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Nuclear Molecules in Low Energy Fission of Actinides?

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Abstract

A comparison is presented of the fine structure (FS) of the both energy-mass and energy-charge distributions of the fission fragments of thermal neutron induced fission of Uranium in the data obtained at different spectrometers. Some peculiarities of the FS observed can be treated as a manifestation of two different types of collective vibrations of the fissioning system on its way to scission.

Introduction

In the refs.[1,2] were stated for the first time about the revealing of the fine structure being different from that produced by the proton odd-even effect in the mass-energy(M-E) spectra of the fission fragments (FF) from the ^{233}U(n_{th},f) reaction. The detail description of the data processing is presented in ref. [3]. The present work is devoted to a comparison of the FS obtained using experimental data from three different spectrometers and discussing the FS origin.

Experiment

The experimental data were obtained predominantly at two time-of-flight spectrometers: at the MEPhI reactor [4] and Cosi-Fun-Tutte [5] (Grenobl, France). The first spectrometer was situated on a vertical experimental port in a thermal column of the research MEPhI reactor. The mass of fragment was obtained by FF time-of-flight of a predetermined distance between two microchannel plate of time pick-off detectors. Their kinetic energy was measured by surface-barrier semiconductor detector. The study of (n_{th},f) reactions with high statistics is carried out having a target location near the reactor core and an electrostatic particle guide system installed that to increase the efficiency ratio of the spectrometer by a factor of 50. A special procedure proposed in [6] was used to calibrate spectrometer. The second spectrometer was installed in the high flux reactor at ILL (Grenoble, France). This spectrometer has a double arm configuration. One arm was used to measure the velocity, kinetic energy and nuclear charge of the fission fragments. The other arm was only used to measure the kinetic energy and charge of the fragment.

The velocity measurements were carried out by two pick up detectors on microchannel plates. The kinetic energy and nuclear charge of FF were measured by the ionization chamber [7]. From the kinetic energy and velocity , the mass M of the fragment was deduced. The resolution of the kinetic energy and velocity measurements was good enough to obtain mass resolution better then 1 amu. Nuclear charge measurements were performed by the method proposed in [8]. The achieved resolution is about 1ch.u. The time-of-flight spectrometer drawback is the presume of the false events which result from the scattering of FF on the supporting grid of the entrance window to the chamber. To eliminate this effect, the selection procedure was used. Due to this procedure only those events were selected where the mass of fragment deduced from the energy – time-of-flight measurements and the fragment mass obtained within double energy method using the energy signal from the second arm of spectrometer differ not more then 15 amu. This selection mechanism was specially tested to avoid the distortion of the mass and energy distributions. A number of events in light mass-peak is $8\cdot 10^5$ after data processing by procedure described. Only part of the results obtained will be discussed below. For the others we refer to Ref. [9,10].

Comparative analysis of the FS of two-dimensional FF distributions

The task of the FS revealing one can set leaning upon the following examples. As known the yield Y(M|E) of the FF with mass M at fixed value of E (a kinetic energy of the light fragment E_L or a total kinetic energy TKE) is equal to the following sum

$$Y(M|E) = \Sigma Y(M|Z,E),$$

where Y(M|Z,E) is an isotope distribution at fixed E. The latter distribution has approximately Gaussian shape. The spectrum Y(M|E) shows up as a smooth curve with local peaks on it being linked with the tops of the isotopes distributions for even charges (Fig.1a).

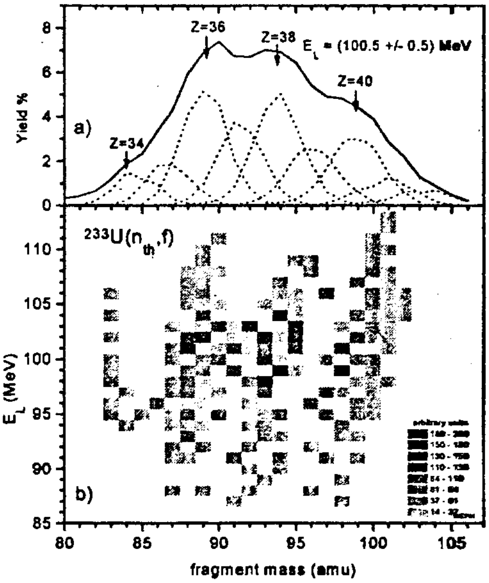

Fig.1. The cut of the P(M, E_L) distribution at E_L=100.5 MeV. The isotopic distributions are shown by dashed line (a). Manifestation of the proton odd-even effect at the E_L-M plane (b)

On the E_L-M plane the fine structure produced mainly by proton odd-even effect looks like the sequence of ridges going approximately perpendicular to the mass-axis (Fig.1b). Similar structures were demonstrated for the first time in Ref. [11]. By definition the local areas of the two-dimensional distribution with increased yields of the FF in respect to ones, supplied by the smoothed global distribution (Fig.1b), will be treated as fine structure. In the example under discussion the fine structure indicates the presence of poor resolved spectral components which constitute the E-M distribution.

The decomposition of the M-E distribution given above is not unique. Really, if the low energy fission prove to be a multimodal process, which is - with out any doubt, the FF E-M distribution should be the sum of the components being an image of the appropriate fission mode into the space of the E-M observables each. One can expect that the modal structure will manifest itself as FS too, for instance in the E-M distribution. Such structure being completely different from that produced by the odd-even effect have been revealed with a help of the data processing methods described in ref.[3]. It is displayed in the fig.2. Every curve presented in the figure constitutes a host of points of locally enhanced yields (peaks) in the E-M matrix. A tipical cut of the E-M matrix where such peacs are seen is shown in Fig.3a. There is a good agreement between the locations of the peacs obtained by the processing of the data measured at the MEPhI and Cosi-Fan-Tutte spectrometers (Fig.3a,b).

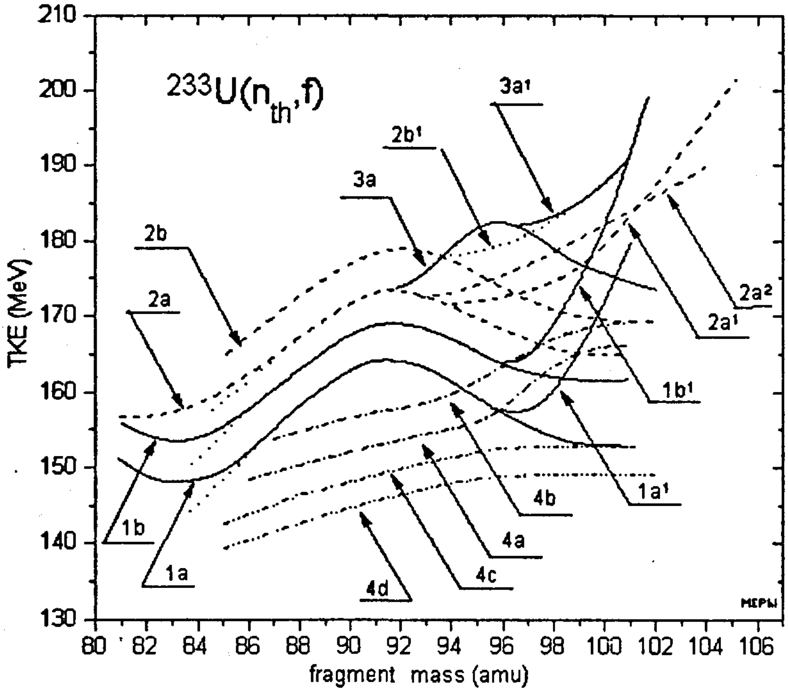

Fig.2. Fine structure of the TKE-M FF distribution. Curves 1-4correspond to the maxima of the local peaks being different from that produced by the proton odd-even effect

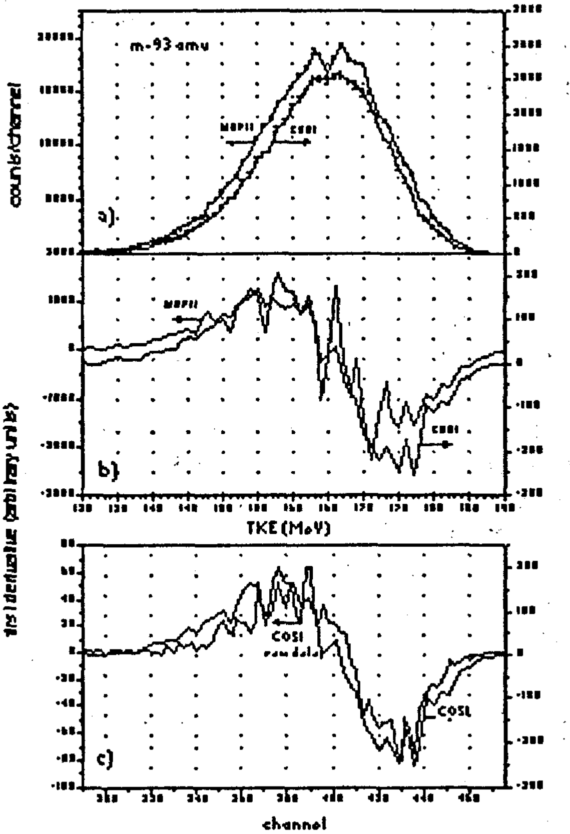

Fig.3. Comparison of the data obtained at Cosi-Fun-Tutte (left axis) and MEPhI (right axis) spectrometers: a) TKE spectra; b) first derivatives of TKE spectra; c) first derivatives of amplitude (raw data) and energy spectra for fragment mass 93 amu

High mass resolution of the Cosi-Fan-Tutte spectrometer permitted to compare the fine structures in the amplitude distribution (before any mathematical transformations – "raw data") and in the energy distributions for the fixed mass line. It is seen from Fig.3c, that the calibration procedure does not distort the structures, which attend in the initial "raw" data.

It should be stressed that the local peacs in MEPhI data have in everage larger amplitudes than those in Cosi-data. This tendency is tipical for all cuts M=const. The nature of the difference mentioned will be discussed below. We failed to extract the FS in E-M spectrum obtained at Cosi-Fun-Tutte spectrometer as contrast as in the MEPhI data owing to both the less level of statistics (roughly by one order of magnitude) and less amplitude of the FS effect under discussion. At the same time the most pronounced structures depicted in Fig.2 are revealed well in the TKE-Z spectrum where Z is a nuclear charge of the fragment (Fig.4). To compare Fig. 3 and 4, one should resort to the dependence of the mean nuclear charge on the FF energy taken from ref. [12] (Fig.5).

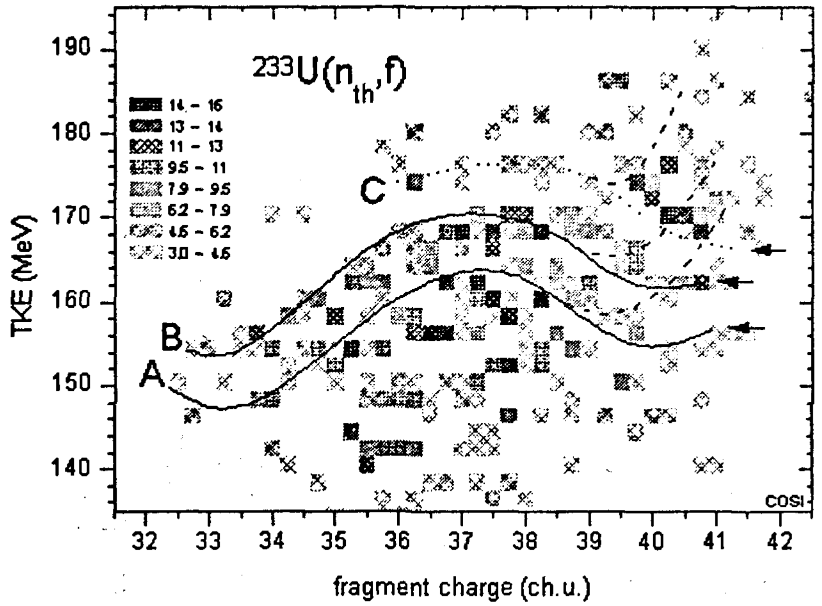

Fig. 4. Fine structure in the FF charge-TKE distribution

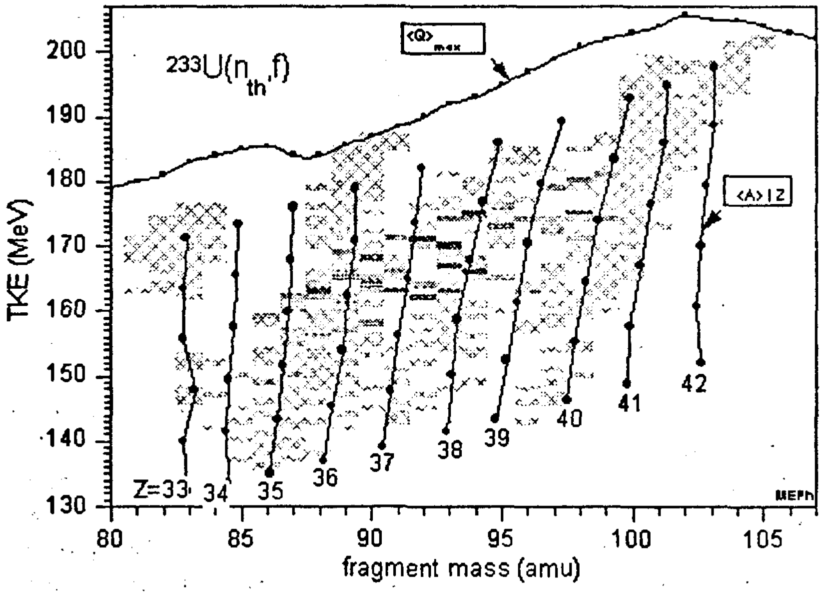

Fig. 5. Mean mass values for FF isotopic distribution. Smoothed maximal Q-values of reaction for each FF pair are presented by line in the upper part of the figure

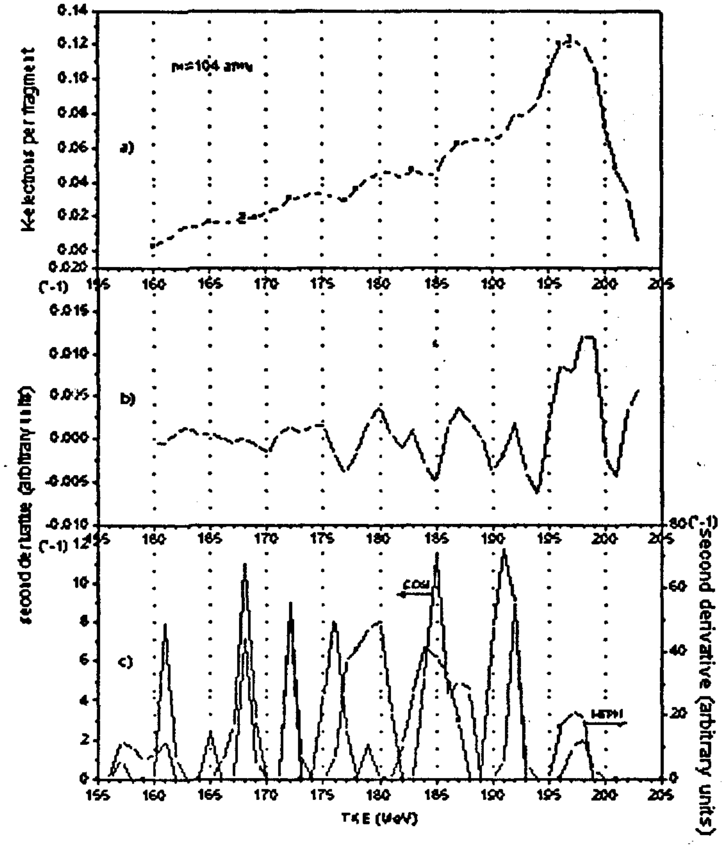

Fig. 6. The yield of k-electrons per fission fragment with the mass M=104 amu originated in the $^{235}U(n_{th},f)$ reaction [13] (a).The second derivative of the spectrum shown in the upper part of the figure (b). Comparison of the fine structure of the TKE-M FF distribution in the reaction $^{233}U(n_{th},f)$ studied at Cosi-Fun-Tutte (left axis) and MEPhI (right axis) spectrometers (c)

One more correlation in the data presented in Fig.6 seem to be of great interest. The yield of the electrons of the internal conversion (k-electrons) as a function of the TKE is shown in Fig.6a. The data are taken from ref.[13] for the reaction $^{235}U(n_{th},f)$. In fig.6b the second derivative of the spectrum multiplied by "-1" (after rejection of the negative part (W(TKE)) is depicted.

The peaks in this figure show up the FS in a more pronounced manner. Also, good agreement is observed between Fig.6b and 6c where the same functions W(TKE) are shown calculated for the cut M=104 amu of the E-M spectra obtained for the reaction $^{233}U(n_{th},f)$ at the MEPhI and Cosi-Fun-Tutte spectrometers. So, there is a correlation (coincidence) in the FS peaks location on the TKE axis for the FF yields, on the one hand, and k-electrons yields, on the other hand. As is known, larger FF yields correspond to a larger density of the final states (a higher excitation energy E*) of the fissioning nucleus before scission. The k-electrons yield in a function of the TKE is proportional to the FF excitation energy as well [13]. A common nature of FS in the FF and k-electrons yields is the existence of peaks of E*, and it suggests how to explain the difference in the amplitudes of the FS peaks in the MEPhI and Cosi-Fun-Tutte data.The reason could be the following. The FF registration efficiency η(M.E) for the MEPhI spectrometer depends on the ionic charge of the fragment q. The smooth trend of the efficiency in the functions of M and E is taken into account by a special calibration procedure [4]. The local peaks of the η(M,E) function due to the enhanced values of q(M,E) produced by the enhanced k-electrons yield stay uncompensated. This is the reason for the effective amplification of FS under discussion.

Summarizing, one can conclude that owing to the electrostatic guide system and the data handling procedure with the use of the MEPhI spectrometer, an enhanced sensitivity is observed to the local variation of E* of the fissioning system at scission.

Discussion

In Ref.[1] the attention was attracted to the resemblance of curves 1,3 (Fig.2) and the shape of the nucleus-nucleus potential as a function of the distance between the centers of the nuclei involved. The dicluster model of fission modes [14,15,2] gives a qualitative insight into the nature of this resemblance. Withing the model, the distinct fission mode is specific due to the preformation of two clusters (magic nuclei) in the frame of a unitary fissioning system at the early phase of its elongation. The clusters keep unchanged their shape and composition along all the descents to the scission. The nucleons beyond the clusters form a neck which evolves under the influence of the Coulomb and nuclear fields of the clusters. The structures shown in Fig.2 provide additional evidence of the validity of basic points of the model. At first, one should pay attention to the "twofold structure" of practically all the most pronounced curves presented. We mean that the pairs of curves with similar shapes go almost equidistant. (Fig.2). One can suggest that β-vibrations of the clusters give rize to that effect. In terms of this hypothesis, curve 1b, b' corresponds to the ground state of Te and Ge nuclei being "modeforming" clusters for the fission mode manifesting itself as the curve at hand in the space of E and M experimental observables. The second curve 1a,a' is connected with the first excited level of the β-vibrations of the clusters mentioned. The distance along the E axis between the curves of the pair agrees with the estimations of the energy of the β-vibrations for nuclei-clusters [16].

Another type of collective vibrations seems to manifest itself via parts 2a' and 2a" of curve 2a. Their shapes and relative location are similar to those of the dependence of the interaction energy between two deformed nuclei on the distance between their centers for two orientations: "nose to nose" and when the big axes of the spheroids describing the shape of the nuclei form some angle not equal to zero (Fig.7).

The first orientation corresponds to the ground state the second one is appropriate to the first excited state of the butterfly-like vibrations. The typical assessment of such a vibration energy given in Ref.[17] does not contradict the maximum distance between curves 2a, 2a" along the E axis.

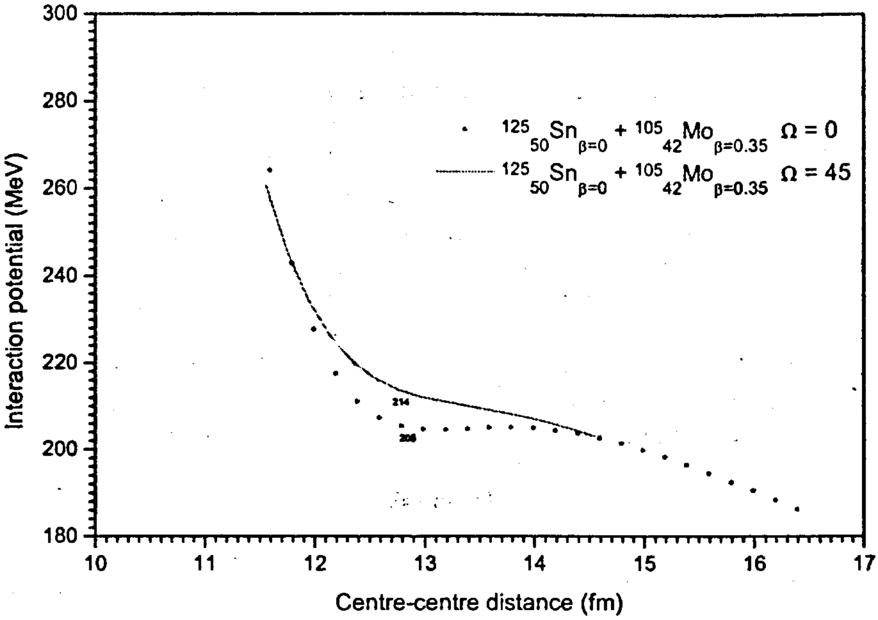

Fig. 7. Nuclear-nuclear interaction potential; Ω(degrees) is an angle between the big axises of the quadropole deformed (β) interacting nuclei

Conclusions

1. The comparison of the fine structure of the FF mass-energy and nuclear charge-energy spectra measured at three different spectrometers let us to conclude on their objective origin.

2. Due to the electrostatic guide system and data handling procedure with the use of the MEPhI spectrometer, an enhanced sensitivity is observed to the local variations of the excitation energy of a fissioning system at the scission point.

3. The peculiarities of the fine structure of the FF TKE-M and TKE-Z spectra let us to treat them as a manifestation of collective vibrations (β and butterfly-like types) of a fissioning system at the descent from the fission barrier. In other words, the system at the descent looks like a molecule.

Acknowledgements

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