# Dynamics of heavy-ion induced fusion-fission process using $\alpha$-particle evaporation measurements

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## Introduction

Nuclear fission presents an excellent example of a large-scale re-arrangement of the strongly interacting nucleons in a nuclear system. Heavy-ion induced fusion-fission plays a crucial role in reaching to the island of stability in the super-heavy mass region. Despite the continued intensive research for the last several decades, the heavy-ion induced fusion- fission reveals often surprises. Several fission observables from the direct detection of fission fragments (FFs) such as the mass-distributions, angular-distributions, kinetic energy distribution, and mass-angle correlations deviate the expectations of fission decay from an equilibrated compound nucleus when it is induced by heavy-ion fusion reactions [1]. Traditionally, several terms, such as "quasifission", "pre-equilibrium fission" [2, 3], "slow quasifission" [4], etc. have been associated with aforesaid different observations. However, the underlying mechanism is not very well understood.

It is of significant interest to further investigate the heavy-ion induced non-equilibrium fission via other experimental probes. Among others, the particle emission is also a quite useful probe to learn about the overall complex fission dynamics. During the heavy-ion induced fission, neutron and charged-particle (mainly proton and $\alpha$-particle) emissions take place from various stages namely from the fissioning compound system (pre-scission) and from the accelerated fission fragments (post-scission) [5–8]. Pre-scission neutron and charged particle emission spectra and multiplicities provide important information on the statistical and dynamical aspects of heavy-ion induced fission reactions [6–9]. Using these particle emission probes, it has been firmly established that fission, in general, is a slow process [5, 9, 10]. In case of $\alpha$-particle emission, it is also observed that a part of the pre-scission $\alpha$ particles is emitted very near to the neck region in the fission process just before the scission, and this is referred as the near scission emission (NSE) or ternary emission [6, 11]. The pre- and post-scission $\alpha$ particles obey the kinematics of particle evaporation from a mono-nucleus, but the NSE component has a different emission pattern being preferentially emitted perpendicular to the subsequent scission-axis with a Gaussian energy distribution [6].

Earlier, a systematic study has been carried out for pre- and near-scission $\alpha$-particle multiplicities ($\alpha_{\rm pre}$ and $\alpha_{\rm nse}$) as a function of $Z^2/A$ and the excitation energy of the compound nuclei ($E_{CN}$) for various target-projectile combinations [6]. It is shown that, except for two systems, $\alpha_{\rm pre}$ values when normalized to $E_{CN}^{2.3}$ show a systematic linearly increasing trend with the $\alpha$-particle emission $Q$-value ($Q_\alpha$). Global understanding of the wide range data provides a tool to unravel the underlying physical mechanism. It has also been established that the fraction of $\alpha_{\rm nse}$ remains nearly the same at around 10% of the total pre-scission multiplicity for a variety of heavy-ion reaction partners, populating compound nuclei of different excitation energies. These features of $\alpha_{\rm nse}$ in heavy-ion fission indicate that $\alpha$-particles emitted from the neck region near the scission point are due to the statistical emission process. This is in contrary to the low energy fission where it is a pure dynamical process [12]. This changeover from dynamical to statistical emission suggests that during the actual tearing up of the neck, the nuclear viscosity increases with increasing temperature.

In addition to the multiplicity, one of the very important observables of the near scission emission, is the peak energy ($\epsilon_p$) of the Gaussian energy distribution of the $\alpha$ particles. In the low-energy fission (spontaneous, photo, neutron-induced fission) it is almost constant around 15.5 MeV irrespective of $Z^2/A$ of the fissioning nuclei [12]. But, in heavy-ion fission the $\epsilon_p$ values are very much scattered [13]. It seems from available data that NSE peak energy depends on both, the fissility as well as the excitation energy of the fissioning nucleus. A clear understanding of the NSE peak energy would provide a crucial insight on the scission configuration and nuclear viscosity. In this context it is utmost important to measure the NSE peak energy in the two dimensional space of fissility and the excitation energy.

A systematic study to understand the global

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trend of $\alpha$-particle emission parameters for a wide variety of fissioning systems can provide a detailed physical insight. A significant deviation from the global trend must be carefully addressed. The aforesaid two system which shows significantly lower $\alpha_{\rm pre}$ than the global trend [6] are $^{16}$O + $^{232}$Th [11] and $^{19}$F + $^{232}$Th [14]. In $^{19}$F + $^{232}$Th reactions, the deviation remains the same for several beam energies. In the case of $^{16}$O + $^{232}$Th reaction, the data were available for only at one beam energy of 144 MeV [11], and that shows deviation in $\alpha_{\rm pre}$ of similar magnitude as of $^{19}$F + $^{232}$Th reaction when it is compared with the systematic trend [6]. It is very intriguing that these reactions do not follow the global trend. It is possible that the reaction dynamics is different for these two systems. Previously, the $^{16}$O and $^{19}$F induced fissions of $^{232}$Th have shown very distinct angular anisotropy behavior than the neighboring projectiles, such as, $^{11}$B and $^{12}$C [2]. This trend was attributed to entrance channel dynamical effects related to the Businaro-Gallone mass asymmetry. The entrance channel mass asymmetry parameter, $\alpha$, is more than the Businaro-Gallone critical asymmetry value ($\alpha_{\rm BG}$) for the $^{11}$B and $^{12}$C induced fission. While reaching at $^{16}$O-induced fission, owing to $\alpha < \alpha_{\rm BG}$, the entrance channel mass flow direction flips. The aforesaid phenomenon of pre-equilibrium fission was invoked to explain discontinuous behavior observed in angular anisotropy data.

Very recently, a careful re-measurement of $\alpha$-particle multiplicity in $^{16}$O + $^{232}$Th reaction at a bombarding energy which lies well within the range of discontinuous angular anisotropy data were reported [15]. The pre-scission $\alpha$-particle multiplicity ($\alpha_{\rm pre}$), is observed to be significantly lower than the global trend reported earlier. Statistical model calculations also show a much shorter fission-time to reproduce the experimental $\alpha_{\rm pre}$. By assimilating the previous measurements, it is observed that the $\alpha_{\rm pre}$ makes a changeover from high to a very low value while crossing the Businaro Gallone point in mass asymmetry in the entrance channels in heavy-ion induced fission of $^{232}$Th. This discontinuous behavior is similar to the one observed earlier in fission fragment angular anisotropy data [2]. Observed similarities between the results of $\alpha_{\rm pre}$ and angular anisotropy for the same set of reactions with similar energetics, clearly suggest the role of non-equilibrium fission in $\alpha$-particle multiplicity data. Such a discontinuous behavior has not been observed for the pre-scission neutron multiplicity ($\nu_{\rm pre}$) data. A transition to quasifission is clearly observed in $^{16}$O + $^{238}$U fission at beam energies just below the Coulomb barrier from fission fragment mass and angular distributions, however, the $\nu_{\rm pre}$ does not show any discontinuity with decreasing beam energy [16]. These recent results on $\alpha_{\rm pre}$ demonstrate that it could be a potential probe to gain further insight about the non-equilibrium fission.

It is worth to highlight here that, however, the $\alpha_{\rm pre}$ has been suppressed in systems with $\alpha < \alpha_{\rm BG}$ due to an admixture of non-equilibrium fission, still the fractional $\alpha_{\rm nse}$ remains nearly the same at around 10%. It further strengthens the conclusion made earlier that in heavy-ion induced fission, the emission mechanism for ternary $\alpha$-particles is same as usual pre-scission emission. But, since these are emitted very close to to the neck-rupture stage, they exhibit characteristically different energy and angular distributions.

New insight about the heavy-ion induced fission dynamics obtained using the $\alpha$-particle emission will be presented. Author would like to thank his collaborators and BARC-TIFR Pelletron-Linac facility staff.

## References

[1] A. N. Andreyev, K. Nishio, K-H Schmidt, Rep. Prog. Phys. 81 (2018)016301.

[2] V. S. Ramamurthy, *et al.*, Phys. Rev. Lett. 65 (1990) 25.

[3] R. G. Thomas, *et al.*, Phys. Rev. C 67 (2003) 041601.

[4] T. Banerjee, *et al.*, Phys. Rev. C 102 (2020) 024603.

[5] D. J. Hinde, *et al.*, Phys. Rev. C **39**, 2268 (1989).

[6] Y. K. Gupta *et al.*, Phys. Rev. C **84**, 031603 (R) (2011).

[7] Y. K. Gupta *et al.*, Phys. Rev. C **86**, 014615 (2012).

[8] Y. K. Gupta *et al.*, Phys. Rev. C **98**, 041601(R) (2018).

[9] A. Saxena, *et al.*, Phys. Rev. C 49 (1994) 932.

[10] J. P. Lestone, *et al.*, Nucl. Phys. A 559 (1993) 277.

[11] M. Sowinski,*et al.*, Z. Phys. A- Atoms and Nuclei 324 (1986) 87.

[12] I. Halpern, Annu. Rev. Nucl. Sci. 21, 245 (1971).

[13] Y. K. Gupta *et al.*, Proc. DAE Symp. Nucl. Phys., 64 503(2019).

[14] A. Chatterjee, *et al.*, Phys. Rev. C 52 (1995) 3167.

[15] Y. K. Gupta *et al.*, Phys. Lett. B 834 (2022)137452.

[16] K. Banerjee, *et al.*, Phys. Rev. C 83 (2011) 024605.