The Cosmic ray proton plus helium energy spectrum measured by the ARGO-YBJ experiment in the energy range 3-300 TeV Postprint

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Abstract

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Full Text

Preamble

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Abstract

The ARGO-YBJ experiment is a full-coverage air shower detector located at the Yangbajing Cosmic Ray Observatory (Tibet, People' s Republic of China, 4300 m a.s.l.). The high altitude, combined with the full-coverage technique, allows the detection of extensive air showers in a wide energy range and offers the possibility of measuring the cosmic ray proton plus helium spectrum down to the TeV region, where direct balloon/space-borne measurements are available. The detector has been in stable data taking in its full configuration from November 2007 to February 2013. In this paper, the measurement of the cosmic ray proton plus helium energy spectrum is presented in the region 3–300 TeV by analyzing the full collected data sample. The resulting spectral index is $\gamma = -2.64 \pm 0.01$. These results demonstrate the possibility of performing an accurate measurement of the spectrum of light elements with a ground-based air shower detector.

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Introduction

Cosmic rays are ionized nuclei reaching the Earth from outside the solar system. Many experimental efforts have been devoted to the study of cosmic ray properties, and in the last decades many experiments have focused on the identification of cosmic ray sources and on understanding their acceleration and propagation mechanisms. Despite a very large amount of data collected so far, the origin and propagation of cosmic rays are still under discussion. Supernova remnants (SNRs) are commonly identified as the source of galactic cosmic rays since they could provide the amount of energy needed to accelerate particles up to the highest energies in the Galaxy. The measurement of the diffuse gamma-ray radiation in the energy range 1–100 GeV supports these hypotheses on the origin and propagation of cosmic rays [?]. Moreover, the TeV gamma-ray emission from SNRs, detected by ground-based experiments, can be related to the acceleration of particles up to 100 TeV [?, ?]. A very detailed measurement of the energy spectrum and composition of primary cosmic rays will lead to deeper knowledge of the acceleration and propagation mechanisms.

Since the energy spectrum spans a huge energy interval, experiments dedicated to the study of cosmic ray properties are essentially divided into two broad classes. Direct experiments operating on satellites or balloons are able to measure the energy spectrum and the isotopic composition of cosmic rays on top of the atmosphere. Due to their reduced detector active surface and limited exposure time, the maximum detectable energy is limited to a few TeV. New generation instruments, capable of long balloon flights, have extended the energy measurements up to 100 TeV. All information concerning cosmic rays above 100 TeV is provided by ground-based air shower experiments, which observe the cascade of particles produced by the interaction between cosmic rays and the Earth' s atmosphere. Ground-based experiments detect extensive air showers produced by primaries with energies up to 10^{20} eV; however, they do not allow easy determination of the abundances of individual elements, and measurement of the composition is therefore limited only to the main elemental groups. Moreover, due to a lack of model-independent energy calibration, the determination of the primary energy relies on the hadronic interaction model used in the description of the shower' s development.

The ARGO-YBJ experiment is a high-altitude full-coverage air shower detector that was in full and stable data taking from November 2007 to February 2013. As described in section II, the detector is equipped with digital and analog readout systems working independently to study cosmic ray properties in the energy range 1-10^4 TeV, which is one of the main physics goals of the ARGO-YBJ experiment. The high space-time resolution of the digital readout system allows the detection of showers produced by primaries down to a few TeV, where balloon-borne measurements are available. The analog readout system was designed and built to detect showers in a very wide range of particle density at ground level and to explore the cosmic ray spectrum up to the PeV region. In 2012, a first measurement of the cosmic ray proton plus helium (light component) spectrum obtained by analyzing a small sample collected during the first period of data taking with the detector in its full configuration (using only the digital readout information) was presented [?].

In this paper, we report the analysis of the full data sample collected by the ARGO-YBJ experiment in the period from January 2008 to December 2012 and the measurement of the light component energy spectrum of cosmic rays in the energy range 3-300 TeV by applying an unfolding procedure based on Bayesian probabilities. The analysis of the analog readout data and the corresponding cosmic ray spectrum up to the PeV energy region is in progress and will be addressed in a future paper.

II. The ARGO-YBJ Experiment

The ARGO-YBJ experiment (Yangbajing Cosmic Ray Observatory, Tibet, P.R. China, 4300 m a.s.l.) is a full-coverage detector made of a single layer of Resistive Plate Chambers (RPCs) with 93% active area [?, ?], surrounded by a partially instrumented guard ring designed to improve event reconstruction. The detector consists of 1836 RPCs, arranged in 153 clusters each made of 12 chambers. The digital readout consists of 18360 pads each segmented into 8 strips. A dedicated procedure was implemented to calibrate the detector to achieve high pointing accuracy [?]. The angular and core reconstruction resolutions are respectively 0.4° and 5 m for events with at least 500 fired pads [?, ?]. The installation of the central carpet was completed in June 2006. The guard ring was completed during spring 2007 and connected to the data acquisition system [?] in November 2007. A simple trigger logic based on coincidence between pad signals was implemented. The detector has been in stable data taking in its full configuration for more than five years with a trigger threshold Npad = 20, corresponding to a trigger rate of about 3.6 kHz and a dead time of 4%. The high granularity and time resolution of the detector provide a detailed three-dimensional reconstruction of the shower front. The high altitude location and segmentation of the experiment offer the possibility to detect showers produced by charged cosmic rays with energies down to a few TeV. The digital readout of the pad system allows reconstruction of showers with a particle density at ground level up to about 23 particles/m^2, which corresponds to primaries up to a few hundred TeV. To extend the detector operating range and investigate energies up to the PeV region, each RPC has been equipped with two large-size electrodes called Big Pads [?]. Each Big Pad provides a signal whose amplitude is proportional to the number of particles impinging on the detector surface. The analog readout system allows detailed measurement of showers with particle density at ground up to more than 10^4 particles/m^2.

III. Data Analysis

A. Unfolding of the cosmic ray energy spectrum

As widely described in [?, ?], the determination of the cosmic ray spectrum from the measured space-time distribution of charged particles at ground level is a classical unfolding problem that can be addressed using the Bayesian technique [?]. In this framework, the detector response is represented by the probability $P(M_j|E_i)$ of measuring a multiplicity M_j due to a shower produced by a primary of energy E_i. The estimated number of events in a certain energy bin E_i is therefore related to the number of events measured in a multiplicity bin M_j by the equation

$$\hat{N}(E_i) \propto \sum N(M_j)P(E_i|M_j)$$

where η_{ij} is constructed using Bayes' theorem:

$$P(E_i|M_j) = \frac{P(M_j|E_i)P(E_i)}{\sum_k P(M_j|E_k)P(E_k)}$$

The values of the probability $P(M_j|E_i)$ are evaluated by means of a Monte Carlo simulation of shower development and detector response. The quantity $P(E_i|M_j)$ represents the probability that a shower detected with multiplicity M_j has been produced by a primary of energy E_i. The values of $P(M_j|E_i)$ are evaluated through an iterative procedure starting from a prior value $P^{(0)}(E_i)$, in which at the n-th step $P^{(n)}(E_i)$ is replaced by the updated value

$$P^{(n+1)}(E_i) = \frac{\hat{N}^{(n)}(E_i)}{\sum_k \hat{N}^{(n)}(E_k)}$$

where $\hat{N}^{(n)}(E_i)$ is evaluated in the n-th step according to the equation above. An initial prior $P^{(0)}(E_i) \sim E^{-2.5}$ was chosen, and the effect of using different prior distributions has been evaluated as negligible. The iterative procedure ends when the variation of all $\hat{N}(E_i)$ in two consecutive steps is evaluated as negligible, namely less than 0.1%. Typically convergence is reached after 3 iterations.

B. Air shower and detector simulations

The development of showers in the Earth's atmosphere has been simulated using the CORSIKA (v. 6980) code [?]. The electromagnetic component is described by the EGS4 code [?, ?], while high-energy hadronic interactions are reproduced by the QGSJET-II.03 model [?, ?]. Low-energy hadronic interactions are described by the FLUKA package [?, ?]. Showers produced by protons, helium, CNO nuclei, and iron have been generated with a spectral index $\gamma = -1$ in the energy range $(0.316 - 3.16 \times 10^4)$ TeV. About 5×10^7 showers have been generated in the zenith angle range 0–45 degrees and azimuth angle range 0–360 degrees. Showers were sampled at the Yangbajing altitude, and the shower core was randomly distributed over an area of (250×250) m^2 centered on the detector. The resulting CORSIKA showers have been processed by a GEANT3-based code [?] to reproduce the detector response, including the effects of time resolution, RPC efficiency, trigger logic, accidental background produced by each pad, and electronic noise.

C. Event selection

The ARGO-YBJ experiment was in stable data taking in its full configuration for more than five years, during which more than 5×10^{11} events were recorded and reconstructed. Several tools have been implemented to monitor detector operation and reconstruction quality. The detector control system (DCS) [?] continuously monitors RPC current, high voltage distribution, gas mixture, and environmental conditions (temperature, pressure, humidity). In this work, the analysis of events collected during the period 2008–2012 is presented. Data and simulated events have been selected according to a multi-step procedure to obtain high-quality events and ensure reliable and unbiased evaluation of the Bayesian probabilities.

The first step concerns run selection. To obtain a sample of high-quality runs, the working condition of the detector and the quality of the reconstruction procedure have been analyzed using the criteria described below:

- At least 128 clusters out of 130 must be active and connected to the DAQ and trigger systems. This criterion selects runs taken with almost the whole apparatus in data taking, discarding runs that could bias the analysis because of switched-off clusters.
- Only runs with a duration $T > 1800$ s have been considered. Runs with short duration are generally produced when a problem in the apparatus occurs, and these have been removed from the analysis.
- The trigger rate for each run must stay within the range 3.2–3.7 kHz. A trigger rate outside this range usually indicates non-standard detector operation, and these runs have been discarded.
- To monitor the quality of event reconstruction, the mean value of the unnormalized χ^2 obtained by fitting the shower front must be less than 135 ns^2 (see Figure 1). Nearly all runs with $\bar{\chi}^2 > 135$ ns^2 encountered

some sort of problems.

[Figure 1: see original paper] Distribution of the trigger rate (top) and of the unnormalized $\bar{\chi}^2$ (bottom) of all runs collected by the ARGO-YBJ experiment (black lines). The resulting 2008-2012 sample selected according to the criteria described in section III is also reported (dashed red lines).

The procedure described above selects a data sample of about 3×10^{11} events, corresponding to a live time of about 24000 hours.

The following selection criteria (fiducial cuts) have been applied to both Monte Carlo and experimental data to improve reconstruction quality and obtain the best estimation of the Bayesian probabilities:

- Only events with reconstructed zenith angles $\vartheta_R \leq 35°$ have been considered. The resulting solid angle Ω is about 1.13 sr.
- The measured shower multiplicity M must be in the range $150 \leq M \leq 5 \times 10^4$. This selection cut was introduced to reduce bias effects in the estimation of the Bayesian probabilities that are mainly located at the edges of the simulated energy range. Moreover, the highest multiplicity cut avoids saturation effects of the digital readout system.
- The cluster with the highest multiplicity must be contained within an area of about 40×40 m^2 centered on the detector. This cut was applied to reject events with their true shower core position located outside the detector surface.

To select showers induced by proton and helium nuclei, the following criterion has been used:

- **Density cut**: The average particle density (ρ_{in}) measured by the central area (20 inner clusters) of the detector must be higher than the particle density (ρ_{out}) measured by the outermost area (42 outer clusters): $\rho_{\text{in}} > 1.25\rho_{\text{out}}$. This selection criterion based on the lateral particle distribution was introduced to discard events produced by nuclei heavier than helium. In fact, in showers induced by heavy primaries, the lateral distribution is wider than in light-induced ones. By applying this criterion to events with the core located in a narrow area around the detector center, showers mainly produced by light primaries have been selected. The contamination of elements heavier than helium does not exceed a few percent, as discussed in section IV A 4.

[Figure 2: see original paper] Distribution of reconstructed core positions of showers selected by applying the criteria described in section III C. The boxes represent the clusters layout.

[Figure 3: see original paper] Energy distribution of all Monte Carlo events (black) and of those surviving the fiducial cuts (blue) and the density cut (green and red) described in section III C according to the Hörandel model [**?**].

In Figure 2, the coordinates of the reconstructed core position of events surviving the selection criteria described above are reported. The plot shows that the contribution of events located outside an area of 40×40 m^2 is negligible. In Figure 3, the event rate obtained using the Hörandel model for input spectra and isotopic composition [?] and surviving the selection criteria described above is reported as a function of energy for both proton plus helium (light component) and heavier elements (heavy component). The plot shows that the selected sample is essentially made of light nuclei.

IV. The Light Component Spectrum

The analysis was performed on the sample selected by the criteria described in section III. Simulated events have been sorted into 16 multiplicity bins and 13 energy bins to minimize statistical error and reduce bin migration effects. The Monte Carlo data sample was analyzed to evaluate the probability distribution $P(M|E)$ and the energy resolution, which turns out to be about 10% for energies below 10 TeV and of the order of 5% at energies of about 100 TeV. The multiplicity distribution extracted from data has been unfolded according to the procedure described in section III A. Results are reported in Figure 4 for each year of data taking and also for the full sample. To investigate the stability of the detector over a long period, the analysis was performed separately on data samples collected during each solar year in the period 2008–2012. The values of the proton plus helium flux measured at 50 TeV are reported in Table I. A power-law fit has been performed on the measured spectrum of each year and of the full data sample; the resulting spectral indices are reported in Figure 5. Both the spectral indices and flux values are in very good agreement, demonstrating the long-period reliability and stability of the detector. The spectral index $\gamma = -2.64 \pm 0.01$, obtained by analyzing the full data sample, is in good agreement with the one measured using a smaller data sample collected in the first months of 2008 [?], which was not corrected for contamination from heavier nuclei (see section IV A 4).

In Table II and Figure 6, the flux obtained by analyzing the full data sample is reported. The spectrum covers a wide energy range, spanning about two orders of magnitude, and is in excellent agreement with the previous ARGO-YBJ measurement. Statistical errors are of the order of 1‰; more than 10^5 events have been selected in the highest energy region, while at the lowest energies more than 10^7 events have been selected. Systematic errors are discussed in the next section. The ARGO-YBJ data are in good agreement with the CREAM proton plus helium spectrum [?]. At energies around 10 TeV and 50 TeV, the fluxes differ by about 10% and 20%, respectively. This means that the absolute energy scale difference between the two experiments is within 4% and 6%. The uncertainty on the absolute energy scale has been evaluated by exploiting the Moon shadow tool at a level of 10% for energies below 30 TeV [?]. At present, the ARGO-YBJ experiment is the only ground-based detector able to investigate the cosmic ray energy spectrum in this energy region.

A. Systematic uncertainties

A study of possible systematic effects has been performed. Four main sources of systematic uncertainties on the flux measurement have been considered in this work: variation of the selection cuts, reliability of the detector simulation, different interaction models, and contamination by heavy elements.

1. Selection criteria The fiducial selection criteria have been fine-tuned to obtain an unbiased evaluation of the Bayesian probabilities, leading to the best estimation of the cosmic ray proton plus helium energy spectrum. A possible source of systematic error is related to the values of the fiducial cuts on observables used in the event selection procedure. The uncertainty on the measured spectrum has been estimated by applying large variations (about 50%) to the fiducial cuts and turns out to be about 3%. The bins located at the edges of the measured energy range are affected by an uncertainty of about $±$5%. Variation of the quality cuts does not give a significant contribution to the total systematic uncertainty.

2. Reliability of the detector simulation A systematic effect could arise from inaccuracies in the simulation of the detector response. The quality of the simulated events has been estimated by comparing the distribution of observables obtained by applying the same selection criteria to Monte Carlo simulations and the data sample collected in each different year. As an example, in Figure 7 the multiplicity distribution obtained from Monte Carlo events is reported together with the multiplicity distribution of the data. The ratio between the two distributions is also reported, showing good agreement. The contribution to the total systematic uncertainty due to the reliability of the detector simulation has been evaluated using the unfolding probabilities and turns out to be about $±$6%.

3. Hadronic interaction models To estimate effects due to the particular choice of the high-energy hadronic interaction model in Monte Carlo simulations, a dataset has been generated using the SIBYLL 2.1 model [**?**, **?**]. These data have been compared with the QGSJET dataset used in this analysis. In Figure 8, the ratio between the multiplicity distributions obtained using the QGSJET model and the one obtained using SIBYLL is reported as a function of primary energy. The plot shows that the variation of the multiplicity distributions obtained with the two hadronic models is of a few percent, giving a negligible effect on the measured spectrum.

4. Contamination of heavier elements A possible systematic effect lies in the contamination of elements heavier than helium. The selection criterion based on particle density rejects a large fraction of showers produced by heavy primaries, as shown in Figure 3. The fraction of heavier elements, estimated using QGSJET-based simulations according to the Hörandel model [**?**], is reduced and can be considered negligible at energies up to 100 TeV. In the lower energy bins, the contamination is about 1%, whereas in the bins below 100 TeV the contamination does not exceed a few percent, and in the higher energy bins it is about 10%. The unfolding procedure has been set up to account for the amount of heavier nuclei passing the selection criteria. The contribution of this effect is therefore not included in the total systematic uncertainty.

5. Summary of systematic errors The total systematic uncertainty was determined by quadratically adding the individual contributions. The results are affected by a systematic uncertainty of the order of $±$5% in the central bins, while the edge bins are affected by a larger systematic uncertainty of less than $±$10%.

V. Conclusions

The ARGO-YBJ experiment was in operation in its full and stable configuration for more than five years, during which a huge amount of data has been recorded and reconstructed. The peculiar characteristics of the detector, such as the full-coverage technique, high-altitude operation, and high segmentation and space-time resolution, allow the detection of showers produced by primaries in a wide energy range from a few TeV up to a few hundred TeV. Showers detected by ARGO-YBJ in the multiplicity range 150-50000 strips are mainly produced by primaries in the (3-300 TeV) energy range. The relation between the shower size spectrum and the cosmic ray energy spectrum has been established using an unfolding method based on Bayes' theorem. The unfolding procedure has been performed on data collected during each year and on the full data sample. The resulting energy spectrum spans the range 3-300 TeV, giving a spectral index $\gamma = -2.64 \pm 0.01$, which is in very good agreement with the spectral indices obtained by analyzing the sample collected during each year, thereby demonstrating the excellent stability of the detector over a long period.

The resulting spectral indices are also in good agreement with the one obtained by analyzing the first data taken with the detector in its full configuration [**?**]. Special care was devoted to determining the uncertainties affecting the measured spectrum. The uncertainty on the results is due to systematic effects of the order of $±$5% in the central energy bins. This measurement demonstrates the possibility to explore cosmic ray properties down to the TeV region with a ground-based experiment, providing at present one of the most accurate measurements of the cosmic ray proton plus helium energy spectrum in the multi-TeV region.

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Note: Figure translations are in progress. See original paper for figures.