Energy dependence of the probability for asymmetric fission of ^{213}At

E. N. Gruzintsev, M. G. Itkis, V. N. Okolovich, A. Ya Rusanov,
G. N. Smirenkin, and V. N. Tolstikov
Institute of Nuclear Physics, Academy of Sciences of Kazakh SSR

(Submitted 24 August 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **36**, No. 8, 304–307 (20 October 1982)

The mass distribution of the fragments of the fission of ^{213}At in the reaction ^{209}Bi(α, f) has been measured for α energies in the range 34.7–50 MeV. Over the entire energy range studied, the asymmetric mode is an improbable, slightly energy-dependent mode for the ^{213}At fission. This property of the ^{213}At fission represents a qualitative distinction from the fission of heavy nuclei.

PACS numbers: 25.85.Ge, 27.80. + w

There is a gap in our understanding of the physics of nuclear fission at low excitations because there are no sufficiently long-lived target nuclei for experiments between ^{209}Bi and ^{226}Ra. The difficulty is particularly serious in attempts to study the fission asymmetry, whose properties change rapidly as we go through this region: The preactinides near Bi undergo asymmetric fission, while nuclei heavier than Ra undergo a perdominantly asymmetric fission. Attempts to observe an asymmetric fission of Bi induced by protons and α particles have proved unsuccessful.[1-4] Not until a recent study[5] was it shown that the fragment mass distribution in the reaction ^{209}Bi(α,f) contains an asymmetric component at an α energy[1)] $E_\alpha = 37.3$ MeV; this energy causes fission of ^{213}At. A measure of the importance of the asymmetric component is the yield ratio $Y_a/Y_s \cong 2.5 \times 10^{-3}$. In this reaction we see many aspects of the asymmetric fission of heavy nuclei: an average heavy-fragment mass $M = 138$, an increase in the average kinetic energy of the fragments, a correlation with the shell structure of the fragments, etc. At the same time, the upper estimate[4] $Y_a/Y_s \leqslant 1\%$ found for this reaction in the immediate vicinity of the fission threshold implies that the asymmetric fission of ^{213}At remains an improbable process at all energies, in contrast with the situation for the actinides and Ra. Just what the energy dependence of Y_a/Y_s is and whether it is another puzzling aspect of the ^{213}At fission are the questions pursued in the experiments which we are reporting here.

As in the first experiments in this direction,[5] we studied the mass distribution $Y(M)$ by studying the energy spectrum of the paired fragments with Si-Au detectors. Figure 1 shows the results found on the $Y(M)$ distribution, normalized to $\Sigma_M Y(M) = 200\%$ (the data from Ref. 5 are included here). We see that with decreasing E_α the asymmetric fission becomes progressively more apparent, and at the lowest energies we see structure near the mass $M = 132$ and near the complementary fragment mass $M = 81$. The reason for this behavior is that as the nucleus cools there is a decrease in the variance $\sigma^2 \sim \sqrt{U}$ of the predominant symmetric component $Y_s(M)$, which is described by Gaussian distributions (the dashed curves) in Fig. 1; here $U = E - E_f$ is the

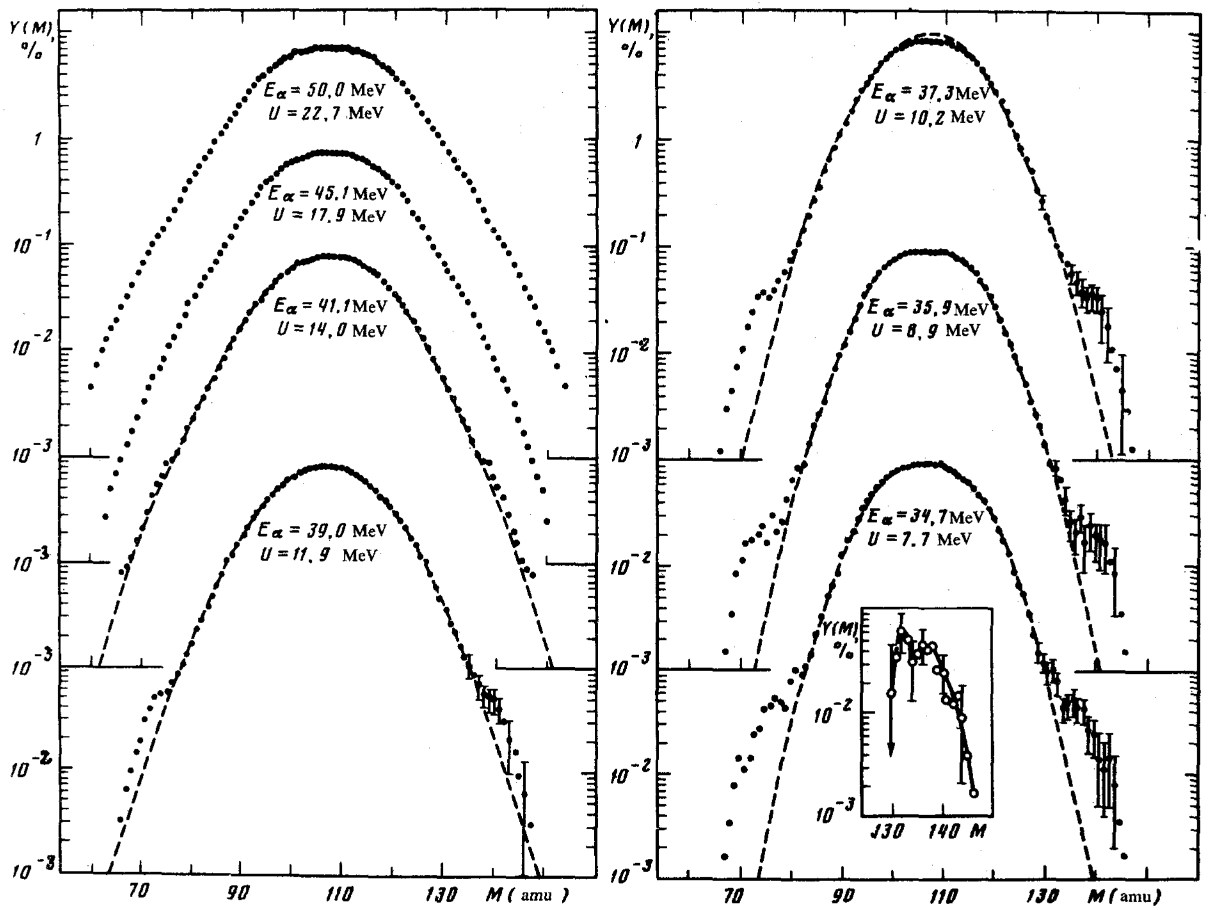

FIG. 1. Fission mass distributions $Y(M)$ for the nucleus ^{213}At. The inset shows the asymmetric component, $Y_a(M)$, for $E_\alpha = 34.7$ MeV (see the text proper).

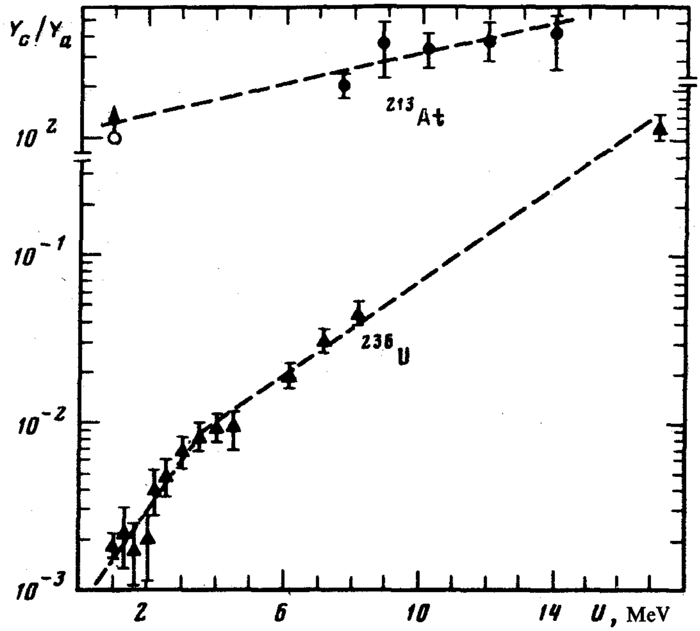

FIG. 2. Ratio of the maxima of the symmetric and asymmetric fission modes, Y_s/Y_a, vs the excitation energy at the saddle point for the nuclei ^{213}At (●—present study; $\overset{\uparrow}{\bullet}$—Ref. 4) and ^{236}U (▲—Ref. 6).

excitation energy at the saddle point, and $E_f = 17$ MeV is the height of the ^{213}At fission barrier. The values of E_α and U are shown for each $Y(M)$ distribution.

The mass distribution of the asymmetric fission was found as the difference between the total yield and the symmetric yield: $Y_a(M) = Y(M) - Y_s(M)$. The clearest example, for the lowest energy, is shown in the inset in Fig. 1. Working from all the data over the interval $E_\alpha = 34.7$–41.1 MeV ($U = 7.7$–14.0 MeV) in which it was possible to distinguish an asymmetric component, we used the maxima of $Y_a(M)$ and $Y_s(M)$ to construct the U dependence of the ratio Y_s/Y_a; the result is shown in Fig. 2. The point with the arrow is the lower estimate of this ratio given in Ref. 4. From a comparison with the corresponding results for ^{236}U—a typical actinide—we can clearly see the extent of the changes in the energy dependence in this new nuclear region. We see that ^{213}At differs markedly from heavy nuclei not only in the absolute value of Y_s/Y_a (the difference is by five orders of magnitude in Fig. 2) but also in the rate of change of this ratio as a function of the energy U (over the U interval studied here, the change is by a factor of five; the change from the fission threshold is by a factor > 50).

Various theoretical models predict qualitatively correct results for the predominant type of fission in both nuclear regions. On the other hand, the literature reveals no theoretical predictions for the asymmetric fission of the preactinides; there are no predictions of either the order of magnitude of the effect or its energy dependence. Working from the statistical model, we can approximate the yield ratio Y_s/Y_a and its derivative with respect to the excitation energy E by

$$\ln \frac{Y_s}{2Y_a} = 2\left(\sqrt{a_s U_s} - \sqrt{a_a U_a}\right) \cong \sqrt{aU}\left(\frac{\delta_a}{a} - \frac{\delta V}{U}\right), \tag{1}$$

$$\frac{d}{dE}(\ln \frac{Y_s}{2Y_a} = \sqrt{\frac{U_s}{a_s}} - \sqrt{\frac{U_a}{a_a}} \cong (1/2)\sqrt{a/U}\left(\frac{\delta_a}{a} + \frac{\delta V}{U}\right), \tag{2}$$

where $U_i = E - V_i$ is the excitation energy, V_i is the deformation potential energy, and a_i is the level-density parameter of the fissile nucleus at the time of rupture for the fission mode i ($i = s, a$). In these approximate expressions, we are making use of the fact that $\delta V = V_s - V_a = -\delta U$ and $\delta_a = a_s - a_a$ are small in comparison with $U \cong U_s \cong U_a$ and $a \cong a_s \cong a_a$, respectively; the factor of 2 on the left side of (1) and (2) results from the normalization of the sum of the yields to 200%. Precisely the same relations can be derived by an alternative approach for explaining asymmetric fission, which has the fission mode determined at the saddle point, rather than at the rupture point, as above. In this other approach the role of V_i is played by the height of the fission barriers for the two fission modes, in one of which the nuclear configuration retins its mirror symmetry, while in the other it loses it (in the asymmetric mode).

For heavy nuclei we have $\delta V > 0$ and $\delta_a > 0$, explaining the predominantly asymmetrc nature of the fission and the rapid increase in the symmetric component at low excitation energies. In order to find a predominance of symmetric fission from (1) and (2) in the preactinide region, we must assume the opposite sign: $\delta V < 0$, i.e., $V_s < V_a$. In this case the terms on the right side of (2) differ in sign and may cancel out, causing the weak dependence of the ratio Y_s/Y_a (observed experimentally), but only in a bounded energy interval. To interpret the new energy dependence of the ratio Y_s/Y_a found in ^{213}At will require a comprehensive theoretical analysis and new experiments, but each step forward will be severely hindered by the rapid decrease in the fission probability with decreasing U and Z.

Calculations[7] of the deformation potential energy by the shell-correction method show that the condition $V_s < V_a$ can be satisfied at the saddle point. According to Ref. 7, in the lead region there are two saddle points, of which the higher-lying is highly asymmetric ($M_1/M_2 \cong 2$), in rough correspondence with the observed asymmetry of the ^{213}At fission. It would be very interesting to see theoretical predictions for the asymmetric fission of a broader range of preactinides, not only in the approach of Ref. 7 but also from models in which the fission mode is determined at the rupture point, including models for nuclei lighter than ^{213}At, which have already come under experimental study. We hope that bridging these gaps in the experimental and theoretical information on fission in the preactinide region will prove useful for solving many puzzling questions in the description of fission asymmetry.

1)The α-particle energy cited in Ref. 5 was 36 MeV, but this value was subsequently refined. It was measured by two methods, which yielded compatible results.

---

[1] T. Sugihara, J. Roesner, and J. W. Meadows, Phys. Rev. **21**, 1179 (1961).
[2] F. Plasil *et al.*, Phys. Rev. C **7**, 1196 (1973).
[3] M. G. Itkis *et al.*, Yad. Fiz. **22**, 864 (1975) [Sov. J. Nucl. Phys. **22**, 447 (1975)].
[4] I. M. Kuks *et al.*, Yad. Fiz. **27**, 54 (1978) [Sov. J. Nucl. Phys. **27**, 28 (1978)].

[5] E. N. Gruzintsev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 449 (1982) [JETP Lett. **35**, 557 (1982)].

[6] P. P. D'yachenko, B. D. Kuz'minov, and M. Z. Tarasko, Yad. Fiz. **8**, 286 (1968) [Sov. J. Nucl. Phys. **8**, 165 (1969)].

[7] V. V. Pashkevich, Preprint R4-5581, Dubna, 1971.

Translated by Dave Parsons
Edited by S. J. Amoretty