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Presence of Barrier Distributions in Heavy Ion Fusion

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Abstract: *The term fusion barrier distribution provides a clear method to test the effect of nuclear structure on the behavior of nuclear matter and dynamics of nuclear reactions, especially for energies where penetrability effects are considered. It presents an unexpected enhancement, as compared with conventional models of tunneling through a one-dimensional penetration model. The quantum mechanical barrier penetration effects play a central role, where the fusion cross section has been vanished suddenly as the bombarding energy becomes less than the barrier. We concluded that Wong form is the more exact and acceptable form to deduce the excitation functions as well as the barrier distribution for heavy ion fusion when concerning channel coupling and tunneling effects in comparison with the one dimension barrier penetration function*

Keywords*: barrier distribution, barrier height, excitation function , penetrability*
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I. Introduction

In low-energy heavy-ion fusion, the term Coulomb barrier commonly refers to the barrier formed by both the Coulomb and nuclear (nucleus-nucleus) interactions in a central (s-wave) collision. This barrier is frequently called fusion barrier (for light and medium mass heavy-ion systems) or capture barrier (heavy systems). The terminology transfer barrier has not been used much and could be applied only to the transfer of charged particles (or clusters). The coulomb barrier, in addition to nuclear and Coulomb contributions, may include other contributions coming from the different degrees of freedom such as the angular momentum (centrifugal potential), the vibrational and rotational states in both interacting nuclei. Experimenters may use the term Coulomb barrier distribution when either coupled-channel effects operate or a collision partner is deformed as the barrier features depend on orientation. In other words, the enhancement of fusion barrier is a direct result of coupling relative motions and other degrees of freedom. The coupling gives rise to the distribution of fusion barriers and passage over the lowest barrier which is responsible for fusion enhancement at energies below the barrier. The analysis of barrier distribution has brought a significance advance in the study of the fusion of heavy nuclei and the entire heavy ion reaction process. It is found that the most important output of barrier distributions technique is that many advances could be applied to our understanding of the dynamical processes of the heavy ion collision [1]. It was discovered that, the quantum mechanical barrier penetration effects play a central role in near- and sub-barrier fusion reactions, where the fusion cross section has been vanished suddenly as the bombarding energy becomes less than the interaction barrier [2-4]. The barrier height $\boldsymbol{V_B}$ (Coulomb plus nuclear part) is the main term of the total energy $\boldsymbol{V_T}$ required for a specified reaction channel [4-7]. For nuclear part we used either proximity or unified form [5]. The macroscopic quantum tunneling was firstly treated by Dasso and ,Broglia [8,9]. In the case of rotational nucleus, where the classical picture of a deformed object oriented in different directions in space is appropriate, it is easy to appreciate the existence of a distribution of fusion barriers [10-12]. The reaction cross section through a definite channel of an energy E is given by WKB approximation gives as a summation over all penetrating partial waves [13].

$$\sigma_{rec} = \pi \lambda\!\!\!^{-2} \sum_{l=0}^{\infty} (2l+1) T_l(E) P_l(E) \qquad (1)$$

where $\lambda\!\!\!^{-}$, T_l (E) and P_l (E) are the reduced De Broglie wave length of the incident ion, the transmission coefficient and the probability of penetration respectively. For fusion we assume $\sigma_{rec} = \sigma_{fus}$ and $P_l \approx 1$. The upper limit in the last equation becomes $l_{\max}$ [1], and

$$\sigma_{\boldsymbol{fus}}(E) = (\pi \hbar^2 / 2 R^2 E_{\mathbf{cm}}) \sum_{\ell=0}^{l_{man}} (2\ell+1) T(l, E) \qquad (2.a)$$

While a logarithmic form is given by Wong as :

$$\sigma_{\boldsymbol{fus}}(E) = (\hbar\omega R^{\mathbf{2}} / 2E) \; \boldsymbol{ln}\{ 1+ \exp[(2 \pi / \hbar \omega)(E - V\boldsymbol{B}(\mathbf{r}))] \} \qquad (2.b)$$

A sharp cut-off approximation assumes that relative angular momentum l smaller than a particular critical angular momentum l_{cr} contribute to complete fusion, while higher values of l_{fus} are associated with direct[13] (peripheral) process . This approximation gives the fusion cross section [14] similar to that given by equation(2.a) replacing l_{max} by l_{fus} as :

$$\sigma_{fus} = \frac{\pi\hbar^2}{2\mu E_{cm}}(l_{fus}+1)^2 \qquad (2.c)$$

II. Calculations of Barrier Distribution D(E)

Analysis of barrier distribution has brought a significance advance in the study of heavy ion fusion and the entire heavy ion reaction process. It is the best function for theoretical interpretation of the reaction dynamics, indicating fingerprints of the target and projectile structure. The coupling of relative motion to internal degrees of freedom, i.e. surface vibration modes ,rotations and single or multi-nucleon transfer channels give rise to a distribution of barriers in these reactions[10-12] Also quasi elastic barrier distribution has been concerned[15]. Sahu et al [16], pointed out what is meant by barrier distribution and parameters affecting it in the case of the above barrier resonance (ABR) where,

$$D(E) = d^2(E\sigma)/dE^2 = (\pi\hbar^2/2\mu)\sum_{\ell=0}^{\infty}(2\ell+1)\frac{d^2}{dE^2}T(l,E) \qquad \textbf{(3)}$$

Substituting from equation (2.a) in equation(3), we can express

$$\mathbf{D(E) = (2\pi^3/\mu\,\omega^2)}\sum_{\ell=0}^{l_{man}}(2\ell+1)T(l,E)\,(T(l,E)-1)(T(l,E)-2) \qquad \textbf{(4.a)}$$

Similarly**,** substituting from (2.b) into (3), and as a function of the new variable

$\mathbf{y = exp}[-\mathbf{E\,\sigma/a}]$, $\mathbf{a} = \boldsymbol{\pi}\,R^2/\mathbf{b}$, and $\mathbf{b} = (2\boldsymbol{\pi}/\hbar\boldsymbol{\omega})$ **,** the function **D(E)** reads :

$$\mathbf{D(E) = a\,b^2\,y\,(y-1)} \qquad \textbf{(4.b)}$$

On the other hand **D(E)** from measured by point difference [16,17] reads :

$$\mathbf{D(E) = [(E-\Delta E)\,\sigma_- - 2E\,\sigma + (E+\Delta E)\,\sigma_+]\,(\Delta E)^{-2}} \qquad \textbf{(5)}$$

Where $\boldsymbol{\sigma_- = \sigma(E-\Delta E)}$, $\boldsymbol{\sigma_+ = \sigma(E+\Delta E)}$ and Δ E is energy step

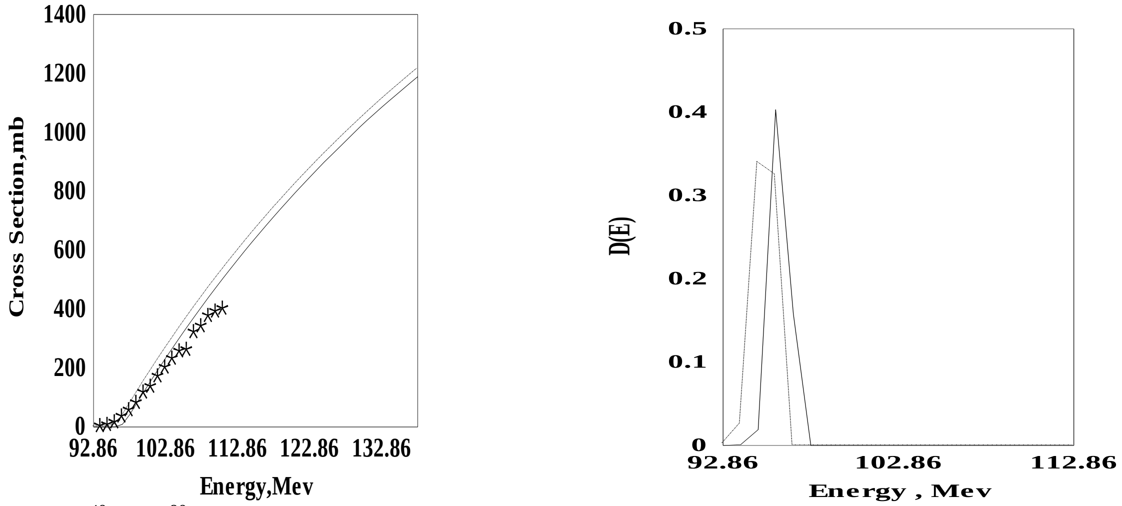
III. Results and Discussion

The check of the concerned forms for D(E), has been started from the use of WKB approximation for fusion cross section taking into account both of the proximity and unified nuclear potentials through equations (2.a and 2.b) then applying the outputs on equation (4.a and 4.b) respectively we deduce the barrier distribution for some of the studied pairs and compare with those deduced from measured data, equation(5), to see to what rate the calculated ones are acceptable for wider energy ranges . In table (1) it is shown the studied pairs barrier heights : $\mathbf{B_1}$ is measured experimentally [17] , $\mathbf{B_2}$ is calculated using Paris potential [17,18] and **B** is the presently calculated one while l_{max} is the calculated values for both equations (2.a , 4.a) .

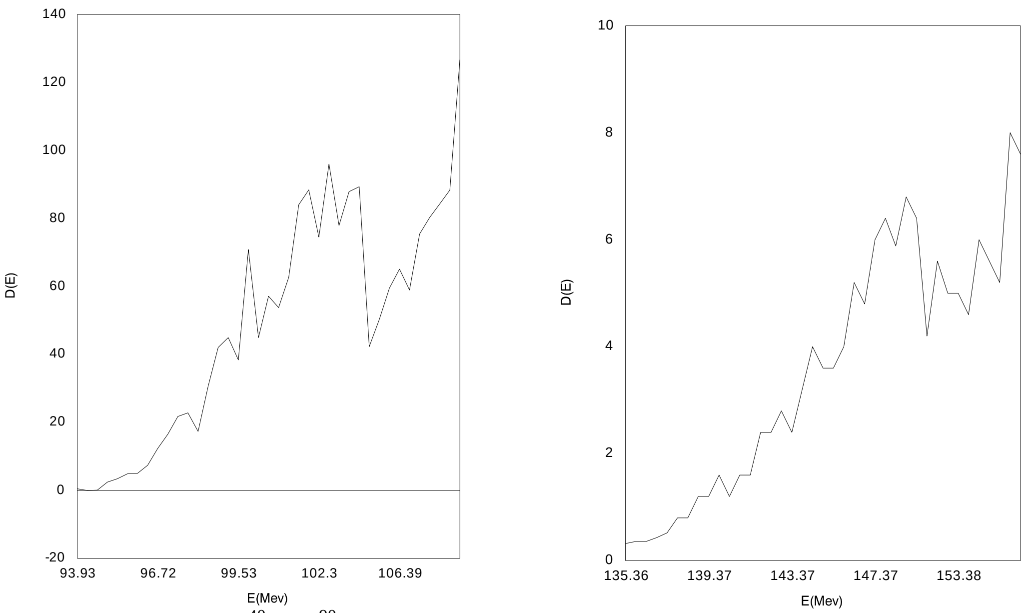
X	Y	R_{fus}	B_1	B_2	B	l_{max}
C^{12}	Zr^{92}	10.79	32.3	31.15	30..53	43
Be^{9}	Pb^{208}	12.37	38.2	38.05	36.61	44
O^{16}	Zr^{92}	10.89	42.0	41.14	40.27	49
C^{12}	Pb^{204}	12.2	57.6	57.3	55.49	51
O^{16}	Sm^{148}	11.64	59.8	59.61	58.43	55
O^{17}	Sm^{144}	11.65	60.6	59.63	58.38	57
O^{16}	Sm^{144}	11.58	61.0	59.94	58.77	55
Si^{28}	Zr^{92}	11.14	70.9	69.59	68.66	65
S^{36}	Zr^{96}	11.49	76.7	75.45	76.03	74
S^{34}	Y^{89}	11.26	76.9	75.42	75.62	71
S^{32}	Y^{89}	11.17	77.8	76.04	*76.26*	69
S^{36}	Zr^{90}	11.35	78.	76.01	*76.94*	73
F^{19}	Au^{197}	12.26	80.8	81.9	79.46	64
Cl^{35}	Zr^{92}	11.29	82.9	81.15	*82.13*	73
F^{19}	Pb^{208}	12.37	83.	83.25	81.74	65
Ca^{40}	Zr^{96}	11.43	94.6	94.32	95.32	78
Ca^{40}	Zr^{90}	11.29	96.9	95.	96.45	77
Si^{28}	Sm^{144}	11.74	104.	101.72	100.78	73
Ca^{40}	Sn^{124}	11.77	113.1	114.96	115.54	84

Si^{28}	Pb^{208}	12.39	128.1	128.1	126.17	80
O^{16}	Pb^{208}	12.29	74.5	75.4	73.27	59

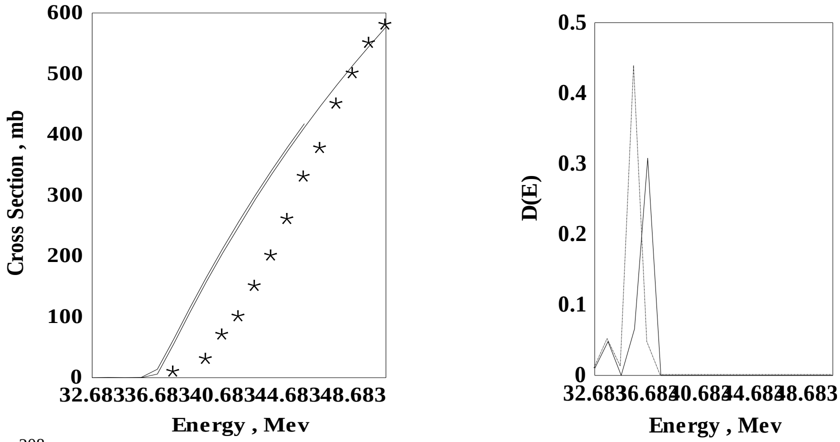
Table(I) Barrier radius **R_{fus} (fm)** and barrier height **B(Mev)** for the undertaken pairs



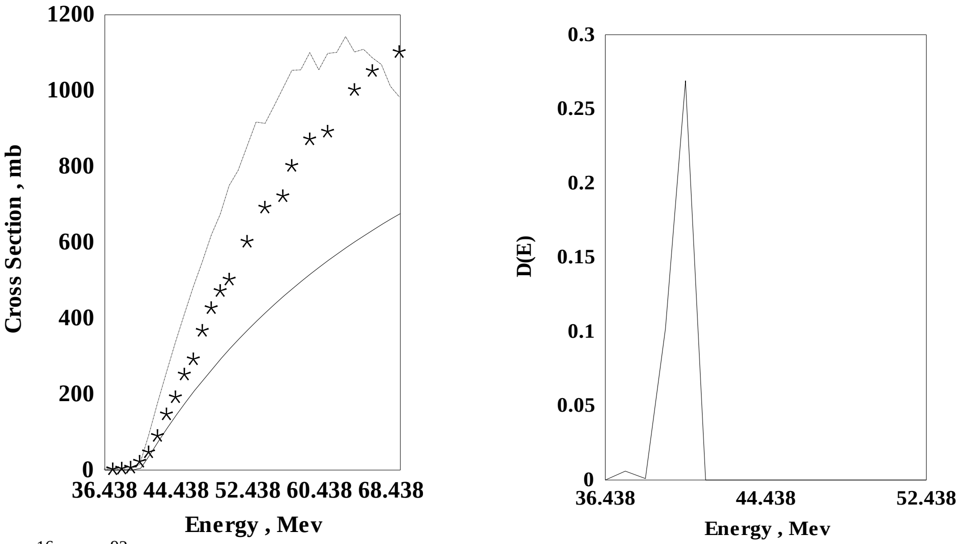
Fig(1) Ca^{40} + Zr^{90} , left is the excitation function treated by WKB (dashed)Wong (solid) as given by equations (2.a) and (w2.b) respectively in comparison with the measured, crosses from [19] , right is the barrier distribution treated by both of the deduced forms (4.a) and (4.b) , it is clear that the solid curve peak (from Wong) is in more agreement with that calculated or measured as in table(I)



Fig(2) for the same pair Ca^{40} + Zr^{90} , where the barrier distribution is treated by the point difference for the measured excitation function of references [19](left) and [20] (right) using equation (5), the more interest comment is the appearance of different peaks for both cases far from the barrier height as in table(I).



Fig(3) for $^{9}Be + ^{208}Pb$ left is the excitation functions due to both of equations(2.a dashed and 2.b solid) using unified potential which appears in good agreement with the measured data from [21] .Also the barrier distribution is treated by equations(4.a and 4.b) indicating an appearance of another peak before the barrier referring to the use of light projectile as we suppose, and a higher peak acceptable to that shown in table(I)



Fig(4) ***for*** $O^{16} + Zr^{92}$, left is the excitation function treated by Wong equation (2.b), using both proximity(dashed) and unified (solid) in comparison with the measured, crosses from [22] , right is the barrier distribution treated by the deduced form (4.b). Similar to the notice in figure(3), it is clear that a small peak appears before barrier, which may be interpreted due to semi-light projectile and the higher one is in more agreement with that calculated or measured in table(I)

IV. Conclusion

When applying barrier distributions (4.a ,4.b and 5) to heavy ion fusion and referring to the figures, we can conclude the following notes :

1- The use of equation (4.a) still the more exact when concerning the barrier penetration principle even when seeing that the corresponding excitation function (equation 2.a) is far from agreement with the measured data.
2- . The use of equation (4.b) gives the more agreeable height of the barrier when compared with those in table(I) and from mathematical point of view is the right for applying the mode of distribution of the barrier as second derivative of the product (E σ) with respect to E, also the form (2.b) for excitation function gives higher rate of agreement with the measured data.
3- As we see in figures(2), where the barrier distribution is treated by the point difference for the measured data in tow references, we can point out that the appearance of different peaks for both cases far from the barrier height as in table(I) may guide us to deduce that this type of distribution technique is neither fit nor significant to depend on.
4- The more exact and acceptable form to deduce the excitation functions for heavy ion fusion near and above the barrier (up to twice times), is the Wong form (2.b) which concern channel coupling. On the other hand

our results point out that, when concerning one dimension barrier penetration function(2.a), it is clear that the calculation is far from agreement with the measured data.

5- The appearance of the small peak in the barrier distribution curves at values less than barrier heights for the last two pairs, may be interpreted as indication to the tunneling effect in heavy ion fusion below the barrier even when changing the nuclear force models.

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