Study of 20-inch PMTs dark count generated large pulses

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ABSTRACT: The main goal of the JUNO experiment is to determine the neutrino mass ordering with a 20 kt liquid-scintillator detector. The 20-inch PMT is crucial as one of JUNO key instruments to realize an excellent energy resolution of at least 3\% at 1 MeV. The knowledge on PMT’s characterisation and feature is critical for detector performance understanding. Large pulses from PMT dark count such as from the flasher or others are one of the serious concerns for detector noise control. Focusing on the large pulses from 20-inch PMT dark count, this paper is trying to investigate the causes by measurements with a muon tagging system. It is found that the large pulses of 20-inch PMT dark count is contributed mainly from muons hitting the PMT glass, and we have a preliminary understanding of the results with a simulation based on Geant4.

KEYWORDS: Cherenkov and transition radiation; Photon detectors for UV, visible and IR photons (gas) (gas-photocathodes, solid-photocathodes)

ArXiv ePrint: 2206.07456

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1 Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) [1, 2] is under construction at Jiangmen, Guangdong, China. The experiment aims to study neutrino mass ordering with 3% energy resolution at 1 MeV, a precise determination of neutrino oscillation parameters, and other neutrino physics with 20 kton liquid scintillator viewed by up to 20,000 high quantum efficiency (QE) 20-inch PMTs. JUNO selected two kinds of 20-inch PMTs whose typical photon detection efficiency higher than 27% [3–5]: 5,000 of Hamamatsu Photonics K.K. (HPK, R12860) dynode PMT [6] and 15,000 of the newly developed MCP PMT from North Night Vision Technology Co., LTD (NNVT, GDB6201) [7], as shown in figure 1.

Photomultiplier tubes (PMT) are widely used in particle physics experiments for the light detection sensitive to single photon, such as Super-K [8, 9], KamLAND [10], SNO [11], Mini-BooNE [12], IceCube [13], Chooz [14], Daya Bay [15], and RENO [16]. PMT’s performance and its characterizations have been studied in detail with good understanding [5, 17–29]. Some large pulses of PMT made a lot of trouble to recent world-wide rare event neutrino experiments, and additional analysis strategy is introduced to suppress its effect, such as Double Chooz [30], Daya Bay [31],
IceCube [32] and RENO [33]. Additional studies are done on flasher and large pulses already as in [34, 35]. It is also valuable to mention that the flashers from PMT HV divider of JUNO is studied in [25]. As known, it will generate a large pulse by Cerenkov radiation when a muon is crossing through the PMT glass (Hamamatsu PMT R5912) as studied in [36, 37]. PMT large pulse still needs further study to identify either flasher or others to have a better rejection to noise, in particular for the 20-inch PMTs and the coming rare event detection projects, such as JUNO [1, 2], HyperK [38, 39].

In this article, we will show a detailed study on the large pulses of 20-inch PMT associated with muon tagged by a plastic scintillator coincidence system. Section 2 will provide a short description on the testing system and configurations. Section 3 will show the measurement results under different conditions. A dedicated simulation is done for better understanding and compared with the measurements as shown in section 4. Finally, a short summary is reached in section 5.

2 Experimental setup

For better pressure tolerance, the glass thickness of both types of JUNO selected PMTs is designed larger for most part of the glass bulb. The typical glass thickness\textsuperscript{1} is measured with few PMT samples as shown in figure 2, which is thicker than the widely used Hamamatsu R5912 1–3 mm [41]. Considering the huge dimension, high QE and larger thickness of the glass bulb of the JUNO selected 20-inch PMTs, it is expected to have a higher muon hitting rate at sea level and stronger Cerenkov light intensity for a muon passing through the glass.

2.1 Testing system

A muon coincidence system of two small plastic scintillators is used to identify the 20” PMT’s pulse correlated with muons from different directions as shown in figure 3. A muon will be tagged by the coincidence of the two plastic scintillators (PS1 and PS2, distance in height is around 80 cm) to select the muons going through the glass bulb of the 20-inch PMT. The dimension of the scintillators

\textsuperscript{1}The thickness of 20-inch NNVT PMT and HPK PMT glass at different positions is measured by an ultrasonic thickness gauge TT112 [40].
Figure 2. Glass thickness of the photocathode hemisphere of 20-inch PMTs. Left: measurement positions at different zenith angles; right: the measured glass thickness of HPK and NNVT PMTs.

is $22 \times 32.5 \times 5 \text{ cm}^3$ of PS1, and $16 \times 35 \times 1 \text{ cm}^3$ of PS2, respectively. The PMTs (XP2020 [42]), coupled to the scintillators by a light guide, have a very narrow width of their output pulses (FWHM $\sim 2.4 \text{ ns}$), which is much smaller than that of the 20-inch PMTs (FWHM $7 \sim 10 \text{ ns}$). The PS1 will be moved to several locations to select muons with different incident angles, and the 20-inch PMT can be placed with the glass bulb up (as shown in figure 3) or down to check the effect of the Cerenkov light direction. The waveforms of the three signal channels of the two scintillator modules and the 20-inch PMT will be acquired in the same time window following the coincidence trigger by a digitizer of CAEN DT5751 [43], which has 1 GSample/s, 1 Vpp dynamic range with 1 mV precision under 50 $\Omega$ impedance. The power of all the used PMTs is supplied by an SHR desktop HV module [44].

More detailed information on the signals' processing electronics is shown in figure 4, where a few electronics modules are used for signal splitting (Linear FIFO CAEN Mod. N625 [45]), $\times 10$ fast amplification (CAEN Mod. N979 [46]), low threshold discrimination (CAEN Mod. N845 [47]), logic counter (CAEN Mod. N1145 [48]), and logic coincidence (CAEN Mod. N455 [49]).

The coincidence window length used for trigger generation sets to 100 ns, and the window length of the waveform data-taking sets to 1 $\mu$s, where the primary signal is shifted to around 450-650 ns for both the scintillators and the 20-inch PMT. Furthermore, the system can set to several trigger configurations manually (trigger mode):

1. Triggered by only one of the three signal channels (PMTs) for the measurement of the dark count, mainly for the 20-inch PMT.

2. Triggered by a two-coincidence of PS1 and 20-inch PMT for muons and gammas that pass through the 20-inch PMT.

3. Triggered by a triple-coincidence of PS1, PS2, and 20-inch PMT for purer muons that pass through the 20-inch PMT.

With the record waveforms, a charge integration window of 20-inch PMT is selected relative to the peak location of the primary pulse in $[-15, 45]$ ns for the NNVT PMT and $[-15, 50]$ ns for the HPK PMT, while the window for baseline is shifted before the primary pulse by 100 ns and selected
in $[-115, -55]$ ns and $[-115, -50]$ ns respectively as shown in figure 5. The hit time, and pulse amplitude will be derived from the waveform too. The signal of plastic scintillators is processed similarly to the 20-inch PMT.

### 2.2 PMT settings

The 20-inch PMT works with an optimized HV divider of positive HV [50, 51]. The working point of the 20-inch PMT sets to around a gain of $10^7$ for both types of PMTs to simulate the future JUNO conditions. Following the traditional PMT gain calibration methods, such as a DC current-based method [52], a charge spectrum method with pulse light source [53, 54], and the gain determination algorithms [55, 56], a method (peak gain) based on the peak of single photoelectron (SPE) taken with the dark count is used to simplify the testing and analysis process. Derive from the measured SPE spectra of charge and amplitude of 20-inch PMTs as shown in figure 6, the SPE amplitude is around 7.0 mV for NNVT PMT with a gain of $1.2 \times 10^7$ and 6.0 mV for HPK PMT with a gain of $1.0 \times 10^7$. An analysis threshold in the amplitude of 3 mV is used for both types of PMTs, and the calibrated gain is used for the photoelectron calculation. The dark count rate (DCR) is also measured under the set point with a quarter p.e. threshold\(^2\) here. It is

\(^2\)The threshold is also used for the following muon-related testing.
around 16 kHz for NNVT PMT and 44 kHz for HPK PMT, respectively, where a tiny light leakage in single-photon level (around 20–30 kHz) is found during the testing of HPK PMT from the used black cloth covering of the system.

A similar procedure is applied to the PMTs of the scintillators, a working point settles down too. The amplitude of SPE is around 4.3 mV for PS1 and 5.4 mV for PS2, and the gain is $0.35 \times 10^7$ of PS1 and $0.34 \times 10^7$ of PS2 respectively. The relationship between the amplitude and charge gain is different to the 20-inch PMTs, which is mainly from the shape features of the pulses as discussed in section 2.1. The count rate of the scintillators with PMT is also measured with an amplitude threshold of around 30 mV (without amplifier), it is around 3 kHz for PS1 and 1 kHz for PS2 respectively. The measured charge spectra of the plastic scintillators are shown in figure 7, where the typical effective light yield to muon is around 140 p.e. for PS1 and 40 p.e. for PS2. The differences in counting rate and muon response come from the thickness of the scintillators. Another offline charge cut of the scintillators will be used for purer muon selection: 70 p.e. for PS1 and 20 p.e. for PS2.\(^3\) All the measured parameters are shown in table 1.

### Table 1. Set point of all the PMTs

| PMT          | HV (V) | SPE amplitude (mV) | Gain ($\times 10^7$) | Count rate (kHz) |
|--------------|--------|--------------------|----------------------|------------------|
| 20-inch NNVT | 1770   | 7.0                | 1.20                 | 16               |
| 20-inch HPK  | 1677   | 6.0                | 1.00                 | 44               |
| PMT1 w/ PS1  | –2200  | 4.3                | 0.35                 | 3                |
| PMT2 w/ PS2  | –1800  | 5.4                | 0.34                 | 1                |

\(^3\)The threshold is settled down on balance to remove the gammas and to keep a higher muon detection efficiency.
Figure 6. Measured SPE spectra of 20-inch HPK or NNVT PMTs, where a Gaussian fit in red line is applied around the peaks. Top left: MCP PMT SPE amplitude spectrum; top right: MCP PMT SPE charge spectrum; bottom left: HPK PMT SPE amplitude spectrum; bottom right: HPK PMT SPE charge spectrum. Note that the calibrated PMT gain is used for the charge calculation in p.e.

Figure 7. Measured charge spectra of the scintillators with a threshold of around 10 p.e. The response differences come from their thickness as stated.
3 Measurement results

Except for the rate of the dark count, more features are measured for a better understanding of the sources of the dark count from thermal emission, or flashers of the 20-inch PMT, muons, natural radioactivity, such as the dark count rate (DCR) versus threshold, the amplitude and charge spectra of the dark count.

In this section, a detailed measurement of the dark count of 20-inch PMT is done first. Then, the dark count related to muons is further measured under several configurations. All the results will be discussed one by one.

3.1 Dark count

3.1.1 Dark count rate (DCR)

The dark count is mainly sourced from the thermal electron emission of the PMT photocathode in the dark. Its amplitude should be in SPE level generally [52, 57], which is mostly less than 3 p.e. and it is much smaller than 1 Hz for signals larger than 3 p.e. (assuming DCR in SPE ~ 10 kHz and 10 ns coincidence window). A threshold survey is done for the dark count rate of 20-inch PMT as shown in figure 8. Due to the tightness of the device, there is a tiny light leakage during the measurement of HPK PMT as mentioned, which results in a higher count rate when the threshold less than 10 mV. Comparing with expectation, it is clear that there shows an obvious rate higher than 10 Hz when the threshold is higher than 20 mV (around 3 p.e. according to table 1), even higher than 50 mV (around 10 p.e.) in amplitude for both types of PMTs. It is over the contribution only from the thermal noise DCR. The higher rate of large pulses of NNVT PMT than HPK PMT is related to the response features of NNVT PMT on amplitude as shown in figure 6, where the NNVT PMT shows a wider distribution on amplitude than HPK PMT even both of them at SPE level.

![Figure 8. Dark count rate of 20-inch PMTs vs. threshold.](image)

3.1.2 Dark count waveform

The waveforms are further taken during the threshold survey for both types of PMTs with the system.\(^4\) The distributions of amplitude and charge of the DCR are shown in figure 9, where all the plots

\(^4\)The data taking dead time is assumed to be random even for high enough trigger rate, and no systematic effect on the overall distribution.
are normalized to the result of the lowest threshold according to their event numbers higher than 200 mV. All the spectra of amplitude (charge) of both types of PMTs are following a similar overall trend, and show a structure in steps:

1. The first step is from 0 to ~10 mV (0 to ~3 p.e. in charge), which should be mainly contributed by the thermal electron emission. The result of HPK PMT suffers from tiny light leakage.

2. The second step is from ~10 mV to ~100 mV (~3 p.e. to ~20 p.e. in charge), which still needs further understanding.

3. The third step is from ~100 mV to ~500 mV (~20 p.e. to at least ~150 p.e. in charge), which still needs further understanding and is the focus of this study.

Figure 9. The normalized amplitude (left) and charge (right) spectra of 20-inch PMTs’ dark count at different thresholds. Top left: 20-inch NNVT PMT amplitude spectrum; top right: 20-inch NNVT PMT charge spectrum; bottom left: 20-inch HPK PMT amplitude spectrum; bottom right: 20-inch HPK PMT charge spectrum. Please note that the thresholds listed in the legend are set to the leading edge discriminator, while the amplitude of the events is derived from the taken waveforms, which will be affected by the system noise and could be less than the set threshold.
3.2 Muon hit PMT glass

With the system, trigger mode #3 (the triple coincidence of PSs and 20-inch PMT, see section 2.1) sets for muon-related signal testing. The parameters (see figure 5) are derived from the measured waveforms. It is checked first on the hit-time correlation of both PSs (shown on the left of figure 10) to exclude possible random noise, where only the events selected in a window of [470, 510] ns of the x-axis and [500, 530] ns of the y-axis for the following analysis, named as hit-time cut. The hit-time correlation between PS1 and 20-inch PMT (shown on the right of figure 10) is limited in a similar way for the following analysis.

![Figure 10](image)

(a) PS1 vs. PS2  
(b) 20-inch PMT vs. PS1

Figure 10. 2D hit-time correlation between the two scintillators (left), and PS1 and 20-inch PMT (right).

When the PS1 is located at the position 0.15 m relative to the central axis of 20-inch PMT (zenith angle ($\theta$) of muon incident is around $27^\circ \pm 16^\circ$), the measured charge spectra after the hit-time cut (tagged by “Trigger #3”) of 20-inch MCP PMT can be found on the left of figure 11, where the charge spectrum of the dark count measured with a threshold of 20.5 mV for NNVT PMT and a threshold of 25 mV for HPK PMT (trigger mode #1, tagged by “PMT dark count”) is also shown. A further selected spectrum after the offline charge cut of PSs as mentioned in section 2.2 (tagged by “Trigger #3 w/ PS cut”) is drawn too. All the curves are normalized to the spectrum of the dark count according to the event number of the large pulses. Firstly, it is found on the left of figure 11 for NNVT PMT that the muon-related events are mainly related to the large pulses with a typical charge around 76 p.e. — step 3 as discussed in section 3.1.2. Secondly, the muon-related events also contribute to part of lower than 40 p.e. located at step 2 as discussed in section 3.1.2. Similar features can be identified for the 20-inch HPK PMT as shown on the right of figure 11, where the typical signal intensity in charge is around 30 p.e. located at step 3 too. It is clear that the muon-related events mainly concentrated in the range of step 3, and partially extended to step 2.

To survey more directions of muons going through the 20-inch PMT, another two data sets are taken when PS1 is located at 0.5 m (zenith angle ($\theta$) is around $43^\circ \pm 11^\circ$) and 1.0 m (zenith angle ($\theta$) is around $58^\circ \pm 7^\circ$) relative to the 20-inch PMT central axis. The measured charge spectra after the PSs’ offline charge cut as mentioned in section 2.2 (corresponds to the signal that the muon hits the PSs) are shown in figure 12 for both types of PMTs. All the measurements provide consistent results on the muon-related signal strength, while the difference is mainly concentrated on the measured
event rate from the different solid angle. The measured muon rate by PMT only is selected with a charge larger than 40 p.e. for NNVT PMT and larger than 10 p.e. for HPK PMT, respectively. The typical charge and event rate are collected and summarized in table 2, where the rate is related to the specified arrangement layout of the locations of the two scintillators during each measurement, which could have some uncertainty, especially for PS1.

3.2.1 20-inch PMT coincidence only with PS1

Another configuration with trigger mode #2 (20-inch PMT coincidence only with PS1, see section 2.2) is used for the measurements of 20-inch PMT for cross-checking of muon-related events, where

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Figure 11. Measured charge spectra of 20-inch PMTs. Left: MCP PMT; right: HPK PMT. Red: dark count spectrum (tagged by “PMT dark count”), same as in figure 9; purple: the measured spectrum selected only with the hit-time cut of PSs; blue: after the offline charge cut of the PSs as mentioned in section 2.2. Please note that the dark count spectra are taken with a threshold of 20.5 mV for NNVT PMT and a threshold of 25 mV for HPK PMT to relatively increase the statistics of large pulse and avoid the SPE issue for the HPK PMT measurement as mentioned.

Figure 12. Measured charge spectra of 20-inch PMTs in different muon directions after the PSs’ offline charge cut as mentioned in section 2.2. Left: 20-inch NNVT PMT; right: 20-inch HPK PMT. Red: zenith angle ($\theta$) is around $27^\circ \pm 16^\circ$; purple: zenith angle ($\theta$) is around $43^\circ \pm 11^\circ$; blue: zenith angle ($\theta$) is around $58^\circ \pm 7^\circ$. 
Table 2. Signal strength and rate of different muon directions. The PSs’ offline charge cut as mentioned in section 2.2 is tagged as “w/ PS cut”. The charge cut of 20-inch PMTs used here is larger than 40 p.e. for NNVT PMT and 10 p.e. for HPK PMT, respectively, and tagged as “w/ PMT cut”. The measured rate only with PS1 will be discussed in section 3.2.1, and tagged as “only w/ PS1”.

| Configuration (θ) | PMT | rate only w/ PS1 (w/ PS cut) (Hz) | rate w/ double PSs (w/ PS cut) (Hz) | Typical intensity (p.e.) |
|-------------------|-----|---------------------------------|-----------------------------------|-------------------------|
| 0.15 m (θ ~27° ± 16°) | NNVT | 31.41 (26.27)(12.49) | 1.32 (0.93)(0.89) | 76 |
|                   | HPK | 13.12 (9.45)(8.97) | 0.88 (0.59)(0.59) | 30 |
| 0.5 m (θ ~43° ± 11°) | NNVT | 16.33 (13.01)(7.66) | 0.65 (0.42)(0.40) | 76 |
|                   | HPK | 11.87 (8.06)(7.71) | 0.49 (0.26)(0.26) | 31 |
| 1.0 m (θ ~58° ± 7°) | NNVT | 11.25 (8.37)(5.24) | 0.41 (0.26)(0.24) | 85 |
|                   | HPK | 8.36 (5.46)(5.12) | 0.34 (0.19)(0.19) | 33 |

PS1 is located at 0.15 m relative to the PMT central axis. The 2-D hit-time correlation between the 20-inch PMT and PS1 is shown on the left of figure 13, which shows about three regions, and a more complex pattern than that of trigger mode #3 as shown in figure 10. The region of the “L” shape on the 2-D hit-time plot is from the random coincidence of the 20-inch PMT and the PS1, where the data acquisition window is set relative to the trigger time determined by the latter arrival of the 20-inch PMT or PS1. Region “o” is the target generated by the muons or gammas going through the 20-inch PMT and the PS1 at the same time, which is confirmed by checking on the relative hit-time difference. The charge spectrum filtered by the hit-time with the region “o” is shown on the right of figure 13, where all the curves are normalized to the spectrum of the PMT dark count. All the plots show consistent results for the muon-related events, while the lower part of trigger mode #2 has an obvious exceeding of that of trigger mode #3. It is possibly related to the natural radioactivity or the muons hitting on the PMT glass. Based on the results, it is possible that step 2 may be mainly contributed by the muon or the natural radioactivity of the surroundings.

3.2.2 PMT photocathode down

Concerning the correlation between the Cerenkov light direction and photocathode acceptance when a muon goes through the glass bulb, another special test is done further with the PMT downward photocathode; in contrast to the upward photocathode. The trigger mode #3 is also used for the test only with 20-inch NNVT PMT. The measured charge spectra are shown in figure 14 with the raw spectra and after further PSs’ offline cut. It also shows obvious muon-related events, which is consistent with the photocathode directed upwards. But the typical intensity of photocathode towards to down is around 50 p.e. which is only about 66% of photocathode towards to up. The direction of the Cerenkov light will affect the PMT acceptance for a muon passing through the PMT glass bulb.

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5The region of the “L” shape, the region tagged by “o”, and the others, the entries of which are mainly from random coincidence.
Figure 13. 2-D hit-time correlation between 20-inch NNVT PMT and the PS1 of trigger mode #2 (left) and the measured charge spectra of 20-inch PMTs (right). Please note that the “PS cut” means the offline cut of PS charge as discussed in section 2.2.

Figure 14. Measured charge spectra of 20-inch NNVT PMT when its photocathode toward to down.

4 Simulation

Geant4 [58] is widely used for particle physics detector simulation. A Geant4 simulation of the whole setup with muons passing through the PMT glass bulb was done and compared with the experimental measurements. The results will help in the understanding of the measurements and prospect the features of this process in the future JUNO detector.

4.1 Simulation setup

The simulation project sets up with the 20-inch PMT (HPK or NNVT) and two plastic scintillators inside a standalone dark box, where all the parameters are configured following the study in [59]. The realized geometry can be found in figure 15. The muon generator is based on the muon momentum distribution at sea level [60].

There are a few critical configurations to mention:
(1) Construct the geometry models of PS1, PS2, 20-inch NNVT PMT, and HPK PMT, and realize optical processes for Cerenkov radiation in PMT glass. A uniform thickness of PMT glass is used in the simulation.

(2) Verify the simulation process related to the PMT glass including Cerenkov radiation (see figure 16(a)) and QE curve of photocathode (see figure 16(b)).

(3) Muons are generated following the distribution with $4\pi$ solid angle randomly on a plane $10 \times 10 \text{ m}^2$ just above PS2.

Photons will be generated by Cerenkov radiation when a muon is passing through the PMT glass if its speed exceeds the phase velocity of light in the glass. The produced photon number depends on the refractive index ($n$) of the passing through a medium, here is the refractive index model of glass. Assume the glass index $n = 1.5$ in the wavelength range, the distribution of generated photon number by muon within the wavelength range of 80 nm–800 nm is shown in figure 16(a), where the photon production yield is about 274 ph./mm (about 26 ph./mm within 400 nm–700 nm), basically consistent with theoretical calculation.

The used QE curves of the 20-inch PMT [61, 62] are shown in figure 16(b), where the QE value at 420 nm is used as a normalization factor (the shape of the QE curve is unchanged.) to check for a relative effect of QE. The QE of NNVT PMT shorter than 300 nm is higher than that of HPK PMT, which will result in a higher output strength of NNVT than HPK PMT. By default, the uniform glass thickness is set to 3 mm for both types of PMTs, and the QE at 420 nm is set to 27.3% for NNVT PMT and 30.8% for HPK PMT, respectively.

The typical generated number of photons is around 1771–1793 (100%) in a wavelength range of [80, 800] nm (considering muon in and out of the PMT glass bulb) when a muon goes through the PMT glass. The photon number hitting the photocathode is around 1246–1267 (70%), which is contributed a lot by total reflection from glass to air (outside PMT volume). The final strength on
the photocathode of NNVT after QE conversion is 45–50 p.e. (2.8%) and that of HPK is 30–36 p.e. (2.0%). As mentioned, the difference between the two types are mainly source from the shape of the QE curve, especially the wavelength range of 80–320 nm.

### 4.1.1 Effect of glass thickness and QE

The glass thickness and QE coefficient of 20-inch PMT have a significant effect on the detected signal strength from the muon-related Cerenkov radiation. A survey on glass thickness and QE normalization factor is done individually, as shown in figure 17. The output strength of muon related signal is nearly linear to the glass thickness and the QE: ~ 16 p.e./mm for NNVT PMT and ~ 13 p.e./mm for HPK PMT respectively; ~ 8 p.e./2.7% for NNVT PMT and ~ 6 p.e./2.7% for HPK PMT, the difference is mainly from the difference of QE shape of the two PMT types.
4.1.2 Simulation for muons

The simulation output is consistent among different trigger modes for both types of PMTs as shown in figure 18(a) for NNVT PMT and figure 18(b) for HPK PMT with $27^\circ \pm 16^\circ$, where all the curves are scaled to a similar statistics around the typical peak. The ratio to only the 20-inch PMT (trigger mode #1) is around 1.9–2.9% with one PS (trigger mode #2) and 0.2% with two PSs (trigger mode #3) respectively. The simulated distribution of detected signal strength by photocathode for different muon angles can be found in figure 18(c) for NNVT PMT and figure 18(d) for HPK PMT with an artificial scale too. The typical values of simulation and measurements are list in table 3, where the original muon rate in simulation is assumed to 200 Hz/m² at ground.

![Graphs](image)

**Figure 18.** Typical output from the simulation of 20-inch PMTs. Top left: simulation of NNVT PMT for $27^\circ \pm 16^\circ$; top right: simulation of HPK PMT for $27^\circ \pm 16^\circ$; bottom left: simulated signal strength of different angles of NNVT PMT; bottom right: simulated signal strength of different angles of HPK PMT.

Figure 19 is trying to identify the effect of muon direction or muon hitting location on PMT glass shown in figure 18(a) and figure 18(b) further. The muons hitting the PMT glass are separated from two groups: the muons hitting the PMT photocathode (tagged by “Hit photocathode”) and the muons not hitting the PMT photocathode (tagged by “Not hit photocathode”). It shows that even if the muon is not hitting the PMT glass with the photocathode directly (only passing through the other
end of the glass bulb), the PMT still can “see” the photons from the muon. The total reflection effect of PMT glass is helping in this case. The shape difference of the charge spectra between NNVT and HPK PMTs for “Not hit photocathode” is the main source of the different shapes of PMT glass bulbs of the two types of PMTs as shown in figure 15.

![Figure 19](image)

**Figure 19.** Effect of muon hitting location: passing through or not the photocathode of 20-inch PMTs.

The rate and the signal strength both of the measurement and simulation are shown in table 3, where the measured rate of 20-inch PMT is scaled after a charge cut larger than 50 p.e. for NNVT PMT and 10 p.e. for HPK PMT as discussed. The measured rate is higher than the simulated one, which is possible from the random coincidence, radioactivity, and geometry and location uncertainty of the system. Considering this, another calculation is updated in table 3, which is much close to the simulation numbers with a more strict cut. The simulation shows a more narrow distribution than measurements where the height of the $y$-axis is artificially normalized, and the measurements have a long tail than the simulation. As discussed in section 2.2, here the charge in p.e. is calculated with the peak gain, which has a large bias for the NNVT PMT [56]. A corrected signal strength[^6] also updated in table 3 tagged by “Cor.”, which is more consistent with simulation. Figure 20(a) and figure 20(b) show the charge spectra comparison between simulation and measurements which is normalized to the higher part of each curves, while the NNVT result is scaled with the gain factor already.

### 4.2 Comparison of PMT photocathode up and down

The simulation of the NNVT PMT photocathode toward to down and up is shown in figure 20(c) for NNVT PMT. The reason for showing an obvious signal even the generated Cerenkov photon departing from the photocathode is similar to that showed in figure 19 that the effect of total reflection from PMT glass to air or vacuum is confirmed. While the collected photon number of PMT photocathode towards to down is less than that of PMT photocathode towards to up. It is around 76% of the output of photocathode towards to down to photocathode towards to up, which is consistent with the measurement.

[^6]: Here the gain factor 1.6 is used according to [56].
Table 3. Comparison of simulation and measurement at zenith angle $\theta = 27^\circ \pm 16^\circ$ of trigger mode #3. The rate of the simulation is counted in three columns: the total muon hit rate (tagged by “all”), the muon hit rate passing the photocathode (tagged by “photo-”) and the muon hit rate not passing the photocathode (tagged by “not photo-”). In the column tagged by “Test rate 1”, the rate of PMT only of the measurement is counted only in the range of >40 p.e. for NNVT, >10 p.e. for HPK following the understanding. Concerning the difference between the simulation and measurements, please note that there is no consideration of the noise, radioactivity, and other possible sources in the simulation. The test results of #2 and #3 still include the possible contributions from the accidental coincidence, radioactivity, and the contribution of the PS geometry and location uncertainty. In the column tagged by “Test rate 2”, the coincidence rates are further checked with more strict cuts to remove possible noise: 80 p.e. for MCP PMT, 20 p.e. for HPK PMT and 140 p.e. for PS1 of trigger mode #2, and 120 p.e. for PS1 and 35 p.e. for PS2 of trigger mode #3.

| PMT | Configure (trig. mod.) | Sim. (p.e.) | Test (Cor.) (p.e.) | Sim. rate (all)(Hz) | Sim. rate (photo-) | Sim. rate (not photo-) | Test rate 1 (Hz) | Test rate 2 (Hz) |
|-----|------------------------|-----------|-------------------|---------------------|-------------------|----------------------|----------------|----------------|
| NNVT | 20” only (#1) | 50 | / ( electronics) | 77.98 | 56.86 | 21.12 | 69.33 | 26.95 |
| | 20” & PS1 (#2) | 47 | 79 (49) | 2.24 | 1.41 | 0.83 | 12.49 | 2.38 |
| | 20” & PS1 & PS2 (#3) | 45 | 76 (47.5) | 0.18 | 0.17 | 0.01 | 0.89 | 0.20 |
| HPK | 20” only (#1) | 36 | / | 87.04 | 57.57 | 29.47 | 75.19 | 47.63 |
| | 20” & PS1 (#2) | 32 | 34 | 1.69 | 1.03 | 0.66 | 8.97 | 2.4 |
| | 20” & PS1 & PS2 (#3) | 30 | 33 | 0.17 | 0.14 | 0.03 | 0.59 | 0.19 |

Figure 20. Comparison between the measurements and the simulation of 20-inch PMTs. The measured data is selected with the offline cut of PS as discussed in section 2.2 of the trigger mode #3.
5 Summary

In this paper, we investigated the large pulses of 20-inch PMT dark count, which are mainly from the generated photons of the muons crossing through the PMT glass by the Cerenkov radiation for both types of dynode and MCP PMTs. We set up a waveform data-taking system of a muon coincidence system to get the muon-related PMT large pulses in the dark. The signal strength of the muon passing through the PMT glass is derived from the measured spectra with different muon incident zenith angles for both PMT types, but the difference in muon zenith angles has little effect on the strength. The signal strength of muon passing through the PMTs of the photocathode toward down is little smaller than that of the photocathode toward up. The results of the measurements and a simulation based on Geant4 are checked, and preliminary understood, which shows that the charge output of muons passing through both types of PMTs is linear to the PMT glass thickness and QE coefficient.

Acknowledgments

This work was supported by the National Natural Science Foundation of China No. 11875282, the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA100102).

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