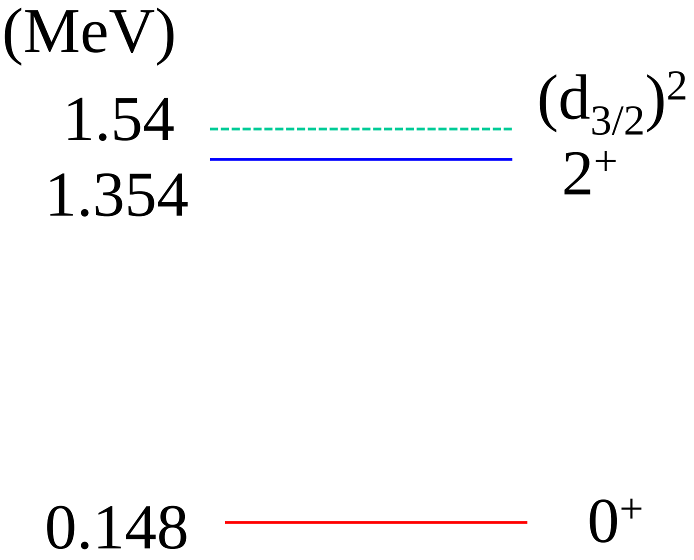
(C. Caesar et al., PRC88('13)034313)

continuum shell model: E_{2+} = 1.8 MeV

(A. Volya and V. Zelvinsky, PRC74 ('14) 064314)

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




(MeV)

1.54 $(d_{3/2})^2$

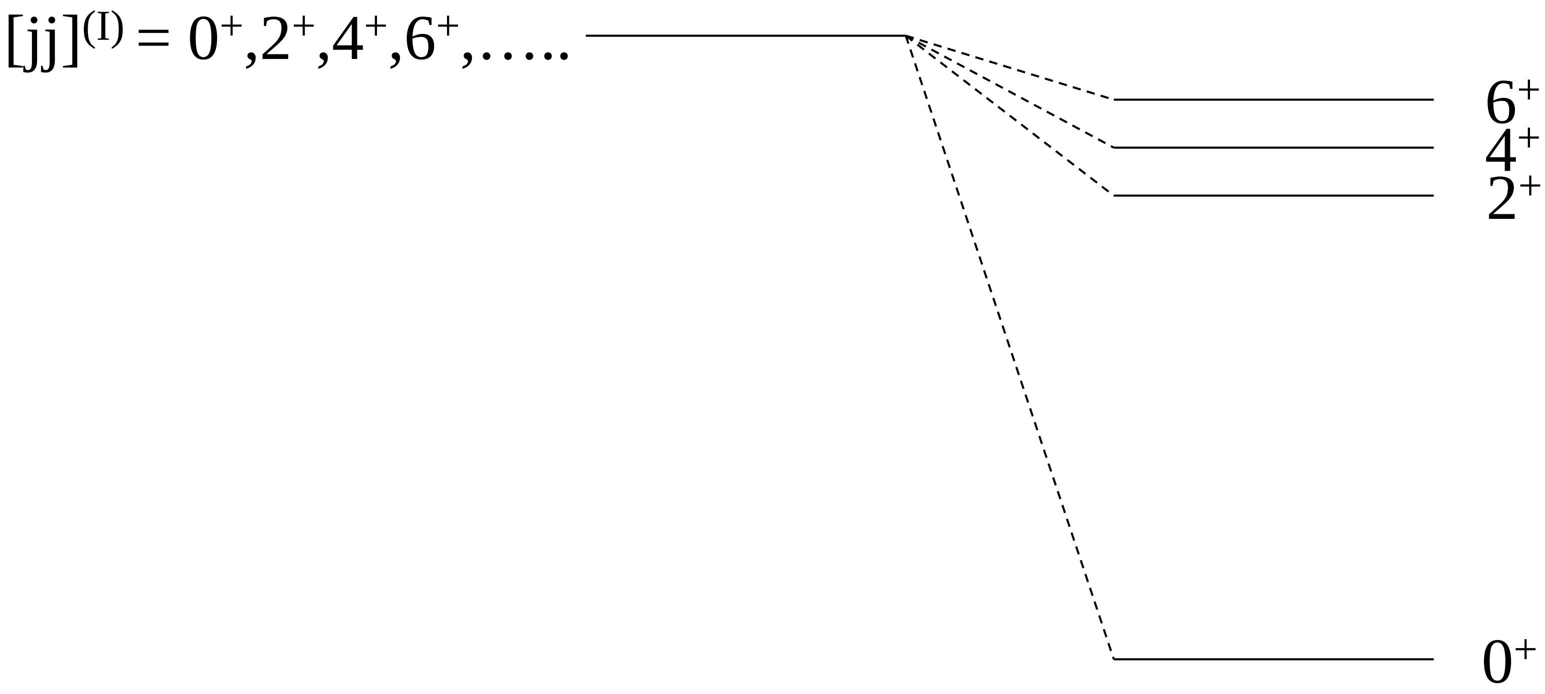
1.354 2^+

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,
PRC90('14)027303



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

6^+

4^+

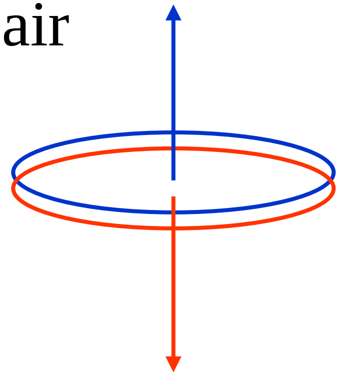
2^+

0^+

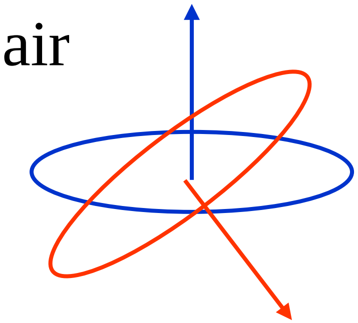
without residual interaction

with residual interaction

I=0 pair



$I \neq 0$ pair



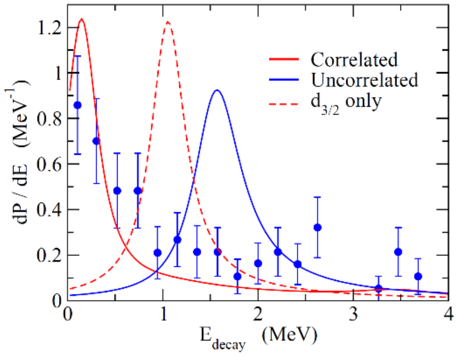
	^{25}O (3/2^{+})	**^{26}O (2^{+})**
Experiment	+ 770^{+20}_{-10} keV	~ 1.3 MeV
USDA	1301 keV	1.9 MeV
USDB	1303 keV	2.1 MeV
sdpf-m (Utsuno)	?	2.6 MeV
chiral NN+3N	742 keV	1.6 MeV
continuum SM (Volya-Zelevinsky)	1002 keV	1.8 MeV
3-body model (Hagino-Sagawa)	770 keV (input)	1.354 MeV

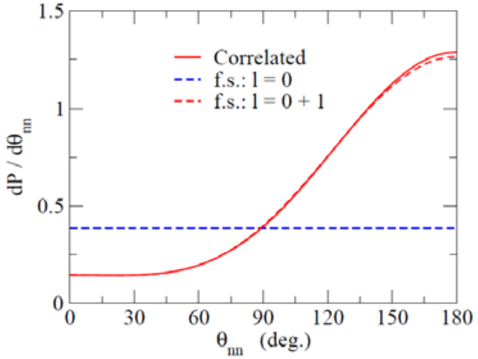
Summary

2n emission decay of ^{26}O ⟵ three-body model with density-dependent zero-range interaction: continuum calculations: relatively easy

- ✓ Decay energy spectrum: strong low-energy peak
- ✓ Energy distribution of 2 neutrons: three-body resonance
- ✓ 2^+ energy
- ✓ Angular distributions: enhanced back-to-back emission

⟷ dineutron emission





□ open problems

- ✓ Analyses for ^{16}Be, ^{13}Li (especially angular distributions)
- ✓ Decay width?