Singularities of interactions of iron-group relativistic nuclei in cosmic rays with Ag and Br nuclei with maximum number of interacting nucleons

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(Submitted November 29, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **25**, No. 2, 127–131 (20 January 1977)

We have analyzed the interactions of relativistic nuclei having the presently attainable maximum number of interacting nucleons. The energy spectra and angular distributions of charged particles with energy <500 MeV are presented in various energy bands.

PACS numbers: 13.85.Mh

This study was prompted by the hypothesis[1–4] that a shock wave, in which the density of nuclear matter is increased by 3—7 times, can be produced in an interaction of high-energy nuclei. Since the most favorable conditions for the applicability of the hydrodynamic approach arise in collisions in which the largest number of nucleons takes part, it is important to separate these events experimentally and to study their singularities.

We investigated 45 interactions of cosmic-ray nuclei having energies ≥ 1 GeV/nucleon and charges $Z>10$ with Ag and Br nuclei in relativistic emulsions. The events were selected in accordance with the criterion [1)] $N_h \geq 28$,[5–7] which

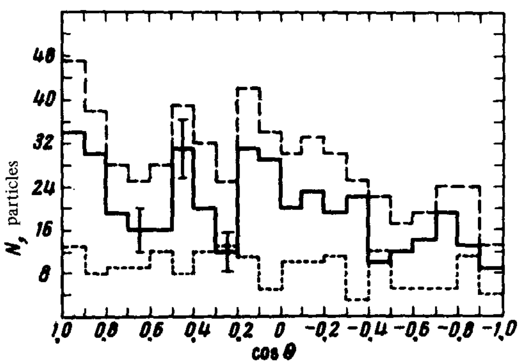

FIG. 1. Angular distribution of low-energy charged particles from the target nucleus with ionization corresponding to a proton range ≤ 4 mm ($E_p<31$ MeV; $E_\alpha<220$ MeV/nucleon, black tracks), in interactions of nuclei having $Z=10$—26 with total splitting of the nuclei Ag and Br ($N_h \geq 28$): dashed lines—45 events, 575 particles; solid—25 events with $n_{\rm int} \sim 20$, 399 particles, $N_b \geq 13$; dotted—20 events with $n_{\rm int} \gtrsim 30$—40, 176 particles, $N_b \leq 12$.

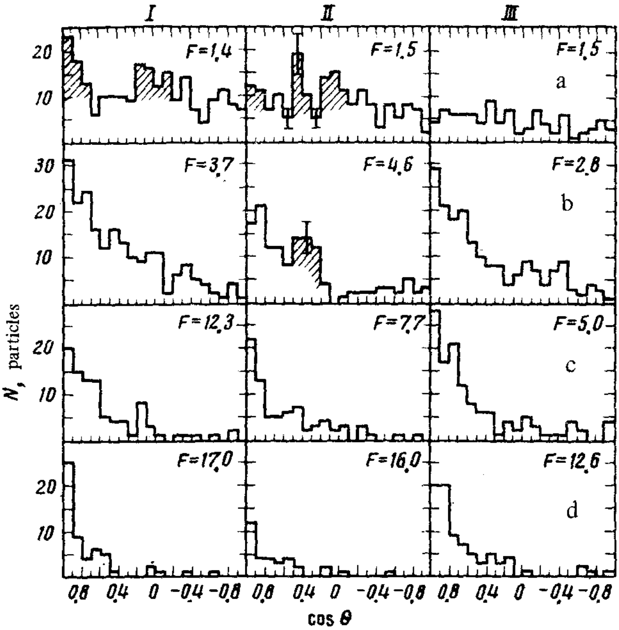

FIG. 2. Angular distributions of charged particles with proton energies <500 MeV in which the number of incident-nucleus nucleons falling into the target nucleus is $n_{int} \sim 20$ (I, II) and $n_{int} \gtrsim 40$ (III). The energies of the charged particles are: a) 0—31 MeV, b) 31—200 MeV, c) 200—380 MeV, and d) 380—500 MeV. I—incident nuclei with $Z \leq 20$ and $N_b \geq 13$; 15 interactions. II—incident nuclei with $Z = 22$—26 and with $N_b \leq 13$; 11 interactions. III—incident nuclei with $Z = 22$—26 and with $N_b \leq 12$; 11 interactions. F is the ratio of the number of particles in the front and rear hemispheres relative to the direction of motion of the incident nucleus.

corresponds to separation of collisions of nuclei with $n_{int} \gtrsim 20$ interaction nucleons of the incident nucleus. Out of the 45 events, 27 were due to nuclei with $Z = 22$—26.

Baumgardt *et al.*[4] observed peaks in the angular distributions of the particles from the target nucleus ($E_p < 28$ MeV, $E_\alpha < 200$ MeV/nucleon), which they interpreted as a manifestation of a Mach shock wave produced in nucleus—nucleus interactions. The type and energy of the particles were not identified, and it was assumed that the main contribution to the peaks is made by α particles with energy $E_\alpha = 30$—200 MeV/nucleon.

TABLE I.

n_{int}	Number of events	$\overline{N}_{af}$	$\overline{N}_g$	$F(N_g)$	$\overline{N}_{gi}$	$\overline{N}_b$	$\overline{N}_{bf}$	$\overline{n_s - Z}$
∼20	25	1.7 ± 0.2	23.2 ± 1.0	5.8 ± 0.6	3.2 ± 0.4	14.6 ± 0.8	1.0 ± 0.2	14.1 ± 1.1
≳40	11	0.5 ± 0.2	34.5 ± 1.8	4.2 ± 0.6	6.1 ± 0.8	8.3 ± 0.9	0.4 ± 0.2	39.8 ± 2.3

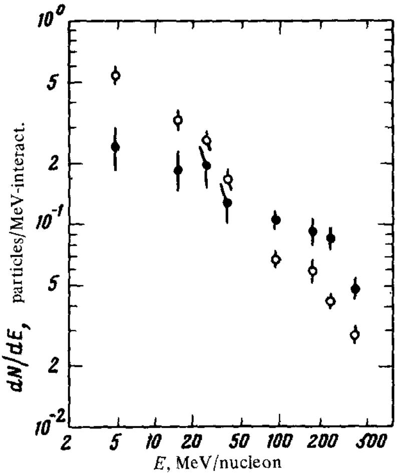

FIG. 3. Energy distribution of charged particles with proton energy <500 MeV. ● —events in which the number $n_{int} \gtrsim 40$ incident-nucleus nucleons landing in the target nucleus; 11 events. ○ —events with $n_{int} \lesssim 30$; 34 events.

We present here a range and ionization analysis of each of the emitted strongly-ionizing particles. Certain irregularities are observed in the angular distributions of the protons and α particles with energies $E_p < 31$ MeV and $E_\alpha < 200$ MeV/nucleon, obtained for all 45 interactions (Fig. 1, dashed histogram). These irregularities do not appear, however, for a separate group of events with a large number of interacting nucleons, $n_{int} \gtrsim 30$ (Fig. 1, dotted histogram, 20 events). The observed effect is due to a group of events where, according to our estimates, $n_{int} \gtrsim 20$ (Fig. 1, solid histogram, 25 events).[2)] The irregularities appear mainly in the distributions of the slow particles, $E_{p,\alpha} < 31$ MeV/nucleon, inasmuch as the fraction of the α particles with energies $E = 31$—200 MeV/nucleon is only ~15%.

The angular distributions were measured for different emitted-particle energy intervals and different groups of incident nuclei (Fig. 2). In the low-energy region, a certain excess of particles in the angle interval 0—37° is due to the interaction of the nuclei with $Z = 10$—20 (Fig. 2(Ia)), while in the interval 60—66° it is due to interactions of nuclei with $Z = 20$—26 (Fig. 2(IIa)). There are indications of an excess of protons of energy 31—200 MeV in the interval 60—79° (Fig. 2(IIb)).

The average characteristics of the interactions in which the irregularities are observed ($n_{int} \approx 20$) are given in Table I (line 1). The forward directivity of the protons with $E_p = 31$—380 MeV and $F = 5.5$, observed in these interactions, is much larger than in disintegrations with $N_h \geq 28$ due to protons,[8] pions,[9] and light nuclei (d, α),[8] where $F = 2.6$—3.

We have separated and investigated a group of interactions (events II) which can be classified, in accordance with their characteristics, as events with the maximum number of nucleons, $n_{int} \gtrsim 40$, entering the target nucleus. These events, when compared with the remainder, reveal the following (table, line 2): a smaller number $\bar{N}_{\alpha f}$ of the incident-nucleus α particles and fragments, which characterize the degree of its disintegration; a larger number $\bar{N}_g$ of protons with energy 31—500 MeV, which are mainly the recoil protons; a larger number $\bar{N}_{gt}$ of protons of energy 380—500 MeV, which can be attributed mainly to the interacting protons of the incident nucleus; smaller numbers N_b of low-energy particles and $\bar{N}_{bf}$ of fragments with $Z \geq 4$ from the target nucleus; a larger multiplicity $\overline{(n_s - Z)}$ of the produced mesons.[3)]

The main features of the group of interactions with $n_{\text{int}} \sim 40$, when compared with events with $n_{\text{int}} \sim 20$, is the smaller directivity in the forward hemisphere of the protons with $E > 31$ MeV ($F = 4.2$ and 5.8, respectively) and the harder energy spectrum of the particles with $E = 31$—500 MeV (Fig. 3). In addition, the energy spectrum for the events with $n_{\text{int}} \sim 40$ does not reveal the rise, typical of the evaporation spectrum, in the low-energy region. Events with $n_{\text{int}} \sim 40$ are a special type of complete disintegration of the nuclei Ag and Br, with a maximum fraction of protons with energy 31—500 MeV ($\sim 80\%$). For these interactions one does not observe the irregularities in the angular distributions of the secondary particles at an angle 60—66° (Fig. 2(IIIa)), which were attributed in[4] with the appearance of a Mach shock wave.

The hard energy spectrum of the secondary particles, the larger fraction of the high-energy protons in the disintegration products, and the relatively weak directivity of these protons in the forward hemisphere, all point to an explosive disintegration of the nuclei Ag and Br within a nuclear time interval. It is possible that a hydrodynamic approach can be used to describe such a process.

[1)] $N_h = N_g + N_b$, where N_g is the number of protons of energy 31 MeV $< E < 500$ MeV and N_g is the number of protons and α particles with energies $E_p < 31$ MeV and $E_\alpha < 220$ MeV/nucleon.

[2)] This group exhibits a statistically significant deviation ($p(\chi^2) = 0.015$) from isotropic distribution, obtained when account is taken of the observed ratio of the particles emitted in the forward and rear hemispheres.

[3)] n_s is the number of charged particles with ionization $I > 1.4 I_0$, where I_0 is the lowest ionization of the relativistic singly-charged particle.

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