Observation of the shape isomer states in fission fragments from fission of low excited actinides

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Abstract. The results of two methodically different experiments dedicated to the effect of a break-up of fission fragment while it passing through a solid-state foil are discussed. The hypothesis is confirmed that some part of fission fragments which were born in the shape isomer states undergo a break-up due to inelastic scattering in the foil.

1. Introduction

The phenomenon of the delayed fission of actinides was discovered in FLNR (JINR) in 1961. The effect was explained by the population of the shape isomer states in the second well of the double humped fission barrier and subsequent spontaneous fission of the mother nucleus via these states. The nuclei with such specific decay channel were called fission isomers. The shape isomerism is not unique peculiarity of the actinide nuclei. Calculations of the potential energy surface (PES) of the lighter nuclei show local potential minima in the multidimensional deformation space which can give rise to shape isomer states [1]. Deexcitation by the emittance of the k_x-radiation of the low lying (below the top of the fission barrier) shape isomer states in fission fragments (FFs) was reported in Ref. [2]. In our previous experiments [3, 4], we observed for the first time the break-up of the FF while it passes through the solid-state foil that is delayed in regards to the moment of conventional binary fission. We hypothesized that this effect is caused by the inelastic scattering of the FF in the shape isomer state. New arguments in favor of this hypothesis are presented below.

2. Experiment and results

The experiment Ex1 was performed at the LIS (Light Ions Spectrometer) spectrometer in FLNR (JINR) [5]. The layout of the setup is shown in figure 1(a). LIS is a double-armed time-of-flight spectrometer which includes three microchannel based timing detectors TD_1, TD_2, TD_3 and a PIN diode. PIN diode provided information for estimation of both FF's energy and time-of-flight. Copper degrader-foil D of 4.11 microns thick was placed in the TD_2 detector. The data acquisition system consisted of the fast digitizer CAEN DT5742 that allows measuring the signal's value at the input with an interval of 0.2 ns, and a personal computer. The digital images of the signals from all the detectors were registered for further off-line processing. The construction of the spectrometer allows to measure the mass of the fragment flying towards the PIN diode twice. The M_{tt} mass is obtained with the TOF-TOF (Time-Of-Flight) method using a "start" signal from TD_1 and two "stop "signals from TD_2 and TD_3. The TD_2 and the PIN diode provide TOF and energy E for calculation of M_{te} mass (TOF-E method). *Thus, we know the mass of each FF before (M_{tt}) and after (M_{te}) it crosses the degrader-foil in TD_2.*

Correlation mass distribution M_{tt}–M_{te} obtained for the heavy FFs mass peak is presented in figure 1(b). Projection of the plot onto M_{te} axis is shown in figure 1c. The experimental spectrum differs substantially from that known in conventional binary fission (shown in gray). The strongest peak corresponds to the M_{te} = 128 u associated with the magic ^{128}Sn nucleus.

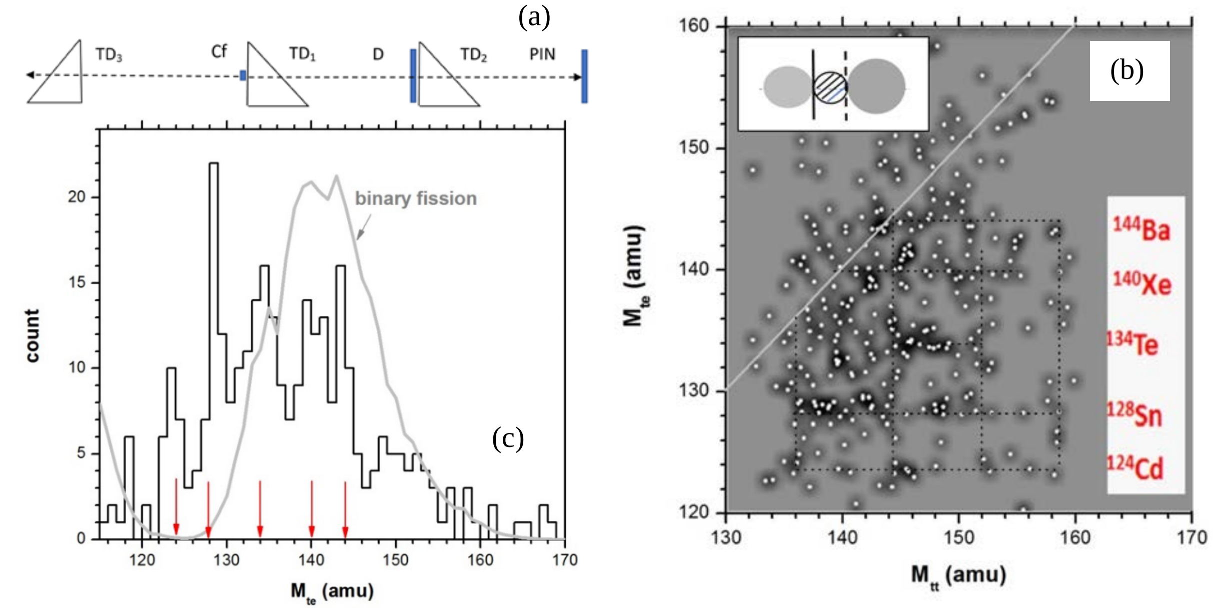

Figure 1. Lay-out of Ex1 experiment (a). Time-of-flight spectrometer LIS includes three timing detectors TD_1, TD_2, TD_3, PIN diode 1.8x1.8 cm^2, ^{252}Cf(sf) source and degrader foil D inserted into TD_2 detector. All three time-of-flight paths are equal in length, L = 15 cm. (b) – correlation distribution of the FF M_{te} and M_{tt} masses measured by TOF–E and TOF–TOF methods, respectively. Schematical view of the prescission configuration is shown in top insert. Position of the first rupture is marked by the solid vertical line the dashed line shows the position of the break-up. The hatched part of the mother nucleus will form the third missing fragment. Position of the magic isotopes on the M_{te} axis is shown in the right insert. White tilted line connects the dots where M_{te}= M_{tt}. (c) – projection of the distribution onto M_{te} axis. Masses of the magic nuclei are marked by arrows.

The experiment Ex2 was performed using VEGA (Velocity-Energy Guide based Array) setup [6] at the MT-25 microtron (FLNR, JINR) with the beam energy E_e = 22 MeV. The scheme of the spectrometer is shown in figure 2(a). The FFs from the (γ, f) reaction in the target (1) were captured by the electrostatic guide system (EGS) consisting of a tube (2) and the central wire (3). The FF's energy E and velocity V required for the calculation of the FF's mass were measured at the time-of-flight spectrometer, consisting of the microchannel-plates based timing detector (4) and the mosaic of four PIN diodes (5). The data acquisition system was similar to that used in Ex1. Our approach to the data processing is presented in Ref. [7].

Presence of the EGS is a principal difference between VEGA setup and other time-of-flight spectrometers used in our experiments earlier. Some fraction of the ions emitted from the target can be involved in the spiral-like movement along the guide axis. According to Ref. [8], the collection efficiency of the guide is proportional to the applied voltage and inversely proportional to fragment energy. Only minor part of the ions already caught in the guide will be lost along the flight pass. Thus, the EGS allows it to increase a counting rate at the detector placed several meters away from the target.

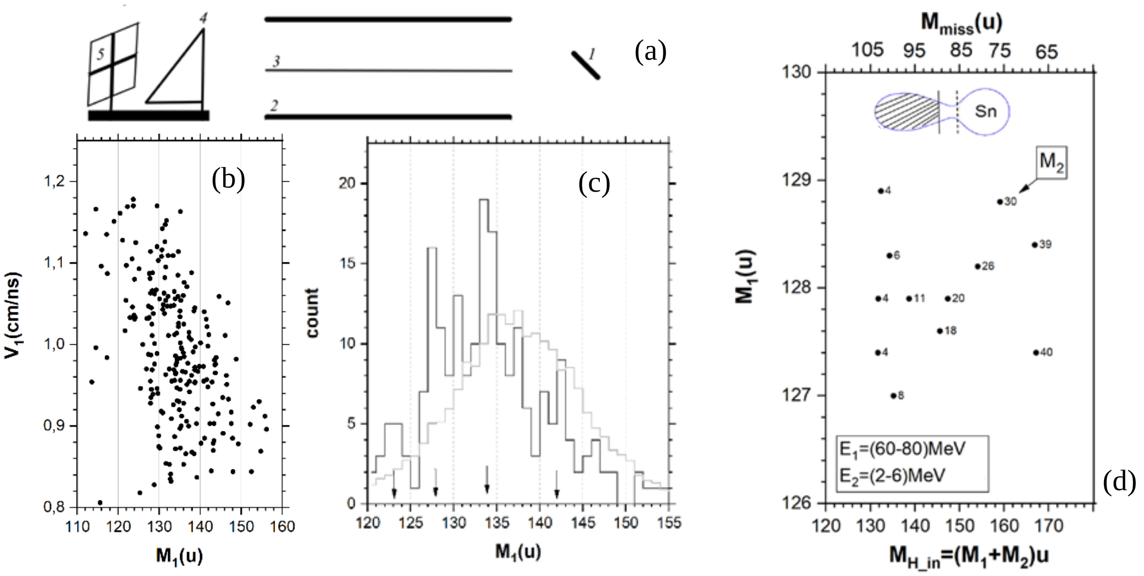

Figure 2. Lay-out of Ex2 experiment on studying ^{235}U(γ, f) reaction at the VEGA setup (a). The spectrometer includes a target of ^{235}U (1), electrostatic guide system (EGS) four meters long consisting of a tube (2) at zero potential and the central wire (3) at a potential -6 kV, timing detector (4) and a mosaic of four PIN diodes (5); (b) – mass-velocity distribution of heavy FFs for multiplicity $m = 2$, (c) – projection of this distribution onto M_1 axis. The spectrum of heavy FFs for $m = 1$ is shown in gray. (d) – mass-correlation distribution of M_{H_in}, M_2, M_miss under condition $M_1 \approx 128$ u. Schematical view of the prescission configuration is shown in top insert. Position of the first rupture is marked by the solid vertical line the dashed line shows the position of the break-up. The hatched part of the mother nucleus will form the third missing fragment. Experimental values of E_1 and E_2 energies are varied in the ranges shown in the bottom insert.

The mass-velocity distribution of the heavy FFs from the ^{235}U(γ, f) reaction for the FF multiplicity $m = 2$ is shown in figure 2(b). The FF multiplicity $m = 2$ means that two fragments with the masses M_1 and M_2 were detected in two different PIN diodes (figure 2(a)) in coincidence. By definition, the FF masses of each event are indexed in such a way that $M_1 > M_2$. The comparison of the heavy FFs mass spectra for the FF multiplicity $m = 2$ (in black) and $m = 1$ (in gray) is presented in figure 2(c). The ratio of the yields $Y(m = 2)/Y(m = 1)$ for all detected events is about 10^{-2}. The spectra differ substantially. This is a strong indication of the nonrandom character of the coincidence between the fragments in the fission events with $m = 2$. The missing mass in each fission event is defined as follows: $M_{miss} = (235–M_1–M_2)$ u. Experimental information about the events with M_1 in the range of $M_1 = (127–129)$ u and $V_1 = (0.92–1.07)$ cm/ns (i.e., for the well resolved vertical line in figure 2(b)) is summarized in figure 2(d). The "initial" mass of the heavy FF before it passes through the foil of the timing detector (4) is defined by the expression $M_{H\_in}= M_1 + M_2$. In order to compare the results of Ex1 and Ex2 in the same mass ranges of the heavy FFs, the values of M_{H_in} are limited to the right by a mass of 180 u in figure 2(d).

3. Discussion

The main result of Ex1 is a clear demonstration of the break-up of the heavy FF while it passes through the metal foil. As can be inferred from figure 1(b), the FF in the wide range of initial M_tt masses turns into the magic nucleus, mainly ^{128}Sn, which manifest as the most pronounced peak in the M_te spectrum in figure 1(c). The missing mass linked to this transformation lies in the range of $M_\mathrm{miss} = (8\div30)$ u. The energy of the FF from conventional binary fission is less than the Coulomb barrier for the nuclear interaction with the degrader, i.e., the fusion-fission reaction FF–Cu nucleus is prohibited. The FF break-up leading to missing of some part of the initial (M_{tt}) mass of the fragment is supposed to be due to the inelastic scattering of the FF in the degrader. In the frame of the Coulomb fission mechanism [9], we can roughly estimate possible excitation energy of the FF due to its interaction with the Cu nucleus several tens KeV. *Thus, it is likely that we observe the Coulomb induced fission of heavy FF from the shape isomer state located in a shallow well, and the life time of this state exceeds 15 ns estimated by a mean FF flight time between the detectors TD_1 and TD_2.*

New data from the (γ, *f*) reaction in Ex2 has shed additional light on the ternary decay channel discussed above. The following scenario could explain the main peculiarities of the fission events presented in figure 2. The heavy FF from the binary photo-fission of ^{235}U in the target (1) (figure 2(a)) is caught in the EGS (elements 2, 3). After approximately 400 ns, it reaches the start detector (4) where it undergoes the break-up while crossing the emitting foil of the start detector (4). Two resultant decay products with the masses M_1 and M_2 are detected in two different PIN diodes of the mosaic (5). Very low energy value of the light fragment with mass M_2 (see the bottom intersect in figure 2(d)) should be expected if the intermediate fragment undergoing the break-up is a pear-shaped nucleus which flies “headfirst” into the start detector. After the rupture, the lighter part of the “pear” deaccelerates due to Coulomb repulsion between the break-up products.

The prominence of M_1 = 128 u (figures 2 (b), 2(c)) is expected for the prescission configuration of the mother nucleus shown in the upper intersect in figure 2(d). Such shape was predicted in the fission valley (3) in Ref. [10]. In this case, the fragment with relatively light mass M_2 is a part of a rather thick and short neck. According to the labels showing M_2 near the points in figure 2(d), the range for M_2 = (4÷40) u is realized which is very close to the range for M_{miss} = (8÷30) u in Ex1.

The results and discussion above could be summarized as follows. In both experiments, in completely different experimental approaches and for two different fissioning systems, the manifestation of the same physical phenomenon is observed. At the same time, the experiments complement each other. In Ex1 only one product of the break-up is measured (top insert in figure 1(b)), while the masses and energies of break-up products become known in Ex2 (bottom insert in figure 2 (d)). Thanks to the use of the EGS in Ex2, the lower estimate of the FFs shape isomers life-time has been updated from 15 ns to 400 ns.

4. Conclusions

The results of two methodically different experiments aimed at studying ^{252}Cf(sf) and ^{235}U(γ, *f*) reaction confirm the hypotheses that some part of fission fragments which were born in the shape isomer states undergo a break-up due to inelastic scattering in the solid-state foil. One of the break-up products is a magic nucleus mainly ^{128}Sn and ^{134}Te. The experimental lower limit of the FFs shape isomer life times is estimated to be approximately 400 ns.

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