Many-body decay modes of massive nuclear-unstable fragments

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Experiments demonstrate that massive nuclear-unstable fragments which arise in the breakup of ^{238}U nuclei by 1-GeV protons undergo a many-body decay. The most probable number of charged particles formed in the process is 8 ± 1.

Nuclear-unstable, few-nucleon systems are known to form in nuclear reactions at low and intermediate energies. The three-body decay of 2^+ states of the nuclei ^6He, ^6Li, and ^6Be was studied in Ref. 1. A greater number of experiments have been carried out to learn about two-body decays through measurements of kinematic correlations between two emitted particles. The most massive nuclear-unstable formations which have been studied by the two-body correlation method turn out to be in excited states of the ^{10}B nucleus that decay in the channels[2] $^{10}B \to {}^6Li + \alpha$ and $^{10}B \to {}^9Be + p$. However, nuclear-unstable entities with far greater masses form in nuclear reactions at intermediate energies. In events which have been observed in the breakup of ^{238}U nuclei by 1-GeV protons, the two detectable massive fragments have been accompanied by the formation of a third, nuclear-unstable fragment, comparable in mass to the first two. The mechanism for this unusual ternary-fission process was studied with the help of a two-arm time-of-flight spectrometer. It was found that the probability for the production of nuclear-unstable fragments with masses of at least 45 a.u. is $W_3/W_2 = (9 \pm 2) \times 10^{-3}$ of the probability for the detection of all events with two detectable massive fragments.[3] The average lifetime of the massive nuclear-unstable fragments has been estimated[4] at $(1.8 \pm 0.2) \times 10^{-21}$ s.

With lifetime this short, all the particles which arise from the decay of massive nuclear-unstable fragments, in experiments of any sort, will have trajectories which

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emerge from the same point as that from which the two tracks from the additional detectable fragments emerge. This circumstance can be exploited for an experimental study of the decay modes of massive nuclear-unstable fragments by a track method. The measured probability for the ternary fission also raises the hope that it will be possible to visually observe both the two massive detectable fragments and the charged accompaniment particles which are the end result of the decay of the massive nuclear-unstable fragments. The most suitable method for studying this decay has proved to be the detection of charged particles in substrate-free layers of a nuclear emulsion containing ^{238}U nuclei.[5] In the experiments which were carried out, it was guaranteed that the massive detectable fragments resulting from the breakup of ^{238} U nuclei by relativistic protons could be reliably identified. It was thus possible to distinguish the latter from fragments of the breakup of silver and bromine nuclei without any major difficulty. The tracks of all charged particles accompanying the two massive detectable fragments were detected simultaneously in each event. The sensitivity of the emulsion layers made it possible to see protons with energies up to 100 MeV; however, the charges and masses of the accompaniment particles were not identified.

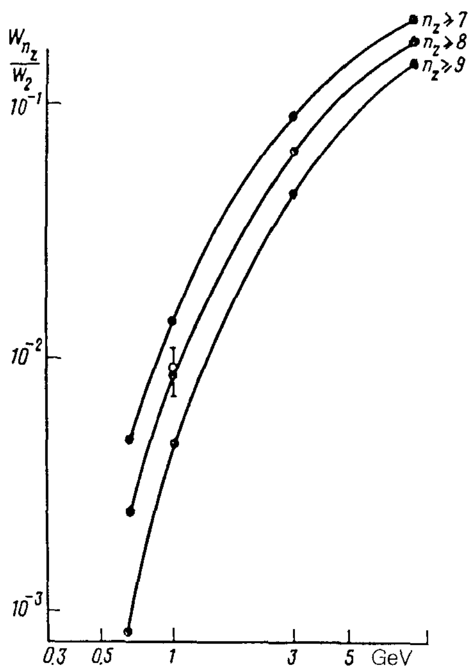

FIG. 1. Relative probabilities for the breakup of ^{238}U nuclei accompanied by the formation of two massive fragments and several charged accompaniment particles. The energy of the incident protons is plotted along the abscissa. The measured probabilities have been normalized to the probability for binary fission. The solid lines, drawn through the filled circles, show the results of emulsion experiments at proton energies of 0.66, 3, and 9 GeV. The open circle is the relative probability found in Ref. 3 for the production of massive nuclear-unstable fragments. Each curve corresponds to the limiting value of n_z, the number of tracks of charged accompaniment particles.

As a result of the bombardment of a nuclear emulsion containing ^{238}U nuclei by 1-GeV protons, we detected 4042 breakup events in which two massive fragments were observed. For each event we determined the number (n_z) of tracks of charged particles accompanying the two massive fragments. The values found for n_z ranged from 0 to 13. We wished to compare the experimental data on the probability for the production of massive nuclear-unstable fragments found with the two-arm time-of-flight spectrometer[3] with data on many-body breakup in the layers of nuclear emulsion. For this purpose we calculated the probabilities W_{n_z}/W_2 for the appearance of events with a multiplicity n_z above a given value in the emulsion layers. The probabilities were calculated with respect to the total number of events found with two massive detectable fragments. The values found for W_{n_z}/W_2 from the emulsion experiment turned out to be $(14.3 \pm 2) \times 10^{-3}$, $(8.7 \pm 2) \times 10^{-3}$, and $(4.6 \pm 2) \times 10^{-3}$ for $n_z \geqslant 7$, 8, and 9, respectively. An agreement with the earlier measurements of the relative probability for massive nuclear-unstable fragments, $W_{3*}/W_2 = (9 \pm 2) \times 10^{-3}$, is found for $n_z \geqslant 8$. Since the values found for W_{n_z}/W_2 in the emulsion experiment show a rapid decrease in this ratio with increasing n_z, we can take $n_z = 8$ as representing the most probable number of charged particles which arise from the decay of massive nuclear-unstable fragments.

Figure 1 compares the experimental data found by the two methods. The filled circles are the emulsion data on the probability for observing many-body breakup events; the open circle shows the probability found for the production of nuclear-unstable fragments in the breakup of ^{238}U nuclei by 1-GeV protons in the experiments on the two-arm time-of-flight spectrometer. Shown in the same figure are values of W_{n_z}/W_2 for $n_z \geqslant 7$, 8, and 9 as found in earlier emulsion experiments on the breakup of ^{238}U nuclei by protons with energies of 0.66, 3, and 9 GeV. We drew several smooth curves through the experimental values of the probabilities for each value of n_z. These curves show that the relative probabilities for many-body breakup increase rapidly with increasing energy of the incident protons. This conclusion is supported by the measured distribution of the multiplicity of charged particles accompanying the two massive fragments in the breakup of ^{238}U nuclei by 0.46-GeV protons. At this energy, essentially no events with the n_z values in the figure were observed. This figure clearly demonstrates that the uncertainty in the value found for n_z is no greater than 1, since the most probable number of charged particles emitted in the decay of massive nuclear-unstable fragments resulting from the breakup of ^{238}U nuclei by 1-GeV protons is 8 ± 1.

In conclusion we should point out that the many-body nuclear decay called "multifragmentation" is presently being studied as a process that competes with fission.[1] In the particular case of the breakup of the ^{238}U nucleus by relativistic protons into three massive fragments, one of which is nuclear-unstable and decays into several smaller fragments, it has been shown that the two processes occur simultaneously, in the same nuclear reaction.

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