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Energy spectrum of cosmic ray protons and helium nuclei measured by the ARGO-YBJ experiment

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For the ARGO-YBJ Collaboration

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ABSTRACT

The ARGO-YBJ experiment is a full-coverage air shower detector operating at the Yangbajing International Cosmic Ray Observatory (Tibet, PR China, 4300 m a.s.l.). The detector was in stable data taking in its full configuration from November 2007 to February 2013. More than 5×10^{11} events have been collected and reconstructed. Due to its characteristics (full-coverage, high segmentation, high altitude operation) the ARGO-YBJ experiment is able to investigate the cosmic ray energy spectrum in a wide energy range and offer the possibility of measuring the cosmic ray light component spectrum down to the TeV region, where direct balloon-borne measurements are available. In this work we present the measurement of the proton and helium spectra in the energy range 1–300 TeV by using a large data sample collected between January 2008 and December 2011.

1. Introduction

In the last decades several experiments have been focused on the study of the cosmic ray properties, providing a lot of information about their origin, composition and acceleration, and propagation mechanisms. Cosmic rays are charged nuclei produced and accelerated outside the solar system and reaching the Earth's atmosphere. The arrival directions are randomized by the galactic magnetic field, making difficult for the identification of cosmic ray sources. Supernova Remnants (SNRs), however, have been commonly identified as the source of galactic cosmic rays, since they could provide the necessary amount of power in order to accelerate particles up to hundreds of TeVs. Measurements of the TeV gamma-ray emission from supernova remnants showed that SNRs are able to accelerate particles up to 100 TeV [1]. Detectors installed on satellites and balloons are able to detect the cosmic ray particles at the top of the atmosphere. These experiments are able to measure the energy spectrum and the isotopic composition of individual elements. New generation balloon-borne experiments are able to extend the energy measurement up to $\sim$100 TeV. Since the cosmic ray flux has a strong decrease as the energy increases, direct detection of cosmic rays with energy greater than 100 TeV is difficult. Data concerning the cosmic ray energy spectrum above $\sim$100 TeV are provided by ground-based air shower experiments. Air shower experiments are able to detect the shower of secondary particles produced by the interaction between cosmic rays and the Earth's atmosphere. The characteristics of the cosmic ray particles, like energy and mass, are not directly accessible and have to be inferred from the measured secondary particles distribution at a ground level. Ground-based experiments do not allow the determination of the abundances of individual elements and the composition measurement is limited to the abundances of the main groups of nuclei. In addition, due to a lack of a model-independent energy calibration, the relation between the observed quantities and the characteristics of the primary cosmic rays depends on the hadronic interaction model used to describe the development of the shower. The ARGO-YBJ experiment is a full-coverage air shower array which was in full and stable data taking from November 2007 to February 2013 at the Yangbajing International Cosmic Ray Observatory (Tibet, PR China). The full-coverage technique, combined with the high granularity and spacetime resolution, allows the measurement of the distribution of charged particles in the shower front with unprecedented details. The high-altitude allows the detection of showers produced by primaries of energies down to the TeV region. One of the main scientific goals of the ARGO-YBJ experiment is the measurement of the cosmic ray energy spectrum in the energy range $1–5\times10^{3}$ TeV. An overlap between ground-based and balloon-borne measurements of the cosmic ray spectrum in a wide energy range could provide a cross-calibration between the two experimental techniques. In this work the measurement of the light-component (protons and helium

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nuclei) spectrum, measured by the ARGO-YBJ experiment in the energy range 1–300 TeV, is presented. The values have been obtained by using a data sample of more than5000 h collected between January 2008 and December 2011.

2. The ARGO-YBJ experiment

The ARGO-YBJ [2,3] detector is a full coverage air shower array made by a single layer of Resistive Plate Chambers (RPCs) operated in a streamer mode with ~93% active area. The detector is located at the Yangbajing International Cosmic Ray Observatory (Tibet, PR China) at an altitude of about 4300 m a.s.l. The detector has been in stable data taking in its full configuration from November 2007 to February 2013 with a trigger threshold $N_{Trig} = 20$, corresponding to 20 charged particles hitting the RPC carpet. Data were taken with a trigger rate of about 3.6 kHz and a dead time of about 4%. The detector is logically arranged in 153 clusters of 12 RPCs each. The full-coverage carpet is made of 130 clusters and is surrounded by a partially instrumented guard ring made of 23 clusters, designed to improve the reconstruction of external events. The total active area of the detector is about 6700 m^2. Each RPC is read-out by 80 strips (6.75×61.80 cm^2 each) logically arranged in 10 pads (55.6×61.8 cm^2). Signals coming from the 18,360 pads and 1,46,880 strips are the experimental output of the detector. A trigger logic requiring a number of fired pads $N_{Pad} \geq N_{Trig}$ within a time window of 420 ns was implemented. The whole system provides a time resolution of about 1.8 ns, which allows a detailed three-dimensional reconstruction of the shower front. The digital signal readout of the RPCs can be used to study the primary spectrum up to energies of a few hundred TeV. In order to extend the detector operating range up to the PeV region, where particle densities are larger than 10^3/m^2, each RPC has been equipped with two large-size electrodes (big pads, 1.23×1.39 m^2). These electrodes provide a signal whose amplitude is expected to be proportional to the number of charged particles impinging on the detector.

3. Data analysis

The ARGO-YBJ experiment measures the space–time distribution of the particles in the shower front. The position and arrival time of each particle are recorded and the main characteristics of the shower (core position and arrival direction) are reconstructed. Due to large fluctuations in the development of the shower and in the first interaction point, a direct correlation between the shower multiplicity M (i.e. the number of fired strips recorded in each shower) and the primary particle energy cannot be established. The determination of the primary energy from the observed multiplicity distribution is a classical unfolding problem that can be solved by applying an unfolding method based on Bayes' theorem [4]. A detailed description of the unfolding of the cosmic ray spectrum is given in [5,6]. A full Monte Carlo simulation of the development of the shower and of the detector response is needed in order to evaluate the conditioned probabilities required in the unfolding procedure.

3.1. The Monte Carlo data sample

Showers have been simulated by using the CORSIKA [7] code, including QGSJETII.03 [8,9] and FLUKA [10,11] packages in order to describe high-energy and low-energy hadronic interactions. The electromagnetic component of the shower has been simulated by using the EGS4 [12] routines. Showers produced by protons, helium, CNO and iron nuclei have been generated in the zenith angle range 0–45° in the energy range (0.3–10^4) TeV according to a power law distribution. Showers have been sampled at the Yangbajing altitude. A full detector simulation based on GEANT3 [13] has been performed on the resulting CORSIKA showers taking into account the accidental background of each pad and the measured RPC's efficiency and time resolution. The Monte Carlo events have been produced in the same format as data and processed via the same reconstruction code.

3.2. Data and event selection

A first selection based on the data quality and on the quality of the reconstruction process was performed on the full data sample collected during the period January 2008 to December 2011, consisting of about 4×10^{11} events. The following selection criteria have been applied:

(i) at least 128 clusters of the central carpet in the data acquisition
(ii) a trigger rate between 3.0 and 4.0 kHz
(iii) χ^2 of the reconstruction algorithm less than 140.

The resulting data sample of 7×10^{10} events, corresponding to more than 5000 h, was analyzed. In order to avoid the contamination of external events and to obtain an accurate estimation of the Bayesian probabilities, the following selection criteria have been applied to both Monte Carlo and data samples:

(i) reconstructed zenith angle in the range $0° \leq \vartheta_{REC} \leq 35°$;
(ii) measured shower multiplicity $350 \leq M \leq 50,000$;
(iii) coordinates of the cluster with the highest multiplicity in the range $-20\ \text{m} \leq (X,Y)_{MAX} \leq 20$ m, measured from the detector center.

In Fig. 1 the distribution of the reconstructed core coordinate X_{core} is shown for both data and Monte Carlo events surviving the selection criteria. The contribution of events outside an area of 40×40 m^2 is negligible. Since showers produced by light elements have a well-shaped core, the discrimination between light and heavy components can be achieved by selecting showers with higher particle density in the core region. We have compared the average particle density measured by the 20 central clusters of the detector (ρ_{IN}) with the one measured by the 42 clusters in the outermost area (ρ_{OUT}). By requiring $\rho_{IN} > k \cdot \rho_{OUT}$ showers mainly induced by light elements have been selected. In Fig. 2 the fraction of selected Monte Carlo events for each primary mass is reported as a function of the primary energy. The fraction of iron nuclei is

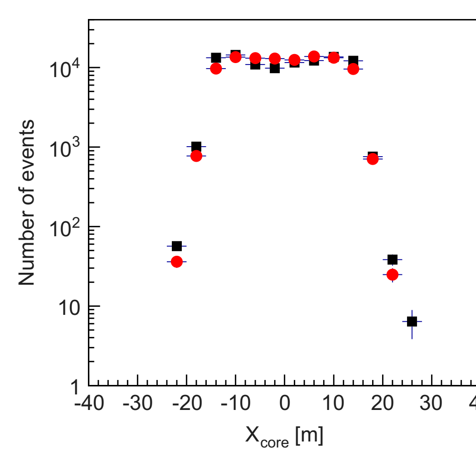

Fig. 1. Distribution of the reconstructed shower core coordinate X_{core} for both data (red dots) and Monte Carlo (black squares) samples. For a better comparison the two distributions have been normalized to the same number of events. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)