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Investigation of the unbound ^{21}C nucleus via transfer reaction

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Abstract. The cross section of the transfer reaction ^{20}C(d,p)^{21}C at 30.0 MeV is investigated. The continuum-discretized coupled-channels method (CDCC) is used in order to obtain the final state wave function. The smoothing procedure of the transition matrix and the channel-coupling effect on the cross section are discussed.

1 Introduction

Interpretation of the properties of unbound nuclei which populate beyond the drip-line or as exited states of unstable nuclei, is one of the most important subjects in nuclear physics. This will be helpful to determine the drip-line in the nuclear chart. Very recently, for example, evidence for an unbound ground state of ^{26}O was reported [1] which could extend the definition of the region for the existence of nuclei to the unbound state region. Unbound nuclei can exist as a product of a nuclear reaction because of their very short life-time compared with that of usual unstable nuclei. Reaction studies are thus important to investigate the properties of unbound nuclei.

In this study we focus on ^{21}C and aim to elucidate a resonance structure and roles of the non-resonant continuum states. Clarification of ^{21}C properties will lead us to deeper understanding of ^{22}C, the neutron drip-line nucleus of carbon isotopes, which contains n-^{20}C subsystems. ^{22}C is known as a Borromean nucleus, like ^{6}He and ^{11}Li, and is considered to be an s-wave two-neutron halo nucleus. One may expect a rather simple n-^{20}C structure for ^{21}C, because in ^{20}C the $d_{5/2}$ sub-shell is closed with a naive shell-model picture.

Because of difficulty in performing n+^{20}C scattering experimentally, we consider the one neutron transfer reaction ^{20}C(d,p)^{21}C in order to investigate ^{21}C, the structure of the n-^{20}C system actually. The interaction between the third particle (proton in this case) and the n-^{20}C system may give coupled-channel (CC) effects on ^{21}C. To describe the ^{21}C energy spectrum reliably, accurate calculation of the transfer cross section is necessary. Couplings between a resonance and non-resonant continuum states of n-^{20}C will particularly be important.

2 Model

The transition matrix in the post form for the neutron transfer reaction ^{20}C(d,p)^{21}C, in the framework of the coupled-channel Born approximation (CCBA), is given by

$$T^{i_0}_{\mathrm{CCBA}} = \left\langle \Psi^{(-)}_{\beta} \middle| V_{\beta} \middle| \Psi^{(+)}_{\alpha} \right\rangle, \tag{1}$$

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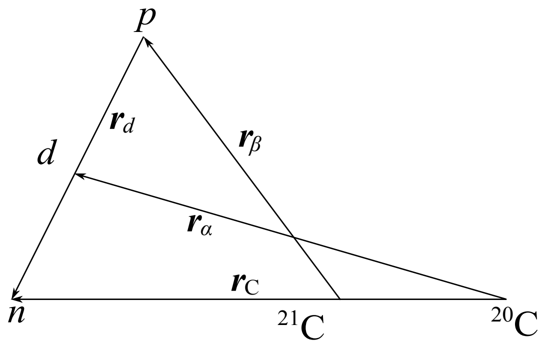

Figure 1. Illustration of the coordinates relevant to the ^{20}C(d,p)^{21}C reaction.

where the initial state wave function $\Psi_\alpha^{(+)}$ is defined by

$$\Psi_\alpha^{(+)} = \psi_d(\boldsymbol{r}_d)\chi_\alpha^{(+)}(\boldsymbol{r}_\alpha). \tag{2}$$

$\chi_\alpha^{(+)}$ is the distorted wave generated by the optical potential U_α between the deuteron and ^{20}C. Definition of the coordinates is given in Fig. 1. The wave function $\Psi_\beta^{(-)}$ in the final channel is obtained by means of the continuum-discretized coupled-channels method (CDCC) [2–4]. In CDCC $\Psi_\beta^{(-)}$ is expanded by a set of the wave functions $\{\psi_{\rm C}^i\}$ of ^{21}C as

$$\Psi_\beta^{(-)} = \sum_i \psi_{\rm C}^i(\boldsymbol{r}_{\rm C})\chi_\beta^{ii_0(-)}(\boldsymbol{r}_\beta), \tag{3}$$

where i is the energy index specifying a discretized continuum state of ^{21}C. The index i_0 indicates the transferred state of ^{21}C in the asymptotic region. Thus, the transition matrix of Eq. (1) describes the transition from the d-^{20}C channel to the p-^{21}C channel in which ^{21}C is located in the i_0th channel. Note that wave functions with $i \neq i_0$ appear in Eq. (3) because of the CC effects. One may obtain $\chi_\beta^{ii_0(-)}$ by solving standard CDCC equations [2–4].

In order to obtain the energy distribution of the transfer cross section, we adopt the smoothing method developed for breakup reactions [5]:

$$\tilde{T}(k,\Omega) = \sum_{i_0} \left\langle \varphi_{\rm C}(k) \middle| \psi_{\rm C}^{i_0} \right\rangle T_{\rm CCBA}^{i_0}, \tag{4}$$

where $\varphi_{\rm C}(k)$ is the scattering wave function between n and ^{20}C with the relative wave-number k, and Ω is the solid angle of the outgoing proton in the center-of-mass frame. The double differential cross section $d^2\sigma/(d\varepsilon d\Omega)$ of the transfer reaction can be calculated with $\tilde{T}(k,\Omega)$ in a straightforward manner; the energy distribution $d\sigma/d\varepsilon$ is obtained by integrating $d^2\sigma/(d\varepsilon d\Omega)$ over Ω.

3 Result

We set the incident energy of deuteron to 30.0 MeV that satisfies the momentum matching for the transition to the $d_{3/2}$ resonance state of ^{21}C. As for the initial channel, we adopt the one-range Gaussian potential V_{pn} [6] that reproduces the deuteron binding energy, and assume that the deuteron wave function ψ_d has only the s-wave component. V_{pn} is chosen as the transition interaction V_β in Eq. (1), and we use the zero range approximation to the form factor in Eq. (1):

$$\psi_d(\boldsymbol{r}_d)V_{pn}(\boldsymbol{r}_d) \rightarrow D_0\delta(\boldsymbol{r}_d), \tag{5}$$

where $D_0 = 1.25\times10^2$ MeV·fm$^{3/2}$. For the optical potential U_α of the d-^{20}C system, the global optical potential [7] is used.

As mentioned above, $\Psi_\beta^{(-)}$ is obtained with CDCC based on the n + ^{20}C+p three-body model. For the n-^{20}C potential $V_{n\mathrm{C}}$, the Woods-Saxon potential [8] that reproduces the ground state property of ^{22}C is adopted. The p-^{20}C optical potential $U_{p\mathrm{C}}$ is calculated microscopically by a single folding model; the Melbourne nucleon-nucleon g-matrix [9] is folded by a ^{20}C density of the Woods-Saxon form. In order to obtain the continuum states of ψ_C^i, we adopt the pseudo state method that expands ψ_C^i with Gaussian basis functions. By diagonalizing the Hamiltonian of the n-^{20}C system, we obtain several eigen states of ^{21}C which we show in the left panel of Fig. 2. Note that in this study we include only the $d_{2/3}$ components of ψ_C^i.

We show in the right panel of Fig. 2 the energy spectrum of the ^{20}C(d,p)^{21}C reaction in an arbitrary unit. The horizontal axis is the relative energy ε between neutron and ^{20}C. The solid and dashed lines are the results of CCBA calculation with and without CC effects, respectively. One sees very small CC effects in the present case. This result suggests that the $d_{3/2}$ resonant state (the ground state) of ^{21}C and the n-^{20}C nonresonant continuum states are well separated during the transfer process. This will be partly due to the resonance energy of about 1.0 MeV of ^{21}C; around this energy the nonresonant neutron in the d-wave hardly penetrates the centrifugal barrier. It will be interesting to see the CC effects when s-wave nonresonant states are taken into account.

The dots and triangles are the results of CCBA for transition to each pseudo state of the n-^{20}C system, with and without CC effects, respectively. One sees clearly the importance of the smoothing

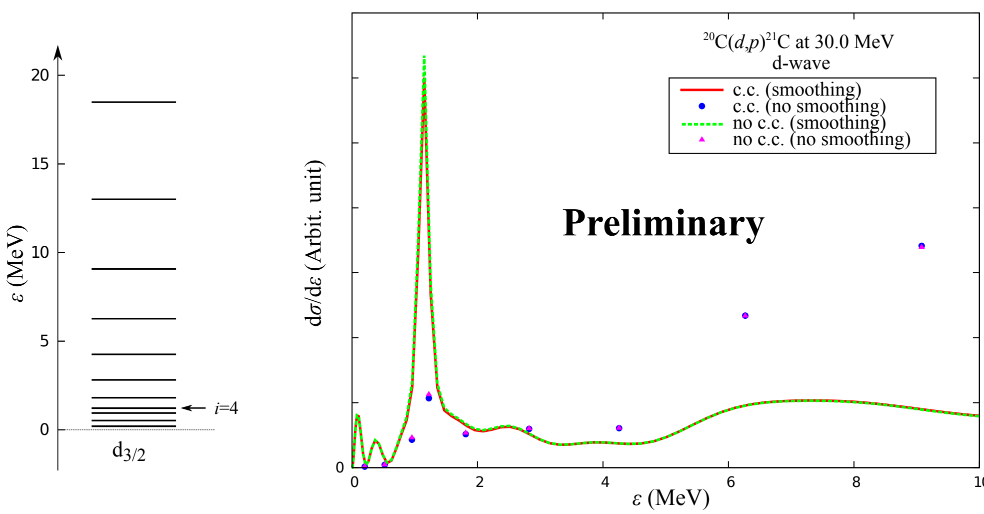

Figure 2. (left panel) The pseudo states of ^{21}C are shown. The fourth state at around 1.2 MeV is the resonant state of the $d_{3/2}$ orbit. (right panel) The transfer cross section of ^{20}C(d,p)^{21}C as a function of the ^{21}C excitation energy. The solid (dashed) line is the smoothed cross section and dots (triangle) corresponds to its value before smoothing with (without) the channel-coupling.

procedure of Eq. (4). It will be very difficult, or almost impossible, to generate the solid (dashed) line by interpolating the dots (triangles), without using Eq. (4).

4 Conclusion

We have calculated the cross section of the transfer reaction ^{20}C(d,p)^{21}C at 30.0 MeV with the CCBA approach. The final state wave function has been obtained by using CDCC that explicitly treats the coupling between the resonant and nonresonant states of the n-^{20}C system. The smoothing procedure was found to be essential to obtain a cross section to be compared with experimental data. The CC effects were found to be negligible in this calculation in which only the d-wave neutron is included.

It is known that there is no convergence of the radial integration of the transition matrix, Eq. (1), in the zero range limit when the residual nucleus is unbound. This is due to the oscillating behavior of the n-^{20}C wave functions in the asymptotic region, and some treatments were suggested [10–12] to resolve this problem. In the present study, we took 80 fm for the space of the n-^{20}C wave function in the pseudo states approach, which could be quite far away from the convergence.

The aforementioned prescription to achieve fast convergence is based on the zero-range approximation. If we perform finite-range calculation, clear convergence is obtained with no special treatment. This extension of the present study is ongoing. Inclusion of the s-wave states of the n-^{20}C system, which is expected to have a virtual state, is another important future work.

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