Observation of asymmetric fission of ^{213}At in the reaction ^{209}Bi (α,f)

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The fragment mass distribution in the fission of the nucleus ^{213}At by 36-MeV α particles is a bell-shaped curve Y_s (M) with a clearly expressed asymmetric admixture Y_a (M), for which the ratio of the yields at the peaks is $Y_s^{\max}/Y_a^{\max} \simeq 2.5\times 10^2$. This new type of fission of preactinide nuclei exhibits several of the properties typical of the asymmetric fission of heavy nuclei.

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Extensive experimental results have given rise to the belief that the fission of heavy nuclei at low excitation energies is primarily asymmetric, while nuclei lighter than Ra undergo a symmetric fission. At substantial excitations, this symmetric fission becomes predominant for all the nuclei that have been studied. The experimental data on the asymmetric fission stop at radium, $Z = 88$, while the lighter nuclei with $Z = 84$–87 are not amenable to a study of fission because of their instability. Attempts have been made to detect an asymmetric component in the fragment mass distribution from the fission of ^{209}Bi (which is the heaviest of the stable preactinide elements) by charged particles, but these attempts have not met with success.[1–4]

Semiconductor detectors have recently been used to measure the mass distribution Y(M) and the kinetic-energy distribution Y(E_k) of the fragments of the fission of various nuclei caused by charged particles in the isochronous cyclotron of the Institute of Nuclear Physics, Academy of Sciences of the Kazakh SSR. In (α, f) reactions in lead and bismuth at energies $E_\alpha \leqslant 40$ MeV in the region of a highly asymmetric fragment mass ratio, $M_H/M_L = 1.8$-2.0, significant irregularities are observed systematically in the dependence of E_k and of its dispersion σ^2_{Ek} on the fragment mass. Similar effects in $E_k(M)$ and $\sigma^2_{E k}$ have been observed elsewhere.[5,6]

The results of this study of the reaction ^{209}Bi (α, f) for two energies—a minimum energy $E_\alpha = 36$ MeV (20 000 events) and a maximum energy $E_\alpha = 50$ MeV (40 000 events)—and for excitation energies U_f of 9 and 23 MeV, respectively, at the saddle point are shown in Fig. 1. The data have not been corrected for neutron emission; the distributions Y(M) have been normalized to $\overline{M} = A/2 = 106.5$ amu. All the characteristics of the ^{213}At fission at $E_\alpha = 36$ MeV shown in Fig. 1—the yield Y(M), the total kinetic energy of the fragments (E_k), and the dispersion of this kinetic energy ($\sigma^2_{E k}$)—exhibit deviations from the smooth dependences characteristic of symmetric fission, which occurs in this experiment at the energy $E_\alpha = 50$ MeV. These deviations go beyond the statistical errors, and they are correlated. The distribution Y(M) for $E_\alpha = 36$ MeV is described by a superposition of Gaussian functions. The dashed curves in Fig. 1 show the results of a decomposition into a symmetric component Y_s and an asymmetric component Y_a with $\overline{M}_H = 136$

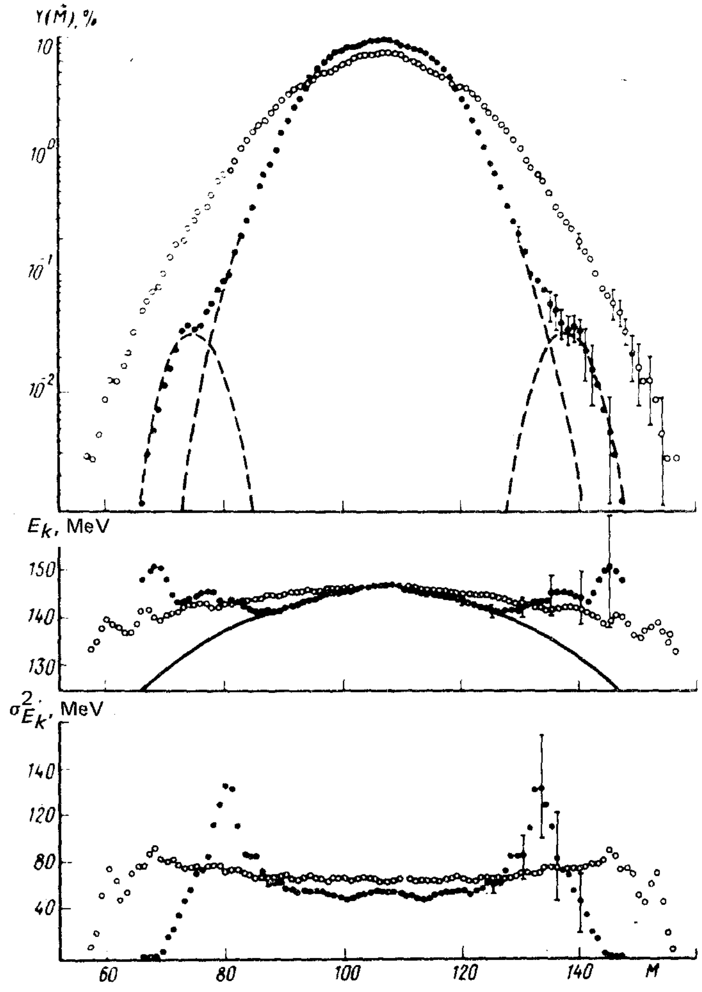

FIG. 1. The mass yields $Y(M)$, the fragment kinetic energy E_k, and its dispersion signal $\sigma^2_{E_k}$, plotted as functions of the fragment mass. ○–$E_\alpha = 50$ MeV; ●–$E_\alpha = 36$ MeV.

amu and $\overline{M}_L = 75$ amu. There are about 50 events in the asymmetric peak. It is extremely unlikely that the asymmetric component is of background origin, e.g., a consequence of the fission of small impurities of thorium or uranium. In such a case we should not observe a peak of the light fragment ^{213}At, since the light peaks for Th and U correspond to masses of 92 and 98 and lie deep within the $Y(M)$ bell-shaped curve. Although this distribution has been symmetrized to smooth out the fluctuations stemming from the small statistical base of detected events, we observed two peaks, of approximately the same shape, corresponding to the predicted asymmetry of the ^{213}At distribution. Furthermore, the absence of any significant impurities of highly fissionable elements in the ^{209}Bi target is confirmed by measurements of the fission cross section.[7] Our confidence in the interpretation of the results of this analysis of the fragment mass distribution also rests on the observation of corresponding deviations at the edges of the E_k distribution which correlate with the most probable values $E_k \approx 50$ and 93 MeV, which follow from the value of E_k^a for $M_H/M_L = 1.9$.

It may thus be asserted that in the fission of ^{213}At by 36-MeV α particles we have, for the first time, determined the asymmetric fission yield in the peaks, $Y_a^{max} = 0.03\%$ with $Y_s^{max} = 8.2\%$. Quantitatively, $Y_a(M)$ has the basic properties of the asymmetric fission of heavy nuclei: The average mass of the heavy fragment agrees within 1-2 amu with its value for the actinides, confirming the remarkable stability of this characteristic, extending this behavior to nuclei with A up to 213, and also extending the asymmetry of the fission to $M_H/M_L = 1.9$. The previous boundaries,[8] $A = 225$ and $M_H/M_L = 1.6$, for ^{225}Ra, have thus been moved. As for the actinides, the left slope of the heavy peak $Y_a(M)$ corresponds to masses $M_H = 132$–134, which are associated with the formation of fragments which are similar in terms of nucleon states to the doubly magic nucleus $Z = 82$, $N = 50$. The shell effects can also be seen in the increase in the kinetic energy $E_k(M)$ at these masses. This increase does not stop before $M_H = 145$ and is apparently caused by the structure of the light fragment, $M_L = 68$, in which the $Z = 28$, $N = 40$ shell is filled. Shell effects in the $E_k(M)$ dependence correspond to the region of a substantial decrease in the structureless component calculated from the liquid-drop model of Nix and Swiatecki[9] (shown in the central part of Fig. 1 by the solid curve). Consequently, and in contrast with the actinides, the "shell" peak in $E_k(M)$ apparently reaches only the level of the "liquid-drop" peak in $E_k(M_H)$ for ^{213}At. We hope to be able to offer a more definite conclusion regarding shell effects in the dependence $E_k(M)$ and also to report more reliable data on the shape of the $Y(M)$ after we have analyzed the results of measurements (already carried out) for other energies and other nuclei. We will also draw upon new experiments at lower excitation energies, which are very difficult to carry out because the fissionability of the preactinide nuclei falls off sharply with decreasing energy. Our hope is that the decrease in fissionability will be offset by a decrease in the width of the $Y_s(M)$ distribution, which will ultimately make it possible to extract further information on the asymmetric component.

The results obtained in this study are important not only because of the very fact that asymmetric fission occurs in the preactinide region but also because this fission manifests itself in a new capacity (in comparison with the actinides): as an improbable type of fission. It apparently remains so[4] all the way up to the ^{213}At fission threshold. Pashkevich[10] has theoretically predicted two saddle points for nuclei in the lead region, one of which is highly asymmetric (predicted at $M_H/M_L \approx 2$) and lies above a saddle point with a small asymmetric deformation. This picture would seem to be in qualitative agreement with the observed properties of the asymmetric fission of ^{213}At, but other calculations by the shell-model correction method[11] have not revealed a transitional state with a large asymmetric deformation.

In summary, the interpretation of the results of this study remains an open question, but the very fact that asymmetric fission of ^{213}At does occur experimentally opens up a new area in our understanding of the complex problem of the asymmetry of nuclear fission.

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