

Dynamical cluster decay model applied to very light mass compound systems of mass $A \sim 30$ formed in heavy ion reactions

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Abstract.

The study of the decay of $^{32}\text{S}^*$ and $^{31}\text{P}^*$ compound systems formed in $^{20}\text{Ne}+^{12}\text{C}$ and $^{19}\text{F}+^{12}\text{C}$ reactions, respectively, is further extended on the basis of collective clusterization process within the dynamical cluster model (DCM) of Gupta and collaborators, with the effects of deformations and orientations included, at an excitation energy $E_{CN}^*=60$ MeV. In the present study, we have investigated the effects of deformations and orientations on the target, i.e., ^{12}C like yield, denoted C-yield (σ_C), which contains fusion-fission (FF) decay cross-section, σ_{FF} , from compound nucleus process and deep inelastic orbiting (DIO) cross-section, σ_{DIO} , from non-compound nucleus process. As observed in one of our earlier study for $^{32}\text{S}^*$ system there is a competition between FF and DIO, while, for $^{31}\text{P}^*$ there is a contribution of FF cross-section only, in the total C-yield. The comparative analysis of C-Yield for the considerations of spherical and oriented nuclei, shows similar results with the only difference of the values of neck length parameter (ΔR), which are more for the later case. The calculated cross-sections σ_C show good agreement with experimental data for both the considerations.

1. INTRODUCTION

Within last couple of decades, light heavy ion collisions have been studied over a wide range of low bombarding energies per nucleons ($E_{lab} \leq 10$ MeV) for various target + projectile combinations [1, 2, 3]. The fission process in very light systems has distinctive features *w.r.t.* heavy systems. In contrast to heavy systems, where symmetric break up is favoured, the dependence of macroscopic potential energy surface due to nuclear deformations and shape asymmetry favours the break up of lighter systems into two unequal fragments. There is a competition between fusion-fission and deep inelastic orbiting processes for these systems [4, 5]. In the fusion-fission (FF) process, a completely equilibrated compound nucleus (CN) is formed, which decays in various exit channels, independent of the entrance channel, whereas deep inelastic orbiting (DIO) is the process of formation of long lived dinuclear molecular complex which acts as a 'door way to fusion' resulting into non compound nucleus (nCN) formation with strong memory of entrance channel.

The dynamics of very light compound systems $^{32}\text{S}^*$ and $^{31}\text{P}^*$ formed in $^{20}\text{Ne}+^{12}\text{C}$ and $^{19}\text{F}+^{12}\text{C}$ reactions, respectively, is studied using the dynamical cluster decay Model (DCM)



of Gupta and collaborators [6, 7] with quadrupole deformations (β_2) and hot, compact optimal orientations of nuclei included. The structure information of CN enters into the model via preformation probability P_0 of the fragments. It is relevant to mention here that the decay of these systems was also studied [8] within the DCM with spherical consideration of the decaying fragments. However, the deformation effects were also included within the description of Süssmann central radii $C_t = C_1 + C_2$, where $C_i = R_i - b^2/R_i$ (in fm) for the decaying fragments, $R_i = [1.28A_i^{1/3} - 0.76 + 0.8A_i^{1/3}][1 + 0.0007T^2]$ fm and surface thickness parameter $b=0.99$ fm. The study clearly points out the competition between FF and DIO in the C-yield of $^{32}\text{S}^*$ whereas it counts only from the CN process for the $^{31}\text{P}^*$ decay.

In the present work we intend to study the deformation and orientation effects in the C-yield of $^{32}\text{S}^*$ and $^{31}\text{P}^*$. For that we have also made calculations for the purely spherical considerations, i.e., with $R_t = R_1 + R_2$, in order to make comparisons. The quadrupole deformation (β_2) and compact optimum orientations lowers the barrier height [9] which effects the FF cross-section σ_{FF} of CN. It has been given in the experimental data that the degree of competition between two classes FF and DIO is co-related with the number of open channels for the decay of light dinuclear system. Large number of open channels favours the occurrence of FF process with regard to mechanism which retain the memory of entrance channel [10].

Within the DCM, an empirical estimate of nCN decay, i.e., σ_{DIO} can be obtained from FF cross-section,

$$\sigma_{DIO} = \sigma_C^{Expt.} - \sigma_{FF}^{DCM}. \quad (1)$$

For nCN process we take $P_0=1$ for the incoming channel, since the target and projectile is considered to have not yet lost their identity.

In this paper, using the DCM for pure spherical consideration as well as deformations and orientations effects included for nuclei, we calculate the C-yield for the decay of $^{32}\text{S}^*$ and $^{31}\text{P}^*$ compound systems. The contribution of competing mechanisms is calculated for explaining the experimental data.

The DCM is briefly described in section 2. The calculations and discussions are given in section 3. The work is summarized and concluded in section 4.

2. The dynamical cluster-decay model (DCM)

The DCM [6, 7] is based on the collective coordinate of mass (and charge) asymmetry $\eta = (A_1 - A_2)/(A_1 + A_2)$ ($\eta_Z = (Z_1 - Z_2)/(Z_1 + Z_2)$), relative separation R , the quadrupole deformations $\beta_{\lambda i}$ ($\lambda = 2$) and orientations of two nuclei and fragments.

Using the decoupled approximation to R - and η -motions, the DCM defines the decay cross section, in terms of partial waves, as;

$$\sigma = \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_c} (2\ell + 1) P_0 P; \quad k = \sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \quad (2)$$

where, P_0 , the preformation probability, refers to η -motion and P , the penetrability, to R -motion, both depend upon angular momentum ℓ , temperature T , deformations $\beta_{\lambda i}$ and compact optimum orientations θ_i [9]. The tunnelling probability P , for each η , is calculated as the WKB integral,

$$P = \exp\left(-\frac{2}{\hbar} \int_{R_a}^{R_b} \{2\mu[V(R, \beta_{\lambda i}, \theta_i, T) - Q_{eff}]\}^{1/2} dR\right), \quad (3)$$

with first and second turning points R_a and R_b . Q_{eff} is the Q-value of the decay process (Fig.1(a) and (b)) and the first turning point is given as: $R_a(T) = R_1(\alpha_1, T) + R_2(\alpha_2, T) + \Delta R(T)$, where $R_i(\alpha_i) = R_{0i}(T)[1 + \sum_{\lambda} \beta_{\lambda i} Y_{\lambda}^{(0)}(\alpha_i)]$ and $R_{0i}(T) = [1.28A_i^{1/3} - 0.76 + 0.8A_i^{1/3}][1 + 0.0007T^2]$.

The P_0 is given by the solution of Schrödinger eqn. in η , at a fixed $R=R_a$, the first turning point for the penetration path for different ℓ -values,

$$\left\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} \frac{1}{\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} + V(\eta, \beta_{\lambda i}, \theta_i, T)\right\} \psi^\nu(\eta) = E^\nu \psi^\nu(\eta) \quad (4)$$

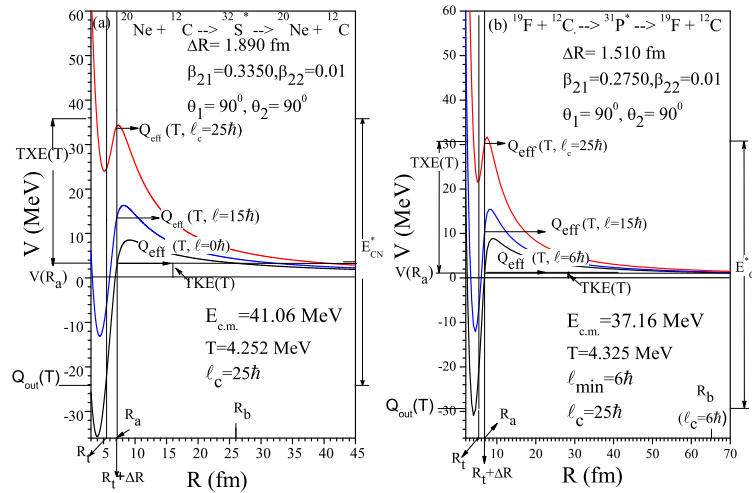


Figure 1. Scattering Potential for (a) $^{32}\text{S}^* \rightarrow ^{20}\text{Ne} + ^{12}\text{C}$, and (b) $^{31}\text{P}^* \rightarrow ^{19}\text{F} + ^{12}\text{C}$, with effects of deformations and optimum orientations included, at different ℓ -values.

with $\nu=0,1,2,3\dots$ referring to ground-state ($\nu = 0$) and excited-states solutions. Then the preformation probability is given by

$$P_0(A_i) = |\psi(\eta(A_i))|^2 \sqrt{B_{\eta}} \frac{2}{A}. \quad (5)$$

For fixed $R=R_a$, the fragmentation potential is given by

$$V(R, \eta, \beta_{\lambda_i}, \theta_i, T) = \sum_{i=1}^2 [V_{LDM}(A_i, Z_i, \beta_{\lambda_i}, T)] + \sum_{i=1}^2 [\delta U_i] \exp\left(-\frac{T^2}{T_0^2}\right) + V_c(Z_i, \beta_{\lambda_i}, \theta_i, T) + V_P(A_i, Z_i, \beta_{\lambda_i}, \theta_i, T) + V_\ell(A_i, \beta_{\lambda_i}, \theta_i, T). \quad (6)$$

The DCM treats all the decay processes as the dynamical collective mass motion of the preformed clusters through the interaction barrier.

3. Calculations and discussions

Figs. 1(a) and 1(b) give the scattering potentials (with the effects of deformations and compact orientations included) at different $\ell(\hbar)$ values for the decay of $^{32}\text{S}^*$ and $^{31}\text{P}^*$, respectively. We notice here that the value of ℓ_{min} (minimum ℓ value at which WKB integral starts contributing) = $6\hbar$ and $0\hbar$ for the decay of $^{31}\text{P}^*$ and $^{32}\text{S}^*$, respectively, in the respective exit channels. Note that, in an earlier study [8], the values for the same were $\ell_{min} = 9\hbar$ and $0\hbar$ for the decay of $^{31}\text{P}^*$ and $^{32}\text{S}^*$, respectively. Interestingly, $\ell = \ell_c (= 25\hbar)$ for both the cases and the barrier does not vanish because these values of angular momentum, due to the general instabilities of the composite system against fission, lies well below the LDM angular momentum limit for which the fission barrier vanishes [11]. It is pointed out here that in an earlier study [8] barriers almost vanished at $\ell = \ell_{max} (= 23\hbar$ and $22\hbar$ for $^{32}\text{S}^*$ and $^{31}\text{P}^*$, respectively). It is relevant to mention here (as also given in the introduction) that this study was carried with the spherical considerations of the nuclei but within the description of Süssmann central radii, which incorporates some deformation effects.

Fig. 2 shows a comparative analysis of preformation probability P_0 plotted at two extreme values at $\ell = 0$ and ℓ_c for the decay of $^{32}\text{S}^*$ and $^{31}\text{P}^*$ formed in entrance channel reactions $^{20}\text{Ne} + ^{12}\text{C}$ and $^{19}\text{F} + ^{12}\text{C}$, having same excitation energy $E_{CN}^* = 60$ MeV with deformations taken

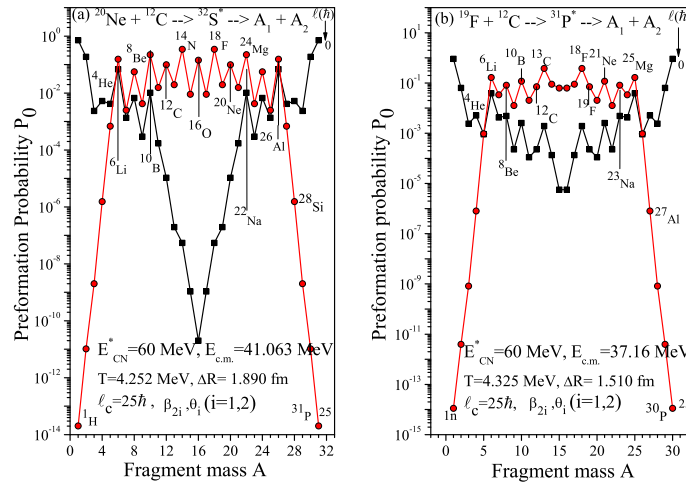


Figure 2. Preformation Probability P_0 as a function of fragment mass A for the decay of (a) $^{32}\text{S}^*$, and (b) $^{31}\text{P}^*$, at different ℓ -values.

upto β_2 and the hot optimum orientations. The preformation probability P_0 of the fragments (before tunnelling through the barrier) accounts for the structure effects in the decay process of the nuclear system. Here, we again observe, like an earlier study [8], that for $^{31}\text{P}^*$ C-yield is very strongly preformed with $A=13$ (closely followed by $A=12$), whereas for $^{32}\text{S}^*$ C-yield with $A=12$ is preformed with very strong competition from other fragments like ^{10}B and ^{14}N . In the calculation we have counted the contributions of σ_{FF} from masses $A=11,12,13$ and $A=12,13$ for the C-yield in the decay of $^{32}\text{S}^*$ and $^{31}\text{P}^*$, respectively. Fig. 3 shows that the P starts

Table 1. The contributions of σ_{FF} and σ_{DIO} summed up to $\ell_c(\hbar)$ for the C – yield (σ_C) from $^{32}\text{S}^*$. Whereas the same from $^{31}\text{P}^*$ have only contribution from σ_{FF} .

System	Parameter	$\ell_c (\hbar)$	$\Delta R_{FF}(\text{fm})$	$\Delta R_{DIO}(\text{fm})$	$\sigma_C (\text{mb})$			
					DCM			Expt.[5]
					FF	DIO	total	
$^{32}\text{S}^*$ $^{31}\text{P}^*$	$C_t + \Delta R$	22	1.35	0.949	49.6	72.1	121.7	122.6
		22	1.30	-	48	-	48	47.92±4.37
$^{32}\text{S}^*$ $^{31}\text{P}^*$	$R_t + \Delta R$ (Sph.)	27	1.685	1.34	72.8	49.1	121.9	122.6
		26	1.460	-	50.4	-	50.4	47.92±4.37
$^{32}\text{S}^*$ $^{31}\text{P}^*$	$R_t + \Delta R$ (Ori.)	25	1.890	1.529	73.2	50.4	123.2	122.6
		25	1.510	-	48.4	-	48.4	47.92±4.37

contributing at higher ℓ -values (it increases very fast upto higher ℓ -values). At ℓ_c it approaches to the maximum value near to one. But P_0 contribute at all ℓ -values, i.e., almost constant for all the ℓ -values.

Table 1 presents the contribution of σ_{FF} and σ_{DIO} for the C-yield, with the different spherical considerations along with that of oriented nuclei, from the compound system $^{32}\text{S}^*$ and the only contribution of σ_{FF} from $^{31}\text{P}^*$. It is very important to point out here that the earlier calculations [8] for the σ_C , with the spherical considerations having Süsmann central

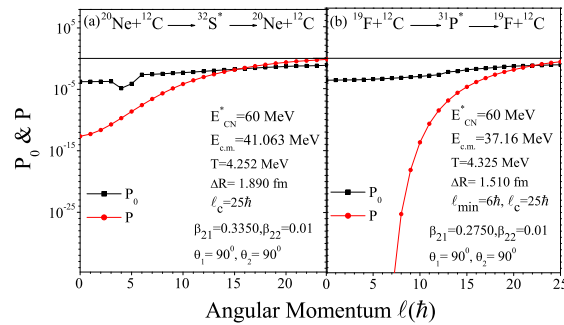


Figure 3. Preformation probability P_0 and Penetration probability P as a function ℓ for the ^{12}C decay of (a) $^{32}\text{S}^*$ and (b) $^{31}\text{P}^*$.

radii $C_t + \Delta R$ incorporating deformation effects, have been improved further while adding the contributions (from σ_{FF} and σ_{DIO}) up to the $\ell=\ell_c$ for the decay of $^{32}\text{S}^*$. Note that the calculated σ_C for the considerations of spherical and oriented nuclei, shows almost similar results with the only difference of the values of neck length parameter (ΔR) having highest values for the consideration of oriented nuclei. The calculated cross-sections show good agreement with experimental data for the different considerations. It will be highly interesting to further extend the the present study to investigate the effect of different excitation energies on the comparative contributions of σ_{FF} and σ_{DIO} in the C-yield of $^{32}\text{S}^*$.

4. Summary and Conclusions

Within the DCM, we have studied the decay of $^{32}\text{S}^*$ and $^{31}\text{P}^*$ at $E_{CN}^*=60$ MeV, having both the considerations of spherical as well oriented nuclei. The comparison of contributions of σ_{FF} and σ_{DIO} in the σ_C from $^{32}\text{S}^*$ have been presented explicitly for these different considerations and the same for $^{31}\text{P}^*$ system as well which is having purely CN decay, i.e., σ_{FF} contributions only. We further plan to extend the study to investigate the contributions of σ_{FF} and σ_{DIO} for C-yield from $^{32}\text{S}^*$ at different excitation energies, as the experiment data for the same is also available. It is relevant to mention here that the calculations based on DCM not only successfully explains the dynamics of reactions under study, but also provide the very significant information about the quantitative contribution of the various processes in the decay of these very light mass compound systems having $A\sim 30$.

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