Symmetric and asymmetric scission properties : Identical shape elongations of fissioning nuclei

著者	大槻　勤
journal or publication title	Physical review letters
volume	82
number	17
page range	3408-3411
year	1999
URL	http://hdl.handle.net/10097/35813

doi: 10.1103/PhysRevLett.82.3408

Symmetric and Asymmetric Scission Properties: Identical Shape Elongations of Fissioning Nuclei

Y. L. Zhao,[1,2] I. Nishinaka,[2] Y. Nagame,[2] M. Tanikawa,[3] K. Tsukada,[2] S. Ichikawa,[2] K. Sueki,[1] Y. Oura,[1] H. Ikezoe,[2] S. Mitsuoka,[2] H. Kudo,[4] T. Ohtsuki,[5] and H. Nakahara[1]
[1]*Graduate School of Science, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan*
[2]*Advanced Science Research Center, Japan Atomic Energy Research Institute, Ibaraki 319-1195, Japan*
[3]*Department of Chemistry, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan*
[4]*Department of Chemistry, Niigata University, Niigata 950-21, Japan*
[5]*Laboratory of Nuclear Science, Tohoku University, Taihaku-ku, Sendai 982, Japan*
(Received 18 August 1998)

The shape elongation β of a fissioning nucleus (of mass A_f) undergoing mass-symmetric and mass-asymmetric deformation is experimentally determined. The results indicate that, either for the mass-symmetric or for the mass-asymmetric deformation, the value of shape elongation is nearly independent of A_f and temperature. Three types of shape elongations are observed: The liquid drop property governed mass-symmetric deformation with $\beta \sim 1.65$; the mass-asymmetric deformation with $\beta \sim 1.53$; and the shell influenced mass-symmetric deformation with $\beta \sim 1.43$. [S0031-9007(99)09036-5]

PACS numbers: 24.75.+i, 25.85.–w, 27.80.+w, 27.90.+b

Fission phenomena of atomic nuclei have been extensively investigated [1], but many aspects are not yet well understood. For instance, the formation mechanism of the fragment mass yield curve and the variances of distributions of various quantities still remain as puzzles. As heavier nuclei are studied, such as the Fm isotopes, fission properties show dramatic changes [2–5]. For these nuclei, fission produces very sharp mass yield curves with a very large release of total kinetic energy (TKE) [4,6] which was found to deviate from the predictions based on existing systematics [7,8]. In the spontaneous fission of heavy actinides, "bimodal fission" phenomenon has been found [9–13]. The existence of two independent fission pathways which correspond to symmetric and asymmetric mass division processes has been confirmed [14,15]. A nucleus such as a heavy actinide consists of more than 250 nucleons, and it is difficult to understand why such a change of only one or two units of nucleon can completely alter such a complicated process like the mass-symmetric or mass-asymmetric deformation in nuclear fission which includes many kinds of collective motions of a large body of nucleons. In this work, the fission process of an atomic nucleus is studied via a new viewpoint of deformation properties of fissioning nuclei. New results of deformation properties of atomic nuclei are obtained, by which many aspects of fission phenomena can be systematically understood, and fission properties of a new heavy nucleus might be predicted. The results provide some answers to questions mentioned above, and reveal new properties, in particular, for the heavy nucleus.

The fission of ^{233}Pa, ^{239}Np, ^{245}Am, and ^{249}Bk was first studied. They were produced from ^{232}Th, ^{238}U, ^{244}Pu, and ^{248}Cm using proton beams (14.7 MeV for thorium and uranium, and 15.0 MeV for plutonium and curium) provided by the JAERI (Japan Atomic Energy Research Institute) tandem accelerator. The fission products were detected by a double velocity time-of-flight system. Details of experiments are given elsewhere [16]. From the measured velocities, v_1^{cm} and v_2^{cm} of complementary fragments in the c.m. system, the primary mass of fission product and total kinetic energy release in each mass splitting process are obtained from $A_1 = A_f \times (1 + v_1^{\mathrm{cm}}/v_2^{\mathrm{cm}})^{-1}$ and $\mathrm{TKE}(A_1, A_2) = A_f v_1^{\mathrm{cm}} v_2^{\mathrm{cm}}/2$, respectively, where A_f is the mass of the fissioning nucleus.

In order to allow an estimation of the degree of deformation at scission for different combinations of A_1 and A_2 pairs, a shape elongation, β, is defined as $\beta = D(A_1, A_2)/D_0(A_1, A_2)$. The $D(A_1, A_2)$ (fm) is the distance between the two charge centers of complementary fragments prior to rupture. The $D_0(A_1, A_2)$ is the distance between the charge centers of two touching spherical nuclei, and r_0 of 1.17 is used. The β, therefore, is a measure of how much the scissioning nucleus deviates from the spherical shape. As discussed in Refs. [7,17], the measured TKE value in fission is approximately equal to the Coulomb repulsion energy between the two nascent fragments, i.e., $\mathrm{TKE}(A_1, A_2) = Z_1 Z_2 e^2/D(A_1, A_2)$, where Z_1 and Z_2 are the atomic numbers of the complementary fragments.

The Z_1 and Z_2 of fragments in fission of the 24 MeV proton induced ^{238}U were measured by Kudo *et al.* using an ion-guided isotope separator on line and were published in Ref. [18]. In Fig. 1(a), deviation of the most probable charge measured by experiment from that expected by the UCD (unchanged charge distribution) model is indicated. In Fig. 1(b), the shape elongation of the scissioning nucleus is plotted versus the mass of the heavy fragment in the $p + {}^{238}$U fission. The data of crosses are obtained by the measured Z_1 and Z_2, while open circles are obtained by the UCD approximation.

 0031-9007/99/82(17)/3408(4)$15.00

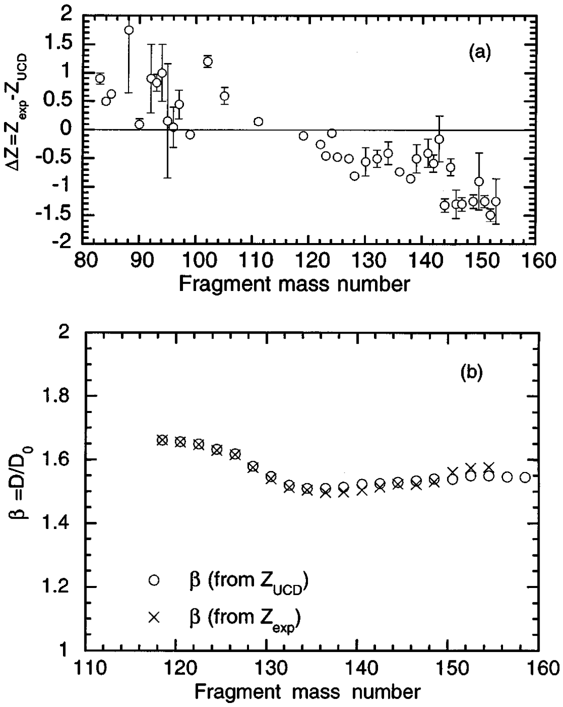

FIG. 1. (a) The difference between the most probable charge obtained by experiment and that by the UCD model as a function of the mass of the fission product in proton induced fission of ^{238}U at 24 MeV. (b) Test of the ambiguity brought into the value of shape elongation deduced by the UCD approximation. Values of shape elongations obtained from the measured charges of fission products and from the UCD approximation are indicated by crosses and open circles, respectively.

A very small difference between them is indicated. Accordingly, in this study the UCD model is used.

The results of the four fission systems presently studied are given in Fig. 2(a), and indicated by different symbols. The shape elongation of the scissioning nucleus is shown as a function of the mass of the heavy fragment. The data begin from the center of the symmetric mass division at $A_1 = A_f/2$. Interesting features in this plot are summarized in the following. (1) A relatively large β value is observed in the symmetric product region (hereafter referred to as $\beta_{\rm sym}$). (2) For a given fissioning nucleus, $\beta_{\rm sym}$ is nearly constant of the fragment mass number. (3) Among different fissioning nuclei, the varying trend of $\beta_{\rm sym}$ is somewhat complicated and will be further discussed later based on experimental data from a much wider range of more than 30 fissioning nuclei. (4) A relatively small β value is observed in the asymmetric product region (hereafter referred to as $\beta_{\rm asym}$). (5) The $\beta_{\rm asym}$ is nearly invariant even if the fissioning nucleus is changed. (6) Among different fissioning nuclei, the varying trend of the $\beta_{\rm asym}$ along the axis of mass asymmetry is nearly the same.

In order to clarify if these observations are fortuitous phenomena, the investigation was expanded to a much wider range of the fissioning nucleus. The experimental data for TKE(A_1, A_2) in literature [2,6,19] were analyzed to obtain the β values. Some representative results are shown in Fig. 2(b), which includes atomic nuclei in the region of actinium (e.g., ^{227}Ac), light-actinide (e.g., ^{233}Pa), medium-heavy actinide (e.g., ^{252}Cf), and heavy-actinide (e.g., ^{259}Lr). Even in such a wide A_f range, the results are essentially the same with those in Fig. 2(a). Although vertical scattering of the data points in Fig. 2(b) is somewhat larger than that in Fig. 2(a), this is probably due to poor statistics in the measurement of the spontaneous fission of heavy nuclides.

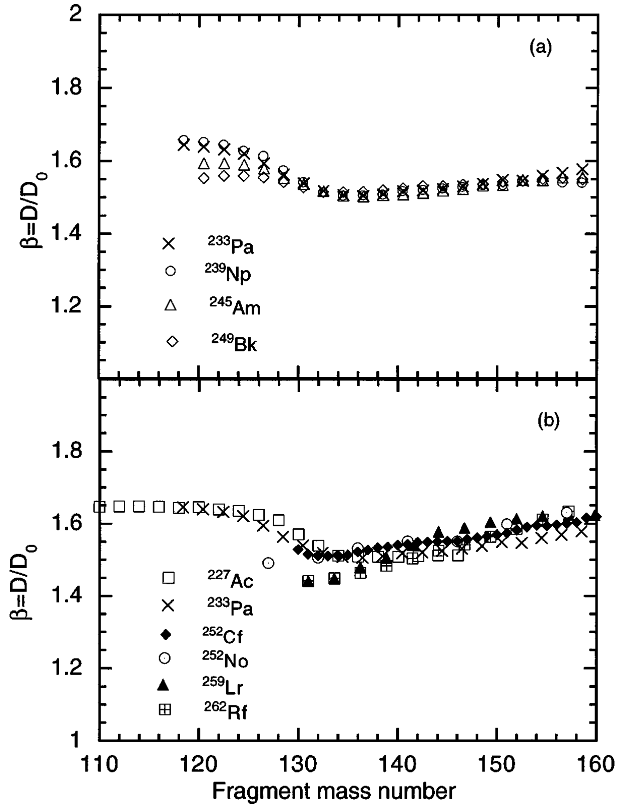

FIG. 2. Shape elongation of the scissioning nucleus as a function of the mass of the heavy fragment. The data obtained from the present experiment are plotted in (a), and those obtained by the analysis of literature data are shown in (b). The reaction systems corresponding to different symbols are as follows: crosses, p + ^{232}Th at 14.7 MeV; open circles, p + ^{238}U at 14.7 MeV; open triangles, p + ^{244}Pu at 15.0 MeV; open diamonds, p + ^{248}Cm at 15.0 MeV; open squares, p + ^{226}Ra at 13 MeV; solid diamonds, ^{252}Cf (sf); circle-dots, ^{252}No (sf); filled triangles, ^{259}Lr (sf); and square with a cross sign, ^{262}Rf (sf).

In the following, shape elongations of scissioning nuclei which undergo the symmetric and asymmetric mass division are, respectively, studied. In Fig. 3, the $\beta_{\rm asym}$ (solid circles) is plotted as a function of the mass of the fissioning nuclei, A_f. Each data point represents the result of one fissioning nucleus which is indicated by the name with an arrow. The studied reactions include

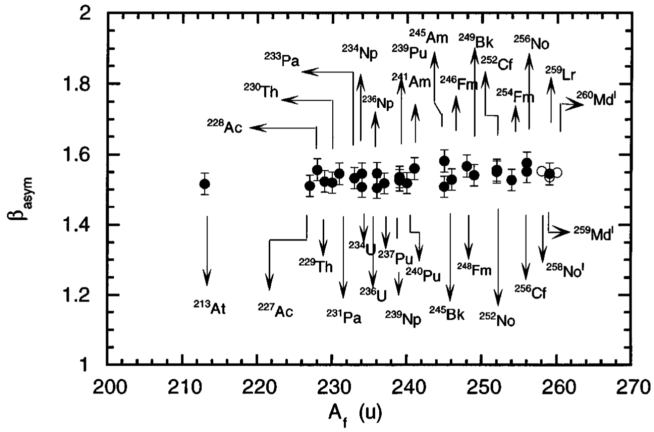

FIG. 3. Shape elongations of scissioning nuclei that undergo the mass-asymmetric deformation path in the fission process versus the mass of the fissioning nucleus. Solid circles are observed for nuclei which experienced the common mass-asymmetric deformation process. Open circles are those corresponding to the low TKE component reported in the "bimodal fission" of very heavy nuclei.

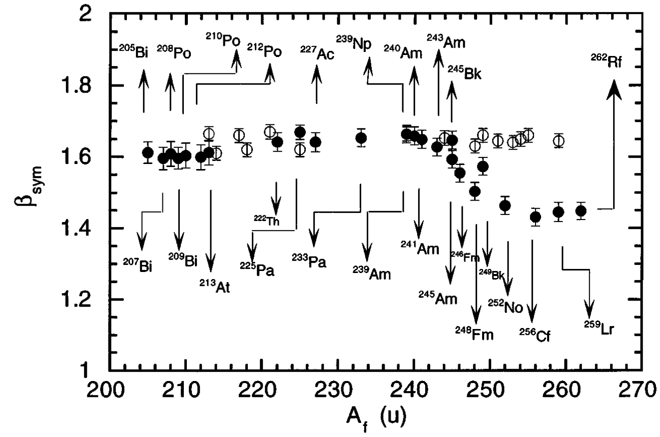

FIG. 4. Shape elongations of scissioning nuclei that undergo the mass-symmetric deformation in the fission process versus the mass of the fissioning nucleus. Solid circles are observed for nuclei at low excitation energies ($E_X < 30$ MeV), while open circles are those at high excitation energies ($E_X > 65$ MeV).

the spontaneous, neutron, proton, and α-induced fission with the excitation energies of the compound nucleus being less than 30 MeV. The value in Fig. 3 is the $\beta_{\rm asym}$ for a typical asymmetric mass division leading to the fragment mass $A_1 = 140$. Taking it to represent the mass-asymmetric fission is due to the following reasons. (1) The fragment mass of $A = 140$ is almost in the peak of the asymmetric mass yield distribution with the maximum occurrence. (2) It is nearly the mean mass of nuclei in the asymmetric fission process. (3) According to the results in Figs. 2(a) and 2(b), taking the $\beta_{\rm asym}$ value of any fragment in the asymmetric product region will not essentially alter the result from the one given in Fig. 3.

From a linear fit to the data in Fig. 3, the shape elongation of the scissioning nucleus undergoing fission through the asymmetric deformation path is therefore determined to be 1.53 ± 0.03. It is independent of the mass of the fissioning nucleus. This result indicates that any atomic nucleus undergoing the mass-asymmetric deformation motion will reach a similar deformation degree at scission. The origin of the mass-asymmetric deformation is probably related to the effects of nuclear shells of the fissioning nucleus [20], but the present observation of the same degree of deformation at the time of scission is a new property of an atomic nucleus, and needs to be explained by nuclear theory.

In the mass-symmetric deformation path, the shape elongation of the scissioning nucleus is given in Fig. 4 versus A_f. The value in Fig. 4 is the shape elongation of the scissioning nucleus leading to the paired fragments $A_1 = A_2 = A_f/2$. The $\beta_{\rm sym}$ values for low-energy fission with the excitation energy of <30 MeV are shown by solid circles. Based on the value of the $\beta_{\rm sym}$, two types of the shape elongation for the mass-symmetric deformation path are seen. The first is for nuclei in the region from preactinide up to the actinide with $A_f \sim 245$, where $\beta_{\rm sym}$ values are nearly constant. The second is for nuclei in the region around $A_f = 260$, where a constant $\beta_{\rm sym}$ is again observed but the value is much smaller than that of the first one. This difference provides a direct evidence for the correctness of the speculation, first pointed out by Hoffman *et al.*, that the properties of the symmetric fission of light and heavy actinides are different [2,4].

In between the first and second $\beta_{\rm sym}$ types ($A_f = 245-255$), a transition region exists, where $\beta_{\rm sym}$ gradually decreases as A_f becomes heavier. The deformation property smoothly varies between the two types with no sudden change. From the gross features of fragment mass yield curves, one generally concludes that the fission mode of the symmetric mass division nearly vanishes in this transition A_f region. This leads to an opinion of the sudden change of the fission mode when the nucleus becomes heavier than $A_f > 256$, as mentioned in the introduction. The results in Fig. 4, however, indicate a gradual transition of fission properties from the light to heavy atomic nucleus. The reason for the smaller deformation of the very heavy fissioning nucleus with $A_f \sim 260$ is probably due to the effects of fragment shells in the mass-symmetric deformation process. As a fissioning nucleus becomes heavy and goes close to $A_f \sim 260$, one or both of the paired fragments fall into a mass number of $A \sim 130$ which is under a strong influence of the shell structures of $N = 82$ and/or $Z = 50$.

The preceding argument is based on the results from fissioning nuclei at low energies where the shell effects probably survive. It is hence significant to see what happens if the temperature of an atomic nucleus is increased to high enough for washing away the shell structure. For this purpose, the measured TKE(A_1, A_2) data for symmetric fission at higher energies [21,22] were analyzed to obtain the β_{sym} values which are given in Fig. 4 by open circles. The excitation energies of fissioning nuclei are higher than 65 MeV. It is indicated that (i) for all high-energy fission, the β_{sym} values are constant; (ii) the β_{sym} values for high-energy and for low-energy fission in the region of $A_f < 245$ are nearly the same. (iii) Unlike those for low-energy fission, the β_{sym} values for high-energy nuclei in the region of $A_f > 245$ are not lowered. It is generally considered that the fission characteristics such as kinetic energy distributions and broad symmetric mass yield curves observed in the high-energy fission of nuclides in the preactinide region are mostly explained by the dynamical model based on the liquid drop model. Then, the phenomenon (i) indicates that the degree of deformation of the scissioning nucleus for the mass-symmetric deformation motion governed by liquid drop property is the same for any fissioning mass. The phenomenon (ii) indicates that as long as fissioning nuclei undergo the mass-symmetric deformation without much effect of fragment shells, their degrees of deformation at scission are nearly the same, regardless of excitation energies. The phenomenon (iii) is an explicit evidence of disappearance of shell effect in the high-energy nucleus, and, conversely, it is also a demonstration of the existence of shell effects in the low-energy symmetric fission of very heavy nuclei.

The "bimodal fission" mechanism has been proposed by Hulet *et al.* [9–11] based on the experimental finding of the two kinds of total kinetic energies in the symmetric mass division process of the spontaneous fission of very heavy nuclei. It is interesting to note, however, that open circles in Fig. 3, which show the shape elongation of the low TKE component of the bimodal fission process, lie on the line of solid circles which are observed for the mass-asymmetric deformation influenced by shell structures.

Three types of the degree of the deformation of the fissioning nucleus are observed and discussed above. It also has to be pointed out that there exist three fundamental types of the fragment mass yield curve in nuclear fission. By studying the correlation between the shape elongation of the scissioning nucleus and the shape of the fragment mass yield curve, it is found that nuclei with a given type of shape elongation lead to a given pattern of a fragment mass yield curve, and that the larger the size of the shape elongation, the larger is the dispersion of the mass yield distribution.

In conclusion, we have studied the fission process via a new viewpoint of shape elongation of the scissioning nucleus. Three types of shape elongation corresponding to three types of deformation motion were found. Each type of the degree of the deformation of the scissioning nucleus showed to be independent from the fissioning mass and its temperature. A difference in the mass-symmetric deformation of very heavy nucleus at high and low excitation energies was found, and the latter was under strong influence of fragment shells. For the first time, it was experimentally found that scissioning nuclei with a given shape elongation lead to a given shape of the fragment mass yield curve, and that the dispersion of the mass yield curve is proportional to the size of the shape elongation of the scissioning nucleus. They offer important clues for theoretical understanding of the still unresolved problem of nuclear fission and also, more generally, of the bulk property of a nucleus as a whole.

We thank Professor Y. Abe of Kyoto University, Dr. T. Wada of Konan University, and Dr. S. Yamaji of RIKEN for their valuable discussions. We also thank Professor J. V. Kratz of Mainz University and Professor D. C. Hoffman of University of California (Berkeley) for their valuable discussions on the fission properties of the heavy nucleus. Fruitful discussions on this study with Professor P. Armbruster of GSI (Darmstadt) are gratefully acknowledged. Y. L. Z. expresses his appreciation to Professor Liu Yuanfang (Peking University) and Professor Wu Xizen (CIAE) for helpful discussions. We thank the crew of the JAERI tandem accelerator for providing good beams.

[1] R. Vandenbosch and J. R. Huizenga, *Nuclear Fission* (Academic Press, New York and London, 1973).

[2] D. C. Hoffman *et al.*, Phys. Rev. C **21**, 972 (1980).

[3] E. K. Hulet *et al.*, Phys. Rev. C **21**, 966 (1980).

[4] D. C. Hoffman and M. R. Lane, Radiochim. Acta **70/71**, 135 (1995).

[5] D. C. Hoffman, T. M. Hamilton, and M. R. Lane, *Nuclear Decay Modes,* edited by D. N. Poenaru (Institute of Physics Publishing, Bristol and Philadelphia, 1996), p. 393.

[6] M. R. Lane *et al.*, Phys. Rev. C **53**, 2893 (1996).

[7] V. E. Viola, K. Kwiatkowski, and M. Walker, Phys. Rev. C **31**, 1550 (1985).

[8] J. P. Unik *et al.*, in *Proceedings of the 3rd IAEA Symposium on Physics and Chemistry of Fission, Rochester, 1973* (IAEA, Vienna, 1974), Vol. 2, p. 19.

[9] E. K. Hulet *et al.*, Phys. Rev. Lett. **56**, 313 (1986).

[10] E. K. Hulet *et al.*, Phys. Rev. C **40**, 770 (1989).

[11] J. F. Wild *et al.*, Phys. Rev. C **41**, 640 (1990).

[12] J. H. Hamilton *et al.*, Prog. Part. Nucl. Phys. **35**, 635–704 (1995).

[13] G. T. Ter-Akopian *et al.*, Phys. Rev. Lett. **77**, 32 (1996).

[14] Y. Nagame *et al.*, Phys. Lett. B **387**, 26 (1996).

[15] T. Ohtsuki *et al.*, Phys. Rev. Lett. **66**, 17 (1991).

[16] Y. L. Zhao *et al.* (to be published).

[17] B. D. Wilkins, E. P. Steinberg, and R. R. Chasman, Phys. Rev. C **14**, 1832 (1976).

[18] H. Kudo *et al.*, Phys. Rev. C **57**, 178 (1998).

[19] Y. L. Zhao, Ph.D. thesis, and references therein, Tokyo Metropolitan University, Tokyo, Japan, 1999.

[20] P. Möller and J. R. Nix, Nucl. Phys. **A229**, 269 (1974).

[21] V. E. Viola and T. Sikkeland, Phys. Rev. **130**, 2044 (1963).

[22] M. G. Itikis *et al.*, Sov. J. Nucl. Phys. **52**, 15 (1990).