The Primary Cosmic Ray All Nucleon Spectrum As Seen By ARGO-YBJ

S. Bussino, E. De Marinis and S. M. Mari for the ARGO-YBJ Coll.*
Roma Tre University and INFN, Rome, Italy
(∗) see Collaboration list in [5]

Abstract

An analysis based on the Bayes theorem is applied to study the Primary Cosmic Ray spectrum with the ARGO-YBJ detector. The method is discussed in the framework of the superposition model, in order to assess the detector capability to measure the spectral index of the all-nucleon spectrum.

1. Introduction

In this paper we discuss in detail the possibility of using the ARGO-YBJ detector in order to study the all-nucleon spectrum in the TeV region. A Bayesian unfolding procedure, described in details in [3], is applied to the ARGO-YBJ setup [2] to obtain a measurement of the spectral index of the incoming primaries. The analysis method is shortly summarized with a particular attention to the physics and to the computational tools required to reach the final result. Finally the sensitivity of the detector is evaluated.

2. Fundamental Relations and Data Analysis

The observable in ARGO-YBJ detector is M(K), which represents the number of the events with a given number K of fired pads, collected in a period T within a solid angle Ω. The number of the detected events is given by an integral of the incoming particle flux $J(E) \propto E^{-\gamma}$ folded with the detector effective area $A_{eff}(E, K)$, integrated on the solid angle Ω :

$$M(K) = \Omega \cdot T \int A_{eff}(E, K) J(E) dE \tag{1}$$

The energy distribution J(E) of the incoming particle has to be evaluated by an unfolding procedure. We introduce the normalized distributions, $\bar{J}(E)$ and $\bar{M}(K)$, and the quantity $\bar{A}_{eff}(E, K)$ defined as follows:

$$\bar{J}(E) = \frac{J(E)}{\int J(E')dE'},\ \bar{M}(K) = \frac{M(K)}{n_{exp}},\ \bar{A}_{eff}(E, K) = \frac{A_{eff}(E, K)}{n_{exp}} \tag{2}$$

pp. 255–258

Table 1. The values obtained for the spectral index are shown for protons, helium nuclei and the all-nucleon spectra. The data were generated with $\gamma = -2.8$ for protons and $\gamma = -2.68$ for helium. The effective γ corresponding to the all-nucleon spectrum is -2.77.

	Proton	Helium	All-nucleon
γ MC	2.80	2.68	2.77
γ unfolded	2.81 ± 0.04	2.69 ± 0.04	2.76 ± 0.04

where n_{exp} is the total number of events accepted by the trigger. $\bar{A}_{eff}(E, K)$ is computed by a Monte Carlo simulation. The normalized quantities are simply related one to each other by means of the Bayes's Theorem relation [3]. For simplicity and for computational purposes, the integral over the energy is expressed as a discrete summation over n_E energy bins:

$$\bar{J}(E) = \frac{\sum_K G(E,K)\bar{M}(K)}{\sum_{n_E}\sum_K \bar{A}_{eff}(E,K)\bar{M}(K)}$$
$$G(E,K) = \frac{\bar{A}_{eff}(E,K)\bar{M}(K)}{\sum_{n_E}\bar{A}_{eff}(E,K)\bar{J}(E)} \qquad (3)$$

The problem is fully resolved by means of a iterature procedure. By assuming an arbitrary starting distribution for $\bar{J}(E)$ we compute $G(E, K)$. We use this value of $G(E, K)$ to obtain a new $\bar{J}(E)$. Then the $G(E, K)$ can be evaluated again, and a new and a more accurate distribution of $\bar{J}(E)$ is obtained. The iterative procedure ends when further variations on the value of $\bar{J}(E)$ are evaluated as negligible. The events were generated by using Corsika code [4] in the energy range 1-50 TeV with an energy distribution given by $N(E)dE \propto E^{-1}dE$, within a cone of $\theta = 15°$ around the vertical direction. The use of the spectral index $\gamma = 1$ reduces the statistical errors in the higher energy region. The events have been processed by a GEANT-based Monte Carlo code, in order to simulate the detector response. The event sample has been weighted in order to obtain different slopes and analized by the Bayes procedure. This calculation has been performed separately for proton and helium primary distributions. The reconstructed spectra of proton and helium are shown in fig. 1. The results obtained by applying this unfolding procedure to the ARGO-YBJ simulated events are shown in Table 1.

3. The all-nucleon spectrum

We constructed a sample of events from incoming protons and helium nuclei, by using JACEE fluxes [1]: $\phi = (2.79 \pm 0.77) \cdot 10^4 \cdot E^{-2.8\pm0.04} m^{-2}s^{-1}sr^{-1}GeV^{-1}$ for protons and $\phi = (8.85 \pm 0.68) \cdot 10^3 \cdot E^{-2.68\pm0.05} m^{-2}s^{-1}sr^{-1}GeV^{-1}$ for helium nuclei. The corrispondent all-nucleon spectrum can be described by a single power law with an equivalent $\gamma = 2.77$. We try to unfold the all-nucleon spectrum by using the effective area for protons as it follows by a "superposition principle". We applied a cut on the data accepting only events with multiplicity less then 4500 fired pads in order to select the region where the pad multiplicity distribution to proton induced showers and helium nuclei induced showers are similar: in such a way we identified a multiplicity region slightly affected by the differences between the incoming nuclei. This region of the multiplicity distribution is shown in fig. 2. We have seen that, in this particular condition of cuts on pad multiplicity, the effective area for helium nuclei induced showers can be described with good approximation by the effective area for proton induced showers. The mixed spectrum is shown in fig. 3 superimposed with the unfolded distribution. The spectral index of this distribution is in good agreement with the slope of the input spectrum (see Table 1.) showing that under this condition the superposition model is a faire approximation.

4. Conclusion

Assuming a mixed primary compositionof only protons and helium nuclei, the unfolding procedure based on the Bayes's Theorem can be succesfully applied to the ARGO-YBJ data to obtain from the experimental data the energy distribution of the primary particles. The present work shows that an appropriate cut can be applied to the data in order to determine the effective spectral index of the "all-nucleon spectrum". The application of this approach to unfold the different components of the primary radiation is presently under study.

5. References

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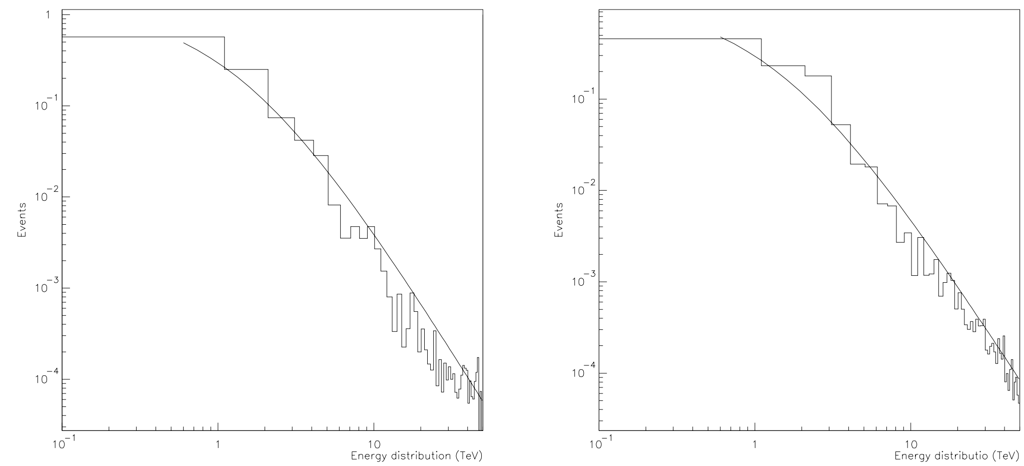
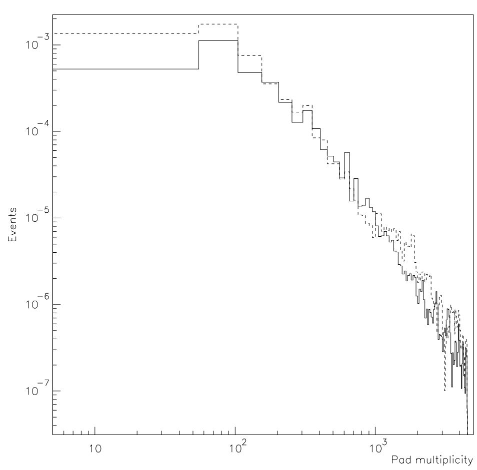


Fig. 1. Proton (left) and helium nuclei (right) unfolded spectra. The power law fit curve is also shown. The values of the spectral indexes are shown in Table 1.



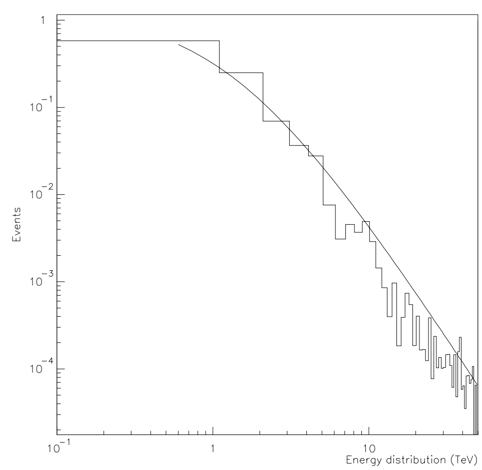


Fig. 2. (Left) The multiplicity distributions for protons (full line) and helium nuclei (dashed line) are shown.

Fig. 3. (Right) The unfolded spectrum of the mixed sample is shown. The value of the effective slope is shown in the last column of Table 1.