Estimate of the lifetime of massive nuclear-unstable fission fragments of ^{238}U nuclei split by 1-GeV protons

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The momentum spectra of complementary fragments from splitting of ^{238}U nuclei were measured with collinear and noncollinear separation of the fragments for events with large nucleon losses. The change in the momentum distributions on going from the collinear to the noncollinear geometry is employed to estimate the lifetime of the massive nuclear-unstable fragments.

In the study with the help of a double-arm time-of-flight spectrometer of nuclear fission induced by 1-GeV protons in targets consisting of heavy nuclei, events which at the time were attributed to an explosion of the nucleus were observed.[1] These events were characterized by large nucleon losses and the presence of two massive fragments whose separation kinematics differed markedly from the two-body case. Subsequent investigations of the splitting of heavy nuclei by relativistic protons, which were performed using different experimental methods,[2-4] led to the conclusion that massive nuclear-unstable fragments are formed. A nuclear reaction in which the two-body kinematics breaks down appears to be a process in which the nucleus is split into three fragments of comparable mass. At the stage of separation of the fragments under the action of Coulomb repulsion the nuclear-unstable fragment decays into separate nucleons and very light nuclei, thereby justifying the use of the term nuclear explosion.[1] An important consequence of the proposed reaction mechanism is that the degree of unbalance of the momenta of the two detected nuclear-stable fragments depends on the lifetime of the moving nuclear-unstable fragment. It was expected that this effect should manifest itself in the measurement of momentum spectra of complementary fragments that have different separation angles.

The experiments with complementary fragments, formed when ^{238}U nuclei are split by 1-GeV protons, were performed with the help of a double-arm time-of-flight spectrometer with collinear (180°) and noncollinear (170°) arrangements of the spectrometer arms. The axis of the stationary arm in each case was orthogonal to the direction of the primary beam. The basic configuration of the experiment is shown in Fig. 1, and the procedural details were published in Refs. 1–4. In the experiment with the collinear geometry 2.2×10^4 fission events were recorded and in the experiment with the noncollinear geometry 8.8×10^4 events were recorded. To compare the data with the results of a three-body fission experiment,[4] we selected events in which the nucleon losses were $\Delta M = A_0 - (M_1 + M_2) \geqslant 75$ amu. There were 204 such events in the experiment with the collinear geometry and 444 such events in the noncollinear geometry. These events were employed to construct distributions along the projections

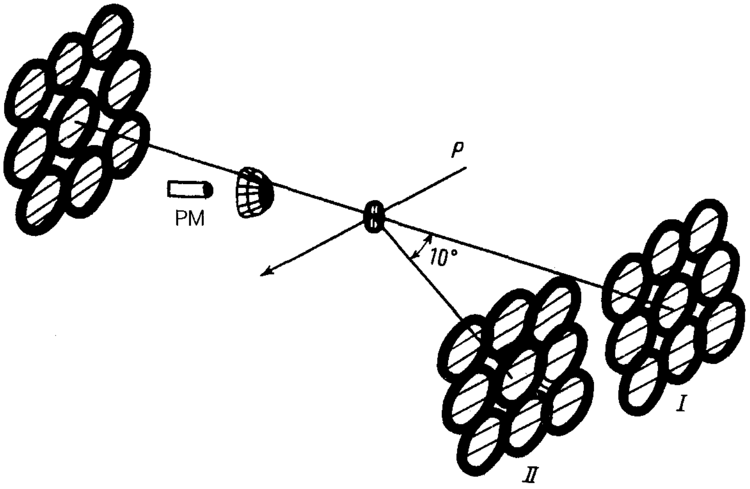

FIG. 1. Schematic diagram of the arrangement of the semiconductor detectors in the double-arm time-of-flight spectrometer. The elements of the independent start-signal device are indicated. I—Collinear geometry, II—noncollinear geometry.

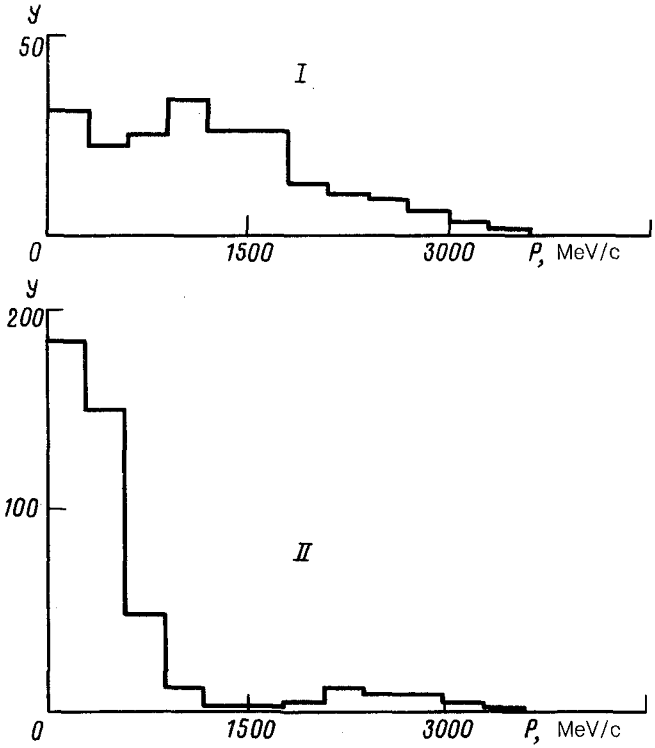

FIG. 2. Spectra of the projections of the momentum transfer in experiments with collinear and noncollinear geometry for events with nucleon losses $\Delta M \geqslant 75$ amu.

$P = P_1 - P_2$ of the total momentum transferred to the two fragments onto the axis perpendicular to the direction of the primary beam (Fig. 2). Both spectra were analyzed in an identical manner under the assumption that they are the sum of two distributions: The first distribution is a normal distribution with zero mean and $\sigma_p = 449$ MeV/c and the second distribution complements the normal distribution. The quantity $\sigma_p = 449$ MeV/c best corresponds to the momentum distribution measured in the noncollinear geometry. The analysis showed that the relative probability of the complementary distribution changes from $Y_{\rm I} = 93.6^{+6.4}_{-13.2}\%$ to $Y_{\rm II} = 10.6 \pm 1.6\%$ on going from the collinear to the noncollinear geometry. In the process the average value of the projection of the transferred momentum increases from $P_{\rm I} = 980 \pm 390$ MeV/c to $P_{\rm II} = 2530 \pm 100$ MeV/c. The experiments in the collinear and noncollinear geometries thus attribute the decrease in the number of the events in the complementary distribution to the increase in the average value of the momentum transfer. The decrease in the fraction of events is a natural consequence of radioactive decay, while the average value of the momentum transfer increases as a result of the longer lifetime of the nuclear-unstable fragment at the Coulomb repulsion stage. It was found that events in which the nuclear-unstable fragments decayed in the intervals between the final time $t_{\rm fin}$ and initial time $t_{\rm in}$ of acceleration were recorded in

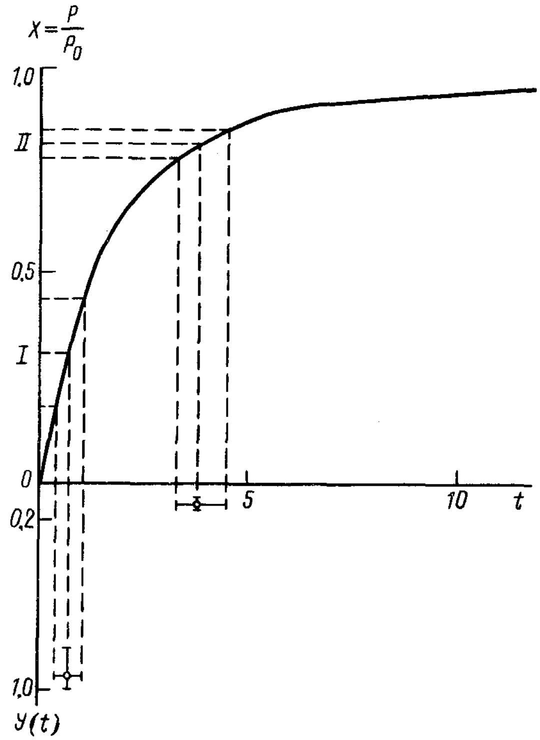

FIG. 3. Graphical explanation of the procedure used to analyze the experimental data. The solid curve was calculated using Eq. (1). The dashed lines show the transition from momentum intervals to time intervals for the collinear and noncollinear geometries of the experiment.

each of the two experimental distributions. They were estimated with the help of the analytical expression

$$t = \tau \left\{ \frac{1}{2} \ln \frac{1+x}{1-x} + \frac{x}{1-x^2} \right\}, \tag{1}$$

which was obtained for the motion of two bodies under the action of the Coulomb repulsion. In this formula $x = P/P_0$, where P is the time-dependent momentum, and P_0 is the maximum possible momentum acquired by a fragment as a result of acceleration. The temporal parameter τ is

$$\tau = 2e^2 Z_1 Z_2 \mu^2 P_0^{-3}. \tag{2}$$

In this expression Z_1Z_2 and μ, which are, respectively, the product of the charges and the reduced mass of the separating fragments, affect the value of τ relatively little. The momentum P_0, for which the experimentally measured value of the average momentum of the nuclear-stable massive fragment $P_0 = 3000 \pm 20$ MeV/c was taken, is the determining factor.[3] Ultimately, for the splitting of the ^{238}U nucleus by 1-GeV protons the temporal parameter τ was found to be 2×10^{-21} s. The normalized experimental data for the collinear and noncollinear geometries lead to a system of two equations containing the constant λ which determines the time dependence of the decay

$$N(t) = N_0 e^{-\lambda t}. \tag{3}$$

As a result of solving the system of equations, we found that $\lambda = (5.7 \pm 0.5) \times 10^{20}$ s^{-1}, which corresponds to the average lifetime of the massive nuclear-unstable fragments $\lambda^{-1} = (1.8 \pm 0.2) \times 10^{-21}$ s. The computational procedure is illustrated in Fig. 3.

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