Multiplicity of charged particles accompanying fragments of ^{238}U fission by protons with 0.46–9 GeV

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The multiplicity of charged particles accompanying fragments of the fission of ^{238}U nuclei by relativistic protons has been determined experimentally. The maximum multiplicity observed increases from 8 at a proton energy of 0.46 GeV to 26 at 9 GeV. Events with charged-particle accompaniments in the range 8–26 are used to discuss how the nature of the decay of massive unstable-nucleus fragments depends on the energy.

The multiplicity of the charged particles produced in the interactions of colliding beams is being studied experimentally and theoretically in high energy physics.[1] Dzhalaganiya *et al.*[2] have analyzed the multiplicity of particles produced in nucleus–nucleus interactions of ^{22}Ne with a momentum of $4.1 \cdot A$ GeV/c with emulsion nuclei. That charged particles do accompany two massive fragments of a fission of heavy nuclei by relativistic protons is a well-established experimental fact. The multiplicity of these particles is of interest in connection with research on the decays of massive unstable-nucleus fragments which are peer partners for the two stable-nucleus fragments which are detected as a heavy nucleus broken up by relativistic protons into three fragments which are comparable in mass.[3]

In this letter we are reporting experimental data on the multiplicity n of the charged particles accompanying two massive fragments of the fission of ^{238}U nuclei by protons with energies of 0.46, 0.66, 1, 3, and 9 GeV. The experiments were carried out in proton beams at the Dubna and Gatchina accelerators. Layers of nuclear emulsion containing ^{238}U nuclei were used. The important aspects of the procedures for detecting the fission fragments and the accompanying charged particles in the emulsion layers were published in Ref. 4 and in papers cited there. The experimental results are shown in Fig. 1 as a plot of the relative probability $W(\geqslant n)$ for the appearance of events with a multiplicity greater than or equal to n, for the five energies of the protons causing the fission. The values of $W(\geqslant n)$ have been normalized to the total number of detected events for each proton energy. The experimental results show that the multiplicity of the charged particles accompanying two massive fragments of the fission of ^{238}U nuclei by protons increases monotonically as the proton energy is increased from 0.49 to 9 GeV. The maximum multiplicity found experimentally increases from 8 to 26.

Only in the experiments with a 1-GeV proton beam was information obtained on the decay modes of unstable-nucleus fragments with masses $M \geqslant 45$ amu produced in the fission of ^{238}U nuclei into three fragments comparable in mass. These results were

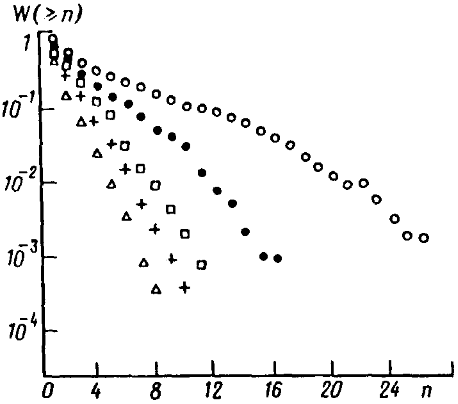

FIG. 1. The probability $W(\geqslant n)$, for the appearance of events in which there is a proton-induced fission of ^{238}U nuclei into two massive fragments which are detected and in which the multiplicity of the charged-particle accompaniment is greater than or equal to n. Δ—Proton energy of 0.46 GeV; +—0.66; □—1; ●—3; ○—9 GeV.

found through a self-consistent analysis of the results of two different experiments, which used a two-arm time-of-flight spectrometer and layers of nuclear emulsion with substrates.[4] It was found that events in which ^{238}U nuclei are split by 1-GeV protons and in which the unstable-nucleus fragments have masses $M \geqslant 45$ amu corresponded to those events (found in the emulsion layers) in which the number of accompanying charged particles, n, was no less than 8. For this reason, the experimental results in Fig. 1 allow us to speak confidently of the production and decay of unstable-nucleus fragments with masses $M \geqslant 45$ amu during the bombardment of ^{238}U nuclei by only those protons which have energies of 1, 3, and 9 GeV. It is natural to suggest that as the more massive unstable-nucleus fragments decay, they give rise to a high charged-particle multiplicity. This suggestion leads to the conclusion that the masses of the unstable-nucleus fragments should increase with increasing energy of the incident protons. This increase, however, would simultaneously lead to a decrease in the masses of the other fission fragments which are detected. Although the methods available for identifying fission fragments in emulsion layers can reliably distinguish fragments produced in reactions with ^{238}U nuclei from fragments of silver and bromine nuclei, they are not capable of determining the masses of these fragments. Nevertheless, the criteria for the identification of fission fragments were satisfied during the analysis of the experimental data, regardless of the energy of the incident protons. Consequently, the masses of the fragments which were detected could not have varied widely; for example, they could not have varied over a range wider than the mass ranges of the groups of heavy and light fission fragments at low excitation energies. The stability of the mass distributions of the fission fragments produced in the fission of ^{238}U nuclei by relativistic particles has also been demonstrated recently in experiments which involved the identification of each fragment nuclide.[5] The fact that the multiplicity of the charged-particle accompaniment increases with increasing energy of the incident protons must therefore be reconciled with the stability of the mass distributions of the fragments which are detected. This can be done by attributing the observed increase in the multiplicity not so much to the increasing masses of the unstable-nucleus fragments as to a progressively deeper splitting of these fragments. Even if approximately the same mass spectrum of unstable-nucleus fragments forms at all proton energies from 1 to 9 GeV, the decay of these fragments may depend on the particular energy at which they were formed. At higher energies, decays into progressively smaller fragments are permissible.

Since the binding energy of all the nucleons in the ^{238}U nucleus is 1802 MeV, at proton energies above this value there may be decays of the target nucleus into any combination of charged particles, provided that the net electric charge of the particles is equal to the charge of the target nucleus, increased by the charge of the incident proton. For the ^{238}U nucleus, this figure is 93, and the maximum multiplicity of the charged particles which are produced must also approach this value. However, despite the fact that an energy of 9 GeV is five times this threshold, the maximum observed multiplicity is 28. Two massive fragments are evidence of a fission mechanism for their appearance, while the 26 accompaniment charged particles arise from the decay of a third massive unstable-nucleus fragment. If we make the crude assumption that the charges of all three fragments are about the same, then the fragment which decayed would have to have a charge of 31, which is far closer to 26 than 93 is to 28. Those events with an accompaniment charged-particle multiplicity in the range 8–26 constitute other cases of a complete decay of unstable-nucleus massive fragments with charges near $z=31$. These simple arguments are based on the principle that the electric charge remains an integer during the fission of heavy nuclei by relativistic protons. The splitting mechanism itself is a process of fission into several (three, in the case at hand) massive fragments, one of which, an unstable-nucleus fragment, undergoes a complete decay, called "multifragmentation" in the literature. The energy of the protons causing the splitting affects the nature of the multifragmentation process. With increasing proton energy, the multifragmentation goes into an asymptotic regime in which the binding energy of the smaller fragments which are produced ceases to affect the yield of these particles. The maximum multiplicity of the fragments approaches a value which is equal to the charge of the decaying fragment, z.

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