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Chapter

Fusion Reaction of Weakly Bound Nuclei

Fouad A. Majeed, Yousif A. Abdul-Hussien and Fatima M. Hussian

Abstract

Semiclassical and full quantum mechanical approaches are used to study the effect of channel coupling on the calculations of the total fusion reaction cross section σ_{fus} and the fusion barrier distribution D_{fus} for the systems ^{6}Li + ^{64}Ni, ^{11}B + ^{159}Tb, and ^{12}C + ^{9}Be. The semiclassical approach used in the present work is based on the method of the Alder and Winther for Coulomb excitation. Full quantum coupled-channel calculations are carried out using CCFULL code with all order coupling in comparison with our semiclassical approach. The semiclassical calculations agree remarkably with the full quantum mechanical calculations. The results obtained from our semiclassical calculations are compared with the available experimental data and with full quantum coupled-channel calculations. The comparison with the experimental data shows that the full quantum coupled channels are better than semiclassical approach in the calculations of the total fusion cross section σ_{fus} and the fusion barrier distribution D_{fus}.

Keywords: fusion reaction, breakup channel, weakly bound nuclei, fusion barrier

1. Introduction

In recent years, big theoretical and experimental efforts had been dedicated to expertise the effect of breakup of weakly bound nuclei on fusion cross sections [1, 2]. This subject attracts special interests for researchers and scholars, because the fusion of very weakly bound nuclei and exotic radioactive nuclei is reactions that have special interests in astrophysics which play a very vital role in formation of superheavy isotopes for future applications [3–8]. Since the breakup is very important to be considered in the fusion reaction of weakly bound nuclei, the following should be considered: the elastic breakup (EBU) in which neither of the fragments is captured by the target; incomplete fusion reaction (ICF), which happens when one of the fragments, is captured by the target; and complete fusion following BU (CFBU), which happens in all breakup fragments that are captured by the target, is called the sequential complete fusion (SCF). Therefore, the total breakup cross section is the sum of three contributions: EBU, ICF, and CFBU, whereas the sum of complete fusion (including two body fusions and CFBU) and incomplete fusion is called total fusion (TF) [1, 8–10]. Fusion reactions with high-intensity stable beams which have a significant breakup probability are good references for testing the models of breakup and fusion currently being developed. The light nuclei such as ^{6}Li breakup into ^{4}He+^{2}H, with separation energy Sα = 1.48 MeV; 11B breakup into

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^{4}He+^{7}Li with separation energy Sα = 8.664 MeV and ^{12}C breakup into three α particles induced by neutrons or protons by ^{12}C (p, p′) 3α [3, 11, 12]. The breakup channel is described by the continuum discretized coupled-channel (CDCC) method. The continuum that describes the breakup channel is discretized into bins [13, 14]. To study the coupled-channel problem, this requires a profound truncation of the continuum into discrete bin of energy into equally spaced states. The CDCC method is totally based on this concept. Surrey group extended the discretization procedure discussed in [14] for the deuteron case to study the breakup and fusion reactions of systems involving weakly bound nuclei [15, 16]. Recently, Majeed and Abdul-Hussien [17] utilized the semiclassical approach based on the theory of Alder and Winther. They carried out their calculations to investigate the role of the breakup channel on the fusion cross section σ_{fus} and fusion barrier distribution D_{fus} for ^{6,8}H halo [17]. Semiclassical coupled-channel calculations in heavy-ion fusion reactions for the systems ^{40}Ar + ^{110}Pd and ^{132}Sn + ^{48}Ca were carried out by Majeed et al. [18]. They argued that including the channel coupling between the elastic channel and the continuum enhances the fusion reaction cross section σ_{fus} and the fusion barrier distribution D_{fus} calculations quite well below and above the Coulomb barrier for medium and heavy systems. This study aims to employ a semiclassical approach by adopting Alder and Winther (AW) [19] theory originally used to treat the Coulomb excitation of nuclei. The semiclassical approach has been implemented and coded using FORTRAN programming codenamed (SCF) which is written and developed by Canto et al. [20]. The fusion cross section σ_{fus} and fusion barrier distribution D_{fus} are calculated here utilizing the semiclassical approach. The results from the present study are compared with the quantum mechanical calculations using the FORTRAN code (CC) [21] and with the experimental data for the three systems ^{6}Li + ^{64}Ni, ^{11}B + ^{159}Tb, and ^{12}C + ^{9}Be.

2. The semiclassical theory

2.1 The single-channel description

The semiclassical theory is used to estimate the fusion cross section in the one-dimensional potential model which assumes that one can describe the degree of freedom only of the relative motion between the colliding heavy ions [19, 20]. The semiclassical theory deals with the Schrödinger equation assuming independent energy and angular momentum and the potential energy for the radial part of the relative motion through quantum tunneling:

$$\left[-\hbar^2\nabla^2/2\mu + V(r) - E\right]\Psi(\mathrm{r}) = 0 \tag{1}$$

where μ is the reduced mass of the system and $V(r)$ is the total potential energy of the system. Semiclassical reaction amplitudes can be evaluated as a function of time, assuming the particle trajectory to be determined by classical dynamics, including Coulomb and real nuclear and centrifugal potentials, which can be written in the form

$$V(r) = V_C(r) + V_N(r) + V_l(r) \tag{2}$$

In coupled-channel effects on the elastic channel, the imaginary part should be added to the nuclear potential, represented by complex potential as

$$V_N(r) = U_N(r) - iW(r) \tag{3}$$

The method can be extended to describe interference of different l waves due to strong nuclear attraction and absorption caused by the imaginary nuclear potential [6, 20, 22]. When the two nuclei come across the potential barrier into the inner region, the fusion occurs according to the semiclassical theory, and the penetrability probability below barrier can be evaluated using WKB approximation [5, 6, 19, 23, 24]:

$$P_{fus}^{WKB}(l,E) = \frac{1}{1 + \exp\left[2\int_{r_b^{(l)}}^{r_a^{(l)}} \kappa_l(r)dr\right]} \tag{4}$$

Then, the latter can be rewritten as follows:

$$P_{fus}^{WKB}(l,E) = \frac{1}{1 + \exp\left[\frac{2\pi}{\hbar\Omega_l}(V_b(l) - E)\right]} \tag{5}$$

where $\kappa_l(r)$ is the local wave number and $r_b^{(l)}$ and $r_a^{(l)}$ are the inner and outer classical turning points at the fusion barrier potential. If one approximates the fusion barrier by a parabolic function, then the penetrability probability above barrier is given by the Hill-Wheeler formula [3, 19]:

$$P_{fus}^{WH}(l,E) = \frac{1}{1 + \exp\left[\frac{2\pi}{\hbar\Omega_l}(E - V_b(l))\right]} \tag{6}$$

where $V_b(l)$ and Ω_l are the height and the curvature parameter of the fusion barrier for the partial wave, respectively, and E is the bombarding energy. Ignoring the l dependence of ω and of the barrier position R_b and assuming that the l dependence of $V_b(l)$ is given only by the difference of the centrifugal potential energy, one can obtain Wong's formula which is given in Section 5. The fusion cross sections can be estimated by the one-dimensional WKB approximation by the following relations [21, 24]:

$$\sigma_{fus}(E) = \frac{\pi}{\kappa^2}\sum(2l+1)P_{fus}^{WKB}(l,E) \tag{7}$$

$$P_{fus}^{\gamma}(l,E) = \frac{4k}{E}\int dr\left|u_{\gamma l}\left(k_\gamma, r\right)\right|^2 W_{fus}^{\gamma}(r) \tag{8}$$

where $u_{\gamma l}\left(k_\gamma, r\right)$ represents the radial wave function for the partial wave l in channel γ and $W_{fus}^{\gamma}(r)$ is the absolute value of the imaginary part of the potential associated to fusion in that channel.

The complete fusion cross section in heavy ions evaluated using semiclassical theory is based on the classical trajectory approximation r. And the relevant intrinsic degrees of freedom of the projectile, represented by ξ with applying the continuum discretized coupled-channel (CDCC) approximation of Alder and Winther (AW) theory [16], have been proposed [17]. The projectile Hamiltonian is then given by

$$h = h_0(\xi) + V(\xi, r) \tag{9}$$

where $\mathrm{h}_0(\xi)$ is the intrinsic Hamiltonian and $\mathrm{V}(\xi, \mathrm{r}) = \mathrm{V}_N(\xi, \mathrm{r}) + \mathrm{V}_C(\xi, \mathrm{r})$, $\mathrm{V}(\xi, \mathrm{r})$ is the interaction between the projectile and target nuclei. The Rutherford trajectory depends on the collision energy, E, and the angular momentum, l. In this case the trajectory is the solution of the classical motion equations with the potential

$V(r) = \langle \Psi_0 | V(r,\xi) | \Psi_0 \rangle$, where Ψ_0 is the ground state (g.s.) of the projectile. In this way, the interaction becomes time-dependent in the ξ-space $V_l(\xi.t) = V\left(r_{l(t)}, \xi\right)$, and the eigenstates of the intrinsic Hamiltonian $|\Psi_\gamma\rangle$ satisfy the Schrödinger equation [25, 26]:

$$h|\Psi_\gamma\rangle = \varepsilon|\Psi_\gamma\rangle \tag{10}$$

After expanding the wave function in the basis of intrinsic eigenstates

$$\Psi(\xi,t) = \sum a_\gamma(l,t)\Psi_\gamma(\xi)e^{-i\varepsilon_\gamma t/\hbar} \tag{11}$$

and inserting Eq. (11) into the Schrödinger equation for $\Psi(\xi,t)$, the AW equations can be obtained:

$$i\hbar\,\dot{a}_\gamma(l,t) = \sum_\epsilon \langle \Psi_\gamma | V(\xi,t) | \Psi_\gamma \rangle e^{i\left(\varepsilon_\gamma - \varepsilon_\epsilon\right)t/\hbar} \gamma\epsilon(l,t) \tag{12}$$

These equations should be solved with initial conditions $a_\gamma(l, t \to -\infty) = \delta_{\gamma 0}$ which mean that before the collision $(t \to -\infty)$, the projectile was in its ground state. The final population of the channel γ in a collision with angular momentum l is $P^\gamma_{fus}(l,E) = \left|a_\gamma(l, t \to -\infty)\right|^2$. Eq. (8) gives the general expression for the fusion cross section in multichannel scattering [26].

2.2 The coupled-channel description

The variables employed to describe the collision are the projectile-target separation vector $\vec{r}$ and the relevant intrinsic degrees of freedom of the projectile ξ. For simplicity, we neglect the internal structure of the target. The Hamiltonian is then given by [27]

$$H = H_0(\xi) + V\left(\vec{r}, \xi\right) \tag{13}$$

where $H_0(\xi)$ is the intrinsic Hamiltonian of the projectile and $V(\vec{r}\,, \xi)$ represents the projectile-target interaction. Since the main purpose of the present work is to test the semiclassical model in calculations of sub-barrier fusion, the nuclear coupling is neglected. Furthermore, for the present theory-theory comparison, only the Coulomb dipole term is taken into account. The eigenvectors of $H_0(\xi)$ are given by the equation [27]

$$H_0|\varphi_\beta\rangle = \varepsilon_\beta|\varphi_\beta\rangle \tag{14}$$

where ε_β is energy of internal motion. The AW method is implemented in two steps. First, one employs classical mechanics for the time evolution of the variable $\vec{r}$. The ensuing trajectory depends on the collision energy, E, and the angular momentum, ℓ. In its original version, an energy symmetrized Rutherford trajectory $\vec{r_\ell}\,(t)$ was used. In our case, the trajectory is the solution of the classical equations of motion with the potential $V(\vec{r}) = \langle \varphi_0 | V(\vec{r}\,, \xi) \varphi_0 \rangle$, where $|\varphi_0\rangle$ is the ground state of the projectile. In this way, the coupling interaction becomes a time-dependent interaction in the ξ-space, $V_\ell(\xi,t) \equiv V(\vec{r_\ell}\,(t), \xi)$. The second step consists in treating the dynamics in the intrinsic space as a time-dependent quantum mechanics problem. Expanding the wave function in the basis of intrinsic eigenstates [19]

$$\psi(\xi,t) = \sum_{\beta} a_{\beta}(\ell,t)\varphi_{\beta}(\xi)e^{-i\varepsilon_{\beta}t/\hbar} \tag{15}$$

and inserting this expansion into the Schrödinger equation for $\psi(\xi,t)$, one obtains the AW equations [27]

$$i\hbar\dot{a}_{\beta}(\ell,t) = \sum_{\alpha} a_{\gamma}(\ell,t)\langle\varphi_{\beta}|V_{\ell}(\xi,t)|\varphi_{\beta}\rangle e^{-i\left(\varepsilon_{\beta}-\varepsilon_{\gamma}\right)t/\hbar} \tag{16}$$

These equations are solved with the initial conditions $a_{\beta}(\ell,t\to-\infty) = \delta_{\beta 0}$, which means that before the collision $(t\to-\infty)$, the projectile was in its ground state. The final population of channel β in a collision with angular momentum ℓ is $P_{\ell}^{(\beta)} = \left|a_{\beta}(\ell,t\to+\infty)\right|^2$ and the angle-integrated cross section is [19]

$$\sigma_{\beta} = \frac{\pi}{k^2}\sum_{\ell}(2\ell+1)P_{\ell}^{(\beta)} \tag{17}$$

To extend this method to fusion reactions, we start with the quantum mechanical calculation of the fusion cross section in a coupled-channel problem. For simplicity, we assume that all channels are bound and have zero spin. The fusion cross section is a sum of contributions from each channel. Carrying out partial-wave expansions, we get [28]

$$\sigma_F = \sum_{\beta}\left[\frac{\pi}{k^2}\sum_{\ell}(2\ell+1)P_{\ell}^{F}(\beta)\right] \tag{18}$$

with

$$P_{\ell}^{F}(\beta) = \frac{4k}{E}\int W_{\beta}^{F}(r)\left|u_{\beta\ell}\left(k_{\beta},r\right)\right|^2 dr \tag{19}$$

Above, $u_{\beta\ell}\left(k_{\beta},r\right)$ represents the radial wave function for the ℓth partial wave in channel β, and W_{β}^{F} is the absolute value of the imaginary part of the optical potential associated to fusion in that channel.

To use the AW method to evaluate the fusion cross section, we make the approximation [27]

$$P_{\ell}^{F}(\beta) \simeq \overline{P}_{\ell}^{(\beta)}T_{\ell}^{(\beta)}\left(E_{\beta}\right) \tag{20}$$

where $\overline{P}_{\ell}^{(\beta)}$ is the probability that the system is in channel β at the point of closest approach on the classical trajectory and $T_{\ell}^{(\beta)}\left(E_{\beta}\right)$ is the probability that a particle with energy $E_{\beta} = E-\varepsilon_{\beta}$ and reduced mass $\mu = M_P M_T/(M_P+M_T)$, where M_P, M_T are the masses of the projectile and target, respectively, tunnels through the potential barrier in channel β [19].

We now proceed to study the CF cross sections in reactions induced by weakly bound projectiles. For simplicity, we assume that the g.s. is the only bound state of the projectile and that the breakup process produces only two fragments, F_1 and F_2. In this way, the labels $\beta = 0$ and $\beta \neq 0$ correspond, respectively, to the g.s. and the breakup states represented by two unbound fragments. Neglecting any sequential contribution, the CF can only arise from the elastic channel. In this way, the cross section σ_{CF} can be obtained from Eq. (20), dropping contributions from $\beta \neq 0$. That is [19],

$$\sigma_{CF} = \frac{\pi}{k^2}\sum_{\ell}(2\ell+1)P_{\ell}^{Surv}T_{\ell}^{(0)}(E) \tag{21}$$

where

$$P_{\ell}^{Surv} \equiv \overline{P}_{\ell}^{(0)} = |a_0(\ell, t_{ca})|^2 \tag{22}$$

is usually called survival (to breakup) probability [19].

3. Fusion barrier distribution

Nuclear fusion is related to the transmission of the incident wave through a potential barrier, resulting from nuclear attraction plus Coulomb repulsion. However, the meaning of the fusion barrier depends on the description of the collision. Coupled-channel calculations include static barriers, corresponding to frozen densities of the projectile and the target. Its most dramatic consequence is the enhancement of the total fusion reaction cross section σ_{fus} at Coulomb barrier energies V_b, in some cases by several orders of magnitude. One of the possible ways to describe the effect of coupling channels is a division of the fusion barrier into several, the so-called fusion barrier distribution D_{fus} and given by [20, 29]

$$D_{fus}(E) = \frac{d^2F(E)}{dE^2} \tag{23}$$

where $F(E)$ is related to the total fusion reaction cross section through [29]

$$F(E) = E\sigma_{fus}(E) \tag{24}$$

The experimental determination of the fusion reaction barrier distribution has led to significant progress in the understanding of fusion reaction. This comes about because, as already mentioned, the fusion reaction barrier distribution gives information on the coupling channels appearing in the collision. However, we note from Eq. (24) that, since fusion reaction barrier distribution should be extracted from the values of the total fusion reaction cross section, it is the subject to experimental as well as numerical uncertainties [29–31]:

$$D_{fus}(E) \approx \frac{F(E+\Delta E) + F(E-\Delta E) - 2F(E)}{\Delta E^2} \tag{25}$$

where ΔE is the energy interval between measurements of the total fusion reaction cross section. From Eq. (25), one finds that the statistical error associated with the fusion reaction barrier distribution is approximately given by [30]

$$\delta D_{fus}^{stat}(E) \approx \frac{\sqrt{[\delta F(E+\Delta E)]^2 + [\delta F(E-\Delta E)]^2 + 4[\delta F(E)]^2}}{(\Delta E)^2} \tag{26}$$

where $\delta F(E)$ means the uncertainty in the measurement of the product of the energy by the total fusion reaction cross section at a given value of the collision energy. Then the uncertainties can approximately be written as [30]

$$\delta D_{fus}^{stat}(E) \approx \frac{\sqrt{6}\delta F(E)}{(\Delta E)^2} \tag{27}$$

4. Results and discussion

In this section, the theoretical calculations are obtained for total fusion reaction σ_{fus}, and the fusion barrier distribution D_{fus} using the semiclassical theory adopted the continuum discretized coupled channel (CDCC) to describe the effect of the breakup channel on fusion processes. The semiclassical calculations are carried out using the (SCF) code, while the full quantum mechanical calculations are performed by using the code (CC) for the systems ^{6}Li + ^{64}Ni, ^{11}B + ^{159}Tb and ^{12}C + ^{9}Be. The values of the height V_c, radius R_c, and curvature $\hbar\omega$ for the fusion barrier are displayed in **Table 1**.

4.1 The reaction ^{6}Li + ^{64}Ni

The calculations of the fusion cross section σ_{fus} and fusion barrier distribution D_{fus} are presented in **Figure 1** panel (a) and panel (b), respectively, for the system ^{6}Li + ^{64}Ni. The dashed blue and red curves represent the semiclassical and full quantum mechanical calculations without coupling, respectively. The solid blue and red curves are the calculations including the coupling effects for the semiclassical and full quantum mechanical calculations, respectively. Panel (a) shows the comparison between our semiclassical and full quantum mechanical calculations with the respective experimental data (solid circles).

The experimental data for this system are obtained from Ref. [32]. The real and imaginary Akyüz-Winther potential parameters obtained by using chi-square

System	V_c	R_c	$\hbar\omega$	Refs
^{6}Li + ^{64}Ni	12.41	9.1	3.9	[32]
^{11}B + ^{159}Tb	40.34	10.89	4.42	[33]
^{12}C + ^{9}Be	4.28	7.43	2.61	[34]

Table 1.
The fusion barrier parameters are height V_c (MeV), radius R_c(fm), and curvature $\hbar\omega$ (MeV).

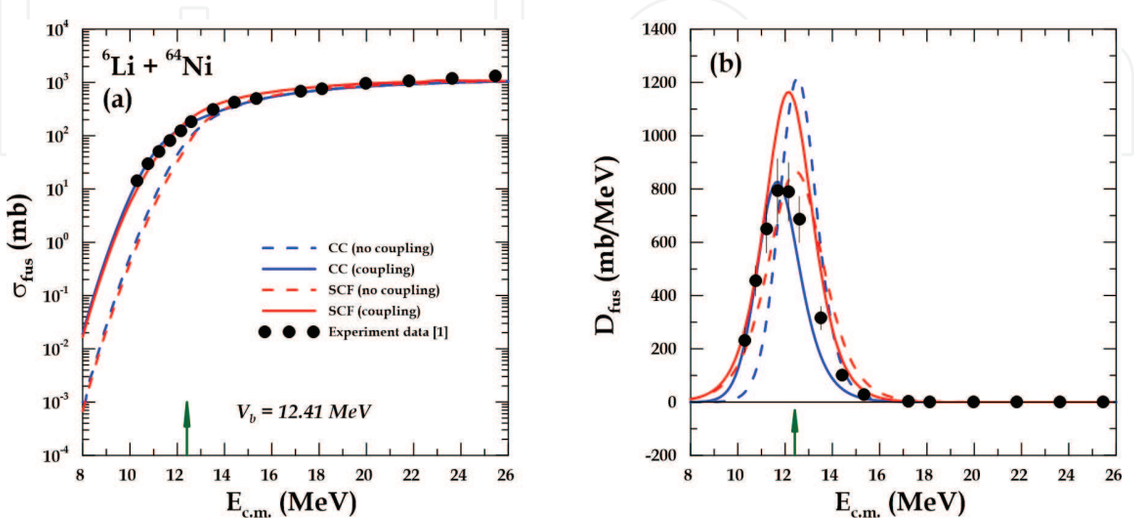


Figure 1.
The comparison of the coupled-channel calculations of semiclassical treatment (red curves) and full quantum mechanical (blue curves) with the experimental data of complete fusion (black-filled circles) [32] for ^{6}Li + ^{64}Ni system. Panel (a) refers to the total fusion reaction cross section σ_{fus} (mb), and panel (b) provides the fusion reaction barrier distribution D_{fus} (mb/MeV).

method are the strength $W_0 = 50\,MeV$, radius $r_i = 1.0\,fm$, and diffuseness $a_i = 0.25\,fm$, and for the real part, the depth is $V_0 = 35.0\,MeV$, radius is $r_0 = 1.1\,fm$, and diffuseness is $a_0 = 0.8\,fm$. The χ^2 values obtained for the total fusion cross section σ_{fus} are 1.5057 and 1.1286 in the case of no coupling for semiclassical and quantum mechanical calculations, respectively. The χ^2 values obtained for the case of coupling effects included are 0.2431 and 0.3115 for semiclassical and quantum mechanical calculations, respectively. The χ^2 values show clearly that semiclassical calculations including coupling effects are more consistent with the experimental data than full quantum mechanical including coupling effects. The χ^2 values obtained using single-channel calculations for the fusion reaction barrier distribution D_{fus} are 0.1823 and 1.1914 for semiclassical and quantum mechanical calculations, respectively. The χ^2 values obtained when coupled channels are included are 0.1827 and 0.1321 for semiclassical and quantum mechanical calculations, respectively; the fusion barrier distribution D_{fus} has been extracted from the experimental data using Wong fit model along with the three-point difference method. The comparison with the experimental data for D_{fus} shows that the quantum mechanical calculations are in better agreement than the semiclassical calculations including the coupling effects.

4.2 The reaction $^{11}B + ^{159}Tb$

In similar analysis we compare our theoretical calculations of the fusion cross section σ_{fus} and fusion barrier distribution D_{fus} with the corresponding experimental data in panels (a) and (b) of **Figure 2**, respectively, for the system $^{11}B + ^{159}Tb$. The experimental data for this system is obtained from Ref. [33]. The real and imaginary Akyüz-Winther potential parameters are obtained by using chi-square method: $V_0 = 126.1$ MeV, $r_0 = 1.2$ fm, and $a_0 = 0.5$ fm and $W_0 = 55.9$ MeV, $r_i = 0.986$ fm, and $a_i = 0.614$ fm. The χ^2 values 0.9473 and 0.2486 are obtained for σ_{fus} using semiclassical and quantum mechanical distribution calculations without including the coupling, respectively, while the χ^2 for σ_{fus} using the semiclassical and quantum mechanical distribution calculations including the

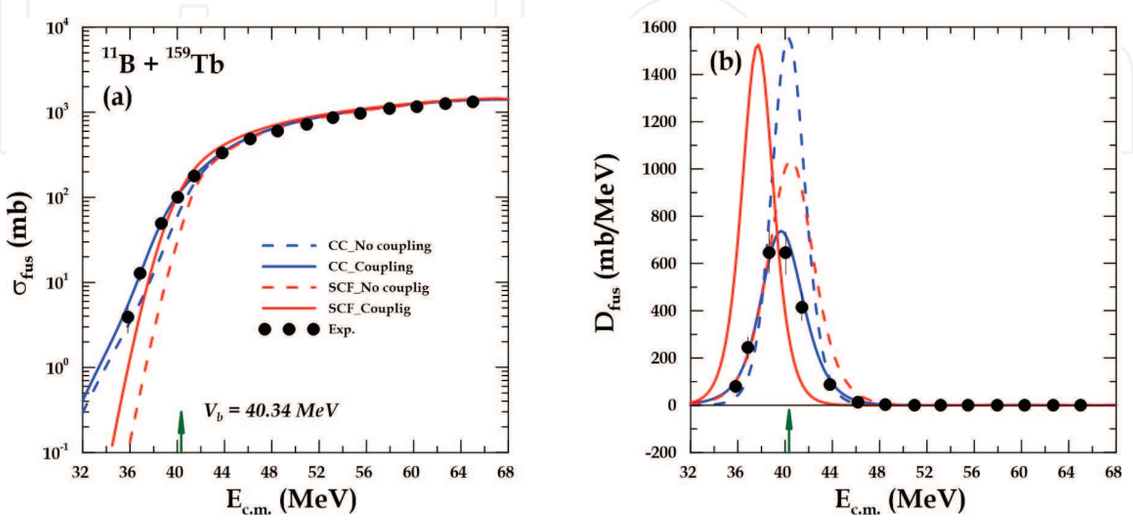


Figure 2.
The comparison of the coupled-channel calculations of semiclassical treatment (red curves) and full quantum mechanical (blue curves) with the experimental data of complete fusion (black-filled circles) [33] for $^{11}B + ^{159}Tb$ system. Panel (a) shows the total fusion reaction cross section σ_{fus} (mb), and panel (b) gives the fusion reaction barrier distribution D_{fus} (mb/MeV).

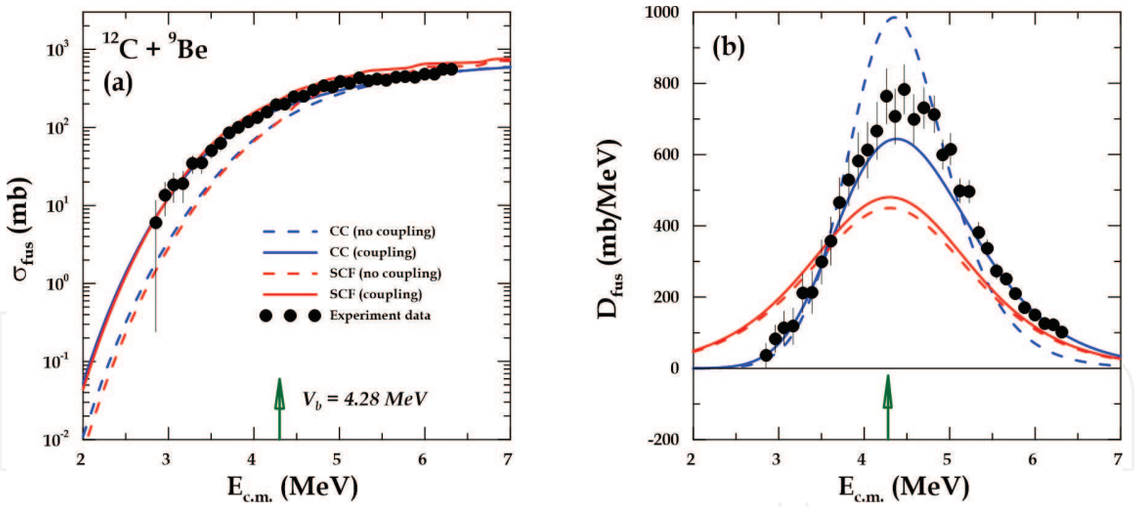


Figure 3.
The comparison of the coupled-channel calculations of semiclassical treatment (red curves) and full quantum mechanical (blue curves) with the experimental data of complete fusion (black-filled circles) [34] for $^{12}C + {}^{9}Be$ system. Panel (a) shows the total fusion reaction cross section σ_{fus} (mb), and panel (b) gives the fusion reaction barrier distribution D_{fus} (mb/MeV).

coupling effects are 0.2681 and 0.1657, respectively. The χ^2 for the fusion barrier distribution D_{fus} using the semiclassical and quantum calculations are 0.5828 and 1.2329 for no coupling and 4.5969 and 0.0616 including coupling effects, respectively. The χ^2 values for σ_{fus} and D_{fus} give clear evidence that the quantum mechanical calculations are in better agreement than the semiclassical calculations as compared with experimental data.

4.3 The reaction ^{12}C + ^{9}Be

Figure 3 (panels (a) and (b)) presents the comparison between our theoretical calculations for σ_{fus} and D_{fus} using both semiclassical and quantum mechanical calculations with the corresponding experimental data for the system ^{12}C + ^{9}Be. The experimental data for this system are obtained from Ref. [34]. The real and imaginary Akyüz-Winther potential parameters are obtained by using chi-square method: $V_0 = 40.3\,MeV$, $r_0 = 1.11\,fm$, $a_0 = 0.590\,fm$, $W_0 = 0\,MeV$, $r_i = 1.1\,fm$, and $a_i = 0.50\,fm$. The χ^2 values obtained from the comparison between the results and experimental data for σ_{fus} are 1.0633 and 1.1447 without coupling, and 0.4924 and 0.2072 with coupling, for semiclassical and quantum mechanical calculations, respectively. The obtained χ^2 values for D_{fus} using semiclassical and quantum mechanical calculations are 1.2383 and 0.6185 without coupling and 0.9875 and 0.1868 with account for coupling, respectively.

5. Conclusion

The semiclassical and quantum mechanical calculations for the total fusion reaction σ_{fus} and the fusion barrier distribution D_{fus} calculations below and around Coulomb barrier were discussed for the systems ^{6}Li + ^{64}Ni, ^{11}B + ^{159}Tb, and ^{12}C + ^{9}Be. We conclude that the breakup channel is very important to be taken into consideration to describe the total fusion reaction σ_{fus} and the fusion barrier distribution D_{fus} for reaction of light projectiles. The full quantum mechanical calculations are closer to the experimental data than the semiclassical calculations;

however, semiclassical ones can be considered a successful tool for studying fusion reaction of systems involving light projectiles.

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