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# The revelation of the quark-gluon plasma in the inelastic collisions of the primary cosmic protons with air nuclei at energies 3–6 TeV in the center-of-mass system(*)

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**Summary.** — The five-fold decrease with increasing energy in the observed ratio between the observed energy in the cores of air showers and the total number of electrons in these showers suggests a large dissipation of the primary energy in a shower as the observed number of electrons exceeds $10^6$. The apparent existence of events wherein thousands of pions of 3–6 GeV are generated in the colliding nucleon-nucleon c.m. system, suggests the formation of a "united gluon field", without quarks, in the c.m. system of the colliding nucleons and its subsequent hadronization upon expansion, including passing through a quark-gluon plasma.

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PACS 96.40.De – Composition, energy spectra, and interactions.
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## 1. – Air shower observation

The investigation of extensive air showers (EAS) has revealed a number of contradiction to the assumption that the break of the EAS spectrum around an electron number $N_\mathrm{e} \simeq 10^6$ is a break in the primary cosmic ray spectrum [1]. The spectra of the EAS generated by primary protons deep in the atmosphere and of the showers generated by the primary cosmic ray nuclei have no break (fig. 1). The absorption of the electron flux between atmosphere depths of 720 g/cm$^2$ and 960 g/cm$^2$ is different for showers with age parameter $S < 0.7$ and $S > 1.05$. The absorption lengths of the EAS with $S < 0.7$ in the atmosphere being $\lambda_\mathrm{abs} \leq 90$ g/cm$^2$ and with $S > 1.05$ being $\lambda_\mathrm{abs} \geq 160$ g/cm$^2$. This confirms the correct identification of these primary cosmic ray particles as protons and heavier nuclei accordingly. Figure 2 shows that the assumption that the break in the

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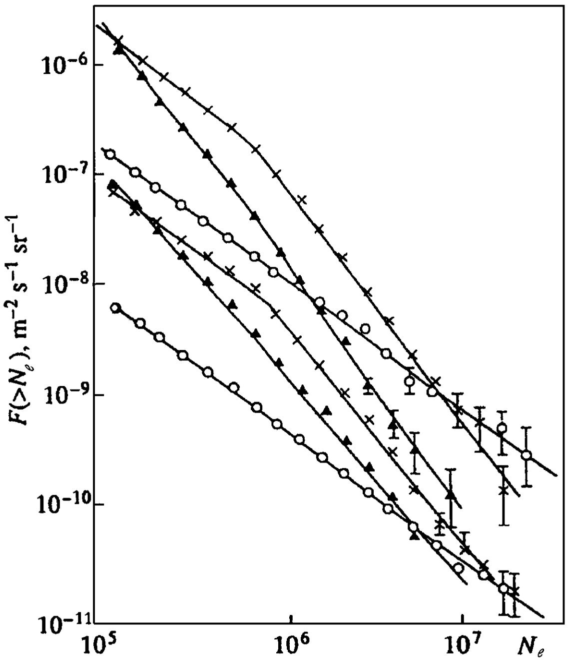

Fig. 1. – Spectra of EAS with $0.75 \leq S < 1.05$ (crosses). $S \geq 1.05$ (closed triangles), and $S < 0.75$ (open circles) for two intervals of the zenith angle $\Theta$: $\Theta < 25°$ for the three upper spectra and $\Theta > 25°$ for the three lower spectra.

EAS energy spectrum is connected with the break in the energy spectrum of primary protons has to be accompanied by a second assumption about an increasing flux of primary nuclei. These two suppositions can be replaced by the single proposition that there is a large increase in the multiplicity of the secondary hadrons in inelastic nucleon-nucleon collisions at energies higher than 3–6 TeV in the nucleon-nucleon center-of-mass (c.m.) system. One can see in fig. 2 that the coefficient of connection between the primary proton energy and the observed number of electrons in the shower increases by more than a factor of four.

The impossibility to observe the inverse break [2] by means of the installation with the wide separated detectors is connected with the necessity to have the experimental data about electron flow in more than five detectors, which are placed up to an area of $\sim 10^4$ m$^2$ around the EAS core. This inverse break was confirmed in the hadron experiment [3].

An underestimation of the energies of the primary particles, which generate EAS with a number of electrons $N_e > 10^6$ can be seen in the experimental observed disappearance of primary nuclei at energies $\sim 3$–$5 \cdot 10^{18}$ eV instead of $5 \cdot 10^{19}$ eV, as it was in the result of the resonance disintegration of nuclei in the collisions with relic protons [4].

The break in the electron number spectrum of EAS and, at higher energies, the return break, may be understood in the context of: 1) the five-fold decrease in the relative energy in the EAS cores for showers with a number of electrons $N_e \geq 5 \cdot 10^6$, 2) the predominance of the showers absorbed between the breaks similar to the hadron-electron avalanches (fig. 2), and 3) the underestimation of the energy by which one observes the relic cutoff

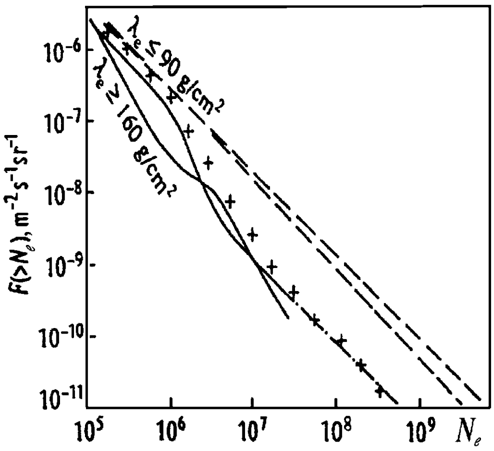

Fig. 2. – Integrated electron number spectrum of EAS at an atmosphere depth of 760 g/cm$^2$ (+) and its two components with the different values of the absorption ($\Lambda_a$) of the electron number. Stroke straight lines conform to the expected spectrum of EAS in the case of the standard model of the hadron multiproduction.

of primary nuclei [4]. All of these experimental results together contradict the supposed existence of a break in the primary cosmic ray energy spectrum at energies of about $\sim (2\text{–}3) \cdot 10^{15}$ eV and suggest a significant increase of the multiplicity of the secondary hadrons at energies of the colliding nucleons higher than 3–6 TeV in the nucleon-nucleon c.m. system.

If this underestimation of the primary energy of the EAS beginning at the knee of the EAS spectrum with a number of electrons $N_\mathrm{e} \simeq 10^6$, is taken into account, then the energy spectrum derived from the satellite studies of cosmic rays at energies $E_0 < 10^4$ GeV can be extended up to $10^{10}$ GeV. Hence the energy dependence of the total cosmic ray flux can be represented by $F(E_0) = (2.0{\pm}0.2)E_0^{-2.7\pm0.03}$ cm$^{-2}$s$^{-1}$sr$^{-1}$GeV$^{-1}$ through this entire energy range [5]. It should be noted here that this spectrum of the cosmic rays flux includes the galactic as well as the extragalactic cosmic rays.

Another particular feature of interest is the softness of the cosmic ray spectrum $F(\geq E_0) \sim E_0^{-1.7}$ in comparison with the spectra of $\gamma$-quanta from the local galactic and extragalactic sources $F(\geq E_\gamma) \sim E_\gamma^{1.4\pm0.1}$ [6]. Besides, different sources have their limit of the highest energies for the acceleration of protons and nuclei. One can suppose that a unified energy spectrum of the cosmic rays can be formed in extragalactic space by energy losses through the repeated elastic collisions with relic photons.

## 2. – The hadron high multiplicity production in the c.m. system and the revelation of the quark-gluon plasma

The experimental results presented in the previous section (fig. 3) lead to a conclusion concerning the increase of the multiplicity of secondary hadrons in high-energy inelastic hadron collisions, but do not provide a quantitative estimate of this increase. A new hard claim concerning the properties of hadron inelastic collisions emerged after the discovery of a large number of non-relativistic neutrons with a significant time delay relative to the detection of the main EAS front of the relativistic particles [6] (fig. 3). It is possible that

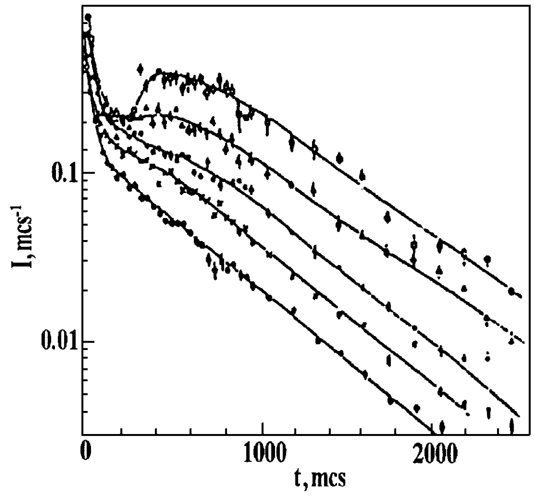

Fig. 3. – Temporal distributions of the number of neutron $I$ for the different total multiplicity of neutrons detected in monitor: 316–400, 500–630, 794–1000, 1258–1584, 1995–2511 (from bottom to top).

the observed hundred-fold increase in the number of non-relativistic neutrons corresponds to a comparable increase in the hadron stream close to the observation level. And this sharp increase of the hadron stream in the cascade may be due the high-multiplicity production of hadrons in the first interaction of the primary protons with nuclei of the atmosphere. This extremely high hadron multiplicity is possible if half of the energy in the c.m. system of the colliding nucleons is distributed among the secondary pions with extreme low energies in the c.m. system. If one supposes the energies of secondary pions in the c.m. system to be 0.5 GeV or 5 GeV for the secondary nucleons, we obtain the tenfold difference in the multiplicity after the first interaction but approximately the same number of hadrons after three or, at the generation of protons with energies of 5 GeV in the c.m. system, four generations of the following cascades in the atmosphere. An advantage of this experiment is that it deliberately includes an observation threshold for EAS with primary energies below the threshold of the change in the multi-hadron production discussed above. The analysis of 848 showers with electron numbers $N_\mathrm{e} > 10^6$ revealed 25 showers, which were accompanied by a large number of neutrons: from 1260 up 2510 neutrons in one section of the neutron monitor within a time interval of 3.6 ms. It is a new phenomenon, which was not observed at smaller energies. The problem of explaining such showers with long delays relative to the shower front and the double-peaked shape of the neutron arrival time distribution can be solved only by the proposition of the change in the process of the generation of the EAS. The lateral distribution of these non-relativistic neutrons is estimated to range up to 20 m and the total number of the non-relativistic neutrons is interpreted to exceed 10% of the number of electrons in showers with $N_\mathrm{e} > 5 \cdot 10^6$. Such a neutron flux is possible if the first interaction of the primary cosmic ray produces an extremely high multiplicity of secondary hadrons. This in turn may mean that the gluon fields of the colliding nucleons form a single excited gluon clot in the center-of-mass system of the colliding particles. The gluon clot then transforms into the quark-gluon plasma, and its subsequent hadronization, mainly into pions, results in the generation of more than 6000 hadrons with energies of 0.5 GeV, or mainly into nucleons with energies of 5 GeV in the c.m. system. The subsequent cascade development of the sheaf of the many thousands hadrons proceeds through the standard hadron multi-production process, but only over two-to-four cascade generations. Such a cascade scheme appears to conform exactly to the experimental results which were obtained in the observation [6]. The selection of the 25 showers out of 848 showers with a number of electrons $> 10^6$ is determined by the energy threshold of this new process in the inelastic collisions (the number of the electrons in EAS $N_{\mathrm{e}} \geq 3.5 \cdot 10^6$) and by a selection of the depth of the first interaction of the primary protons in the atmosphere to be $\geq 200$ g/cm$^2$. The assumption of an extremely high multiplicity of secondary hadrons in the first inelastic interaction of primary protons in the atmosphere can explain the electron number spectrum of EAS in fig. 1 and 2 without the supposition of some knee in the primary cosmic ray spectrum.

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