# Systematic model-dependent behaviour of fusion involving weakly bound projectiles $^{6,7}$Li

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## Introduction

Many measurements on complete fusion (CF) cross section at above barrier energies involving weakly bound stable projectiles (e.g., $^6$Li, $^7$Li and $^9$Be) show suppression by various degrees compared to theoretical estimates as well as experimental CF cross sections of reactions involving strongly bound projectiles. However, there is no concrete picture at sub-barrier energies. The conclusions based on coupled-channels (CC) calculations using different codes (e.g., FRESCO or CCFULL) may differ as the theoretical models used to calculate fusion are not same. In a recent paper on complete fusion in $^7$Li+$^{152}$Sm system [2], the fusion cross sections calculated by CCFULL and FRESCO have been shown to be different despite using same bare potential. It was observed that with the inclusion of only inelastic couplings, the results of FRESCO were much closer to the experimental data in the above barrier region, while the CCFULL results overpredict the data over the entire range. To explore the above observation in different systems involving $^{6,7}$Li as projectile, in the present work, a systematic and detailed study has been carried out by means of CC calculations using both FRESCO and CCFULL. The aim is to analyze the differences between the two models of calculations.

## Calculations

Here, only those reactions whose CF cross sections are already measured and available in literature have been considered. For each system, we have used the same channels, potentials and coupling parameters as used in the original papers (Table 1), as mentioned in [1] and references therein. Couplings with projectile states above the breakup threshold were not included. For comparing the fusion data of the two different models, we make use of a reduction method [1] that eliminates the geometrical aspects of each system, such as heights and interaction radii of the barriers, sizes and charges of participating nuclei as well as the static effects present in weakly bound nuclei due to their clustered structure. This expresses the differences only in terms of dynamic effects of channel couplings particularly around the barrier energy. In this prescription, a parabolic approximation of the fusion barrier is made, as had been done by Wong [3], and the cross sections $\sigma_F^{exp}$ and collision energies $E_{c.m.}$ are reduced to dimensionless forms, by defining $F(x)$, called the Fusion Function [1], that effectively points out model-dependent differences in fusion within a single system, with

$$x = \frac{E_{c.m.} - V_B}{\hbar\omega} \; ; \quad F(x) = \frac{2E_{c.m.}}{\hbar\omega R_B^2}\sigma_F^{exp}\frac{\sigma_F^W}{\sigma_F^{CC}}$$

Here, $\sigma_F^{CC}$ is the fusion cross section of a CC calculation including all relevant bound channels, and $\sigma_F^W$ is the cross section corresponding to only the elastic channel (Wong's approximation), with $V_B$, $R_B$, $\hbar\omega$, respectively, the barrier height, interaction radius and curvature. When no couplings are involved (Wong model), a general function of x, called the Universal Fusion Function (UFF) describes the fusion process, UFF$(x)$ = ln $[1 + \exp(2\pi x)]$. Any deviation of $F(x)$ from UFF is attributed to dynamic channel coupling effects. However, $F(x)$ for different systems using $\sigma_F^{CC}$ from FRESCO and CCFULL could be different due to the inherent difference in the theoretical formalism

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of each model.

## Results and Conclusions

Figure 1 shows results obtained using FRESCO and CCFULL for various systems. It is observed that the CCFULL results overpredict the fusion data much higher than that done by FRESCO, even though both models include the same inelastic excitations and bare potential. This is particularly notable in the case of $^{7}$Li, where CCFULL calculations predict a suppression of fusion over the entire range (Fig. 1(d)), while FRESCO predicts an enhancement below barrier (x<0) and suppression above (Fig. 1(c)). For $^{6}$Li, both models predict an enhancement below barrier and suppression above (Fig. 1(a,b)). The enhancement observed in the region $E < V_B$ is due to breakup coupling, as all other relevant bound channels have been included in the CC calculations. For $^{7}$Li, CCFULL predicts suppression over the entire range, which could be due to the underlying difference of the coupling mechanism of the two models, on account of the larger ground state deformation of $^{7}$Li as compared to $^{6}$Li. Such microscopic differences in the structure of the two isotopes lead to different reorientation terms in the channel couplings, particularly in CCFULL, which solves the coupled equations based on the isocentrifugal approximation. More realistic CC calculations, taking into account the interplay between all relevant bound channels and fusion, are done in the framework of the CDCC approach (FRESCO).

TABLE I: Reaction channels included in the CC calculations; P and T correspond to projectile and target states, respectively.

| Reaction | Channels and Couplings |
|---|---|
| $^{6}$Li+$^{64}$Ni | $2^+$ (T; vib[a]) |
| $^{6}$Li+$^{90}$Zr | $2^+$,$3^-$(T; vib) |
| $^{6}$Li+$^{144}$Sm | $3^-$(T; vib) |
| $^{6}$Li+$^{152}$Sm | $2^+$,$4^+$(T; rot[b]) |
| $^{6}$Li+$^{159}$Tb | $2^+$,$4^+$(T; rot) |
| $^{6}$Li+$^{209}$Bi | $3^-$, $5^-$(T; vib) |
| $^{7}$Li+$^{144}$Sm | $\frac{1}{2}^-$(P; rot), $2^+$,$3^-$(T; vib) |
| $^{7}$Li+$^{152}$Sm | $(1/2)^-$(P ;rot), $2^+$,$4^+$(T; rot) |
| $^{7}$Li+$^{159}$Tb | $(1/2)^-$(P; rot), $2^+$,$4^+$(T; rot) |
| $^{7}$Li+$^{197}$Au | $(1/2)^-$(P; rot), $\frac{1}{2}^+$(T; vib) |
| $^{7}$Li+$^{209}$Bi | $(1/2)^-$(P; rot), $3^-$,$5^-$(T; vib) |

[a]vib : vibrational coupling
[b]rot : rotational coupling

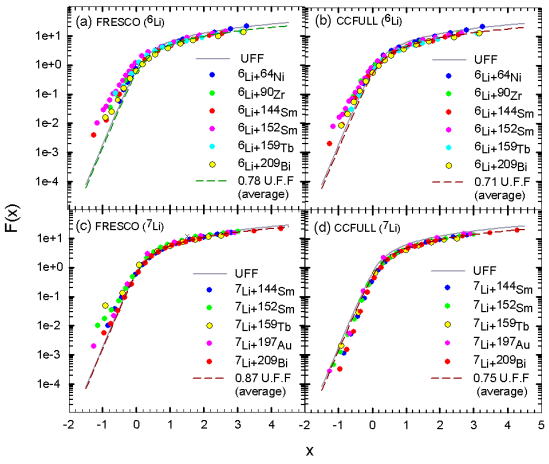


FIG. 1: Experimental fusion functions using the results of FRESCO and CCFULL for several systems involving $^{6,7}$Li. The solid line represents the UFF.

FRESCO calculates the fusion cross sections by imposing boundary conditions on the incoming (incident channel) and outgoing coupled wave functions governed by an imaginary potential and accounts for the flux which is lost from the direct channels to the fusion reaction. It was observed that the inclusion of a similar imaginary potential into CCFULL does not produce any significant deviations from the results already obtained. Here, the fusion cross section depends on the tunneling coefficient for each partial wave across the barrier. This leads to a significant difference between the fusion functions calculated by the two models.

## References

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