A first measurement of the Strip Size Spectrum with the ARGO-YBJ experiment

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***Abstract*— The ARGO-YBJ experiment, constituted by a full coverage carpet of Resistive Plate Chambers (RPCs), is located at the YangBaJing Cosmic Ray Laboratory (4300 m a.s.l., Tibet, P.R. China). The shower size is measured by means of strips of 55.6×61.8 cm^2 (strip density ∼22 strips/m^2).**

In this paper we present a first measurement of the strip size spectrum performed with a portion of the full detector (ARGO-42, ∼1820 m^2 out of ∼6700 m^2). In this analysis the measured spectrum is due to primaries with energies extending from ∼10 TeV up to ∼100 TeV, an energy range where direct measurements are available. The results are compared with the expectations according to RUNJOB and JACEE models.

I. Introduction

The spectra of all Extensive Air Shower (EAS) observables can be described by power laws over a wide range of primary energies. In the PeV region the spectra show a small steepening, the so-called *"knee"*. This feature, known since more than 40 years, reflects the convolution of the steepening of all the single mass spectra.

The energy range between 10^{14} and 10^{16} eV has long been recognized as crucial to understand the cosmic ray acceleration at all energies, because the knee appears to mark a transition from one acceleration process to another [1], [2]. Describing the processes by which galactic cosmic rays achieve their enormous energies remains a fundamental goal of astrophysics. A careful measurement of the single mass energy spectra in the knee region is of fundamental importance to discriminate between different interpretations. Unfortunately, due to the steepness of the energy spectrum the direct measurement of the primary radiation can be performed, with adequate statistics, only for energies up to $\sim 10^{14}$ eV/nucleon.

The most recent results come from two balloon experiments, JACEE and RUNJOB [3], [4]. JACEE has measured the proton and Helium spectra up to ∼ 800 TeV without observing any knee-like structure [5]. However, above 80 – 90 TeV the data does not have enough statistics to either assess or reject the presence of a break [6]. JACEE claims a flatter He spectrum compared to the proton one, in agreement with the earlier SOKOL result [7]. The differential spectral indexes reported are $\gamma_p = (-2.80 \pm 0.04)$ and $\gamma_{He} = (-2.68 \pm 0.06)$.

The RUNJOB experiment data suggests, unlike JACEE, that the spectra of proton and Helium nuclei are almost parallel, with index $\simeq -2.80$ for both, and an uncertainty between 10 and 20% [9]. Since the beginning of this experiment, He flux was lower than that of most other experiments by about 40%. Even after the statistics was increased, this tendency has not changed [10]. JACEE data shows a gradual increase in the mass number at higher energies, while RUNJOB results seem to be almost constant over the wide energy range 20 – 1000 TeV/particle [11].

All the experimental evidences for a knee feature in the primary cosmic ray spectrum are of indirect kind, i.e., are based on the reconstruction and interpretation of EAS observables. Because of the reduced resolution in the measurement of the primary mass, the air shower arrays typically separate events as "proton-like" or "iron-like", with results which critically depend on MonteCarlo predictions. As a consequence, the results can only be displayed as a function of the total energy per particle with the so-called *"all-particle"* spectrum, i.e., as a function of the total energy per nucleus, and not per nucleon. In addition, up to now, EAS data has never been calibrated with the direct measurements.

Despite large progresses in building new multi-component EAS experiments and in the analysis techniques to infer energy spectra and chemical composition, the key questions concerning the origin of the knee are still open.

In particular, one of the most important questions to be solved is the position of the proton knee. In fact, the existing experimental data is in substantial disagreement: the proton spectrum measured by the TIBET-ASγ experiment shows a knee-like structure around 200 TeV, while the KASCADE data suggests a steepening at a few PeV. Direct measurements carried out by RUNJOB and JACEE, as discussed above, do not exhibit any spectral break up to the highest measured energy (∼ 800 TeV). The knowledge of the primary proton spectrum is fundamental to understand the cosmic rays acceleration mechanisms and propagation processes in the Galaxy. A careful measurement of the proton spectrum in the energy region from 1 TeV to 100 PeV is one of the main tasks of the future cosmic ray experiments.

The ARGO-YBJ experiment, installed at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l.), offers the unique opportunity to investigate the cosmic ray spectrum over a large energy range (about 3 decades) because of its ability to operate down to a few TeV, thus overlapping the direct measurements, by measuring small size air showers (strip or digital read-out) and up to the PeV region by measuring the RPCs charge (analog read-out [12]).

Since December 2004 a portion of the full carpet, 42

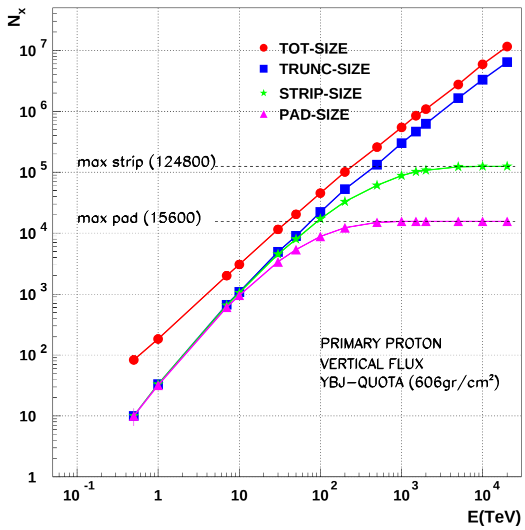

Fig. 1. Average strip and pad sizes compared to the total and truncated sizes for proton-induced air showers on the ARGO-YBJ central carpet.

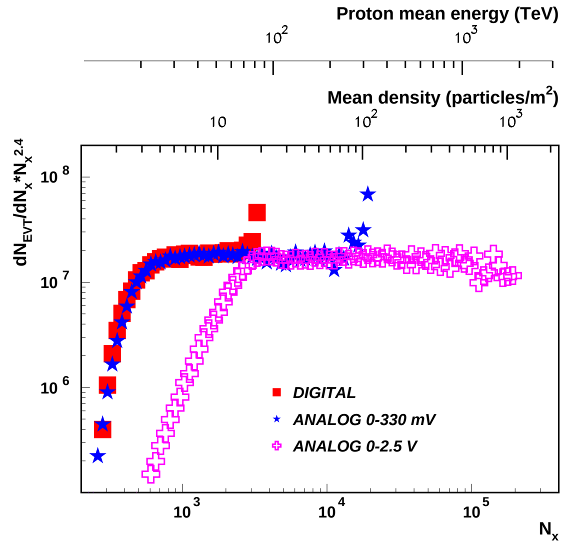

Fig. 2. Comparison between the digital strip size spectrum and the analog big pad spectrum. Two different amplitude scales have been used to extend the energy range. In the upper scale the corresponding proton mean energy is reported.

Clusters (ARGO-42, $\sim$1820 m^2 out of $\sim$6700 m^2), has been put in data taking with a so-called *"Low Multiplicity Trigger"*, requiring at least 60 fired pads on the whole detector [13]. The corresponding median energy of proton-induced triggered showers is $\approx$6 TeV. In this paper we present a first measurement of the strip size spectrum performed with the ARGO-42 detector.

II. The ARGO-YBJ detector

The ARGO-YBJ detector is constituted by a single layer of RPCs with $\sim$93% of active area. This carpet has a modular structure, the basic module being a Cluster (5.7$\times$7.6 m^2), divided into 12 RPCs (2.8$\times$1.25 m^2 each). Each chamber is read by 80 strips of 6.75$\times$61.8 cm^2, logically organized in 10 independent pads of 55.6$\times$61.8 cm^2 [14]. The central carpet, constituted by 10$\times$13 clusters, is enclosed by a guard ring partially instrumented ($\sim$40%) in order to improve the rejection capability for external events. The full detector is composed by 154 clusters for a total active surface of $\sim$6700 m^2. A lead converter 0.5 cm thick will uniformly cover the apparatus in order to improve the angular resolution. The main features of the ARGO-YBJ experiment are: (1) time resolution $\sim$1 ns; (2) space information from strips; (3) time information from pads. Due to its small size pixels, the detector is able to image the shower profile with an unprecedented granularity, with high duty cycle ($\approx$ 100%) in the typical field of view of an EAS array ($\sim$2 sr).

A. The digital read-out

The particle density measurement with the digital read-out provided by the strip system is limited to showers with a primary energy up to $\approx$ 100 TeV (for proton-induced events) due to a strip density of $\sim$22 strips/m^2. In Fig. 1 we show the average strip and pad sizes (N_s and N_{pad}) as a function of the primary energy for proton-induced showers. For comparison, the total shower size N_{ch} and the so-called "truncated size" N_{ch}^{tr}, i.e., the size sampled by the ARGO-YBJ carpet, are also plotted. In calculations only quasi-vertical (zenith angle $\theta < 15°$) showers with core reconstructed inside a small fiducial area (260 m^2 around the center of the carpet corresponding to the inner 6 clusters) have been used. An average strip efficiency of 95% and an average strip multiplicity m = 1.2 have been taken into account. As can be seen from the figure, log(N_s) is a linear function of log(E) up to about 100 TeV (corresponding to a particle density of $\approx$ 12-15 m^{-2}) and "saturates" above 1000 TeV. Accordingly, the digital response of the detector can be used to study the primary spectrum up to energies of a few hundreds of TeV.

B. The analog read-out

In order to extend the dynamic range up to PeV energies, a charge read-out has been implemented by instrumenting every RPC also with two large size pads of dimension 140$\times$125 cm^2 each (the so-called "big pads") [12]. The signal from the big pad is read by a 12 bits ADC. Different signal amplitude scales (0-330 mV, 0-2.5 V and 0-20 V) have been implemented in order to extend the particle density measurement up to $\approx 10^4$ particles/m^2.

Since November 2004 the analog read-out has been put in data taking into increasing portions of the full carpet with a trigger requiring more than 32 particles on at least one Cluster. In Fig. 2 a comparison between the measured digital strip size spectrum and the analog big pad spectrum is shown. Two different amplitude scales have been used in this

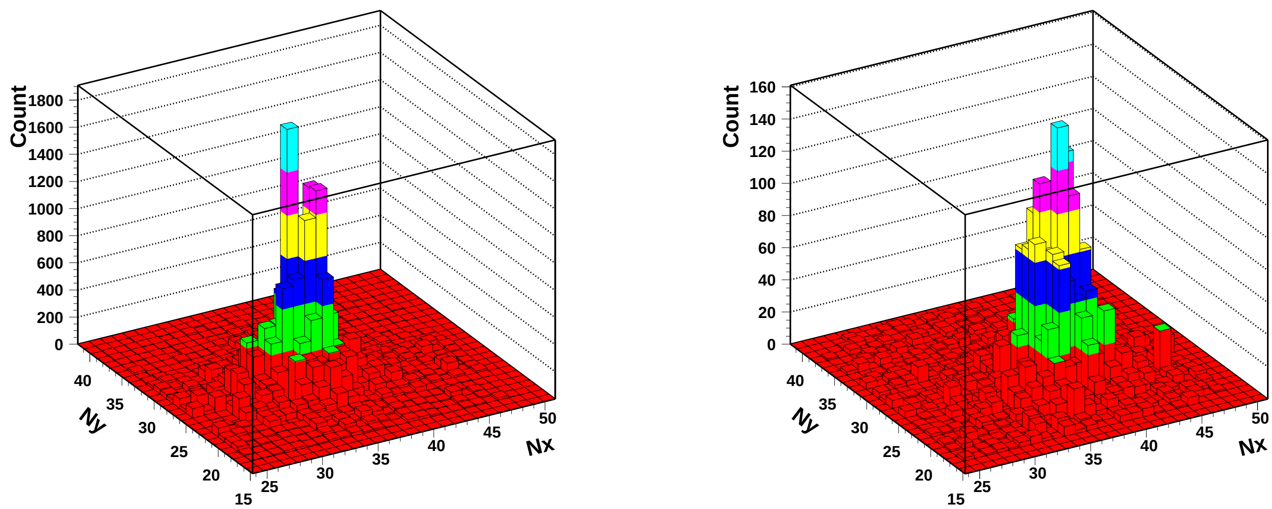

Fig. 3. Different events recorded by the analog read-out system. On the z axis the ADC counts are reported. The x and y axes display the big pad numbers.

analysis to extend the dynamic range (0-330 mV and 0-2.5 V). The reference amplitude of a m.i.p. signal is about 2 mV for the lower amplitude scale. In the upper scales the mean particle density and the corresponding proton mean energy are reported. As can be seen, the lower scale (0-330 mV) is sensitive to events with smaller particle densities covering the same energy region of the digital read-out and allowing cross calibrations between them. Therefore, the different amplitude scales guarantee a density measurement over more than 2 energy decades, up to the knee region.

As an example, in Fig. 3 two different contained events recorded with the charge read-out (amplitude scale 0-20 V) are displayed. In the left plot the maximum signal corresponds to about 3500 particles/m^2 while, in the right one, to a smaller shower with about 300 particles/m^2. The shower core structure of these events is evident.

III. Measurement of the strip size spectrum with ARGO-42

A. The simulation

In order to investigate the sensitivity of a digital measurement of the cosmic ray primary spectrum and to determine an appropriate event selection criterion we have simulated, via the Corsika/QGSJet v. 6.5 code [15], showers induced by 5 different mass groups: H, He, CNO, NeMgSi and Fe, with particle spectra ranging from 1 TeV to 1 PeV according to the RUNJOB and JACEE measurements (see Table I) in the zenith angle interval 0-20 degrees. The detector response has been simulated via a GEANT3-based code. The core positions have been randomly sampled in an energy-dependent area centred on the detector. The strip size spectrum has been measured selecting quasi-vertical ($\theta \leq 15°$) events [17] inside a fiducial area A$_f$=25×25 m^2, centred on the detector, by requiring that the cluster with highest particle multiplicity is one of the inner 4×5 clusters (∼900 m^2) including the fiducial area. The shower core positions of the selected events are hence reconstructed by means of the Maximum Likelihood Method [18]: any core lying outside the fiducial area A$_f$ is further rejected. As an example, in Table II the efficiency and the contamination of the adopted selection criterion are reported for proton-induced showers. Their percentages are defined as follows: $C = \frac{N_{FA}}{N_{ac}-N_{FA}} \times 100\%$ and $\epsilon = (1 - \frac{N_{FR}}{N_{ac}-N_{FA}}) \times 100\%$ where N$_{FA}$ is the number of falsely accepted showers, N$_{FR}$ the number of falsely rejected showers and N$_{ac}$ the total number of accepted events. The normalization is done with respect to the number of showers that have been correctly accepted: N$_{ac}$ − N$_{FA}$. The reconstruction efficiency ϵ_{rec} of the procedure is reported in the fourth column. The median energy of selected events, for proton and iron-induced showers (left and right plot, respectively), is shown in Fig. 4. The figure refers to events which fire a number of strips in the interval 4000-6000 on the ARGO-42 detector. The distributions has been fitted by a gaussian function. As expected, at fixed multiplicity, the primary energy of iron showers is larger than that of proton ones.

TABLE II

N$_s$	ϵ	C	ϵ_{rec}
> 600	82%	15%	98%
> 800	84%	11%	96%
> 1000	86%	9%	96%
> 3000	93%	5%	98%
> 5000	96%	6%	98%
> 7000	98%	6%	99%

b

TABLE I

JACEE AND RUNJOB POWER LAW FITS TO PRIMARY ENERGY SPECTRA.

element	JACEE	RUNJOB
p	$0.111^{+0.008}_{-0.006} \times E^{-2.80\pm0.04}$	$(0.103 \pm 0.006) \times E^{-2.78\pm0.05}$
He	$(8.07 \pm 0.24) \cdot 10^{-2} \times E^{-2.68^{+0.04}_{-0.06}}$	$(6.85 \pm 0.50) \cdot 10^{-2} \times E^{-2.81\pm0.06}$
CNO	$(2.15 \pm 0.21) \cdot 10^{-2} \times E^{-2.50\pm0.05}$	$(2.46 \pm 0.25) \cdot 10^{-2} \times E^{-2.65\pm0.05}$
NeMgSi	$(1.75 \pm 0.17) \cdot 10^{-2} \times E^{-2.57\pm0.05}$	$(1.82 \pm 0.18) \cdot 10^{-2} \times E^{-2.68\pm0.05}$
Fe	$(8.0 \pm 0.80) \cdot 10^{-3} \times E^{-2.41\pm0.05}$	$(1.81 \pm 0.18) \cdot 10^{-2} \times E^{-2.57\pm0.05}$

Units are: m^{-2} s^{-1} sr^{-1} TeV^{-1}. p and He spectra are taken from [8], [5], CNO from [16], while NeMgSi and Fe spectra have been extracted from the experimental points, because they are not reported in the literature, assuming uncertainties of $\sigma(N_0)$=10% on the normalization coefficient and $\sigma(\gamma) = \pm$ 0.05 on the power law index.

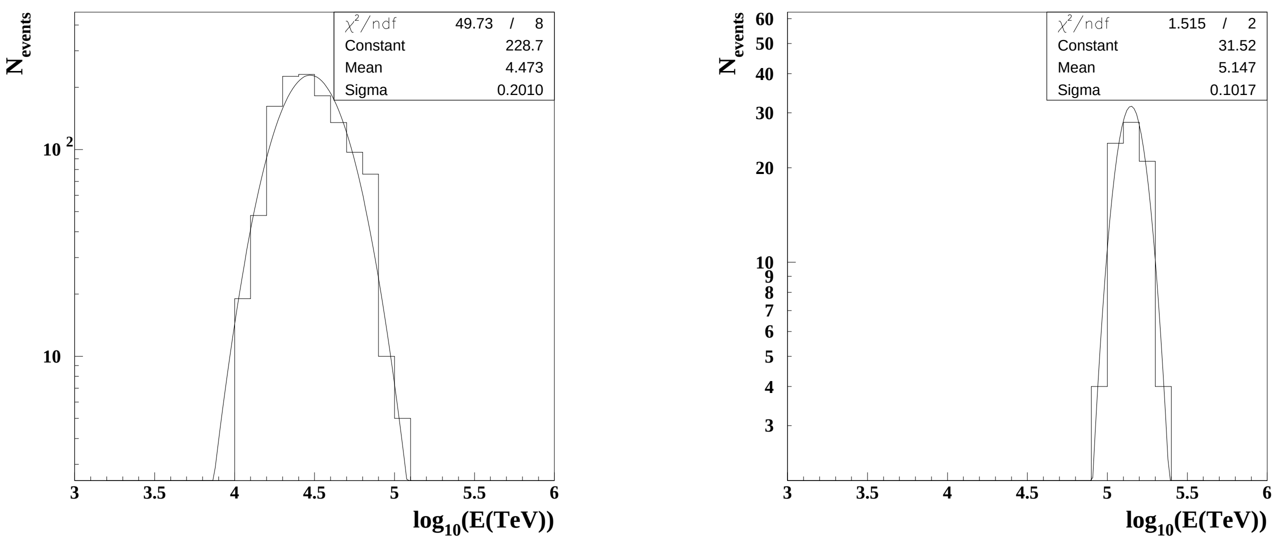

Fig. 4. Median energy of proton and iron-induced showers (left and right plot, respectively) which fire a number of strips in the interval 4000-6000 on the ARGO-42 detector. The events have been selected with the procedure described in the text. The distributions have been fitted with a gaussian function.

B. The ARGO-42 data analysis

Since December 2004 a portion of the full carpet, 42 Clusters (ARGO-42, ~1820 m^2 out of ~6700 m^2), has been put in data taking with a so-called *"Low Multiplicity Trigger"*, requiring at least 60 fired pads on the whole detector [13]. In this analysis we selected, with the procedure described above, a sample of $\sim 5 \cdot 10^7$ showers.

The resulting strip size spectrum is shown in Fig. 5 in the form (units: m^{-2} s^{-1} sr^{-1})

$$\frac{dN_{ev}}{dN_s} \cdot N_s^{2.3} \equiv J(N_s) \cdot N_s^{2.3}.$$

The strip size spectra expected according to RUNJOB and JACEE models are also shown for comparison. The shaded regions reflect the uncertainties on the measured flux (see Table I). We point out that the actual number of fired strips depends on the RPC efficiency and strip multiplicity which are known with an uncertainty of ≈1% and ≈5%, respectively. Therefore, the simulated spectra could be affected of a systematic error ≤10% [19]. For the measured spectrum only statistical errors are plotted. Calculations are in progress to evaluate the effect of different hadronic models on the MC results.

The investigated strip size interval ΔN_s = 600 - 10000 corresponds to proton primaries in the energy range ≈10 - 100 TeV.

IV. CONCLUSIONS

The ARGO-YBJ detector is the only EAS array allowing to measure the all particle spectrum over about 3 orders of magnitude overlapping the data from direct measurements. In fact, the digital read-out of ARGO-YBJ should allow one to scan, in a simple way, the energy range from ≈10 to a few hundreds of TeV. Larger energies, up to the PeV region, can be investigated by means of the analog read-out.

A first measurement of the strip size spectrum with a portion of the ARGO-YBJ detector (~1820 m^2 out of ~6700 m^2) has been compared with the expectations according to RUNJOB

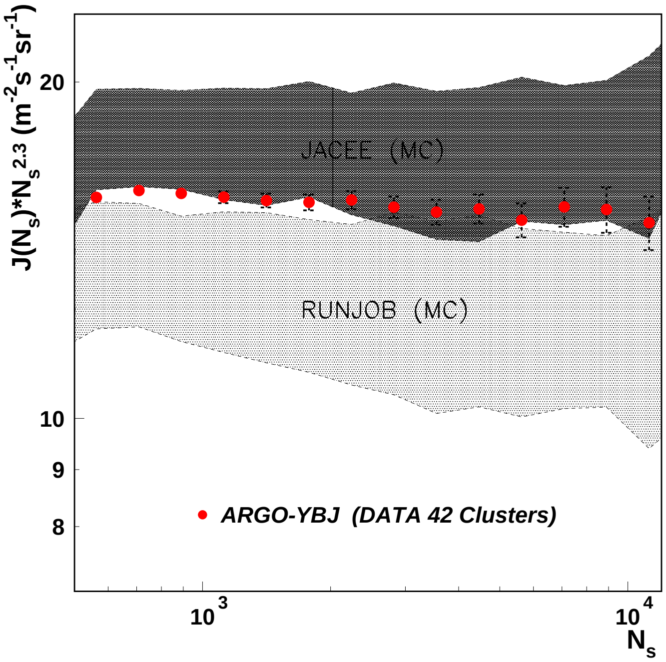

Fig. 5. The strip size spectrum measured with ARGO-42 compared with the expectations according to RUNJOB and JACEE models. The shaded regions reflect the uncertainties on the measured fluxes. For the data only statistical errors are plotted.

and JACEE composition models, showing a fair agreement with the direct measurements.

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