Multifragmentation of nuclei by high-energy protons

A. S. Botvina, A. S. Il'inov, and I. N. Mishustin
Institute of Nuclear Research, Academy of Sciences of the USSR; I. V. Kurchatov Institute of Atomic Energy, Moscow

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A model is proposed for the disintegration of nuclei by high-energy protons. The model includes cascade, fragmentation, and evaporation stages. Multifragmentation of the residual nuclei plays an important role, although it is ignored in the standard cascade-evaporation model.

Although the production of nuclear fragments during the bombardment of nuclei by high-energy protons has been under study[1] for more than 25 years now, the mechanism for this process remains somewhat unclear. Considerable progress has recently been achieved toward an understanding of the behavior of nuclei at excitation energies comparable to their binding energies (Refs. 2–5, for example). The predominant pathway for the decay of such systems is the multiple production of nuclear fragments (multifragmentation), which is a manifestation of a phase transition of a liquid-gas type in nuclear matter. In the present letter we demonstrate that the multifragmentation of the residual nuclei is a necessary part of the complex proton-nucleus interaction. This process can be broken down into three stages: cascade, fragmentation, and

TABLE I. Relative probability (w_R) for the production, after the cascade stage, of a residual nucleus with the given excitation energy $\epsilon_R = E_R/A_R$ and with the specified average values of the mass number ($\langle A_R \rangle$), charge ($\langle Z_R \rangle$), and velocity ($\langle \beta_R \rangle \equiv \langle v_R \rangle / c$). The calculations were carried out for the interaction of 4.9-GeV protons with Ag nuclei.

ϵ_R, MeV/nucleon	0 – 2	2 – 4	4 – 6	6 – 8	8 – 10	10 – 12	12 – 14	> 14
w_R,%	29.6	15.3	11.4	8,4	8,8	6,9	5,1	14.5
$\langle A_R \rangle$	104.5	98.1	93.5	90.8	87,2	84.2	81,9	76,6
$\langle Z_R \rangle$	45.6	43.1	41.2	40.2	39.4	38.3	37.1	35,6
$\langle \beta_R \rangle$	0,0015	0.0034	0.0080	0.0124	0,0144	0,0193	0.0231	0.0306

evaporation stages. This breakdown is justified on the basis of the large differences in the scale times corresponding to the different stages.

In the first stage, a cascade of successive collisions of fast particles (N, π, . . .) with intranuclear nucleons develops. In the course of this cascade, each nucleus abandons the particles of the continuous spectrum and forms an excited residual nucleus. At initial energies $\lesssim 10$ GeV, this stage is described by the standard model of an intranuclear cascade,[6] but at higher energies the finite hadron formation length must be taken into account.[7] We have carried out Monte Carlo calculations on the intranuclear cascade. The results show that the residual nuclei formed after the intranuclear cascade have broad distributions in excitation energy E_R, mass number A_R, and charge Z_R (Table I).

In the second stage, the residual nucleus either evaporates nucleons and light nuclei or breaks up into several excited fragments, depending on how much excitation energy it has acquired. The explicit incorporation of a stage of multifragmentation fundamentally distinguishes our approach from the versions of the cascade-evaporation model that have been published. Calculations[2–5] have shown that the multifragmentation process appears at excitation energies $\epsilon_R \sim 5$ MeV/nucleon, corresponding to a nuclear temperature $t_{\lim} \sim 7$ MeV. At lower excitation energies, the predominant mechanism is evaporation from a thermalized residual nucleus. As can be seen from Table I, at a proton energy as low as 5 GeV a significant fraction of the residual nuclei has an excitation energy above 5 MeV/nucleon. Following Refs. 4 and 5, we use a Monte Carlo method with a statistical distribution of final-state probabilities to model the multifragment decay of such nuclei. Each final state of the system is characterized by a vector $\{\mathrm{N}_{AZ}\}$, whose components are the multiplicities of the fragments with the given values of A and Z. In the present study, conservation of the mass number and of the charge of the system is taken into account on the average over the ensemble through the introduction of corresponding chemical potentials μ and ν. In this case it is easy to derive[3] an explicit expression for the inclusive (average) mass distribution:

$$\langle \mathrm{N}_{AZ} \rangle = V_f \lambda_t^{-3} A^{3/2} \exp[-t^{-1}(F_{AZ}^{int} - \mu A - \nu Z)]. \tag{1}$$

Here $\lambda_t = (2\pi\hbar^2/m_N t)^{1/2}$ is the thermal wavelength, m_N is the mass of a nucleon, t is the temperature of the system (found from the known total energy of the system), V_f

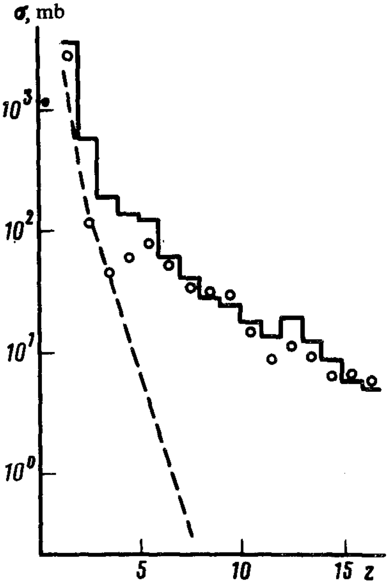

FIG. 1. Fragment charge distribution in the reaction p(4.9 GeV) + Ag. Points—Experimental[8]; solid and dashed lines—calculations, respectively, with and without multifragmentation.

is the free volume accessible to the translational motion of the fragments at the time the system breaks up, and $F^{\rm int}_{AZ}$ is the free energy associated with the internal excitation of a fragment, which is parametrized in liquid-drop form.[2,3,5] Isolated multifragment-decay events $\{N_{AZ}\}$ are played out in accordance with inclusive distribution (1) under the constraints of conservation of mass number and charge.

Finally, the third stage corresponds to the decay of the primary fragments. For fragments with mass number $A \leqslant 16$ this process is described by the model of the Fermi decay of light nuclei.[6] For heavier nuclei, as for the decay of residual nuclei with $t < 7$ MeV, we use the Blatt-Weisskopf statistical model,[6] in which the emission of heavy clusters, up to ^{18}O, is taken into account along with the evaporation of nucleons. After the evaporation, an ensemble of cold fragments and nucleons forms; these particles are observed experimentally.

Figure 1 shows the fragment charge distributions formed in the interaction of 4.9-GeV protons with Ag nuclei according to calculations on the basis of this model. The model gives a good description of the experimental data of Ref. 8. The evaporation version of the calculation, without a fragmentation stage, predicts an exponential mass distribution which is starkly at odds with experiment (Fig. 1).

Figure 2 shows the results calculated for the inclusive fragment energy spectra. The energy and momentum distributions of the fragments for each reaction pathway are found from the known $\{N_{AZ}\}$ mass distribution and the total kinetic energy of the fragments, $E_{\rm kin}$, by requiring that the phase volume that they occupy be maximized:

$$\int \frac{d^3 p_1 \ldots d^3 p_n}{(2\pi\hbar)^{3n}}\, \delta(p_1 + \ldots + p_n)\, \delta\left(\frac{p_1^2}{2m_1} + \ldots + \frac{p_n^2}{2m_n} - E_{kin}\right), \qquad (2)$$

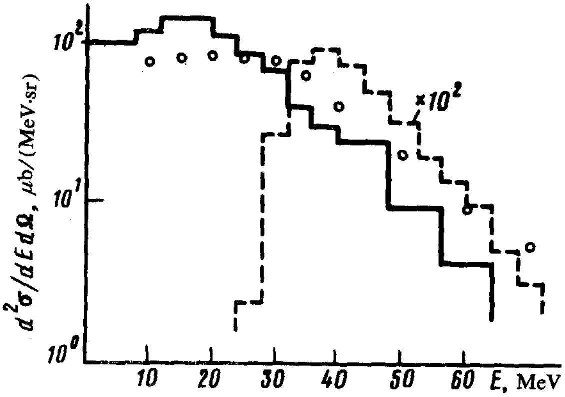

FIG. 2. Energy spectrum of fragments with $Z = 8$ at an angle of 90° in the laboratory frame in the reaction p(4.9 GeV) + Ag. The notation is the same as in Fig. 1.

where n is the number of fragments in the final state, and $\mathbf{p}_i$ and m_i are their momenta and masses ($i = 1,...,n$). The kinetic energy E_{kin} is the sum of the repulsive Coulomb energy and the energy of the thermal motion of the fragments, determined by the temperature of the system. The changes in the energy and momentum of the primary fragments in the course of their subsequent decay are taken into account. Comparison with the experimental data (Fig. 2) shows that the calculated spectra agree fairly well with the experimental data, although they are softer. A more accurate description of the Coulomb interaction of the fragments with each other would apparently be required to eliminate this discrepancy. The purely evaporation version of the model again disagrees sharply with the experimental data.

These calculations thus show convincingly that the multifragmentation of highly excited residual nuclei is a necessary component of the proton-nucleus interaction.

An important consequence of the model developed here is the prediction that the fragmentation of nuclei in proton-nucleus reactions occurs only after a threshold has been reached. The threshold proton energy is about 1 GeV. Our calculations show that the relative yield of residual nuclei with excitation energies above 5 MeV/nucleon (required for fragmentation) in the reaction p + Ag is 0%, 1.5%, and 50% at beam energies of 0.48, 1, and 4.9 GeV, respectively.

The topics discussed here will be examined in greater detail in a following paper.

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