Sequential And Double Sequential Fission Observed In Heavy Ion Interaction Of (11.67 MeV/u)^{197}Au Projectile With ^{197}Au Target

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The heavy ion interaction of 11.67 MeV/u $^{197}Au + ^{197}Au$ has been investigated using mica as a passive detector. By employing Solid State Nuclear Track Detection Technique the data of elastic scattering as well as inelastic reaction channel was collected. The off-line data analysis of multi-pronged events was performed by measuring the three-dimensional geometrical coordinates of correlated tracks on event-by-event basis. Multi-pronged events observed in this reaction were due to sequential and double sequential fission. Using a computer code PRONGY based on the procedure of internal calibration, it was possible to derive quantities like mass transfer, total kinetic energy loss and scattering angles.

Keywords: Heavy Ion Interaction, mica track detector, multi- pronged events, sequential fission, double sequential fission

1. INTRODUCTION

One of the most remarkable features of the reactions between heavy projectiles and heavy targets is the ability of the nuclear system to convert hundreds of MeV and GeV of relative kinetic energy into internal excitation and deformation energy. The two heavy and excited fragments produced after the first stage of the interaction can decay into various decay modes from evaporation to multi-fragmentation including fission. The advanced particle detection systems [1] generate a rich source for theoretical modeling of the underlying nuclear processes [2,3,4]. The collision of complex nuclei with each other, however, continues to defy a unified microscopic description. It is generally taken tactful to analyze reactions with respect to definite windows of incidence energies and projectile-target combinations. At low energies (Elab<10 MeV/u) the major part of the total reaction cross-section is accounted for by the fusion-evaporation process with a single heavy residual nucleus. However, a binary process of fusion-fission type has also been observed together with quasi-elastic and deep inelastic scattering [5].These data are well explained on the basis of statistical model [6]. At the higher projectile energies the collision with heavy targets gives rise to conditions favourable for the production of quark-gluon plasma with specific effects on the nature and yield of observed particles. However, many of the results on particle production can also be explained reasonably well by using Monte-Carlo event generators without invoking plasma formation [7].The intermediate energy region is rather broad, scattering from ~ 10 MeV/u to several hundred MeV/u. The reaction mechanism at energies below 20 MeV/u is dominated by mean field effects and changes gradually to single particle effects for incident particle energy beyond Fermi energy.

In the present study from the analysis of multi-pronged events it has been observed that all the analyzed 3- and 4-pronged events were due to sequential and double sequential fission. For experimental verification we used mica as Solid State Nuclear Track Detector. This track detector system has been used in number of similar studies [8,9, 10,11].

2. EXPERIMENTAL DETAILS

Target of ^{197}Au having thickness 1.29 mg/cm^2 was bombard with ^{197}Au ions of beam energy 11.67 MeV/u at UNI-LAC (GSI) Darmstadt, Germany. Thin layers of target material were vacuum deposited on three sheets of mica. The target-detector assemblies were exposed to a normal beam of ^{197}Au projectile having fluence of about 2.53 $\times10^6$ particles / cm^2. After exposure the target material was dissolved off with HNO$_3$. The mica detectors were then etched for 45

minutes in 40% HF. The total scanned area was 55.52 cm^2. Samples were scanned with an optical microscope (Leitz Orthoplan) at a magnification of about 400 ×. The method of conversion of projected track lengths and azimuthal angles to actual track lengths and polar angles has been given in references [12,13].

3. ANALYSIS OF THREE AND FOUR PRONG EVENTS

For the conversion of three dimensional coordinates of multi-prong data i. e. track lengths and polar angles into physical quantities such as masses and velocities, we have used the well-known method of Gottschalk et al [14]. For this purpose a computer code PRONGY was used.

The following coupled equations are solved for the analysis of three-pronged events,

$$\sum_{i=1}^{N} m_i V_i(l_i, m_i) \hat{e}_i = \vec{P}_{in} \tag{1}$$

$$V_i(l_i, m_i) = \sum_{\mu=0}^{2} \sum_{\nu=0}^{4} C_{\mu\nu} m_i^{\mu} l_i^{\nu} \tag{2}$$

where m_i denotes the mass of the *ith* fragment, l_i is the track length, V_i is the velocity, $\vec{e}_i$ is the unit vector along the track direction, $\vec{P}_{in}$ is the incident momentum and N being the multiplicity of an event. The coefficients $C_{\mu\nu}$ were determined by an internal calibration method [14].

In the analysis of 4-pronged events, four unknown masses are to be determined. So in addition to equation (1) and (2), one more equation i.e equation for the conservation of masses is used.

$$\sum_{i=1}^{N} m_i = m_P + m_T \tag{3}$$

where m_P and m_T are the projectile and target masses respectively.

4. RESULTS AND DISCUSSION

Total number of measured three and four-pronged events were 410 and 65 while total number of analyzed three and four- pronged events were 278 and 44 respectively i. e. 68% events were analyzed in both the cases.

After assigning velocities to the individual tracks, in each event, it is easy to determine the relative velocity between fission fragments. For three-pronged events, one out of three possible combinations of relative velocities and for four-pronged events, two out of six possible combinations were consistent with the expected value of equilibrated fission, i. e. about 2.4 cm/ns. Therefore in case of three-pronged events one such pair and in case of four-pronged events two such pairs were identified as fission fragments. These results strongly support the view of sequential and double sequential fission processes in the heavy ion reaction under study.

The values of fission fragments and pre-fission masses of three and four- pronged events are given in Table I and II. The

mean values and the standard deviations have been obtained by Gaussians fits to the experimental plots.

TABLE I: Fission fragment masses (in the second reaction step) and intermediate stage masses (in the first reaction step) of three-pronged events.

mi (u)	mj (u)	mk (u)	mij (u)
91 ± 66	156 ± 77	147 ± 90	247 ± 99

TABLE II: Fission fragment masses (in the second reaction step) and intermediate stage masses (in the first reaction step) of four-pronged events.

mi (u)	mj (u)	mk (u)	ml (u)	mij (u)	mkl (u)
88 ± 40	126 ± 40	68 ± 34	112 ± 36	214 ± 19	180 ± 18

4.1. Mass Transfer

Mass transfer is given by

$$\Delta m = \frac{|m_{ij} - m_H| + |m_k - m_L|}{2} \quad \text{(for 3-pronged events)} \tag{4}$$

$$\Delta m = \frac{|m_{ij} - m_H| + |m_{kl} - m_L|}{2} \quad \text{(for 4-pronged events)} \tag{5}$$

where m_H and m_L are the masses of heavier and lighter interacting ions. The distributions of mass transfer plotted on event by event basis for three and four-pronged events are shown in Fig. 1. It can be noted that on the average a mass of (50 ± 24) u and (17 ± 12) u has been transferred for 3- and 4-pronged events. So it is clear that mass transfer in 3-pronged events is high as compared to 4-pronged events.
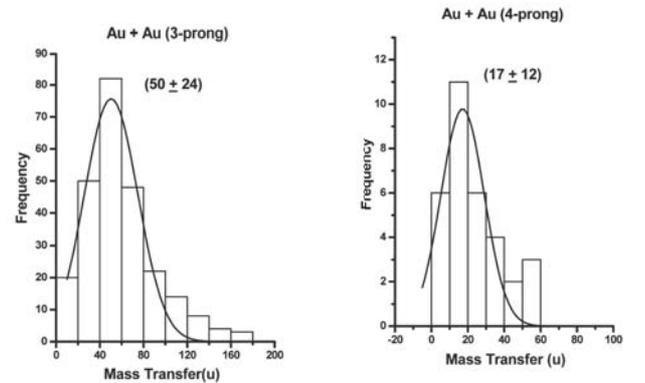

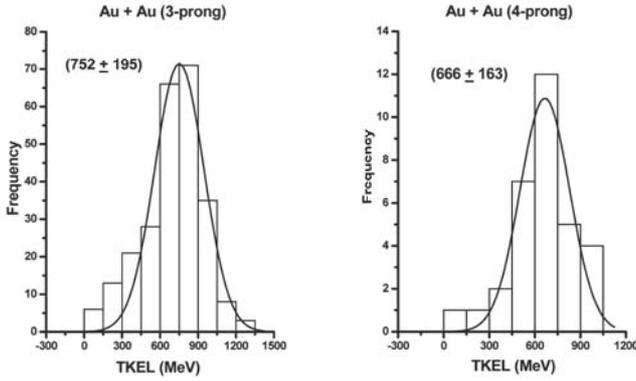FIG. 1: Distributions of mass transfer in first reaction step for 3- and 4-pronged events.

FIG. 2: Distributions of TKEL in the first reaction step for 3- and 4-pronged events.

FIG. 3: Energy spectra for Au + Au reaction.

4.2. Total Kinetic Energy Loss (TKEL)

Total kinetic energy loss which is a measure of energy damping in the first step of the reaction is given by

$$TKEL = E_{Lab} - \sum_{i=1}^{n} \left(E_{i,track} - E_f \right) \qquad (6)$$

where E_{Lab} is the laboratory energy, $E_{i,track}$ is the kinetic energy associated to each track, n is the multiplicity of the event and E_f is the energy released in fission given by

$$E_f = \frac{m_i m_j v_{ij}^2}{2 \left(m_i + m_j \right)} \text{ for 3-pronged events}$$

$$E_f = \left[\frac{m_i m_j v_{ij}^2}{2 \left(m_i + m_j \right)} \right] + \left[\frac{m_k m_l v_{kl}^2}{2 \left(m_k + m_l \right)} \right] \text{ for 4-pronged events}$$

Fig. 2 shows the distributions of TKEL in 3-and 4-pronged events. For 3-pronged events TKEL is (752 ± 195) MeV while for 4-pronged events it is (666 ± 163) MeV. Average TKEL for 3-pronged events is slightly larger than that of the corresponding value in case of 4-pronged events.

Fig. 3 shows the energy loss spectra integrated over all reaction angles and multiplicities. The kinetic energy available above the Coulomb barrier is given by

$$E_{avail} = E_{CM} - E_{Coul} \qquad (7)$$

which is denoted by arrow on the horizontal axis. Its value is 532 MeV for Au + Au reaction at 11.67 MeV/u beam energy. The first peak at (0.8 ± 125) MeV is due to elastic binary events and quasi elastic 3-pronged events while the second peak at (693 ± 344) MeV is due to events obtained as a result of sequential and double sequential fission following deep inelastic collision.

4.3. Scattering Angles

The angular distributions of pre-fission masses (m_{ij} and m_{kl}) and the surviving mass (m_k) for three and four-pronged events in the first step are shown in Fig. 4. The angles subtended by m_{ij}, m_{kl} and m_k with respect to beam direction in
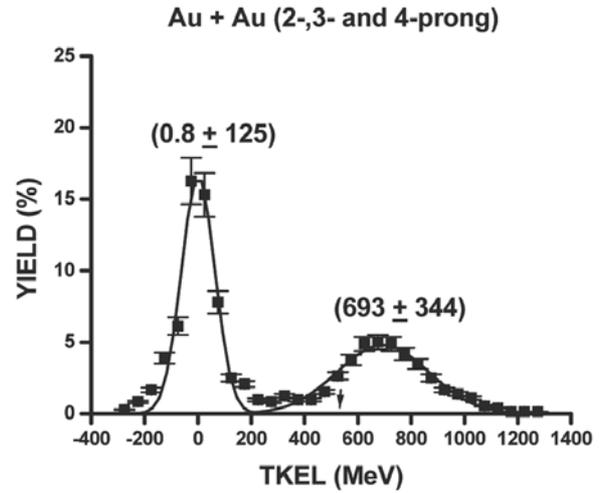
laboratory frame of reference are denoted by Θ_{ij}, Θ_{kl} and Θ_k respectively. It can be seen that in 3-pronged events pre-fission mass (m_{ij}) scattered at smaller angle i.e. $(18.7 \pm 12.5)^o$ while surviving mass (m_k) scattered at larger angle i.e. $(38.2 \pm 24.8)^o$. In case of 4-pronged events pre-fission mass (m_{ij}) scattered at smaller angle i.e. $(28.4 \pm 13.1)^o$ while pre-fission mass (m_{kl}) scattered at larger angle i.e. $(33.5 \pm 19.6)^o$.
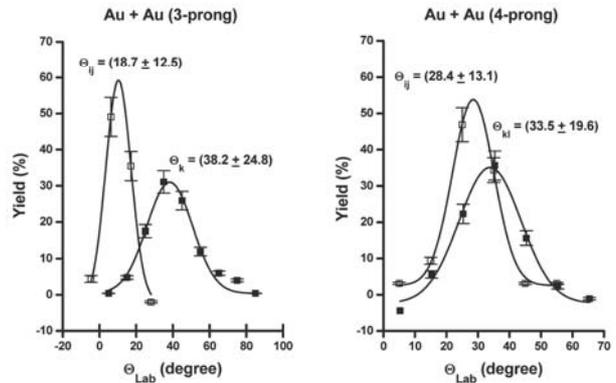

FIG. 4: Angular distributions of intermediate stage masses in the first reaction step for 3- and 4-pronged events.

5. CONCLUSIONS

In case of all the analyzed three-pronged events the value of one of the relative velocity of the emitted fragments out of the three possible pairs has been found in the vicinity of 2.4 ± 0.4 cm/ nsec as expected from the equilibrated fission, while the other two values were far from this value. Similarly for all analyzed four-pronged events two values out of six possible pairs were near to the expected value. So the investigations about the separation velocities of correlated fragments reveal the sequential and double sequential nature of all the analyzed three and four-pronged events in the heavy

ion interaction of 11.67 MeV/ u Au + Au.

It has also been observed that mass transfer in three-pronged events was high as compared to four-pronged events and also average TKEL for three particle exit channel was slightly larger than that of the corresponding value in four particle exit channel. After the first stage of the reaction, two intermediate masses show mass transfer among them depending on the TKEL at that stage of the reaction. Higher value of mass transfer is accompanied by large TKEL. In the second stage of the reaction, one or both the fragments undergo fission, giving three or four particles at the exit channel.

From the scattering angles of the intermediate masses it has been observed that the heavier of the two focused in the forward directions while the lighter one had broader peaks at higher values.

[1] H. Stelzer (1976). Nucl. Instrum. Methods, 133, 409.

[2] S.I. Cavallaro (1998). Phys. Rev. C57, 731.

[3] M.B. Tsang et al. (1997). Phy. Rev. C55, R557.

[4] C. Williams et al. (1997). Phy. Rev. C55, R2132.

[5] C. Beck et al. (1998). Eur. Phys. J. A2, 281.

[6] T. Matsuse et al. (1997). Phy. Rev. C55, 1380.

[7] A. Drabrowski et al. (1998). Nucl. Phys. A633, 357.

[8] I.E. Qureshi et al. 1997. Radiat. Meas., Vol. 28, 283.

[9] E.U. Khan , Qureshi I E, Shahzad M I, Khattak F N and Khan H.A (2001). Nuclear Physics A 690, 723-730.

[10] Tabassum Nasir, J.J. Baluch, E.U. Khan, F.N. Khattak and M.I. Shahzad (2006). Chinese Physics Letters Vol. 23, No. 10, 2714.

[11] Tabassum Nasir, E.U. Khan, J.J. Baluch, I.E. Qureshi, M. Sajid, , M.I. Shahzad, (2008). Radiation Measurements 43, S274-S278.

[12] I.E. Qureshi , M.I. Shahzad , S. Manzoor, H.A. Khan, 1994. The Nucleus 31, 25-33.

[13] E.U. Khan et al. (1991). Nucl. Tracks Radiat Meas., Vol. 19 No. 1-4, pp. 631-636.

[14] P.A. Gottschalk , G. Grawert, P. Vater and R. Brandt (1983). Phys. Rev. C27, 2703-2719.