Decay modes of resonant and non-resonant continuum states of $^6$He

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The Coulomb breakup reaction cross sections of halo nuclei show low-lying enhancements above the breakup thresholds. It has been expected that the weakly-bound halo neutrons are responsible for these low-lying enhancements. These breakup cross sections can be understood by the transitions into non-resonant continuum states.

Observed peak structures in breakup reactions of halo nuclei


11Be breakup

6He breakup
Observed peak structures in breakup reactions of halo nuclei

- For one-neutron halo nuclei, the Coulomb breakup is a powerful tool to investigate their ground-state structures.
- The E1 transition strength can be understood by the direct breakup process into non-resonant continuum states.
- The shape of the peak reflects the spatial extension of a halo neutron, which is related to its separation energy and the ground-state configuration.

\[
\frac{dB(E1)}{dE_x} \propto \left| \langle \exp(i\mathbf{q} \cdot \mathbf{r}) | \hat{O}(E1) | \Phi_{gs}(\mathbf{r}) \rangle \right|^2 \\
\langle \exp(i\mathbf{q} \cdot \mathbf{r}) | \hat{O}(E1) | \Phi_{gs}(\mathbf{r}) \rangle \propto \int e^{iqr^3} \Phi_{gs}(r) \, dr
\]
Observed peak structures in breakup reactions of halo nuclei

- For two-neutron halo nuclei, the situation becomes complicated.
- The peak cannot be reproduced by the direct breakup into phase space.
- The correlations in the continuum states are key to understand the Coulomb breakup reactions of two-neutron halo nuclei.
- In our calculations, no three-body resonance is obtained.
- What kinds of correlations make the low-lying enhancement?
- In the core+n+n systems, binary subsystems of core-n and n-n can form the resonances and/or virtual states.

YK et al., PRC 81, 044308 (2010).

YK et al., PRC 87, 034606 (2013).
Observed peak structures in breakup reactions of halo nuclei

- It is also interesting problem to investigate the nuclear breakup reaction of $^6$He.
- In the nuclear breakup, the $2^+$ resonance at 1 MeV above the breakup threshold is populated.
- We can learn the structure of the excited state of two-neutron halo nuclei from this kind of reactions.
- The $2^+$ resonance has a similar single-particle configuration to g.s.
- Is there any possibility of the measurement of the n-n correlation in the excited resonant states?

T. Matsumoto et al., PRC 82, 051602 (2010).
Our approach to describe the breakup reactions

- Complex scaling method (CSM)
  - The CSM is one of the methods to solve the eigenvalue problems with outgoing boundary conditions.
  - In the CSM, the relative coordinates and momenta are transformed as
    \[
    U(\theta) : \mathbf{r} \rightarrow \mathbf{r}e^{i\theta}, \quad \mathbf{k} \rightarrow \mathbf{k}e^{-i\theta}
    \]

- Applying this transformation to the Hamiltonian and wave function, we obtained complex-scaled Schrödinger equation as
  \[
  \hat{H}\chi(\mathbf{r}) = E\chi(\mathbf{r}) \rightarrow \hat{H}^\theta \chi^\theta(\mathbf{r}) = E^\theta \chi^\theta(\mathbf{r})
  \]
  where
  \[
  \chi^\theta(\mathbf{r}) = U(\theta)\chi(\mathbf{r}) = e^{\frac{3}{2}i\theta}\chi(\mathbf{r}e^{i\theta})
  \]
  \[
  \hat{H}^\theta = U(\theta)\hat{H}U^{-1}(\theta)
  \]
Search for resonances using CSM

- Under the transformation in CSM, the integral contour in the momentum space is rotated, and then, the resonance pole is obtained as a residue.
- The CSM enables us to solve the resonances on the same footing as the bound states.
- In the complex energy plane, the continuum states are classified into several families of the decay channels.
- This classification is useful to discuss the decay modes.
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\[ \text{ex) obtained spectra of } 2^+ \text{ states of } ^6\text{He} \]
We describe the three-body scattering states of core+n+n by using CSM.

We start with the following equation;

\[ \Psi^{(\pm)} = \Phi_0 + \lim_{\varepsilon \to 0} \frac{1}{E - \hat{H} \pm i\varepsilon} \hat{V} \Phi_0 \]

where $\Phi_0$ is a solution of an asymptotic Hamiltonian.

We apply CSM to the Green’s function and expand the complex-scaled Green’s function with the complete set of eigenstates of Hamiltonian.

\[ U^{-1}(\theta) \frac{1}{E - \hat{H}_\theta} U(\theta) = \sum_n U^{-1}(\theta) |\chi^\theta_n\rangle \frac{1}{E - E^\theta_n} \langle \tilde{\chi}^\theta_n | U(\theta) \]

It is noted that the outgoing boundary conditions are taken into account by imaginary parts of energy eigenvalues.

Using the complex-scaled Green’s function, we obtain the three-body scattering states as

\[ |\Psi^{(+)}\rangle = |\Phi_0\rangle + \sum_n U^{-1}(\theta) |\chi^\theta_n\rangle \frac{1}{E - E^\theta_n} \langle \tilde{\chi}^\theta_n | U(\theta) \hat{V} |\Phi_0\rangle \]

\[ \langle \Psi^{(-)}| = \langle \Phi_0 | + \sum_n \langle \Phi_0 | \hat{V} U^{-1}(\theta) |\chi^\theta_n\rangle \frac{1}{E - E^\theta_n} \langle \tilde{\chi}^\theta_n | U(\theta) \]

YK et al., PTP 122, 499 (2009).
core+n+n three-body model for $^6$He

To construct the complex-scaled Green’s function, we use the core+n+n three-body orthogonality condition model.

Hamiltonian

$$\hat{H} = \sum_{i=1}^{3} t_i - T_{cm} + \sum_{i=1}^{2} V_{\alpha-n}(r_i) + V_{n-n} + V_{\alpha nn} + \lambda |\Phi_{PF}\rangle \langle \Phi_{PF}|$$

- $V_{\alpha-n}$: KKNN potential
- $V_{n-n}$: Minnesota force
- $V_{\alpha nn}$: effective three-body $\alpha nn$ potential

Wave function

- We describe the w.f. as a linear combination of two types of bases.
- The radial part of basis function is expanded with the Gaussian bases.

$$\chi(nn) = \chi_V (r_1, r_2) + \chi_T (r, R)$$

COSM (V-type)

- $r, j_1$
- $r_2, j_2$
- shell model-like

ECM (T-type)

- $r, l$
- $R, L$
- di-neutron-like
Coulomb breakup reaction of $^6\text{He}$

YK et al., PRC 81, 044308 (2010).
Coulomb breakup reaction of $^{6}\text{He}$

- We calculate the Coulomb breakup reaction using the equivalent photon method and the E1 strength distribution.

$$\frac{d^6\sigma}{dkdK} = \frac{16\pi^3}{9\hbar c} \cdot N_{E1}(E_\gamma) \cdot \frac{d^6 B(E1)}{dkdK}$$

$$\frac{d^6 B(E1)}{dkdK} = \frac{1}{2J_{gs} + 1} \left| \langle \Psi^{-}(k, K) | \hat{O}(E1) | \Phi_{gs} \rangle \right|^2$$

- We have two choices of relative momenta in the calculation of the E1 strength distribution.
Coulomb breakup reaction of $^6$He

- We calculate the differential cross section w.r.t. the excitation energy of $^6$He.
- The calculated cross section is convoluted by the experimental resolution.

$$
\frac{d\sigma}{dE} = \int dk \int dK \frac{d^6\sigma}{dkdK} \delta \left( E - \frac{\hbar^2 k^2}{2\mu} - \frac{\hbar^2 K^2}{2M} \right)
$$

- Calculated cross section well reproduces the observed data.
- We find no resonance in the final 1$^-$ states.
- The FSI plays a key role in the Coulomb breakup reaction.
Decay mode of non-resonant continuum states

- To investigate the correlations in the final states, we calculate the invariant mass spectra for binary subsystems.
- The experimental efficiencies are not taken into account.

\[
\frac{d\sigma}{d\varepsilon} = \int dk \int dK \frac{d^6\sigma}{dkdK} \delta \left( \varepsilon - \frac{\hbar^2 k^2}{2\mu} \right)
\]

- For $\alpha$-n, the peak is obtained at the energy corresponding to the $^5\text{He}(3/2^-)$.
- The sequential decay via the $^5\text{He}(3/2^-) + n$ is important in the breakup.
- For n-n, the spectrum shows the peak just above the threshold.
- This corresponds to the virtual-state correlation of n-n in final states.

For $\alpha$-n subsystem

For n-n subsystem
Short summary for Coulomb breakup of $^6$He

- In the Coulomb breakup of $^6$He, the breakup process is dominated by the sequential decay via the $^5$He($3/2^-$)+n.  
- The threshold of the $^5$He($3/2^-$)+n channel is open at $\sim 0.7$ MeV, and hence, the Coulomb breakup cross section has the peak at $\sim 1.0$ MeV just above the $^5$He($3/2^-$)+n threshold due to the threshold effect.  
- On the other hand, the n-n correlation has a sizable effect on the Coulomb breakup in reproducing the observed cross section.  
- It is noted that this n-n correlation is that in the final state and does not correspond to the dineutron in the ground state.
Nuclear breakup reaction of $^{6}$He

YK et al., PRC 88, 021602 (2013).
Nuclear breakup reaction of $^6$He

- We investigate the $^6$He+C @ 240MeV/nucleon.
- To calculate the cross section, we need to treat the scattering between the projectile and target in non-perturbative way.
- We employ the CDCC to describe the reaction.
- We solve the CDCC with the pseudo state method, in which the discretized continuum states are obtained within the $L^2$ basis functions.

$$T = \langle \psi^-(k, K) \chi^-(P) | V | \Psi^+ \rangle$$

$$\approx \sum_n \langle \psi^-(k, K) | \Phi_n \rangle \langle \Phi_n \chi^-(P) | V | \Psi^+ \rangle$$
Nuclear breakup reaction of $^6$He

- We include the $0^+$, $1^-$, and $2^+$ states for the final states in the CDCC calculation.
- We can well reproduce the observed cross section using the CDCC and $\alpha+n+n$ three-body model.
- We obtain the sharp peak coming from the $2^+$ resonance at 1 MeV above the three-body breakup threshold.

T. Matsumoto et al., PRC 82, 051602 (2010).
Nuclear breakup reaction of $^6$He

- We calculate the double-differential cross section (DDX) as functions of relative energies of core+n+n systems to investigate the decay mode.

\[
\frac{d^2\sigma}{d\varepsilon_1 d\varepsilon_2} = \frac{(2\pi)^4 \mu_R}{\hbar^2 P_0} \int dK dP |T(k, K, P)|^2 \\
\times \delta \left( E_{\text{tot}} - \frac{\hbar^2 P^2}{2\mu_R} - \varepsilon_1 - \varepsilon_2 \right) \\
\times \delta \left( \varepsilon_1 - \frac{\hbar^2 k_1^2}{2\mu_r} \right) \delta \left( \varepsilon_2 - \frac{\hbar^2 K^2}{2\mu_y} \right)
\]

- To obtain DDX as a continuous function of relative energies, we need the overlap functions.

\[
T = \langle \psi^{(-)}(k, K) \chi^{(-)}(P) | V | \Psi^{(+)} \rangle \\
\approx \sum_n \langle \psi^{(-)}(k, K) | \Phi_n \rangle \langle \Phi_n \chi^{(-)}(P) | V | \Psi^{(+)} \rangle
\]

- The three-body scattering states are calculated by using CSM.
Specific decay mode of the $2^+$ resonance of $^6\text{He}$

- DDX in two types of Jacobi coordinate sets.
  - Both of DDX’s have the ridge structures at the energy of $\alpha+n+n$ as $\sim 1$ MeV.
  - The shapes of DDX’s show the dominance of the excitation to the $2^+$ resonance at $E = 0.98$ MeV with $\Gamma = 0.27$ MeV.
- To investigate the decay modes of the $2^+$ resonance, we next calculate the invariant mass spectra for binary subsystems.

![Diagram](image)
Specific decay mode of the $2^+$ resonance of $^6\text{He}$

- To clarify the decay mode of the $2^+$ resonance, we calculate the invariant mass spectra by gating on the total energy as $0.98\pm0.135$ MeV, which corresponds to the resonance energy and decay width of the $2^+$ resonance.
- The result of $\alpha$-n indicates that two neutrons are emitted with equal sharing of the total energy of the $\alpha+n+n$ system.
- The spectrum for the n-n subsystem shows a two-peak structure.
  - The 1st peak corresponds to the virtual-state correlation as similar to that in the Coulomb breakup case.
  - The 2nd peak shows that the back-to-back emission of n-n because the total energy of $\alpha+n+n$ is exhausted by the relative motion of n-n.

For $\alpha$-n subsystem

![Graph for $\alpha$-n subsystem]

For n-n subsystem

![Graph for n-n subsystem]
Summary

- We investigate the breakup mechanism of $^6\text{He}$ applying the CSM to the $\alpha+n+n$ three-body model.
  - For the Coulomb breakup, we use the equivalent photon method.
  - The breakup reaction of $^6\text{He}+\text{C}$ is described by using the CDCC.

- The FSI plays a key role in the Coulomb breakup of $^6\text{He}$.
  - The sequential decay via the $^5\text{He}(3/2^-)+n$ dominates the cross section.
  - The n-n virtual-state correlation in the final state can be seen in the n-n invariant mass spectra.

- In the nuclear breakup of $^6\text{He}$, we can see that the specific mode in the decay from the $2^+$ resonance.
  - Two neutrons are emitted with equal sharing of the total energy.
  - the virtual-state correlation has a sizable effect on the cross section as similar to the Coulomb breakup.
  - In addition to the virtual-state correlation, the back-to-back emission of two neutrons could be found in the decay from the $2^+$ resonance.