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The mass composition of cosmic rays according to data obtained in the SOKOL-2 satellite experiment

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Abstract

The mass number of cosmic-ray nuclei was obtained using the data from the SOKOL-2 satellite experiment. The mean logarithm of the mass number was determined by two independent methods – the direct method using a charge detector and indirect method using cascade shape information obtained by the ionization calorimeter. We obtained the energy dependence of the mean logarithm of the mass number in the energy range 3–200 TeV. The analysis of the SOKOL-2 data showed the applicability of the indirect methods to determine the mass number. The values of the mean logarithm of the mass number obtained by different experiments are consistent.
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Keywords: Cosmic rays; Mass number; Calorimeter

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1. Introduction

The chemical composition of cosmic rays reflect the processes of both generation and propagation in the Galaxy. The mean logarithm of mass number ⟨lnA⟩ is a generalized parameter characterizing the cosmic-ray composition. The ⟨lnA⟩ value is determined by the initial mass distribution at generation, and by the process of cosmic rays acceleration in the sources and conditions of further propagation. There are different models of cosmic-ray acceleration in supernova remnants and other sources. The experimental verification of the models is sensitive to the ⟨lnA⟩ value (Berezhko, 2009).

In direct experiments (for example, (Atkin et al., 2015, 2017; Ivanenko et al., 1993; Panov et al., 2009)) where the charge of a primary cosmic-ray particle is measured, the mean logarithm of the mass number is determined by the obtained data.

The generalized parameter can be applied at ultrahigh energies for the analysis of extended atmospheric showers, where the separation of elements is impossible. At the same time, the minimum energy threshold in such experiments can be lower than 1000 TeV (ARGO (Zhao et al., 2015), Tunka (Prosin et al., 2016)). The primary-nucleus mass-number dependence on the characteristics of the cascade in the atmosphere (for example, the depth of a shower maximum (Sveshnikova et al., 2014)) is used. It is necessary to compare direct and indirect experiments. Thus the test of indirect methods is useful.

We have developed a technique for restoring the mass number of the primary nucleus by the shape of the cascade in an ionization calorimeter. This technique can be used as an independent test for direct experiments in high-energy cosmic-ray physics.

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2. The SOKOL-2 experiment

The SOKOL-2 satellite experiment (Ivanenko et al., 1993) was performed in 1985–1986. The ionization calorimeter was mounted on the Kosmos-1713 satellite. The device consisted of two Cherenkov charge detectors (directed and undirected) and 10 iron absorber layers separated by scintillator detectors (Fig. 1). Light signals from these detectors were registered using photomultiplier tubes.

For the last 30 years the SOKOL-2 is the single direct cosmic-ray experiment at energies above 3 TeV, in which the charge of primary particles was measured, and a very thick ionization calorimeter (85 cm of iron) has been used. Such a calorimeter gives high precision when it employed for energy measurements (10–15% depending on the energy range). The hadron cascade was registered almost completely in a calorimeter.

The SOKOL-2 experiment was performed to investigate cosmic rays at the energy range 10^{12}–10^{14} eV. The energy spectra of various groups of nuclei were reconstructed. Fig. 2 shows proton and all particles spectra. Fig. 3 shows spectra of helium nuclei and different groups of nuclei. These spectra can be applied for astrophysical analysis.

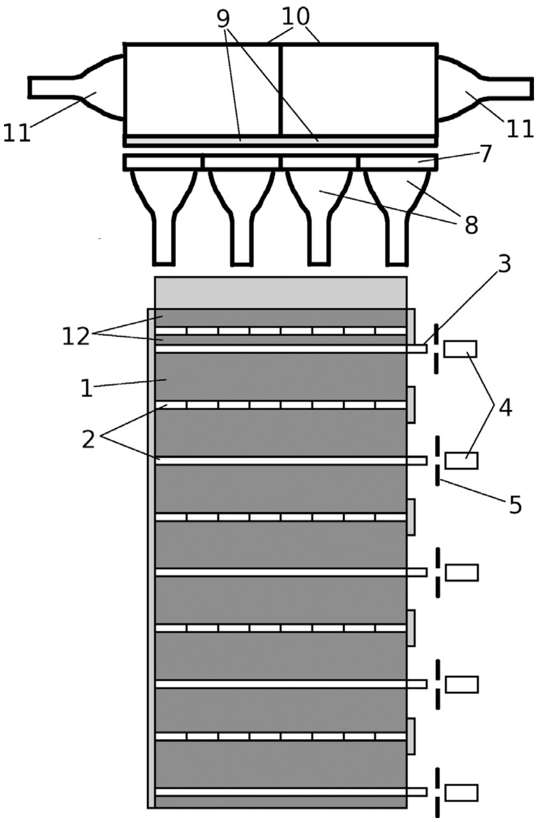

Fig. 1. The design of the SOKOL device. The apparatus consisted of two thin (2 and 3 cm indicated by 12) and eight thick (10 cm indicated by 1) iron absorbers, plastic scintillator layers of 2 cm thickness (2), perspex light guides (3), vacuum photomultiplier tubes FEU-84 (4, 8, 11), shutters for control of sensitivity (5), perspex Cherenkov radiators (indirected (7) and directed (9)), light diffuser scattered photons emitted in Cherenkov radiators (10).

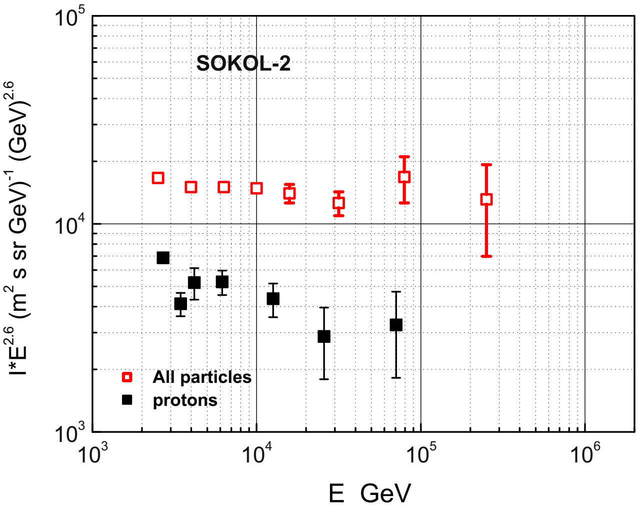

Fig. 2. Energy spectra for protons and all particles obtained by the SOKOL-2 experiment in 1985–1986. The filled boxes (black) are protons and open boxes (red) are all particles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

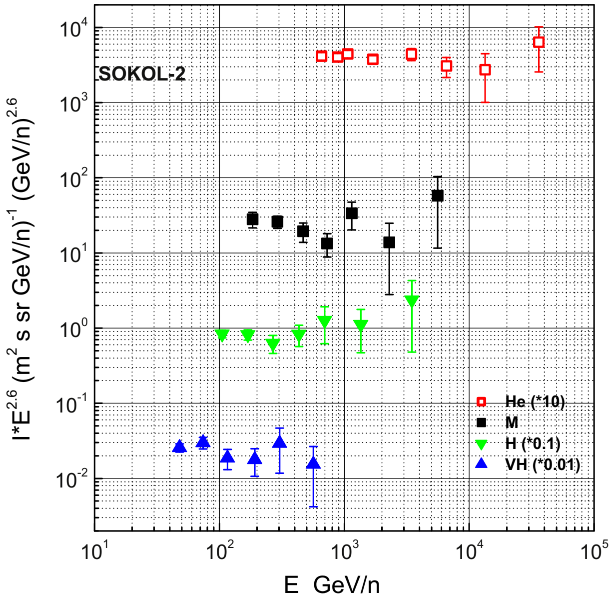

Fig. 3. Energy spectra for helium nuclei and different groups of nuclei measured by the SOKOL-2 experiment in 1985–1986. The open boxes (red) are helium nuclei, the filled boxes (black) are the M group of nuclei ($6 \leqslant Z \leqslant 9$), the filled inverse triangles (green) are the H group of nuclei ($10 \leqslant Z \leqslant 20$), the filled triangles (blue) are the VH group of nuclei ($Z \geqslant 21$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Protons and nuclei are separated by charge Cherenkov detectors. Cherenkov photons emitted in perspex radiators are collected and registered by photomultipliers.

The spectra of separate nuclei (except for protons and helium) were not made because of a lack of statistics. Moreover back scattered particles from the calorimeter can deteriorate charge measurement results. However the

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