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Non-Coplanar Nuclei in Heavy-Ion Reactions

Sahila Chopra, Hemdeep, Arshdeep Kaur, Raj K. Gupta

Abstract—In recent times, we noticed an interesting and important role of non-coplanar degree-of-freedom ($\Phi \neq 0^0$) in heavy ion reactions. Using the dynamical cluster-decay model (DCM) with Φ degree-of-freedom included, we have studied three compound systems ^{246}Bk*, ^{164}Yb* and ^{105}Ag*. Here, within the DCM with pocket formula for nuclear proximity potential, we look for the effects of including compact, non-coplanar configurations ($\Phi_c \neq 0^0$) on the non-compound nucleus (nCN) contribution in total fusion cross section σ_{fus}. For ^{246}Bk*, formed in ^{11}B+^{235}U and ^{14}N+^{232}Th reaction channels, the DCM with coplanar nuclei ($\Phi_c = 0^0$) shows an nCN contribution for ^{11}B+^{235}U channel, but none for ^{14}N+^{232}Th channel, which on including Φ gives both reaction channels as pure compound nucleus decays. In the case of ^{164}Yb*, formed in ^{64}Ni+^{100}Mo, the small nCN effects for Φ=0^0 are reduced to almost zero for $\Phi \neq 0^0$. Interestingly, however, ^{105}Ag* for $\Phi = 0^0$ shows a small nCN contribution, which gets strongly enhanced for $\Phi \neq 0^0$, such that the characteristic property of P_{CN} presents a change of behaviour, like that of a strongly fissioning superheavy element to a weakly fissioning nucleus; note that ^{105}Ag* is a weakly fissioning nucleus and P_{surv} behaves like one for a weakly fissioning nucleus for both $\Phi = 0^0$ and $\Phi \neq 0^0$. Apparently, Φ is presenting itself like a good degree-of-freedom in the DCM.

Keywords—Dynamical cluster-decay model, fusion cross sections, non-compound nucleus effects, non-coplanarity.

I. INTRODUCTION

We have analyzed in this work that non-coplanar degree-of-freedom (Φ) is an important variant in hot fusion reactions. Using the dynamical cluster-decay model (DCM) [1], for case of nuclear proximity pocket formula of Blocki et al. [2], we have studied three compound systems ^{246}Bk* [3], [4], ^{164}Yb* [5], [6], and ^{105}Ag* [7], [8], formed in various different reactions at many incident center-of-mass energies $E_{c.m.}$. In these three nuclear systems, 'compact' coplanar configurations (Φ_c=0^0) present best cases of large non-compound-nucleus (nCN) component in the measured fusion cross section σ_{fus}. In case of ^{246}Bk*, formed in ^{11}B+^{235}U and ^{14}N+^{232}Th entrance channels, for Φ=0^0, the quasi-fission (qf)-like nCN component is present in fission cross section of ^{11}B+^{235}U channel, but not in ^{14}N+^{232}Th channel. Here, the (qf-like) nCN component is defined as the measure of disagreement between the calculated and measured fission cross section, taken as a measure of σ_{fus}. However, with non-coplanar degree-of-freedom included ($\Phi \neq 0^0$), interestingly in ^{11}B+^{235}U$\rightarrow^{246}$Bk* reaction, the nCN contribution is reduced to zero at all incident $E_{c.m.}$, with ^{14}N+^{232}Th reaction channel keeping the same result (σ_{nCN}=0) for both cases (Φ=0^0 and $\Phi \neq 0^0$). On the other hand, in the other two reactions ^{64}Ni+^{100}Mo$\rightarrow^{164}$Yb* and ^{12}C+^{93}Nb$\rightarrow^{105}$Ag*, the effect of non-coplanarity ($\Phi \neq 0^0$) on σ_{nCN} is negligibly small (σ_{nCN} decreased to almost zero for $\Phi \neq 0^0$ case) in the first case, but gets strongly enhanced in the second case such that its (^{105}Ag*) characteristic properties change, rather leads to a consistent picture for $\Phi \neq 0^0$ from an inconsistent one for Φ=0^0.

The defining of compound nucleus (CN) fusion probability P_{CN} and survival probability P_{surv} have proved a helping hand for explaining the importance of non-coplanarity degree-of-freedom [9], [10]. One of the important result of the variation of P_{CN} with CN excitation energy E^* is the classification of various nuclear systems in to (i) P_{CN}=1 (σ_{nCN}=0) for small E^* but decreases as E^* increases, and (ii) P_{CN} increases with increasing E^* at lower E^* and goes to unity at higher E^*. On the other hand, P_{surv} classified compound nuclear system in to these groups, namely, the weakly fissioning nuclei, radioactive nuclei, and the strongly fissioning superheavy nuclei, with magnitudes of P_{surv}, respectively, $\sim$1, $\sim$10^{-6} and $\sim$10^{-10}. For example, ^{105}Ag* with co-planar degree-of-freedom ($\Phi = 0^0$), shows the behaviour of the variation of P_{CN} with E^* similar to superheavy systems ^{286}Cn* and ^{292}Fl*, having P_{CN} <<1 and increasing with E^*, whereas P_{surv} belongs to weakly fissioning group, decreasing with increasing E^*. For P_{CN}, this happens because ^{105}Ag* is found [7] to contain a large nCN component and the two superheavy systems are also known to decay dominantly via the qf process. However, on including the Φ degree-of-freedom, the nCN cross section for ^{105}Ag* gets strongly enhanced such that the behavior of P_{CN} as a function of E^* changes from increasing to decreasing and hence belongs to the group of weakly fissioning nuclei, like for P_{surv} as a function of E^*. Thus, as expected, ^{105}Ag* with non-coplanar degree-of-freedom included ($\Phi \neq 0^0$) is a weakly fissioning nucleus for both P_{CN} and P_{surv}. Similar interesting, though different, results are obtained for CN ^{164}Yb* and ^{246}Bk*, and further such studies with non-coplanarity included are called for. One such case [9] is the Pt-isotopes ($^{176-196}$Pt*) with $\Phi \neq 0^0$.

Section II gives the formulation of the dynamical cluster-decay model used here. Calculations are discussed in Section III, and our conclusion is presented in Section IV.

II. DYNAMICAL CLUSTER-DECAY MODEL (DCM)

The DCM is based on the well known Quantum mechanical fragmentation theory (QMFT) [1] which, in binary fragmentation process, uses collective coordinates of mass (and charge) asymmetries η (and η_Z) [$\eta = (A_1 - A_2)/(A_1 + A_2)$, $\eta_Z = (Z_1 - Z_2)/(Z_1 + Z_2)$], and relative separation R, with multipole deformations $\beta_{\lambda i}$ (λ=2,3,4; i=1,2), orientations θ_i and the azimuthal angle Φ between the principal planes of two nuclei. In terms of these coordinates, for ℓ partial waves,

S. Chopra, Hemdeep, A. Kaur and R. K. Gupta are with the Department of Physics, Panjab University, Chandigarh, 160014 India (e-mail: chopra.sahila@gmail.com).

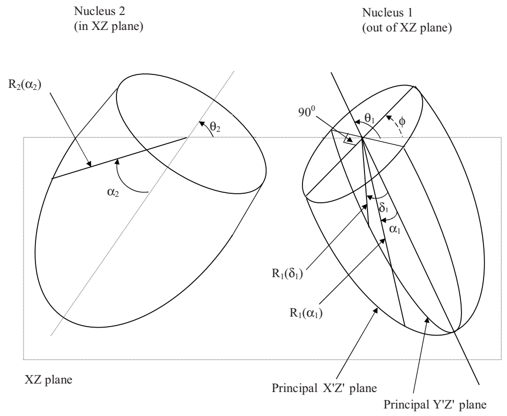

Fig. 1 Two unequal nuclei, oriented at angles θ_1 and θ_2, with their principal planes X'Z' and XZ making an azimuthal angle Φ. The angle Φ is shown by a dashed line, since it is meant to be an angle coming out of the plane XZ. Nucleus 2 is in XZ plane and for the out-of-plane nucleus 1, another principal plane Y'Z', perpendicular to X'Z', is also shown. The orientation angels θ_i are measured anti-clockwise from the collision Z axis, and the angles α_i (and δ_i) of radius vectors are measured in the clockwise direction from the nuclear symmetry axis

we define the CN-decay/ fragments-formation cross section for each pair of exit/ decay channel as

$$\sigma_{(A_1,A_2)} = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{max}}(2\ell+1)P_0P; \quad k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \quad (1)$$

where P_0 is fragment preformation probability, referring to η motion at fixed R-value and P, the barrier penetrability, to R motion for each η-value, both dependent on T and ℓ. The reduced mass $\mu = mA_1A_2/(A_1+A_2)$ with m as the nucleon mass. ℓ_{max} is the maximum angular momentum, defined for light-particles (LPs) evaporation residue cross section $\sigma_{ER} \rightarrow 0$. Then, it follows from (1) that

$$\sigma_{ER} = \sum_{A_2=1}^{4 \text{ or } 5}\sigma_{(A_1,A_2)} \quad \text{or} \quad = \sum_{x=1}^{4 \text{ or } 5}\sigma_{xn}, \quad (2)$$

and

$$\sigma_{ff} = 2\sum_{A_2=5 \text{ or } 6}^{A/2}\sigma_{(A_1,A_2)}. \quad (3)$$

The above equation is also applicable to the case where the ff process is measured only up to the, so-called, intermediate mass fragments (IMFs; 5$\leq$ A_2 $\leq$20, 3$\leq$ Z_2 $\leq$10) with sum taken up to the maximum measured value of A_2 and without the multiplying factor 2. The same equation (1) is also applicable to the nCN decay process, calculated here as the quasi-fission (qf)-like decay where P_0=1. In other words, for σ_{nCN} we use DCM(P_0=1) for each decay channel. In case the σ_{nCN} were not measured, it can be estimated empirically from the calculated and measured σ_{fus}, as

$$\sigma_{nCN} = \sigma_{fus}^{Expt.} - \sigma_{fus}^{Cal.}. \quad (4)$$

where, $\sigma_{fus}^{Cal.} \equiv \sigma_{CN}^{Cal.}$. Thus, using (1) in (2) and (3), the DCM predicts not only the total fusion cross section σ_{fus}, the sum of the cross sections of constituents ER, ff and nCN, but also the individual cross sections σ_{ER}, σ_{ff} and σ_{nCN}. With the help of these cross sections, we can calculate the CN fusion probability P_{CN} and survival probability P_{surv}.

The CN formation probability P_{CN} is defined as

$$P_{CN} = \frac{\sigma_{CN}}{\sigma_{fusion}} = 1 - \frac{\sigma_{nCN}}{\sigma_{fusion}}, \quad (5)$$

and the CN survival probability P_{surv}, the probability that the fused system will de-excite by emission of neutrons or LPs (equivalently, the ER), rather than fission, as

$$P_{surv} = \frac{\sigma_{ER}}{\sigma_{CN}}, \quad (6)$$

where, $\sigma_{fus} = \sigma_{CN} + \sigma_{nCN}$ and $\sigma_{CN} = \sigma_{ER} + \sigma_{ff}$.

The important parameter of the DCM is the neck-length parameter ΔR, which is directly related to the "barrier lowering", and hence to fusion hindrance phenomenon in heavy-ion reactions. The choice of parameter ΔR, for a best fit to the data, allows us to relate in a simple way the $V(R_a,\ell)$ at $R=R_a$ [defining the first turning point in $V(R)$] to the top of the barrier $V_B(\ell)$ for each ℓ, by defining their difference $\Delta V_B(\ell)$, the effective "lowering of the barrier", as

$$\Delta V_B(\ell) = V(R_a,\ell) - V_B(\ell). \quad (7)$$

Note, ΔV_B for each ℓ is defined as a negative quantity since the actually used barrier is effectively lowered. Thus, the fitting parameter ΔR controls the "barrier lowering" ΔV_B.

To calculate the cross sections for non-coplanar nuclei ($\Phi \neq 0^0$) (see fig. 1), we use the same formalism as for $\Phi = 0^0$ (see, [11]), but by replacing for the out-of-plane nucleus (i=1 or 2) the corresponding radius parameter $R_i(\alpha_i)$ with its projected radius parameter $R_i^P(\alpha_i)$ in both the Coulomb and proximity potentials [12]. For Coulomb potential, it enters via $R_i(\alpha_i)$ itself, and for the proximity potential via the definitions of both the mean curvature radius $\bar{R}$ and the shortest distance s_0, i.e., compact configurations with orientations θ_{ci} and Φ_c [13], [14]. For compact configurations, the interaction radius is smallest and the barrier is highest.

The $R_i^P(\alpha_i)$ is determined by defining, for the out-of-plane nucleus, two principal planes $X'Z'$ and $Y'Z'$, respectively, with radius parameters $R_i(\alpha_i)$ and $R_j(\delta_j)$, such that their projections into the plane (XZ) of the other nucleus are (see Fig. 1)

$$R_i^P(\alpha_i) = R_i(\alpha_i)\ \cos\Phi \qquad \text{i=1 or 2}, \quad (8)$$

and

$$R_j^P(\delta_j) = R_j(\delta_j)\ \cos(\Phi-\delta_j) \qquad \text{j=i=1 or 2}. \quad (9)$$

Then, maximizing $R_j(\delta_j)$ in angle δ_j, we get

$$\begin{aligned} R_i^P(\alpha_i) &= R_i^P(\alpha_i=0^0) + R_i^P(\alpha_i\neq 0^0) \\ &= R_j^P(\delta_j^{max}) + R_i(\alpha_i \neq 0^0)\ \cos\Phi, \end{aligned} \quad (10)$$

with δ_j^{max} given by the condition (for fixed Φ),

$$\tan(\Phi-\delta_j) = -\frac{R_j'(\delta_j)}{R_j(\delta_j)}. \quad (11)$$

Thus, the Φ-dependence of projected radius vector $R_i^P(\alpha_i)$ is also contained in maximized $R_j^P(\delta_j^{max})$. For further details,

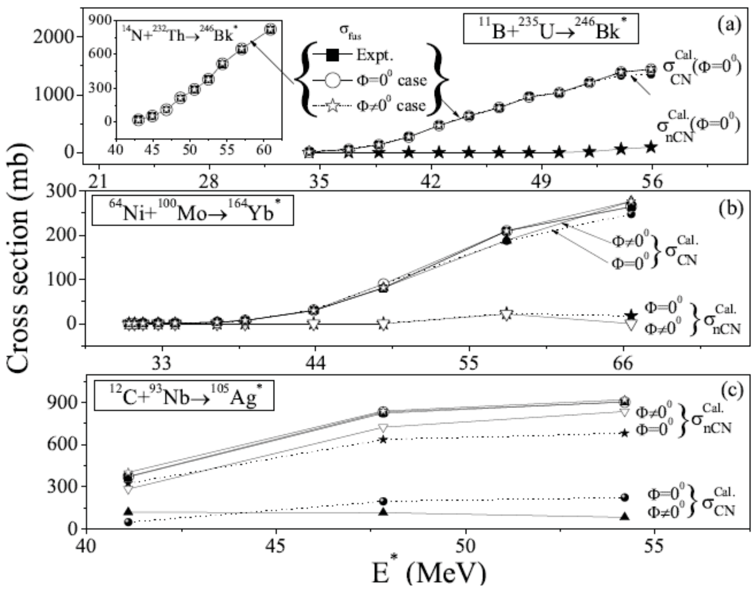

Fig. 2 Comparing the cross sections of three nuclear systems ^{246}Bk*, ^{164}Yb* and ^{105}Ag*, using DCM with Φ_c=0^0 and $\Phi_c \neq 0^0$, for showing the effect of non-coplanarity on non-compound nucleus (nCN) contribution σ_{nCN} in σ_{fus}

see [12]. Then, for nuclear proximity potential, denoting by V_P^{12} the potential for the nucleus 1 to be out-of-plane, and by V_P^{21} for the nucleus 2 to be out-of-plane, the effective nuclear proximity potential $V_P = \frac{1}{2}[V_P^{12} + V_P^{21}]$.

III. Calculations and Results

In this section, we compare our results of using the DCM for three nuclear systems ^{246}Bk*, ^{164}Yb* and ^{105}Ag*, to see the effect of non-coplanarity degree-of-freedom ($\Phi \neq 0^0$) on nCN contribution in σ_{fus}. The interesting result is that the effect of non-coplanarity is different in different reactions.

In Fig. 2(a), the CN ^{246}Bk*, formed in two incoming reaction channels ^{11}B+^{235}U and ^{14}N+^{232}Th at sub-, near- and above-barrier energies [15], [16], is highly fissile and decays totally via fission cross section, taken as the measure of fusion cross section σ_{fus}^{Expt} (=σ_{fiss}^{Expt}). No contribution due to the emission of LPs (A≤4), IMFs (5≤A≤20) or qf-like nCN processes are explicitly recorded in these experiments. However, in Fig. 2(a), calculations [3], [4] for coplanarity of nuclei (Φ=0^0) show that, in contrast to experiments [15], [16], a non-CN/ qf component is present in the fission cross section of ^{11}B+^{235}U channel, but not in ^{14}N+^{232}Th channel. We notice that for ^{11}B+^{235}U channel, ^{246}Bk* with $\Phi = 0^0$ has the nCN component at higher three energies, and at other energies it shows a good agreement with the experimental data (compare $\sigma_{CN}^{Cal.}$, $\Phi = 0^0$ with σ_{fus}^{Expt}). However, $\Phi \neq 0^0$ nullify completely this disagreement between experimental data and calculated results, and both the channels (main figure and inset) show σ_{fus} as pure CN cross section for $\Phi \neq 0^0$.

Fig. 2 (b) shows the case of ^{164}Yb*, where allowing non-coplanarity ($\Phi \neq 0^0$) fits the data nearly exactly, with a strongly reduced nCN contribution. For Φ=0^0 case, the nCN contribution is non-zero at the highest two energies, which for $\Phi \neq 0^0$ reduces to only one of them. Thus, for ^{164}Yb*,the nCN contribution is reduced almost to zero, and the reaction for $\Phi \neq 0^0$ could be taken as pure CN reaction. The deviations of $\sigma_{fus}^{Cal.}$ from σ_{fus}^{Expt}, with and without Φ, are simply due to large errors in data [17].

Fig. 2 (c) shows the interesting result of non-coplanarity on nCN contribution in the case of ^{105}Ag*. We notice that, for a best fit to data [18], in going from $\Phi = 0^0$ to $\Phi \neq 0^0$, instead of decreasing, the nCN contribution has increased considerably. An important effect of this result is that now the variations of both P_{CN} and P_{surv} support the fact that ^{105}Ag* belongs to the same group of weakly fissioning nuclei, i.e., both P_{CN} and P_{surv} decrease with increasing E^* for Φ ≠0^0.

Another important result follows from the neck-length parameter ΔR value, in going from $\Phi = 0^0$ to $\Phi \neq 0^0$. We found a similar trend of ΔR variation in ^{164}Yb* and ^{105}Ag*, but a reverse one in the case of ^{246}Bk*. For $^{164}Yb^*$ only fusion-evaporation residue (ER) cross section is measured at extreme sub-barrier energies, and in ^{105}Ag* we have the measured data for evaporation residues ER and the IMFs. In these two cases, we have found that ΔR is larger in case of $\Phi \neq 0^0$ as compared to $\Phi = 0^0$ case. Alternatively, in ^{246}Bk*, experimentally only fission data is available, and according to DCM its ΔR is small in the case of $\Phi \neq 0^0$ as compared to the case of $\Phi = 0^0$ [4].

IV. Conclusion

Concluding, non-coplanarity is an important, independent degree-of-freedom, which must be included in every study of heavy ion reaction.

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Sahila Chopra Ph.d student, Panjab University, Chandigarh (India), was born at Panipat (Haryana), India, on July 14, 1984. Sahila's educational back ground is M.Sc (Physics) 2007 from Kurukshetra University, M.Phil (Physics) 2009 from Vinayak Mission University, and awarded Women Scientist-A (WOS-A), Department of Science & Technology, Govt. of India, Research Project at Panjab University, Chandigarh, India in 2013-2017.

Hemdeep Ph.d student, Panjab University, Chandigarh (India), was born at Sanghol (Punjab), India, on September 8, 1992. Hemdeep's educational back ground is M.Sc (Hon's) Physics 2015 from Panjab University and since January 2016 Junior Research Fellow (JRF) of Council of Sc. & Industrial Reseach (CSIR) and University Grants Commission (UGC), Govt. of India, at Panjab University, Chandigarh, India.

Arshdeep Kaur Assistant Professor of Physics, Dev Samaj College for Women, Sector 45, Chandigarh, (India) since 2013, doing research for her Ph.d at Panjab University, Chandigarh (India), was born at Kotla (Punjab), India, on October 24, 1986. Arshdeep's educational back ground is M.Sc (Hon's, Gold Medalist) Physics 2010 from Panjab University, Chandigarh, India.

Raj K. Gupta Professor Emeritus Panjab University, Department of Physics, Chandigarh (India), was born at Narwana (Haryana), India, on June 18, 1938. Guptas educational background is M.Sc. (Physics), Ph.D. in year 1967, Panjab University, Chandigarh (U.T.), India. Guptas major field of study is Theoretical Nuclear Physics. He has made over 250 research publications in International Journals and over 400 contributions to International and National Conferences and Meetings. Books published by him are: Heavy Elements and Related New Phenomena, World Scientific Publications, Singapore 1999, Vols. I and II, jointly with Walter Greiner; New Horizons of Physics Series: Physics of Particles, Nuclei and Materials - Recent Trends, Narosa Publishers, New Delhi, 2002. He has been honoured with Life Time Achievement Award by Organizing Committee of International Nuclear Physics Conference, held at Chitkara University, Brotiwala (HP), India, on 19.11.2012. He has been a 2005-06 Mercator Professor of German Research Society (DFG), 2006-2009 Ramanna Fellow of Department of Sc. & Tech., Govt. of India, 1993-95 UGC National Fellow, 1990-91 DFG Guest Professor, 1991-92 WE-Heraeus Stiftung Guest Professor, 1984-85 Hari Om Prize and Gold Medal Awardee, 1973-75 Dozenten Fellow of Alexander von Humboldt Stiftung, Germany and 1971 IAEA/UNESCO Fellow at ICTP, Trieste, Italy. He has completed over 25 research projects funded by various Indian and German Funding Agencies. His research interests are in Heavy Ion Physics, Cluster Radioactivity, Fission, Fusion and Quantum Groups and Algebra. Prof. Gupta is a Life Member of Indian Physics Association, Indian Association of Physics Teachers and Indian Association of Nuclear Chemists and Allied Scientists.