R&D on the extension of the MCP-PMT lifetime

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A Micro-Channel-Plate PMT (MCP-PMT) has an excellent time resolution, but the disadvantage is a short photocathode lifetime, which means a drop of the quantum efficiency. It is a major issue for application to detectors at high intensity experiments, such as the Belle II experiment.

We succeeded in improving the lifetime of the MCP-PMT by suppressing the residual gas and applying atomic layer deposition. To extend the lifetime further, understanding the mechanism of the photocathode deterioration is essential. Therefore we studied correlations of the amount of ions with the lifetime by analyzing the after-pulse. The results indicate that the cause of the photocathode deterioration could be hydrogen ions, heavy ions (mass number larger than 100), or neutral gas.

KEYWORDS: micro-channel-plate, after-pulse, quantum efficiency

1. Introduction

A square-shaped Micro-Channel-Plate PMT (MCP-PMT) was developed for the Belle II Time-Of-Propagation (TOP) counter [1–3]. The excellent time resolution of the MCP-PMT, about 30 ps, is essential for the TOP counter to be capable of good particle identification. The height and width are 27.6 mm and the thickness is 13.1 mm. Figure 1(a) is a photograph of the MCP-PMT. It has two 400-μm thick MCPs made of lead glass. The diameter of the micro channel is 10 μm and the bias angle is 13 degrees. The photocathode is NaKSbCs and the average quantum efficiency (QE) is 28.8% at 360 nm wavelength.

The photocathode is damaged by the neutral gases and feedback ions desorbed from the MCPs [4]. The lifetime of the MCP-PMT is defined by the accumulated output charge at which the QE drops to 80% of the beginning. The QE decreases as follows [5].

\[
\frac{QE(Q)}{QE(0)} = 1 - 0.2 \left( \frac{Q}{\tau} \right)^2 .
\]

Where \( Q \) is the accumulated output charge, \( \tau \) is the lifetime, \( QE(0) \) is the initial QE. A thin aluminum layer on the second MCP and a ceramic block were applied to prevent the residual gas from reaching the photocathode. The structure is shown in Fig. 1(b). The Al layer can reduce ions and neutral gas. The ceramic block fills the gaps between the MCPs and the outer tube to block neutral gas. The lifetime of this type of MCP-PMT, called conventional MCP-PMT, was measured for twelve samples, and the average was 1.1 C/cm² [6]. ALD coating [7] on the MCP surface improved the lifetime. The lifetime of eight samples was measured to be 10.5 C/cm² [5].

In this paper, further improvement of the lifetime is reported. To extend the lifetime much further than that, understanding the mechanism of the photocathode deterioration is essential. Therefore we studied correlations of the amount of ions with the lifetime by analyzing the after-pulse, which is discussed in the latter part of this paper.
2. Improvement of the lifetime

To improve the lifetime of the ALD MCP-PMT, some processes to reduce the residual gas were applied. Eight ALD MCP-PMT samples with those processes were produced to evaluate the effect on the lifetime. The measured lifetimes for those samples are shown below.

2.1 Setup of the lifetime measurement

Figures 2 and 3 show the setup of the lifetime measurement. An LED flashes at a repetition rate of 100 kHz to degrade the photocathode. Several photons per flash are detected by the MCP-PMT. The output charge from the MCP-PMT is measured by a CAMAC ADC during the LED run. A single photon laser with 400 nm wavelength is used to monitor the variation of the QE by measuring the relative hit rate. The hit rate is measured by a CAMAC TDC. A reference PMT is used to check the intensity of the laser. The absolute QE spectrum is measured between the lifetime tests in another test bench by using light from a xenon lamp [6].

![Fig. 1. Photograph (a) and part of the cross section (b) of the MCP-PMT.](image1)

![Fig. 2. Block diagram of the lifetime measurement setup.](image2)

2.2 Result of the lifetime measurement

Figure 4 shows the result of the lifetime measurement. The lifetime was deduced fitting Eq. 1. The relative QE at 400 nm did not drop significantly for some samples. For those samples, the lower bound of the lifetime was estimated from the QE drop at a longer wavelength, which was more significant than the one at 400 nm. All samples have a longer lifetime than 13.6 C/cm². Therefore, it was confirmed that the lifetime is improved by the additional processes. These types are called life-extended ALD MCP-PMTs.
Fig. 3. Photograph of the inside of the dark box.

Fig. 4. Result of the lifetime measurement. The dots with an error bar represent the relative QE measured by the hit rate of the MCP-PMT. The round points show the result of the absolute QE measurement. The vertical black dashed line shows the accumulated charge estimation at 50 ab$^{-1}$ of the Belle II integrated luminosity at 5.0 $\times$ 10$^{5}$ gain of the MCP-PMT.

2.3 MCP-PMT without the Al layer

We made two life-extended ALD MCP-PMTs without the Al layer on the second MCP to investigate the residual gas from the second MCP. Figure 5 shows the result of the lifetime measurement of two samples. The lifetime was 3.3 C/cm$^2$ and 3.8 C/cm$^2$. They have a shorter lifetime than the ALD types with the Al layer. It indicates the residual gas from the second MCP is still a dominant factor of the QE drops.

3. After-pulse measurement

3.1 After-pulse and feedback ion

The lifetime of the MCP-PMT is yet shorter than usual PMTs. To utilize the MCP-PMT in other high intensity experiments, further study for extension of the lifetime is necessary. To understand the mechanism of the QE drop, we measured the effect of the feedback ions. The ion species are identified by analyzing the after-pulse distribution. The multiplied electrons ionize the residual gas, which are fed back to the photocathode along the electric field. When they reach and react with the photocathode, some electrons are emitted. They are the source of the after-pulse. The delay time with respect to the photon signal is related to the flight time of the ion. It can be written as a function of the mass of the ion ($m_{ion}$) and the applied voltage ($V$): $t \propto \sqrt{m_{ion}/V}$. Therefore, the feedback ion species
can be identified from the delay time.

3.2 Setup of the after-pulse measurement

Figure 6 shows the setup for the measurement of the after-pulse. The laser radiates single photons to the MCP-PMT. The MCP-PMT signal is divided into two. One is fed to a CAMAC TDC1 to measure the first pulse timing. The other is fed to another CAMAC TDC2, which detected the after-pulse only as the first pulse is vetoed. The delay time of the after-pulse is measured as a timing difference between TDC1 and TDC2. Seven conventional MCP-PMTs, four normal ALD MCP-PMTs, five life-extended ALD MCP-PMTs, and two life-extended ALD MCP-PMTs without the Al layer were measured in this setup.

3.3 Result

Figure 7 shows the delay time of the after-pulse with respect to the one of the laser photon signal. The first peak at around 8 ns corresponds to the after-pulse by H+ and ringing noise, which can not be separated from the after-pulse. The second peak at around 15 ns is He+ and the third peak at around 35 ns is H2O+. The forth peak corresponds to heavy ions which mass number is larger than 100. Any type of the MCP-PMT has H+ and He+ contribution. It was found that the ALD types contain many water ions. It could be due to the ALD process, where water is usually used as the precursor. The heavy ions are only observed in the samples without the Al layer. Therefore, the Al layer effectively stops the heavy ions as well as neutral gas, but cannot stop the lighter ions as much. The correlation
between the rate of each after-pulse component and the lifetime of the MCP-PMT is shown in Fig. 8.

![Graph showing the relationship between the rate of each after-pulse component and the lifetime of the MCP-PMT.](image)

**Fig. 7.** Delay time distribution of the after-pulse. One of the samples of each type is shown.

![Graph showing after-pulse rate for hydrogen, helium, and water ions as a function of measured lifetime.](image)

**Fig. 8.** After-pulse rate for hydrogen (a), helium (b), and water (c) ions as a function of the measured lifetime.

The after-pulse rate for H\(^+\) is counted from the entries in 0–12 ns. It seems no correlations between the H\(^+\) rate and the lifetime. Due to the contamination of the ringing noise, however, it is premature to make a conclusion. Therefore the after-pulse ratio for H\(^+\) is affected by the noise and an additional measurement with suppression the noise is necessary to make a conclusion.
The He\(^+\) rate from 12–20 ns has no clear correlations with the lifetime, either. It indicates that He\(^+\) does not affect the photocathode degradation. The rate for H\(_2\)O\(^+\) from 20–50 ns does not have a correlation with the lifetime because the ALD types are larger lifetime than the conventional types.

Since the lifetime was significantly reduced by removing the Al layer, the heavy ions or neutral gases, which the Al layer stop could be a cause of the photocathode deterioration.

### 4. Conclusion

We succeeded in improving the lifetime of the MCP-PMT by suppressing the residual gas. The life-extended ALD MCP-PMTs are expected to survive in Belle II, but its lifetime is still shorter than usual PMTs. To understand the reason of the short lifetime, we studied the correlation of the residual gases with the lifetime. The results indicate that the QE drops could be caused by hydrogen ions, heavy ions, or neutral gases.

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