Performance of new 8-inch photomultiplier tube used for the Tibet muon-detector array

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Abstract: Since 2014, a new hybrid experiment consisting 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) has been continued by the Tibet ASγ collaboration to measure the chemical composition of cosmic rays in the wide energy range including the “knee”. In this experiment, YAC-II is used to select high energy core events induced by cosmic rays in the above energy region, while MD is used to estimate the type of nucleus of primary particles by measuring the number of muons contained in the air showers. However, the dynamic range of each MD cell is only 5 to 2000 photoelectrons (PEs) which is mainly designed for observation of high-energy celestial gamma rays. In order to obtain the primary proton, helium and iron spectra and their “knee” positions with energy up to 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 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. 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 magnitudes.

Keywords: Cherenkov detectors; Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others)

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1 Introduction

The energy spectrum of cosmic rays is roughly described by a power law over a wide energy range covering more than 10 decades while there exist some structures in the spectrum; this may suggest a remarkable feature of the nonthermal acceleration mechanism of high-energy cosmic rays. Among the power index changes appeared in the all-particle spectrum, the “knee” is the most well known. That is, the power index suddenly steepens from approximately $-2.7$ to $-3.1$ at around $4 \times 10^{15}$ eV, resulting in a distinctive “knee” shape in the spectrum [1]. Its origin is an outstanding problem in astroparticle physics [2, 3]. For this explanation, many authors have proposed various models such as a change of acceleration mechanisms at the sources of cosmic rays (supernova remnants, pulsars, etc.), an assumption of nearby sources emitting high energy cosmic rays, a change of cosmic ray propagation in the Galaxy (diffusion, drift, escape from the Galactic disk), and some unknown new processes in the atmosphere during air-shower development [4–8]. Hence, in order to resolve the origin of the knee, it is critical to measure the primary chemical composition or mass group at energies of $50$ TeV–$10^{16}$ eV, especially, to measure the primary energy spectra of individual components and determine a break energy of the spectral index for individual components [2, 9, 10].

In 2014, an important upgrade of the Tibet ASγ project was completed, and we then started a new hybrid experiment consisting of 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) [1, 11, 12]. For an air shower event, the Tibet-III array provides the arrival direction ($\theta$) and the air shower size ($N_e$) which are interrelated to primary energy, the YAC-II array measures the high energy electromagnetic particles in the core region so as to obtain the characteristic parameters of air-shower cores, at the same time, the underground MDs record the high-energy muons above 1 GeV.
The MD array now consists of 5 pools set up 2.5 meters underground, each with 16 cells, covering a total area of \( \sim 4500 \text{ m}^2 \). Each cell of the MD array is composed of a concrete water tank with a cubic form of 7.2 m wide, 7.2 m long, 1.5 m deep and two 20-inch PMTs (R3600) are mounted downward on the ceiling. The method for obtaining the light-component spectrum of primary cosmic rays at the “knee” energies with the Tibet AS\( \gamma \) experiment is described in the paper [11, 13], and we then found that the MD array plays an important role in mass separation at high energy range according to Monte Carlo simulation. However, the dynamic range of each MD cell is only 5 to 2000 photoelectrons (PEs) which is mainly designed for observation of high-energy celestial gamma rays. In order to observe air showers of nuclear component origin, we need to observe primary particles with energy up to \( 10^{16} \) eV. According to Monte Carlo simulation, a set of two PMTs in each MD cell is required to measure the number of photons over a wide dynamic range from 100 to \( 10^9 \) PEs, as shown in figure 1.

In this paper, we firstly compare the characteristic features between R5912-PMT made by Japan Hamamatsu and CR365-PMT made by Beijing Hamamatsu. Since Beijing Hamamatsu produces this type of 8-inch-in-diameter PMTs for the first time, so it is needed to test the performance of PMTs whether they are intend to satisfy our request, also to provide valuable feedback to the company producing them. Then, we use a set of two PMTs and measure the linearity of the PMT response as a function of the light intensity to meet our requirements.

![Figure 1](image.png)

Figure 1. The correlation between primary energy and number of photoelectrons(PEs) observed with the each MD cell based on Monte Carlo simulation.

2 The experimental setup

In order to study the performance of these PMTs, the following quantities have been measured:

1. photoelectron spectra,
2. gain as a function of high voltage,
3. ion feedback and after-pulsing,
4. dark count rate,

5. linearity of PMT output signals,

6. dynamic range of PMT.

The entire test system is mainly composed of Pulse Generator (Agilent Technologies 81160A), Laser (PiL044SM-SN-513B), Filter, High Voltage power supply (CAEN N1470), Gate Generator (ORTEC GG8020), Low Threshold Discriminator (CAEN N845), Scaler (ORTEC 772 counter), Oscilloscope (Tektronix TDS3032C), ADC (Lecroy 2249A, the resolution is 0.25 pC/count), and data acquisition (DAQ) computer. The test system is schematically shown in figure 2. The light source used for this test was a picosecond laser (PiL044SM-SN-513B) which has very narrow pulse width and high stability. Signal frequency applied to the laser is controlled by the pulse generator (fixed) and the light intensity is controlled by the control box (variable). At the same time, the pulse generator generates the NIM signals to use as triggers. Before reaching the PMT, the light passes through the neutral density attenuation filters. With different filters, we were able to change the light intensity by more than 5 orders of magnitude. When we measure 1), 2), 5) and 6), the signals from the PMT are then fed into a charge-integrating ADC in a camac crate where they are measured and then read out by the DAQ computer; when we measure 3), the signals from the PMT are then fed into an oscilloscope and then read out by the DAQ computer; when we measure 4), the signals from the PMT are fed into a low threshold discriminator and then into a scaler.

Figure 2. Schematic view of the test system. When we measure 1), 2), 5) and 6), the signals from the PMT are then fed into a charge-integrating ADC in a camac crate where they are measured and then read out by the DAQ computer; when we measure 3), the signals from the PMT are then fed into an oscilloscope and then read out by the DAQ computer; when we measure 4), the signals from the PMT are fed into a low threshold discriminator and then into a scaler.

3 Results

Using this test system, the single photoelectron (SPE) spectra, multi photoelectrons spectra, gain as a function of voltage, ion feedback and after-pulsing, dark count rate at 1/3 photoelectron (PE) threshold and linearity of PMT output signals are measured for CR365 and R5912. Details of each test are described in the following sections.
3.1 Single photoelectron spectra

In order to get the absolute gain of the PMT at a certain voltage, the SPE spectrum is measured. Figure 3 shows the SPE spectra for CR365 at 1500V and R5912 at 1350V corresponding to \( \sim 1.5 \times 10^7 \) gain. The first peak is the pedestal and the second peak is due to 1 photoelectron events. To quantify the resolution of the single photoelectron spectrum, the peak to valley ratio is used. The peak to valley ratio is the ratio of the maximum value of the histogram of the SPE spectrum to the minimum value between the pedestal and the maximum. The SPE peak to valley ratio for CR365 and R5912 are both close to 2 which indicate that both PMTs have a good charge resolution for detecting a single photoelectron.

![Figure 3. Single photoelectron (SPE) spectra at \( \sim 1.5 \times 10^7 \) gain measured for CR365 and R5912. The SPE peak to valley ratio for CR365 and R5912 are both close to 2 which indicate that both PMTs have a good charge resolution for detecting single photoelectron.](image)

3.2 Multi photoelectron spectra

We also measured the spectra of multiple photoelectrons (multi-PEs) for CR365 and R5912 both at 1800V as shown in figure 4 and figure 5. Here, the resolution of ADC is 0.25 pC/count. An exponential fit was carried out to describe the background and a multi-gaussian fit was carried out to describe the real signal which is described in equation (3.1). \( N_{pe} \) is the average multi-PEs number, \( \sigma \) is standard deviation of a photoelectron, \( C \) is the ADC count of a photoelectron [14].

\[
f(x) = a e^{-bx} + \sum \frac{(N_{pe}^n)(e^{-N_{pe}})}{n!}(2n\pi\sigma^2)^{1/2}e^{-(x-nC)^2/(2n\sigma^2)}
\]

In figure 4, the solid line denotes the PMT response function (3.1), together with the fitted parameters as shown in the figure. The first exponential dash curve is the background and the following dashed curves represent the partial charge distributions corresponding to \( n = 1, 2, 3, \ldots \) PEs emitted by the photocathode. It is found that the position of the single, double and triple-photon peaks is about
54, 108 and 162 at 1800V and the corresponding widths is about 16, $16\sqrt{2}$ and $16\sqrt{3}$, respectively. Similar results of R5912 can also be found in figure 5. Both figures indicate that the multi-PEs spectra of CR365 and R5912 can be well reproduced by this multi-gaussian function. It means that both PMTs have a good charge resolution for detecting multi PEs.

**Figure 4.** The response of CR365 versus number of photoelectrons shows a good charge resolution for detecting multi photoelectrons. The blue points show the experimental data. The red solid line denotes the PMT response function (3.1).

**Figure 5.** The multiple photoelectrons spectrum of R5912 also shows a good charge resolution for detecting multi photoelectrons. The blue points show the experimental data. The red solid line denotes the PMT response function (3.1).
3.3 Gain as a function of high voltage

One of the important features is the gain curve with respect to the supplied high voltage (HV). To get the gain as a function of HV, the laser light intensity has been fixed while the PMT HV has been varied. The relationship between gain ($G$) and input high voltage ($V$) is described by

$$G = \alpha V^\beta$$

(3.2)

with $\alpha$ and $\beta$ to be determined from measurements. The fit parameters are $\beta = 8.96 \pm 0.10$ for R5912, $\beta = 8.27 \pm 0.06$ for CR365, respectively. The absolute gain for each PMT was measured at a known voltage from the SPE spectrum, and this can be used to convert the relative gain measurement into the absolute gain at different HV. Figure 6 shows the absolute gain for CR365 and R5912 which is about three times of that CR365 at 1800 V.

![Figure 6. The absolute gain for CR365 and R5912 as a function of high voltage. The gain of R5912 is about three times of that CR365 at 1800 V.](image)

3.4 Ion feedback and after-pulsing

For a new product of PMT, ion feedback and after-pulsing is a very important parameter, because it is directly related to the cleanliness of the vacuum in a PMT, which is the critical manufacturing problem of all PMTs. Afterpulses could cause a miscalculation of low level signals following a large amplitude pulse and degrade energy resolution. Here, afterpulse percentage is defined as:

$$AP(\%) = 100 \frac{Q_{\text{after}}}{Q_{\text{signal}}}$$

(3.3)

where $Q_{\text{signal}}$ is the charge deposited while the LED is flashing, $Q_{\text{after}}$ is the charge after the main pulse, integrating over 10 $\mu$s. We measured the afterpulse percentage of CR365 and R5912 at
$\sim 1.5 \times 10^7$ gain and the corresponding value is about 5.4\% and 4.2\%, respectively, as shown in figure 7 and figure 8. Both PMTs satisfy our requirements, especially, when our goal is to measure higher signals.

**Figure 7.** The afterpulse percentage of CR365 is about 5.4\% at $\sim 1.5 \times 10^7$ gain.

**Figure 8.** The afterpulse percentage of R5912 is about 4.2\% at $\sim 1.5 \times 10^7$ gain.
3.5 Dark count rate

The dark count rate is the rate at which signals above a certain threshold are observed in a PMT while no light incident on the photocathode. There is a correlation between the dark pulse rate and the lifetime of a PMT, as the smaller noise of a PMT, the longer its lifetime. To check the dark noise, the data of R5912 and CR365 have been compared. Of course, to know the magnitude of the 1/3 PE threshold for a PMT, the absolute gain of the PMT must be known. The anode dark rate after 2 hours in dark at a gain of $\sim 1.5 \times 10^7$ are both less than 3 kHz when the thresholds are set at 1/3 photoelectron.

3.6 Linearity of PMT

In order to extend the dynamic range of MD from 100 PEs to $10^6$ PEs, the linearity of the PMT output signals is essentially important. In this work, the linearity of each R5912 and CR365 is measured by using laser light source and filters as shown in figure 2. The light intensity is varied by use of different neutral density transmission filters and the corresponding response is fitted with a function $y = ax^b$ where $x$ is the relative transmission. Figure 9 shows the linear behavior for CR365 at 1500 V and R5912 at 1350 V as a function of input light corresponding to $\sim 1.5 \times 10^7$ gain. The points show the experimental data. The lines are fitting lines. The fitting slope of CR365 is $b = 1.05 \pm 0.01$ and the result of R5912 is $b = 1.03 \pm 0.01$. In this paper, the maximum linear current is defined as the peak current where the deviation from the ideal linear current reaches $\pm 5\%$. From this figure, we can find that a peak linear current of CR365 is approximately 100 mA and R5912 almost achieved about 130 mA. In order to compare the characteristics of the 8-inch PMTs obviously, we selected two PMTs with a relatively high gain in the above tests. However, if we want to measure the number of photoelectrons up to $10^6$, we will select proper PMTs with a lower gain in the following tests, as discussed in the next section.

![Figure 9](image-url)  
Figure 9. Anode peak current versus input light for the CR365-PMT at 1500 V and R5912-PMT at 1350 V corresponding to a $\sim 1.5 \times 10^7$ gain. The points show the experimental data. The lines are fitting lines where $b$ is $1.05 \pm 0.01$ for CR365 and $1.03 \pm 0.01$ for R5912, respectively.
3.7 Extend the dynamic range of MD

Monte Carlo simulations indicate that the highest energy showers may give rise to peak signals as large as $10^6$ PEs. The PMTs, therefore, must be linear up to such large signals. In order to extend the dynamic range of MD from 100 PEs to $10^6$ PEs, we are planning to add two 8-inch PMTs in each MD cell which are responsible for the range of 100 - 10000 PEs and 2000–1000000 PEs, respectively. First of all, we selected a CR365-A PMT with a $\sim 10^6$ gain at 1500 V to ensure the linearity in the dynamic range of 100–10000 PEs. Then, with the increase of amount of incident light, we use a 1% filter to reduce the the input light of CR365-B which also has a $\sim 10^6$ gain at 1500 V to realize a linear measurement of 2000–1000000 PEs. Figure 10 is the output signal of two CR365-PMTs versus input light which can meet our requirements. That is, the MD is expected to have the wide dynamic range in 6 orders of magnitude.

![Figure 10](image)

**Figure 10.** Measurement of dynamic range of CR365-A PMT and CR365-B PMT which are responsible for the range of 100–10000 PEs and 2000–1000000 PEs. The points show the experimental data. The solid lines are fitting lines.

4 Conclusion

In this paper, we compared the characteristic features between R5912-PMT and CR365-PMT. Our test experiments confirmed that there exists no serious difference between CR365-PMT and R5912-PMT, and CR365 is within the specifications given by Beijing Hamamatsu. We then tested the linearity of the PMT response by varying the light intensities and found that they satisfy our requirements with respect to the MD having the wide dynamic range in 6 orders of magnitude. In the near future, we will test the performance stability of this type of PMT.
Acknowledgments

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