Study of halo nature via reaction and neutron removal cross sections

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We analyzed the reaction and neutron removal cross sections for $^{14,15,16}\text{C}$ scattering by the continuum-discretized coupled-channels and eikonal reaction theory. In the analysis, breakup effects of $^{15}\text{C}$ is significant to reproduce the experimental data. For $^{16}\text{C}$, we found that main configuration of the ground state is the $d$-dominant, in which the valence two neutrons are in the $0d_{5/2}$-orbit. We also investigated validity of the new definition of $H$. In higher incident energies, we confirmed that the new definition is useful.
1. Introduction

Neutron-rich nuclei near the neutron dripline have exotic properties such as halo structure \([1, 2]\) and shell evolution \([3]\). Elucidation of these properties has been much attracted. The measurement of reaction cross section \(\sigma_R\) is a powerful experimental tool for not only determining matter radii of nuclei but also searching for halo nuclei. In addition, theoretical analyses for \(\sigma_R\) are easier compared with other reactions. Recently \([4, 5, 6, 7]\), we analyzed \(\sigma_R\) for the scattering of Ne and Mg isotopes from a \(^{12}\)C at 240 MeV/nucleon \([8, 9]\) by the double-folding model based on the Melbourne \(g\)-matrix \([10]\) with no free parameter, and well reproduced the experimental data. In the analyses, enhancements of \(\sigma_R\) for \(^{31}\)Ne and \(^{37}\)Mg comparing with neighboring isotopes have been seen, and then \(^{31}\)Ne and \(^{37}\)Mg are expected to be halo nuclei with large deformation.

As other useful tool for investigating halo structure, there is the neutron removal reaction, \(\sigma_{\text{rmv}}\). For halo nuclei, the neutron removal cross section is also enhanced as same as the reaction cross section. The enhancement of \(\sigma_{\text{rmv}}\) corresponds to the weak binding mechanism of halo nuclei, meanwhile the enhancement of \(\sigma_R\) represents the large radius. Thus a lot of experimental studies on measuring of \(\sigma_R\) and \(\sigma_{\text{rmv}}\) have been performed to explore new halo nuclei \([11, 12]\), and the sudden enhancement of \(\sigma_R\) and \(\sigma_{\text{rmv}}\) is one of good indicator of searching of halo nuclei.

For theoretically, the Glauber model \([13]\) has been applied to analyse for \(\sigma_R\) and \(\sigma_{\text{rmv}}\) so far. Recently the eikonal reaction theory (ERT) \([14]\) has been proposed to treat Coulomb breakup effects accurately, which cannot be described by the Glauber model. In ERT, Coulomb breakup processes are described by the continuum-discretized coupled-channels method (CDCC) \([15]\). In this work, we report analyses of \(\sigma_R\) and \(\sigma_{\text{rmv}}\) for \(^{14,15,16}\)C scattering with ERT and CDCC. In the present calculation, \(^{15}\)C is described by the \(^{14}\)C + \(n\) two-body model, and \(^{16}\)C by the \(^{14}\)C + \(n + n\) three-body model. We also discuss the structure of \(^{15}\)C and \(^{16}\)C, and relationship between the enhancement of \(\sigma_{\text{rmv}}\) and the halo structure.

2. Theoretical Framework

For the scattering of \(^{15}\)C and \(^{16}\)C, we assume the \(n + ^{14}\)C two-body model for \(^{15}\)C and the \(n + n + ^{14}\)C three-body model for \(^{16}\)C. The Schrödinger equation for the scattering on a target (T) is defined as

\[
(H - E)\Psi = 0
\]  
(2.1)

for the total wave function \(\Psi\), where \(E\) is an energy of the total system. The total Hamiltonian \(H\) is defined by

\[
H = K_R + U + h,
\]  
(2.2)

where \(h\) denotes the internal Hamiltonian of \(^{15}\)C or \(^{16}\)C, \(R\) is the center-of-mass coordinate of the projectile relative to T. The kinetic energy operator associated with \(R\) is represented by \(K_R\), and \(U\) is the sum of interactions between the constituents in the projectile (P) and T defined as

\[
U = U_n(R_n) + U_{14C}(R_{14C}) + \frac{e^2Z_PZ_T}{R},
\]  
(2.3)
for $^{15}$C and
\[
U = U_{n_1}(R_{n_1}) + U_{n_2}(R_{n_2}) + U_{14C}(R_{14C}) + \frac{e^2 Z_p Z_T}{R}
\]
(2.4)
for $^{16}$C, where $U_x (x = n, n_1, n_2; ^{14}$C) is the nuclear part of the optical potential between x and T as a function of the relative coordinate $R_x$.

The optical potential $U_x$ is constructed microscopically by folding the effective $g$-matrix nucleon-nucleon interaction based on chiral nucleon force [16] with densities of x and T. For $^{14}$C, the matter density is determined by the HFB calculation with the Gogny-D1S interaction [17], where the center-of-mass correction is made in the standard manner [6]. The folding potentials thus obtained include the nuclear-medium effect. CDCC with these microscopic potentials is the microscopic version of CDCC. In CDCC, the total scattering wave function $\Psi$ is expanded in terms of finite number of internal wave functions of P including bound and discretized continuum states. The details of CDCC are shown in Ref. [15].

For the $^{14}$C + n two-body model of $^{15}$C, the Pauli-forbidden states are excluded by the orthogonality condition model (OCM) [18]. The Hamiltonian is
\[
h_2 = K_\rho + V_{nc},
\]
(2.5)
where $K_\rho$ is the kinetic-energy operator with respect to the relative coordinate $\rho$ between n and the core nucleus ($^{14}$C). The interaction $V_{nc}$ between n and $^{14}$C is taken from Ref. [19], and well reproduces properties of the ground and 1st-excited states of $^{15}$C. The matter radius of $^{15}$C predicted by this model is $\bar{r}(^{15}$C) = 2.87 fm that is much larger than $\bar{r}(^{14}$C) = 2.51 fm.

For $^{16}$C, the Hamiltonian is
\[
h_3 = K_{\rho_1} + K_{\rho_2} + V,
\]
(2.6)
which consists of the kinetic-energy operators $K_{\rho_1}$ and $K_{\rho_2}$ with respect to two Jacobi coordinates and the interaction $V$ defined by
\[
V = V_{n_1n_2} + V_{n_1c} + V_{n_2c} + V_3,
\]
(2.7)
where $V_{n_1n_2}$ is the two-nucleon force acting between two valence neutrons, $n_1$ and $n_2$, and $V_{n_1c}$ ($V_{n_2c}$) is the interaction between $n_1$ ($n_2$) and $^{14}$C. We use the Bonn-A two-nucleon force [20] as $V_{n_1n_2}$ and the nucleon–$^{14}$C interaction of Ref. [19] as $V_{n_1c}$ and $V_{n_2c}$. The interaction $V_3$ is the 3BF acting among $n_1$, $n_2$, and $^{14}$C. The three-body wave function of $^{16}$C is antisymmetrized for the exchange between $n_1$ and $n_2$. Meanwhile the exchange between each valence neutron and each nucleon in $^{14}$C is treated approximately by OCM.

For the configuration of valence neutrons of $^{16}$C, we construct two types of the ground state wave function of $^{16}$C by optimizing $V_3$. One is called “the s-dominant”, where the valence two neutrons are in the $1s_{1/2}$ orbit mainly. For another wave function referred as “the d-dominant”, the valence two neutrons are in the $0d_{5/2}$ orbit mainly. The detail of the calculation is shown in Refs. [21], [22]. In the present analysis, we discuss which is better configuration.
3. Results and Discussions

Figure 1 shows reaction cross sections for $^{14,15,16}$C scattering on $^{12}$C and $^{28}$Si targets. For $^{15}$C and $^{16}$C, the open marks show the result without breakup effects, meanwhile the solid marks represent the result calculated by CDCC. For $^{15}$C, one sees that breakup effects are significant to reproduce the experimental data. For $^{16}$C, the triangle and circle show the result with the $s$-dominant and $d$-wave configurations, respectively. Breakup effects for the $s$-dominant are much larger than those for the $d$-dominant, and for $^{28}$Si target the result with the $s$-dominant overestimates the experimental data. As the result, main configuration of valence two neutrons of $^{16}$C is expected to be $(0d_{5/2})^2$.

Figure 1: Reaction cross sections $\sigma_R$ for $^{14,15,16}$C + $^{12}$C scattering at 83 MeV/nucleon (right panel) and for $^{14,15,16}$C + $^{28}$Si at about 50 MeV/nucleon (left panel). The experimental data are taken from Ref. [23] for $^{12}$C target and Ref. [24] for $^{28}$Si target.

In Ref. [25], we proposed a measureable parameter $\mathcal{H}$ quantifying the halo nature of one-neutron halo nuclei. The $\mathcal{H}$ is defined by

$$\mathcal{H} = \frac{\sigma_{\text{abs}}(a) - \sigma_{\text{abs}}(c)}{\sigma_{\text{abs}}(n)},$$

(3.1)

where $\sigma_{\text{abs}}(x)$ means the absorption cross section for a particle $x$, and $a$ is a one-neutron halo nucleus described as the $c + n$ two-body model. We investigated the one-neutron separation energy ($S_n$) dependence of $\mathcal{H}$, and found that the most developed halo represented by $\mathcal{H} = 1$ is realized only for $s$-wave halo nuclei in $S_n = 0$ limit. Thus $\mathcal{H}$ is expected to be a new indicator of the halo structure.

In this paper we propose a new definition of $\mathcal{H}$ with the one-neutron stripping cross section, $\sigma_{1n-\text{str}}$, as

$$\mathcal{H} = \frac{\sigma_{1n-\text{str}}(a)}{\sigma_{\text{abs}}(n)},$$

(3.2)
Figure 2: Comparison of one-neutron stripping cross sections with the difference between absorption cross sections for $^{15}$C and $^{14}$C.

In the Galuber approximation, $\sigma_{1n-str}$ can be approximated by $\sigma_{abs}(a) - \sigma_{abs}(c)$ in high incident energies. To check the validity of the new definition of $H$, we calculate $\sigma_{1n-str}$ for $^{15}$C by using the eikonal reaction theory, and the difference between absorption cross sections for $^{15}$C and $^{14}$C. In Fig. 2, the incident energy dependence of $\sigma_{1n-str}$ (solid circles) and $\sigma_{abs}(^{15}C) - \sigma_{abs}(^{14}C)$ (solid squares) is shown. One sees that the above two cross sections are in good agreement with each other at 200 MeV/nucleon. The difference below 100 MeV/nucleon comes from the breakup cross section mainly. In this analysis, validity of new definition of $H$ is confirmed when the incident energy is higher than 200 MeV/nucleon.

4. Summary

We analyzed the reaction and neutron removal cross sections for $^{14,15,16}$C scattering by the continuum-discretized coupled-channels and eikonal reaction theory. In the present calculation, the reaction cross sections for $^{15}$C is well reproduced by CDCC with breakup effects. Furthermore we found that main configuration of the ground state of $^{16}$C is the $d$-dominant, in which the valence two neutrons are in the $0d_{5/2}$-orbit. Finally, we investigated validity of the new definition of $H$. In higher incident energies, we found that the new definition is useful.

References


