Beyond the neutron-drip line
~ two-neutron decay of unbound nuclei ~

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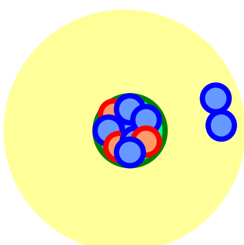
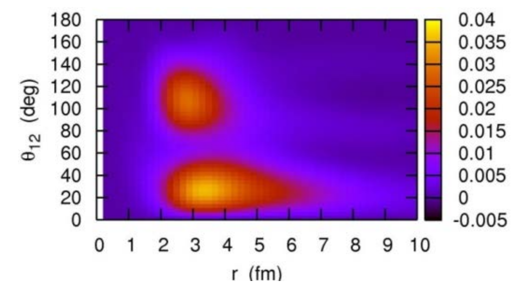
RIKEN/ University of Aizu





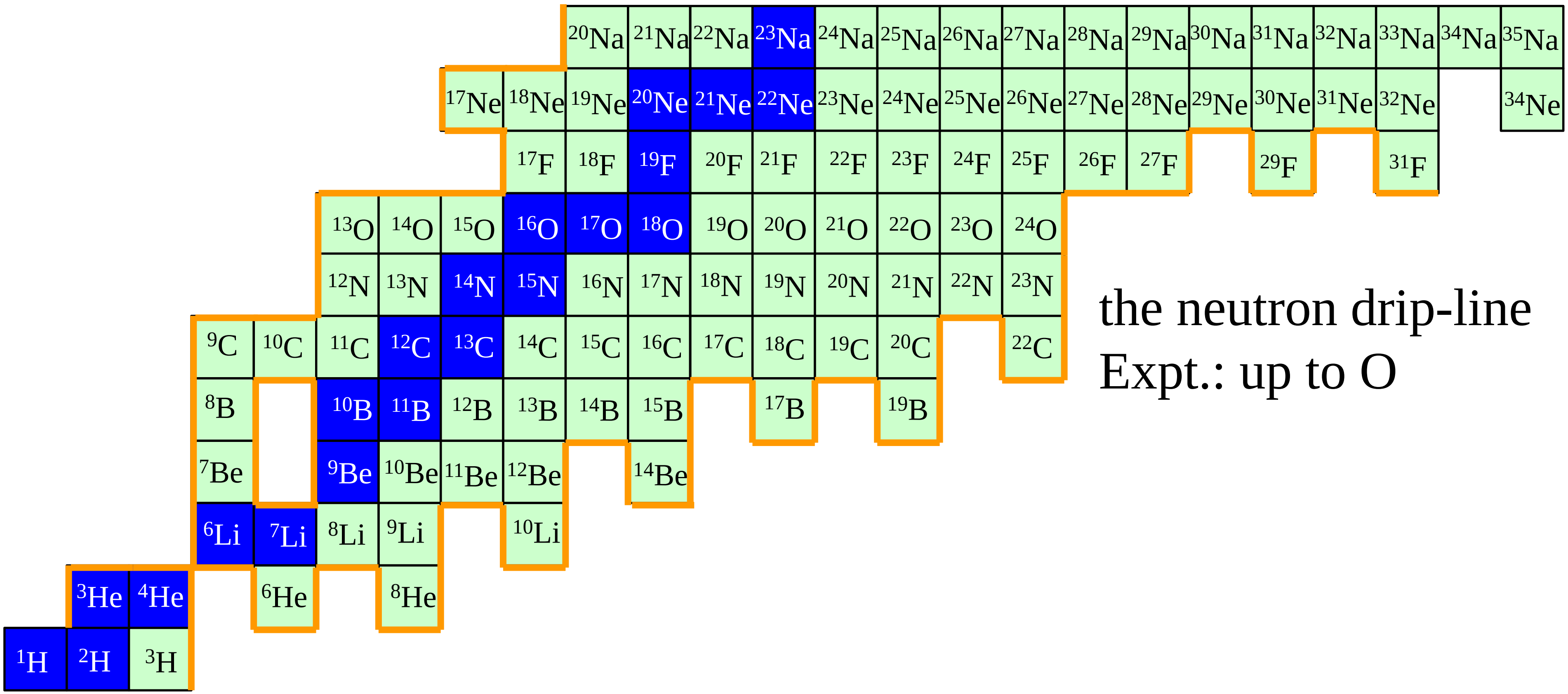
1. Three-body model analysis for decay of ^{26}O
2. Application to ^{10}He
3. Summary and future perspectives

Ito Int. Research Center Symp. “Perspectives of the Physics of Nuclear Structure” Nov. 1-4, 2017, U of Tokyo

Introduction

An important question in physics of unstable nuclei:

where are the neutron- and proton- drip lines located?



Introduction

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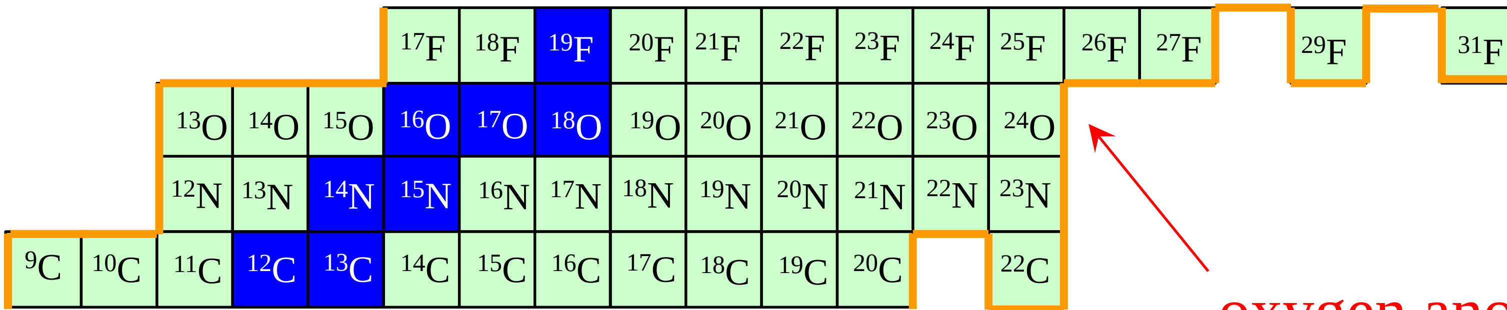
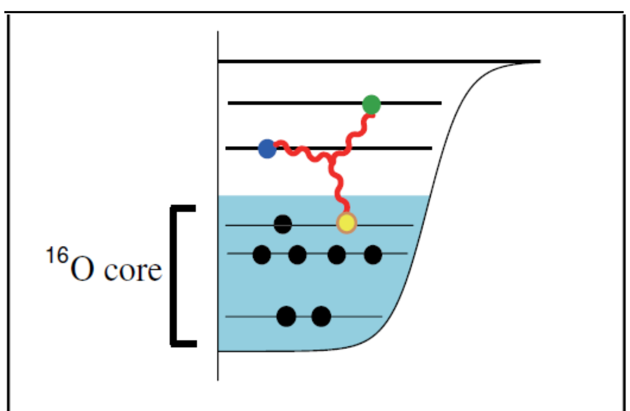
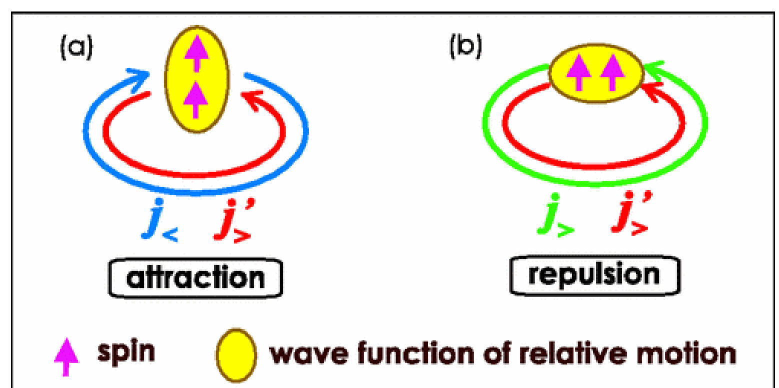


oxygen anomaly

why at N=16 for O
while N $\geqq$ 22 for F?

T. Otsuka et al.,
PRL95 (‘05) 232502, PRL105 (‘10) 032501
Effects of three-body and tensor forces





Introduction

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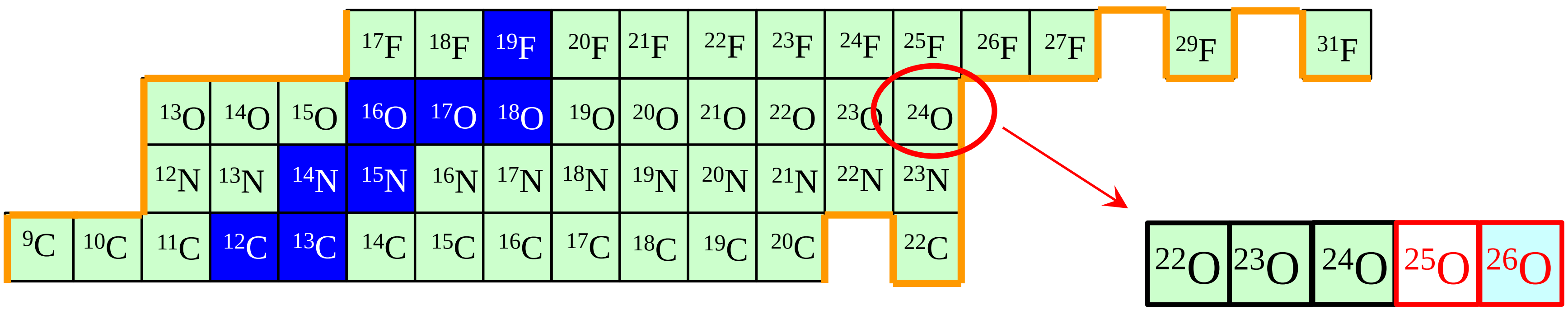


$$^{26}\mathrm{O} \rightarrow {}^{24}\mathrm{O} + n + n$$

My talk today:

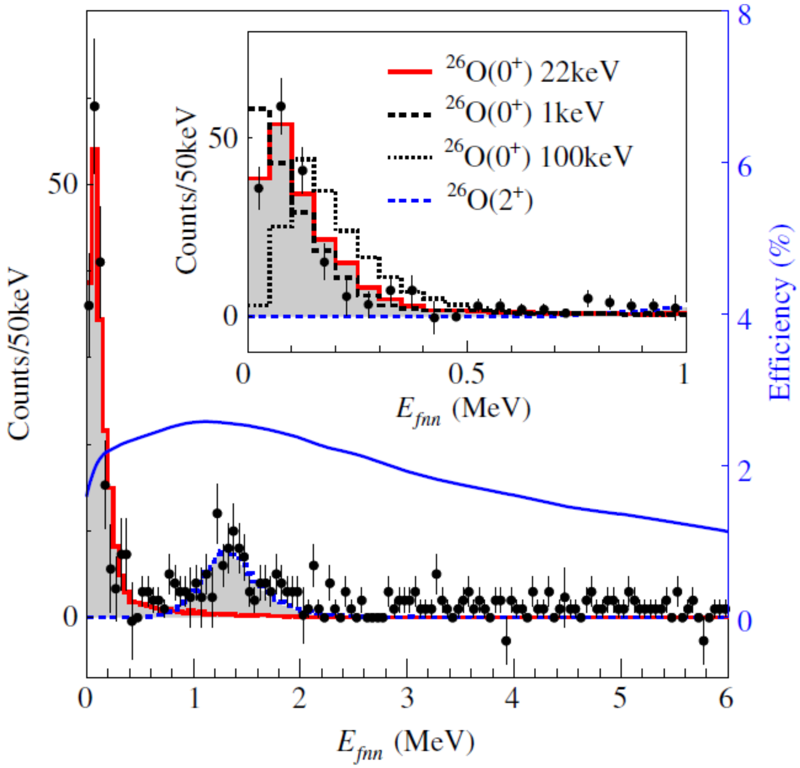
Decay dynamics of the unbound ^{26}O nucleus

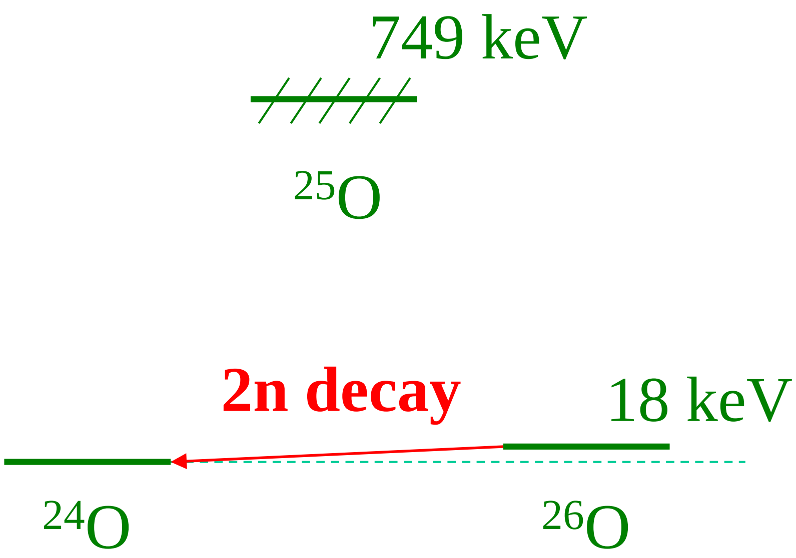
role of nn correlation?

Experimental data for decay spectrum

Expt. : $^{27}F \rightarrow {}^{26}O \rightarrow {}^{24}O + n + n$

- MSU: E. Lunderberg et al., PRL108 ('12) 142503
- GSI: C. Caesar et al., PRC88 ('13) 034313
- RIKEN: Y. Kondo et al., PRL116('16)102503



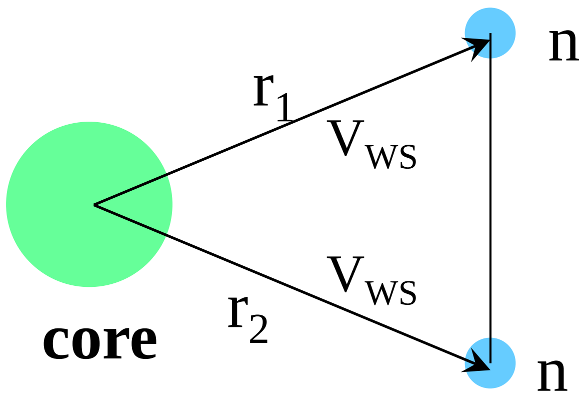


Y. Kondo et al., PRL116('16)102503 $\longrightarrow$ $E_{\rm decay}(^{26}{\rm O}) = 18 \pm 3 \pm 4$ keV

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

<u>core + n + n model</u> with density dependent contact *nn* interaction

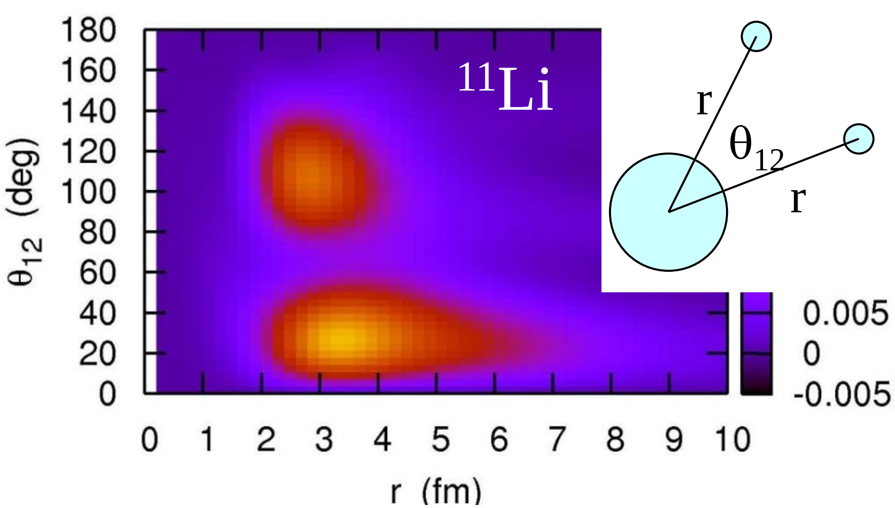
G.F. Bertsch and H. Esbensen, Ann. of Phys. 209 ('91) 327
K.H. and H. Sagawa, PRC72 ('05) 044321

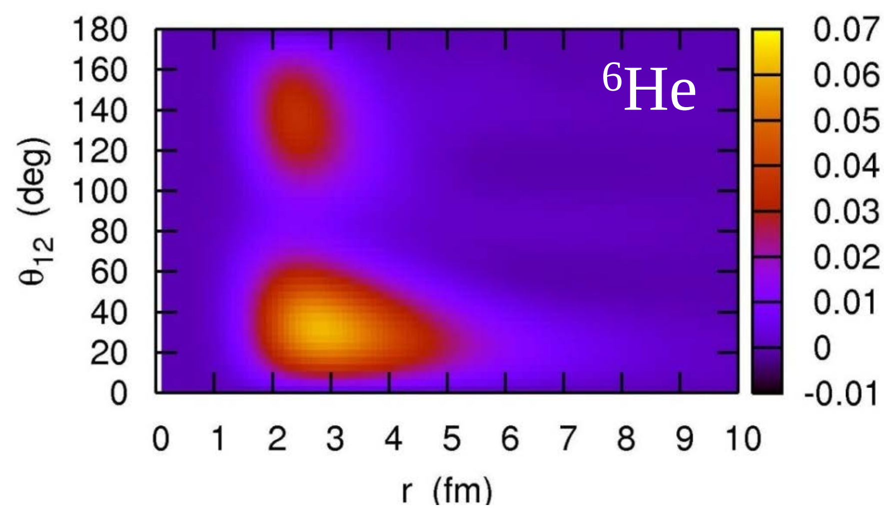


Density-dependent delta-force

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

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

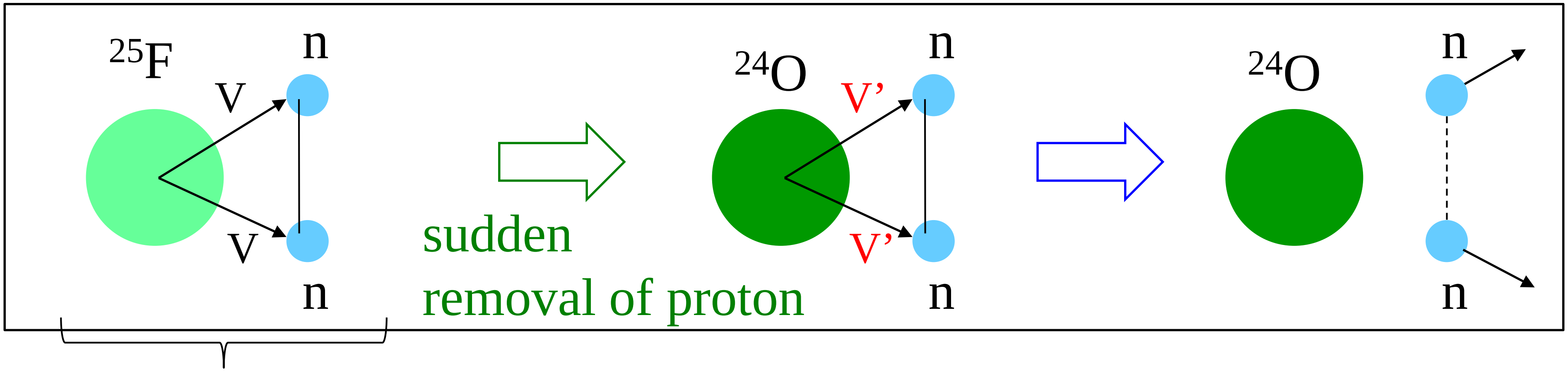




3-body model analysis for ^{26}O decay

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

cf. Expt. : $^{27}\mathrm{F} + {}^{9}\mathrm{Be} \to {}^{26}\mathrm{O} \to {}^{24}\mathrm{O} + n + n$



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

$\underline{\Psi_{nn}(^{27}\mathrm{F})} \otimes |^{25}\mathrm{F}\rangle \Rightarrow \underline{\Psi_{nn}(^{27}\mathrm{F})} \otimes |^{24}\mathrm{O}\rangle \Rightarrow$ spontaneous decay

→ the same config. (the reference state)

$$\frac{dP}{dE} = |\langle \Psi_{nn}(^{27}\mathrm{F}) | \Psi_{nn}(^{26}\mathrm{O}; E)\rangle|^2$$

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

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

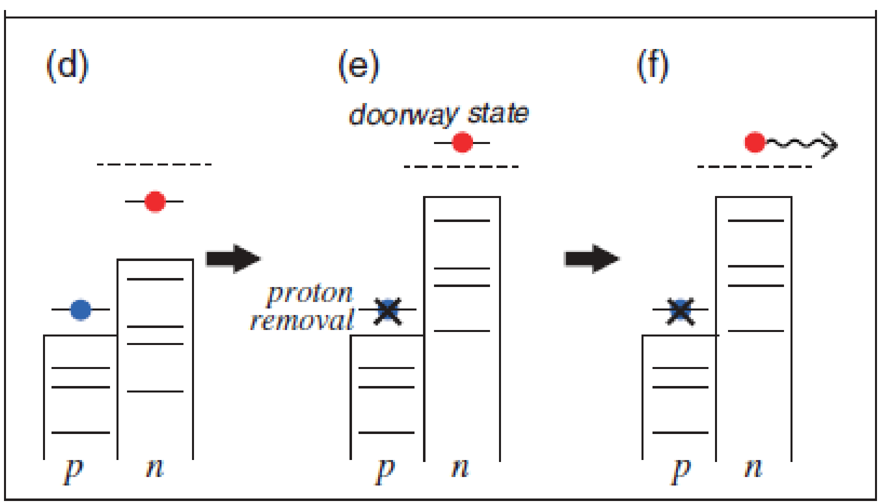
$$\Psi_{nn}(^{27}\mathrm{F}) \otimes |^{25}\mathrm{F}\rangle \Rightarrow \Psi_{nn}(^{27}\mathrm{F}) \otimes |^{24}\mathrm{O}\rangle \Rightarrow$$

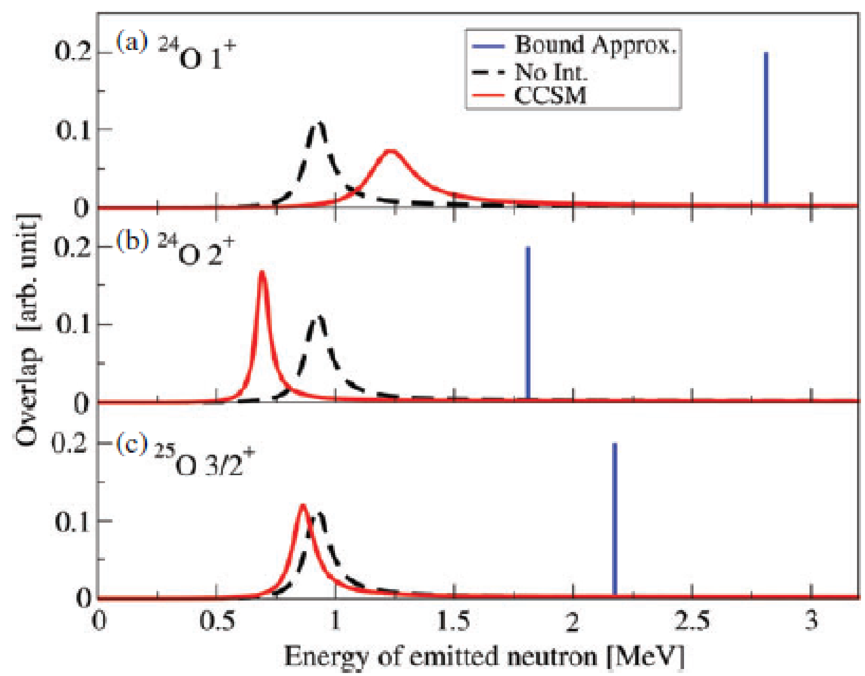
spontaneous decay

$$\frac{dP}{dE} = |\langle \Psi_{nn}(^{27}\mathrm{F}) | \Psi_{nn}(^{26}\mathrm{O}; E)\rangle|^2$$

cf. Door-way state approach

K. Tsukiyama, T. Otsuka, and R. Fujimoto, PTEP 2015, 093D01





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

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

$$\Psi_{nn}(^{27}\mathrm{F}) \otimes |^{25}\mathrm{F}\rangle \Rightarrow \Psi_{nn}(^{27}\mathrm{F}) \otimes |^{24}\mathrm{O}\rangle \Rightarrow$$ spontaneous decay

$$\frac{dP}{dE} = |\langle \Psi_{nn}(^{27}\mathrm{F})|\Psi_{nn}(^{26}\mathrm{O}; E)\rangle|^2$$

- Green's function method

$$\frac{dP}{dE} = \int dE' |\langle \Psi_{E'}|\Phi_{\mathrm{ref}}\rangle|^2 \,\delta(E-E') = \frac{1}{\pi}\Im\langle\Phi_{\mathrm{ref}}|\frac{1}{H-E-i\eta}|\Phi_{\mathrm{ref}}\rangle$$

$= G(E)$

Correlated Green's function: continuum effects

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

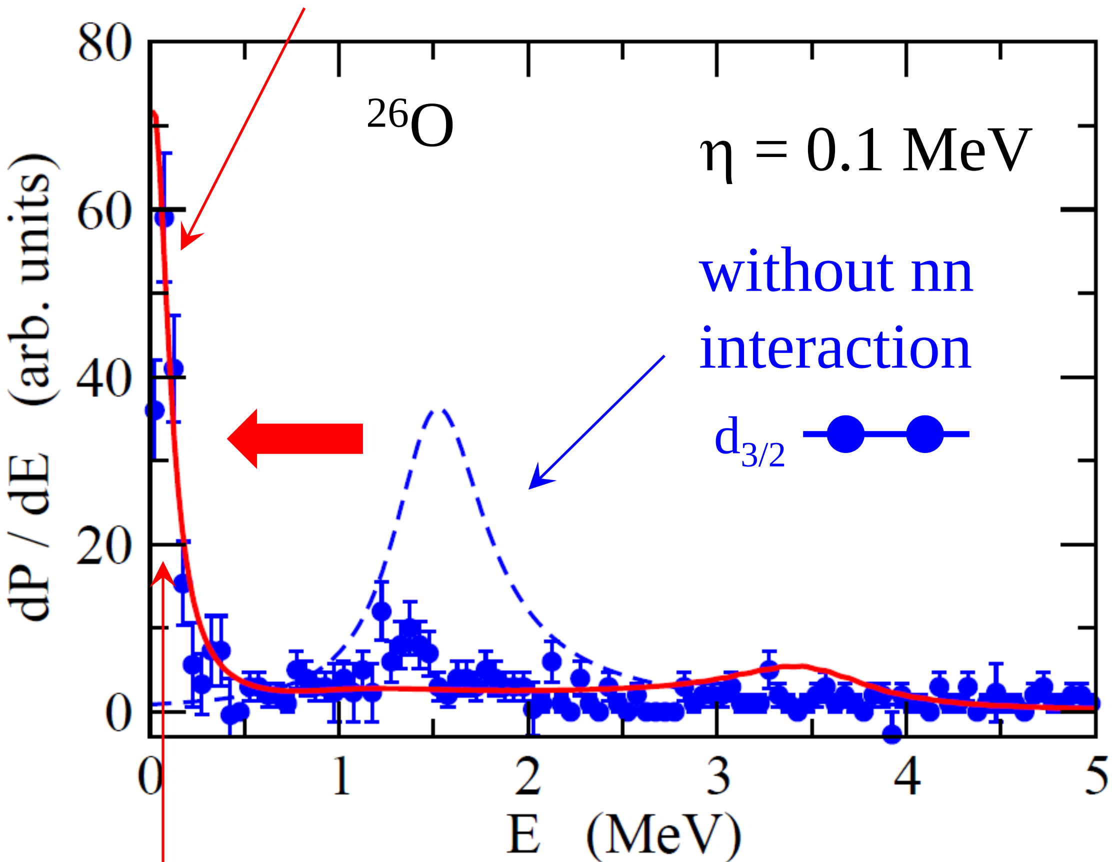
$\longleftarrow$ zero-range interaction

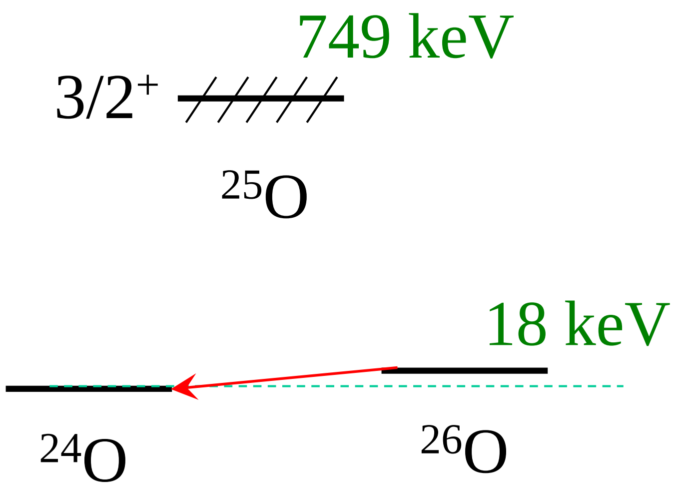
Decay energy spectrum

$$|\Phi_{\rm ref}\rangle = \left|[1d_{3/2}]^2\right\rangle \text{ in } {}^{27}\text{F}$$

K.H. and H. Sagawa,
- PRC89 (‘14) 014331
- PRC93(‘16)034330

with nn interaction





$E_{\rm peak}$ = 18 keV (input)

Data: Y. Kondo et al., PRL116(’16)102503

Decay energy spectrum

$|\Phi_{\mathrm{ref}}\rangle = \left|[1d_{3/2}]^2\right\rangle$ in ^{27}F

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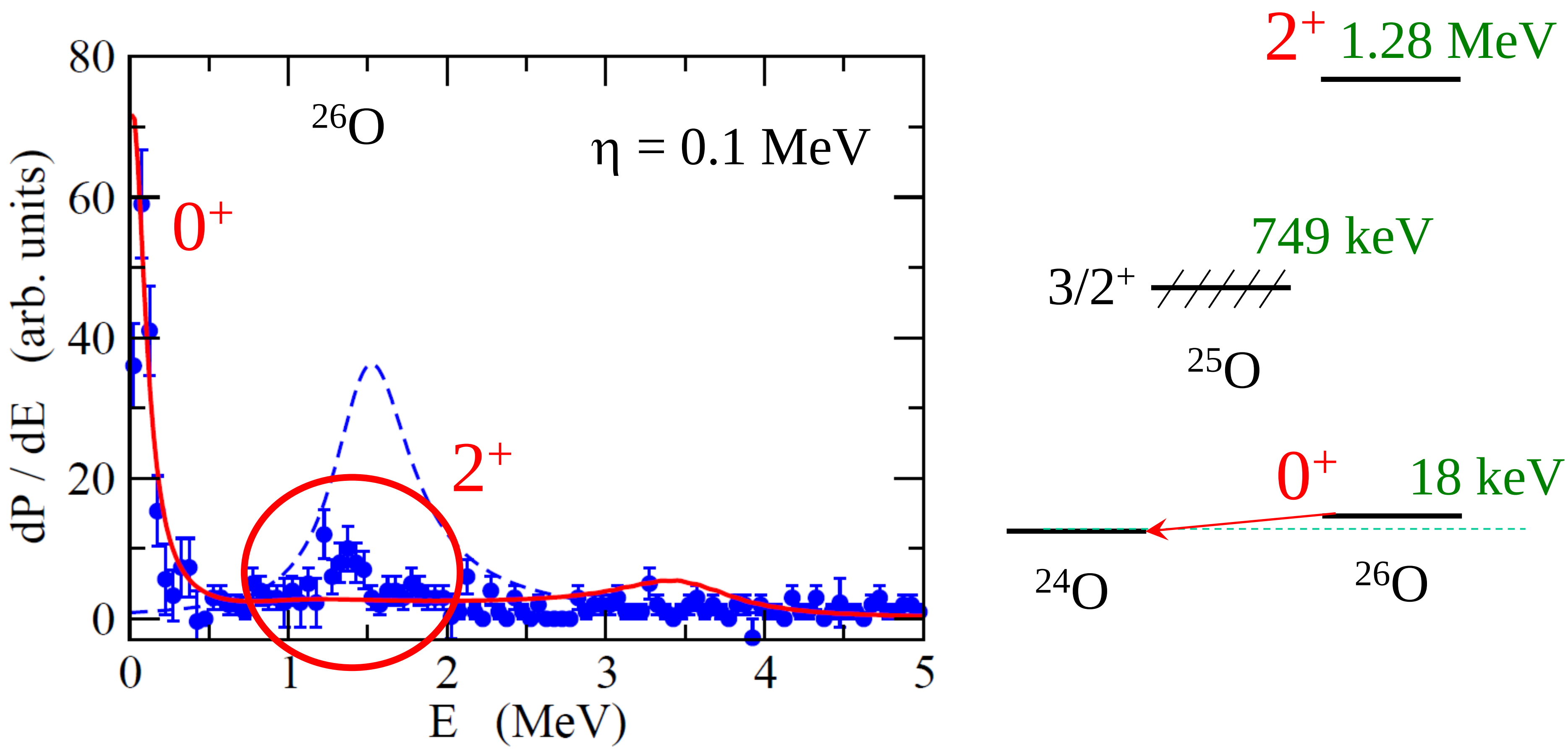


a prominent second peak
at $E = 1.28^{+0.11}_{-0.08}$ MeV

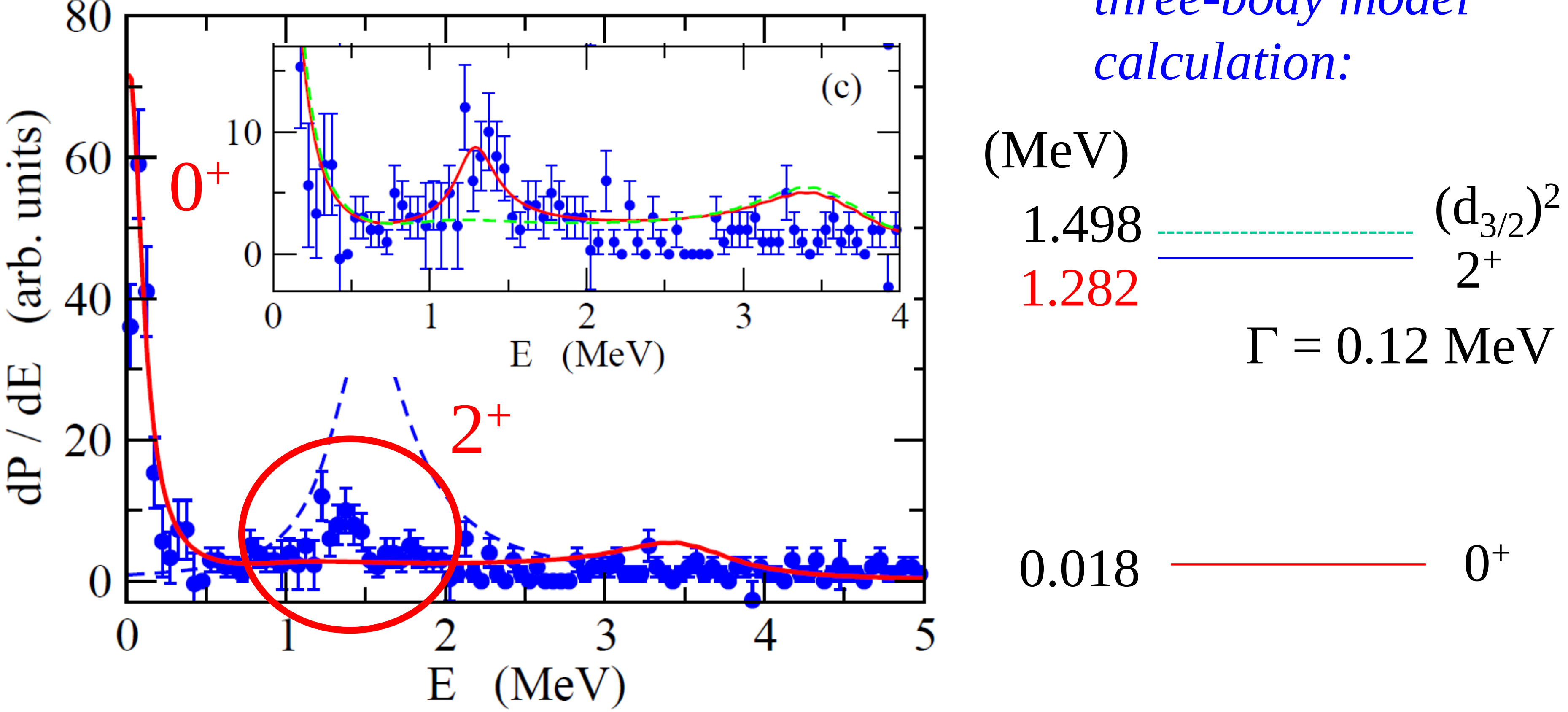
Data: Y. Kondo et al., PRL116('16)102503

Decay energy spectrum

$$|\Phi_{\text{ref}}\rangle = \left|[1d_{3/2}]^2\right\rangle \text{ in } {}^{27}\text{F}$$

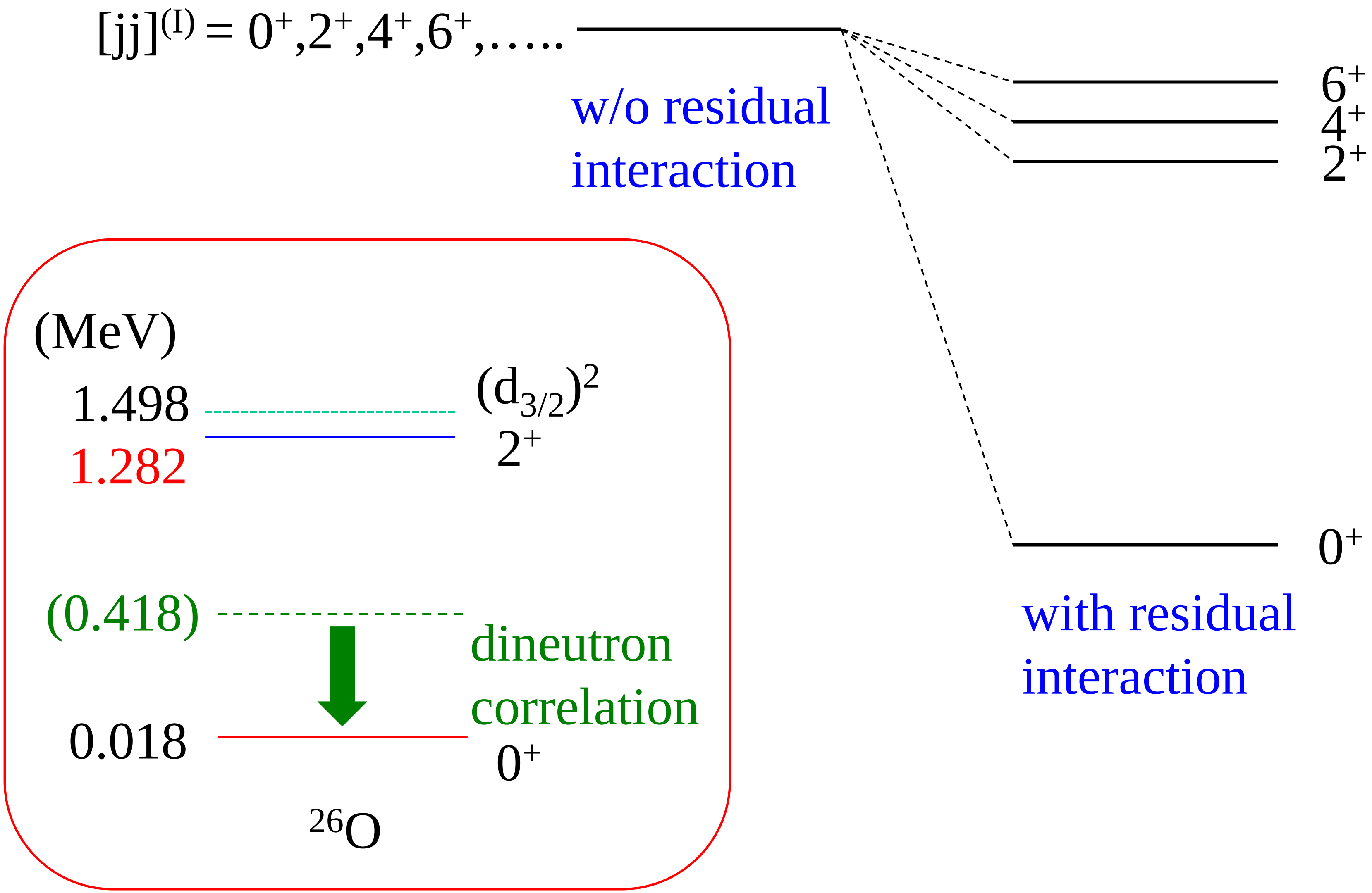
K.H. and H. Sagawa,
- PRC89 ('14) 014331
- PRC93('16)034330

three-body model calculation:



a prominent second peak
at $E = 1.28\ ^{+0.11}_{-0.08}$ MeV

Data: Y. Kondo et al., PRL116('16)102503 a textbook example of pairing interaction!

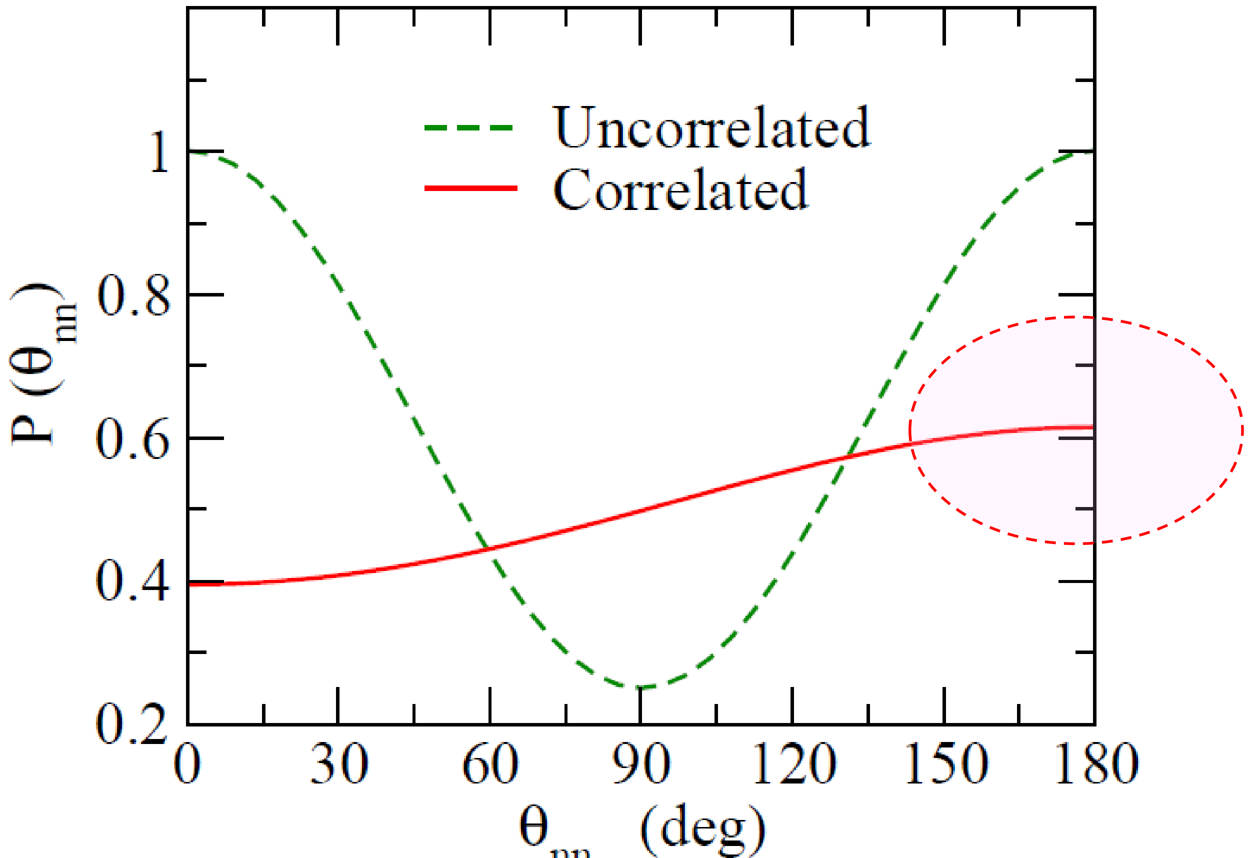


cf. Gamow shell model: similar result
S.M. Wang et al., PRC96 (‘17) 044307

Angular correlation of two emitted neutrons

$$P(\theta) \sim |\langle \boldsymbol{k}_1 \boldsymbol{k}_2 | \Psi_{\rm 3bd}(E)\rangle|^2$$

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

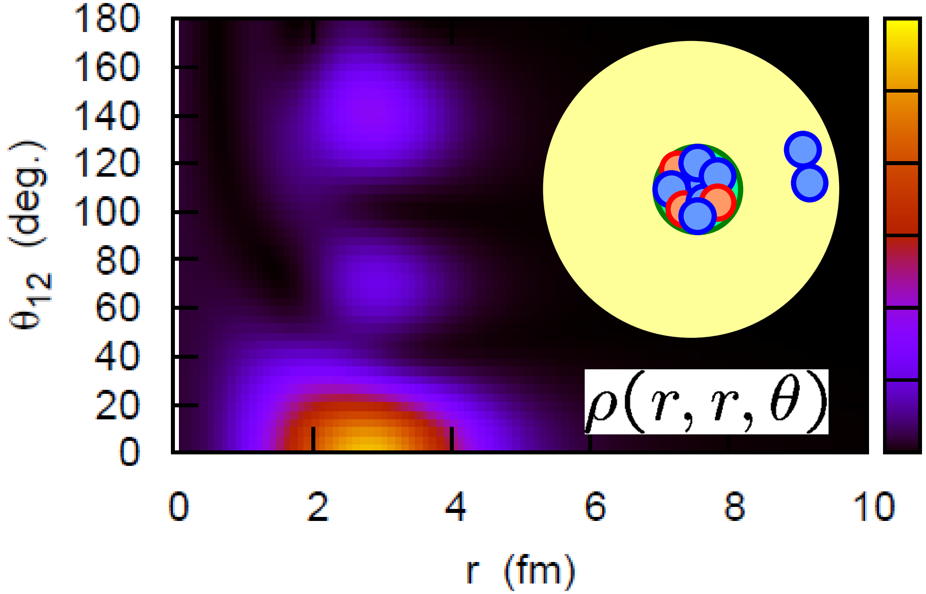


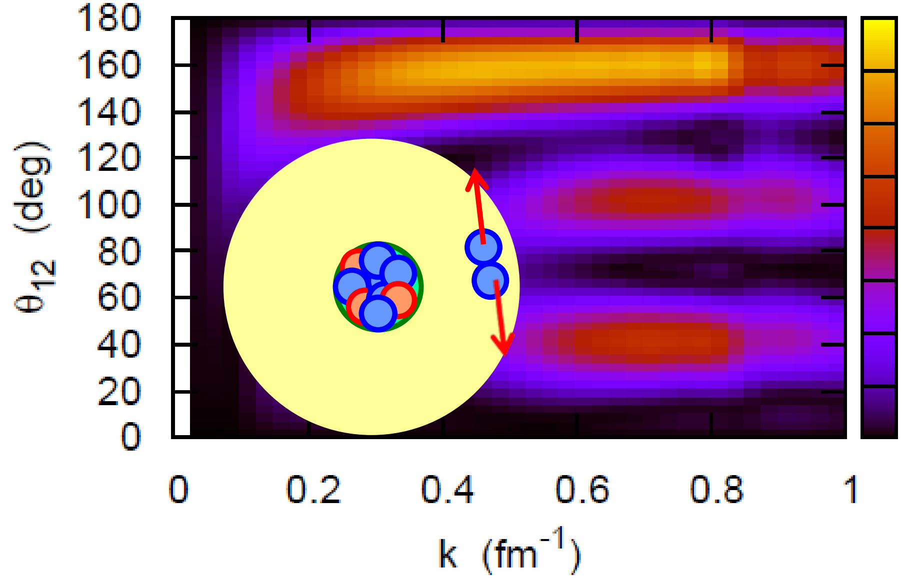
correlation → enhancement of back-to-back emissions

Di-neutron correlation

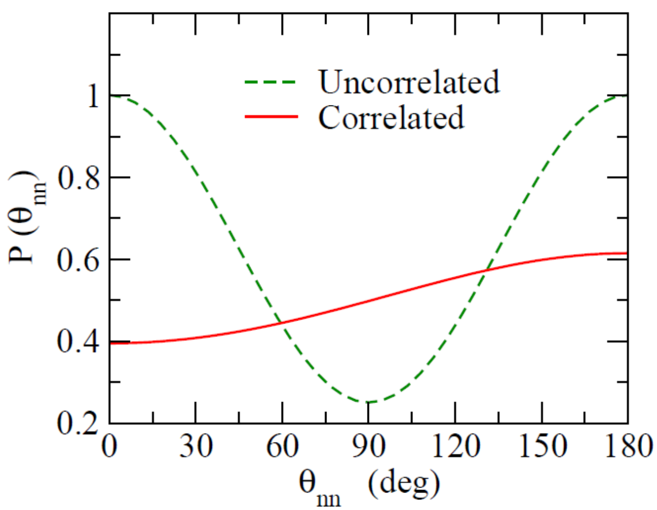
^{26}O in a large box

spatially compact pair → large relative momentum





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



enhancement of back-back emission
→ a clear evidence for di-neutron correlation

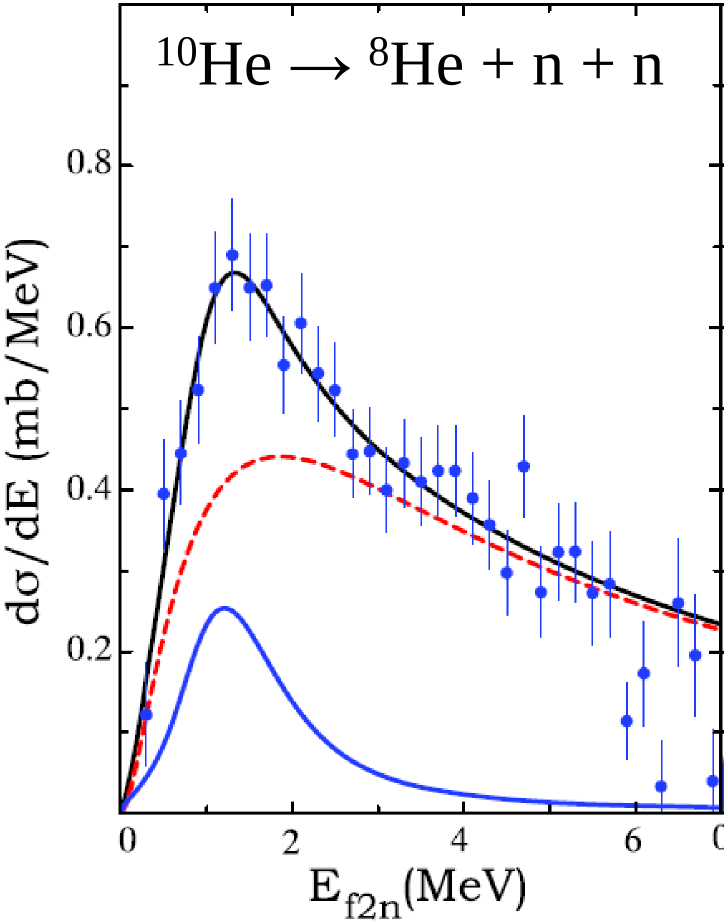
Application to ^{10}He decay

GSI Expt. : $^{11}Li \rightarrow {}^{10}He \rightarrow {}^{8}He + n + n$ (H.T. Johansson et al., NPA842 ('10)15)

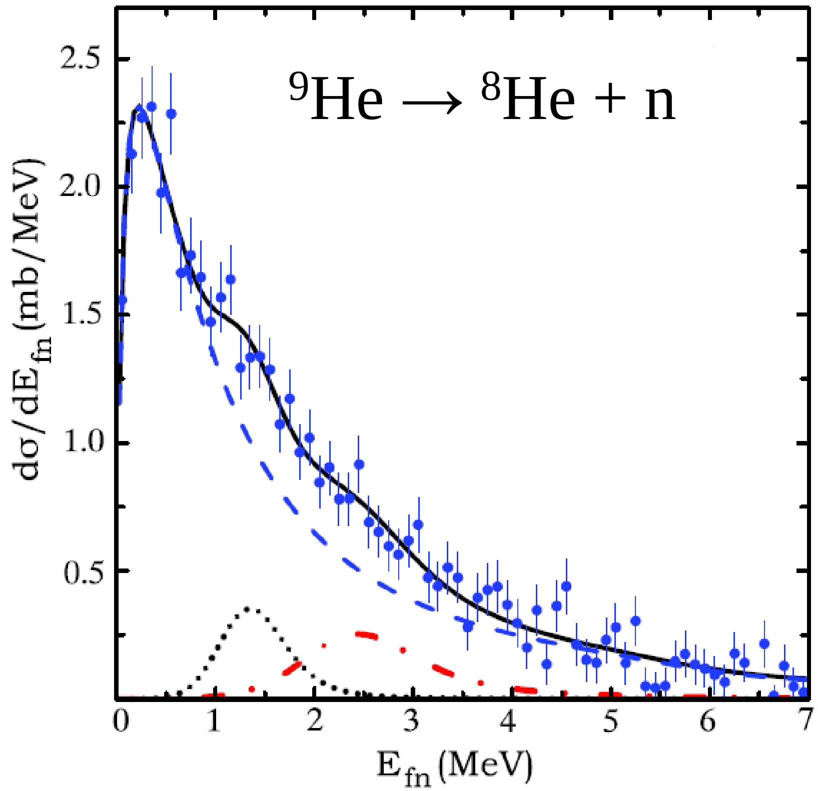
cf. A.A. Korsheninnikov et al., PLB326 ('94) 31

three-body model:

$^{8}He\ [(s_{1/2})^2,(p_{3/2})^4] + n + n$



H.T. Johansson et al., NPA847 ('10) 66

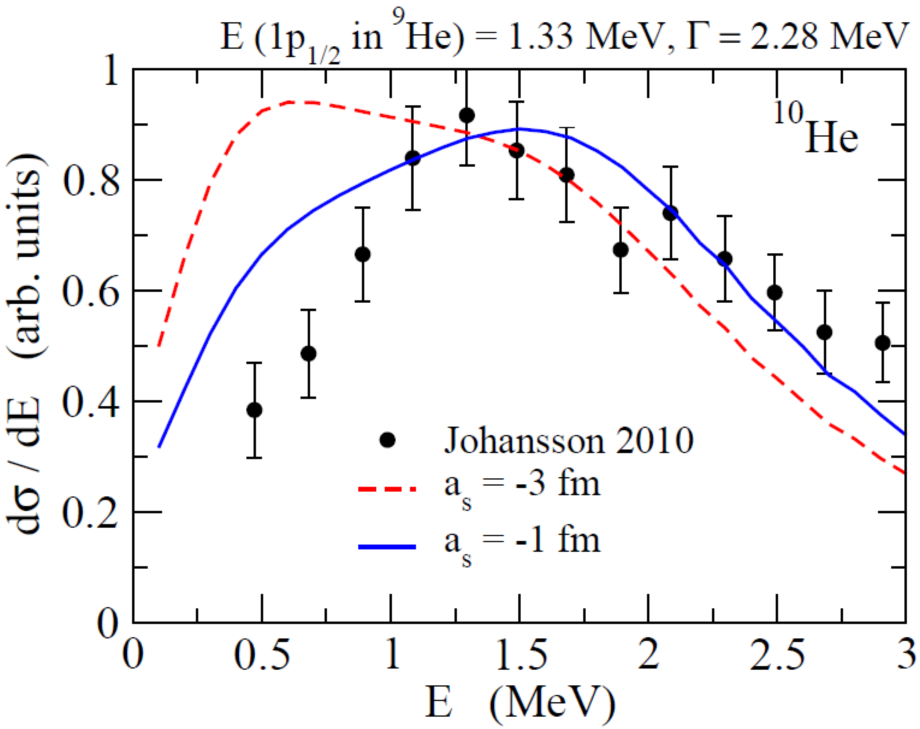


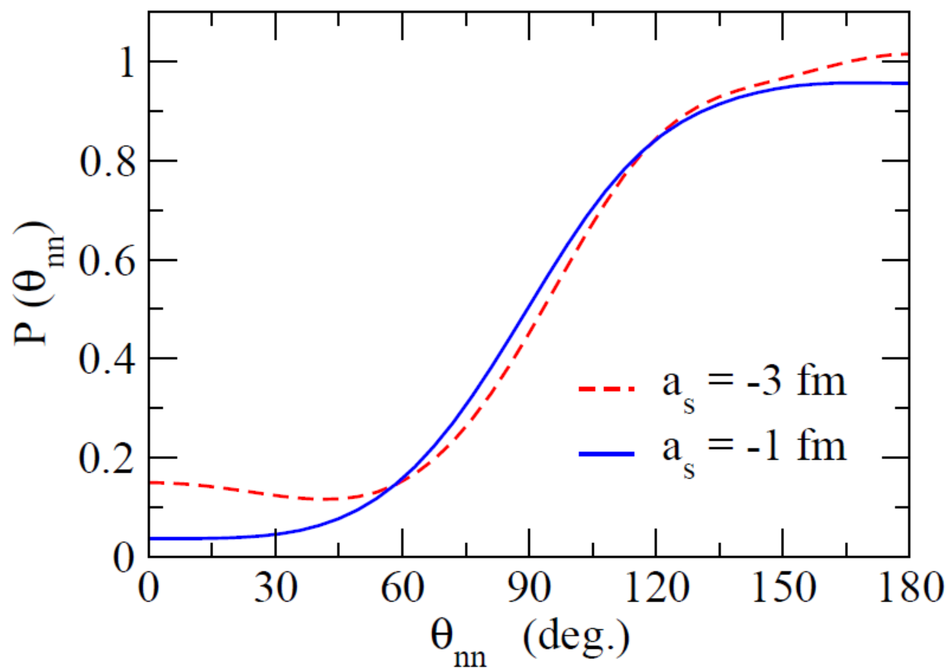
H.T. Johansson et al., NPA842 ('10) 15

Application to ^{10}He decay

three-body model: ^{8}He $[(s_{1/2})^2,(p_{3/2})^4]$ + n + n

ref. state ^{11}Li (g.s.) K.H. and H. Sagawa, PRC72('05)





cf. H.T. Johansson et al., NPA842 ('10) 15

a_s (^{8}He-n) = -3.17(66) fm

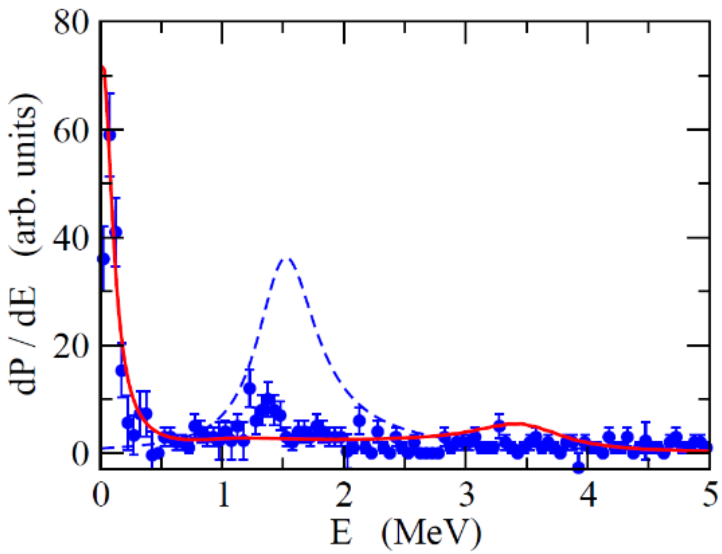
$1/2^-$ (^{9}He) : E=1.33 MeV, Γ=0.1 MeV

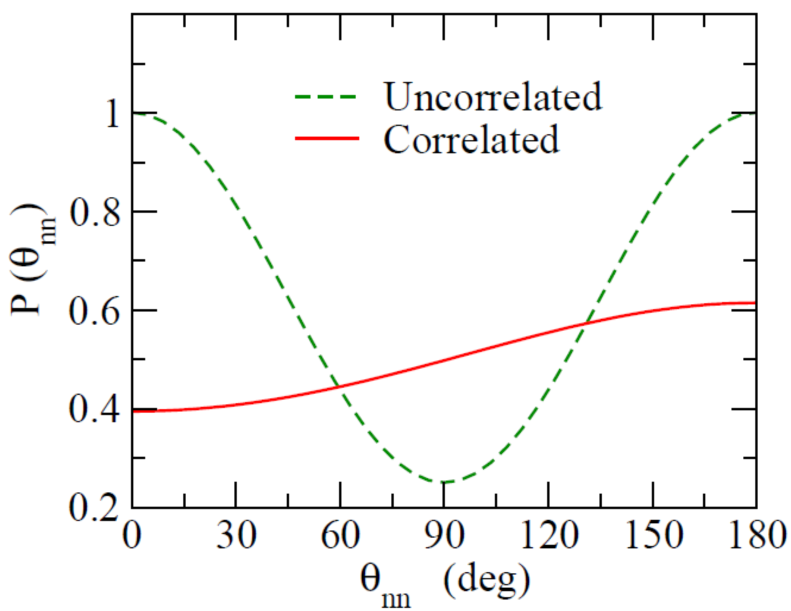
enhancement of
back-to-back
as in the decay of ^{26}O

Summary

- 2n emission decay of ^{26}O ← three-body model
  - ✓ Decay energy spectrum: strong low-energy peak
  - ✓ 2^+ energy: excellent agreement with the data
  - ✓ Angular distributions: enhanced back-to-back emission

    ⟷ dineutron correlation



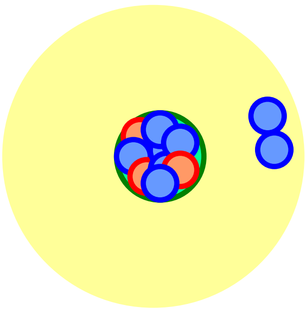


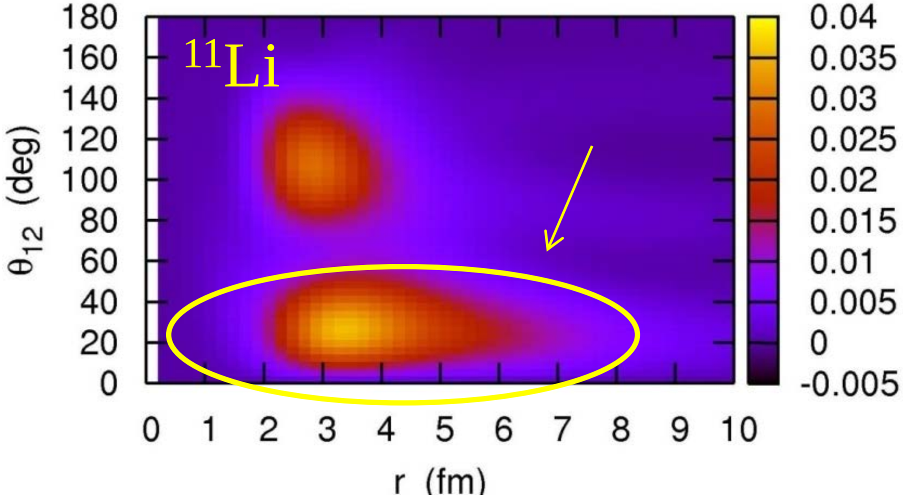
- application to 2n decay of ^{10}He

Future perspectives

Decay of unbound nuclei beyond the drip lines

….as a probe for di-neutron correlations inside nuclei





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

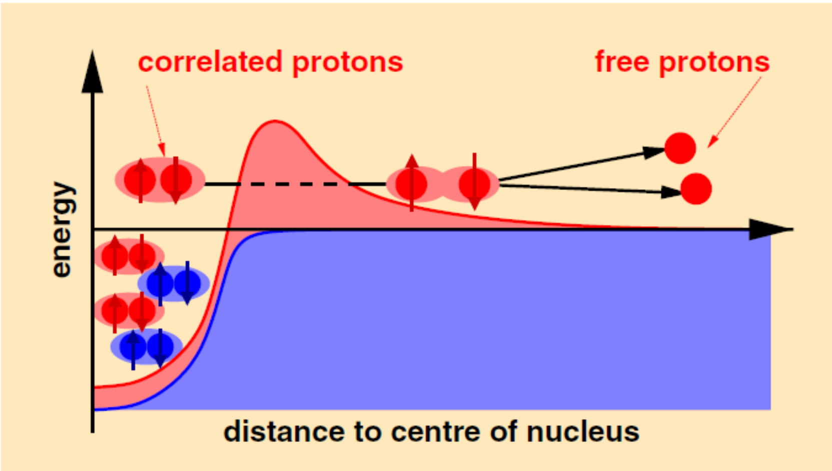
How to probe it?

- Coulomb breakup
  - ✓ disturbance due to E1 field
  - ✓ cluster sum rule (the mean value of θ_{nn})
- pair transfer reactions
- two-proton decays
- two-neutron decays

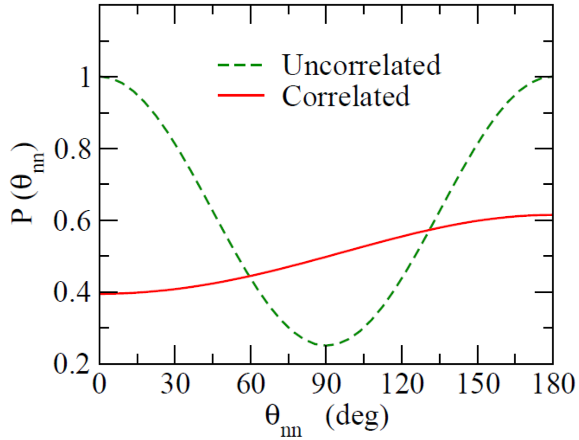
spontaneous emission without a disturbance

Future perspectives

2n decay of unbound nuclei



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



back-to-back emission

Can correlations be probed?

- 2p emission: long range Coulomb
- 2n emission: only centrifugal

Experimental challenges

- ✓ measurement of ang. corr.
- ✓ spin measurement

Theoretical challenges

- ✓ core deformation (^{16}Be)
- ✓ 3-body to 5- and 7-body

  core+4n (^{13}Li)
  core+6n (^{10}He)

- ✓ 4n emission (^{28}O)