Manifestation of deformed shells in the fission of samarium by 1-GeV protons

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The fission of samarium nuclei by 1-GeV protons has been studied with a two-arm time-of-flight spectrometer. In the region of large nucleon losses, an asymmetric fragment mass distribution is found. The reaction mechanism is discussed.

The two-arm time-of-flight spectrometer described in Ref. 1 has been used to study the fission of samarium induced by protons with an energy of 1 GeV. The measurements were taken in a collinear arrangement of the arms, perpendicular to the axis of the proton beam. The target consisted of 430 μg/cm^2 of a natural mixture of samarium isotopes deposited on a nickel substrate 120 μg/cm^2 thick. Over 44 h of exposure to the proton beam, 183 samarium fission events were detected. These events were identified reliably among the many-particle disintegrations of the target nucleus with the help of the total kinetic energy and the sum of the masses of the additional fragments. The experimental procedure is described in Ref. 2.

Figure 1 shows the momentum distribution of the fission fragments detected and

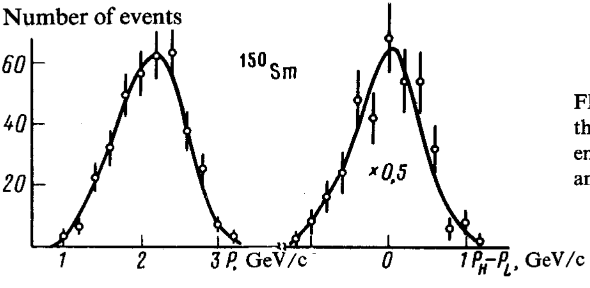

FIG. 1. Distributions of the momenta of the detected fragments and of the difference between the momenta of the heavy and light additional fragments.

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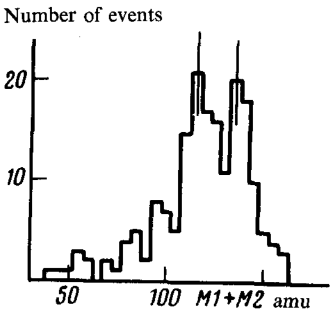

FIG. 2. Distribution of the sum of the masses of the additional fragments detected.

the distribution of the difference between the momenta of the heavy and light additional fragments. The widths of these distributions are slightly greater than for heavy target nuclei,[1] but events in which momentum is conserved for the final masses of the additional fragments are again the most probable events. This result means either a statistical equilibrium at the time of the fission of the samarium or the absence of any significant emission from the fragments detected.

Figure 2 shows the distribution of the sum of the masses of the additional fragments detected. Two loss ranges with qualitatively different fragment characteristics are separated by a dip with a rather weak statistical basis at a nucleon loss $\Delta M = 20$ amu.

Figure 3 shows two-dimensional distributions of the velocities of the additional fragments for these two ranges. Events with $\Delta M < 20$ amu correspond to ordinary fission, without shell effects. For these events the average total kinetic energy of the

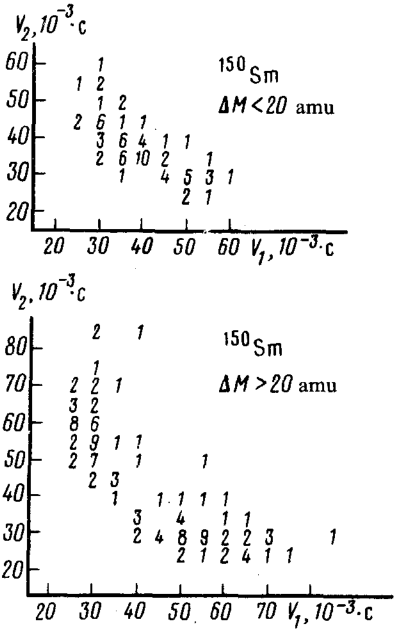

FIG. 3. Velocity distributions of the additional fragments in the ranges of low and high nucleon losses.

fragments is 96 ± 3 MeV, and the average velocity of the fragments is $(38.5 \pm 0.7) \times 10^{-3} \cdot c$, in agreement with the systematics of the average velocities of the fission fragments of heavy nuclei.[2] The mass and energy distributions of the fragments, Gaussian in this range, are characterized by standard deviations $\sigma_M = 1.53 \pm 1.1$ amu, $\sigma_E = 12.8 \pm 1.0$ MeV, and $\sigma_{E_k} = 10.5 \pm 1.1$ MeV.

The events at $\Delta M > 20$ amu are distinguished by double-humped distributions of the velocity, mass, and kinetic energy of the fragments. The average fragment velocity is $(44 \pm 1) \times 10^{-3} \cdot c$. The total kinetic energy of the fragments is 12 ± 3 MeV lower than at $\Delta M < 20$ amu. Double-humped distributions have been found previously[3–6] for fission fragments of nuclei of intermediate mass. In Refs. 3–5, the double-humped nature of the mass distributions of the fragments for nuclei lighter than samarium was attributed to a shell structure, but in Ref. 6 the double-humped velocity distribution of the fission fragments of silver was interpreted as evidence of an instability of the shape of the fissile nucleus with respect to a mass asymmetry. The presence of a well-localized peak in the mass distribution of the heavy fragments for $\Delta M > 20$ amu, with an average mass of 74 ± 2 amu, agrees with Strutinsky's predictions[7] of the appearance of new shells, $Z, N = 36$–38, upon a deformation corresponding roughly to the deformation of rare-earth nuclei. This circumstance and also the absence of this instability at low nucleon losses are evidence for the explanation of the mass asymmetry on the basis of shell effects.

The results found experimentally on the fission of intermediate-mass nuclei, with large nucleon losses, can be explained on the basis of a nonequilibrium process involving a collective interaction of the incident proton with target nucleons, which gives rise to a highly excited multibaryon cluster.[2] Since the excitation energy of this cluster is usually greater than the binding energy of its constituent nucleons, its subsequent decay into individual nucleons, α particles, and light fragments is of the nature of an explosion.[1] This stage of the reaction is apparently identical for all nuclei with sufficiently large mass. The need for the transfer of some of the excitation energy of the residual nucleus to collective degrees of freedom in order to overcome the fission barrier[8] and the significant increase in this barrier explain the substantial change in the characteristics with decreasing mass of the target nucleus.

In the case of the fission of a nucleus after the emission of a highly excited cluster (or of its decay products), the residual nucleus as a whole acquires the recoil momentum, and experimentally we detect large values of the perpendicular component of the momentum transferred to the system from the two fragments detected. The fission of the residual nucleus, on the other hand, at the time the cluster is emitted should cause the fragment velocities to be slightly higher than in binary fission and should rule out any significant transverse momenta. For heavy nuclei we observe both of these effects, but with decreasing mass of the target nucleus the probability for the subsequent fission decreases rapidly.

The dominance of the "explosion" in the fission of intermediate-mass nuclei induced by high-energy particles explains the qualitative changes in the excitation function, beginning with the rare-earth elements.[5,6,9] The low excitation energy of the residual nucleus at the saddle point of the fission barrier promotes the manifestation of shell effects and a low emission from the fission fragments.

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