Highlights from the ARGO-YBJ Experiment

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Abstract. In this work we will report on some of the main results of the ARGO-YBJ experiment including the observation of galactic and extragalactic gamma ray sources and the measurements on the charged cosmic ray flux in the $10^{12} - 10^{15}$ eV energy range.

1. Introduction

The ARGO-YBJ experiment is a full coverage extensive air shower array resulting from a collaboration between Chinese and Italian institutions [1, 2]. The detector is operating in the YBJ International Cosmic Ray Observatory, located in the village of Yangbajing, about 90 km north-west from Lhasa, in the Tibet region (People’s Republic of China) at an altitude of 4300 m above sea level, corresponding to a vertical atmospheric depth of about 600 g/cm$^2$. The apparatus, extensively described in [1, 2], is a single layer detector logically divided into 153 units called clusters ($7.6 \times 5.7$ m$^2$) each made by 12 Resistive Plate Chambers (RPCs) operated in streamer mode. Each RPC ($1.23 \times 2.80$ m$^2$) is read out by using 10 pads ($62 \times 56$ cm$^2$), which are further divided into 8 strips ($62 \times 7$ cm$^2$) providing a larger particle counting dynamic range [3, 4]. The signals coming from all the strips of a given pad are sent to the same channel of a multihit TDC. The whole system provides a single hit (pad) time resolution at the level of 1.5 ns, which allows a complete and detailed three-dimensional reconstruction of the shower front with unprecedented space-time resolution. In order to fully investigate transient phenomena with an even smaller energy threshold, an independent scaler mode acquisition system has also been put in operation [5]. Finally, a system for the RPC analog charge readout [6, 7] from larger pads, each one covering half a chamber (the so called big pads), has been installed. This allows extending the detector operating range from about 100 TeV up to PeV energies.

A suitable calibration procedure has been developed in order to remove systematic time offsets in the read-out chain (due to front-end and TDC boards, cable lengths, etc.) [8]. In addition to several checks, the performance of the detector (angular resolution, pointing accuracy, energy calibration) and the operation stability are monitored on a monthly basis by observing the Moon shadow, i.e. the deficit in the charged cosmic ray (CR) flux detected in its direction (see below and [9]). The measured angular resolution is better than 0.5° for CRs with $E > 5$ TeV improving up to about 0.3° for $E > 10$ TeV. The absolute pointing of the detector is stable at a level of 0.1° and the uncertainty on the absolute rigidity scale is less than 13% in the range $1 - 30$ TeV/Ze [10].

The whole system is in stable data taking with the full apparatus of 153 clusters since November 2007, with the trigger condition $N_{pad} \geq 20$ and a duty cycle of about 86%. The trigger rate is at the level of 3.5 kHz with a dead time fraction of 4%.
Many results are being obtained in different topics [11]. Due to lack of space, in the following only some aspects of gamma ray astronomy and charged cosmic ray physics, together with hadronic interaction studies, will be covered. The study of the anisotropies of the CR arrival directions is reported in [12], while the search for Gamma Ray Bursts and the measurement of the average Interplanetary Magnetic Fields by means of the Sun shadow in the cosmic ray flux are described in [13, 14] and [15] respectively.

2. Gamma Ray Astronomy

The dataset considered in this study contains all the showers with zenith angle \( \theta < 50^\circ \) collected from November 2007 to February 2011. The total effective observation time is 1024 days and the total number of events is \( 1.7 \times 10^{11} \). Four known VHE \( \gamma \)-ray sources have been detected by ARGO-YBJ with a statistical significance greater than 5 standard deviations (s.d.), i.e. the Crab Nebula, Mrk 421, MGRO J1908+06 and MGRO J2031+41.

ARGO-YBJ observed a TeV signal from the Crab Nebula with a statistical significance greater than 17 s.d., proving that the cumulative sensitivity of the detector reached 0.3 Crab units level. The energy spectrum was measured in the energy range \( \sim 0.5-10 \) TeV [11, 16] and is in good agreement with other observations. No variations of the CRAB flux with a statistical significance larger than 5 s.d. have been detected in time scales of days or months. Nevertheless, two flux enhancements of significance about 3 s.d. have been observed in the whole data set [17]. Remarkably, they are in coincidence with the occurrence of the flares detected by AGILE and Fermi at lower energies [18, 19].

ARGO-YBJ has monitored Mrk421 for more than 3 years above 0.3 TeV, studying the correlation of the TeV flux with X-ray data. We observed this source with a total significance of about 14 s.d., averaging over quiet and active periods. As it is well known, this AGN is characterized by a strong flaring activity both in X-rays and in TeV \( \gamma \)-rays. Many flares are observed in both X-ray and \( \gamma \)-ray bands simultaneously. The \( \gamma \)-ray flux observed by ARGO-YBJ shows a clear correlation with the X-ray flux. No lag between the X-ray and \( \gamma \)-ray photons longer than 1 day has been found. The evolution of the spectral energy distribution has been investigated by measuring spectral indices at four different flux levels, observing an hardening of the spectra in both X-ray and \( \gamma \)-ray bands. All these observational results strongly favor the synchrotron self-Compton process as the underlying radiative mechanism. ARGO-YBJ results of Mrk421 observations are summarized in [20, 21]. In Fig.1 the daily Mrk421 light curves as measured by many instruments at different energies are shown. In the same figure the energy spectra measured in correspondence of the two flares on February and April 2010 are also reported (see also [22] for details).

Finally, the sources MGRO J1908+06 and MGRO J2031+41 have been detected with a statistical significance of 6.0 and 5.8 standard deviations respectively and their energy spectra have been measured (see details in [16]).

3. Charged Cosmic Rays and Hadronic Interactions

As reported above, the observation of the Moon shadow in the CR flux allows a comprehensive test of the detector performance. The same effect has also been observed by ARGO-YBJ in the direction of the Sun [15]. The angular size of the deficit in the Moon direction depends on the detector resolution and the Moon angular diameter. The angular shift \( \Delta \alpha \) of the shadow is due to the bending of CR path in the geomagnetic field and allows to calibrate the scale of the primary energy according to the formula \( \Delta \alpha \sim 1.58^\circ Z/E[TeV] \). Finally the position of the deficit for events with high rigidity allows to estimate the absolute pointing accuracy. Using the data collected in the period Jul. 2006 - Nov. 2010 and requiring more than 100 strips fired in each event, the deficit appears with a significance higher than 70 s.d. (Fig. 2).
Negatively charged primary particles in the CR flux would result in a shadow in the opposite direction, the Earth-Moon system acting as a magnetic spectrometer. A search for a primary antiproton signal has then been performed resulting in the two upper limits to the antiproton-to-proton flux ratio shown in Fig.2 (see [11] for further details).

The experiment low energy threshold allowed, for the first time, a detailed study of the CR spectrum in a region usually covered by direct measurements only. This is very useful in order to compare different techniques with completely different systematics. As an example, ground based experiments must rely on the shower simulations based on a given hadronic interaction model, while this is not the case for direct measurements. The energy spectrum of the CR light component (i.e. proton and helium) was measured by means of an unfolding procedure based on the Bayes theorem. As can be seen in Fig.3, ARGO-YBJ results are consistent with direct measurements, this being an important check of the reliability of the techniques adopted by ground based arrays. More details can be found in [11].

The proton-air cross section has been measured by exploiting the CR flux attenuation for different zenith angles, i.e. atmospheric depths (see [23] for a complete description). The detector location and features ensure the capability of reconstructing showers in a very detailed
way. This allowed fixing the energy ranges and constraining the shower ages. At the same time the information on particle density, lateral profile and shower front extension have been used to select showers having their maximum development within a given distance/grammage from the detection level. This made possible the unbiased observation of the expected exponential falling of shower intensities as a function of the atmospheric depth through the sec$^2 \theta$ distribution. The Glauber theory has then been applied in order to get the corresponding p-p total cross section $\sigma_{p-p}$. As can be seen in Fig.3, ARGO-YBJ data lie in an energy region still unexplored by p-p and p-$\bar{p}$ experiments and favour the asymptotic $\ln^2(s)$ increase of total hadronic cross sections as obtained in [24] from a global analysis of accelerator data.

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Figure 3. Left: Light CR component (i.e. p+He) energy spectrum resulting from ARGO-YBJ data together with previous measurements. Right: The p-p total cross section obtained by ARGO-YBJ [23], together with results from other cosmic ray and accelerator experiments.