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Elastic scattering of ^{8}B from ^{12}C with internal three-cluster structure of ^{8}B

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We study theoretically the elastic scattering of ^{8}B from ^{12}C at $E_{\rm lab} = 95$ MeV. The ^{8}B nucleus consists of weakly bound ^{7}Be and proton, while the ^{7}Be nucleus has an internal cluster structure of $\alpha + {}^3$He. We treat the last proton in ^{8}B in the adiabatic recoil approximation and also take into account the excitation of ^{7}Be including resonance states by a coupled-channel method with consideration of the cluster structure. It turns out that the excitation to the resonance state of ^{7}Be in ^{8}B is important for the ^{8}B elastic scattering.

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Owing to the development of radioactive nuclear beams we have now a powerful experimental tool for studying unstable nuclei. Of particular interest is to use a halo nucleus as a projectile and to measure elastic and inelastic scattering cross sections. A halo nucleus has the feature that the binding energy of the last nucleon is extremely small and therefore the spatial extent of the halo nucleon (nucleons) is very large. It is interesting to investigate theoretically the role of the halo nucleon (nucleons) in the elastic and inelastic processes.

It is known that ^{8}B is a typical example of halo nucleus: The binding energy of the last proton is only 0.137 MeV and ^{8}B has a proton halo structure with the core ^{7}Be nucleus [1]. Therefore, some authors have attempted to describe the elastic scattering of ^{8}B by including the $^8{\rm B} \rightarrow {}^7{\rm Be} + p$ breakup effect [2,3]. Meanwhile, this system has another interesting feature that the core ^{7}Be nucleus is also a weakly bound system of $\alpha + {}^3$He, the separation energy of which is 1.583 MeV, and has a well-developed cluster structure. As shown recently for the case of the $\alpha + {}^{12}$C cluster states in ^{16}O [4], the rotational coupling between the well-developed cluster states is considerably strong. Indeed, the ^{7}Be-induced reaction has been analyzed by taking into account the excitation to the $\alpha + {}^3$He cluster states [5], which includes the resonance states, as well as the bound excited one. In this sense, it is interesting to study how these weakly bound systems $p + {}^7$Be and $\alpha + {}^3$He play their roles in the elastic scattering of ^{8}B with a target nucleus, where the breakup energy into the three body-system $\alpha + {}^3{\rm He} + p$ is only 1.72 MeV.

The purpose of this Rapid Communication is to study theoretically the elastic scattering cross section of ^{8}B with ^{12}C at $E_{\rm lab} = 95$ MeV [6] as an example of elastic scattering of halo nuclei with an internal cluster structure of the core. In principle, we should formulate this elastic scattering process in terms of the three-cluster structure of ^{8}B and the target nucleus. This means that we have to deal with a four-body scattering problem, which should be a large-scale calculation. However, the halo property of the ^{8}B nucleus in the elastic scattering reminds us of the study of weakly bound deuteron elastic scattering in terms of the sudden approximation [7]. In this approximation, the elastic scattering amplitude is written as the coherent sum of the proton scattering amplitude with the other neutron as a spectator, and the neutron scattering amplitude with the other proton as a spectator. It was shown that the sudden approximation gave the equivalent result to that of the continuum-discretized coupled-channel (CDCC) calculation [7]. When we apply the sudden approximation to the case of a halo nucleus, the scattering process is described as the sum of the component of the valence nucleon scattering with the core as a spectator, and that of the core with the valence nucleon as a spectator. It is expected that the contribution of the former component is very small compared to that of the latter one owing to the difference of the mass between the core nucleus and the valence nucleon, and therefore, can be dropped off. The similar idea has already been suggested by Johnson *et al.* [8] in the study of elastic scattering of halo nuclei using a new type of adiabatic approximation, which we call as *adiabatic recoil approximation*. In their method, the halo nucleon is treated as a spectator and its effect is treated by the form factor and the recoil effect through the mass difference between the core nucleus and the projectile one (core plus halo nucleon). Namely, the elastic scattering cross section is written in terms of the cross section of the pointlike projectile nucleus with the target nucleus scattering by the core-target interaction and the form factor of the halo nucleon.

As has been mentioned, ^{8}B consists of three clusters. The binding energy of the last proton with the rest ($E_{\rm B} = 0.137$ MeV) is much smaller than that of $\alpha + {}^3$He in ^{7}Be ($E_{\rm B} = 1.583$ MeV), and the spatial extension of the halo proton is much larger than that of the $\alpha + {}^3$He system.

This fact indicates that the halo proton is weakly coupled with ^{7}Be and should act as a spectator in the collision process. Hence, we may be able to apply the adiabatic recoil approximation for the elastic scattering of ^{8}B by assuming the motion of the halo proton is adiabatic in the course of the elastic scattering. However, when one of the two clusters in the core ^{7}Be nucleus make collision with the target nucleus, both

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clusters make strong interaction with one another because they are spatially close. In other words, the cluster structure of the core nucleus ^{7}Be is expected to make a dynamical contribution to the scattering process, and hence, we ought to describe this process in terms of the coupled-channel (CC) approach. Considering the preceding specific feature of ^{8}B, we formulate the ^{8}B elastic scattering and investigate how each dynamical system plays its role in the elastic scattering process.

In the present Rapid Communication, we take the following two steps: adiabatic treatment for the halo nucleon and dynamical treatment of the core nucleus. We first describe the adiabatic recoil approximation [8] to deal with a halo nucleon as spectator, in which the projectile nucleus is treated as a pointlike particle. Here we denote the projectile by $A = C + h$, while the target nucleus is denoted by B. The Hamiltonian of the total system is written as

$$H = T_{\mathbf{R}} + T_{\rho} + V_{Ch} + V_{CB} + V_{hB}, \tag{1}$$

where $T_{\mathbf{R}}$ indicates the kinetic energy between the projectile A and the target B. The interaction between the core nucleus C and the target B is written as V_{CB}, and that between the halo nucleon h and B as V_{hB}. We are then supposed to solve the following Schrödinger equation:

$$H\Psi^{(+)}(\boldsymbol{\rho}, \boldsymbol{R}) = E\Psi^{(+)}(\boldsymbol{\rho}, \boldsymbol{R}), \tag{2}$$

where $\boldsymbol{\rho}$ and $\boldsymbol{R}$ are the relative coordinate between C and h and that between A and B, respectively. When $\boldsymbol{R}$ is sufficiently large, $\Psi^{(+)}(\boldsymbol{\rho}, \boldsymbol{R})$ is written as

$$\Psi^{(+)}(\boldsymbol{\rho}, \boldsymbol{R}) = \varphi(\boldsymbol{\rho})e^{\imath K\cdot R} + \text{ outgoing waves}. \tag{3}$$

Here, $\boldsymbol{K}$ is the relative momentum between the projectile and target nuclei and relates with the total energy E as $E = \frac{\hbar^2\mathbf{K}^2}{2\mu}$, where $\mu = \frac{M_A+M_B}{M_A M_B}$ is the projectile-target reduced mass. The internal wave function $\varphi(\boldsymbol{\rho})$ is obtained by solving the equation

$$(T_{\rho} + V_{Ch})\varphi(\boldsymbol{\rho}) = -\epsilon\varphi(\boldsymbol{\rho}). \tag{4}$$

In the adiabatic recoil approximation, the energies ϵ of all states in the projectile nucleus are replaced with that of the ground state ϵ_0, and interaction between the halo nucleon and the target V_{hB} is dropped off, where the interaction V_{hB} includes the Coulomb potential between the proton and the target. Then Eq. (2) for the three-body scattering problem is now reduced to the equation for easily solvable two-body problem:

$$(T_{\mathbf{R}} + V_{CB} - E_0)\Psi^{(+)}_{AD}(\boldsymbol{\rho}, \boldsymbol{R}) = 0, \tag{5}$$

where $E_0 = E + \epsilon_0$. The total wave function can be written as a factorized form,

$$\Psi^{(+)}_{AD}(\boldsymbol{\rho}, \boldsymbol{R}) = \varphi(\boldsymbol{\rho})e^{ia_h K\cdot\rho}\chi^{(+)}_{\boldsymbol{K}}(\boldsymbol{R}'), \tag{6}$$

where $a_h = \frac{M_h}{M_h+M_C}$, $\boldsymbol{R}'$ is the relative coordinate between C and B, and Eq. (5) is reduced to the equation for $\chi^{(+)}_{\boldsymbol{K}}(\boldsymbol{R}')$ as

$$[T_{\mathbf{R}'} + V_{CB}(\boldsymbol{R}') - E_0]\chi^{(+)}_K(\boldsymbol{R}') = 0. \tag{7}$$

It should be noted that the kinetic energy $T_{\mathbf{R}'}$ contains the projectile-target reduced mass μ, and $\chi^{(+)}_{\boldsymbol{K}}(\boldsymbol{R}')$ describes the elastic scattering of the pointlike projectile nucleus with the reduced mass μ, by the interaction V_{CB}. The T matrix of the elastic scattering is

$$\begin{aligned} T_{\text{el}} &= \int d\boldsymbol{\rho} \int d\boldsymbol{R}\varphi^*(\boldsymbol{\rho})e^{-\imath K'\cdot R}V_{CB}(\boldsymbol{R}')\Psi^{(+)}_{AD}(\boldsymbol{\rho}, \boldsymbol{R}) \\ &= F(\boldsymbol{Q})\left[\int d\boldsymbol{R}'e^{-\imath K'\cdot R'}V_{CB}(\boldsymbol{R}')\chi^{(+)}_K(\boldsymbol{R}')\right]. \end{aligned} \tag{8}$$

Finally, the elastic scattering cross section in the adiabatic recoil approximation is written as

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{el}} = |T_{\text{el}}|^2 = |F(\boldsymbol{Q})|^2\left(\frac{d\sigma}{d\Omega}\right)_{\text{point}}, \tag{9}$$

where

$$F(\boldsymbol{Q}) \equiv \int d\boldsymbol{\rho}|\varphi(\boldsymbol{\rho})|^2 e^{\imath\boldsymbol{Q}\cdot\boldsymbol{\rho}} \tag{10}$$

is the form factor and $\boldsymbol{Q} = a_h(\boldsymbol{K} - \boldsymbol{K}')$. The elastic scattering cross section is expressed as that of the pointlike projectile nucleus with the target multiplied by the form factor of the halo nucleon.

Even after we have expressed the elastic scattering cross section of the ^{8}B + ^{12}C system in the adiabatic recoil approximation in the three-body picture of the ^{7}Be + p + ^{12}C system, we still have to work out the scattering of the ^{7}Be core with the internal cluster structure of α + ^{3}He and the target nucleus ^{12}C as the next step, because dynamical excitation of the α + ^{3}He cluster degree of freedom in ^{7}Be is essentially important [5] in a proper description of ^{7}Be scattering by target nuclei, as discussed earlier. Of course, the scattering wave function of this step is in principle different from $\chi^{(+)}_K(\boldsymbol{R}')$ of Eq. (7), because $\chi^{(+)}_K(\boldsymbol{R}')$ is for the elastic scattering of the pointlike ^{8}B projectile nucleus with an inert ^{7}Be core. Instead of solving Eq. (7), we solve the CC equations considering the excitation effect of the ^{7}Be nucleus, and the resultant elastic scattering cross section is substituted into the pointlike projectile nucleus scattering cross section $(\frac{d\sigma}{d\Omega})_{\text{point}}$ in Eq. (9).

Before proceeding to this step, we first analyze the experimental data of ^{7}Be elastic scattering to test the validity of the present CC framework. To include the dynamical effect of ^{7}Be in the ^{7}Be + ^{12}C elastic scattering, we solve the CC equation

$$\begin{aligned} &\left[-\frac{\hbar^2}{2\mu'}\nabla'^2 + U_{\beta\beta}(\mathbf{R}') - (E_0 - \epsilon_\beta)\right]\tilde{\chi}_\beta(\mathbf{R}') \\ &\quad = \sum_{\beta'\neq\beta} U_{\beta\beta'}(\mathbf{R}')\tilde{\chi}_{\beta'}(\mathbf{R}'), \end{aligned} \tag{11}$$

where $\mu' = \frac{M_C+M_B}{M_C M_B}$ (core-target reduced mass), β and β' represent channels labeled by the states of ^{7}Be, and $U_{\beta\beta'}(\mathbf{R}')$ represents the diagonal ($\beta = \beta'$) or coupling ($\beta' \neq \beta$) potential. For ^{12}C, we only consider the ground state, because its excitation effect is expected to be small compared with the ^{7}Be excitation effect [5,9]. In the present study, the real part of the nuclear potential is given by the double-folding model (DFM). Generally, the DFM potential consists of the direct and exchange parts as

$$V_{\beta\beta'} = \sum_{i\in C, j=\in B} [\langle ij|v_D|ij\rangle + \langle ij|v_{EX}|ji\rangle] = V^D_{\beta\beta'} + V^{EX}_{\beta\beta'}. \tag{12}$$

The direct part is written in the form as

$$V^D_{\beta\beta'}(\mathbf{R}') = \int \rho^C_{\beta\beta'}(\boldsymbol{r_1})\rho^B(\boldsymbol{r_2})v_D(\rho, E/A, s)\, d\boldsymbol{r_1}d\boldsymbol{r_2}, \tag{13}$$

where $\mathbf{s} = \mathbf{r}_2 - \boldsymbol{r}_1 + \mathbf{R}'$, and the exchange part is

$$V^{EX}_{\beta\beta'}(\mathbf{R}') = \int \rho^C_{\beta\beta'}(\boldsymbol{r_1}, \boldsymbol{r_1} + \boldsymbol{s})\rho^B(\boldsymbol{r_2}, \boldsymbol{r_2} - \boldsymbol{s})v_{EX}(\rho, E/A, s) \times \exp\left\{\frac{ik(\boldsymbol{R}')\cdot s}{\mu'}\right\} d\boldsymbol{r_1}d\boldsymbol{r_2}. \tag{14}$$

In Eqs. (13) and (14), $\rho^C_{\beta\beta'}$ represents the transition density between the state in the channel β and that in the channel β' of the core nucleus C (^{7}Be), while ρ^B represents the ground-state density of the target nucleus B. The density matrix $\rho(\mathbf{r}, \mathbf{r}')$ in Eq. (14) is approximated in the same manner as in Ref. [10]

$$\rho(\mathbf{r}, \mathbf{r}') = \frac{3}{k^{\rm eff}_F \cdot s} j_1\left(k^{\rm eff}_f \cdot s\right)\rho\left(\frac{\mathbf{r}+\mathbf{r}'}{2}\right), \tag{15}$$

where $k^{\rm eff}_f$ is the effective Fermi momentum [11] defined by

$$k^{\rm eff}_F = \left\{(3\pi^2\rho)^{2/3} + \frac{5C_s[\nabla\rho^2]}{3\rho^2} + \frac{5\,\nabla^2\rho}{36\rho}\right\}^{1/2}, \tag{16}$$

where we adopt $C_s = 1/4$ following Ref. [12]. For the effective nucleon-nucleon potential, we adopt the CDM3Y6 interaction [13]. Because CDM3Y has no imaginary part, we assume that the shape of the imaginary part is that of the real potential. Then, the diagonal or coupling potential is written as

$$U_{\beta\beta'}(R') = (1 + \imath N_W)V_{\beta\beta'}(R') + V^{\rm coul}_{\beta\beta'}(R'), \tag{17}$$

where $V^{\rm coul}_{\beta\beta'}(R')$ is the double-folded Coulomb potential, and N_W is the normalization factor for the imaginary potential, which is determined phenomenologically.

In the CC calculation, we include the ground ($\frac{3}{2}^-$), $\frac{1}{2}^-$, $\frac{7}{2}^-$, and $\frac{5}{2}^-$ states in ^{7}Be. The former two states are bound states, while the latter ones are resonance states. Their diagonal and transition densities are given by the following procedure: Because it is known that ^{7}Be has a well-developed $\alpha + {}^3$He cluster structure, we first assume that the ^{7}Be wave function is written as

$$\Phi^C_{I\ell} = \phi^D\left[\phi^E_{\frac{1}{2}} \times \varphi^{(I)}_\ell(\boldsymbol{r})\right]_I, \tag{18}$$

where $\phi^D(\phi^E_{\frac{1}{2}})$ is the α(^{3}He) cluster wave function of Gaussian type with an appropriate size. The ^{3}He has a half intrinsic spin $\phi^E_{\frac{1}{2}}$ and couples with the relative wave function $\varphi^{(I)}_\ell(\boldsymbol{r})$ between α and ^{3}He to total spin I. Thus, the two bound states and the two resonance states mentioned earlier are the spin doublet in the $2p$ state ($\ell = 1$) and that in the $1f$ state ($\ell = 3$), respectively, where we take into account the Pauli principle between the clusters. We assume that $\varphi^{(I)}_\ell(\boldsymbol{r})$ can be obtained by a simple potential model calculation, namely, the separation energy method, in which the potential geometry is assumed to be the Woods-Saxon type for the central part and the Thomas type with the Woods-Saxon form factor for the spin-orbit part. The potential parameters for the ground and $\frac{1}{2}^-$ states are determined so as to reproduce the separation energies to α and ^{3}He, the values of which are 1.58 and 1.14 MeV for the $\frac{3}{2}^-$ and $\frac{1}{2}^-$ states, respectively, and the root-mean-square matter radius of the ground state is 2.40 fm. The potential parameters are listed in Table I, which gives the quadrupole moment of the ground state $Q_m = -5.36$ fm^2 and electric transition strength $B(E2, \text{g.s.} \to \frac{1}{2}^-) = 15.3\ e^2$ fm^4 (where g.s. stands for ground state). These results are similar to those of the RGM (resonating-group-method) calculation [14]: $Q_m = -4.89$ fm^2 and $B(E2, \text{g.s.} \to \frac{1}{2}^-) = 22.7\ e^2$ fm^4. For the remaining resonance states ($\frac{7}{2}^-$ and $\frac{5}{2}^-$), the potential parameters are determined so as to reproduce the $\alpha + {}^3$He scattering phase shifts [15], including the resonance energies 3.12 and 5.16 MeV, and we use the momentum-bin prescription in the CDCC method [9] to make a wave packet. Using the obtained ^{7}Be wave function $\Phi^C_{I\ell}$, the diagonal or transition density is defined as

TABLE I. The potential parameters for α-^{3}He relative motion. $V_{\rm ce}$ and $V_{\rm ls}$ are the strength parameters for the central part and the spin-orbit part, respectively. The quantities R_0 and R_C are the radii of the nuclear potential and of the Coulomb potential and a_0 is the diffuseness parameter.

	$V_{\rm ce}$ (MeV)	$V_{\rm ls}$ (MeV)	R_0 (fm)	R_C (fm)	a_0 (fm)
$3/2^-, 1/2^-$	93.8	4.0	2.05	2.05	0.70
$7/2^-, 5/2^-$	90.0	7.0	2.05	2.05	0.70

$$\rho^C_{\beta\beta'}(\boldsymbol{r}_1) = \left\langle\Phi^C_{I\ell}\right|\sum_i \delta(\boldsymbol{r_i} - \boldsymbol{r}_1)\left|\Phi^C_{I'\ell'}\right\rangle. \tag{19}$$

The quantum numbers associated with the spins are indicated by β in the left-hand side of Eq. (19). The density matrix in Eq. (15) is given by the density calculation (19). ρ^B in Eqs. (13) and (14) is the ground-state density of ^{12}C, for which we use the one obtained by the 3α RGM calculation [16].

First, we study the elastic scattering of the ^{7}Be nucleus from the target nucleus by solving the preceding CC equation. Because the experiment was performed with a mixed target of ^{12}C and ^{14}N [6], we calculate the elastic scattering cross sections for both ^{12}C and ^{14}N targets and sum them with the appropriate ratio. The ^{14}N density is derived from the observed electron-scattering charge form factor. The normalization factor N_W for the imaginary potential in Eq. (17) is assumed to be common for the ^{12}C and ^{14}N targets, and is chosen as 0.2 by fitting the full CC calculations to the experimental data. The calculated results are smeared with an angular resolution of 1° and are shown in Fig. 1. The dot-dashed curve represents the result of the single-channel calculation, while the dotted, dashed, and solid curves represent those of the CC calculations adding the excitation channels one by one. The solid curve is the full-channel calculation. It is found that the effect of

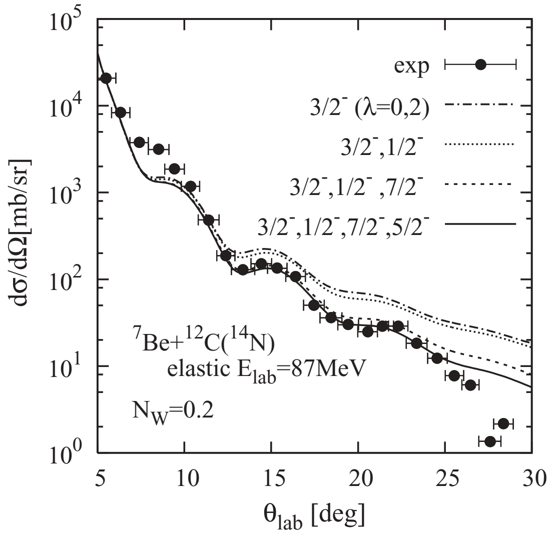

FIG. 1. The elastic scattering cross section of ^{7}Be with ^{12}C and ^{14}N targets. The solid circles are the experimental data, which are taken from Ref. [6]. The dot-dashed curve represents the result of the single-channel calculation, while the dotted, dashed, and solid curves represent those of the CC calculations adding the excited states one by one.

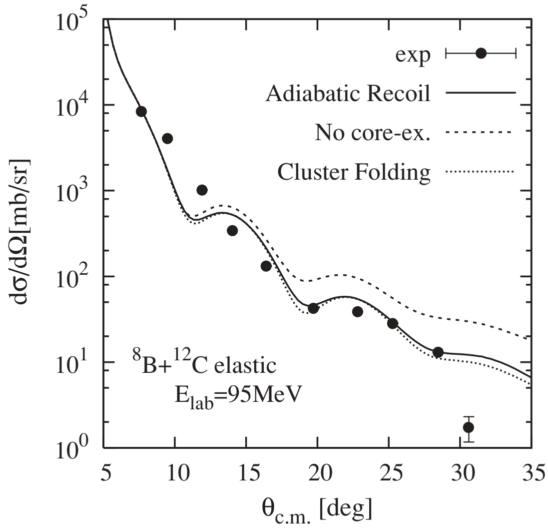

FIG. 2. The elastic scattering cross section of ^{8}B with ^{12}C calculated using the adiabatic recoil approximation. The experimental data (solid circles) are taken from Ref. [6], where the natural carbon target is used. The solid curve shows the result of the full calculation including the excitation of the core ^{7}Be nucleus, while the dashed curve does not include the excitation of the core ^{7}Be nucleus. The dotted curve shows the results of the calculation with cluster folding model under the same Hamiltonian of the adiabatic recoil approximation.

the CCs is important for bringing down the cross section at the backward angles. Among the three states, the excitation to the resonance state with $\frac{7}{2}^-$ is found to have the largest contribution to the elastic scattering.

We seem to miss slightly the cross sections around 8°.

Based on the preceding results, we proceed to the next step: We calculate the elastic scattering of ^{8}B with a ^{12}C target at $E_{\rm lab} = 95$ MeV by using the adiabatic recoil approximation. To obtain the pointlike projectile cross section $(\frac{d\sigma}{d\Omega})_{\rm point}$ in Eq. (9), we solve the same CC equation as the $^7\mathrm{Be} + {}^{12}\mathrm{C}$ case except for the reduced mass μ (instead of μ') and the incident energy $E_{\rm lab} = 95$ MeV (instead of $E_{\rm lab} = 87$ MeV). The form factor $F(\boldsymbol{Q})$ in Eq. (10) is calculated from the $p + {}^7\mathrm{Be}$ wave function $\varphi(\boldsymbol{\rho})$, the size of which is chosen as $\langle\rho^2\rangle^{\frac{1}{2}} = 4.51$ fm [17]. The result is shown in Fig. 2. The calculated angular distribution is smeared with an angular resolution of 0.7°. The solid curve represents the result where the pointlike projectile cross section is obtained by solving the full CC calculation and is found to reproduce the experimental data (solid circles). To see the excitation effect of ^{7}Be in the process of the ^{8}B elastic scattering, we also show the cross section obtained by using the pointlike projectile cross section with the single-channel calculation by the dashed curve. Comparing the solid and dashed curves, it is found that the core excitation effect is significant at backward angles in the ^{8}B elastic scattering.

We also study the proton breakup effects ($^8\mathrm{B} \to {}^7\mathrm{Be} + p$). To estimate the effect of the $^8\mathrm{B} \to {}^7\mathrm{Be} + p$ breakup process on the $^8\mathrm{B} + {}^{12}\mathrm{C}$ elastic scattering, we perform the cluster folding model calculation for the $({}^7\mathrm{Be} + p) + {}^{12}\mathrm{C}$ system. As for the potential between ^{7}Be and ^{12}C, we use the Woods-Saxon type, and the parameters of which are determined so as to reproduce the result of the full CC calculation as shown by the solid curve in Fig. 1. In the search process, we use the computer code ALPS [18]. Here, we drop the contribution of the $p + {}^{12}\mathrm{C}$ potential for the cluster folding calculation so that we can compare this calculation with the adiabatic recoil approximation under the same assumption of Hamiltonian. Inclusion of the $p + {}^{12}\mathrm{C}$ potential is found to give a small change on the cross section at the forward angle. This fact shows that the contribution of the p-^{12}C Coulomb potential, which is dropped under the adiabatic recoil approximation, causes a smaller cross section at the forward angle. This approximation to drop the Coulomb potential of the halo proton cannot be used for elastic scattering with heavy nuclei as ^{208}Pb, because the Coulomb interaction becomes much larger than the light target case considered here. The cluster folding model calculation with the preceding $^7\mathrm{Be} + {}^{12}\mathrm{C}$ potential includes the excitation effect of ^{7}Be but does not include the $^8\mathrm{B} \to {}^7\mathrm{Be} + p$ breakup effect. The result is shown by the dotted curve in Fig. 2. The difference between the solid and dotted curves is smaller than that between the solid and dashed curves especially at the backward angles, which indicates that the $^8\mathrm{B} \to {}^7\mathrm{Be} + p$ breakup effect is not crucial in the ^{8}B elastic scattering process, compared with the excitation effect of ^{7}Be.

Finally, we show that the result does not depend largely on the size of the halo in Fig. 3. The solid, dashed, and dotted curves represent the results with the form factors of the halo wave function, the sizes of which are $\langle\rho^2\rangle^{\frac{1}{2}} = 4.51$ [17], 3.73 [19], and 5.49 fm [20], respectively. From these results of Figs. 2 and 3, it seems that the contribution of the valence proton to the elastic scattering is small in spite of the small separation energy. This implies that the conclusion on the minor role of the $^8\mathrm{B} \to {}^7\mathrm{Be} + p$ breakup effect on the elastic

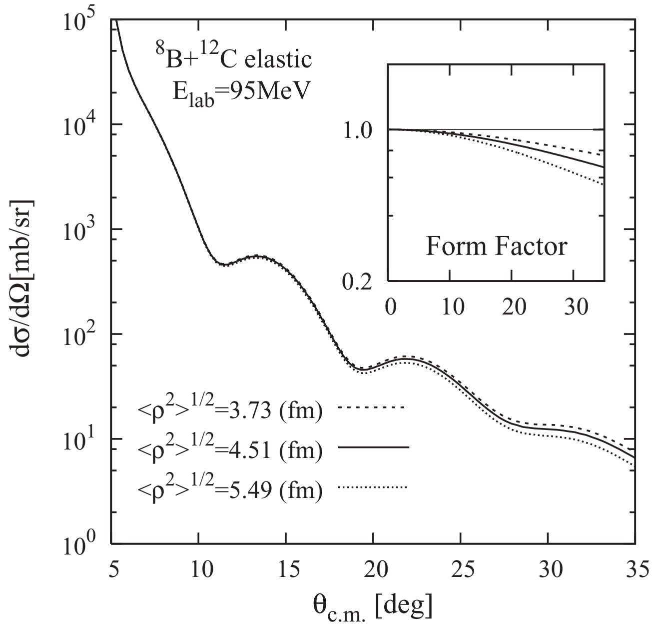

FIG. 3. The elastic scattering cross section of ^{8}B with ^{12}C calculated using the adiabatic recoil approximation. The solid, dashed, and dotted curves represent the results with the form factors of the halo wave function, the sizes of which are $\langle \rho^2 \rangle^{\frac{1}{2}} = 4.51$ [17], 3.73 [19], and 5.49 fm [20], respectively. The inset shows the corresponding form factors.

scattering will not change by a more detailed treatment of the ^{8}B internal structure as an $\alpha + {}^3$He $+ p$ three-body system. Hence, it is essential to take into account the cluster structure of ^{7}Be and describe the inelastic excitation of the internal cluster states for the description of ^{8}B elastic scattering.

In summary, we have studied the elastic scattering of ^{8}B from ^{12}C at $E_{\rm lab} = 95$ MeV. The interesting feature of ^{8}B is the halo structure of the last proton, which has the binding energy of $E_{\rm B} = 0.137$ MeV. At the same time, the core nucleus ^{7}Be itself has a cluster structure with α and ^{3}He, whose binding energy is 1.583 MeV. Although, in principle, we should treat the fragility of these three internal clusters $\alpha + {}^3$He $+ p$ all together, the difference of the binding energies between the $p + {}^7$Be and $\alpha + {}^3$He systems enables us to treat them in the different approaches: The fact that the state of the proton halo is especially fragile motivates us to use the adiabatic recoil approximation. However, ^{7}Be has an internal cluster structure and the low-lying intrinsic states are considered in the CC method. Although the elastic scattering of the halo proton with the target nucleus contributes only slightly, the core ^{7}Be nucleus excitation to the resonance state is found to be important in the scattering process of ^{8}B.

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