Investigation of Fusion Suppression and Projectile Breakup using Classical Trajectory Method

Amar Das*
Department of Physics, Suren Das College,
Hajo-781102, India; Department of Physics,
Gauhati University
Guwahati-781014, India

Harun Al Rashid
Department of Physics, BBK College,
Nagaon, Barpeta-781311, India;
Department of Physics, Gauhati University
Guwahati-781014, India

K. Kalita, Nabendu K. Deb, Lakhyajit Sarma
Department of Physics,
Gauhati University
Guwahati-781014, India

C. K. Phookan
Department of Physics,
Haflong Government College
Haflong-788819, India

***Abstract*—Fusion suppression from below to above the Coulomb barrier and projectile breakup for the reactions ^{6}Li + ^{152}Sm, ^{7}Li + ^{27}Al, ^{8}Li + ^{208}Pb, ^{10,11}B + ^{209}Bi can be explained using a two-dimensional classical trajectory model. Using the descriptive semiclassical trajectory model of the projectile nucleus, the equations of orbits were categorized into two different trajectories, that is, breakup and no-breakup. The breakup fraction is a function of impact parameter whose cut-off value is determined through the corresponding sharp cut-off model according to which for the fusion there is an angular momentum limit. To understand fusion suppression, we present a formula given by the ratio of the sum of the products of breakup fraction, impact parameter and probability and the sum of the products of impact parameter and probability at various impact parameter ranging from head on collision to the sharp cut-off impact parameter. The calculated fusion cross section of the systems considered in this work are in good agreement with the corresponding experimental fusion cross section.**

Keywords*—Projectile breakup; fusion cross section; classical trajectory model; impact parameter; CCFULL; CDCC

I. 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 [1-11]. Loosely bound projectiles such as ^{6,7,8}Li are of great interest towards fusion reaction as separation energy of these nuclei are low and hence have high chance for breakup. For an instance, ^{6}Li nucleus breaks up into ^{2}H and ^{4}He having separation energy of 1.48 MeV. ^{7}Li picks a proton and forms ^{8}Be which breaks up into ^{4}He + ^{4}He with separation energy being 1.67 MeV and ^{8}Li breaks up into ^{5}He + ^{3}H with breakup energy of 5.23 MeV. As ^{7,8}Li are loosely bound projectiles so their threshold energy is low and it is found that ^{7}Li has lower breakup threshold energy than ^{8}Li so breakup probability is higher for ^{7}Li as compared to that of ^{8}Li. Various experiments have been done to study the breakup of loosely bound projectiles. Likewise, nuclei such as ^{10,11}B, ^{12,13}C are also found to be loosely bound in certain cases [10,11], in spite of their breakup threshold energies being higher than those of ^{6,7}Li or ^{8}Be. Such 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 (NCB). In such cases, theoretical cross sections are expected to be higher than the corresponding experimental values and this phenomenon is commonly known as fusion suppression. In recent years, reactions with loosely bound projectiles were studied on different heavy targets such as ^{209}Bi, ^{208}Pb, ^{159}Tb, ^{152}Sm, ^{144}Sm, ^{124}Sn, ^{89}Y, etc [12-18]. In these systems, the fusion suppression factors are reported approximately in the range from ≈ 15% to 40%. Coupled-channel code CCFULL [19] is generally used to calculate the theoretical cross section of the reactions induced by loosely or tightly bound projectiles without considering breakup process. On the other hand, Continuum-discretized coupled channels method (CDCC) [20] and the classical method are used to calculate the breakup yields for the reactions induced by loosely bound projectile. There is a drawback in the CDCC method where the breakup of the projectiles occurs within the eigen functions comprising of continuum states. Accordingly, these states are stopped approximately at some higher values of the angular momentum and the linear momentum. Such discretization of the continuum states and approximations may lead to inaccuracies of the outcome [21, 22]. Also, CDCC is independent of time due to which it cannot be the reliable method towards distinguishing between CF and ICF events. Such limitations are overcome using two-dimensional classical trajectory model [23] in which the loosely bound projectile is considered as a two-body system under the combined effect of Coulomb and nuclear potentials.

TABLE I. PROJECTILE BREAKUP WITH BREAKUP THRESHOLD ENERGY.

Projectile	Breakup Path	Threshold Energy
^{6}Li	^{4}He+^{2}H	1.48 MeV
^{7}Li	^{1}H+^{7}Li » ^{8}Be » ^{4}He+^{4}He or ^{3}H+^{4}He	2.46 MeV
^{8}Li	^{3}H+^{5}He	5.23 MeV
^{10}B	^{4}He+^{6}Li	4.46 MeV
^{11}B	^{4}He+^{7}Li	8.66 MeV
^{12}C	^{4}He+^{8}Be	7.36 MeV

In this paper, an attempt has been done to work with a new formula to determine the fusion suppression factor and then will apply the same for the reactions ^{6}Li+^{152}Sm, ^{7}Li+^{27}Al, ^{8}Li+^{208}Pb, ^{10,11}B + ^{209}Bi, whose fusion excitation data are available in the literature and where fusion suppression is observed. In our calculation we used the method based on two-dimensional classical trajectory model [23]. We determined projectile breakup fraction using impact parameter whose cut off value for fusion is found out using quantum mechanical formula [24], thereby determining a simple method for finding fusion suppression factor. The projectile breakup channels and the breakup threshold energy of the projectiles considered in our work are shown in table 1.

II. FORMALISM

The three-body Lagrangian, as shown in (1), in two dimensions are constructed for the projectile and target system with the assumption that the projectile is two-point particles [23]. The Wood-Saxon form of the nuclear potential is used here whose parameters are taken from optical model analysis of the elastic scattering data.

$$L = \frac{1}{2} m_1 \left(\dot{q}_1^2 + \dot{p}_1^2 \right) + \frac{1}{2} m_2 \left(\dot{q}_2^2 + \dot{p}_2^2 \right) + \frac{1}{2} m_3 \left(\dot{q}_3^2 + \dot{p}_3^2 \right) - V_{12} - V_{13} - V_{23} \qquad (1)$$

where q_i and p_i are two coordinate axes and subscripts 1, 2 and 3 represent the two fragment of the projectiles and the target respectively. V_{12}, V_{13}, V_{23} are the interacting potentials between the components produced by projectile breakup and the target. The interacting potential and solution of Lagrangian equation of motion has been done similar to the one done by our groups [25].

For our classical model two conditions need to be satisfied, that is, $r_1 = r_2$ and $v_1 = v_2$, where r_1, r_2 and v_1, v_2 are the distances and velocities, respectively, of the two projectile breakup fragments with respect to their centre of mass. The first condition can be obtained by finding the centre of mass position of the breakup particles and second condition is obtained by fixing the centre of mass when an internal force acts on it. The values give certain solution of trajectories due to which we can find two types of trajectories as shown in Fig. 1.

Next, the cut-off impact parameter for fusion needs to be determined. This can be done from a study of fusion cross sections using the method of one-dimensional quantum mechanical tunnelling over the fusion barrier. Nuclear reactions are the interactions between the target and the projectile as a function of the distance between their centre of masses. This interaction consists of the short range attractive nuclear force and the long range repulsive Coulomb force. When these repulsive and attractive components are balanced at a certain inter-nuclear distance, the interaction potential becomes maximum. This potential is then termed as Coulomb barrier. The Coulomb barrier is a function of the coulomb factor Z_PZ_T, where Z_P and Z_T denote the atomic masses of the projectile and the target respectively. Larger the charge product, larger is the repulsive force, thereby lesser being the chance for fusion and hence the fusion cross section being on the lower side. Classically, fusion between two nuclei is possible only if the incident projectile energy is more than the Coulomb barrier. But it has been seen that even for the energies below the Coulomb barrier, *i.e.*, sub-barrier energies, the nuclear fusion takes place. This phenomenon, which is also regarded as quantum mechanical tunnelling, is termed as one-dimensional barrier penetration model (1-DBPM) [3-8]. The total fusion cross section is calculated as the sum of the partial fusion cross sections as provided in [26].

III. METHODOLOGY

Using Monte Carlo simulation technique, the impact parameters of a large number of trajectories are found out. To maximise the breakup fraction, θ is fixed at 0° as per the prescription provided in [23] and the distance between the target and the projectile is varied randomly to eliminate the

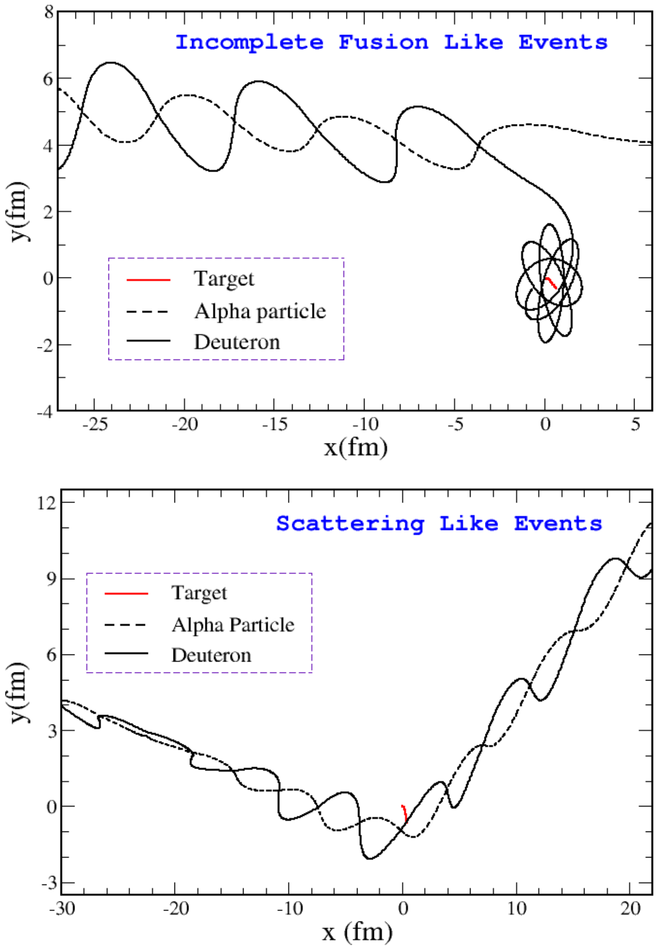

Fig. 1: Different Types of Trajectories (^{6}Li+^{152}Sm)

dependency of the breakup fraction on this distance. θ is the arbitrary orientation of the breakup fragments which is measured from their centre of mass to the direction of the p-axis.

Different types of trajectories found from the numerical solutions are shown in Fig. 1. For the sharp cut-off model for fusion, all no-breakup channels below the cut-off impact parameter is considered as complete fusion events. Projectile breakup induces fusion suppression due to which trajectories are broadly categorised into the breakup trajectory and the no-breakup trajectory. In this paper, main emphasis is given to find the breakup point of the projectile as breakup which refers to the separation among its fragments being increasing with time.

The difference between theoretical and experimental cross section (Fusion suppression) is because a fraction of projectile breaks up near the heavy target. The fraction of projectiles undergoing breakup will certainly depend upon the impact factor. For large number of trajectories, we define the breakup fraction as

$$\text{Breakup Fraction } (B_i) = \frac{\text{Total trajectories undergoing breakup}}{\text{Total trajectories considered}}$$

(2)

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

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

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, as

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

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

IV. RESULT AND DISCUSSION

We used the above formalism towards the reactions $^{7}Li+^{27}Al$, $^{8}Li+^{208}Pb$, $^{10,11}B+^{209}Bi$, $^{12}C+^{208}Pb$ using Woods-Saxon parameters V (V_o, r_o, a_o) of the nuclear potentials. The parameter used in our calculations are: $V_{\alpha\text{-}152Sm}$ = (60.5 MeV, 1.107 fm, 0.607 fm), $V_{d\text{-}152Sm}$ = (91.82 MeV, 1.013 fm, 0.938 fm), $V_{d\text{-}\alpha}$ = (75.5 MeV, 1.85 fm, 0.71 fm) [13,27,28], $V_{\alpha\text{-}\alpha}$ = (53.75 MeV, 1.628 fm, 0.613 fm) [29], $V_{\alpha\text{-}209Bi}$ = (60.0 MeV, 1.392 fm, 0.656 fm) [23, 30] and $V_{\alpha\text{-}208Pb}$ (79.5 MeV, 1.0 fm, 0.893 fm) [31], $V_{\alpha\text{-}27Al}$ (125.58 MeV, 1.245 fm,0.795 fm) [32], $V_{3H\text{-}27Al}$ = (160 MeV, 1.12 fm, 0.675 fm) [33],$V_{\alpha\text{-}6He}$ =(102.5 MeV, 0.522 fm, 0.92 fm) [34], $V_{\alpha\text{-}6Li,\alpha\text{-}7Li}$ = (85.98 MeV, 1.15 fm, 0.8 fm) [35], $V_{3H\text{-}208Pb}$ =(160 MeV, 1.20 fm, 0.66 fm) [36], $V_{5He\text{-}208Pb}$ = (137 MeV, 1.23 fm, 0.49 fm) [37]. For calculating breakup fraction 50 trajectories are taken as sample for each chosen impact parameter. The trajectories are randomly sampled and the breakup fractions are calculated for all the system we have taken from below barrier to above barrier. To determine the fusion suppression value, we first calculated the theoretical fusion cross section, σ_{theo}, where breakup is absent. The theoretical fusion cross section is calculated using CCFULL. The Woods-Saxon potential parameter considered for the reactions are: $V_{6Li\text{-}152Sm}$ = (131 MeV, 1.01 fm, 0.64 fm) [13], $V_{7Li\text{-}27Al}$ = (62 MeV, 1.20 fm, 0.65 fm), $V_{8Li+208Pb}$ = (119.2 MeV, 1.1 fm, 0.63 fm) [38], $V_{10B\text{-}209Bi}$ = (70.4 MeV, 1.12 fm, 0.794 fm) [39], $V_{11B+209Bi}$ = (178 MeV, 1.1 fm, 0.63 fm) [40], The empirical fusion suppression factor (f_{exp} = 1- $\sigma_{exp}/\sigma_{theo}$) calculated using the experimental values of cross section were shown in table 2 for all the systems from below barrier to above barrier and are shown in Fig. 2. Using σ_{theo}, we have calculated the critical angular momentum L_C for all the reactions. The barrier parameters for the above calculation ($\hbar\omega$, V_b, R_b) are taken from the result of the CCFULL code. L_C can also be calculated by single barrier potential model (SBPM) as 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 Lc we have determined the cut-off impact parameter, b_c, for all the systems which is required in calculating the fusion suppression (f_{cal}) via (3). Then we used f_{cal} for calculating fusion cross section, $\sigma_{cal} = \sigma_{theo}$ (1 - f_{cal}).

TABLE II. THE CALCULATED AND EXPERIMENTAL FUSION SUPPRESSION

System	Fusion Suppression calculated by our model (%)	Experimental Fusion suppression (%)	Reference
$^{6}Li+^{152}Sm$	28.8	28-32	[13]
$^{7}Li^{+27}Al$	32.2	-	-
$^{8}Li+^{208}Pb$	29.7	30	[38]
$^{10}B+^{209}Bi$	16	15	[10]
$^{11}B+^{209}Bi$	8.7	7	[10]

The comparison between the experimental and the calculated fusion cross sections is shown in the Figs. 2-6 for all the reactions studied. In table 2 we have compared the model predicted and experimental fusion suppression.

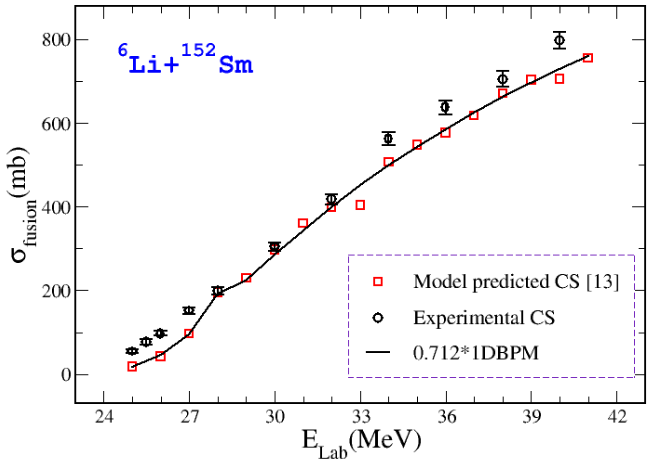

Fig. 2: Model predicted and experimental cross section as a function of energy $^{6}Li+^{152}Sm$

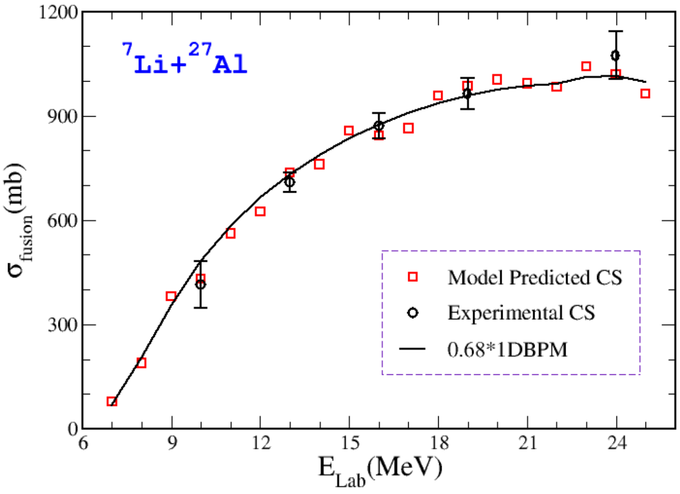

Fig. 3: Model predicted and experimental cross section as a function of energy ^{7}Li+^{27}Al

V. CONCLUSION

To explain projectile breakup and fusion suppression for reactions induced by ^{6,7,8}Li, ^{10,11}B projectiles the classical trajectory model is applied. The equation of motion is obtained from three body Lagrangian for the system of the projectile (^{2}H+^{4}He, ^{3}H+^{5}He, α-particle + ^{3}H, ^{4}He+^{6}Li, ^{4}He+^{7}Li) and the target. We then defined breakup and no-breakup trajectories from the numeric solution. To explain the fusion suppression a simple formula given in (3) is proposed whereby breakup fractions (B_i) are calculated by varying impact parameter from head-on collision to its cut off value. By comparing the theoretical fusion cross section and one-dimensional quantum mechanical tunnelling predictions over the barrier we determined the cut-off impact parameter for all the reactions. It has been seen that the predicted cross section and the experimental fusion cross section shows good agreement with each other. This method can be used for other reactions induced by loosely bound projectiles if Wood-Saxon parameters can be obtained by optical model analysis of elastic scattering data. Our aim is to find the fusion suppression factor from sub-barrier to the above barrier and this problem can be divided into two parts. First part is the calculation of cut-off impact parameter for the fusion and second part is to find the breakup fraction up to cut-off impact parameter. First part is solved by quantum mechanical method. Second part has been solved by using classical trajectory method. Since our prediction and experimental data are in good agreement so, it can be suggested that breakup reaction of all projectiles can be successfully studied using classical Newtonian laws. This method would improve our insights because quantum mechanical methods (like CDCC), used for calculating breakup, only works under certain approximation which cannot give accurate result under all criterion [21, 22].

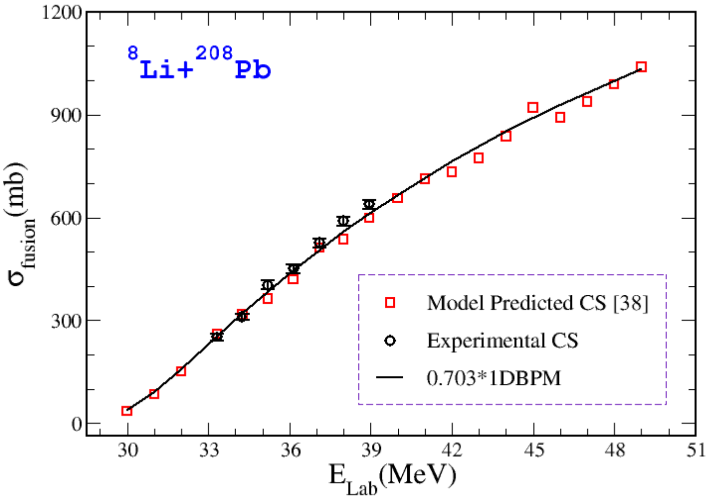

Fig. 4: Model predicted and experimental cross section as a function of energy ^{8}Li+^{208}Pb

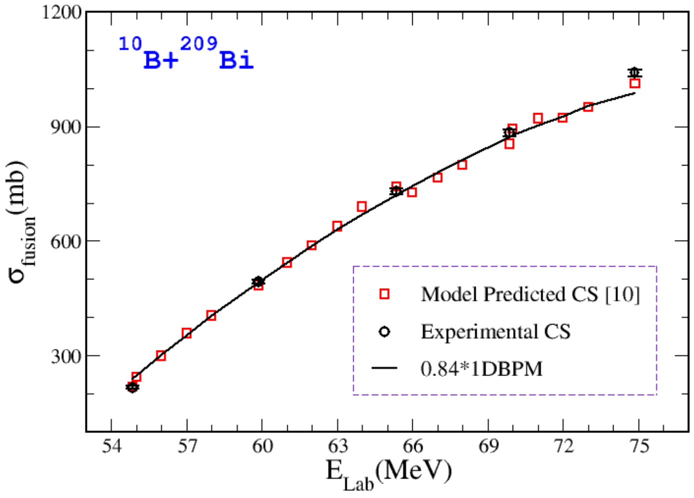

Fig. 5: Model predicted and experimental cross section as a function of energy ^{10}B+^{209}Bi

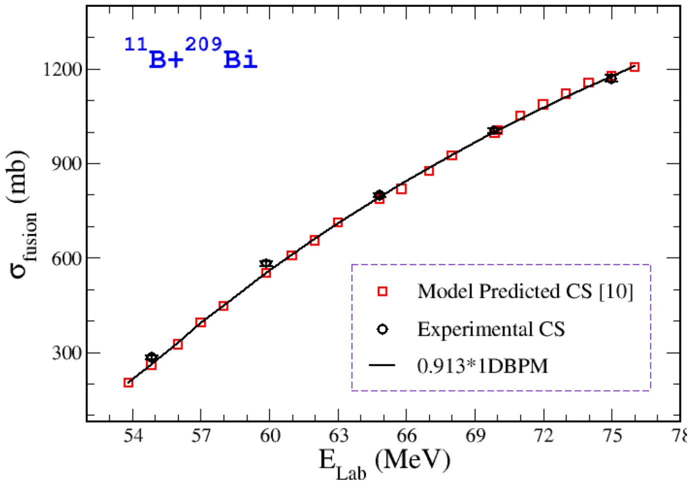

Fig. 6: Model predicted and experimental cross section as a function of energy ^{11}B+^{209}Bi

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