PROCEEDINGS OF SCIENCE

Characteristics comparison of the 3-inch photomultipliers from Hamamatsu and NVN for the NEON Neutrino Telescope

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Neutrino Observatory in the Nanhai (NEON) is a proposed cubic-kilometre scale high-energy neutrino observatory located in the South China Sea. The observatory consists of tens of thousands of optical modules (OMs), where photomultiplier tubes (PMTs) are equipped, for capturing Cherenkov light produced by secondary particles of neutrino interactions with Earth. Each OM consists of over thirty 3-inch PMTs. In this work, we measure the characteristics of two types of PMTs, Hamamatsu R14374 and NVN N2031, including their dark count rates, gain, quantum efficiency, and peak-to-valley ratio. All measured parameters will be compared according to the requirements of our scientific goals.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

PoS(ICRC2023)1012

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1. Introduction

Neutrino Observatory in the Nanhai(NEON) is a proposed cubic-kilometre scale high-energy neutrino observatory in the South China Sea which will be constructed at a depth of 4km. The experiment aims at detecting high-energy astrophysical neutrinos.

The observatory will be placed in the ocean with a 3D array of optical modules (OMs) which contains multiple 3-inch photomultiplier tubes (PMTs). Each OM would be mounted on a vertical cable starting at a base on the seabed and would be stabilized at the top by a deep-sea buoy. Through our simulation, each PMT should identify one photon event. The performance of PMT greatly impacts the accuracy of the reconstruction and further affects the realization of scientific goals.

With the improvement of the detection performance, certain types of PMTs have been developed in neutrinos detectors. Among those, Hamamatsu R14374(used by KM3NET)[5] and NVN N2031 meet our preliminary requirements. To gain insight into the two different tubes, we measured several parameters of interest for the detection.

In this work, we measured the key parameters of two kinds of tubes(four for each kind): gain, dark count rates, quantum efficiency, and peak-to-valley ratio. Table(1) shows the result of the PMT parameters measured by us under the corresponding voltage with the scheme shown in Fig(1). Firstly, the hybrid method of fitting gain will be introduced, to improve the measurement of accuracy and the compliance with the theoretical gain-highvoltage relationship. Under a certain operating voltage, the quantum efficiency, dark performance including dark count rate and dark current, and peak-to-valley ratio are measured. In section3, all the parameters will be discussed according to the requirements of our scientific goals.

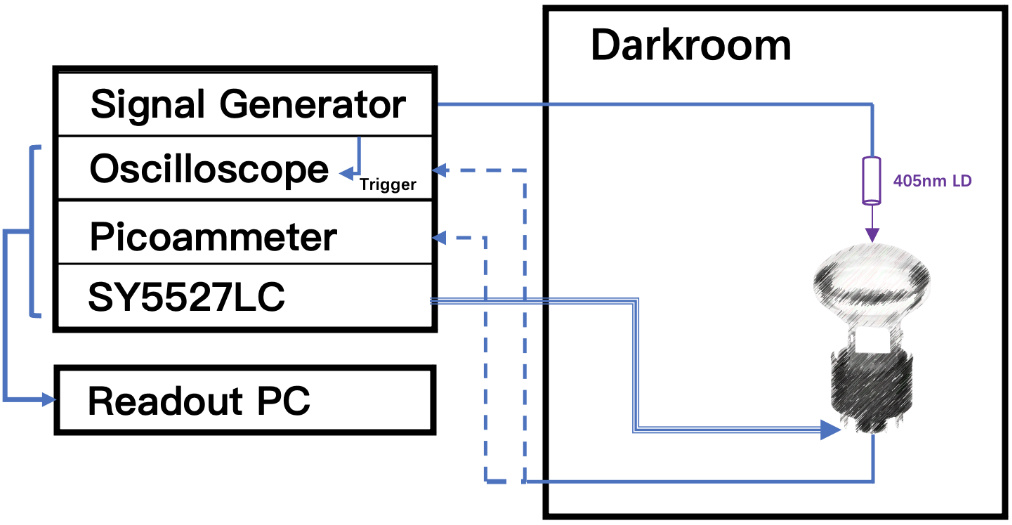

Figure 1: Test setup for the measurements.

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2. Measured Parameters

2.1 Gain-highvoltage relation

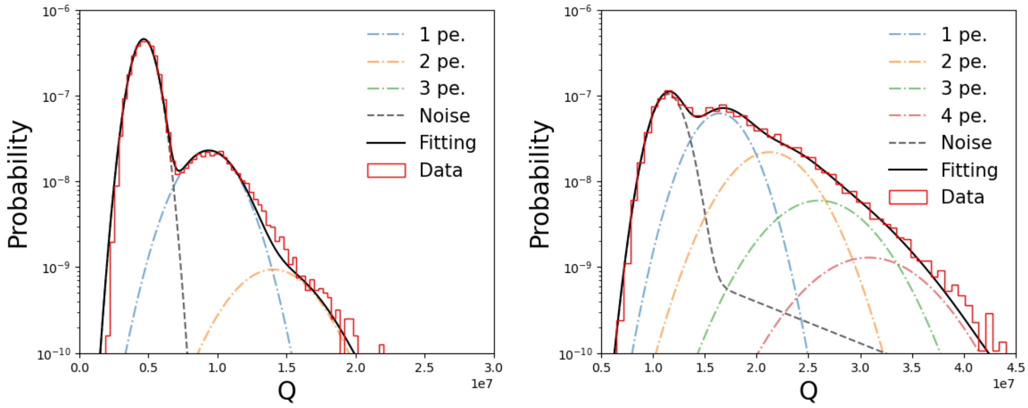
The gain is an important parameter to indicate the performance of PMTs, which describes the ratio of electrons in the anode to photoelectrons in the cathode. The gain of PMTs installed in NEON will be calibrated around 5×10^6 with different voltages. Lower working voltage helps improving safety and slow the rate of ageing.

The pulse light signal is adjusted to signal photoelectrons(spe) and applied to the PMT, which means the average photoelectron per pulse is 0.1[1], to simulate the weak light underwater. To study the nature of PMTs, the approximate model for fitting the charge distribution is[2]:

$$S(x) \approx (1-w) * Norm(Q_0, \sigma_0) + w\theta(x - Q_0) \times exp[-\alpha(x - Q_0)]e^{-\mu} \tag{1}$$

$$+ Poisson(\mu) \otimes Norm(Q_0 + Q_{sh} + nQ_1, \sigma_1\sqrt{n}) \tag{2}$$

Part(1) of the equation can describe the noise, and (2)is an ideal signal. These parameters will be fitted using Monte Carlo Markov Chain (MCMC) in `emcee`[4]and locally optimized using `iminuit` based on the estimated values given by the MCMC method, which is called the hybrid method. Among those parameters, $Q_1 = Gain$ according to the feature of PMTs.



(a) Hybrid fitting for $\mu \approx 0.1$(spe).

(b) Hybrid fitting for $\mu \approx 1$

Figure 2: The charge distribution of NVN N2031 with the average photon number is 0.1 and 1 per pulse. Different colours of dotted lines represent Gaussian charge distributions formed by different numbers of photons.

The typical distribution of NVN N2303 and its fitting is shown in Fig(2). Although the model was once simplified and used for large $\mu \geq 2$[2], the background of the thermionic emission part (w) is quite small. So we fit for low μ conditions such as spe and $\mu \approx 1$, it shows a good fit to the data and maintains the consistency of gain in multi-photon cases.

The hybrid method helps us to improve the accuracy of gain measurement greatly from about 2% to about 0.5% compared to fitting by peak search and single Gaussian function as shown in Fig(3a). The hybrid method gives a good fit even at low gains and a low SNR but two Gaussian

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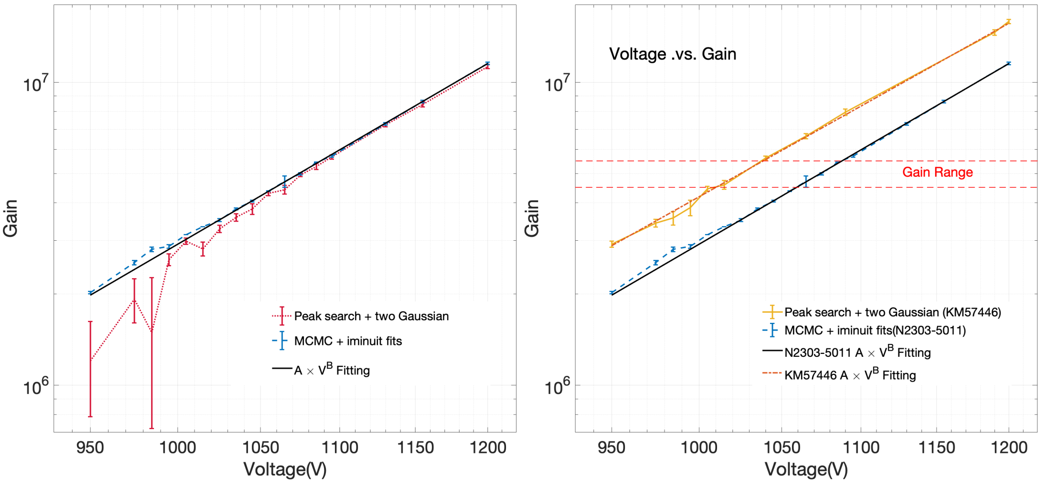

(a) Two different fitting method for gain of NVN **(b)** Fit by power-law function.

Figure 3: (3a) shows the relationship between high voltage and gain using different fitting methods of NVN N2303-5011. The red dotted line represents simple peak finding and Gaussian fitting method with a 95% confidence interval error bar. The blue dashed line represents the global optimal solution found using MCMC and iminuit local optimization, with the error bar representing the standard error of parameter fitting. (3b) shows the high voltage-gain relationship of KM57446 and N2303-5011 after fitting with a power-law function. Peak search and two Gaussian fits are used for Hamamatsu while NVN is by MCMC+iminuit. The Red dashed line band is the gain we select([4.5e6,5.5e6]).

fitting fails. Therefore, the result of the hybrid method will be used for evaluating and improving the result of simple Gaussian fitting.

In addition, since the multiplication factor of dynodes changes with the inter-stage voltage in a power-law manner[3], the gain also increases overall in a power-law manner as the PMT applied voltage increases. Fig(3b) shows the gain-highvoltage relation fitted by the function $Gain = A \cdot V^{\delta}$, which gives a feature of Hamamatsu R14374 KM57446 and NVN N2303-5011. The result of the hybrid model can fit the gain-highvoltage equation well. The deviation near 990V can be considered as when Q_1 is small and the noise ratio increases with the decrease of voltage, the approximate deviation of the model from the accurate value. In the fitting of Hamamatsu R14374, we skip the hybrid method fitting due to the small error bars.

2.2 Quantum efficiency

Quantum efficiency(QE) can describe the light sensitivity limit of the photomultiplier tube in an ideal state, which is the probability of generating photoelectrons after photons hit the surface of the photomultiplier tube. As an important parameter in simulation, quantum efficiency is needed to be relatively uniform and as high as possible.

When a stable light source with N photons per second is imposed on PMTs, the current is:

$$I_A = \eta \times A \times Gain \times N \tag{3}$$

The collection efficiency of PMT can be assumed as 100% for a high voltage of photocathode-to-first dynode. Picoammeter KEITHLEY 6485 is used for current detection directly from the PMT

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signal in Fig(1). The light is 405nm laser diode. Because the light source is not calibrated, N2304-5507 is used as a standard light detection element and uses factory measurements as calibration values. For the PMTS we tested, the quantum detection efficiency is around 28%. The accuracy of QE is about 1% due to the noise from 2nd and following dynodes.

2.3 Dark performance

The dark current and dark count rate are important parameters for PMT under a completely dark state after enough preheating time. Dark current is a small amount of current flow of anode output and the first indicator of whether the pipe is preliminarily qualified. The dark count rate is the frequency of dark signals over a set trigger. The counting rate during operation is very important for array detection of the marine environment and the background count rate is confirmed.

The signal of the PMT is directed to a picoammeter to measure the dark current. The Oscilloscope of Pico 6000 series capture the waveform of PMT in the dark and send data to PC to calculate the dark count rate. Each PMT needs to be preheated for at least 5 hours, waiting for the dark count to decrease and stabilize. In the data analysis step, we set a trigger with about 0.3spe to eliminate the noise and retain over 90% of a single photoelectron signal.

The dark count rate is strongly affected by the ringing and preheating time. According to the trigger logic of the readout electronics, a certain rising speed is required to trigger the signal when it passes the trigger, which greatly reduces the influence of ringing. Besides, preheating time needs to be much longer for each PMT. In the following work, we plan to adjust the voltage-divider circuit to smooth the ringing and make the darkroom design more reasonable to get a more accurate calibration.

2.4 Peak-to-valley ratio

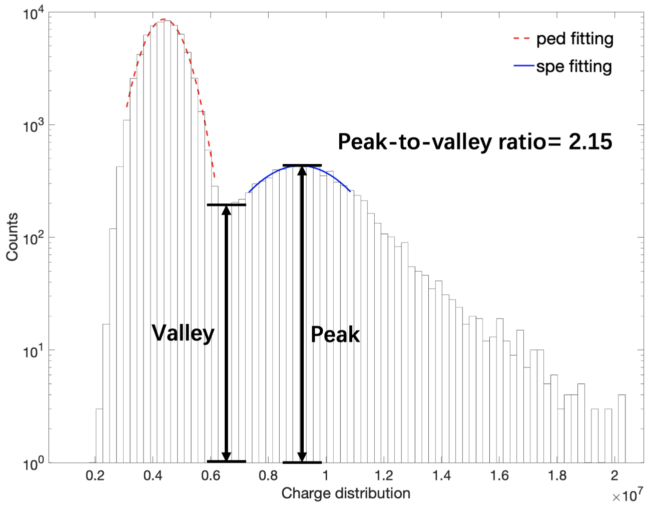

Figure 4: The definition of peak-to-valley ratio

The peak-to-valley ratio is the ratio of the count of the spe peak to the count of the valley between the pedestal and spe as Fig(4) shows. It describes the ability of PMT to resolve single

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photon signals. The larger the peak-to-valley ratio, the better the resolution of the corresponding single photon signal. The peak-to-valley ratio of every PMT is presented in table(1). Tubes with a peak-to-valley ratio greater than 2 will be selected and used for detection.

3. Discussion and Conclusion

Table 1: PMT parameters measured in room temperature.

Serial number	Voltage (V)	Gain	Peak-to-valley ratio	Dark current(nA)	Dark count rate(Hz)	405nm QE(%)
N2304-1128	985	5.50e6	2.62	0.56	459	29.7
N2303-1135	1058	5.35e6	2.15	1.32	1993	29.9
N2303-5507	1005	5.34e6	2.05	1.35	526	**28.5**
N2303-1365	990	4.85e6	2.26	0.35	360	27.8
KM57217	1000	5.01e6	2.14	0.6	437	29.0
KM61655	1025	5.05e6	2.98	0.87	633	29.8
KM57154	1000	4.88e6	2.25	1.23	1178	27.1
KM57446	1010	5.13e6	3.05	1.56	912	28.2

The article presents the results of testing various parameters of the photomultiplier tube (PMT) used for underwater neutrino detection in table(1). The PMT with the prefix "N" refers to NVN's N2031 model, while the PMT with the prefix "KM" corresponds to Hamamatsu's R4374 model. Higher QE, SNR and PMT production consistency are important for NEON. By adjusting the operating voltage using the hybrid fitting method, the PMT gain is around 5e6. Most of the tubes we measure can meet the requirements at a voltage of about 1000V. The smaller the operating voltage, the lower the requirements on the circuit, we hope that PMT can still maintain high-performance operation at a lower operating voltage.

The quantum detection efficiency of the two PMTs in 405nm is currently stable in the range of $27\% - 29\%$, and it is hoped that there will be higher quantum detection efficiency in the future to increase the accuracy of reconstruction. We plan to test absolute QE for different wavelengths and get a more accurate calibration of QE measurement.

The dark count rate is related to the height of the trigger set and the voltage divider circuit. In this study, the dark count rate is not completely corresponding to the dark current due to ringing that causes the trigger count to rise. The dark performance of both is acceptable as the dark count rate is significantly lower than sea noise (K40 and others). Noise from the dark count rate can be eliminated through proper calibration. In our plan, the preheating time need to be longer and the voltage-divider circuit will be improved to smooth ringing and lower trigger rate even further.

The peak-to-valley ratios of all the PMTs are greater than 2, and one of them has a ratio greater than 3. A higher peak-to-valley ratio has a higher signal-to-noise ratio for PMT. PMTs from Hamamatsu generally have higher values in P/V parameters, indicating better performance to resolve single photons. In the future, PMTs with high peak-to-valley ratios will be chosen to ensure good signal quality and noise discrimination in the sea.

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In preliminary experiments, the nonlinearity within 1000 p.e. of both is no more than 5%. A large number of PMT measurements and production consistency test will be carried out. The hardware needs to serve scientific objectives, and its measurements will be integrated into future simulations and reconstructions. This integration will assist in refining our requirements for the hardware parameters.

4. Acknowledgements

This work is supported by the National Natural Science Foundation of China (NSFC) grants 12005313, 12205388, 12261141691 and 42150105.

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