PROPOSAL FOR EXPERIMENT AT BARC-TIFR PELLETRON-LINAC FACILITY

1^{th} April 2024

TITLE:
Measurement of charged particle emission spectra in $^{12}C + ^{209}Bi$ fission reaction

1 Introduction

Nuclear fission presents an excellent example of tremendous 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 [1, 2]. The complexity of the process is evident from the fact that even after eight decades of research still it often reveals surprises. Several fission observables from the direct detection of fission fragments (FFs) such as the mass-distributions, angular-distributions, mass-angle correlations, and kinetic-energy distributions deviate the expectations of fission decay from an equilibrated compound nucleus when it is induced by heavy-ion fusion reactions [3]. The term, "Non-Equilibrium (NEQ) Fission" is generally used to label such observations. Over the years, several forms, such as "Quasifission" [4, 5, 6], "Pre-Equilibrium Fission" [7, 8, 9, 10], "Slow Quasifission" [11, 12], etc. have been associated with aforesaid different observations, but it is not well established whether the underlying mechanisms are different or they originate from a common dynamic source.

It is, therefore, of significant interest to further investigate the above mentioned closely associated forms of NEQ 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 α-particle) emissions take place from various stages namely from the fissioning compound system (pre-scission) and from the accelerated fission fragments (post-scission) [13, 14, 15, 16, 17, 18, 19, 20, 21]. 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 [22, 23, 16, 17, 18]. Using these particle emission probes, it has been firmly established that fission, in general, is a slow process [22, 23, 24, 25, 26]. In case of α-particle emission, it is also observed that a part of the pre-scission α 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 [16, 25, 27]. The pre- and post-scission α 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 [16].

2 Objective

Very recently, it is shown that the pre-scission α -particle multiplicity 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 [28] as shown in

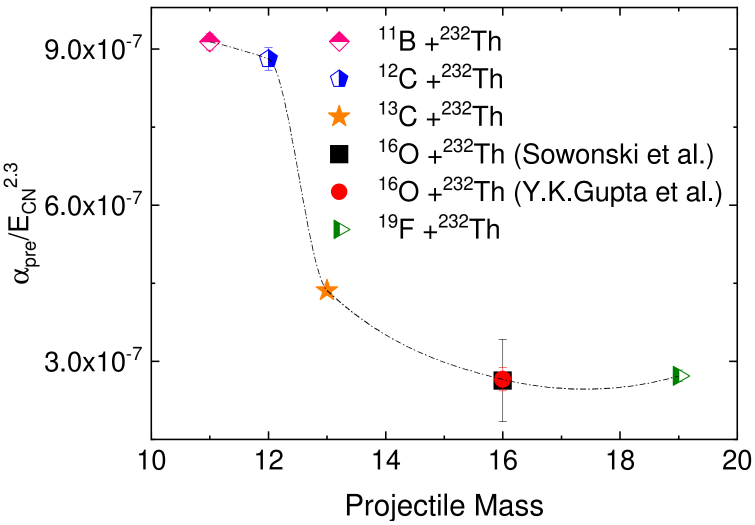

Figure 1: The $\alpha_{\rm pre}$ normalized with $E_{CN}^{2.3}$ as a function of projectile mass in heavy-ion induced fission of ^{232}Th. The $\alpha_{\rm pre}$ data for ^{11}B [16], ^{12,13}C [17, 18], ^{16}O (144 MeV, 96 MeV) [27, 28], and ^{19}F [29] induced fissions were taken from previous measurements. In case of ^{12}C and ^{19}F induced fission, it is a weighted average of different energy data points. Here, E_{CN} is the excitation energy of the initial compound nuclear system. The dash-dotted line is a guide to eye.

Fig.1. Similar discontinuous behavior was observed earlier in fission fragment angular anisotropy data [7]. While the measured anisotropies in ^{11}B and ^{12}C-induced fission were found to be in agreement with the predictions of the standard Halpern-Strutinsky theory, they were anomalously large in the case of ^{16}O and ^{19}F induced fission. In a latter work [10] from the measurements of ^{13}C induced fission, it was shown that the discontinuity in the angular anisotropy data is gradual instead of a sharp one, which is exactly similar as observed in our recent work. These results have been explained in terms of entrance channel dynamical effects related to the Businaro-Gallone mass asymmetry ($\alpha_{\rm BG}$). It is proposed that in going from highly asymmetric to more symmetric systems, the entrance channel mass flow direction is reversed at a certain point and the compound nucleus formation passes through a di-nuclear configuration. In entrance channels with $\alpha < \alpha_{\rm BG}$, the fissioning nucleus separates prematurely when the fission barrier (B_f) becomes comparable to the temperature (T).

In the aforesaid work, beams ^{11}B, ^{12,13}C, ^{16}O, ^{19}F were bombarded on ^{232}Th target to study the entrance channel mass asymmetry effect on pre-scission α particle multiplicity. The excitation energies for all the five heavy-ion induced reactions, selected for the comparison of $\alpha_{\rm pre}$, lie in the range of 45 to 100 MeV, which is the similar range where the discontinuity in angular anisotropy data has been observed. Moreover, the ratio, B_f/T for all these fissioning systems, is in the range of 0.6 to 1.6. Observed similarities between the results of $\alpha_{\rm pre}$ and angular anisotropy for the same set of reactions with similar energetics, point towards the role of non-equilibrium fission in α-particle multiplicity data. Such a discontinuous behavior has not been observed for the pre-scission neutron multiplicity ($\nu_{\rm pre}$) data. Rather, it is shown in Fig. 7 of Ref. [23] that the $\nu_{\rm pre}$ after normalizing with $E_{\rm CN}$ remains almost the same over a wide fissility range. Insensitivity of the $\nu_{\rm pre}$ with respect to non-equilibrium fission has been observed in an another work also [33]. 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 [33]. It is conjectured that characteristic times for neutron emission is much smaller than the α-particle emission, making it to be insensitive to the non-equilibrium fission.

It is quite legitimate to investigate if such a discontinuous behavior of $\alpha_{\rm pre}$ is expected in lower mass regions also or it is limited only in the heavy mass region only? In the heavier mass region, the neutron richness of the composite systems populated through heavy-ion fusion reactions is on the higher side, making neutron emissions to be more favorable. The isospin parameter $I = (N - Z)/A$ is a good indicator of neutron richness. In ^{11}B, ^{12}C, ^{13}C, ^{16}O, and ^{19}F induced fission of ^{232}Th, using which the aforesaid discontinuous results were obtained, the parameter I is close to 0.215. It would be of significant interest to investigate the above discussed discontinuous behavior using the same beams but a lower mass target. The next possible lower mass feasible nucleus than ^{232}Th is ^{209}Bi. Using ^{209}Bi as the target and any of the beams from ^{11}B, ^{12}C, ^{13}C, ^{16}O, and ^{19}F, the charged particle multiplicities have not been measured so far. The isospin parameter, I for the ^{209}Bi target with above beams would be around 0.19. Similar to the ^{232}Th target, for ^{209}Bi also, the entrance channel mass asymmetry parameter, α is greater than the $\alpha_{\rm BG}$ for ^{11}B and ^{12}C beams whereas it is opposite direction for ^{16}O and ^{19}F beam. Therefore, it would be very interesting to measure the α-particle multiplicity spectra in ^{11}B, ^{12}C, ^{13}C, ^{16}O, and ^{19}F induced fission of ^{209}Bi. In order to reduce the systematic uncertainties and infer about any possible entrance channel effect it is desirable to get the data at least for two/three reactions using the same experimental set-up. With this motivation, we propose here to measure the charged particle multiplicity spectra in ^{12}C+^{209}Bi fission reaction.

3 Details about the experimental setup

A typical experimental setup which we have been using for the measurements of α-particle multiplicity spectra is shown in the Fig. 2. A metallic foil of ^{209}Bi deposited on a carbon backing will be used as the target. Fission fragments (FFs) produced in the reaction will be detected using four large area Multi-Wire Proportional Counters (MWPCs) [30], placed in folding angle configuration. Fission events will be separated from other reaction products by plotting cathode pulse heights from one MWPC against the other. Sixteen CsI(Tl) detectors will be used for the detection of charged particles. Pulse shape discrimination using zero crossover as well as ballistic deficit techniques will be employed to identify different charged particles. Energy calibration of the CsI(Tl) detectors up to 8 MeV will be carried out using ^{229}Th α-source. It will be extended in the higher energy region up to around 25 MeV using ^{12}C(^{12}C, α)^{20}Ne reaction. Additional one day beam time will be required for the in-beam energy calibration.

3.1 Beam energy calculation

The fusion barrier for ^{12}C+^{209}Bi reaction is 62.9 MeV (lab frame). Beam energy as much above the barrier as possible is desirable because pre-scission α-particle multiplicity increases non-linearly with excitation energy of the composite system. At present 75 MeV ^{12}C beam with a decent current is feasible from Pelletron accelerator facility. The 75 MeV energy of ^{12}C would correspond to an excitation energy of around 38 MeV

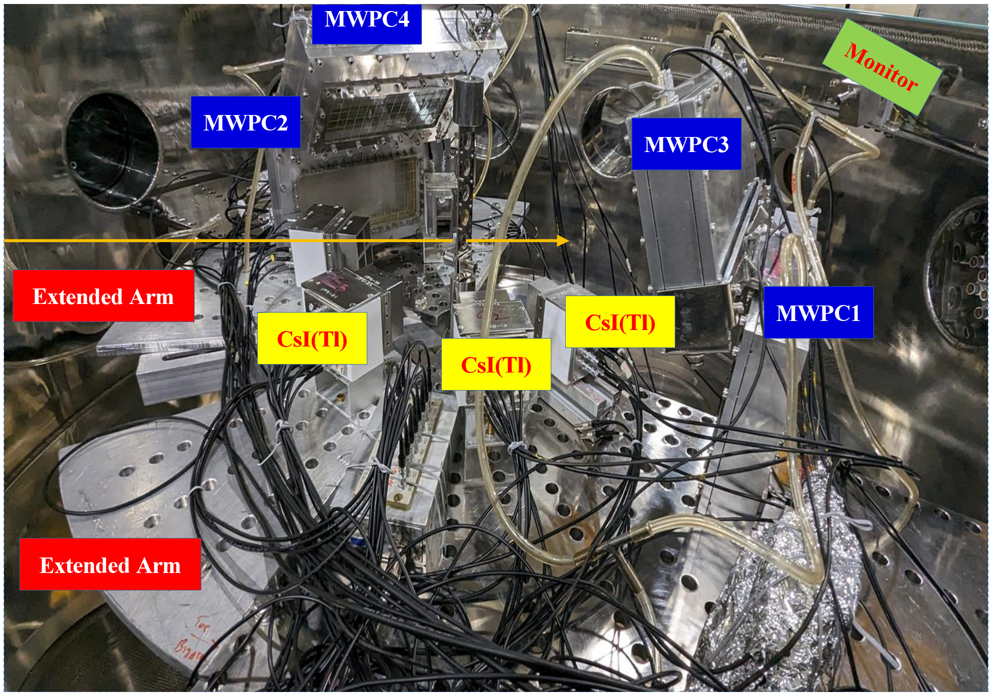

Figure 2: A typical experimental setup for the measurements of charged particle multiplicity spectra in heavy-ion fission reactions.

of the compound nucleus populated with ^{209}Bi target. This excitation energy would be in the close proximity of the energy bracket of the reactions studied with ^{232}Th target which demonstrated the signature of non-equilibrium fission from pre-scission α-particle multiplicity.

3.2 Target Preparation

A self supporting target of ^{209}Bi with a thickness of 1.5 mg/cm^2 target would be prepared at TIFR target lab using the evaporation technique.

4 Estimate of the beam-time duration

The experiment will be carried out in general purpose scattering chamber in Linac Hall-1. Four MWPCs will be used in the folding angle configuration for the fission fragment detection. Sixteen CsI(Tl) detectors will be used for charged particle detection at several angles with respect to the beam direction. Detailed calculations about the beam time estimate is depicted in the Fig. 4. The fission cross-section of the ^{12}C + ^{209}Bi reaction was measured at various beam energies by JIN Gen-Ming et al. [34]. We utilized this fission cross-section data and re-plotted it as a function of beam energy in the laboratory frame, as depicted in Figure 3. Based on this fission cross-section and considering low particle multiplicities, approximately 5 days of beam time would be necessary to accumulate around 1000 counts in a single CsI(Tl) detector. Additionally, one day of beam time would be required for energy calibration using DC beam of ^{12}C with 25 MeV.

RUNNING TIME:

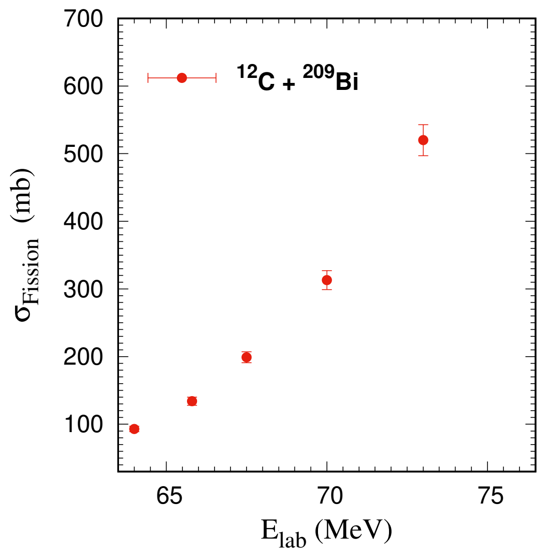

Figure 3: Fission cross section corresponding to the ^{12}C+^{209}Bi reaction at different ^{12}C beam energy using mica detector[34].

Beam energy (MeV)	75	
Excitation energy of CN (MeV)	38	
nano	1.00E-09	
e	1.60E-19	
nano/e	6250000000	
1mbarn	1.00E-27	
Effective solid angle for fission events (sr)	0.156	
Solid angle of one CsI detector (sr)	0.029	
Pre-scission Alpha Particle Multiplicity	3.01E-03	From Systematics
pi	3.14E+00	
Target Thickness(g/cm^2)		0.0015
avogadro's number (Av no)		6.02E+23
Reaction		12C + 209Bi
Target Mass number (A)		209
no of atoms in the target per cm^2 (Nt)	(Av no * target thicknes'	4.32211062201E+18
Charge state		6
Beam current (pnA)		2
Beam current(nA)		12
Incident particle per second on Target(Ni)	Beam Current(pnA)/e	01.25E+10
Fission cross section(mb) (sigma) (PACE4)		500
Total number of fission event per second in 4pi	Ni*Nt*sigma	2.7013E+04
Total no of fission event per second in 1 MWPC		3.3534E+02
Per fission no of alpha particle in one CsI detector	Alpha(pre)*SA/4pi	6.9469E-06
No of alpha-particles in one second		2.3296E-03
Requred no of alphas particles in coincidence		1000
Time requred for this much alpha counts in second		429260.32
Time requred for this much alpha counts in days		4.97
Total Days Required		**5 Days**

Figure 4: Beam time estimates for the α -particle multiplicities in ^{12}C + ^{209}Bi reaction.

Beam on Target	5 days
Energy calibration	1 day
Total beam time request	6 days

It is to be noted that both the experiments for charged particle multiplicity measurements in ^{209}Bi fission induced by ^{11}B (PI: Nidhi Sirswal) and ^{12}C (PI: Pawan Singh) will be executed in a same experimental setup. Therefore, it is requested to schedule both the beam times in the same cycle one-after another.

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