Fusion suppression on nuclear reaction induced by loosely bound projectiles

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Introduction

Due to the availability of intense beams and the improved experimental facilities in the recent decades, a renewed interest has been developed towards understanding of fusion cross section [1]. In loosely bound projectiles like ^{6,7}Li, ^{9}Be, etc. emanates interesting phenomenon towards fusion reaction as separation energy of these nuclei are low and hence have high chances for breakup. As an instance, ^{6}Li breakup into ^{2}H + ^{4}He and ^{9}Be breaks up into ^{4}He + ^{4}He + n with separation energy 1.48 MeV, 1.67 MeV respectively. The breakup threshold energy in this case is low due to which the breakup probability of this nucleus as a projectile rises and hence forms the basis of numerous experiments. These projectiles directly break up when it is projected with certain energy towards the heavier target nuclei during fusion process. Such occurrences were observed in at least four different types of events: projectile fusing with target without breakup, a case of direct complete fusion (DCF); projectile breaking up into fragments which then later fuses with target, a case of sequential complete fusion (SCF); one of the breakup fragments fusing with target, a case of incomplete fusion (ICF); and none of the breakup products and the target fuse with one another, a case of no capture breakup (NCBU). In such cases, theoretical cross sections are expected to be higher than the corresponding experimental values a phenomenon commonly known as fusion suppression.

Various versions of the classical model are available in the literature to explain the fusion suppression of systems involving weakly bound projectile. Classical trajectory model [1] can easily identify scattering, no-capture breakup and incomplete fusion. It can also be incorporated in the CDCC formalism. Modified version of this model, classical dynamical model [2] developed later could determine the breakup of the projectile by empirically obtaining breakup probability function whose parameters are obtained from sub-barrier no capture breakup measurements. This method could successfully determine the breakup yields and the fusion suppression factors for a number of systems. In this paper, we will present a modified formula in place of the formula used by Phookan et.al [3] for the fusion suppression factor and then apply the same for the reactions ^{6}Li + ^{152}Sm,^{209}Bi and ^{9}Be + ^{209}B whose fusion excitation data are available in the Refs. [4,5,6] and where fusion suppression is observed.

Theory

The three-body Lagrangian, as shown in equation 1, in two dimensions are constructed for the projectile and the target system with the assumption that the projectile is two-point particles [1]. The Wood-Saxon form of the nuclear potential is used here whose parameters were taken from optical model analysis of the elastic scattering data

$$L=\frac{1}{2}m_1\left(\acute{q}_1^2+\acute{p}_1^2\right)+\frac{1}{2}m_2\left(\acute{q}_2^2+\acute{p}_2^2\right)+\frac{1}{2}m_3\left(\acute{q}_3^2+\acute{p}_3^2\right)-V \qquad (1)$$

And $V = V_{12}+V_{13}+V_{23}$
The detail about the interaction potential is taken from Ref. [2].

Methodology

The difference between theoretical and experimental cross section (Fusion suppression) is due to the fraction of projectile break-up near the heavy target. For large number of trajectories, we define breakup fraction as

$$\text{Breakup Fraction } (B_i) = \frac{\text{Total Trajectories which undergo breakup}}{\text{Total Trajectories we considered}} \quad (2)$$

Here subscript *i* represents the impact parameter at which B_i is evaluated. Thus the fusion suppression factor (f_i) is given by

$$f_i = \frac{\sum_i b_i B_i P_i}{\sum_i b_i P_i} \quad (3)$$

The fusion suppression factor defined above is based on our classical model. It is the weighted average of the breakup fractions at different parameters given by the product of impact parameter for i^{th} trajectory, b_i and the probability, P_i, given by

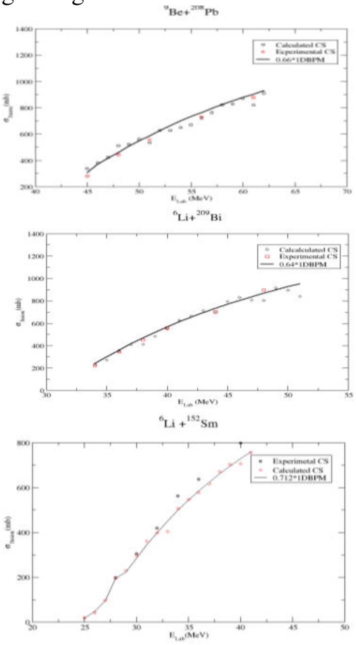
$$P_i = \begin{cases} 1 & if b_i \le b_c, \\ 0 & if b_i > b_c. \end{cases} \quad (4)$$

The range of impact parameter for our calculation is from zero to above critical value with an increase in steps of 0.2 fm.

Result

The fusion suppression ($f_{exp} = 1 - \sigma_{exp}/\sigma_{theo}$) and the experimental values of cross section calculated were plotted in the graphs for all the systems from below barrier to above barrier are shown in the figure. Using σ_{theo}, we have calculated the critical angular momentum L_C for all the reactions. The barrier parameters for the above calculation (ħω, E_o, R_b) are taken from the output of the CCFULL code. L_C can also be calculated by single barrier potential model SBPM and it is derived on the basis of σ_{theo} being approximated by the result of SBPM. The SBPM fusion cross section is obtained by using CCFULL calculation. Using L_C we can determine the cut off impact parameter for all the system. With the help of this cut off impact parameter, fusion suppression (f_{cal}) is calculated. Then we used f_{cal} for calculating fusion cross section, σ_{theo} (1 − f_{call}). The comparison of theoretical and experimental cross section is shown in the figure below for our systems.

To explain projectile breakup and fusion suppression for reaction induced by ^{6,7,8}Li, ^{7,9,10}Be, ^{10,11}B, ^{12}C projectiles the classical trajectory model is applied. To explain the fusion suppression, B_i is calculated by varying impact parameter from head-on collision to its cut off value. By comparing the theoretical fusion cross section and 1-D quantum mechanical tunneling predictions over the barrier we determined the cut-off impact parameter for all the reactions. It has been seen that the calculated cross section and the experimental fusion cross section shows good agreement with each other.



Summary

The proposed theoretical results and experimental data agrees well so it would be a good tool that breakup reaction of all projectiles can be successfully studied using classical Newtonian laws.

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