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Effect of halo structure on ^{11}Be + ^{12}C elastic scattering

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Abstract. The $^{11}\mathrm{Be} \to {}^{10}\mathrm{Be} + n$ breakup effect on $^{11}\mathrm{Be} + {}^{12}\mathrm{C}$ elastic scattering at $E/A = 49.3\,\mathrm{MeV}$ is studied by continuum-discretized coupled-channels (CDCC) method based on the $^{10}\mathrm{Be} + n + {}^{12}\mathrm{C}$ three-body model. The CDCC calculation well reproduces the experimental data of the elastic scattering, and the breakup effect of the ^{11}Be nucleus is found to be significant. Furthermore, the reaction dynamics of the $^{11}\mathrm{Be} \to {}^{10}\mathrm{Be} + n$ breakup process is investigated and a dynamical polarization potential (DPP) is evaluated.

PACS. 25.60.-t Reactions induced by unstable nuclei – 24.10.Eq Coupled-channel and distorted-wave models – 25.60.Bx Elastic scattering

Nuclear reactions involving neutron-rich nuclei have been one of the most important subjects in nuclear physics. Particularly in light neutron-halo nucleus induced reactions, it is very interesting to investigate how the halo structure affects the reaction mechanism. Due to the weakly-bound nature, the projectile halo nucleus would be easily excited into core-plus-neutron breakup states by the nuclear and Coulomb fields of target nucleus. Therefore, the breakup process is expected to play an important role in the halo nucleus induced reaction.

One of the practical and reliable methods to study the three-body reaction process is the continuum-discretized coupled-channels (CDCC) method [1]. In this paper, we apply the CDCC method to investigate the $^{11}\mathrm{Be} \to {}^{10}\mathrm{Be} + n$ breakup effect on the elastic scattering of ^{11}Be by ^{12}C at $E/A = 49.3\,\mathrm{MeV}$. Our aim is to study the dynamical effect of the halo structure on the nuclear reaction mechanism in the full quantum mechanical framework.

In the present calculation, the $^{10}\mathrm{Be} + n$ internal wave functions are calculated by the Woods-Saxon form potential with geometry $r_0 = 1.00\,\mathrm{fm}$ and $a_0 = 0.53\,\mathrm{fm}$. The depths V_0 is adjusted ℓ-dependently to reproduce the binding energy of the ground state $(2s, -0.503\,\mathrm{MeV})$ for s-wave, the first excited state $(1p, -0.183\,\mathrm{MeV})$ for p-wave, and the resonance energy $(1.275\,\mathrm{MeV})$ for d-wave, respectively. The potential depth for f-wave is taken to be the same as that for p-wave. Here, the spin-orbit interaction is neglected for simplicity. The continuum states of $^{10}\mathrm{Be} + n$ relative motion up to $1.2\,\mathrm{fm}^{-1}$ are taken into account and are discretized into momentum bins of widths $\Delta k = 0.133\,\mathrm{fm}^{-1}$ for s-, p- and f-waves, while for d-wave $\Delta k = 0.157\,\mathrm{fm}^{-1}$, which is determined not to divide the resonance peak at $E_\mathrm{r}(^{11}\mathrm{Be}) = 1.275\,\mathrm{MeV}$ into two bins. The discretized states are treated as usual discrete excited states in the same manner of the ordinary coupled-channels theory. The diagonal and coupling potentials of the $^{11}\mathrm{Be} + {}^{12}\mathrm{C}$ system are calculated by folding the ^{10}Be-^{12}C and n-^{12}C optical potentials with the bound-state and discretized-continuum-state wave functions of the $^{10}\mathrm{Be} + n$ system. The parameters of optical potentials are taken from ref. [2].

Figure 1 shows differential cross-section angular distributions (ratio to Rutherford) of the $^{11}\mathrm{Be} + {}^{12}\mathrm{C}$ elastic scattering at $E/A = 49.3\,\mathrm{MeV}$. The solid curve shows the result of the CDCC calculation, and the dotted curve shows the result of the single-channel calculation using the folding-model interaction. The experimental data [3] represented by the solid circles are found to be well reproduced by the CDCC calculation. The difference between the single-channel and CDCC calculations indicates that the breakup effect on the elastic scattering is significant. From further analysis, it is found that the couplings to the second ($\hat{E}_x = 0.954\,\mathrm{MeV}$, where $\hat{E}_x$ represents the mean energy of the bin) and third ($\hat{E}_x = 2.592\,\mathrm{MeV}$) bins of the p-wave continuum state as well as the d-wave resonance state have important contribution to the breakup effect. The large effect of resonance state is reasonable because of the large overlap of the resonance wave function with

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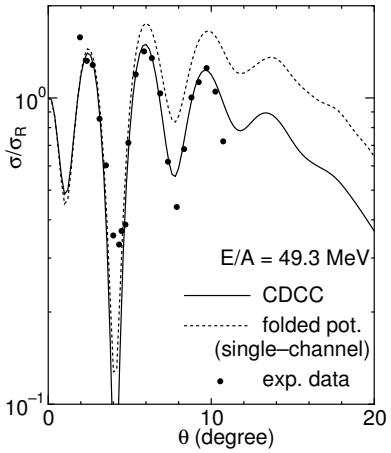

Fig. 1. Angular distribution for $^{11}\mathrm{Be} + ^{12}\mathrm{C}$ elastic scattering at $E/A = 49.3\,\mathrm{MeV}$. The solid circles are the experimental data, and the dotted and solid curves represent the results of the single-channel and CDCC calculations, respectively.

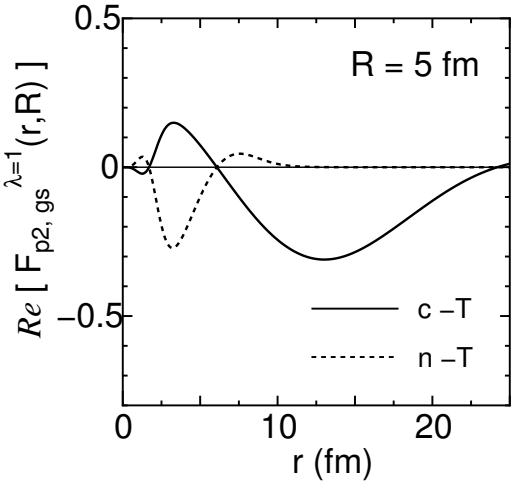

Fig. 2. The real part of $F^{\lambda=1}_{p2,\mathrm{g.s.}}(r,R)$ defined in eq. (1) as a function of the separation r between neutron and core nucleus. R represents the separation between the center-of-mass of ^{11}Be and target nucleus, and is fixed at $R = 5.0\,\mathrm{fm}$. The solid and dotted curves represent the core-target (c-T) and neutron-target (n-T) components, respectively.

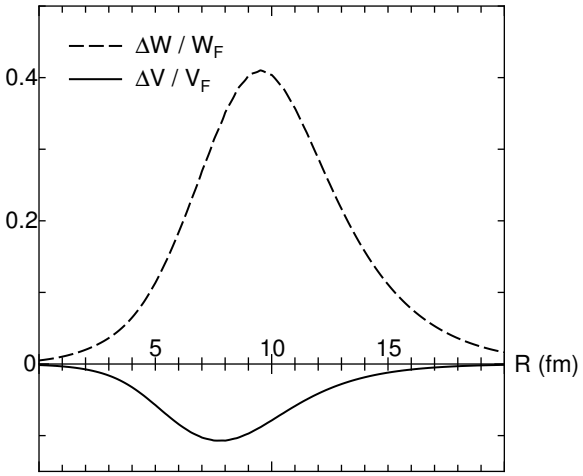

Fig. 3. Ratio of a dynamical polarization potential to the folded potential. The solid and dashed curves represent the real and imaginary parts, respectively.

the ground-state one. However, the overlap integral of the continuum wave function with the ground-state one is not so large in general.

To clarify the reason why the p-wave continuum breakup state has a large contribution, we investigate the coupling potential. Here, we discuss only the second bin of the p-wave continuum state ($p2$). First, we define a function $F^{\lambda=1}_{p2,\mathrm{g.s.}}(r,R)$ as

$$F^{\lambda=1}_{p2,\mathrm{g.s.}}(r,R) = \Phi_{p2}(r)\; V_1(r,R)\; \Phi_{\mathrm{g.s.}}(r), \qquad (1)$$

where $V_1(r,R)$ represents the potential between core (^{10}Be) and target (c-T), or that between neutron and target (n-T) with multipolarity $\lambda = 1$. r and R represent the separation between core and neutron, and that between the center-of-mass of ^{11}Be and target nucleus, respectively. $\Phi_\alpha(r)$ is the $^{10}\mathrm{Be} + n$ wave function in state α (α represents g.s. or $p2$). Integrating $F^{\lambda=1}_{p2,\mathrm{g.s.}}(r,R)$ over r and summing the c-T and n-T components, we obtain the coupling potential between the ground state and the second bin of p-wave continuum state as a function of R.

Figure 2 shows the real part of $F^{\lambda=1}_{p2,\mathrm{g.s.}}(r,R)$ as a function of r. R is fixed at 5.0 fm. It is found that the c-T component represented by the solid curve has a large amplitude in the long-range region, while the n-T components represented by the dotted curve is localized in the short-range region. Since these two components are summed up in the calculation of the coupling potential, the short-range parts cancel each other. However, the long-range part of the c-T component survives, resulting in comparable magnitude of coupling potential with that between the ground state and the d-wave resonance breakup state. This large amplitude of the c-T component is due to the long-range tail of the valence neutron wave function of the ground state. Namely, the large contribution from the p-wave breakup state reflects the characteristic of the weakly bound halo structure of the ^{11}Be nucleus.

In order to see the breakup effect of ^{11}Be shown in fig. 1 in the potential form, we evaluate dynamical polarization potential (DPP). We search effective potential of the form $U_{\mathrm{eff}} = U_{\mathrm{F}} + \Delta U$, which reproduces the result of the CDCC calculation in the single-channel framework and, consequently, simulates the breakup effect. Here, U_{F} denotes the folded potential for the elastic channel, which is the same as used in the CDCC calculation. We assume the Woods-Saxon derivative form for both the real (ΔV) and imaginary (ΔW) parts of ΔU and their parameters are searched by using a computer code ALPS [4]. The evaluated DPP is shown in fig. 3 as ratio to the folded potential. The DPP has a weakly repulsive real part (solid curve) and a long-range imaginary part of absorptive nature (dashed curve). These results also show a characteristic of the weakly-bound neutron-halo structure of the projectile nucleus.

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