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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}C scattering by the continuum-discretized coupled-channels and eikonal reaction theory. In the analysis, breakup effects of ^{15}C is significant to reproduce the experimental data. For ^{16}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 $\mathscr{H}$. In higher incident energies, we confirmed that the new definition is useful.

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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 $\sigma_{\rm R}$ is a powerful experimental tool for not only determining matter radii of nuclei but also searching for halo nuclei. In addition, theoretical analyses for $\sigma_{\rm R}$ are easier compared with other reactions. Recently [4, 5, 6, 7], we analyzed $\sigma_{\rm R}$ 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 $\sigma_{\rm R}$ 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, $\sigma_{\rm rmv}$. For halo nuclei, the neutron removal cross section is also enhanced as same as the reaction cross section. The enhancement of $\sigma_{\rm rmv}$ corresponds to the weak binding mechanism of halo nuclei, meanwhile the enhancement of σ_R represents the large radius. Thus a lot of experimental studies on measuring of $\sigma_{\rm R}$ and $\sigma_{\rm rmv}$ have been performed to explore new halo nuclei [11, 12], and the sudden enhancement of $\sigma_{\rm R}$ and $\sigma_{\rm rmv}$ is one of good indicator of searching of halo nuclei.

For theoretically, the Glauber model [13] has been applied to analyse for $\sigma_{\rm R}$ and $\sigma_{\rm rmv}$ 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 $\sigma_{\rm R}$ and $\sigma_{\rm rmv}$ 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 $\sigma_{\rm rmv}$ 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

$$(H-E)\Psi = 0 \tag{2.1}$$

for the total wave function Ψ, where E is an energy of the total system. The total Hamiltonian H is defined by

$$H = K_R + U + h, \tag{2.2}$$

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

$$U = U_n(R_n) + U_{^{14}\rm C}(R_{^{14}\rm C}) + \frac{e^2 Z_{\rm P} Z_{\rm T}}{R}, \tag{2.3}$$

for ^{15}C and

$$U = U_{n_1}(R_{n_1}) + U_{n_2}(R_{n_2}) + U_{^{14}\mathrm{C}}(R_{^{14}\mathrm{C}}) + \frac{e^2 Z_{\mathrm{P}} Z_{\mathrm{T}}}{R} \tag{2.4}$$

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 Ψ 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 orthogonalitiy condition model (OCM) [18]. The Hamiltonian is

$$h_2 = K_\rho + V_{n\mathrm{c}}, \tag{2.5}$$

where K_ρ is the kinetic-energy operator with respect to the relative coordinate ρ between n and the core nucleus (^{14}C). The interaction $V_{n\mathrm{c}}$ 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

$$h_3 = K_{\rho_1} + K_{r_1} + V, \tag{2.6}$$

which consists of the kinetic-energy operators K_{ρ_1} and K_{r_1} with respect to two Jacobi coordinates and the interaction V defined by

$$V = V_{n_1 n_2} + V_{n_1\mathrm{c}} + V_{n_2\mathrm{c}} + V_3, \tag{2.7}$$

where $V_{n_1 n_2}$ is the two-nucleon force acting between two valence neutrons, n_1 and n_2, and $V_{n_1\mathrm{c}}$ ($V_{n_2\mathrm{c}}$) is the interaction between n_1 (n_2) and ^{14}C. We use the Bonn-A two-nucleon force [20] as $V_{n_1 n_2}$ and the nucleon–^{14}C interaction of Ref. [19] as $V_{n_1\mathrm{c}}$ and $V_{n_2\mathrm{c}}$. 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 refered 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 [23] and ^{28}Si [24] 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 over-estimates the experimental data. As the result, main configuration of valence two neutrons of ^{16}C is expected to be $(0d_{5/2})^2$.

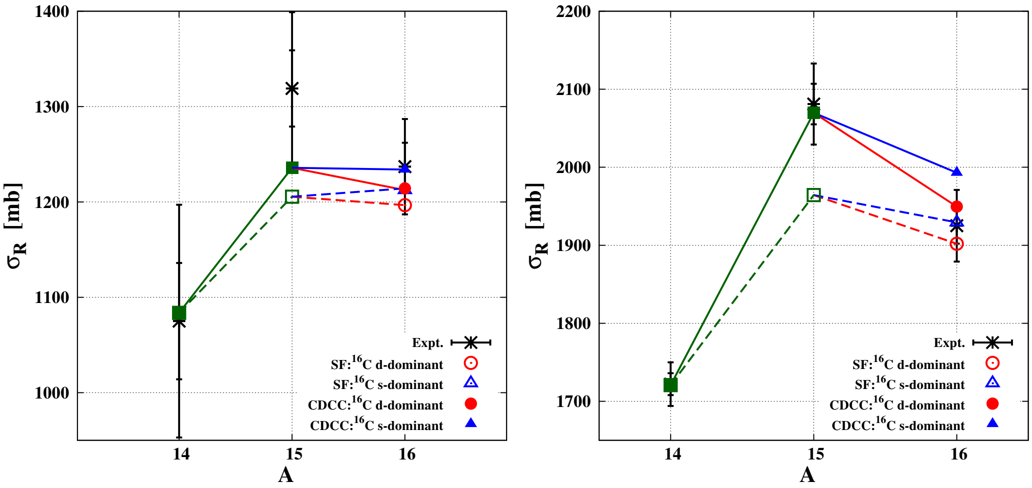

Figure 1: Reaction cross sections $\sigma_{\rm R}$ for ^{14,15,16}C + ^{12}C scattering at 83 MeV/nucleon (right panel) and for ^{14,15,16}C + ^{28}Si at about 50 MeV/nucleon (left panel). The experimental data are taken from Ref. [23] for ^{12}C target and Ref. [24] for ^{28}Si target.

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

$$\mathscr{H} = \frac{\sigma_{\rm abs}(a) - \sigma_{\rm abs}(c)}{\sigma_{\rm abs}(n)}, \tag{3.1}$$

where $\sigma_{\rm abs}(x)$ 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 $\mathscr{H}$, and found that the most developed halo represented by $\mathscr{H}=1$ is realized only for s-wave halo nuclei in $S_n = 0$ limit. Thus $\mathscr{H}$ is expected to be a new indicator of the halo structure.

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

$$\mathscr{H} = \frac{\sigma_{1n\text{-str}}(a)}{\sigma_{\rm abs}(n)}. \tag{3.2}$$

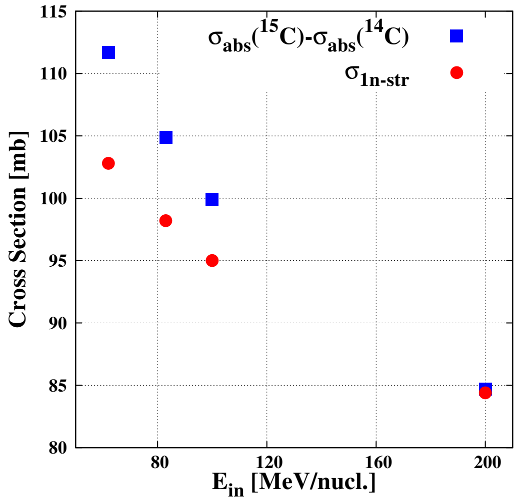

Figure 2: Comparison of one-neutron stripping cross sections with the difference between absorption cross sections for ^{15}C and ^{14}C.

In the Galuber approximation, $\sigma_{1n\text{-str}}$ can be approximated bye $\sigma_{\text{abs}}(a) - \sigma_{\text{abs}}(c)$ in high incident energies. To check the validity of the new definition of $\mathscr{H}$, we calculate $\sigma_{1n\text{-str}}$ 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 $\sigma_{1n\text{-str}}$ (solid circles) and $\sigma_{\text{abs}}(^{15}\text{C}) - \sigma_{\text{abs}}(^{14}\text{C})$ (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 $\mathscr{H}$ is confirmed when the inicident 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. Finaly, we investigated validity of the new definition of $\mathscr{H}$. In higher incident energies, we found that the new definition is useful.

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