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Development of Yangbajing air shower core detector for a new EAS hybrid experiment *

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Abstract: Aiming at the observation of cosmic-ray chemical composition in the “knee” energy region, we have been developing a new type of air-shower core detector (YAC, Yangbajing Air shower Core detector array) to be set up at Yangbajing (90.522° E, 30.102° N, 4300 m above sea level, atmospheric depth: 606 g/m^2) in Tibet, China. YAC works together with the Tibet air-shower array (Tibet-Ⅲ) and an underground water Cherenkov muon detector array (MD) as a hybrid experiment. Each YAC detector unit consists of lead plates of 3.5 cm thickness and a scintillation counter which detects the burst size induced by high energy particles in the air-shower cores. The burst size can be measured from 1 MIP (Minimum Ionization Particle) to 10^6 MIPs. The first phase of this experiment, named “YAC-Ⅰ”, consists of 16 YAC detectors each with a size of 40 cm×50 cm and distributed in a grid with an effective area of 10 m^2. YAC-Ⅰ is used to check hadronic interaction models. The second phase of the experiment, called “YAC-Ⅱ”, consists of 124 YAC detectors with coverage of about 500 m^2. The inner 100 detectors of 80 cm×50 cm each are deployed in a 10×10 matrix with a 1.9 m separation; the outer 24 detectors of 100 cm×50 cm each are distributed around these to reject non-core events whose shower cores are far from the YAC-Ⅱ array. YAC-Ⅱ is used to study the primary cosmic-ray composition, in particular, to obtain the energy spectra of protons, helium and iron nuclei between 5×10^{13} eV and 10^{16} eV, covering the “knee” and also connected with direct observations at energies around 100 TeV. We present the design and performance of YAC-Ⅱ in this paper.

Key words: scintillation detector, cosmic rays, air shower, primary mass

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1 Introduction

The all-particle energy spectrum of primary cosmic rays is well expressed by a power law, $\mathrm{d}N/\mathrm{d}E \propto E^{-\gamma}$, over many orders of magnitude, with γ changing sharply from 2.7 to 3.1 at about 4 PeV [1]. The break of the all-particle energy spectrum is called the “knee” [2, 3], and the corresponding energy range (10^{15}–10^{16} eV) is called the “knee region”. Although the existence of the knee is well confirmed by many experiments, there still exists a debate on its origin. In order to clarify the sharpness of the knee, the most precise measurements possible of the primary spectra of individual components, including the knee, are essential. The best ways to study the chemical compositions are direct measurements of primary cosmic rays on board balloons or satellites, but the energy range of such measurements with sufficient statistics is limited to 10^{14} eV because of the limited exposure time and small detection area. The task of studying the chemical components of the knee region therefore still relies on ground-based indirect measurements.

The study of the mass composition of primary cosmic

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rays around the knee has been made in the last decade by the Tibet-EC (emulsion chamber) experiment using a high threshold (> TeV) air-shower core detector sensitive to the primary particle mass [4]. It aimed to separate air-shower events induced by primary light components such as protons and helium nuclei. The observations show low intensities of proton and helium spectra which amount to less than 30% of the all-particle spectrum, suggesting that the knee is dominated by nuclei heavier than helium. The weaknesses of this experiment are: 1) the statistics are limited due to the selection of high-energy core events; 2) the reconstruction of the primary energy spectrum is based on air-shower (AS) simulations, in which the hadronic interaction model is not fully established yet, although the model dependence of AS core events at the high observation level is at most a few tens of percent, as previously reported [4]. To overcome these problems, we have recently upgraded the Tibet-EC experiment and started a new low threshold core detector named YAC (Yangbajing Air shower Core detector), which is capable of observing the core events with high statistics as well as testing the interaction models.

In order to further expand the energy region of the Tibet-EC experiment, the YAC detector has been developed to lower the threshold energy as much as possible with a wider dynamic range. The detection threshold energy of the YAC detector can be set several 10 times lower than EC (about 300 GeV, corresponding to a primary energy of several times 10 TeV) by adopting a scintillator instead of X-ray film for the detection of cascade showers induced in the lead plate by high energy AS core particles. A wide dynamic range of 1–10^6 MIPs (Minimum Ionization Particles) for the burst size detection is realized by installing 2 PMTs (high-gain and low-gain PMTs). Using wave-length-shifting fibers to collect the scintillation light improves the geometrical uniformity. This new experimental condition improves the statistics of high energy core events by a factor of 100, when compared with the Tibet-EC experiment. The new hybrid experiment aims to observe the energy spectra of protons, helium and iron, whose energy range will overlap with direct observations at lower energies from experiments such as CREAM [5, 6] and ATIC [7], and with the Tibet-EC experiment at higher energies. Furthermore, we can add an underground muon detector (MD) to this experiment to increase the mass separation power of primary particles. Hence, the new Tibet hybrid experiment consists of the YAC array, Tibet-III array [1] and underground MD array (Fig. 1).

The design of the YAC detector is described in Section 2. The YAC experiment is scheduled in two steps, named "YAC-Ⅰ" and "YAC-Ⅱ". YAC-Ⅰ is a small array consisting of 16 prototype detectors covering an area of about 10 m^2, located near the center of the Tibet-Ⅲ array. This array will operate for a few months to observe AS core events of primary energies around 10^{14} eV, where the mass composition of primary cosmic rays is fairly well-known by direct observations [5–7]. Therefore, the role of YAC-Ⅰ is to test the interaction models currently used by Monte Carlo (MC) simulations such as QGSJET01 [8], SIBYLL2.1 [9], DPMJET [10] and lately EPOS-LHC [11] and QGSJETII-04 [12]. YAC-Ⅱ is an array of 124 detectors covering an area of ~500 m^2 to obtain proton, helium and iron spectra with high statistics in the energy range between 5×10^{13} eV and 10^{16} eV, which will be smoothly connected to those obtained by direct observations in the lower energy region. In this paper, the design of YAC-Ⅱ and its performance are described.

2 The YAC-Ⅱ experiment

2.1 Detector layout of the YAC-Ⅱ array

The YAC array is set up at Yangbajing (90.522° E, 30.102° N, 4300 m above sea level, atmospheric depth: 606 g/m^2) in Tibet, China. This array works together with the Tibet-III and underground MD array as a hybrid experiment, as shown in Fig. 1.

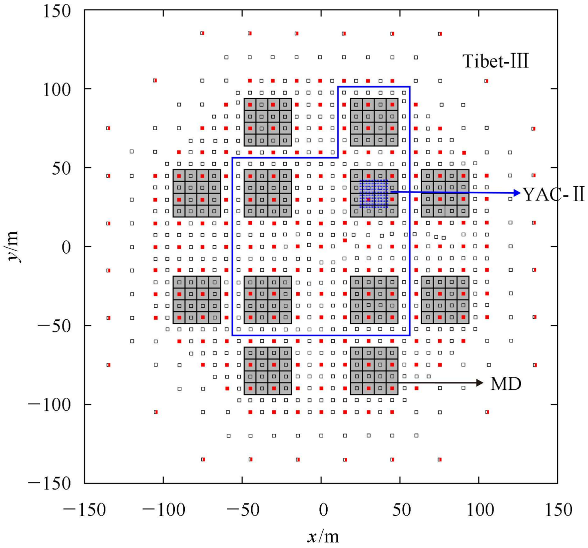

Fig. 1. (color online) Schematic view of (YAC-Ⅱ+Tibet-Ⅲ+MD) array. The YAC-Ⅱ array contains 124 core detectors (blue open squares) and is located near the center of Tibet-Ⅲ/ (~50000 m^2). The Tibet-Ⅲ array consists of 576 fast timing (FT) detectors (black open squares), 28 density (D) detectors (red half open squares) and 185 FT/D detectors (red solid squares) at the periphery. The MD array consists of 12 underground water pools (gray solid squares), each of which has 16 units. 5 water pools (~4500 m^2) in blue wire frame have been built.

YAC-Ⅱ consists of 124 core detectors covering an area of about 500 m^2, as shown in Fig. 2. The inner 100 detectors, 80 cm×50 cm each, are deployed in a 10×10 matrix with a 1.9 m separation; the outer 24 detectors, 100 cm×50 cm each, are distributed around these to reject non-core events whose shower cores are far from the YAC-Ⅱ array. The main purpose of YAC-Ⅱ is to observe the energy spectra of the light components as well as iron nuclei in the primary cosmic rays between 5×10^{13} eV and 10^{16} eV, as mentioned in Section 1.

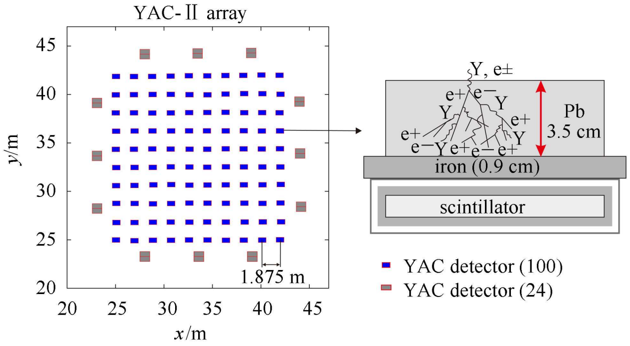

Fig. 2. (color online) Left: Magnified schematic view of the YAC-Ⅱ array (~500 m^2). The detectors of this array are classified in 2 types: the inner 100 detectors of 0.4 m^2 each (blue solid squares) and the outer 24 detectors of 0.5 m^2 each (gray solid squares). Right: The schematic view of each detector, comprising a lead plate of 3.5 cm thickness, an iron plate of 0.9 cm thickness and a plastic scintillator of 1 cm thickness.

2.2 Design of the YAC-Ⅱ detector

The design of the YAC-Ⅱ detector essentially follows that described in Ref. [13] but in this work some improvements were made as follows:

(1) Lead plates: A lead layer is used to select high energy particles in the AS core in the energy range from several GeV to several 10 TeV, as shown in Fig. 2. It is found from an optimization calculation that a lead layer of thickness 3.5 cm (6.3 radiation lengths) meets the requirements for both lower and higher energies. A 0.9 cm thick iron plate placed between the scintillator and lead plates is used to support the weight of the lead plates, as shown in Fig. 2. High energy electromagnetic particles near the AS axis develop into cascade showers in the lead absorber and these shower particles enter the scintillator counter. Here, the number of shower particles detected in the scintillator is defined as the burst size (N_b). The scintillation light produced by shower electrons in the scintillator below the lead layer is transmitted to the PMTs via the wave-length-shifting fibers (WLSF BCF-92, SAINT-GOBAIN, round cross section with 1.5 mm diameter), as shown in Fig. 3. The determination of the burst size (N_b) is calibrated by using the charge count value of a single-muon peak.

(2) Scintillation counter: In order to have a certain position resolution of high energy particles in the air shower cores, the size of an inner detector unit is taken to be 80 cm×50 cm, as shown in Fig. 3. One unit scintillation counter is divided into 20 pieces of 4 cm width. To get better uniformity of light output when a high energy particle hits different positions on a scintillation counter unit, 40 WLSFs are installed parallel to each other in the center of each scintillator and connected to the high-gain PMT (R4125) while 20 WLSFs installed in the center of each scintillator are connected to the low-gain PMT (R5325). Such a design guarantees geometrical uniformity of the detector response within 6%.

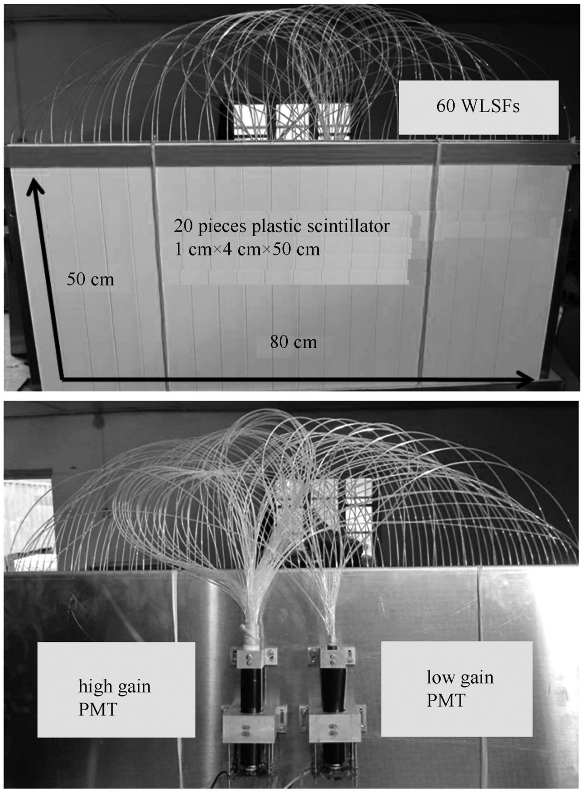

Fig. 3. View of the scintillation detector. Top: top view and bottom: back view. The scintillation detector unit consists of 20 pieces of scintillator whose size is 50 cm×4 cm×1 cm, light-isolated from each other using reflecting material. All the fibers are adjusted to the same length of 110 cm. All 20 fibers attached to the low-gain PMT (R5325) and 40 fibers attached to the high-gain PMT (R4125) are installed in the center of the scintillator at equal distances.

(3) PMT: In order to record electromagnetic showers in the energy range from several GeV to several 10 TeV, a wide dynamic range from 10 MIPs to 10^6 MIPs is required for the PMTs. In addition, taking into account

the importance of single-particle measurement in the system calibration, the dynamic range of the PMTs should be from 1 MIP to 10^6 MIPs. This is realized by adopting a high-gain PMT (HG-PMT, HAMAMATSU R4125) and a low-gain PMT (LG-PMT, HAMAMATSU R5325) which are responsible for the range of $1-3\times10^3$ MIPs and 10^3-10^6 MIPs, respectively.

(4) WLSFs: To save the wave-length-shifting fibers, a short length (110 cm, half of the fiber length used in the old detectors [13]) of fiber is used, of which one end is connected with the PMT and another end is plated with aluminum for reflection, as shown in Fig. 3. Since the reflection rate reaches 99% and only the gain of the PMT is recorded from each detector, there is no influence on the experimental data. Considering the large temperature difference in Yangbajing within one year or even one day, a heat-insulator layer is used inside each detector unit box.

The YAC-Ⅱ array has been operating together with the Tibet-Ⅲ/ array and the underground MD array, as shown in Fig. 1, since March 2014. The Tibet-Ⅲ/ array is used to measure the shower size and the arrival direction of each air shower. Any four-fold coincidence of the FT detectors is used as the trigger condition for air-shower events. The air-shower direction can be estimated with an error smaller than 0.2° above 100 TeV [1], and the primary energy resolution is estimated to be 12% at energies around 10^{15} eV by our simulation [14].

The trigger rate of YAC-Ⅱ is about 3.5 Hz with a dead-time rate of ∼1%. If one YAC-Ⅱ detector gives a trigger signal, all ADC data from all YAC-Ⅱ units are recorded. The trigger signal is also sent to the DAQ system for the Tibet-Ⅲ/ array and MD array. The ADC modules of YAC-Ⅱ are calibrated every 4 hours. The ADC pedestal values are measured every 10 minutes. Each DAQ system has an independent GPS clock module. The matching between YAC, Tibet-Ⅲ/ and MD data is made by their arrival time stamps recorded by the GPS clock. The GPS coincidence interval is shorter than 1 ms. The average time difference is 8.1 μs±0.4 μs.

3 Calibration and performance of the YAC-Ⅱ detector

3.1 Probe calibration

In this hybrid experiment, the burst size is defined as the PMT output (charge) divided by that of the single-particle peak, which is determined by a probe calibration using cosmic rays, typically muons. For this purpose, a small scintillator 25 cm×25 cm×3.5 cm with a PMT (H1949) is put on the top of each detector during the maintenance period. This is called a probe detector, and is shown in Fig. 4. Fig. 5 shows the charge distribution of a single particle in a detector unit. The peak is defined as one MIP (1 MIP=2.12±0.01 pC). Therefore, the determination of the burst size N_b is calibrated by using a single-particle peak.

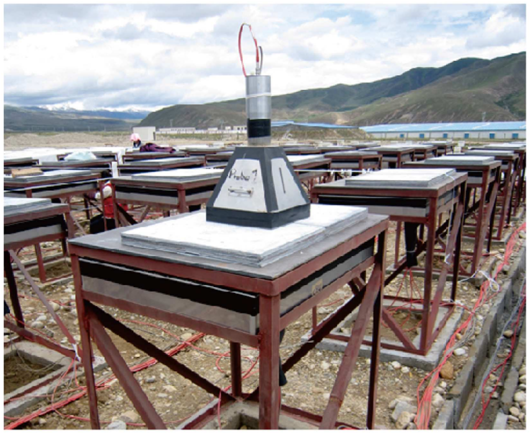

Fig. 4. (color online) View of the probe calibration.

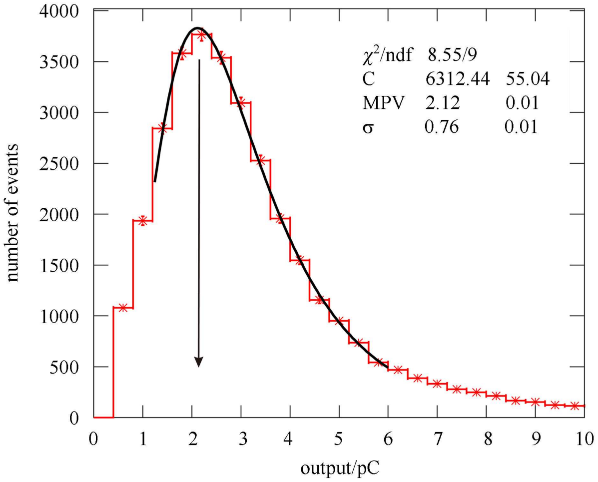

Fig. 5. (color online) Charge distribution of a single muon in the first detector unit. The peak, called a single-particle peak, is defined as one MIP. The single-particle peak of this detector is 2.12±0.01 pC.

3.2 Linearity of PMTs

For each PMT (R4125 and R5325) used in YAC-Ⅱ, the linearity with respect to high voltage is better than 1%, as shown in Fig. 6. The high-gain PMT (R4125) is used to measure light yield from 1 MIP to a few thousand MIPs, while the low-gain PMT (R5325) covers the dynamic range from a few hundred to 10^6 MIPs. The dynamic range of the PMTs is measured using an LED light source and optical filters. In the test experiment we fixed the positions of the LED, filter and PMT. By using different filters, we can get light of different intensities. The LED is driven by a TTL pulse with a width of 25 ns. The details are described in Ref. [13].

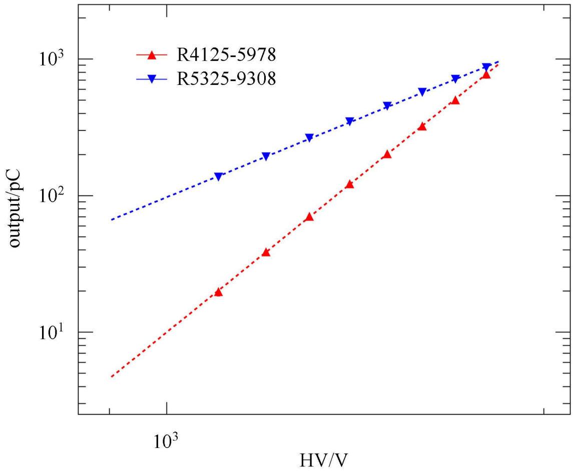

Fig. 6. (color online) The linearity between the output (pC) and the high voltage supplied to the high-gain PMT (R4125, Red) and low-gain PMT (R5325, Blue). The points show the experimental data. The red dotted line is a fitting line.

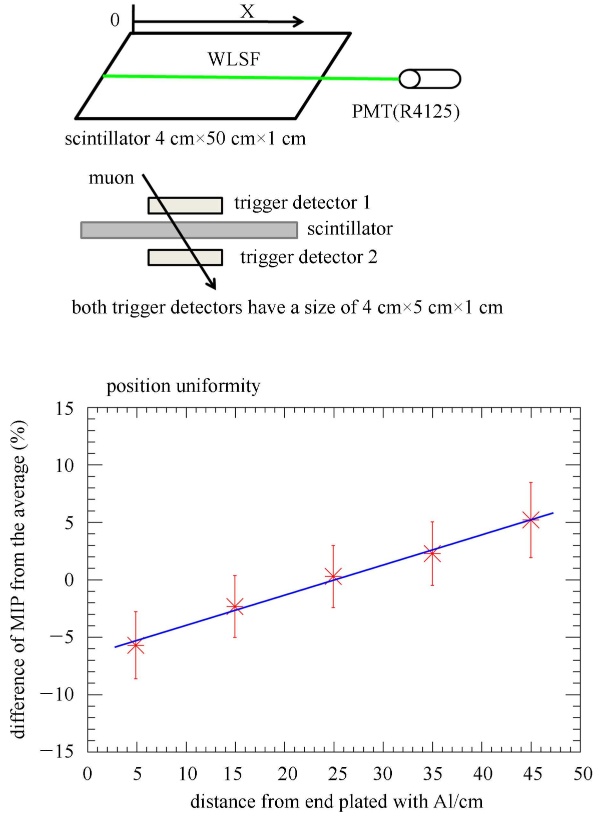

Fig. 7. (color online) Top: experiment set-up for single muon measurement. Bottom: uniformity of the YAC-Ⅱ detector.

3.3 Uniformity of the detector

When charged particles pass through the scintillator on different positions, the light transmitted to the PMT by the WLSFs will vary within a small range which is called the “position dependence” or “uniformity” of the detector. The uniformity of the YAC-Ⅱ detector has been measured using cosmic-ray single muons selected by a triple coincidence, as shown in Fig. 7. As shown in the figure, the uniformity in scintillator of length 50 cm is better than 6%.

3.4 Linearity of PMT plus scintillator

The linearity and the saturation of the plastic scintillator and PMT used in the YAC detector have also been calibrated by using the accelerator beam of the BEPCⅡ (Beijing Electron Positron Collider, IHEP, China). The accelerator-beam experiment shows good linearity between the incident particle flux and YAC-Ⅱ output below 5×10^6 MIPs and the saturation effect of the plastic scintillator satisfies the YAC detector requirements. The details are described in Ref. [15].

3.5 Correlation between high-gain and low-gain PMTs

Since we cannot measure a single muon using the low-gain PMT (R5325) directly, we calibrate the low-gain PMT output using the the correlation between high-gain PMT (R4125) and low-gain PMT (R5325) in their overlapping region. After running the detectors consistently for about 10 days, we obtained the gains of the low-gain PMT (R5325) and high-gain PMT (R4125) for the same burst events which were recorded by the ADC, as shown in Fig. 8. From Fig. 8, it is found that there is a clear linear relationship between the data from the two PMTs. We can then obtain the ratio (the slope of the line in Fig. 8) between them. With further calculation it may be possible to get N_b only from output signals from the low-gain PMT.

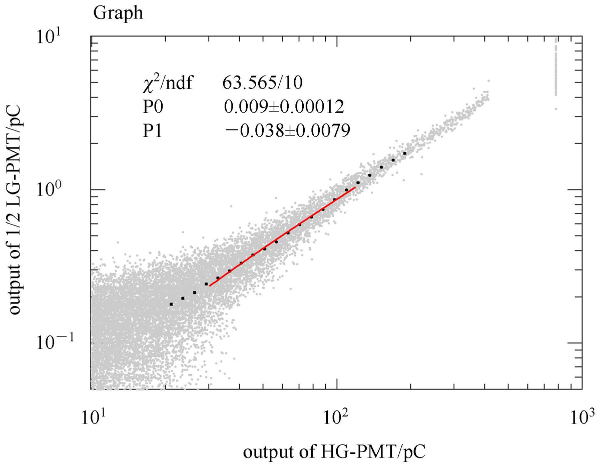

Fig. 8. (color online) The correlation between output signals from high-gain PMT (R4125) and low-gain PMT (R5325) obtained during 10 days' operation of YAC-Ⅱ.

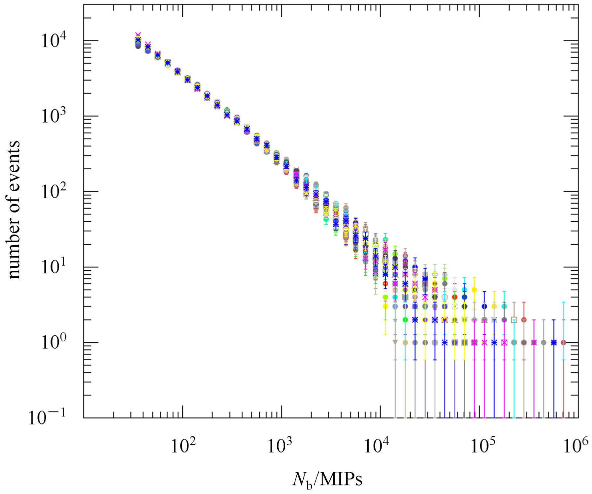

Fig. 9. (color online) The N_{b} spectrum with experimental data from YAC-Ⅱ over 10 days. It is shown that the difference in the N_{b} spectra between the 124 YAC detectors is less than 20%.

3.6 Consistency of the gains of different detector units

Setting a lower detection threshold (say, taking 30 mV as the discrimination threshold) and "any 1" (at least any one unit of the 124 units should be fired) as the trigger condition, YAC-Ⅱ was operated for 10 days to measure the N_{b} spectrum of each detector unit. Some differences are found between the N_{b} spectra of the different units. By slightly adjusting the working voltage of the PMTs, consistent spectra are obtained. In Fig. 9, it is shown that the difference in the N_{b} spectrum between the 124 YAC detectors is less than 20%.

4 Summary

A new air-shower core detector (YAC-Ⅱ) has been set up at Yangbajing and started data taking in March 2014. Each detector of the YAC-Ⅱ array consists of a 0.4 m^2 plastic scintillator, equipped with a high-gain PMT and a low-gain PMT, beneath a 3.5 cm lead plate. The dynamic range of detector response is from 1 MIP to 10^6 MIPs. Using wave-length-shifting fibers to collect the scintillating light guarantees geometrical uniformity of the YAC detector response within 6%. This new experimental condition improves the statistics of the high energy core events compared with the Tibet-EC experiment by a factor of 100. Using the trigger conditions that at least any-one detector is fired, with a detection threshold larger than 30 mV, the event rate reaches 3.5 Hz with a dead-time rate of 1%. A study of Monte Carlo simulation shows that it is feasible to study the primary cosmic-ray composition using the YAC-Ⅱ array [16, 17].

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