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MANIFESTATION OF SHELL EFFECTS IN THE INTERACTION OF HEAVY NUCLEI WITH IONS OF A [illegible] 40

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Калпакчиева Р. и др.

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Проявление оболочечных эффектов при взаимодействии ионов с A > 40 с тяжелыми ядрами

Представлены экспериментальные результаты по изучению массовых распределений осколков деления, образующихся в реакции $^{40}Ar + ^{243}Am$. Проводится теоретический анализ полученных результатов на основе диффузионной модели. Делается вывод о возможности асимметричного способа деления тяжелых слабовозбужденных ядер, образующихся в реакциях с тяжелыми ионами.

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Kalpakchieva R. et al.

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Manifestation of Shell Effects in the Interaction of Heavy Nuclei with Ions of A > 40

The results of experiments on the mass distribution of fission fragments formed in the reaction $^{40}Ar + ^{243}Am$ at low excitation energies are presented. The mass distributions are calculated on the basis of the diffusion model. A conclusion is drawn on a possible asymmetric mode of decay of the heavy systems studied.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1978

Shell effects are known to play a significant role in the fission of actinide nuclei having excitation energy $E^* \lesssim 30$-40 *MeV*. They manifest themselves in various characteristics of the process, such as the mass distributions, the fragment kinetic energies, the number of neutrons emitted by the fragments, etc. The asymmetric mass distributions of the fission fragments of all studied nuclei from uranium [1] to $^{252}102$ (*ref.* [2]) and $^{265}105$ (*ref.* [3]) and also the symmetric mass distributions for spontaneous fission of the heavier fermium isotopes ^{258}Fm (*ref.* [4]) and ^{259}Fm (*ref.* [5]) are interpreted as being due to shell effects. The highest yields in the mass distributions in all these cases are connected with the formation of the doubly magic nucleus $^{132}_{50}Sn$. The structure in the average total kinetic energy release as a function of fragment mass for the actinide nuclei is also due to shell effects but lately it has been found that for some heavy nuclei ($^{252}102$ (*ref.* [2]), ^{256}Cf (*ref.* [4])) there is no decrease in $\overline{TKE}(M)$ for symmetric division. Besides, the average neutron yield as a function of fragment mass has a saw-tooth shape, which is washed out at higher excitation energies.

Until recently the characteristics of low energy fission have been studied for the nuclei formed in light-particle-induced reactions or for spontaneous fission. As far as heavy ion reactions are concerned, it has been found that they allow the production of heavy compound nuclei of $Z > 100$ with excitation energy sometimes as low as 18-25 *MeV* and small angular momentum, i.e., weakly excited heavy nuclei which are, in general, difficult to produce in the ground state. It seemed interesting to see whether and how shell effects would manifest themselves in reactions of this kind. At such low energies in heavy-ion-induced reactions, as it was shown for the first time in *ref.* [6], shell effects were well pronounced (as in the case of the low energy fission of practically all actinides) and it could be assumed, in analogy with the actinides, that the characteristics of low-energy induced and spontaneous fission of one and the same nucleus did not differ significantly.

Further, it is particularly interesting to investigate nuclei with $Z \geq 110$, as an enhanced nuclear stability is theoretically predicted in the region of the magic numbers $Z = 114$ and $N = 184$. These nuclei, owing to their shell structure, are expected to have a high fission barrier ($B_f \sim 5\text{-}10$ *MeV*). There are sufficient grounds to believe that the fission barrier will also exist for excited superheavy nuclei inasmuch as shell effects remain with increasing temperature and angular momentum. That is why the investigation of the fission of weakly excited heavy and superheavy compound nuclei should allow to obtain important information about the characteristics of the spontaneous fission of such nuclei, and the height of their fission barriers. In addition, it is a problem of special interest to theory. But it must be pointed out that investigations of the fission of the superheavy nuclei formed in reactions with heavy ions involve a number of problems connected, with, first, the reaction mechanism and the probability of producing such nuclei, and, second, the high fissility of the target nuclei.

With all this in mind, we used the angular correlation method [7] to study the fission of heavier systems. This method allowed us to kinematically separate the products of reactions occurring with a full momentum transfer from the bombarding ion. We studied the reaction

at four bombarding energies- 300, 240, 222 and 214 *MeV*. The contour diagrams of the total kinetic energy of reaction products as a function of mass are shown in *fig. 1*. In the distributions shown two groups of products can be distinguished: one group (A) centered around the projectile and targed masses, and another, wider distribution (C,B) covering the intermediate-mass region from about 60 to

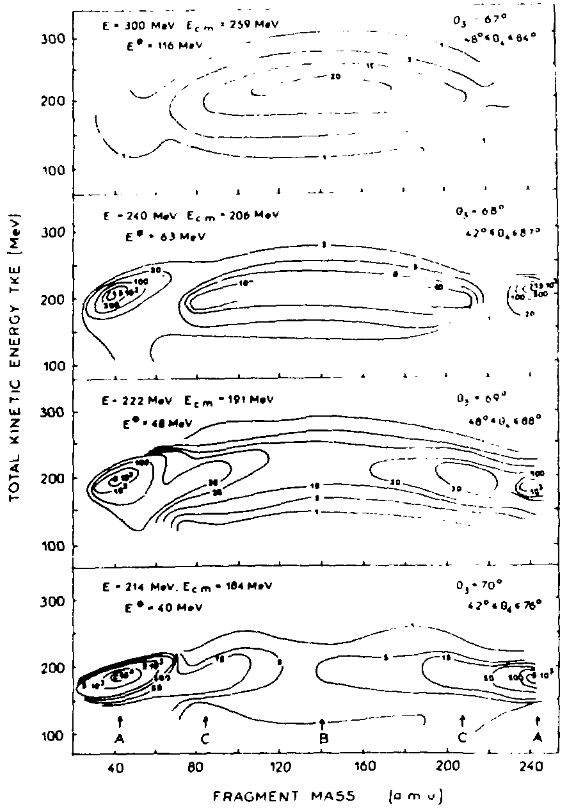

Fig.1. Total c.m. kinetic energy vs fragment mass contour diagrams for the system $^{40}Ar + ^{243}Am$ *at four different values of bombarding energy.*

about 220 *a.m.u.* This latter region is the one which we are interested in. It can be seen that at $E^* > 100$ *MeV* the mass distribution is a Gaussian with its maximum in the region of $A_f \approx (A_p + A_t)/2 \approx 140$, and dispersion ΔA_f (FWHM) ≈ 100, which can be expected for the fission of a highly excited compound nucleus. As the projectile energy decreases, the mass distribution becomes asymmetric with the most probable heavy product mass lying in the region of $A_f \approx 200$-210 *a.m.u.* It should be noted that a similar behavior of the mass distribution for the reaction $^{238}U + {}^{48}Ca$ has been observed by H.-J.Sann et al. [8].

Figure 2 shows the angular distributions for different mass regions in the reaction $^{40}Ar + {}^{243}Am$ at a bombarding energy of 222*MeV*. It can be seen that the angular distribution for the region (C,B) has an anisotropy different from that of the region (A). The angular distribution of products of masses in the range $60 < A_f < 220$ is isotropic.

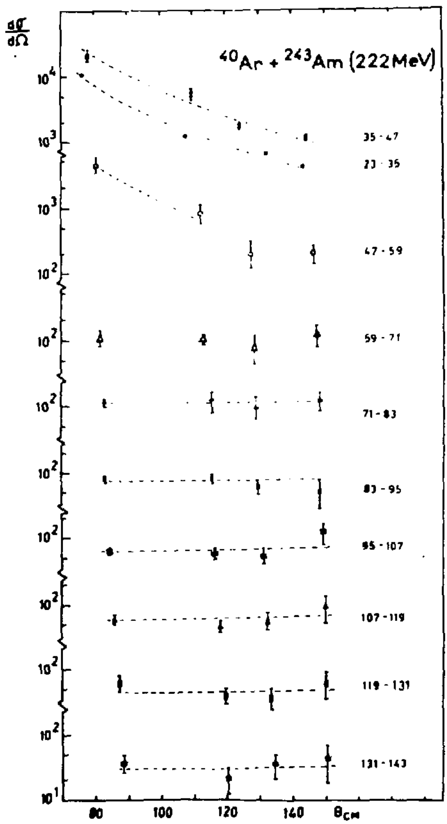

Fig.2. Angular distributions of reaction products from different mass regions. The dashed lines are drawn to guide the eye.

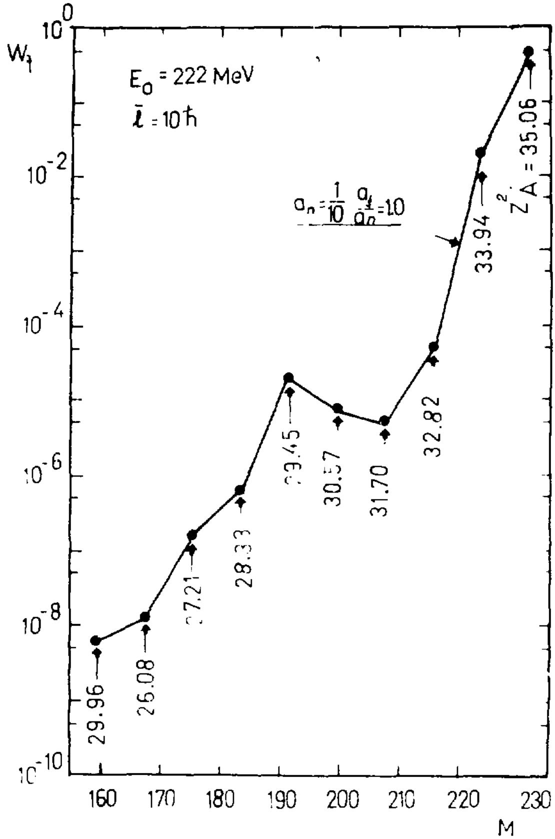

Fig.3. Calculated fission probabilities of the heavy nuclei produced in the reaction $^{40}Ar + ^{243}Am$ *as a function of mass.*

One can draw the conclusion that the products of the regions (A) and (C,B) have been formed in different processes.

Two assuptions can be made concerning the origin of the products with masses 60-220. The first one is connected with the possible mechanism of deep inelastic transfer reactions leading to the production of nuclei separated from the target by 20-40 mass units. These nuclei may have an excitation energy estimated, with the help of the experimentally obtained values of TKE, to be 40-80 *MeV* for the case, where the system excitation energy is ~ 40 *MeV*. Thus these nuclei can themselves fission and will therefore no more satisfy the condition of two-body events' detection and this in turn will lead to an artificial decrease of the detected yield of nuclei from uranium to lead. The fission probability W_f for these heavy nuclei can be calculated using the relation.

$$W_f = 1 - \prod_i \frac{\Gamma_{ni} + \Gamma_p}{\Gamma_{ni} + \Gamma_p + \Gamma_f}$$

The quantities Γ_n and Γ_p are calculated on the basis of the principle of detailed balancing. The fission width Γ_f is calculated using the Bohr-Wheeler formula. The parameters a_n, a_f and r_0, contained in the expressions for Γ_n, Γ_p and Γ_f, are chosen by comparision with experimental data [9]. However, as can be seen from *fig. 3*, the probability W_f of such a process is very low. Therefore the observed asymmetry in the mass distribution cannot be explained in this way.

The second assumption is connected with the existence of a shell structure in the composite system $^{283}113$ at $E^* < 50$ *MeV*. Traditionally the role of sheil effects is analysed by calculations of the cross sections of reaction products on the basis of different models. To do this, the evolution of the formed complex system along the mass or charge asymmetry coordinate is usually studied. An analysis of the evolution can, in principle, be done in two different ways: (i) dynamically (e.g., with the help of the fragmentation theory [10]), when the process is determined by an effective collective Hamiltonian, whose parameters (potential energy and mass coefficients) are usually taken on the basis of the two-centre shell model, or (ii) statistically (with the help of non-equilibrium statistical mechanics, e.g., in the frame of the diffusion mechanism [11], based on kinetic-type equations).

At present these two ways are intensively developed and have proved to be quite useful for the description of different characteristics of the interaction of heavy ions with nuclei.

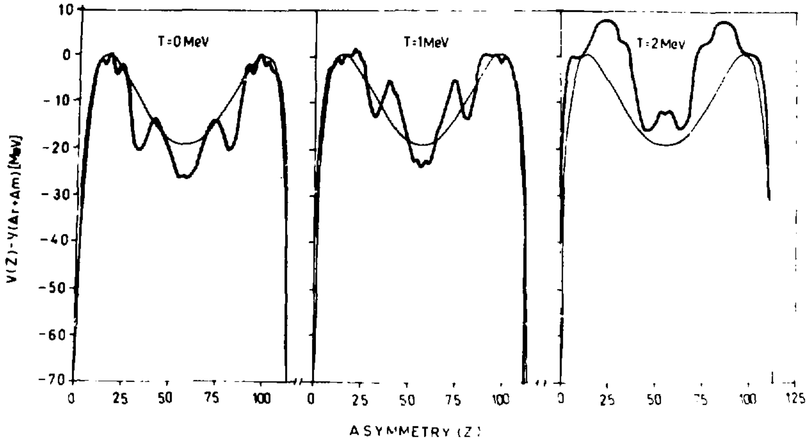

Fig.4. Potential energy V_Z of the system $^{283}113$ as a function of the asymmetry parameter Z for three values of the nuclear temperature $T = 0$, 1 and 2 MeV. The thick and thin curves show the results obtained taking and without taking the shell effects into account, respectively.

A qualitative analysis of the reaction $^{10}Ar + ^{243}Am$ in the frame of the two-centre shell model has been done in ref. [12]. On the basis of the calculated potential energy surfaces a conclusion was drawn that the presence and existence, in a wide region of distances between the centres of the fragments, of a well pronounced mimimum in the potential energy surfaces close to the doubly magic nucleus ^{208}Pb would lead to strongly asymmetric fission. However, the authors of *ref.* /12/ did not analyse either the product yield or the time evolution of the process.

Let us now see what an analysis of the evolution of the system $^{40}Ar + ^{243}Am$ can give in terms of the diffusion mechanism. For this purpose we have used a somewhat modified version /13/ of the diffusion model developed by Moretto /11/ modelling the system's relaxation in the space of asymmetry coordinates (the atomic number Z of one of the fragments) by means of a stochastic process obeying the Master equation

$$dW_Z(t)/dt = \sum_{Z'} [\Lambda_{ZZ'} W_{Z'}(t) - \Lambda_{Z'Z} W_Z(t)],$$

where $W_Z(t)$ is the probability to find the system at a moment t in an asymmetry configuration Z. The transition probabilities $\lambda_{ZZ'}$ between configurations Z' and Z are connected with the potential energy of the system V_Z, which includes the binding energy of the system, the Coulomb interaction of the subsystems and the rotational energy.

In order to estimate the influence of the system's shell structure on the diffusion process, in calculating V_Z a shell correction $\delta E = \delta E(T=0) \cdot \delta E(T \neq 0)$ (T is the temperature of the system) was added to the liquid-drop component of the binding energy. Here, the corrections for the ground state, $\delta E(T=0)$, were the experimentally known values (or their extrapolations) taken from the nuclear mass tables[14], while the correction for the heated nucleus, $\delta E(T \neq 0)$, was calculated by means of Strutinsky's technique taking into account the nuclear temperature, as described in *ref.*[15] *Figure 4* presents the dependence of the potential energy V_Z of the system $^{283}113$ on the asymmetry parameter Z for three different values of the nuclear temperature, viz $T = 0$, 1 and 2 *MeV* (or excitation energies $E^* = 0$, 40 and 120 *MeV*, respectively). It can be seen that at $T = 0$ and 1 *MeV* the studied system has two well pronounced minima in the potential energy corresponding to the region of the magic number $Z = 82$ and to the complementary fragment with $Z \sim 30$. There is also a minimum corresponding to symmetric fission of the system, which may be somewhat enhanced because of its closeness to the shell $Z = 50$. As the excitation energy increases (beginning from values of $T \sim 1.2$ *MeV*), the minima at $Z \sim 30$, 82 begin quickly to wash out and at $T = 1.4$ *MeV* almost fully vanish. The presence of minima in the potential energy naturally leads to maxima in the probability distribution function $W(Z)$ and, consequently, to an increase in the cross sections of producing elements of $Z \sim 30$, 50-60, and 82. In principle, the noted dependence of the potential energy on the excitation energy adequately reflects the presented experimental data for the reaction $^{40}Ar + {}^{243}Am$.

Let us further see what the time characteristics of the process are. In *fig. 5*, the distributions $W(Z)$ for three

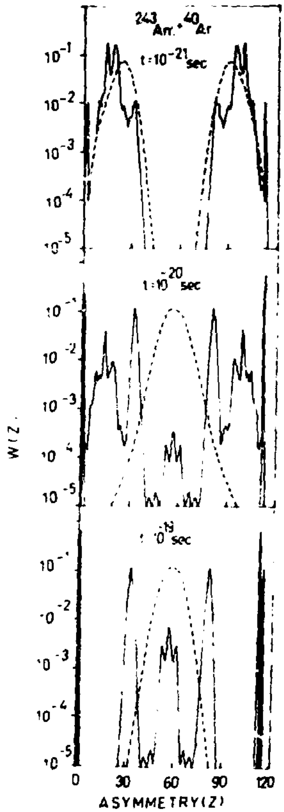

Fig.5. Calculated probability distributions W(Z) *for three values of the diffusion time* $t = 10^{-21}$, 10^{-20} *and* 10^{-19} *sec in the case of* T = *1 MeV. The full and dashed curves show the results obtained taking and without taking the shell effects into account, respectively.*

values of the diffusion time ($t = 10^{-21}$, 10^{-20} and 10^{-19} sec) are presented for T = 1 *MeV* ($E^* = 40$ *MeV*). It is seen that a better agreement with the experimental data can be obtained at greater diffusion times ($t > 10^{-19}$ *sec*). At such great times a nuclear system is close to statistical equilibrium/11, 16/.

On the basis of the experimental data and theoretical estimations of the mass distribution of the reaction products in the decay of the heavy complex system $^{283}113$ at $E^* \approx 50$ *MeV* a conclusion can be drawn that the observed asymmetry is rather a consequence of shell effects due to shells with $Z = 82$ and $N = 126$, in contrast to the well known actinide region. The data on the angular distributions and the analysis of the time evolution of the system show that in the present case we are dealing with a state of the complex nuclear system $^{283}113$ close to statistical equilibrium, and with an interaction time of the order of magnitude characteristic of the lifetime of heavy compound nuclei.

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