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FUSION–FISSION OF SUPERHEAVY NUCLEI AT LOW EXCITATION ENERGIES

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1 Introduction

Interest in the study of the fission process of superheavy nuclei interactions with heavy ions is connected first of all with the possibility of obtaining information, the most important for the problem of synthesis, on the production cross section of compound nuclei at excitation energies of ≈15-30 MeV (i.e. when the influence of shell effects on the fusion and characteristics of the decay of the composite system is considerable), which makes possible prediction on its basis of the probability of their survival after evaporating 1, 2 or 3 neutrons, i.e. in "cold" or "warm" fusion reactions. However, for this problem to be solved, there is a need for a much more penetrating insight into the fission mechanism of superheavy nuclei and for a knowledge of such fission characteristics as the fission - quasi-fission cross section ratio in relation to the ion-target entrance channel mass asymmetry and excitation energy, the multiplicity of the pre and postfission neutrons, the kinetic energy of the fragments and the peculiarities of the mass distributions of the fission and quasi-fission fragments etc. Undoubtedly all these points are of great independent interest to nuclear fission physics.

In this connection this work presents the first preliminary results of the experiments on the fission of superheavy nuclei in the reactions $^{208}Pb+^{48}Ca \rightarrow ^{256}No$, $^{248}Cm+^{22}Ne \rightarrow ^{270}Sg$, $^{248}Cm+^{26}Mg \rightarrow ^{274}Hs$, $^{238}U+^{48}Ca \rightarrow ^{286}112$, $^{244}Pu+^{48}Ca \rightarrow ^{292}114$, $^{248}Cm+^{48}Ca \rightarrow ^{296}116$, $^{208}Pb+^{58}Fe \rightarrow ^{266}Hs$, $^{248}Cm+^{58}Fe \rightarrow ^{306}122$, $^{208}Pb+^{86}Kr \rightarrow ^{294}118$ carried out at FLNR JINR in the last year. The choice of the indicated reactions has undoubtedly been inspired by the results of the recent experiments on producing the nuclides $^{283}112$, $^{287}114$, $^{289}114$ at Dubna [1,2] and $^{293}118$ at Berkeley [3] in the same reactions.

2 Experiment

The experiment was carried out on the extracted beam of ^{22}Ne, ^{26}Mg, ^{48}Ca, ^{58}Fe and ^{86}Kr ions of the FLNR JINR U-400 accelerator, using a set-up that included:

- the two-armed time-of-flight reaction products spectrometer CORSET built with the use of microchannel plates (MCP);
- 24 detector time-of-flight neutron spectrometer DEMON using scintillation modules [4];
- a 4 detector scintillation γ-quanta multiplicity spectrometer.

The reaction fragments spectrometer allows one to obtain the mass energy and angular distributions of fission fragments and scattered particles. It is based on 2 identical movable time-of-flight arms. The start detectors used MCP amplifiers equipped with an electrostatic mirror for the electrons knocked out by a particle passing through a 25×35 mm thin 120 $\mu g/cm^2$ gilded mylar foil placed at 30 mm from the target.

As stop detectors, 4 coordinate sensitive MCP modules of 40×60 mm operating zone were used in each arm, the modules being place at 180 mm from the target. The detectors were installed symmetrically relative to the beam at an angle of about 60° depending on the reaction type.

The spectrometer was calibrated and adjusted with the use of ^{226}Ra α-particle sources, the fission fragments of ^{252}Cf and elastic scattering peaks directly during the experiment. The following values were obtained for its main characteristics:

Time resolution	150-225 ps
Measuring range of the angles of divergence of reaction products for each arm:	
- in the reaction plane Θ	44°
- beyond the Ψ-plane	28°
Angular resolution	0.1°
Solid angle of one arm	370 mst
Mass resolution	≈3 amu

The spectrometer for γ-ray multiplicity consisted of four 63×63 mm NaJ(Tl) detectors, which were placed in lead collimators and installed in the lower hemisphere at 35 cm from the target. The threshold of γ-quanta registration was 100 keV. To reduce the accidental coincidences, the time between pulses from fission fragments and γ-rays were measured. The time resolution of the γ ray detectors was 7 ns.

The neutron spectrometer detectors (built with the use of a Ne213 liquid scintillator) arranged in groups of three were located at 130 cm from the target at angles of 17°, 0°, -17° beyond the reaction plane and at angles of 45°, 65°, 155°, -65°, -90°, -135° in the reaction plane. Some detectors were located in the vertical plane along the beam axis at angles of 10°, 25°, 74.5°, 90°, 105.5°, 163°. The signals due to neutrons and γ-radiation were separated by analysing the shape of the pulse generated by the photomultiplier.

The discrimination thresholds were set during calibrating ^{22}Na, ^{88}Y, ^{60}Co, ^{137}Cs, ^{226}Ra. To ensure the stability of the energy scale, the calibration was repeated several times during the experiment.

As the target, 120-170 μg/cm^2 ^{208}Pb, ^{238}U, ^{248}Cm and ^{244}Pu spectrometric layers deposited on a 40- 50 μg/cm^2 carbon backing were used.

The ion beam energy was periodically measured with an accuracy of ± 1 MeV with use of a semiconductor detector, using its scattering by tantalum and gold foils, and constantly monitored with a semiconductor monitor immediately in the reaction chamber, using the scattering of the beam nuclei by the target. The total ion current that had passed through the target was measured with the help of a Faraday cup, taking account of the dead time of the collecting system and its rest time.

The data processing was carried out with the use of traditional techniques, assuming the process under study to be a two-body process. The losses of the energy of the fragments in the target, backings and start detectors were taken into account. Special attention was paid to the angular folding correlations of the fragments both in and beyond the reaction plane. Only those events were selected and then analyzed that corresponded to the two-body process of complete momentum transfer. The neutron energy and angular distributions for selected masses and energies of fragments were obtained using a JUNO data visualization and analysis program.

3 Characteristics of mass and energy distributions of SHE fission fragments

Fig.1 shows the data on mass and energy distributions of fission fragments of ^{256}102, ^{286}112, ^{292}114 and ^{296}116 nuclei produced in the reactions with ^{48}Ca at one and 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}102 to the quasi-fission mechanism of decay in the case of the ^{286}112 nucleus and more heavy nuclei. It is very important to note that despite a dominating contribution of the quasi-fission process in the case of nuclei with Z=112-116, in the symmetric region of fission fragment masses (A/2 ± 20) the process of fusion-fission of compound nuclei, in our opinion, prevails. It is demonstrated in the framings (see the right-hand panels of Fig.1) from which it is also very well seen that the mass distribution of fission fragments of compound nuclei is asymmetric in shape with the light fission fragment mass = 132-134.

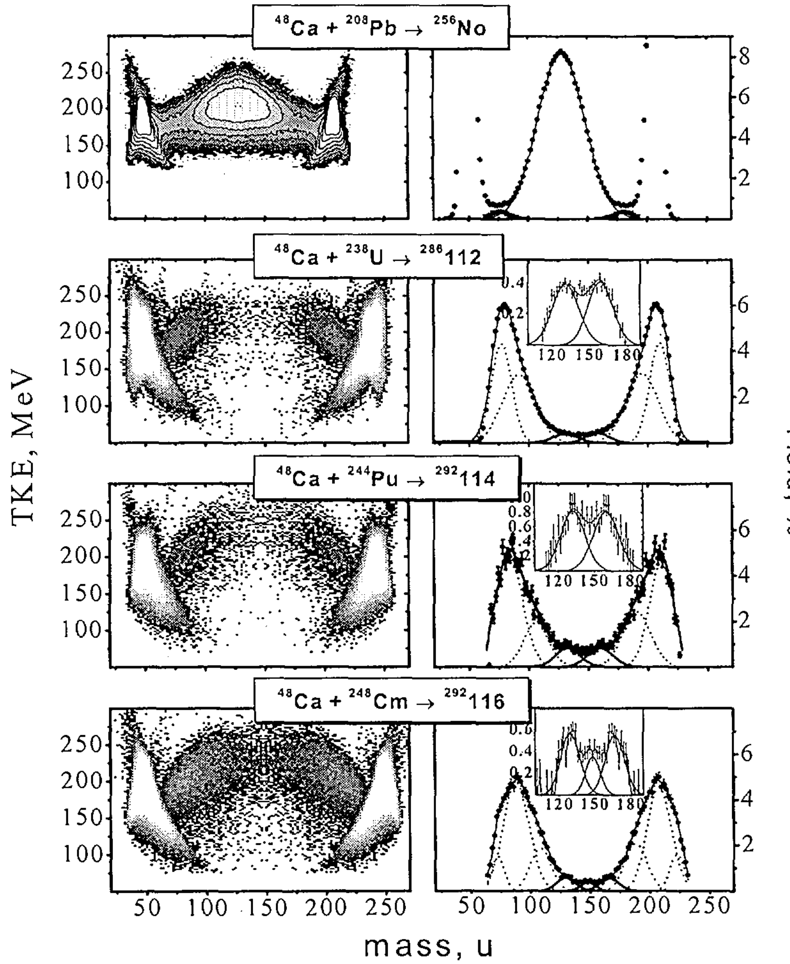

Figure 1. Two-dimensional TKE-Mass matrices (left-hand side panels) and mass yields (right-hand side panels) of fission fragments of ^{256}102, ^{286}112, ^{292}114 and ^{296}116 nuclei produced in the reactions with ^{48}Ca at the excitation energy E*≈33 MeV.

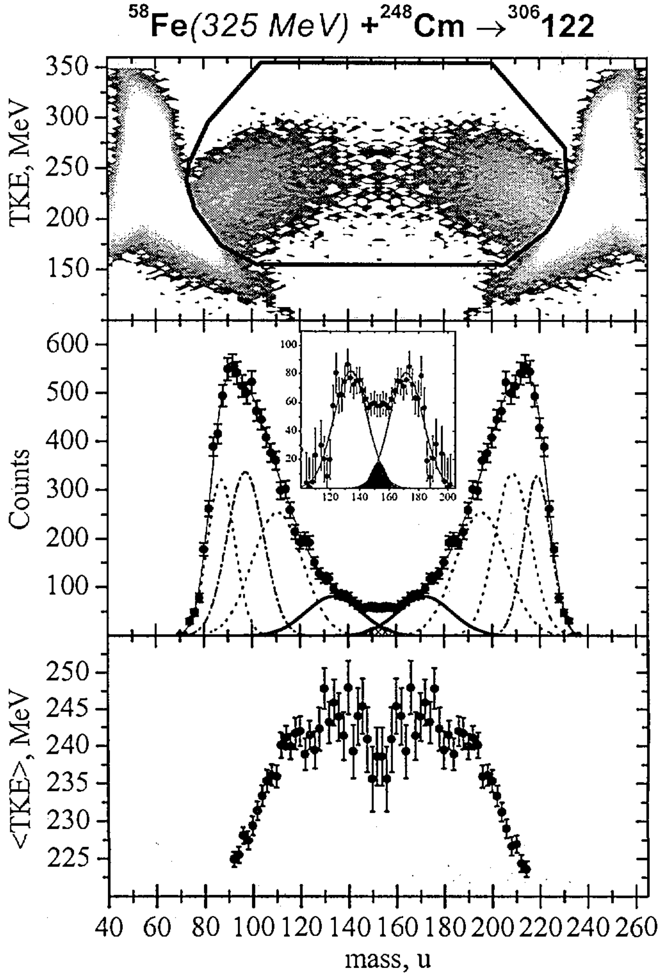

Figure 2. A two-dimensional TKE-Mass matrix, the mass yield and average TKE as a function of the mass of ^{306}122 fission fragments.

Fig. 2 shows similar data for the reaction ^{58}Fe + ^{248}Cm leading to the formation of the heaviest compound system ever studied by us, namely, ^{306}122 (N=184), i.e., to the formation of the spherical compound nucleus, which agrees well with theoretical predictions [5]. As seen from Fig.2, in this case we observe an even stronger manifestation of the asymmetric mass distribution of $^{306}122$ fission fragments with the light fragment mass 132. The corresponding structures are also well seen in the dependence of the TKE on the mass (the lower panel of Fig.2).

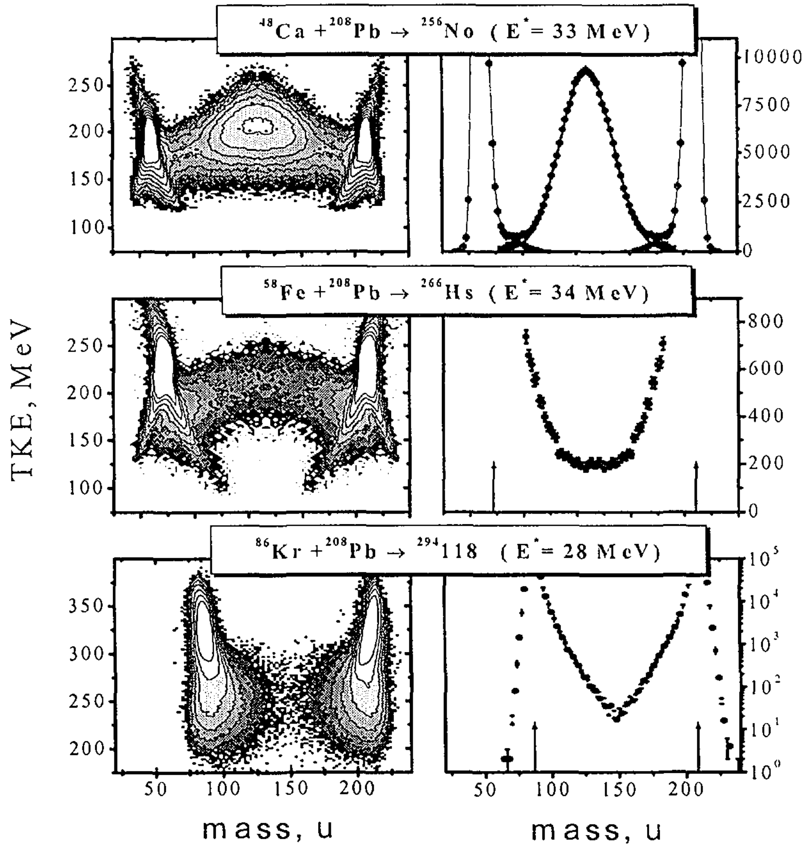

Figure 3. Two-dimensional TKE-Mass matrices and mass yields of fission fragments for the reactions $^{208}Pb + ^{48}Ca$, $^{208}Pb + ^{58}Fe$, $^{208}Pb + ^{86}Kr$ at an excitation energy of ≈30 MeV.

Fig.3 shows mass and energy distributions of fission fragments for compound nuclei ^{256}No, ^{266}Hs and $^{294}118$ formed in the interaction between a ^{208}Pb target and ^{48}Ca, ^{58}Fe and ^{86}Kr ions at the excitation energy of ≈ 30 MeV. It is important to note that in the case of the reaction $^{208}Pb + ^{86}Kr$

the ratio between the fragment yields in the region of asymmetric masses and that in the region of masses A/2 exceeds by about 30 times a similar ratio for the reactions with ^{48}Ca and ^{58}Fe ions. It signifies to that fact that in the case of the $^{208}Pb + ^{86}Kr \rightarrow ^{294}118$ reaction in the region of symmetric fragment masses the mechanism of quasi-fission prevails.

Figures 4, 5, 6 show similar data for the reactions $^{208}Pb + ^{58}Fe \rightarrow ^{266}Hs$, $^{244}Pu + ^{48}Ca \rightarrow ^{292}114$ and $^{248}Cm + ^{48}Ca \rightarrow ^{296}116$ obtained at different excitation energies.

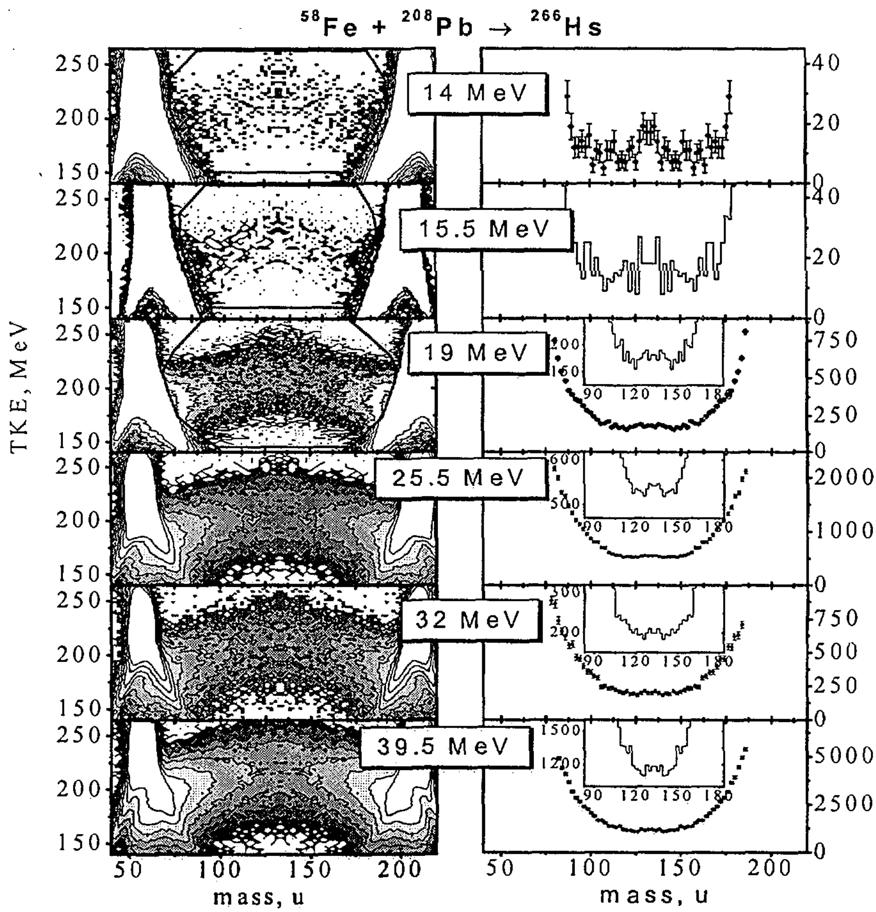

Figure 4. Two-dimensional TKE-Mass matrices and mass yields of fission fragments for the reaction $^{208}Pb + ^{58}Fe \rightarrow ^{266}Hs$ at different excitation energies.

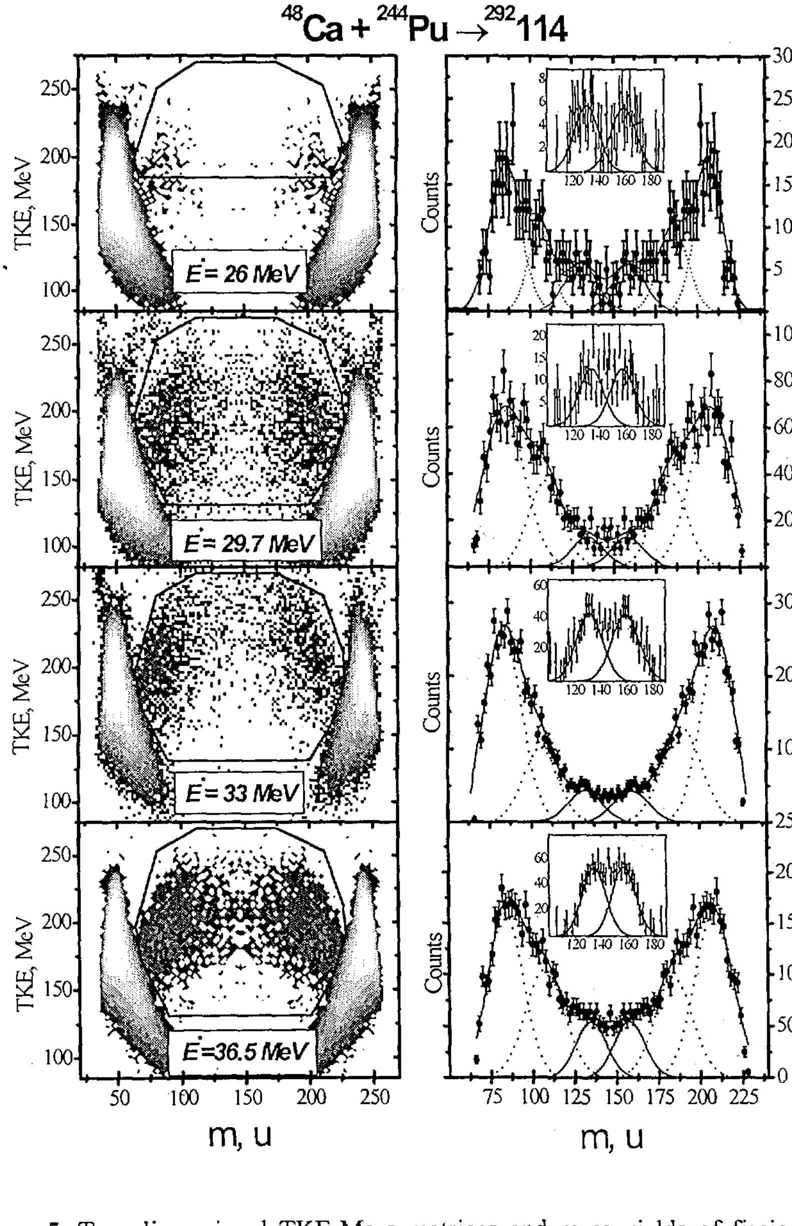

Figure 5. Two-dimensional TKE-Mass matrices and mass yields of fission fragments for the reaction $^{244}Pu + ^{48}Ca \rightarrow ^{292}114$ at different excitation energies.

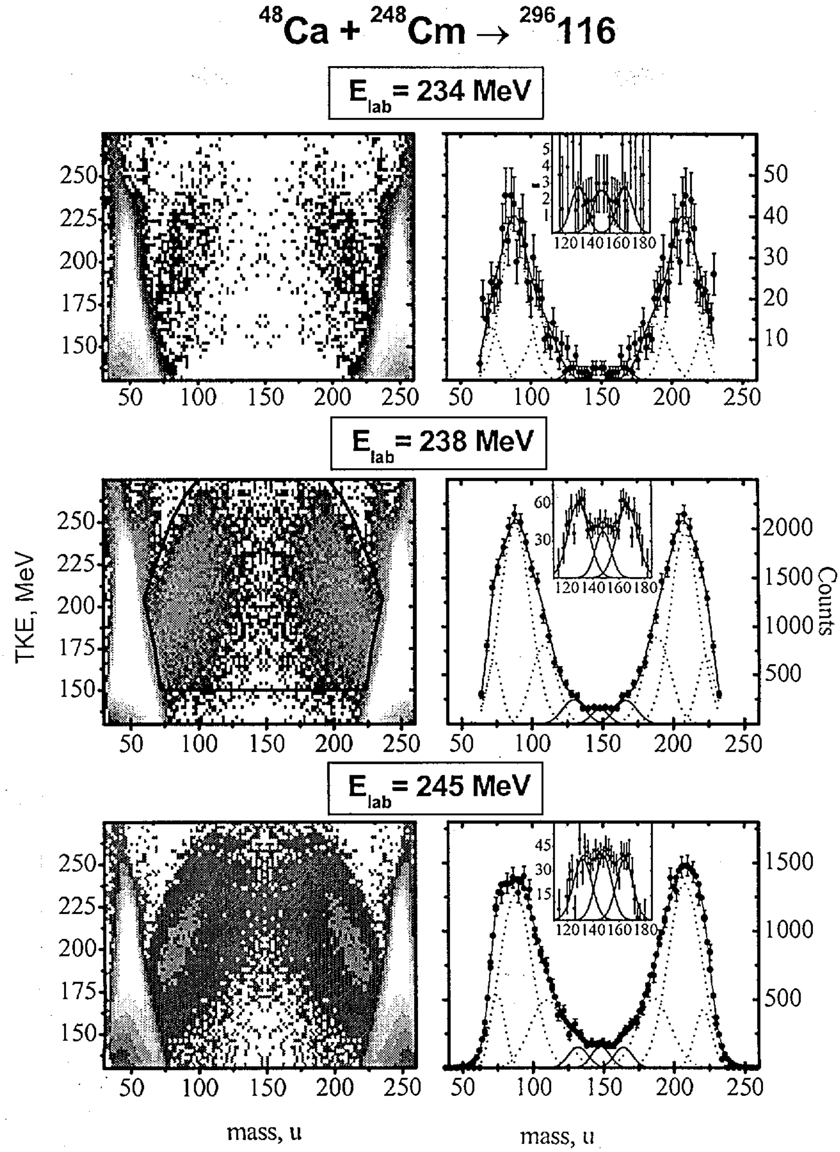

Figure 6. Two-dimensional TKE-Mass matrices and mass yields of fission fragments for the reaction $^{248}Cm + ^{48}Ca \rightarrow ^{296}116$ at different excitation energies.

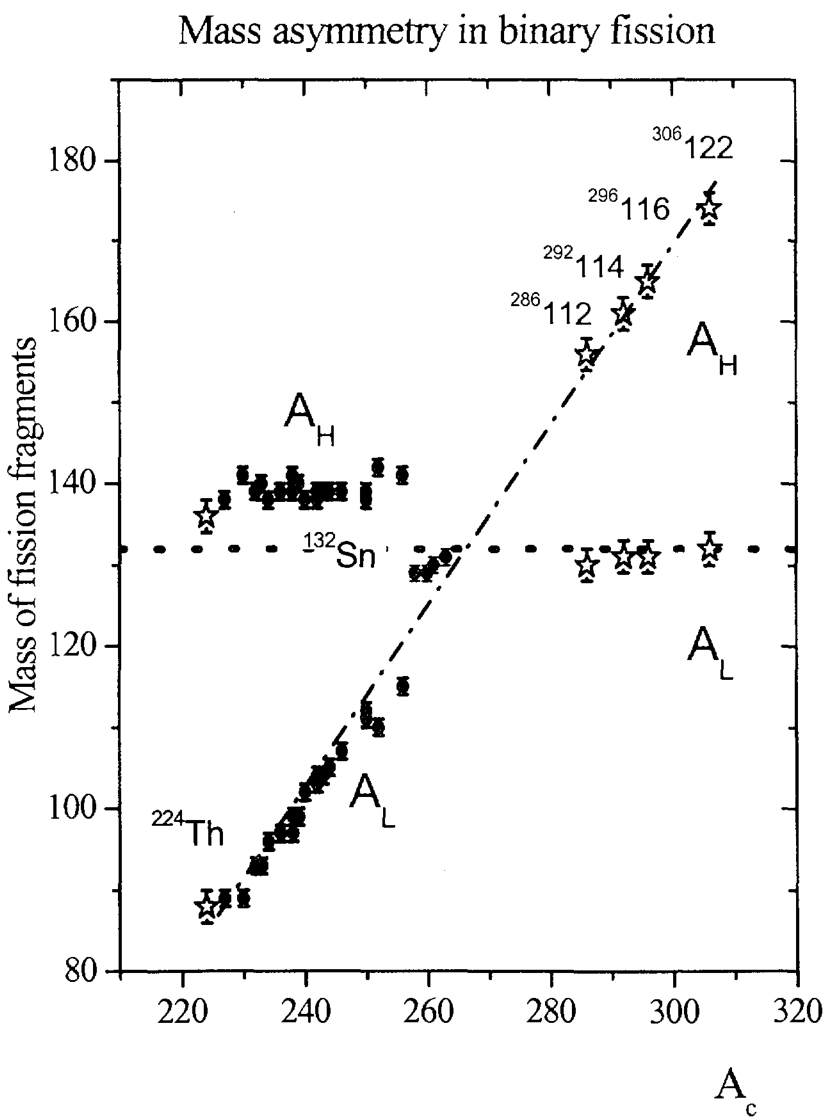

Figure 7. The dependence of the light and heavy fragment masses on the compound nucleus mass.

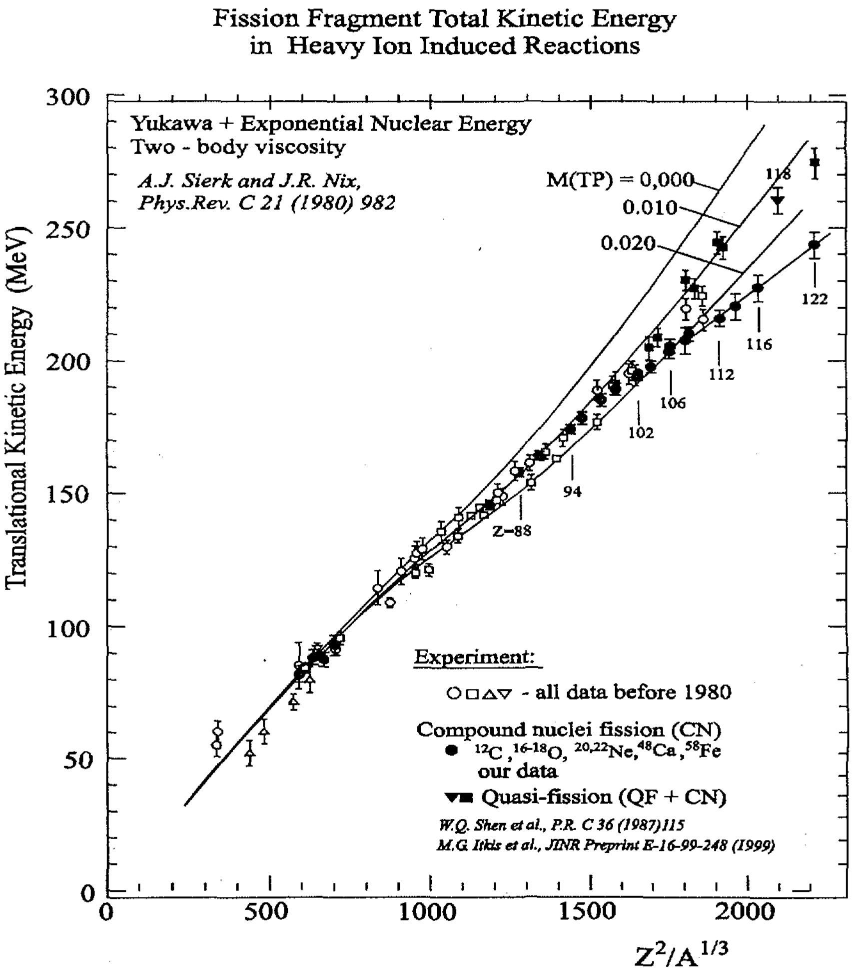

Figure 8. The dependence of TKE on the Coulomb parameter $Z^2/A^{1/3}$.

In analyzing the data presented in Figs. 1-6 one can notice two main regularities in the characteristics of mass and energy distributions of fission fragments of superheavy compound nuclei:

1. Fig. 7 shows the dependence of the light and heavy fragment masses on the compound nucleus mass. It is very well seen that in the case of superheavy nuclei the light spherical fragment with masses 132-134 plays a stabilizing role, in contrast to the region of actinide nuclei.

2. Fig. 8 shows the TKE dependence on the Coulomb parameter $Z^2/A^{1/3}$, from which it follows that for the nuclei with Z>100 the TKE value is much smaller in the case of fission as compared with the quasi-fission process.

4 Capture and fusion-fission cross sections

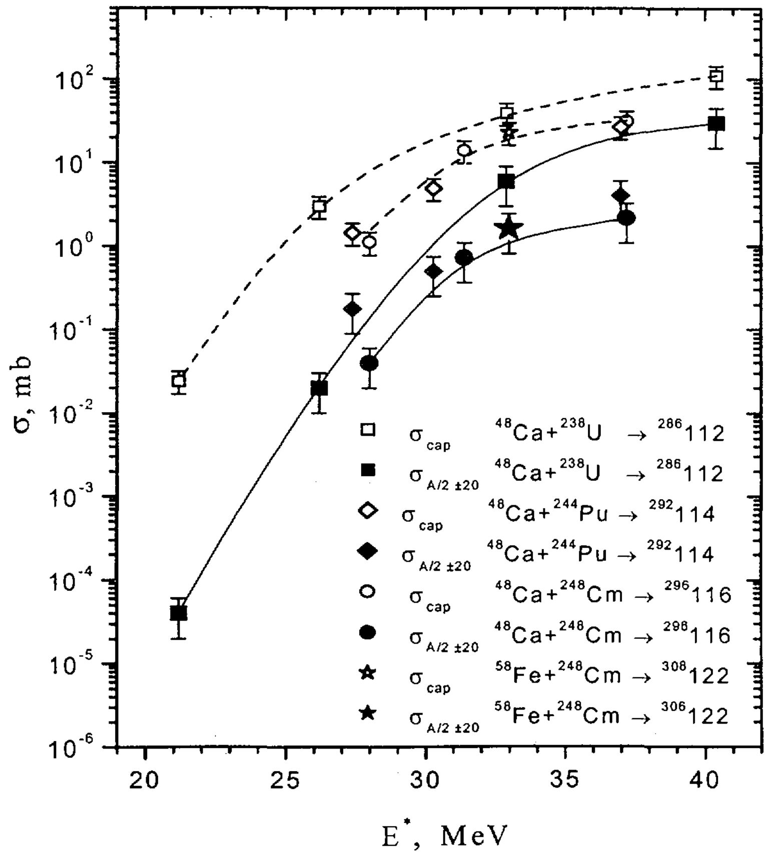

Figure 9. The capture cross section σ_c and the fusion-fission cross section σ_{ff} for the reactions $^{48}Ca+^{238}U$, ^{244}Pu, ^{248}Cm, and $^{58}Fe+^{248}Cm$ as a function of the excitation energy.

Figures 9 and 10 show the results of measurements of the capture cross section σ_c and the fusion-fission cross section σ_{ff} for the studied reactions as a function of the initial excitation energy of the compound systems.

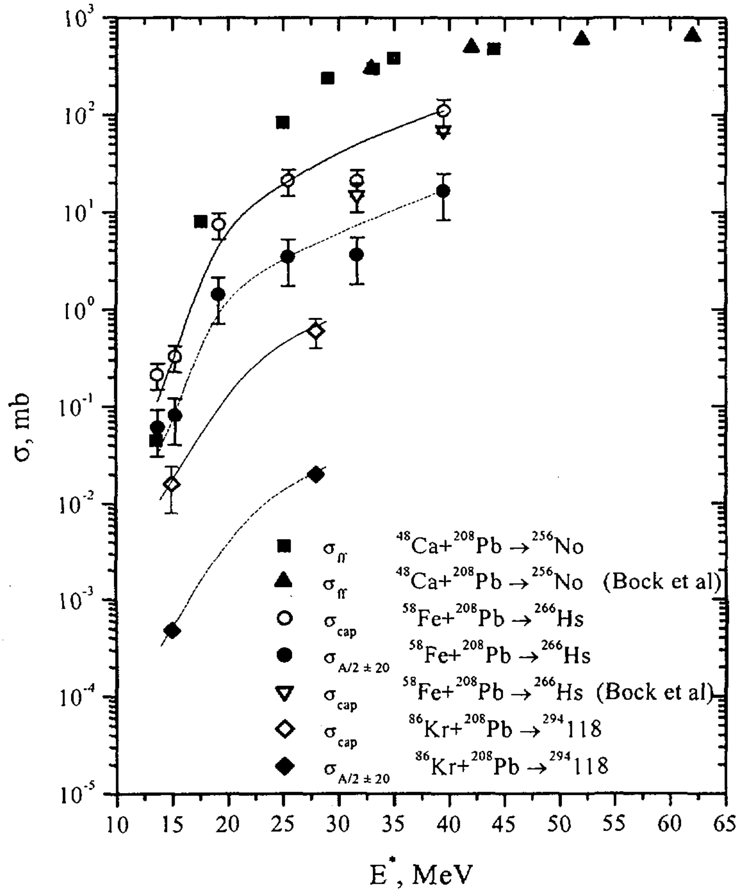

Figure 10. The capture cross section σ_c and the fusion-fission cross section σ_{ff} for the reactions ^{48}Ca, ^{58}Fe, $^{86}Kr+^{208}Pb$ as a function of the excitation energy.

Comparing the data on the cross sections σ_{ff} at $E^* \approx$ 14-15 MeV (cold fusion) for the reactions $^{208}Pb + ^{58}Fe$ and $^{208}Pb + ^{86}Kr$, one can obtain the following ratio: $\sigma_{ff}(108)/\sigma_{ff}(118) \geq 10^2$. In the case of the reactions from ^{238}U

+ ^{48}Ca to ^{208}Cm + ^{58}Fe at E* ≈ 33 MeV (warm fusion) the value of Z changes by the same 10 units as in the first case, and the ratio σ_{ff} (112)/ σ_{ff}(122) is ≈ 4-5 which makes the use of asymmetric reactions for the synthesis of spherical superheavy nuclei quite promising.

Another interesting result is connected with the fact that the values of σ_{ff} for ^{256}102 and ^{266}108 at E* = 14-15 MeV are quite close to each other, whereas the evaporation residue cross sections σ_{xn} [6] differ by almost three orders of magnitude (σ_{ff}/σ_{xn}) which is evidently caused by a change in the Γ_f/Γ_n value for the above mentioned nuclei. At the same time, for the ^{294}118 nucleus formed in the reaction ^{208}Pb + ^{86}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 (σ_{ff}≈500 nb is the upper limit) as compared with σ_{ff} for ^{256}102 and ^{268}108 produced in the reactions ^{208}Pb + ^{48}Ca and ^{208}Pb + ^{58}Fe at the same excitation energy. But when using the value of ≈ 2.2 pb for the cross section σ_{ev}(1n) from work [3], one obtains the ratio $\sigma_{xn}/\sigma_{ff} \approx 4\cdot10^{-6}$ for ^{293}118, whereas for ^{266}108 the ratio is $\sigma_{xn}/\sigma_{ff} \approx 10^{-6}$.

In one of recent works [7] 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.

5 Neutron and gamma-ray multiplicities in the fission of superheavy nuclei

Emission of neutrons and gamma-rays in correlation with fission fragments in the decay of superheavy compound systems at excitation energies of near or below the Coulomb barrier had not been properly studied before this publication. At the same time such investigations may be extremely useful for an additional identification of fusion-fission and quasi-fission processes and thus a more precise determination of the cross sections of the above mentioned processes in the total yield of fragments. On the other hand, the knowledge of the value of the fission fragment neutron multiplicity may be used in the identification of SHE in the experiments on their synthesis.

The first results of such investigations are presented in Figs. 11-12 for the reactions $^{208}Pb + ^{48}Ca \to ^{256}No$, $^{238}U + ^{48}Ca \to ^{286}112$, $^{244}Pu + ^{48}Ca \to ^{292}114$ and $^{248}Cm + ^{48}Ca \to ^{296}116$ at energies near the Coulomb barrier. As seen from the figures, in all the cases the total neutron multiplicity M_{tot} 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). Another important peculiarity of the obtained data is the large values of $M_{tot} \approx 9$ and 10.5 for the fission of $^{292}114$ and $^{296}116$ compound nuclei, respectively. As well as for M_{tot} noticeable differences have been observed in the values of γ-ray multiplicities for different mechanisms of superheavy compound nucleus decay.

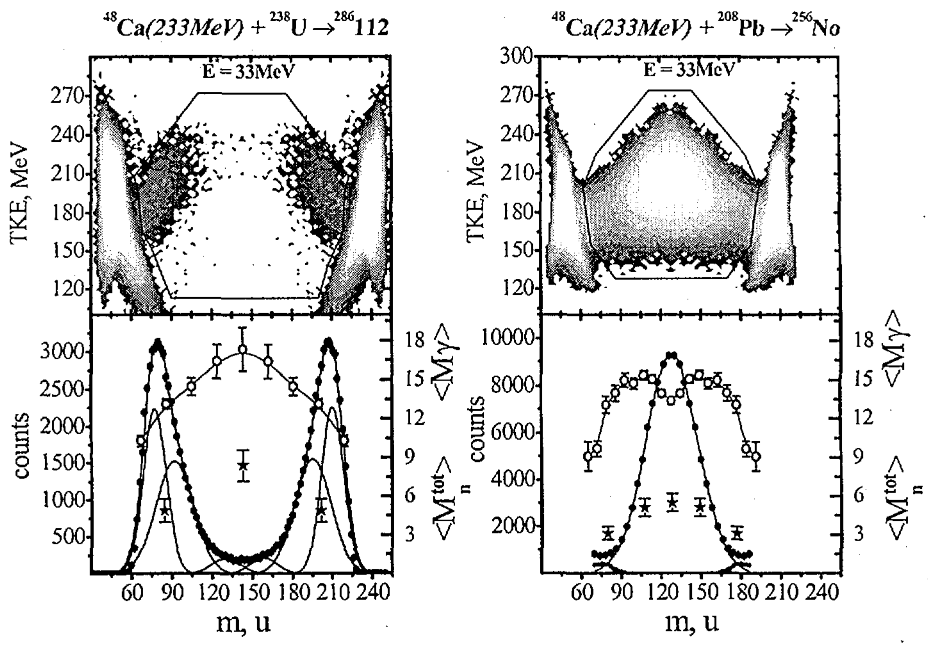

Figure 11. *Two-dimensional TKE-Mass matrices* (top panels) and the mass yields (the solid circles), neutron (the stars) and gamma ray (the open circles) multiplicities in dependence on the fission fragment mass (bottom panels) for the reactions $^{238}U + ^{48}Ca \to ^{286}112$ and $^{208}Pb + ^{48}Ca \to ^{256}No$.

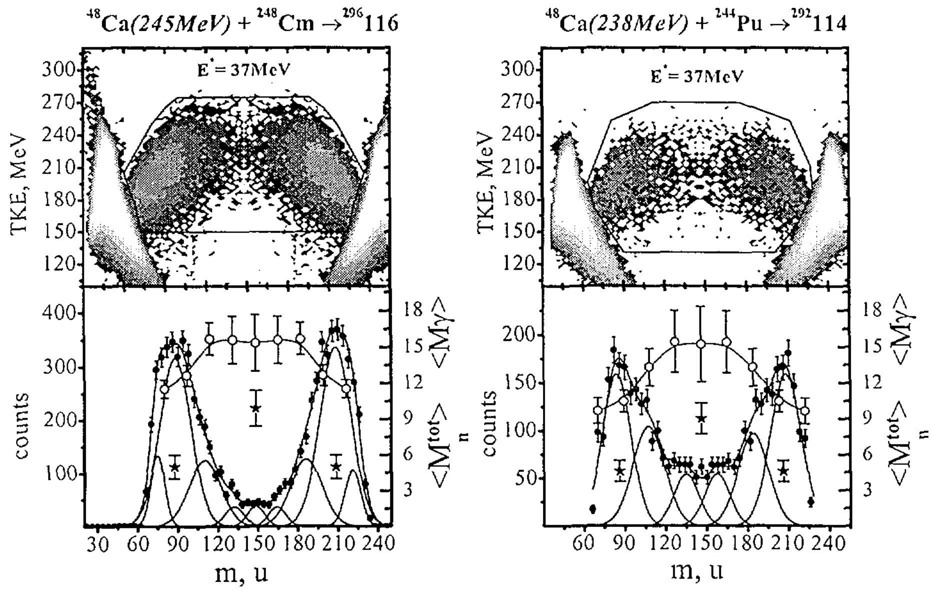

Figure 12. The same as in Fig.11, but for the reactions ^{248}Cm + ^{48}Ca→ ^{296}116 and ^{244}Pu + ^{48}Ca → ^{292}114.

6. CONCLUSIONS

As a result of the experiments carried out, for the first time the properties were studied of the fission of the compound nuclei ^{256}No, ^{270}Sg, ^{266}Hs, ^{271}Hs, ^{274}Hs, ^{286}112, ^{292}114, ^{296}116, ^{294}118 and ^{306}122, produced in reactions with ions ^{22}Ne, ^{26}Mg, ^{48}Ca,. ^{58}Fe and ^{86}Kr at energies close to and below the Coulomb barrier.

On the basis of those data a number of novel important physics results were received:

a) it was found, that the mass distribution of fission fragments for compound nuclei ^{286}112, ^{292}114, ^{296}116 and ^{306}122 is asymmetric one, whose nature, in contrast to the asymmetric fission of actinides, is determined by the shell structure of the light fragment with the average mass 132-134. It was established that TKE, neutron and γ-ray multiplicities for fission and quasi-fission of superheavy compound nuclei are significant different;

b) the dependence of the capture (σ_c) and fusion-fission (σ_{ff}) cross sections for nuclei ^{256}No, ^{266}Hs, ^{274}Hs, ^{286}112, ^{292}114, ^{296}116, ^{294}118 and ^{306}122 on the excitation energy in the range 15–60 MeV has been studied. It should be emphasized that the fusion-fission cross section for the compound nuclei produced in reaction with ^{48}Ca and ^{58}Fe ions at excitation energy of $\approx$30 MeV depends only slightly on reaction partners, that is, as one goes from ^{286}112 to ^{306}122, the σ_{ff} changes no more than by the factor 4–5. This property seems to be of considerable importance in planning and carrying out experiments on the synthesis of superheavy nuclei with Z>114 in reaction with ^{48}Ca and ^{58}Fe ions. In the case of the reaction ^{86}Kr+^{208}Pb, leading to the production of the composite system ^{294}118, contrary to reactions with ^{48}Ca and ^{58}Fe, the contribution of quasi-fission is dominant in the region of the fragment masses close to A/2;

c) the phenomenon of multimodal fission was first observed and studied [8,9] in the region of superheavy nuclei ^{256}No, ^{270}Sg, ^{266}Hs, ^{271}Hs and ^{274}Hs.

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