Four- and three-body breakup mechanism of $^6$Li elastic scattering

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Abstract. We investigate a breakup mechanism of $^6$Li elastic scattering on heavy targets ($T = ^{209}$Bi or $^{208}$Pb) with the four-body version of the continuum-discretized coupled-channels method (four-body CDCC). Four-body CDCC successfully reproduces measured elastic cross sections with no adjustable parameter, and we can then clearly discuss the four-body dynamics.

Our analysis shows that $d\alpha$ breakup ($^6$Li + $T \rightarrow d + \alpha + T$) is much more essential than $np\alpha$ breakup ($^6$Li + $T \rightarrow n + p + \alpha + T$) in $^6$Li scattering.

1. Introduction

In reactions of weakly-bound nuclei, projectile breakup plays an important role and the treatment of projectile-breakup effects is essential to describe scattering. The continuum-discretized coupled-channels method (CDCC) was proposed as a method for treating breakup effects [1, 2, 3]. Nowadays, CDCC is applied to not only three-body scattering (two-body projectile + $T$) but also four-body scattering (three-body projectile + $T$) [4, 5, 6, 7], where $T$ denotes a target. CDCC for three- and four-body scattering are now called three- and four-body CDCC, respectively.

$^6$Li + $^{209}$Bi scattering near the Coulomb barrier energy ($E_{\text{Coul}} \approx 30$ MeV) was first analyzed with three-body CDCC based on the $d+\alpha + ^{209}$Bi three-body model [8]. However, the calculation could not reproduce the measured elastic cross section without introducing a normalization factor for the optical potentials. This problem was solved by four-body CDCC based on the $n + p + \alpha + ^{209}$Bi four-body model [6]. The four-body calculation describes the experimental data without introducing any adjustable parameter. As an interesting finding, we showed that three-body CDCC can reproduce the cross section if the phenomenological $d$-optical potential is replaced by the single-folding potential that does not include $d$-breakup effects [6]. This suggests that $d$ (i.e. the $n$-$p$ subsystem of $^6$Li) hardly breaks up during $^6$Li scattering. In this work, we investigate the breakup mechanism within the four-body CDCC framework and validate the evidence.

2. Decomposition of the CDCC model space

We only recapitulate the treatment of model space in four-body CDCC; see Ref. [3, 7] for the detail. In four-body CDCC, the Schrödinger equation is solved in the model space $P$ spanned by
the ground and discretized-continuum states of $^{6}$Li: $P = \sum_{\gamma=0}^{N} \langle \Phi_{\gamma} |$, with $\Phi_{\gamma}$ represents the $\gamma$-th eigenstate, and the $\gamma = 0$ and $\gamma = 1-N$ correspond to the ground and discretized-continuum states, respectively. The $\Phi_{\gamma}$ are obtained as pseudostates by using the Gaussian expansion method [9].

In this paper, we investigate the breakup mechanism by restricting the model space $P$. For this purpose, we first specify whether the breakup state $\Phi_{\gamma}$ ($\gamma = 1-N$) is the $d_{\alpha}$-dominant or $np_{\alpha}$-dominant breakup state by calculating the squared overlap between $\Phi_{\gamma}$ and the $d_{\alpha}$ ground state $\phi_{(d\alpha)}$: $\Gamma_{\gamma}^{(d_{\alpha})} = |\langle \phi_{(d\alpha)} | \Phi_{\gamma} \rangle|^{2}$. If $\Gamma_{\gamma}^{(d_{\alpha})}$ is larger (smaller) than 0.5, the state is defined as a $d_{\alpha}$-dominant state $\Phi_{\gamma}^{(d_{\alpha})}$ ($np_{\alpha}$-dominant state $\Phi_{\gamma}^{(np_{\alpha})}$). With the $d_{\alpha}$- and $np_{\alpha}$-dominant state above, the CDCC model space $P$ can be decomposed into the three parts $P = P_{0} + P_{d_{\alpha}} + P_{np_{\alpha}}$, where

$$P_{0} = \langle \Phi_{0} |, P_{d_{\alpha}} = \sum_{\beta} |\Phi_{\beta}^{(d_{\alpha})} \rangle \langle \Phi_{\beta}^{(d_{\alpha})} |, P_{np_{\alpha}} = \sum_{\delta} |\Phi_{\delta}^{(np_{\alpha})} \rangle \langle \Phi_{\delta}^{(np_{\alpha})} |. \quad (1)$$

In the following discussion, we calculate cross sections by switching on and off to clarify the reaction dynamics.

3. Results

First, we show the validity of four-body CDCC. Figure 1 shows the angular distribution of elastic cross section for $^{6}$Li + $^{209}$Bi scattering at 32.8 MeV. The three-body CDCC calculation (dashed line) underestimates the experimental data as reported in Ref. [8]. We then apply four-body CDCC in order to explain this discrepancy. Four-body CDCC (solid line) perfectly reproduces the experimental data without introducing any adjustable parameter. $^{6}$Li + $^{209}$Bi scattering near the Coulomb barrier energy is thus described by four-body CDCC. Therefore, we can clearly discuss the breakup mechanism below.

![Figure 1.](image)

Next, we show $^{6}$Li + $^{208}$Pb scattering at 39 MeV in Fig 2, which is almost the same as $^{6}$Li + $^{209}$Bi scattering at 32.8 MeV. The solid and dotted lines correspond to the full and 1ch calculations, respectively. These are nothing but the calculations in $P$ and $P_{0}$, respectively. The difference comes from breakup effects and the full calculation reproduces the experimental data well by virtue of breakup effects.

Now, we switch on only the subspace $P_{np_{\alpha}}$ or $P_{d_{\alpha}}$ from $P_{0}$ in order to investigate the breakup mechanism. The dot-dashed line (a) represents the calculation of $P_{0} + P_{np_{\alpha}}$ and it is close to 1ch calculation (dotted line). On the other hand, the dashed line (b) corresponds to the calculation of $P_{0} + P_{d_{\alpha}}$ and it simulates the full calculation (solid line) almost perfectly. It should be noted
that the number of $d\alpha$-dominant states is much less than that of $np\alpha$-dominant states in the present model space $P$. As seen above, $d\alpha$ breakup is favored in $^6$Li scattering. This property is now called $d\alpha$-dominance, and we have found that the $d\alpha$-dominance is realized in a wide energy range [7]. It has been thus confirmed that $d$ (i.e. the $n$-$p$ subsystem of $^6$Li) hardly breaks up during $^6$Li scattering.

![Figure 2](image)

**Figure 2.** (Color online) Elastic cross sections for $^6$Li + $^{208}$Pb scattering at 39 MeV. The solid and dotted lines correspond to the results of full and 1ch calculations, respectively. The dot-dashed line (a) represents the calculation with the model space $P_0 + P_{np\alpha}$, whereas the dashed line (b) shows the calculation with $P_0 + P_{d\alpha}$. The experimental data is taken from Ref. [12].

4. Summary
We have investigated four-body dynamics of $^6$Li elastic scattering ($n+p+\alpha+T$, $T = ^{209}$Bi or $^{208}$Pb). The elastic scattering are successfully described in the four-body CDCC framework without introducing any adjustable parameter. We can then clearly analyze the breakup mechanism. Our analysis shows that the $d\alpha$-dominant breakup is much more essential compared with the $np\alpha$-dominant breakup for describing the scattering ($d\alpha$-dominance). This justifies the fact that $d$ (i.e. the $n$-$p$ subsystem of $^6$Li) hardly breaks up during $^6$Li scattering.

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