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Cosmic ray light component (p+He) energy spectrum measured by the ARGO–YBJ experiment in the 3–3000 TeV energy range

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Summary. — The energy spectrum and composition of Cosmic Rays (CR) play an important role in the understanding of the acceleration and propagation mechanisms of high-energy particles. The ARGO–YBJ experiment (Yanbajing, Tibet, P. R. China, 4300 m a.s.l.) is a ground-based air shower detector designed in order to detect showers produced by primaries in the 1–10^4 TeV energy range. The high spacetime resolution of the detector allows a precise measurement of the lateral particle distribution. This information can be exploited in order to discriminate showers produced by primaries of different mass. In this work the measurement of the Proton plus Helium energy spectrum is presented in the 1–3000 TeV energy range. A deviation from a single power law is clearly evident at energies less than 1 PeV.

1. – Introduction

The Cosmic Ray (CR) energy spectrum spans a huge energy range (from MeV up to $\sim 10^{20}$ eV), corresponding to a variation of the intensity of several orders of magnitude. The all-particle energy spectrum can be roughly described by a power-law, showing a "knee" at energies around 3.5 PeV. Despite a great experimental and phenomenological effort the origin of the knee remains unclear. The origin of knee in the all particle spectrum is probably related to the steepening of the proton and helium spectra. Due to the rapid decrease of the intensity as the energy increases, all information about CRs above 100 TeV is provided by ground-based air shower experiments. Due to a lack of a 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.

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Moreover large fluctuations in the hadronic interactions make it hard to separate primaries of different masses and the determination of the composition is essentially limited to large mass groups. A precise measurement of the proton and helium spectra in the energy region from few TeV to 10 PeV is of fundamental importance in the understanding of the origin of the knee.

1·1. *The ARGO–YBJ experiment.* – The ARGO–YBJ experiment [1, 2] is a full coverage air shower detector operated in the Yangbajing International Cosmic Ray Observatory (Tibet, P.R. China, 4300 m a.s.l.). The detector is made of a single layer of resistive plate chambers (RPCs) equipped with two independent readout systems (digital and analog). The two systems have been designed and developed in order to explore the cosmic ray energy spectrum and composition in a wide energy range from few TeV up to the PeV region. The high segmentation and spacetime resolution of the digital readout allow the detection of showers produced by low energy primaries and provides a detailed reconstruction of showers up to $\sim 23\,\mathrm{particles/m^2}$ corresponding to a primary energy up to a few hundreds of TeV. In order to extend the operating range of the detector and fully investigate the PeV energy region, each RPC has been equipped with two large electrodes, each providing a signal that is proportional to the number of charged particles impinging the detector surface. The analog readout system uses eight different gain scales (G0, …, G7). Data from the highest gain scale (G7) have been used for calibration purposes. The intermediate gain scale (G4) overlaps with the digital readout data in an energy range between 10 and 100 TeV, providing a cross-calibration of the two techniques. Data from the lowest gain scales (G1 and G0) allow the detection of showers with about $10^4\,\mathrm{particles/m^2}$. in the core region. A dedicated calibration procedure has been implemented for each gain scale [3]. In order to cover the 1–10^4 TeV energy range different approaches have been followed:

- Analysis of the digital readout data, sensitive to the energy range 3–300 TeV [7, 8].
- Bayesian analysis of the analog data. It uses the information coming from the RPC analog readout. The energy spectrum is extracted from the observed particle distribution at ground level by using a bayesian unfolding procedure. The discrimination between light and heavy primaries is based on the lateral distribution.
- Event-by-event reconstruction of the primary energy by measuring the particle densities (and their lateral distribution) close to the shower axis [4].
- Hybryd analysis. It is carried out by combining the data coming from ARGO–YBJ and a wide field of view Cherenkov telescope, exploring the 100 TeV–3 PeV region [5].

In this work the analysis of the digital readout data and the bayesian analysis of the analog readout are described.

2. – Data analysis

The development of a shower presents large intrinsic fluctuations and the primary energy cannot be determined on an event-by-event basis. As widely described in [6-8], the determination of the cosmic ray energy spectrum from the spacetime distribution of charged particles at ground level is a classical unfolding problem that can be dealt with the bayesian technique [9]. In order to evaluate the conditioned probabilities needed

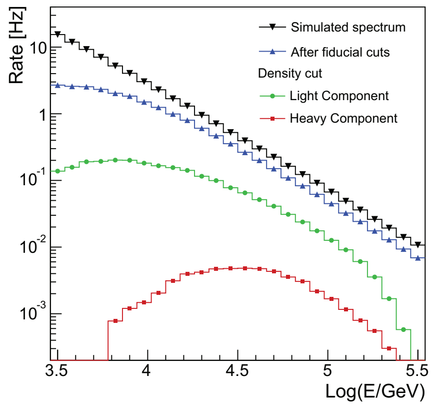

Fig. 1. – Energy distribution of all simulated events and of those surviving the fiducial cuts and the density cut described in sect. **2**˙1.

in the unfolding procedure a detailed simulation of the development of the shower in the Earth's atmosphere and of the detector response has been performed. A sample of simulated events was generated by using the CORSIKA code [10], including FLUKA and QGSJETII.03 hadronic interaction models. Showers produced by protons, helium, CNO and iron nuclei have been generated in the energy range (0.316–31600) TeV and in the zenith angle range 0–45 degrees according to the energy spectra described in [11]. Both the digital and analog output of the detector have been simulated by using a GEANT3 based code.

2˙1. *Digital readout data.* – The digital readout of the ARGO–YBJ experiment has been operated in its full configuration for more than five years and more than 5×10^{11} events have been recorded and reconstructed. A first selection has been based on the working condition of the detector and on the quality of the reconstruction procedure. By requiring quasi-vertical ($\vartheta_R \leqslant 35°$) events with the core located in an area of $40 \times 40\,\mathrm{m}^2$ measured from the detector center any bias effects in the estimation of the probabilities needed in the unfolding procedure has been reduced. A subsequent criteria based on the particle density, moreover, allows the selection of showers manly produced by light primaries. In fig. 1 the fraction of events surviving the fiducial cuts and the subsequent density cut is reported. The plot shows that showers surviving the selection criteria are essentially produced by protons and helium nuclei. The resulting energy spectrum spans the 3–300 TeV energy range and is it reported in fig. 2.

2˙2. *Analog readout data.* – The measurement of the spectrum up to 3 PeV has been carried out by exploiting the RPC analog readout system of the ARGO–YBJ experiment. As a first step, several studies have been performed on the simulated data sample in order to identify a suitable energy estimator and a set of parameters that allow the discrimination between showers produced by light and heavy primaries respectively. The number of particles within 8 m from the core position (Np_8) seems to be well correlated with primary energy and is not affected by bias effects related to the finite detector size. The lateral distribution of charged particles have been studied at several distances from the core position with high precision. Showers produced by light primaries have a well-shaped core and the largest fraction of particles is localized around the core region.

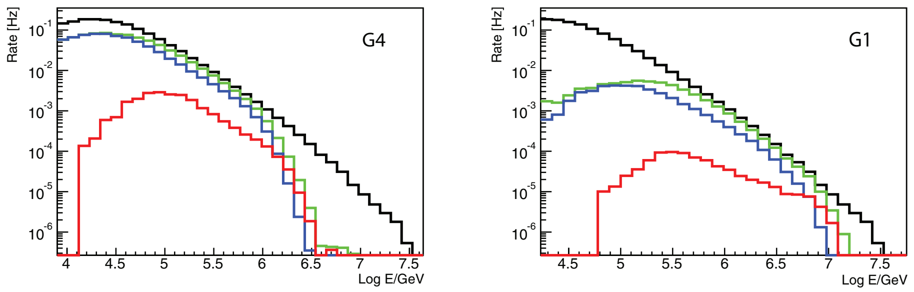

Fig. 2. – Energy distribution of all simulated events and of those surviving the fiducial cuts and the density cut described in sect. **2**˙1.

Showers generated by heavy nuclei, otherwise, show larger particle density at distances far from the core. The ratio β between the particle density at several distances from the core position and the particle density measured in the core region can therefore be exploited in order to discriminate light primaries. In this work we present the analysis of the first data collected during 2010. The analysis has been performed on the data collected by using the G4 and G1 gain scales. A series of fiducial cuts based on Np_8, reconstructed zenith angle and core position have been applied to both Monte Carlo and experimental data samples. In fig. 2 the fraction of events surviving the fiducial cuts and the discrimination cut is presented for both G1 and G4 data samples. The plot shows clearly that the selected samples are essentially made of showers produced by light primaries. The G4 and G1 data sets have been analyzed in order to measure the $N(Np_8)$ distribution, while the Monte Carlo data sample has been used in order to evaluate the probabilities needed in the unfolding procedure. The resulting spectra are shown in fig. 3. The energy spectrum obtained by analyzing the G4 data sample spans the energy range between 10 and 150 TeV, overlapping the spectrum measured by

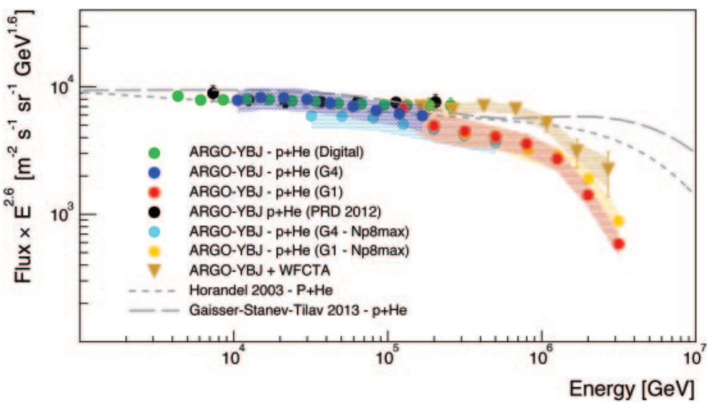

Fig. 3. – Cosmic ray proton plus helium spectrum measured by ARGO–YBJ. Results of the digital data (green) [8], Analog data with the bayesian technique (red and blue), Analog data with event-by-event energy reconstruction (light blue and yellow) [4] and Hybrid (brown) [5] analyses are reported. The curves of the proton plus helium spectrum according to the Hörandel [11] and GST [12] models are also shown.

using the digital readout data. These results are fairly consistent between each other, both concerning the spectral index and flux intensity, demonstrating the reliability of the response of the analog readout system. The analysis of the G1 dataset extend the energy range up to the PeV region, clearly showing a deviation from a single power law at energies of about 700 TeV. The total systematic errors have been estimated as of the order of $\pm 10\%$.

3. – Conclusions

The ARGO–YBJ experiment has been taking data in its full configuration for more than five years. The detector has been equipped with two independent readout systems. The high segmentation and spacetime resolution of the digital readout system allows the detection of showers produced by primaries in a wide energy range, from a few TeV up to a few hundreds of TeV. The analog readout system has been designed and implemented in order to sample showers with about 10^4 particles/m^2 around the core region, corresponding to a primary energy up to the PeV region. Three independent datasets have been analyzed in order to investigate the cosmic ray energy spectrum in the region (3–3000) TeV. The relation between the shower size and the primary energy has been established by using a Bayesian unfolding procedure. The discrimination between showers produced by light and heavy primaries has been obtained by using a selection criterion based on the lateral distribution of charged particles in the shower front. The analysis of the digital data sample collected during the ~ 5 years lifespan of the experiment has been performed. The resulting spectrum spans the energy range (3–300) TeV, giving a spectral index $\gamma = -2.64 \pm 0.01$, in excellent agreement with the one obtained by analyzing the first data taken with the detector in its full configuration [7]. The analysis of the analog readout data sample has been performed in order to measure the p+He spectrum in the energy region (10–3000) TeV energy range. The resulting spectrum remarkably agrees with the one obtained by analyzing the digital readout full data sample in a wide energy range from 10 TeV up to 150 TeV. A deviation from a single power law is clearly evident at energies of about 700 TeV, showing a rapid decrease of the light component flux at higher energies. These results demonstrates the possibility of exploring the cosmic ray properties in a wide energy range with a single ground-based experiment and open new scenarios about the evolution of the light component energy spectrum towards the highest energies and the origin of the knee.

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