ENTRANCE CHANNEL EFFECTS ON FISSION FRAGMENT MASS DISTRIBUTION IN ^{12}C+ ^{169}Tm SYSTEM*

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With an aim to study different aspects of heavy-ion induced reactions following the evolution of compound nucleus formed via complete and/or incomplete fusion, the production cross sections of evaporation residues and fission-like fragments were measured in ^{12}C+^{169}Tm reaction at $E_{\rm lab} = 77.18$, 83.22, and 89.25 MeV. The recoil-catcher activation technique followed by offline γ spectroscopy was employed to measure the cross sections. Herein, we present the production cross sections of 26 fission-like fragments identified in this work. An attempt has been made to study the isotopic yield distribution and the mass distribution of fission-like fragments to discern various reaction mechanisms. The mass distribution of fission-like fragments was found to be symmetric and broad substantiating their formation from compound nuclear processes. The mass variances (σ_M^2) has been found to increase monotonically with excitation energy above the Coulomb barrier for deformed ^{169}Tm target, and with increase in mass asymmetry of the system.

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1. Introduction

The heavy-ion (HI) induced reactions have been extensively investigated over the last few decades as they offer a drastic rearrangement of nucleons in a many-body system [1]. HI-induced reactions have some peculiar characteristics: *(i)* since both the interacting partners are HIs, therefore, the projectile needs sufficient incident energy to overcome the Coulomb barrier; *(ii)* HIs carry high input angular momentum in the entrance channel which leads to the population of high spin states in composite nuclei, and *(iii)* formation of compound nucleus (fusion reactions), direct reactions and deep inelastic collisions (DIC) or incomplete fusion (ICF) reactions, an intermediate between compound nucleus and direct reactions. At low incident energies, complete fusion (CF) [2] is a dominating mode of reaction in which the entire projectile coalesces with the target nucleus with all the nucleonic degrees of freedom. However, it has been found that the incomplete fusion [3], in which the projectile fuses partially with target leading to the formation of incompletely fused composite, onsets at slightly above barrier energies. The linear momentum transferred in ICF reactions is found to be less than that in CF reactions [4]. The excited compound nucleus, formed in CF and/or ICF reactions, subsequently decays via light nuclear particle(s) and characteristic γ rays leading to the formation of evaporation residues.

It is pertinent to mention here that the compound nucleus formed via complete and/or incomplete fusion may also proceed towards fission, the *fusion–fission process*, depending upon the available excitation energy and other entrance channel parameters such as mass-asymmetry ($\mu = \frac{M_{\mathrm{T}}-M_{\mathrm{P}}}{M_{\mathrm{T}}+M_{\mathrm{P}}}$), deformation of interacting nuclei, *etc.* The final reaction products may be populated via the emission of light nuclear particle(s) and characteristic γ rays from the fission fragments [5]. Over the last few decades, the phenomenon of nuclear fusion–fission with heavy ions has been prodigiously investigated for a wide range of fissility, excitation energy, and target deformation [6–8]. It has been observed that the variance (σ_M^2) of fission fragments mass distribution in fusion–fission reactions is strongly dependent on target deformation. For spherical targets, the variance is rather narrow, and varies smoothly with the excitation energy (E^*), while for deformed targets, particularly above the Coulomb barrier, the (σ_M^2) is broader, and increases monotonically with E^* [8]. Although a large amount of cross-section data has been generated in light- and heavy-ion induced reactions on highly fissile actinide targets, yet there is a dearth of comprehensive understanding of underlying dynamics in the pre-actinide region. In an effort to investigate different aspects of heavy-ion induced fission in pre-actinide region, we measured the production cross sections of fission-like events in ^{12}C+^{169}Tm reaction at low incident energies *i.e.*, $E_{\mathrm{lab}}/A \approx 6.3$, 6.9, and 7.4 MeV/nucleon.

2. Experimental procedure, results and discussion

The experiments were performed at the Inter-University Accelerator Center (IUAC) New Delhi, India using the pelletron accelerator facilities. The measurements were carried out with the beams of ^{12}C ($E_{\rm lab}$ = 77.18, 83.22, and 89.25 MeV) bombarded on deformed ^{169}Tm target ($\approx$ 900 μg/cm^2). An Al foil of sufficient thickness was kept behind the target to stop the recoiling products. The production cross sections of evaporation residues populated via complete and/or incomplete fusion and fission-like fragments were measured using recoil-catcher activation technique followed by offline γ spectroscopy. The evaporation residues were identified by their characteristic γ rays and validated by decay curve analysis. In this communication, we report the 26 fission-like residues identified at different energies. Decay γ lines assigned to these residues along with other spectroscopic properties are given in Table I. The details of the experiment and data analysis are delineated in Ref. [9].

TABLE I

List of fission-like fragments identified in the present work.

E_γ [keV]	I_γ [%]	Nuclide	Half-life [$T_{1/2}$]	E_γ [keV]	I_γ [%]	Nuclide	Half-life [$T_{1/2}$]
728 634.8	35.6 91.2	^{74}Br^m	46 min	201 947.7	96.4 10	^{87}Zr ^{89}Rb	1.68 h 15.15 min
202.98	18	^{74}Kr	11.50 min	266.9	7.4	^{93}Y	10.18 h
286	88	^{75}Br	96.7 min	367.2	75	^{94}Ru	51.8 min
264	11.4	^{75}Ge	82.78 min	336.4	69.9	^{95}Ru	1.64 h
154.6	21.1	^{75}Kr	4.29 min	657.8	98.2	^{97}Nb	72.1 min
315.7	39	^{76}Kr	14.8 h	787.4	93.4	^{98}Nb^m	51.3 min
146.59	37	^{77}Kr	74.4 min	306.83	89	^{101}Tc	14.02 min
613.8	54	^{78}As	90.7 min	630.2	16.1	^{102}Tc^m	4.35 min
668.1	23.4	^{79}Rb	22.9 min	358	89	^{104}Tc	18.3 min
443.3	17	^{81}Sr	22.3 min	941.6	25	^{104}Ag	69.2 min
881	98	^{84}Br	31.76 min	159	10.2	^{105}Tc	7.6 min
454	40	^{85}Zr	7.86 min	131.47	41.3	^{105}In	5.07 min
627.7	32.6	^{86}Y	14.74 h				

2.1. Isotopic yield distribution

Charge distribution studies entail the analysis of distribution of nuclear charge between two complimentary fission fragments for a given mass split of the composite system undergoing fission. These studies are performed by measuring the independent yields of the members of isobaric chain (isobaric yield distribution), or isotopes of a particular element (isotopic yield distribution). The isobaric yield distribution is determined by (*i*) the most probable atomic number (Z_p) for the fission product which has the highest yield among all the products of given mass chain A, and (*ii*) the fractional yield for an isotope obtained by dividing the yield of the isotope by the total yield of mass chain. In order to obtain the most probable atomic number (Z_p) and width of the distribution (σ_Z), at least three members of the isobaric mass chain are required. Since it is difficult to measure three independent yields in an isobaric chain, the charge distribution parameters are evaluated using the isotopic yield distribution. In the present studies, this approach has been used to obtain charge distribution parameters using experimentally measured yields of Kr and Tc isotopes. As a representative case, the isotopic yield distribution of Kr and Tc isotopes at $E^* \approx 69$ MeV corresponding to $E_\mathrm{lab} = 89.25$ MeV is shown in Fig. 1 (a) and (b), respectively. The variance of isotopic yield distribution (σ_A^2) is estimated to be 3.90 ± 0.20 for Kr isotopes and 3.27 ± 0.18 at $E^* \approx 69$ MeV. The details of the procedure used to obtain isotopic and isobaric yield distribution at $E_\mathrm{lab} = 89.25$ and 83.22 MeV are given in Ref. [9].

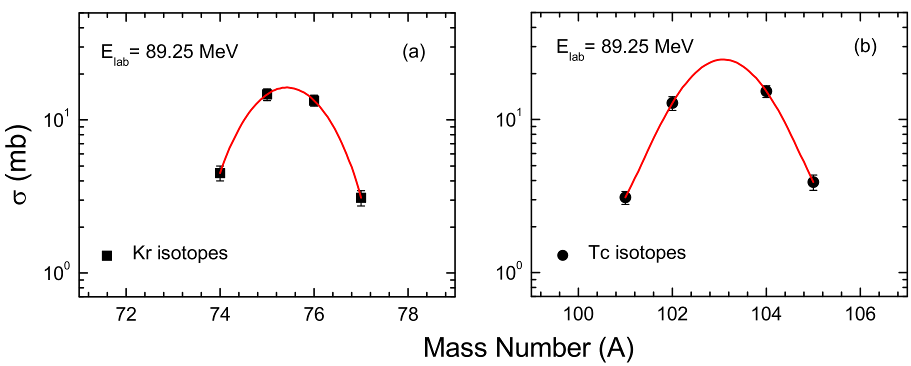

Fig. 1. (a) Isotopic yield distribution, and (b) fractional independent yield distribution of Kr isotopes at $E_\mathrm{lab} = 89.25$ MeV. The solid lines are the fitted Gaussian distribution.

2.2. Mass distribution

The mass distribution of fission fragments produced in the ^{12}C+^{169}Tm reaction is obtained by plotting the experimentally measured cross sections as a function of mass number. It is found to be symmetric and can be fitted with one Gaussian function manifesting the formation of fission fragments from compound nuclear processes at $E_\mathrm{lab} = 89.25$, 83.22, and 77.18 MeV [9]. The centroid and width parameters obtained from the analysis of mass distribution are found to be 88.18 ± 0.22 and 20.83 ± 0.62, 89.76 ± 0.29

and 20.11 ± 0.63, 91.4 ± 0.5 and 18.80 ± 0.96 at $E_{\rm lab}$ = 89.25, 83.22, and 77.18 MeV, respectively. In Fig. 2 (a), the measured variance (σ_M^2) of the mass distribution is plotted at different excitation energies, $E^* \approx 69$, 63, and 57 MeV. As shown in the figure, the variation of the variances (σ_M^2) increases with the excitation energy indicating larger spread at higher energies, and follows the same trend as reported by Ghosh *et al.* [8] for deformed ^{232}Th target at above the barrier energies. The variation of (σ_M^2) at and below the barrier energies needs to be further investigated. In order to understand how distribution of fragments depends on the choice of entrance channel parameters, mass variance for different projectile–target combinition [9] is plotted as a function of mass asymmetry ($\mu = \frac{M_{\rm T}-M_{\rm P}}{M_{\rm T}+M_{\rm P}}$) in Fig. 2 (b). As shown in this figure, there is a linear increase in dispersion parameter with mass asymmetry.

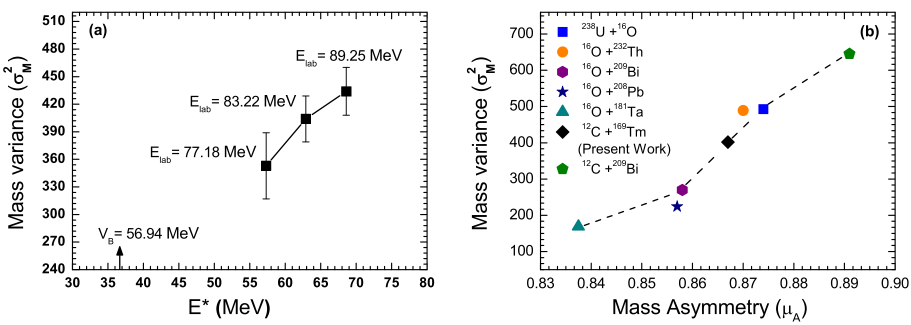

Fig. 2. (a) Variation of mass distribution with excitation energy (E^*) for deformed thulium target. The arrow points to E^* corresponding to Coulomb barrier. (b) Mass variance (σ_M^2) as a function of mass asymmetry for different projectile–target system. The solid and dashed lines are drawn to guide the eyes.

3. Summary and conclusions

The production cross sections of 26 fission-like events formed in ^{12}C+ ^{169}Tm reaction were measured at $E_{\rm lab}$ = 77.18, 83.22, and 89.25 MeV. The present work suggests that fission is one of the competing modes of de-excitation of complete and/or incomplete fusion composites at energies where evaporation of light nuclear particle(s) and/or γ-rays is prominent. The mass distribution was found to be symmetric and broad at the three energies, and the variance of distribution was found to increase with excitation energy and mass asymmtery. Isotopic and isobaric yield distribution parameters were obtained from the analysis of experimental yields of Kr and Tc isotopes, and were found to compare well with the values reported in the literature.

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