Mass and angular distributions of the reaction products in heavy ion collisions.

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Abstract. The optimal reactions and beam energies leading to synthesize superheavy elements is searched by studying mass and angular distributions of fission-like products in heavy-ion collisions since the evaporation residue cross section consists an ignorable small part of the fusion cross section. The intensity of the yield of fission-like products allows us to estimate the probability of the complete fusion of the interacting nuclei. The overlap of the mass and angular distributions of the fusion-fission and quasifission products causes difficulty at estimation of the correct value of the probability of the compound nucleus formation. A study of the mass and angular distributions of the reaction products is suitable key to understand the interaction mechanism of heavy ion collisions.

1. Introduction

The mixing the fusion-fission and quasifission contributions due to overlap their mass-angle distributions in measured data leads to ambiguities at estimation of the fusion probability. The significance of this mixing depends on the total mass of colliding nuclei and their mass-asymmetry. If mass and charge numbers of the light nucleus is much smaller than ones of heavy nucleus \( A_1 << A_2 \) the colliding system is very mass asymmetric. In this case overlap of the mass distributions of the fusion-fission and quasifission is very small since during evolution of dinuclear system, which is formed after capture of projectile by target-nucleus, the nucleon transfer from light fragment to the heavy one is hindered by the barrier at the Businaro-Gallone point of the driving potential. But the mass asymmetry reactions used to synthesize superheavy elements is between the Businaro-Gallone point and mass symmetric region \( A_1 \approx A_2 \). In this area, the gradient of the potential energy surface produces the forces causing diffusion of nucleons from heavy fragment to light fragment.

As a result, the part of mass distribution of quasifission fragments in the mass asymmetric region increases. Therefore, it is actual to study the mass distribution of the fission-like products to find ways to separate quasifission from the fusion-fission products. The sketch of the sequences of nuclear reaction mechanisms in heavy ion collisions is shown in the left part of Fig. 1. Its right
Figure 1. (Color on-line) The sketch of the sequences of nuclear reaction mechanisms in heavy ion collisions (left part) and their relations between experimental data of the mass and energy distribution of binary fragments (right part) in case of the $^{48}$Ca+$^{248}$Cm reaction.

part is the mass and energy distributions measured for the deep-inelastic collisions, quasifission, and fusion-fission reactions in the $^{48}$Ca+$^{248}$Cm reaction [1]. The aim of this work is to establish the mechanism preceding to the formation of the group of products of reaction. It is seen that there is overlap between mass distributions of deep-inelastic collision and capture event products which are projectile- and target-like. They can be separated due to their different kinetic energies (see right part of Fig. 1). At the capture events the full momentum transfer takes place and their products have smaller kinetic energies than the deep-inelastic collision products having not completely damped momenta. The difference between these two type reactions is explained in Fig. 2. In this figure the full momentum transfer corresponds to capture the curve of the path showing the decrease of the kinetic energy into potential well.

Figure 2. The nucleus-nucleus potential and damped kinetic energy in the entrance channel in the $^{48}$Ca+$^{248}$Cm reaction for the head-on collision ($L = 0$).
The paths of the kinetic energy collected in the potential well are capture events which lead to formation of the dinuclear system. Its evolution is related by the nucleon exchange between fragments and decay through quasifission barrier which is the border of the potential well. The arrows "c” and "d” in Fig.3 show some quasifission events with different charge distributions. The arrow "b” shows the flow of events directed to complete fusion when all nucleons from the light fragment transferred to heavy one.

Figure 3. The nucleus-nucleus potential and damped kinetic energy in the entrance channel in the $^{48}$Ca+$^{248}$Cm reaction for the head-on collision ($L = 0$).

So, the capture events presented by arrow “a” in Fig. 3 are distributed to the complete fusion "b” and quasifission "c” and "d” events. The evolution of the DNS demonstrates competition between complete fusion and quasifission. The transfer of all nucleon from the light fragment to heavy nucleus leads to formation of the rotating mononucleus which is excited too. Rotation of the non-equilibrated mononucleus causes decreasing the fission barrier. Therefore, at definite value of the orbital angular momentum the fission barrier disappears completely. In this case, the non-equilibrated mononucleus becomes unstable and undergoes to fission from some excited state. The splitting of mononucleus before reaching its equilibrium state is called fast fission which produces binary fragments (see the left part of Fig.1). The mass distribution of the fragments of the fast fission can be mixed with the ones of the fusion-fission and quasifission. The compound nucleus is equilibrated mononucleus having the non-zero fission barrier can registered as superheavy element if it must survive against fission emitting neutrons and charged particles (see left part of Fig.1). The study of correlations between mass and angular distribution of fragments of full momentum transfer reactions expected to be important in separation of the pure fission fragments of the compound nucleus with a compact shape from the quasifission products when they are mixed.

The quasifission is full-momentum transfer reaction. Mainly five collective motions related with the evolution of DNS formed at capture should be analyzed:

i) the nucleon exchange and mass drift (change of the mass asymmetry) between fragments takes place continuously with intensity depending on the shell structure of interacting nuclei and on the dissipated energy into nucleon motion from the bombarding energy;

ii) at the same time the DNS rotates with the angular velocity which depends on the initial orbital angular momentum and its moment of inertia;

iii) the relative distance between DNS fragments fluctuates that is allowed by the potential
well of the nucleus-nucleus interaction potential;
iv) deformation and surface vibration of the DNS fragments;
v) “butterfly” mode of vibration of the DNS fragments around axis perpendicular to the line connecting their centres-of-mass.

2. Mass and charge distribution evolution in the interacting system

The relation between the mass-angle distribution characteristics and landscape of the total potential energy as a function of the DNS charge and mass asymmetry show an important role of the entrance channel parameters and compound nucleus fissilities in the overlap of the characteristics of the reaction products formed by different mechanisms.

The dominating role of the quasifission process is noted by experimentalists too. The quasifission process is a hindering factor to complete fusion. For this reason, the cross section for producing a heavy evaporation residue (ER) is calculated by taking into account fusion probability $P_{CN}$ and the expression can be written as

$$\sigma_{ER} = \sigma_{cap} P_{CN} W_{sur},$$  \hspace{1cm} (1)

where $\sigma_{cap}$ is the capture cross section and $W_{sur}$ is the probability that the compound nucleus (CN) survives against fission. Experimentally, the capture cross section is defined as the sum of the quasifission ($\sigma_{QF}$), fusion-fission ($\sigma_{CN-fiss}$), and ER ($\sigma_{ER}$) cross sections,

$$\sigma_{cap} = \sigma_{QF} + \sigma_{CN-fiss} + \sigma_{ER},$$  \hspace{1cm} (2)

They assume that in the symmetric region of the fragment masses ($A/2 \pm 20$) fusion-fission process coexists with quasifission [1]. The experimental mass distribution of the fission-like products is fitted with the set of the Gaussian functions to separate the contributions of the fusion-fission products from the ones of quasifission. The mass yield of the fusion-fission process obtained as difference between experimental spectra and quasifission peak in the mass symmetric region [1, 2]. $P_{CN}$ is defined as the probability for compound nucleus formation from the configuration of two nuclei in contact. In the reactions with massive nuclei the ER cross section is less than a few nanobarns and contributes insignificantly to the fusion cross section. Thus we can estimate the fusion probability using the measured mass-energy distributions as the ratio between the number of events attributed to fusion-fission and all fissionlike fragments. Therefore, it is important to study in detail the reaction mechanisms producing the fissionlike fragments and to be able to separate the contributions from the different mechanisms to the registered yield of the reaction products. The ratio of the different contributions into yield of the fissionlike products depends on the mass asymmetry of colliding nuclei, orientation angles of their axial symmetry, beam energy and orbital angular momentum in the entrance channel.

It is obvious the differences between the values of $P_{CN}$ extracted from the measured data of the capture and complete fusion events depend on how are correctly estimated capture and fusion cross sections from the measured data. Therefore, the reliable experimental determinations of $P_{CN}$ and consequently the understanding the entrance channel effect on the $P_{CN}$ values are strongly related to the choice of assumptions for the data analysis.

The experimental results of the mass-total kinetic energy matrices for the $^{36}$S, $^{48}$Ca+$^{238}$U reactions at energies close to the Coulomb barrier taken from [3] are presented in Fig. 4. The mass distributions for fission-like fragments presented by open circles are sum of the events which are inside the region limited by thick lines on mass-total kinetic energy matrices in the top of Fig. 4. The determination of the fusion probability

$$P_{CN} = \frac{\sigma_{fus}}{\sigma_{cap}} = \frac{\sigma_{CN-fiss} + \sigma_{ER}}{\sigma_{QF} + \sigma_{CN-fiss} + \sigma_{ER}}.$$  \hspace{1cm} (3)
from the mass distributions for fission-like fragments depends on the assumption used at separation of the quasifission and fusion-fission events. This procedure gives the ratio $\sigma_{\text{CN-\text{fiss}}} / \sigma_{\text{QF}}$. We should note that the position of the border of the region in the top of Fig. 4 under discussion is incorrect since a lot of events of the quasifission related with the formation of the products with mass numbers $A_1 < 44$ and $A_2 > 230$ are ignored. So, the incorrect choice of the region borders leads to decrease the denominator of Eq. 3. As a result the experimental fusion probability is already overestimated. The verify this statement we can analyze the results of theoretical charge (mass) distribution for the quasifission and fusion-fission products calculated by the master equation [4, 5] for the nucleon transfer between interacting nuclei. It is seen the overlap of these two yields in the range of mass $80 < A_1 < 120$. The calculation has been made for the $E_{\text{lab}} = 185$ MeV, orbital angular momentum value $L = 20\hbar$ and orientation angle $\alpha_2 = 45^\circ$. The amount of the fusion-fission events is small in case of the $^{48}\text{Ca} + ^{238}\text{U}$ reaction since the fusion probability.

Mass and charge distributions of the quasifission products $Y_{\text{qf}}(Z, A)$ are calculated by solving the transport master equation [4, 5] for the probability of the charge distribution $P_Z$ in the DNS fragments:

$$\frac{\partial}{\partial t} P_Z(E^*_Z, t) = \Delta_{Z+1}^{(\pm)}(E^*_Z) P_{Z+1}(E^*_Z, t) + \Delta_{Z-1}^{(\pm)}(E^*_Z) P_{Z-1}(E^*_Z, t)$$

$$+ (\Delta_{Z}^{(-)}(E^*_Z) + \Delta_{Z}^{(+)}(E^*_Z) + \Lambda_{\text{qf}}^{(Z)}(E^*_Z)) P_Z(E^*_Z, t), \quad (4)$$

where $Z = 2, 3, ..., Z_{\text{tot}} - 2$ and the transition coefficients $\Delta_Z^{(\pm)}$ determine the probability of nucleon transfer between interacting nuclei "P" and "T" of the dinuclear system characterized with the charge numbers $Z$ and $Z_{\text{tot}} - Z$, $Z_{\text{tot}}$ is the total charge number of the system; $E^*_Z$ is its excitation energy which is determined by the initial energy of collision $E_{\text{c.m.}}$, the minimum value of the potential well $V_{\text{min}}^{(Z)}$ in the nucleus-nucleus interaction and the energy balance of the nucleon transfer as a difference of the DNS total energy $U$ values of for the entrance channel.
and the charge (mass) asymmetry $Z(A)$:

$$E^*(Z,A) = E_{c.m.} - V_{\min}(Z,A) - U(Z,A),$$

where

$$\Delta U(Z,A) = U(Z_P,A_P) - U(Z,A)$$

$$= B_1(Z_P,A_P) + B_2(Z_T,A_T) + V_{\min}(Z,P,A)$$

$$- (B_1(Z,A) + B_2(Z_{CN} - Z,A_{tot} - A) + V_{\min}(Z,A).$$

Figure 5. (Color on-line). The mass distributions for fusion-fission (solid line) and quasifission (dashed line) products calculated by solution of the transfer master equation [4, 5] for the $^{36}$S+$^{238}$U reaction at beam energy $E_{lab} = 185$ MeV.

So, the dependence the DNS excitation energy on the charge asymmetry is related with the change of its intrinsic energy by the change of mass and charge numbers of its constituents from the ones of projectile and target nuclei. The corresponding mass numbers $A$ are found by the minimization of the total energy of dinuclear system as a function of $A$: $A^f_\Sigma$ is the Kramer’s rate for the decay probability of the dinuclear system into two fragments with charge numbers $Z$ and $A_{tot} - Z$ and it is proportional to $\exp(-B_{qf}(Z)/T)$ where $B_{qf}(Z)$ is quasifission (pre-scission) barrier against decay and $T$ is the effective temperature of the system. Details of calculation of $B_{qf}$ and $T$ are presented in Ref. [9].

The peculiarities of the mass distribution related with the appearance of the strong yield of charge numbers are determined by the dependence of the transition coefficients $\Delta_Z^{(\pm)}$ on the single-particle structure of the proton and neutron subsystems in the interacting nuclei.

The transition coefficients $\Delta_Z^{(\pm)}$ depends on the energy ($\varepsilon_i$), spin ($J_i$) and occupation numbers ($n_i$ of the single-particle states of the nuclei with charge number $Z$ and $Z_{tot} - Z$:

$$\Delta_Z^{(\pm)} = \frac{4}{\Delta t} \sum_{i,j} |g_{ij}^{(Z)}|^2 \sin^2(\Delta t (\varepsilon_i^{(Z)} - \varepsilon_j^{(Z)})/(2\hbar))$$

$$\times (2J_i + 1)(2J_j + 1)n_{i,j}^{(Z)}(T) (1 - n_{i,j}^{(Z)}(T))$$
where the matrix elements $g_{ij}$ describe one-nucleon exchange between the nuclei, and their values are calculated microscopically using the expression obtained in Ref. [11]. The occupation numbers of the single-particle states depend on the effective temperature of the nuclei. $\Delta t = 10^{-22}\,\text{s}$ is used in these calculations.

The contribution of the quasifission products to the yield of the $^{36}\text{S} + ^{238}\text{U}$ reaction products at the beam energy $E_{\text{lab}} = 185\,\text{MeV}$ (has been estimated by the numerical solution of Eq. (4) with the initial conditions $Y_Z(Z_P = 16) = 1$ and $Y_Z(Z_T = 92) = 1$. The single-particle characteristics of the proton and neutron structures of the interacting nuclei are found by the solution of the Schrödinger equation with the Woods-Saxon potential for the set of nuclei $Z = 2−108$ ($A = 4−274$). The last filled level of the single-particle scheme the proton and neutrons are shifted to the values of the proton $(S_p)$ and neutron $(S_n)$ separation energies [12], respectively, to make the the single-particle scheme more realistic. The contribution of the fusion-fission products of the $^{36}\text{S} + ^{238}\text{U}$ reaction has been estimated by the numerical solution of Eq. (4) with the initial condition $Y_Z(t = 0) = \exp(-(Z - Z_0)^2/(2\sigma^2))/\sqrt{2\pi}\sigma)$, where $Z_0 = (Z_P + Z_T)/2$ and $\sigma = 4$.

The charge distribution of the quasifission products $Y_{qf}(Z, A)$ is determined by the sum of the DNS decay products during its lifetime $t_{\text{int}}$:

$$Y_{qf}(Z, A) = \sum_{t=0}^{t = t_f} Y_A S^0_{\ell}(E^*_Z)P_Z(E^*_Z, t)\Delta t, \quad (8)$$

where $\Delta t$ is the step of time in the numerical calculations.

This method has been applied to analyze the mass distributions of the fission-like products observed in the experiment of the $^{48}\text{Ti} + ^{208}\text{Pb}$ reaction [15]. Figure 6 represents the comparison of the theoretical predicted mass yield with the experimental ones. Theoretical yield of the reaction products presented in fig. 7 shows that there is the overlap of the mass distributions of the QF and FF products near mass numbers $A \approx 64$. This peak $A \approx 64$ is related to the formation of the isotopes of Fe and Ni with the neutron numbers $N = 38$ and 40.

Theoretical fusion probability is determined by the estimation of capture cross section and competition between complete fusion and quasifission cross sections in the framework of the dinuclear system model [5, 6]. The competition between the complete fusion of nuclei in DNS and quasifission (decay of DNS into two fragments) processes decreases the value of the fusion cross section:

$$\sigma_{\text{fus}}(E_{\text{c.m.}}) = \frac{\ell_d(E_{\text{c.m.}})}{\sum_{\ell=0}^{\ell_d(E_{\text{c.m.}})} (2\ell + 1)\sigma_{\text{cap}}(E_{\text{c.m.}}, \ell)P_{\text{CN}}(E_{\text{c.m.}}, \ell)}. \quad (9)$$
The maximum value of \( \ell \) leading to capture \( \ell_d(E_{\text{c.m.}}) \) depends on the beam energy and it is calculated by the solution of the radial motion equations (see ref. [5]). Since the capture cross section is equal to the sum of the complete fusion and quasi-fission cross sections, \( \sigma_{\text{cap}} = \sigma_{\text{fus}} + \sigma_{qf} \), the quasi-fission cross section is calculated by the expression

\[
\sigma_{qf}(E_{\text{c.m.}}) = \sum_{\ell=0}^{\ell_d} (2\ell + 1)\sigma_{\text{cap}}(E_{\text{c.m.}}, \ell)(1 - P_{\text{CN}}(E_{\text{c.m.}}, \ell)).
\]  (10)

It should be stressed that quasi-fission of dinuclear system can take place at all angular momentum values from \( \ell = 0 \) to \( \ell_d \).

The quasi-fission barrier and fusion probability depend on the angular momentum. Angular distribution of the reaction products is sensitive to the value of the orbital angular momentum since the rotational angle of the DNS formed at the capture is determined by its angular momentum and moment of inertia. This physical quantity was studied by us in Ref. [14].

3. Angular distribution of quasi-fission products.

The angular distribution of the fusion-fission fragments is expected to be an isotropic while the quasi-fission products are distributed anisotropically [8]. The lifetime of the fissioning system is an important quantity determining the value of the rotational angle after its formation. The time for formation and fission of compound nucleus is much longer than the lifetime of dinuclear system producing quasi-fission products. Therefore, in fusion-fission, the fissioning nucleus having angular momentum can make many rotations before fission losing memory about initial orientations and correlation between the fusion-fission fragment masses and angles can disappear.

![Nucleus-nucleus interaction potential](image)

**Figure 7.** The nucleus-nucleus interaction potential \( V(R) \) (solid line) for the \(^{36}\text{S} + ^{238}\text{U}\) system: the quasi-fission barrier \( B_{qf} \) as the a depth of the potential well. The harmonic oscillator (dashed line) is used to approximate the potential well at \( R = R_m \).

The lifetime of dinuclear system is determined by the depth of the potential well \( B_{qf} \) (so called quasi-fission barrier) and amount of its excitation energy \( E_{DNS}^* \). The requested decay time \( \tau_Z \) is estimated by

\[
\tau(\ell, T_Z) = \frac{\hbar}{\Gamma_{qfiss}(T_Z)}
\]  (11)
if we know the excitation energy $E^*_Z$ and quasifission barrier $B_{qf}^{(Z)}$ of the dinuclear system for its decay on fragments with charge numbers $Z$ and $Z_{tot} - Z$, by using the one-dimensional Kramers rate [16]

$$\Gamma_{qfiss}^{(Z)}(\Theta) = K_{rot} \omega_m \left( \sqrt{\gamma^2 / (2 \mu_{qf})^2 + \omega_{qf}^2} - \gamma / (2 \mu_{qf}) \right)$$

$$\times \exp \left( -B_{qf}/T_Z \right) / (2 \pi \omega_{qf}).$$

(12)

Here the frequency $\omega_m$ and $\omega_{qf}$ are found by the harmonic oscillator approximation to the nucleus-nucleus potential $V(R)$ shape for the given DNS configuration $(Z, Z_{tot} - Z)$ on the bottom of its pocket placed at $R_m$ and on the top (quasifission barrier) placed at $R_{qf}$ (see Fig.7), respectively:

$$\omega_m^2 = \mu_{qf}^{-1}(R) \left| \frac{\partial^2 V(R)}{\partial R^2} \right|_{R=R_m},$$

(13)

$$\omega_{qf}^2 = \mu_{qf}^{-1}(R) \left| \frac{\partial^2 V(R)}{\partial R^2} \right|_{R=R_{qf}}.$$  

(14)

\[\text{Figure 8. (Color online). The dependence of the quasifission barrier } B_{qf} \text{ providing the DNS stability on its angular momentum } L \text{ and mass number one of its fragments.}\]

The calculated values of $\hbar \omega_m$ and $\hbar \omega_{qf}$ were equal to 46.52 MeV and 22.37 MeV, respectively. The used value of the friction coefficient $\gamma$ is equal to $8 \cdot 10^{-22}$ MeV fm$^{-2}$s which was found from our calculations; $\mu_{qf} \approx \mu = A_1 \cdot A_2 / A_{tot}$, where $A_1$ and $A_2$ are the mass numbers of the quasifission fragments.

Depending on the orbital angular momentum $L$ and beam energy $E_{c.m}$ in the entrance channel, the DNS may break up soon after capture, or may stick together for more than one rotation. As long as the projectile-like and target-like nuclei break apart within half a rotation, quasifission events show a strong correlation between mass ratio and angle.

The angular distribution of the quasifission fragments has been theoretically studied by us in Ref. [13]. It was found by estimation of the rotational angle $\theta_{DNS}$ during the lifetime ($\tau(T_Z)$) of the system:

$$\theta_Z = \theta_{\text{capture}} + \Omega_Z \cdot \tau_Z(T_Z(E^*_Z(\ell))),$$

(15)
where the DNS angular velocity is calculated as ratio of the its angular momentum $L$ and moment of inertia $J_{DNS}$:

$$\Omega_Z = \frac{L}{J_{DNS}}. \quad (16)$$

$\theta_{capture}$ is the angle between the beam direction and line connecting the mass centres of nuclei at capture. At the given value of $L$ the value of $\Omega_Z$ depends only on the DNS moment of inertia at the charge asymmetry $Z$.

The rotational angle is proportional to the DNS lifetime and during this time the mass distribution between the DNS fragments is changed.

The effective temperature $T_Z(E^*_Z(\ell))$ of the rotating DNS with the charge asymmetry $Z$ is determined by its excitation energy $E^*_Z(\ell)$:

$$T_Z(E^*_Z(\ell)) = \frac{E^*_Z(\ell)}{a}, \quad (17)$$

where $a$ is the level density parameter taken as $a = A_{tot}/12 \text{ MeV}^{-1}$. The collective enhancement factor of the rotational motion $K_{rot}$ to the level density should be included because the dinuclear system is a good rotator. It is calculated by the well known expression [17]:

$$K_{rot}(E^*_D) = \begin{cases} (\sigma_\perp^2 - 1) f(E_{DNS}) + 1, & \text{if } \sigma_\perp > 1 \\ 1, & \text{if } \sigma_\perp \leq 1 \end{cases},$$

where $\sigma_\perp = J_{DNS} T / \hbar^2$; $f(E) = (1 + \exp[(E - E_{cr})/d_{cr}])$; $E_{cr} = 120 \beta^2 A^{1/3}$ MeV; $d_{cr} = 1400 \beta A^{2/3}$, $\beta$ is the effective quadrupole deformation for the dinuclear system. We find it from the calculated $J_{DNS}$.

The mass distribution evolution as diffusion process is determined by the DNS lifetime and shell effects in the nucleon structure in the interacting nuclei. At the same time the DNS lifetime depends on its mass (charge) asymmetry since the quasifission barrier $B_{qf}$ is found as the depth of the potential well. At capture of the projectile-nucleus by the target-nucleus the formed DNS acquires angular momentum and it rotates around own centre-of-mass.

It should be noted the evolution of the mass distribution between the DNS fragments and its rotation around the centre-of-mass system take place simultaneously. In other words the during rotation of DNS its momentum inertia is changed and its lifetime depends on the mass asymmetry since the quasifission barrier is related on the charge and mass asymmetry. It is clear that the more mass asymmetric configurations of DNS rotates longer than the less mass asymmetric configurations. Certainly the DNS configurations having large population due to shell effects or/and initial charge and mass numbers of projectile- and target- nuclei can show intense yield of the reaction products. But large quasifission barrier causes hindrance decay from the mass asymmetric configurations and DNS has more chance for decay from less mass asymmetric configurations. The possibility to reach the more symmetric configuration depends on the DNS excitation energy $E^*_D$ and peculiarities of the driving potential. The both of these last quantities depends on the DNS angular momentum $L$. Therefore, simultaneous calculations of the mass and angular distributions as a function of the beam energy $E_{c.m.}$ and orbital angular momentum are important for the study of the reaction mechanism producing quasifission products.

The left panel of Fig. 4 and Fig. 5 show that the mass distributions of the quasifission products are sufficient in the mass number ranges $60 \div 90$ and $180 \div 210$. We can conclude that the lifetime of the rotating DNS is enough for evolution of the mass distribution from the initial values $A_P = 36$ and $A_T = 238$ into the corresponding mass ranges. The maximum distribution of the quasifission products is related with the formation of the $^{68,70}$Ni
isotopes. The conjugate heavy fragments are Hg isotopes with the magic neutron numbers around $N \approx 126$. While the mass distribution is changed the DNS is rotating. The dependence of the rotating angles on the mass and charge numbers of the interacting nuclei is presented in Fig. 9 for the pairs of nuclei $^{36}$S+$^{238}$U (9b), $^{46}$Ar+$^{228}$Th (9c), $^{50}$Ca+$^{224}$Rn (9d), $^{62}$Cr+$^{212}$Po (e) and $^{64}$Ni+$^{210}$Hg (f).

The fusion probability is $^{36}$S+$^{238}$U is about $P_{\text{CN}} = 0.3$, therefore, the contribution of the fusion-fission products are comparable with the one of the quasifission products as seen from the right panel of Fig. 4. In case of the $^{48}$Ca+$^{238}$U reaction, the fusion probability is much smaller $P_{\text{CN}} = 0.1$ and the yield of the fusion-fission products is smaller than the yield of quasifission products. We conclude that the study of the mass and angular distribution of the reaction products allows us to estimate fusion probability. The uncertainties in estimation of the fusion probability from the analysis of the fission-like products is related with separation of the

Figure 9. (Color online). The angular momentum distribution calculated for the DNS formed at capture in the $^{36}$S+$^{238}$U reaction at $E_{\text{lab}}=185$ MeV (corresponding excitation is $E_{\text{CN}} = 46$ MeV)(a). Rotational angles for the DNS calculated for its configurations consisting from the interacting fragments $^{36}$S+$^{238}$U (b), $^{46}$Ar+$^{228}$Th (c), $^{50}$Ca+$^{224}$Rn (d), $^{62}$Cr+$^{212}$Po (e) and $^{64}$Ni+$^{210}$Hg (f).
contributions of quasifission and fusion-fission products when there is a doubt of their overlap.

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