Mechanisms of Coulomb breakup reactions of $^6$He and $^{11}$Li

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Abstract. We investigate the three-body Coulomb breakup reactions of two-neutron halo nuclei and discuss the effect of binary subsystem correlations such as the of core-$n$ and $n$-$n$. Furthermore, we calculate the invariant mass spectra. It is found that the final-state interactions of core-$n$ and $n$-$n$ binary subsystems dominantly determine the observed structures of the breakup cross sections, such as the low-lying enhancements.

1. Introduction
Since the discovery of neutron halo nuclei — such as $^{11}$Be, $^6$He, and $^{11}$Li — extensive studies have been performed to understand their exotic structure caused by the weakly-bound nature of the valence neutrons. Theoretically, using the models based on the core + valence neutrons picture, the halo structure of the ground states and their excitations have been investigated [1, 2]. In two-neutron halo nuclei, it has been suggested that the correlation between two halo neutrons is important in reproducing the observed small two-neutron separation energies and large matter radii [1].

Experimentally, the Coulomb breakup reactions have been performed to expose the role of the $n$-$n$ correlation in the two-neutron halo nuclei [3, 4]. The observed Coulomb breakup cross section provided us with interesting information on the weak-binding properties and the breakup mechanism of the halo nuclei. To investigate the properties and the breakup mechanism of halo nuclei, there are at least two problems to be solved: (i) clarifying the dominant breakup process such as the direct breakup to a noninteracting three-body continuum or sequential decay via the resonance of the binary subsystem, (ii) evaluating the influence of the final-state interactions (FSI) on the cross section.

In this study, we calculate the Coulomb breakup reaction of two-neutron halo nuclei, $^6$He and $^{11}$Li, and clarify the relation between the subsystem correlations of core-$n$ and $n$-$n$ and the Coulomb breakup cross section. To calculate the Coulomb breakup cross section, we use the complex-scaled solutions of the Lippmann-Schwinger equation (CSLS) [6, 7]. We calculate not only the breakup cross section with respect to the total energy of the system but also the
invariant mass spectra of core-\(n\) and \(n-n\) by using CSLS, and discuss the effects of the binary subsystem correlations on the cross section.

2. Method

To evaluate the Coulomb breakup cross sections, it is necessary to obtain the scattering states, \(\Psi^{(-)}(k, K)\), which is given as the function of the relative momenta, \(k\) and \(K\). Here, we obtain \(\Psi^{(-)}(k, K)\) using CSLS [6, 7]. The incoming scattering state \(\Psi^{(-)}\) in the bra-representation is described as

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

where \(\Phi_0\) is a solution of an asymptotic Hamiltonian \(\hat{H}_0\), and the interaction \(\hat{V}\) is defined by subtracting \(\hat{H}_0\) from the total Hamiltonian \(\hat{H}\).

The Green’s function in Eq. (1) is replaced with the complex-scaled Green’s function in CSLS, and the relation between the Green’s function in Eq. (1) and the complex-scaled one is given as

\[
\lim_{\varepsilon \to 0} \frac{1}{E - \hat{H} + i\varepsilon} = U^{(-)}(\theta) \frac{1}{E - \hat{H}^{\theta}} U(\theta) = \sum_n U^{(-)}(\theta) |\chi_n^{\theta}\rangle \frac{1}{E - E_n^{\theta}} \langle \chi_n^{\theta}| U(\theta).
\]

In the derivation of the right-hand-side of Eq. (2), we insert the complete set constructed with \(\{\chi_n^{\theta}\}\), being the eigenstates of complex-scaled Hamiltonian \(\hat{H}^{\theta}\). We obtain \(\Psi^{(-)}(k, K)\) as

\[
\langle \Psi^{(-)}(k, K) \rangle = \langle \Phi_0(k, K) \rangle + \sum_n \langle \Phi_0(k, K) \rangle |\hat{V}| U^{-1}(\theta) |\chi_n^{\theta}\rangle \frac{1}{E - E_n^{\theta}} \langle \chi_n^{\theta}| U(\theta).
\]

The scattering state in CSLS consists of two terms: the first term corresponds to the states of the noninteracting continuum, and the second is the effects of FSI. This decomposition of the scattering states is useful to estimate the effects of the correlations in the ground and final states on the Coulomb breakup cross section.

3. Results

In Fig. 1 we first show the Coulomb breakup cross section with respect to the total energy of \(^6\)He and \(^{11}\)Li in comparison with the observed ones [3, 4]. In both cases, the calculated cross sections show the low-lying enhancements, and well reproduce the observed data. We also estimate the effect of FSI on the cross sections by taking only the first term in Eq. (3) in the calculation, and it is found that FSI plays significant roles in reproducing the Coulomb breakup cross sections.

To discuss what kinds of FSI are important in the Coulomb breakup reactions, we calculate the invariant mass spectra for binary subsystems. In Fig. 2, we show the calculated invariant mass spectra for \(^{11}\)Li. From the results, we confirm that both invariant mass spectra for \(^9\)Li-\(n\) and \(n-n\) show the low-lying enhancements. It is also found that the virtual-state correlations of \(^9\)Li-\(n\) and \(n-n\) subsystems have significant contributions in spectra. One the other hand, the \(p\)-wave resonances in \(^{10}\)Li does not contribute to the invariant mass spectra for \(^9\)Li-\(n\) subsystem since the resonance energies of the \(p\)-wave resonances, which are obtained at 275 keV and 506 keV in our calculation, are higher than the total energy of the peak position of the breakup cross section shown in the right panel of Fig. 1.

We also calculate the invariant mass spectra for \(^6\)He. From the obtained results, the invariant mass spectra for the \(\alpha-n\) subsystem shows the peak at around 0.7 MeV corresponding to the \(^5\)He(3/2\(^-\)) resonance. The \(\alpha-n\) correlation is clearly confirmed in the invariant mass spectra of the Coulomb breakup cross section. For the \(n-n\) subsystem, the low-lying enhancement is seen near the zero-energy region, which indicates the importance of the \(n-n\) virtual state in the final states. (For details, see Refs. [6, 7])
Figure 1. Obtained Coulomb breakup cross sections of $^6$He and $^{11}$Li, measured from the threshold energy of core + $n + n$. The left and right panels represent the cross sections for $^6$He and $^{11}$Li, respectively. The observed data, shown as solid squares, are taken from Ref. [3] for $^6$He and from Ref. [4] for $^{11}$Li.

Figure 2. Invariant mass spectra of the Coulomb breakup reaction of $^{11}$Li. The left and right panels present the invariant mass spectra for $^9$Li-$n$ and $n-n$, respectively. In the left panel, three types of spectra are presented: The total distribution (solid), $s$-wave component (dotted), and $p$-wave component (dashed). Two arrows in the left panel indicate the position of the $p$-wave resonances in our calculation.

From the results for $^6$He and $^{11}$Li, it is found that the invariant mass spectra for core-$n$ subsystems reflects the characters of the core-$n$ correlations in two-neutron halo nuclei, while the behaviors of the spectra for $n-n$ subsystem are commonly dominated by the $n-n$ virtual-state correlation in two nuclei.

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