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SPONTANEOUS FISSION OF ^{244}Cm STUDIED BY THE TWO-VELOCITIES METHOD AT THE FOBOS* SPECTROMETER

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Abstract

The two - velocities method was used to measure the mass - energy distribution of fission fragments (FF) originating from the spontaneous fission (sf) of ^{244} Cm. Especially, the energy regions of cold compact (CCF) and cold deformed fission (CDF) have been investigated. The FF mass distributions of CCF- and CDF products are basically different for spontaneous and thermal neutron induced fission of Cm isotopes. Evidence for the existence of a supershort fission mode has been observed.

1. INTRODUCTION

Very recent investigations in the field of nuclear fission [1] present an abundant material for a new approach of understanding of this process, especially for the role of cluster degrees of freedom. One of the most promising ways to get new results is the measurement of the mass and charge spectra of cold fragmentation products. It is well known, that the fragment mass spectra in CCF and CDF are characterized by prominent structures [2] caused by shell and pairing effects.
During the last years, a lot of data has been collected on the CCF, but the CDF has been studied much less. In particular, there is a lack of data on spontaneous CDF.
The subject of this work is an experimental study of the mass - energy distribution of $^{244}Cm(sf)$ fragments, including not only the CCF, but for the first time also the CDF region.

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2. EXPERIMENTAL SET-UP

The experiment was carried out at the FOBOS facility of the Flerov Laboratory of Nuclear Reactions of the JINR Dubna [3].

This array is a "gas-detector ball" consisting of 30 position - sensitive avalanche counters (PSAC) and 30 axial (Bragg) ionization chambers behind them. In the present experiment, only two groups of 3 PSAC each were used to determine the velocity vectors of complementary fission fragments via a TOF - TOF measurement. A small transmission avalanche counter (PPAC) placed near the source delivered the time reference signal. The flight path amounted to 47 cm. All counters were operated at 400 Pa of pentane in a gas flow-through regime. A reduced bias of 480 V was applied to effectively discriminate the huge rate of about 10^6 alpha - particles per fission. The ^{244}Cm(sf) source consisted of 9.8 μg fissioning material deposited on a 50 μg/cm^2 thick Al_2O_3 backing .

In total, about 10^5 FF coincidences have been collected. From the measured velocities the fragment mass ratio and the kinetic energies have been determined event - by - event utilizing a procedure [4] which takes into account the energy losses in the source and backing layers as well as in the counter materials.The energy losses have been calculated assuming the FF proton - neutron ratio to be equal to that of ^{244}Cm. An absolute time calibration of the spectrometer has not been done. For calibration mean values of the light and heavy FF mass (M_L , M_H) as well as total kinetic energies (TKE) of the ^{244}Cm(sf) fragments were taken from refs. [5,6,7] (although only in ref. [6] the two - velocities method was employed).

The experimental mass resolution (ΔM) was estimated from the widths of the mass peaks in the CCF region. It does not exceed 3 amu (fig. 1). This value well corresponds with the results obtained from a simulation which took into account the real thicknesses of the counter window foils as well as the geometry of the FOBOS array. The value of ΔM is mainly determined by the relatively thick (300 μg/cm^2) windows of the PPAC.

3. RESULTS

In fig. 2 the mass yields of primary FF of ^{244}Cm(sf) obtained in our experiment are compared with corresponding results from refs. [6,8]. Further comparisons are made in figs. 3 and 4 considering the single - fragment energy before neutron emission and the standard deviation of the single - fragment energy distribution, respectively. A satisfactory agreement is found.

As an initial result of our measurements, we obtained the unnormalized yield functions Y(M,E) and Y(M,TKE), where M means the mass of the primary fragment and E its kinetic energy. In order to analyze the fine structure of the FF mass distribution in dependence on the excitation energy (E*) of the fissioning system at the scission point, the function Y(M,TKE) has been transformed into the respective Y(M,E*), where E* is defined by the expression E* = Q - TKE and Q is the mean energy of reaction for the production of FF at a fixed mass ratio M_L / M_H . The values Q (M_L / M_H) were calculated as the weighted means over Q_{Max} (M_L / M_H) taken from the tables of ref. [9]. As a weight function we used a Gaussian with a FWHM = 3 amu in correspondence with the experimentally obtained mass resolution.

As always has been observed earlier [8], the yield around the double magic fragment with mass number A = 132 is strongly suppressed in the region of CCF (fig. 1). On the other hand, such masses dominate in the CDF region, that is at high E* (fig. 5).
We want to notice here, that the mass yield of the thermal neutron induced *cold* fragmentation of the neighboring isotope ^{245}Cm substantially differs from that obtained for ^{244}Cm(sf) : there, masses near M = 132 amu dominate in the CCF, whereas in the CDF a yield enhancement at $M \approx 142$ amu prevails [10].
The general tendency of the heavy fragment mass yield for ^{244}Cm(sf) in dependence on E* is shown in the contour plot of the conditional probability $P(M|E^*)$ for the formation of a fragment of mass M at E* (fig. 6). The distribution $P(M|E^*)$ was obtained by the transformation

$$P(M|E^*) = P(M,E^*) / P(E^*) \qquad (1)$$

where the probability $P(M,E^*)$ was evaluated from the measured yield - function $Y(M,E^*)$ by the normalization

$$P(M,E^*) = Y(M,E^*) / \Sigma_{M,E^*} Y(M,E^*) \qquad (2)$$

and $P(E^*)$ is the density function of the excitation energy

$$P(E^*) = \Sigma_M P(M,E^*). \qquad (3)$$

From fig. 6 it is easy to get an analytical expressions for the top lines of the ridges observed. Starting, e.g., from M_H = 148 amu one obtains for the dependence of the maximum yield on E* and M_H

$$E^* / \mathrm{MeV} = \alpha \cdot (148 - M_H / \mathrm{amu}) \qquad (4)$$

As demonstrated in figs. 5 ÷ 8, the distribution $P(E^*)$ is nearly the same for the reactions ^{244}Cm(sf) and $^{235}U(n_{th},f)$, but the functions $P(M|E^*)$ differ significantly. The $^{235}U(n_{th},f)$ data have been obtained by use of the TOF spectrometer at the reactor of the MPHEI Moscow [11].

4. Discussion

As demonstrated in fig. 1, at low E* there are increased yields for the mass ratio M_L / M_H equal to 94/150, 96/148, 101/143 and 106/138.
By definition, the CCF fragments should be born near to their ground states. From estimations made in ref. [12] it follows, that nonspherical fragments in their ground states should be favored for TKE values approaching the Q value. This is the more probable for FF pairs realizing a high Q value. Furthermore, at least one of the two prefragments should have a structure with a closed or nearly closed nucleon shell. The deformation of such a prefragment corresponding to a minimum of the shell correction should be nearly equal to the equilibrium deformation of the fragment after scission.

The peaks seen in fig. 1 are related to the conditions mentioned above for the appearance of CCF fragment pairs. Essential parameters of these FF of ^{244}Cm(sf) are given in the table.

Table 1: Physical parameters characterizing the CCF fragments of ^{244}Cm(sf).

Light FF (1)	deformed shell neutrons (2)	protons (2)	β_{gs} (3)	Heavy FF (4)	Q_{el} (HF) [barn] (5)
$^{94}_{38}Sr_{56}$		B'	0.24	$^{150}_{58}Ce_{92}$	5.0
$^{96}_{38}Sr_{58}$	B	B'	0.34	$^{148}_{58}Ce_{90}$	4.2
$^{101}_{40}Zr_{61}$		B'	0.37	$^{143}_{56}Ba_{87}$	2.1
$^{106}_{42}Mo_{64}$	C		0.35	$^{138}_{54}Xe_{94}$	3.9

The columns contain the following data:

(1) The light FF with a nearly closed nucleon shell responsible for the high Q value of the fission.

(2) These nucleon shells are characterized by the following parameters taken from ref. [13]

B : $\beta_2 = 0.35 \div 0.44$; $N = 57 \div 60$ (closed neutron shell)

C : $\beta_2 = 0.53 \div 0.64$; $N = 63 \div 66$ (closed neutron shell)

B': $\beta_2 = 0.33 \div 0.42$; $Z = 37 \div 40$ (closed proton shell)

(3) The ground state deformation of the light FF taken from ref. [9].

(4) The heavy FF corresponding to those of column (1) (fig. 1).

(5) The electrical quadrupole moments of the heavy FF taken from ref. [9].

Thus the fine structure in the mass yield distribution in the CCF of ^{244}Cm(sf) can be explained by the manifestation of shell effects in only the light fragment and, additionally, by the considerably large ground-state deformation of the corresponding heavy fragment. As it follows from the data presented in the table, fragmentation with small E* occurs from enough elongated scission configurations. Possibly, *cold* fission out of such configurations occurs because the elongation of the nucleus at the scission point is much larger than at the saddle point and, therefore, more compact configurations with spherical fragments near M = 132 amu observed in the cold fission of ^{245}Cm(n_{th} ,f) become “missing” in the spontaneous fission.
The overall “diagonal" pattern of the conditional probability distribution $P(M|E^*)$ (fig.6) and the enhanced fragment yields at $M_H \approx 134$ amu for high E* (figs. 5 and 6) can be interpreted in the framework of the cluster conception of fission proposed in ref. [14]. According to this model, one can assume a most probable configuration of the fissioning nucleus near scission to consist of two touching prefragments with two closed deformed nucleon shells ($^{94}_{38}Sr_{56}$) and a cloud of the remaining nucleons forming the neck in-between. The nucleus can further elongate and a spontaneous neck rupture can take place up to the moment when the masses of the two fragments after scission are identical. This is the reason for the global behavior of the mass yield with increasing E*

(fig.6), starting at mass splits observed in the cold fission down to a symmetric fission at high E*. At a certain stage of the fission process the transformation of the system into two highly deformed shell prefragments ($^{134}{}_{52}Te_{82}$ with a neutron shell at the deformation $\beta_2 = 1.1$ [16] and $^{110}{}_{44}Ru_{66}$ with a shell at $\beta_2 = 2.2$ related to the region C' of the proton shell correction map of ref. [13]) becomes possible. The stiffness of these nuclei prevents further elongation of the fissioning system and this process stops.
Calculations of E* have been done employing an interaction potential of the two touching prefragments Te and Ru in a prescission configuration. The nuclear interaction potential was evaluated using the double folding method with the parameters given in ref. [17]. A good agreement with the experiment has been obtained. A calculation of the fragment yields in dependence on E* and M in accordance to the map presented in fig.6 is in progress now.
An interesting peculiarity in the mass - energy distribution of ^{244}Cm(sf) is observed at the mass ratio 84/160 at low E* (figs.1 and 6). A similar bump has already been observed in ref. [18]. It is isolated from the other FF in energy and mass. By some analogy to the symmetric fission component (two Sn fragments) of ^{258}Fm(sf), such a located bump may be stipulated by a special fission mode characterized by fragments with fully occupied nucleon shells. To proof the existence of such hypothetical "supershort" fission mode a new experiment is in preparation now.

5. CONCLUSIONS

i) The structures in the FF mass distribution observed in the CCF of ^{244}Cm(sf) result from a manifestation of deformed nucleon shells in the light FF in correspondence to the shell correction map of ref. [13].
ii) A continual decrease of the most probable heavy fragment mass with increasing E* is observed from the energy cuts of the probability distribution $P(M|E^*)$ (figs.5 and 6).
iii) The peak at $A \cong 134$ in the CDF of ^{244}Cm(sf) is stipulated by an elongated stage of the fissioning nucleus characterized by the pair of stiff superdeformed prefragments $^{134}{}_{52}Te_{82}$ and $^{110}{}_{44}Ru_{66}$.

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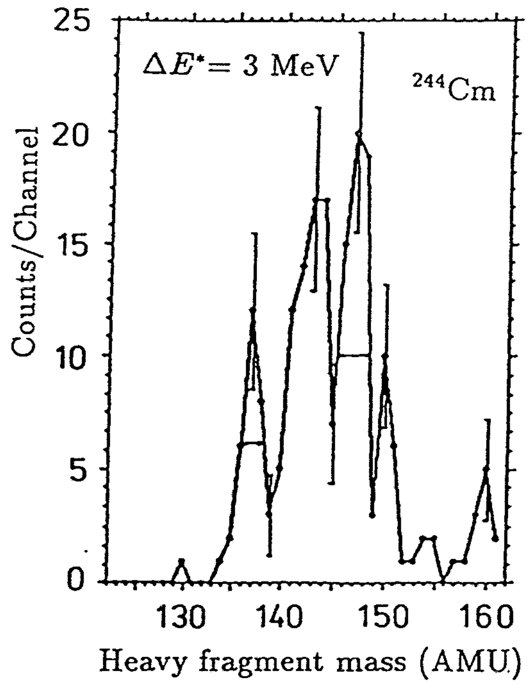

Fig. 1 Fragment mass distribution for CCF of ^{244}Cm (sf) for excitation energies E* in the region of 0 ÷ 3 MeV.

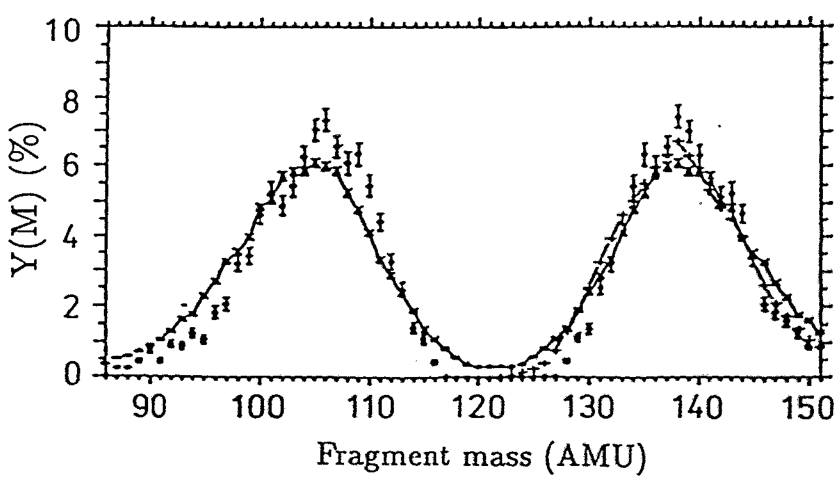

Fig. 2 Mass yield of primary fission fragments of ^{244}Cm(sf). The results of this work (dashed line) are compared with those of ref. [6] (•) and ref. [9] (+).

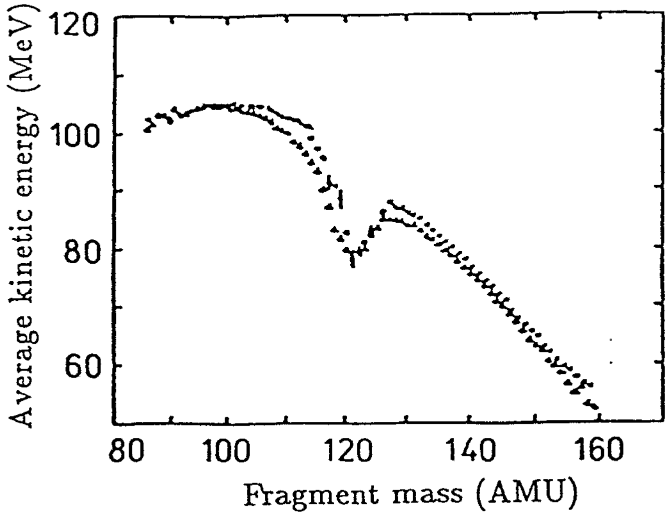

Fig. 3 Single-fragment energy before neutron emission as a function of the fragment mass. Our results (Δ) are compared with those of ref. [7] (•).

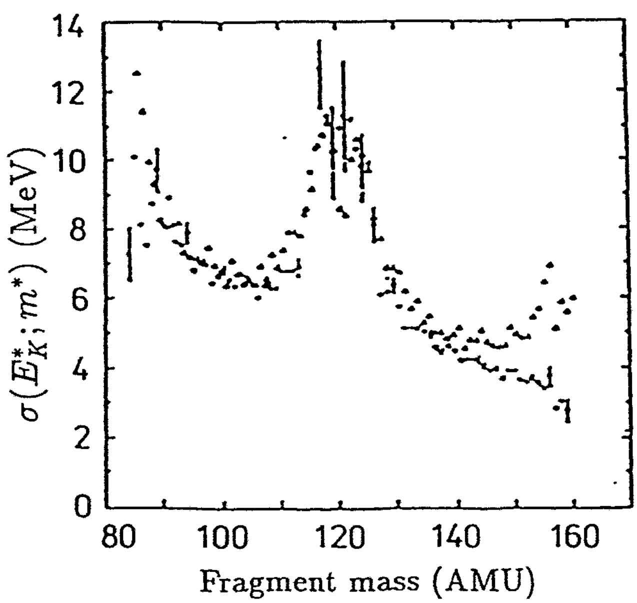

Fig. 4 Standard deviation of the primary single-fragment energy distribution as a function of the fragment mass. The triangles represent our results, full circles the data of ref. [7].

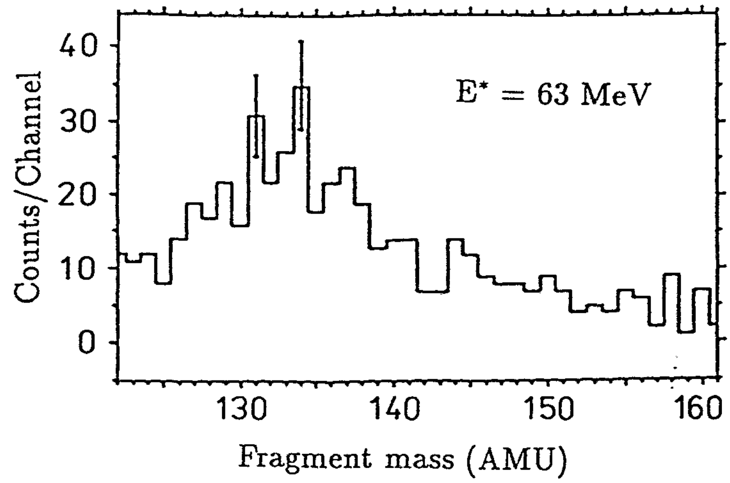

Fig. 5 The mass spectrum for CDF of ^{244}Cm(sf) at E* = 63 MeV. The width of the excitation energy window is ΔE* = 1 MeV.

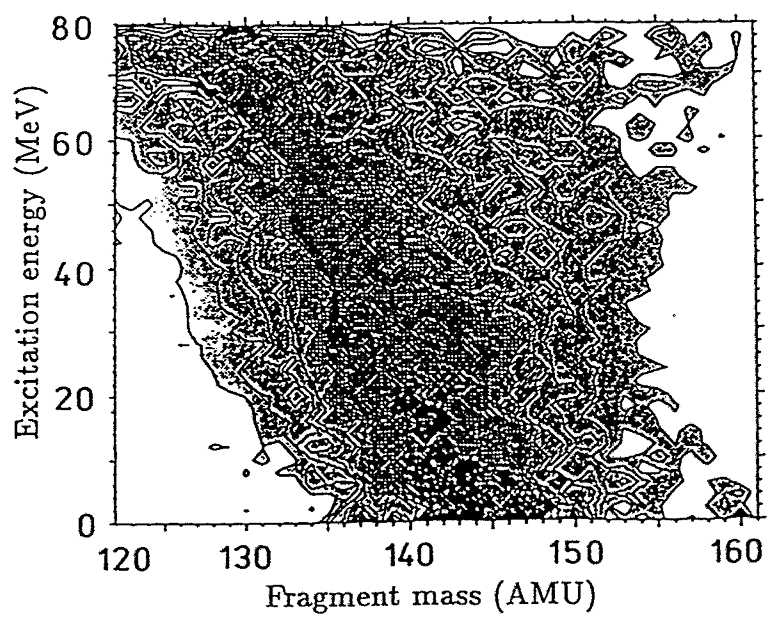

Fig. 6 The conditional probability P(M|E*) for the formation of a fission fragment with the mass M at the excitation energy E* in ^{244}Cm(sf).

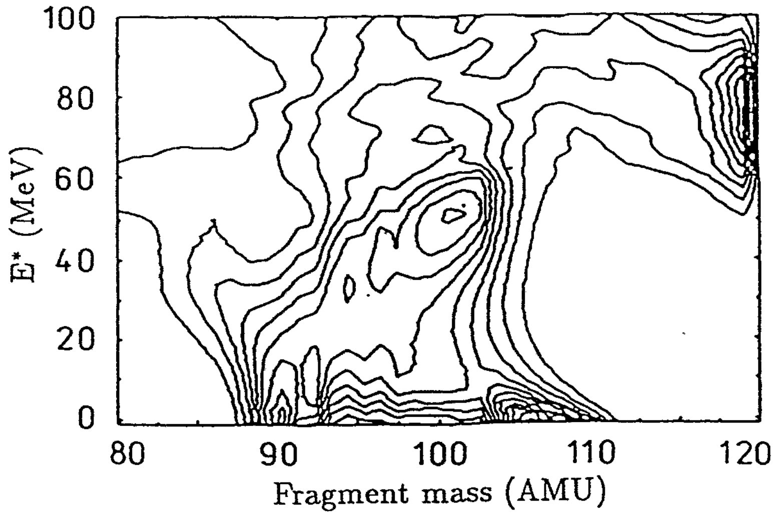

Fig. 7 The conditional probability P(M|E*) for the reaction $^{235}U(n_{th},f)$ (after ref. [12]).

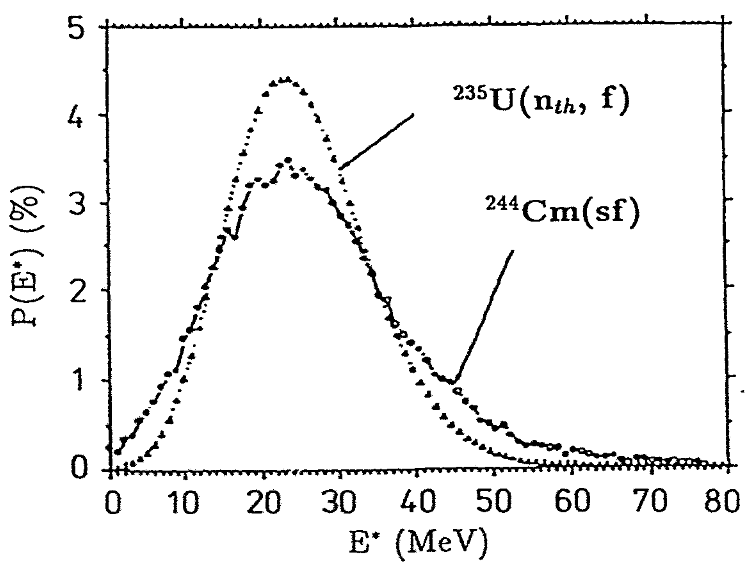

Fig. 8 Comparison of the excitation energy distributions P(E*) for the reactions $^{235}U(n_{th},f)$ (after ref. [12]) and $^{244}Cm(sf)$ (our results). For convenience the maximum of the function for $^{244}Cm(sf)$ is shifted to the position of the ^{236}U maximum.