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Global view on fission channels

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A global view on the properties of fission channels is presented. Surprisingly, the positions of the two asymmetric fission channels are found to be constant in atomic number over the whole range of systems investigated.

1. Introduction

In a previous publication [1] we have reported on a systematic experimental study of fission-fragment element yields and kinetic energies in the fission of 70 neutron-deficient actinides and pre-actinides between ^{205}At and ^{234}U. In the present work (for more details see [2]), the data of this experiment are interpreted within the concept of independent fission channels [3,4] according to which the fissioning system follows specific valleys in the potential energy in the direction of elongation. In this picture, the fission channels are characterized by several parameters, e.g. the average mass or nuclear-charge split, the mass or nuclear-charge width, and the mean total kinetic energy, respectively the elongation of the scission configuration. We extract the values of these parameters for three fission channels from the measured data of 15 of the systems, which show features of multi-modal fission. The systematic survey of fissioning systems in the transition from single-humped to double-humped element distributions around ^{226}Th extends the systematic view on how the intensities and other relevant parameters of the fission channels vary as a function of the nuclear composition of the fissioning nucleus.

2. Experiment

At GSI Darmstadt, a new technique to investigate low-energy fission has been developed [5,6]. Relativistic secondary projectiles are produced via fragmentation

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of a 1 *A* GeV primary beam of ^{238}U and identified in nuclear mass and charge number by the fragment separator. In a dedicated experimental set-up, the giant resonances are excited by electromagnetic interactions in a secondary lead target, and fission from excitation energies around 11 MeV is induced. The fission fragments are identified in nuclear charge, and their velocity vectors are determined. From these data, the element yields and the total kinetic energies are deduced. Details of the experimental approach are given in Ref. [1].

3. Results

As an example, the measured element-yield distribution and the total kinetic energy of ^{232}Pa are shown in Figure 1. In a simultaneous fit to elemental yields and

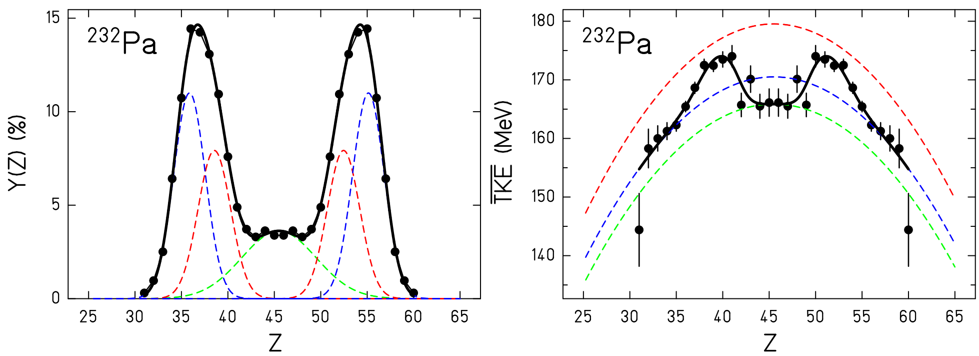

Fig. 1. (Color online) The data points mark the measured elemental yields (left) and average total kinetic energies (right) as a function of the nuclear charge of the fission fragments for ^{232}Pa. The full lines show descriptions in the frame of independent fission channels. Dashed lines depict the contributions of the individual channels. The sequence from symmetry to largest asymmetry in the yields is: super long, standard I, standard II. The sequence from lowest to highest TKE is: super long, standard II, standard I. (See text for details.)

total kinetic energies, it was possible to reproduce these data with the assumption of independent fission channels. A satisfactory description is obtained with three channels, "Standard I" close to $N = 82$, "Standard II" around $N = 88$ in the heavy fragment, and "Super long" at symmetry, according to the notations introduced by Brosa et al. [4]. Each channel is represented by a Gaussian distribution in the yields and a specific elongation of the scission-point configuration. For each fission channel, position, width, and area of the Gaussian representing the nuclear-charge yields as well as the tip distance of the scission configuration were treated as free parameters. From the good simultaneous description of nuclear-charge yields and total kinetic energies as demonstrated in Figure 1 (see also Figure 1 in Ref. [2]) we conclude that the concept of independent fission channels is well suited to describe the present data. For a detailed view on the values of extracted parameters for all systems studied in the present work, see Table 1 in Ref. [2]. In the present paper, we will discuss only relative yields and positions of different channels; for discussion on other parameters see Ref. [2].

4. Discussion

The parameters obtained in the present work are compared with existing systematics of the three most intense fission channels known from other fissioning systems, see Appendix of Ref. [2] for reference to data. The data on elemental yields seem to support the idea, stated by Itkis et al. [7], that the weights of the fission channels are principally determined by an interplay of the neutron shells at $N = 82$ and $N \sim 88$ with the liquid-drop potential.

In Figure 2, we compare the relative yields of the three independent fission channels determined in the present work with the body of previously available data. There is a clear tendency to be observed in Figure 2: The relative yield of the

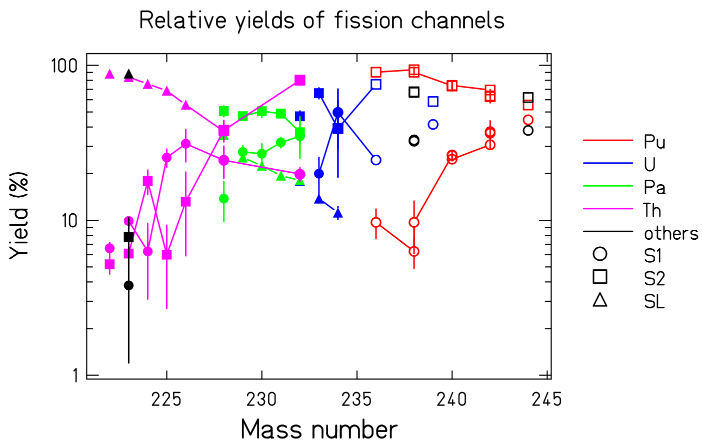

Fig. 2. (Color online) Relative yields of the three independent fission channels Standard I (S1), Standard II (S2) and Super long (SL). For reference to data, see Appendix of Ref. [2]. All data are given in mass numbers. Values measured in nuclear charge were converted to mass numbers using the unchanged-charge-density assumption and neglecting neutron evaporation. The shape of the symbol marks the fission channel.

symmetric Super-long fission channel shows an exponential decrease with increasing mass number. For systems with $A > 234$, the yield of the Super-long channel becomes so low that it could not be determined any more. At the same time, the complementary yield of the lumped asymmetric component increases with increasing mass. Moreover, the relative weight of the standard I fission channel grows strongly with increasing mass number. This is clearly seen in case of isotopic chains of protactinium and plutonium, which were investigated under good conditions and with good statistics over a long mass range. It is tempting to interpret this finding in the following way: With increasing mass, the N/Z ratio of the fissioning system increases and comes closer to the value of ^{132}Sn. If we relate the Standard I fission channel to the common influence of the $Z = 50$ and $N = 82$ shells in the heavy fission fragment, it is reasonable that this influence increases if the nuclides produced in the Standard I fission channel move closer to ^{132}Sn on the chart of the nuclides.

In Figure 3, the positions of the Standard I and Standard II fission channels are shown. A systematic variation as a function of mass number for a given element is clearly seen for all elements, in spite of some fluctuations. The fluctuations are roughly consistent with the magnitude of the statistical uncertainties of the fit, depicted by the error bars. The data are restricted to spontaneous fission and to initial excitation energies up to a few MeV above the fission barrier, where structural effects are expected to be strong. The average slope of the isotopic trend seems

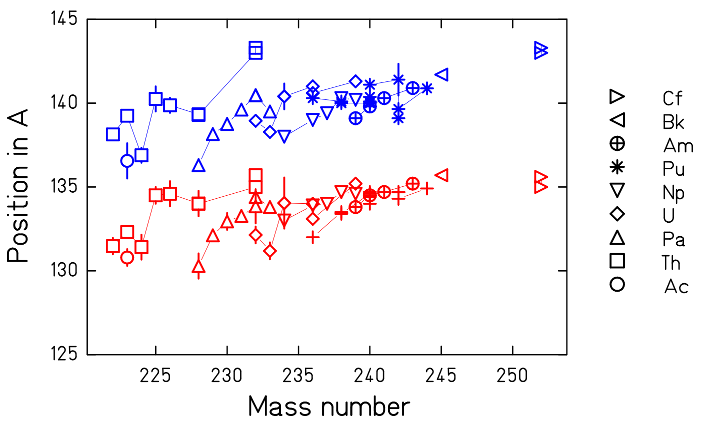

Fig. 3. (Color online) Mean positions of the three independent fission channels Standard I (S1), Standard II (S2) and Super long (SL). All data are given in mass numbers. Values measured in nuclear charge were converted to mass numbers using the unchanged-charge-density assumption and neglecting neutron evaporation. The shape of the symbol indicates the element. For reference to data, see text.

to be slightly larger than 0.5. This means that *the positions of the Standard I and Standard II fission channels vary in neutron number and are rather stable in proton number*. This surprising result has already been observed for the position of the lumped asymmetric component, the total yield of Standard I and Standard II, see Figure 22 of Ref. [1]. From Figure 3 we see that this feature extends over the whole range of elements where such data are available, that means up to americium. The stability of the positions of the two standard fission channels in atomic number is even more evident from Figure 4. For most of the systems, the mean nuclear charge

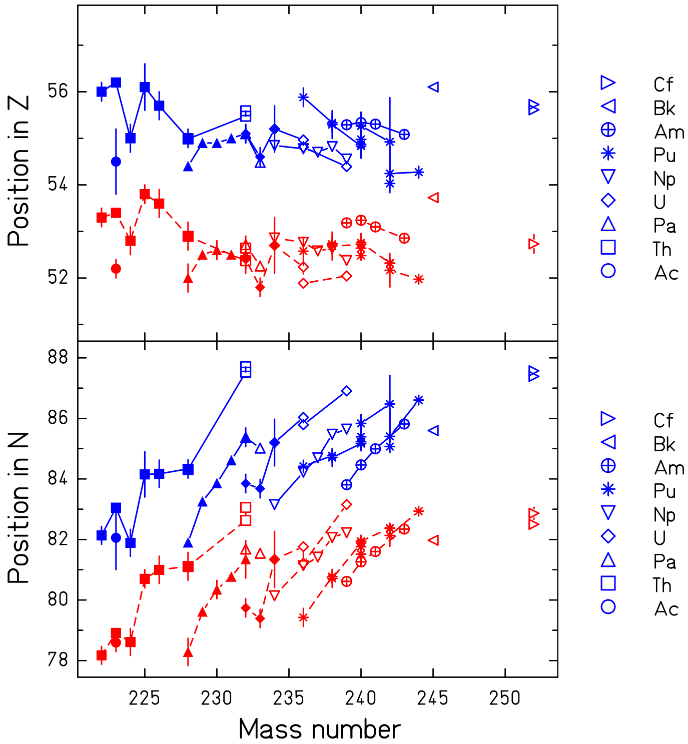

Fig. 4. (Color online) Mean positions of the two standard fission channels in atomic number (upper part) and neutron number (lower part) deduced from the data in Figure 3. Values were converted from measured atomic numbers or mass numbers using the unchanged-charge-density assumption and neglecting neutron evaporation. The shape of the symbol denotes the element as given in the legend of the figure. The values of Standard I (Standard II) for the isotopes of a given element are connected by dashed (full) lines and marked by red (blue) symbols.

of the Standard I fission channel is close to 52.5, while the mean nuclear charge of the Standard II fission channel is close to 55, with no clear systematic variation as a function of atomic number or neutron excess. Correspondingly, the variation of neutron excess for fissioning systems in an isotopic chain of a given element is reflected by a strong variation of the position of the two standard channels in neutron number as demonstrated in the lower part of Figure 4. This finding sheds a new light on the well known observation of Unik et al. [8], who stated that the position of the heavy component of the fission-fragment distribution in asymmetric fission is approximately constant in mass over the whole range of fissioning systems investigated. On the basis of Figures 3 and 4, we can re-formulate this statement more precisely: *It is not the mass number but the atomic number, which is primarily kept constant.* The variation of the mean mass number of the heavy component for the measured systems remains relatively small only due to the limited N/Z range of the fissioning systems, which could be investigated up to now. It is beyond the scope of the present work to discuss the theoretical implications of this finding, but we would like to stress that it is quite surprising, since shell-model calculations suggest that the neutron shells are generally stronger than the proton shells, and thus neutron shells are assumed to have a dominant influence on the fission process compared to proton shells. Therefore, shell-model calculations rather suggest that the positions of the two standard fission channels should be stable in neutron number.

5. Conclusions

The global analysis of the characteristics of the fission channels revealed interesting trends and features, which were not at all obvious from a restricted view on part of the data. The most salient feature is that the positions of the heavy components of the asymmetric fission channels do not vary in atomic number, while they move strongly in mass as well as in neutron number. The body of data presently available is consistent with the assumption that the parameters of the independent fission channels vary in a smooth and consistent way between actinium and californium. However, the quality of the experimental results is far from being satisfactory, and the extension of the systems investigated in atomic number and in particular in neutron excess is still rather restricted.

Acknowledgements

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6. References

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