Systematics for pre-scission α particle emission in heavy-ion fission

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Introduction

During the heavy-ion fission, neutron and charged-particle emission takes place from various stages namely from the fissioning compound nucleus (pre-scission) and from the accelerated fission fragments (post-scission) [1, 2]. Pre-scission neutron and charged particle emission spectra and multiplicities provide important information on the statistical and dynamical aspects of heavy-ion induced fusion-fission reactions [3]. In case of α-particle emission, a part of pre-scission α-particles is also emitted very near the neck region which is termed as near scission emission (NSE).

Earlier, a systematic study has been carried out for pre-scission α-particle multiplicity (α_{pre}) as a function of Z^2/A and the excitation energy of the compound nuclei (E_{CN}) for various target-projectile systems [3]. It is shown that, except for two systems, α_{pre} values when normalized to $E_{CN}^{2.3\pm0.1}$ show a systematic linearly increasing trend with the α-particle emission Q-value (Q_α) [3].

A significant deviation from the global trend must be carefully addressed. In the earlier systematic study, the α_{pre} values in ^{16}O (144 MeV) + ^{232}Th and ^{19}F + ^{232}Th reactions were significantly lower than the global trend. It is very intriguing to understand the reasons for not following the global trend by these reactions. It is possible that either, there are issues in the data itself, or the particle emission mechanisms are different in these systems, or the method of bringing all the data at equal footing to get a global trend has some limitations.

In addition to the multiplicity, another important observables of the α-particle emission during the fission, is the peak energy (ϵ_p) of the near-scission component. 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 [6]. Constant value of the ϵ_p in the low energy fission indicates increasing pre-scission kinetic energy of the fissioning system with increasing Z^2/A which suggests two-body viscosity during the descent from saddle to just before the scission point. But, the ϵ_p values in heavy-ion fission are very much scattered and do not yield any information about the nuclear viscosity at elevated temperatures. In this context it is utmost important to measure the NSE peak energy in the two dimensional space of fissility and the excitation energy. With these motivations, we have measured the α-particle energy spectra in coincidence with fission fragments for ^{16}O + ^{232}Th reaction at a beam energy of 96 MeV.

Experimental Details

^{16}O beam of 96 MeV was obtained from 14-MV BARC-TIFR Pelletron facility, Mumbai. A self-supporting metallic foil of ^{232}Th ($\sim$1.6 mg/cm^2) was used as the target. The FFs from reaction were detected using two large area Multi-Wire Proportional Counters (MWPCs), placed in folding angle configuration. The MWPCs were placed at 60° and 100° with angular openings of ±15° and ±25°, respectively. Coincidence between two MWPCs defined the fission (single) events. The α particles emitted in the reaction were detected by twelve collimated CsI(Tl)-Si(PIN) detectors, covering a wide range of relative angles of α particles with respect to beam direction and the FFs. Time correlations between the α particles and FFs were recorded. All the CsI(Tl) detectors were energy calibrated periodically during the experiment using ^{229}Th source. Extrapolation of the light yield produced in CsI(Tl) detectors beyond 8.4 MeV was estimated using in-beam data from ear-

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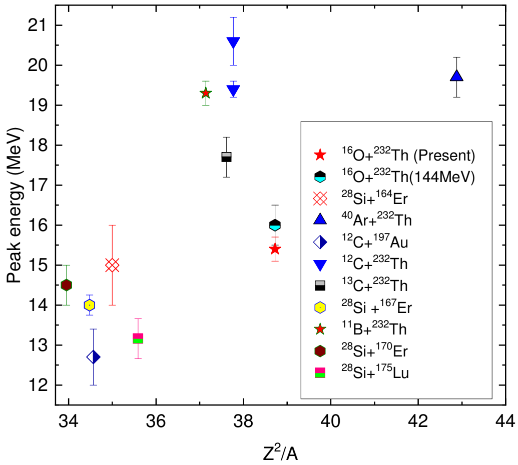

FIG. 1: The peak energies of NSE α-particles as a function of Z^2/A from heavy-ion fission.

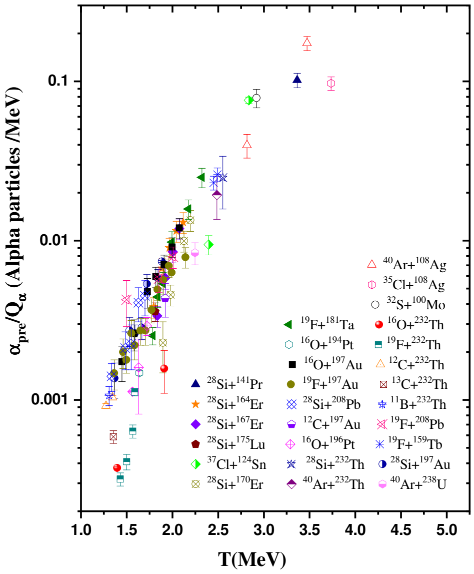

FIG. 2: The α_{pre} normalized with Q_α as a function of compound nucleus temperature.

lier measurements [3–5].

Data Analysis and Results

A Moving Source Disentangling Analysis was carried out including the four usual fusion-fission sources, namely, the compound nucleus (pre-scission), both the FFs (post-scission), and the near scission emission (NSE) [3–5]. The multiplicities corresponding to pre-(α_{pre}), post-(α_{post}), and near-scission (α_{nse}) were obtained respectively to be $(2.4 \pm 0.1)\times10^{-3}$, $(0.06 \pm 0.01)\times10^{-3}$, and $(0.31 \pm 0.02)\times10^{-3}$. The near-scission peak energy (ϵ_p) was determined to be 15.4 ± 0.3 MeV which is similar to the measurements carried out earlier at 144 MeV. Currently available data for the peak energy are shown in the Fig. 1. It seems from available data that NSE peak energy depends on both, the fissility as well as the excitation energy of the fissioning nucleus.

The pre-scission neutron multiplicity (ν_{pre}) for the present reaction was estimated from literature to be 1.57 [7]. Statistical model calculations were carried out using the code JOANNE2 [8]. The experimental ν_{pre} and α_{pre} are reproduced using the transient time (τ_{tr}=9 zs) and saddle to scission time (τ_{ssc}=22 zs). These fission times are in good agreement with widely accepted values. The α_{pre} after normalizing with excitation energy ($E_{CN}^{2.3}$) from present work of 96 MeV coincides with previously reported data of 144 MeV and again deviates from the systematics. These circumstantial evidences indicate to reexamine the procedure adopted for bringing all the data at an equal footing.

A new systematics for the pre-scission α-particle emission has been developed for the heavy-ion fusion-fission data encompassing a wide range of compound nuclear systems. The α_{pre} values after normalizing with α-particle emission Q-value (Q_α) is plotted as a function of initial compound nuclear temperature as shown in the Fig. 2. It presents a more illuminating global behavior of the pre-scission multiplicity and brings a consistency of ^{16}O + ^{232}Th reaction data with the global trend. Interestingly, the new systematics clearly exhibits the effect of neutron excess on the pre-scission α-particle multiplicity. It is noticed that at lower temperatures, the neutron rich systems such as the ^{12,13}C + ^{232}Th, ^{16}O + ^{232}Th, and ^{19}F + ^{232}Th exhibits somewhat lower multiplicities than the global trend. Details of the results in these new contexts will be presented.

References

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

[2] D. Hilscher and D. Rossner, Ann. Phys. (Paris) 17, 471 (1992).

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

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

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

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

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

[8] J. P. Lestone, Phys. Rev. Lett. 70, 2245 (1993).