Experimental Feature in the Primary-Proton Flux at Energies above 10 TeV according to the Results of Searches for Primary Particles in Nuclear Emulsions Exposed in the Stratosphere (RUNJOB Experiment)

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Received November 7, 2006; in final form, April 5, 2007

Abstract—In the RUNJOB experiment, a long-term exposure of x-ray emulsion chambers in the stratosphere from 1995 to 1999 with the aim of studying the composition and spectra of primary cosmic particles in the energy range 10–1000 TeV per nucleon revealed about 50% proton tracks. The remaining events of the proton group did not feature any candidate for a track of a singly charged particle within the search region determined from measurements of the coordinates of background nuclei going close to the sought track. Methodological factors that could explain this experimental observation are considered. A possible physical reason associated with the presence of a neutral component in the flux of primary protons in the energy region above 10 TeV is also analyzed.

PACS numbers: 98.70.Sa

DOI: 10.1134/S1063778808020075

INTRODUCTION

Balloon-borne experiments involving a long-term exposure (about six to seven days) of x-ray emulsion chambers in the stratosphere were performed from 1995 to 1999 by the RUNJOB Collaboration, which includes Russian and Japanese researchers. Within ten successful long-term flights between Kamchatka and Wol'sk, two-sided nuclear emulsion films were exposed at an altitude of about 32 km. The total statistical sample underlying the ultimate results of the Russian–Japanese experiment in question contains 521 events, of which 360 are those of primary-proton interactions [1]. The measuring facility used, which included a strongly magnifying microscope that involved an automatically moving objective table and a CCD Scanning system, made it possible to perform high-precision searches for nucleons and nuclei of primary cosmic rays. For individual events, the accuracy in finding primary particles was as high as a few microns. According to data from processing the RUNJOB’95–99 chambers, the proton group contained about 50% events where no candidate for a track of a primary singly charged particle was found within the search region of radius about $3\sigma$, where $\sigma$ is the root-mean-square error of the method for determining the coordinates of the sought-particle track. In examining methodological factors that could explain this experimental observation, the proton tracks were continued over several higher lying layers from the RUNJOB-6A and RUNJOB-5A chambers. The results obtained in this way and an analysis of methodological issues concerning searches for relativistic singly charged particles in the emulsion layers of x-ray emulsion chambers are reported in the present article.

SEARCHES FOR PRIMARY PARTICLES IN THE RUNJOB EXPERIMENT

Upon hitting an x-ray emulsion chamber (see Fig. 1), nucleons and nuclei of primary cosmic rays interacted with target matter, producing a jet of secondary particles, which consisted predominantly of charged and neutral pions. Neutral pions gave rise to electron–photon showers, which were recorded in the x-ray films of a calorimeter as black spots. Over the exposure time of six to seven days, more than 500 spots were identified visually in the lower x-ray film.

The electron–photon showers discovered in the x-ray films were then found in the corresponding emulsion layers arranged immediately below the x-ray films. With the aid of various event–selection criteria (such as those in the zenith angle and in the total energy deposited into the neutral component), nuclear and electromagnetic cascades were traced from below upward to the interaction vertex. When the density of particles in a cascade became insignificant for generating a visually distinguishable black
spot in the x-ray films, the respective track was continued in the nuclear emulsions under a microscope of magnification not less than ×100. Via a layer-by-layer inspection, the jet of secondary particles was traced up to the level above which the interaction vertex was in the target plate. The track of the primary particle whose zenith (θ) and azimuthal (ϕ) angles are identical to their counterparts for particles in the jet and in the electron-photon shower was sought in the emulsion layer above this plate.

In the case of a long-term exposure of nuclear-emulsion plates, the rate of particle arrival at the array is high both for primary cosmic-ray particles of energy above the geomagnetic threshold (3 GV) and for secondary particles produced in the residual atmosphere (∼10 g/cm²). Specifically, 50 to 70 particle tracks of different length and direction traverse the area of $S = 10^4 \mu m^2$ over an exposure time of $T_{\text{expos}} \sim 150$ h. In order to separate reliably the sought particle from the background, the range of searches must be such as to ensure fulfillment of the condition [2]$$N_{\text{backgr}} \Delta S \Delta \Omega \ll 1,$$

where $N_{\text{backgr}}$ is the number of background particles over the detector-exposure timer $T_{\text{expos}}$ per unit solid angle per unit detector area, $\Delta S$ is the accuracy of the area being considered, and $\Delta \Omega = \sin \theta \Delta \varphi \Delta \theta$ is the solid angle that is determined by the accuracies of the zenith ($\Delta \theta$) and azimuthal angles ($\Delta \varphi$).

In addition, a candidate particle must satisfy the following criteria:

(i) The deviations of the measured values of the azimuthal and zenith angles of particle arrival must not exceed 3°.

(ii) The ionization produced by a particle is nearly identical in all layers being considered.

(iii) The trajectory of a candidate particle must not go systematically beyond the accuracy of the calculated trajectory of the nuclear–electromagnetic cascade (a candidate particle is traced in several layers above the interaction vertex).

(iv) A candidate particle of charge number $Z > 2$ must not be present in layers where a shower is already seen.

In order to reduce the error in the prediction of the position of the sought particle and, hence, the area of the region of its searches, the RUNJOB experiment employed the measuring facility described above and a method that makes it possible to determine the coordinates of this particle from measurements of tracks of background nuclei occurring close to the jet of secondary particles (at a distance of about 1 cm from it) in emulsion layers lying immediately after the interaction vertex. The accuracy of the prediction was