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High-Energy Gamma Rays in the RUNJOB Experiment

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Abstract—The latest results of studies of the gamma-ray spectra recorded together with charged particles in the Russian–Nippon Joint Balloon (RUNJOB) experiment are presented. A comparison of the experimental spectra with the results of the calculations based on assumptions of different intensities of the gamma-ray spectra demonstrates that the previously published intensities of primary cosmic rays measured in the RUNJOB experiments are underestimated.

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1. INTRODUCTION

The Russian–Nippon Joint Balloon (RUNJOB) experiment was one of the first experiments in which primary cosmic rays at energies just below the knee in the spectrum of primary cosmic rays in the range 10–1000 TeV were measured by direct methods [1]. The final cosmic-ray spectra were reported in our recent paper [2]. In the present paper, we make an attempt to analyze the previously published intensities of primary cosmic rays with the use of the untapped RUNJOB experimental data on both the cascades from gamma rays and the cascades from charged particles and gamma rays entering the chamber at large zenith angles.

At a depth of approximately 10 g cm^{-2}, at which the balloon investigations have been performed in the framework of quasi-scaling models, the slope of the spectra of the secondary component is close to that of the spectrum of primary nucleons [3]. Therefore, the measurements of gamma-ray fluxes at small depths in the atmosphere allow one to judge the intensity and slope of the spectrum of primary nucleons. Of course, the number of secondary particles at the observation level is considerably smaller (a few percent) than the number of primary particles. However, gamma rays entering the chamber lose all their energy to the electromagnetic cascades; as a result, the fraction of gamma rays among the selected events amounts to several tens of percent [3]. The fraction of gamma rays is especially large (70–80%) among the cascades at large angles [3], because gamma rays are the secondary component and their intensity increases with an increase in the traveled path up to the depth h = 100 g cm^{-2}. We separately examined a sample of cascades at large angles with $\cos\theta = 0.2$–0.4, which should consist predominantly of gamma rays. Moreover, the depth of the chamber for cascades at large angles becomes equal to 13–25 cu, which is sufficient to determine the energy of particles over the entire energy range by the same (photometric) method with the use of X-ray films [1].

2. GAMMA-RAY SPECTRA

The experimental events identified as gamma rays were collected in databases. The identification procedure was described in detail in [1]. The error in the identification of the experimental events did not exceed 10%. The complete statistics of gamma rays amounted to 900 events, and approximately 400 events were characterized by the energy threshold E_g = 3 TeV. This result is comparable to the statistics of protons in the RUNJOB

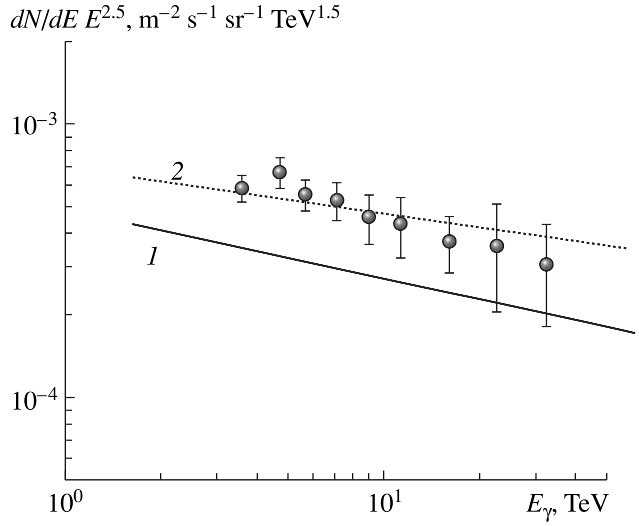

Fig. 1. Comparison between the experimental energy spectra of gamma rays (circles) and (*1*, *2*) the spectra calculated with the MC0 code under the assumption of different intensities of the primary spectra (solid and dashed lines).

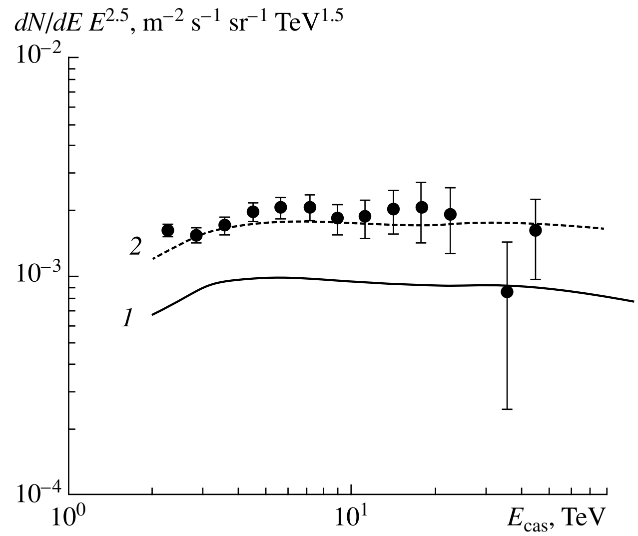

Fig. 2. Comparison between the experimental energy spectra of all cascades at large angles (circles) and (*1*, *2*) the spectra calculated with the MC0 code under the assumption of different intensities of the primary spectra (solid and dashed lines).

experiment [2]. The gamma-ray spectrum at an observation depth of 10 g cm^{-2} is approximated by the relationship

$$dN/dE = (3.6 \pm 0.35)E^{-2.81 \pm 0.06}\ \mathrm{m^{-2}\ h^{-1}\ sr^{-1}\ TeV^{-1}}.$$

It should be noted that, first, our gamma-ray spectrum is in good agreement with the gamma-ray spectrum previously measured at the atmosphere boundary in other experiments at an energy of approximately 2 TeV. This agreement indicates that the procedures used for identifying the experimental events and measuring the gamma-ray energies are quite correct. Second, the slope of the spectrum is consistent with the slopes of the proton spectrum ($\gamma = -2.78 \pm 0.06$) and the spectrum of helium nuclei ($\gamma = -2.74 \pm 0.12$) measured in the RUNJOB experiment.

Figure 1 shows the experimental gamma-ray spectrum (multiplied by $E_g^{2.5}$) in comparison with the gamma-ray spectra calculated under the following assumption. The transmission of primary cosmic-ray particles through the atmosphere and the gamma-ray spectra at a depth of 11 g cm^{-2} were simulated with the MC0 code [4]. The interaction model included in this code is very similar in the characteristics (cross section, inelasticity coefficients, multiplicities) to the widely accepted quark–gluon string model QGSJET01 [5]. In these calculations, the primary spectra were represented by the approximate relationships derived for the spectra previously measured in the RUNJOB experiment [2] for five groups of particles, namely, *p*, He, C–N–O, Si–Ne, and Fe. The spectrum obtained in this variant of the calculation is shown by the solid line in Fig. 1. For protons and helium, which contribute 95% to the all-nucleon spectrum and, hence, to the gamma-ray spectrum, the spectra were approximated by the following relationships (the energy is expressed in gigaelectron-volts):

$$dI(p)/dE = 1.86 \times 10^{-4}(E/8900)^{-2.78},\ \mathrm{m^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}}$$
$$dI(\mathrm{He})/dE = 1.34 \times 10^{-5}(E/18\,800)^{-2.74},\ \mathrm{m^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}}. \quad (1)$$

It can be seen from Fig. 1 that the experimental gamma-ray spectrum lies above the calculated spectrum. This difference indicates a disagreement between the results obtained: the gamma-ray spectrum does not confirm the nucleon spectrum measured in the same experiment. One of the factors responsible for this disagreement can be the incorrectness of the MC0 model. On the other hand, the intensity of the primary spectra of the main components, i.e., protons and helium, can be somewhat underestimated. In the second variant of the calculation, the primary spectra were approximated with increased intensities of the main components, including helium. This calculation was carried out according to the following relationships with due regard for the upper limit of the intensities determined in other experiments (the energy is expressed in gigaelectron-volts):

$$dI(p)/dE = 2.64 \times 10^{-4}(E/8900)^{-2.80},\ \mathrm{m^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}},$$
$$dI(\mathrm{He})/dE = 3.40 \times 10^{-5}(E/18\,800)^{-2.68},\ \mathrm{m^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}}. \quad (2)$$

In this variant of the calculation, the calculated intensities of gamma rays appear to be in agreement with the experimental intensities.

A similar analysis was performed for cascades at large angles with $\cos\vartheta = 0.2$–0.4. The sample to be analyzed involved only 600 cascades with a measured energy of higher than 3 TeV. In this sample (the results were obtained for two chambers in which the primary particles forming a particular cascade were identified), the fraction of cascades from gamma rays amounts to approximately 45%, the fraction of cascades from protons and nuclei reaches approximately 40%, and the fraction of cascades from events associated with the interactions occurring in chambers walls and air is approximately equal to 15%. The obtained spectrum of cascades at large angle is depicted in Fig. 2. Since the particles have a complex composition, comparison of the experimental spectra with the results of the calculations permits us to solve only a direct problem, i.e., to simulate the transmission of protons, helium nuclei, and gamma rays through the chamber and to determine the cascade energy E_{cas} according to the procedure used in the experiment. Therefore, the calculated curves describe the flux of primary cosmic-ray particles whose transmission through the atmosphere was calculated with the MC0 code and transmission through the chamber was simulated with the GEANT3.21 code (modified in [6] with due regard for the detection of electromagnetic cascades with the use of X-ray films).

As can be seen from Fig. 2, the results obtained for cascades at large angles are similar to those presented in Fig. 1. More specifically, the intensities of the experimental spectra of the cascades are higher than those obtained in the first variant of the calculation and agree closely with the intensities calculated in the second variant.

We analyzed the possible reasons for the observed disagreement between the results obtained in the same experiment. It was revealed that the angular distributions of the experimental and calculated cascades differ from each other; more precisely, the cascades from cosmic-ray particles at large angles are predominant in the experimental angular distributions. This difference indicates either a higher efficiency of detection of the cascades at large angles or a higher loss of the cascades from cosmic-ray particles at small angles. As a result, the effective observation depth in the atmosphere turns out to be larger than the calculated depth. This discrepancy between the experimental and calculated angular distributions calls for a closer examination and, quite possibly, can be responsible for the observed disagreement between the gamma-ray and nucleon spectra measured in the RUNJOB experiment.

3. DISCUSSION

The observed disagreement between the results obtained for the gamma-ray spectra and the spectra of primary particles in the same experiment can have several explanations. One of the factors responsible for this disagreement can be the incorrectness of the MC0 model. Moreover, this disagreement can be associated with the fact that the intensity of the primary spectra of the main components (protons and helium) are somewhat underestimated. We analyzed the possible reasons for the observed disagreement between the results obtained in the same experiment. It was found that the angular distributions of the experimental and calculated cascades differ from each other and that the cascades from cosmic-ray particles at large angles are predominant in the experimental angular distributions. This difference suggests either a higher efficiency of detection at large angles or a higher loss of the cascades from particles at small angles. As a consequence, the effective observation depth in the atmosphere appears to be larger than the calculated depth. This discrepancy between the experimental and calculated angular distributions requires a more detailed analysis and, possibly, can be responsible for the disagreement between the gamma-ray and nucleon spectra measured in the RUNJOB experiment.

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