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GAMMA-RAY MULTIPLICITIES IN SUB-BARRIER FISSION OF ^{226}Th

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The γ rays from the multimodal fission of the ^{226}Th formed in ^{18}O + ^{208}Pb was investigated at the sub-barrier energies. The corresponding excitation energies at the saddle point, E^*_{sp}, ranged from 16.4 to 19.2 MeV. The average γ-ray multiplicities and relative γ-ray energies as a function of the mass of the fission fragments exhibit a complex structure and strong variations. Such strong variations have never been previously observed in heavy ion-induced fusion-fission reactions. Obtained results may be explained with the influence of shell effects on the properties of the fission fragments. Present work is the one in series of investigations of the multimodal fission phenomena in At-Th region.

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

Гамма-множественность при подбарьерном делении ^{226}Th

Г.Г.Чубарян и др.

Представлены результаты измерений множественности γ-квантов из осколков при мультимодальном делении ^{226}Th, образованного в подбарьерной реакции слияния-деления ^{18}O + ^{208}Pb. Энергия возбуждения составного ядра в седловой точке, E^*_{sp}, составляла 16,4 и 19,2 МэВ. Полученные средние γ-множественности и относительная средняя энергия γ-квантов в зависимости от массы осколков деления имеют сложную структуру и изменяются в широком диапазоне. Столь сильная вариация множественности у-квантов наблюдена впервые в реакциях слияния-деления с тяжелыми ионами. Полученные результаты могут быть объяснены влиянием оболочечных эффектов на характеристики осколков де-

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ления. Данная работа продолжает цикл исследований мультимодального деления в переходной области ядер At-Th.

Работа выполнена в Лаборатории ядерных реакций им. Г.Н.Флерова ОИЯИ.

Introduction

It is well known that dramatic changes occur in the mass and energy distributions of certain spontaneously fissioning Fermium isotopes and some other transuranic elements [1,2]. For the isotopes ^{258,259}Fm and ^{260}Md, fission produces narrow symmetric mass distributions and fragments with relatively high kinetic energies. Only small changes in the nucleonic composition radically alter this picture.

Dramatic changes in the symmetric/asymmetric character of the fission probabilities can be accounted for by theories, which incorporate a micro-macroscopic approach including the effects of nuclear shell structure on the formation of the fragments. Detailed calculations of the nuclear potential energy surface indicate the possibility of a co-existence of various (at least two) distinct fission modes [3]. Multimodal fission phenomena have also been observed in the Pb-At region in proton and alpha induced reactions [4], as earlier predicted [5].

Unfortunately, with light charged particles it is not possible to extend this work into the largely unstudied At-Th region due to the absence of suitable targets. In this region dramatic changes are expected to occur in the fission properties as a function of the nucleonic composition and the excitation energy. The transition form symmetric to asymmetric fission along with the accompanying changes in the barrier height and the saddle-to-scission times can be expected to strongly influence the fission mass and energy distributions, the fission cross sections, the fragment y-ray multiplicities as well as the pre- and post- fission neutron multiplicities.

A new strategy for probing the At-Th region was developed several years ago utilizing heavy ion beams in near- and sub-barrier fusion-fission reactions [6]. Similar experiments have been performed at GSI to investigate Coulomb fission reactions of secondary radioactive beams [7].

The current paper focuses on the results of studies of the γ-ray multiplicities from the fission fragments of the neutron deficient isotope ^{226}Th formed in reactions 78 and 75 MeV $^{18}O + ^{208}Pb$. The experiments were conducted on the tandem at LNS-INFN in Catania.

Results and Analysis

The main problem in studying low energy fission ($20 < E^* < 30$ MeV) in the above-mentioned transition region using heavy ion beams is the very small fusion-fission cross section near the Coulomb barrier. By choosing the appropriate target-projectile combination, one can achieve the lowest possible excitation energy.

In our experiments fission fragments were detected using a high efficiency time-of-flight spectrometer consisting of an array of position sensitive PPAC's. The γ-ray multiplicities were measured with six 63x63 mm NaI detectors. Detailed description of experimental set-up and procedures are presented in [6].

The characteristics of the reactions studied are summarized in the Table. This table lists the beam energies, E_i, the excitation energies, E^*, the fission barriers, E_f, the saddle point excitation energies, E^*_{sp}, the average γ-ray multiplicities $\langle M_\gamma \rangle$, and the standard deviation of the γ-ray multiplicities $\langle \sigma_{M_\gamma} \rangle$.

Figure 1 (a) shows relative average y-ray energies, $\langle E_\gamma \rangle$ (top, solid circles), $\langle M_\gamma \rangle$, (middle, open circles) as a function of the mass of fragments for the reaction ^{208}Pb(^{18}O,*f*) at $E_i = 78$ MeV. The mass distribution of the fission fragments is presented in the bottom of the Figure. The variation of the $\langle M_\gamma \rangle$ with fragment mass is dramatic. Near symmetry $\langle M_\gamma \rangle$ is about 12. As one deviates from symmetry, $\langle M_\gamma \rangle$ stays approximately constant over a small mass interval and then plunges almost precipitously. Around $A \approx 94$ and 132, small shoulders are observed and then $\langle M_\gamma \rangle$ falls to a minimum value of about 8 around $A \approx 86$ and 142. At larger mass asymmetries, the multiplicity rises and then appears to fall.

Table. Parameters for the fission of ^{226}Th

Reaction	E_i, MeV	σ_f mb	E^* MeV	E_f MeV	E^*_{sp} MeV	$\langle M_\gamma \rangle$	$\langle \sigma_{M_\gamma} \rangle$
^{18}O + ^{208}Pb	78	8 ± 0.4	26.1	6.9	19.2	9.81 ± 0.03	4.78 ± 0.07
	75	0.042 ± 0.007	23.3		16.4	9.56 ± 0.60	5.26 ± 1.35

Such a structure and strong variation in $\langle M_\gamma \rangle$ have never been previously observed in heavy-ion induced fission. The dependence of $\langle E_\gamma \rangle$ on mass also exhibits a strong variation. Near symmetry it has wide minimum and increases sharply while approaching the range of asymmetry in mass distribution. Around masses mentioned above, $\langle E_\gamma \rangle$ has well pronounced local maximums. For the largest masses, approximately in the range where $\langle M_\gamma \rangle$ rises again, $\langle E_\gamma \rangle$ appears to fall. The total variation of $\langle E_\gamma \rangle$ is about 30%. It seems likely that the marked structure in $\langle M_\gamma \rangle$ and $\langle E_\gamma \rangle$ is due to strong shell effects in the cold fission fragments, where predominantly rare, but high-energy γ-ray transitions are possible.

It is interesting to compare the present results with liquid drop calculations [8]. The dashed curve in Fig. 1(a) shows the results of such calculations assuming total fragment spin $l = 15h$ and $S_T = 2(\langle M_\gamma \rangle - 6)$ [9]. The calculations predict a maximum at symmetry, however, the calculated values are larger than the experimental values. This is not particularly surprising since the assumed orbital angular momentum is a rough estimate. Furthermore, no corrections have been made for the spin removed by evaporated neutrons. The calculations do not include the influence of shell effects, which should have a significant impact on the fragments shape and the relevant temperatures.

As it was shown in [1,2,4,6], TKE may be a convenient tool for separation of distinct fission modes. Figure l(b-d) shows $\langle M_\gamma \rangle$ as a function of the fragment mass for three

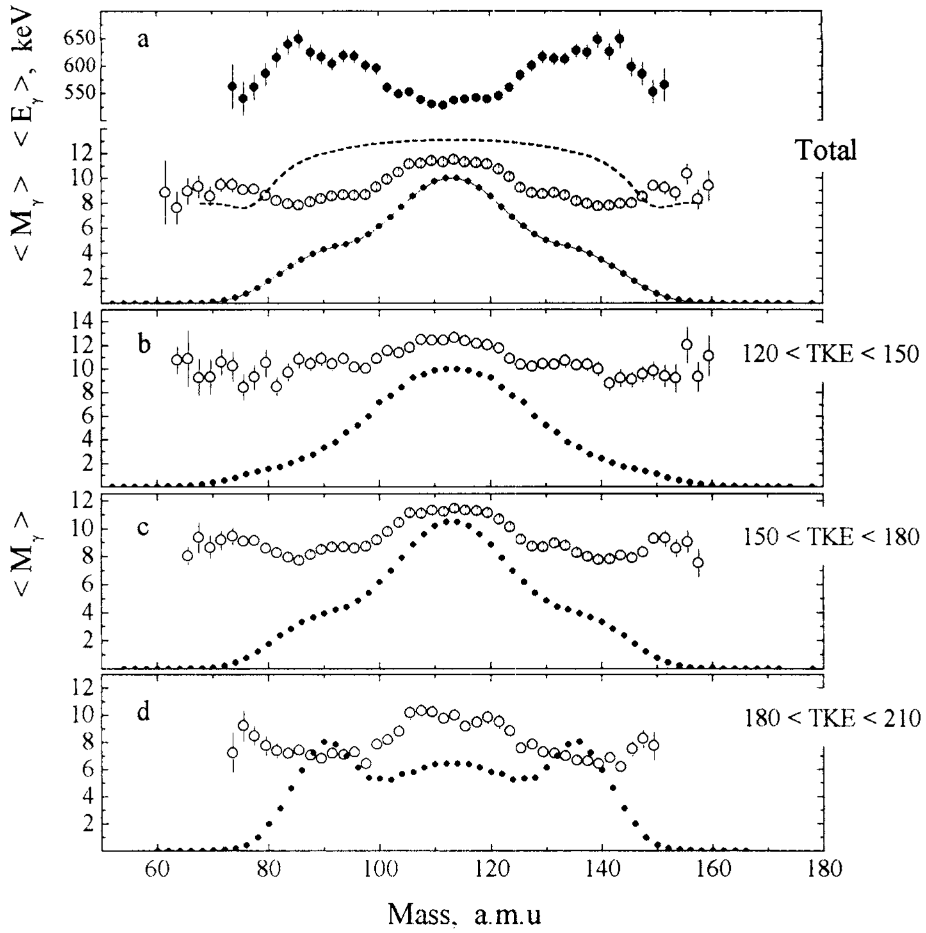

Fig.1. $\langle M_\gamma \rangle$ and $\langle E_\gamma \rangle$ as a function of the fission fragment mass. See details in the text

selected ranges of TKE. Mass distributions for the same TKEs' are also presented. For low TKEs', where the input of the asymmetric masses is small, $\langle M_\gamma \rangle$ reaches its highest values, in the mean time the variation of $\langle M_\gamma \rangle$ is the smallest. On the contrary, at the highest TKE where the yield of asymmetric fission fragments is dominating, variation of the $\langle M_\gamma \rangle$ is the largest, but has the lowest absolute value.

Gamma-ray multiplicities as a function of the TKE for different ranges of mass are shown in Fig.2(a-c). For all selected ranges (total, symmetric and asymmetric) $\langle M_\gamma \rangle$ exhibits the same behavior, but absolute values are different. $\langle M_\gamma \rangle$ is approximately 30 % higher for symmetric masses than for asymmetric part of the mass distribution, where the influence of shell structure on the fission fragments is the strongest.

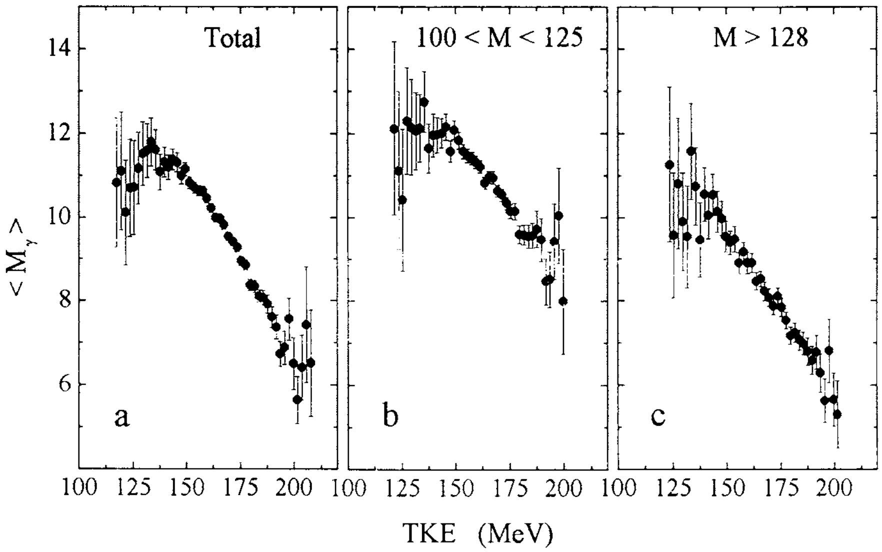

Fig.2. $\langle M_\gamma \rangle$ as a function of fission fragment total kinetic energy. See detals in the text

Summary

The properties of γ rays from the fission fragments of the neutron deficient isotope of ^{226}Th have been investigated using near- and sub-barrier fusion-fission reactions. The data gathered in this work provide a detailed view of the evolution of the $\langle M_\gamma \rangle$ and $\langle E_\gamma \rangle$ with the mass of the fission fragment.

Complex structure and strong variation of the $\langle M_\gamma \rangle$ and $\langle E_\gamma \rangle$ as a function of mass and TKE may be explained with the influence of shell structure of the fission fragments on the yield and energy of the γ rays.

For accurate fit of $\langle M_\gamma \rangle$ dependences one needs shell corrected theoretical calculations of the shapes and temperatures of the fission fragments at the scission point.

Results of the present work are in good agreement and are supplementing the conclusions made in [6].

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