STUDY OF ENTRANCE CHANNEL EFFECTS ON FUSION–FISSION AND QUASI-FISSION PROCESSES*

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We have studied the mass distribution of ^{256,260}Rf compound nuclei produced in the ^{48}Ti + ^{208}Pb and ^{28}Si + ^{232}Th reactions at an excitation energy of 57 MeV. The results confirmed the presence of quasi-fission processes in the ^{48}Ti + ^{208}Pb system and a non-negligible contribution in the ^{28}Si + ^{232}Th system. The observed mass distributions of the fission fragments are also compared with the predictions from dinuclear system calculations.

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1. Introduction

One of the key activities in the field of nuclear research involves the exploration of nuclei beyond the naturally existing nuclear landscape. Nuclear fusion reactions are used to synthesize super-heavy nuclei. Fusion-fission and quasi-fission processes constitute the dominant decay channels for heavy and super-heavy nuclei [1, 2]. The reaction dynamics of heavy and super-heavy nuclei is scrutinized extensively by investigating the competition between fusion–fission and quasi-fission processes. Signatures of these processes are confirmed through different experimental probes such as fission fragment angular distribution, mass distribution, mass–energy distribution, and mass-gated neutron multiplicity. However, the sensitivity of

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these kinematic variables is limited as the mass symmetric region may be populated both by the fusion–fission and quasi-fission processes. The role of entrance channel effects (deformation, orientation, and shell effects of colliding partners) on the fusion–fission and quasi-fission processes is used to explore the properties of these processes [3–5]. These studies shed light on the reaction dynamics and evolution of several degrees of freedom in the compound nucleus. This further helps in the selection of the proper target, projectile, and bombarding energy to maximize the formation probability of super-heavy nuclei. With this motivation, we have performed a complete fission study for ^{256,260}Rf compound nuclei formed in the ^{48}Ti+^{208}Pb and ^{28}Si+^{232}Th fusion reactions at the excitation energy ranging from 57 MeV to 85 MeV. The choice of these reaction systems offers a possibility of comparing the fission dynamics of different isotopes of Rf nuclei, and to study the role of entrance channel deformation and shell effects on the fusion–fission and quasi-fission processes. In the current work, we are reporting the results from the experiments performed for the aforementioned reactions using the National Array of Neutron Detectors (NAND) array [6] at Inter-University Accelerator Centre (IUAC), New Delhi.

2. Experimental details

The experiments were performed using a pulsed beam of ^{48}Ti and ^{28}Si from the 15UD Pelletron + LINAC accelerator facility at IUAC. The experimental details for the ^{48}Ti+^{208}Pb reactions were given in Ref. [7]. For the second experiment, ^{28}Si beam (current = 0.9 pnA and repetition rate = 250 ns) with the laboratory energy of 159.4 MeV was bombarded on thin ^{232}Th target of thickness of 130 μg/cm^2 with carbon backing (20 μg/cm^2). To reduce the shadowing of fission detectors, the target ladder was kept at an angle of 15° with respect to the beam axis. Fission fragments were detected using two large area position-sensitive multiwire proportional counters (MWPCs) (16.26 cm × 11.18 cm) [8]. For both the reactions, MWPCs were installed in the forward and backward directions at respective folding angles and optimized distances from the target.

The beam flux was monitored using two silicon surface barrier detectors (SSBD), kept at ±12.5° with respect to the beam direction. The experimental arrangements inside the target chamber are shown in figures 1 and 2. Fission fragments detected in any of the MWPCs in coincidence with the radio frequency were used as a trigger for the list mode data collection with the acquisition software LAMPS [9].

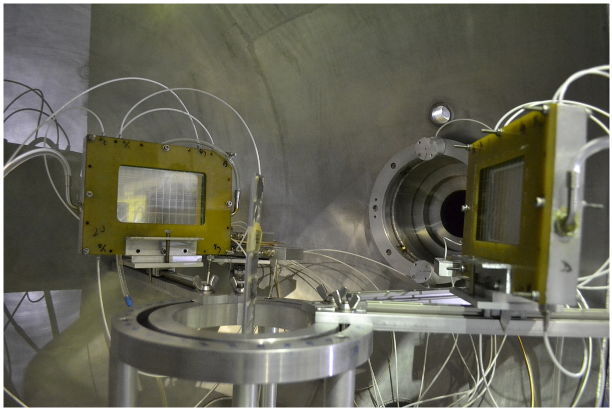

Fig. 1. Inside view of the target chamber depicting detector arrangement for the ^{48}Ti+^{208}Pb reaction.

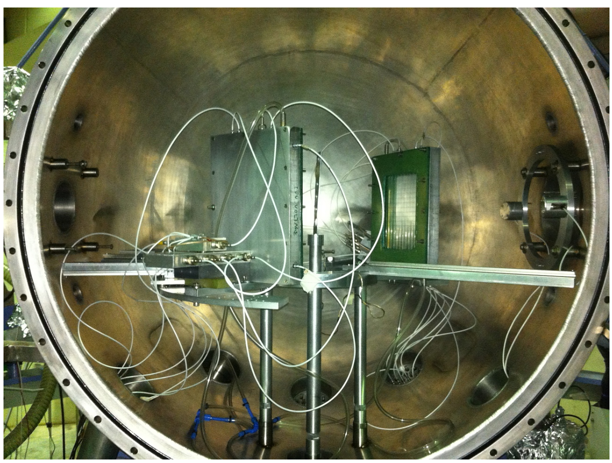

Fig. 2. Inside view of the target chamber depicting detector arrangement for the ^{28}Si+^{232}Th reaction.

3. Results and discussion

In the present article, the mass distribution is measured for near superheavy compound nuclei ^{256,260}Rf at an excitation energy of 57 MeV with an aim to distinguish the quasi-fission and fusion–fission processes. For both the ^{48}Ti+^{208}Pb and ^{28}Si+^{232}Th systems, the mass distribution analysis was carried out using the Time-of-Flight (TOF) method [7]. The fragment velocities in the center-of-mass frame were calculated from the corrected velocities in the laboratory frame using kinematic transformations. The velocity vectors were decomposed into two components: one in the direction parallel to the beam ($v_{||}$) and other in the direction perpendicular to the beam ($v_{\perp}$). Figures 3 and 4 illustrate the two-dimensional distribution of reconstructed $v_{||}/v_{\rm cm}$ *versus* $v_{\perp}$ for ^{48}Ti+^{208}Pb and ^{28}Si+^{232}Th reactions, respectively, which indicate the presence of a larger fraction of events from full momentum transfer in the ^{28}Si+^{232}Th system as compared to the ^{48}Ti+^{208}Pb system. The measured mass distribution is shown in figure 5 for the ^{28}Si+^{232}Th reaction.

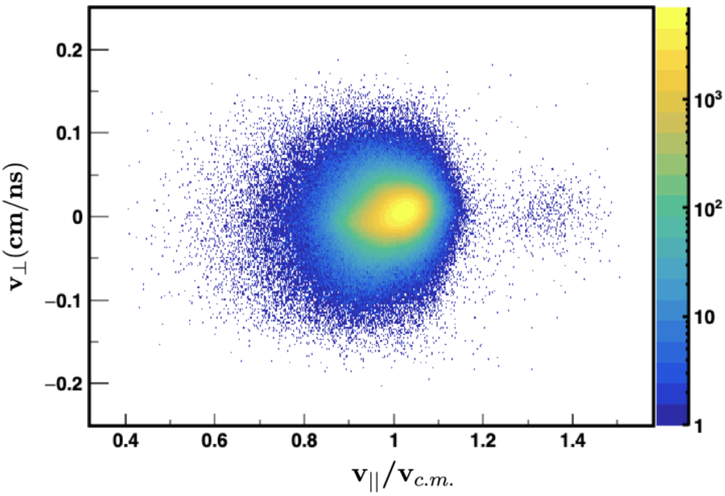

Fig. 3. The two-dimensional distribution of $v_{||}/v_{\rm cm}$ *versus* $v_{\perp}$ for the ^{48}Ti+^{208}Pb reaction.

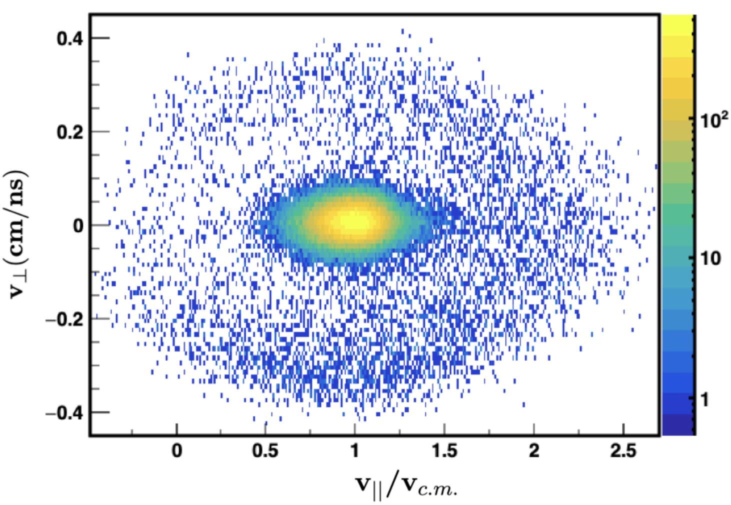

Fig. 4. The two-dimensional distribution of $v_{||}/v_{\rm cm}$ *versus* $v_{\perp}$ for the ^{28}Si+^{232}Th reaction.

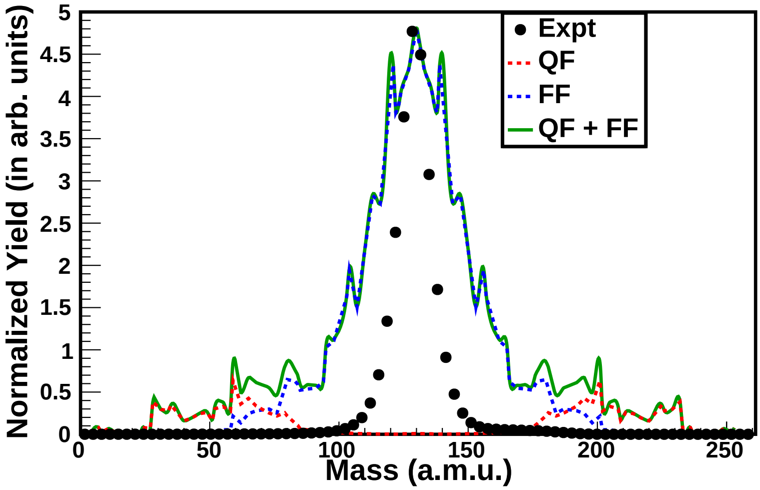

Fig. 5. Mass distribution for the ^{28}Si+^{232}Th system.

The extracted FWHM of mass distribution for the ^{28}Si+^{232}Th system (16 amu) is significantly smaller as compared to the value reported for the ^{48}Ti+^{208}Pb reaction (65 amu) in Ref. [7]. This indicates larger contribution from the fusion–fission process in the ^{28}Si+^{232}Th system than that for the ^{48}Ti+^{208}Pb owing to the larger entrance channel charge product (Z_1Z_2, where Z_1 and Z_2 are the atomic numbers of projectile and target nuclei respectively) for the ^{48}Ti+^{208}Pb reaction as compared to the one for the ^{28}Si+^{232}Th reaction. It is also validated through cross-section predictions from the dinuclear system (DNS) calculations [7, 10], which shows the absence of strong hindrance to complete fusion for the silicon-induced reaction. For the ^{48}Ti+^{208}Pb reaction, the presence of non-compound nuclear processes is evident from the comparison of the experimental results with the DNS calculations, which predicts $\sim 35\%$ contribution from the quasi-fission processes. For the ^{28}Si+^{232}Th system, the DNS calculations are in progress and preliminary calculations as shown in Fig. 5 are indicating no overlap of yield of the quasi-fission and fusion–fission processes in a symmetric region. Besides this, it is also showing that the DNS calculations give a larger mass width than the experimental one. This discrepancy could be resolved in the future by incorporating the contribution of the different orbital angular momentum and orientation angles in the DNS calculations. The reported results suggest that the entrance channel charge product effects play a more important role than the entrance channel deformation for the present study.

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REFERENCES

[1] D.J. Hinde *et al.*, *Phys. Rev. C* **53**, 1290 (1996).

[2] M.G. Itkis *et al.*, *EPJ Web Conf.* **17**, 12002 (2011).

[3] D.J. Hinde *et al.*, *Phys. Rev. Lett.* **89**, 282701 (2002).

[4] B.B. Back *et al.*, *Phys. Rev. C* **53**, 1734 (1996).

[5] R. Rafiei *et al.*, *Phys. Rev. C* **77**, 024606 (2008).

[6] P. Sugathan *et al.*, *Pramana* **83**, 807 (2014).

[7] Meenu Thakur *et al.*, *Eur. Phys. J. A* **53**, 133 (2017).

[8] A. Jhingan *et al.*, *Rev. Sci. Instrum.* **92**, 033309 (2021).

[9] R. Ruby Santhi, A. Chatterjee, in: Y.K. Gupta, P.C. Rout, L.M. Pant, B.K. Nayak (Eds.) «Proceedings of the 64$^{\text{th}}$ DAE Symposium on Nuclear Physics», Vol. 64, University of Lucknow, India, 23–27 December, 2019, p. 928.

[10] A. Nasirov *et al.*, *Eur. Phys. J. A* **49**, 147 (2013).