Multiple production of particles in the interaction of iron-group cosmic-ray nuclei with energies 4–500 GeV/nucleon and Ag and Br nuclei at small impact parameters

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The characteristics of multiply created particles (number, half-angles, pseudovelocity distribution) in central collisions of heavy nuclei ($Z \geq 20$) with Ag and Br nuclei in a photoemulsion are obtained for the first time at energies up to 500 GeV/nucleon. A new theoretical interpretation of the experimental data is proposed.

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The purpose of this paper is to study the central collisions of nuclei with very high energies. In order to discover such events, interactions of nuclei with $Z \geqslant 20$, accompanied by high multiplicity of relativistic particles ($N_s = 50$–554) and simultaneously a large number of highly ionized particles ($N_h > 20$) were selected. The estimated number of in-

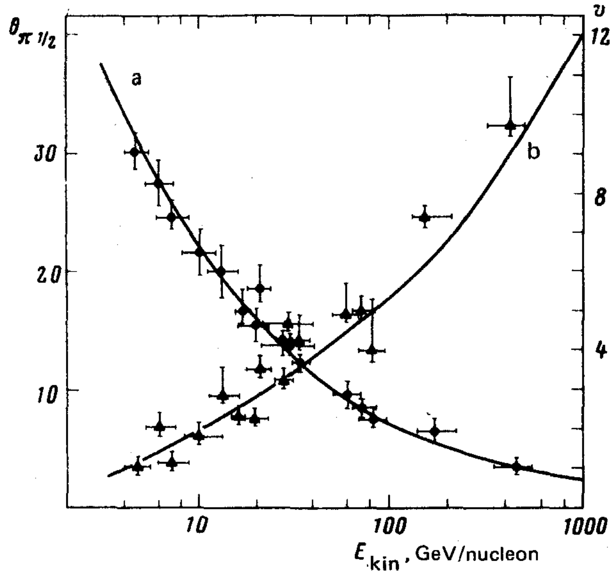

FIG. 1. As a function of the energy of the incident nucleus: (a) one-half the meson departure angles, $\theta_{\pi 1/2}$; (b) specific meson multiplicity $\nu = N_{\pi^\pm}/n_{\rm int}$. In each interaction: $N_{\pi^\pm} = N_s - (z - 2N)$, where z is the charge of the incident nucleus, N_α is the number of relativistic α particles, $n_{\rm int} = 2.15(z - 2N_\alpha - n_{n\rm int})$, where $n_{n\rm int}$ is the number of noninteracting relativistic protons, departing at angles <0.3 p, p is the momentum of the incident nucleus in (GeV/s)/nucleon; the points show experimental values and the curves show the calculation.

teracting nucleons in the incident nucleus for the events selected was $n_{\rm int} = 30$–56. The energy of the primary nuclei was determined from the total energy of all secondary particles $E \sim \Sigma_i \langle p_\perp \rangle / \sin\theta_i$. Other energy estimates (from the departure angles of noninteracting and interacting protons in the incident nucleus) agree with the first estimate to within ~30%. Large N_s allows obtaining reliable information from separate interactions.

The following information was obtained from the experiment: one-half the meson departure angles $\theta_{\pi 1/2}$ (Fig. 1a), specific meson multiplicities $\nu = N_{\pi^\pm}/n_{\rm int}$ (Fig. 1b), and the distribution of relativistic particles over the pseudovelocity η (Fig. 2). As is evident from Fig. 2, the width of the η distribution increases with increasing energy. Figure 3 shows the energy dependence of the amplitude of the pseudovelocity distribution $A_\eta = (\Delta N_s/\Delta\eta)/N_{\pi^\pm}$ at one-half the meson departure angle. The quantity A_η, inverse to the distribution width, decreases with increasing energy for $E \gtrsim 15$–20 GeV/nucleon. The model of nuclear pionization, which successfully describes the interaction of heavy nuclei for $E \gtrsim 15$ GeV/nucleon,[1] cannot describe this behavior of the amplitude A_η (and the η distribution as a whole).

Thus, the experimental results indicate that a new approach to describing collisions of nuclei at very high energies is necessary. This is also indicated by the development of the thermodynamic model in application to elementary processes at high energies.[2]

In formulating a new approach, we will adhere to the analogy of the picture of multiple production in a recently proposed thermodynamic model,[2] which successfully explains many characteristics of diverse elementary processes occurring at different energies. The most probable channel for nuclear interaction is separation and fusion into a single compound system (CS) of the gluon fields of the nucleons in the interacting nuclei. In contrast to the model of nuclear pionization[1] and according to Ref. 2, we assume that only part of the CS energy is thermal energy. The rest of the energy occurs in the form of longitudinal collective motion of subsystems, comprising the hadronic matter of the CS. Valence quarks of nucleons are realized in the form of leading baryonic clusters of the incident and target nuclei. Their decay in this scheme is examined in the same way as in Ref. 1.

The kinematics of the interaction is determined by the laws of conservation of energy and momentum for the three-cluster system. In the center-of-mass system

$$(m_p C^2 + 3/2\, T_\mathrm{B})(N_1\gamma_1 + N_2\gamma_2) + E_{cs} = E_{cms},$$

$$(m_p C^2 + 3/2\, T_\mathrm{B})(N_1\sqrt{\gamma_1^2 - 1} + N_2\sqrt{\gamma_2^2 - 1}) = 0, \tag{1}$$

$$E_{cs} = \langle k \rangle [E_{cms} - m_p C^2 (N_1 + N_2)],$$

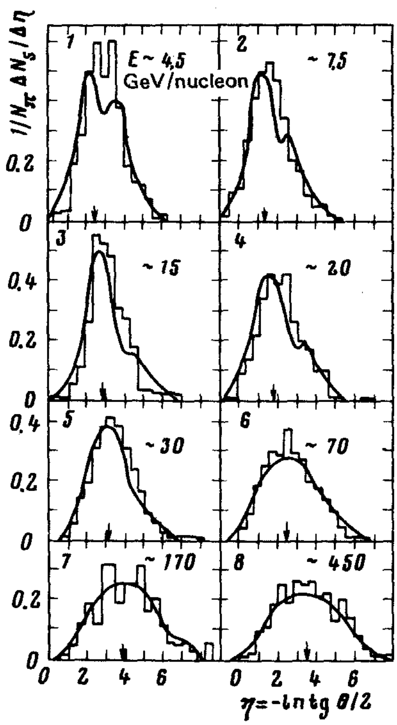

FIG. 2. The distribution of relativistic particles over the pseudovelocity $\eta = -\ln \mathrm{tg}\theta/2$ for kinetic energies of the incident nuclei. In the distributions, $N_c(N_s, N_{\pi\pm})$, where N_c is the number of events, assumes the values: 1) 6 (334, 284); 2) 6 (400, 365); 3) 3 (436, 364); 4) 5 (685, 562); 5) 3 (671, 562); 6) 3 (747, 675); 7) 1 (193, 174); 8) 1 (554, 528); the arrows indicate the value of η corresponding to $\theta_{\pi 1/2}$; the histograms show the experimental values and the curves show the calculation.

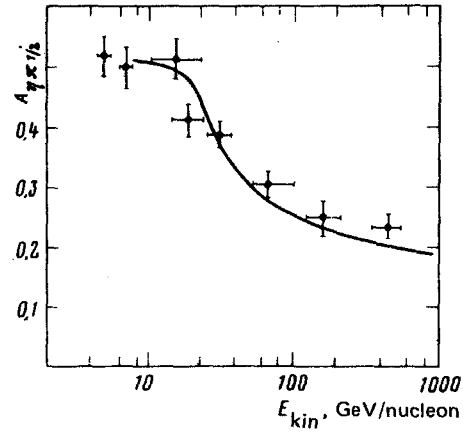

FIG. 3. Amplitude of the pseudovelocity distribution $A_\eta = (\Delta N_s/\Delta\eta)/N_{\pi^\pm}$ at one-half the departure angle of mesons (averaged over the range $\Delta\eta = \pm 0.6$ relative to $\theta_{\pi 1/2}$) as a function of the energy of the incident nucleus; the points are the experimental values and the curves indicate the calculation.

where $T_B = 0.1$ GeV; γ_1 and γ_2 are the temperature and Lorentz factors of the baryonic clusters; E_{cms}, N_1, and N_2 are the energy (in the center-of-mass system) of the overlapping parts of nuclei and the number of nucleons in them; $\langle k\rangle = 0.5$ is the average coefficient of rigidity; m_p is the proton mass; and E_{CS} is the total CS energy. In analogy with Ref. 2, the thermal energy of the CS is $W_{CS} = E_{CS}\delta_T$, where $\delta_T = y_m/\mathrm{sh}\,y_m$. The quantity $y_m = a\ln(1 + C_1 w/C_2)$ determines the velocity interval in which the CS matter is uniformly distributed and, in addition, $w = \langle k\rangle(\sqrt{S_{pp}} - 2m_pC^2)$. The parameter $a \approx 1$ is introduced in order to describe the possible deviations of the quantity y_m from its value in a pp interaction, where $a \equiv 1$. Further calculations were carried out using the equations of the thermodynamic model[2] with $a = 1$ and assuming that hadronization of CS into mesons occurs at the same temperatures (and, therefore, energy densities as well) as in an elementary event.

The results of the calculation agree well with experiment (Figs. 1-3). The agreement between calculation and experiment in Fig. 1a makes it possible, using the predictions of the model, to determine the interaction energy from the quantity $\theta_{\pi 1/2}$. It should be emphasized that, according to relations (1), the quantities ν and $\theta_{\pi 1/2}$ depend on the ratio of the interacting (overlapping) nuclear masses $m = N_1/N_2$. In central collisions "Fe" + Ag, Br we have $m = 0.75$-0.85, which is close to the case of pp interaction. As m is decreased, the quantities ν and $\theta_{\pi 1/2}$ increase. Qualitatively, this characteristic explains the experimentally observed difference between the quantities ν and $\theta_{\pi 1/2}$ in central "Fe" + Ag, Br interactions and the corresponding values in collisions between protons and light nuclei and Ag, Br nuclei on the one hand and the closeness of the results of this work to the case of pp collisions on the other (not shown in Fig. 1).

Conclusions. The new data on interaction of "Fe" + Ag, Br nuclei at high energies agree with the approach proposed here, constructed according to a unified scheme, including the process of multiple creation in elementary interactions. The closeness of a to unity apparently indicates the fact that in nuclear interactions dissipative processes are balanced by an additional contribution of energy to collective motion in the CS due to the presence of multinucleonic successive interactions. This interesting problem deserves further study. At energies of 4-15 GeV/nucleon, the approach proposed is evidently equivalent to the model of nuclear pionization, i.e., it automatically reproduces its results.

[1]) Joint Institute for Nuclear Research.

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