A method to measure transit time spread of photomultiplier tubes with Cherenkov light

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Abstract With the technology of coincidence method, transit time spreads (TTSs) of PMTs are measured with Cherenkov light on the photocathode window of photomultiplier tube (PMT) produced by cascade γ radiation source, ^{60}Co. TTSs with single and multi-photoelectron which are analyzed by convolution of Poisson and Gaussian are obtained. The study to XP2020 and XP2020Q PMTs shows that TTSs are consistent with data supplied by Philips. TTSs are inversely proportional to the square roots of number of photoelectrons. The method is feasible when single and multi-photoelectron can be distinguished.

Key words Transit time spread (TTS), Cherenkov light, Photomultiplier tube (PMT), Single photoelectron (SPE), Cascade γ radiation source

1 Introduction

A photomultiplier tube consists of a photocathode and a series of dynodes in an evacuated glass enclosure. Photons that strike the photoemission cathode induce electron emissions due to the photoelectric effect. The electrodes, which are maintained at a more positive potential, accelerate electrons towards the dynodes that generate additional electrons. The amplified signals are finally collected at the anode where it can be measured.

PMT has an exceptionally fast time response. The time response is determined primarily by the transit time required for the photoelectrons emitted from the photocathode to reach the anode, and by the transit time difference between each photoelectron as well. It depends on the dynode type and the supply voltage. The time response of PMTs can be characterized by transit time spread (TTS), i.e. spread of the electron transit time, an important property of PMT. For measurement of precise time, TTS will be a key parameter to select PMTs[1]. Normally TTS is evaluated by measuring the electron transit time for "single photoelectron events" under the condition that the entire surface area of the photocathode is uniformly irradiated by laser photons. The method is usually employed to obtain the catalog values of TTS by major suppliers of PMTs. However, an expensive picosecond laser has to be used. In the paper, TTS will be measured by Cherenkov radiation.

Cherenkov radiation was discovered by Cherenkov P, *et al* in 1934[2]. It is produced by charged particles passing through an optically transparent medium at speeds greater than the speed of light in that medium. The radiation is confined to the surface of the Cherenkov cone angle θ_c, relative to the particle direction. For a particle in velocity βc in a medium with refraction index of n, it is

$$\cos\theta_c = 1/n\beta \tag{1}$$

The number of photons produced per unit path length of a particle with charge Ze and per unit energy interval of the photons (eV·cm^{-1}) is

$$\frac{d^2N}{dEdx} = \frac{2\pi\alpha^2Z^2}{hc}\sin^2\theta_C \approx 370Z^2\sin^2\theta_C \tag{2}$$

or, equivalently

$$\frac{d^2N}{dEdx} = \frac{2\pi\alpha Z^2}{\lambda^2}[1-\frac{1}{\beta^2n^2(\lambda)}] \tag{3}$$

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Received date: 2009-05-31

The time width of Cherenkov light is less than the time of the particle passing through the medium. A particle in velocity of 10^8 m/s takes less than 20 ps to passes through a medium of 2 mm thickness. Using the properties of Cherenkov light, many new detectors have been manufactured[3–6]. However, in some cases, Cherenkov light has adverse influences on experiments[7].

In this work, we used Cherenkov light to measure TTS of PMTs for γ-ray detection. A γ-ray hitting the window of a PMT interacts with the matter of the window and produce electrons. If the electron energy is high enough, it will emit Cherenkov photons in the window. The photons will induce electron emission in the photoemission cathode. Amplified by the dynodes, the electrons are collected by anode, which gives a signal output. If the time interval between the γ-ray interacting with the window and signal output can be measured, TTS is obtained.

A cascade radiation source, such as ^{60}Co that emits 1.332 MeV and 1.173 MeV γ-rays, is the best candidate to perform the experiment. Since the time difference between the cascade gamma rays is less than 1 ps[7], the two gamma rays can be regarded to emit simultaneously. Therefore, one gamma can supply the start signal of the time interval. The other that induces output signal gives the stop signal of the time interval. This will be discussed in Section 2. Compared with the picosecond laser method, this is an obviously inexpensive method.

The number of photoelectrons produced by a gamma photon interacting with the window of a PMT could be simulated with GEANT, as shown in Table 1.

Table 1 Simulated photoelectron numbers produced by Cherenkov light in PMTs under ^{60}Co γ-rays

PMT	Single photoelectron / %	Two photoelectrons / %	Three photoelectrons / %
XP2020	49.9±1.3	30.0±1.0	20.2±0.8
XP2020Q	45.4±1.3	31.9±1.1	22.6±0.9

2 Experimental

Fig.1 shows the experimental setup with the two PMTs and the ^{60}Co source. The cascade γ-rays interact with a plastic scintillator, coupled with PMT1, and the window of PMT2. The signal output of PMT1, caused by photons generated by one gamma ray in the plastic scintillator, was split into two via a leading edge discriminator, CFD (constant fraction discriminator). One was a start signal of TDC, while the other was a gate signal of ADC. The signal output of PMT2, caused by Cherenkov light, was fanned out into two. One via CFD was a stop signal of the TDC, and the other was an input signal of the ADC. The gate signal of ADC is from PMT1 output signal, and the input signal of ADC is from the PMT2 output signal. It requires that the cascade γ-rays produce output signals at PMT1 and PMT2, respectively. TDC has the similar process. The outputs of ADC and TDC transmit into a computer via CAMAC controller. In order to avoid time walk, H6533 was selected as PMT1. XP2020 and XP2020Q were selected as PMT2 for TTSs measurement. The divider circuit of PMT2 is shown in Fig.2. Fig.3 shows the amplitude distribution of thermionic emission of XP2020 at –2500 V. It is a self-gated spectrum of the PMT under test.

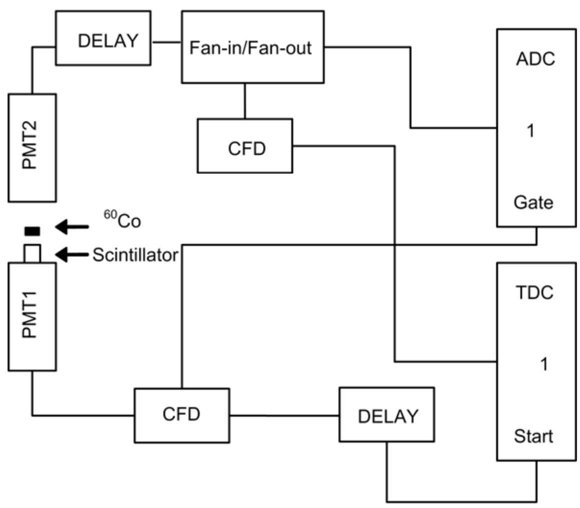

Fig.1 Block diagram of experimental setup.

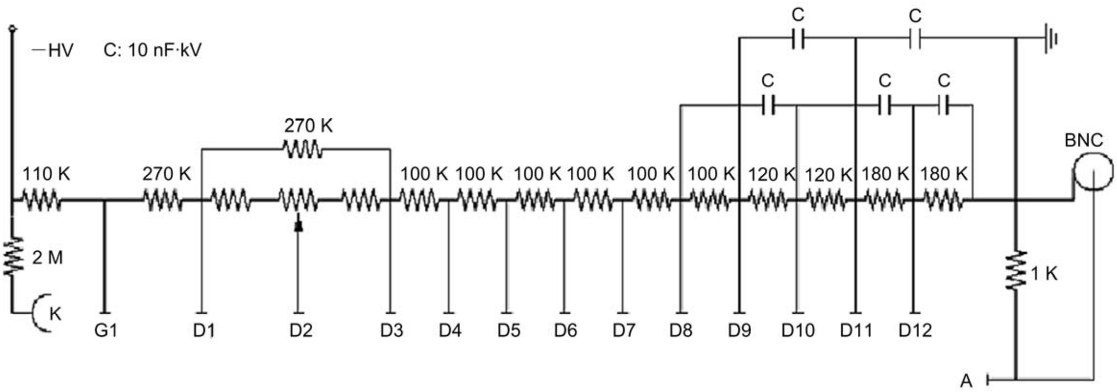

Fig.2 Divider circuit of PMT2.

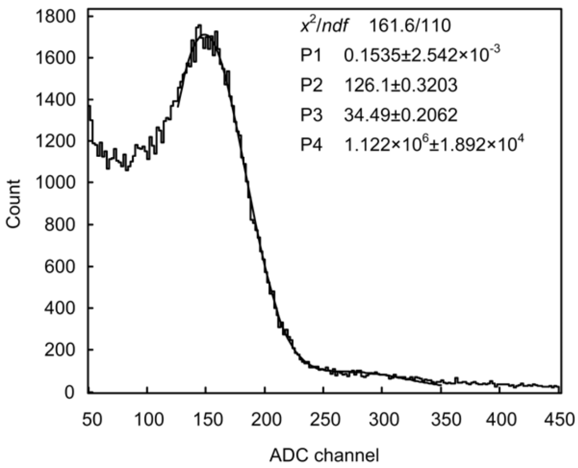

Fig.3 Self-gated spectra of the PMT under test. The solid line is the fit with Eq.(7).

3 Results and discussion

3.1 Measurement of time resolution of the start signals

The time walk of start signal affects the TTS measurement of PMT2, and it should be eliminated from TTS. Three PMTs, one XP2020 and two H6533, called H65331 and H65332, were coupled with scintillators. In the experimental setup in Fig.1, three PMTs were used as the PMT1 and PMT2 . Thus, three time resolutions could be obtained as Eqs.(4–6):

$$\sigma^2_{H65331} + \sigma^2_{H65332} = \sigma^2_{12} \quad (4)$$

$$\sigma^2_{H65331} + \sigma^2_{XP2020} = \sigma^2_{1XP} \quad (5)$$

$$\sigma^2_{H65332} + \sigma^2_{XP2020} = \sigma^2_{2XP} \quad (6)$$

where σ_{H65331} and σ_{H65332} are the standard deviations of the time walk of the H65331 and H65332, σ_{XP2020} is the standard deviation of the time walk of the XP2020, σ_{12} is the standard deviation of the time walk between the two H6533, σ_{1XP} is the standard deviation of the time walk between the H65331 and XP2020, and σ_{2XP} is the standard deviation of the time walk between the H65332 and XP2020. All the standard deviations of the time walks included the scintillators. The time resolution of electronics was about 20 ps (r.m.s). Solving the equations, σ_{H65331} is 76±9 ps. It is the standard deviation of the time walk of PMT1 used.

3.2 TTS measurement

With the experimental setup, the TTSs of XP2020 and XP2020Q were obtained. Fig.4 is the amplitude distribution of XP2020 under ^{60}Co γ-rays. The background distribution was obtained without ^{60}Co source. The structures of the two amplitude spectra and time spectra (Fig.5) are similar. It means that the background is contributed by cosmic rays. Compared with Fig.3, the amplitude spectra of Fig.4 is mainly from the contribution of the single photonelectron (SPE). However, there are obvious multi-photoelectron contributions which will affect the TTS measurement. In order to eliminate the effect, the distribution was fitted by the convolution of a Poisson and a Gaussian:

$$f(x) = \sum_{n=1}^{\infty} \frac{N_{pe}^n e^{-N_{pe}}}{n!} (2\pi n\sigma^2)^{-1/2} e^{-(x-nC)^2/(2n\sigma^2)} \quad (7)$$

where N_{pe} is the number of average photoelectrons, σ is the standard deviation of the distribution of SPE, and C is the peak position of SPE.

In the fitting to distributions, pedestals were subtracted. The fitted curve is shown in Fig.4 with a solid line. The other lines show the contributions of the numbers of different photoelectrons. The contribution of multi-photoelectron can be observed. To get the TTS, a cut to amplitude distribution was chosen as from Ch.140 to Ch. 200. The time spectrum is shown in Fig.5a. With the fit of Gaussian distribution function and the subtracting of time walk, the TTS was obtained. Figs.5b and c show the time spectra of double and triple photoelectrons with different cuts.

Table 2 lists the TTSs of different number of photoelectrons with two PMTs. There are two errors. The first is statistical error, and the second is the contributions of other photoelectrons. It can be seen that TTSs are almost the same with Philips data of 250 ps[8]. In the last column, the TTSs were obtained without any cut to channels. They are also similar to the Philips data. The reason is that the contribution of SPE is dominant from the amplitude spectrum. But they are not TTSs.

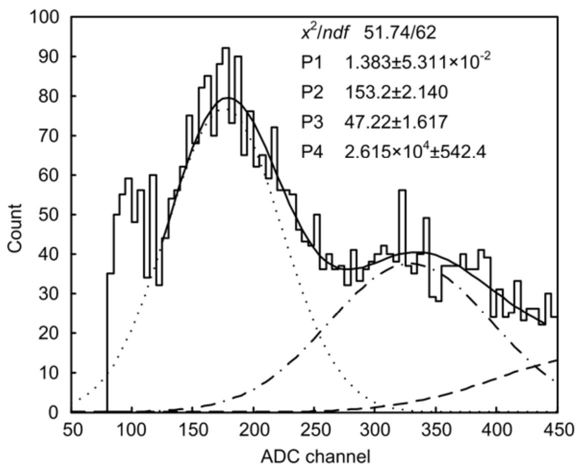

Fig.4 Amplitude spectra of Cherenkov light of XP2020 with ^{60}Co γ-rays.

The relations between number of photoelectrons and TTSs are shown in Fig.6. The fit lines reveal TTS is inversely proportional to the square root of number of photoelectrons. The same result can be found in Ref.[9]. With Eq.(7), the contributions of different photoelectrons can be obtained. They are listed in Table 3 which is similar with the simulation results shown in Table1.

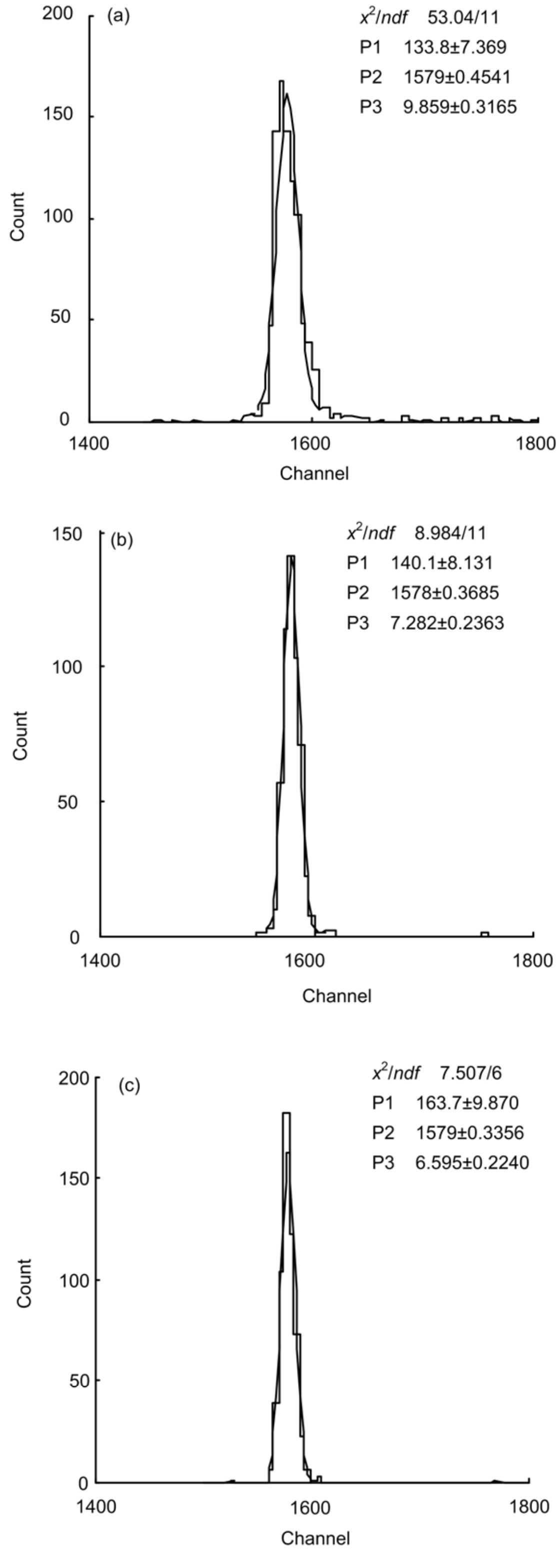

Fig.5 Time spectra of different numbers of photoelectrons of XP2020, P1=amplitude, P2=centroid and P3=width, (a) SPE with a cut from Ch.140 to Ch.200; (b) Double photoelectrons with a cut from Ch.300 to Ch.370; (c) Triple photoelectrons with a cut from Ch.460 to Ch.580.

Table 2 Transit time spreads (in ps) with different number of photoelectrons with different PMTs

PMT	Single photoelectron	Double photoelectrons	Triple photoelectrons	No cut to channel
XP2020	274±12±3	196±7±5	174±7±9	254±4±1
XP2020Q	258±11±3	194±9±5	163±16±9	230±6±1

Table 3 Ratios of three photoelectrons of Cherenkov light of PMTs in experiments with ^{60}Co source

PMT	γ source	Ratio of SPE / %	Ratio of two photoelectrons / %	Ratio of three photoelectrons / %
XP2020	^{60}Co	50.1±0.4	34.7±0.5	15.2±0.3
XP2020Q	^{60}Co	47.5±0.7	36.1±0.5	16.4±0.3

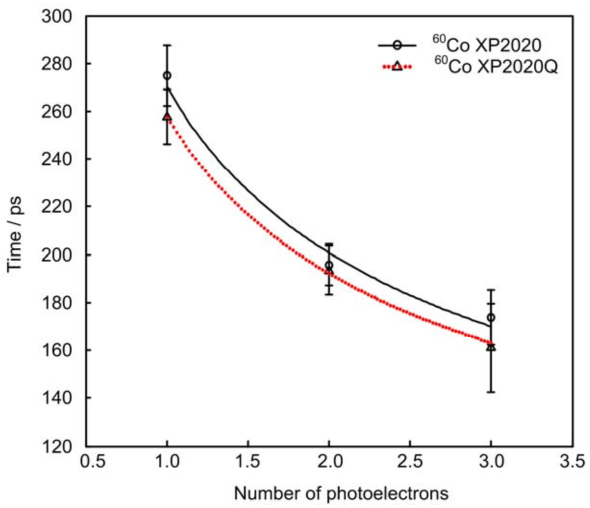

Fig.6 Relation between TTS and number of photoelectrons.

4 Conclusion

Using coincidence method, it is feasible to measure TTS of a PMT with Cherenkov light on the photocathode window of PMT produced by cascade γ radiation source, when the amplitude of single and multi-photoelectrons can be distinguished. The convolution of Poisson and Gaussian can fit the amplitude of Cherenkov radiation well. The TTSs of PMTs of XP2020 and XP2020Q are consistent with data supplied by Philips. And TTSs are inversely proportional to the square root of number of photoelectrons.

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