SOME FEATURES OF COMPOUND NUCLEUS FORMATION AND DECAY IN REACTIONS INDUCED BY HEAVY IONS WITH ENERGIES HIGHER THAN 10 MeV/NUCLEON

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Reactions involving the formation and decay of compound nuclei with excitation energies up to 140 MeV have been studied. It was shown that that cross section for compound nucleus formation was about 20% of the total one. The decrease in the cross section is discussed in terms of the effect of the angular momentum on the reaction mechanism. The excitation functions of reactions with 3 to 12 neutrons evaporated from the compound nucleus are compared with the predictions of the statistical model. The mass and isotope distributions of the fission products in reactions of uranium with carbon ions of different energies have been maesured. The results obtained are discussed from the point of view of the reaction mechanism and possibilities of synthesizing isotopes.

1. *Introduction*

In the studies of the properties of nuclear matter, the nuclei far from the region of beta-stability are of great interest. In a number of cases, heavy ion induced reactions provide unique possibilities for producing these nuclei. It is of special interest to investigate reactions proceeding via compound nucleus formation, which in the course of neutron evaporation, lead to the production of very neutron-deficient isotopes. Removal from the beta-stability region to that of proton-excessive nuclei is uniquely related to the number of neutrons emitted, which is in turn determined by the excitation energy of the compound nucleus. Therefore, the U-200 isochronous cyclotron put into operation at the JINR Laboratory of Nuclear Reactions, which is capable of accelerating heavy ions to energies of 20 MeV/ /nucleon [1], has provided the possibility of studying the formation and decay of compound nuclei at considerably higher excitation energies than those available before. It is noteworthy that the decay of heavy compound nuclei via fission is a problem of great importance in nuclear synthesis since it may lead to the production of nuclei with large neutron excess in the form of fragments [2, 3]. Fission reactions induced by high energy ions may

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offer qualitatively new possibilities of both producing new isotopes and elements and investigating their properties. A number of recent publications [4, 5] have been devoted to discussions of the possibilities of synthesizing superheavy nuclei in a new stability region near Z = 114 by fusion and fission of compound nuclei. In this respect a study of the mechanism of the interaction between a complex particle and nuclei at high excitation energies is of great importance.

The present paper deals with the study of the excitation functions in complete fusion reactions as follows: $^{130}Te(^{12}C, xn)^{142-x}Ce$; $^{130}Te(^{13}C, xn)^{143-x}Ce$; $^{130}Te(^{12}C, \alpha xn)^{138-x}Ba$; $^{130}Te(^{13}C, \alpha xn)^{139-x}Ba$; $^{124}Sn(^{16}O, xn)^{140-x}Ce$; $^{124}Sn(^{18}O, xn)^{142-x}Ce$. The mass and isotope distributions of fission fragments produced by the bombardment of ^{238}U by ^{12}C and ^{16}O ions have also been studied.

2. *Experimental procedure*

The experiments were carried out using internal heavy ion beams from the U-200 cyclotron and external heavy ion beams from the U-300 cyclotron of the JINR Laboratory of Nuclear Reactions. The characteristics of the heavy ion beams are given below.

Ion	Beam energy, MeV	Ion current, μA	Type of beam
^{12}C	155	0.8—1.2	internal
^{13}C	150	0.6—1	internal
^{18}O	175	0.8—1.2	internal
^{12}C	82	0.5	external
^{16}O	135	0.5	external
^{18}O	120	0.5	external

The excitation functions of the compound nucleus formation reactions were derived by the gamma-spectrometric method, which consisted in measuring reaction products in a stack of twenty targets sandwiched with recoil catchers. This technique has been described in detail in Ref. [4].

In order to investigate the energy dependence of the width of mass and isotope distributions of the fission fragments, we irradiated simultaneously three targets manufactured of U_3O_8 deposited onto an aluminium backing. The backing thickness, 8 mg/cm^2, was such as to enable all of the fission fragments to be stopped in the backing. Each target was covered by an aluminium foil 6 mg/cm^2 thick from the side of the beam in order to avoid losses of fission fragments in the rear semisphere. After irradiation, each uranium target, together with a respective backing and recoil catcher, was treated chemically. To plot the mass distributions the rare earths and yttrium were separated, while for the isotope distributions, cerium and europium were separated in some experiments. The measurements of the gamma-activity of the targets and recoil catcher, in the case of studying the excitation functions of complete fusion reactions, and the activity of the chemical fractions separated to plot the mass and isotope distributions, were carried out using a gamma-ray spectrometer consisting of a Ge(Li) detector and amplitude analyzer. Since the energy resolution of the spectrometer was 2–2.5 keV, it was possible, while measuring the excitation functions of complete fusion reactions, to separate reliably the gamma lines in the energy spectrum belonging to the transitions of the isotopes under investigation without using the radiochemical separation technique.

The relative isotopic yield was determined from the intensity of its gamma-transition, taking into account the gamma-ray yield per one beta-decay and using the data from Refs [5, 6]. Errors in determining the relative yields did not exceed 15%. The absolute cross section values were derived by two methods: First, by measuring the ion current in a separate experiment at ion beams extracted from the U-300 cyclotron, and second, by making use of the reaction $^{27}Al(^{12}C, -2p, -n)^{24}Na$ and the data from Ref. [7]. Errors in the absolute cross section values for isotropic production were no more than 30%.

The energy measurements were carried out using energy calibration at the external beam from the U-300 cyclotron with an error of ± 5 MeV. This technique has been described in detail in Ref. [4].

3. Analysis of experimental results

3.1. Excitation functions of compound nucleus formation reactions

The excitation functions of reactions involving neutron evaporation from the compound nuclei ^{143}Ce and ^{142}Ce are shown in Figs 1 and 2. In the reactions $^{130}Te + ^{12}C$ and

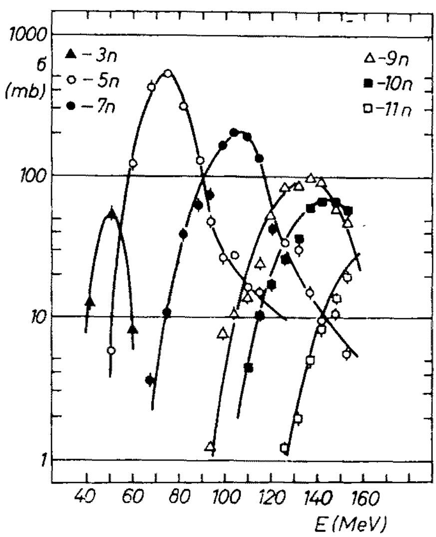

Fig. 1

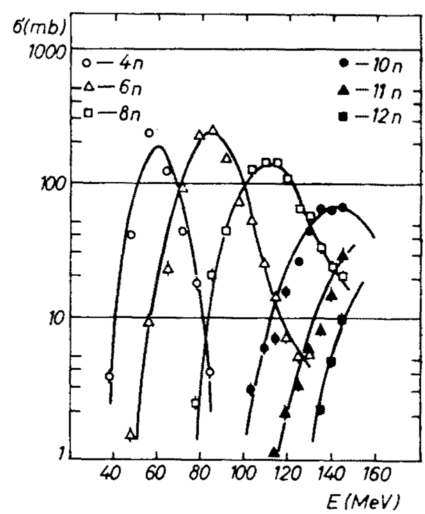

Fig. 2

Fig. 1. Excitation functions for the reaction $^{130}Te(^{12}C, xn)^{142-x}Ce$

Fig. 2. Excitation functions for the reaction $^{130}Te(^{13}C, xn)^{143-x}Ce$

$^{130}Te + ^{13}C$, the yield of products formed as a result of evaporation of 3 to 12 neutrons from the compound nuclei have been measured. By comparing the excitation functions obtained with the results from Refs [8–10], one can conclude that the excitation functions of xn-reactions in general agree well with the statistical concepts of particle evaporation from an excited nucleus. However, in some cases the right-hand part of the excitation functions has a tail extending into the high energy region. This is possibly due to the fact that a small portion of neutrons are emitted prior to the establishment of statistical equilibrium. The half-with of the excitation function is 20–25 MeV, which is also in agreement with the data available on xn-reactions.

The excitation functions for reactions involving the evaporation of alpha particles from the compound nucleus ^{143}Ce are presented in Fig. 3. Though the excitation functions of these reactions are analogous in shape to those for xn-reactions, they are noticeably wider and the maximum of the α xn-reaction is displaced in energy, as compared with the corresponding xn-reaction by an average of 20 MeV.

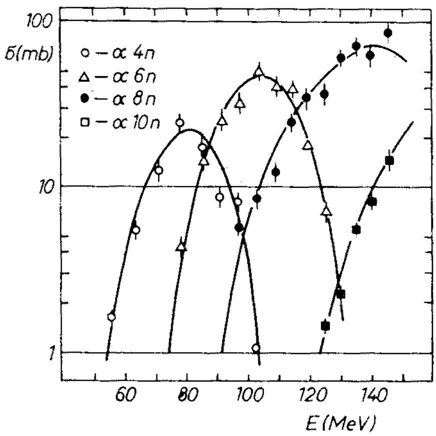

Fig. 3

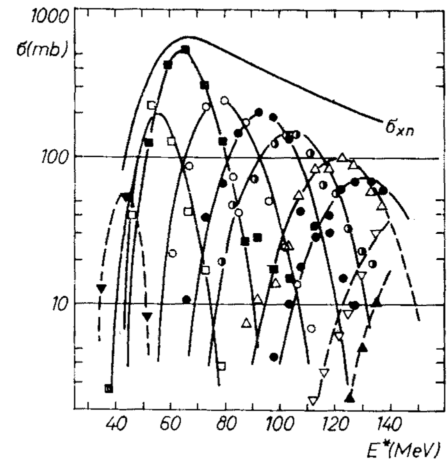

Fig. 4

Fig. 3. Excitation functions for the reaction ^{130}Te(^{13}C, αxn)$^{139-x}$Ba

Fig. 4. Excitation functions for reactions involving evaporation of 3 to 12 neutrons from the compound nucleus produced by bombarding ^{130}Te by ^{12}C and ^{13}C ions. Solid curves represent calculations using Jacson's model [11]. The curve σ_{xn} is obtained by the summation of cross sections of all xn-reactions at each excitation energy

In view of the fact that the compound nuclei ^{142}Ce and ^{143}Ce produced in our experiments are similar both in mass and in charge, the excitation function data obtained by us for these two nuclei can be brought together. The combined results for xn-reactions in the bombardment of ^{130}Te by ^{12}C and ^{13}C ions are presented in Fig. 4. The abscissa axis is the excitation energy of the compound nucleus. The curve σ_{xn} represents the total cross sections of reactions involving neutron emission as a function of the excitation energy of the compound nucleus. It is clearly seen that the curve reaches its maximum at $E^* = 60$–70 MeV and then falls down with energy. The experimentally derived excitation functions can be compared with those calculated in the framework of the statistical theory by using, for simplicity, say Jacson's method [11], which requires the introduction of J_{crit} as a calculation parameter. The calculated results for the reaction ^{130}Te (^{12}C, xn)

$^{142-x}$Ce at $x = 5$–10 are presented in Fig. 4. It should be noted that even though the $x = 5$ agreement between the calculated and experimental values of the excitation function exists at $J_{crit} = 30\hbar$, with further increase of the number of neutrons emitted, such an agreement can be achieved at smaller values of J_{crit}. This is probably due to an increased probability for charged particles to evaporate as the excitation energy of the compound nucleus increases. Thus, on the basis of the calculated excitation functions for xn-reactions one cannot draw definite conclusions in this case about the value of the critical angular momentum of the compound nucleus. It is, however, apparent that the maximum value

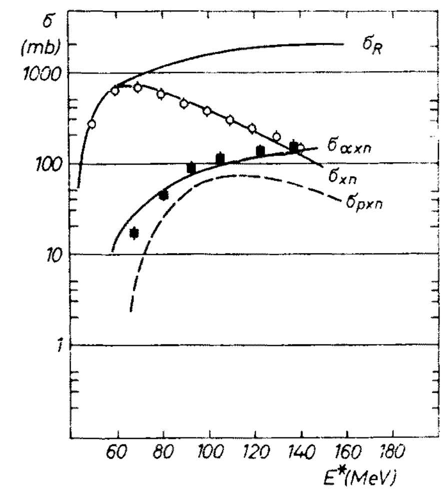

Fig. 5. Partial cross sections of reactions involving evaporation of neutrons, protons and alpha particles from the compound nucleus ^{142}Ce as a function of its excitation energy. Dots represent experimental results. Curves are calculated using the statistical model [12]

of the parameter $J_{crit} = 30\,\hbar$ is the closest one to this quantity, since at excitation energies of 60 to 80 MeV the decay of a compound nucleus proceeds in the main by neutron emission. The same value of J_{crit} is obtained from the calculations in the framework of the statistical model using the Monte Carlo method which takes the statistical nature of the problem into account [12]. This method was used to calculate the partial cross sections for reactions involving evaporation of neutrons, alpha particles, and protons from the compound nucleus ^{142}Ce. In Fig. 5 the calculated values of σ_{xn}, $\sigma_{\alpha xn}$, and σ_{pxn} as a function of excitation energy are shown. Here σ_{pxn} and $\sigma_{\alpha xn}$ are sums of cross sections of all of the reactions proceeding via emission of a proton or an alpha particle from the compound nucleus, followed by neutron evaporation. The calculations employed the values of the parameters $r_0 = 1.3$ fermi and $a = 0.1$ MeV^{-1}. These values were chosen following the treatment of a large number of experimental data. In addition to the $\sigma_{\alpha xn}$ values obtained in our experiments, the experimental points obtained by summing up the cross sections of all xn-reactions at every excitation energy value are also shown in Fig. 5. A good agreement between the calculated and experimental data is observed for both types of reactions involving the decay of the compound nuclei ^{142}Ce.

The energy dependence of the cross section $\sigma_C(E)$ for compound nucleus formation, obtained by summation of the partial cross sections σ_{xn}, $\sigma_{\alpha xn}$, and σ_{pxn} is shown in Fig. 6. Since the products of pxn-reactions were not identified in our experiment, in order to determine the σ_C values, we used the calculated value of σ_{pxn}, which, according to

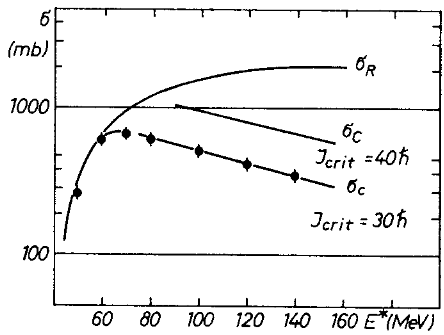

Fig. 6. Cross section for formation of the compound nucleus ^{142}Ce in the reaction ^{130}Te+^{12}C at different excitation energies

Ref. [13], is rather small as compared with that for xn- and α xn-reactions. In addition, the good agreement between the calculated and experimental values of σ_{xn} and $\sigma_{\alpha xn}$ at specified parameters of the model allows one to hope that the calculated σ_{pxn} values do not differ much from the true ones. In the same Fig. 6, the variations of the total cross sections $\sigma_R(E)$ and $\sigma_C(E)$, calculated at $r_0 = 1.3$ fermi and two angular momenta $J_{crit} = 30\hbar$ and 40 $\hbar$ using the common relations [14] are given. It is clearly seen that good agreement between the calculated and experimental values of σ_C is achieved at $J_{crit} = 30\ \hbar$. From comparing the variations of $\sigma_R(E)$ and $\sigma_C(E)$ one can see that in the energy range from the reaction Coulomb barrier up to an excitation energy of 60–65 MeV, the cross section

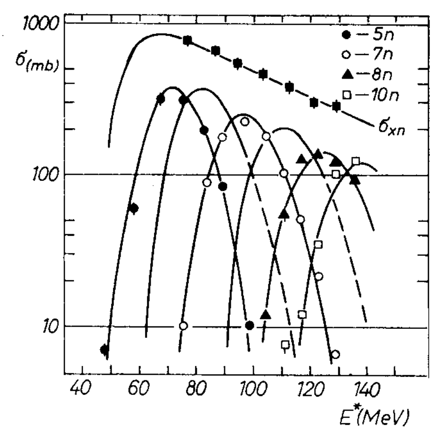

Fig. 7. Excitation functions of the reaction ^{124}Sn(^{18}O, xn)$^{142-x}$Ce. The calculated results using Jacson's model [11] are shown by curves. The curve σ_{xn} represents the results of calculation by the statistical model at $J_{crit} = 40\ \hbar$ (Ref. [12]). The square dots are obtained by summing the cross sections of xn-reactions at the corresponding excitation energies

for compound nucleus formation is the same as the total one. At these energies no limitations are imposed on fusion of carbon and tellurium nuclei. In the region of $E^* = 65$–80MeV the σ_C value reaches its maximum to decrease then smoothly with energy. At an excitation energy of 140 MeV, the cross section for compound nucleus formation is about 20% of the total one, which is fully due to the critical angular momentum effect. A similar analysis of the experimental data on the reactions $^{124}Sn(^{18}O, xn)\,^{142-x}Ce$ and $^{124}Sn\,(^{16}O, xn)\,^{140-x}Ce$ leads one to conclude that J_{crit} for these reactions is equal to 40 $\hbar$. The calculated and experimental excitation functions for reactions with the formation of ^{142}Ce are presented in Fig. 7. From comparing the J_{crit} values for ^{142}Ce produced by reactions with carbon and oxygen ions, one can conclude that the magnitude of the critical angular momentum depends on the mode of compound nucleus formation, and it increases with reduced mass. This is in agreement with the data available [8–10]. At the same time it is noteworthy that we have not observed the dependence of the critical angular momentum on the ion energy.

3.2. Mass and isotope distributions of fragments produced by fission of heavy nuclei

An increase in the mass of a compound nucleus results in the occurrence of competition between particle evaporation and fission. For nuclei with $Z^2/A \geqslant 30$ at high enough excitation energies, fission is one of the main modes of decay. A detailed study of the fission mechanism [3, 15] has shown a number of features characterizing the nucleus at high excitation energies and large angular momenta. In particular, symmetric fission is most likely to occur at high excitation energies. The mass and charge distributions of these fission fragments are described well by the Gauss function. In this case the cross section for producing an isotope with given Z and A values can be defined using the formula

$$\sigma(A, Z) = \frac{\sigma_f}{\pi[\sigma_A^2 \cdot \sigma_Z^2]^{1/2}} \exp\left[-\frac{\left[A_f - \frac{A_c}{2}\right]^2}{\sigma_A^2}\right] \exp\left[-\frac{(Z-Z_p)^2}{\sigma_Z^2}\right].$$

Here σ_f is the total cross section for the fission of the compound nucleus; σ_A^2 and σ_Z^2 are the widths of the mass and charge distributions, respectively; A_c is the mass of the fissioning compound nucleus.

It is seen from this relation that the yield of heavy nuclei increases with the widths of the mass and charge distributions. The investigation of the variations of the σ_Z^2 and σ_A^2 parameters [3, 15] has shown that from $Z^2/A = 37$ a sharp broadening of the mass and charge distributions of fission fragments occurs. In the same papers an increase in the σ_Z^2 and σ_A^2 parameters with compound nucleus excitation energy up to projectile energies of 8 MeV/nucleon has been observed. The study of the energy dependences of σ_Z^2 and σ_A^2 at ion energies higher than 10 MeV/nucleon is of considerable interest in connection with investigating the possibilities of obtaining substantially larger mass and charge distributions. In order to obtain isotope and mass distributions, we employed the method of calculation described in Refs [15, 16]. In Fig. 8 the mass distributions of the fission fragments for three values of carbon ion energies are shown. The curves were drawn through the experimental points using the method of least squares. It is seen in the figure that at $E = 90$ MeV the mass curve maximum corresponds to the fragment mass $A_f = 125$, which is half of the mass of the compound nucleus ^{250}Cf resulting from the complete fusion of a carbon ion with a uranium nucleus. The value of $\sigma_A^2 = 630$ is in good agreement with the estimates

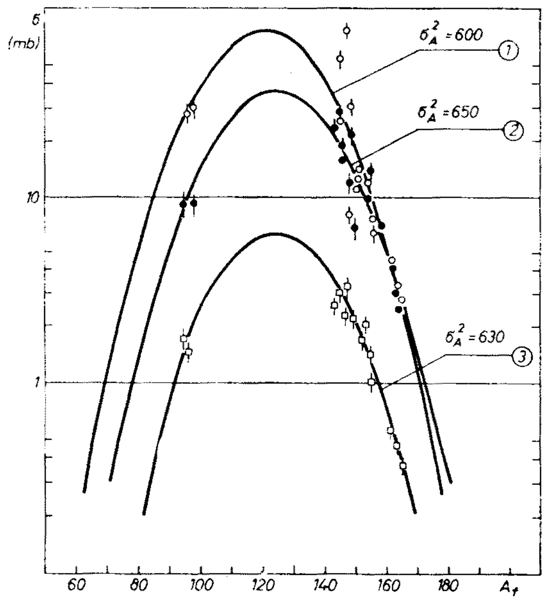

Fig. 8. Mass distributions of fission fragments produced by bombarding ^{238}U with carbon ions of the following enegies: 1) $E^* = 150$ MeV, 2) $E^* = 120$ MeV, 3) $E^* = 90$ MeV

made on the basis of Ref. [3]. As the ion energy increases up to 120 MeV, the width of the mass distribution increases inconsiderably, and the experimental points display comparatively large deviations from the Gaussian curve. The same situation exists in the mass distribution at the carbon ion energy of 150 MeV. Moreover, in this case the width of the mass distribution somehow decreases, and the most probable mass of the fragment is displaced towards the smaller values of A. This fact can, in principle, be explained as due to the contribution from fission products after incomplete fusion. As has been shown in Ref. [17], the cross section for the incomplete fusion reaction substantially increases with energy. On the basis of the same data, one can suppose that incomplete fusion reactions will mainly be represented by a capture of one or two alpha particles, in the course of which the excited nuclei ^{246}Cm and ^{242}Pu are formed, which decay by fission. If one takes into account the partial contribution from these types of interaction, the isotope and consequently mass distributions of the fission fragments can be plotted.

In Fig. 9 the mass distributions obtained, taking into account the contribution from incomplete fusion reactions, are shown for three different values of carbon ion energy. The experimental points are clearly seen to be in rather good agreement with the calculated curves. In Fig. 10 the width of the mass distribution per one tenth of its maximum value, as a function of excitation energy of the compound nucleus ^{250}Cf is shown. The dotted line corresponds to the estimates made by extrapolating the known data [3] to the region of the Z^2/A values and excitation energies under investigation. One can see in the figure that the width of the mass distributions remains practically unchanged as the excitation

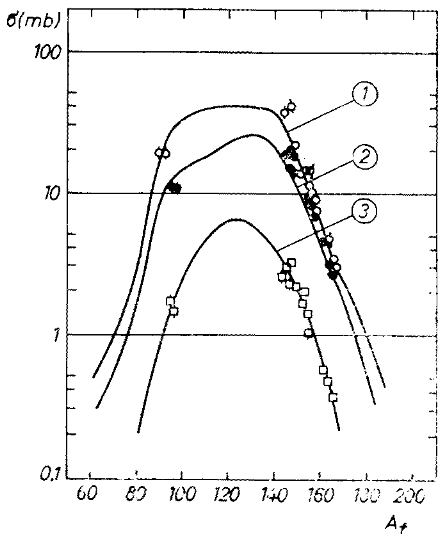

Fig. 9. Mass distributions of fission fragments produced by bombarding uranium with carbon ions taking into account the incomplete fusion reactions. The curves correspond to the carbon ion energies as follows: 1(E^* = 150 MeV, 2) E^* = 120 MeV, 3) E^* = 90 MeV

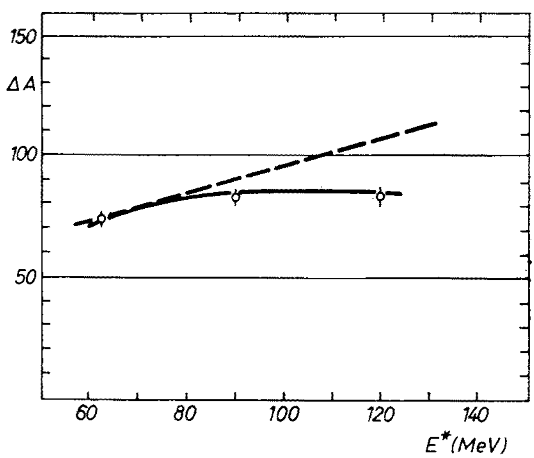

Fig. 10. The width of the total mass distribution of fission fragments as a function of the excitation energy of the compound nucleus ^{250}Cf produced in the reaction $^{238}U+^{12}C$. The dashed line corresponds to the ΔA values estimated on the basis of Ref. [3]

energy increases, whereas in the absence of incomplete fusion reactions it is expected to increase considerably at $E = 120$ MeV. This implies that heavy ions with energies higher than 10 MeV/nucleon are not advantageous in terms of the production of neutron-excessive nuclei in the form of fission fragments. One can, however, note that heavy fragments corresponding to a higher degree of asymmetry can be produced only by fission of completely fusing nuclei. Consequently, the cross section for their production is also dependent on the ratio of the complete to incomplete fusion reactions, and ultimately it depends on the magnitude of the critical angular momentum.

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