Structure information from fusion barriers

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Abstract. It is shown that the analysis of fusion barrier distributions is not always an unambiguous test or a 'fingerprint' of the structure information of the colliding nuclei. Examples are presented with same fusion barrier distributions for nuclei having different structures. The fusion excitation functions for $^{16}O+^{208}Pb$, using the coupled reaction channel (CRC) method and correct structure information, have been analysed. The barrier distributions derived from these excitation functions including many of the significant channels are featureless, although these channels have considerable effects on the fusion excitation function. However, a simultaneous analysis of the fusion, elastic and quasi-elastic channels would fix the structure and the reaction unambiguously.

1. Introduction

The experimental measurements of the fusion barrier distribution (BD) represent a new stage in the study of heavy ion fusion. The fusion BD analysis is a valuable tool to understand the fusion mechanism of two heavy nuclei and the role of their internal degrees of freedom leading to fusion. The fusion BD has been shown to be sensitive to the data related to the nuclear structure, such as the nuclear shapes, the multiple excitations and the anharmonicity of nuclear surface vibrations etc. For this purpose, high precision measurements of the fusion cross-section data are required and have been reported for many systems [1–5]. The fusion BD analyses of these data provided impetus to understanding of the fusion mechanism and generated a widespread interest in this study. In a recent review on the fusion BD [5] it has been stated that, 'they are also the functions best suited to the theoretical interpretation of the reaction dynamics, often presenting an unambiguous *fingerprint* of the target and projectile structure'. In ref. [3] one finds a similar discussion on the importance of the study of fusion BD. In some of the reported studies [1,2], the parameters related to structure, such as the deformation lengths and signs, the diffuseness of the inter-nuclear potentials have been varied to understand their effects on the fusion BD. Although there has been no explicit attempt so far to extract the parameters of the nuclear structure exclusively from the fusion studies, one may be tempted to think that this BD analysis can provide an unambiguous test for structure of the participating nuclei.

Since fusion is a cumulative absorption process from the coupled channel system, we investigated how unambiguous would be the structure information derived from the fusion studies. Some of the earlier reports on the fusion BD analysis have already revealed the ambiguity of nuclear structure information derived from fusion studies. The reports of [1–4] also gave an idea on this subject. The limitations of extracting the precision nuclear structure information from the fusion studies has been discussed in ref. [6]. The aspect of ambiguity of the structure information from the fusion is of relevance, particularly in the light of increasing use of the fusion BD analysis. In this paper, we present the ambiguities or limitations in deriving the nuclear structure information from the fusion studies. We demonstrate this aspect explicitly by giving specific examples by using various codes which are currently used to estimate fusion. The present study shows the need to understand the implicit assumptions used in the simplified coupled channel fusion codes in order to derive correct physical conclusions.

2. Coupled channels method for fusion

In this section, we review briefly the coupled channels method, the eigen channels approach and the simplifications generally used for estimating fusion in various numerical fusion codes. The heavy ion reactions are well understood on the basis of coupled reaction channel (CRC) method. This CRC method gives a set of coupled Schrödinger's equations and a self consistent solution can be obtained by iteration method, as used in the CRC codes like FRESCO [7]. In the absence of particle transfer, the CRC formulation reduces to the coupled channels (CC) method for inelastic couplings as in ECIS [8]. Fusion in the CRC codes is estimated using short ranged imaginary potentials in each of the coupled channels. This simulates the incoming wave boundary condition (IWBC) and the cumulative absorption of flux in all the channels coupled is identified as fusion

$$(T_i + V_i(r) - E_i)\psi_i(r) = \sum_j V_{ij}(r)\psi_j(r), \qquad (1)$$

where, T_i is the kinetic energy operator, $E_i = E - \epsilon_i$ is the energy of relative motion and ϵ_i is the excitation energy for the channel i. For a two channel case with vibrational couplings, eq. (1) can be represented by

$$\begin{pmatrix} T_1 + V(r) - E & 0 \\ 0 & T_2 + V(r) - E \end{pmatrix} \begin{pmatrix} \psi_1(r) \\ \psi_2(r) \end{pmatrix} = \begin{pmatrix} 0 & V_{12}(r) \\ V_{21}(r) & -\epsilon_2 \end{pmatrix} \begin{pmatrix} \psi_1(r) \\ \psi_2(r) \end{pmatrix}.$$

In general, $V_{ij}(r) \neq 0$, different for all i, j and also involves some diagonal terms for the case of rotational couplings. One often considers couplings only to elastic channel and the mutual couplings among other channels are ignored to simplify the calculations. This is not valid for the cases of higher order couplings, multi phonon vibrations and transfer. Further, eq. (1) involves the angular momentum couplings of several partial waves leading to a given total J. This scheme of enormous iterative calculations can be grossly simplified by several approximations for fusion calculations [5], for example;

1. The isocentrifugal approximation leading to $T_i = T_0$ for all channels i, especially useful for the inelastic partition.

2. Adiabatic approximation leading to $\epsilon_i \approx 0$, generally used for the nuclei with static deformation.

3. Same radial shape for V_{ij} for all i, j, especially for linear couplings to the inelastic channels.

Under the above approximations (1–3), for vibrational couplings eq. (1) becomes,

$$(T_0 + V(r) - E)\psi_i(r) = -F(r)\sum_j \Gamma_{ij}\psi_j(r) \tag{2}$$

with $V_{ij}(r) = -F(r)\Gamma_{ij}$. Diagonalization of the matrix in eq. (2) using unitary transformation operator U gives

$$(T_0 + V(r) + \lambda_\alpha F(r) - E)\Psi_\alpha(r) = 0, \tag{3}$$

where $U_{\alpha i}^{\dagger}\Gamma_{ij}U_{j\beta} = \lambda_\alpha \delta_{\alpha\beta}$. The eigen channel wave functions, potentials and eigenvalues respectively are

$$\Psi_\alpha = U_{\alpha i}\psi_i$$

$$V_\alpha = V + \lambda_\alpha F,$$

$$w_\alpha = |<\psi_0|\Psi_\alpha>|^2. \tag{3a}$$

Equation (3) is the eigen channel (α) reduction of eq. (2). This reduction is strictly valid if the approximations (1–3) listed above hold. However, if $\epsilon_i \neq 0$, then the unitary transformation operator U is r dependent. In such a case, the diagonalization is performed at a fixed radial separation r, ignoring the terms $U''(r)$ and $U'(r)$ and incorporating the finite range corrections [9]. The eigen potentials (V_α) for the channel α can be simplified as

$$V_\alpha(r) = V(r) + \lambda_\alpha(r) = V(r_b) + \frac{1}{2}V''(r_b)(r - r_b)^2$$

$$+\lambda_\alpha(r_b) + \lambda_\alpha'(r_b)(r - r_b) + \frac{1}{2}\lambda_\alpha''(r_b)(r - r_b)^2, \tag{4}$$

where r_b is the uncoupled barrier position and the eigen barrier position ($r_{b\alpha}$) is

$$r_{b\alpha} = r_b - \frac{\lambda_\alpha'(r_b)}{V''(r_b) + \lambda_\alpha''(r_b)}. \tag{5}$$

There were improvements over this approximation for incorporating the finite range effects around the uncoupled barrier position (r_b). In some of the simplified fusion codes, expansion of an eigen potential is made around the eigen barrier position of that channel. In the simplified CC codes, fusion is estimated by evaluating the transmission through the potential barriers ($V_{b\alpha}$) of the eigen channels. One commonly uses the Hill–Wheeler expression for the transmission ($T(E)$) through a parabolic barrier of height $V_{b\alpha}$ and curvature ($\hbar\omega$) leading to [9,10]

$$T(E) = \sum_\alpha |U_{\alpha 0}|^2 \left[1 + \exp\left(\frac{2\pi(V_{b\alpha} - E)}{\hbar\omega}\right)\right]^{-1} \tag{6}$$

$$\hbar\omega = \sqrt{\frac{-\hbar^2}{\mu}\left(\frac{\mathrm{d}^2 V(r)}{\mathrm{d}r^2}\right)_{r_b}}. \tag{7}$$

By ignoring the ℓ dependence of $\hbar\omega$ and $r_{b\alpha}$ etc., the fusion excitation function is obtained in terms of the discrete eigen barriers B_α ($\equiv V_{b\alpha}$) using the procedure of [11]

$$\sigma_F(E) = \sum_\alpha \sigma_F(E, B_\alpha)\,\omega_\alpha = \frac{r_b^2 \hbar\omega}{2E}\sum_\alpha |U_{\alpha 0}|^2 \ln\left[1 + \exp\left(\frac{2\pi(E - V_{b\alpha})}{\hbar\omega}\right)\right]. \tag{8}$$

The second derivative of $E\sigma_F$ with respect to energy can give the information about the eigen barriers. However, the transmission factor results in a finite width for the eigen barriers. Therefore, the second derivative of $E\sigma$ using eq. (8) may not lead to a clear identification of the discrete eigen barriers, especially for a weak coupling case or when some of the barriers are closely spaced. The definition of (continuous) distribution of barriers for fusion, $D(B)$, is given by

$$\sigma_F(E) = \int_0^\infty \sigma_F(E, B)\,D(B)\mathrm{d}B \tag{9}$$

$$D(E) = \frac{1}{\pi r_b^2}\frac{\mathrm{d}^2(E\sigma)}{\mathrm{d}E^2}. \tag{10}$$

Fusion BD analysis is based on the simplified CC calculations for fusion as discussed before. The code CCFUS [12] is based on most of these approximations, using eqs (1), (3)–(8) together with linear couplings and single phonon excitations [9,10]. As is well known, the results of CCFUS code for fusion are only in qualitative agreement with that of the CRC calculations, and therefore improvements were required. Some of these inadequacies have been overcome in the fusion code CCFULL [13]. In this code, the couplings are treated to all orders, multi phonon excitations are considered and the transmission for fusion is obtained by directly integrating the coupled equations avoiding the need for iterations. The results of this code are in close agreement with those of CRC calculations. Owing to these simplifications, the fusion codes [12,13], take much less computation time. Consequently, it has become feasible to perform CC fusion calculations with a large coupling scheme to interpret the experimental data. In this context, one needs to understand the underlying approximations of various fusion codes in order to draw proper conclusions, as also pointed out in [6]. Further, the eigen channel approximation which lead to fusion BD may not be rigorously valid in the CRC calculations. This aspect can be studied by constructing the fusion BD resulting from the CRC calculations.

3. Ambiguity of structure information derived from fusion

In this section, we consider some results of fusion BD analysis reported by various groups using these simplified fusion codes. We discuss the model dependence of these conclusions

and the structure information derivable from these reports. Equations (8), (10) suggest that the high precision data of $E\sigma$ gives the distribution of barriers for fusion. Equation (10) results in a smooth barrier distribution rather than the discrete eigen barriers of eq. (8). This was demonstrated for $^{16}O+^{154}Sm$ system by including the elastic channel and the 2^+ and 4^+ inelastic states of Sm [14] (see figure 2 of [14]). It should be noted that the position of the barriers and weights would be roughly reproduced, provided the eigen barriers are well separated and have appreciable weight. It follows that if the coupling scheme includes several channels, inversion of the calculated cross-sections using eq. (10) may not indicate many distinct peaks in the fusion BD. This procedure yields a few eigen barriers corresponding to the stronger channels. Therefore, the correspondence of peaks of fusion BD with the eigen barriers would be lost owing to the complex coupling scheme.

The static deformation of Sm strongly influences the sub-barrier fusion of $^{16}O+^{154}Sm$ system. The precision measurements for the fusion and the analysis of the fusion BD for this system were already reported in [1,2,4,5]. The diffuseness of the inter-nuclear potential was taken to be $a = 1.27$ fm in [2] ($a = 1.1$ fm in [4]) to explain the high energy cross-sections and due to other considerations. This value of the diffuseness is large and uncommon in the optical model analysis of elastic scattering of the heavy ion systems. The static quadrupole and the hexa-decoupole deformation parameters were varied in order to get best fits to fusion excitation functions, for $^{16}O+^{154}Sm$ and $^{16}O+^{186}W$ systems, as shown in figures 6a, b, c, d of [5]. It can be seen from these figures that some of the parameters fit the fusion BD reasonably well, for example see the dotted and solid curves of figure 6 of [5]. Considering only the static deformations of the target, the deformation parameters for these ^{154}Sm and ^{186}W determined from the best fits to the fusion data do not closely agree with the values obtained from non-fusion methods [2]. The $r_0 \approx 1.06$ fm was used in this work and the use of larger r_0 for deformation lengths (βr_0) in the analysis would reduce the discrepancy. However, the predictions of inelastic cross-sections are very sensitive to these deformation lengths, as shown for the ECIS calculations in the next section. Therefore a rough agreement of these parameters obtained by these methods is not an unambiguous test of the structure information from the fusion studies. It has been suggested that inclusion of more channels in the coupling scheme could reduce this discrepancy of deformation parameters extracted from the fusion data analysis [2]. The discrepancy has been almost resolved by the addition of inelastic and transfer channels in the coupling scheme as shown by the dotted curve of figure 12 of [4]. The calculated fusion BD is in good agreement with the experimental BD for the case of ^{154}Sm. However, for the case of ^{186}W, the predicted BD does not closely agree with the experimental data beyond 67 MeV as shown by dotted curves in figure 12 of [4]. These results suggest that the derived structure information remains ambiguous unless a proper analysis of fusion data including all significant channels is carried out.

In the case of $^{16}O+^{144}Sm$ system, both precision measurements of the fusion data and the theoretical analysis of data were reported. The ^{144}Sm nucleus exhibits collective vibrational excitations. Earlier reported coupled channel (CC) analysis of this system included the 2^+ and the 3^- states of ^{144}Sm and the known BE2 values [4]. This coupling scheme reproduced the fusion excitation function and also its BD very well [4]. However, Hagino *et al* [15] re-analysed fusion BD of this system, including the 2-phonon harmonic as well as the anharmonic vibrations of Sm in the coupling scheme. The deformation parameters for these states change when the multi-phonon vibrations are considered. In their rigorous analysis, there was a discrepancy between the coupled channel predictions and the

experimental data when only harmonic vibrations were considered. It was shown that the inclusion of anharmonicity of surface vibrations of ^{144}Sm is necessary to reduce the discrepancy with the experimental data [15]. These calculations reproduced the fusion BD very well along with correct structure information [15].

The calculations of both [4,15] showed good fits to fusion BD, whereas, the derived structure information in these two cases is totally different. Thus the conclusions depend on the use of correct physical model for fusion together with prior knowledge of the structure like the consideration of anharmonicity aspect discussed above.

For the case of ^{40}Ca+^{90,96}Zr systems, both precision measurements of the fusion data and the theoretical analysis of the data have been reported [16]. The shape of the fusion BD are very different for these two systems. The detailed CC analysis including up to 4-phonon excitations could explain reasonably the experimental fusion BD of ^{40}Ca+^{90}Zr system. However, similar CC calculations could not predict the experimental BD for the case of ^{96}Zr. This disagreement between the calculated BD and the experimental results may be due to an additional structure information that is not included in the coupling scheme. It has been suggested that consideration of the multi-neutron transfer channels involving positive Q values in the coupling scheme may resolve this disagreement with the experimental BDs [16]. Therefore, the ^{96}Zr case is an example of strong influence of transfer channels on the fusion BD. Consideration of inelastic channels couplings is not enough to predict the fusion BD and any attempt to adjust the coupling parameters to fit the data would have led to erroneous structure information.

These examples demonstrate that one needs to know the structure information in order to predict the fusion. The fusion study can thus be used as a tool for an affirmative evidence of the structure information. In the next section, we demonstrate these aspects using the CCFUS and CCFULL codes.

4. Model calculations for fusion

4.1 *Coupled channels calculations*

First, we consider an example of ^{16}O+^{144}Sm system using a two channel coupling scheme and the CCFUS program for two distinct cases. In the first case, we consider coupling of the elastic (0^+, g.s.) channel to a 3^- inelastic state of ^{144}Sm whereas in the second case, we replace the 3^- state with a 2^+ state. It should be noted that in this hypothetical study, the first case involves an odd parity state (3^-) of angular momentum and its decay properties are very different from the second case (2^+ state). The fusion BD for the above cases are shown in figure 1a by the short and long dashed curves respectively. The parameters used are also shown in figure 1a. The deformation parameter of the 2^+ state of the second case is adjusted to reproduce the barrier distributions of the first case, while using physical excitation energies in both the cases. The fusion BD using these effective parameters are shown by a solid curve in figure 1a. The results for the fusion BD are almost the same for these two sets of widely different nuclear structure, as shown by the short dashes and solid curves in figure 1a. In this example we used CCFUS code, as this code has been used directly or with a few modifications in many of the fusion data analyses reported so far. These results shown in figure 1a are the artifacts generated by the CCFUS code that is based on various approximations and in particular the linear coupling approximation. It

may be possible that the non-linear effects of couplings might lead to the unique structure information from fusion BD analysis. Therefore, we repeated this study using the CCFULL code [13], which treats couplings to all orders and has other merits mentioned earlier. Figure 1b shows the results of this calculations and the parameters used are mentioned therein. Similar to the conclusions from figure 1a, the agreement of short dashes and solid lines of figure 1b shows that nuclei with two different structure yield nearly the same fusion
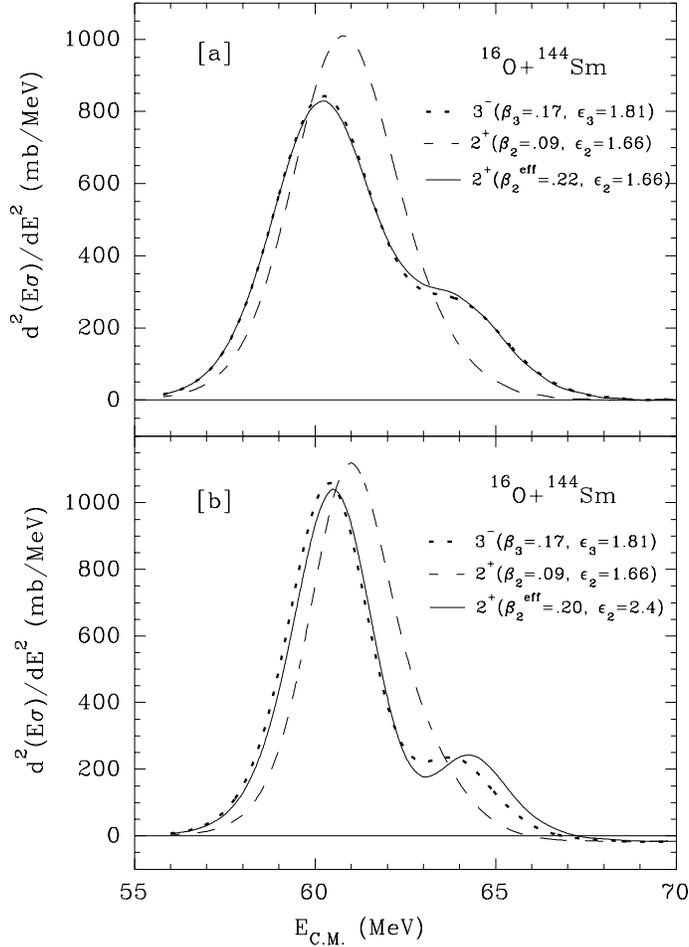

Figure 1. (**a**) Fusion barrier distributions obtained using CCFUS for the various cases of coupling elastic channel to case (i) only 3^- inelastic state (short dashes) and case (ii) only 2^+ state of ^{144}Sm (long dashed line). The solid line represents couplings to only 2^+ state but with effective β value ($\beta_2^{\text{eff}} = 0.22$). The excitation energies (MeV) for these cases are mentioned in the figure. (**b**) Fusion barrier distributions corresponding to various cases of figure 1a, but obtained using CCFULL code. The deformation parameters and the excitation energies (MeV) values are mentioned in the figure.

barrier distributions. The experimental fusion BD at the above barrier energies has large uncertainties for all the systems reported so far, for example see in [5]. This is due to the slow variation of fusion cross-section in this energy region as discussed in [6]. Thus, the fusion BDs shown in figure 1b by short dashes and solid curves are thus in agreement within the typical uncertainties.

In the next example, the fusion BDs are calculated for the ^{16}O+^{144}Sm system for two cases by coupling the elastic channel (0^+, g.s.) to (i) 3^-, 2^+ and 5^- states and (ii) only 3^- and 2^+ states of ^{144}Sm using the CCFUS code. The fusion BD corresponding to these two cases are very different, as shown by the short and long dashed lines in figure 2a. However, by adjusting the deformation parameters of the second case, it is possible to reproduce the fusion BD of the first case (see solid lines). The parameters adjusted are mentioned in the figure. Thus, the fusion BDs of a four channels coupling scheme are reproduced by the three channels coupling scheme with an effective set of parameters.

We repeated similar calculation using CCFULL code to understand the uniqueness of structure information for the same reasons as mentioned earlier. In this study we considered couplings of elastic channel to the inelastic states for two cases; case (i) 3^- and 5^- inelastic states, and case (ii) only 3^- state of ^{144}Sm. In the presence of the non-linear effects, we will examine whether the fusion BD resulting from a three channels coupling scheme of case (i) above can be simulated by a two channel coupling scheme. Figure 2b shows the results of this study, along with the parameters used. The close agreement of the solid lines and the short dashes of figure 2b shows that the cases of two different structure resulted in the same fusion BD.

The anomalies presented in the above hypothetical case studies would be resolved by the simple measurements of inelastic scattering or the decay properties of the nucleus. Therefore, fusion BD may not indicate unambiguously all the channels which are relevant for the coupling scheme. Further, the structure information derived from fusion channel alone may not be unique and is thus ambiguous. These model studies demonstrate that the use of simplified fusion codes for the analysis of fusion BD may not lead to an unambiguous test for the structure information. The structure information is obtained from the precision methods like the Coulomb excitations, inelastic scattering and the gamma ray spectroscopy etc. However, the fusion BD can be used for structure information only in a qualitative way.

The simplified fusion codes predict only the fusion results and do not give information about the other channels. As mentioned earlier, the ECIS [8] code is a coupled channels program that gives a simultaneous description of the elastic and the inelastic channels by the iterative solutions. Therefore, we performed model ECIS calculations and fusion is obtained using short ranged imaginary potentials. The potentials used have Woods Saxon form and the parameters are V_0=162.0 MeV, $r_0 = 1.0$ fm $a_0 = 0.90$ fm, $W_0 = 10.0$ MeV, $r_i = 1.0$ fm, $a_i = 0.20$ fm and the $r_c = 1.2$ fm. The ECIS calculations were performed for the two cases of first example discussed above and with the parameters given in figure 1a. The fusion BD predicted by the ECIS code for the two cases are shown in figure 3b. These BDs are not identical unlike the results in figure 1a. These results have been confirmed using the CRC code FRESCO. Further, the differences for fusion of these two cases increase for the second order vibrational model compared to the first order, for the same parameters. Figure 3a shows the reaction, fusion and the inelastic
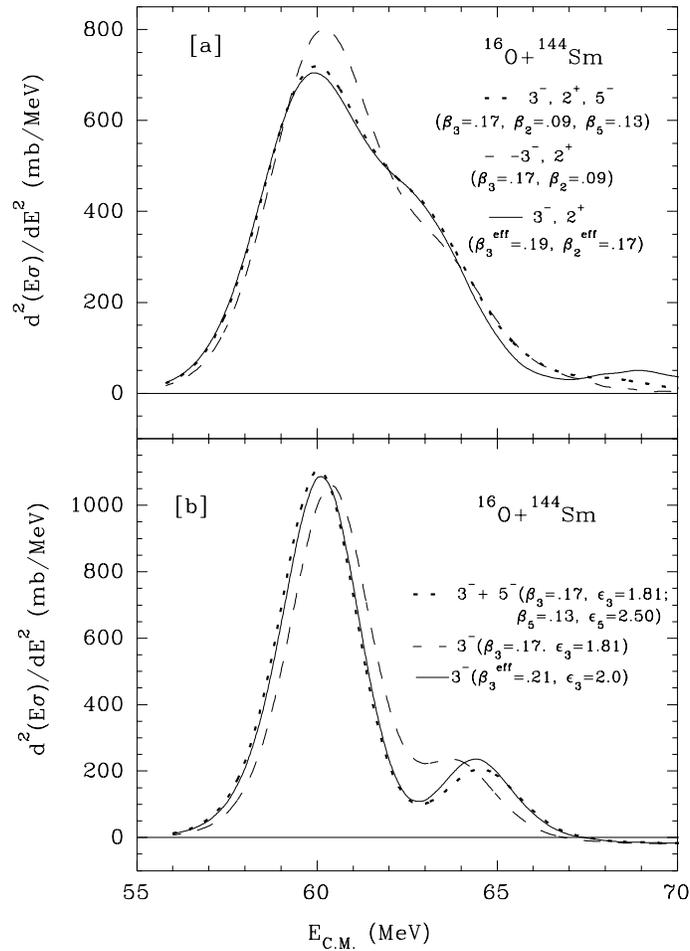
Figure 2. (**a**) Fusion barrier distributions obtained using CCFUS by coupling elastic channel to case (i) 3^-, 2^+ and 5^- inelastic states (short dashes), and case (ii) 3^- and 2^+ inelastic states (long dashes) of ^{144}Sm. The excitation energies used are: $\epsilon_3 = 1.81$ MeV, $\epsilon_2 = 1.66$ MeV and $\epsilon_5 = 2.5$ MeV. The solid line corresponds to coupling of only 3^- and 2^+ states using $\beta_3^{\text{eff}} = 0.19$ and $\beta_2^{\text{eff}} = 0.17$, with excitation energies as given above. (**b**) Fusion barrier distributions obtained using CCFULL by coupling elastic channel to case (i) 3^- and 5^- states (short dashes), and case (ii) 3^- state only (long dashes) of ^{144}Sm. The solid line corresponds to coupling of only 3^- state using effective β and excitation energies (MeV) as mentioned in the figure.

excitation functions using ECIS code for these cases. The fusion cross-sections for the two cases are approximately the same, where as the reaction and inelastic cross-sections widely differ as shown in figure 3a. These inelastic cross-sections are sensitive to deformation lengths. The anomaly in this example is resolved by a simple measurement of the elastic
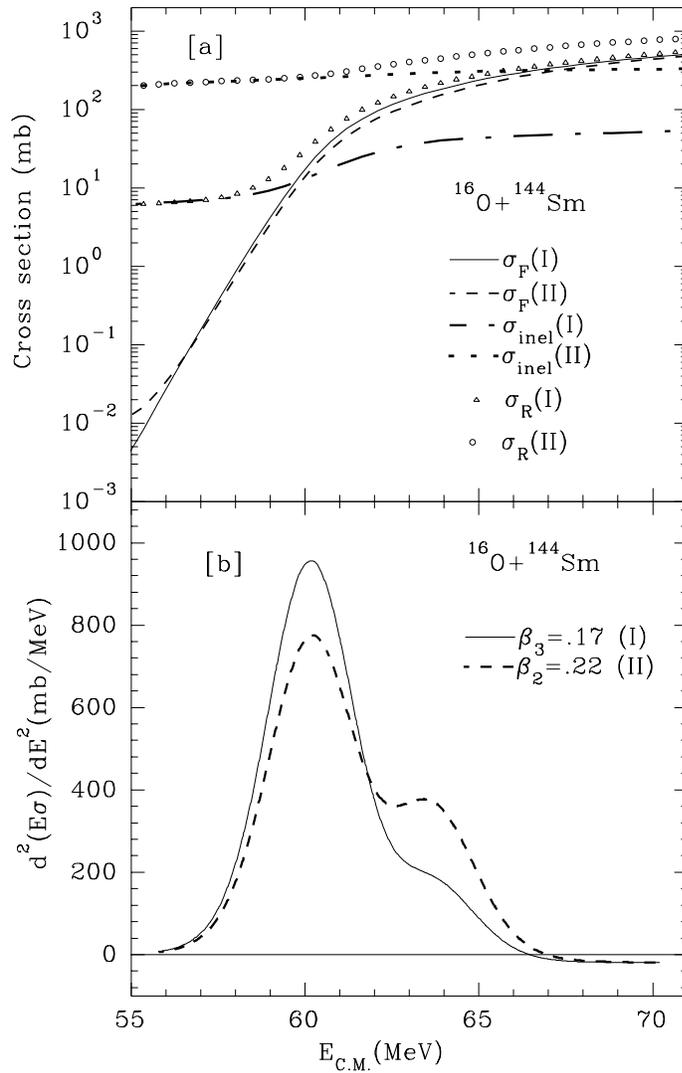
Figure 3. (**a**) Excitation functions of fusion (σ_F), inelastic (σ_{inel}) and reaction (σ_R) obtained using ECIS code for two cases of figure 1a (i.e., $\beta_3 = 0.17$ for case (I) and $\beta_2^{\text{eff}} = 0.22$ for case (II)), using ECIS. (**b**) Fusion barrier distributions calculated from the fusion cross-sections for the these two cases.

scattering, as the reactions of the two cases widely differ. Hence rigorous calculations or detailed measurements for many channels can remove the ambiguity resulting from the approximations of the simplified fusion codes. These anomalies arise not only due to various approximations in the fusion codes, but also due to the mechanism of fusion and the complex coupling scheme.

4.2 *Coupled reaction channels calculations*

In the previous section, results of model calculations for fusion from the coupled channels method have been discussed. It is therefore necessary to show realistic calculations for fusion including both inelastic and transfer couplings. In the following, we analyse the results of the CRC calculations for $^{16}O+^{208}Pb$ system using the code FRESCO [7]. We used the version of the code with linear coupling approximation. This coupling scheme is same as in [17] which includes many of the significantly contributing inelastic and transfer channels and the predictions were in close agreement with the available experimental data. We study the effects of each channel on fusion BD for this system. The resulting fusion excitation functions and BDs are shown in figures 4 and 5 respectively for various cases as indicated in the figures. The couplings to 3^- state of ^{16}O enhanced the fusion cross-sections by a large extent compared to the couplings to 3^- state of ^{208}Pb, as shown in figure 4a. The barrier distribution for the former case has shifted to lower energies in addition to affecting its shape at high energies (87 MeV) compared to the BD of the uncoupled case. Couplings of the inelastic channels
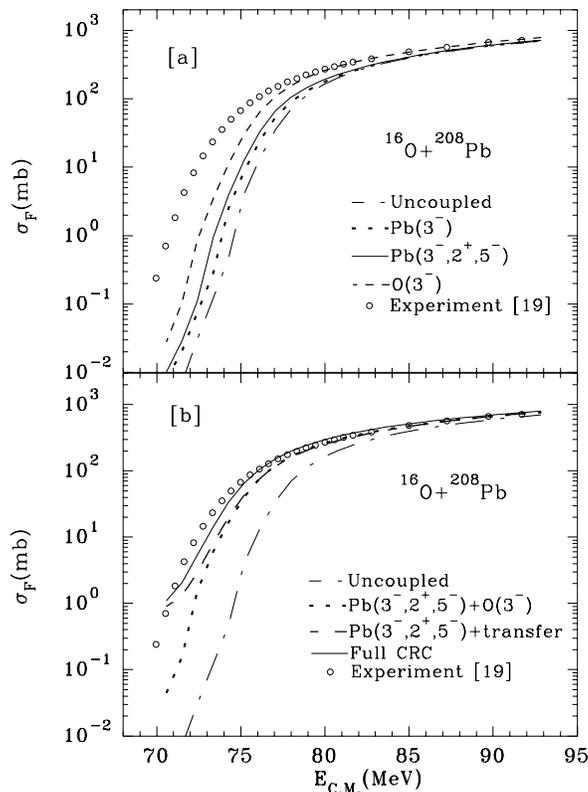

Figure 4. Fusion excitation functions calculated for $^{16}O+^{208}Pb$ system for various coupling schemes including the inelastic and transfer channels and compared with the experimental values.
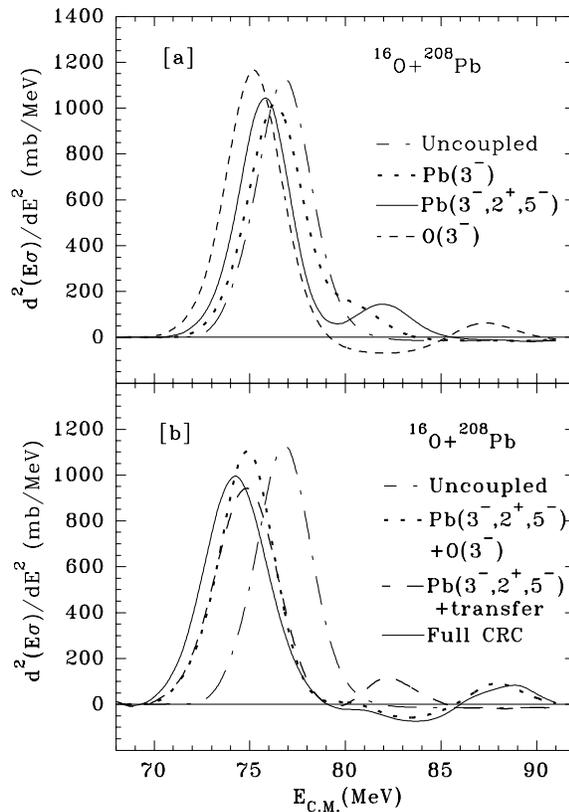
Figure 5. Fusion barrier distributions corresponding to the excitation functions of figure 4.

of Pb also shift the uncoupled barrier in addition to producing a bump around 80–85 MeV (solid curve). The effects of couplings to inelastic states of both O and Pb are shown in figures 4b and 5b. Owing to these couplings the bump in barrier distributions has shifted to higher energies. The results for the case of full couplings, i.e., the coupling scheme of [17] are shown by solid curve in figure 5b. As shown there, the inclusion of transfer channels lowered the position of the main barrier with a slight reduction in the height and broadened the distribution. The fusion BD for the case of all inelastic couplings and also for the case of full coupling scheme with transfer shifted the bump of BD to high energies (see figure 5b). The latest experimental data and model analysis for fusion of this system [18,19] did not indicate any structure for fusion at high energies. The importance of all order couplings for 3^- state of oxygen was demonstrated by Hagino *et al* [20]. The above conclusions for the BD predicted by the CRC calculations that include 3^- state of oxygen (solid curve of figure 5b) may be incorrect unless all order coupling treatment is performed for this channel coupling. Therefore, the full CRC calculations without this 3^- state of oxygen have also been performed to understand the effect of all other channels. This result is shown by thick dashed line in figure 5b. Proper calculation with the inclusion

of this oxygen 3^- state is likely to result only in a shift of approximately 2 MeV of this thick dashed curve, as expected from the results of [20].

The CRC calculations predicted a broad single peak and a weak bump at high energies instead of 14 eigen barriers for the fusion, whereas the 14 channels included in the coupling scheme contribute significantly to fusion. Thus, the structure and channel coupling information are smeared out owing to the complex coupling scheme, the transmission factors and the mechanism leading to fusion. The eigen barriers that are close in position are smeared out resulting in a broad peak in the barrier distributions. The approach of eigen barriers loses relevance when finite excitation energies are considered in the CRC calculations. Therefore, the fusion BD may yield very limited structure information in the CRC calculations of complex systems. It should be noted that a simultaneous fit of the experimental elastic, inelastic and transfer angular distributions using CRC formalism validates the choice of the coupling scheme, the coupling parameters used and the spectroscopic factors used for transfer reactions. Hence, in such a case only one can comment on information about couplings and structure of the nuclei without ambiguity, rather than from the analysis of fusion barrier distributions alone.

5. Conclusions

We suggest that fitting the precision data of the fusion excitation function alone may not lead to correct description of fusion mechanism. Therefore the aspect of deriving the structure information from the fusion BD alone, depends on the use of correct physical model for fusion. In addition, a simultaneous analysis of the fusion and elastic or the quasi-elastic channels would remove any ambiguity rather than analysis of fusion channel alone. The fusion BD from CRC calculations did not yield distinct structure information than the corresponding fusion excitation functions for various cases of couplings for $^{16}O+^{208}Pb$ system. We believe that the analysis of fusion BD is a novel concept which provided valuable insight of the fusion mechanism as pioneered and reported by various groups. However, fusion is a cumulative absorption process and therefore proper care is to be exercised in identifying the fusion barrier distributions as the *fingerprints* of nuclear structure information.

Acknowledgements

References

[1] J X Wei, J R Leigh, D J Hinde, J O Newton, R C Lemmon, S Elfstrom, J X Chen and N Rowley, *Phys. Rev. Lett.* **67**, 3368 (1991)
[2] R C Lemmon, J R Leigh, J X Wei, C R Morton, D J Hinde, J O Newton, J C Mein, M Dasgupta and N Rowley, *Phys. Lett.* **B316**, 32 (1993)

[3] J D Bierman, P Chan, J F Liang, M P Kelly, A A Sonzogni and R Vandenbosch, *Phys. Rev. Lett.* **76**, 1587 (1996)

[4] J R Leigh, M Dasgupta, D J Hinde, J C Mein, C R Morton, R C Lemmon, J P Lestone, J O Newton, H Timmers, J X Wei and N Rowley, *Phys. Rev.* **C52**, 3151 (1995)

[5] M Dasgupta, D J Hinde, N Rowley and A M Stefanini, *Annu. Rev. Nucl. Part. Sci.* **48**, 401 (1998)

[6] C H Dasso, *J. Phys.* **G23**, 1203 (1997)

[7] I J Thompson, *Comput. Phys. Rep.* **167**, 7 (1988)

[8] J Raynal, *Phys. Rev.* **C23**, 2571 (1981); *Computing as a language of Phys.* (IAEA, Vienna, 1972) p. 281

[9] C H Dasso and S Landowne, *Phys. Lett.* **B183**, 141 (1987)

[10] R A Broglia, C H Dasso, S Landowne and G Pollarolo, *Phys. Lett.* **B133**, 34 (1983)

[11] C Y Wong, *Phys. Rev. Lett.* **31**, 766 (1973)

[12] C H Dasso and S Landowne, *Comp. Phys. Comm.* **46**, 187 (1987)

[13] Computer Code CCFULL K Hagino, N Rowley and A T Kruppa, preprint Nucl-Th/9903074

[14] N Rowley, G R Satchler and P H Stelson, *Phys. Lett.* **B254**, 25 (1991)

[15] K Hagino, N Takigawa and S Kuyucak, *Phys. Rev. Lett.* **79**, 2943 (1997)

[16] H Timmers, L Corradi, A M Stefanini, D Ackermann, J H He, S Beghini, G Montagnoli, F Scarlassara, G F Sagato and N Rowley, *Phys. Lett.* **B399**, 35 (1997)

[17] I J Thompson, M A Nagarajan, J S Lilley and M J Smithson, *Nucl. Phys.* **A505**, 84 (1989)

[18] C R Morton, D J Hinde, J R Leigh, J P Lestoe, M Dasgupta, J C Mein, J O Newton and H Timmers, *Phys. Rev.* **C52**, 243 (1995)

[19] C R Morton, A C Beriman, M Dasgupta, D J Hinde, J O Newton, K Hagino and I J Thompson, *Phys. Rev.* **C60**, 44608 (1999)

[20] K Hagino, N Takigawa, M Dasgupta, D J Hinde and J R Leigh, *Phys. Rev. Lett.* **79**, 2014 (1997)