Measurement of the Cosmic Ray primary spectrum with ARGO-YBJ experiment

B Panico$^{1,2}$, G Di Sciascio$^2$, R Iuppa$^{1,2}$

$^1$ Universitá Roma Tor Vergata Via Della Ricerca Scientifica, 1, 80133 Roma
$^2$ INFN Sezione Roma Tor Vergata Via Della Ricerca Scientifica, 1, 80133 Roma

E-mail: beatrice.panico@roma2.infn.it
giuseppe.disciascio@roma2.infn.it
roberto.iuppa@roma2.infn.it

Abstract. The study of cosmic ray physic of $10^{12} - 10^{15}$ primary cosmic energy is one of the main goals of ARGO-YBJ experiment. The detector, located at the Yangbajing Cosmic Ray Laboratory (Tibet, 4300 m a.s.l., 606 g/cm$^2$), is an EAS array consisting of a continuous carpet of RPCs. The low energy threshold of the detector allows to study an energy region characterized by the transition from the direct to the indirect measurements. In this talk we will report on the measurement of the cosmic ray energy spectrum at different zenith angles. The phenomenology of horizontal air shower ($\theta > 70^\circ$) will be described and discussed.

1. The ARGO-YBJ experiment
The detector is composed of a central carpet large $\sim 74 \times 78$ m$^2$, made of a single layer of Resistive Plate Chambers (RPCs) with $\sim 93\%$ of active area, enclosed by a guard ring partially ($\sim 20\%$) instrumented up to $\sim 100 \times 110$ m$^2$. The basic data acquisition element is a cluster ($5.7 \times 7.6$ m$^2$), made of 12 RPCs ($2.8 \times 1.25$ m$^2$ each). Each chamber is read by 80 external strips of dimension $6.75 \times 61.8$ cm$^2$ (the spatial pixels), logically organized in 10 independent pads of area $55.6 \times 61.8$ cm$^2$ which represent the time pixels of the detector [1]. In order to extend the dynamical range up to PeV energies, each chamber is equipped with two large size pads ($139 \times 123$ cm$^2$) to collect the total charge developed by the particles hitting the detector [2]. The full detector is composed of 153 clusters for a total active surface of $\sim 6700$ m$^2$. The whole system is in stable data taking with the full apparatus since November 2007 with a duty cycle $\geq 85\%$.

2. Data analysis
The measured event rate is modulated on a long time period by the instrumental response and by the 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 15600) have been used. The fluctuations 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’s 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 setup 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 3 standard deviations from the mean value. These selections leads to a data set of about 250 days in 2009.

2.1. Strip spectrum Vertical Events
The following analysis refers to events with reconstructed zenith angle of the shower less than 15° and reconstructed shower core position inside a fiducial area $A_{fid}=40 \times 40 \text{ m}^2$ centered on the detector. This selection provides that the contamination of external events erroneously reconstructed inside $A_{fid}$ is less than 15% and the reconstruction efficiency is greater than 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. The rates are normalized to the number of efficient pads and at the nominal pressure at YBJ site, following the relation

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

where $R_0$ is the daily measured rate, $N$ is the number of bad pads whose mean number is $N_0=307$, $p$ is the daily pressure value and $p_0 = 606 \text{ g/cm}^2=594.14 \text{ mbar}$ is the nominal pressure at the YBJ site. The two coefficient $\alpha$ and $\beta$ are the spectral index of the pad spectrum and the coefficient for the barometric effect, respectively. The selected events have been divided into “differential classes” defined by strip multiplicity $\Delta N_s$. The width of the fired strip bins corresponds to $\Delta \log(N_s) = 0.1$. 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%).

![Figure 1](image.png)

Figure 1: (a) Contribution of the different groups of cosmic rays (b) Comparison between the experimental data (stars) and the differential expected rates according to different spectra. The solid line is the best fit to data (see text for details).

2.2. Monte Carlo simulation
The air shower development in the atmosphere has been simulated with the CORSIKA v. 6.7.2 code [3]. Cosmic rays have been generated in the energy range from 100 GeV to 4 PeV according to different spectra given in [4, 5, 6, 7]. About $10^9$ showers induced by protons,
helium, CNO, MgSi and Fe nuclei have been sampled in the zenith angle interval $0^\circ$ - $20^\circ$. 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 $3.5 \times 10^3 \times 3.5 \times 10^3 \text{m}^2$, centered on the detector.

The effective areas $A_{eff}(\varepsilon)\cdot N_s$, for events with core inside the fiducial area, are folded with the energy spectrum of each primary nucleus to obtain the expected rate for each primary mass $i$. The expected integral rate of quasi vertical showers induced by protons, helium and CNO nuclei with CREAM spectra, reconstructed inside the fiducial area $A_{fid}$, is shown in Fig.1(a). 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) $R_P/R_{He}/R_{CNO}/R_{heavy}$ 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%.

2.3. 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.1(a). In Fig. 1(b) 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 ($\Delta N_S = 6310$-10000). 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.1(b) are best fits with the following spectral indices: -1.28$\pm$0.03 for data (solid line), -1.22$\pm$0.03 for Hörandel spectrum (short-dashed line), -1.32$\pm$0.03 for RUNJOB spectrum (dot-dashed line), -1.28$\pm$0.02 for JACEE spectrum (long-dashed line) and -1.17$\pm$0.03 for CREAM spectrum (dotted line). The uncertainties associated to different measurements are not shown in Fig.1, being of the order of 15%.

2.4. Horizontal Showers
In this preliminary analysis we selected events firing more than 100 strips on the ARGO central carpet only in the runs collected in the period January-March 2009 in which the dead pad number is less than 3% of the total pads. The events are selected as in the previous analysis. Besides they have been divided into differential classes in angle and for strip multiplicity intervals, $\Delta N_S = 0.2$. For each bin, the measured rate has been estimated and it has been corrected for the dead time (4%). The measured strip spectrum for each bin of zenith angle is shown in Fig.2(a). In Fig.2(b) is reported the spectral index measured for each angular class. For the events with $\theta > 80^\circ$ the best power law fit to the data gives a spectral index of -3.60$\pm$0.02. This result is consistent with the size spectrum of HAS produced by muons bremsstrahlung in the primary energy region $10^3$-$10^6$ GeV/nucleon calculated in [8]. A detailed comparison with expectations from Monte Carlo simulations is under way.

3. 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 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. Exploiting the high granularity and the excellent angular resolution of the ARGO-YBJ detector small HAS are reconstructed with unprecedented details. A preliminary study of showers as a function of different zenith angle is reported.

References

[1] Aielli G et al. 2006 Nucl.Instrum.Meth. A562 92–96
[2] Iacovacci M et al. 2009 Proc. of the 31st ICRC (Lodz)
[3] Heck D et al. 1998 Report FZKA 6019
[4] Yoon Y S et al. 2011 Astroph. Journ. 728 122–129
[5] Horandel J 2003 Astrop. Phys. 19 193–220
[6] Asakimori K et al. 1998 Astroph. Journ. 502 278–283
[7] Apanasenko A et al. 2001 Astrop. Phys. 16 13–46
[8] Parente G et al. 1995 Astrop. Phys. 3 17–28