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The thoretically predicted region of stability of superheavy elements with atomic numbers $A \geq 110$ has recently been the subject of extensive experimental studies. This is understandable since the discovery of superheavy nuclei and the experimental proof of the existence of a new region of stability would be a qualitatively new step toward the better understanding of the properties of nuclear matter. One of the ways of producing superheavy elements is synthesis by nuclear reactions. Wide possibilities in this respect have been offered by the production of sufficiently intensive beams of heavy ions of $A > 40$. However, the initial experiments with heavy ions such as Ge, Kr and Xe have already shown that the mechanism of nuclear reactions induced by these ions can differ substantially from that observed in the case of ions with $A < 40$.

Excited heavy nuclei with $Z^2/A \geq 40$ are known to decay mainly by fission. As a result, one can obtain physical information about fissioning compound nuclei by detecting fission fragments and by investigating the regularities of their production by heavy ion reactions.

The experiments carried out in 1972 at Dubna using the tandem cyclotron of the JINR Laboratory of Nuclear Reactions, as well as the subsequent radiochemical experiments [1-3] have shown that the reactions $^{181}Ta + {}^{136}Xe$ and $^{238}U + {}^{136}Xe$ with cross sections of about 100 mb lead to the formation of fragments of binary fission. However, the experiments carried out by the Orsay group [4,5] to study fission of compound nuclei in reactions induced by krypton ions have led to the determination of only the upper limit (<10 mb) on the formation of binary fission fragments in the bombardment of Th by 350-370 MeV krypton ions. By comparing these data with the cross section for the formation of a compound nucleus with $A_c < 250$, obtained also in reactions involving Kr ions, the authors have arrived at the conclusion that complete fusion is practically impossible in reactions of krypton ions with thorium and uranium. However, the experiments carried out by the American group headed by G.Seaborg [6], , in order to investigate by radiochemical methods the nuclear reaction products formed by bombarding a uranium target by 600 MeV krypton ions, have shown that in this reaction the fragments of binary fission are formed with a noticeable cross section (40-60 mb). In view of this ambiguity in the determination of the production probability for heavy compound nuclei we made an attempt to systematize some experimental data on fusion and fission of heavy nuclei in reactions induced by heavy ions such as Fe, Cr, Ge, Kr and Xe, obtained using the U-300 and tandem-cyclotron of the JINR Laboratory of Nuclear Reactions.

1. Specific Features of the Formation of Compound Nuclei With Mass $A_0 \approx 300$ in Reactions Induced by Kr, Ge and Xe Ions

The distribution of excited fission fragments over Z and A is determined by the specific features of the fission mechanism, and the processes of redistribution of mass and charge in the compound system as a result of its collective motion. Therefore it seems interesting to compare the fission mechanism of a heavy excited compound nucleus, produced in two different ways in reactions with ions of $A \leq 40$ and in reactions involving Kr and Xe ions as projectiles. The heaviest compound nucleus is $^{278}110$, whose fissionability parameter is $Z^2/A = 43.5$. Its fission was investigated fairly well in the reaction $^{238}U + {}^{40}Ar$ (ref. [7]). Nuclei with close masses can be produced in the reactions $^{181}Ta + {}^{84}Kr$ and $^{133}Cs + {}^{136}Xe$. For these reactions we measured the effective cross sections for the formation of different products with a wide range of masses and charges using gamma-spectroscopy with preliminary radiochemical separation of reaction products [3]. The experimental data were processed in the same way as in the case of fission of compound nuclei formed as a result of fusion with ^{12}C, ^{16}O, ^{22}Ne and ^{40}Ar ions (ref. [8]). Of the fission fragments produced, isotopes with masses close to a half of the compound nucleus mass and with charges by 10 units removed from the target or projectile have been separated. A more detailed description of the selection criteria for fission fragments from different reaction products is given in ref. [2]. The mass and isotopic distributions of the fission fragments were compared with the results obtained for the compound nucleus $^{278}110$ in complete fusion reaction resulting from the bombardment of uranium with ^{40}Ar ions. The mass distributions of primary products formed in the reactions Ta + Kr and Cs + Xe, as well as those of fission fragments in the reaction U + Ar are described well by Gaussian distributions. This indicates that in the compound nuclei formed in these reactions statistical equilibrium is established prior to fission. In table 1 the measured mass and isotopic distributions are presented, the difference between their widths for the three reactions being very small. Thus the data obtained suggest that the distribution of the products of symmetric fission depends on the characteristics of the compound system formed in the reaction, whereas the formation of nuclei with masses close to the projectile and target nucleus the characteristics of the interacting nuclei play an important role.

This fact makes it possible to use the classical compound nucleus model suggested by Bohr /9/ for the calculation of compound nucleus formation cross section in reactions with heavy ions such as Kr and Xe using the partial cross sections of product formation in separate channels of its decay, i.e., in reactions involving fission to two fragments. Therefore, integrated cross sections for the formation of fragments can be used to determine compound nucleus cross section

$$\sigma_c = \frac{1}{2} \int_{A_f} \sigma(A_f)\, dA_f. \qquad (1)$$

Table 1

Reaction	Compound nucleus	Z^2/A	B_C^L MeV	E_I^L MeV	E^* MeV	Masses of nuclei investigated	Width of isotopic distribution (mass units)	Width of mass distribution (mass units)	Compound nucleus formation cross section σ_c(mb)	σ_c/σ_r
$^{238}U+^{40}Ar$	$^{278}110$	43.5	206	270	70	90 – 95	8.0 ± 1.0	82 ± 10	950	0.7
						118 – 160	8.2 ± 2.0			
						192 – 203	7.0 ± 1.5			
$^{181}Ta+^{84}Kr$	$^{265}109$	44.8	408	550	85	59 – 62	6.6 ± 1.0	90 ± 10	350	0.3
						132 – 151	7.3 ± 1.0			
						194 – 206	6.9 ± 1.2			
$^{133}Cs+^{136}Xe$	$^{269}109$	44.2	648	840	77	166 – 171	7.2 ± 1.5	85 ± 15	70	0.06
						191 – 200	6.6 ± 1.2			

The compound nucleus formation cross sections calculated to be several hundreds of millibarns for the reactions U + Ar, Ta + Kr and Cs + Xe are presented in table 1. The total cross sections calculated using the formula

$$\sigma_c = \pi r_{eff}^2 \left(A_T^{1/3} + A_b^{1/3}\right)^2 \left(1 - \frac{B_c}{E_b}\right), \qquad (2)$$

where the effective interaction radius was taken equal to 1.35 f, are also given in table 1. From the experimental data presented in this table one can see that the cross section of complete fusion with compound nucleus formation is substantially smaller than the total cross section σ_r. The small magnitude of the complete fusion cross section is sometimes attributed to the critical angular momentum of the compound nucleus formed [10-12]. The complete fusion cross section calculated on the basis of the macroscopic model in which compound nucleus is regarded as a rotating liquid drop [10] is expected to approach zero for compound nucleus masses in the vicinity of 300. However, table 1 shows that the cross section of complete fusion reaction with compound nucleus formation in bombardment by very heavy ions lies between 70 and 350 mb. It should be noted that the cross sections for complete fusion with the formation of the same compound nucleus (with close Z^2/A and E^*) are different for different target-projectile combinations, i.e., the complete fusion cross section is determined by the dynamic processes in the entrance channel to a larger extent than by the equilibrium shapes of the compound nucleus. The same dependence of the fusion cross section on the entrance channel dynamics has been observed experimentally [13].

By comparing the experimental data with the calculation taking into account the dynamics of the entrance channel [14] one can see that the calculation describes fairly well the tendency of a decrease in the complete fusion cross section with the increasing atomic number of the projectile. Thus the main conclusion that can be drawn from the data obtained is that if the fragments of symmetric fission characterize the decay channel of the compound nucleus, then excited compound nuclei with A around 300 are formed in reactions induced by ions with $A > 40$, in particular in the $Th + Ge$ reaction, which was used to synthesize superheavy nuclei [15].

However, the features of the decay of superheavy nuclei formed as compound nuclei will be determined mainly by their excitation energies. Therefore, in element synthesis it is in principle very important to investigate the minimum compound nucleus excitation energy which is determined by the fusion threshold of two interacting nuclei.

2. Determination of Fusion Threshold for Reactions of Heavy Nuclei with ^{40}Ar, ^{52}Cr, ^{58}Fe, and ^{74}Ge Ions

A number of investigations dealing with the determination of fusion thresholds and the effective radius of the reaction of heavy nuclei with ions such as Kr have been carried out at l'Institut de Physique Nucleaire at Orsay [16, 17]. These investigations have shown that in reactions induced by krypton ions a substantial increase in the Coulomb barrier is observed as compared with reactions induced by ions with $A < 20$. In this case it was of interest to obtain information as to in what way the energy threshold of fusion reactions changes in going from relatively light to heavy projectiles. We measured the energy dependences of fission (compound nucleus formation) cross sections and transfer reactions of the interaction of the magic nucleus ^{208}Pb and the deformed nucleus ^{238}U with ^{40}Ar, ^{52}Cr (ref. [18]) and ^{58}Fe ions, as well as in the reaction of ^{232}Th with ^{74}Ge ions [19].

For reactions with argon, chromium and iron ions we used thin targets and external beams obtained from the U-300 cyclotron of the JINR Laboratory of Nuclear Reactions. The beam energy resoltuion in this case was equal to 1.0%. For reactions with germanium ions we used thick targets and an internal beam from the tandem cyclotron of the JINR Laboratory of Nuclear Reactions with an energy resolution of about 2%. The targets were fastened onto the lateral face of a cylinder which rotated during irradiation. This permitted measurement of the entire excitation function in one experiment. Following the radiochemical separation of fission fragments from irradiated targets we measured the gamma-activity of these reaction products using a Ge(Li) gamma-spectrometer and determined isotopic yields. The production cross sections for different isotopes were determined from their relative yields taking into account the target thickness and ion beam intensity. The inaccuracy in determining the cross section for a maximum energy did not exceed 10%, whereas the statistical inaccuracy for a minimum energy was 30-40%. In the experiments, the production cross sections for individual isotopes were also measured. The dependence of the fission cross section on the projectile energy was calculated taking into account the mass and isotopic distributions of the fission fragments. In addition, for each reaction we measured the cross sections for the formation of isotopes produced as a result of the transfer of one or several nucleons. Figures 1 and 2 show the fission and nucleon transfer cross sections for the reactions investigated as a function of energy. The energy thresholds for fission and transfer reactions are seen to differ by

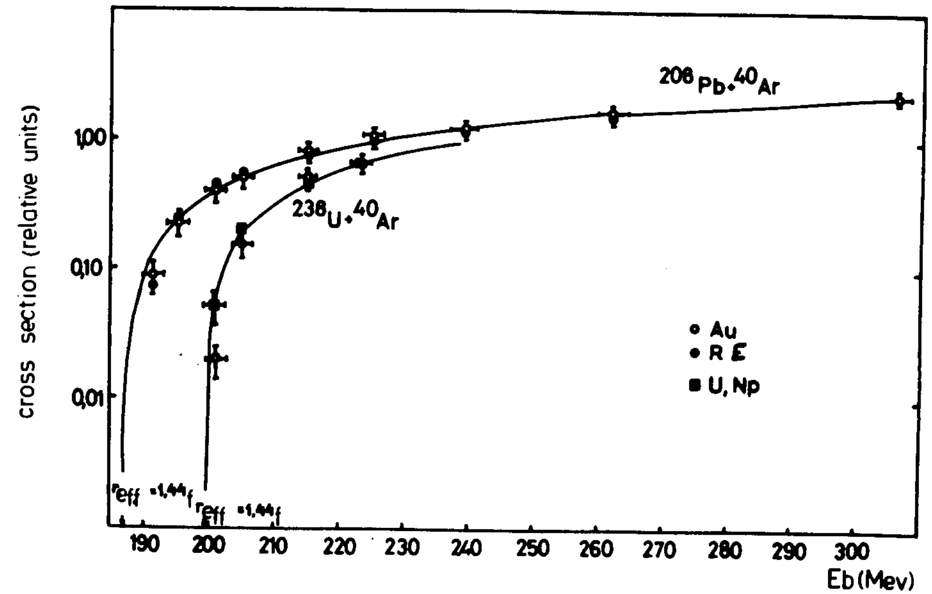

Fig. 1. The energy dependence of the cross sections for fission and transfer reactions. Open circles correspond to the cross sections determined from the yields of gold isotopes in reactions $^{238}U(^{40}Ar, f)Au$ and $^{208}Pb(^{40}Ar, -3p \pm xn)Au$, closed circles - to rare earth isotopes (REE) in the reaction $^{208}Pb(^{40}Ar, f)REE$, squares - to U and Np isotopes produced as a result of transfer reaction on a uranium target.

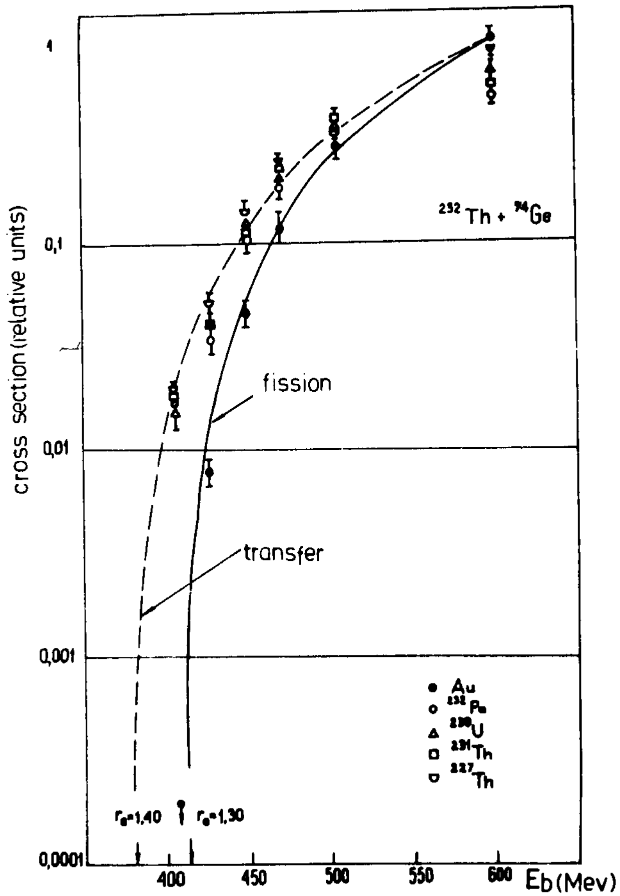

Fig. 2. The energy dependence of cross sections for fission and transfer of 1-5 nucleons, for the reaction $^{232}Th + ^{74}Ge$.

$\Delta E \approx 30$ MeV in the case of Th + Ge . For reactions with ^{58}Fe, ^{52}Cr and ^{40}Ar ions, the experimentally observed difference between the energy dependences of the fission reactions and single-nucleon transfer reactions does not exceed 3 MeV. In order to determine the effective interaction radius of fission reactions, we calculated the energy dependences of the fission cross sections using the conventional inverted-parabola method /20/. . The dependences of fission cross sections, calculated by the method described above and based on the best agreement with experimental data are presented in figs. 1 and 2.

If one assumes the Coulomb barrier to be determined as

$$B_c = \frac{e^2 Z_T Z_b}{r_{eff}\ (A_T^{1/3} + A_b^{1/3})}, \qquad (3)$$

for the fission reaction $^{232}Th(^{74}Ge, f)$ r_{eff} = = 1.3 f, whereas for transfer reaction r_{eff} will be equal to 1.4 f. It is noteworthy that this quantity for fission and transfer reactions induced by ^{58}Fe, ^{52}Cr and ^{40}Ar ions appeared to be the same, $r_{eff} = 1.44 \pm 0.02$ f. The same fusion barrier value for the $^{208}Pb + ^{40}Ar$ reaction has been obtained in ref. /39/ by measuring directly the excitation function of the compound nucleus ^{248}Fm. We do not give absolute errors for the reaction Th + Ge since the energy dependences were calculated using the calculated range-energy values /21/, which can in principle differ from experimental ones for ions as heavy as Ge.

There exist a number of approaches to the interpretation and determination of the threshold of the interaction of two complex nuclei. In refs.[22,23] it was shown that the energy threshold of fusion or the interaction barrier height is not only the Coulomb potential. Nuclear interaction plays an important part in the determination of their values. The relevant calculation was carried out in ref.[23]. . It showed that with the increasing atomic number of projectiles the value of the effective radius r_{eff} of the interaction between two complex nuclei decreases. This calculation assumed the dependence $r_{eff} = f(Z, A)$ to be smooth taking into account the number of neutrons in the interacting nuclei. The results of this calculation are presented in fig. 3, where one can also see the experimental values of r_{eff} obtained in our and other papers. The calculated dependences of r_{eff} on Z of the target nucleus disagree with experimental ones. By comparing these results one can conclude that the calculation describes only qualitatively the tendency of a decrease of the reaction effective radius with the increasing atomic number of projectiles. However it is practically impossible to make quantitative estimates on the basis of these calculations[23].

In ref.[38] the reaction barriers for different nuclear reactions including those investigated in the present paper have been calculated. The calculation has been carried out on the basis of the optical approach, and the nuclear potential parameter is determined from the liquid-drop model. The calculation is in good agreement with the experi-

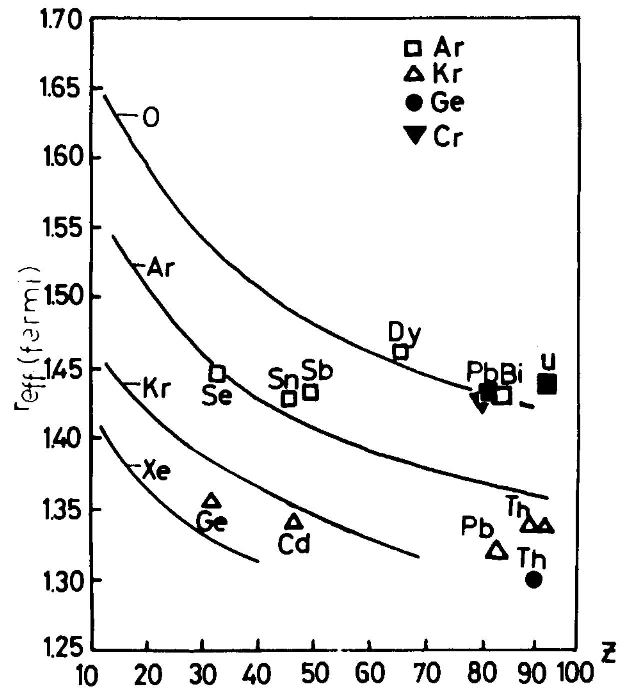

Fig. 3. The interaction effective radius as a function of the atomic number Z of the target nucleus. Solid curves present the calculated data from ref.[23] . Closed circles are the data of the present paper.

mental data up to the projectile mass of 52. However, the use of this model for reactions induced by the heavier ions, where the barrier increases considerably, is somewhat complicated.

The difference between the calculated and experimental data is most likely to indicate that the mechanism of the interaction between two nuclei is very complicated depending not only on kinematics, but on other characteristics describing the properties of the interacting nuclei.

Another result obtained from the study of the energy dependences is the observation of a difference between the energy thresholds of fission and transfer reactions in the case of Th + Ge (see fig. 2). This result leads to the conclusion that each reaction channel has its corresponding energy threshold. No dependence of this kind was observed in reactions induced by ions with $A_b < 40$, where the r_{eff} value was shown to be nearly constant in the experiment for the main inelastic channels of the reaction [24,25]. This decrease of the r_{eff} value of deep inelastic reactions (fission and complete fusion) in going to the heavier interacting nuclei can be explained in different ways. The authors of some theoretical investigations [26,27] attribute the change in the r_{eff} value to the dynamic deformations of nuclei as a result of the effect of strong Coulomb fields during the interaction. A simpler explanation of the decrease in r_{eff} was suggested in ref. [23], where it was shown that in going to the heavier interacting nuclei due to the presence of the strong Coulomb potential, the effective radius of the interaction approaches the strong absorption radius, which is determined from the condition

$$\frac{\partial (V_{coul} + V_{centr} + V_{nucl})}{\partial R}\Big|_{R = R_{c.N.}} = 0 . \qquad (4)$$

In other words, deep inelastic processes (e.g., fusion and fission) occur practically at the complete overlapping of nuclear surfaces, while for ions with mass $A < 40$ the effective radius is larger than that of strong absorption by the magnitude $\Delta r = 0.1$-0.15 f. At the same time, for multinucleon transfer reactions in the vicinity of the Coulomb barrier the main contributors to the cross section are, as usual, the surface collisions, and the effective radius changes slightly with moving to the heavier interacting particles. A number of recent theoretical papers are devoted to quantitative calculations of the difference between the interaction barrier and the fusion barrier (refs. [28, 29]). Fig. 4 shows the dependence of this difference on the projectile mass, calculated in ref. [29]. One can see that this model describes the experimental values unsatisfactorily, especially in the region of relatively light masses.

At present, there are a number of other models, in which an attempt is being made to estimate quantitatively the effective radius of the interaction and of the fusion barrier [30, 31]. However, none of these models describe completely the complex process involved in the interaction of two heavy nuclei. Therefore, further accumulation of

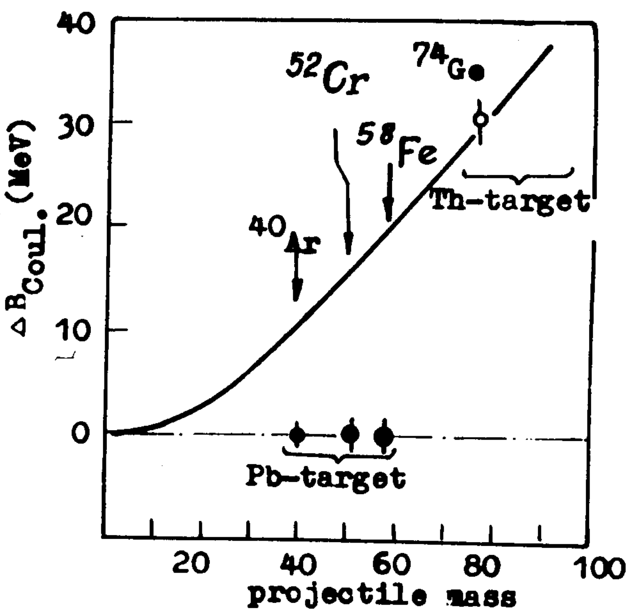

Fig. 4. The difference between the interaction barrier and reaction threshold as a function of the projectile mass. Solid curve represents the calculated results [29]. Points are the experimental results of the present paper.

relevant experimental data is needed. This problem is very important not only for the understanding of the interaction mechanism, but also for the solution of the problem of producing weakly excited compound nuclei in the region of heavy and superheavy elements [32].

3. Nuclear Reactions Induced by Xe Ions and Formation of Composite Systems with $Z > 125$

One of the methods of synthesizing nuclei in the proposed region of stability is based on fission of very composite systems to fragments with $Z \approx 100$-114. This method was suggested by G.N.Flerov in 1964 (ref. [33]), and at present experiments are being carried out at Dubna in order to produce a superheavy element by fission of uranium by xenon ions [34].

However, to enable one to estimate the formation probability for fission fragments with atomic number $Z \approx 110$-114 and $N \approx 184$, knowledge of the mechanism of fission of heavy composite systems with the fissionability parameter Z^2/A = 50-58 is needed. It should be noted that at $Z^2/A > 45$ the liquid-drop fission barrier is practically absent,and nuclear stability against fission is entirely determined by the shell correction in nuclear deformation energy. Therefore, with the increasing excitation energy of the nucleus the barrier height changes substabtially, which in turn may lead to changes in the mechanism of nuclear fission (e.g., the relationship between binary and ternary fission probabilities, the excitation energy of fission fragments, the energy regularities in the fission process, etc.). In addition, according to ref. [35], , in moving to the heavier projectilies with $A_b > 80$ there may arise some factors preventing the formation of a compiund nucleus.

To answer some questions associated with the mechanism of fission of nuclei as heavy as these, and with the determination of the cross section for the formation of superheavy fission fragments, we measured the mass and isotopic distributions of fission fragments in reactions induced by Xe ions. These distributions were compared with the results previously obtained using ^{12}C, ^{20}Ne, ^{40}Ar and ^{84}Kr ions. The technique used to determine the mass and isotopic distributions of fission fragments was similar to that described in sect. 1.

The $^{181}Ta + ^{136}Xe$ reaction was investigated more thoroughly that others because the fission barrier for ^{181}Ta is 30 MeV, and this eliminates considerably the background due to fission fragments from nuclei with masses close to the mass of the target nucleus. These nuclei might be produced with large cross sections in multinucleon transfer reactions. For these reasons one could plot the entire mass distributions for the case $^{238}U + ^{136}Xe$. Fission of nuclei adjacent to uranium and direct fission can lead to a noticeable distortion of the mass distribution of the products fromed as the fragments of double fission of the compound nucleus, especially in the region of light masses. Therefore in the Ta + Xe reaction we determined the yield of reaction products in the mass region of 86 to 246 a.m.u. (see table II), and for the reaction U + Xe we measured only the yield of symmetric fission fragments with $A_f \approx 170-200$, where the contribution from fission of nuclei with $A < 250$ was negligible.

The mass distribution of the products formed in the $^{238}U + ^{136}Xe$ reaction is presened in fig. 5. The substantial increase in

Table 2

REACTION	Compound system	$\frac{Z^2}{A}$	E_I^L Mev	Total ion flux (particles)	Masses of nuclei investigated	E_c^* Mev	Width of isotopic distribution (mass units)	Width of mass distribution (mass units)	σ Comp. nucleus formation cross section σ_c (mb)	$\frac{\sigma_c}{\sigma_r}$
$^{181}Ta + ^{136}Xe$	$^{317}_{127}$	50.9	840	$1 \cdot 10^{15}$	86 - 90 146 - 160 193 - 199 223 - 225	50	7.9±2.0 7.0±1.6	89±20	150	0,03
$^{238}U + ^{129}Xe$	$^{367}_{146}$	58.1	950	$2.5 \cdot 10^{14}$	194 - 199	80	8.5±2,2			
$^{238}U + ^{136}Xe$	$^{374}_{146}$	57	840	$1 \cdot 10^{15}$	193 - 199	25	7,4± 2,0	~100	~100	~0,02

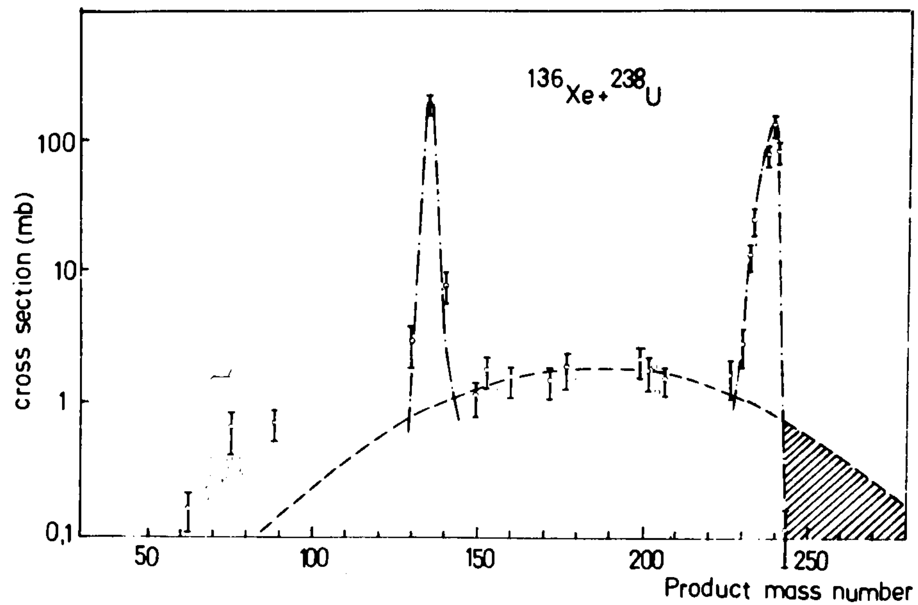

Fig. 5. Mass distribution of reaction products formed in the bombardment of ^{238}U by 900 MeV ^{136}Xe ions.

the yield of reaction products with light masses can be explained as being due to their formation at the expense of fission of nuclei adjacent to uranium after transfer and incomplete fusion reactions. The same effect was observed in ref. /6/ in the bombardment of ^{238}U by ^{84}Kr ions. The mass region of 170-200 can be attributed to the binary fission fragments of the composite system formed in the reaction $^{238}U + ^{136}Xe$.. By making some assumptions about the shape of the mass distribution of binary fission fragments one can roughly estimate the composite system cross section. The estimated cross section,

together with other characteristics of the fissioning system for three reactions is presented in table II. By analyzing the data obtained in terms of fission reactions one can show that these processes, for the reactions Ta + Xe and U + Xe , as well as reactions induced by lighter projectilies, obey the statistical laws, i.e., the isotopic distributions of binary fission fragments have the shape of symmetric curves with maxima corresponding to the most probable fragment masses, A_p, calculated using the equal charge displacement hypothesis /8/; the mass distributions of the fragments can also be described by a symmetric curve with respect to the half mass $A_{c/2}$ of the compound nucleus. The experimental dependence of the mass distribution width for fission fragments from different compound nuclei upon the fissionability parameter Z^2/A is presented in fig. 6. One can see from this figure that this width for composite systems with $Z^2/A > 50$ reaches a large value and is in good agreement with extrapolated results assuming fission of a heavy compound nucleus to two fragments. No abnormal yield of products with mass in the vicinity of $A_c/3$ has been observed experimentally. This indicates that the ratio of the cross section of prompt ternary fission to that of binary fission, $\sigma_{3f}/\sigma_{2f} \leq 10\%$. . This contradicts the estimated probability for ternary fission of heavy composite systems /36/ . These estimates suggest that for compound nuclei with $Z \geq 100$ fission to three fragments will be the main mode of decay. However, by considering the cross sections for the formation of fission fragments with $A \geq 240$

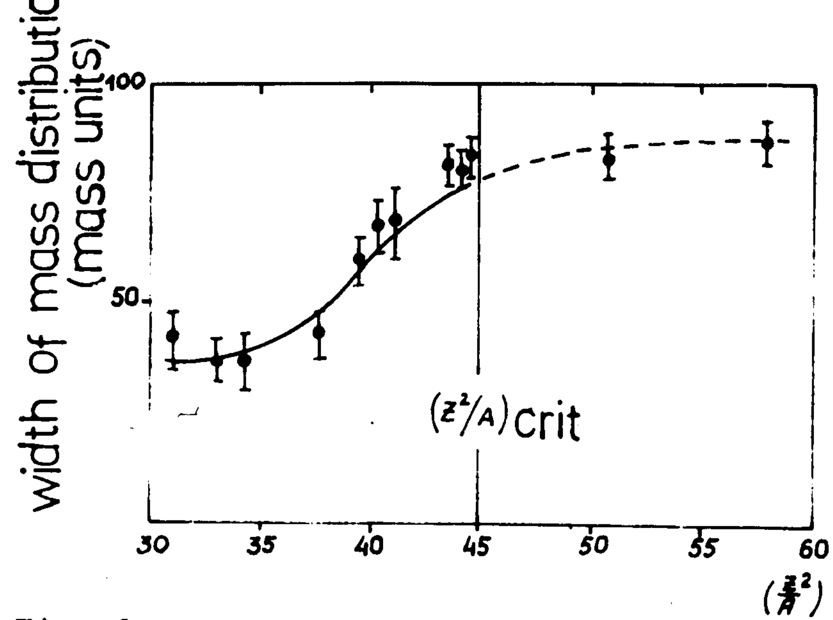

Fig. 6. Mass distribution width as a function of the fissionability parameter of the fissioning compound nucleus.

one can see that their magnitudes are a factor of 100 smaller than those expected from the symmetric mass distribution of binary fission fragments. This fact can be explained as being the result of the instability of such heavy nuclei. This mechanism of nuclear fission was investigated previously in reactions induced by ^{20}Ne and ^{40}Ar ions and was termed cascade fission /37/.

The data obtained indicate that with an increase in the projectile mass, along with a considerable increase in the cross section for multinucleon transfer reactions, in a number of cases the formation of nuclei is observed whose decay products have the mass and charge distributions close to those

expected in the case of complete fusion of the interacting nuclei with the subsequent fission of the excited compound nucleus to two fragments. The large mass dispersion of the fission fragments formed permits the conclusion about the possibility of using heavy ion reactions to synthesize new neutron-rich isotopes of nuclei with $Z > 75$ with a considerable cross section. The results described in the present paper allow one to estimate correctly the production cross sections for superheavy niclei in the reaction $^{238}U + ^{136}Xe$. The estimated cross section for isotopes with $Z = 110-114$ and $N = 184$, formed as fission fragments from the excited compound nucleus $^{376}146$ is equal to $10^{-30} - 10^{-31}$ cm^2 . The probability for producing superheavy nuclei in the ground state will be determined by the competition between neutron evaporation and fission of an excited heavy fragment. This competition in turn is a function of both the excitation energy and nuclear deformation. However, the lack of experimental data makes it difficult to estimate quantitatively the probability for formation of superheavy nuclei in the ground state.

In conclusion we take pleasure in expressing our thanks to Academician G.N.Flerov for permanent attention to the work and valuable advice during its performance, to B.I.Pustylnik for helpful discussions, to Nguen Tac Anh for his assistance in carrying out the experiments, and to L.V.Pashkevich for preparing the English version of the paper.

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