Study of EMI 8” PMTs for Reactor Neutrino Experiment *

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Abstract This article is about the study of two kinds of EMI 8” PMTs, D642KB and 9350KA. Several characteristics including relative quantum efficiency(QE), linearity, gain, dark current, afterpulse ratio and incident angle effect have been tested. Specially, dedicated systems have been set up for the measurements of relative quantum efficiency and incident angle effect. The performances of the two kinds of EMI PMTs are described here.

Key words reactor neutrino experiment, PMT, quantum efficiency, linearity, gain and dark current, afterpulse ratio, incident angle effect

1 Introduction

Many neutrino experiments in the last decade have proved that neutrino is massive. It is very intriguing and is a great challenge to the Standard Model. Among the six parameters in neutrino oscillation, θ_{12}, Δm^2_{21}[1], θ_{23} and $|\Delta m^2_{32}|$[2] have been determined, while the other parameters, θ_{13}, the sign of Δm^2_{32} and the phase angle of lepton CP-violation $\delta_{\rm CP}$, are still unknown. Because of the importance of θ_{13} which is a controlling factor in the lepton CP-violation measurement, people pay more attention to the measurement of θ_{13}. The CHOOZ experiment has given an upper limit on θ_{13}: $\sin^2 2\theta_{13} < 0.1$[3]. Recently, more and more experiments with higher precision are proposed to take off the veil of θ_{13} and continue the understanding of neutrino sector in the Standard Model and looking for new physics beyond it.

With available facilities, the best way of measuring θ_{13} is short baseline reactor experiment measuring the surviving probability of $\overline{\nu}_{\rm e} \rightarrow \overline{\nu}_{\rm e}$, which not only can use the vacuum oscillation formula, but also is independent of $\delta_{\rm CP}$ and θ_{23}. In reactor neutrino experiments, the scintillation photons generated by the $\overline{\nu}_{\rm e}$ via inverse β-decay in a large mass of liquid scintillator are detected by photomultipliers(PMTs) with large cathode housing. Daya Bay is one of the proposed reactor neutrino experiment in the world and large amounts of PMTs are needed consequently. In such an experiment, PMTs should be selected from candidate PMTs which show good and uniform characteristics during testing. Now there are two kinds of EMI 8” PMTs (D642KB and 9350KA) from Macro experiment at IHEP. We have done a series of detailed studies on several samples of these tubes in order to obtain some experiences for the PMTs mass test in the future.

In this work we design dedicated systems to measure the relevant characteristics of these PMTs and compare the respective results when using D642KB and 9350KA. The PMTs are conditioned in dark boxes to annihilate the effects of visible light.

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2 Method and measurement results

2.1 Relative quantum efficiency

We choose the method and system setup described in Ref. [4] to measure the relative quantum efficiency and make some reasonable modifications. This method is designed to measure the cathode currents of two PMTs simultaneously, one is to be measured and the other one is a reference PMT. In Fig. 1(a) we illustrate the system setup.

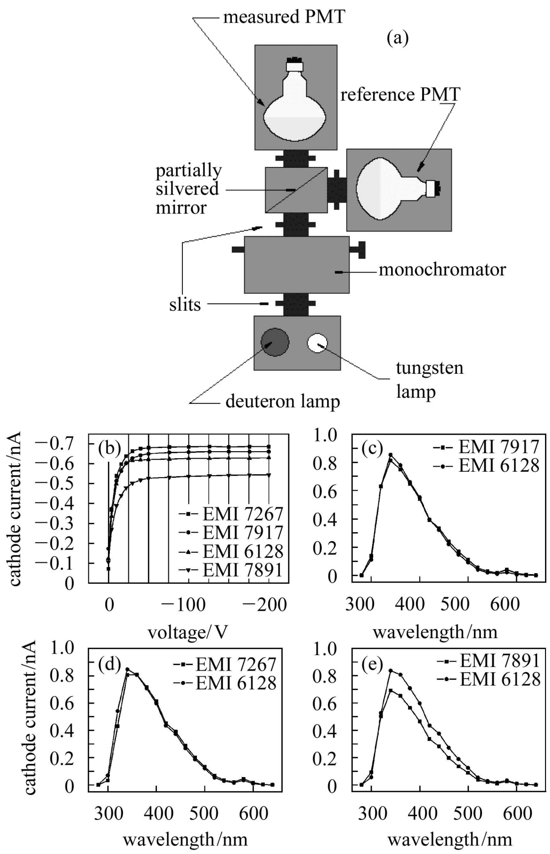

Fig. 1. (a) The relative quantum efficiency system setup; (b) Cathode current as the function of the operating voltage; (c) Cathode currents of PMT 9350KA-7917 and the reference PMT D642KB-6128; (d) Cathode currents of PMT D642KB-7267 and the references PMT D642KB-6128; (e) Cathode currents of PMT 9350KA-7891 and the reference PMT D642KB-6128. The cathode currents in (c), (d), (e) are absolute values.

The light from a deuterium lamp passes through a split and then enters a monochromator. The light with a certain wavelength which can be adjusted by the monochromator goes through another split and hits on a specifical silvered mirror and then the transmitting light and reflection light from the mirror enter two dark boxes respectively with the same intensity. The PMTs are placed at the center of the dark boxes, and the apertures of them are equal to make sure that there are the same number of photons hitting on the photocathodes of these two PMTs. When continuous light hits the photocathode electrons emit continuously, and then they are collected by the first dynode of PMTs. In order to measure the cathode currents of PMTs, we modify the negative high voltage bases of these PMTs by short-circuit all the other dynodes to the first dynode, and connect a Keithley 6485 picoammeter between the first dynode and the ground to measure the DC current.

Since the photon number hit on the two PMTs is equal, the ratio of the quantum efficiency to the cathode currents is constant for each PMT, and then we can acquire the following equation:

$$\frac{\mathrm{QE}_{\mathrm{measured}}}{\mathrm{QE}_{\mathrm{ref}}}=\frac{I_{\mathrm{measured}}}{I_{\mathrm{ref}}}\ , \tag{1}$$

where $\mathrm{QE}_{\mathrm{measured}}$ is the quantum efficiency of the PMT to be measured and $\mathrm{QE}_{\mathrm{ref}}$ is the quantum efficiency of the reference PMT. I_{measured} and I_{ref} are their cathode currents respectively. Once we obtain the $I_{\mathrm{measured}}/I_{\mathrm{ref}}$, we can know the relative quantum efficiency of the PMT to be measured.

Three samples of the two kinds of PMTs are picked out. Two of them are 9350KA and their serial numbers are 7891 and 7917. The last one is D642KB and its serial number is 7267. The reference PMT is a D642KB tube and serial number is 6128.

Firstly we choose an appropriate high voltage(HV) supplied to the first dynode. Generally speaking, for a constant incident light, the cathode current increases as the HV increases at first because of the increasing collection efficiency of the first dynode. However, once the collection efficiency of the first dynode reaches to a certain value along with the increasing HV, the cathode current reaches into a plateau. From Fig.1(b) we can find that the cathode current maintains constant when the HV goes up to around −50V. We choose −150V as the working voltage supplied to the PMTs.

When the light from the deuterium lamp hits on both of the two PMTs in dark boxes, their cathode currents are measured. After subtracting the dark currents from these measured cathode currents we can obtain the right cathode currents. The wavelength range of the incident light is from 280nm to 700nm in 20nm steps controlled by the monochromator. The results are presented in Fig. 1(c) — Fig. 1(e). These three figures show the cathode currents given at each wavelength. The cathode currents of 9350KA-7917 and D642KB-7267 are approximately equal to the reference PMT D642KB-6128 at various wavelength. Using Eq. (1) we can say that their quantum efficiency spectrums are also vary similar. However, the cathode currents of 9350KA-7891 are a little smaller than D642KB-6128, and its quantum efficiency is smaller than the other three PMTs at various wavelength.

2.2 Gain and dark current

The DC gain and the dark current curves of several PMTs are measured by the picoammeter mentioned above and the absolute gains of them are obtained through the single photon-electron spectrum. The classic method to obtain absolute gain by single photon-electron peak is described in detail in Ref. [5]. Here we explain the measurement of the DC gain and the dark current.

The system setup is shown in Fig. 2(a). It is simplified from the QE system setup. The deuterium lamp emits continuous light and the filters between light source and the PMT in dark box control the light intensity. The attenuation factor of the filters is 1/10000. No filters are used when we measure the cathode current of the PMT, while several filters must be used when measuring its anode current to protect the anode. After the cathode and anode current are measured, we can obtain the DC gain of this PMT at its working voltage:

$$\mathrm{Gain} \equiv \frac{I_{\mathrm{Anode}}}{I_{\mathrm{Cathode}}} \times 10000 \ , \qquad (2)$$

where I_{Anode} is the anode current of the PMT to be measured and I_{Cathode} is its corresponding cathode current. Both of the anode and cathode currents are subtracted by the dark current, which is measured when the shutters are closed. The DC gain and the dark current curves are obtained by varying the working voltage from 600V to 2200V in 200V steps.

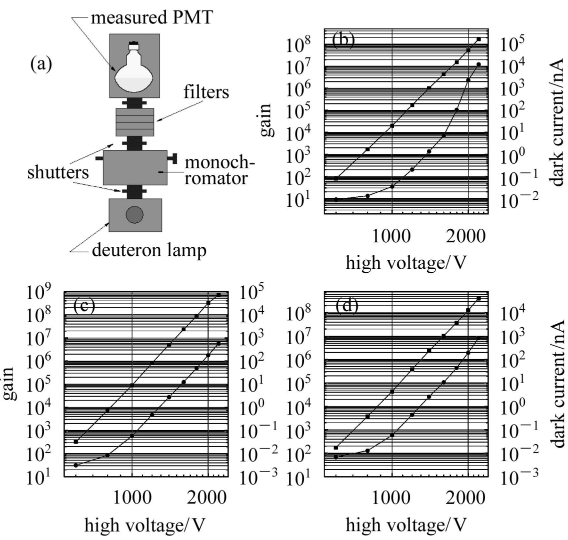

Fig. 2. (a) System setup for DC gain and dark current measurement; (b), (c), (d) gain and dark current for D642KB-7267, 9350KA-6521 and D642KB-7347. The round marker line is dark current and square marker line is gain. Dark currents are absolute values.

Results are shown in Fig. 2(b)—Fig. 2(d). For the samples of D642KB-7347 and 9350KA-6521, the gain curve and dark current curve are parallel when the working voltage is between 1000V and 2000V, and the dark current curve trends to be horizontal when voltage is lower than 1000V because the dark current is mainly composed by electronic noise . For D642KB-7267, the voltage range where the gain and dark current curves are parallel, from 1000V to 1600V, is smaller than that of D642KB-7347 and 9350KA-6521. This result means that the working range of D642KB-7267 is smaller than the others, since its signal-noise ratio becomes worse as soon as the working voltage is higher than 1600V.

2.3 Linearity

The definition of pulse linearity is the proportionality between the input light amount and the output current in pulse operation mode. When intense light pulses are to be measured, it's necessary to know the pulse linearity range of the PMT. For different kinds of signal measurements, it is necessary for us to know the dynamic range of tubes.

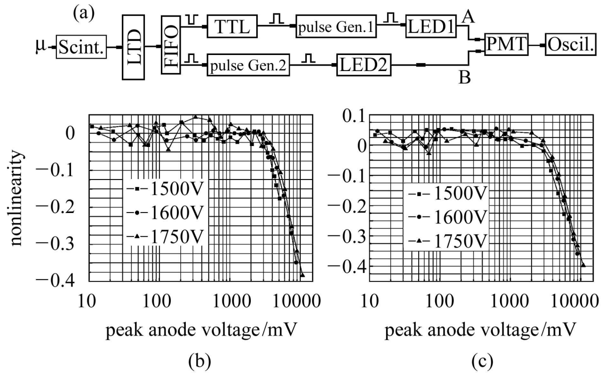

Fig. 3. (a) Linearity measurement system setup; (b), (c) Nonlinearity as function of peak anode pulse amplitude for D642KB-7267 and 9350KA-7917.

The system illustrated in Fig. 3(a) measures the nonlinearity of the PMTs as a function of the peak anode current and determines their linearity ranges consequently. Two pulse generators, external triggered by cosmic rays signals, are used to drive two blue LEDs in succession and then make the two LEDs emitting together. The brightness of each LED can be tuned to make the intensity of light pulse generated by the two LEDs different. As a result, the PMT can see a sequence of light pulses: a light pulse(A) from one LED, a brighter light pulse(B) from the other LED, and then an even brighter light pulse(C) from the two LEDs simultaneously. The current output from the PMT corresponding to the three different intensities of light pulses are recorded by the oscilloscope. If the PMT is really linear, we can obtain:

$$C = A + B \ , \tag{3}$$

The deviation from linearity is defined as:

$$\text{Nonlinearity} = \frac{C-(A+B)}{A+B} \tag{4}$$

The measurement results are demonstrated in Fig. 3(b), Fig. 3(c) and Table 1. The figures show that the deviation from linearity can be constrained in 5% when the anode peak voltage is less than 4000mV (the corresponding anode peak current is 4000mV/50Ω=80mA) at about $\sim 10^7$ gain. The anode peak voltage of single photoelectron is around 20mV, so that the dynamic range of photoelectron number is about 4000mV/20mV≃200. Some detailed calculation results from the data are given in Table 1 where the anode peak voltage has been converted to anode peak current.

Table 1. The PMTs current output as the nonlinearity is 5% at nearly the same gain.

type	D642KB		9350KA
serial number	6128	7267	7917
at gain	2.5×10^7 (1850V)	3.1×10^7 (1750V)	2.5×10^7 (1650V)
5% nonlinearity/mA	63.6	84	77

2.4 Afterpulse ratio (APR)

The ions ionized by the accelerated electrons in tubes will cause afterpulses after the main pulse. The delay between the afterpulse and main pulse can be up to a few microseconds, so the distribution in the time window of an event signal from the afterpulses will result in the overestimate of the signal and may cause a fake signal.

The after pulse ratio is defined as:

$$\text{APR} = \frac{Q_{\text{AP}}}{Q_{\text{main}}} \ , \tag{5}$$

where Q_{main} is the total charge in the main pulse, Q_{AP} is the total charge in the afterpulses[4]. Since the charge of one afterpulse is equal to that of one electron approximately, the APR can be rewritten as:

$$\text{APR} = \frac{eN_{\text{AP}}}{neN_{\text{main}}} = \frac{1}{n}\left(\frac{N_{\text{AP(noise)}}}{N_{\text{main}}} - \frac{N_{\text{noise}}}{N_{\text{main}}}\right) \ , \tag{6}$$

where $N_{\text{AP(noise)}}$ is the number of afterpulses including noise in a certain time window, N_{main} and N_{noise} are the numbers of main pulses and noise in the same time window, e is the charge of one electron, and n is the mean number of photoelectrons emitted from the photocathode, and $n = 1$ if the photocathode only emits one photoelectron or nothing each time. In our measurement, we use the Lecroy 2249W ADC to record the number of main pulses, afterpulses and noise, and the DUAL TIMER to control the time window which the afterpulses arrive at after the main pulse. The time window, namely the digitizing gate, is 500ns width in our measurement. There are totally 40 time windows with the digitizing time from 200ns to 20200ns after the main pulse. The total APR value of one PMT is the sum of APR in each time window. Fig. 4(a)—Fig. 4(c) are the distribution of APR as a function of the time window.

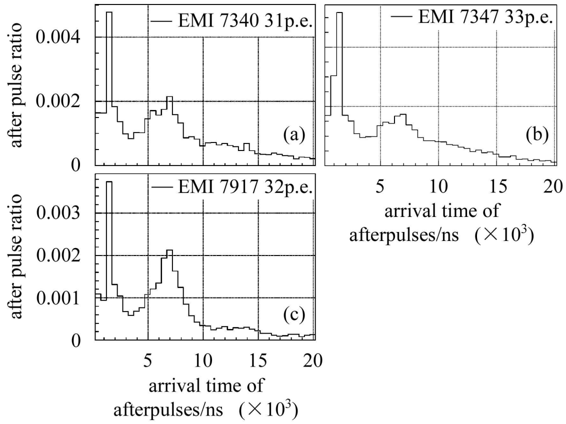

Fig. 4. (a), (b), (c) The APR distribution as a function of the arrival time of afterpulses relative to the main pulse for D642KB-7340, D642KB-7347 and 9350KA-7917.

It can be seen that the two types of EMI tubes have the same afterpulse arrival time distribution, and the distribution of all these three samples have two peaks. One peak is around 1.2μs, the other peak is around 6.7μs. The first peak could be caused by the Cs^+ ions. It's said that Cs^+ could present in all PMTs with bialkali photocathodes[4]. And maybe the helium contamination causes the second peak. The results, measured with three different PMTs, are listed in Table 2. We can find that all of APRs are less than 5% which is very small.

Table 2. The APR values of sample PMTs.

type	D642KB		9350KA
serial number	7340	7347	7917
APR	3.9%	3.9%	2.8%

2.5 Incident angle effect

Incident light is not always perpendicular to the photocathode surface. The PMT's output to perpendicularly incident light is different from that to slanting incident light. This difference could reduce the energy and position resolution in detector. The test of incident angle effect examines the performance of photocathodes when they are exposed to slanting incident light.

The system setup for the measurement is shown in Fig. 5. The goal of this system is to obtain the photocathode response to the incident light with different directions. First of all, the light with 470nm wavelength comes from a monochromator. Then this light is transmitted by a white fiber whose endpoint is placed at the focus point of the lens. The blue light from the fiber becomes a parallel light beam with a diameter of 20cm after passing through the lens and distributes uniformly on the whole photocathode surface of the PMT. The PMT fixed on the support structure can be rotated with different angles relative to the direction of the incident light from −90° to 90° in 15° steps. Since the light source is continuous, we use the same method described in the section of relative quantum efficiency to measure the cathode current.

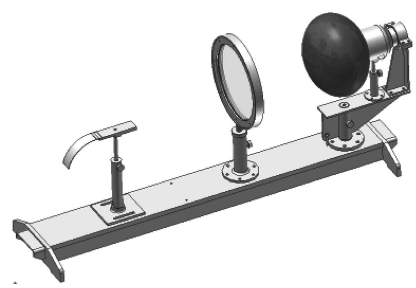

Fig. 5. System setup for incident angle effect measurement.

Additionally, there are two other tests for correction. One test rotated these tubes symmetrically around their central vertical axis. No significant differences were observed when their dynodes at the starting position were oriented horizontally, vertically or at 45°. The other test rotated the whole test system while keeping the configuration of the PMT, the lens and the light source constant to see if earth magnetic field may change the response of tubes. The results show that the effect of earth magnetic filed is far smaller than that of the incident angle in our experiment's condition.

Fig. 6(a)—Fig. 6(c) show the measurement results of angular dependence. The square markers are the cathode current values and the dashed line is the theoretical cosine function curve in these figures. These figures show an obvious and inevitable result that the bigger the incident angle becomes, the smaller the cathode current is. If there is no incident angle effect, the cathode current value should be consistent with the cosine curve because of the decrease of the photocathode projection. However, the cathode response of all the tubes shows that the cathode current value is lager than the cosine value of each incident angle.

This result indicates that the photocathode is more sensitive to slanting incident light compare with the simple plane geometry of cosine curve response.

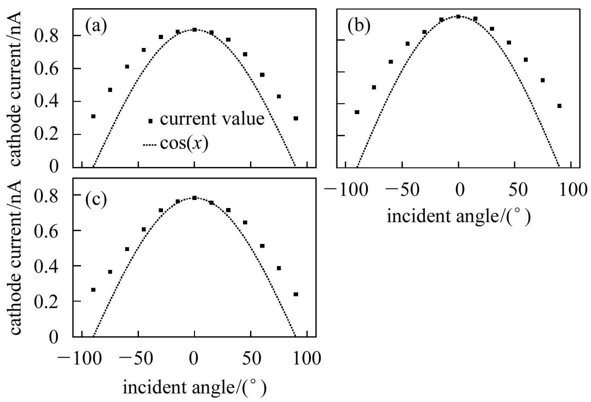

Fig. 6. (a), (b), (c) Cathode current response to the incident angle for D642KB-7267, D642KB-7347 and 9350KA-7917. Cathode currents are absolute values.

3 Summary and conclusion

In this work we studied some characteristics of two kinds of EMI tubes in order to understand the differences between these two kinds of PMTs and that among the tubes of one kind.

The measurement results from some sample tubes show that their performances are similar, especially the afterpulse distribution and the incident angle effect. The afterpulse ratio is small and the incident angle effect is obvious. The 5% linear range is about 200 photoelectrons at 10^7 gain and floats a little with different PMTs. The dynamic range where the gain and dark current curves are parallel differs from different tubes. Some of these tubes are unstable at high voltage above 1600V. The difference of maximum quantum efficiency between different PMTs also exists. However, the difference between the objects of the two kinds of the EMI tubes is no bigger than that between two objects in one kind. More important, the developed testing systems and methods supply abundant frames and experiences for the PMTs mass test of the future reactor neutrino experiment in China.

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反应堆中微子实验中的光电倍增管性能研究*

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摘要 介绍了对EMI公司两种8英寸光电倍增管D642KB和9350KA的研究情况; 测量了相对量子效率、线性、增益、暗电流、后脉冲和对入射光的角度响应等光电倍增管的几项主要性能, 其中相对量子效率和角度响应使用了特制的试验装置来达到测量目的; 描述了这两种光电倍增管的各单项性能.

关键词 反应堆中微子实验 光电倍增管 量子效率 线性 增益与暗电流 后脉冲 角度效应

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