Fusion-fission and quasifission competition in the $^{32}\text{S} + ^{184}\text{W}$ reaction

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Abstract. The angular distribution of fission fragments for the $^{32}\text{S} + ^{184}\text{W}$ reaction at center-of-mass energies of 118.8, 123.1, 127.3, 131.5, 135.8, 141.1 and 144.4 MeV were measured. The experimental fission excitation function is obtained. The fragment angular anisotropy is found by extrapolating the fission angular distributions. The measured fission cross sections are decomposed into fusion-fission, quasifission and fast-fission contributions by the dinuclear system model. The total evaporation residue and fusion-fission excitation functions are calculated in the framework of the advanced statistical model. The hindrance to complete fusion at small collision energies increases due to the increase of quasifission events and it is explained by the elongated shape of the dinuclear system which is formed in collisions with small orientation angles to the beam direction. An increase of the hindrance to complete fusion at large beam energies is explained by the dependence of the quasifission and intrinsic fusion barriers of dinuclear system on its angular momentum: at large angular momentum the quasifission barrier decreases and the intrinsic fusion barrier increases. In this reaction the contributions of fusion-fission and quasifission fragments are comparable.

1. Introduction
Studies of fusion-fission reactions between heavy ion projectile and heavy target nuclei have demonstrated to be very useful in developing an understanding of the nuclear reaction dynamics.

The study of dynamics of processes in heavy ion collisions at the near Coulomb barrier energies showed that complete fusion does not occur immediately in case of the massive nuclei collision [1, 2, 3, 4, 5]. The quasifission process competes with formation of compound nucleus (CN). This process occurs when the dinuclear system prefers to break down into fragments instead of to be transformed into fully equilibrated CN. The number of events going to quasifission increases drastically by increasing the sum of the Coulomb interaction and rotational energy in the entrance channel [6, 7]. Another reason decreasing yield of ER is the fission of a heated and rotating CN which is formed in competition with quasifission. The stability of massive CN
decreases due to the decrease of the fission barrier by increasing its excitation energy $E_{CN}^*\ell$ and angular momentum $\ell$ [8, 9]. Because the stability of the transfermium nuclei are connected with the availability of shell correction in their binding energy [11, 12] which are sensitive to $E_{CN}^*$ and values of the angular momentum. To find favorable reactions (projectile and target pair) and the optimal beam energy range leading to larger cross sections of synthesis of superheavy elements, we should establish conditions to increase as possible the events of ER formation.

The presence of quasifission fragments in the measured yield of fission-like fragments is determined by the large values of anisotropy in their angular distribution (see Refs.[1, 14, 13], and references therein) and by the increased yield of fragments with masses near proton magic numbers 28, 50, 82 and neutron magic numbers 50, 82, 126 [15, 16].

In this contribution we have analyzed the angular distribution of fission fragments of the $^{32}\text{S}^+\,^{184}\text{W}$ reaction and we obtained fission excitation function at the center-of-mass energies of 118.8, 123.1, 127.3, 131.5, 135.8, 141.1 and 144.4 MeV. The fragment angular anisotropy $A_{\exp}$ is found by extrapolating the fission angular distributions to angles 0° and 90° by the method used in Ref. [17]. Then, the mean square angular momentum $\langle L^2 \rangle$ values were obtained. Hereafter we use for simplicity $\ell$ from the definition $L = l \hbar$. We assumed the calculated capture cross sections to be equal to the experimental data of fission-like fragments in order to decompose the measured fission cross section into fusion-fission, quasifission and fast fission contributions by the dinuclear system model [2, 3, 7, 18]. The quasifission is a break of the DNS into two fragments bypassing the stage of the CN formation. The fast fission process is the inevitable decay of the fast rotating mononucleus into two fragments without reaching the equilibrium compact shape of CN. Such mononucleus is formed from the dinuclear system survived against quasifission. At large values of the angular momentum $\ell > \ell_f$, where $\ell_f$ is a value of $\ell$ at which the fission barrier of the corresponding CN disappears, mononucleus immediately decays into two fragments [19]. As distinct from fast fission, the quasifission can occur at all values of $\ell$ at which capture occurs. The total ER and fusion-fission excitation functions are calculated in the framework of the advanced statistical model [8, 9, 10]. The ER cross sections for the $^{32}\text{S}^+\,^{184}\text{W}$ reaction are small in comparison with the other contributions forming capture cross section.

To determine the ER cross section $\sigma_\text{ER}(E)$ we have to know at first the partial capture cross sections $\sigma_\text{capture}(E)$, the two factors $P_{\text{CN}}$ and $W_{\text{sur}}$ corresponding to competition between complete fusion and quasifission at the second stage, and to competition between cooling of the heated and rotating CN by evaporation of light particles and its fission into two fragments at the third stage of reaction. This way of calculation was suggested in the dinuclear system (DNS) concept [2] and the estimation of $P_{\text{CN}}$ and $W_{\text{sur}}$ is the key point for the research of the fusion reaction products, especially for the synthesis of superheavy elements.

2. EXPERIMENTAL PROCEDURE

The experiment was performed at HI-13 tandem accelerator at China Institute of Atomic Energy, Beijing. A collimated $^{32}\text{S}$ beam with incident energies $E_{\text{lab}} = 140, 145, 150, 155, 160, 165$ and 170 MeV bombarded on a target of $^{184}\text{W}$ which was mounted at center of the scattering chamber. The $^{184}\text{W}$ target with thickness about 200 $\mu$g/cm$^2$ was evaporated on an about 20 $\mu$g/cm$^2$ carbon foil backing. Typical $^{32}\text{S}$ beam current was 800-1000 enA monitored by a shielded suppressed Faraday cup at periphery of the chamber, because of the variety according to the bombarding energy and scattering angle. The beam energy loss in traveling half the target were calculated and was about 0.5 MeV.

At the forward angles, an array of five Si detectors with depletion depth ranging from 200 to 300 $\mu$m, which covered the angular range of $\theta_L = 14^\circ - 35^\circ$, 35°-55° and 55°-75° were mounted on the movable arm in the chamber and five masks were placed in the front of each detector for assuring the angular resolution. The detectors to the target distance was 27 cm. The Rutherford scattering was monitored at forward angle of $\theta_L = 15^\circ$ 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 × 50 mm² in area and each detector consisted of 24 strips. Due to a lack of readout electronics, the strips were tied together in groups of eight for readout. 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 processes observed 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 fission kinetic energies taken from the Viola systematics [20].

To obtain the absolute cross sections, we measured the solid angle by using the α-particles from the 241Am source and the elastic scattering products. Centering of the beam on the target was ensured by the four monitor detectors. A gate was set on the fission event and data were collected by the coincident mode.

3. EXPERIMENTAL RESULTS

3.1. Fission fragment angular distributions

The fission fragment angular distributions were measured using the coincident detectors and are shown in Fig. 1. In fitting the angular distribution of the fission fragments we used the familiar expression as in Ref. [17]:

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

assuming \( M=0 \), i.e. assuming the spins of the target and projectile were zero, where \( J_0 \) is the zero order Bessel function with imaginary argument and error function \( \text{erf}(x) \) is defined as

\[ \text{erf}(x) = (2/\pi^{1/2}) \int_0^x \exp(-t^2)dt. \]

The measured values of \( \sigma_{\text{capture}} \) and the deduced values of \( A_{\text{exp}} \) and \( K_0^2 \) for the \( ^{32}\text{S} + ^{184}\text{W} \) reaction are presented in Table 1. \( J_{\text{max}} \) is obtained by reproducing the capture cross section.
Table 1. The measured capture cross sections and the deduced values of $A_{\text{exp}}$, $K_0^2$ and $\langle l^2 \rangle$ for the $^{32}\text{S} + ^{184}\text{W}$ reaction. The $E_{\text{c.m.}}$ are the energies calculated as corresponding to the beam energies in the center of the target.

| $E_{\text{c.m.}}$ (MeV) | $E_{\text{CN}}^*$ (MeV) | $\sigma_{\text{capt}}$ (mb) | $A_{\text{exp}}$ | $K_0^2$ ($\hbar^2$) | $\langle l^2 \rangle$ ($\hbar^2$) |
|------------------------|------------------------|-----------------------------|-------------------|---------------------|---------------------|
| 118.8                  | 37.2                   | 0.04                        | 1.51              | 114.71              | 234                 |
| 123.1                  | 41.5                   | 2.35                        | 2.16              | 124.35              | 577                 |
| 127.3                  | 45.8                   | 22.97                       | 2.27              | 132.09              | 671                 |
| 131.5                  | 50.0                   | 81.01                       | 2.74              | 140.01              | 975                 |
| 135.8                  | 54.3                   | 132.27                      | 3.06              | 148.67              | 1225                |
| 141.1                  | 58.5                   | 189.33                      | 3.28              | 157.35              | 1435                |
| 144.4                  | 61.8                   | 237.06                      | 3.8               | 155.09              | 1737                |

The $K_0^2$ value is found by fitting the angular distribution at known $J_{\text{max}}$ from the total fission cross section. It is seen from Fig. 1 that the anisotropy of angular distribution increases by increasing collision energy $E_{\text{c.m.}}$.

### 3.2. Capture cross section

In order to deduce the capture cross section from the data, the Si strip detectors operating in the coincidence mode were used. Each fission event was selected on the basis of the correct value of energy and of the folding angle corresponding to complete momentum transfer using the forward Si detectors as a "trigger" detector. After correction for the efficiency of the Si strip detectors, a differential cross section $d\sigma/d\Omega(\theta)$ was obtained. The total cross section was deduced from the integration of the differential cross sections.

The resulting experimental values of the capture cross sections are shown in Table 1 and Fig. 3 where they are compared with the theoretical results. The total fission cross section is assumed to be equal to the theoretical capture cross section and it was decomposed into fusion-fission and quasifission parts in the framework of the DNS model mentioned in Section 1. The comparison of the measured capture cross section, anisotropy, mean square values of angular momentum, and variance $K_0^2$ with the corresponding experimental data is discussed in Section 4.

### 3.3. Anisotropy of fission-fragments and mean square angular momentum values

The experimental values of the anisotropy $A_{\text{exp}}$ are found by extrapolating the fission angular distributions to angles 0° and 90° by the method used in Ref. [17]. The anisotropies as a function of center-of-mass energies are shown in Table 1 and Fig. 7 where they are compared with the theoretical results. Using the approximate relation between the anisotropy and the mean square angular momentum (see Section 4 for details), the mean square angular momentum values $\langle l^2 \rangle$ are deduced from the experimental anisotropies. The data are shown in Table 1 and Fig. 8.

### 4. Theoretical description and comparison with measured data

The experimental data for the excitation function of fission-like products in the $^{32}\text{S} + ^{184}\text{W}$ reaction were analyzed in the framework of the dinuclear system model (DNS) [6, 7, 18, 21, 22]. The capture, fusion, quasifission and fast fission excitation functions have been calculated for this reaction.
Figure 2. The potential energy surface for a dinuclear system leading to the formation of the $^{216}\text{Th}^*\text{CN}$ as a function of the relative distance $R$ between centers of interacting nuclei and their charge numbers $Z$, panel (a); the nucleus-nucleus interaction potential $V(R)$ shifted on the $Q_{gg}$-value for the $^{32}\text{S} + ^{184}\text{W}$ reaction, panel (b); the driving potential, $U_{dr}(Z, R_{m})$, which is a curve linking minimums corresponding to each charge asymmetry in the valley of the potential energy surface as a function of $Z$, panel (c).

According to the DNS model a capture event is the trapping of the collision path into the potential well after dissipation of the sufficient part of the relative kinetic energy of a projectile nucleus in the center-of-mass coordinate system. At capture the full momentum transfer from the relative motion of nuclei into excitation energy of dinuclear system takes place. Certainly the presence of a potential pocket and adequacy of the collision energy $E_{c.m.}$ to overcome the interaction barrier of the entrance channel $V_B$ are necessary conditions to occur capture. Thus capture leads to forming dinuclear system which characterized by mass (charge) asymmetry of its nuclei, rotational energy $V_{rot}$ and excitation energy $E_{DNS}$. The relative energy of nuclei is relaxed, therefore, the total kinetic energy of fragments formed at its decay are close to the Viola systematics [20].

The nucleus-nucleus potential $V(Z, A, R)$ is a sum of the Coulomb $V_C(Z, A, R)$ and nuclear interaction $V_N(Z, A, R)$, as well as the rotational energy $V_{rot}(Z, A, R, \ell)$:

$$V(Z, A, R, \ell) = V_C(Z, A, R) + V_N(Z, A, R) + V_{rot}(Z, A, R, \ell)$$  \hspace{1cm} (3)

where $Z = Z_1$ and $A = A_1$ are the charge and mass numbers of one of fragments forming DNS, respectively, while the charge and mass numbers of another fragment are equal to $Z_2 = Z_{CN} - Z$ and $A_2 = A_{CN} - A$, respectively, where $Z_{CN}$ and $A_{CN}$ the charge and mass numbers of being formed CN; $R$ is the relative distance between the centers of nuclei forming the dinuclear system.

The partial capture cross section is found by solution of kinetic equation for the relative motion and orbital angular momentum $\ell$ for the different orientation angle $\alpha_T$ of the target nucleus as it was performed in Refs. [6, 18]. The fusion cross section is calculated from the
branching ratio $P_{CN}(Z)$ of the decay rates of overflowing the border of the potential well ($B_{qf}^{(*)}$) along $R$ at a given mass asymmetry (decay of DNS-quasifission) over the barriers on mass asymmetry axis $B_{fus}^{(*)}$ for the complete fusion or $B_{sym}^{(*)}$ in opposite direction to the symmetric configuration of DNS (see Fig. 2):

$$P_{CN}^{(Z)}(E_{DNS}^{(*)}) \approx \frac{\Gamma_{fus}^{(*)} (B_{fus}^{(*)}, E_{DNS}^{(*)})}{\Gamma_{qf}^{(*)} (B_{qf}^{(*)}, E_{DNS}^{(*)}) + \Gamma_{fus}^{(*)} (B_{fus}^{(*)}, E_{DNS}^{(*)}) + \Gamma_{sym}^{(*)} (B_{sym}^{(*)}, E_{DNS}^{(*)})},$$

where $\Gamma_{fus}$, $\Gamma_{qf}$ and $\Gamma_{sym}$ are corresponding widths determined by the level densities on the barriers $B_{fus}^{(*)}$, $B_{sym}^{(*)}$ and $B_{qf}$ involved in the calculation of $P_{CN}$ are used in the model [18, 7, 4] based on the dinuclear system concept [23]. Here $E_{DNS}^{(*)}(Z, A, \ell) = E_{cm} - V(Z, A, \ell, R_{m})$ is the excitation energy of dinuclear system in the entrance channel, where $Z$ and $A$ are charge and mass numbers of the projectile nucleus. $V(Z, A, R_{m}, \ell)$ is the minimum value of the nucleus-nucleus potential well (for the DNS with charge asymmetry $Z$) and its position on the relative distance between the centers of nuclei is marked as $R = R_{m}$ in Fig. 2b. The value of $B_{qf}$ for the decay of DNS with the given charge asymmetry of fragments is equal to the depth of the potential well in the nuclear-nuclear interaction (see Fig. 2b). The intrinsic fusion barrier $B_{fus}^{(*)}$ is connected with mass (charge) asymmetry degree of freedom of the dinuclear system and it is determined from the potential energy surface (Fig. 2a):

$$U(Z; R, \ell) = U(Z, \ell, \beta_1, \alpha_1; \beta_2, \alpha_2) = B_1 + B_2 + V(Z, \ell, \beta_1, \alpha_1; \beta_2, \alpha_2; R) - (B_{CN} + V_{CN}(\ell)).$$

Here, $B_1, B_2$ and $B_{CN}$ are the binding energies of the nuclei in DNS and the CN, respectively, which were obtained from [24]; the fragment deformation parameters $\beta_i$ are taken from the tables in [25, 26, 24] and $\alpha_i$ are the orientation angles of the reacting nuclei relative to the beam direction: $V_{CN}(\ell)$ is the rotational energy of the CN. The distribution of neutrons between two fragments for the given proton numbers $Z$ and $Z_2$ or ratios $A/Z$ and $A_2/Z_2$ for both fragments were determined by minimizing the potential $U(Z; R)$ as a function of $A$ for each $Z$.

The driving potential $U_{dr}(Z) = U(Z, R_{m})$ is a curve linking minimums corresponding to each charge asymmetry $Z$ in the valley of the potential energy surface from $Z = 0$ up to $Z = Z_{CN}$ (see Fig. 2a and 2c). We define the intrinsic fusion barrier for the charge asymmetry $Z$ of dinuclear system as $B_{fus}^{(*)}(Z, \ell) = U(Z_{max}, R_{m}(Z_{max}), \ell) - U(Z, R_{m}(Z), \ell)$, where $U(Z_{max}, \ell)$ is a maximum value of potential energy in the valley along the way of complete fusion from the given $Z$ configuration.

The masses and charges of the projectile and target nuclei are not constant during capture and after formation of the dinuclear system. The intense proton and neutron exchange between constituents of DNS is taken into account by calculation of the complete fusion probability $P_{CN}$ as fusion from all populated DNS configurations according to the formula

$$P_{CN}^{(*)}(E_{DNS}^{(*)}(Z, A, \ell); \{\alpha_i\}) = \sum_{Z_{sym}}^{Z_{max}} Y_Z^{(*)}(E_{DNS}^{(*)}(Z, A, \ell)) P_{CN}^{(*)}(E_{DNS}^{(*)}(Z, A, \ell); \{\alpha_i\})$$

where $E_{DNS}^{(*)}(Z, A, \ell) = E_{DNS}^{(*)}(Z, A, \ell) + \Delta Q_{gg}^{(*)}(Z)$ is the excitation energy of DNS with angular momentum $\ell$ for a given value of its charge-asymmetry configuration $Z$ and $Z_{CN} - Z; \Delta Q_{gg}^{(*)}(Z)$ is the change of $Q_{gg}$-value by changing the charge (mass) asymmetry of DNS; $Y_Z^{(*)}(E_{DNS}^{(*)}(Z, A, \ell))$ is the probability of population of the ($Z, Z_{CN}-Z$) configuration at $E_{DNS}^{(*)}(Z, A, \ell)$ and given orientation angles ($\alpha_1, \alpha_2$). It was obtained by solving the master equation for the evolution of the dinuclear system charge asymmetry (for details see Refs. [18, 13]). $Z_{sym} = (Z_1 + Z_2)/2$ while $Z_{max}$ corresponds to the point where the driving potential reaches its maximum ($B_{fus}^{(*)}(Z_{max}) = 0$) (see Refs. [7, 27]).
The calculations were performed for the $E_{\text{c.m.}} = 119.5 - 149.5$ MeV energy range and initial values of the orbital angular momentum $\ell = 0 - 120\hbar$. Due to the deformed shape of $^{184}\text{W}$ ($\beta_2 = 0.24$ and $\beta_4 = -0.095$) in the ground state we included in our calculations a dependence of the excitation function of capture, complete fusion and quasifission on the orientation angle $\alpha_T$ of its axial symmetry axis. The ground state shape of $^{32}\text{S}$ is spherical but the quadrupole ($2^+$) and octupole ($3^-$) collective excitations in spherical nuclei are taken into account as amplitudes of the zero-point motion mode of surface vibration. The deformation parameters of the first excited quadrupole state $\beta_2^{(2+)} = 0.312$ (taken from Ref. [25]) and the ones of the first excited octupole state $\beta_3^{(3-)} = 0.41$ (taken from Ref. [26]). The final results of the capture and complete fusion are obtained by averaging the contributions calculated for the different orientation angles ($\alpha_T = 0$, 15, 30, ..., 90°) of the symmetry axis of the target nucleus:

$$\langle \sigma_{\text{fus}}(E_{\text{c.m.}}, l) \rangle = \int_0^{\pi/2} \sin \alpha_T \sigma_{\text{fus}}(E_{\text{c.m.}}, l; \alpha_T) d\alpha_T. \quad (7)$$

This methods were developed and used in the Refs. [18, 21, 22]. The results of calculation of the excitation functions are presented in Fig. 3. In this figure we compare theoretical results with the experimental data for the capture cross section of this work. The agreement between the experimental and theoretical capture cross sections was reached by changing the radius parameter $C_R$ entered to rescale the nuclear radius:

$$R_1 = C_R \sqrt{(R_p^2 Z_1 + R_n^2 (A_1 - Z_1))/A_1}, \quad (8)$$

where $R_p$ and $R_n$ are the proton and neutron radii, respectively, obtained from Ref. [28]:

$$R_p = 1.237(1 - 0.157(A - 2Z)/A - 0.646/A)^{1/3}, \quad (9)$$
$$R_n = 1.176(1 + 0.25(A - 2Z)/A + 2.806/A)^{1/3}. \quad (10)$$

The presented results are obtained at $C_R = 0.925$ for all values of $E_{\text{c.m.}}$. Using Eq.(7) we calculated the partial fusion cross sections which were used to estimate the cross sections of ER and fusion-fission by the advanced statistical model [8, 9]. Taking into account the dependence of the fission barrier ($B_f$) of the rotating CN on its angular momentum we found a value of $\ell$ at which $B_f$ disappears using the rotating finite range model by A. J. Sierk [29]: $\ell_B = 68$. Then we calculate the fast fission contribution for $\ell > \ell_B$

$$\sigma_{\text{fast fission}}(E_{\text{c.m.}}) = \sum_{\ell = \ell_B}^{\ell = \ell_{\text{max}}} (2\ell + 1) \sigma_{\text{fus}}(E_{\text{c.m.}}, \ell) \quad (11)$$

where $\ell_{\text{max}}$ is the maximum value of angular momentum of the dinuclear system for the given value of $E_{\text{c.m.}}$. The value of $\ell_{\text{max}}$ is found by solving the equations of motion for the radial distance and orbital angular momentum with the given values of $E_{\text{c.m.}}, \ell_0$ and $R_{\text{max}} = 20$ fm.

In Fig. 3 are also presented the total fusion-fission and ER cross sections obtained by the advanced statistical model (see Refs. [8, 9, 10], and references therein) describing the full deexcitation cascade of the $^{216}\text{Th}^*$ CN formed in the $^{32}\text{S} + ^{184}\text{W}$ reaction. The code takes into account the competition between evaporation of light particles (n, p, α, and γ) and fission processes along each step of the deexcitation cascade of CN. The effective fission barrier for CN and intermediate excited nuclei along the cascade are obtained taking into account the macroscopic fission barrier, predicted by the rotating droplet model as parameterized by Sierk [29], together with the microscopic corrections allowing for the angular momentum and
temperature fade-out of shell corrections [24] to the fission barrier (see Refs. [3, 27, 30], and reference therein).

The cross section of ER formed at each step \( x \) of the deexcitation cascade after the emission of \( \nu(x)n+y(x)p+k(x)\alpha+s(x)\gamma \) particles (\( \nu, y, k, s \) are numbers of neutrons, protons, \( \alpha \)-particles and \( \gamma \)-quanta) from the hot CN is calculated by the formula [7, 27, 3]:

\[
\sigma_{\text{ER}}(E^*_x) = \sum_{l=0}^{l_d} \sigma^{(x-1)}_{l}(E^*_x) W_{\text{sur}(x-1)}(E^*_x, l),
\]

where \( \sigma^{(x-1)}_{l}(E^*_x) \) is the partial cross section of the intermediate nucleus formation at the \( (x-1) \)th step and \( W_{\text{sur}(x-1)}(E^*_x, l) \) is the survival probability of the \( (x-1) \)th intermediate nucleus against fission along the deexcitation cascade of CN; \( E^*_x \) is an excitation energy of the nucleus formed at the \( x \)th step of the deexcitation cascade. It is clear that \( \sigma^{(0)}_{l}(E^*_0) = \sigma^{\text{ fus}}_{l}(E^*) \) at \( E^*_c, \text{CN} = E^*_0 = E_{\text{c.m.}} + Q_{\gamma\gamma} \), where \( Q_{\gamma\gamma} \) is energy balance of reaction. The numbers of the being emitted neutrons, protons, \( \alpha \)-particles, \( \gamma \)-quanta, \( \nu(x)n, y(x)p, k(x)\alpha, \) and \( s(x)\gamma \), respectively, are functions of the step \( x \). The emission branching ratio of these particles depends on the excitation energy and angular momentum of the being cooled intermediate nucleus \( A = A_{\text{CN}} - (\nu(x) + y(x) + 4k(x)) \) and \( Z = Z_{\text{CN}} - (y(x) + 2k(x)) \) [3]. We note that in Fig. 3 the maximum value of the excitation function of the total evaporation residues is about 0.12 mb and the complete spectrum is contributed mainly by the evaporation of charged particles which are accompanied with a small number of neutrons along the deexcitation cascade of CN.

4.1. Two regions of strong hindrance to complete fusion

Thus the experimental capture excitation function is decomposed into contributions of fusion-fission, quasifission, fast fission and total ER. One can see in Fig. 3 that at lowest energies \( E_{\text{c.m.}} < 125 \text{ MeV} \), the fusion cross section is sufficiently lower than the quasifission contribution. The intense of hindrance to complete fusion is estimated by the fusion factor \( P_{\text{CN}} \) and it is determined by Eqs. (4) and (6). We present in Fig. 4 the calculated values of \( P_{\text{CN}} \) as a function of the beam energy. It is seen the hindrance to fusion is strong at very small and large values of the collision energy \( E_{\text{c.m.}} \).

The yield of quasifission is dominant at the sub-barrier beam energies leading to capture of deformed nuclei only with the small orientation angle of its symmetry axis relative to the beam direction. This phenomenon was found by Hinde and his colleagues [14] in the \( ^{16}\text{O} + ^{238}\text{U} \) reaction where they observed the increase of the anisotropy of angular distribution of the fission fragments when beam energy decreases to the sub-barrier region. Its analysis has been discussed

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**Figure 3.** Comparison of the experimental data with theoretical results.

**Figure 4.** Theoretical value of \( P_{\text{CN}}(Z) \) for \( ^{32}\text{S} + ^{184}\text{W} \) system.
Figure 5. Driving potential calculated for the two different values of the orientation angles of target nuclei: $\alpha_T = 15^\circ$ (solid line) and $\alpha_T = 45^\circ$ (dashed line) for the $^{32}\text{S} + ^{184}\text{W}$ reaction.

in Ref. [13] in connection with the explanation of the observed large angular anisotropy of the fission fragments. As an alternative suggestion for the origin of the observed anomaly, Liu et al. in Ref. [31] have put forward a new version of the preequilibrium fission model. The anomalous bump exists in the variation of the fragment anisotropy with the incident energy for the systems such as $^{19}\text{F}$, $^{16}\text{O} + ^{232}\text{Th}$. Based on these studies, a new model of $K$ pre-equilibrium fission was proposed, which can well explain the observed anomalous anisotropy. The authors of Ref. [14] analyzed in detail the angular anisotropy of fragments at low energies to show the dominant role of the quasifission in collisions of the projectile with the target nucleus when the axial symmetry axis of the latter is oriented along or near the beam direction. Large values of the anisotropy were obtained at low energies and these data were assumed to be connected with quasifission because a mononucleus or dinuclear system formed in the near tip collisions has an elongated shape.

This shape can be far from the one corresponding to the saddle point. The driving potential used in the DNS model depends on the shape of dinuclear system which is formed in collisions with the different orientation angles of the axial symmetry axis of deformed target. The small values of the fusion probability $P_{\text{CN}}$ at lowest energies in the $^{32}\text{S} + ^{184}\text{W}$ reaction are explained by the large values of $B_{\text{qf}}$ for the dinuclear system formed at collisions of projectile with target oriented close to beam direction, i.e. when $\alpha_T$ is small. To demonstrate this conclusion we present in Fig. 5 the driving potential (upper panel) and quasifission barrier (lower panel) for the decay of dinuclear system as a function of the orientation angles of the target nucleus. It is seen from the upper panel of Fig. 5 that the value of driving potential corresponding to the projectile charge number $Z=16$ for the small orientation angle $15^\circ$ (solid line) of the target is lower than that corresponding to the larger orientation angle $45^\circ$ (dashed line). The fusion probability is larger if a value of the driving potential $U_{\text{dr}}(Z_{\text{proj}})$ corresponding to the initial charge number of the light fragment $Z_L$ of dinuclear system is as possible at the same level or higher than its maximum value at $Z=9$ along the way to complete fusion which means the transfer of all nucleons of light nucleus into heavy nucleus: $Z_L \rightarrow 0$ and $Z_H \rightarrow Z_{\text{CN}}$.

The decrease of its values at collision energies $E_{\text{cm}} > 135$ MeV is explained by decreasing the quasifission barrier $B_{\text{qf}}$ as a function of the orbital angular momentum $\ell$. Because the depth
of the potential well being $B_{qf}$ for a given charge asymmetry decreases due to the increase of the rotational energy $E_{rot}$ of the dinuclear system (for details see [7]). At the same time the intrinsic fusion barrier $B_{fus}^*$ increases by increasing $\ell$. At small collision energies only small values of $\ell$ are populated because capture does not occur if the initial energy of projectile is not enough to overcome the Coulomb barrier of the entrance channel.

It is seen from Fig. 6 that the values $\ell > 45$ are populated at collision energies $E_{c.m.} > 135$ MeV. Therefore, we conclude that the contribution of quasifission becomes dominant at $E_{c.m.} > 135$ MeV and it has an effect on the anisotropy of angular distribution which increases by increasing the collision energy. This is connected with the fact that at these energies all orientation angles $\alpha_T$ can contribute to the formation of compound nucleus because the Coulomb barrier for large orientation angles may be overcomed. As we know, in collisions with large $\alpha_T$ the fusion probability is large. The decrease of $P_{CN}$ at larger energies is explained by the decrease of the quasifission barrier $B_{qf}$ by increasing $\ell$ in collisions with all orientation angles.

4.2. Anisotropy of fission fragment angular distribution and variance $K_0^2$ of $K$ distribution

To clarify the role of quasifission fragments in the observed anisotropy $A_{exp}$, we calculated the contributions of the quasifission ($A_{qf}$) and fusion-fission ($A_{CN}$) fragments. We used the expression of the approximated anisotropy of the fission fragment angular distribution suggested by Halpern and Strutinski in Ref. [32] and Griffin in Ref. [33]:

$$A \approx 1 + \frac{(l^2)_{\parallel}}{4(3)_{eff}^{(i)}T_i},$$

where

$$\frac{1}{3_{\parallel}} = \frac{1}{\bar{3}_{\parallel}} - \frac{1}{\bar{3}_{\perp}}.$$ (13)

Here $3_{eff}^{(i)}$ is the effective moment of inertia for the CN on the saddle point $i = CN$ or it is the effective moment of inertia for the dinuclear system on the quasifission barrier $i = DNS$. In the last case, we calculate $3_{eff}$ for the dinuclear system taking into account the possibility of different orientation angles of its constituent nuclei (see Appendix A of Ref.[13]), assuming that after capture the mutual orientations of the DNS nuclei do not change sufficiently. $3_{\parallel}$ and $3_{\perp}$ are the moments of inertia around the symmetry axis and a perpendicular axis, respectively.

Their values for $3_{eff}^{(CN)}$ are determined in the framework of the rotating finite range model by Sierk [29]. The temperature of CN on the saddle point is found by the expression:

$$T_{CN} = \left[\frac{E_{c.m.} + Q_{gs} - B_f(\ell) - E_n}{A_{CN}/12}\right]^{1/2},$$ (14)

where $B_f(\ell)$ is the fission barrier height. $B_f(\ell)$ is calculated in terms of the rotating liquid drop model by Sierk [29]. $E_n$ is the energy carried away by the pre-saddle fission neutrons. The
Figure 8. Mean square value of the angular momentum (upper panel) versus the collision energy $E_{\text{c.m.}}$ for the $^{32}\text{S}+^{184}\text{W}$ reaction. The experimental data are shown in comparison with the results of DNS model which are obtained by averaging $\ell^2$ by partial cross sections of the quasifission (dashed line) and complete fusion (solid line) events. In the lower panel the experimental and theoretical values of $K_0^2$ are compared.

The temperature of DNS on the quasifission barrier is determined by the expression:

$$T_{\text{DNS}} = \left[ \frac{(E_{\text{DNS}}^* - B_{\text{qf}})}{A_{\text{CN}}/12} \right]^{1/2}.$$  \hspace{1cm} (15)

An important physical quantity in the formula (13) is the variance $K_0^2$ of the Gaussian distribution of the $K$ projection:

$$K_0^2 = \frac{\Theta_{\text{eff}} T_{\text{saddle}}}{\hbar^2}. $$  \hspace{1cm} (16)

The experimental values of $K_0^2$ are used to fit the angular distribution of fission fragments by formula (1) (see Ref.[17, 34]).

In Fig. 7 we compare the anisotropy measured (circles) in this work with the theoretical results for the anisotropy of the quasifission (dashed line) and fusion-fission (solid line) fragments as a function of the center-of-mass energy (bottom axis) and excitation energy of the CN (top axis). The averaged theoretical anisotropy over the contributions of both mechanisms are presented by the dot-dashed line. It is seen that the averaged values of anisotropy are closer
to the experimental data $A_{\text{exp}}$. Consequently we confirm that the measured cross section of the fission fragment formation and their angular distribution are results of mixing of the quasifission and fusion-fission products. In the upper panel of Fig.8, we compare experimental and theoretical values of mean square values of angular momentum. The experimental $\langle L^2 \rangle$ values are obtained from the measured anisotropy $A_{\text{exp}}$ and $K_0^2$ values used to fit measured angular distributions presented in Fig. 1. The theoretical values for fusion-fission and quasifission fragments are calculated by averaging $\ell^2$ using the partial cross sections of the quasifission (dashed line) and complete fusion (solid line) events. The experimental data are well described with the averaged values of $L^2$ between the complete fusion and quasifission cross sections:

$$\langle L^2 \rangle = \frac{\sigma_{\text{fus}} \langle L^2 \rangle_{\text{fus}} + \sigma_{\text{qf}} \langle L^2 \rangle_{\text{qf}}}{\sigma_{\text{fus}} + \sigma_{\text{qf}}}.$$  \hfill (17)

In the lower panel of Fig.8, the experimental results of $K_0^2$ are compared with the theoretical values obtained from the description of $A_{\text{exp}}$ (dashed line in Fig.7) and $\langle L^2 \rangle$ (dot-dashed line in Fig.8) extracted from the experimental data of the angular distribution of fission fragments. This comparison shows again the dominancy of the quasifission fragments into measured data at low energies.

5. CONCLUSION

The fission angular distributions for the $^{32}\text{S} + ^{184}\text{W}$ reaction have been measured. We obtained the experimental cross sections of fission-like, anisotropy $A_{\text{exp}}$, and $\langle l^2 \rangle$ values compared with the results of the DNS model calculations. Assuming the measured fission cross sections is equal to the capture cross section they were decomposed into fusion-fission, quasifission and fast fission contributions by the dinuclear system model. The hindrance to complete fusion at small collision energies increases due to the increase of the quasifission events and it is explained by the elongated shape of the dinuclear system which is formed in collisions with small orientation angle of the symmetry axis of $^{184}\text{W}$ to the beam direction. Because of collisions with small orientation angles the intrinsic fusion barrier $B_{\text{fus}}^*$ is larger and quasifission barrier $B_{\text{qf}}$ is smaller in comparison with the corresponding barriers in the case of collision with large orientation angles. An increase of the quasifission contribution at large beam energies is connected by the angular momentum dependence of the quasifission $B_{\text{qf}}$ and intrinsic fusion $B_{\text{fus}}^*$ barriers: at large angular momentum of dinuclear system $B_{\text{qf}}$ decreases and $B_{\text{fus}}^*$ increases. The large quasifission barrier increases the life-time of dinuclear system allowing it to transform into a CN [18, 7]. It is concluded that the effects of competition between fusion and quasifission in the reaction play an important role in the dynamics process. The total evaporation residue and fusion-fission excitation functions are calculated in the framework of the advanced statistical model. The maximal value of the total cross section of the evaporation residue is 0.12 mb and fusion-fission cross section is comparable with the quasifission cross section. The contribution of the fast fission appears at $E_{\text{c.m.}} > 131$ MeV and it is sufficiently small in comparison with contributions of fusion-fission and quasifission reactions.

ACKNOWLEDGMENTS

This work was supported by the Major State Basic Research Development Program under Grant No. G2000077400 and the National Natural Science Foundation of China under Grant Nos. 10375095, 10735100, and 10811120019. A.A. Nasirov is grateful to the Istituto Nazionale di Fisica Nucleare and Department of Physics of the University of Messina for the support received in the collaboration between the Dubna and Messina groups.

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