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Probing quasifission in reactions forming ^{210}Rn nucleus

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We studied the competition between fusion and quasifission by populating the compound nucleus (CN) ^{210}Rn through different entrance channels - ^{16}O+^{194}Pt and ^{30}Si+^{180}Hf, at energies around the Coulomb barrier. The larger widths of the fission fragment mass distribution in the ^{30}Si+^{180}Hf reaction which could not be explained by using transition state models, indicated the onset of quasifission in this reaction. Further, the evaporation residues (ERs) produced in these reactions were measured using the gas-filled recoil mass separator HYRA at IUAC. The measurements showed reduced ER cross sections for the ^{30}Si+^{180}Hf reaction when compared with that of ^{16}O+^{194}Pt at similar excitation energies, confirming the presence of quasifission in the ^{30}Si+^{180}Hf reaction. The experimental results are analysed using the dinuclear system (DNS) and statistical models to understand the possible influence of potential energy surfaces (PES) and different entrance channel conditions in heavy ion fusion reactions.

The 26th International Nuclear Physics Conference
11-16 September, 2016
Adelaide, Australia

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PoS(INPC2016)194

1. Introduction

In heavy-ion collisions, fusion-fission and quasifission [1, 2, 3] are the two competing reaction processes that cause a strong reduction in the ER formation probability. A complete understanding of the quasifission mechanism and its competition with fusion-fission reaction is essential to make reliable predictions for the best projectile-target combinations to synthesise new super-heavy elements (SHE) [4, 5, 6]. Extensive experimental and theoretical efforts have been made recently to understand the complex dynamics involved in the heavy-ion induced fusion reactions and their decay processes. These reactions are observed to be strongly influenced by the various entrance channel parameters [7, 8, 9, 10, 11, 12] such as energy, angular momemtum, entrance channel mass asymmetry, nuclear structure of the interacting nuclei [13, 14, 15, 16], etc. Quasifission admixed with fusion-fission events can be inferred from anomalous fission fragment angular anisotropies [17, 18], broadened fission fragment mass distributions [19, 20, 21], mass-angle correlations [20, 22, 23] and strong reduction in ER cross section [7].

We have previously studied the fission fragment mass distribution and mass-angle distributions for the ^{30}Si+^{180}Hf reaction [24]. The results are compared with ^{16}O+^{194}Pt reaction, populating the same CN. Mass-angle correlation is not observed in the ^{30}Si+^{180}Hf reaction in the energy range studied, indicating the absence of fast quasifission processes in this reaction. However, the widths of the fragment mass ratio distributions are significantly larger for this reaction when compared with that of ^{16}O+^{194}Pt reaction [Fig. 1]. Calculations assuming the saddle point and scission point models indicated the presence of quasifission events in this reaction, along with a major fusion-fission component. These quasifission events are interpreted as slow quasifission with longer sticking times as they could not exhibit any mass-angle correlation.

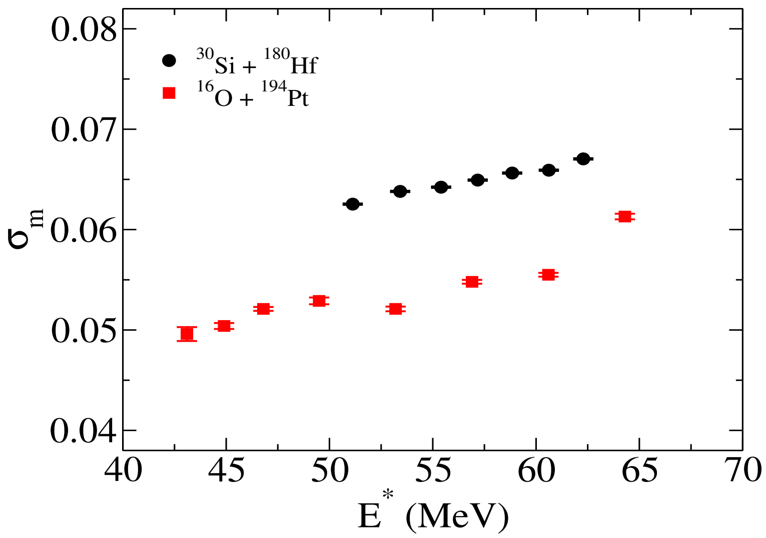

Figure 1: Experimental mass ratio widths of the fragments from the ^{16}O+^{194}Pt and ^{30}Si+^{180}Hf reactions at similar compound nuclear excitation energies.

A systematic analysis [25] of ER cross section data for a number of reactions leading to CN in the 200 amu mass region recently reported approximate boundaries from where the average fusion probabilities deviate from unity. More experimental evidences with a range of Z_PZ_T values and entrance channel mass asymmetries, are required to explore the characteristics of quasifission and fusion-fission processes in mass $\sim$ 200 region. ER cross section measurements are also very important to test the model predictions of quasifission probabilities in this mass region. In the present work, we explore the importance of the entrance channel effects on the fusion-fission reaction dynamics by comparing the excitation functions of ERs measured for different reactions populating the same CN, ^{210}Rn.

2. EXPERIMENTAL METHODS AND RESULTS

The ER excitation function measurements were performed using the pulsed beam from the 15UD Pelletron + LINAC accelerator facility at the Inter University Accelerator Centre, New Delhi. ^{30}Si beams with pulse separation of 2 μs were used to bombard the isotopically enriched ^{180}Hf target of thickness 150 μg/cm^2 on 40 μg/cm^2 thick carbon backing. The ER cross sections were measured for the ^{30}Si + ^{180}Hf reaction in the beam energy range 138.7 to 178.8 MeV.

The recoil mass separator, HYRA (HYbrid Recoil mass Analyzer) [26, 27] was used for the separation and identification of the ERs from the intense beam background. HYRA is a dual mode, dual stage mass separator, with its first stage can be operated in gas-filled mode or vacuum mode. The first stage of HYRA having electro-magnetic configuration Q1Q2-MD1-Q3-MD2-Q4Q5 (Q and MD stand for magnetic quadrupole and magnetic dipole, respectively), in gas-filled mode filled with helium at an optimized pressure of 0.15 Torr, was used for the present study. HYRA magnetic fields for all the ion optical elements were calculated using a simulation code TERS [28]. At each energy point, magnetic fields were scanned in a range of $\pm$10% of the calculated values, for optimizing the field settings. Under optimum field values and gas pressure, velocity and charge-state focusing take place which enhances the transmission efficiency. The gas-filled region of the HYRA was separated from the beam line which is maintained at high vacuum by a 650 μg/cm^2 thick carbon window foil.

Two silicon detectors were used inside the target chamber, placed at $\theta = \pm 25^\circ$ to detect the Rutherford scattered beam-like particles for absolute normalization of ER cross sections. These detectors were also used for positioning the beam at the center of the target. ERs were detected at the focal plane of HYRA using a position sensitive multiwire proportional counter (MWPC) of active area 6 inch $\times$ 2 inch followed by a silicon strip detector of active area 2.4 inch $\times$ 2.4 inch. The MWPC (operated with isobutane gas of about 2.5 mbar pressure) provided position signals (both X and Y positions), an energy loss signal (from the cathode), and a timing signal (from the anode). The data were collected and analyzed using the IUAC data-sorting software CANDLE. A time-of-flight (TOF) spectrum was generated with the timing pulse from the MWPC anode as start and the radio frequency (RF) signal, delayed suitably, as stop. The energy loss (ΔE) vs TOF spectrum helped in achieving unambiguous identification of ERs from the beam-like and the target-like contaminations. Fig. 2 shows the two-dimensional plot of ΔE versus TOF at 147.4 MeV beam energy.

Total ER cross sections (σ_{ER}) were calculated using the relation

$$\sigma_{ER} = \frac{Y_{ER}}{Y_{mon}} \left(\frac{d\sigma}{d\Omega}\right)_R \Omega_M \frac{1}{\varepsilon_{HYRA}} \tag{2.1}$$

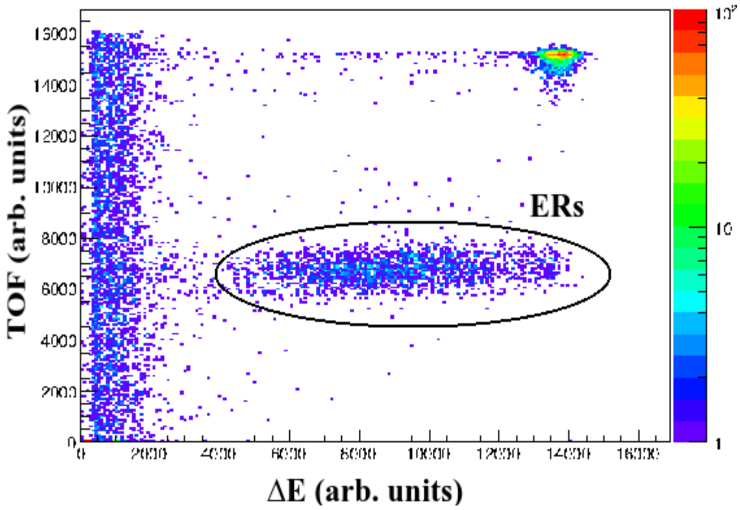

Figure 2: Two-dimensional plot of ΔE vs TOF for the reaction ^{30}Si + ^{180}Hf at 147.4 MeV beam energy.

where Y_{ER} is yield of the ERs at the focal plane, Y_{mon} is the yield of elastically scattered projectiles registered by the monitor detector, $(\frac{d\sigma}{d\Omega})_R$ is the differential Rutherford scattering cross section, Ω_M is the solid angle subtended by the monitor detector, and ε_{HYRA} is the transmission efficiency of the HYRA.

Transmission efficiency is the ratio of the number of ERs reaching the focal plane to the total number of ERs produced at the target chamber. It is a function of various parameters [27, 28] such as the entrance-channel mass asymmetry, beam energy, the target thickness, the exit channels of interest, the angular acceptance of the separator, the magnetic field and gas pressure settings, and the size of the focal plane detector. Entrance channel mass asymmetry, target thickness, angular acceptance of the HYRA, and size of the focal plane detector remain unchanged throughout the experiment, while the rest of the parameters change. Therefore, ε_{HYRA} would be different for different E_{lab}.

In the present study, we estimated ε_{HYRA} using the ^{30}Si + ^{186}W reaction [29] as the calibration system following the method described in Ref. [27, 28]. σ_{ER} for this reaction had been available in the literature [29]. We measured the ER cross section for ^{30}Si + ^{186}W at different E_{lab} and ε_{HYRA} is obtained by substituting σ_{ER} in Eq. (2.1). The ER angular distribution for the two reactions were simulated using TERS and were compared within the angular acceptance of HYRA. The efficiency obtained for ^{30}Si + ^{186}W reaction is hence normalized to get the transmission efficiency for the present systems. The transmission efficiencies at different energies are used to obtain the experimental total ER cross sections using Eq. (1). The overall errors in the estimated cross sections are $\leq 20\%$, which include contributions from the statistical error and the systematic error in the estimation of ε_{HYRA}.

Experimental ER cross sections for the ^{30}Si+^{180}Hf reaction is compared with that of the ^{16}O+^{194}Pt reaction in Fig. 3. Significant reduction in ER cross section for ^{30}Si+^{180}Hf has been observed, confirming the presence of quasifission in this reaction. Present results are in very good agreement with our previous observations in fission fragment mass ratio distribution in these reactions. The hindrance to complete fusion is related with the increase in the competing quasifission events during the evolution of the DNS formed after the capture of the projectile by the target. The entrance channel effects on the characteristics of the formed reaction products can be studied by comparing the experimental data with the theoretical results obtained using DNS and advanced statistical model calculations.

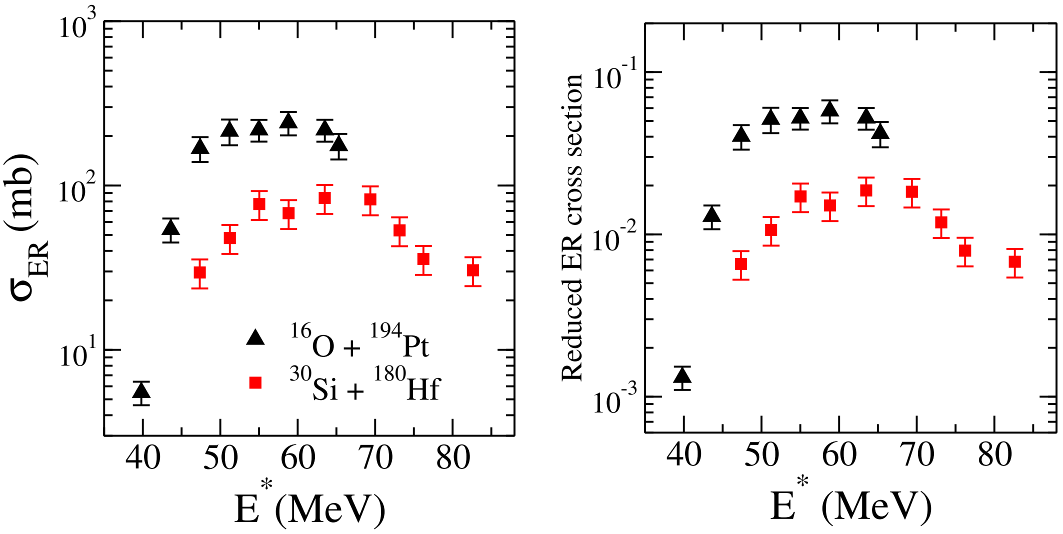

Figure 3: The absolute and reduced ER cross sections for the ^{16}O+^{194}Pt and ^{30}Si+^{180}Hf reactions populating the CN ^{210}Rn as a function of CN excitation energy.

3. Theoretical calculations

The theoretical calculations are done in two steps. First, the fusion probability and partial fusion cross sections were calculated using the DNS model. These information were then used in statistical model to simulate the decay of the CN formed in each reaction studied. According to DNS model, the fusion process is considered as the evolution of a DNS caused by the transfer of nucleons from the light nucleus to the heavy one. The probability of complete fusion, P_{CN} depends on the competition between the complete fusion and quasifission. In this concept, the fusion cross section is calculated using the equation,

$$\sigma_{fus}(E) = \sum_{\ell=0}^{\ell_d(E)} (2\ell+1)\sigma_{cap}(E,\ell)P_{CN}(E,\ell). \tag{3.1}$$

Since the capture cross section is equal to sum of the fusion and quasifission cross sections, ie., $\sigma_{cap} = \sigma_{fus} + \sigma_{qfis}$, the quasifission cross section can be calculated as,

$$\sigma_{qfis}(E) = \sum_{\ell=0}^{\ell_d(E)} (2\ell+1)\sigma_{cap}(E,\ell)[1-P_{CN}(E,\ell] \tag{3.2}$$

where P_{CN} is the fusion probability of the DNS, which can be calculated using the expression [31],

$$P_{CN}(E^*_{DNS},\ell;\alpha_i) = \sum_{Z_{sym}}^{Z_{max}} Y_Z(E^*_{DNS}) P^Z_{CN}(E^*_{DNS},\ell;\alpha_i). \tag{3.3}$$

Here Z_{sym} is the charge symmetry and Z_{max} corresponds to the value of Z at which driving potential is the maximum. E^*_{DNS} is the excitation energy of the DNS [31] for a given value of charge configuration $(Z, Z_{tot} - Z)$ where $Z_{tot} = Z_P + Z_T$. Z_P and Z_T are the atomic numbers of the projectile and target, respectively. $Y_Z(E^*_{DNS})$ is the probability of population of the DNS in such a configuration with $(Z, Z_{tot} - Z)$ at E^*_{DNS}, ℓ and given orientation α_i.

Results of the partial cross sections of the CN formation are used to calculate ER cross sections at given values of the CN excitation energy and angular momentum by the statistical model [32]. The total ER cross section at an intermediate excitation energy E^*_x is given by

$$\sigma^x_{ER}(E^*_x) = \sum_{\ell=0}^{\ell_d} (2\ell+1)\sigma^x_{ER}(E^*_x,\ell). \tag{3.4}$$

where $\sigma^x_{ER}(E^*_x,\ell)$ is the partial cross section of ER formation obtained after all the energetically possible de-excitations such as neutron, proton, alpha particle and gamma emissions of the intermediate nucleus, with excitation energy E^*_x at each step x of de-excitation cascade [32, 33]. The survival probability of the intermediate nucleus against fission W^x_{sur} is also considered in each step of the decay cascade. Thus,

$$\sigma^x_{ER}(E^*_x,\ell) = \sigma^x_{ER}(E^*_{x-1},\ell) W^x_{sur}(E^*_x,\ell) \tag{3.5}$$

with the CN as the starting point.

4. Results and Discussions

The comparison of the theoretical excitation functions of capture, fusion and ER cross sections with the experimental ER data for the reactions ^{16}O+^{194}Pt and ^{30}Si+^{180}Hf are presented in Fig 4 (a) and (b). We also performed the model calculations for the ^{50}Ti+^{160}Gd [34] reaction for which 4n+5n channel cross sections are known. This reaction also populates ^{210}Rn as the CN (Fig. 5 (c)). Comparison of the three reactions populating same CN allows us to reveal the role of the entrance channel properties in the formation of the reaction products.

The ER excitation functions for the ^{30}Si+^{180}Hf reaction are much lower than the ones of the ^{16}O+^{194}Pt reaction. The main reason causing this difference is the decrease in fusion cross section due to the competing quasifission process. The higher Coulomb factor ($Z_P Z_T = 1008$) and large deformation of the ^{180}Hf target ($\beta = 0.273$) could be favouring quasifission process in the ^{30}Si+^{180}Hf reaction.

Fig. 5 shows the calculated values of fusion probability, P$_{CN}$ for the three reactions forming the same CN ^{210}Rn. For ^{16}O+^{194}Pt, P$_{CN}$ values are observed to be close to unity in the energy range

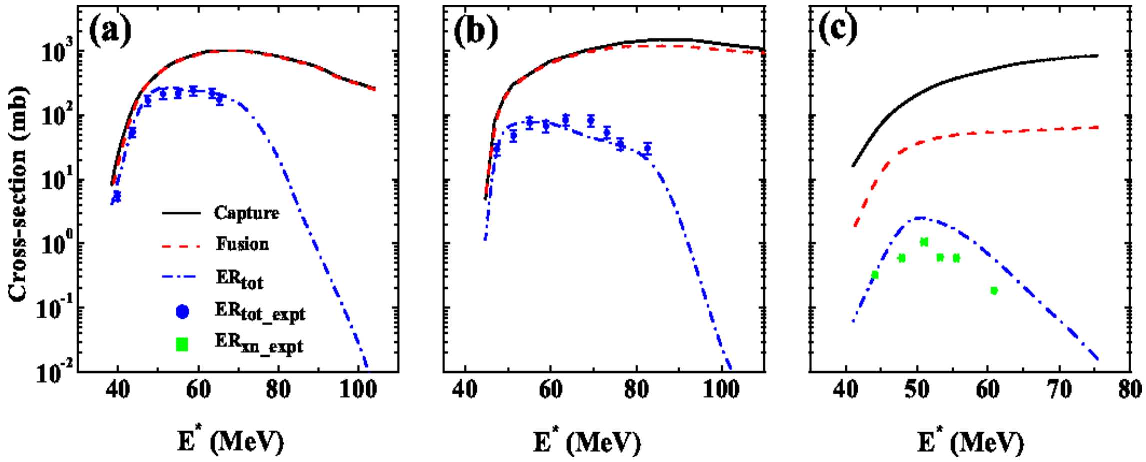

Figure 4: Experimental total ER and and theoretical calculations for total ER, fusion, and capture cross sections for different systems populating ^{210}Rn CN are shown in Fig 4 (a) and (b). Experimental ER cross sections for 4n+5n channels for the ^{50}Ti+^{160}Gd reaction compared with the model calculations are shown in Fig 4 (c).

studied in this work, which is in agreement with the experimental observations [21, 27, 30, 24]. P$_{CN}$ values show a decreasing trend with increase in beam energy. This may be due to the increase in angular momentum with beam energy.

As we go to more symmetric systems, fusion probability decreases significantly, clearly indicating the escape of capture flux through noncompound nuclear channel, quasifission. The decrease in fusion probability with increase in charge product ($Z_P Z_T$) in these reactions indicates that the Coulomb factor plays a major role in the dynamics of nuclear collisions.

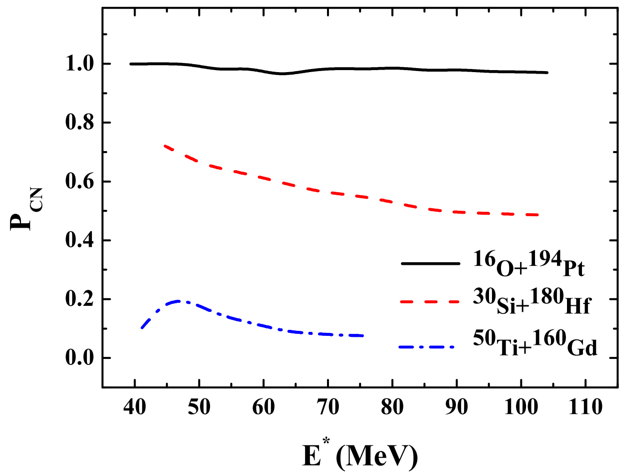

Figure 5: Calculated values of P$_{CN}$ for different reactions forming the CN ^{210}Rn.

5. Summary

We measured ER cross sections for the ^{30}Si+^{180}Hf reaction forming the CN ^{210}Rn. The results are compared with an asymmetric reaction ^{16}O+^{194}Pt forming the same CN. The comparison shows a reduction in ER cross section for the more symmetric ^{30}Si+^{180}Hf system. We used combined dinuclear system and advanced statistical models to study this entrance channel effects on the ER yields in reactions leading to the same CN. The increase in quasifission probability causes the difference between ER cross sections in the systems reported in this work. We also compared our results with the more symmetric system, ^{50}Ti+^{160}Gd. The fusion probability shows a sharp fall with increase in Coulomb factor in this work.

6. Acknowledgements

The authors are grateful to the Pelletron and linac accelerator staff of the Inter University Accelerator Centre for their excellent support during the experiments. One of the authors (AS) acknowledges the award of MANF by University Grants Commission (UGC), India, in the form of fellowship to carry out this work. MS acknowledges the KSCSTE fellowship.

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