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Quasifission and difference in formation of evaporation residues in the $^{16}O + ^{184}W$ and $^{19}F + ^{181}Ta$ reactions

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ABSTRACT

The role of the entrance channel has been studied to ascertain a cause of the observed difference between the evaporation residue cross sections normalized to the fusion cross sections in the $^{19}F + ^{181}Ta$ and $^{16}O + ^{184}W$ reactions at high excitation energies. The theoretical analysis performed in the framework of the dinuclear system and advanced statistical models showed that the more intense yield of evaporation residues in the $^{16}O + ^{184}W$ reaction in comparison with that in the $^{19}F + ^{181}Ta$ reaction was explained by the large capture and fusion cross sections in the former reaction, which is in agreement with the experimental data. The observed decrease in the evaporation residue cross section normalized to the fusion cross section in the $^{19}F + ^{181}Ta$ reaction, in comparison with one in the $^{16}O + ^{184}W$ reaction at large excitation energies, is caused by the unintentional inclusion of the quasifission and fast fission contributions in the fissionlike fragment yields that were used in reconstructing the experimental fusion cross section in the normalizing procedure. The range of the angular momentum distribution for both systems was similar, but the partial cross sections are different, showing the presence of a difference in the hindrance to complete fusion in both reactions.

1. Introduction

The observed yield of evaporation residues (ER) in experiments is a result of the de-excitation of a heated and rotating compound nucleus (CN) formed in complete fusion reactions in competition against fission in heavy ion collisions. Comparison of the experimental results for the $^{16}O + ^{184}W$ [1] and $^{19}F + ^{181}Ta$ [2] reactions leading to the same ^{200}Pb CN systems shows that ER cross section and moments of gamma multiplicity distribution of the former system are significantly higher than those of the latter system. This means that the complete fusion cross section for the former reaction is larger, as well. The significant difference between the fusion probabilities for the reactions under discussion is caused by the large capture probability for the $^{16}O + ^{184}W$ reaction because the potential well of the nucleus–nucleus interaction for the more asymmetric system is wider and deeper. Therefore, the measured cross sections of the fissionlike and ER fragment yields for the $^{16}O + ^{184}W$ reaction are larger than those for the $^{19}F + ^{181}Ta$ reaction (see Figs. 1 and 2). These facts directly indicate the experimental signature of an entrance channel effect even with systems that are not very different with respect to their entrance channel mass asymmetry. The similar conclusion was made in the work of Berriman et al. [3] from the observed unexpectedly broader mass distributions of fission fragments and suppression of ER cross sections in a very asymmetric $^{19}F + ^{197}Au$ reaction. But the results of angular distribution measurement reported in Ref. [4] did not show any significant contribution from quasifission in this reaction. We would like to stress that measurements of the ER cross sections are unambiguous in comparison with the determination of the anisotropy of the angular distribution of the fissionlike fragments [5]. Unfortunately, up to now, at the analysis of the angular distribution of the observed fissionlike fragments and reconstruction of the fusion cross section [6], quasifission was assumed to occur only at values of angular momentum larger than L_{fus} as suggested by B.B. Back in Ref. [7]. But angular momentum distributions of the fusion–fission and quasifission products overlap. This is discussed later (see Fig. 3). The new theoretical analysis of the dynamics and correlations between mass-angle distributions of the fissionlike reaction products, as well as experimental studies of fis-

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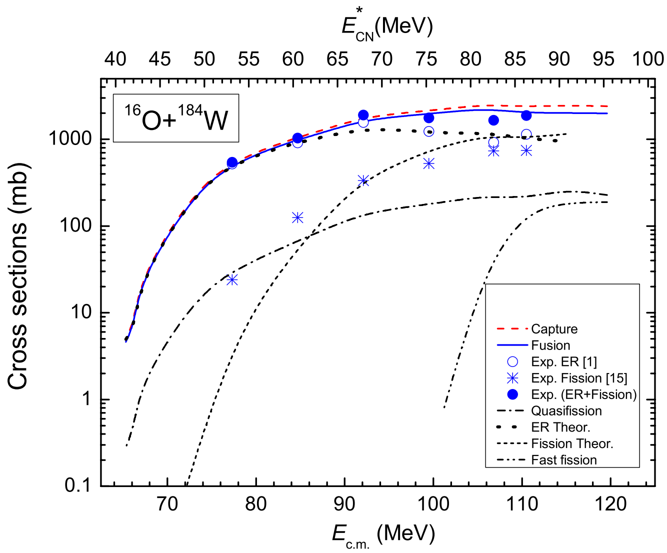

Fig. 1. Comparison of the experimental values of the fusion (filled circles) [1], evaporation residues (open circles) [1] and fission excitation function (stars) [15] for the $^{16}O + {}^{184}W$ reaction with the theoretical results obtained by the DNS model for the capture (dashed line), complete fusion (solid line), evaporation residues (dotted line), quasifission (dot-dashed line), fusion–fission (short-dashed line), and fast fission (dot-dot-dashed line).

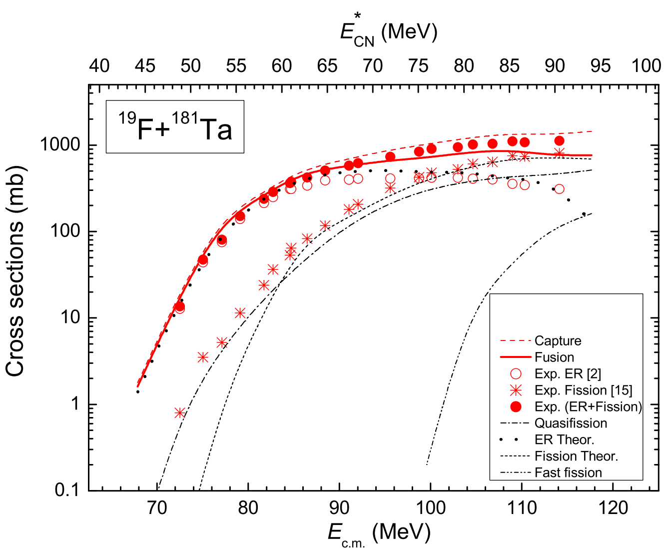

Fig. 2. As in Fig. 1, but for the $^{19}F + {}^{181}Ta$ reaction.

sionlike products in coincidence with neutron, charged particle and γ-quantum emission can allow to conclude about the contribution of the quasifission in the reactions of heavy ion collisions.

The theoretical ER cross sections obtained for these reactions in the framework of the dinuclear system (DNS) model [8–11] and advanced statistical model [12–14] are in the good agreement with the corresponding experimental data [1,2,15] (see Figs. 1 and 2).

A hindrance to formation of CN in the $^{19}F + {}^{181}Ta$ reaction at large energies is connected with increasing contribution of the quasifission process: part of the DNS formed after full momentum transfer (capture) breaks down into two fragments during its evolution instead of forming CN. Certainly, decreasing the number of CN leads to a decrease in ER events. The theoretical values of the quasifission contribution are presented in Fig. 2 by the dot-dashed line, while the fast fission is represented by dot-dot-dashed line. Theoretical values of the fusion–fission cross section are shown by short-dashed line. Fast fission is the inevitable decay of the fast rotating mononucleus into two fragments without reaching the equilibrium compact shape of CN [16]. Such a mononucleus is formed from the DNS that resisted quasifission, but it immediately decays into two fragments if the value of its angular momentum is larger than L_f, at which the fission barrier of the corresponding CN disappears. So, only in collisions with large values of the orbital angular momentum the fast fission of the being formed CN causes decreasing the yield of ER. Distinct from fast fission, quasifission can occur at all values of L at which the capture occurs [11,17].

The authors of Ref. [18] have compared the dependencies of the ER cross section normalized to the fusion cross section (σ_{ER}/σ_{fus}) on the excitation energy for the $^{16}O + {}^{184}W$ [1] and $^{19}F + {}^{181}Ta$ [2] reactions in the range of $E^*_{CN} = 50$–90 MeV to clarify the reasons causing the difference in the ER cross sections. The expected reasons assume to be connected with surviving of heated and rotating CN against fission. Due to the normalizing procedure, the decrease in the ER cross section connected with the decrease in the fusion cross section is canceled according to the aim of the analysis of the experimental data in Ref. [18]. The obtained values of σ_{ER}/σ_{fus} for the $^{16}O + {}^{184}W$ reaction are significantly higher than those of the $^{19}F + {}^{181}Ta$ system at higher excitation energies. Therefore, the observed difference between the values of σ_{ER}/σ_{fus} at energies $E^*_{CN} > 67$ MeV could be explained by the properties of a heated and rotating CN experiencing competition between fission and formation of ER after the emission of light particles.

This Letter is devoted to clarifying reasons causing the difference between the values of σ_{ER}/σ_{fus} measured for the $^{16}O + {}^{184}W$ and $^{19}F + {}^{181}Ta$ reactions at energies $E^*_{CN} > 67$ MeV and to demonstrate the presence of an ambiguity in the determination of the fission cross section and, consequently, the fusion cross section used in the normalizing procedure by the authors of Ref. [18]. Because this ambiguity leads to incorrect fusion cross section that is an important physical quantity to plan experiments, for example, to synthesize new superheavy elements. Therefore, in this work, the difference in the complete fusion and partial fusion cross sections in the reactions under discussion are explored as functions of the excitation energy and angular momentum of CN, respectively.

Our analysis shows that the reduction of the σ_{ER}/σ_{fus} values for the $^{19}F + {}^{181}Ta$ reaction in comparison with those of the $^{16}O + {}^{184}W$ system at higher excitation energies is explained by the increase in the quasifission and fast fission contributions to the fission cross section used in Ref. [18]. In addition, we explored the difference in the formation of CN and their spin distributions to explain the dependence of the σ_{ER}/σ_{fus} ratio as a function of excitation energy and angular momentum. Our calculations demonstrate that quasifission occurs in the whole range of angular momentum leading to capture: $L_{min} < L_{qf} < L_{cap}$, where L_{min} and L_{cap} are the minimal and maximal values, respectively, of the "L-window" for capture [11,17]. This means that the suppression of complete fusion for the $^{19}F + {}^{181}Ta$ reaction increases clearly at energies higher than $E^*_{CN} = 67$ MeV, for all values of the orbital angular momentum (see Fig. 3).

2. Main reasons causing hindrance to formation of evaporation residues

There are three main processes causing hindrances to ER formation in reactions with massive nuclei: quasifission, fusion–fission, and fast fission [17]. All of these processes produce binary fragments in different stages of reaction. Moreover, the angular and mass distributions of some parts of their products can overlap [5, 17]. Ignoring this mixing may lead to ambiguity at analysis of the

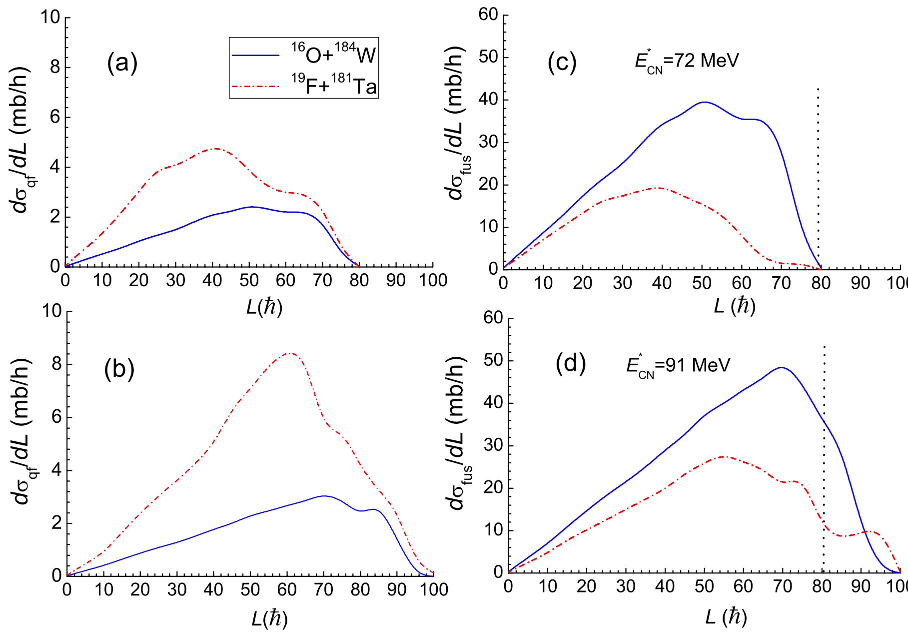

Fig. 3. Partial quasifission ((a) and (b) panels) and fusion ((c) and (d) panels) cross sections as a function of the angular momentum for the $^{16}O + ^{184}W$ (solid line) and $^{19}F + ^{181}Ta$ (dashed line) reactions. In the panel (a) the beam energies of reactions induced by ^{16}O and ^{19}F are $E_{c.m.} = 96.2$ MeV and 95.7 MeV, respectively. These energies correspond to the same excitation energy of CN (^{200}Pb) $E^*_{CN} = 72$ MeV for the both systems shown in the panel (c). Analogously, in the panel (b) the beam energies are $E_{c.m.} = 115.2$ MeV and $E_{c.m.} = 114.7$ MeV, respectively. The corresponding excitation energy of CN is 91 MeV shown in the panel (d). In (c) and (d), the vertical dashed line at $L_f = 80\hbar$ separates complete fusion and fast fission reactions (about L_f see text).

experimental data connected with the binary fragments. This problem should be studied carefully.

The ER formation process is often considered as the third stage of the three-stage process. The first stage is capture-formation of the DNS after full momentum transfer into the deformation energy of nuclei, their excitation energy, and rotational energy from the initial relative motion of the colliding heavy ions in the center-of-mass system. Capture takes place if the initial energy of the projectile in the center-of-mass system is enough to overcome the interaction barrier (Coulomb barrier + rotational energy of the entrance channel) [11]. The study of the dynamics of heavy ion collisions at energies near the Coulomb barrier shows that complete fusion does not occur immediately in collisions of massive nuclei [8,7,17,19,20]. After formation of the DNS, the quasifission process competes with the formation of CN. Quasifission occurs when the DNS prefers to break down into fragments instead of being transformed into a fully equilibrated CN. The number of events contributing to quasifission increases drastically by increasing the sum of the Coulomb interaction and rotational energy in the entrance channel [9,10,17].

Another reason for the decreasing yield of ER with increasing excitation energies is the usual fission of a heated and rotating CN that was formed in competition with quasifission. The stability of a massive CN decreases due to the decrease in the fission barrier by increasing its excitation energy E^*_{CN} and angular momentum L [12–14].

The theoretical values of the quasifission partial cross sections for the $^{19}F + ^{181}Ta$ and $^{16}O + ^{184}W$ reactions are presented in the left panels of Fig. 3. It is seen from these figures that the quasifission takes place at all values of L leading to capture. The angular momentum distributions of CN (^{200}Pb) formed in these reactions at the excitation energies $E^*_{CN} = 72$ and 91 MeV are presented in the right panels of Fig. 3. The spin distributions of CN formed in each of these reactions differ mainly by the probability but not by the values of the angular momentum ranges. This means that the number of CN formed in both reactions under discussion are different, but they have a similar range of the angular momentum L. The vertical dotted lines at $L_f = 80\hbar$ in these panels separates the complete fusion ($L_f < 80\hbar$) and fast fission ($L_f \geqslant 80\hbar$) regions of the angular momentum.

The quasifission and fast fission processes produce binary fragments which can overlap with those of the fusion–fission channel and the amount of mixed detected fragments depends on the mass asymmetry of entrance channel, as well as on the shell structure of the reaction fragments being formed. The suggestion for the experimental studies of the difference between characteristics of the fusion–fission, quasifission and fast fission products can be made when their mass (charge), kinetic energy and angular distributions are explored in detail by dynamical calculations allowing to obtain the relaxation times of these processes. Therefore, the correct estimation of the CN formation probability in the reactions with massive nuclei is a difficult task for both experimentalists and theorists. Different assumptions about the fusion process are used in different theoretical models which can give different cross sections. The experimental methods used to estimate the fusion probability depend on an unambiguous identification of the complete fusion products among the quasifission products. The difficulties arise when the mass (charge) and angular distributions of the quasifission and fusion–fission fragments strongly overlap, depending on the reaction dynamics. As a result, the complete fusion cross sections may be overestimated [17].

We confirm that the compared ratios of the cross sections between evaporation residues and complete fusion σ_{ER}/σ_{fus} for the $^{16}O + ^{184}W$ and $^{19}F + ^{181}Ta$ reactions discussed in [18] are not free from the above-mentioned ambiguity in the determination of the fusion cross section σ_{fus}. Theoretical values of the fusion cross section include only evaporation residues and fusion–fission cross sections

$$\sigma_{fus} = \sigma_{ER} + \sigma_{ff}. \tag{1}$$

The experimental values of fusion cross section, which were reconstructed from the detected fissionlike fragments [15], and

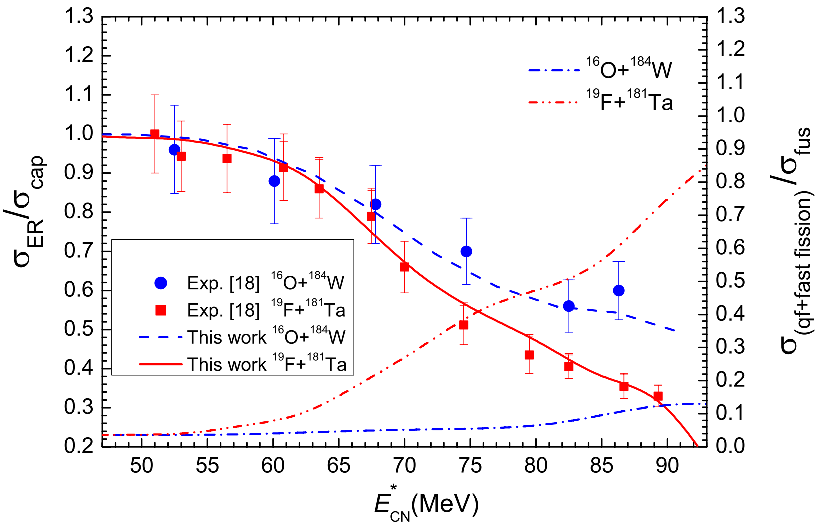

Fig. 4. Comparison of the experimental values of the evaporation residue cross sections normalized with respect to the capture cross sections for the $^{16}O + ^{184}W$ (solid circles) [18] and $^{19}F + ^{181}Ta$ systems (solid squares) [18] with the corresponding theoretical results (dashed and solid lines, respectively) as a function of the excitation energy E^*_{CN} of CN (left axis). Theoretical results of the sum of the quasifission and fast fission cross sections (normalized with respect of the fusion cross sections) for the $^{16}O + ^{184}W$ (dot-dashed line) and $^{19}F + ^{181}Ta$ (dot-dot-dashed line) systems are presented versus E^*_{CN} and compared on the right axis.

evaporation residues in Ref. [18] can be presented as following:

$$\sigma^{(exp)}_{fus} = \sigma_{ff} + \sigma_{qf} + \sigma_{fast\ fis} + \sigma_{ER}, \tag{2}$$

where σ_{ff}, σ_{qf}, and $\sigma_{fast\ fis}$ are the contributions of fusion–fission, quasifission and fast fission processes, respectively, and σ_{ER} is the ER contribution. According to the statement of the authors of Ref. [18], the complete fusion cross sections are obtained by adding fission cross sections [15] to the measured data of the evaporation residue cross sections [2].

In Ref. [15], the complete fusion cross section is derived from a statistical model where only neutron evaporation and fission are included. We think that the fission data from Ref. [15] contain quasifission fragments and, at larger beam energies, also fast fission contributions, which appear as hindrances to complete fusion. Therefore, we can state that the definition of the experimental fusion cross section is similar with the definition of capture [17]: $\sigma^{(exp)}_{fus} = \sigma_{cap}$. This argument is confirmed by our results obtained in the framework of the DNS model. We calculate the total ER and fusion–fission excitation functions in the framework of the advanced statistical model [12–14].

3. Study of difference in evaporation residue formation in $^{16}O + ^{184}W$ and $^{19}F + ^{181}Ta$ reactions

The study of the normalization procedure used in Ref. [18] showed that in our opinion, the evaporation residue cross section was practically normalized to the capture cross section:

$$R = \sigma_{ER}/\sigma^{(exp)}_{fus} = \sigma_{ER}/\sigma_{cap}. \tag{3}$$

Eq. (3) means that the presence of quasifission and fast fission products among fissionlike products leads to a decrease the evaporation residue cross section normalized to the reconstructed fusion cross section.

In Fig. 4, the results of the measured values of the ratio R for the $^{16}O + ^{184}W$ (solid circles) and $^{19}F + ^{181}Ta$ (solid squares) systems [18] are compared with the corresponding theoretical values (dashed and solid lines for the these two reactions, respectively) (left axis) as a function of the excitation energy E^*_{CN} of CN. The experimental values of ratio R are approximately equal for both reactions up to an excitation energy $E^*_{CN} = 67$ MeV; at larger excitation energies, the values of R corresponding to the $^{16}O + ^{184}W$ reaction become larger than ones obtained for the $^{19}F + ^{181}Ta$ reaction (see the left axis of Fig. 4). The authors of Ref. [18] explained the observed reduction of the ER cross sections for the $^{19}F + ^{181}Ta$ system by the suppression of partial ER cross sections at higher spin values. But the reason of this suppression is not clarified. So, they stressed the importance of spin distribution measurements. The difference between the values of the ratio R for the $^{16}O + ^{184}W$ and $^{19}F + ^{181}Ta$ reactions at large $E^*_{CN} > 67$ MeV energies expects to be connected with the ER formation stage in competition with fission of CN.

In difference from the conclusion of authors of the abovementioned paper, we explained the deviation between the experimental values of R for the $^{19}F + ^{181}Ta$ reaction (solid squares) and those of the $^{16}O + ^{184}W$ reaction (solid circles) at $E^*_{CN} > 67$ MeV by the increase of contributions of the quasifission and fast fission processes in the reconstructed values of the experimental fusion cross section ($\sigma^{(exp)}_{fus}$) in Ref. [18] for the $^{19}F + ^{181}Ta$ reaction. To prove this statement we show the calculated sum of the quasifission and fast fission cross sections normalized to the pure fusion cross section ($(\sigma_{qf} + \sigma_{fast\ fission})/\sigma_{fus}$) versus E^*_{CN} for the $^{16}O + ^{184}W$ (dot-dashed line) and $^{19}F + ^{181}Ta$ (dot-dot-dashed line) reactions on the right axis of Fig. 4. The theoretical curves of R for the both reactions are close in the $E^*_{CN} = 50$–67 MeV energy range where the quasifission cross section is comparable with fusion–fission cross section and their sum is very small in comparison with the ER cross section for both reactions under discussion (see Figs. 1 and 2). There is no influence of the entrance channel at small energies. At larger excitation energies $E^*_{CN} > 67$ MeV the theoretical and experimental values of R corresponding to the $^{16}O + ^{184}W$ reaction become larger than ones obtained for the $^{19}F + ^{181}Ta$ reaction (see the left axis of Fig. 4).

Our calculation of R by formula (3) which includes the contributions of quasifission and fast fission in the yield of fissionlike fragments well reach the experimental points presented for both reactions. Therefore, the difference in values of R for those reactions is explained by the ambiguity in the identification of the true fusion–fission products because the values of σ_{ER} are measured unambiguously. The mixture of fissionlike fragment yields

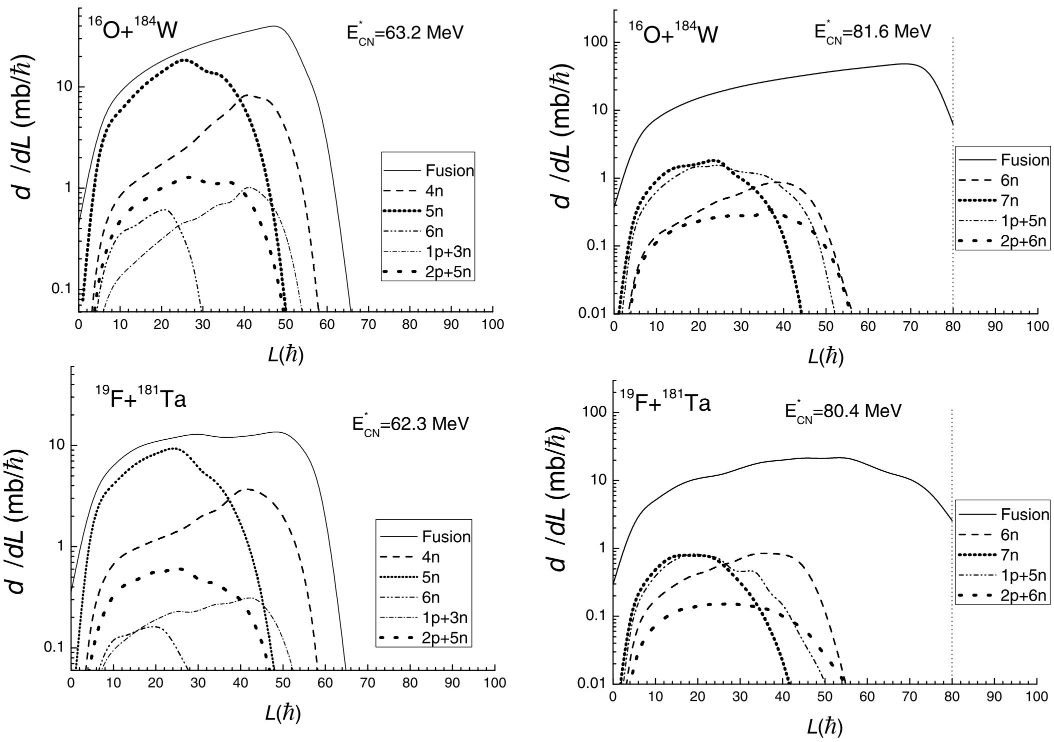

Fig. 5. Spin distribution of evaporation residue cross sections as a function of the angular momentum L. The upper part is for the $^{16}O + ^{184}W$ reaction, the lower part is for $^{19}F + ^{181}Ta$ reaction, both at two E^*_{CN} energies: approximately 62–63 MeV and 80–81 MeV.

were used in reconstructing the experimental fusion cross section in the normalizing procedure.

In other hand, if we use the correct pure fusion cross section by formula (1) in the calculation of the ratio R we obtain for both reactions the same slopes for the values R versus E^*_{CN} (like of the experimental points of the $^{16}O + ^{184}W$ reaction), confirming the result that the de-excitation dynamic of compound nuclei formed by the two above-mentioned reactions is the same. Therefore, if the experimental values of fusion cross section are depurated from the quasifission and fast fission contributions then the values of the ratio R have the same slope for the both $^{19}F + ^{181}Ta$ and $^{16}O + ^{184}W$ reactions. Instead, since the quasifission contribution for the $^{19}F + ^{181}Ta$ reaction is higher than the one for the $^{16}O + ^{184}W$ reaction, the present data demonstrate a relevant influence of this effect in the entrance channel also for such kind of mass asymmetric reactions.

The closeness of the theoretical and experimental values of R for the reactions under discussion is connected by using the capture cross section which is equal to sum the quasifission, fast fission and complete fusion cross sections. Increasing of the quasifission and fast fission contributions by increasing the beam energy is seen from Figs. 1 and 2. It means that explanation of this result in Ref. [18] by the suppression of fusion of higher L values is not confirmed by us although our theoretical and their experimental results are in good agreement. Our another important conclusion is that quasifission occurs at all values of L (see Fig. 3) leading to capture of nuclei in the entrance channel. This result should be taken into account in calculation of the angular distribution of the quasifission products [5] which can be used to check presence of the quasifission contribution in the given reaction [4]. Moreover, in Fig. 5, we report the spin distributions of evaporation residue cross sections calculated by us for E^*_{CN} values of approximately 62–63 and 80–81 MeV as an example for the two reactions. This figure shows that in both cases of the considered E^*_{CN} values (the one at energy lower than $E^*_{CN} = 67$ MeV, the other higher than 67 MeV), the corresponding evaporation residues (for example, the residues after 4n, 5n, 6n, 1p + 3n, 2p + 5n emissions) obtained in the two reactions cover the same angular momentum range.

In conclusion, we distinguish two points: (i) the apparent different behavior of the experimental values of the σ_{ER}/σ_{fus} ratio at large excitation energies is not due to the different decay dynamics of CN formed in the $^{16}O + ^{184}W$ and $^{19}F + ^{181}Ta$ reactions, but it is connected by the unintentional inclusion of the quasifission and fast fission contributions in the fissionlike fragment yields that were used in reconstructing the experimental fusion cross section in the normalizing procedure. The quasifission and fast fission cause a relevant hindrance to fusion and, consequently, to the ER and fusion–fission product formations in the $^{19}F + ^{181}Ta$ reaction at the large beam energies; (ii) the different yields of ER and fusion–fission fragments for the two reactions are caused by different capture cross sections formed in the first stage of the reacting nuclei. We note that quasifission fragments contaminate the detected fission fragments and, therefore, the determination of the fusion cross section. Therefore, if we include the calculated quasifission and fast fission contributions in the fusion–fission cross section which was used to normalize the ER cross section to the fusion cross section, we obtain a good agreement with the experimental data of the σ_{ER}/σ_{fus} ratio for the two studied reactions. Our results for the spin distributions of CN and evaporation residues demonstrate the same de-excitation dynamics of the CN formed in the two reactions.

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