International Journal of ChemTech Research
CODEN (USA): IJCRGG, ISSN: 0974-4290, ISSN(Online):2455-9555
Vol.10 No.6, pp 945-955, 2017

Fusion Reactions of Some Medium Systems by employing Semiclassical and Quantum Treatments

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Abstract : The semiclassical Coupled-Channels calculations for the medium systems $^{6}Li+^{64}Ni$, $^{6}He+^{64}Zn$ and $^{16}O+^{62}Ni$ are discussed. The total fusion reaction cross section σ_{fus}, and the fusion barrier distribution D_{fus} for these systems has been calculated using a semiclassical approach based on the method of Alder and Winther for Coulomb excitation. The results obtained from our semiclassical calculations are compared with the available experimental data and with a full quantum Coupled-Channels calculations. The (X^2) for the case of no coupling and coupling effects included shows clearly that the present semiclassical calculations are more consistent with the experimental data than the full quantum mechanical calculations.
Keywords : Semiclassical treatment, Quantum treatment, Medium systems, The coupled channel.

1. Introduction

The fusion of the colliding nuclei evolves from a one-dimensional to multidimensional barrier penetration process as the relative energy for collision approaches the barrier. The multidimensional barrier-penetration model describes the enhancement observed in the fusion cross section at energies below the barrier [1]. The barrier distribution function [1–3], has contain as an important tool to probe the reaction dynamics of nucleus-nucleus collision at energies around the Coulomb barrier of the colliding system [4].The interplay essentially modifies the effective interaction potential for collision and in turn splits the nominal Coulomb barrier into multiple barriers [5]. The barrier distributionfunction derived from the measured fusion excitation function(D_{fus}), therefore, provides useful information regarding the effect of coupling between the channels and can be used to understand the consequence of these couplings on fusion reaction [6]. The fusion of complex nuclei, governed by a delicate balance between the attractive nuclear and repulsive Coulomb interactions, cannot be understood as simple barrier penetration by a synthesis less object with a potential depending only on the distance between the centers of the interacting systems. The tunneling probability is extremely sensitive to the plasticity of the intrinsic synthesis that can evolve during the process and to the interplay of many open and virtual channels [7, 8]. The procedures of nuclear fusion remains one of the most intriguing and intensively studied phenomena. The study of this process is very important, for synthesis of medium nuclei and understanding of astrophysical nucleogenesis. This allowed, in particular, systematic investigations of fusion of stable as well as exotic nuclei at energies well below the Coulomb barrier [9,10]. For practical purposes, it becomes necessary to approximate the continuum by anite set of states, as in the Continuum Discretized Coupled-Channels method (CDCC) [11–13]. The major aim of fusion reaction studies involving tightly bound stable nuclei over the last four decades has been to produce medium elements and to understand the mechanism of quantum tunneling in complex many-body systems. Further, the analysis of fusion data supplies very useful information about the nuclear interaction at distances corresponding to the outer side of the Coulomb barrier [14,15]. The satisfactorily explained using simple one-dimensional barrier penetration concepts within the (WKB) approximation [16]. The aim of the present work emphases semiclassical and Quantum mechanical treatments to study the effect of the coupled-channel calculations on total fusion reaction cross section σ_{fus}, and the fusion barrier distributionD_{fus} for the systems $^{6}Li + ^{64}Ni$, $^{6}He + ^{64}Zn$ and $^{16}O + ^{62}Ni$ by adopting a semiclassical approach which uses the Continuum Discretized Coupled-Channel (CDCC) approximation. The semiclassical calculations have been implemented and coded using Fortran codenamed (SCF) developed by H. D. Marta et al., [17], while the full quantum mechanical calculations were performed using the CC developed by L. F. Canto, P. R. S. Gomes, R. Donangelo and M. S. Hussein, [17] and the results will be compared with the available experimental data.

2. Theoretical framework

A standard theoretical approach is thus to explicitly deal with nuclear intrinsic degrees of freedom in addition to the relative motion between the colliding nuclei. Let asconsider the reaction described by the total wave function$\Psi(\mathbf{r},\xi)$,where $\mathbf{r}$stands for the projectile and target nuclei separation vector and $\xi$for the set of intrinsic coordinates of the projectile and target nuclei. The dynamics of this reaction is determined by the Hamiltonian,

$$H = H_0 + T + U \qquad (1)$$

where$H_0 \equiv H_0(\xi, p_\xi)$is the intrinsic Hamiltonian, $T \equiv -\hbar^2\boldsymbol{\nabla}^2/2\mu$is the kinetic energy operator of the relative motion between the projectile and target nuclei, and $U \equiv U(\mathbf{r},\xi)$is the interaction potential. The eigen states of the intrinsic Hamiltonian,$|\beta\rangle$, satisfy the Schrödinger equation [17],

$$\left(e_\eta - H_0\right)|\beta\rangle = 0 \qquad (2)$$

The orthonormality is,

$$\langle\beta'|\beta\rangle = \int d\xi\varphi^*_{\beta'}(\xi)\varphi_\beta(\xi) = \delta_{\eta\eta'} \qquad (3)$$

where$\varphi_\beta(\xi)\left(\varphi_{\beta'}(\xi)\right)$is the wave function corresponding to the state $|\beta\rangle(|\beta\rangle)$ in the ξ- representation. The interaction potential is split as,

$$U = U' + U'' \qquad (4)$$

where$U'$is diagonal in channel space,

$$U' = \sum_\beta |\beta\rangle U'_\eta \langle\beta| \qquad (5)$$

$$U'' = \sum_\beta |\beta\rangle U''_{\beta,\beta'} \langle\beta'| \qquad (6)$$

Where

$$U'_\beta(\boldsymbol{r}) = \int d\xi\left|\varphi_\beta(\xi)\right|^2 U'(\mathrm{r},\xi) \qquad (7)$$

$$U''_{\beta,\beta'}(\mathrm{r}) = \int d\xi\varphi^*_{\beta'}(\xi)U''(\mathrm{r},\xi)\varphi_\beta(\xi) \quad (8)$$

The potential $U^{'}$is arbitrary, except for the condition of being diagonal in channel space. However, once it is chosen, $U^{''}$is given by the relation$U^{''} = U - U^{'}$. Frequently, it is convenient to choose $U^{'}$ such that $U^{''}$ispurely off diagonal. In such cases the components of $U^{''}$can be written [17],

$$U^{''}_{\beta,\beta^{'}}(\mathbf{r}) = \int d\xi \varphi^{*}_{\beta^{'}}(\xi) U^{''}(\mathbf{r},\xi)\varphi_{\beta}(\xi) - \delta_{\beta\beta^{'}} U^{'}_{\beta}(\mathbf{r}) \qquad (9)$$

from the Schrödinger equation, we can start to derive the coupled channel equations,

$$(E - H)\left|\Psi_{\beta}(\beta_0 \mathbf{k}_0)\right\rangle = 0 \qquad (10)$$

and the channel-expansion,

$$\left|\Psi_{\beta}(\beta_0 \mathbf{k}_0)\right\rangle = \sum_{\beta} \left|\psi_{\beta}(\beta_0 \mathbf{k}_0)\right\rangle |\beta\rangle \qquad (11)$$

The notation $|\Psi(\beta_0 \mathbf{k}_0)\rangle$indicates that the collision is started in channelβ_0, with wave vector $\mathbf{k}_0$, and the energy scale is chosen such that $e_{\beta_0} = 0$. Owing to the off diagonal part of the reaction, The Schrödinger equation solution has components $\left|\Psi_{\beta}(\beta_0 \mathbf{k}_0)\right\rangle$for both $\beta = \beta_0$ and $\beta \neq \beta_0$, the infinite expansion ofEq. (11) is truncated so as to include only the most relevant channels or closed coupling approximation. To account forthe loss of flux through neglected channels, one may include an imaginary part in the channel potentials$U^{'}_{\beta}(\mathbf{r})$.To find the wave function, we must write the Hamiltonian as [17],

$$H = H_0 + H^{'} + U^{''} \qquad (12)$$

$$H^{'} = T + U^{'} \qquad (13)$$

When we put Eqs. (11) and (12) into Eq. (10), and take the scalar product with each intrinsic state $\langle\beta|$, then we get the coupled channel equations,

$$\left(E_{\beta} - H^{'}_{\beta}\right)\left|\psi_{\beta}(\beta_0 \mathbf{k}_0)\right\rangle = \sum_{\beta^{'}} U^{''}_{\beta,\beta^{'}}(\mathbf{r}) \left|\psi_{\beta^{'}}(\beta_0 \mathbf{k}_0)\right\rangle \qquad (14)$$

or,

$$\left[E_{\beta} + \frac{\hbar^2}{2\mu}\Delta - U^{'}_{\beta}(\mathbf{r})\right]\psi_{\beta}(\mathbf{r}) = \sum_{\beta^{'}} U^{''}_{\beta,\beta^{'}}(\mathbf{r})\psi_{\beta^{'}}(\mathbf{r}) \qquad (15)$$

Where,

$$E_{\beta} = E - e_{\beta} (16)$$

$E_{\beta}$is the total energy of the relative motion in channel $\beta$and,

$$H^{'}_{\beta} = T + U^{'}_{\beta} \qquad (17)$$

The Eq. (15) switched to the more compact notation $\left|\psi_{\beta}(\beta_0 \mathbf{k}_0)\right\rangle \longrightarrow \psi_{\beta}(\mathbf{r})$,and the channel potentials are written as,

$$U^{'}_{\beta} = V_{\beta} + iW_{\beta} \qquad (18)$$

where the flux in channel βaccounted by the imaginary part W_{β}lost to other channels which were not included in the coupled channel equations. A consequence of the non-Hermitian nature of $H$is that the continuity equation breaks down. In the usual case where the channel coupling interaction $U''_{\beta}$is Hermitian, the continuity equation is written by the relation [18].

$$\nabla \cdot \sum_{\beta} \mathbf{J}_{\beta} = \frac{2}{\hbar} \sum_{\beta} W_{\beta}(\mathbf{r}) \left|\psi_{\beta}(\mathbf{r})\right|^{2} \neq 0 \quad (19)$$

where$\mathbf{J}_{\beta}$is the probability current density in channelβ. Integrating the above equation inside a large sphere with radius larger than the interaction range and using the definition of the absorption cross section σ_{β}[19 – 21],

$$\sigma_{\beta} = \frac{k}{E} \sum_{\beta} \langle \psi_{\beta} | W_{\beta} | \psi_{\beta} \rangle \qquad (20)$$

If the absorptive potential can be written as,

$$W_{\beta} = W_{\beta}^{D} + W_{\beta}^{F} (21)$$

With W_{β}^{D}accounting for the flux lost to other direct reaction channels and W_{β}^{F}accounting for fusion absorption, the fusion reaction cross section can be written as [19,21],

$$\sigma_{F} = \frac{k}{E} \sum_{\beta} \langle \psi_{\beta} | W_{\beta}^{F} | \psi_{\beta} \rangle \qquad (22)$$

there are strong effects in fusion reactions arising from couplings among several channels.

3. Fusion Barrier Distribution

Nuclear fusion is related with the transmission of the incident wave through a potentialbarrier, resulting from nuclearattraction plus Coulomb repulsion. However, the meaning of thefusion barrier depends on the description of the collision. Coupled channel calculations involvestatic barriers, corresponding to frozen densities of the projectile and the target. It's most dramatic consequence is the enhancement of the total fusion reaction cross section σ_{fus} at Coulomb sub-barrier energies V_b, in some cases by several orders of magnitude. The possible way to describe theeffect of coupling channels is as a division of the fusion barrier into several, the so-called fusion barrier distributionD_{fus} and given by [17,3],

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

when$F(E)$ is related with the total fusion reaction cross section through,

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

The experimental determination of the fusion reaction barrier distribution has lead to significant progress in the understanding,. This comes about because, as already mentioned, the fusion reaction barrier distribution gives information on the coupling channels appearing in the collision. However, from Eq. (23), we note that, because it must be extracted from the values of the total fusion reaction cross section, it is subject to experimental as well as numerical uncertainties. The usual procedure is to estimate the second derivative appearing in Eq. (23) through a three-point difference method [23,24],

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

whereΔE 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 [24],

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

Where $\delta F(E)$ is mean 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. When the uncertainties are approximately be written as [23]

$$\delta D_f^{stat}(E) \approx \frac{\sqrt{6}\delta F(E)}{(\Delta E)^2} \quad (27)$$

4. Results and Discussion

The total fusion reaction cross section σ_{fus} and the fusion barrier distribution D_{fus} have been calculated for the systems ^{6}Li+^{64}Ni, ^{6}He+^{64}Zn and ^{16}O+^{62}Ni. We utilized the semiclassical theory adopted the continuum discretized coupled channel (CDCC) method to describe the effect of the breakup channel on fusion processes. The semiclassical calculations has been performed using the (SCF) code, while the full quantum mechanical calculations has been performed by using the code (CC) for these systems. The Akyüz-Winther potential parameters used in thepresent calculations are tabulated in Table I.

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

The calculations of the fusion cross section σ_{fus} , and fusion barrier distribution D_{fus} is presented in Fig.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 corresponding experimental data (solid circles). The experimental data for this system are obtained from Ref. [25].The green arrow in figure 1.2. and 3. Represents the position of the Coulomb sub-barrier V_b. In the case of no-coupling both semiclassical and full quantum mechanical calculations underestimate the experiential data of complete fusion below the Coulomb sub-barrier, the inclusion of the coupling in both calculations shows that the full quantum mechanical are more closer than semiclassical treatment ones in comparison with the experimental data of complete fusion below the Coulomb sub-barrier. The comparison of the calculated fusion reaction barrier distribution D_{fus} for both semiclassical and full quantal mechanical ones along with the experimental data of complete fusion extracted using the three-point difference method is shown in panel (b) in Figure 1.The calculated chi-square values for the total fusion cross section, and fusion barrier distribution for both semiclassical and quantum mechanical coupled channel compared with their corresponding experimental data for CC and SCF codes for ^{6}Li+ ^{64}Ni system are:

A)Below V_b The best calculated chi-square value obtained is $(\chi^2 = 0.000916)$ for CC Code as shown in Table 3, which corresponds to the full quantum mechanical coupled channel calculations including are in best agreement with the experimental data for the total fusion cross section σ_{fus}. For the fusion barrier distribution D_{fus} calculations the lowest obtained is $(\chi^2 = 0.005683)$ for CC Code and which corresponds to the full quantum mechanical coupled channel calculations are in best agreement with their corresponding experimental data.

B) Above V_b

The best calculated chi-square value obtained is $(\chi^2 = 0.023027)$ for SCF Code as shown in Table 2, which corresponds to the semiclassical calculations including coupling channel are in best agreement with the experimental data for the total fusion cross section σ_{fus}.For the calculations of the fusion barrier distribution D_{fus} the lowest obtained is $(\chi^2 = 0.022313)$ for SCF Code and which corresponds to the semiclassical

calculations including coupling channel are in best agreement with their corresponding experimental data.

Table 1.The parameters of Akyüz-Winther potential along with Coulomb barrier coefficients: height, radius, and curvature, Vb, Rb, and ℏω, respectively.

System	V_0(MeV)	r_0 (fm)	a_0 (fm)	V_b (MeV)	R_b (fm)	ℏω(MeV)
$^{6}Li + ^{64}Ni$	35.0	1.100	0.800	12.41	8.82	5.083
$^{6}He + ^{64}Zn$	43.0	1.100	0.800	8.401	9.40	4.115
$^{16}O + ^{62}Ni$	66.1	1.100	0.800	31.38	9.36	5.073

Table 2: The chi-square values of $^{6}Li + ^{64}Ni$ system for the total fusion cross section σ_{fus} and the fusion barrier distribution D_{fus} calculations for SCF and CC codes for under and above V_b with experimental data.

system	SCF				CC			
	No coupling		Coupling		No coupling		Coupling	
^{6}Li + ^{64}Ni	Below V_b	Above V_b	Below V_b	Above V_b	Below V_b	Above V_b	Below V_b	Above V_b
σ_{fus}	0.114154	0.036414	0.001281	**0.023027**	0.071568	0.041296	**0.000916**	0.030237
D_{fus}	0.018408	0.027179	0.023364	**0.022313**	0.260815	0.037033	**0.005683**	0.027337

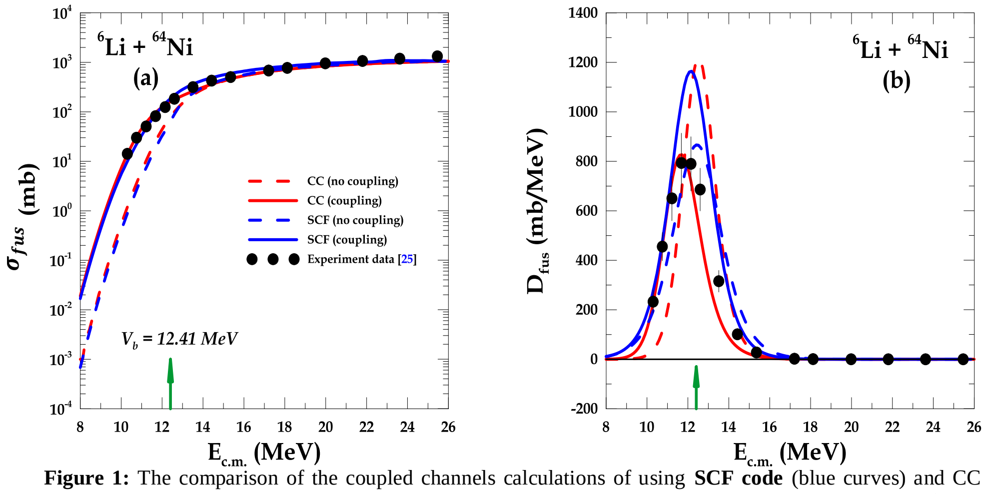

Figure 1: The comparison of the coupled channels calculations of using **SCF code** (blue curves) and CC **code** (red curves) with the experimental data (black filled circles and Violet filled squares) for **^{6}Li + ^{64}Ni**system. Panel **(a)** for the total fusion cross section **σ_{fus}(mb)**, and Panel (b) for the fusion barrier distribution D_{fus} (mb/MeV).

4.2 The reaction ^{6}He + ^{64}Zn

The comparison between semiclassical and quantum mechanical calculations along with the experimental data for the total fusion reaction cross section σ_{fus} and the fusion reaction barrier distribution D_{fus} is shown in panels (a) and (b) of Figure 2 , respectively.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.The experimental data for the system ^{6}He + ^{64}Zn are obtained from Ref. [26]. The calculated chi-square values for the total fusion cross section, and fusionbarrier distribution for both semiclassical and quantum mechanical coupled channel compared with their corresponding experimental data for CC and SCF codes for $^6He + ^{64}Zn$ systemare:

A) Below V_b

The calculated chi-square are tabulated in Table 3. The valuesare found $(\chi^2 = 0.001670)$ for SCF Code in the case coupling channel calculations and which corresponds to semiclassical calculations including coupling are in best agreement with the experimental data for the calculations of the total fusion cross section σ_{fus}.The best obtained value of chi-square for the fusion barrier distributionD_{fus} calculations is $(\chi^2 = 0.009947)$for CC code and which correspond the which corresponds to the full quantum mechanical calculationsincluding coupling effects, which means that they are able to reproduce the experimental data better than other calculations.

B) Above V_b

The calculated chi-square values tabulated in Table 3 are$(\chi^2 = 0.140415)$ for CC Code in the case of coupling channel calculations and which corresponds to the full quantum mechanical no coupled channel calculations are in best agreement with the experimental data for the calculations of the total fusion cross section σ_{fus}.The best obtained value of chi-square for the fusion barrier distribution calculations $D_{fus}$is $(\chi^2 = 0.118142)$for CC Code and which corresponds to the full quantum mechanical coupled channel .

Table 3: The chi-square values of $^6He + ^{64}Zn$ system for the total fusion cross section σ_{fus} and the fusion barrier distribution D_{fus} calculations for SCF and CC codes for under and above V_b with experimental data.

system	SCF				CC			
	No coupling		Coupling		No coupling		Coupling	
$^6He + ^{64}Zn$	Below V_b	Above V_b	Below V_b	Above V_b	Below V_b	Above V_b	Below V_b	Above V_b
σ_{fus}	0.698044	0.260299	**0.001670**	0.526217	0.356861	0.159234	0.002214	**0.140415**
D_{fus}	0.018097	0.180659	0.098469	0.275272	0.092432	0.652218	**0.009947**	**0.118142**

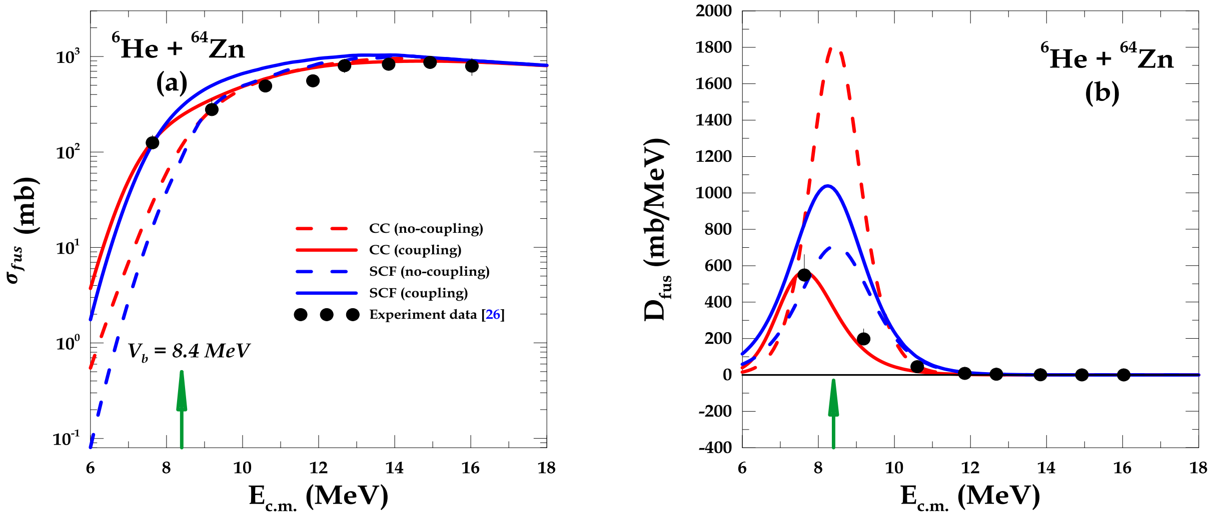

Figure 2: The comparison of the coupled channels calculations of using **SCF code** (blue curves) and **CC code** (red curves) with the experimental data (black filled circles) for ^{6}**He** + ^{64}**Zn** system. Panel **(a)** for the total fusion cross section σ_{fus}**(mb)**, and Panel **(b)** for the fusion barrier distribution D_{fus} **(mb/MeV)**.

4.3 The reaction ^{16}O + ^{62}Ni

Figure 3 panel (A) and (B) presents the comparison between our theoretical calculations for the total fusion reaction cross section σ_{fus} and the fusion reaction barrier distribution D_{fus} using both semiclassical and quantum mechanical calculations with the corresponding experimental data for the system ^{16}O + ^{62}Ni the experimental data for this system are obtained from Ref. [27]. 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. The calculated chi-square values for the total fusion cross section, and fusion barrier distribution for both semiclassical and quantum mechanical coupled channel compared with their corresponding experimental data for CC and SCF codes for ^{16}O + ^{62}Ni systemare:

A) Below V_b

The calculated chi-square values tabulated in Table 4 are $(\chi^2 = 0.015697)$ for SCF Code in the case of coupling channel calculations and which corresponds to semiclassical calculations including no coupling are in best agreement with the experimental data for the calculations of the total fusion cross section σ_{fus}.The best obtained value of chi-square for the fusion barrier distributionD_{fus}calculations is $(\chi^2 = 0.010746)$for CC code and which correspond the which corresponds to the full quantum mechanical calculations including coupling effects, which means that they are able to reproduce the experimental data better than other calculations.

B)Above V_b The calculated chi-square values tabulated in Table 4 isfound to be $(\chi^2 = 0.777724)$for CC Code in the case of without couplingchannel calculations and which corresponds to the full quantum mechanical without coupled channel calculations are in best agreement with the experimental data for the calculations of the total fusion cross section σ_{fus}.The best obtained value of chi-square for the fusion $(\chi^2 = 0.014914)$ for CC code and which correspond to the full quantum mechanical calculations including coupling effects, which means that they are able to reproduce the experimental data better than other calculations.

Table 4: The chi-square values of ^{16}O + ^{62}Ni system for the total fusion cross section σ_{fus} and the fusion barrier distribution D_{fus} calculations for SCF and CC codes for under and above V_b with experimental data.

system	SCF				CC			
	No coupling		Coupling		No coupling		Coupling	
^{16}O + ^{62}Ni	Below V_b	Above V_b	Below V_b	Above V_b	Below V_b	Above V_b	Below V_b	Above V_b
σ_{fus}	0.034347	0.797637	**0.015697**	0.857557	0.025086	**0.777724**	0.015889	0.779946
D_{fus}	0.018888	0.087675	0.012025	0.038773	0.061254	0.034102	**0.010746**	**0.014914**

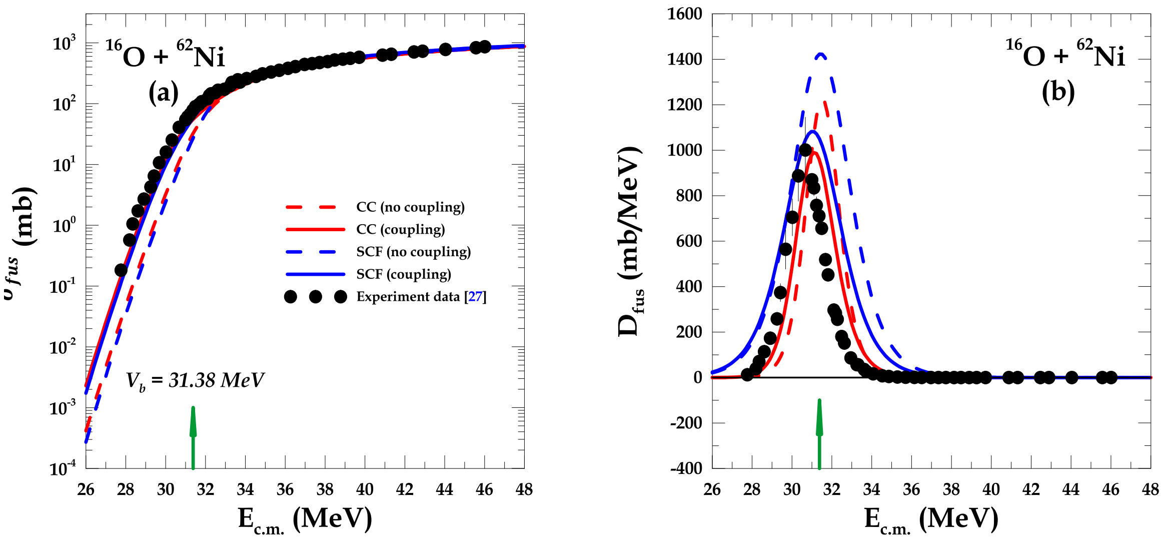

Figure 3: The comparison of the coupled channels calculations of using **SCF code** (blue curves) and **CC code** (red curves) with the experimental data (black filled circles) for **^{16}O + ^{62}Ni**system. Panel (a) for the total fusion cross section $\boldsymbol{\sigma_{fus}}$**(mb)**, and Panel (b) for the fusion barrier distribution $\boldsymbol{D_{fus}}$ **(mb/MeV)**.

5. Conclusion

The semiclassical approach including the coupling between the elastic channeland the continuum proves to be very successful in describing the total fusionreaction cross sectionσ_{fus} and the fusion reaction barrier distribution D_{fus}calculations above and below Coulomb barrier for medium system. A comparison of our semiclassical calculations with fully quantum mechanical ones shows good agreement,above and below the Coulomb barrier. We have shown thatthe coupling in the classically forbidden regions is essential todescribe correctly the fusion process at sub-barrier energies.We could not construct the second derivative to calculate the fusion barrier distribution form the measured data accurately, therefore we could not make clear judgment of whether our semiclassical or coupled-channel calculations agreed with the experimentalfusion barrier distribution. This work can be extended to study more medium systems to confirm its validity to fusion reaction calculations

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