Two neutron decay from the $2^+_1$ state of $^6$He

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Decay mode of the $2^+_1$ resonant state of $^6$He populated by the $^6$He breakup reaction by $^{12}$C at 240 MeV/nucleon is investigated. The continuum-discretized coupled-channels method is adopted to describe the formation of the $2^+_1$ state, whereas its decay is described by the complex-scaled solutions of the Lippmann-Schwinger equation. From analysis of invariant mass spectra with respect to the $\alpha$-n and n-n subsystems, coexistence of two decay modes is found. One is the simultaneous decay of two neutrons correlating with each other and the other is the emission of two neutrons to the opposite directions. The latter is found to be free from the final state interaction and suggests existence of a di-neutron in the $2^+_1$ state of $^6$He.

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Introduction. Elucidation of unbound nuclei outside the drip line [1] as well as unbound excited (resonant) states of unstable nuclei [2] is a hot subject in nuclear physics. These particle-unbound states have been investigated by means of decay-particle measurements. Clarification of their decay mode is crucial to extract structural information on the unbound states. Furthermore, the decay mode itself is an interesting subject for understanding of the dynamical properties of them. If we consider a particle-unbound state that decays into three particles, we have several possibilities of the decay mode. For instance, in the decay process of the $2^+_1$ state of $^6$He into $\alpha$ and two neutrons, the following decay modes can be considered. 1) Emission of one neutron is followed by that of the other from the 3/2$^-$ resonance (ground state) of $^6$He; below we call this state just $^6$He. 2) Two neutrons are emitted simultaneously (not via $^5$He), with correlating with each other, i.e., preferring the low two-neutron (2n) relative energy. 3) Same as 2) but two neutrons are emitted independently. These decay modes have been intensively discussed for two-proton (2p) decay phenomena [3,4]. In the true 2p decay, by definition, 1) is forbidden because of the condition that the ground state of a 2p-decay nucleus is located below the (core+p)-p threshold energy, where (core+p) is a two-body resonant state. If one considers, however, an excited state of a 2p-decay nucleus, 1) also may happen in general. Following the terminology used in preceding studies, we call 1), 2), and 3) the sequential decay, the di-neutron decay, and the democratic decay, respectively. Although sometimes the democratic decay means both 2) and 3), we differentiate 2) from 3) in this study. Clarification of the decay mode of three-body systems will be a fascinating subject in view of nontrivial dynamics of three-body decaying systems. To achieve this, we need a framework that describes dynamics of both the formation and decay of particle-unbound states.

In Ref. [6], the method of the complex-scaled solutions of the Lippmann-Schwinger equation (CSLS) was developed. In CSLS the Lippmann-Schwinger formalism is combined with the complex scaling method (CSM) [5]; CSLS allows an accurate description of decay of many-body systems. Then CSLS was applied to the Coulomb breakup of $^6$He by $^{208}$Pb at 250 MeV/nucleon to study a possible correspondence between breakup observables and the di-neutron correlation in the ground state of $^6$He [6]. This work can also be interpreted as an investigation of the decay mode of the nonresonant 1$^-$ state of $^6$He excited by $^{208}$Pb. The main conclusion of Ref. [6] was the dominance of the sequential decay through $^6$He governed by the final state interaction (FSI). Another important finding was a peak in the 2n invariant mass spectrum. Since this peak is located around the 2n virtual state energy, it suggests the di-neutron decay. It should be noted, however, that the peak was found to be generated by a rearrangement process due to the FSI from the $^5$He+n configuration to the $\alpha$+2n in the decay process. This indicates that even the decay mode changes, from the sequential decay to the di-neutron decay in this case. Thus, the FSI is found to play a crucial role in the decay of the 1$^-$ nonresonant state of $^6$He.

A possible shortcoming of the work of Ref. [6] is that the breakup process by $^{208}$Pb was simplified by a one-step electric dipole (E1) transition. Although this simplification is expected to work quite well for breakup processes by $^{208}$Pb at intermediate energies, it severely restricts the applicability of CSLS. To study the decay mode of a resonant state, more realistic description of the formation of the resonance will be necessary. In this work, we extend the CSLS analysis in Ref. [7] by incorporating a sophisticated reaction model to describe the formation of particle-unbound states. We focus on the $2^+_1$ resonance of $^6$He and aim at clarifying its decay mode. We consider $^6$He breakup reaction by $^{12}$C at 240 MeV/nucleon as a formation process of the $2^+_1$ $^6$He resonance. We describe this process by means of the continuum-discretized coupled-channels method (CDCC) [9,11]. CDCC is a non-perturbative quantum-mechanical model that has

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been successfully applied to various breakup reactions in a wide range of incident energies. Theoretical foundation of CDCC is given in Refs. [11–12]. The decay of the $2^+_1$ resonance into $\alpha$ and two neutrons is then investigated by CSLS. This combination of CDCC and CSLS, CDCC-CSLS, is a powerful method to describe formation and decay of particle-unbound states in a unified manner.

**Formalism.** We assume that the $^6\text{He}+^{12}\text{C}$ scattering is described as an $\alpha+n+n+^{12}\text{C}$ four-body system. The total Hamiltonian is defined by

$$H = K_R + U + H_6$$

with

$$U = U_n^{\text{Nucl}} + U_n^{\text{Nucl}} + U_\alpha^{\text{Nucl}} + U_\alpha^{\text{Coul}},$$

$$H_6 = K_y + K_r + v_{nn} + v_{\alpha n} + v_{\alpha n},$$

where $H_6$ is an internal Hamiltonian of $^6\text{He}$. The relative coordinate between $^6\text{He}$ and $^{12}\text{C}$ is denoted by $R$, and the internal coordinates of $^6\text{He}$ are denoted by a set of Jacobi coordinates \( \xi = (y, r) \). The kinetic energy operator and the reduced mass associated with the coordinate $s$ is represented by $K_s$ and $\mu_s$, respectively. The $n-n$ ($\alpha$-$n$) interaction is denoted by $v_{nn}$ ($v_{\alpha n}$), and $U_x^{\text{Nucl}}$ and $U_x^{\text{Coul}}$ are the nuclear and Coulomb potential between $x$ and $^{12}\text{C}$, respectively.

In CDCC, with the pseudostate discretization method [12–13], the scattering is assumed to take place in the model space $P$ defined by

$$P = \sum_{i} |\Phi_i\rangle\langle\Phi_i|,$$

where $\Phi_i$ is the $i$th eigenstate obtained by diagonalizing $H_6$ with $L^2$-type basis functions. The four-body Schrödinger equation is then solved in the model space:

$$P(H - E_{\text{tot}})P|\psi_{\text{CDCC}}^{(+)\text{CDCC}}⟩ = 0.$$  

The model space assumption has already been justified by the fact that calculated elastic and breakup cross sections converge with respect to extending the model space. Details of how to solve the four-body CDCC equation [14] are shown in Refs. [15–19].

The CDCC $T$-matrix element to the $i$th discrete breakup state $\Phi_i$ with an eigenenergy $\varepsilon_i$ is given by

$$T_i^{\text{CDCC}} = \langle\Phi_i|\chi_i^{(-)}(P_i)|U - U_{6\text{He}}^{\text{Coul}}|\psi_{\text{CDCC}}^{(+)\text{CDCC}}⟩,$$

where $U_{6\text{He}}$ is the Coulomb interaction between $^6\text{He}$ and $^{12}\text{C}$. The final-state wave function $\chi_i^{(-)}$ with the incoming boundary condition for the relative motion regarding $R$ is defined by

$$[K_R + U_{6\text{He}}^{\text{Coul}} - (E_{\text{tot}} - \varepsilon_i)]|\chi_i^{(-)}(P_i)⟩ = 0,$$

where the asymptotic relative momentum $P_i$ (in the unit of $\hbar$) for $\Phi_i$ satisfies $E_{\text{tot}} - \varepsilon_i = (\hbar^2 P_i^2)/(2\mu_R)$. Using the CDCC $T$-matrix element, the exact $T$-matrix element to a continuum breakup state is well approximated by

$$T_\varepsilon(p, k, P) \approx \sum_i \langle\Phi_i|\chi_i^{(-)}(P_i)|\Phi_i⟩T_i^{\text{CDCC}}$$

$$= \sum_i f_i(p, k)T_i^{\text{CDCC}},$$

where the momenta $p$, $k$, and $P$ are the asymptotic relative momenta regarding the coordinate $y$, $r$, and $R$, respectively, and $\Phi_i^{(-)}$ is the exact three-body continuum wave function of $^6\text{He}$ with the total energy $\varepsilon = (h^2p^2)/(2\mu_y) + (h^2k^2)/(2\mu_y)$. To obtain the smoothing function $f_i(p, k)$, we use CSLS that describes the three-body scattering states with correct boundary conditions:

$$f_i(p, k) = \langle\varphi_0(p, k)|\Phi_i⟩ + \int_{\varepsilon_i} \langle\varphi_0(p, k)|\bar{V}U^{-1}(\theta)|\Phi_n^\theta⟩ \frac{1}{\varepsilon_i - \varepsilon_n^\theta} \langle\Phi_n^\theta|U(\theta)|\Phi_i⟩,$$

where $\bar{V} = v_{nn} + v_{\alpha n} + v_{\alpha n}$ and $U(\theta)$ is the complex-scaling operator. $\varphi_0$ is a three-body plane wave with a set of relative momenta $(p, k)$, and $\Phi_n^\theta$ and $\varepsilon_n^\theta$ are the $\theta$th eigenstate and its eigenenergy, which are obtained by diagonalizing the complex-scaled $^6\text{He}$ Hamiltonian, $H_6^\theta$, by $L^2$-type basis functions. In the present calculation, we adopt the Gaussian expansion method (GEM) [20] to obtain $\Phi_i$ and $\Phi_n^\theta$.

To investigate the decay mode of the $2^+_1$ state of $^6\text{He}$, we calculate the double differential cross sections with respect to the relative energies, $\varepsilon_1$ and $\varepsilon_2$, of binary subsystems:

$$\frac{d^2\sigma}{d\varepsilon_1d\varepsilon_2} = \frac{(2\pi)^4}{h^2P_0} \int dpdkdP \left| T_\varepsilon(p, k, P) \right|^2$$

$$\times \delta \left( E_{\text{tot}} - \frac{h^2P^2}{2\mu_R} - \varepsilon_1 - \varepsilon_2 \right)$$

$$\times \delta \left( \varepsilon_1 - \frac{h^2k^2}{2\mu_y} \right) \delta \left( \varepsilon_2 - \frac{h^2p^2}{2\mu_y} \right),$$

where $P_0$ is the incident momentum of $^6\text{He}$ in the center-of-mass (c.m.) system.

**Numerical input.** As for the interactions $v_{nn}$ and $v_{\alpha n}$ in $H_6$, we take the Minnesota [21] and the KKNN [22] potential, respectively. We increase the depth of $v_{\alpha n}$ by 3% to reproduce the ground state energy of $^6\text{He}$. The antisymmetrization between a valence neutron and a neutron in $\alpha$ is treated approximately with the orthogonality condition model [23].

In GEM, we take the Gaussian range parameters $r_i$ ($i = 1, 2, ..., N$) that lie in geometric progression. In the diagonalization of $H_6$, we use $(N, r_1, r_N) = (10, 0.5 \text{ fm}, 10 \text{ fm})$ for each of the Jacobi coordinates; for the coordinate between two neutrons we take $r_1 = 0.1 \text{ fm}$. In the diagonalization of $H_6^\theta$, we adopt $(N, r_1, r_N) = (20, 0.2 \text{ fm}, 40 \text{ fm})$. It is known that finer and wider bases are required to properly describe the many-body resonant and continuum solutions simultaneously in the CSM [24].
We include 66, 82, and 100 eigenstates of \( H_0 \) for the \( 0^+, 1^-, \) and \( 2^+ \) states of \(^6\text{He}\), respectively, in the CDCC calculation. These states are located below \( \varepsilon = 30 \text{ MeV} \). We solve Eq. (3) by means of eikonal CDCC \(^{11, 25, 26}\) up to \( R = 30 \text{ fm} \). The distorting potentials between the constituents of \(^6\text{He}\) and \(^{12}\text{C}\) are calculated by a microscopic folding model. Nuclear densities of \( \alpha \) and \(^{12}\text{C}\) are obtained by Hartree-Fock calculation with the Gogny force \(^{27}\). As for the effective nucleon-nucleon interaction, we adopt the Melbourne g-matrix \(^{28}\). The present calculation has no free adjustable parameters. The numerical results shown below are converged with the model space described above.

Results. We show in Fig. 1 the double-differential breakup cross section (DDBUX) calculated by CDCC-CSLS. In panel (a), we show the DDBUX with respect to the subsystem energies of \( \alpha \)-n and \( n-n \), respectively (see the text for detail).

Next we show the invariant mass spectrum and discuss the decay mode of the \( \alpha + n + n \) system, that of the \( 2^+ \) resonant state in particular. The solid line in Fig. 2 shows \( d\sigma/d\varepsilon_{\alpha-n} \) and the dashed line shows its resonant part extracted by gating \( \varepsilon \) within the range of the energy of the \( 2^+ \) state, i.e., \( \varepsilon = 0.98 \pm 0.27/2 \text{ MeV} \). The rest shown by the dotted line is interpreted as the nonresonant part of \( d\sigma/d\varepsilon_{\alpha-n} \). For the nonresonant part, one sees the peak around 0.7 MeV corresponding to the energy of \(^5\text{He}\), which is the same as in the spectrum for the Coulomb breakup \(^7\). Thus, one can conclude that for the nonresonant decay, i.e., for the decay from nonresonant continuum states of the \( \alpha + n + n \) system, the sequential decay is dominant.

The property of the resonant part is quite different from this. A peak is found around 0.5 MeV, about half the total energy \( \varepsilon \) of the \( 2^+ \) state, which is somewhat lower than the energy of \(^5\text{He}\). Therefore, one can find that the sequential decay is suppressed in this case. Instead, the result (dotted line) indicates that two neutrons are emitted with equally sharing the total energy of the three-body system. Thus, the di-neutron decay or the democratic decay or both is suggested.

This result can be explained as follows. When \(^5\text{He}\) is formed under the condition of \( \varepsilon \sim 1.0 \text{ MeV} \), the other neutron has very low energy below about 200 keV. Since
the \((p3/2)^2\) configuration is dominant in the \(2^+_1\) state of \(^6\)He, the second neutron has a centrifugal barrier with respect to \(\alpha\). Therefore, the second neutron hardly penetrates the barrier, which results in the suppression of the \(^5\)He+\(n\) configuration, hence the sequential decay, in the decay of the \(2^+_1\) state of \(^6\)He. It should be noted that for the Coulomb breakup, in which the decay from the \(1^-\) state is dominant, the second neutron can be an s-wave. Thus, the suppression of the sequential decay is not the case. Another remark is that for the nonresonant decay (dashed line) there is no restriction on \(\varepsilon\), which also allows the sequential decay.

To pin down the decay mode of the two neutrons, next we discuss \(d\sigma/d\varepsilon_{n-n}\) shown in Fig. 3. Two peaks are found in the spectrum. The first peak around 0.2 MeV suggests the di-neutron decay, as in the previous study of the Coulomb breakup \([7]\). It should be noted that this di-neutron decay does not mean the direct emission of a di-neutron existed in the \(2^+_1\) state. As in the Coulomb breakup case, this di-neutron is found to be formed by the FSI in the decay process. The two neutrons are emitted with correlating with each other, indicating that the two have the same energy and are emitted to the same direction. On the other hand, the second peak (or shoulder) around 0.8 MeV, which turns out to come from the resonant part, suggests a completely different decay mode. The \(2n\) relative energy at the second peak, 0.8 MeV, almost exhausts the total energy of the \(2^+_1\) state (\(\sim 1.0\) MeV). Therefore, it suggests that two neutrons are emitted to the opposite directions with equally sharing the total energy, i.e., the democratic decay is realized.

The democratic decay of the \(2^+_1\) state is an important finding of the present study. Because of the kinematics of the two neutrons in this mode, it is expected that the FSI plays no important role. In fact, the \(n-n\) interaction favors the virtual state of the \(2n\) system, which corresponds to the first peak in \(d\sigma/d\varepsilon_{n-n}\). Furthermore, the \(n-n\) interaction that favors the sequential decay is also not important in the decay of the \(2^+_1\) state as shown in Fig. 2. Therefore, one can conclude that the second peak in \(d\sigma/d\varepsilon_{n-n}\) is free from the FSI and directly reflects the structural property of the \(2^+_1\) state of \(^6\)He. The di-neutron correlation in a many-body system is characterized by the spatial correlation between the two neutrons, which indicates a relatively high momentum between them. This is consistent with the kinematics corresponding to the democratic decay found in the present study. Thus, the second peak in \(d\sigma/d\varepsilon_{n-n}\) is possible evidence of a di-neutron in the \(2^+_1\) state of \(^6\)He. It should be noted that the existence of the \(2^+_1\) state is, obviously, due to the FSI. What clarified above is that the FSI plays no essential role during the democratic decay, i.e., after the formation of the \(2^+_1\) state.

**Summary.** We investigated the decay mode of the \(2^+_1\) resonant state of \(^6\)He formed by the breakup of \(^6\)He by \(^{12}\)C at 240 MeV/nucleon. The formation and decay processes were described by CDCC and CSLS, respectively. A clear ridge structure was found in the DDBUX corresponding to the \(2^+_1\) resonant energy. Analysis of the invariant mass spectra showed that the sequential decay of the \(2^+_1\) state through \(^6\)He was suppressed because of the small phase space, in contrast to the conclusion of the previous analysis of the Coulomb breakup process. Instead, we found the coexistence of the di-neutron decay and the democratic decay. The former is due to the FSI, while the latter is free from the FSI. The democratic decay is possible evidence of the existence of a di-neutron in the \(2^+_1\) state of \(^6\)He.

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