Fissions in $^{32}\text{Si}^+^{184}\text{W}$ and $^{34}\text{Si}^+^{186}\text{W}$ reactions at near- and sub-barrier energies

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Abstract. Fission fragments of $^{32}\text{Si}^+^{184}\text{W}$ and $^{34}\text{Si}^+^{186}\text{W}$ reactions have been measured by silicon-strip detectors at energies around the Coulomb barrier. The mass distributions of fission fragments for the $^{34}\text{Si}^+^{186}\text{W}$ system were derived and their widths were reproduced by the statistical model. The angle distributions of fission fragments for the $^{32}\text{Si}^+^{184}\text{W}$ system were fitted to extract the anisotropy, $A_{\text{exp}}$, and the variance of initial $K$ distribution, $K_{20}$. Both $A_{\text{exp}}$ and $K_{20}$ are larger than the theoretical values predicted by the saddle-point transition-state model, while they can be explained by the low-momentum-dependent pre-equilibrium fission model. It denotes that the pre-equilibrium fission rather than the quasi-fission occurs in the S+W system.

1. Introduction

Synthesis of superheavy element is a hot topic of current interest in nuclear physics. Fusion reaction is a key way to form the superheavy nucleus. In heavy-ion induced reactions, fission is a main competing reaction with respect to fusion and its dynamic process is rather complicate as a nucleus is first formed and then splits into two parts. Although qualitative and sometimes quantitative descriptions of many aspects of the fusion-fission process have been achieved, as yet it is not completely understood. Comprehensive investigation of fusion-fission reactions at energies near the Coulomb barrier will provide a valuable clue for synthesizing the superheavy nucleus.

From the aspect of reaction mechanism, fission induced by heavy-ion can be identified as, i) the complete fusion-fission (CFF) process, where the composite system overcomes the unconditional saddle point to form a compound nucleus with all the degrees of freedom achieving their equilibrium and then separates into two fragments, ii) the pre-equilibrium fission (PEF) process, where the compound nucleus is formed with all the other degrees of freedom except the $K$ degree of freedom ($K$ is the projection of total spin onto the symmetric axis) reaching the equilibrium before fission, iii) the quasi-fission (QF) process, where the compound nucleus is not formed to the full, that is the mass degree of freedom is out of complete equilibrium, and iv) the fast fission process, where the composite system directly goes to fission due to the vanishing of fission barrier.
Mass distribution and angular distribution are the main experimental observations to discriminate the fission mechanism mentioned above. In this talk, we would like to present the results of fission measurements for the $^{32}$S+$^{184}$W and $^{34}$S+$^{186}$W reactions at near- and sub-barrier energies and discuss the possible fission mechanism in the S+W system.

2. Experimental procedure

For $^{32}$S+$^{184}$W system, the experiment was performed at the HI-13 tandem accelerator at the China Institute of Atomic Energy. Collimated $^{32}$S beams with incident energies $E_{\text{beam}} = 140$, 145, 150, 155, 160, 165, and 170 MeV, respectively, bombarded on a $^{184}$W target with thickness about 200 $\mu$g/cm$^2$ supported by a about 20 $\mu$g/cm$^2$ carbon foil backing. The beam energy loss in traveling half the target was estimated about 0.5 MeV. At the forward angles, an array of five Si(Au) surface-barrier detectors with a depletion depth of 300 $\mu$m was mounted on the movable arm in the chamber. The typical $^{32}$S beam current range was about 200 enA monitored by a Faraday cup. The Rutherford scattering was monitored at a forward angle of $\theta_{\text{Lab}} = 15^\circ$ by four Si(Au) surface barrier detectors for the normalization of the cross-section measurements. In addition to these individual Si detectors, two groups of Si-strip detectors were mounted on opposite sides of the beam. These Si-strip detectors were $48 \times 50$ mm$^2$ in area and each detector consisted of 24 strips. Data from these strip detectors were recorded in the coincidence mode with the requirement that each detector was struck by a fission fragment and the folding angle between the hits corresponded to a full momentum transfer event. To calculate the kinematics it was assumed all observed processes can be treated as binary reactions. This assumption was tested by examining the folding angle distribution of coincident fragments in the Si detector and the Si-strip detectors. The average folding angle agrees with the expectations based on total kinetic energies (TKE) taken from the systematics of Viola et al. [1].

For $^{34}$S+$^{186}$W system, the experimental procedure was similar to that of the $^{32}$S+$^{184}$W system, but done at the tandem booster accelerator at Japan Atomic Energy Agency. $^{34}$S beams with energy of 148, 163, and 180 MeV, respectively, bombarded on a $^{186}$W target with thickness about 200 $\mu$g/cm$^2$ supported by a about 20 $\mu$g/cm$^2$ carbon foil backing. Three individual Si(Au) detectors fixed at the forward angles of 35.6$^\circ$, 60.6$^\circ$, and 85.6$^\circ$, respectively, and two Si-strip detectors with areas of $50 \times 50$ mm$^2$ at the backward angles were employed in the same way to measure the fission fragments in a coincident mode. The fragment masses can be obtained from such double energies measurement by the conservation laws of mass and momentum, i.e.,

\[
\begin{align*}
    m_1 E_{k1} \sin^2 \theta_1 &= m_2 E_{k2} \sin^2 \theta_2 \\
    m_1 + m_2 &= m_c
\end{align*}
\]

where $m_1$ and $m_2$ are the masses of two fission fragments, $m_c$ is the mass of compound nucleus, $\theta_1$ and $\theta_2$ are the emission angles of two fragments relative to the beam direction, $E_{k1}$ and $E_{k2}$ are the kinematic energies recorded by the detectors. Then the $m_1$ and $m_2$ can be deduced as,

\[
\begin{align*}
    m_1 &= \frac{E_{k2} \sin^2 \theta_2}{E_{k1} \sin^2 \theta_1 + E_{k2} \sin^2 \theta_2} \cdot m_c \\
    m_2 &= \frac{E_{k1} \sin^2 \theta_1}{E_{k1} \sin^2 \theta_1 + E_{k2} \sin^2 \theta_2} \cdot m_c
\end{align*}
\]

The energy measured by the silicon detector need to be corrected during the calculation, as following, i) the pulse-height-defect correction [2], ii) the energy-loss correction, and iii) the neutron-evaporation correction [3]. These corrections were automatically performed in a program by an iterative method.

The typical mass-energy distributions measured by the Si(Au) at forward 60.6$^\circ$ coincident with the backward strip detectors at $-79.6^\circ$, $-75.4^\circ$, $-71.2^\circ$, $-67.0^\circ$, and $-62.8^\circ$ are illustrated in Fig. 1 a) - e), respectively. The complement angle of 60.6$^\circ$ is exact $-75.4^\circ$, assuming the fission
with full momentum transfer. From the figure one can see that the symmetric fissions gradually change to the asymmetric fissions with the angles moving from the backward to forward. The total fissions summed of all the angles are plotted in Fig. 1 f). Overall, it shows the feature of symmetric fission.

3. Experimental results and discussions
The mass and TKE distributions of fission fragments for the $^{34}$S+$^{186}$W reactions at the beam energy of 163 MeV are shown as the solid symbols in Fig. 2 for the forward angles of 85.6$^\circ$, 60.6$^\circ$, and 35.6$^\circ$, respectively. At $\theta_{sd} = 85.6^\circ$, about 20-30% fission events were lost due to the geometric coverage. In the plots of yield distributions, the solid lines are Gaussian curves with standard deviation, i.e. mass width $\sigma_A$. The total yields were normalized to 200% because one fission event has two fragments. In the plots of $<TKE>$ distributions, the solid lines represent the Viola TKE [1]. In the plots of $\sigma^{2}_{TKE}$ distributions the solid lines describe the symmetric components assuming $<TKE>^2 / \sigma^{2}_{TKE} = \text{constant}[4]$. The deviations of these distributions have the same values for the different angles. It means the mass and TKE distributions are insensitive to the changes of angle, implying that the mass and energy degrees of freedom achieved equilibrium before fission. In order to check this implication, the mass width varying with the excitation energy is pictured in Fig. 3. The solid curve is the prediction of the scission-point statistical model [5],

$$\sigma^{2}_{A} = \frac{T_{\text{sci}}}{k} = \frac{1}{k} \sqrt{\frac{8.5E^{+}}{A}}. \quad (3)$$
Figure 2. Mass and TKE distributions of fission fragments for the $^{34}\text{S} + ^{186}\text{W}$ reactions at the beam energy of 163 MeV.

where $T_{\text{sci}}$ is the scission-point temperature, $k$ is the stiffness parameter ($k = 0.0048$ MeV/u), $E^{+}$ is the excitation energy at scission-point, and $A$ is the mass of compound nucleus. From Fig. 3 one can see that the experimental mass widths are in agreement with the predictions of the statistical model within errors.

The angular distributions of fission fragments for the $^{32}\text{S} + ^{184}\text{W}$ reactions are displayed in Fig. 4. In fitting the angular distributions of the fission fragments the following expression was employed [6],

$$W(\theta) = \sum_{I=0}^{I_{\text{max}}} (2I + 1)^2 \exp \left[ -\left( I + \frac{1}{2} \right)^2 \sin^2 \theta / 4K_0^2 \right] J_0 \left[ i\left( I + \frac{1}{2} \right)^2 \sin^2 \theta \right] \text{erf} \left[ (I + \frac{1}{2}) / \sqrt{2K_0^2} \right]$$

assuming $M = 0$, that is, assuming that the spins of the target and projectile were zero, where $I$ is the total spin of compound nucleus, $K_0^2$ is the variance of initial $K$ distribution, $J_0$ is the zero-order Bessel function with imaginary argument, and erf($x$) is the error function. The experimental anisotropy, $A_{\text{exp}}$, and $K_0^2$ were extracted by these fittings and compared with the theoretical calculations to understand the fission dynamics. Figure 5 shows the $A_{\text{exp}}/A_{\text{theory}}$ values varying with the ratios of the reaction energy to the Coulomb barrier, where the traditional saddle-point transition-state (SPTS) model [7] and the low-momentum-dependent pre-equilibrium fission model [8] were utilized, respectively. It is seen from the figure that the experimental anisotropies are obviously larger than those calculated by SPTS model, while the pre-equilibrium fission model reproduces the experimental values much better, especially at low energies.
Figure 3. Mass widths varying with the excitation energy at the scission-point for the $^{34}\text{S}+^{186}\text{W}$ system.

Figure 4. Angular distributions of fission fragments for the $^{32}\text{S}+^{184}\text{W}$ reactions.
From the above results one can see that both mass and TKE distributions are explained well by the scission-point statistical model for the $^{34}\text{S}+^{186}\text{W}$ system. It denotes that both mass and TKE achieve their equilibrium before fission. In other words, there is no obvious QF component in the fission of the $^{34}\text{S}+^{186}\text{W}$ reaction. For the $^{32}\text{S}+^{184}\text{W}$ system, the angular distributions deviate from the anticipation of SPTS model while conform to the expectation of pre-equilibrium fission model. Combining these two system, one may draw the following conclusions, i) the mass and energy distributions have no sensitivity to the non-equilibrium fission like the pre-equilibrium fission but the angular distribution has, ii) the relaxation time of the $K$ degree of freedom is long than that of the mass and energy degrees of freedom, iii) the mass-energy-angle correlated measurement should be a powerful means to analyze the detailed fission dynamics, which is strongly required in the future.

4. Summary
In summary, fission fragments of the $^{32}\text{S}+^{184}\text{W}$ and $^{34}\text{S}+^{186}\text{W}$ reactions have been measured by silicon-strip detectors at energies around the Coulomb barrier. The mass distributions of the $^{34}\text{S}+^{186}\text{W}$ system and the angle distributions of the $^{32}\text{S}+^{184}\text{W}$ system were obtained, respectively. The mass widths of $^{34}\text{S}+^{186}\text{W}$ are in good agreement with the predictions of the scission-point statistical mode, which does not show the quasi-fission component. The traditional SPTS model fails to explain the experimental anisotropy of $^{32}\text{S}+^{184}\text{W}$ but the low-momentum-dependent pre-equilibrium fission model can do that. Combining these two systems to analyze, it denotes that the pre-equilibrium fission rather than the quasi-fission occurs in the S+W system. The mass-energy-angle correlated measurement is strongly desired to analyze the fission dynamics in detail.
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