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Массовое распределение осколков деления в реакции $^{208}Pb + ^{48}Ca$

Приводятся экспериментальные результаты по измерению массовых распределений осколков деления составного ядра, образующегося в реакции $^{208}Pb+^{48}Ca$ при энергии возбуждения 25 МэВ.

В опытах использовалась радиохимическая методика. Были получены массовые и изотопные распределения осколков деления составного ядра $^{256}102$. Массовые распределения имели четко выраженную асимметрию, причем асимметричное деление с образованием тяжелого осколка в области масс A_H = 142–145 оказывается в 1,5–1,7 раза более предпочтительным симметричному распределению $A_H = A_L \approx 128$.

Асимметрия в массовом распределении осколков свидетельствует о сохранении оболочечных эффектов в ядре $^{256}102$ при энергии возбуждения 25 МэВ.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

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The Mass Distribution of Fission Fragments in the Reaction $^{208}Pb + ^{48}Ca$

The mass distribution of fragments resulting from the fission of the compound nucleus produced in the reaction $^{208}Pb+^{48}Ca$ at an excitation energy of 25 MeV has been measured. The asymmetric mass distribution obtained indicates the presence of shell effects in the nucleus $^{256}102$ at such excitation energy.

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

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It is known that the problem of the artificial production of heavy nuclei is essentially the one of producing weakly excited compound nuclei, which deexcite by emitting a small number of neutrons. In refs. /1,2/, it is shown that the fusion of "magic" nuclei such as lead isotopes with ions heavier than argon leads to the formation of compound nuclei having a very low excitation energy, sometimes ~20-30 MeV. Due to this circumstance, the compound nucleus emits as few as 2 or 3 neutrons, thus increasing substantially the yield of the final product in the ground state.

The ^{48}Ca ions seem to be unique in this respect /3/. For instance, it has been established experimentally that the cross section for the reaction $^{208}Pb(^{48}Ca,2n)^{254}102$ is equal to about 4 μb, i.e., a factor of nearly 100 larger than the cross section of the known reaction $^{238}U(^{22}Ne,4n)^{256}102$ /4/. The high yield of the element 102 nuclei in experiments using ^{48}Ca ions is conditioned by the fact that the compound nucleus $^{256}102$ has an excitation energy of 18 MeV in the vicinity of the reaction Coulomb barrier, and, therefore, competition between fission and neutron evaporation exists only at the first two stages of the neutron cascade.

At the same time, we believe that at such a low compound nucleus excitation energy the fission process itself may show some structural effects similar to those involved in fission of uranium or plutonium at low energies /5/.

Therefore, the purpose of the present work was to measure the mass distribution of fission products formed in the reaction $^{208}Pb + {}^{48}Ca$.

Experimental Procedure and Results

Since the ^{208}Pb and adjacent nuclei producible in multinucleon transfer reactions have a high fission barrier, a radiochemical method has been used to separate reaction products and determine the mass spectrum of the fragments produced as a result of fission of the compound nucleus $^{256}102$.

A target was prepared of a ^{208}Pb (enriched to 98.3%) layer, 0.8 mg/cm^2 thick deposited onto a thick Al catcher foil. The admixture of heavy metals and rare earth elements in the catcher foil was not greater than 10 ppm. The target was placed at 30° with respect to the beam direction, and was water-cooled. The intensity of the ^{48}Ca ion beam was 1.5×10^{12} part/s, the ion energy was chosen to be 220 MeV, i.e., 8 MeV higher than the reaction Coulomb barrier. In the case of a "thick" ^{208}Pb target, this projectile energy determines the $^{256}102$ maximum excitation energy to be equal to 25 MeV. The procedure of radiochemical separation of the isotopes of I, Te, Ag, Ba and rare earth elements took two hours. The accuracy of the determination of the chemical yield was not poorer than 10%.

The identification of the isotopes and determination of their yields were performed by measuring the γ-radiation of the samples using a Ge(Li) detector with an energy resolution of about 2 keV (at $E_\gamma = 660$ keV). The cross sections for the formation of different reaction products are presented in the table.

On the basis of the data obtained we have plotted the isotopic and mass distributions of fission fragments under the following assumptions used commonly in such cases, i.e.,

(i) the isobaric distribution of fission fragments is described by the Gaussian

$$W(Z - Z_p) = \frac{1}{\sqrt{\pi\sigma_z^2}} \exp\left[-\frac{(Z-Z_p)^2}{\sigma_z^2}\right]$$

and is related to the isotopic distribution in the following way

$$\sigma_N^2 = \sigma_z^2 \left[\frac{\partial Z_p}{\partial A_f}\right]^{-2},$$

(ii) the relation $Z_p(A_f)$ satisfies the equal charge displacement postulate, and

(iii) the average number of the neutrons emitted by fission fragments is proportional to their masses.

The values of σ_z^2 and $\bar{\nu}$ are the parameters calculated in such a way as to obtain the best fit to the points of the isotopic distribution, which, is, by definition, a Gaussian of the form

$$W(A_f^\circ - A_p) \sim \exp\left[-\frac{(A_f^\circ - A_p)^2}{\sigma_N^2}\right].$$

Figure 1 shows the isotopic distributions of I, Te (symmetric fission) and rare earth elements(asymmetric fission),which are characterized by practically the same dispersion, but differ in the number of fission neutrons, $\bar{\nu}$ (these values are 6.5 and 8.5 for symmetric and asymmetric fragments, respectively). These $\bar{\nu}$ values lie within reasonable limits as the experimentally obtained value of $\bar{\nu}$ for spontaneous fission of $^{252}102$ is 4.2±0.3 /6/. The mass distribution of fission fragments is shown in fig. 2. Despite the spread of the experimental points, asymmetric fission involving the formation of a heavy fragment with mass lying between 142 and 145 proves to be predominant over symmetric fission to fragments with masses $A_h = A_l \approx 128$.

As the projectile energy increases, the fission cross section increases rapidly, and, as shown in fig. 2, at E_{lab} = 250 MeV (E^* = 53 MeV) the mass distribution becomes nearly symmetric.

Therefore we think that the asymmetric fission fragment distribution observed in the fission of the nucleus $^{256}102$ with a maximum excitation energy of 25 MeV is due to the shell effects that manifest themselves in the low-energy fission of practically all actinide elements up to ^{256}Fm.

Table

Isotope Production Cross Sections in the Reaction $^{208}Pb + ^{48}Ca$.

Isotope	$T_{1/2}$	$E_\gamma(\kappa_\gamma)$keV	σ mb	Isotope	$T_{1/2}$	$E_\gamma(\kappa_\gamma)$keV	σ mb
^{126}I	13d	389(0.35)	0.14	^{143}Ce	35h	293(0.46)	0.78
^{130}I	12.4h	536(1.00)	0.56	^{144}Ce	284d	133(0.11)	0.80
^{131}I	8.04d	364(0.82)	0.72	^{147}Nd	11d	91(0.15)	1.10
^{132}I	2.28h	773(0.75)	0.52	^{148}Pm	5.4d	550(0.26)	0.44
^{133}I	21h	530(0.87)	0.19	^{150}Pm	2.68h	334(0.74)	0.22
^{135}I	6.7h	1260(0.29)	0.045	^{151}Pm	27.8h	340(0.21)	0.34
^{131m}Te	30h	150(0.36)	0.16	^{153}Sm	46.4h	103(0.28)	0.09
^{132}Te	78h	228(0.88)	0.06	^{156}Sm	9.4h	88(0.3)	0.22
^{112}Ag	3.13h	617.4(0.42)	0.65	^{149}Eu	106d	328(1.0)	0.04
^{113}Ag	5.3h	259(0.014)	0.85	^{157}Eu	15.1h	413(0.27)	0.10
^{92}Y	3.5h	943(0.14)	0.34	^{159}Gd	18.0h	363(0.10)	0.18
^{93}Y	9.6h	267(0.072)	0.65	^{156}Tb	5.4d	534.3(0.7)	0.05
^{133m}Ba	38.9h	176(0.183)	0.14	^{160}Tb	72d	879(0.30)	0.16
^{135m}Ba	28.7h	268(0.16)	0.35	^{161}Tb	6.9d	75(0.10)	0.15
^{140}Ba	12.8d	537.2(0.34)	0.22	^{157}Dy	8.1d	326(0.95)	0.02
^{140}La	40.2h	487(0.46)	0.81	^{171}Er	7.5h	308(0.64)	0.025
^{137}Ce	9.0h	446(0.023)	0.10	^{172}Er	49.5h	407(0.44)	0.016
^{139}Ce	137d	165.8(0.8)	0.46	^{173}Tm	8.2h	399(0.89)	0.05
^{141}Ce	32.5d	145.4(0.48)	1.05				

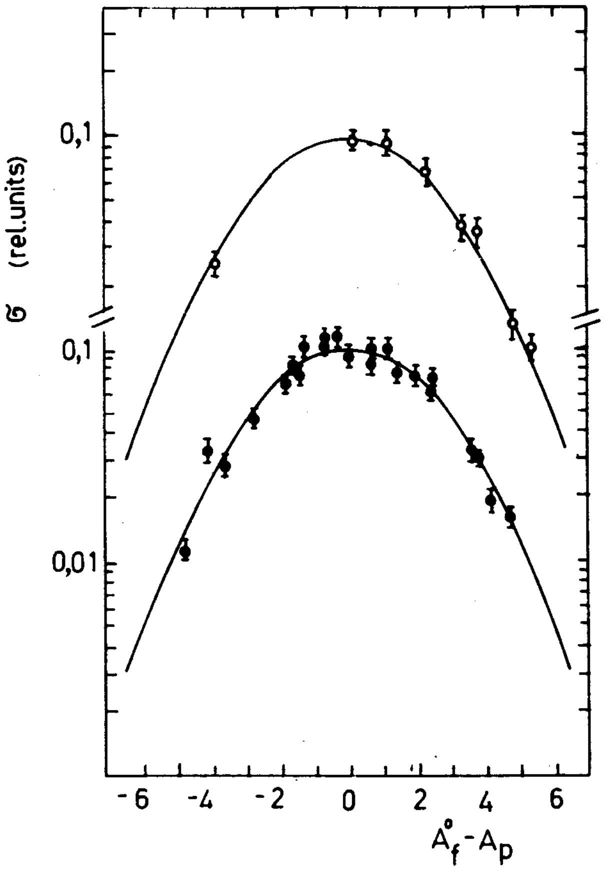

Fig. 1. Isotopic distribution of symmetric (upper curve) and asymmetric (lower curve) fission fragments in the reaction ^{208}Pb + ^{48}Ca. The compound nucleus excitation energy is 25 MeV. The distribution dispersion σ_N^2 is equal to 12 in both cases, while $\bar{\nu}$ is 6.5 and 8.5 for symmetric and asymmetric fragments, respectively.

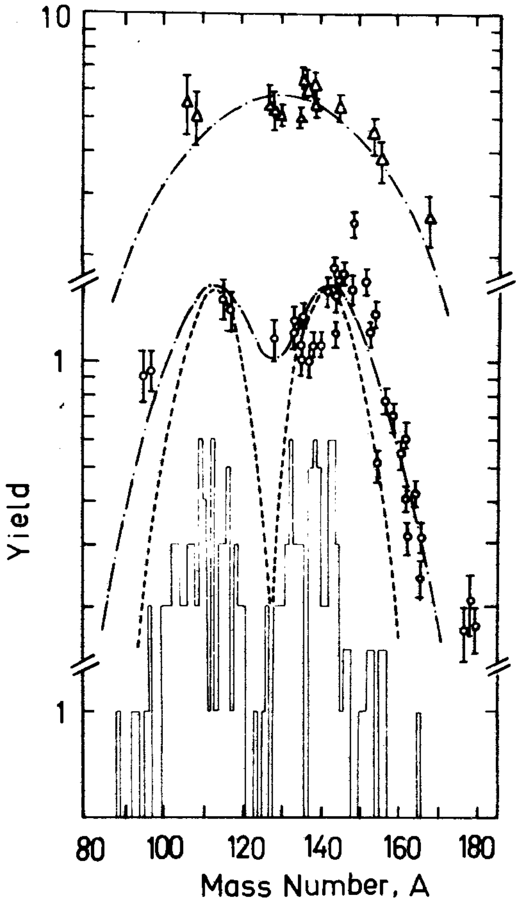

Fig. 2. Experimental mass distributions of fission fragments from the compound nucleus $^{256}102$ at two excitation energies: 25 MeV (circles) and 53 MeV (triangles). The dash-dotted lines are drawn through experimental points to guide the eye. The histogram and dashed line show the mass distributions of spontaneous fission fragments from $^{252}102$ /8/, and ^{256}Fm /7/.

The position of the maxima of the mass distribution of the fission fragments from $^{256}102$ is in agreement with analogous data obtained on spontaneous fission of ^{256}Fm and $^{252}102$ /7,8/. However, the mass distribution dispersion with respect to the average masses of the light and heavy fission product groups for the excited nucleus $^{256}102$ is somewhat wider than in the case of spontaneous fission. This fact seems to be the main reason for the substantial decrease in the ratio Y_{asymm}/Y_{symm} compared with the data obtained in experiments on spontaneous fission of ^{256}Fm and $^{252}102$.

It is noteworthy that the integral yield of fission fragments at E_{lab} = 220 MeV is about 50 mb. This value constitutes a considerable portion of the total cross section for the reaction $^{208}Pb + {}^{48}Ca$ and is in good agreement with the cross section for the reaction $^{208}Pb(^{48}Ca, 2n)^{254}102$, equal to 4 μb.

The data obtained indicate that similar reactions may be used to study nuclear fission from low-lying states. It is of certain interest to investigate fission of superheavy nuclei, the mechanism of which may differ qualitatively from that of transuranic elements.

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