Fission of ^{238}U nuclei by 1-GeV protons into three fragments of comparable mass

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(Submitted 9 July 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **54**, No. 6, 311–314 (25 September 1991)

The probabilities and kinematics for the fission of ^{238}U nuclei by 1-GeV protons into three massive, detectable fragments and into two fragments with large nucleon losses are compared. It is concluded that each process constitutes the fission of a heavy nucleus into three fragments which are comparable in mass.

The two-body nature of the fission of heavy nuclei was established in some pioneering studies many years ago.[1] Since then, research on the fission of nuclei into three fragments of comparable mass has usually included an effort to detect all three fragments without fail, under the assumption that they have identical properties at the time of production.[2] Experiments of the fission of heavy nuclei by relativistic protons, however, suggest that there may be important differences between the massive fragments which are formed. It has been established experimentally[3] that the fissionability of ^{238}U nuclei by 1-GeV protons—i.e., the ratio of the cross section for the production of two massive fragments to the total inelastic cross section, $\sigma_f/\sigma_{\rm in}$—is 0.865 ± 0.036. In addition to the two massive fragments, one also observes some accompaniment particles, which represent nucleon losses from the standpoint of the fragments. Some-

0021-3640/91/180304-05$01.00

times these losses are so large that their total mass is sufficient to form yet another massive fragment.[4] In this case the deep fission of ^{238}U nuclei accompanied by the formation of two massive fragments and a large number of accompaniment particles may be thought of as a fission into three fragments of comparable mass, one of which is nuclear-unstable. A recent estimate[5] of the mean life of these fragments yielded $(1.8 \pm 0.2) \times 10^{-21}$ s. When heavy nuclei are bombarded by relativistic protons, there can of course also be a nuclear fission into three detectable fragments with comparable masses. In the present letter we compare experimental data found in a study of the fission of ^{238}U nuclei by 1-GeV protons—data on the probabilities for the two processes and on the separation kinematics of the massive fragments.

The experiments were carried out in the proton beams of the Gatchina synchrocyclotron with a two-arm time-of-flight spectrometer and backing-free photoemulsion layers 200 μm thick, saturated with ^{238}U nuclei. To improve the conditions for the detection of three-prong events which would fall in the category of events with fragments of comparable masses, we raised the sensitivity threshold of the emulsion layers to the ionization-loss values corresponding to charged fragments with $Z = 10$. It thus became possible to bombard the layers with a proton flux density of 6×10^{11} cm^{-2}. With the good transparency, it became possible to observe up to 100 double-fission events in the field of view, 180 μm in diameter. In the search for triple-fission events, we allowed for the scattering of double-fission fragments by Ag and Br nuclei.

As a result of this experiment we detected 3.43×10^5 two-prong events and 133 events with three tracks belonging to fragments with comparable masses. One of the detected events is shown in Fig. 1. After correcting for the imperfect efficiency of the scan in the search for three-prong events, we found the ratio of the probabilities for the fission of ^{238}U nuclei by 1-GeV protons into two and three massive detectable fragments to be $W_3/W_2 = (4.7 \pm 0.5) \times 10^{-4}$. To find the corresponding ratio for triple-fission events with one nuclear-unstable fragment, we made use of experimental data on the momentum spectra of double fragments in the cases of collinear and noncollinear separation. These measurements were carried out on a two-arm time-of-flight spectrometer. The angle between the two arms was 180° in the case of the collinear geometry and 170° in the case of the noncollinear geometry. The axis of the stationary arm was perpendicular to the direction of the primary beam in each case.

The minimum mass of the nuclear-unstable fragments which formed was determined in the collinear geometry by comparing the measured and calculated mean values of the projection of the missing-mass velocity onto the separation axis of the two detectable fragments. The missing mass for each event was found as the difference

$$\Delta M = A_0 - (M_1 + M_2) \tag{1}$$

between the mass of the target nucleus, A_0, and the sum of the masses of the detectable fragments, $M_1 + M_2$. The mean values of the projections of the velocity of the missing mass were calculated under the assumption of an anisotropic separation of all the accompaniment particles making up the missing mass. Specifically, we worked from the formula

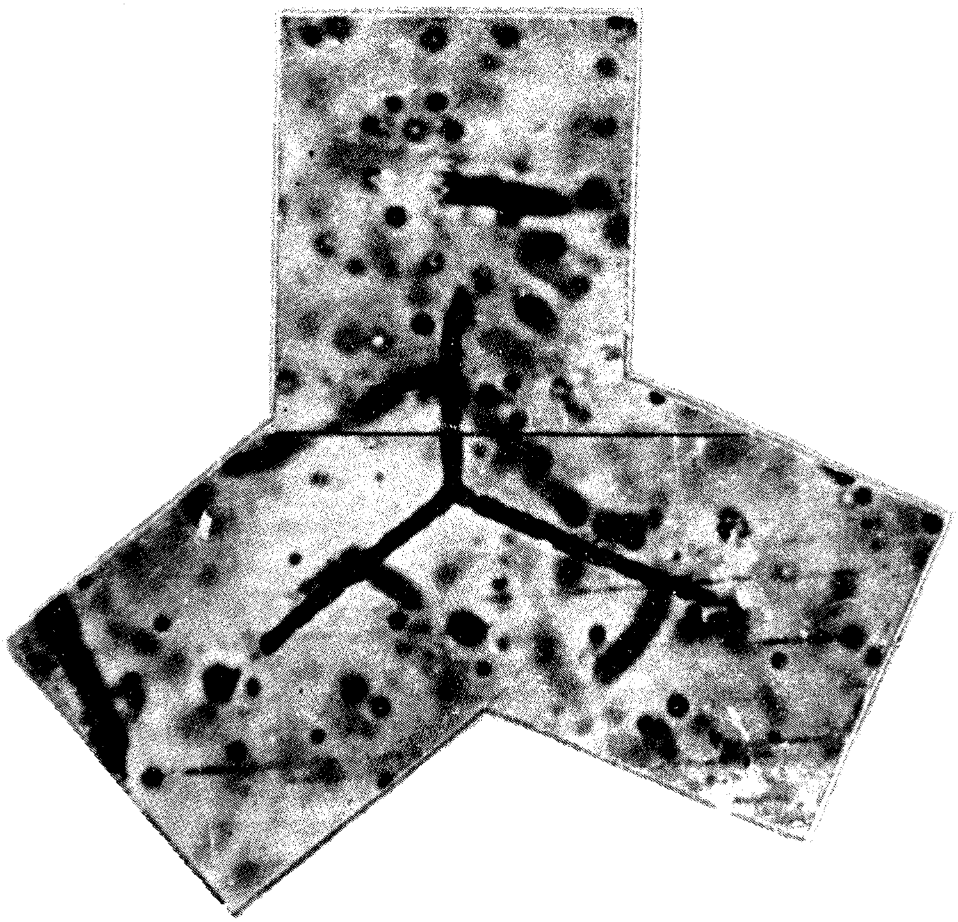

FIG. 1. Three-prong fission of a ^{238}U nucleus by a 1-GeV proton into three detectable fragments of comparable mass.

$$< V > = \sqrt{\frac{2}{\pi}} \frac{[(\sigma_{\text{in}})^2 + \frac{1}{3}(\Delta M + 1)q^2]^{1/2}}{\Delta M + 1}. \tag{2}$$

Here σ_{in} represents the momentum resolution of the instrument, and q is the mean square momentum per missing-mass nucleon. These parameters have been found previously[6] for several values of the missing mass: $\sigma_{\text{in}} = 190 \pm 10$ MeV/c and $q = 126 \pm 3$ MeV/c. Figure 2 compares the experimental results (the points and the solid line) with calculated results (the dashed line). For nucleon losses up to $\Delta M = 45$ amu, the experimental and calculated data agree well, providing evidence for a two-body kinematics of the separation of the massive fragments and an independent isotropic emission of accompaniment particles. Beginning at $\Delta M = 45$ amu, the experi-

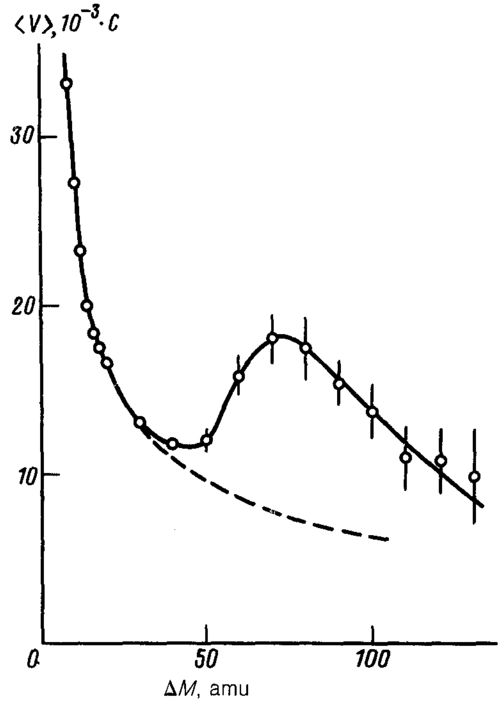

FIG. 2. Mean value of the projection of the missing-mass velocity onto the separation axis of the two massive fragments versus the quantity $\Delta M = A_0 - (M_1 + M_2)$, expressed in atomic mass units. The velocity unit is 0.001 of the speed of light c.

mental mean values of the velocity projection swing substantially higher than the calculated values. This effect corresponds to a transition from two-body to three-body kinematics. We adopted $\Delta M = 45 \pm 5$ amu as the threshold value, i.e., as the minimum mass of a nuclear-unstable fragment which could be determined reliably in experiments with a two-arm time-of-flight spectrometer. However, we do not mean to rule out the possible formation of nuclear-unstable fragments with smaller masses. The total number of nuclear-unstable fragments with masses $\Delta M \geqslant 45$ amu was found by comparing the experimental data on the collinear separation geometry and the noncollinear separation geometry of the two detectable fragments. The experimental data were analyzed by the same method as has been used to estimate the lifetime of the nuclear-unstable fragments.[5] In determining the number of double-fission events used for normalization, we allowed for the distributions of the momentum projection of the system of the two detectable fragments onto the direction of the primary beam. These distributions characterize the efficiency at which double fragments separated by various angles can be detected by the two-arm time-of-flight spectrometer.[6] We ultimately found the value $W_{3*}/W_2 = (9 \pm 2) \times 10^{-3}$. This figure characterizes the relative probability for the triple fission of ^{238}U nuclei by 1-GeV protons in which one of the fragments of comparable masses is nuclear-unstable. This value is nearly 20 times the probability for fission into three detectable fragments.

There are many common features in the separation kinematics in the two processes. Most of the events detected are coplanar; the measured deviation from a coplanar arrangement in the various events did not exceed the measurement error. The distribution of the angles between each two of the three tracks in the photoemulsion events had a mean value which agreed with the most probable value, $\langle \varphi \rangle = 119 \pm 1°$, and a full width at half-maximum $\mathrm{FWHM}_{\varphi} = 49.7 \pm 1.7°$. The measured mean value of the angle agrees well with the value of 120° which is characteristic of the separation of identical fragments due to Coulomb forces. The imbalance of the momenta of the double detectable fragments, which was measured with the help of the two-arm spectrometer in the collinear geometry and the noncollinear geometry, also agreed with the kinematics of a separation under the influence of Coulomb forces for three massive fragments, one of which is nuclear-unstable.[5] These results suggest that a massive nuclear-stable detectable third fragment forms in the fission of ^{238}U nuclei by 1-GeV protons from nuclear-unstable fragments of the fission of this nucleus into three fragments of comparable mass.

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Translated by D. Parsons