Three-body model study of unbound nucleus $^{26}\text{O}$
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1. di-neutron correlation and three-body model approach
2. Nuclei beyond drip line and 2n-decay
3. Summary and future perspectives
Exotic structure close to drip lines

- Halo, Giant halo/skin structure
- Shell evolution
- Di-neutron and di-proton correlations
- Shape evolution, shape coexistence
- Anti-halo effect

How to probe these exotic structures?

Nuclear reactions

- Coulomb breakup reactions
- Nuclear breakup reactions
- Nucleon transfer reactions
- Direct two-nucleon decays
- Sequential two-nucleon decays
- n-n correlation measurements
- Charge exchange reactions
Next generation RI beam facilities: e.g., RIBF (RIKEN, Japan)

Direct 2n decay
Possible candidates
$^{10}\text{He, }^{13}\text{Li, }^{16}\text{Be, }^{26}\text{O,}$

Direct 2p decay
$^{17}\text{Ne, }^{20}\text{Mg}$
Nuclei beyond drip lines
---- direct two neutron decays -----

- Decay of 3-body unbound system
  - **Sequential** decay via core + n resonance
  - Direct 3-body decay
    - Democratic decay (phase space decay)
    - Di-neutron emission
    - Back-to-back emission

Coulomb breakup

Direct 2n decay
Possible candidates

\(^{26}\text{O}, ^{10}\text{He}, ^{13}\text{Li}, ^{16}\text{Be}\)
\( ^{27}\text{F} \rightarrow ^{26}\text{O} \rightarrow ^{24}\text{O} + 2n \)

2-neutron decay (MoNA@MSU)

Large uncertainty of experimental study
- Only upper limit is given for the ground state energy
- Large systematic error in the lifetime measurement

C. Caesar et al. PRC 88, 034313 (2013)

\( ^{27}\text{F} \rightarrow ^{24}\text{O} + 2n \)

Er < 120 keV (95% CL)
\( \tau < 5.7 \text{ ns} \)

Excite state at 4.2 MeV?

R3B-LAND at GSI


\( ^{24}\text{O} + n + n \)

\( T_{1/2} = 4.5^{+1.1}_{-1.5} \text{ ps} \)

(3 ps systematic error)
Di-neutron correlations and three-body model

\[ H = \frac{p_1^2}{2m} + \frac{p_2^2}{2m} + V_{nC}(r_1) + V_{nC}(r_2) + V_{nn} + \frac{(p_1 + p_2)^2}{2A_cm} \]

All parameters are determined empirically to fit the s.p. energies of neighboring nuclei and n-n scattering lengths.

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.Hagino and H. S., PRC72('05)044321

H. S. and K. Hagino, EPJA review (2015)

\[ \nu(r_1, r_2) = \nu_0(1 + \alpha \rho(r)) \times \delta(r_1 - r_2) \]
Decay energy spectrum

\[ ^{24}\text{O} + n \] potential

Woods-Saxon potential to reproduce
\[ e_{2s1/2} = -4.09 \pm 0.13 \text{ MeV}, \]
\[ e_{1d3/2} = +770^{+20}_{-10} \text{ keV}, \]
\[ \Gamma_{1d3/2} = 172(30) \text{ keV} \]

\[ \text{nn interaction} \]

density-dep. contact interaction
\[ E\left(^{27}\text{F}\right) = -2.69 \text{ MeV} \]

\[
\frac{dP_I}{dE} = \sum_{k} |\langle \psi_k^{(I)} | \phi_{\text{ref}}^{(I)} \rangle|^2 \delta(E - E_k)
= -\frac{1}{\pi} \sum_{k} \langle \phi_i^{(I)} | \psi_k^{(I)} \rangle \frac{1}{E_k - E - i\eta} \langle \psi_k^{(I)} | \phi_i^{(I)} \rangle
\]

\[
G^{(I)}(E) = G_0^{(I)}(E) - G_0^{(I)}(E) \nu (1 + G_0^{(I)}(E) \nu)^{-1} G_0^{(I)}(E)
\]

\[
G_0^{(I)}(E) = \sum_{1,2} \frac{|\langle j_1 j_2 \rangle^{(I)} \rangle \langle (j_1 j_2 \rangle^{(I)} |}{\varepsilon_1 + \varepsilon_2 - E - i\eta}
\]

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

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

FSI → Di-neutron correlations

$$G^{(I)}(E) = G_0^{(I)}(E) - G_0^{(I)}(E)v(1 + G_0^{(I)}(E)v)^{-1}G_0^{(I)}(E)$$
i) Decay energy spectrum for $^{26}\text{O}$ decay

with nn interaction

$\eta = 0.21$ MeV

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

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

cf. $e_{1d3/2}^{(25}\text{O}) = 0.770$ MeV
ii) distribution of opening angle for two-emitted neutrons

K. Hagino and H. S.,
PRC89 ('14) 014331

Heisenberg uncertainty principle between $r$ and $p$

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

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

density of the resonance state (with the box b.c.)
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.
($E_{\text{decay}} \sim 0.14$ MeV, $e_1 \sim e_2 \sim 0.07$ MeV)
Excited $2^+$ state in $^{26}$O

× Ab initio shell model with three-body interaction
Energy spectrum of contact interaction

\[ v(r_1, r_2) = \delta(r_1 - r_2) \left\{ v_0 + \frac{v_\rho}{1 + \exp[(r_1 - R_\rho)/a_\rho]} \right\}, \]

\[ [jj]^{(1)} = 0^+, 2^+, 4^+, 6^+, \ldots. \]

Without residual interaction:

\[ I = 0 \text{ pair} \]

With residual interaction:

\[ I \neq 0 \text{ pair} \]
Three-body model calculation of the $2^+$ state in $^{26}$O

K. Hagino$^{1,2}$ and H. Sagawa$^{3,4}$

$E(0^+)=5.0$ keV
$E(2^+)=1.338$ MeV

$^{25}$O resonance of $d3/2$ state $e(d3/2)=0.77$ MeV

$2^+$ with a simple configuration $(d3/2)^2$: $E_x=1.54$ MeV (unperturbed)

FIG. 1. (Color online) (Top) The decay energy spectrum for the two-neutron emission decay of $^{26}$O. The dashed and the solid lines are for the $0^+$ and $2^+$ states, respectively. The dotted line shows the uncorrelated spectrum obtained by ignoring the interaction between the valence neutrons. (Bottom) The decay energy spectrum obtained by superposing the $I=0$ and $I=2$ components. The dashed line is the same as the one in the top panel, that is, the decay energy spectrum for the pure $I=0$ configuration. The experimental data, normalized to the unit area, are taken from Ref. [5].
<table>
<thead>
<tr>
<th></th>
<th>$^{25}$O ($3/2^+$)</th>
<th>$^{26}$O ($2^+$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment</strong></td>
<td>$+770^{+20}_{-10}$ keV</td>
<td>~ 1.3 MeV</td>
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<tr>
<td><strong>USDA</strong></td>
<td>1301 keV</td>
<td>1.9 MeV</td>
</tr>
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<td><strong>USDB</strong></td>
<td>1303 keV</td>
<td>2.1 MeV</td>
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<td>sdpf-m</td>
<td>2.15 MeV</td>
<td>2.6 MeV</td>
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<tr>
<td>chiral NN+3N</td>
<td>742 keV</td>
<td>1.6 MeV</td>
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<tr>
<td>continuum SM (Volya-Zelevinsky)</td>
<td>1002 keV</td>
<td>1.8 MeV</td>
</tr>
<tr>
<td>3-body model (Hagino-Sagawa)</td>
<td>770 keV (input)</td>
<td>1.35 MeV</td>
</tr>
</tbody>
</table>
Summary

Di-neutron correlation: spatial localization of two neutrons

✓ Theory: large model space (parity mixing)
✓ scattering to the continuum states
  enhancement of pairing on the surface

how to probe it?

• Direct two-neutron emission decay (\(^{26}\text{O},^{14}\text{Be}\))
  ✓ decay energy spectrum
  ✓ Final state interaction=di-neutron correlations
  ✓ opening angle of two emitted neutrons (back-to-back)

\(^{26}\text{O}\)

ground state: very small width (\(\Gamma \sim 10^{-10}\text{MeV}\))
  very small resonance energy (\(E_x < 140\text{keV}\))

\(^2\text{+_}\): The three-body model with a contact pairing interaction gives \(E_x = 1.3\text{MeV}\). \(ab\ initio\) and USD shell model calculations give higher energy than \(E_x > 1.6\text{MeV}\).