Resonance and non-resonance effect of continuum states of $^6$Li on elastic scattering angular distributions

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Abstract. CDCC calculations of elastic scattering angular distributions for reactions of the weakly bound projectile $^6$Li with targets $^{28}$Si and $^{58}$Ni at energies around the Coulomb barrier are presented. Special emphasis is given to account for the effect of couplings from $^6$Li resonance states $l = 2, J^\pi = 3^+, 2^+, 1^+$. Similarly, the effect produced by non-resonant state couplings is studied. The convergent calculations are carried out with global $\alpha$-target and $d$-target interactions. The calculated elastic scattering angular distributions are in general in good agreement with the measurements for the systems considered in this work. It is found that the calculations with only resonance states are very similar to that with all couplings (resonance+non-resonance). So, the absence of these states have a strong effect on elastic scattering (non-resonance states calculation). It is shown that the effects increase as the collision energy increases. An interpretation of the strength of the different effects is given in terms of the polarization potentials that emerge from the different couplings.

1. Introduction

Reaction mechanisms involving weakly bound nuclei, both stable and radioactive, have been a subject of strong research [1, 2, 3]. One of the most interesting topics, is the effect of breakup on elastic scattering and fusion reaction mechanisms. It is now known that couplings of the elastic channel to continuum breakup states of the weakly bound projectile, as well as, continuum-continuum couplings are essential to fit the experimental data. This is so since, couplings to and between continuum states give rise to a strong repulsive polarization potential that decreases fusion absorption. Besides the non-capture breakup process, other nuclear mechanisms are present for reactions with weakly bound nuclei. For instance, sequential and direct complete fusion, incomplete fusion and nucleon transfer. Coupled channel calculations show that couplings between the incident elastic channel to fusion ones, give place to an attractive dynamical polarization potential $V_F$ that lowers the nominal Coulomb barrier $V_B$. So, the net effect of $V_F$ is to enhance fusion mainly for energies around the barrier. Similarly, couplings to breakup channels produce a repulsive dynamical polarization potential $V_{BU}$, that is particularly strong at energies below the barrier. In this energy range, $V_{BU}$ overcomes $V_F$, so that the net effect is twofold: a) An increase in the fusion barrier, that leads to a net fusion suppression, and b) Most of the reaction cross section is accounted for the breakup process. Probably, one of the most appropriate method to calculate the effect of breakup on elastic and fusion reaction mechanisms of weakly bound systems is the Continuum Discretized Coupled-Channel (CDCC)
This approach has been applied to a large range of weakly bound nuclear systems, for instance; 2n-halo $^6$He on $^{49}$Co and $^{208}$Pb [6, 7], $^6$Li with targets $^{28}$Si, $^{50}$Co, $^{58}$Ni, $^{144}$Sm and $^{208}$Pb [4, 6, 8, 9, 10, 11, 12, 13]. Also, for $^7$Li with $^{28}$Si [14, 15] and $^{144}$Sm [16], the n-halo $^{11}$Be with $^{208}$Pb [17] and the p-halo $^8$B with $^{58}$Ni [10, 18]. In CDCC calculations for reactions with the weakly bound $^6$Li, this is portrayed with a $\alpha - d$ cluster structure [6, 19]. Ground, resonant ($l = 2, j^x = 3^+, 2^+, 1^+$) and non-resonant states are included. Resonance states are identified with energies, $\varepsilon_{3+} = 0.71$ MeV, $\varepsilon_{2+} = 2.83$ MeV, $\varepsilon_{1+} = 4.18$ MeV (above threshold) and widths $\Gamma_{3+} = 0.024$ MeV, $\Gamma_{2+} = 1.7$ MeV and $\Gamma_{1+} = 1.5$ MeV respectively.

In the CDCC model, the continuum space is discretized in a finite number of states up to a maximum energy $\epsilon_{\text{max}}$, the energy discretization is carried out with energy step $\Delta \epsilon$, maximum relative angular momentum $l_{\text{max}}$ between the breakup fragments where tests of convergence of the calculations respect to these quantities are performed. The purpose of the present work is to calculate the effect on elastic scattering angular distributions, of the resonant continuum states of the weakly bound nucleus $^6$Li$\rightarrow d + \alpha$, in reaction with the $^{28}$Si and $^{58}$Ni targets at energies around the Coulomb barrier. This is achieved by following two different processes: (a) omitting the discrete states belonging to the resonances from the whole continuum spectrum, b) Consider only resonance discrete states, that is omit non-resonance ones. In this manner, we can disentangle the importance of couplings to resonance states in the CDCC calculations. On the same footing, the polarization potentials associated with couplings to resonance states are calculated and the effect of resonance couplings on elastic scattering is explained in terms of these potentials.

Systematic global d-target and $\alpha$-target interactions, which depend on the target mass $A$ and incident collision energy $E_{\text{lab}}$ are used in the calculations. Woods-Saxon potentials of Ref. [20] are used for the $d$-target interaction $V_{dT}$. The parameterization of these potentials has been obtained by a large analysis of experimental elastic and inelastic cross sections for reactions of deuteron with a large variety of nuclear target masses ($12 < A < 238$) and of incident energies ($E_{\text{lab}} < 183$ MeV). On the other hand, the density dependent double-folding Sao Paulo potential (SPP) [21] with adequate $\alpha$-particle mass densities, is used to describe the $\alpha$-target interaction $V_{\alpha T}$. The non-local SPP has been widely used with success to describe elastic and inelastic scattering, as well as, nucleon transfer cross sections for a number of nuclear systems. An extensive systematics of nuclear densities has been performed in Ref. [22] to produce a parameter-free interaction. In our calculations, the $\alpha$-target interaction depends also only on the target mass $A$ and kinetic energy of the $\alpha$-particle respect to the initial incident energy of $^6$Li. As for the $\alpha - d$ cluster structure of $^6$Li, use is made of the Woods-Saxon parameterization given in Ref. [19]. Ground, unbound resonant and non-resonant continuum scattering states of $^6$Li are generated with this interaction.

The paper is organized as follows. In section 2, a brief description of the CDCC formalism is given. Section 3 addresses the CDCC calculations for elastic scattering angular distributions, polarization potentials and how the effect of resonant continuum states of $^6$Li is calculated. Finally, a summary is given in section 4.

2. CDCC formalism for a three-body system

A detailed description of the CDCC formalism is given in Refs. [4, 5]. In this paper we present only the basic equations that are required to perform our calculations. We consider the two-body cluster model structure of $^6$Li ($\alpha$-d) with ground state energy $E_{g.s.} = -1.47$ MeV. The model space for continuum states is that given in Ref. [19], where convergence at energies above the barrier has been checked. The wave function for breakup continuum states of $^6$Li reads as,

$$\psi_{ij}^P(r, k) = \{Y_{lm}(\hat{k}) \otimes \chi_{\mu \sigma \sigma'}\}_{ij} \frac{\varphi_{lsj}(r, k)}{r},$$

(1)
where the internal wave function of the \( \alpha-d \) system is \( \chi_{ I_{\mu s}} \), with \( I = 0 \) and \( s = 1 \). \( \varphi_{lsj}(r,k) \) describes the \( \alpha-d \) relative radial motion with asymptotic wave-number \( k \), orbital angular momentum \( l \) and total angular momentum \( j \).

The continuum states \( \varphi_{lsj}(r,k) \) in Eq. (1) are not square-integrable. However, Ref. [4] provides a recipe for constructing square-integrable wave functions known as bin states. A bin state, \( u^{(i)}_{\beta}(r) \), is made of scattering wave functions within a given interval \( i \), of continuum \( k \) values, \( k_{i-1} < k < k_{i} \), i.e.,

\[
u^{(i)}_{\beta=lsj}(r) = \sqrt{\frac{2}{\pi \eta}} \int_{k_{i-1}}^{k_{i}} w_{i}(k,l)e^{-i\delta_{k}(l)} \varphi_{lsj}(r,k)dk,
\]

where \( \delta_{k}(l) \) are scattering phase-shifts of \( \varphi_{\beta} \) and \( w_{i}(k,l) \) are weight functions defined by,

\[
\eta_{i} = \int_{k_{i-1}}^{k_{i}} |w_{i}(k,l)|^2 dk.
\]

Actually, the weight functions \( w_{i} \) associated to non-resonant bin states are usually set as \( w_{i}(k,l) = 1 \), while for resonant states \( w_{i}(k,l) = \sin[\delta_{k}(l)] \).

The total wave function of the three-body system (\( \alpha-d\)-target) is given by,

\[
\Psi(R,r) = \sum_{\beta} F_{\beta}(R)\psi_{\beta}^{ P}(r)\Phi_{\beta}^{T},
\]

where \( \Phi_{\beta}^{T} \) and \( F_{\beta}(R) \) correspond to the inert target and projectile-target relative motion in the \( \beta \)-channel respectively. Projecting the equation of motion of the system onto the projectile states \( \beta \), the following coupled equations are obtained,

\[
\left[ \hat{T}_{R} + U^{(J)}_{\beta\beta}(R) - (E - \varepsilon_{\beta} - \varepsilon_{T}) \right] F^{(J)}_{\beta}(R) = -\sum_{\beta'} U^{(J)}_{\beta\beta'}(R)F^{(J)}_{\beta'}(R).
\]

Here, \( \varepsilon_{T} \) and \( \varepsilon_{\beta} \) are the internal energies of the target and projectile in the \( \beta \)-state. \( U^{(J)}_{\beta\beta}(R) \) and \( U^{(J)}_{\beta\beta'}(R) \) are the radial dependent diagonal and non-diagonal matrices of the interaction potentials \( \hat{V}_{dT} + \hat{V}_{\alpha T} \). These are given by,

\[
U^{(J)}_{\beta\beta'}(R) = < u_{\beta} \left| \hat{V}_{dT} + \hat{V}_{\alpha T} \right| u_{\beta'} >,
\]

where the integration is carried out over the internal radial coordinate \( r \) and the angular coordinates of \( R \). The left-hand side of Eq.(6) are diagonal continuum couplings, in particular the term \( U^{(J)}_{00}(R) \) corresponds to the optical potential in the elastic channel. The right-hand side of Eq.(6) corresponds to off-diagonal continuum couplings.

### 3. Effect of non-resonance and resonance states

In this section CDCC calculations of elastic scattering angular distributions are presented for the projectile \( ^{6}\text{Li} \) with targets \( ^{28}\text{Si} \) and \( ^{58}\text{Ni} \), for incident energies just above the corresponding Coulomb barriers. The calculations are performed with the code FRESCO [23], where care is taken of the radial parameters \( R_{j} \) of the \( \hat{V}_{dT} \) interaction. This is so, since in the code FRESCO, the general relation \( R_{j} = r_{j}(A_{1}^{1/3} + A_{2}^{1/3}) \) is considered while a shorter \( R_{j} = r_{j}A^{1/3} \) is used in Ref. [20] where \( A_{1} = 2 \) and \( A \) the target mass. To calculate the ground, resonant \( (l = 2, j_{\pi} = 3^{+}, 2^{+}, 1^{+}) \) and non-resonant discrete breakup states of \(^{6}\text{Li} \), we used the parameterization given in Ref. [19] for the interaction \( V_{ad}(r) \).
Table 1. Calculated values (MeV) for resonance energies and widths of $^6$Li

| Res | $E_{cal}$ | $\Gamma_{cal}$ | $E_{exp}$ | $\Gamma_{exp}$ |
|-----|-----------|---------------|-----------|---------------|
| $3^+$ | 0.73 | 0.034 | 0.716 | 0.024 |
| $2^+$ | 3.09 | 1.3 | 2.84 | 1.7 |
| $1^+$ | 4.67 | 4.2 | 4.18 | 1.5 |

The discretization of the continuum is made as follows; the maximum angular momentum for the relative motion of the $\alpha - d$ fragments is $l_{max} = 3$, larger values do not have any effect on the calculations. So, bin states for $l = 0, j^\pi = 1^+$ and $l = 1, j^\pi = 0^-, 1^-, 2^-$ are constructed with step $\Delta \varepsilon = 0.5$ MeV up to $\varepsilon_{max} = 6.8$ MeV. Finer and variable steps are used for resonant states $l = 2, j^\pi = 3^+, 2^+, 1^+$, so as to obtain centroid excitation energies and widths close to the corresponding measured values. Table 1 shows the calculated values with the interaction $V_{\alpha d}$ of Ref. [19].

For bin states $l = 3, j^\pi = 4^+, 3^+, 2^+$, a larger step $\Delta \varepsilon = 1.0$ MeV is used. Convergence tests at $\varepsilon_{max} = 7.0, 7.5$ and $8.0$ MeV were done with no effect on elastic angular distributions. Similarly, larger steps $\Delta \varepsilon = 0.75$ and $1.0$ MeV were used with no appreciable effect on elastic scattering. Coulomb potential multipoles are included up to $L_Q = 4$. As regards the normalization coefficients of the interaction $V_{\alpha T}$, we set these as $N_R = 1$ and $N_I = 0.78$. This

Figure 1. (Color online) (a) Elastic scattering angular distribution for $^6$Li+$^{28}$Si (solid-line) at $E_{lab} = 11$ MeV and elastic channel calculation without couplings to continuum states (dotted line). Data taken from Refs. [24, 25, 26, 27]. (b) Calculations with non-resonant (dashed-dotted line) and resonant (dashed-line) discretized states. (c) Polarization potentials for the full (solid-line), non-resonant (dashed-dotted line) and resonant (dashed-line) discretized spaces. (d) Percentage effects of non-resonant (dashed-dotted line) and resonant (dashed-line) discretized states.
values are the result of a large systematic analysis of elastic scattering data of many nuclear systems performed by L.C. Chamon et al., Refs. [21, 22]. So, here we assume these values.

The solid line in Fig.1a shows the CDCC calculation including all couplings, for elastic scattering of $^6$Li with $^{28}$Si at $E_{lab} = 11$ MeV. This energy $E_{c.m.} = 9.05$ MeV is slightly above the Coulomb barrier $V_B = 6.7$ MeV. The experimental data are those reported in Refs. [24, 25, 26, 27]. The dotted line represents the calculation with only the elastic channel coupling, that is, only the term $U_{\beta=0\theta=0}^{(f)}(R)$ is considered in Eq.(6). This result, far from the data, was already expected, since it is well known that couplings to continuum states are essential to achieve agreement with the data. The dashed-dotted line of Fig.1b, represents the calculation when the excited states in the region of the resonances are ignored, that is, when couplings to and among these states are omitted in Eq.(5). It is observed that the omission of these states has some effect on elastic scattering (solid-line) at large angles. The dashed-line corresponds to the calculation where only couplings among resonant discretized are considered. This calculation is closer to the full calculation with all couplings. This result shows clearly that resonant state couplings play a very important role in the description of the elastic scattering data.

In Fig.1c, we show the results for the polarization potentials that emerge from couplings from the three kinds of calculations, i.e., all couplings (full-line), resonance states (dashed-line) and among non-resonance states (dashed-dotted line). The results were obtained using the prescription given in Ref. [23]. All polarization potentials have very small strength but the potential that emerges from calculations including only resonant states (dashed-dotted line) is more repulsive than that for non-resonant states (dashed-line).

Fig.1d shows the calculation for $S_i(\theta)$, defined as,

$$S_i(\theta) = \{[(\frac{\sigma_{el}}{\sigma_{Ruth}})_{F}(\theta) - (\frac{\sigma_{el}}{\sigma_{Ruth}})_{i}(\theta)]/(\frac{\sigma_{el}}{\sigma_{Ruth}})_{F}(\theta)\} \cdot 100,$$  

(7)

where $F$ represents the calculation with the full discretized space and $i = NR, R$, correspond to those calculations without the resonance discretized space and with only the resonance space, respectively. That is, $S_i(\theta)$ corresponds to the percentage disagreement from the full calculations for the elastic scattering cross sections to calculations without resonant states $S_{NR}(\theta)$ and with only resonant states $S_R(\theta)$, respectively. Clearly, the absence of resonance state couplings has a large effect on elastic scattering, being more important at large angles, when $S_{NR}(\theta)$ reaches a value of about 25%. However, when only resonant states are considered, the disagreement is smaller of about 10%.

Next, we investigate the energy dependence of resonance states by performing calculations at higher energies. Figs.2 shows the same sort of calculations as described above at $E_{lab} = 13$ MeV ($E_{c.m.} = 10.7$ MeV). The conclusions from Figs. 2a, 2b, 2c and 2d are very similar to those for the lowest energy. Fig.2a shows that a close result to the data is achieved and that couplings to continuum states are essential. In Fig.2d, it is observed that the maximum disagreement for $S_{NR}$ is only slightly above 25% at backward angles, while $S_R$ reaches a maximum of about 15%. Here, also the elastic scattering calculation with only resonant states represented by the dashed-line of Fig.2b is closer to the full calculation (solid-line) than the one without resonant states (dashed-dotted line). This is due to the more repulsive polarization potential for resonant states, as represented by the dashed-line of Fig.2c respect to the case without these states (dashed-dotted line). Although, the results up to here presented are for energies $E_{lab} = 11$ MeV and 13 MeV, which are above the barrier and are close to each other, it is easy to observe the increasing effect of the resonance states of $^6$Li. As a matter of fact, at $E_{lab} = 13$ MeV, some oscillation of $S_{NR}$ (green-dashed-dotted line) appears at large dispersion angles. These oscillations are even more evident at the higher energy $E_{lab} = 27$ MeV. Fig.3a shows that the CDCC calculations give a reasonable fit for dispersion angles less than 110 degrees. For larger angles the data present a strong diffraction pattern. However, the result with only resonance
Figure 2. (Color online) Same as Fig.1 for $^6$Li+$^{28}$Si at $E_{lab} = 13$ MeV.

states remains very close to the full calculations as seen by the dashed-line of Fig.3b, indeed, there is a maximum disagreement at about 80 degrees (19%) as the dashed-line of Fig.3d shows. On the other side, the non-resonance state calculation presents strong effects of nuclear (attractive) and Coulomb (repulsive) polarizations as shown by the dashed-dotted line of Fig.3d.

Figs.4 and 5 give the results for the energies $E_{lab} = 12$ and 18 MeV ($E_{c.m.} = 10.9$ and 16.3 MeV) for the system $^6$Li+$^{58}$Ni. These energies are below and above the barrier energy $V_B = 12.4$ MeV. The solid-lines of Figs.4a and 5a show a good agreement with data of Refs. [28, 29] and that couplings to continuum breakup states of $^6$Li are very important to achieve these fits (dotted-lines). Also, the dashed-lines of Figs.4b and 5b indicate that resonance state couplings play a more important role than non-resonance ones for elastic scattering. This fact is explained by the more repulsive net polarization potentials corresponding to resonance states couplings alone as the dashed-lines of Figs.4c and 5c show. Finally, it is very interesting to observe that the effect of omitting resonance discrete states in the CDCC calculations of elastic scattering angular distributions increases as the collision energy increases. This is seen by the dashed-dotted lines of Figs.4d and 5d, where the percentage disagreement $S_{NR}$ rises from around 3.5% to 30%. Similarly, it can be observed that the percentage disagreement $S_R$ (dashed-lines), that is when only resonance states couplings are considered, also increases with the energy but at a lower rate. In this case, $S_R$ rises from around 1% to 15% for the energies 12 and 18 MeV respectively. As a matter of fact, the shapes of $S_{NR}$ and $S_R$ tend to be similar and to produce similar effects for higher energies. It is interesting to point out that the calculations of $S_{NR}$ and $S_R$ at 18 MeV show incipient oscillations at large dispersion angles, similar to those for $^6$Li+$^{28}$Si at 27 MeV. Probably, it would be interesting to study this behavior for even higher energies.

The effects of resonance discretized states for the systems studied in this work $^6$Li+$^{28}$Si and $^6$Li+$^{58}$Ni are rather similar. For both, the maximum values of the functions $S_R$ and $S_{NR}$ are around 10% and 30% respectively for the energies studied. However, for the heavier target $^{144}$Sm [30] at the energy $E_{lab} = 30$ MeV ($V_B = 23.84$ MeV), $S_R$ and $S_{NR}$ have values around 20% and
Figure 3. (Color online) Same as Fig.1 for $^6\text{Li}^{+}{^28}\text{Si}$ at $E_{\text{lab}} = 27$ MeV.

Figure 4. (Color online) Same as Fig.1 for $^6\text{Li}^{+}{^58}\text{Ni}$ at $E_{\text{lab}} = 12$ MeV. Data from Refs. [28, 29].
40% respectively. So, it is clear that the effects of the resonances of $^6$Li depend on the target mass and are more evident for heavier targets than those considered in this work.

4. Summary and conclusions

CDCC calculations of elastic scattering angular distributions have been performed for the nuclear systems $^6$Li+$^{28}$Si and $^6$Li+$^{58}$Ni at energies around the Coulomb barrier. In the calculations, the cluster structure of the projectile $^6$Li→ $\alpha$ + $d$ is assumed, with global interactions for the $\alpha$-target and $d$-target sub-systems. In general, good agreement between the calculations and the data has been achieved. For all of the energies studied in this work, it has been shown that calculations with to only the elastic channel are insufficient to fit the data, so, couplings to breakup states of $^6$Li are very important. On the same footing, the effect on elastic scattering due to couplings to resonance states of $^6$Li, namely, $l = 2$, $J^\pi = 3^+$, $2^+$ and $1^+$ has been calculated. This effect has been calculated by following two approaches, (a) by omitting from the whole energy discrete space the states corresponding to the resonances and (b) by considering only resonance state couplings. For both nuclear systems, the calculations for the case (a) show a strong effect so that in most cases the data are not fitted. However, the calculations with only resonance state couplings are closer to the data, showing that these states play a more important role for elastic scattering. The different effects of resonance and non-resonant state couplings on elastic scattering are better understood in terms of the polarization potentials that emerge from these couplings. It has been shown that resonance states produce stronger repulsive polarization potentials than non-resonance ones. In order to quantify the effect of resonance and non-resonance states, the percentage quantities, $S_R$ and $S_{NR}$ as functions of the dispersion angle $\theta_{c.m.}$ were studied. For the energies considered in this work, $S_{NR}$ is mostly positive and reaches higher values as the energy increases. On the other hand, $S_R$ shows also increasing values but at a lower rate. So, in the CDCC calculation of elastic scattering angular distributions, couplings from resonant states are more important than non-resonant ones at low
collision energies. However, as the energy increases, resonant state couplings seem to result less significant and both calculations tend to produce similar effects.

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