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# Four- and three-body channel coupling effects on $^6$Li elastic scattering with CDCC

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**Abstract.** We investigate breakup dynamics in $^6$Li elastic scattering on heavy targets (T = $^{209}$Bi or $^{208}$Pb) near the Coulomb barrier energy. Since the subsystem of $^6$Li has a bound state as deuteron ($n + p = d$), a four-body channel ($^6$Li + T $\rightarrow n + p + \alpha +$ T) and a three-body channel ($^6$Li + T $\rightarrow d + \alpha +$ T) get entangled during scattering as a breakup channel. Both channels are precisely treated with the four-body version of the continuum-discretized coupled-channels method (four-body CDCC). Four-body CDCC well reproduces measured elastic cross sections with no adjustable parameter. We then estimate the channel coupling effects by dividing the breakup channel into four- and three-body channels. It is found that $^6$Li breakup is mainly induced by a three-body channel.

## 1 Introduction

Projectile breakup is essential in reactions of weakly-bound nuclei and appears as a strong coupling effect between elastic and breakup channels. The continuum-discretized coupled-channels method (CDCC) was proposed for treating various kinds of channels including breakup (continuum) channels [1–3]. The coupling effect was first confirmed in deuteron scattering and later verified in halo nuclei near the drip-line in which a two-body projectile + target (T) three-body problem was assumed. Nowadays, CDCC is widely applied to describe three-body dynamics.

Our interest is now going to four-body dynamics in scattering of three-body projectiles. CDCC for three- and four-body scattering are now called three- and four-body CDCC, respectively. It is interesting to consider the difference of four-body scattering between $^6$He and $^6$Li as typical examples. Since $^6$He is a Borromean nucleus in which no binary subsystem is bound, only a four-body channel ($^6$He + T $\rightarrow n + n + \alpha +$ T) exists as a breakup channel. This property makes four-body dynamics relatively simpler and this is the reason why four-body CDCC was first applied to $^6$He scattering [4, 5]. On the other hand, $^6$Li has a bound state in the $n + p$ subsystem. Therefore, not only a four-body channel ($^6$Li + T $\rightarrow n + p + \alpha +$ T) but also a three-body channel ($^6$Li + T $\rightarrow d + \alpha +$ T) exists in its breakup channel. This situation makes it more difficult to understand four-body dynamics of $^6$Li scattering.

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$^{6}$Li + $^{209}$Bi scattering near the Coulomb barrier energy ($E_{\rm b}^{\rm Coul} \approx 30$ MeV) was first analyzed with three-body CDCC based on the $d+\alpha$ + $^{209}$Bi three-body model [6]. However, the calculation could not reproduce the measured elastic cross section without a normalization factor 0.8 to $d$-$^{209}$Bi and $\alpha$-$^{209}$Bi optical potentials. This problem was solved by four-body CDCC based on the $n + p + \alpha$ + $^{209}$Bi four-body model [7]. The calculation well describes the experimental data with no adjustable parameter. As an interesting result, it was reported that $d$ breakup in $^{6}$Li is strongly suppressed during the elastic scattering. In this work, we focus on four-body dynamics of $^{6}$Li elastic scattering from the point of view of four- and three-body channel coupling effects.

## 2 Theoretical framework and Model Hamiltonian

We recapitulate four-body CDCC based on the $n + p + \alpha$ + T four-body model; see Ref. [3, 7] for the detail. The scattering state $\Psi$ with the total energy $E$ is governed by the four-body Schrödinger equation with the model Hamiltonian $H_4$:

$$(H_4 - E)\Psi = 0, \qquad H_4 = K_{\boldsymbol{R}} + U_n + U_p + U_\alpha + \frac{e^2 Z_{\rm Li} Z_{\rm T}}{R} + h_{np\alpha}, \tag{1}$$

where $K_{\boldsymbol{R}}$ stands for the kinetic energy operator with respect to the relative coordinate $\boldsymbol{R}$ between $^{6}$Li and T, and $U_x$ ($x = n, p, \alpha$) represents the optical potential between $x$ and T. Since Coulomb-breakup effects are negligibly small for the present elastic scattering [6, 7], the Coulomb part of $U_p$ and $U_\alpha$ is then approximated into $e^2 Z_{\rm Li} Z_{\rm T}/R$, where $Z_{\rm A}$ is the atomic number of nucleus A. $h_{np\alpha}$ denotes the internal Hamiltonian of $^{6}$Li in the three-cluster model. In CDCC, Eq. (1) is solved in the model space $P$ spanned by the ground and discretized continuum states of $^{6}$Li:

$$P = \sum_{\gamma=0}^{N} |\Phi_\gamma\rangle \langle\Phi_\gamma| , \tag{2}$$

where $\Phi_\gamma$ represents the $\gamma$-th eigenstate with eigenenergy $\varepsilon_\gamma$; note that the $\gamma = 0$ and $\gamma = 1$–$N$ correspond to the ground and excited states in $P$, respectively. The $\Phi_\gamma$ are obtained by diagonalizing $h_{np\alpha}$ with the Gaussian basis functions [8].

In order to disentangle breakup dynamics, we divide the CDCC model space $P$ in the following way. $P$ can be decomposed into the ground-state part $P_0$ and the breakup-state part $P^*$ as $P = P_0 + P^*$ for

$$P_0 = |\Phi_0\rangle \langle\Phi_0| , \quad P^* = \sum_{\gamma=1}^{N} |\Phi_\gamma\rangle \langle\Phi_\gamma| . \tag{3}$$

For later discussion, $P^*$ is further divided into a subspace $P_{np\alpha}$ dominated by $np\alpha$ configurations and a subspace $P_{d\alpha}$ by $d\alpha$ configurations. The subspaces are defined as follows. The probability of $d\alpha$ configurations in the breakup state $\Phi_\gamma$ is obtained by the overlap between $\Phi_\gamma$ and the $d$ ground state $\phi^{(d)}$: $\Gamma_\gamma^{(d\alpha)} = \left|\langle\phi^{(d)}|\Phi_\gamma\rangle\right|^2$. We then define a breakup state with $\Gamma_\gamma^{(d\alpha)} > 0.5$ ($\Gamma_\gamma^{(d\alpha)} \leq 0.5$) as a $d\alpha$-dominant ($np\alpha$-dominant) state. The subspace $P_{d\alpha}$ ($P_{np\alpha}$) is a model space spanned by $d\alpha$-dominant ($np\alpha$-dominant) breakup states. Consequently, the model space $P$ of CDCC calculations is expressed as

$$P = P_0 + P_{d\alpha} + P_{np\alpha}. \tag{4}$$

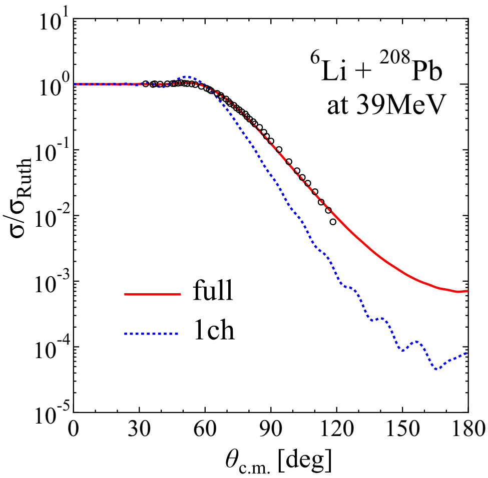


**Figure 1.** (Color online) Elastic cross sections (normalized by the Rutherford cross section) for $^6$Li + $^{208}$Pb scattering at 39 MeV. The solid line represents the result of four-body CDCC calculation with full channel coupling, whereas the dotted line shows the result of 1ch calculation with no channel coupling. The experimental data is taken from Ref. [11].

## 3 Results

We only show the results of $^6$Li+$^{208}$Pb elastic scattering at 39 MeV; see Ref. [7] for the analysis of $^6$Li+$^{209}$Bi scattering and the detail of model setting. As for $U_n$, we take the potential of Koning and Delaroche [9] determined from the measured elastic cross section of $n$ + $^{209}$Bi. For simplicity, the spin-orbit interaction is neglected and $U_p$ is assumed to have the same geometry as $U_n$. The potential $U_\alpha$ is taken from Ref. [10] determined from measured differential cross sections of $\alpha$ + $^{209}$Bi scattering at 19–22 MeV.

The angular distribution of elastic cross sections for $^6$Li + $^{208}$Pb scattering at 39 MeV are plotted in Fig 1. The one-channel (1ch) calculation with no breakup (dotted line) underestimates the experimental data, whereas the four-body CDCC calculation (solid line) reproduces the experimental data. The enhancement from the dotted to solid lines is induced by channel coupling effects, indicating $^6$Li breakup effects are quite important. Thus, $^6$Li scattering on heavy targets are well described by four-body CDCC with no adjustable parameter.

Next, we consider four- and three-body channel coupling effects on the present $^6$Li scattering. For this purpose, the subspaces $P_{d\alpha}$ and $P_{np\alpha}$ are switched off from the full calculation, respectively. Figure 2 shows the angular distribution for $^6$Li + $^{208}$Pb scattering at 39 MeV, and the solid and dotted lines are the same as in Fig. 1. When the model space is limited to $P_0 + P_{np\alpha}$, the dot-dashed line is obtained [see Fig. 2(a)] and close to the result of 1ch calculation (dotted line). On the other hand, when the model space is limited to $P_0 + P_{d\alpha}$, we have the dashed line [see Fig. 2(b)] that well simulates the full calculation (solid line). Note that the number of $d\alpha$-dominant states in $P$ is as few as about one-eighth of that of $np\alpha$-dominant states. The result indicates that the coupling between $P_0$ and $P_{d\alpha}$ is dominant. In other words, $^6$Li breakup is mainly induced by the $d + \alpha$ breakup, and the $d$-breakup is suppressed in $^6$Li scattering.

## 4 Summary

We have analyzed the four-body dynamics of $^6$Li elastic scattering. The elastic scattering of $^6$Li + $^{208}$Pb at 39 MeV is well described by four-body CDCC based on the $n + p + \alpha$ + $^{208}$Pb model. The breakup channels are approximately divided into four- and three-body channels and the coupling effects are estimated. $^6$Li breakup is mainly caused by a strong transition between the elastic ($P_0$)

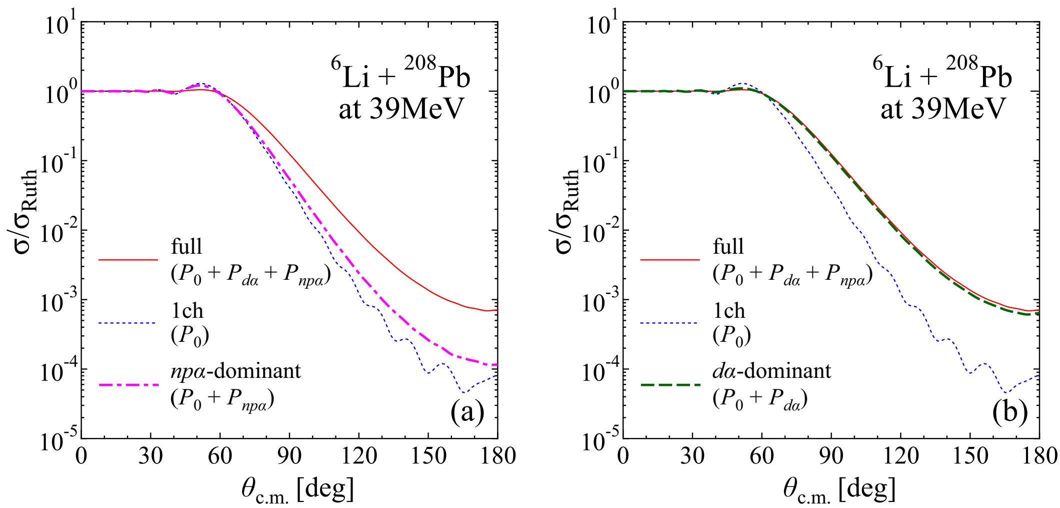


**Figure 2.** (Color online) Elastic cross sections (normalized by the Rutherford cross section) for $^6$Li + $^{208}$Pb scattering at 39 MeV. The solid (dotted) line represents the result of full (1ch) calculation. The dot-dashed line in the panel (a) shows the calculation in which the model space is limited to $P_0 + P_{np\alpha}$, whereas the dashed line in the panel (b) denotes the one with $P_0 + P_{d\alpha}$.

and three-body channel ($P_{d\alpha}$), suggesting $d$-breakups effect are suppressed in $^6$Li scattering. We will investigate what causes the suppression, and the energy and target dependence in the forthcoming paper.

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