

## Dynamical decay of $^{32}\text{S}^*$ and $^{31}\text{P}^*$ formed in $^{20}\text{Ne}+^{12}\text{C}$ and $^{19}\text{F}+^{12}\text{C}$ reactions, respectively, at $E_{CN}^* = 60$ MeV

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**Abstract.** The target-like C-yield in the decay of 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 at  $E_{CN}^*=60$  MeV, is studied for the contribution of fusion-fission (ff) decay cross section  $\sigma_{ff}$  and the deep inelastic (DI) orbiting  $\sigma_{orb}$  from the compound nucleus (CN) and non-compound nucleus nCN processes, respectively. The calculations are performed using the collective clusterization of fragments within the dynamical cluster-decay model (DCM) of Gupta and collaborators. Besides studying the competition between ff and DI orbiting phenomenon in the C-yield of these systems, we exclusively investigate the preformation and barrier penetration probabilities  $P_0$  and  $P$  as a function of angular momentum  $\ell$  values which subsequently affects the contributions of  $\sigma_{ff}$  and  $\sigma_{orb}$ . For calculating the contribution of  $\sigma_{ff}$  in the C-yield, we have added the contributions from all the minimized intermediate mass fragments (IMFs) for  $Z=6$  in the calculated fragmentation potentials for  $^{32}\text{S}^*$  (IMFs  $^{11,12,13}\text{C}$  are minimized) and for  $^{31}\text{P}^*$  (IMFs  $^{12,13}\text{C}$  are minimized), while calculating subsequently,  $P_0$  and the  $P$  for these IMFs. The distribution of preformed clusters/fragments as a function of fragment mass visibly explore the nuclear structure effects for the C-yield in decay of these compound systems, wherein, it is shown to be more favoured in the decay of  $^{31}\text{P}^*$  in comparison to  $^{32}\text{S}^*$  decay. The contribution of  $\sigma_{orb}$  to the C-yield is calculated from  $P$  at different allowed  $\ell$ -values (upto  $\ell_{max}$  and also  $P \leq 1$ ) of the outgoing fragments (same as that in the entrance channel, i.e.,  $P_0=1$ ). Though preliminary but useful results indicates the competition between the CN and nCN process in the C-yield for the compound system  $^{32}\text{S}^*$  only while the decay of  $^{31}\text{P}^*$  is of pure CN origin, as observed in the experimental study. The calculations are in good comparison with the available experimental data.

### 1 Introduction

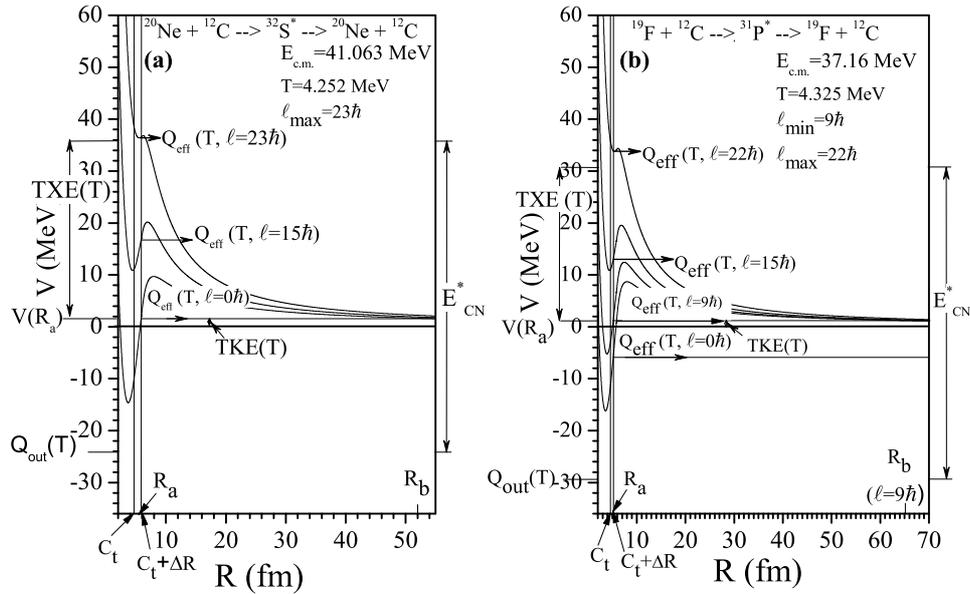
Heavy-ion reactions present novel and interesting features to understand the dynamics of very light mass nuclear systems ( $A \sim 20-30$ ). The processes of fusion-fission (ff) and a deep inelastic (DI) orbiting mechanism are in competition for these systems [1, 2]. In the ff mechanism, a completely equilibrated compound nucleus (CN) is formed, which decays into various exit channels, independent of entrance channel but depending on their masses [3–5], whereas in a deep inelastic (DI) orbiting mechanism a long lived dinuclear molecular system is formed with strong memory of entrance channel which subsequently decays into target-projectile like fragments and contribute  $\sigma_{orb}$  to the overall decay cross section. For a very light compound system, standard rotating liquid drop model (RLDM) predicts strong inhibition of ff mechanism, as compared to DI scattering/ orbiting process [6].

The decay of very light mass compound nuclei  $^{32}\text{S}^*$  and  $^{31}\text{P}^*$  formed in  $^{20}\text{Ne}+^{12}\text{C}$  and  $^{19}\text{F}+^{12}\text{C}$  reactions, respectively, are studied here using the Dynamical Cluster-decay Model (DCM) of Gupta and collaborators [3–5]. In

terms of the barrier picture, a cluster-decay process in this model is in fact a fission process with structure effects of the CN also included via the preformation probabilities  $P_0$  of the fragments. The DCM, based on the concept of preformed-clusters, is shown to be an effective alternative to the statistical Hauser-Feshbach analysis and/ or the statistical fission models for the decay of a hot and rotating compound nucleus.  $^{20}\text{Ne}^*$  is the lightest compound system studied so far, using the DCM [5]. It is highly motivating to investigate the decay of such lighter mass systems for competing reaction mechanisms involved, such as ff and specifically DI orbiting phenomenon, alongwith the role of nuclear structure characteristics in the collision dynamics. It is relevant to mention here that sufficient experimental data is available for these systems [2]. The experimental study has shown that DI orbiting phenomenon is dominant in the decay of  $^{32}\text{S}^*$  for target-like C-yield, in comparison to the decay of  $^{31}\text{P}^*$  for C-yield where ff is prominent.

In the present study we will investigate the decay of  $^{32}\text{S}^*$  and  $^{31}\text{P}^*$  into the intermediate mass fragments (IMFs) having  $Z=6$ , i.e., C-yield only. So instructively, both the compound systems are equally excited at the excitation energy  $E_{CN}^*=60$  MeV, in order to compare their decays. It

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**Figure 1.** Scattering Potential for (a)  $^{32}\text{S}^* \rightarrow ^{20}\text{Ne} + ^{12}\text{C}$ , and (b)  $^{31}\text{P}^* \rightarrow ^{19}\text{F} + ^{12}\text{C}$  decays at different  $\ell$ -values.

is relevant to mention here that in the experimental study [2], both the  $^{20}\text{Ne} + ^{12}\text{C}$  and  $^{19}\text{F} + ^{12}\text{C}$  reactions have been investigated using the number of open channels (NOC) model [7] in which (Table I of [2]) they have pointed out that NOC for the later reaction are much more than in the former one. Hence, the measured C-yield, i.e., the C-yield<sup>Expt.</sup> in the decay of  $^{20}\text{Ne} + ^{12}\text{C}$  is nearly more than double in the decay of  $^{31}\text{P}^*$ . Also the analysis indicates that the enhancement in fragment yield for  $^{20}\text{Ne} + ^{12}\text{C}$  reactions at different centre-of-mass energies  $E_{c.m.}$  cannot be explained by the equilibrium orbiting model [8].

Keeping into view all these facts, it will be quite exciting to study the above noted reactions within the dynamical fragmentation process of the DCM and to evaluate the C-yield in terms of  $\sigma_{ff}$  and  $\sigma_{orb}$ , i.e.,

$$C - \text{yield}^{DCM} = \sigma_{ff} + \sigma_{orb} \quad (1)$$

and their comparison with the C-yield<sup>Expt.</sup> [2]. We also look for the effects of angular momentum alongwith nuclear structure effects in the decay of  $^{32}\text{S}^*$  and  $^{31}\text{P}^*$  into the IMFs having  $Z=6$ . These compound systems are negative  $Q_{out}$ -value systems that means they would decay only if they are produced in heavy ion reactions with compound nucleus excitation energy sufficiently enough so that

$$E_{CN}^* + Q_{out}(T) = TKE(T) + TXE(T) \quad (2)$$

where  $E_{CN}^* = E_{c.m.} + Q_{in}$ ,  $TXE(T)$  and  $TKE(T)$  are, respectively, total excitation energy and total kinetic energy of the outgoing fragments respectively (Fig.1(a), (b)).

In this work, within the DCM, we calculate the C-yield<sup>DCM</sup> in the decay of  $^{32}\text{S}^*$  and  $^{31}\text{P}^*$  compound systems and contributions of  $\sigma_{ff}$  as well as  $\sigma_{orb}$ , whichever is required to fit the experimental data. The DCM is briefly described in Sect. 2. Our calculations and discussion, using the DCM, are given in Sect. 3. The study is concluded and summarized in Sect. 4.

## 2 The dynamical cluster-decay model (DCM)

The DCM [3–5], based on the quantum mechanical fragmentation theory (QMFT), is worked out in terms of the collective coordinates of mass asymmetry  $\eta = \frac{A_1 - A_2}{A_1 + A_2}$  and relative separation  $R$ , which allows to define the decay cross-section, as

$$\sigma = \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_{max}} (2\ell + 1) P_0 P; \quad k = \sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \quad (3)$$

in terms of the partial waves, where the preformation probability  $P_0$  refers to  $\eta$  motion and the penetrability  $P$  to  $R$  motion. With  $\mu = mA_1A_2/(A_1 + A_2)$  the reduced mass and  $\ell_{max}$ , the maximum angular momentum, is defined for light particles LPs ( $A \leq 4, Z \leq 2$ ) cross-section  $\sigma_{LPs} \rightarrow 0$ .

The tunneling/ penetration probability  $P$  is calculated as the WKB integral,

$$P = \exp\left(-\frac{2}{\hbar} \int_{R_a}^{R_b} \{2\mu[V(R, T) - Q_{eff}]\}^{1/2} dR\right), \quad (4)$$

with first and second turning points  $R_a$  and  $R_b$  (Fig.1(a) and (b)). The choice of parameter  $R_a$  in Eq. (4), for a best fit to the data, allows us to relate in a simple way the  $V(R_a, \ell)$  to the top of the barrier  $V_B(\ell)$  for each  $\ell$ .

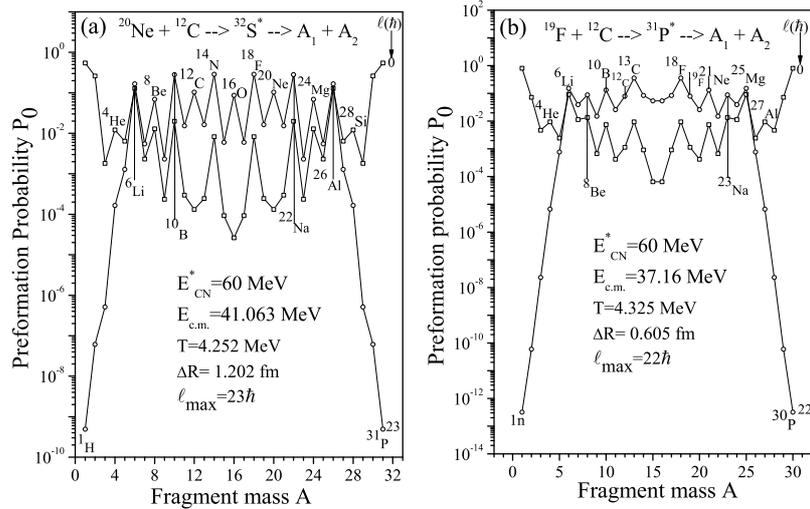
In Eq. (3),  $P_0$ , the preformation probability referring to  $\eta$  motion, contains the structure information of the compound nucleus, and is the solution of the stationary Schrödinger equation in  $\eta$ , at a fixed  $R=R_a$ ,

$$\left\{ -\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} \frac{1}{\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} + V(R, \eta, T) \right\} \psi^\nu(\eta) = E^\nu \psi^\nu(\eta), \quad (5)$$

with

$$P_0(A_i) = |\psi(\eta(A_i))|^2 \sqrt{\frac{2}{B_{\eta\eta} A}}, \quad (6)$$

Here, the mass fragmentation potential  $V(\eta, T)$ , at fixed  $R = R_a$ , is the sum of liquid drop energy  $V_{LDM}$ , shell



**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  $\ell$ -values.

corrections, Coulomb, nuclear proximity and angular momentum dependent potentials  $E_C$ ,  $V_P$ ,  $V_\ell$ , all T-dependent. The mass parameters  $B_{\eta\eta}$ , defining the kinetic energy term in Hamiltonian, are the smooth classical hydrodynamical masses.

The same equation (3) is used for  $\sigma_{nCN}$  or  $\sigma_{orb}$ , calculated as the DI orbiting (orb) process, since incoming nuclei keep their identity, and hence  $P_0=1$ , and then  $P$  is calculated for *incoming channel*.

### 3 Calculations and results

In this section, we present our calculations for the C-yield in the decay of  $^{32}\text{S}^*$  and  $^{31}\text{P}^*$  using the DCM, i.e., C-yield<sup>DCM</sup>. First, we calculate the contribution of  $\sigma_{ff}$  in the decay within dynamical collective clusterization process and compare it with measured contribution (C-yield<sup>Expt.</sup>), and then, if required, the difference will be treated as  $\sigma_{orb}$  ( $=C - \text{yield}^{Expt.} - \sigma_{ff}^{DCM}$ ). This will be fitted by using Eq. (3) for  $P_0=1$  and calculating  $P$  for the fragments taken same as in the entrance channel, i.e., here  $^{20}\text{Ne}+^{12}\text{C}$  for the DI orbiting/ scattering of  $^{32}\text{S}^*$ .

Fig. 2 shows the variation of  $P_0$  as a function of fragment mass  $A$  for the decay of (a)  $^{32}\text{S}^*$  and (b)  $^{31}\text{P}^*$ , at different  $\ell$ -values. Fig. 2(a) clearly shows that the IMF  $^{12}\text{C}$  has strong competition from  $^6\text{Li}$ ,  $^{10}\text{B}$  and  $^{14}\text{N}$  in the decay of  $^{32}\text{S}^*$ , whereas  $^{13}\text{C}$  is strongly favoured (preformed) in the decay of  $^{31}\text{P}^*$  followed by  $^6\text{Li}$ ,  $^{10}\text{B}$  and  $^8\text{Be}$  (Fig. 2(b)). Note that in the calculation for the IMFs decay of  $^{32}\text{S}^*$  for  $Z=6$   $^{11,12,13}\text{C}$  are minimized, whereas for  $^{31}\text{P}^*$  IMFs  $^{12,13}\text{C}$  are minimized for  $Z=6$ . It may be pointed out here that  $^{12}\text{C}$  and  $^{13}\text{C}$  are strongly favoured in the decay of  $^{32}\text{S}^*$  and  $^{31}\text{P}^*$ , respectively. For calculating the contribution of  $\sigma_{ff}$  in the C-yield, we calculate  $P_0$  and the  $P$  for these IMFs, i.e.,  $^{11,12,13}\text{C}$  for  $^{32}\text{S}^*$  and  $^{12,13}\text{C}$  for  $^{31}\text{P}^*$ . Moreover, in general, all the IMFs in the decay of  $^{32}\text{S}^*$  and  $^{31}\text{P}^*$  are favoured at the higher  $\ell$ -values, which is true for the LPs at the lower  $\ell$ -values or vice-versa. The trend for the LPs

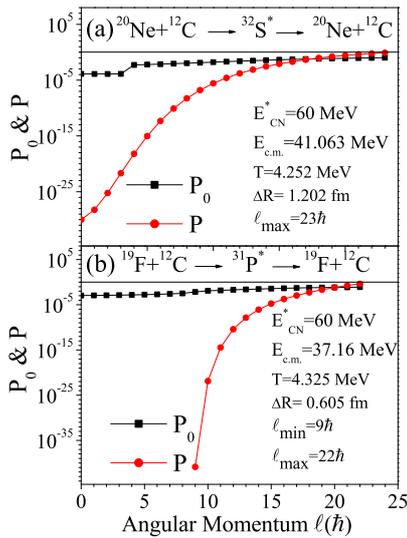
as well as IMFs observed here is in line with that for the light mass compound nuclei [3, 4].

Fig. 1 gives the scattering potential for (a)  $^{32}\text{S}^* \rightarrow ^{20}\text{Ne} + ^{12}\text{C}$  and (b)  $^{31}\text{P}^* \rightarrow ^{19}\text{Ne} + ^{12}\text{C}$ , decays at different  $\ell$ -values. We notice that the value of  $\ell_{min}$  (minimum  $\ell$  value at which WKB integral starts contributing)  $=9\hbar$  and  $0\hbar$  for the decay of  $^{31}\text{P}^*$  and  $^{32}\text{S}^*$  in the respective exit channels. Except for this observation, rest of the features in the dynamical scattering of both the compound systems into the exit channel (same as the entrance channel) are almost similar. Fig. 3 shows the variation of  $P_0$  and  $P$  as a function of  $\ell$  for the decay of (a)  $^{32}\text{S}^*$  and (b)  $^{31}\text{P}^*$  into the respective entrance channel like fragments. Comparatively we find that the  $P_0$  contribute at all the  $\ell$  values (almost constant or increasing slowly/ gradually) whereas  $P$  starts contributing at the higher  $\ell$  values only (increases very fast till higher  $\ell$  values). At  $\ell_{max}$   $P$  approaches the maximum value, i.e., near to one. Here, we have added the contribution of  $\ell$  values upto the  $\ell_{max}$  only while calculating the  $\sigma_{ff}$  for the respective systems, as given in Table. 1, contributing to the C-yield<sup>DCM</sup>.

In Table. 1, we see that the  $\sigma_{orb}$  is very large for  $^{32}\text{S}^*$  whereas its contribution for  $^{31}\text{P}^*$  is nil. Hence, the C-decay of  $^{31}\text{P}^*$  is purely of CN origin. Significantly, the contribution of  $\sigma_{ff}$  in the C-yield<sup>DCM</sup> is similar for both the compound systems  $^{32}\text{S}^*$  and  $^{31}\text{P}^*$ , whereas for the later it is the only contribution. The comparison with C-yield<sup>Expt.</sup> [2] is excellent for the C-yield<sup>DCM</sup> from  $^{31}\text{P}^*$ , whereas for the C-yield<sup>DCM</sup> from  $^{32}\text{S}^*$ , further investigation is called for in order to improve comparison with the C-yield<sup>Expt.</sup>. Note that the present calculations have been performed considering the fragments spherical, the effects of the oriented deformed nuclei will be matter of great interest in the present case specifically to improve the comparison with C-yield<sup>Expt.</sup> from  $^{32}\text{S}^*$ . Moreover, interestingly we see that the values of  $\Delta R$  for the ff of  $^{31}\text{P}^*$  and for the DI scattering/ orbiting of  $^{32}\text{S}^*$  are very close, whereas  $\Delta R$  for the ff of  $^{32}\text{S}^*$  is almost double of these values. It means

**Table 1.** The contributions of  $\sigma_{ff}$  in the CN decay and  $\sigma_{orb}$  for nCN decay calculated as DI orbiting process, summed up to  $l_{max}(\hbar)$  for the C-yield<sup>DCM</sup> of  $^{32}\text{S}^*$ , whereas for the C-yield<sup>DCM</sup> of  $^{31}\text{P}^*$  only  $\sigma_{ff}$  contributes. The experimental data C – yield<sup>Expt.</sup> [2] is also given here for comparisons.

Compound System	Type of Decay	$E_{c.m.}$ (MeV)	T (MeV)	$l_{max}$ ( $\hbar$ )	$\Delta R$ (fm)	$C - yield^{DCM}$		$C - yield^{Expt.}$	
						$\sigma_{ff}$ (mb)	$\sigma_{orb}$ (mb)	$\sigma_{ff} + \sigma_{orb}$ (mb)	$\sigma_{ff} + \sigma_{orb}$ (mb)
$^{32}\text{S}^*$	CN	41.063	4.252	23	1.202	55.85		151.14	
	nCN	41.063	4.252	23	0.619		95.29		122.6
$^{31}\text{P}^*$	CN	37.16	4.325	22	0.605	51.98		51.98	47.92±4.37



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

ff of compound system  $^{32}\text{S}^*$  is the fast process and  $\sigma_{orb}$  is the additional contribution in the C-yield.

#### 4 Summary and Conclusions

We have studied the decay of compound systems  $^{32}\text{S}^*$  and  $^{31}\text{P}^*$ , both at  $E_{CN}^* = 60$  MeV, and calculated  $\sigma_{ff}$  as the dynamical fragmentation process using the DCM. Though preliminary but interesting results point out that the C-yield calculated for these systems is of purely CN origin for  $^{31}\text{P}^*$ , whereas nCN contribution  $\sigma_{orb}$  is evident for  $^{32}\text{S}^*$ . The comparison with the experimental data C-yield<sup>Expt.</sup> [2] is excellent for the C-yield<sup>DCM</sup> from  $^{31}\text{P}^*$  where the only contribution comes from  $\sigma_{ff}$ . However, there is lot of scope to improve the comparison of C-yield<sup>Expt.</sup> with the C-yield<sup>DCM</sup> ( $=\sigma_{ff} + \sigma_{orb}$ ) from  $^{32}\text{S}^*$ . We further plan to study the problem with deformation and orientation effects included for the nuclei. Moreover, the large contribution of  $\sigma_{orb}$  for the C-yield from  $^{32}\text{S}^*$  motivate us to study the decay of the same at other energies

as well for which experimental data is available [2]. Furthermore, the complete study of decay of  $^{32}\text{S}^*$  and  $^{31}\text{P}^*$  into other IMFs will be quite exciting.

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