FLUCTUATIONS OF DEVELOPMENT MAXIMUM DEPTH AND NUCLEAR COMPOSITION OF PRIMARY COSMIC RADIATION

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ABSTRACT

The EAS cascade curves from the Cerenkov light lateral distribution measurements are recovered and the maximum depth fluctuations of the shower development σX_m both on the Cerenkov and charged EAS components are defined. At $E_0 \simeq 10^{18}$ eV the mean content of protons is greater than 85%, and p-air cross section $\sigma_{p-air} \leq 750$mb.

1. Method. The lateral distributions of the EAS Cerenkov light Q(R) in the interval of the core distances R = 20 ÷ 1500 m, and in a wide range of primary energies $E_0 = 8.10^{16} \div 1,5.10^{19}$ eV on the EAS Cerenkov light observations at the Yakutsk array for 1970-1983 are analyzed. In Fig.1 the average cascade curves of the EAS electrons $N_e(X)$ recovered from Q(R) by the method [1] are presented. Errors of $N_e(X)$ due to the measurement errors of Q(R), the uncertainty of the angular distribution function of the electrons in partial showers [2] and aerosol distribution in atmosphere [3] are shown by dashes.

2. Results. Dependence of the average depth of maximum $\bar{X}_{max}$ on E_0 is as follows:

$$\bar{X}_m = (720\pm16) + (73\pm14)\cdot \lg(E_0/10^{18}) \qquad (1)$$

It is the main not only for a choiceof the EAS development model (here and further we shall mean by it a choice of the multiplicity law and the energy spectrum of secondary particles) but also for the determination of the energy dependence of hadron-air cross section and of nuclear composition of primaries.

The cascade curves presented in Fig.1 and described by the gamma distribution allow to obtain the total energy E_{EM} of the EAS electron-photon component on the energy dissipated by electrons over the observation level X_0.

$$E_{EM} = \frac{\beta}{t_0}\sqrt{1 + 3.5\,(X_m/X_0)^6}\cdot \int_0^{X_0} N_e(X)\,dX\ , \qquad (2)$$

where β is critical energy and t_0 is a unit of radiation length in the air.

From analysis of relations E_{EM}/E_0 and $N_e(X_m)/N_e(X_m-300)$ we find out that the Landau hydrodynamic model with the multiplicity law of secondary particles $n_s \propto E_0^{1/3}$ and with normal law of their rapidities corresponds the most to the experiment. This model also better agrees with experimental energy-dependent fluctuations in X_m:

$$\sigma X_m = (66\pm4) - (12\pm2) \cdot \lg(E_o/10^{18}) \qquad (3)$$

The dependence (3) is obtained by data of 980 shower events on a slope of the lateral distribution function (LDF) of charged particles (black triangles in Fig.2)and by 150 events on the recovery methods $N_e(X)$ on Q(R)(open squares). This dependence slightly differs from our earlier results [4] owing to more correct account of measurement errors and increase of the EAS statistics. For the comparison in Fig.2 the expected dependences σX_m on E_o are presented for the models HDM and MPM. The latter one has $n_s \propto \ln E_o$ and almost constant energy spectrum of secondary particles in units of rapidities. Nuclear composition of primaries was taken in the calculation as consisting of protons and nuclei of the group VH(A = 51) in different ratios determined by the mean mass number $\langle A \rangle$. Such mass composition at fixed $\langle A \rangle$ gives the largest values of the depth of maximum and its fluctuations in comparison with any other composition of primaries. Therefore at fixed E_o and the EAS development model the low boundaries of errors of $\bar{X}_m$ and σ_{X_m} give the upper estimation $\langle A \rangle$ and σ_{p-air}. An alternative possibility is monochromatic nuclear composition of primaries which leads to the smallest meanings of X_m and σ_{X_m} at fixed $\langle A \rangle$.

3. Discussion. In Fig.2 a different character of the dependence σ_{X_m} on E_o for HDM and MPM at the same meaning $d\bar{X}_m/d\lg E_o$ = ER is explained by the fact that both models preliminarily were reduced to the same $\bar{X}_m$ = 720 g.cm^{-2} at E_o = 10^{18}eV by the variation $\langle A \rangle$. Therefore the composition on MPM with the increase of E_o changes from the enriched heavy nuclei ($\langle A \rangle \simeq 40$) to more mixed one and the fluctuations increase. And on HDM the composition from more mixed ($\langle A \rangle \simeq 6$) becomes a purely proton one and σ_{X_m} decreases. The opposite character of the dependence σ_{X_m} on E_o according to the MPM model at various meanings of ER is caused by the fact that at $(ER)_{calc.} < (ER)_{exp.}$ one should enrich the nuclear composition by heavy nuclei and otherwise - by protons. And only at absolute equality $(ER)_{calc.} = (ER)_{exp.}$ the composition must not change with energy. Obtained σ_{X_m} on (3) is in favour of the increase of the interaction cross section with energy and high values of ER $|d\sigma_{X_m}/d\lg E_o|$ evidence the enrichment of the nuclear composition by protons with the increase of E_o, i.e. $d\langle A \rangle/d\lg E_o < 0$.

In Fig.3 the dependences $\overline{X}_m$ and σ_{X_m} on $\langle A \rangle$ for various meanings of p-air cross sections are presented. Here by selection of the scale the experimental data on $\overline{X}_m$ and σ_{X_m} are combined into the dashed region which allows to localize those meanings σ_{p-air} and $\langle A \rangle$ which satisfy the measurements (choice of meanings of these parameters is shown in the bottom in Fig.3)

Thus, if the Landau hydrodynamical model is realized then according to our measurements the mean content of protons in the primary cosmic rays is greater than 85 % and p-air cross section $\sigma_{p-air} \leq 750$ mb at $E_o = 10^{18}$ eV.

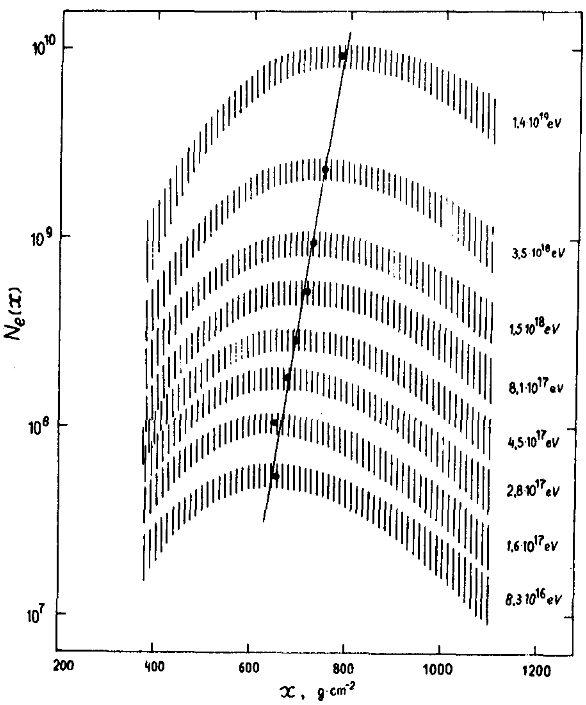

Fig.1. Cascade curves of development of the EAS electrons. Points indicate locations of the maximum depth of the EAS development.

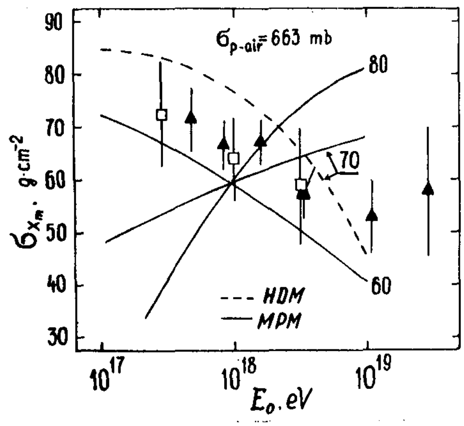

Fig.2.
Dependence of fluctuation value σ_{X_m} of the shower development maximum depth on the primary particle energy. Triangles and squares are experimental data, lines - calculated values. Figures near the curves are $d\overline{X}_m/d\lg E_o$.

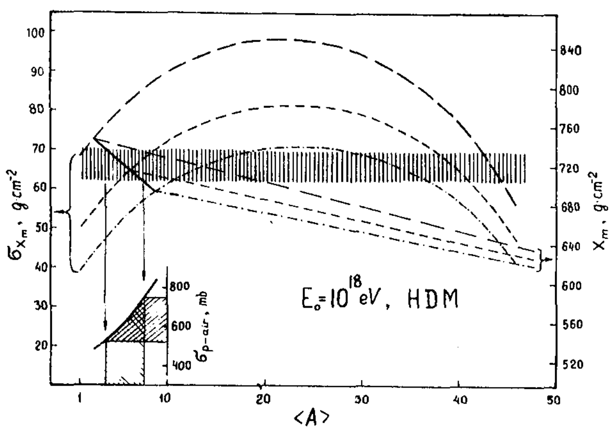

Fig.3. Dependence of the mean value $\overline{X}_m$ and σ_{X_m} on the mean atomic weight of the primary ensemble. Dashed region is the region of measured values X_m and σ_{X_m} with errors. Dashed, dotted and dash-dotted lines show the calculation for σ_{p-air} = = 460, 660 and 840 mb, respectively. Values ⟨A⟩ and σ_{p-air} which satisfy the experiment are determined by a solid line.

References.

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