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Aging behavior of large area MCP–PMT

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Abstract The Institute of High Energy Physics, Chinese Academy of Sciences have designed a new type of photomultiplier tube (PMT) based on microchannel plates (MCPs) with large area photocathode, known as large area microchannel plate photomultiplier tube (MCP–PMT). The aging characteristics of the large area MCP–PMTs are different from dynode PMTs and small proximity-focus MCP–PMT. In this work, a prototype large area MCP–PMT was aged by operating with nearly 1000 photoelectrons per pulse for 3 months, and aging process of the MCP–PMT was discussed based on the aging curve.

Keywords Aging · MCP–PMT · Large area PMT

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1 Introduction

The Daya Bay Reactor Neutrino Experiment (Daya Bay) reported that it had measured a non-vanishing value for the neutrino mixing angle θ_{13} with a significance of 5.2 standard deviations [1, 2]. The Jiangmen Underground Neutrino Observatory (JUNO), scheduled to start around 2020, is planned to study properties of the three generations of neutrinos and the relationship among them [3], with a higher precision than that of Daya Bay [4].

The JUNO project will use a 20″ traditional dynode photomultiplier tube (PMT) or a 20″ large area microchannel plate photomultiplier tube (MCP–PMT) [5, 6]. They will be operated continually under high voltage during the entire data-taking period in JUNO, hence the degradation in performance of the PMT, including its gain, quantum efficiency (QE), linearity, collective efficiency (CE) and energy resolution.

Most PMTs using MCP as multiplier are proximity-focus MCP–PMTs. Their aging can be divided into photocathode aging and MCP aging. The residue gas atoms and atoms absorbed on the MCP pores are ionized by the photoelectron accelerated in the microchannels, and ionized atoms are accelerated by the bias voltage to travel to the PMT photocathode. This, known as the ion feedback, will cause photocathode poisoning, i.e. activity loses of the photocathode when too much ionized atoms are accumulated [7].

As the PMT photocathode is close to the focusing anode, and the vacuum space is comparatively small, the life of the proximity-focus MCP–PMT is mainly determined by the degree of photocathode poisoning [8]. Studies on the aging of proximity-focus MCP–PMTs [8–10] show that photocathode poisoning can be eased by using ion blocking film, stacking in a ‘V’ shape for two MCPs [11], stacking in a ‘Z’ shape for three MCPs, using vacuum transfer equipment, modifying the PMT structure [10] and improving the photocathode material.

In this work, an aging experiment was performed on an 8″ large area MCP–PMT, which was designed recently at Institute of High Energy Physics, Chinese Academy of Sciences [6].

2 Experimental setup

The PMT aging is related to the cumulative output charges of the PMT anode [12], so the PMT aging is related to the number of input photons and the gain. The gain, in turn, is positively correlated with the aging rate. In our study, we fixed our initial gain for the large area MCP–PMT at 1.0×10^7 based on the expected gain at Daya Bay.

2.1 The 8″ large area MCP–PMT

The large area MCP–PMT is a new type of PMT designed for the JUNO experiment. Figure 1 shows structure of the MCP–PMT [6]. Two groups of MCP and an anode are stacked in the insulating trestle. Signals are channeled via the cable bracket. In order to satisfy the JUNO quantum efficiency requirements, the MCP–PMT photocathode is designed as a combination of a transmission and reflection photocathodes, so as to improve the efficiency of photon detection. Both 8″ and 20″ MCP–PMT prototypes were designed using the same type of MCPs. The 8″ prototype having the best single photoelectron spectrum (SPE) was used for the aging experiment.

2.2 Data acquisition system

As shown in Fig. 2, the 8″ MCP–PMT prototype was placed in a dark box, nearby a laser diode (LD) as a light source in wavelength of 410 nm. The LD was operated by

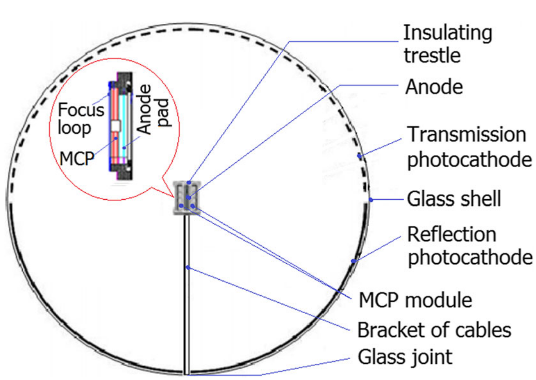


Fig. 1 Structure of MCP–PMT

a Tektronix AFG3102 pulse generator. Single-photon and multi-photon states can be obtained by modifying the generator parameters with an online LabVIEW software.

Two signals were generated by the generator. One was used to operate the LD. Another acted as a synchronized trigger to form the Nuclear Instrument Module (NIM) signal through the low threshold discriminator as a gate signal of the Costruzioni Apparecchiature Elettroniche Nucleari (CAEN) V965 (Charge-to-Digital Converter or QDC) of the Versa Module Europa (VME) crate. The MCP–PMT output signal was measured by the data acquisition system when the signal coincides with the synchronized trigger at specific time intervals.

In the experiment, parameters were tested daily. It was convenient to switch the light condition between a single photoelectron state and a nearly 1000 photoelectron per pulse. Firstly, the multi-photoelectron spectrum (MPE) was tested to analyze the whole aging process of the PMT under a strong light condition. The driver’s duty ratio was 0.002 %. Then, SPE spectrum was tested to calculate gain degradation of the PMT by modifying the driver’s duty ratio to 0.001 %. Finally, the dark noise spectrum (pedestal) of PMT was tested to calibrate stability of the electronic system by turning off the LD.

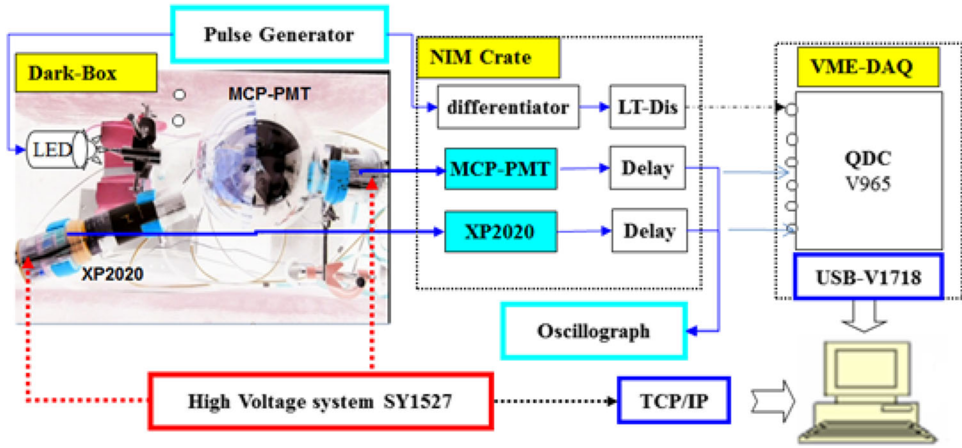
2.3 Stability of long time test system

During the aging period, any small changes of the internal or external environment, such as temperature, light intensity and low voltage of the LD, high voltage of the MCP–PMT, and electronics, would have been amplified by the MCP–PMT and would have caused large changes in the MPE spectrum. Thus, stability of the light source, MCP–PMT and electronic system were monitored during the whole experiment.

As shown in Fig. 2, a 2″ XP2020 PMT [13] was placed at the opposite side of the 8″ MCP–PMT. The XP2020 was run with a weak reflection light from the 8″ MCP–PMT and normal working voltage condition; hence, its aging was negligible. Any changes to the XP2020–MPE spectrum would then be due to the changes in the intensity of LD lighting. As shown in Fig. 3, the XP2020–MPE data varied within 15 %. The intensity of LD lighting changed little during the experiment.

One of the MCP modules in the MCP–PMT was deliberately exposed to the LD to study the aging process while the other MCP module acting as a monitoring MCP was prevented from any light exposure and was used to test the reflected light. By testing of the reflected light, the MCP was able to monitor internal changes of the MCP–PMT, including the internal vacuum and electric field distribution. In Fig. 3, the Monitor–MCP–MPE curve of this monitoring MCP module had a fluctuation to within 20 %. This fluctuation is neglected in this analysis.

Fig. 2 Electronic system of the experiment



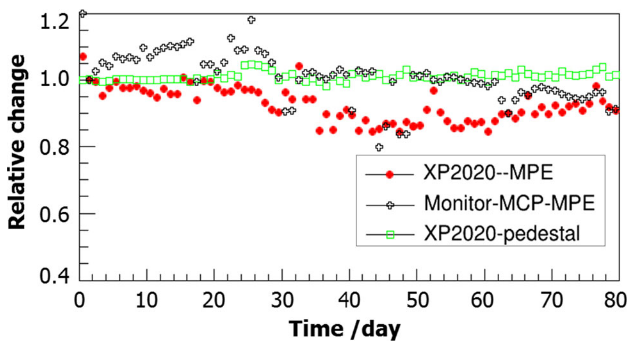


Fig. 3 Spectra of XP2020 MPE, monitor–MCP–MPE and XP2020 pedestal

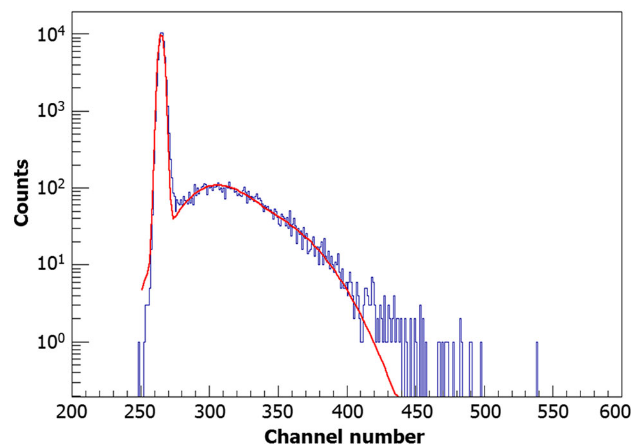


Fig. 4 Typical SPE spectrum of the 8 inch MCP–PMT prototype

The PMTs and data acquisition electronics were sensitive to temperature variation. Small changes in temperature would lead to large changes in the high-voltage power supply and PMT gain. The PMTs, high-voltage supply equipment and electronics were placed in a clean room maintained at 22 ± 1 °C. A CAEN SY1527 high-voltage power supply chassis and A1733 plug-in were used to monitor changes in high voltage and current. As shown in Fig. 3, a horizontal line was found to be a good fit to the dark noise spectrum of the PMT (XP2020-pedestal), indicating that the electronic system was stable.

3 Data analysis

3.1 Aging behavior of photocathode

SPE spectrum of the MCP–PMT is shown in Fig. 4. The gain can be obtained from the difference between the signal peak and pedestal peak [14].

The number of initial photoelectrons N_{pe} was calculated according to the SPE and MPE spectra on the first day of test. Then, the SPE and MPE spectra were collected daily, and the PMT gain ($Gain$), photoelectron loss (N_{pl}), measured number of photoelectrons (N_{px}) and MPE spectrum center address (P_x) were obtained. They can be correlated by Eqs. (1) and (2):

$$P_x = N_{px} Gain, \tag{1}$$

$$(N_{px} + N_{pl}) Gain = N_{pe} Gain. \tag{2}$$

Then, we have

$$P_x + N_{pl} Gain = N_{pe} Gain \tag{3}$$

and

$$N_{pl} = (N_{pe} Gain - P_x)/Gain. \tag{4}$$

Thus, we can get the relative photocathode quantum efficiency $F(x)$:

$$\begin{aligned} F(P_x) &= (N_{pe} - N_{pl})/N_{pe} \\ F(x) &= N_{pe} - (N_{pe} Gain - P_x)/(Gain N_{pe}). \end{aligned} \tag{5}$$

The relative quantum efficiency of the MCP–PMT photocathode as function of anode charge is shown in

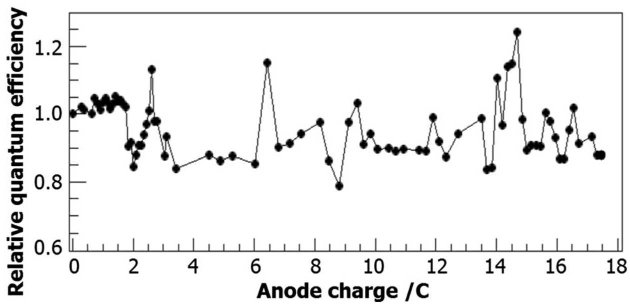


Fig. 5 Relative quantum efficiency of the photocathode as function of anode charge

Table 1 MCP resistances (MΩ)

Time	Group1		Group2	
	MCP1	MCP2	MCP1	MCP2
Start	145	175	120	150
End	145	172	120	145

Fig. 5. In early stage of the aging process of the photocathode, the aging rate was relatively high. When the cumulative output charges of the anode was about 4 C, the quantum efficiency changed by about 18 %. This rate of changes in quantum efficiency almost kept unchanged till 18 C of the cumulative output charges of the anode at the end of aging of the photocathode.

3.2 Body resistance variation of the MCPs

The resistance of MCP–PMT might change during aging process of the MCP. At the start and end of the experiment, the resistances of the MCPs are shown in Table 1. The absolute resistance of the MCPs changed little.

3.3 Aging behavior of the MCPs

The gain of MCP–PMT is associated with the semi-conducting inner surface of MCP, as shown in Fig. 6 [15]. The gain decreases when the surface is damaged by the bombardment of secondary electrons produced during the electron multiplication process in the MCP–PMT. The gain decrease as function of cumulative output charge of the anode is shown in Fig. 7, where the relative gain is the ratio of gain for a certain cumulative output charges of the anode to the gain when the cumulative output charges of the anode are zero. It can be seen that the changes in gain of MCP–PMT can roughly be divided into three stages: (1) 0–6 C, the gain changed slowly; (2) 6–14 C, faster changes in the gain, and (3) 14–17 C, the gain remained almost unchanged.

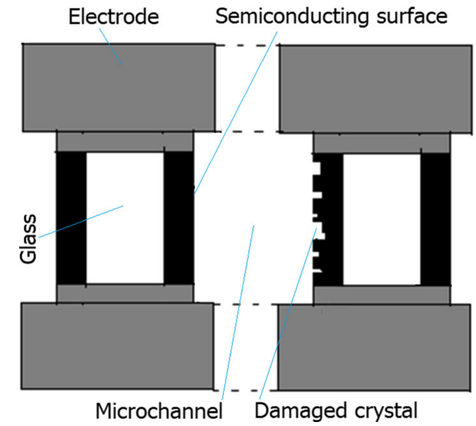


Fig. 6 Structure of the micro pore of MCP

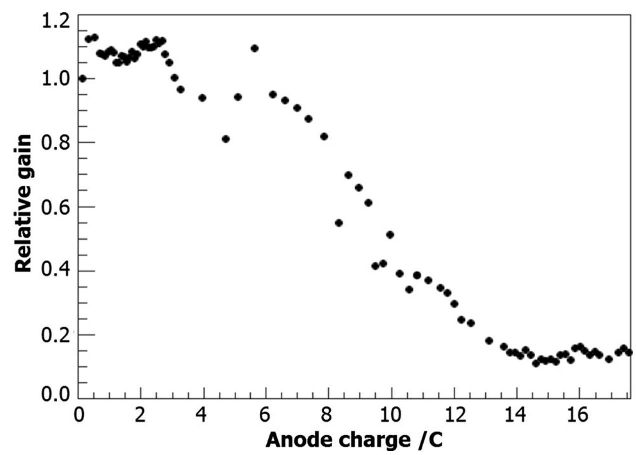


Fig. 7 Relative gain as function of cumulative output charge of the anode

3.4 Aging behavior of the MCP–PMT prototype

The aging of MCP–PMT is a combination of damage to the MCP and degradation of the photocathode. Figure 8 shows the relative PMT variation of the MPE spectrum as function of the cumulative output charges of the anode. The relative PMT variation was calculated by taking the ratio of PMT anode output charge per pulse at a certain cumulative output charges of the anode to the PMT anode output charge per pulse when the cumulative output charges of the anode are zero. It can be seen that the curve in Fig. 8 is similar in trend to the curve in Fig. 7, as the relative photocathode quantum efficiency did not vary much with the cumulative output charges of the anode.

4 Discussion and conclusion

From Fig. 7, the rate of gain change was large at second stage of the aging process. This may be due to the existence of previous damages on the MCP during the aging process.

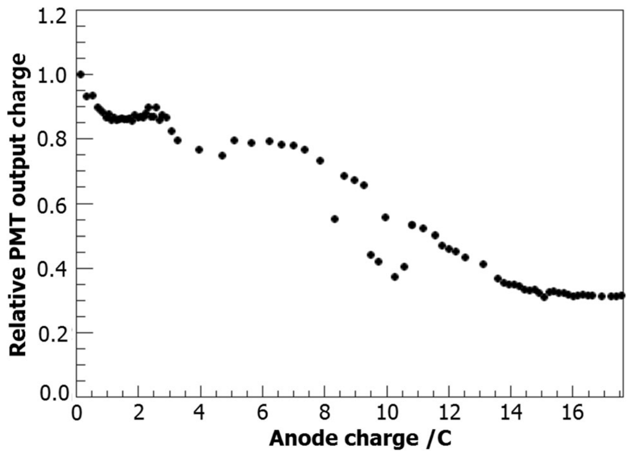


Fig. 8 MPE spectrum as function of cumulative output charge of the anode

The MCP seemed to show no change in the third stage of the aging process, suggesting that the damage to the MCP at this stage is so severe that no further damage unto it can affect its gain. The cause of MCP aging process will be investigated further.

The aging of large area MCP–PMT is a complex process. It is associated with the anode, MCP modules, photocathode and internal vacuum. The area of large area MCP–PMT is larger than that of the MCP module, hence the greatly reduced photocathode poisoning factor. The aging of the photocathode is no longer the main limit of the MCP–PMT. It is known that the main factor to determine the gain is the downstream MCP. In this study, the gain variation is strongly associated with the aging of large area MCP–PMT, i.e. the aging of large area MCP–PMT is mainly related to physical damage of MCPs.

If the JUNO experiment requires that the MCP–PMT shall be run for more than 10 years with an acceptable change of gain to within 50 %, the corresponding point on the aging curve in Fig. 6 would be at the cumulative output charge of the anode of about 10 C. Moreover, the anode signal is mainly composed of background radiation, cosmic rays and the dark noise itself. The JUNO neutrino group has simulated signals caused by radiation from the detector glass, water rock and cosmic rays to a total of about 3 kHz. With a detection efficiency of 20 %, the signal caused by the said sources is at an effective rate of 0.6 kHz. Consequently, the MCP–PMT intrinsic noise frequency can be calculated and should be less than 20 kHz at a gain of 1.0×10^7.

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