Calibration of the Yangbajing air-shower core detector

Y. Zhang, a,b,1 J. Huang, a D. Chen, c L.M. Zhai, c X. Chen, a Y.H. Lin a,b and J.H. Fang a,b

a Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
b University of Chinese Academy of Sciences, Beijing 100049, China
c National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

E-mail: yingzhang@ihep.ac.cn

ABSTRACT: Aiming at the observation of cosmic-ray chemical composition at the ‘knee’ energy region, a new type air-shower core detector (YAC, Yangbajing Air shower Core array) consisting of a lead plate of 3.5 cm thick and a scintillation counter with an area of 0.5 m² has been developed and set up at Yangbajing, 4300 m a.s.l. in Tibet, China since 2014. The main purpose of YAC detector is to separate primary cosmic-ray mass by detecting high energy electromagnetic particles at the air-shower (AS) core generated by the secondary particles after passing through the lead plate. In order to precisely measure the number of shower particles, the calibration procedure of the YAC detector is described in this paper. We found that the linear relationship between YAC scintillation detector output and incident particles is good below $5 \times 10^6$ MIPs while the non-linearity is less than 3%. Such a wide dynamic range shows that YAC experiment may make it possible to obtain the primary mass composition and energy spectrum covering and above the ‘knee’ energy region.

KEYWORDS: Detector alignment and calibration methods (lasers, sources, particle-beams); Photon detectors for UV, visible and IR photons (gas) (gas-photocathodes, solid-photocathodes); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

1Corresponding author.

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https://doi.org/10.1088/1748-0221/15/07/P07014
1 Introduction

The all-particle energy spectrum of primary cosmic rays is roughly described by a power-law $dN/dE \propto E^{-\gamma}$ over many orders of magnitude, with $\gamma$ changes sharply from 2.7 to 3.1 at around a few PeV [1, 2]. Such a structure of the all-particle energy spectrum is called the ‘knee’. The special ‘knee’ structure is closely related to the acceleration, propagation and origin of cosmic rays, which is one of the important issues in cosmic rays physics [3, 4]. Many authors have proposed various models to explain the structure of the ‘knee’, such as a change of acceleration mechanisms at the sources of cosmic rays (supernova remnants, pulsars, etc.) [5], an assumption of nearby sources emitting high energy cosmic rays [6], a change of cosmic ray propagation in the Galaxy (diffusion, drift, escape from the Galactic disk) [7], and some unknown new processes in the atmosphere during air-shower (AS) development [8]. However, its origin has not been well understood due to the lack of detailed information about the chemical composition around the knee. Precise measurements of the primary chemical composition or mass group at energies of 50 TeV–10 PeV are essential ways to resolve the origin of the knee. The early works doing the research of the chemical composition of the knee region were the Tibet emulsion chamber (Tibet-EC) experiment and the KASCADE experiment [9–11]. The results of the Tibet-EC suggest that the main component responsible for making the knee structure is composed of nuclei heavier than helium [9]. However, the experimental statistics of Tibet-EC are poor and the detection threshold is too high (>800 TeV). On the other hand, the KASCADE experiment uses electron-muon size analysis to obtain the energy spectrum of separate mass groups and claims that the knee is due to the steepening of the spectra of light elements with an exponential type cutoff. However, the results of KASCADE are strongly dependent on the hadronic interaction models [10]. To overcome these problems, the Tibet AS$\gamma$ experiment has recently upgraded the Tibet-EC experiment and developed 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 hadronic interaction models [12, 13].
The Tibet-EC experiment was operated at Yangbajing in Tibet during the period from 1996 through 1999. The basic structure of each EC is a multilayered sandwich of lead plates and X-ray films of 40 cm × 50 cm in area, where X-ray films are put every 1.0 cm of lead in the chamber. The X-ray films in ECs are replaced by new ones every year to reduce the background, whose details are described in [14]. 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 [15, 16]. The main improvements of YAC detector include: 1) we use 3.5 cm (corresponding to 6.3 radiation lengths) lead layer to select high energy particles in the AS core in the energy range from several GeV to several 10 TeV; 2) we adopt a scintillator instead of X-ray film for the detection of cascade showers induced in the lead plate by high-energy AS core particles, and the detection threshold energy of the YAC detector can be set 10 times lower than EC (about 300 GeV, corresponding to the primary energy of 20 TeV); 3) we use wave-length-shifting fibers (WLSFs) to collect the scintillation light to improve the geometrical uniformity; 4) we use 2 photomultiplier tubes (PMTs) to realize a wide dynamic range of 1 MIP (Minimum Ionization Particle) to 10^6 MIPs for the charged particles detection. Hence, this new air-shower core detector can lower the detection threshold energy of primary particles to 20 TeV, about one and a half order of magnitude smaller than the previous experiment. This new experimental condition improves the statistics of the high-energy core event compared with the Tibet-EC experiment by a factor of 100. With these improvements, the energy spectra of individual components at energies of 50 TeV–10 PeV can be measured by YAC, which will overlap with direct observations at lower energies such as CREAM [17], CALET [18] and DAMPE [19], and Tibet-EC experiment at higher energies and help us to explicitly observe the break point of the spectral index for individual chemical component.

The merit of YAC detector is to distinguish the primary cosmic-ray nuclei through recording the electromagnetic showers induced by high energy electrons and photons in the AS forward region, as shown in figure 1(a). Among primary particles, proton with the long interaction mean free path can penetrate deep in the atmosphere and produce AS cores near the observation level, resulting in giving smaller lateral spread. Thus, the lateral distribution of high-energy core events originated by proton is relatively small and more like concentric circles, while iron-induced event shows very irregular structure, whose details are described in [13]. With these sensitive parameters, YAC can be used to separate different primary cosmic-ray nuclei by detecting high energy electromagnetic particles in the AS core.

The calibration of YAC detector is critically important which determines the reliability of the detector’s performance. In this paper, we first introduced the design of YAC detector in section 2. Then, the calibration procedure of YAC detector is described in section 3. Section 4 is the summary.

2 Design of the YAC detector

To observe the primary composition at the knee energy region, we have carried out a full Monte Carlo simulation on the design study of the YAC detector, whose details are described in [13]. Based on MC, we designed the structure of YAC detector which comprises a lead plate with the thickness of 3.5 cm, a scintillation counter with an area of 0.5 m^2, 60 WLSFs with the length of 110 cm and 2 PMTs, as shown in figure 1(b). The concrete structure of YAC detector is described as follows:
Figure 1. (a) The observation principle of YAC detector is to distinguish the primary cosmic-ray nuclei by observing the electromagnetic showers induced by high energy electrons and photons in the AS forward region; (b) Schematic view of YAC detector. Each YAC detector unit consists of a lead plate with the thickness of 3.5 cm, a plastic scintillation counter with an area of 0.5 m$^2$ which is divided into 20 pieces, 60 WLSFs with the length of 110 cm and 2 PMTs.

(1) Material layer: lead plate. The function of lead plate is to convert high energy electrons and photons into electromagnetic cascade showers. The energy scope of electrons and photons in AS cores that we are interested in ranges from several GeV to several 10 TeV. We have carried out a full Monte Carlo simulation, and found that when the thickness of lead plate is selected as 3.5 cm, it is suitable for the identification of both light cosmic-ray components and heavy components [13]. It is worthwhile to note that the 3.5 cm thickness of lead plate is not thick enough for observing the cascade showers induced by hadrons. That is, YAC detector is more sensitive to the electromagnetic component after the “amplification” of the 3.5 cm thickness of lead plate. In addition, a 0.9 cm (corresponding to 0.5 radiation length) thick iron plate placed under the lead plate is used to support the weight of the lead plate.

(2) Particle detection layer: plastic scintillator. After high energy electromagnetic particles near the AS axis develop into cascade showers in the lead absorber, these shower particles will enter the plastic scintillation counter and produce scintillation light. In order to have a certain position resolution of high energy particles in the AS cores, the scintillation counter with an area of 0.5 m$^2$ in the core detector is divided into 20 pieces whose size is 50 cm × 4 cm × 1 cm, and light-isolated from each other using reflecting material. Such a design ensures the geometrical uniformity of detector response within 6%[15].
(3) Light transporter: WLSFs. The scintillation light is collected through WLSFs (SAINT-GOBAIN BCF-92, round cross-section with 1.5 mm diameter). One end of the WLSF is attached to a PMT for readout, another end is aluminum-filled for reflecting photons, and the reflection rate reaches 99% [15]. While 20 WLSFs installed in the scintillator slabs attached to the low-gain (LG) PMT, the other 40 WLSFs attached to the high-gain (HG) PMT.

(4) Photoelectric conversion equipment: PMTs. The signals produced in the plastic scintillator are transmitted to two different gain PMTs, respectively, via WLSFs. 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 calibration system, the dynamic range of the PMTs should be from 1 MIP to $10^6$ MIPs. This is realized by adopting a high-gain PMT (HAMAMATSU R4125) and a low-gain PMT (HAMAMATSU R5325) that are responsible for the range of 1–5000 MIPs and $10^3$–$10^6$ MIPs, respectively. Then, the charge information on each hit PMT is digitized by the use of charge-sensitive analog-to-digital converter (ADC).

3 Calibration of YAC detector

In order to obtain the characteristic parameters of AS cores by observing high energy electromagnetic particles in the core region, it is essentially important to precisely measure the number of shower particles generated by the secondary particles after passing through each YAC detector. Therefore, the following calibration procedure of YAC detector is important for obtaining the shower particles information, which is described as follows: 1) High-gain PMT calibration; 2) Low-gain PMT calibration; 3) PMT linearity calibration by LED light source; 4) Scintillation counter calibration by the beam of BEPC; 5) Off-line calibration.

3.1 High-gain PMT calibration

In order to precisely measure the number of charged particles in an AS core event, it is necessary to know a single-particle energy deposit in each YAC detector correctly. Experimentally, the number of charged particles 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 single muons. Here, the number of charged particles observed by each YAC detector is defined as $N_p$. For this purpose, a reference small detector (probe detector) which consists of a PMT (HAMAMATSU H1949) and a scintillator plate 25 cm $\times$ 25 cm $\times$ 3.5 cm thick in size is put on the top of YAC detector, as shown in figure 2(a). When a charged particle punches through both the probe detector and the YAC detector (the probe detector issues a trigger signal), the charge from the PMT corresponding to the energy deposit in the scintillator is digitized and recorded by the ADC, where an ADC gate start signal is issued by the probe detector signal. The resolution of the ADC is 0.25 pC/count. In this case, the relativistic muons made by primary cosmic rays at 10 GeV $\sim$ TeV energies near the top of atmosphere dominate in triggered events against secondary particles, such as electrons, in an air shower. Figure 2(b) shows the experimental charge distribution of a single particle measured by high-gain PMT (R4125) in a YAC detector unit as an example. The red solid circles denote
Figure 2. (a) Schematic view of the probe calibration for YAC detector; (b) Charge distribution of a single particle in a YAC detector. The peak, called a single-particle peak, is defined as one MIP. The red solid circles denote experimental data and the black solid line is the fitting result to the charge distribution by Landau distribution.

experimental data and the black solid line is the fitting result to the charge distribution by Landau distribution. In this figure, a peak with the value $2.02 \pm 0.01$ pC indicates the typical charge when one particle passes through our detector, which we call “single-particle peak”. Therefore, when the charge of the single-particle peak is defined as one particle, we can simply count the number of charged particles measured by high-gain PMT (R4125) in YAC detector.

3.2 Low-gain PMT calibration

Since we cannot measure a single particle using the low-gain PMT (R5325) directly because the low-gain PMT is responsible for the high energy particles and its gain is too low to observe the single-particle peak. Therefore, the single-particle peak of the low-gain PMT is estimated by the correlation between the high-gain PMT and the low-gain PMT for the same events. Figure 3 shows the correlation between the charge of high-gain PMT ($Q_H$) and low-gain PMT ($Q_L$) for the same events which were recorded by the ADC as an example. In this figure, the solid line gives the best fit to this correlation by the function $\log(Q_L) = p_0 \log(Q_H) + p_1$, where $p_0$ and $p_1$ to be determined from the relationship. It is found that there is a good linear relationship between the data from the two PMTs. According to the relationship between the high-gain PMT and the low-gain PMT, the number of charged particles measured by the low-gain PMT can also be obtained.

3.3 PMT linearity calibration by LED light source

As mentioned above, two PMTs of high-gain PMT (R4125) and low-gain PMT (R5325) are equipped to cover a wide dynamic range from 1 MIP to $10^6$ MIPs. Therefore, the linearity of the PMT output signals covering the wide dynamic range in six orders of magnitude is essentially important. In this work, for every PMT (high-gain PMT R4125 and low-gain PMT R5325) used in YAC, the linearity is measured using LED light source and optical filters. The PMT linearity calibration system is schematically shown in figure 4. In the test, we fixed the positions of LED, filters and PMT. The LED is driven by Transistor Transistor Logic (TTL) pulse with the width of 50 nsec. The TTL pulse frequency applied to LED is controlled by the pulse generator while the light intensity is controlled.
Figure 3. The correlation between the charge of high-gain PMT ($Q_H$) and low-gain PMT ($Q_L$) for the same events which were recorded by the ADC. The solid line gives the best fit to this correlation.

Figure 4. Schematic view of PMT linearity calibration system.

by the control box. At the same time, the pulse generator generates the Nuclear Instrumentation Module (NIM) signals to use as triggers. Before reaching the PMT, the light passes through the optical filters. Therefore, the response of PMTs with respect to the intensity of LED can be measured by use of different filters. Figure 5(a) shows the response of the high-gain PMT (R4125) (R) versus the intensity of LED light (I), which can be fitted with a linear function $R = p_0 I$ with $p_0$ to be determined from measurements. In this measurement, when the deviation from the linear fitting line is less than 5%, the output of PMT is considered to be within the linearity range. In this figure, the black solid circles denote the charge output of R4125 with respect to the intensity of LED. The solid red line denotes the best fit result by the linear function, where the fitting slope of R4125 is $p_0 = (1.52\pm0.01) \times 10^6$. The dash black lines denote the 5% deviation from the linear fitting line. From figure 5(a), we found that, taking the scintillation light intensity and the knowledge from the probe calibration into account, R4125 is linear in a dynamic range roughly from 1 to $5 \times 10^3$ MIPs. Figure 5(b) is the same one for low-gain PMT (R5325). One can see that R5325 is linear at least from 1000 to $10^6$ MIPs. That is, the two PMTs configuration of YAC detector can meet our requirement which have the wide dynamic range in six orders of magnitude from 1 MIP to $10^6$ MIPs.
Figure 5. The response of high-gain PMT (R4125) (a) and low-gain PMT (R5325) (b) with respect to the intensity of LED light. The black solid circles denote the experimental data. The solid red line denotes the best fit result by the linear function. The dash black lines denote the 5% deviation from the linear fitting line.

3.4 Scintillation counter calibration by the beam of BEPC

Since the number of charged particles measured by YAC detector is up to $10^6$ MIPs, the saturation effect of the detector needs to be measured which mainly consists of two parts. One is from PMT, another one is from the plastic scintillator. The linearities of the two selected PMTs were firstly investigated in section 3.3. And we found two PMTs have the wide dynamic range in six orders of magnitude from figure 5, so it can be concluded that the saturation effect of the detector comes from the plastic scintillator in the YAC scintillation counter calibration experiment. In this work, a measurement of the saturation effect of the plastic scintillator used in YAC detector was carried out by making use of the accelerator beam of the BEPCII (Beijing Electron Positron Collider, IHEP, China) [20]. The beam intensity usually is about $10^9$ electrons/pulse, which could be attenuated to a range roughly from $10^4$ to $5 \times 10^6$ electrons/pulse by using a scraper and some focusing magnets to adapt our requirements used in the YAC detector. The beam frequency is 50 Hz with a beam size of about 1 cm$^2$ and a beam width of 1.2 ns, while the pulse size and width induced by high energy cosmic rays is greater than the beam characteristics. The beam intensities above $10^8$ electrons/pulse were measured by a Faraday Cup (FC) which has been demonstrated to be capable of absolute measurements with an error lower than 1%. Then, a Thin two-dimensional multi-strip Ionization Chamber (Thin IC) was designed to monitor the beam intensities from $10^5$ to $5 \times 10^8$ electrons/pulse, and a Thick two-dimensional multi-strip Ionization Chamber (Thick IC) was designed to monitor the beam intensities from $10^4$ to $10^7$ electrons/pulse [21]. Using the over-lapping region of FC, Thin IC and Thick IC, the linearity of YAC detector could be investigated. That is, we can use FC to calibrate Thin IC and then extrapolate the monitor range of Thin IC down to $10^5$ electrons/pulse. Also, we can use Thin IC to calibrate Thick IC and extrapolate the monitor range of Thick IC down to $10^4$ electrons/pulse. Finally, Thin IC and Thick IC will be used to calibrate YAC range from $10^4$ to $5 \times 10^6$ electrons/pulse. YAC scintillator packaged in a dark stainless-steel box was placed parallel to the ICs and perpendicular to the direction of the beam used. The arrangement of the detectors is presented in figure 6. Figure 6(a) is the picture of FC. Figure 6(b) is the calibration system of the beam-test. From right to left, there are the beam, Thin IC, Thick IC and YAC scintillation counter.
Figure 6. (a) The picture of FC; (b) The calibration system of the beam-test. From right to left, there are the beam, Thin IC, Thick IC and YAC scintillation counter.

![Figure 6](image)

Figure 7. The resultant charge output of YAC versus the number of incident particles in the beam-test calibration. The red circles and blue squares denote the charge output of YAC versus the number of incident particles which are determined by Thin IC and Thick IC, respectively. The solid black line denotes the best fit result by a linear function.

![Figure 7](image)

The high beam intensity part, near $10^6$ electron/(cm$^2$s), was highly taken into account in this experiment. In this case, high-gain PMT R4125 could not be used. The signal from the plastic scintillation counter was obtained with low-gain PMT R5325. The resultant charge output of YAC versus the number of incident particles in our beam-test calibration is shown in figure 7. In this figure, the red circles and blue squares denote the charge output of YAC (Q) versus the number of incident particles (N) which are determined by Thin IC and Thick IC, respectively. The solid
black line denotes the linear fitting result by the function $Q = p_0 N$, where the fitting slope is $p_0 = (8.95 \pm 0.12) \times 10^{-5}$. As shown in the figure, there is a good linear relationship between the incident particle flux and charge output of YAC below $5 \times 10^6$ MIPs while the non-linearity is less than 3%. Here, the non-linearity is defined as the maximum deviation from the fitting line. Such a wide dynamic range shows that YAC experiment may make it possible to obtain the primary mass composition and energy spectrum covering and above the ‘knee’ energy region.

### 3.5 Off-line calibration

Due to the impact of environment and climate at Yangbajing, the gain of PMTs will drift as time passed by which will cause the single-particle peak (sp) value of the YAC detector changed. As mentioned in section 3.1, the number of charged particles ($N_b$) observed by each YAC detector is defined as the PMT output ($Q$) divided by that of the sp value. That is, $N_b = Q/sp$. Therefore, the $N_b$ spectrum observed by each YAC detector will be no longer consistent due to the variety of sp value, as shown in figure 8(a). In fact, this effect can be carefully treated and corrected by an off-line self-calibration method. That is, we can use the consistent $N_b$ spectrum of the first 5 days as a benchmark when the probe calibration was finished. Then, we can adjust the sp value slightly until the $N_b$ spectrum is closest to the standard spectrum of the first 5 days. Thus, we can obtain the off-line calibrated sp value to make the $N_b$ spectrum of each detector consistent every 5 days. Figure 8(b) shows the consistent $N_b$ spectrum of each detector after off-line calibration. It is shown that the differences of $N_b$ spectrum between the YAC detectors are less than 20% after off-line calibration.

### 4 Summary

YAC detector calibration procedure including five steps of high-gain PMT calibration, low-gain PMT calibration, PMT linearity calibration, scintillation counter calibration and off-line calibration is presented in this paper. We found that the linear relationship between YAC scintillation detector output and incident particles is good below $5 \times 10^6$ MIPs while the non-linearity is less than 3%.
It proves that YAC experiment may make it possible to obtain the primary mass composition and energy spectrum covering and above the ‘knee’ energy region. A new hybrid experiment (YAC+Tibet-III+MD) has started data taking since 2014 to measure the chemical composition of cosmic rays around the ‘knee’ in the wide energy range, and the more results will be reported in the near future.

Acknowledgments

The authors would like to express their thanks to the members of the Tibet AS γ collaboration for fruitful discussions. This work is supported by the National Key R&D Program of China (No. 2016YFE0125500) and by the Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS. Y. Zhang is supported by the National Natural Science Foundation of China (No. 11803038). The National Natural Science Foundation of China (Nos. 11533007, 11673041 and 11873065) also provides support to this study.

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