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Coupling effects of resonant and discretized non-resonant continuum states in ^{4}He + ^{6}Li scattering at 10 MeV/A

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Abstract. Alpha- particle scattering from the resonant (3_1^+) and non-resonant continuum states of ^{6}Li is studied at incident energy 10 MeV/A. The $\alpha + d$ breakup continuum part within the excitation energy $E_{ex} =$ 1.475–2.475 MeV is discretized in two energy bins. Unlike the results at higher incident energies, here the coupled-channel calculations show significant breakup continuum coupling effects on the elastic and inelastic scattering. It is shown that even when the continuum-continuum coupling effects are strong, the experimental data of the ground state and the resonant as well as discretized non-resonant continuum states impose stringent constraint on the coupling strengths of the non-resonant continuum states.

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In nuclear scattering channel coupling of discrete and continuum states is a general phenomenon, and strictly, decoupling is rather an approximation to be justified in each particular situation under consideration. In case of light nuclei with low breakup thresholds coupling with the fragment continuum has been shown to play an important role with feedback to elastic scattering [1, 2] and affecting the breakup cross sections at small relative fragment-energies [3, 4, 5, 6, 7]. For ^{6}Li-nucleus scattering, in particular, couplings of the ^{6}Li ground state with its resonant and non-resonant continuum have been studied on the basis of the coupled discretized continuum channels (CDCC) approach [1, 2]. The coupling has been found to be responsible for various anomalies, experimentally observed both in cross section [8] and in analysing power data [9–13]. The CDCC formalism truncates and discretizes the breakup continuum in a number of different momentum bins which enter in a coupled channels calculation like real discrete states. Unlike the usual coupled-channel calculations in the CDCC framework there is no room for changing the coupling strengths arbitrarily because they are calculated microscopically by using realistic wave functions and the effective nucleon-nucleon interaction through the folding-model procedure. In the CDCC analyses, the number of bins and their widths are so chosen that the resulting spectra of the breakup cross sections (or S-matrix elements) converge, with respect to the refinement of the model space and discretization, which ofcourse depends on the system, the energy, as well as observables which one wish to analyze and their accuracy required. Because of this specific method of truncation the maximum momentum and the widths of bins are not always the same. However, in specifying the coupling strengths and form factors usually some model assumptions are introduced through the description of the system.

In [2], the ground state and discretized breakup continuum states of ^{6}Li are described by a totally antisymmetrized α–d cluster model. This microscopic $\alpha - d$ cluster model reproduces the charge form factors of the ground state and the resonant continuum states obtained from the electron scattering data and therefore taken as a realistic one for generation of the same quantities corresponding to the discretized non-resonant continuum states. The CC potentials are constructed by doubly folding the M3Y effective nucleon-nucleon potential into diagonal and transition density of ^{6}Li and the target density. In this model, the breakup channel coupling is found to have significant effect on the ground state at low incident energies.

In a previous study on ^{6}Li$(\alpha, \alpha')^6$Li* it was shown that at $E_\alpha = 50$ MeV the ^{6}Li $\rightarrow \alpha + d$ breakup cross section is quite large in magnitude [4]. Yet the breakup continuum coupling has negligible effect on the elastic and inelastic scattering [14]. Similar results were obtained in the analysis [14] of the ^{6}Li$(p, p')^6$Li reaction data at $E_p = 65$ MeV [15]. In both the (α, α') and (p, p') studies a fixed portion of the $\alpha + d$ breakup continuum (non-resonant) data was discretized in two energy bins. The centroids of these energy bins are called "non-resonant continuum states". At the above incident energies a small variation of the coupling strengths corresponding to these non-resonant continuum states had no significant effect on the ground state or the 3_1^+ excited state. Nevertheless, the fits to the non-resonant continuum states themselves were greatly altered by such variation [14] which

Table 1. Optical potential parameters

E_{lab} (MeV)	V_0 (MeV)	r_0 (fm)	a_0 (fm)	W_v (MeV)	W_D (MeV)	r_I (fm)	a_I (fm)	r_c (fm)	J_v (MeV fm^3)
40.00	185.26	1.201	0.568	18.92	0.00	1.603	0.901	1.30	561.52

delineated importance of the experimental data in determining the coupling strengths of the non-resonant continuum states. Since the breakup channel coupling, at the above incident energies, are not appreciable to affect the ground state and 3_1^+ excited state calculations, it would be interesting to explore the role of the non-resonant continuum states in cases where such coupling effects are significant.

In $p + {}^6$Li scattering it was observed that the effect of channel coupling is important at lower projectile energies [16]. In fact at 10 MeV incident proton energy, coupling to the first excited state (3_1^+) was found to have significant effect on both the cross section and the analysing power data. Therefore, such coupling effects might be appreciable in the $\alpha + {}^6$Li reaction at $E_\alpha = 40$ MeV, and it has not been studied so far. In this work we have explored this possibility through ^{6}Li(α, α') reaction at $E_\alpha = 40$ MeV. In the following we present experimental data of the ground state (1^+) and the resonant (3_1^+) as well as non-resonant continuum states of the ^{6}Li$(\alpha, \alpha')^6$Li* reaction at $E_\alpha = 40$ MeV and their analyses in a coupled channel formalism.

The ^{6}Li(α, α') reaction was studied using the 40 MeV alpha-particle beam from the Variable Energy Cyclotron of VECC, Calcutta. The details of the experiment are given in [7]. The $^6\text{Li} \rightarrow \alpha + d$ continuum part was taken in a fixed energy bin ($E_{ex} = 1.475$–2.475 MeV) which was subsequently discretized into two energy bins ($E_{ex} = 1.475$–2.185 MeV and $E_{ex} = 2.185$–2.475 MeV) with centroids at 1.83 MeV (C_1^+) and 2.33 MeV (C_2^+) respectively.

The elastic scattering data of the ^{6}Li$(\alpha, \alpha_0)\,^6$Li$(1^+, 0.0$ MeV) reaction were analysed by the code OPTIM. Starting from the optical potential parameters of Bragin *et al.* [17] a thorough search was carried out to obtain the best fit to the elastic angular distribution alone of our 40 MeV data. The optical potential parameters and the volume integral (J_v) are given in Table 1 in usual notations.

The distorted wave Born approximation (DWBA) calculation were carried out using the code DWUCK4 [18]. For both the resonant as well as non-resonant states, the angular momentum $l = 2$ transfer was considered. The angular distributions from DWBA calculations of the excited states were individually normalised to the experimental data of each state to obtain the corresponding deformation parameters (β). The β-values corresponding to the C_1^+, 3_1^+ and C_2^+ states are 0.42, 0.50 and 0.42 respectively. It may be noted here that, at $E_\alpha = 50$ MeV, the deformation parameters of these states were found to be 0.19, 0.53 and 0.19 respectively. This shows stronger excitation of the continuum at $E_\alpha = 40$ MeV.

To understand the effect of continuum-continuum coupling, the data were then analysed in a coupled channels formalism [19] using the code ECIS88 [20]. The vibrational model framework including self coupling was adopted. The transition potentials to the resonant and

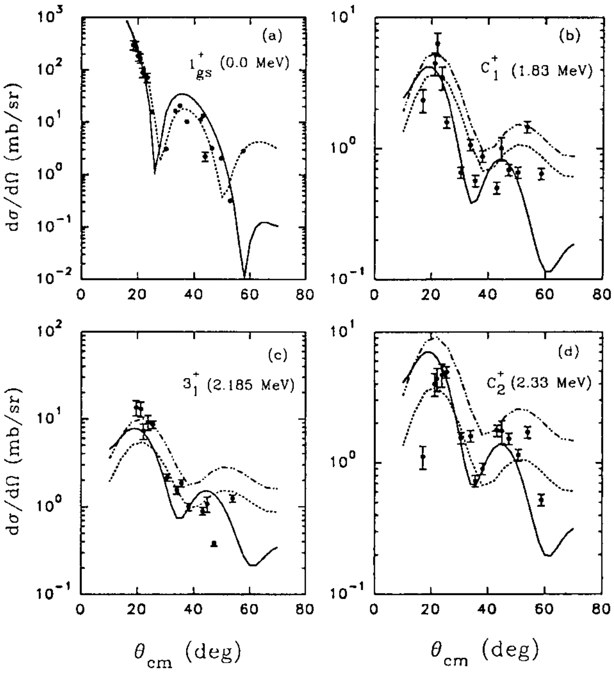

Fig. 1. ^{6}Li(α, α) and ^{6}Li(α, α') angular distribution data at $E_\alpha = 40$ MeV. The solid (*dashed-double dotted*) *lines* represent the coupled channel(DWBA) calculations in one phonon excitation scheme with $\beta_{C_1^+} = 0.50$, $\beta_{3_1^+} = 0.68$ and $\beta_{C_2^+} = 0.65$ corresponding to C_1^+, 3_1^+ and C_2^+ states respectively. The *dashed lines* represent the one step DWBA calculations with $\beta_{C_1^+} = 0.42$, $\beta_{3_1^+} = 0.50$ and $\beta_{C_2^+} = 0.42$ respectively

non-resonant continuum states were assumed to be given by a macroscopic phonon-model. In this framework, the β values obtained above were used as starting parameters for the search of coupling strengths. Both the one-phonon and two-phonon coupling schemes were taken into consideration. The coupling schemes and the details of the procedure are discussed in [21].

One-phonon coupling results exhibit (Fig. 1) that there is significant effect of coupling to both the resonant (3_1^+) and non-resonant (C_1^+, C_2^+) states. The $1^+\,(g.s.) \rightarrow C_1^+ \rightarrow (3_1^+) \rightarrow C_2^+$ coupling is found to alter the fit to the $1^+\,(g.s.)$ and 3_1^+- states from their corresponding fits obtained from the one step DWBA calculations. The coupling specifically improves the forward angle fits to the angular distribution of the 3_1^+ state as it generates a steeper slope compared to the DWBA result.

In order to include higher order coupling effects, the two-phonon coupling calculations were carried out in two steps. The first excited state (3_1^+) is considered as a two-phonon state in one case while in other case, the continuum state (C_2^+) is the two-phonon state. In both the cases, the calculation corresponding to the above

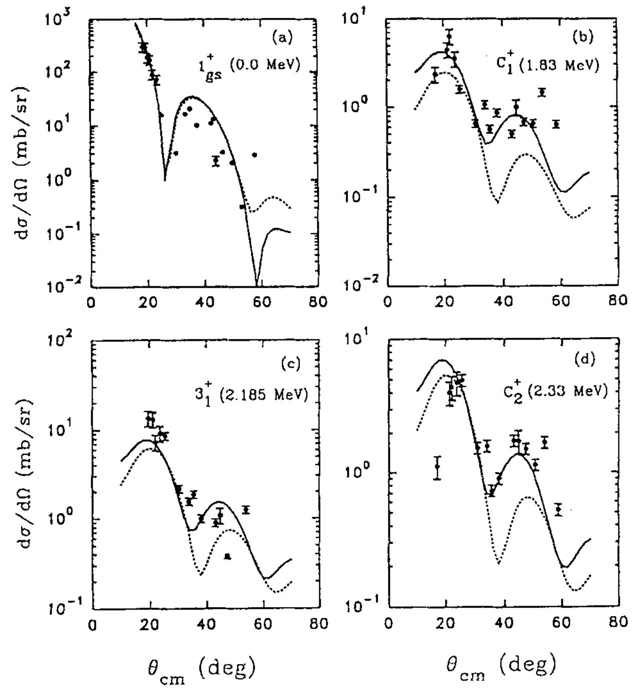

Fig. 2. ^{6}Li(α,α) and ^{6}Li(α,α') angular distribution data at $E_\alpha = 40$ MeV. The *solid* (*dashed*) *lines* represent coupled channel calculations with $\beta_{C_1^+} = 0.50$, $\beta_{3_1^+} = 0.68$ and $\beta_{C_2^+} = 0.65$ ($\beta_{C_1^+} = 0.30$, $\beta_{3_1^+} = 0.48$ and $\beta_{C_2^+} = 0.45$) corresponding to C_1^+, 3_1^+ and C_2^+ states respectively

two-phonon states greatly underestimates the data by factors of 100 and 10 for the 3_1^+ state and C_2^+ state respectively. Increase of the coupling strength of these states could not alleviate the problem. This indeed shows that the excited states are not of two-phonon nature. Furthermore, inclusion of higher order coupling is found to deteoriate the ground state fit immensely. This finding is in consonance with the earlier results at $E_\alpha = 50$ MeV [21].

The fit to the ground state could possibly be improved either by adding more discretized continuum states of higher excitation (not available from our data), or by changing the coupling strengths of the existing ones. In this context we found that a small variations of the coupling strengths of the continuum states, completely destroys the fits to the C_1^+, 3_1^+ and C_2^+ states while it has relatively smaller effect on the 1^+ (*g.s.*) (Fig. 2). Thus, although the ground state fit may be further improved upon by considering arbitrary values of coupling strength of C_1^+ and C_2^+, they will not necessarily reproduce the angular distributions of the continuum excited states. From the simultaneous fit to all the four states, the optimum β-values (or coupling strengths) corresponding to the C_1^+, 3_1^+ and C_2^+ states are found to be 0.50, 0.68 and 0.65 respectively. Unlike the earlier results at $E_\alpha = 50$ MeV [14, 21] these values are different from the β-values obtained from the one-step DWBA analysis.

In summary, in this work we present the ^{4}He + ^{6}Li scattering data at 10 MeV/A. The non-resonant continuum states in the energy range of 1.475–2.475 MeV were assumed to be represented by a couple of discrete states with energies of 1.83 MeV and 2.33 MeV respectively. To study the effects of continuum-continuum coupling at this low incident energy, both one-phonon and two-phonon calculations are carried out. The one-phonon coupling ($1^+ \to C_1^+ \to 3_1^+ \to C_2^+$) is found to have considerable effect on the ground state as well as on the excited states where as the two-phonon coupling effect is found to be negligible. Incidentally, at $E_\alpha = 50$ MeV both the one- and two-phonon couplings effects were found to be negligible. Sakuragi *et al.* [2] had shown that the breakup channel coupling effect is responsible for the necessity of the anomalous reduction factor in the ^{6}Li + nucleus double folded potential [8]. The absence of significant coupling effect on the ground state at $E_\alpha = 50$ MeV possibly justifies the fact that no reduction factor was neccesary in the double folded ^{4}He + ^{6}Li potential [6]. In this context, a similar enquiry at $E_\alpha = 40$ MeV would be useful.

In conclusion, this work reconfirms the earlier findings [14] that the experimental data of the discretized non-resonant continuum states impose a severe constraint on the values of their coupling strengths. It will be interesting to use the present data for a stringent test of the validity of microscopic theories like the CDCC method.

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