Variation in nuclear composition of primary cosmic rays in the energy range 10^{17}–10^{19} eV

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Distributions of the height of maximum development of extensive air showers constructed from measurements of Čerenkov light at the Yakutsk extensive-air-shower installation have been analyzed. The relative numbers of protons and nuclei among the primary particles with energies of 10^{17}–10^{19} eV are estimated.

It was shown in Ref. 1 that the nuclear composition of the primary cosmic rays varies only negligibly over the energy range 10^{15}–10^{17} eV and is similar to the composition of primary particles at $\sim 10^{12}$ eV. For example, the experimental data on the fluctuations in the relative number of muons in extensive air showers (EASs) with a primary energy $\sim 9 \times 10^{16}$ eV do not contradict the suggestion that $\sim (50 \pm 6)\%$ of the primary particles are protons, while $(40 \pm 4)\%$ of the primary cosmic rays with energies $\gtrsim 10^{12}$ eV are protons, according to measurements outside the atmosphere.

We have studied the effective cross section for the inelastic collisions of protons with nuclei of air atoms by working from the distribution of the height of maximum development of EASs in two ranges of the energy of the primary particles, 10^{17}–10^{18} eV and 10^{18}–10^{19} eV (Fig. 1).[2] The right side of these distributions is determined primarily by the effective cross section for the inelastic collisions of protons with nuclei of air atoms. The height of maximum shower development was determined from the spatial distribution of the Čerenkov light over the interval of the distances 100–600 m from the axis of the shower.

Interestingly, there are differences between the distributions (Fig. 1) at these two energies, in the dispersion and the shape of the distribution near its peak. Since the

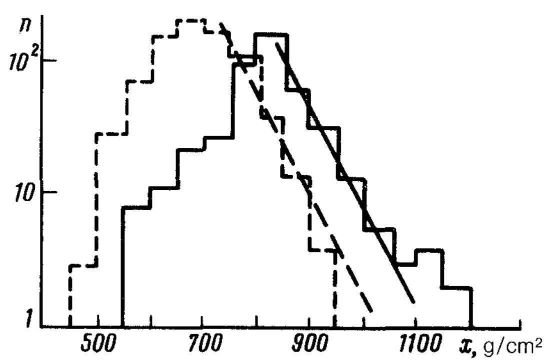
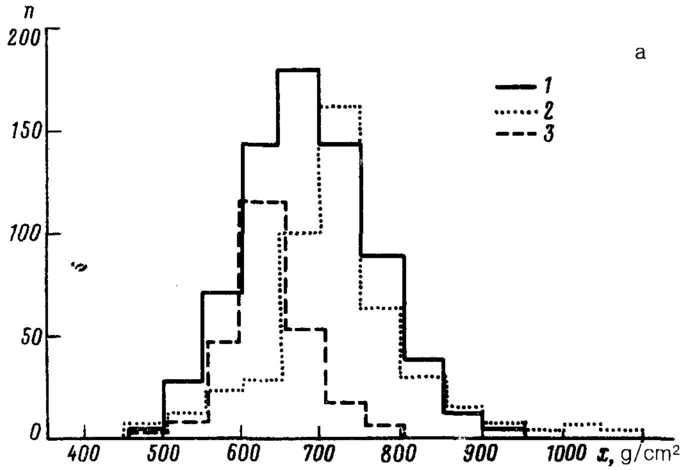


FIG. 1. Distribution of the height of maximum development of extensive air showers for primary particles with energies of 10^{17}–10^{18} eV (dashed histogram) and 10^{18}–10^{19} eV. The straight lines correspond to exponential functions with ranges of 57–60 g/cm^2 (Ref. 2).

right side of the distributions is formed by showers from primary protons, there is a substantial deficiency of showers from primary nuclei in the distribution of showers with respect to the height of the maximum at primary energies of 10^{18}–10^{19} eV.

In Fig. 2, these distributions are presented in linear scale, and the heights of the



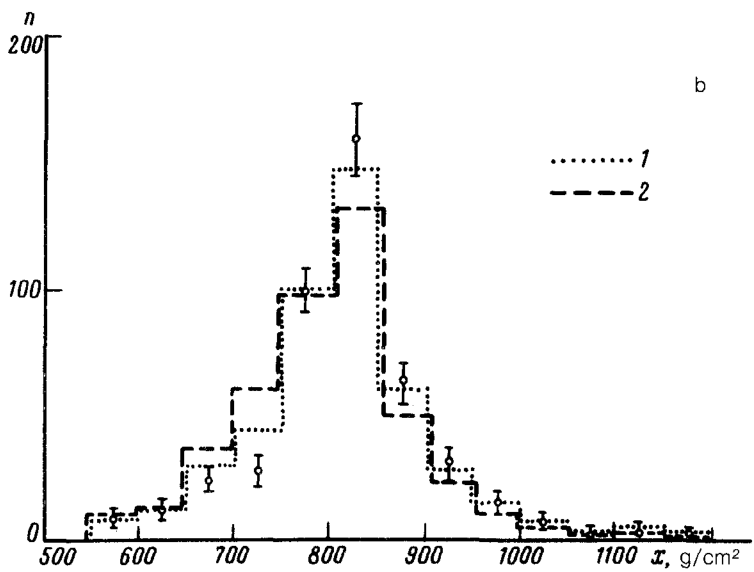


FIG. 2. Number of EASs with a development maximum at a depth x (in grams per square centimeter). a: Histogram 1—Distribution for primary particles with energies of 10^{17}–10^{18} eV; histogram 2—for primary particles with energies of 10^{18}–10^{19} eV; histogram 3—the difference, which is interpreted as consisting of showers from primary cosmic-ray nuclei with energies of 10^{17}–10^{18} eV. b: Experimental data on the height of maximum shower development in the atmosphere for primary particles with energies of 10^{18}–10^{19} eV. The histograms here show the distributions which would be expected if nuclei constituted (1) 10% and (2) 20% of the number of primary particles.

maxima of showers with a primary energy of 10^{18}–10^{19} eV have been shifted up the height scale in order to bring the right-hand (proton) parts of the distributions in Fig. 1 into coincidence. Making the assumption that all the primary cosmic rays with energies in the range 10^{18}–10^{19} eV are protons, and normalizing the distribution in the range 10^{17}–10^{18} eV on the basis of the proton part (deeper than 700 g/cm^2), we can estimate the relative number of nuclei in the primary cosmic rays with energies $\sim 10^{17}$–10^{18} eV. Figure 2(a) shows this distribution, as the difference between two histograms. In determining this difference it is necessary to "smooth" the distributions somewhat in order to avoid negative values in the flux of primary particles. The difference between the depth of the distribution maxima for the primary protons and for the nuclei agrees completely with that which would be expected on the basis of electromagnetic cascade theory for an average of $\gtrsim 10$ nucleons in the cosmic-ray nuclei. The fraction of nuclei in the energy interval 10^{17}–10^{18} eV is found to be $(36 \pm 10)\%$. This estimate is on the low side. The reason is that we have assumed that there are absolutely no nuclei in the flux of primary particles at energies of 10^{18}–10^{19} eV, while the difference between the two distributions of the shower maximum heights for showers from primary particles of different energies characterizes primarily only the change in the relative number of nuclei in the primary cosmic rays with the primary energy. To determine the fraction of nuclei which would be allowed by the distribution of the development maximum heights of showers at primary energies of 10^{18}–10^{19} eV, we use the distribution of heights for showers from primary nuclei and from primary protons: distributions similar to histograms 3 and 2 in Fig. 2(a), i.e., the distributions observed experimentally. The overall distributions expected under the assumption that nuclei constitute 10% and 20% of the flux of primary particles with energies of 10^{18}–10^{19} eV are compared with experimental data on the height of maximum shower development in Fig. 2(b).

In the energy range 10^{16}–10^{19} eV we thus observe a systematic increase in the relative number of protons: $(43 \pm 5)\%$ at $\sim 1.2 \times 10^{16}$ eV, $(50 \pm 6)\%$ at $\sim 9 \times 10^{16}$ eV $(60 \pm 10)\%$ at $\sim 5 \times 10^{17}$ eV, and $(90 \pm 10)\%$ at 5×10^{18} eV. This result means that the "slope change" in the energy spectrum of the primary cosmic rays in the energy interval 10^{15}–10^{16} eV is not a consequence of the particular parameters characterizing the escape of cosmic rays from the local galaxy.

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