Investigation of the wave form of Cerenkov-radiation pulses from extensive air showers

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Experimental data and calculation results are presented on the duration of a Cerenkov pulse of an EAS in the distance range 200–1000 m. The possibility of determining the composition of the primary radiation, of choosing the model of shower development, and of estimating the range of the nuclear interaction at energies above 10^{17} eV is discussed.

The investigation of the wave form of the Cerenkov pulses, initiated in[1, 2] was continued in 1973–1974 in the Yakutsk Comprehensive EAS facility. The receivers for the Cerenkov light from the EAS were four FÉU-65 photomultipliers, one located at the center of the facility and the three others symmetrical about the center at a distance ~250 m. The arrival direction, the axis position, and the particle number N_e in the shower were determined from the data of the Yakutsk EAS facility. We chose for the analysis showers with $N_e \geqslant 10^7$, for which the influence of the selection system distorts the results little. After 280 hours of operation of the facility, 48 showers were registered. In these showers, the distance r from the axis to the detector lies in the range $200 < r_\perp < 1000$ m and the number of particles lies in the range $10^7 < N_e < 2\times 10^8$.

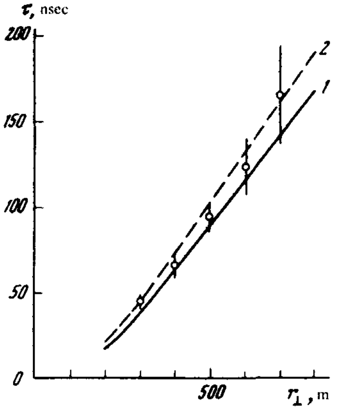

FIG. 1. Average pulse duration vs. distance to the shower axis. Curve 1—calculation for protons by the HMM model, curve 2—the same for the CKP model.

The principal parameters characterizing the Cerenkov pulse are chosen to be the duration at half-height τ and the amplitude A. The accuracies with which τ and A were determined were ~10% and ~20%, respectively. The pulse durations and amplitudes were corrected to take apparatus distortion into account.

For comparison with experiment, we calculated the waveform of the Cerenkov pulses. The angular distribution of the particle showers was taken to be the same as in[3] and it was assumed, as in[4], that the Cerenkov light propagates in the direction of the particle motion;

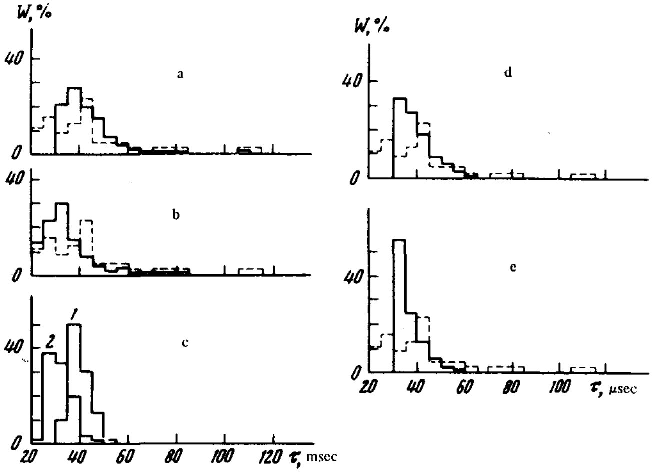

FIG. 2. Distribution with respect to the pulse durations at a distance 300 m. The calculated histograms are shown by solid lines: a-protons, CKP model; b-protons, HMM model; c-nuclei of group M, histogram 2-HMM model, d-approximate calculation for $\lambda = 40$ g/cm^2; e-approximate calculation for $\lambda = 30$ g/cm^2.

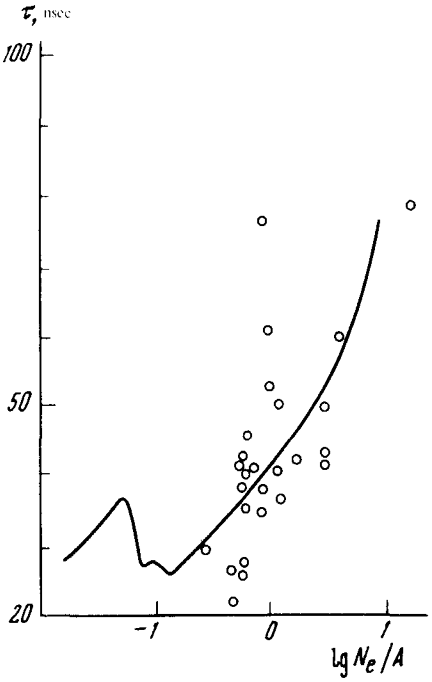

FIG. 3. Pulse duration as a function of the parameter N_l/A. Calculation by the HMM model for a composition $p = 50\%$, $= 25\%$, $M = 12\%$, and $H = 13\%$.

the lateral distribution of the particles was not taken into account. As shown by calculations, allowance for the lateral distribution of the electrons has little effect on the results. Thus, the pulse duration increases by only 7%.

Individual cascade curves were calculated by the Monte Carlo method for the CKP (Cocconi-Koester-Perkins) model ($n_s \sim E_0^{0.25}$) and the HMM (high-multiplicity model; $n_s \sim E_0^{0.5}$) at a primary energy 10^{17} eV. The calculation method is described in detail in[5,6].

Figure 1 shows the calculated and experimental durations τ of the Cerenkov pulses as functions of the distance $r_\perp$ to the shower axis. To increase the statistics, all the pulse durations and amplitudes were referred to a single angle $\theta = 0°$, using the calculated $\tau(\theta)$ and $A(\theta)$ relations.

Within the limits of the statistical errors, the experimental points agree with both the CKP and the HMM models.

In Fig. 2 are compared the experimental and calculated distributions with respect to the pulse duration at a distance 300 m from the shower axis. To plot the experimental distribution, all the durations are referred to a fixed distance $r_\perp = 300$ m, using the calculated $\tau(r_\perp)$ relations.

The best agreement between calculation and experiment is observed for the proton composition. The lower limit of the experimental distribution agrees better with the lower limit of the calculated distribution for the HMM model.

To illustrate the variation of the distribution on going to heavier nuclei, Fig. 2c shows the calculated distributions for the nuclei of group M and for two shower-development models.

An analysis of the calculation shows that the duration of the Cerenkov pulses at large distances from the shower axis (~ 300 m) is practically uniquely connected with the depth X_m of the shower maximum.

Let $X_{\min}$ be the minimal depth of the shower maximum. The results of the calculation do not contradict the assumption that the distribution with respect to the depth of the shower maximum, at a fixed depth X_0 of the first interaction, is given by

$$W(X_m - X_{min}; X_0) \sim \exp[-(X_m - X_{min} - X_0)/l],$$

where $l = 50 \pm 10$ g/cm^2. It is then easy to obtain the distribution with respect to X_m:

$$W(X_m - X_{min}) \sim e^{-\frac{X_m - X_{min}}{\lambda}} - e^{-\frac{X_m - X_{min}}{l}} \qquad (1)$$

where λ is the range of the interaction of the primary particle. In the derivation of (1) it was assumed that $\lambda > l$, and in the opposite case it is necessary to reverse the sign.

Figure 2 shows approximate distributions obtained using formula (1) for the values $\lambda = 40$ and 30 g/cm^2 and for $X_{\min}$ corresponding to the CKP model. Owing to the large value of l, a decrease of λ from 80 to 40 g/cm^2 changes little the pulse distribution. However, a noticeable deviation from experiment (see Fig. 2e) is observed already for $\lambda = 30$ g/cm^2, so that it can be concluded that the proton interaction range is apparently not less than 30–40 g/cm^2. This estimate of the lower bound for the interaction range does not depend on the model assumptions, and can be subsequently refined by increasing the experimental statistics.

In Fig. 3 are compared the calculated and experimental dependences of τ on the parameter N_e/A at a distance 300 m from the shower axis. The calculation was performed for a complicated combination of the primary radiation and points to the sensitivity of this dependence to the chemical composition. Thus, the irregularities in the calculated curve at small values of N_e/A correspond to charges with mass numbers 52 and 15.

To plot the experimental dependence, we used events with zenith angles $\theta < 30°$, and all τ and A were referred to the angle $\theta = 0°$ and to the distance 300 m.

The absence of a reliable absolute amplitude calibration admits of a certain arbitrary shift of the theoretical curve relative to the experimental points along the abscissa axis.

The experimental points indicate a steeper $\tau(N_e/A)$ dependence than the calculation. This may be due to the fact that when N_e is determined standard functions of the lateral distributions of the particles, which do not take into account the "age" of the shower, are used. We hope in the future, by shower reduction using individual lateral distribution functions for the particles and by a reliable absolute amplitude calibration of the Cerenkov pulses, to obtain data on the chemical composition of the primary radiation in the energy region $E_0 > 10^{17}$ eV.

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