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ENERGY SPECTRUM OF PRIMARY COSMIC RAYS WITH ENERGIES 100-2000 TeV AS MEASURED BY THE TACT SETUP

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The setup built for studying Cerenkov radiation of large atmospheric showers also measured the intensity and shape of the energy spectrum of primary cosmic rays in the energy range 10^{14}–10^{15} eV.

In recent years, in connection with the intensive development of the super-high energy gamma astronomy, several experimental installations were built for measuring the Cerenkov radiation generated by large atmospheric showers in the atmosphere. The study of large atmospheric showers, which are produced by the interaction of primary cosmic rays (PCR) with the Earth's atmosphere, makes it possible to reconstruct some properties of primary particles, primarily their energy and direction of incidence. Since gamma-quanta are electrically neutral, their trajectories are not distorted by interstellar magnetic fields and point directly to the source of the quanta. This property is mostly used to search for discrete gamma-sources. The presence of gamma-sources is indicated by an excessive amount of large atmospheric showers coming from some direction over the isotropic background of charged particles of PCR. Other parameters of large atmospheric showers, which depend on the nature of primary particles, are used to increase the statistical reliability of selecting showers that are generated by gamma-quanta.

The Tien Shan Atmospheric Cerenkov Telescope system (TACT) described below has been constructed in the Tien Shan Mountains (Kazakhstan) at the altitude of 3300 m above sea level and consists of six Cerenkov radiation detectors arranged evenly over a circle 115 m in radius. Each detector is a searchlight device with a parabolic mirror 1.5 m in diameter, in whose focus a photomultiplier FEU-49 is mounted. The device operates when a pulse exceeding a preset threshold appears in each of the six detectors. A nanosecond technique was used to analyze the differences in times of arrival of the front of Cerenkov photons from a large atmospheric shower at different points and to measure the number of photons registered by each detector. The collected data enabled the direction of arrival, position of the shower axis, and the primary particle energy to be determined with high accuracy. The personal computer-controlled equipment for acquisition and storage of experimental data was designed according to the CAMAC standards [1].

Preliminary measurements carried out in 1993 verified the stability of operation of the facility and the possibility to correctly determine the parameters of individual showers and to measure the energy spectrum of PCR charged particles. In the present paper we examine the results of measuring this spectrum. These measurements, though being a by-product of the gamma-astronomy investigations, are of considerable interest by themselves in the context of discussions about the PCR energy spectrum shape.

In the material presented below, use was made of 377 events registered under the condition of six-fold coincidence, i.e., when signals arrived from all the six detectors.

The angular distribution of the registered showers is depicted in Fig. 1. The effective zenith angle of 2.75° for this distribution corresponds to the setup effective solid angle of 0.00724 steradian. The accuracy of measurement of time intervals in this experiment was ~ 5 ns, which corresponds to an angular resolution of $\sim 0.5°$.

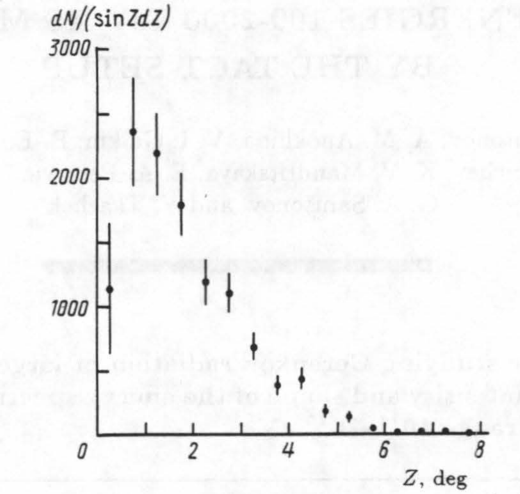

Fig. 1

Angular distribution of the studied showers; Z is the zenith angle (in degrees).

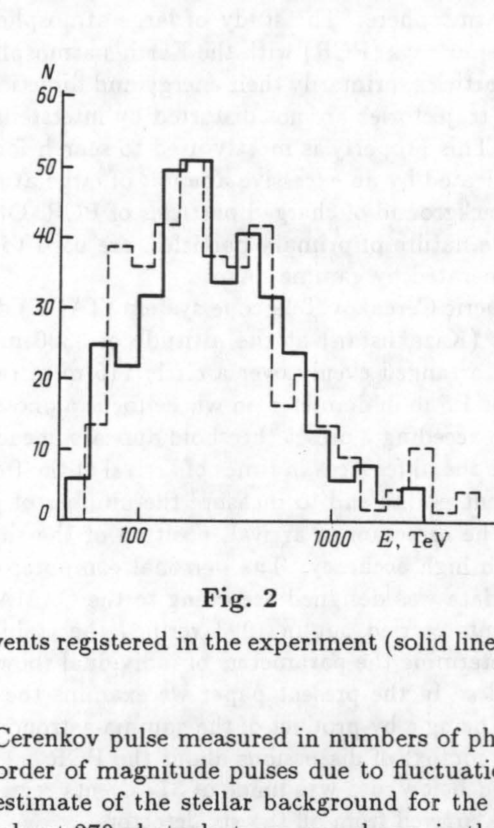

Fig. 2

Energy distributions of events registered in the experiment (solid line) and simulated (dashed line).

The threshold value of the Cerenkov pulse measured in numbers of photoelectrons was chosen in such a way as to exceed by about an order of magnitude pulses due to fluctuations of the background radiation from the stars. The theoretical estimate of the stellar background for the TACT facility is about 2×10^9 photoelectrons/s. A threshold of about 270 photoelectrons was chosen in the course of the experiment. This value corresponds to an energy of PCR nuclei of about 40 TeV (about 20 TeV for primary gamma-quanta). At present, FEU-49 photomultipliers are being replaced by Quasar photoreceivers [2] which have better time characteristics, and the electron measurement channels are also being updated. This will bring about a several-fold lowering of the energy threshold and an improvement of the angular resolution of the setup.

In order to pass from the number of photons recorded to the energy of primary particles a series of calculations were made, whose basic principles are described in [3]. According to these calculations, for

the TACT facility the relation between the total number of Cerenkov photons in the wavelength interval 300–800 nm and the energy interval 100–1000 TeV is described by the expression

$$Q/E = 1.4 \times 10^7 \text{ quanta/Tev.}$$

This formula is valid to within several percent for any charge composition of the PCR: from purely proton to that including only iron nuclei.

To check the effectiveness of the experimental data processing algorithm, a Monte-Carlo simulated bank of artificial events was processed. Energy distributions for registered and simulated events are shown in Fig. 2. The histogram of simulated events, which was obtained assuming a threshold value of 270 photoelectrons, demonstrates satisfactory agreement with the experimental histogram. In the framework of processing of the bank of artificial events, an estimate of the energy measurement accuracy for an isolated event was obtained, which was about 30% for the energy range of 100–1000 TeV.

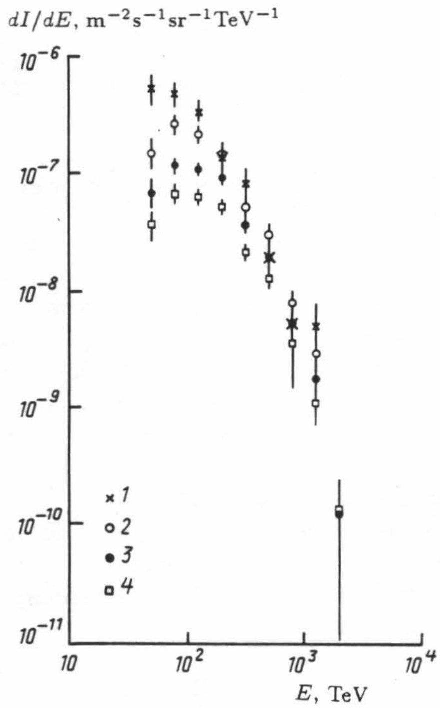

Fig. 3

Differential energy spectra of events registered in circles of the radii $R = 30$ m (1), 60 m (2), 90 m (3) and 120 m (4).

To obtain an undistorted PCR spectrum, only those events should be included in the processing for whose parameters the detection efficiency is close to 100%. The detection efficiency depends on the distance between the shower axis and the setup center, and on the primary particle energy. To assess the efficiency, differential energy spectra of showers with axes fitting in circles with radii of 30, 60, 90 and 120 m were constructed (Fig. 3). For each of these circles there exists an energy from which onward the spectrum becomes power-like. For each of the circles, starting from the largest one, events in the intervals within the power-like spectrum were selected. The final sampling was of 213 events. In Fig. 4, a differential energy spectrum of PCR in the 100–2000 TeV energy range constructed in this way is compared with certain data obtained by other authors [4–7]. The slope indices of the spectra for the intervals of 100–2000, 200–2000, and 200–1500 TeV are 2.60 ± 0.11, 2.69 ± 0.12, and 2.64 ± 0.12, respectively (only statistical errors of index measurements are shown).

Refinement of the PCR spectrum at energies of 10^{12}–10^{15} eV is rather necessary at present in view of possible steepening of the proton spectrum in the 1–100 TeV range [6–8]. In this case the spectrum of all the

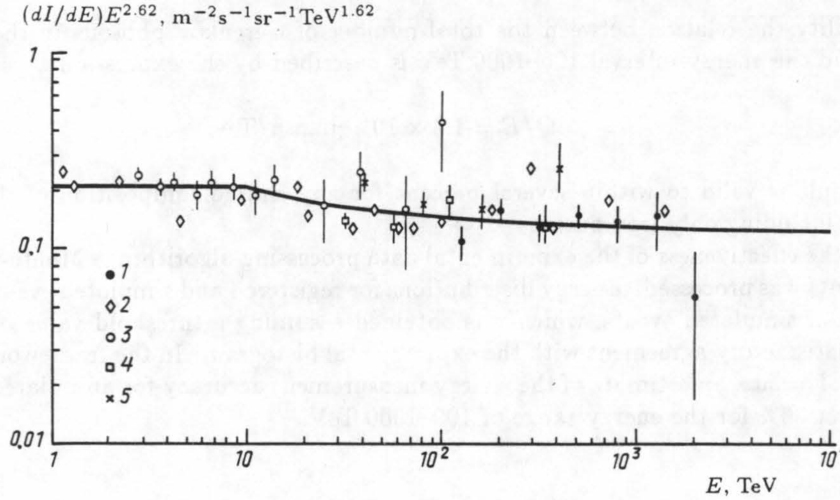

Fig. 4

Differential energy spectrum of PCR; (1) data from the present experiment; (2) data from [4]; (3) data from [5]; (4) from [6]; (5) from [7].

particles must have a characteristic singularity of the step-like type, whose parameters would depend on the character of steepening of the proton spectrum. The solid curve in Fig. 4 illustrates the shape of the "step," when the slope index of the proton spectrum increases by 0.6 starting from 10 TeV. The data available at present for this energy range do not allow any definite conclusion to be drawn. It is necessary to increase the statistical accuracy and, which is especially important, to perform measurements in the range from several to $\sim$ 1000 TeV on the same setup that should have a high enough resolution. By lowering the energy threshold of the TACT system down to several TeV one may try to solve the problem of singularities in the PCR spectrum in the 1–1000 TeV range. The necessary observation time in those conditions is 20–30 h. On the other hand, when longer observation times are used, one should be able to refine data on the break in the PCR spectrum observed at energies $\sim 3 \times 10^{15}$ eV.

The method used in this paper to determine the primary particle energy by means of measuring the integral flux of the Cerenkov radiation generated by large atmospheric showers is the most adequate one, since the quantity we measure is tightly connected with total ionization losses of shower particles in the atmosphere, which in their turn make up about 70% of the primary particle energy. This method has never been used before in the energy range considered.

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