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High energy deuterons in cosmic rays registered by the SOKOL satellite experiment

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Abstract

We present the first measurement of the deuterium to proton ratio in cosmic rays, above 500 GeV/nucleon. The data were obtained as part of the SOKOL satellite experiment. The cascade curves generated by single charged particles in the calorimeter were analysed. A hadronic showers' simulation was performed. Simulated and experimental cascade curves were compared. Neural networks were used to select proton and deuteron events. The deuterium to proton ratio was evaluated as 0.114 ± 0.023, whilst the deuterium to helium ratio was evaluated as 1.64 ± 0.30 for energies between 500 and 2000 GeV/n.

Keywords: Cosmic ray; Deuterium; Ratio

1. Introduction

For many years, deuterons had been observed in cosmic rays at energies of up to ~30 GeV/n (Apparao, 1973; Bogomolov et al., 1995; Picozza et al., 2013; de Nolfo et al., 2000; Vannuccini, 2003; Adriani et al., 2016). Most of the deuterium was produced by the spallation of helium and heavier nuclei as a result of the interaction with the interstellar medium. Thus, measurements of deuteron spectra are useful for research into cosmic ray diffusion mechanisms, in comparison with data for other nuclei.

Different experiments have been based on the application of the Cherenkov threshold counters (Apparao, 1973; Bogomolov et al., 1995) or magnetic spectrometers (de Nolfo et al., 2000; Vannuccini, 2003). These techniques have significant limitations. The geometrical factor of magnetic spectrometers is small (de Nolfo et al., 2000; Vannuccini, 2003) and similar devices cannot be used at high energies.

Measurements at energies greater than 1 GeV/n have been performed only as part of the IMAX (de Nolfo et al., 2000) and CAPRICE98 (Vannuccini, 2003) experiments.

There have been many cosmic ray experiments based upon the use of ionisation calorimeters for energy measurement purposes. The analysis of cascade curves and transverse ionisation distributions have been used to separate electron and proton events in some experiments (Chang et al., 2008; Vasilyev et al., 2014; Atkin et al., 2015).

There are some differences with regard to proton and deuteron cascade curves at the same energies. These differences can be exploited to separate deuteron and proton events.

2. The SOKOL experiment

The SOKOL-2 experiment was performed during 1985–1986 (Ivanenko et al., 1993). The device was placed aboard the KOSMOS-1713 satellite.

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The main aim of this experiment was to measure the energy spectra for different cosmic ray nuclei at energies greater than 1 TeV per particle. The design of the SOKOL apparatus is presented in Fig. 1. The charge measurement system was based on two layers of Cherenkov detectors. The undirected detector (9) was used for the registration of heavy nuclei. The directed partitioned detector (7) was applied to determine light nuclei charges. The particle energy was measured by the thick iron ionisation calorimeter. The calorimeter had a total thickness of ~48 radiation lengths (5.5 proton interaction lengths). The absorber consisted of two thin iron layers, three and two centimetres thick respectively (12), and eight thick iron layers of ten centimetres each. Iron layers were interleaved with scintillator detectors. Generally, the calorimeter consisted of an eighty-five centimetres iron absorber divided by ten scintillator layers. Every scintillator detector was divided into eight parts to determine the shower coordinates.

Trigger criteria were changed during the flight but the main volume of data was obtained with simple conditions.

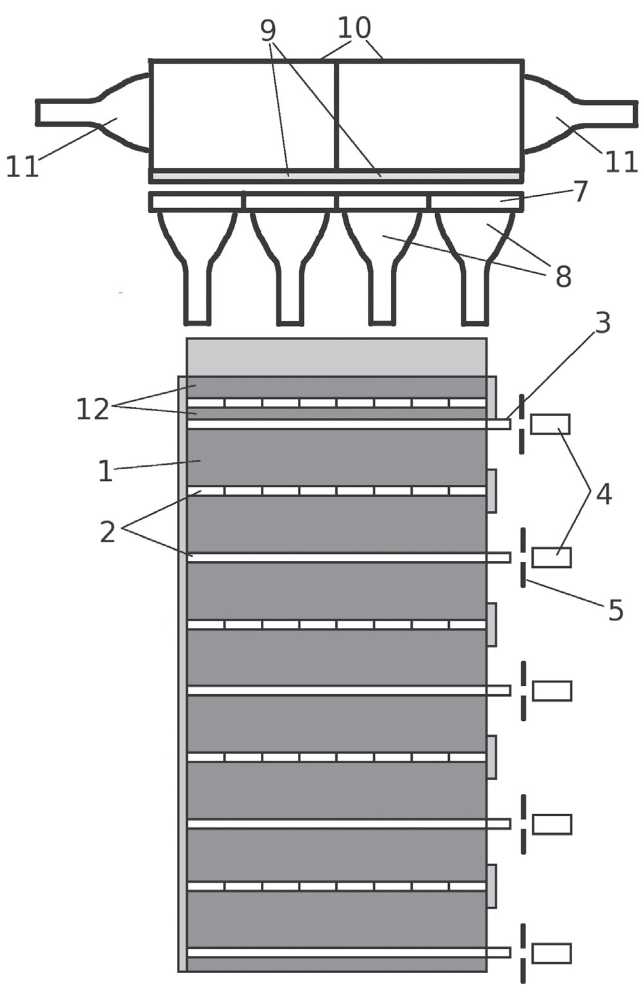

Fig. 1. The design of the SOKOL device. The apparatus consisted of iron absorber (1,12), scintillator layers (2), light guides (3), photomultipliers (4,8,11), shutters (5), perspex Cherenkov radiators (7,9), light diffuser (10).

Energy deposit was more than 1 TeV, more than five scintillator layers worked (so called m5 set of conditions).

The energy spectra and chemical composition of cosmic rays were obtained (Ivanenko et al., 1993). There is a databank that can be used for additional analysis.

3. Simulation and analysis

The simulation of the SOKOL-2 experiment was performed by means of two programs. At first, we applied the GEANT3.21 program (Brun, 1983) with the additional QGSJET hadronic generator, to simulate nucleus-nucleus interactions. The kinetic energy cuts were equal to 10 keV for all types of particles. It was necessary for a correct description of the cascade processes. The device geometry was described, according to Fig. 1. The proton and deuteron showers in the calorimeter were simulated. The spatial and angular distribution of primary particles was simulated as isotropic. Primary particles energies were distributed according to the simple power law ($\gamma = 1.7$). The total number of simulated events is equal to 600,000 for protons and deuterons at the energy range 1–4 TeV per particle, including side events. The event selection was made according to criteria used by the satellite experiment. The values of signals for every scintillator detector were obtained. These data can be compared with the experimental results.

Proton and deuteron showers at the same energy per particle are different. The deuteron-nucleus cross-section is larger than the proton-nucleus one. The deuteron-nucleus interaction is a superposition of two nucleon-nucleus interactions. The inelasticity distributions are different for proton-nucleus and deuteron-nucleus interactions. Therefore the distributions of ionisation at the initial parts of the showers are different too.

For deuteron events, half of the primary energy can be transferred to the spectator nucleon. Thus, deuteron showers are stretched in comparison to proton ones.

The shapes of showers can be analysed. These shower differences are not large, but artificial neural networks (Haikin, 1998) can be applied to determine the deuteron-to-proton ratio.

The set of parameters was determined for the selection of the deuteron-proton showers:

$$y_i = (dE_i/dX)/(dE_{max}/dX), \quad 1 \leqslant i \leqslant 10$$

Thus, ten parameters (scintillator signal to maximal scintillator signal ratios) are chosen to describe the main shower characteristics.

The ten parameters are signals of all the scintillator detectors normalised by the largest value. Thus, the shape of the cascade curve is taken into account.

The artificial neural network was emulated for a non-parametric estimation of the experimental results. The applied neural network consisted of three layers. Every layer included ten neurons. The discrete output was used to separate protons and deuterons. 10^5 proton and

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