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Асимметричное массовое распределение осколков деления составных ядер в реакции $^{40}Ar + ^{243}Am$

С помощью корреляционного метода измерены массовые распределения и полные кинетические энергии осколков деления в реакции $^{40}Ar + ^{243}Am$ при энергиях бомбардирующих ионов 214, 222, 240 и 300 МэВ. Измерены также угловое распределение и анизотропия осколков для ионов с энергией 222 и 300 МэВ. При энергии ионов 300 МэВ было получено симметричное массовое распределение, соответствующее делению сильновозбужденного составного ядра. Однако, с уменьшением энергии бомбардирующих ионов массовое распределение осколков деления становится асимметричным с наиболее вероятной массой тяжелого осколка вблизи 200-210 атомных единиц массы.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

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Asymmetric Mass Distribution from the Fusion-Fission Reaction $^{40}Ar + ^{243}Am$

The mass distributions and total c.m. kinetic energies of fission fragments formed in the reaction $^{40}Ar+^{243}Am$ at bombarding energies of 214, 222, 240 and 300 MeV have been measured using the angular correlation method. Angular distributions and anisotropy for 222 and 300 MeV have also been obtained. A symmetric mass distribution corresponding to the decay of a highly excited compound nucleus was obtained at 300 MeV bombarding energy. However, with decreasing bombarding energy the fission fragment mass distribution becomes asymmetric, the most probable heavy fragment mass being about 200-210 amu.

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

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At present it is well known that theoretical extrapolations of nuclear properties to the region of superheavy elements predict a considerable enhancement in nuclear stability in the vicinity of the magic numbers $Z=114$ and $N=184$. Such predictions rest on the assumption that superheavy elements, due to their shell structure /1/, have a high fission barrier ($B_f \sim 5$-10 MeV).

At the same time, until recently all the experimental attempts to synthesize superheavy elements by nuclear reactions have led only to estimations of the upper limits for their production cross sections. Based on these data, one can, under certain assumptions, estimate the limiting values of their lifetimes, as a rule, with respect to spontaneous fission. A spontaneous fission half-life is known to depend not only on the fission barrier, but also on the mass coefficients determining the dynamics of the fission process. Therefore, on the basis of the investigations carried out it is difficult to draw more or less definite conclusions concerning the fission barriers of superheavy nuclei.

There are sufficient grounds to believe that a fission barrier will exist also in excited nuclei inasmuch as shell effects remain as the temperature and angular momentum of the nucleus increase. One can therefore admit that at an excitation energy of 20-30 MeV shell effects may be still well pronounced and may influence the decay features. As to the mechanism of the fission of weakly excited superheavy nuclei, this is a problem of special interest to theory.

Superheavy nuclei with a relatively low excitation energy (E^*_{min} ~20-40 MeV) may, in principle, be produced as compound nuclei in reactions induced by ions heavier than argon. Such a method has already been used repeatedly to synthesize new neutron-deficient isotopes of transfermium elements [2,3], and, quite recently, elements with atomic numbers 106 and 107 [4,5].

The aim of the present work is to study the mass and energy distributions of the reaction products formed in the bombardment of ^{243}Am with ^{40}Ar ions at bombarding energies lying in the range of 214 to 300 MeV. The energies of paired fragments were measured using a correlation method.

A collimated ^{40}Ar ion beam with a cross section of 2x8 mm^2 hit a target made of a 100 $\mu g/cm^2$ ^{243}Am layer deposited onto a 40$\mu g/cm^2$ carbon backing. To detect reaction products we made use of two movable Si(Au) detectors placed at a distance of 80 mm from the target at angles of Θ_3 and Θ_4 relative to the incident beam direction. The angular apertures of the detectors were 2° and 12°, respectively. A third, stationary detector was located at an angle of 20° to the beam direction and served as a projectile monitor.

The energy and mass calibration of the detectors was performed using the monochromatic ions of ^{40}Ar, , ^{84}Kr and ^{136}Xe elastically scattered onto a thin ^{208}Pb target, this permitting also the use of ^{208}Pb recoil nuclei for calibration. The energy resolution of the detectors in the region of E_{lab}~100 MeV and in the mass range of $40<A<208$ was not worse than 5%. The accuracy of the energy determination in a two-dimensional spectrum was ±3 MeV. A fast-slow coincidence arrangement with a subsequent pulse height analysis permitted measurement of the two-dimensional energy spectrum of reaction products.

In the case of a full momentum transfer from the projectile to two fragments (in a two-body process) the angle of their emission can be unambiguously determined from kinematic conditions. The experimentally found dependence of the number of coincidences on the emission angle has a well pronounced maximum corresponding to the total transfer of the projectile momentum. This permitted the determination of the position and angular apertures of the detectors for recording two-dimensional energy distributions.

Most of the measurements have been carried out for average angle values in the laboratory system of coordinates, $\Theta_3=\Theta_4=70°$ which corresponds to the emission of equal mass fragments at 90° in the c.m. system (Indices 3 and 4 correspond to the quantities related to the outgoing fragments). However, in order to obtain a complete picture of the process over a wide mass range, the measurements covered an angular correlation of 40° corresponding to an angular range of $110°<\Theta_3+\Theta_4<150°$ for a mass ratio $m_3/m_4\leq 6$.

Figure 1 shows contour maps of the total c.m. kinetic energies (TKE) of reaction pro-

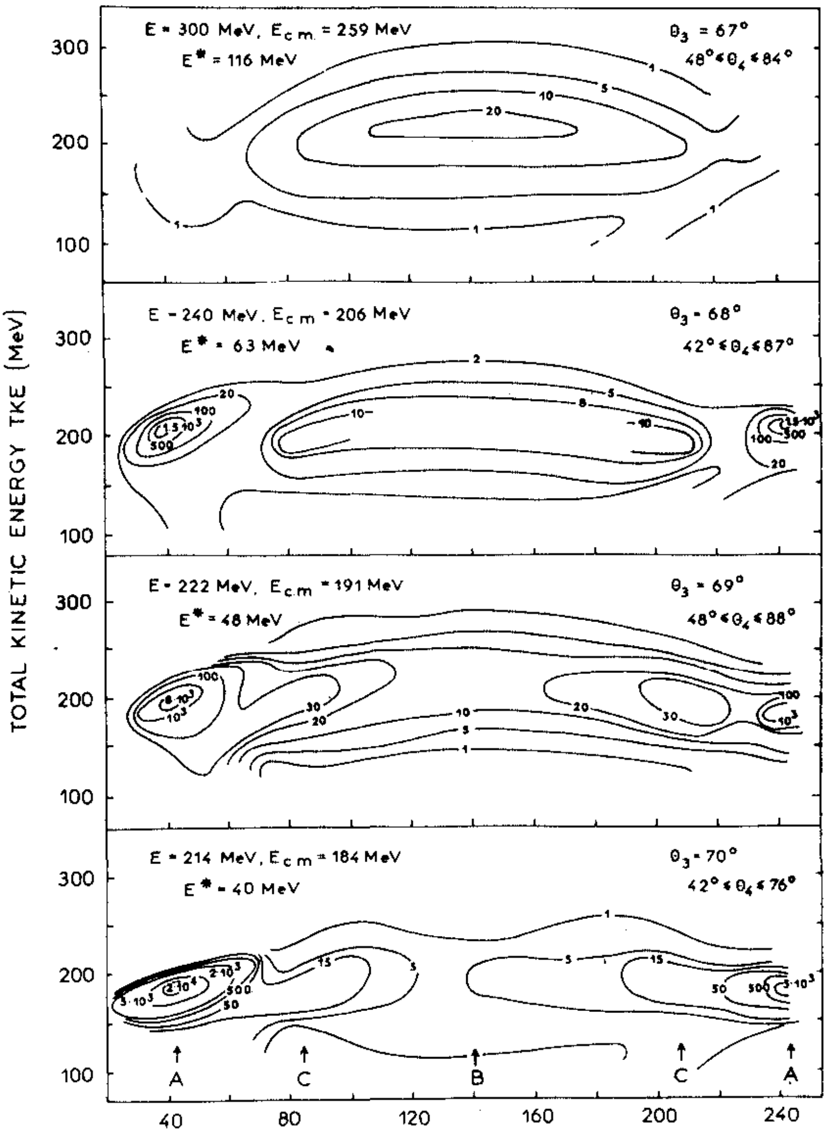

Fig. 1. Fragment mass-total c.m. kinetic energy contour diagrams for the system $^{40}Ar + ^{243}Am$.

ducts as functions of their mass numbers. The data are presented for the four values of bombarding energies: 214, 222, 240 and 300 MeV. The mass distribution of reaction products for 222 and 300 MeV bombarding energies are given in fig. 2a. The anisotropy $(\frac{d\sigma}{d\Omega})_{150^\circ}/(\frac{d\sigma}{d\Omega})_{90^\circ}$ of reaction products for different mass ranges is presented in fig. 2b. The angular distributions of the correlated events for the fragment mass region of 70-110 (this region is marked by index C in Fig. 1) obtained in the reaction $^{40}Ar + {}^{243}Am$ at a bombarding energy of 222 MeV are presented in fig. 3. In this same figure are given the angular distributions of fission fragments with masses ranging from 70 to 220, formed in the bombardment of a ^{243}Am target with 300 MeV ^{40}Ar ions. The mass region of $60 < A_f < 220$ is characterized by a small anisotropy of the angular distribution; the average values of the ratio $(\frac{d\sigma}{d\Omega})_{\Theta}/(\frac{d\sigma}{d\Omega})_{90^\circ}$ are equal to 1.1 ± 0.1 and 1.2 ± 0.1 at bombarding energies of 222 and 300 MeV, respectively.

As one can see from the data presented in fig. 1, there are distributions with maxima in the vicinity of the target and projectile mass numbers (marked as A) and a wider distribution covering the middle mass region $60 < A_f < 220$ (C, B). The main part of the distributions A includes elastic and quasielastic events, the relative intensity of which, at the chosen experimental geometry, decreases with an increase in the ion energy. The position of the maxima A with respect to energy (in the plots shown the total energy,

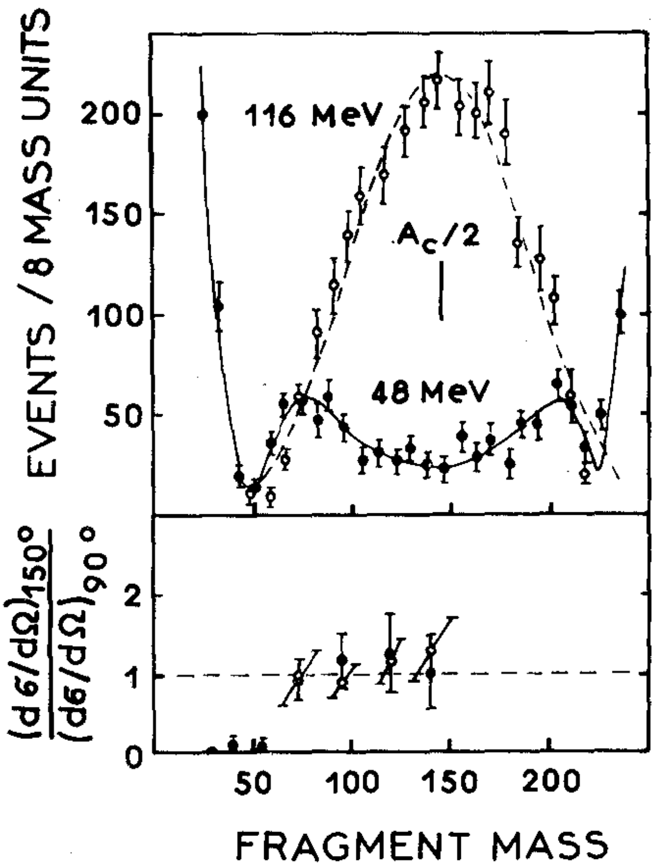

Fig. 2. Mass distribution and angular anisotropy of reaction products in the case of 222 MeV (closed circles) and 300 MeV (open circles) bombarding energies. The mass distribution at 222 MeV is presented in an angular range of $52° \leq \Theta_4 \leq 88°$, where a part of the elastic events are suppressed. This gives a better representation of the fission events.

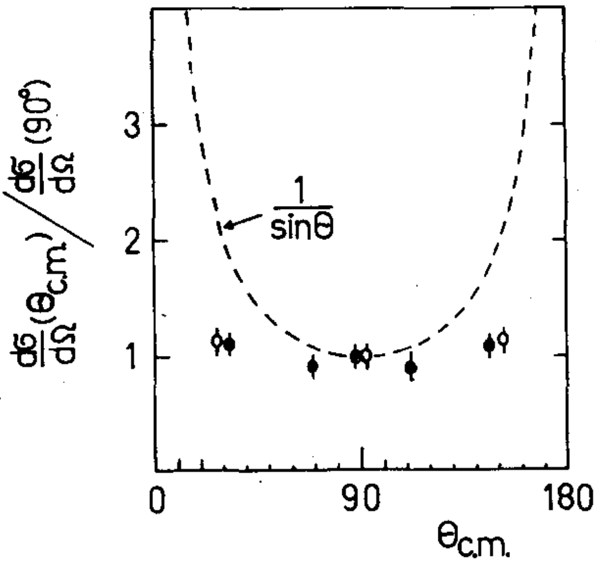

Fig. 3. Angular distribution of fragments at 222 MeV (closed circles) and 300 MeV (open circles).

TKE, is the sum of products c.m. energies) changes with varying projectile energy in agreement with what can be expected for quasi-elastic scattering at the chosen experimental geometry. The mass dispersion of reaction products with respect to the maxima A is, in our opinion, due to more inelastic processes, whose yields, however, decrease rapidly with the number of transferred nucleons.

The products of elastic and quasielastic scattering and deep inelastic transfers are characterized by a large anisotropy in the angular distribution (see fig. 2).

The mass distribution of fission fragments in the symmetric region, marked as B, at

$E_{Ar} = 300$ MeV has a Gaussian shape with a maximum in the vicinity of $A_f = (A_{ion} + A_{target})/2 \approx$ $\approx$ 140 and a dispersion ΔA_f[FWHM] $\approx$ 100 mass units, as could be expected for the fission of an excited compound nucleus. The average value of the total kinetic energy of the given reaction is 208 MeV (222 MeV taking into account neutron evaporation). This is in agreement with the value expected from the well known empirical formula [6] TKE(MeV) $= 0.1065\, Z^2/A^{1/3} + 20.1$ for the nucleus $^{283}113$. In contrast to the A maxima in the region of symmetric masses the total kinetic energy changes only by 5-8 MeV as the ^{40}Ar ion energy varies considerably, from 214 to 300 MeV.

At the same time, it is interesting to note that as the projectile energy decreases, the mass distribution of fission fragments becomes asymmetric. At a bombarding energy of 214 MeV ($E^* \approx 40$ MeV) the yield of fragments is conditioned mainly by asymmetric fission. A strongly asymmetric fission with the ratio $A_h/A_l \approx 2.5$, corresponding to the heavy fragment mass of $A_h \approx 200$-210, appears to be the most probable one.

We are inclined to believe that the asymmetric character of fission at excitation energies $E^* \lesssim 50$ MeV is very likely to be a consequence of shell effects, as is the case of low-energy fission of uranium and plutonium [7].

In contrast to the actinide region, where asymmetric fission is generally accepted to be due to the $Z=50$ and $N=82$ shell effects, in our case the fissioning system has a considerably larger mass and, as a result, effects may appear which are due to other shells such as Z=82 and N=126 (^{208}Pb). This assumption makes it possible to explain the large mass of the heavy fragment (A_h ~208) and the fact that the asymmetry in the mass distribution vanishes rapidly as the excitation energy of the fissioning nucleus increases.

The problem of the nature of fission of superheavy elements is in principle very important since it concerns the existence of a fission barrier in these nuclei. Therefore it would be interesting to investigate other combinations of target and projectile nuclei, which may lead to the formation of heavy compound nuclei, whose fission may involve variations of the effects observed.

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