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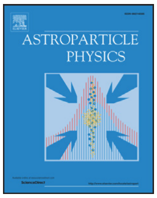

Analysis of gamma-ray families with halos and estimation of mass composition of primary cosmic radiation at energies 1–100 PeV

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ABSTRACT

Characteristics of γ-ray families with halos observed with X-ray emulsion chambers at the Pamirs and data of EAS experiments are analyzed to estimate the summary fraction of proton and helium nuclei (p + He) in the primary cosmic radiation (PCR) at $E_0 = 1$–100 PeV. It is shown that the p + He fraction at $E_0 = 10$ PeV is (39 ± 6) %. The mass composition, estimated by EAS age, remains mixed at $E_0 = 1$–100 PeV with a tendency to become heavier with increasing energy.

1. Introduction

It was earlier assumed that the PCR mass composition at a PCR energy of $E_0 \sim 3$ PeV is light, that is, the fraction of proton and helium nuclei (p + He) predominates [1]. Presently, however, some experiments indicate that the PCR mass composition becomes heavier at $E_0 > 1$ PeV. In particular, the results of hybrid EAS-TOP and MACRO experiments [2,3], Tibet ASγ and BASJE [4,5] experiments, and data on delaying hadrons of the CASA-MIA Collaboration [6] show some decrease of the p + He fraction in the PCR spectrum "knee" range, that is, at $E_0 \sim 3$ PeV. According to data from the KASCADE and KASCADE-Grande experiments [7], the proton components eliminated from the PCR mass composition and, as a result, the proton fraction does not exceed 10% in the range of $E_0 = 1$–100 PeV. Recently, preliminary results of the ARGO-YBJ experiment showed that the p + He fraction starts to decrease at $E_0 \sim 1$ PeV, that is, the PCR mass composition becomes heavier [8] (see Fig. 5).

Experiments that make it possible to estimate the p + He fraction by direct observations of the core of extensive air shower (EAS) use the techniques of X-ray emulsion chambers (XREC). According to XREC, the p + He fraction remains significant at $E_0 \sim 10$ PeV.

The X-ray emulsion chamber of the *Pamir* experiment (Fig. 1) represents a solid-state track chamber installed at the Pamirs at an altitude of 4400 m a.s.l. The air above XREC is, in fact, one of the varieties of the thick target (~600 g/cm^2) where nuclear-electromagnetic cascades (NEC) induced by particles of the PCR take place. Single particles of high-energy electromagnetic components (γ and $e^{\pm}$ called below, for brevity, "γ-rays") of the air cascades initiate electron-photon cascades (EPhC) in the upper lead plates of the chamber, assembled in a stack and called "Gamma-block". These EPhCs are recorded as dark spots by X-ray films placed between and under lead plates if the energy of the incident γ-rays and electrons/positrons is high enough ($E_\gamma \geq 1$ TeV).

Due to the high-energy threshold for particle detection and high special resolution ~100 μm, XRECs make it possible to resolve narrowly collimated bundles of the most energetic particles in the central part (i.e., the core) of the corresponding EASs and thus to study semi-inclusive spectra of secondary particles practically in the whole fragmentation region of the projectile. The XREC experiment is one of the best in providing the lateral resolution of the EPhCs better than 1 mm. This lateral resolution is unattainable on modern operating arrays, including ARGO-YBJ. XREC records so-called γ-ray families, that is, groups of correlated high-energy γ-rays in relatively young EAS cores, related to the same interaction of a PCR nucleus in the air target and having coinciding zenith and azimuth angles.

High special resolution of the X-ray films with two emulsion layers separated by a plastic support of ~200 μm thick makes it possible to determine coordinates, zenith and azimuthal angles of incident particles with accuracies as high as $\Delta x,y \sim 100$ μm, $\Delta\theta \sim 3°$ and $\Delta\varphi \sim 15°$, respectively.

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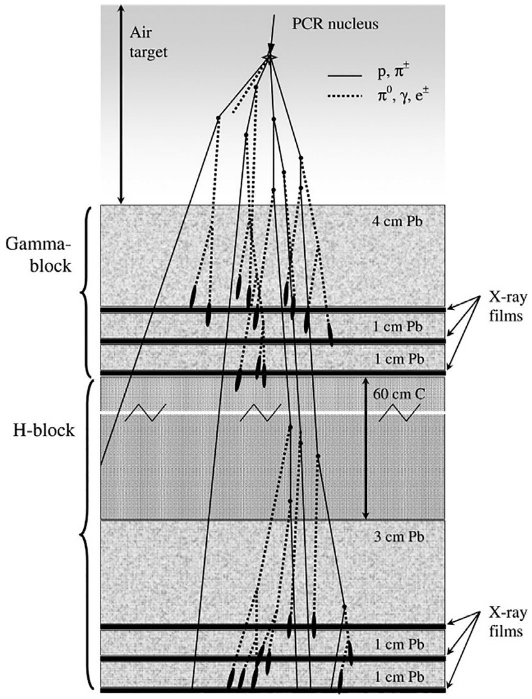

Fig. 1. Layout of the *Pamir* experiment setup at the Pamirs.

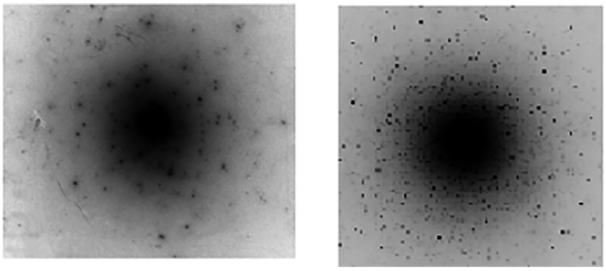

Fig. 2. Scanned image of the «FIANIT» halo event observed in the *Pamir*'s XREC (E_0 ~400 PeV, $S_{\rm halo} = 1020$ mm^2) (left); calculated halo produced by the primary proton ($E_{\rm p} = 420$ PeV, $S_{\rm halo} = 2100$ mm^2) (right).

The darkness of a spot, which can be determined by photometric measurements, is proportional to the density of the cascade electron number and thus to the γ-ray energy E_γ, which can be determined by photometric measurements of the spot. The accuracy of the individual EPhC energy determination is $\sigma(E_\gamma)/E_\gamma = 0.2–0.3$.

The method of energy determination by XREC has been calibrated in accelerator beams of electrons and pions and is used in the experiment for reconstruction of π^0 mass in the decay $\pi^0 \to 2\gamma$ by measuring the energy of two initial γ-rays and the opening angle Φ : $m_{\pi^0} = \Phi\sqrt{E_1E_2}$.

The regions with high optical density in the centers of γ-ray families ("halos") often appear at very high energies. For the first time, the halo phenomenon was observed as exotic phenomena by Japan physicists, who called the event "Andromeda". Similar events were observed in the *Pamir* XREC experiment. Two of such phenomena were named "FIANIT" (Fig. 2) and "Tajikistan".

Since the air target above XREC is thick enough, several generations of NEC contribute to the observed families, which makes the analysis of experimental events rather complicated and requires a detailed simulation of the experiment, including that of the chamber response.

Processing of the experimental data was performed using MC0 (R.A. Mukhamedshin) [9] and quark-gluon string (QGSJet 01) models, which provide a nice fit of high-energy data in a wide accelerator energy range. In practice, we used the very efficient MC0 code, which is close to the QGSJet model and accounts for hard QCD-jet production. Simulation of the chamber response including conditions of experimental event selection and final spatial resolution of particles, is correctly incorporated into the model sampling.

The MC0 model, designed for simulation of hadron-hadron and hadron-nucleus interactions, describes well the XREC experimental data and satisfactorily reproduces the general high-$x_{\rm F}$ LHC data [9].

Analysis of the *Pamir* XREC experiment data using the specially developed MC0 model has shown that the contribution of the EAS hadron component to the formation of gamma-ray families in the Gamma-block (Fig. 1), compared with the contribution of the EPhCs, does not exceed 3% of the total number of separate family particles observed.

The experimental data were also processed using the QGSJet model, which provided the best description of these data in comparison with other models.

However, the following versions of the models applied in EAS experiments use more weak energy dissipation as compared with initial models. The latter circumstance worsened their quality of simulation of EAS core parameters at a distance up to ~50 cm, including, for example, the important parameter of the average radius of γ-ray families.

Analysis of the *Pamir* XREC experiment data with the MC0 model shows that more than 90% of the registered γ-ray families with halo are produced by the p + He component.

2. The measurement technique of the *Pamir* XREC and evaluation of measurement errors

Experimental work with X-ray films (XRF) includes the visual search for dark spots produced by the EPhCs, which are initiated by high-energy γ-rays, electrons, and positrons arriving from the atmosphere. The energy threshold of visual recognition of the EPhCs by their spots is of the order of 1 TeV, depending on the background accumulated by the XRF.

Determination of the EPhC energy is based on photometrical measurement of the degree of spot darkening produced by the electron beam in the XRF emulsion. The relationship between the spot optical density, $D = \log(I_0/I)$ (where I and I_0 are the intensities of light beams passing through a photometer with and without a photometry object, respectively), and energy E_0 of the particle initiating the EPhC is determined by two main factors:

- EPhC features, namely, the lateral distribution functions (LDF) of electrons and positrons at depth t in the absorber, $N(E_0,t,R_0,\varphi)$, where R_0 is the distance from the EPhC axis, and φ is the azimuth angle of the EAS axis;
- XRF emulsion features, that is, the function $D(n)$ of intensity n (µm^{-2}) of an incident e$^\pm$ beam (characteristic darkening curve).

Given the parameters of these functions, it is possible to obtain an expression for the integral darkening in a circle of radius R at depth t, which has the form:

$$D(E_0, t, < R) = -lg\left\{\frac{1}{\pi R^2}\int_0^{2\pi}\int_0^R \exp(-ln(10)DN(E_0, t, R, \varphi))RdRd\varphi\right\} \quad (1)$$

To determine E_0, the experimental darkening values are compared with those calculated by Eq. (1) where the LDFs were obtained for γ-rays using the three-dimensional cascade theory and empirical XRF darkening curve.

The errors of the XRF darkening measurement obtained by Eq. (1) are related to methodological effects: instability of the XRF