Shell effects in fission and quasi-fission of heavy and superheavy nuclei


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Results of the experiments aimed at the study of fission and quasi-fission processes in the reactions $^{12}$C+$^{204}$Pb, $^{48}$Ca+$^{144,154}$Sm, $^{168}$Er, $^{208}$Pb, $^{238}$U, $^{244}$Pu, $^{248}$Cm, and $^{58}$Fe+$^{208}$Pb, $^{244}$Pu, $^{248}$Cm, and $^{64}$Ni+$^{186}$W, $^{242}$Pu are presented in the work. The choice of the above-mentioned reactions was inspired by recent experiments on the production of the isotopes $^{283,112,289,114}$ and $^{283,116}$ at Dubna [1],[2] using the same reactions. The $^{58}$Fe and $^{64}$Ni projectiles were chosen since the corresponding projectile-target combinations lead to the synthesis of even heavier elements. The experiments were carried out at the U-400 accelerator of the Flerov Laboratory of Nuclear Reactions (JINR, Russia), the XTU Tandem accelerator of the National Laboratory of Legnaro (LNL, Italy) and the Accelerator of the Laboratory of University of Jyväskylä (JYFL, Finland) using the time-of-flight spectrometer of fission fragments CORSET[3] and the neutron multi-detector DEMON[4],[5]. The role of shell effects and the influence of the entrance channel on the mechanism of the compound nucleus fusion-fission and the competitive process of quasi-fission are discussed.

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1. MED characteristics of heavy element fission fragments

The reactions $^{48}\text{Ca}+^{144,154}\text{Sm},^{168,170}\text{Er}$ were investigated in order to understand the nature of the competition between the processes of fission and quasi-fission in dependence on the reaction entrance channel. For this purpose the fission cross-section was measured together with the evaporation residue cross-section in a wide energy range of $^{48}\text{Ca}$ ions. At the same time, mass-energy distributions (MED) of fission fragments, taken alone, are also of great interest. In the recent years our efforts were concentrated on the investigation of the multi-modal structure of the fission fragment MED in the region of transition nuclei $213 < A_{CN} < 226$, which so far has been poorly studied. Thus, MED of the $^{216,218,220}\text{Ra}$ compound nuclei produced in reactions with $^{12}\text{C}$ were studied. It was found that the contribution of the asymmetric fission mode in the case of the $^{12}\text{C}+^{204}\text{Pb}$ reaction is 1.5% [6], and it is 30% in the case of the $^{48}\text{Ca}+^{168}\text{Er}$ reaction [7]. We connect such a sharp increase in the yield of asymmetric products in the reaction $^{48}\text{Ca}+^{168}\text{Er}$ with the quasi-fission process (QF), MED of which have a clearly expressed shell structure.

The properties of the fission fragment MED are such that they allow their interpretation by analogy with the low-energy fission of heavy nuclei as a manifestation of an independent mode of nuclear decay which competes with the classical fusion-fission (FF) process. To explain such a difference in the MED a theoretical calculation of the potential energy was made within the three-dimensional version of the "nucleon collectivization" model [8] based on the two-center shell model idea [9]. Figure 1 shows the result of this calculation. One can see that in the case of $^{12}\text{C}+^{204}\text{Pb}$, mass distribution of which is shown in insert panel (a), the process of fusion-fission is the dominating one. In the case of the $^{48}\text{Ca}+^{168}\text{Er}$ reaction, there are two optimal paths at the potential energy surface. One of these paths (the white line marked as QF) leads to the $^{132}\text{Sn}+^{84}\text{Sr}$ exit channel without the compound nucleus formation. This potential energy

![Figure 1: Potential energy surface as a function of mass asymmetry of the entrance channels, elongation and deformation for $^{216}\text{Ra}$. The dark color corresponds to the lower potential energy.](image)

![Figure 2: Experimental angular distributions of fission fragments from the reaction $^{48}\text{Ca}+^{168}\text{Er}$ at $E_{\text{lab}} = 195\text{ MeV}$.](image)
minimum is determined by shell effects of the doubly magic $^{132}\text{Sn}$. The second path corresponds to the classical fusion-fission process and leads to the symmetrical exit channel $^{108}\text{Ru}+^{108}\text{Ru}$, the same as in the reaction with $^{12}\text{C}$ ions. That is why mass distribution of the $^{48}\text{Ca}+^{168}\text{Er}$ reaction products (insert panel (b)) is the superposition of both processes – the symmetrical classical fission and quasi-fission "shoulders". Angular distributions for different fragment masses were measured in order to find experimental evidence of the quasi-fission nature of the "shoulders". Fig. 2 shows the angular distributions for the symmetrical mass range ($M = A/2 \pm 10$, solid circles) and for the "shoulders" ($M = 78 \pm 10$, open circles). The solid curve shows the results of calculations made in the framework of the Transition State Model [10]. As one can see from Fig. 2, the solid line fits well into the data for the symmetrical part of mass distribution, whereas the angular distribution for the "shoulders" has a pronounced forward-backward asymmetry, which is one of the distinctive features of the quasi-fission process.

For a further study of the influence of the entrance channel and deformations of the colliding nuclei on the competition between the fusion-fission and quasi-fission processes the reaction $^{48}\text{Ca}+^{144,154}\text{Sm}$ was chosen. Samarium is attractive as a target due to its numerous stable isotopes. Mass-energy distributions for the reaction $^{48}\text{Ca}+^{144,154}\text{Sm}$ are presented in Fig. 3. The left-hand panels show the data for the reaction with the $^{144,154}\text{Sm}$ targets at approximately the same excitation energy $E^* = 49$ MeV (columns 1 and 2), and at angular momentum (columns 3,4) $\langle I^2 \rangle = 900 h^2$ (columns 3,4). Figure 3: Two-dimensional TKE-Mass matrix, mass yield, average TKE and the variance TKE($M$) as a function of the mass of fragments for the reactions $^{48}\text{Ca}+^{144,154}\text{Sm}$ at the excitation energy $E^* = 49$ MeV (columns 1 and 2), and at angular momentum (columns 3,4) $\langle I^2 \rangle = 900 h^2$ (columns 3,4).
2. MED characteristics of fission fragments of super heavy elements

Figure 4 shows the data on MED of fission fragments of the $^{256}$No, $^{288}$112, $^{292}$114 and $^{296}$116 nuclei produced in the reactions with $^{48}$Ca ions at the same excitation energy $E^* \approx 33$ MeV. The main peculiarity of the data is the sharp transition from the predominant compound nucleus fission in the case of $^{256}$No to the quasi-fission mechanism of decay in the case of the $^{288}$112 and heavier nuclei. It is very important to note that despite the dominating contribution of the quasi-fission process into the total mass yield in the case of nuclei with $Z = 112 - 116$, in the symmetric region of fission fragment masses ($A/2 \pm 20$) the process of fusion-fission of compound nuclei, in our opinion, prevails. It is demonstrated in the framings (see the bottom panels of Fig. 4), where one can see that the mass distribution of fission fragments of compound nuclei is asymmetric in shape with the light fission fragment mass at about 132 – 134 a.m.u. Thus in the case of super heavy elements (SHE) with mass 132 – 134 plays a stabilizing role, in contrast to the region of actinide nuclei, where the heavy fragment is the spherical one.

An experimental two-dimensional TKE-mass plot for the $^{48}$Ca+$^{248}$Cm fusion-fission reaction is shown in Fig. 5 along with the corresponding potential energy surface [8] determining evolution of the nuclear system. After the nuclei have come into contact, the nuclear system typically evolves in the asymmetric quasi-fission channels: path number 1 in Figure 5(a), which populates the area of fragment masses near $A = 208$ in Figure 5(b). The asymmetric quasi-fission channels are closer to the initial state in the configuration space of collective degrees of freedom as compared with the configurations through which the system has to pass on the way to the compound nucleus: trajectory number 3 in Figure 5(a). As a result, only a small part of the incoming flux reaches a compound nucleus configuration, and the fusion cross section turns out to be far less than the capture cross section. The distinction between $\sigma_{\text{fus}}(E^*)$ and $\sigma_{\text{capt}}(E^*)$ becomes still more evident at low excitation energies. Approximating the mass distribution of the quasi-fission fragments (area 1 in Figure 5(b)) by a Gaussian shape, we may easily single out the events in the symmetric region of fission fragments ($A_{\text{CN}}/2 \pm 20$, area of dashed quadrangle in Figure 5(b)) which correspond to a regular fission. For the $^{48}$Ca+$^{248}$Cm fusion-fission reaction, the tail of Gaussian gives no more than 20% of all the events in this region (see the details in [11]).

Figure 4: Two-dimensional matrices TKE-Mass (top panels) and mass yields (bottom panels) of fission fragments of $^{256}$No, $^{288}$112, $^{292}$114 and $^{296}$116 nuclei produced in the reactions with $^{48}$Ca at the excitation energy $E^* = 33$ MeV.
A mass distribution corresponding to the symmetric region of fission fragments \( (A_{CN}/2 \pm 20; \) area of dashed quadrangle in Fig. 5(b)) is shown in Fig. 5(c), compared with the typical mass yield of \(^{238}\text{U}\) fission fragments [12]. As it can be seen from the figure, the mass spectra in the overlapped region practically coincide within the error bars. In the case of \(^{238}\text{U}\) a two-humped fission mass distribution is regulated mainly by a doubly magic heavier fragment \(^{132}\text{Sn}\), which plays the role of a lighter fragment in the case of fission of a \(^{208}\text{Np}\) nucleus at low excitation energies. This means, that symmetric region of fission fragment masses \( (A_{CN}/2 \pm 20) \) seems to originate mainly from the regular fusion-fission process in the reaction \(^{48}\text{Ca}+^{248}\text{Cm} \rightarrow ^{208}\text{Np}\). However, as shown in [8], evolving from the initial configuration of two nuclei in contact into the state of spherical or near-spherical compound nucleus (path number 3 in Figure 5(a)), the system goes through the same configurations through which a compound nucleus goes in regular fission (path number 4 in Figure 4(a)), i.e., configurations close to the saddle point. When in such a configuration and in a state of complete thermodynamic equilibrium, the nuclear system is much likely to go into the fission channel (path number 2 in Figure 5(a)), without overcoming the saddle point, and producing a spherically symmetric compound nucleus. A process of this kind results in fragments that are practically not different from regular fission fragments, since in both cases the system follows the same path from the saddle point to the scission point. This means that among all the events resulting in the system going in regular near-symmetric fission channels, there are such events in which the system does not produce a true spherically symmetric compound nucleus.

Formerly emission of neutrons and \( \gamma \)-rays in correlation with fission fragments in the decay of superheavy compound systems at excitation energies near or below the Coulomb barrier had not been extensively studied. At the same time such investigations may be extremely useful for an additional identification of the fusion-fission and quasi-fission processes and consequently for a more precise determination of the cross-sections of these processes in the total yield of fragments. On the other hand, the knowledge of the value of the fission fragment neutron multiplicity can be used in the identification of SHE in experiments aimed at their synthesis.

The results of such investigations are presented in Table 1. As seen from the table, in all cases the total neutron multiplicity is considerably lower (by more than twice)
for the region of fragment masses where the mechanism of quasi-fission predominates as compared with the region of fragment masses where, in our opinion, the process of fusion-fission prevails in the symmetric region of fragment masses.

Figure 6: The QF cross section ($\sigma_{QF}$) to the capture cross-section ($\sigma_{cap}$) ratio dependence on the mass number of compound nuclei, produced in the reactions with $^{48}$Ca ions at the same excitation energy $E^* \approx 33 - 40$ MeV.

Figure 7: Two-dimensional matrices TKE-Mass (top panels) and mass yields (bottom panels) of fission fragments of $^{216}$Ra, $^{258}$No, $^{296}$116 nuclei produced in the reactions with $^{48}$Ca.

Summing up all the data, we plot the dependence of the quasi-fission relative yield $\sigma_{QF}/\sigma_{cap}$ as a function of the mass of compound nucleus, produced in reactions with $^{48}$Ca ions at the excitation energy $E^* \approx 33 - 40$ MeV (Fig. 6). Solid circles are the measured reactions; the question signs are the combinations to be measured. Our prediction on the behavior of this curve is shown with line. The most possible explanation of such a nontrivial behavior of the ratio $\sigma_{QF}/\sigma_{cap}$ is the corresponding probability of formation of the different spherical shells in the nascent fragments. The graphic example of the shell influence on the MED of the fission fragments is shown on Figure 7.

The knowledge of the total kinetic energy of fission fragments, mean neutron and $\gamma$-multiplicities allows us to calculate the energy balance of the reaction. The results of such calculations for the reaction $^{48}$Ca+$^{208}$Pb ($E^* = 33$ MeV) are shown in Fig. 8. The calculations were made for three mass regions, i.e., for the light ($\Delta M_L = 60 - 88$), heavy ($\Delta M_H = 168 - 196$), and symmetric fission fragments ($\Delta M_S = 108 - 148$), since the neutron multiplicities were determined for these mass regions. Fig. 8(a) shows a two-

Table 1
The measured values of neutron and $\gamma$-multiplicities

<table>
<thead>
<tr>
<th>Reactions</th>
<th>$E_{lab}$ (MeV)</th>
<th>$E^*$ (MeV)</th>
<th>$M_n^{A/2\pm20}$</th>
<th>$M_Q^{QF}$</th>
<th>$M_{\gamma}^{A/2\pm20}$</th>
<th>$M_{\gamma}^{QF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca+$^{208}$Pb</td>
<td>230</td>
<td>33</td>
<td>5.2 $\pm$ 0.7</td>
<td>3.1 $\pm$ 0.5</td>
<td>14.0 $\pm$ 1.3</td>
<td>9.3 $\pm$ 1.8</td>
</tr>
<tr>
<td>$^{48}$Ca+$^{238}$U</td>
<td>232</td>
<td>33</td>
<td>8.4 $\pm$ 1.2</td>
<td>4.9 $\pm$ 0.9</td>
<td>17.5 $\pm$ 1.6</td>
<td>12.6 $\pm$ 1.3</td>
</tr>
<tr>
<td>$^{48}$Ca+$^{244}$Pu</td>
<td>233</td>
<td>32</td>
<td>9.0 $\pm$ 1.2</td>
<td>4.6 $\pm$ 0.9</td>
<td>14.6 $\pm$ 1.8</td>
<td>10.6 $\pm$ 1.6</td>
</tr>
<tr>
<td>$^{48}$Ca+$^{248}$Cm</td>
<td>245</td>
<td>37</td>
<td>9.9 $\pm$ 1.4</td>
<td>5.6 $\pm$ 1.0</td>
<td>14.8 $\pm$ 1.8</td>
<td>12.5 $\pm$ 1.6</td>
</tr>
</tbody>
</table>
dimensional matrix \((TKE - M)\), together with the experimental dependence \(TKE(M)\) (the open circles) and its approximation by the parabola [13], as well as the average \(Q_\pi\) (the dashed line) and maximal \(Q_{\text{max}}\) (the solid line) reaction energies for the ground state of the compound nucleus.

It is clearly seen that the events belonging to the area of the QF shoulders \((M_L = 60 - 70)\) are close in their energy to the maximal reaction energy \(Q_{\text{max}}\), and the fission fragments can be formed in this mass region only due to the excitation energy \(E^* \approx 33\) MeV. So, the fragments are weakly heated in this mass region which leads to the small multiplicities of the emitted neutrons and \(\gamma\)-quanta. The excitation energy of the nuclei at the scission point can be written as [14]:

\[
E_{\text{sc}}^* = \langle Q_\pi \rangle(M) + E^* - TKE(M) - \langle M_{\text{pre}} \rangle \langle E_{\text{pre}} \rangle(M),
\]

where \(\langle Q_\pi \rangle(M)\) is the average \(Q\)-value of the fission process for a given \(M\); \(E^* \approx 33\) MeV; \(TKE(M)\) is the experimental dependence; \(\langle M_{\text{pre}} \rangle \langle E_{\text{pre}} \rangle\) is the mean energy released by a pre-fission neutron, calculated according to [6]. The excitation energy of the fragments is:

\[
E_{\gamma}^*(M) = E_{\gamma}(M) + \sum_{i=0}^{\langle M_{\text{post}} \rangle(M)} \left[ \langle B_n \rangle(M) + \langle E_{n_i}^i \rangle(M) \right],
\]

where \(E_{\gamma}\) is the average \(\gamma\)-quanta energy, \(\langle B_n \rangle\) is the average neutron binding energy and \(\langle E_{n_i}^i \rangle(M)\) is the average energy released by the \(i\)-th neutron. The value of \(\langle E_{n_i}^i \rangle(M)\) for the fragments from the symmetric region \(\Delta M_s\) was calculated using the approximation for the mean level density taken as \(a = 0.093M\) [15] because shell effects were not observed here. For the fragments from the asymmetric mass regions \(\Delta M_{L,H}\) we analyzed two extreme cases - the "heated" and "cold" ones. In the first case (the heated nucleus) \(\langle E_{n_i}^i \rangle(M)\) was calculated using the same level density \(a = 0.093M\). In the second case (the cold nucleus) we took the mean level density as \(a = 0.07M\). Ideally, the reaction energy balance should look like this:

\[
E_{\text{sc}}^*(\Delta M_{H,L}) = E_{\text{sc}}^*(\Delta M_H) + E_{\text{sc}}^*(\Delta M_L) = E_{\text{sc}}^\text{total}(\Delta M_{L,H}) \\
E_{\text{sc}}^*(\Delta M_S) = 2E_{\text{sc}}^*(\Delta M_S) = E_{\text{sc}}^\text{total}(\Delta M_S)
\]

The results of the analysis are demonstrated in the bottom panel of Fig. 8(a), where the excitation energy \(E_{\text{sc}}^*\) calculated according to (1) is shown by the solid line. Black triangles are the \(E_{\text{sc}}^*\) values, averaged over the mass region shown by horizontal lines, open triangles are the \(E_{\text{sc}}^\text{total}\) value for the "cold" (upper triangles) and "heated" (lower triangles) nuclei. It is seen that there is good agreement between the experimental data and calculations. It is also possible to find from experimental data on the neutron and \(\gamma\)-multiplicities how the excitation energy is distributed between the heavy and light fragments. Indicated
by triangles in Fig. 8(b) are the actual excitation energies $E^*_\text{sc}$ which we found for the light, symmetric and heavy fragments. The solid curve shows the excitation energy for individual fragments at the scission point $E^*_{\text{sc}}(M)$, which was obtained in the assumption that the total energy $E^*_{\text{sc}}$ (Eq. (2)) is divided in proportion to their masses: $E^*_{\text{sc}}(M) = (M/A_{\text{CN}})E^*_{\text{sc}}(M)$. One can see that $E^*_{\text{sc}}(\Delta M_i)$ and $E^*_{\text{sc}}(M)$ coincide within the error bars. Therefore, it can be said with confidence that the total excitation energy of the fragment nuclei is divided in proportion to their masses. It means that the fissioning nucleus undergoes complete thermalization at any mass ratio of the fragments, including the quasi-fission region.

Columns (a),(b),(c) of Figure 9 show the data for the reactions of $^{58}\text{Fe}$ projectile on $^{232}\text{Th}$, $^{244}\text{Pu}$ and $^{248}\text{Cm}$ targets, leading to the formation of the compound system $^{290}\text{116}$ and the heaviest compound systems $^{302}\text{120}$ and $^{306}\text{122}$ (where $N = 182 - 184$), i.e. to the formation of the spherical compound nucleus, predicted by theory [16]. As seen from Figure 7, in these cases we observe an even stronger manifestation of the asymmetric mass distributions of $^{306}\text{122}$ and $^{302}\text{120}$ fission fragments with the light fragment mass at about 132. The corresponding structures are seen well in the $(TKE)(M)$ distribution as a function of fragment mass. Only for the reaction $^{58}\text{Fe}+^{232}\text{Th} \rightarrow ^{290}\text{116}$ ($E^* = 53\text{ MeV}$) the valley in the region of $M = A/2$ disappears – this is seen from the mass yield distribution as well as from the $(TKE)(M)$ dependence. This fact is connected with a reducing of the shell effects influence at so high excitation.

Figure 9(d) shows the data for the reaction $^{64}\text{Ni}+^{242}\text{Pu} \rightarrow ^{306}\text{122}$. In this reaction the same nucleus $^{306}\text{122}$ is formed at the same excitation energy as in the previous case.
(Fig. 9(c)), and the asymmetry of the entrance channel changes only slightly. Mass distributions look similar in both cases, with characteristic quasi-fission peaks in the region of doubly magic lead, however, energy characteristics of the fission fragments differ.

In the case of the reaction with $^{58}\text{Fe}$-projectile the dependence $\langle TKE \rangle (M)$ has a valley in the symmetric part and peaks corresponding to mass 132 and complimentary masses. The $^{64}\text{Ni}$-induced reaction yields a totally different dependence: $\langle TKE \rangle (M)$ changes only slightly, by about 5 MeV within the entire range of masses. For the reaction with $^{58}\text{Fe}$ ions, $\langle TKE \rangle (M)$ varies in the limit of 25 MeV.

For the reaction with $^{64}\text{Ni}$ ions the dependence $\sigma_{TKE}^2(M)$ is parabolic and is smaller in amplitude than that in the reaction with $^{58}\text{Fe}$ ions, where it is seen despite low statistics that the variance $\sigma_{TKE}^2(M)$ increases in the central part, which points to the co-existence in this region of both processes – fission and quasi-fission. Thus, it indirectly suggests that in the $^{64}\text{Ni}$-induced reaction the contribution of quasi-fission grows as compared with the reaction with $^{58}\text{Fe}$ ions. This fact may possibly explain the reasons of failed attempts to synthesize element $^{293}118$ in the $^{86}\text{Kr}$ projectile reaction [17], since an increase in the asymmetry of the entrance channel in this case leads to the domination of the quasi-fission process.

Figure 10: Two-dimensional TKE-Mass matrix, mass yield, average TKE and the variance $\sigma_{TKE}^2$ as a function of the fragment mass for the reaction $^{64}\text{Ni} + ^{186}\text{W} \rightarrow ^{250}\text{No}$ at the exitation energy $E^* \approx 31.5$ MeV.

Figure 11: Schematic of mass-yield distributions, normalized to 200% fission fragments yield for SP of trans-Bk isotopes (from [19]) and induced fission (our work).

Figure 10 shows MED of fission fragments of the reaction $^{64}\text{Ni} + ^{186}\text{W} \rightarrow ^{250}\text{No}$. This reaction is of particular interest since the form of the mass distribution has a pronounced structure. In contrast to $^{256}\text{No}$, formed in the reactions with $^{48}\text{Ca}$ ions (Fig. 7), it is seen
that the contribution of quasi-fission fragments into the total mass distribution in the case of the $^{250}\text{No}$ greatly increases. Mass distribution of $^{250}\text{No}$ fission fragments also has a complicated structure – the asymmetric fission mode Standard II [18], connected with the formation of the deformed shell near the heavy fission fragment mass 140, is manifested in this case. Such situation is inherent in the elements from U to Cf. Besides, in the $^{250}\text{No}$ mass distribution, along with the asymmetric fission, there is a symmetric fission component S (Superlong), determined by the influence of the closed proton shell $Z = 50$. (see Fig 8.(b)). The manifestation of these processes is seen in the energy characteristics – dependences of $\langle TKE \rangle(M)$ and $\sigma_{\text{TKE}}^2(M)$. The curve $\sigma_{\text{TKE}}^2(M)$ has humps in the center ($M = 125$) and in the mass range 160 – 170 which confirms the co-existence in these regions of several processes.

The obtained yields of $^{250,256}\text{No}$ fission fragments are included into the diagram of mass distributions by D. Hofmann [19] for the fission of trans-berkelium isotopes (Fig. 11). In the spontaneous and low-energy ($E^* \leq 33$ MeV) fission of No isotopes one can see a change in the form of the fission fragment yield, from the superposition of symmetric (S) and asymmetric (Standard-II) modes for $^{252}\text{No}$, determined by the shells of fission fragments $N = 82$ and $Z = 50$, to the asymmetric form for $^{252}\text{No}$, and a further transition to symmetric fission in the case of $^{256,258,272}\text{No}$. Note that in the case of induced fission symmetric and asymmetric components become wider, and besides, the mass distribution width for spontaneous fission of No isotopes becomes smaller with increasing the neutron number at approaching $N = 164$, i.e. when in symmetric fission both fragments are close to magic ones by the proton and neutron numbers ($Z = 50, N = 82$).

3. Capture and fusion-fission cross sections

Figure 12 shows the results of measurements of the capture $\sigma_{\text{cap}}$ and the fusion-fission $\sigma_{\text{ff}}$ cross sections (defined as $\sigma_{A/2\pm20}$ ) for a few studied reactions as a function of the initial excitation energy of the compound systems.

Comparing the data on the cross sections $\sigma_{\text{ff}}$ for the warm fusion (the reactions from $^{48}\text{Ca}+^{238}\text{U}$ to $^{55}\text{Fe}+^{248}\text{Cm}$ at $E^* \approx 33$ MeV) and for the cold fusion (the reactions $^{58}\text{Fe}+^{208}\text{Pb}$ and $^{86}\text{Kr}+^{208}\text{Pb}$ at $E^* \approx 14 - 15$ MeV [11]), one can obtain the following ratios: $\sigma_{\text{ff}}(112)/\sigma_{\text{ff}}(122) \approx 4 - 5$ in the first case and $\sigma_{\text{ff}}(108)/\sigma_{\text{ff}}(118) \geq 10^2$ for the second one, however the value of $Z$ of the compound nucleus changes by the same 10 units in both cases. That makes the use of asymmetric warm fusion reactions for the synthesis of spherical superheavy nuclei quite promising.

Another interesting result is connected with the fact that the values of $\sigma_{\text{ff}}$ for $^{256}\text{102}$ and $^{266}\text{108}$ at $E^* \approx 14 - 15$ MeV are quite close to each other, whereas the evaporation residue cross sections $\sigma_{\text{xn}}$ [20] differ by almost three orders of magnitude $\sigma_{\text{ff}}/\sigma_{\text{xn}}$ which is evidently caused by a change in the $\Gamma_f/\Gamma_n$ value for the above mentioned nuclei. At the same time, for the $^{294}\text{118}$ nucleus formed in the reaction $^{208}\text{Pb}+^{86}\text{Kr}$, the compound nucleus formation cross section is decreasing at an excitation energy of 14 MeV by more than two orders of magnitude according to our estimations ($\sigma_{\text{ff}} \approx 500$ nb is the upper limit) as compared with $\sigma_{\text{ff}}$ for $^{256}\text{102}$ and $^{268}\text{108}$ produced in the reactions $^{208}\text{Pb}+^{48}\text{Ca}$ and $^{208}\text{Pb}+^{58}\text{Fe}$ at the same excitation energy. But when using the value of 2.2 pb for the cross section $\sigma_{\text{ER}}(1n)$ from work [17], one obtains the ratio $\sigma_{\text{xn}}/\sigma_{\text{ff}} \approx 4 \cdot 10^{-6}$ for $^{294}\text{118}$,
whereas for $^{266}_{108}$ the ratio is $\sigma_{\text{xn}}/\sigma_{\text{ff}} \approx 10^{-6}$. In one of recent works [21] it has been proposed that such unexpected increase in the survival probability for the $^{294}_{118}$ nucleus is connected with the sinking of the Coulomb barrier below the level of the projectile's energy and, as a consequence, leads to an increase in the fusion cross section. However, our data do not confirm this assumption.

4. Conclusion and Outlook

Mass and energy distributions of fragments, fission and quasi-fission cross sections, multiplicities of neutrons and gamma-quanta have been studied for a wide range of nuclei with $Z = 82 - 122$ produced in reactions with $^{12}$C, $^{22}$Ne, $^{26}$Mg, $^{48}$Ca, $^{58}$Fe, $^{64}$Ni and $^{86}$Kr ions at energies close and below the Coulomb barrier. In the case of the fission process as well as in the case of quasi-fission, the observed peculiarities of mass and energy distributions of the fragments, the ratio between the fission and quasi-fission cross sections, in dependence of the nucleon composition and other factors, are determined by the shell structure of the formed fragments. It is important to note that in the case of the quasi-fission process the influence of the shell effects on the observed characteristics is much stronger than in the case of classical fission of compound nuclei.

A further progress in the field of synthesis of superheavy nuclei can be achieved using hot fusion reactions between actinide nuclei and $^{48}$Ca ions as well as actinide nuclei and $^{58}$Fe or $^{64}$Ni ions. Of course, for planning the experiments on the synthesis of superheavy nuclei of up to $Z = 122$, new research and more precise quantitative data obtained in the processes of fusion-fission and quasi-fission of these nuclei in reactions with $^{58}$Fe and $^{64}$Ni ions are required.

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REFERENCES
12. A. A. Goverdovsky (private communication)