Chapter 4

Heavy ion reactions studied on extended-Wong model using proximity potential for non-coplanar nuclei

4.1 Introduction

The low-energy heavy-ion reactions give rise to compound nuclear systems that are excited, carry angular momentum ($\ell$), and decay by emitting multiple light particles (LPs: n, p, $\alpha$) and $\gamma$-rays (constituting the evaporation residue, ER), fusion fission (ff, consisting of the, so-called, intermediate mass fragments IMFs of masses $5 \leq A \leq 20$ and charges $2 < Z < 10$, and the near symmetric and symmetric fission fragments nSF and SF of masses $A/2 \pm 20$), and many a times a non-compound, quasi-fission (qf) or, equivalently, capture process. Such a compound nucleus (CN) decay cross-section is termed as the CN production cross-section, or simply as the fusion cross-section $\sigma_{\text{fus}}$, given as

$$\sigma_{\text{fus}} = \sigma_{ER} + \sigma_{ff} + \sigma_{qf}. \quad (4.1)$$
Note, $\sigma_{qf} \equiv \sigma_{\text{capture}}$. Different compound nucleus reactions result in different combinations of these three processes (ER, ff and qf or capture) or any one of them as a dominant mode. Thus, in the absence of $\sigma_{qf}$, $\sigma_{\text{fus}} = \sigma_{\text{ER}} + \sigma_{\text{ff}}$, and if $\sigma_{\text{ff}}$ is also zero, then $\sigma_{\text{fus}} = \sigma_{\text{ER}}$, also denoted $\sigma_{\text{evr}}$. Alternatively, for a dominant fission decay, $\sigma_{\text{fus}} = \sigma_{\text{f}}$, denoted $\sigma_{\text{fission}}$. On the other hand, if qf or capture is the most dominant process, then we have the case of $\sigma_{\text{fus}} = \sigma_{qf}$ (≡ $\sigma_{\text{capture}}$).

For the (total) fusion cross-section $\sigma_{\text{fus}}$, Wong [1] gave a model in terms of the penetration probability $P$ of the barrier for the incoming channel, which has been applied to $\sigma_{\text{fus}}$ consisting alone of dominant ER [2], [3], fission [4], [5] or capture [6] cross-section. Wong worked out a simplified formula for fusion cross-section in terms the $\ell=0$ barrier properties (position, height and curvature), referred to here as the $\ell=0$ barrier-based Wong formula. Recently, however, Gupta and collaborators [7] showed that the $\ell=0$ barrier-based Wong formula is insufficient to explain the $\sigma_{\text{ER}}$ of Ni-based reactions $^{58}\text{Ni} + {}^{58}\text{Ni}$, $^{64}\text{Ni} + {}^{64}\text{Ni}$ and $^{64}\text{Ni} + {}^{100}\text{Mo}$, known for fusion-hindrance phenomenon in coupled-channels calculations (ccc), and the $\sigma_{\text{capture}}$ of $^{48}\text{Ca}$-based reactions $^{48}\text{Ca} + {}^{238}\text{U}$, $^{244}\text{Pu}$ and $^{248}\text{Cm}$, forming super-heavy nuclei. This happens for $\ell=0$ barrier-based Wong formula because Wong introduced approximations which ignored the already present “barrier modification” effects in Wong expression via its $\ell$-summation. This led Gupta and Collaborators [7] to an $\ell$-summed extended-Wong model where the $\ell$-summation effects are included explicitly. Interestingly, the $\ell$-summed extended-Wong model fits well the above mentioned $^{48}\text{Ca}$-based capture reactions at all the center-of-mass (c.m.) energies $E_{\text{c.m.}}$’s, but require (additional) modifications of the barriers to fit the fusion-evaporation cross-sections $\sigma_{\text{ER}}$ of $^{58,64}\text{Ni}$-based reactions at sub-barrier energies [7]. It may be noted that some “barrier modification” effect are found [7] to be already present in Wong expression due to its in-built $\ell$-dependence via $\ell$-summation, lost in approximations made for obtaining $\ell=0$ barrier-based Wong formula. All the calculations [7] are for use of the nuclear proximity potential, with deformation effects included up.
to hexadecapole deformation $\beta_4$, and orientations $\theta_i$ (i=1, 2) of two nuclei taken in
the same plane (co-planar nuclei, with azimuthal angle $\phi = 0^\circ$).

In this chapter, we study the extended-Wong model for the dominant ER, $\sigma_{ER}$
($\equiv \sigma_{\text{capture}}$), fusion or ER-plus-fission (i.e., $\sigma_{af}=0$) reactions, namely, the $^{58}\text{Ni}+^{58}\text{Ni}$, $^{64}\text{Ni}+^{64}\text{Ni}$ and $^{64}\text{Ni}+^{198}\text{Mo}$ reactions where only $\sigma_{ER}$ is measured [8]-[10], the
$^{48}\text{Ca}+^{238}\text{U}$, $^{244}\text{Pu}$ and $^{248}\text{Cm}$ reactions where all the three components
$\sigma_{ER}$, $\sigma_{ff}$ and $\sigma_{af}$ are measured [11], [12] but $\sigma_{af}$ is dominant, the fission of $^{246}\text{Bk}^*$ formed
in $^{11}B+^{235}\text{U}$ and $^{14}N+^{232}\text{Th}$ reaction channels [4], [5], and the reaction $^{64}\text{Ni}+^{112}$
$\text{Sn} \rightarrow^{176}\text{Pt}^*$ decaying via both the ER and fission processes [16], [17]. For the model,
the nuclear potential is that of the proximity force [20], [21] between two deformed
(upto $\beta_4$) and oriented nuclei, including, for the first time, also the non-co-planar
degree of freedom ($\phi \neq 0^\circ$). The orientation degrees of freedom are integrated over
both the co-planar and non-co-planar configurations of nuclei, i.e., integrated over
both $\theta_i$ and $\phi$.

4.2 Calculations and Results

As already stated above, applications of the extended-Wong model is made to dom­
inantly fission, capture, fusion-evaporation residue, or fusion-evaporation residue-­
plus-fission cross-sections. The hexadecapole deformations $\beta_4$ and non-co-planar
degree of freedom $\phi$ are allowed in all the calculations, except stated otherwise.
The important point to note is that both the orientation degrees of freedom, $\theta_i$ and
$\phi$, are integrated in the extended-Wong model. In the following, we discuss the
applications to various different decay processes on extended-Wong model.

4.2.1 Fission cross-sections

The compound nucleus $^{246}\text{Bk}^*$, formed in $^{11}B+^{235}\text{U}$ and $^{14}N+^{232}\text{Th}$ reaction chan­
nels at sub-, near- and above-barrier energies [4], [5], is highly fissile and decays
totally via fission whose cross-section is taken as the measure of fusion cross-section $\sigma_{fus}^{\text{Expt}}$. No contribution due to the emission of light particles (LPs; $A\leq 4$), intermediate mass fragments (IMFs; $5 \leq A \leq 20$) or non-compound, qf processes are explicitly recorded in these experiments. Thus, the dominantly fissioning $^{246}\text{Bk}^*$ is an ideal case for studying the CN fusion-fission process in a heavy mass nucleus formed in low energy heavy ion reaction.

In these experiments [4], [5], the measured fission fragment anisotropies show the entrance channel effects for the anisotropies of $^{11}\text{B}+^{235}\text{U}$ being consistent, but that of $^{14}\text{N}+^{232}\text{Th}$ anomalous, w.r.t. the statistical saddle-point model (SSPM), which, however, is not supported by the DCM calculations [22] made for quadrupole deformed ($\beta_2$ alone), co-planar ($\phi = 0^o$) nuclei, based on optimum orientations $\theta_i^{\text{opt}}$ [27] ($\equiv \theta_i$ for $\beta_2$ alone, or with $\beta_4 < 0$ or small positive [28]). These calculations [22] show that, in contrast to experiments [4], [5], a non-CN, qf component is present in the fission cross-section of $^{11}\text{B}+^{235}\text{U}$ channel, rather than of the $^{14}\text{N}+^{232}\text{Th}$ channel. The qf component, defined as the measure of disagreement between the calculated and measured fission cross-section

$$\sigma_{qf} = \sigma_{fission}^{\text{Expt}} - \sigma_{fission}^{\text{cal}} \tag{4.2}$$

in $\sigma_{fission}^{\text{Expt}}$ of the $^{11}\text{B}+^{235}\text{U}$ reaction channel is significant for only the top three-four above-barrier energies (for details, see [22]). In the following, we shall see that this result also holds good, for ($\ell$-summed) extended-Wong model for integrated over co-planar orientations ($\phi = 0^o$), but for non-coplanar ($\phi \neq 0^o$) nuclei in the ($\ell$-summed) extended-Wong model the qf-component reduces to zero. In other words, with the non-coplanar degree of freedom included, both the reaction channels $^{11}\text{B}+^{235}\text{U}$ and $^{14}\text{N}+^{232}\text{Th}$ result in pure CN-decay of $^{246}\text{Bk}^*$.

For the fission cross-sections of CN $^{246}\text{Bk}^*$ due to the $^{11}\text{B}+^{235}\text{U}$ and $^{14}\text{N}+^{232}\text{Th}$ incident channels, calculated on ($\ell$-summed) extended-Wong model, we find an
Figure 4.1: Fission cross-sections for the decay of CN $^{246}$Bk*, calculated on $l$-summed extended-Wong model, for both ($\theta_i$, $\phi$) and $\theta_i$-alone ($\phi = 0^0$) integrations, compared with experimental data [4], [5] for (a) $^{14}$N + $^{232}$Th and (b) $^{11}$B + $^{235}$U entrance channel. Results of calculation for $l=0$ barrier-based Wong formula are shown for comparisons. (c) and (d) Variations of best fitted $\Delta V_{\text{mp}}^{\text{emp}}(E_{\text{c.m.}})$, respectively, for the cases of $\phi \neq 0^0$ and $\phi = 0^0$.

The interesting new result of no entrance-channel dependence for $\phi \neq 0^0$ (non-coplanar nuclei), but an entrance-channel dependence for $\phi = 0^0$ case (co-planar nuclei). This is presented in Fig. 4.1, where the Figs. 4.1(a) and 4.1(b) refer to our ($l$-summed) extended-Wong model results, integrated for both the ($\theta_i$, $\phi$) and $\theta_i$-alone ($\phi = 0^0$), compared with experimental data [4], [5], respectively, for the entrance channels $^{14}$N + $^{232}$Th and $^{11}$B + $^{235}$U. Interestingly, for ($\theta_i$, $\phi$)-integration, i.e., for the case of non-coplanar configurations included, the $l$-summed extended-Wong model gives a nice fitting of data for both the incident channels $^{14}$N + $^{232}$Th and $^{11}$B + $^{235}$U at all $E_{\text{c.m.}}$’s, without including any “barrier modification” effects (i.e., $V_{\text{mp}}^{\text{emp}} = 0$), as is explicitly demonstrated in Fig.4.1(c). This means that, with non-coplanar orientations included, the fission of CN $^{246}$Bk* is shown to be a pure compound nucleus decay due to both the $^{14}$N + $^{232}$Th and $^{11}$B + $^{235}$U entrance channels. The same result is obtained for DCM in $\phi = 0^0$ case (next chapter). On the other hand, for the $\phi = 0^0$ case, similar to the DCM calculations in [22] for optimum $\theta_i^{\text{opt}}$ or in the...
following for “compact” $\theta_{\text{c.m.}}$, the explicit $\ell$-summed Wong expression gives an almost exact fit of data for the $^{14}N+^{232}\text{Th}$ channel [Fig. 4.1(a)], but does not fit the data at above barrier energies for the $^{11}B+^{235}\text{U}$ reaction channel, and needs an inclusion of the (additional) “barrier lowering” effects empirically [Fig. 4.1(b)]. The empirical “barrier lowering” parameter $V_B^{\text{emp}}$ vs. $E_{\text{c.m.}}$, so obtained for $\theta_{\text{c.m.}}$-integration ($\phi = 0^\circ$) is shown in Fig. 4.1(d). Apparently, no barrier modification ($V_B^{\text{emp}}=0$) is needed for $^{14}N+^{232}\text{Th}$ channel at all $E_{\text{c.m.}}$’s, as well as at below-barrier energies for the $^{11}B+^{235}\text{U}$ reaction channel, but “barrier lowering” is essential (i.e., $V_B^{\text{emp}} < 0$) for the higher above-barrier energies in the case of $^{11}B+^{235}\text{U}$. Note that the “barrier lowering” effect, or the $\phi$-component representing disagreement between the measured and calculated $\sigma_{\text{fission}}$, at above-barrier energies for $\phi = 0^\circ$, or a pure CN decay for both the incoming channels in $\phi \neq 0^\circ$ case is still contrary to the measured fission anisotropy data [4], [5] mentioned above, and need further experimental verification. Fig. 4.1 also shows the failure of $\ell=0$ barrier-based Wong formula.

4.2.2 Capture cross-sections

Capture, equivalently, $\phi$ process is measured for the $^{48}\text{Ca}+^{238}\text{U}$, $^{244}\text{Pu}$ and $^{248}\text{Cm}$ reactions, where in fact all the three components ($\sigma_{\text{FF}}, \sigma_{\text{ff}}$ and $\sigma_{\phi}$) of fusion cross-section $\sigma_{\text{fus}}$ are measured [11], [12] but $\sigma_{\phi}$ ($\equiv \sigma_{\text{capture}}$) is the most dominant ($\sigma_{\text{fus}} \equiv \sigma_{\phi}$). $^{48}\text{Ca}$ being a doubly magic spherical nucleus, these reactions are the cases of $\phi = 0^\circ$. Hence for Wong model we integrate over $\theta$ alone (co-planar nuclei). All calculations are based on proximity potential with deformation up to $\beta_4$. Once again, we find that the $\ell=0$ barrier-based Wong formula is not adequate for this capture data, but the ($\ell$-summed) extended-Wong model, give an almost exact fitting of the data, without introducing any additional barrier modification effects empirically in the extended-Wong model.

Fig. 4.2 shows the results of our calculation for the ($\ell$-summed) extended-Wong
SECTION 4.2: CALCULATIONS AND RESULTS

Figure 4.2: Fusion (≡capture) cross-sections as a function of $E_{c.m.}$, for $^{48}$Ca$^{+238}$U, $^{244}$Pu and $^{248}$Cm systems, calculated by using the ($\ell$-summed) extended-Wong model and $\ell=0$ based-barrier Wong formula, integrated over $\theta$ ($\phi = 0^\circ$), compared with experimental data \[11\]. Also shown here is the extrapolation of calculations (dot-dash line) to a high, above-barrier energy where the Sharp cut-off approximation is valid. Sharp cut-off model calculations ("stars") are made for $= 90^\circ$ orientations of the deformed reaction partners. For the case of $^{48}$Ca$^{+248}$Cm, the calculated extended-Wong model point (the “triangle”) at the near-barrier energy is for the corresponding interpolated $\ell_{max}$-value from Fig. 4.3.

We have further extended our extended-Wong model calculation to a higher above-barrier energy ($E_{c.m.}=220$ MeV) where the Sharp cut-off model approximation is valid, with the fusion cross-section (in mb) given by

$$\sigma(E_{c.m.} > V_B, \theta, \phi) = 10^{\ell_B} \left[ 1 - \frac{V_B}{E_{c.m.}} \right]$$  \hspace{1cm} (4.3)

Here, since $^{48}$Ca is spherical and the reactions considered are “hot-fusion” reac-
Figure 4.3: Deduced $l_{\text{max}}$ in ($l$-summed) extended-Wong model for $^{48}\text{Ca}+^{238}\text{U}$, $^{244}\text{Pu}$ and $^{248}\text{Cm}$ systems. The same for the above-barrier energy is obtained for the estimated cross-section in Sharp cut-off model (shown as “stars”, and joined by solid lines), and for the case of $^{48}\text{Ca}+^{248}\text{Cm}$, an interpolation to near-barrier energy (dot-dash line) is carried out with $l_{\text{max}}$ value shown by a “triangle”. The lines are only for the guide of eye.

tions [12], $\phi = 0^\circ$ and $\theta = 90^\circ$ for the deformed reaction partner [27]. The result of this calculation is shown in Fig. 4.2 for all the three reactions, denoted as “stars”. Apparently, the extension of last experimental data point at the near-barrier energy to the calculated sharp cut-off model cross-section at the chosen above-barrier energy ($E_{\text{c.m.}} = 220$ MeV) is smooth for first two reactions ($^{48}\text{Ca}+^{238}\text{U}$ and $^{48}\text{Ca}+^{244}\text{Pu}$), but the same for $^{48}\text{Ca}+^{248}\text{Cm}$ need an interpolation of data at the near-barrier energy ($E_{\text{c.m.}} = 205.5$ MeV). For such an inter-polation, we first estimate the $l_{\text{max}}$-value by fitting the Sharp cut-off model cross-section at $E_{\text{c.m.}} = 220$ MeV to the $l$-summed extended-Wong model expression for all the three reactions, also plotted in Fig. 4.3 as “stars”. Then, on joining this estimated $l_{\text{max}}$ for Sharp cut-off model cross-section to below-barrier results, the extrapolations are smooth for $^{48}\text{Ca}+^{238}\text{U}$ and $^{48}\text{Ca}+^{244}\text{Pu}$ systems, but not for the $^{48}\text{Ca}+^{248}\text{Cm}$ system where an interpolation is carried out by joining it straight (avoiding the plateau) through a dot-dashed line. The interpolated $l_{\text{max}}$ value is shown as a “triangle” for $^{48}\text{Ca}+^{248}\text{Cm}$ system in Fig. 4.3, with the estimated cross-section on extended-Wong model also denoted by a
“triangle” in Fig. 4.2. This result calls for a check on the experimental data of $^{48}\text{Ca}+^{248}\text{Cm}$ reaction at the near-barrier energy ($E_{c.m.}=205.5$ MeV). Similar results are obtained [13] for the Skyrme-force-based proximity potential [14] of the semi-classical ETF method with frozen densities, when used in $\ell$-summed Wong model. Furthermore, the role of non-coplanar ($\phi \neq 0^\circ$) degree of freedom in these capture reactions is also explored by giving a small deformation ($\beta_2=0.183$) to $^{48}\text{Ca}$, showing an equally good fit as above for spherical $^{48}\text{Ca}$ ($\phi = 0^\circ$), though with fitted $\ell_{\text{max}}(E_{c.m.})$ increasing by one-to-two units.

### 4.2.3 Evaporation residue cross-sections

The predominantly fusion-evaporation residue cross-sections $\sigma_{ER}$ are measured [8]-[10] for $^{58}\text{Ni}+^{58}\text{Ni}$, $^{64}\text{Ni}+^{64}\text{Ni}$ and $^{64}\text{Ni}+^{100}\text{Mo}$ reactions, known for fusion-hindrance phenomenon in ccc [10], and requiring “barrier modification” effects at sub-barrier energies in both the ccc [15] and Wong model [1]. The DCM also supports the property of “barrier lowering” for these Ni-based reactions at sub-barrier energies, studied only for co-planar ($\phi = 0^\circ$) nuclei in cases of $^{64}\text{Ni}+^{64}\text{Ni}$ and $^{64}\text{Ni}+^{100}\text{Mo}$ reactions [23], [24]. Noting that $^{58}\text{Ni}$ is a spherical nucleus, in the following, we extend this work, again to the above stated two $^{64}\text{Ni}$-based reactions, and to non-coplanar ($\phi \neq 0^\circ$) nuclei. The interesting result is that, even for $\phi$ degree of freedom included in the extended-Wong model, barrier lowering effects are needed for the above said evaporation residue cross-sections $\sigma_{ER}$, in contrast to the fission and capture reactions studied in the previous two sub-sections. The DCM, with non-coplanar effects included, is also found to give the same result as for the $\phi = 0^\circ$ case, stated above.

Fig. 4.4 shows the $\ell$-summed extended-Wong model calculations of fusion-evaporation cross-sections $\sigma_{ER}$, as a function of $E_{c.m.}$, for $^{64}\text{Ni}+^{64}\text{Ni}$ and $^{64}\text{Ni}+^{100}\text{Mo}$ reactions for both the cases of non-coplanar ($\phi \neq 0^\circ$) and co-planar
Figure 4.4: Fusion-evaporation cross-sections calculated on (ℓ-summed) extended-Wong model, integrated over (θ, φ) and θ-alone (φ = 0°), for both the cases of ΔV_B^{emp} = 0 and best fitted ΔV_B^{emp}. compared with experimental data for (a) 64Ni+64Ni [9] and (b) 64Ni+100Mo [10] reactions. In (a) are also illustrated for comparisons the results of calculation for ℓ=0 barrier-based Wong formula. (c) and (d) give the variations of ΔV_B^{emp} with E_{c.m.} for both the cases of φ ≠ 0° and φ = 0°, respectively, for the best fit to data in (a) and (b) for 64Ni+64Ni and 64Ni+100Mo reactions.

(φ = 0°) nuclei, compared with experimental data [9], [10]. The interesting result is that, just as for co-planar nuclei in [7], “barrier modification” (ΔV_B^{emp} ≠ 0) is required for a best fit to data at below-barrier energies, even for the ℓ-summed extended-Wong model. The failure of ℓ=0 barrier-based Wong formula, for no barrier modification effects (ΔV_B^{emp}=0), is also illustrated in Fig. 4.4(a) for the 64Ni+64Ni reaction, which for ΔV_B^{emp} ≠ 0 case is known to give an un-desirable result [7]. For the ℓ-summed extended-Wong model, ΔV_B^{emp} as a function of E_{c.m.} is shown for both the reactions, respectively, in Figs. 4.4(c) and 4.4(d) for the two cases of φ ≠ 0° and φ = 0°. Note that the magnitudes of barrier modification ΔV_B^{emp} in two cases (φ ≠ 0° and φ = 0°) are different, though no particular significance can be attached to the nature of curves in these figures, i.e., its double valued-ness, etc., except that it gives the required ΔV_B^{emp} to fit the fusion-evaporation data. In any case, the role of φ degree-of-freedom for σ_{EB} is simply to re-fit the “barrier lowering”
4.2.4 Evaporation residue-plus-fission cross-sections

In $^{64}$Ni+$^{112,118,124}$Sn and $^{132}$Sn+$^{64}$Ni reactions, both the ER and fission cross-sections are measured [16]-[19] at the above- and below-barrier energies, which in DCM are so-far understood for the case of $\phi = 0^\circ$ alone [31], [32], showing ER and fission as the only viable decay processes, but with prediction of a small qf component at one or two above-barrier energies. ER contribution occurs at both below- and above-barrier energies, whereas the fission contribution appears only at near and
above-barrier energies. Thus, at below or sub-barrier energies $\sigma_{ER} > \sigma_{fission}$. Also, Wong model is not yet applied to these reactions. In DCM, $\sigma_{fus} = \sigma_{ER} + \sigma_{fission}$ where $\sigma_{fission} = \sigma_{nSF} + \sigma_{SF}$, and in Wong model, since different components could not be treated, $\sigma_{fus} = \sigma_{ER} + \sigma_{fission}$. In the following, we consider the application of extended-Wong model to (total) fusion cross-section $\sigma_{fus}$, for integration over both $\theta$ and $\phi$, with a view to see (i) like in pure fission reactions, the role of non-coplanarity ($\phi$) for qf component at above-barrier energies, and (ii) like for other $^{64}$Ni-induced reactions, the role of barrier-lowering at below-barrier energies. We choose to work here with $^{64}$Ni+$^{112}$Sn $\rightarrow ^{176}$Pt* where both $^{64}$Ni and $^{112}$Sn are deformed nuclei.

In Fig. 4.5 for fusion cross-section $\sigma_{fus}$ (sum of $\sigma_{ER}$ and $\sigma_{fission}$) for $^{64}$Ni+$^{112}$Sn reaction, we notice that, for $\phi$ degree of freedom included, the dominantly fission cross-sections at above-barrier energies are nicely fitted, without requiring any additional qf component, but the dominantly ER cross-sections at near and below-barrier
energies require a non-zero barrier-lowering parameter $\Delta V_B$, like that obtained in Fig. 4.6, to fit the fusion cross-section data. The same result holds good for the $\phi = 0^\circ$ case at both above- and below-barrier energies, except for a small change in the magnitude of $\Delta V_B(E_{c.m.})$. Thus, combining these results with the results of earlier sub-sections, the $\phi$ component is simply an artifact of including or not-including the $\phi$ degree of freedom in pure fission cross-section and not in the case of fission as a component of the fusion cross-section. However, barrier-lowering is an essential characteristic of the ER cross-sections at below or sub-barrier energies.

4.3 summary

A study of the applications of the $(t$-summed) extended-Wong model is carried out for fission, capture (equivalently, quasi-fission), fusion-evaporation residue, and fission-plus-evaporation residue reaction cross-sections. For the model, the deformation and orientation dependent nuclear proximity potential is used, with deformations taken up to hexadecapole, and the orientation degrees of freedom integrated over both the co-planar and non-co-planar nuclei in Wong model. The out-of-plane ($\phi \neq 0$) configurations are included here for the first time. The $(t$-summed) extended-Wong model is limited to explain only the (total) fusion cross-section (sum of all decay process, or the most dominant one). The interesting result of this study is that, in each case, the cross-section gets divided in to two regions of c.m. energies, the below or sub-barrier and the above-barrier energies, each referring, respectively, to the concept of “barrier modification” at below-barrier energies, and that of non-compound “quasi-fission” component at above-barrier energies. Note that the same are explored here, for the nuclear proximity potential. For Wong model, pure-fission reactions present the interesting cases of no “barrier-lowering” at sub-barrier energies for the both the cases of including and not-including the $\phi$ degree of freedom and at above-barrier energies, like in the DCM, give rise to an entrance channel-dependent quasi-fission contribution simply as an artifact of not including the $\phi$ degree of free-
dom. In other words, fission is a pure compound nucleus decay in Wong model also. For Wong model, in dominant capture cross-sections, no “barrier-lowering” effects are present. However, in pure evaporation residue and fission-plus-evaporation residue cross-sections, the “barrier-lowering” phenomenon at sub-barrier energies seems to be a must but no quasi-fission component is present at higher energies.
Bibliography


