

## Performance of new 8-inch photomultiplier tube used for the Tibet muon-detector array (Post-print)

**Authors:** Ying Zhang, Jing Huang, Ding Chen, Liu-Ming Zhai, Xu Chen, Xiao-Bin Hu, Yu-Hui Lin, Hong-Bo Jin, Xue-Yao Zhang, Cun-Feng Feng, Huan-Yu Jia, Xun-Xiu Zhou, DANZENGLUOBU, Tian-Lu Chen, LABACIREN, Mao-Yuan Liu, Qi Gao, ZHAXICIREN

**Date:** 2016-08-31T00:00:00+00:00

### Abstract

A new hybrid experiment has been constructed to measure the chemical composition of cosmic rays around the “knee” in the wide energy range by the Tibet AS collaboration at Tibet, China, since 2014. They consist of a high-energy air-shower-core array (YAC-II), a high-density air-shower array (Tibet-III) and a large underground water-Cherenkov muon-detector array (MD). In order to obtain the primary proton, helium and iron spectra and their “knee” positions in the energy range lower than  $10^{16}$  eV, each of PMTs equipped to the MD cell is required to measure the number of photons capable of covering a wide dynamic range of 100 -  $10^6$  photoelectrons (PEs) according to Monte Carlo simulations. In this paper, we firstly compare the characteristic features between R5912-PMT made by Japan Hamamatsu and CR365-PMT made by Beijing Hamamatsu. This is the first comparison between R5912-PMT and CR365-PMT. If there exists no serious difference, we will then add two 8-inch-in-diameter PMTs to meet our requirements in each MD cell, which are responsible for the range of 100 - 10000 PEs and 2000 - 1000000 PEs, respectively. That is, MD cell is expected to be able to measure the number of muons over 6 orders of magnitude.

### Full Text

#### Performance of a New 8-Inch Photomultiplier Tube for the Tibet Muon-Detector Array

\*\*Ying Zhang<sup>{a,b}</sup>, Jing Huang<sup>{a}</sup>, Ding Chen<sup>{c}</sup>, Liu-Ming Zhai<sup>{c}</sup>, Xu Chen<sup>{a}</sup>, Xiao-Bin Hua<sup>{d}</sup>, Yu-Hui Lin<sup>{a}</sup>, Hong-Bo Jin<sup>{c}</sup>, Xue-Yao Zhang<sup>{d}</sup>, Cun-Feng Feng<sup>{d}</sup>, Huan-Yu Jia<sup>{e}</sup>, Xun-Xiu Zhou<sup>{e}</sup>,

DANZENGLUOBUN<sup>f</sup>, Tian-Lu Chen<sup>f</sup>, LABACIREN<sup>f</sup>, Mao-Yuan Liu<sup>f</sup>, Qi Gao<sup>f</sup>, and ZHAXICIREN<sup>f,\*</sup>\*\*

<sup>a</sup>Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

<sup>b</sup>University of Chinese Academy of Sciences, Beijing 100049, China

<sup>c</sup>National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

<sup>d</sup>Department of Physics, Shandong University, Jinan 250100, China

<sup>e</sup>Institute of Modern Physics, Southwest Jiaotong University, Chengdu 610031, China

<sup>f</sup>Physics Department of Science School, Tibet University, Lhasa 850000, China

<sup>\*</sup>Corresponding author. Email: yingzhang@ihep.ac.cn

## Abstract

A new hybrid experiment has been constructed by the Tibet AS collaboration in Tibet, China, since 2014 to measure the chemical composition of cosmic rays around the “knee” across a wide energy range. The apparatus consists of a high-energy air-shower-core array (YAC-II), a high-density air-shower array (Tibet-III), and a large underground water-Cherenkov muon-detector array (MD). To obtain the primary proton, helium, and iron spectra and identify their respective “knee” positions below  $10^{16}$  eV, Monte Carlo simulations indicate that each PMT equipped in an MD cell must measure photon numbers covering a dynamic range of 100- $10^6$  photoelectrons (PEs).

In this paper, we present the first comparative study of the characteristic features between the R5912-PMT manufactured by Hamamatsu Photonics in Japan and the CR365-PMT produced by Hamamatsu Photonics Beijing. If no serious differences are found, we plan to install two 8-inch-diameter PMTs in each MD cell to meet our requirements: one covering the 100-10,000 PE range and the other covering 2,000-1,000,000 PEs. This configuration would enable each MD cell to measure muon numbers across six orders of magnitude.

## Introduction

The cosmic ray energy spectrum follows a power law across more than ten decades of energy, a remarkable feature attributed to nonthermal acceleration mechanisms. The spectral index steepens abruptly from approximately -2.7 to -3.1 around  $4 \times 10^{15}$  eV, creating a distinctive “knee” structure [1][2]. The origin of this knee remains an outstanding problem in astroparticle physics [3][4]. Numerous models have been proposed, including changes in acceleration mechanisms at cosmic ray sources (such as supernova remnants and pulsars), single-source scenarios, propagation effects within the galaxy (diffusion, drift, and escape), and unknown atmospheric processes during air-shower development

[5][6][7][8][9]. Resolving the knee's origin requires precise measurement of the spectral index break point for each individual chemical component [3][10][11].

In 2014, the Tibet AS project completed a major upgrade comprising an air-shower-core array (YAC-II), a high-density air-shower array (Tibet-III), and a large underground water-Cherenkov muon-detector array (MD) [12][13]. For each air shower event, Tibet-III determines the arrival direction ( $\theta$ ) and air shower size ( $N_e$ ), which correlate with primary energy; YAC-II measures high-energy electromagnetic particles in the core region to characterize air-shower cores; and the underground MDs record high-energy muons above 1 GeV. The MD array currently consists of five pools installed 2.5 meters underground, each containing 16 cells and covering a total area of 4500 m<sup>2</sup>. Each MD cell comprises a concrete water tank measuring 7.2 m × 7.2 m × 1.5 m, with two downward-facing 20-inch PMTs (R3600) mounted on the ceiling. The method for obtaining light-component spectra of primary cosmic rays at knee energies using the Tibet experiment is described in [12][14]. To explicitly observe spectral break points for individual components, we must detect primary particles up to 10<sup>16</sup> eV. Monte Carlo simulations show that two PMTs per MD cell must measure photon numbers across a wide dynamic range from 100 to 10<sup>6</sup> PEs, as illustrated in Fig. 1 [Figure 1: see original paper].

This work presents the first comparison between the R5912-PMT from Hamamatsu Japan and the CR365-PMT from Hamamatsu Beijing. Since this marks Beijing Hamamatsu's first production of 8-inch-diameter PMTs, evaluating their performance is essential both to verify they meet our requirements and to provide valuable feedback to the manufacturer. We subsequently tested a pair of PMTs and measured the linearity of their response as a function of light intensity.

## 2 The Experimental Setup

To characterize these PMTs, we measured five key quantities: (1) photoelectron spectra, (2) gain as a function of high voltage, (3) dark count rate, (4) linearity of PMT output signals, and (5) dynamic range. The complete test system comprises a Pulse Generator (Agilent Technologies 81160A), Laser (PiL044SM-SN-513B), neutral density filters, High Voltage power supply (CAEN N1470), Gate Generator (ORTEC GG8020), Low Threshold Discriminator (CAEN N845), Scaler (ORTEC 772 counter), ADC (LeCroy 2249A, 0.25 pC/count resolution), and a data acquisition (DAQ) computer. Figure 2 [Figure 2: see original paper] shows a schematic diagram of the test system.

The light source was a picosecond laser (PiL044SM-SN-513B) featuring extremely narrow pulse width and high stability. A pulse generator controlled the laser's signal frequency (fixed), while a control box varied the light intensity. Simultaneously, the pulse generator produced NIM signals for triggering. Before reaching the PMT, the light passed through neutral density attenuation filters, enabling intensity variation across more than five orders of magnitude. For

measurements of quantities (1), (2), (4), and (5), PMT signals were fed into a charge-integrating ADC in a CAMAC crate for measurement and readout by the DAQ computer. For dark count rate measurement (3), signals were processed through a low-threshold discriminator before being counted by a scaler. All subsequent analysis was performed on the computer.

### 3 Results

Using this test system, we measured single photoelectron (SPE) spectra, multi-photoelectron spectra, gain versus voltage, dark count rate at 1/3 PE threshold, and output signal linearity for both CR365 and R5912 PMTs. Details of each measurement are described below.

#### 3.1 Single Photoelectron Spectra

We measured SPE spectra to determine the absolute PMT gain at specific voltages. Figure 3 [Figure 3: see original paper] shows SPE spectra for the CR365 at 1500 V and the R5912 at 1350 V, corresponding to a gain of approximately  $1.5 \times 10^7$ . The first peak represents the pedestal, while the second peak corresponds to single photoelectron events. We quantified the SPE spectrum resolution using the peak-to-valley ratio, defined as the ratio of the SPE histogram's maximum value to the minimum value between the pedestal and the maximum. Both PMTs exhibit peak-to-valley ratios close to 2, indicating excellent charge resolution for single photoelectron detection.

#### 3.2 Multi-Photoelectron Spectra

We also measured multi-photoelectron (multi-PE) spectra for both PMTs at 1800 V, as shown in Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper]. The ADC resolution was 0.25 pC/count. A multi-Gaussian fit was performed using Equation (1), where  $N_{pe}$  represents the average number of photoelectrons,  $\sigma$  is the standard deviation of the multi-PE distribution, and  $C$  is the ADC count per photoelectron [15].

$$f(x) = \sum_{n=0}^{\infty} \frac{e^{-N_{pe}} N_{pe}^n}{n!} \frac{1}{\sqrt{2\pi n\sigma^2}} \exp\left(-\frac{(x - nC)^2}{2n\sigma^2}\right)$$

As shown in Figures 4 and 5, the multi-PE spectra for both CR365 and R5912 are well reproduced by this multi-Gaussian function, demonstrating that both PMTs provide good charge resolution for multi-photoelectron detection.

#### 3.3 Gain as a Function of High Voltage

The gain curve relative to applied high voltage (HV) represents a crucial performance characteristic. To measure gain versus HV, we fixed the laser light intensity while varying the PMT HV. The relationship between gain ( $G$ ) and

input voltage (V) follows the power law  $G = V^{\alpha}$ , where  $\alpha$  and  $\beta$  are determined experimentally. The fitted parameters are  $\alpha = 8.96 \pm 0.10$  for R5912 and  $\alpha = 8.27 \pm 0.06$  for CR365. We measured the absolute gain for each PMT at a known voltage from its SPE spectrum, enabling conversion of relative gain measurements to absolute values. Figure 6 [Figure 6: see original paper] shows the absolute gain for both PMTs, with the R5912 gain being approximately three times that of the CR365 at 1800 V.

### 3.4 Dark Count Rate

The dark count rate measures the signal rate observed in a PMT above a certain threshold when no light illuminates the photocathode. This parameter correlates with PMT lifetime, as lower noise generally indicates longer operational life. We compared dark noise data between the R5912 and CR365. Determining the appropriate 1/3 PE threshold requires knowledge of the absolute PMT gain. After two hours of dark adaptation, both PMTs exhibit anode dark rates below 3 kHz at a gain of approximately  $1.5 \times 10^7$  when thresholds are set at 1/3 photoelectron.

### 3.5 Linearity of PMT Response

Extending the MD dynamic range from 100 PEs to  $10^6$  PEs requires excellent PMT output linearity. We measured linearity for both R5912 and CR365 using the laser light source and filters shown in Figure 2 [Figure 2: see original paper]. Light intensity was varied using different neutral density transmission filters, and the corresponding response was fitted with the function  $y = ax^b$ , where  $x$  represents relative transmission. Figure 7 [Figure 7: see original paper] demonstrates linear behavior for the CR365 at 1500 V and the R5912 at 1350 V as a function of input light at approximately  $1.5 \times 10^7$  gain. The fitted slopes are  $b = 1.05 \pm 0.01$  for CR365 and  $b = 1.03 \pm 0.01$  for R5912. We define the maximum linear current as the peak current where deviation from ideal linearity reaches  $\pm 5\%$ . Under this criterion, the CR365 achieves a peak linear current of approximately 100 mA, while the R5912 reaches about 130 mA. For this comparative study, we selected PMTs with relatively high gain. However, to measure photoelectron numbers up to  $10^6$ , we will select appropriate PMTs with lower gain for subsequent tests, as discussed in the following section.

### 3.6 Extending the Dynamic Range of the Muon Detector

Monte Carlo simulations indicate that the highest-energy showers may produce peak signals as large as  $10^6$  PEs, requiring PMT linearity up to such large signals. To extend the MD dynamic range from 100 PEs to  $10^6$  PEs, we plan to add two 8-inch PMTs to each MD cell, with one covering the 100-10,000 PE range and the other covering 2,000-1,000,000 PEs.

First, we selected a CR365-A PMT operating at approximately  $10^6$  gain and 1500 V to ensure linearity across the 100-10,000 PE range. Then, as incident

light intensity increases, we use a 1% transmission filter to attenuate the input light to a CR365-B PMT (also at  $\sim 10^6$  gain, 1500 V), enabling linear measurement from 2,000 to 1,000,000 PEs. Figure 8 [Figure 8: see original paper] shows the output signals of these two CR365 PMTs versus input light, confirming that this approach meets our requirements. Consequently, the MD is expected to achieve a wide dynamic range spanning six orders of magnitude.

## 4 Conclusion

This paper presents a comparative study of the R5912 and CR365 PMTs. Our tests confirm no serious differences between the CR365 and R5912, and the CR365 meets the specifications provided by Hamamatsu Beijing. This represents the first direct comparison between these two PMT models. We subsequently tested PMT response linearity by varying light intensity and found that both types satisfy our requirements for achieving a six-order-of-magnitude dynamic range in the muon detector. In the near future, we will evaluate the long-term performance stability of this PMT type.

## Acknowledgments

The authors thank the members of the Tibet AS collaboration for fruitful discussions. This work is supported by grants from the National Natural Science Foundation of China (11533007, 11078002, and 11275212), the Chinese Academy of Sciences (H9291450S3, 2013T2J0006), and the Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS. The Knowledge Innovation Fund (H95451D0U2 and H8515530U1) of IHEP, China, also provided support for this study.

## References

- [1] Kulikov and Khristiansen, JETP, 35: 635, (1958).
- [2] M. Amenomori et al., ApJ, 678: 1165, (2008).
- [3] J.R. Hörandel, Astropart. Phys., 19: 193, (2003).
- [4] J.R. Hörandel, Astropart. Phys., 21: 241, (2004).
- [5] Berezhko, E. G., & Ksenofontov, L. G, J. Exp. Theor. Phys., 89: 391 (1999).
- [6] Erlykin, A. D., & Wolfendale, A. W., Astropart. Phys., 23: 1 (2005).
- [7] Ptuskin, V. S., et al., A&A, 268: 726 (1993).
- [8] Wigmans, R., Astropart. Phys., 19: 379 (2003).
- [9] Nikolsky, S. I., & Romachin, V. A., Phys. At. Nuclei, 63: 1799, (2000).
- [10] M. Amenomori et al., Phys. Lett. B, 632: 58, (2006).
- [11] M. Shibata, Y. Katayose, J.Huang and D. Chen, ApJ, 716: 1076-1083, (2010).
- [12] J. Huang, L.M. Zhai, D. Chen, et al., Astropart. Phys., 66: 18-30, (2015).
- [13] LIU Jin-Sheng, et al., Chinese Physics C, Vol. 39: No.8, 086004 (2015).
- [14] L.M. Zhai, et al., J. Phys. G: Nucl. Part. Phys., 42: 045201 (2015).

[15] E.H. Bellamy et al. Nuclear Instruments and Methods in Physics Research A, 339: 468-476 (1994).

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv – Machine translation. Verify with original.*