Dependence of compound nucleus formation probability on K equilibration time in heavy-ion reactions

C. Yadav[1], R. G. Thomas[1], A. K. Mohanty[1], and S. S. Kapoor[2]
[1]*Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai - 400085, INDIA and*
[2]*INSA Honorary Scientist, Bhabha Atomic Research Centre, Mumbai - 400085, INDIA*

The presence of non-compound nucleus fission (NCNF) processes is a major hurdle in the synthesis of heavy and super-heavy elements by heavy-ion fusion reactions [1]. The cross section (σ_{ER}) for heavy element formation via fusion-evaporation is determined by three factors, i)the capture cross section (σ_{cap}), ii)probability of compound nucleus (CN) formation (P_{CN}), and iii) the probability (P_{surv}) that the formed compound nucleus survives equilibrium fission decay through light particles evaporation leading to evaporation residue (ER). While the first and third factors are simpler to calculate, the second factor P_{CN}, is difficult to estimate due to its complex dependence on various parameters viz. mass asymmetry (α), the charge product (Z_1Z_2) and compound nucleus fissility (χ).

The quasifission (QF) process (expected to occur for $Z_1Z_2 > 1600$) and fast-fission (FF) process (due to vanising fission barrier at high angular momentum) are well known contributors for the NCNF processes. However, there is another mechanism which we call pre-equilibrium fission (PEF) [2] in which the contact configuration is inside the fission barrier yet the system can fission before reaching K equilibration by diffusing over the fission barrier height as seen by the system relaxing in the K degree of freedom. PEF is expected only for systems with $\alpha < \alpha_{BG}$ where α_{BG} is the Businaro-Gallone critical mass asymmetry. Recently, attempts have been reported [3, 4] for the extraction of P_{CN} from various fragment angular distribution data on the assumption that compound nucleus fission occurs for $J < J_{CN}$ and quasifission occurs when $J > J_{CN}$ where J is the angular momentum and J_{CN} is a parameter obtained by fitting the angular distribution data. However, for systems with much smaller Z_1Z_2 (~ 1300 and below) and $Z_{CN} < 96$ this assumption cannot be justified. Also the value of P_{CN} were deduced in Ref.[3] using $\frac{\Im_0}{\Im_{eff}} = 1.5$ for quasifission, where $\Im_0$ is the moment of inertia of a spherical nucleus and $\Im_{eff}$ is effective moment of inertia. Another choice of $\frac{\Im_0}{\Im_{eff}}$ would have yielded a different set of P_{CN} values.

In the present work, we have carried out the analysis of fragment anisotropy data [3, 4] of various systems selected for cases $Z_1Z_2 < 1600$ and $Z_{CN} < 96$ so that both QF and FF are absent and the anomalous anisotropies are only due to PEF. It may also be noted that in such cases J_{cr} (the J above which the fusion pocket vanishes) is less than $J_{B_f=0}$ (the J at which the liquid drop fission barrier vanishes) so that all J's will be contributing to PEF as well. According to PEF model, the observed angular anisotropy of fission fragments in heavy-ion induced reactions can be written as an admixture of two components: the anisotropy from compound nucleus fission (CN) and anisotropy due to non-compound nucleus fission (NCN) and is given as follows:

$$A_{exp} = P_{CN}A_{CN} + P_{NCN}A_{NCN} \quad (1)$$

where, A_{CN} is the anisotropy corresponding to compound nucleus fission, A_{NCN} is the anisotropy due to pre-equilibrium fission (fission before K eqilibration) component. P_{NCN} is the probability of non-compound nucleus fission and $P_{CN}(= 1 - P_{NCN})$, the probability of compound nucleus formation. While the anisotropy from compound nucleus fission, A_{CN} is calculated using standard statistical theory [5] ($A_{CN} = 1 + \frac{<J^2>}{4K_0^2}$;where $K_0^2 = T\Im_{eff}/\hbar^2$), A_{NCN} is calculated using a variance σ_K^2 of the K distribution ($\sigma_K^2 < K_0^2$) and is given as $A_{NCN} = 1 + \frac{<J^2>}{4\sigma_K^2}$.

It may be noted that σ_K^2 is the time dependent variance of the entrance channel K distribution starting with a delta function broadening gradually in time with the time evolution of the di-nuclear system. The time dependence of σ_K is given by [6]

$$\sigma_K^2(t) = K_0^2(1 - \exp(-t/t_K)) \tag{2}$$

where t_K is the characteristic K equilibration time. The weighted average value of σ_K^2 is derived as follows:

$$\sigma_K^2 = \frac{\int_0^\infty \sigma_K^2(t)\frac{dN}{dt}dt}{\int_0^\infty \frac{dN}{dt}dt} \tag{3}$$

Here $\frac{dN}{dt}$ is the fission decay rate where $N = N_0 exp(-t/t_f)$ and t_f is the average fission time. After solving Eq.3, the weighted average value of the variance of K distribution is thus obtained as

$$\sigma_K^2 = \frac{K_0^2}{\left[1 + \frac{t_K}{t_f}\right]} \tag{4}$$

From Eq. 1, P_{NCN} can be written as

$$P_{NCN} = \frac{(A_{exp} - A_{CN})}{(A_{NCN} - A_{CN})} \tag{5}$$

Substituting the expressions for A_{NCN} and A_{CN} and after simplification, one obtains

$$P_{NCN}(t_K/t_f) = \frac{(A_{exp} - A_{CN})}{(A_{CN} - 1)} \tag{6}$$

Eq.6 shows that the deviation from the anisotropy expected for CN depends on P_{CN} as well as the ratio t_K/t_f and the value of P_{CN} cannot be obtained by analysis of anisotropy data without knowing the value of t_K/t_f. Thus the unambiguous extraction of P_{CN} requires the knowledge of t_K/t_f. In principle, the evolution of the K distribution is continuous and the effective K distribution for fission events taking place at different times is different. The fission time (t_f) deduced using full fission barrier height may not be valid as PEF takes place from an intermediate potential energy surface and not from the ground state.

In Fig.1, we have plotted $P_{NCN}(t_K/t_f)$ vs entrance channel mass asymmetry α for various systems in the $E_{c.m.}/V_b$ range ~(1.1 - 1.2). It can be seen from the figure that $P_{NCN}(t_K/t_f)$ varies smoothly with mass asymmetry parameter, α. It is also worth mentioning that the decrease in α also corresponds to an increase in χ_{eff}, the entrance channel fissility. Also shown in the figure are cases with $Z_{CN} > 96$ for which the value of $P_{CN} \times t_K/t_f$ are quite different. This may be due to the additional presence of FF and may also be due to a different t_K/t_f value for these cases as compared to other cases with $Z_{CN} < 96$. Based on the above analysis we conclude that reliable values of P_{CN} cannot be infered from the analysis of fission fragment anisotropies as attemted in some earlier work [3, 4].

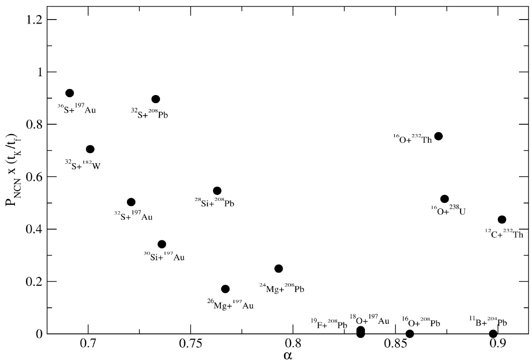

FIG. 1: Plot showing $P_{NCN}(t_K/t_f)$ versus α for various reactions.

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