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# Cluster Model for Near-barrier Fusion Induced by Weakly Bound and Halo Nuclei

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**Abstract.** The influence on the fusion process of coupling transfer/breakup channels is investigated for the medium weight  ${}^6\text{Li}+{}^{59}\text{Co}$  systems in the vicinity of the Coulomb barrier. Coupling effects are discussed within a comparison of predictions of the Continuum Discretized Coupled-Channels model also applied to  ${}^6\text{He}+{}^{59}\text{Co}$  a reaction induced by the borromean halo nucleus  ${}^6\text{He}$ .

**Keywords:** Fusion, breakup, transfer, weakly bound, halo, coupled-channels methods

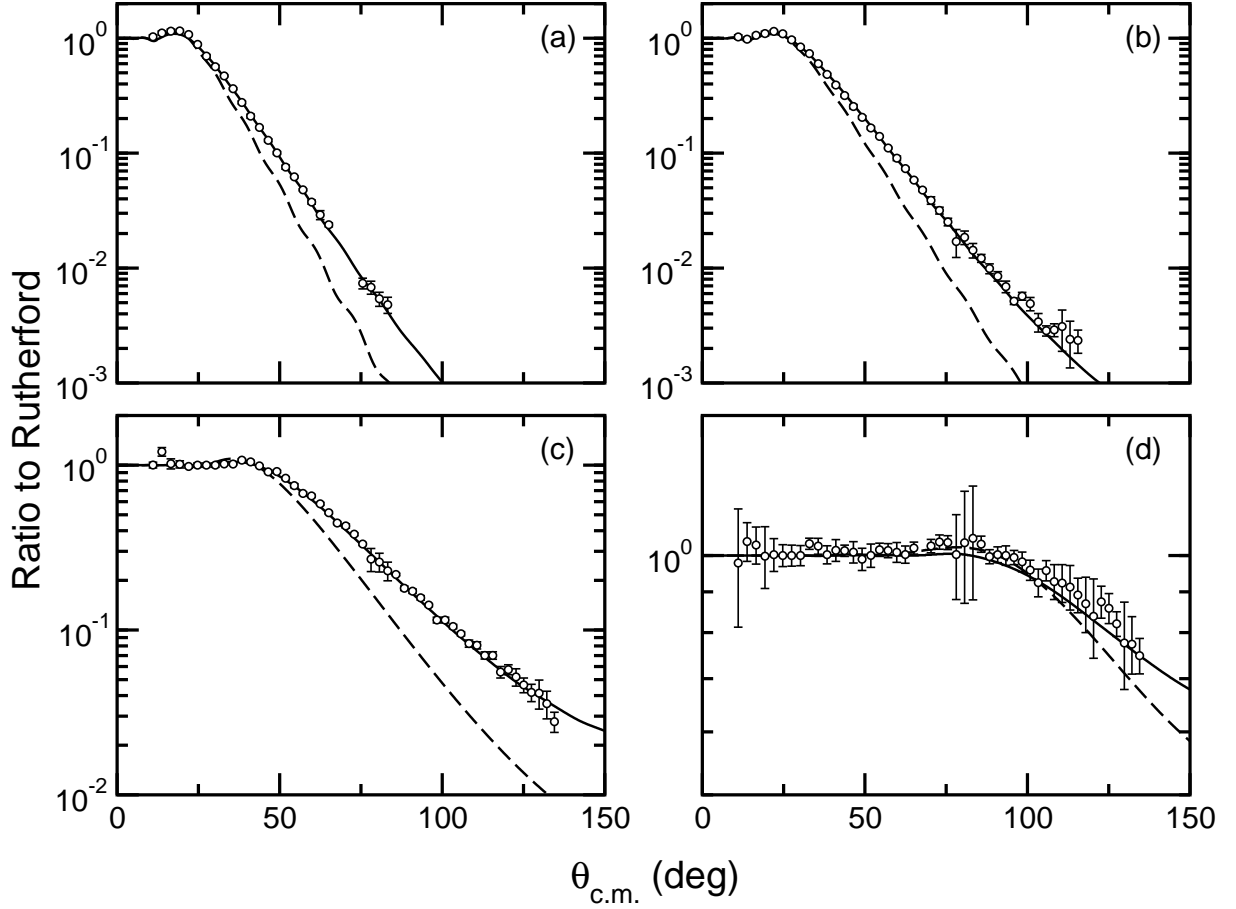
**PACS:** 25.60.Ge, 25.70.Jj, 25.70.Mn, 25.60.Dz, 24.10.Eq

## INTRODUCTION

In reactions induced by light weakly bound nuclei, the influence on the fusion process of coupling to collective degrees of freedom and to breakup (BU) and transfer channels is a key point for a deeper understanding of few-body systems in quantum dynamics [1, 2, 3, 4, 5, 6]. Due to the very weak binding energies of halo nuclei, such as  ${}^6\text{He}$ , a diffuse cloud of neutrons should lead to enhanced tunneling probabilities below the Coulomb barrier as compared to predictions of one-dimensional barrier penetration models [1, 4]. This was understood in terms of the dynamical processes arising from strong couplings to collective inelastic excitations of the target and projectile [4]. However, in the case of reactions where at least one of the colliding nuclei has a sufficiently low binding energy for BU to become a competitive process, conflicting model predictions and experimental results were reported [4]. Recent experimental results with  ${}^6,8\text{He}$  beams show that the halo of  ${}^6\text{He}$  does not enhance the fusion probability, confirming the prominent role of neutron transfers in  ${}^6\text{He}$  induced fusion reactions [7, 8, 9, 10, 11].

Excitation functions for sub- and near-barrier total - complete (CF) + incomplete (ICF) - fusion cross sections measured for the  ${}^6,7\text{Li}+{}^{59}\text{Co}$  reactions [1] when compared to Continuum-Discretized Coupled-Channels (CDCC) calculations [2] indicate a small enhancement of total fusion (TF) for the more weakly bound  ${}^6\text{Li}$  below the Coulomb barrier, with similar cross sections for both reactions at and above the barrier [2]. This result is consistent with BU - although with rather low cross sections even at incident energies larger than the Coulomb barrier [3] - being more competitive for the  ${}^6\text{Li}+{}^{59}\text{Co}$  reaction.

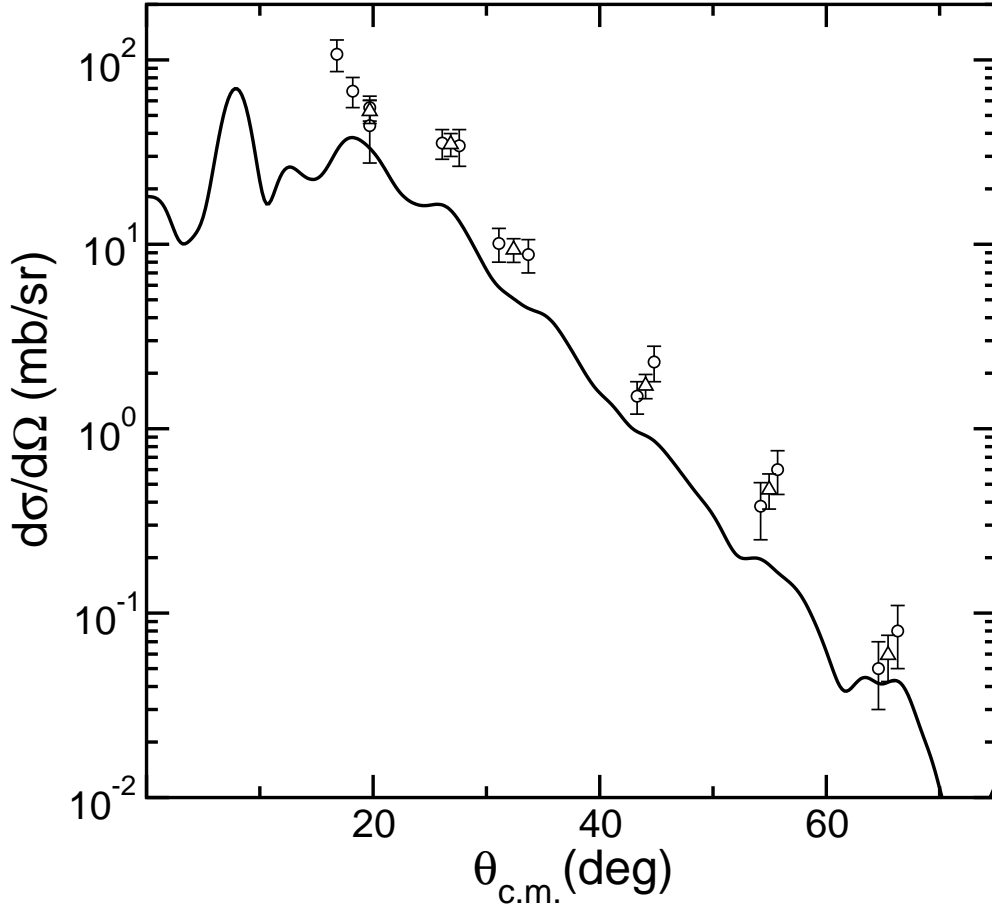
In this contribution we present selected CDCC calculations for elastic scattering, TF, transfer (TR), and BU of weakly bound stable ( ${}^6\text{Li}$  considered as a  $\alpha$ - $d$  cluster) and radioactive ( ${}^6\text{He}$  as a  $\alpha$ - $2n$  cluster) light projectiles from a medium-mass target ( ${}^{59}\text{Co}$ ).



**FIGURE 1.** Elastic scattering for  ${}^6\text{Li}+{}^{59}\text{Co}$  at (a) 30 MeV, (b) 26 MeV, (c) 18 MeV and (d) 12 MeV [5]. The curves correspond to CDCC calculations [3] with (solid lines) or without (dashed lines) couplings with the continuum as discussed in the text.

## FULL CDCC DESCRIPTION OF ${}^6\text{Li}+{}^{59}\text{Co}$ REACTION

In the present work, detailed CDCC calculations for the interaction of  ${}^6\text{Li}$  on the medium-mass target  ${}^{59}\text{Co}$  are applied in order to provide a simultaneous description of elastic scattering, fusion as well as breakup. Details of the calculations concerning the breakup space (number of partial waves, resonances energies and widths, maximum continuum energy cutoff, potentials, ...) have been given in previous publications [2, 5]. The CDCC scheme is available in the general coupled channels code FRESKO [2]. Before investigating whether the proposed CDCC formalism can be also applied to halo structures such as the borromean nuclei  ${}^6\text{He}$ , we present a complete description of the  ${}^6\text{Li} \rightarrow \alpha+d$  cluster as a two-body object. In the fusion calculations the imaginary parts of the off-diagonal couplings were neglected, while the diagonal couplings included imaginary parts [2]. Otherwise full continuum couplings have been taken into account so as to reproduce the elastic scattering data [3, 4]. We have used short-range imaginary fusion potentials for each fragment separately. This is equivalent to the use of incoming

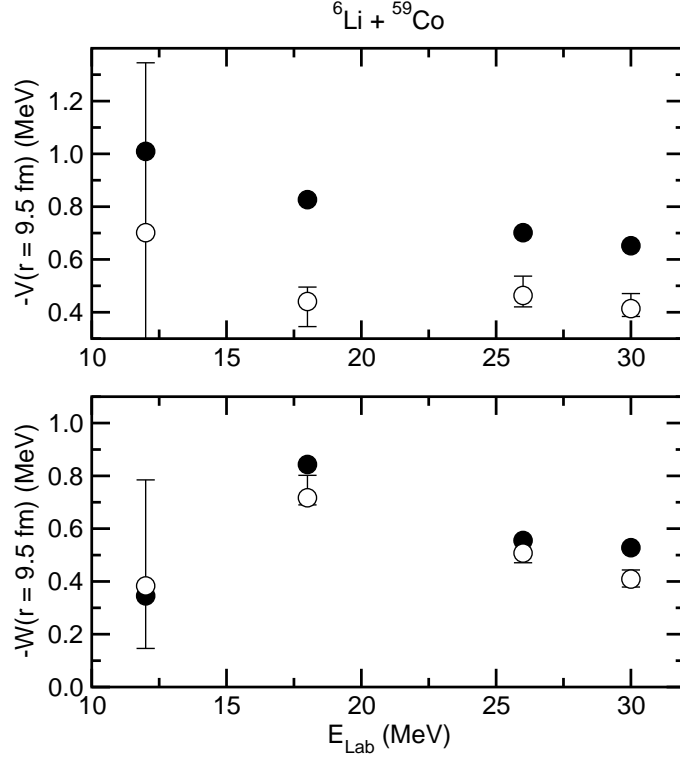


**FIGURE 2.** CDCC calculation for the angular distribution of the  ${}^6\text{Li} \rightarrow \alpha + d$  sequential breakup via the 2.18 MeV  $3^+$  state of  ${}^6\text{Li}$  compared to data of  ${}^6\text{Li}+{}^{59}\text{Co}$  reaction at 41 MeV.

wave boundary conditions applied in previous CCFULL calculations [1].

Results of the comparison of the CDCC calculations for the elastic scattering with data of Ref. [3, 4] are shown in Fig. 1 for  ${}^6\text{Li}+{}^{59}\text{Co}$  at four different incident energies. The two different curves are the results of calculations performed with (solid lines) and without (dashed lines)  ${}^6\text{Li} \rightarrow \alpha + d$  breakup couplings. The agreement between the full calculations and data is very good. The effect of breakup on elastic scattering is illustrated by the difference between the one-channel calculations and the full CDCC results.

The total calculated BU cross sections were obtained by integrating contributions from the states in the continuum up to 8 MeV. They are found to be negligible fractions (between 3.7–9.7 %) of the total reaction cross sections and small compared with the TF cross sections (both the data [1] and two different sets of CDCC calculations [2, 5]). This conclusion can be verified by the angular correlations for the sequential BU of  ${}^6\text{Li}$  via the 2.18 MeV  $3^+$  excited state [5] plotted in Fig. 2 at 41 MeV. Sequential BU via this state is the dominant contribution to the total  ${}^6\text{Li} \rightarrow \alpha + d$  breakup cross section. Our CDCC cross section (22.5 mb) is, however, smaller than the measured value ( $45 \pm 10$



**FIGURE 3.** Energy dependence of the real and imaginary parts of the “bare plus DPP” potentials as generated by the CDCC calculations (filled circles) and the best OM fits potentials (open circles) for the  ${}^6\text{Li}+{}^{59}\text{Co}$  system at a radial distance of  $r = 9.5$  fm.

mb).

The total reaction cross sections obtained either from fits with Optical Model (OM) potentials [5] or CDCC calculations - both OM and “bare plus dynamic polarization” (DPP) potentials are shown in Fig. 3 for  ${}^6\text{Li}$  whereas their equivalent values for  ${}^7\text{Li}$  are given in [5] - confirm the observed small enhancement of TF cross section for the more weakly bound  ${}^6\text{Li}$  nucleus at sub-barrier energies [1]. Fig. 3 illustrates how the surface strengths of the “bare plus DPP” potentials are in good agreement with OM potentials. Apparently, they exhibit the energy dependence characteristic of the “threshold anomaly” (TA), i.e. a rise in the strength of the real part as the incident energy is reduced towards the Coulomb barrier accompanied by a drop in that of the imaginary part. However, this conclusion largely rests on the values at 12 MeV incident energy, and as can be seen from the error bars, the potential strength in the nuclear surface is effectively not determined by the data due to its rather poor precision, a very wide range of values giving equally good fits to the data. The spread in values for the other energies, while much less than that at 12 MeV, is still such that we are unable to draw any concrete conclusions concerning the presence or absence of a TA in  ${}^6\text{Li}+{}^{59}\text{Co}$ . Similar observations have been made for  ${}^7\text{Li}+{}^{59}\text{Co}$  [5] and the question of the occurrence a “BU threshold anomaly” remains widely open.

## PREDICTIONS FOR ${}^6\text{He}+{}^{59}\text{Co}$ FUSION AND CONCLUSIONS

Calculations applied to the two-neutron halo nucleus  ${}^6\text{He}$  is much more complicated since  ${}^6\text{He}$  breaks into three fragments ( $\alpha+n+n$ ) instead of two ( $\alpha+d$ ), and the CDCC method for two-nucleon halo nuclei has not yet been implemented in FRESKO [2]. A dineutron model is adopted for the  ${}^6\text{He}+{}^{59}\text{Co}$  reaction [3, 4, 5]: i.e. we assume a two-body cluster structure of  ${}^6\text{He} = {}^4\text{He}+{}^2\text{n}$  with an  $\alpha$  particle core coupled to a single particle representing a di-neutron ( ${}^2\text{n}$ ) like cluster. Couplings to resonant ( $2^+$ ,  $E_{ex} = 0.826$  MeV) and non-resonant continuum states (up to f-waves) are included. The fact that the dineutron is not an object with both fixed size and fixed energy (Heisenberg principle) might be a critical point in the present model. Results of the CDCC calculations for TF of the  ${}^6\text{He}+{}^{59}\text{Co}$  system were compared to  ${}^4\text{He}+{}^{59}\text{Co}$  and  ${}^6\text{Li}+{}^{59}\text{Co}$ , used as basis reactions (see Refs.[3, 4, 5]). We observed that calculations with and without breakup give much larger TF cross sections for  ${}^6\text{He}$  compared to  ${}^4\text{He}$  and  ${}^6\text{Li}$ . The inclusion of the couplings to the breakup channels notably increases the TF cross section for all energies. The predictions for the  ${}^{59}\text{Co}$  target somewhat over predict the data published for other medium-mass targets such as  ${}^{64}\text{Zn}$  [8] and  ${}^{63,65}\text{Cu}$  [9]. Extended calculations are in progress to quantify the role of 1n- and 2n-transfer channels found to be significant in recent  ${}^6\text{He}$  data [7, 8, 9, 10, 11].

The CDCC method [2] can be used to provide the almost complete theoretical description of all competing processes (TF, elastic scattering, TR and BR) in a consistent way. In this contribution we have shown that the  ${}^6\text{Li}+{}^{59}\text{Co}$  reaction can be fairly well understood in this framework although CDCC does not separate CF from ICF. CDCC results for the  ${}^6\text{He}+{}^{59}\text{Co}$  fusion process are also briefly discussed. A complete understanding of the reaction dynamics involving couplings to the BU and the neutron transfer channels will need high-intensity radioactive ion beams to permit measurements at deep sub-barrier energies and precise measurements of elastic scattering and yields leading to TR channels and to BU itself. The application of four-body (required for an accurate  $\alpha$ -n-n description of  ${}^6\text{He}$ ) CDCC models still under current development [6] will then be highly desirable. It would be interesting to see what difference this more accurate model would have on the BU coupling effect on TF if applied to a fusion calculation in a similar manner to the calculations presented in this contribution.

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