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 excitation functions of capture, complete fusion, and evaporation residue formation in the $^{16}$O+$^{184}$W and $^{19}$F+$^{181}$Ta reactions leading to the same $^{200}$Pb compound nucleus has been studied theoretically to explain the experimental data showing more intense yield of evaporation residue in the former reaction in comparison with that in the latter reaction. The observed difference is explained by large capture cross section in the former and by increase of the quasifission contribution to the yield of fission-like fragments in the $^{19}$F+$^{181}$Ta reaction at large excitation energies. The probability of compound nucleus formation in the $^{16}$O+$^{184}$W reaction is larger but compound nuclei formed in both reactions have similar angular momentum ranges at the same excitation energy. The observed decrease of evaporation residue cross section normalized to the fusion cross section in the $^{19}$F+$^{181}$Ta reaction in comparison with the one in the $^{16}$O+$^{184}$W reaction at high excitation energies is explained by the increase of hindrance in the formation of compound nucleus connected with more quick increase of the quasifission contribution in the $^{19}$F induced reaction. The spin distributions of the evaporation residue cross sections for the two reactions are also presented.

Key words: Complete fusion, angular momentum distribution, evaporation residue, fusion-fission, quasifission, fast fission. 25.70.Jj, 25.70.Gh, 25.85.-w.
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 formed in complete fusion reactions in competition against fission at heavy ion collisions. The experimental values of its cross section are measured with enough good accuracy and it is the leading light for the theoretical models to fix their parameters or for their improvement.

In Ref. [1] the difference in the excitation functions of the ER formation in the $^{16}\text{O}+^{184}\text{W}$ [2] and $^{19}\text{F}+^{181}\text{Ta}$ [3] reactions leading to the same $^{200}\text{Pb}$ compound nucleus was observed in analysis of the measured data. The comparison of experimental results of both the systems shows that ER cross sections and moments of the gamma multiplicity distribution of the $^{16}\text{O}+^{184}\text{W}$ reaction are significantly higher than those of the $^{19}\text{F}+^{181}\text{Ta}$ system at higher excitation energies. Authors concluded that the reduction in the ER cross sections and moments of the spin distribution for the $^{19}\text{F}+^{181}\text{Ta}$ reaction is mainly due to the suppression of fusion of higher values of the orbital angular momentum. The present paper is devoted to the theoretical study of this observed difference in the excitation functions of the ER formation in the $^{16}\text{O}+^{184}\text{W}$ and $^{19}\text{F}+^{181}\text{Ta}$ reactions. Our analysis in the framework of the dinuclear system model [4, 5, 6, 7] and advanced statistical model [8, 9, 10] shows that an appearance of the difference between the presented values of the ratio of the evaporation residues to complete fusion cross sections in Ref. [1] is explained by the increase of the quasifission and fast fission contributions to the measured fission fragments. As well as the difference in the formation of compound nuclei and their spin distributions are explored to explain the dependence of the $\sigma_{\text{ER}}/\sigma_{\text{fus}}$ ratio as a function of excitation energy and angular momentum.

There are two main reasons causing a hindrance to the ER formation in the reactions with massive nuclei: the quasifission and fusion-fission processes. The effects of these binary processes prove in different stages of reaction. The angular and mass distributions of some part of their products can overlap. The ER formation process is often considered as third stage of the three-stage process. The first stage is a capture–formation of the dinuclear system (DNS) after full momentum transfer of the relative motion of colliding nuclei into the deformed shape, excitation energy and rotational energy.
The capture takes place if the initial energy of projectile in the center-of-
mass system is enough to overcome the interaction barrier (Coulomb barrier + rotational energy of the entrance channel). The study of dynamics of processes in heavy ion collisions at energies near the Coulomb barrier shows that complete fusion does not occur immediately in the case of the massive nuclei collisions [4, 11, 12, 13, 14]. 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 a 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 [3, 6, 14]. Another reason decreasing yield of ER by increasing excitation energy is usual fission of a heated and rotating CN which was formed in competition with quasifission. The stability of a massive CN decreases due to the decrease of the fission barrier by increasing its excitation energy $E_{CN}^*$ and angular momentum $L = \ell h$ [8, 9, 10]. In collisions with large values of the orbital angular momentum the yield of ER decreases due to the fast fission of being formed compound nucleus. The fast fission is the inevitable decay of the fast rotating mononucleus into two fragments without reaching the equilibrium compact shape of CN [15]. Such mononucleus is formed from the dinuclear system survived against quasifission but it immediately decays into two fragments if the value of its angular momentum is larger than $\ell_f$ at which the fission barrier of the corresponding CN disappears. So the fast fission process takes place at $\ell > \ell_f$. Distinct from fast fission, the quasifission can occur at all values of $\ell$ at which the capture occurs [4, 14]. So, the main channels decreasing the cross section of complete fusion are quasifission and fast fission processes. Furthermore these channels produce binary fragments which can overlap with the ones of the fusion-fission channel and the amount of the mixed detected fragments depends on the mass asymmetry of entrance channel, as well as the shell structure of the being formed reaction fragments. Therefore, the correct estimation of the cross section of the compound nucleus formation in the reactions with massive nuclei is enough difficult task for both experimentalists and theorists. Different assumptions about the fusion process are used in different theoretical models and they can give different cross sections.

The experimental methods used to estimate the fusion probability depend on the unambiguity of identification of the complete fusion reaction 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 \[14\]. We think the compared ratios of cross sections between evaporation residues and complete fusion

\[ R = \frac{\sigma_{ER}}{\sigma_{fus}}. \]  

(1)

for the \(^{16}\text{O} + ^{184}\text{W}\) and \(^{19}\text{F} + ^{181}\text{Ta}\) reactions \([1]\) are not free from the influence of the above mentioned ambiguity in determination of the fusion cross section \(\sigma_{fus}\). The experimental value of \(\sigma_{fus}\) reconstructed by the detected fission fragments and evaporation residues can be contributed by the following terms

\[ \sigma_{fus}^{(exp)} = \sigma_{ff}^{(exp)} + \sigma_{ER}^{(exp)} + \sigma_{qf}^{(exp)} + \sigma_{fast fis}^{(exp)}. \]  

(2)

where \(\sigma_{ff}^{(exp)}\), \(\sigma_{qf}^{(exp)}\) and \(\sigma_{fast fis}^{(exp)}\) are the contributions of fusion-fission, quasifission and fast-fission processes, respectively, and \(\sigma_{ER}^{(exp)}\) is the ER contribution. According to the statement of authors of Ref. \([1]\) the complete fusion cross sections are obtained by adding fission cross section \([16]\) to the measured data of the evaporation residue cross sections. In Ref. \([17]\) the complete fusion cross section is derived from a statistical model where only neutron evaporation and fission are included. We think that the used fission data from Ref. \([16]\) contain quasifission and in some cases also fast fission contributions which appear as hindrance to the complete fusion. This argument is confirmed by our results obtained in the framework of the dinuclear system model. The total ER and fusion-fission excitation functions are calculated by us in the framework of the advanced statistical model \([8, 9, 10]\).

The evaporation residue cross section normalized to fusion cross section which was analyzed in Ref. \([1]\) can be presented as follows

\[ R^{(exp)} = \frac{\sigma_{ER}^{(exp)}}{\sigma_{fus}^{(exp)}}. \]  

(3)

where \(\sigma_{fus}^{(exp)}\) is the pure fusion cross section \((\sigma_{ER} + \sigma_{ff})\). The equation \(4\) means that a presence of the quasifission and fast fission contributing to the measured data of fusion cross section leads to decrease the ratio between the evaporation residue and fusion cross sections.
2. Study of difference in the evaporation residue formation in the $^{16}$O+$^{184}$W and $^{19}$F+$^{181}$Ta reactions

Authors of Ref. [1] studied the role of the entrance channel in formation of the evaporation residue obtained by comparison of the ratio $R^{\text{(exp)}}$ of the measured evaporation residue cross section $\sigma_{ER}$ to the fusion cross section $\sigma_{\text{fus}}$ in the $^{16}$O+$^{184}$W and $^{19}$F+$^{181}$Ta reactions as a function of the excitation energy $E^*_{\text{CN}}$ and angular momentum of compound nucleus. The ratio $R^{\text{(exp)}}$ for both reactions is approximately equal up to excitation energy $E^*_{\text{CN}}$ of about 67 MeV and at larger excitation energies the values of $R^{\text{(exp)}}$ for the $^{16}$O+$^{184}$W reaction become larger than that for the $^{19}$F+$^{181}$Ta reaction (see in forward Fig. 3 on the left axis). In Ref. [1], the observed deficiency in the ER cross sections for the $^{19}$F+$^{181}$Ta system is explained by the suppression of partial ER cross sections at higher spin values. So, authors of Ref. [1] stressed the importance of spin distribution measurements.

Our calculations show that the difference between the ratios $R^{\text{(exp)}}$ for the $^{16}$O+$^{184}$W and $^{19}$F+$^{181}$Ta reactions at large $E^*_{\text{CN}}$ energies appears due to the more large contributions of quasifission and fast fission into the measured fission fragments in the latter reaction. To understand the appearance of this difference, the fusion cross section has to be analyzed because it is a quantity causing ambiguity in $R^{\text{(exp)}}$ connecting with the identification of the true fusion-fission products. In Ref. [1] the total fusion cross sections were obtained by addition of the fission [16] and evaporation residue cross sections [17]. Therefore, in this work the difference in the formation of compound nuclei and their spin distributions in the reactions under discussion are explored as functions of the excitation energy and angular momentum of compound nucleus. We estimated these contributions and the values of the fusion, fusion-fission, ER, quasifission, and fast fission cross sections. Our results are compared with the available experimental values for the $^{16}$O+$^{184}$W [2] and $^{19}$F+$^{181}$Ta [3] systems as reported in Figs. 1 and 2 respectively. The measured total value of the ER cross section for the $^{16}$O+$^{184}$W reaction is much larger than that for the $^{19}$F+$^{181}$Ta system. This means that the complete fusion cross section for the former reaction is larger too. 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 fission-like and ER fragment yields for the $^{16}$O+$^{184}$W reaction are larger than the ones for the $^{19}$F+$^{181}$Ta reaction (see Figs. 1 and 2). Another reason causing a hindrance at formation of compound nucleus in the $^{19}$F+$^{181}$Ta reaction at large energies is the increasing contribution of the quasifission process. 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. From our results we can conclude that at low energies the fission-like fragments are mainly quasifission products. At beam energies corresponding to the excitation energy $E_{CN}^*$ of about 62 MeV the yield of the fusion-fission and quasifission fragments become comparable and at higher energies the fission cross section overcomes the one of quasifission. The fast fission fragments contribute not so strongly and their maximum value is about 15% of the observed yield of fission-like fragments only at large excitation energies $E_{CN}^* > 85$ MeV.

In Fig. 3 the results of evaporation residue cross sections (normalized with respect to the fusion cross sections) for the $^{16}$O+$^{184}$W (solid circles) and $^{19}$F+$^{181}$Ta (solid squares) systems [1] are compared with the corresponding theoretical values (dashed and dotted lines for the two reactions, respectively) for the corrected ratio $R$ (left axis) as a function of the excitation energy $E_{CN}^*$ of compound nucleus. The theoretical curves of $R$, obtained by formula (4) with the aim of excluding the quasifission and fast fission contributions in the experimental fusion cross section and determining the true
fusion cross sections, are higher than the experimental points used in Ref. [1]. For the $^{16}\text{O}+^{184}\text{W}$ reaction the curve $R$ (dashed line) is a bit higher than the experimental points (almost within the error bars) because the effect of the quasifission and fast fission contributions on the used experimental fusion cross section is small (see the trend of dash-dotted line, and read the sum of the quasifission and fast fission cross sections normalized with respect to the fusion cross section on the right axis of Fig. 3). For the $^{19}\text{F}+^{181}\text{Ta}$ reaction the curve of $R$ (dotted line) is close to the results of $R$ for the $^{16}\text{O}+^{184}\text{W}$ reaction in the $E_{\text{CN}}^*=50–67$ MeV energy range where the experimental points for the two reactions are similar within the error bars. At energies higher than 67 MeV the calculated results of $R$ for the two reactions are in complete agreement each with other while the experimental points for the $^{19}\text{F}+^{181}\text{Ta}$ reaction deviated from the ones for the $^{16}\text{O}+^{184}\text{W}$ reaction. The closest of values of the evaporation residue cross sections normalized with respect to the fusion cross sections for the reactions under discussion means that survival probability of the compound nucleus formed in both reactions has the same dependence on the excitation energy $E_{\text{CN}}^*$. The reason of the deviation between experimental values of $R^{(\text{exp})}$ for the $^{19}\text{F}+^{181}\text{Ta}$ reaction (solid squares) from the ones of the $^{16}\text{O}+^{184}\text{W}$ reaction (solid circles) at large excitation energies $E_{\text{CN}}^*>67$ MeV is explained by the increasing contribution of quasifission into measured fission cross sections for the former reaction (see Fig. 2). The growing contribution of quasifission in the $^{19}\text{F}+^{181}\text{Ta}$ reaction is also clearly shown by the trend of the $\sigma_{(qf+fast\ fission)}/\sigma_{fus}$ ratio versus $E_{\text{CN}}^*$ presented on the right axis of Fig. 3. This effect of the reac-
Figure 3: Comparison of the experimental values of the evaporation residue cross sections (normalized with respect to the fusion cross sections) for the $^{16}$O+$^{184}$W (solid circles) and $^{19}$F+$^{181}$Ta systems (solid squares) [1] with the corresponding theoretical results (dashed and dotted lines, respectively) as a function of the excitation energy $E_{CN}$ of compound nucleus (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.

tion dynamics in the entrance channel on the reaction products appears in the $^{19}$F+$^{181}$Ta reaction at higher energies, while it is small in the $^{16}$O+$^{184}$W reaction. It means that the lower cross section of the evaporation residue for the $^{19}$F+$^{181}$Ta reaction is connected with the capture and complete fusion stages. This conclusion is supported by the comparison of the angular momentum distribution of compound nuclei formed in these reactions. The results presented in Fig. 4 for the excitation energies $E_{CN}^* = 62, 72, 80,$ and 91 MeV show that the spin distributions of compound nuclei differ mainly by the probability but not by the values of angular momentum ranges. This means that the yields of compound nuclei formed in both reactions under discussion are different but they have similar range of the angular momentum $L$. The vertical dotted lines at $L_f = 80\hbar$ separates the complete fusion and fast fission regions of angular momentum.

Moreover, in Fig. 5 we report the spin distributions of evaporation residue cross sections calculated by us for $E_{CN}^*$ values about 62-63 and 80-81 MeV as an example for the two reactions. This figure shows that in the 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 $\sigma_{ER}/\sigma_{fus}$ ratio is not due to the different decay dynamic of compound nuclei formed in the $^{16}$O+$^{184}$W and $^{19}$F+$^{181}$Ta reactions but it is due to the different quasifission contributions which can be considered as hindrance to complete fusion in the entrance channel; ii) the different yields of ER’s and fusion-fission fragments for the two reactions are caused by different capture cross sections formed at the first stage of the reacting nuclei. Different quasifission contributions causing in the $^{19}$F+$^{181}$Ta reaction a relevant hindrance to fusion and consequently in the ER and fusion-fission product formations. The quasifission fragments contaminate the detected fission fragments and the determination of the fusion cross section.

In fact, if we exclude in the detected experimental fission fragments the quasifission and fast fission contributions we obtain a good agreement in the calculations of the $\sigma_{ER}/\sigma_{fus}$ ratios for the two studied reactions. Our results of the spin distributions of compound nuclei and evaporation residues demonstrate the same de-excitation dynamics of the formed compound nuclei in the two reactions.

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Figure 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: about 62-63 MeV and 80-81 MeV.

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