Measurement of the cosmic rays light component (p+He) primary spectrum with ARGO-YBJ

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1. Introduction

There is a general consensus that cosmic rays (CRs) up to the “knee” (\( \sim 3 \times 10^{15} \text{ eV} \)) originate in Galactic Supernova Remnants accelerated by the first order Fermi mechanism in shock waves. The theoretical modelling of this mechanism can reproduce the measured spectra and composition of CRs. The bulk of primary CRs at the energies well below the knee are proton and helium nuclei. Recent measurements carried out by the balloon-borne CREAM experiment [1,2] show that the proton and helium spectra from 2.5 to 250 TeV are both flatter compared to the lower energy measurements. In particular, the proton spectrum in this energy range is found harder than the value quoted in Ref. [3] and obtained by fitting many previous direct measurements. In addition, the proton and helium fluxes measured by CREAM are consistent with the measurements of JACEE [4] and higher, particularly for helium, with respect to RUNJOB [5]. The evolution of the proton and helium spectra and their subtle differences can be an indication of the contribution of different populations of CR sources operating in environments with different chemical compositions [6].

In the knee region the measurements of the CR primary spectrum are carried out only by EAS arrays and the current experimental results are still conflicting. In the standard picture the mass of the knee is light [7,8] being due to the steepening of the p and He spectra. However, increasing the altitude of the experiment locations the measured average mass of cosmic ray primary component at the knee increases as well.

In fact, the results of the Tibet AS\( ^\gamma \) and the BASJE experiments, located at 4300 m a.s.l. and at 5200 m a.s.l. respectively, favour a heavier composition because the proton component is no more dominant at the knee [9,10].

Therefore, protons are the key component for understanding the origin of the knee. In addition, precise knowledge of their fluxes may allow one to calculate the yield of rare secondary CRs as antiprotons and positrons and establish the expected fluxes of the atmospheric neutrinos. Data in the TeV range are important for the neutrino-induced upward muon calculations.

Additional information on the proton spectrum has been obtained from the high energy branch of the sea level muon spectrum [11] and from the energy spectrum of the hadronic component in EAS [12]. A measurement of the Cherenkov light yield at different core distances in EAS performed by the EAS-TOP and MACRO experiments has been used to infer the helium flux at 80 TeV, resulting twice larger than that obtained by JACEE [7].

The ARGO-YBJ detector is well suited to study the spectrum of the “light component” at energies <100 TeV by exploiting its digital readout. In addition, by exploiting the analog readout, the experiment is able to extend its energetic range up to the knee. The capability to measure the CR spectrum over more than 3 energy decades (TeV–PeV) makes ARGO-YBJ the only experiment suitable to anchor ground-based data to direct measurements.

In this paper we report on the measurement of the spectrum of the primary CR light (p+He) component in the energy range \( \sim 10–100 \text{ TeV} \) selecting quasi-vertical showers (zenith angle...
with the reconstructed core position located in a 40 × 40 m² fiducial area. The results are compared with measurements carried out with direct methods.

2. The ARGO-YBJ experiment

The detector is composed of a central carpet large ~ 74 × 78 m², made of a single layer of Resistive Plate Chambers (RPCs) with ≈ 93% of active area, enclosed by a guard ring partially (≈ 20%) instrumented up to ~ 100 × 110 m². The apparatus has a modular structure, the basic data acquisition element being a cluster (5.7 × 7.6 m²), made of 12 RPCs (2.8 × 1.25 m² each). Each chamber is read by 80 external strips of dimension 6.75 × 61.8 cm² (the spatial pixels), logically organized in 10 independent pads of area 55.6 × 61.8 cm² which represent the time pixels of the detector. The readout of 18,360 pads and 146,880 strips is the experimental output of the detector [13]. The relation between strip and pad multiplicities has been measured and found to agree with the Monte Carlo prediction [13].

The readout of the large size pads [14]. The central carpet contains 130 clusters (hereafter, ARGO-130) and the full detector is composed of 153 clusters for a total active surface of ~ 6700 m². Due to the small pixel size, the detector is able to record events with a particle density exceeding 0.003 particles m⁻², keeping good linearity up to a core density of about 15 particles m⁻². This high granularity allows a complete and detailed three-dimensional reconstruction of the front of air showers with an energy threshold of a few hundred GeV. Showers induced by high energy primaries (> 100 TeV) are also imaged by the analog read-out of the large size pads [14].

The whole system, in smooth data taking since July 2006 firstly with ARGO-130, is in stable data taking with the full apparatus of 153 clusters since November 2007 with the trigger condition $N_{\text{trig}} > 20$ pads and a duty cycle ≈ 85%. The trigger rate is 3.5 kHz with a dead time of 4%.

2.1. Event reconstruction

The reconstruction of the shower parameters is carried out through the following steps. At first, a plane surface is analytically fitted (with weights equal to 1) to the shower front. This procedure is repeated up to five times, each iteration rejecting hits whose arrival time is farther than two standard deviations from the mean of the distribution of the time residuals from the fitted plane surface. This iterative procedure is able to reject definitively from the reconstruction the time values belonging to the non-gaussian tails of the arrival time distributions [15]. After this first step the problem is reduced to the nearly-vertical case by means of a projection which makes the fit plane overlapping the detector plane. Thereafter, the core position, i.e. the point where the shower axis intersects the detection plane, is obtained fitting the lateral density distribution of the secondary particles to a modified Nishimura–Kamata–Greisen (NKG) function. Finally, the core position is assumed to be the apex of a conical surface to be fitted to the shower front. The slope of such a conical correction is fixed to $\alpha = 0.03$ ns/m [15]. The fit procedure is carried out via the Maximum Likelihood method [16].

2.2. Detector performance

The performance of the detector and its operation stability have been studied in detail exploiting the CR Moon shadowing effect with all data since July 2006 [17]. The measured angular resolution is better than 0.5° for CR-induced showers with energies $E > 5$ TeV, in good agreement with MC expectations. The long-term stability of the ARGO-YBJ experiment has been checked by monitoring both the position of the Moon shadow and the amount of shadow deficit events in the period November 2007–November 2010, for each sidereal month. The position of the Moon shadow turned out to be stable at a level of 0.1° and the angular resolution stable at a level of 10%, on a monthly basis. These results make us confident about the detector stability in the long-term observation of the Northern sky. The primary energy of the detected showers has been estimated by measuring the westward displacement as a function of the shower multiplicity, thus calibrating the relation between shower size and CR energy. The systematic uncertainty in the absolute rigidity scale is evaluated to be less than 13% in the range from 1 to 30 (TeV/Z), mainly due to the statistical one [17].

3. Data analysis

The measured event rate is modulated on a long time period by the instrumental response and fluctuations of the shower development. In order to minimize the first effect, a sample of high quality runs has been selected by requiring that the total number of pads dead or with a counting rate less than 50% of the mean value (“bad” pads) is less than 3%. In such a way only runs with less than about 500 bad pads (over 15,600) have been used. The fluctuation in the cosmic ray flux may be caused by several factors. One of the most important is the so called “barometric effect”: owing to the mass absorption provided by the Earth atmosphere, variations of the atmospheric pressure result in small fluctuations of the cosmic ray flux. The percentage variation in the cosmic ray intensity caused by a pressure change of 1 mbar is expressed by the use of the barometric coefficient $\beta$. The value of $\beta$ depends on the particular experimental set-up used for the detection, on its geographical location and its local environment. We also excluded from the analysis all data with a pressure value larger than three standard deviations from the mean value. These selections lead to a data set of about 250 days in 2009.

3.1. The zenith angle distribution

The zenith angle distribution of events in various intervals of shower size has been extensively used to study the absorption in atmosphere of EAS generated by primaries with different energies. The angular distribution is expected to follow an exponential behaviour

$$I(\theta) = \frac{N_{\text{att}}}{L_{\text{att}}} \exp \left( - \frac{X_0}{L_{\text{att}}} (\sec \theta - 1) \right)$$

where $N_{\text{att}}$ is the number of strip fired on the detector, $X_0 = 606$ g/cm² is the vertical depth in the YBJ site and $L_{\text{att}}$ is the attenuation length. The angular distribution of events with $N_{\text{att}} > 100$ is shown in Fig. 1. The formula (1) fits the data up to zenith theta angle of 60° corresponding to (sec $\theta - 1$) ~ 1. The fit result gives $L_{\text{att}} = 133.5 \pm 0.4$ g/cm². The flat distribution for (sec $\theta - 1$) ~ 1, corresponding to 60°, is due to a non-attenuated component due to the dependence of barometric coefficient as shown in Fig. 2.

Moreover the dependence of the barometric effect on the zenith angle clearly shows that at $(\sec(\cos \theta) - 1) \geq 1$, corresponding to $\theta \geq 60°$, a non-attenuated component dominates over the cosmic ray hadronic flux. This is shown in Fig. 2 where the barometric coefficient is seen to follow the expected sec $\theta$ dependence, deviating above $\theta 

In Fig. 3 the measured zenith angle distribution of events is shown. The best fit is provided by an $\exp(-n \cdot \gamma \cdot \cos \theta)$ law, with $n = \gamma \cdot X_0 / L_{\text{abs}}$ where $\gamma = 1.61$ is the index of the primary energy
1.5 is due a dominant non-attenuated component. The ratio \( \frac{n}{\beta} \) gives also a measure of the barometric coefficient, which is a function of the pressure at YBJ site, following the relation:

\[
R = R_0 \left[ 1 - \alpha (N - N_0) \right] e^{-\beta (p_0 - p)}
\]

where \( R_0 \) is the daily measured rate, \( N \) is the number of bad pads whose mean number is \( N_0 = 425 \), \( p \) is the daily pressure value and \( p_0 = 606 \text{ g/cm}^2 \) is the nominal pressure at the YBJ site. The two coefficients \( \alpha \) and \( \beta \) are the spectral index of the pad spectrum and the coefficient for the barometric effect, respectively. The corrected event rate is showed by the red points in Fig. 4.

The FWHM of the corrected rate distribution is about \( \pm 2\% \). However, we note some “runs” with rate much scattered from the average. A check of the detector conditions confirms that this effect is due to failures of the electronics as, for instance, a change of the threshold level of the RPC front-end, or a defect in the low voltage supplies of the readout system. We excluded from the analysis all the data with a trigger rate outside the interval \( \pm 3\% \).

### 3.2. Strip spectrum

The following analysis refers to events collected selecting:

1. more than 250 strips on the ARGO-130 carpet;
2. reconstructed zenith angle of the shower less than 15\(^{\circ}\);
3. reconstructed shower core position inside a fiducial area \( A_{\text{fid}} = 40 \times 40 \text{ m}^2 \) centered on the detector.

This selection provides that the contamination of external events erroneously reconstructed inside \( A_{\text{fid}} \) is less than 15\% and the reconstruction efficiency is \( \approx 85\% \).

In order to correct the fluctuations of the cosmic ray flux, the correlation with atmospheric pressure and temperature has been investigated. We found, as expected, the barometric effect dominant. In Fig. 4, for example, the rate of all events, without any core selection, is shown by blue points. The horizontal axis represents the time since 1 January 2009 counted in bins of 1 day. The rates are normalized to the number of efficient pads and at the nominal pressure at YBJ site, following the relation:

\[
R = R_0 \left[ 1 - \alpha (N - N_0) \right] e^{-\beta (p_0 - p)}
\]

where \( R_0 \) is the daily measured rate, \( N \) is the number of bad pads whose mean number is \( N_0 = 425 \), \( p \) is the daily pressure value and \( p_0 = 606 \text{ g/cm}^2 \) is the nominal pressure at the YBJ site. The two coefficients \( \alpha \) and \( \beta \) are the spectral index of the pad spectrum and the coefficient for the barometric effect, respectively. The corrected event rate is showed by the red points in Fig. 4.

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### References


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**Fig. 1.** The zenith angle distribution of EAS measured with ARGO-YBJ. We show the best fit up to \( \theta \approx 60^\circ \), corresponding to \( \sec \theta \\leq 1 \). The flat distribution above 15 is due a dominant non-attenuated component.

**Fig. 2.** The percentage variation of the pressure, barometric coefficient \( \beta \), measured with ARGO-YBJ as a function of the reconstructed zenith angle.

**Fig. 3.** Measured zenith angle distribution; the exponential (solid line) and \( \cos^n \theta \) (dashed line) best fits are also shown.

**Fig. 4.** Event rates before (blue points) and after (red points) the correction of barometric and bad pad effects (see text for details). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
from the mean value. The gaps in the data stream correspond to maintenance periods.

The selected events have been divided into “differential classes” defined by strip multiplicity $N_s$. The width of the fired strip bins corresponds to $\Delta \log(N_s) = 0.2$. For each bin, the measured rate has been corrected for the previous effects, for the dead time (4%) and for the average pad efficiency (95%). In Fig. 5 the barometric coefficient $\beta$ as a function of the shower multiplicity for quasi-vertical events ($\theta \leq 15^\circ$) is shown. The coefficient exhibits a dependence on the strip multiplicity under investigation.

4. Monte Carlo simulation

The air shower development in the atmosphere has been simulated with the CORSIKA v. 6.7.2 code [20]. The electromagnetic interactions are described by the EGS4 package while the hadronic interactions above 80 GeV are reproduced by the QGSJET-II.03 model. The low energy hadronic interactions are described by the FLUKA code. Cosmic rays have been generated in the energy range from 100 GeV to 4 PeV according to different spectra given in [2–5]. About $\sim 10^7$ showers induced by protons, helium nuclei, CNO, MgSi and Fe nuclei have been sampled in the zenith angle interval $0^\circ$–$20^\circ$.

The secondary particles have been propagated down to cut-off energies of 1 MeV (electromagnetic component) and 100 MeV (muons and hadrons). The experimental conditions (trigger logic, time resolution, electronic noises, relation between strip and pad multiplicities, etc.) have been taken into account via a GEANT3-based code. The core positions have been randomly sampled in an energy-dependent area large up to $3.5 \times 10^3 \times 3.5 \times 10^3$ m$^2$, centered on the detector. Simulated events have the same format used for the experimental data and are analyzed with the same reconstruction code.

The effective area $A_{\text{eff}}(E > N_s)$, for events with core inside the fiducial area, is shown in Fig. 6 for showers with a strip multiplicity $N_s > 400$. These values are folded with the energy spectrum of each primary nucleus, to obtain the expected rate for each primary mass $i$

$$R_i(> N_s) = \int \phi_i(E) A_{\text{eff},i}(E, > N_s) \, dE \, d\Omega. \quad (3)$$

The expected integral rate of quasi vertical showers induced by protons, helium and CNO nuclei with CREAM spectra, reconstructed inside the fiducial area $A_{\text{fid}}$, is shown in Fig. 7.

![Fig. 5. The percentage variation of the pressure, barometric coefficient beta, as function of the strip multiplicity for events with zenith angle $\theta \leq 15^\circ$ and reconstructed core in $A_{\text{fid}}$.](image)

![Fig. 6. Effective areas for proton, helium and CNO induced showers with $N_s > 400$ as a function of the primary energy.](image)

![Fig. 7. Expected integral rate of quasi vertical events with core in the fiducial area $A_{\text{fid}}$ induced by protons, helium, CNO, MgSi and Fe nuclei, calculated with spectra obtained by fitting the CREAM data.](image)

The main contribution to the expected rate is provided by proton primaries. The contribution of the other nuclei increases with the strip multiplicity of the event. The relative fractions (in % of the total) $R_P/R_{\text{He}}/R_{\text{CNO}}/R_{\text{heavy}}$ are 67.6/28.2/2.7/0.7 in the first multiplicity bin ($\Delta N_s = 251–398$) and 51.2/40.4/5.4/2.4 in the last multiplicity bin ($\Delta N_s = 6310–10000$) for CREAM spectra. Proton- and helium-induced showers contribute to the rate for more than 90% in the whole strip multiplicity range. The CNO contribution is $< 7\%$, heavier nuclei contribute less than 3%.

5. Comparison with data

To obtain the light ($p+$He) component spectrum, we subtracted from the data the contribution of heavy elements, CNO, MgSi and Fe, calculated with the spectra shown in Fig. 7. In Fig. 8 the experimental event rate, without the contribution of heavy nuclei, is shown as a function of the strip multiplicity (stars) and compared to the expectations according to CREAM, Hörandel, JACEE and RUNJOB ($p+$He) spectra. The rate has been multiplied by $N^{1.25}$.

The median energy for proton- (helium-) induced showers ranges from 4.5 (9) TeV ($\Delta N_s = 251–398$) up to 56 (90) TeV ($\Delta N_s = 6310–10,000$). The statistical error on data is negligible, while the systematic uncertainty is estimated $\pm 10\%$, mainly due to the reconstruction of the core position. The calculation of the systematic errors due to the hadronic models is under way.
The different lines in Fig. 8 are best fits with the following spectral indices: $-1.25 \pm 0.03$ for data (solid line), $-1.21 \pm 0.03$ for Hörandel spectrum (short-dashed line), $-1.32 \pm 0.03$ for RUNJOB spectrum (dot-dashed line), $-1.26 \pm 0.02$ for JACEE spectrum (long-dashed line) and $-1.15 \pm 0.03$ for CREAM spectrum (dotted line). The uncertainties associated to different measurements are not shown in Fig. 8, being of the order of 15%.

6. Conclusions

The high segmentation of the full coverage ARGO-YBJ detector and its location at high altitude allow the detection and the reconstruction of air showers induced by CRs of energies $<100 \text{ TeV}$. Selecting quasi-vertical showers with core located on a fiducial area well inside the ARGO-YBJ central carpet, a sample of events mainly induced by proton and helium primaries is obtained.

The ARGO-YBJ data are consistent with JACEE and Hörandel expectations concerning slope and flux and disfavour the RUNJOB measurement.

For the first time a ground-based measurement of the CR light component spectrum overlaps data obtained with direct methods for more than an energy decade, thus providing a solid anchorage to the CR primary spectrum measurements in the knee region carried out by EAS arrays.

References