Study on SiPM performance at low temperatures

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ABSTRACT: Radon is the main background source of dark matter and neutrino experiments. We designed a liquid scintillation detector to measure the radon concentration (mBq/m³) at low temperatures using silicon photomultipliers (SiPMs) arrays. The SiPM performance characteristics are closely related to the lower detection limit of the detector. In this study, we built an automatic and accurate low-temperature measurement system to study the single photoelectron spectrum, dark noise, energy resolution, optical crosstalk, and after-pulse of the SiPM at different temperatures. As a result, we obtained the variation trend of the SiPM parameters at different temperatures, and the SiPM optimal working conditions were obtained, which can improve the detector’s sensitivity.

KEYWORDS: Silicon photomultiplier; Low temperature; SPE.

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1 Introduction

Radon is the main background source for many low-background detector experiments [1–4]. Currently, the radon measurement methods worldwide mainly include the ionization chamber, electrostatic adsorption, and liquid scintillator measurement methods. Among them, due to the advantages of a high solubility coefficient and a low background, the liquid scintillator measurement method is widely used in dark matter and neutrino experiments, such as Jiangmen neutrino (JUNO) [5, 6] and Jinping underground experiments [7, 8]. Moreover, they all require high sensitivity for low-background detectors for radon measurements. In liquid scintillators, radon and its daughters generate photons through the $\beta - \alpha$ cascaded decay [9, 10], and photon counts are detected using photomultiplier tubes. However, silicon photomultipliers (SiPMs) are the most popular photon detection devices in the composition of liquid scintillation detectors [11]. As novel low-light-sensing optoelectronic conversion devices, SiPMs have attracted significant attention due to their small size, high gain, fast response, and low cost. It comprises a high-density diode [12] matrix with a common output load, each in a finite Geiger-Muller mode for high gain [13–15].

Generally, the detection limit of the detector characterizes the sensitivity in radioactivity measurements [16], which refers to the minimum expected value of radioactivity that can be detected by a certain measurement method under a certain confidence level. Based on the measurement of radon and its daughters’ concentrations, the detection limit is defined as the minimum detectable concentration (MDC) [17], and is presented in Equation 1.1.

$$MDC = \frac{4.65 \sqrt{n_b / t_p}}{\epsilon \cdot \eta \cdot V \cdot \zeta},$$ (1.1)
where $n_b$ is the background count rate (cps), $t_b$ is the counting time of the sample and the background (s), $\varepsilon$ is the detection efficiency of gamma rays or other particles, $\eta$ is the total recovery rate during the separation or concentration process, and $V$ is the sample amount ($m^3$), $\zeta$ is the branching ratio of gamma rays or other particles. Therefore, effectively reducing the background count is the key to achieving high sensitivity of the detector, *i.e.*, to reduce the noise influence when the SiPM detects the photon signal in the experiment. We know that the SiPM temperature characteristics make it easy to generate a lot of thermal noise due to the excessive operating voltage [18–21]. So, the temperature can seriously affect the background count in detection experiments [22, 23]. Moreover, SiPMs have excellent energy resolution and very low dark noise characteristics at low temperatures, which can effectively reduce the detection limit of the detector and improve the detection sensitivity of liquid scintillation detectors to the decay concentration of radon and its decay daughters.

Moreover, the sensitivity of the detector is also related to the light yield of the liquid scintillator. In low-temperature experimental environments, the light yield of the liquid scintillator increases by 2% when the temperature decreases by 10°C from room temperature. Therefore, by reducing the experimental temperature reasonably, the light yield can be effectively increased, thereby improving the detector’s sensitivity.

In this study, we design the low-temperature measurement system [20] to systematically study the single photoelectron (SPE) [21, 24] spectrum, gain, optical crosstalk, after-pulse, time distribution, and energy resolution under different temperatures. By analyzing the amplitude and charge spectrum of the pulse signal, we can obtain the low-temperature effects on the performance characteristics of SiPMs. Moreover, the optimal working conditions of SiPMs are obtained with lower dark noise and better energy resolution.

### 2 Experimental system

#### 2.1 Measurement system

Measuring the radon concentration by the liquid scintillator detector of the SiPM array requires studying the pulse counts obtained on the SiPMs [25–27]. The pulse count per unit time is proportional to the radon concentration so that the radon concentration can be determined. Also, a low-temperature measurement system was designed to study the SiPM performance characteristics (Fig. 1). In the system, two low-voltage power supplies provide the working voltage for the SiPM and the preamplifier. Also, the preamplifier amplifies the output signal by 30 times. The SiPM is placed on the support plate (Fig. 2), and they are placed together in a dark room. Then, the dark room is placed in an automatic control cryostat. The SiPM model used here is the S13360-6050CS; the working voltage is 54.86 V at room temperature, and the size is 6 mm × 6 mm × 6 mm. Its effective photosensitive area is 6 mm × 6 mm, and its spectral response range is 270–900 nm.

When measuring the SPE spectrum, a pulse generator (pulser) drives the light source to illuminate the photocathode of the SiPM and outputs a pulse signal from the anode, which is driven at a frequency of 1 kHz. Among them, a blue-emitting LED ($\lambda = 420$ nm) is used as the light source coupled with the pulser. The pulse signal is used as the measurement signal after the fan-in fan-out. Using the synchronous triggering method, the pulser simultaneously outputs a trigger signal that passes through the low-threshold discriminator (LT-Dis). Then, a FlashADC (FADC, DT5751) is
used to sample the waveforms. When measuring dark noise, the SiPM does not require a light source and only needs to provide a self-triggering signal to the FADC.

During the experimental preparation, we measured the baseline of the SiPM support plate to be 2 mV and the breakdown voltage of the SiPM to be 52 V at room temperature. Also, to reduce electrical interference and noise from the LED, the LED and its circuits are wrapped with shielding materials, such as tin foil, and fixed near the SiPM surface. The measurement of the SPE spectrum requires the pulse waveform to have a stable single-photon signal. It is defined as the occurrence of a single-photon signal once in ten pulses, i.e., the probability of a single photon is 10%.

In the experiments, we measured the SPE spectra without and with the LED by controlling the temperature of the cryostat. The cryostat temperature and the SiPM voltage vary from −60°C to −20°C and 51 to 56 V, respectively. This experiment mainly provides some reference data for the performance characteristics of SiPMs at low temperatures for developing low-background detectors for measuring the concentration of radon and its daughters and selecting the best working conditions for SiPMs to obtain high detection sensitivity. Furthermore, by analyzing the amplitude and charge spectra of the SPE, we further measured parameters, such as optical crosstalk, after-pulse, gain, and energy resolution.

2.2 SPE spectrum of SiPM

The SiPM waveforms are sampled by the FADC, which is then calibrated. During the calibration experiment, the standard input signal is set as a standard square wave sent by the pulser, which is
collected by the oscilloscope through LabVIEW, and the FADC digital acquisition system collects the output signal. Next, data sampling and analysis are performed according to the amplitude from 0–100 mV, with a step size of 10 mV. Their amplitude spectra are shown in Fig. 3, and they are fitted with a Gaussian function to obtain the mean value as the amplitude value. Figure 4 shows the result of the FADC calibration. The associated calibration factor is obtained as 0.91. The charge conversion equation is given as follows:

\[ q = \frac{V_{\text{Fixed}}}{V_{\text{FADC}} \times R} \times t_0, \]  

(2.1)

where \( V_{\text{Fixed}} \) is the standard amplitude value corresponding to each channel (1 mV), and \( V_{\text{FADC}} \) is the amplitude value of each channel after calibration by the FADC (0.91 mV). \( R \) is the internal resistance (50 ohms), and \( t_0 \) is the 1 GHz sampling rate of the FADC (1 ns = 1 × 10^{-9} s). Based on the FADC calibration results, Equation 2.1 was used to estimate the corresponding charge value for each channel to be 21.98 fC to analyze the charge spectrum for subsequent SPE spectrum measurements.

**Figure 3.** Amplitude spectrum with oscilloscope (left) and FADC (right).

**Figure 4.** FADC calibration result using amplitude spectra. Here \( V_{\text{osc}} \) and \( V_{\text{DT}} \) are the mean values obtained after fitting the amplitude spectra collected by the oscilloscope and the FADC with a Gaussian function, respectively.
The photoelectrons generated by the photon incident on the SiPM photocathode in the detector conform to the Poisson distribution after photomultiplication \([24]\),

\[
P(n) = \mu^n e^{-\mu}/n!,
\]

where \(P(n)\) is the probability that the pulse collected on the SiPM contains \(n\) photons, \(\mu\) is the average photon number of the pulse, and \(n\) is the number of photons in the pulse. The light intensity of the LED was adjusted to ensure that 90% and 10% of the probability are a step and a signal, respectively. At this time, the ratio of the single-photon to the multiphoton in the signal is 1:21, \(i.e.,\)

\[
P(n = 1)/p(n > 1) = 21.
\]

Also, the probability of a single photon is about 9.5%. Moreover, when the pulse count is large, the Poisson distribution can be approximated to a Gaussian distribution, so a Gaussian function can be used to fit the data. Fig. 5 shows the charge distribution of the SPE based on log coordinates, which eliminates the effect of baseline deviation and can be fitted with a multiGaussian function to obtain the peak (mean) and width (sigma) of the pulse waveform. Among them, \(Q_1\) is a step mainly derived from electronic circuits and noise, \(Q_2\) is a single-photon signal, and \(Q_3\) is a two-photon signal. The ratio of the single photoelectron signal to the total signal can be estimated as

\[
R = \frac{N_{\text{sig}}}{N_{\text{sig}} + N_{\text{hkg}}} = 9.1\%,
\]

where \(N_{\text{sig}}\) and \(N_{\text{hkg}}\) are the counts of steps and signals, respectively. The results show that the signal measured in the experiment is basically the SPE, and a small amount of multiphoton signal is mixed. The amplitude and charge spectrum of the SPE at different temperatures are analyzed in Fig. 6, where the charge spectrum can be obtained by a simple superposition of the integral areas. Also, for the rigor of the experiment, we also examined the relationship between steps, single-photons, and two-photons for all acquired pulse waveforms.

\[
Q = Q_2 - Q_1,
\]

with

\[
Q_3 = 2 \cdot Q + Q_1.
\]

Here, \(Q\) is the channel of the single-photon charge. When the channels satisfy this equation, one can be sure that the data samples collected in the experiment are reasonable. Using the calibrated SPE spectra, we further investigated the performance parameters of the SiPM at different temperatures, such as gain, optical crosstalk, after-pulse, time distribution, and energy resolution.

### 3 Results and discussion

#### 3.1 Gain

We evaluated the gain by illuminating the SiPM with low photon flux. SPE spectra with clearly distinguishable peaks were obtained from the SiPM anode. The gain of the SiPM is defined as follows:

\[
Gain = \frac{(q_2 - q_1)}{e \times A},
\]
Figure 5. The charge spectra of SPE at $-20^\circ$C.

Figure 6. Amplitude (left) and charge (right) vs. SiPM over-voltage distribution at different temperatures. They were fitted separately with polynomials at different temperatures.

where $q_2$ is the charge of the single-photon ($q_2 = Q_2 \times q$), $q_1$ is the charge of the electronic noise, $e$ is the charge of a single electron, and $A$ is the magnification of the preamplifier. Through the low-temperature measurement system, the temperature of the cryostat was controlled to change the working conditions of the SiPM to study the relationship between the gain and the working voltage of the SiPM at different temperatures and analyze the temperature effect on the SiPM gain. Figure 7 (left) shows the variation of the SiPM gain with voltage under different temperatures; an obvious linear relationship exists between them. Also, as the temperature decreases, the gain increases accordingly.

The over-voltage is the real physical parameter that characterizes the SiPM performance. According to the gain analysis results, the breakdown voltage of the SiPM at different temperatures can be estimated by extending the fitted line shape outwards and calculating their corresponding over-voltages. The over-voltage is the difference between the bias and breakdown voltages. From the law of breakdown voltage and over-voltage variation, as temperature decreases, the breakdown voltage and the over-voltage decrease and increase, respectively.
Figure 7. Gain dependence vs. operating voltage of SiPM at different temperatures.

3.2 Optical crosstalk

During the avalanche process, a small number of carriers that can be absorbed by the Si material are absorbed by the adjacent cells, resulting in the probability of a secondary avalanche, i.e., optical crosstalk [28, 29]. The optical crosstalk limits the photon counting resolution of SiPMs. Therefore, the optical crosstalk probability is an important SiPM property that should be reduced as much as possible. Methods for determining optical crosstalk are based on the SPE spectrum analysis. We estimated the optical crosstalk probability by comparing the counts within the 1 photoelectron (p.e.) threshold to the measured total count rate [30], which is calculated as

\[ P_{cr} = \frac{N_{1p.e.}}{N_{total}}, \]  \hspace{2cm} (3.2)

where \( N_{1p.e.} \) is the count of 1 photoelectron (p.e.), and \( N_{total} \) is the total count of all pulses.

In the experimental analysis, it is usually difficult to distinguish the optical crosstalk and the after-pulse. A two-dimensional scatter plot of the time and charge corresponding to the maximum peak in the pulse waveform were used to study them (Fig. 8). Evidently, a single-photon after-pulse signal and a small amount of optical crosstalk signal are observed. To estimate the counts of the optical crosstalk within the 1 p.e. threshold, the time must be within the pulse signal range (between 400 and 470 ns), and the charge must be a smear to the right of the single-photon peak. We calculated the optical crosstalk rate of a single photon at different temperatures (Fig. 9) and found that although the optical crosstalk probability is very low, it has an obvious linear relationship with temperature. As the temperature decreases, the optical crosstalk rate decreases accordingly. Therefore, the low-temperature environment can greatly reduce the optical crosstalk interference of SiPMs.

3.3 After-pulse

The measurement of the after-pulse rate is also based on the SPE spectrum analysis. The after-pulse are the electrons generated during the avalanche that are captured and released again after a delay lasting from nanoseconds to microseconds, resulting in a new secondary current pulse with a smaller amplitude than the original secondary current, i.e., “small pulses,” where the pulse amplitude is < 1 p.e. [28, 29]. Unfortunately, the after-pulse signals cannot be separated from the true single-photon
Figure 8. Scatter plot of charge and time corresponding to the maximum peak. Here the red and green boxes mark the optical crosstalk and after-pulse events.

Figure 9. Optical crosstalk at different temperatures.

signal, reducing the photon counting resolution. Therefore, the effect of different temperatures on the after-pulse rate must be studied to minimize its interference with the real signal.

Fig. 8 clearly distinguishes the step, single-photon, and two-photon signals. To estimate the after-pulse count of a single photon, the time must exceed 470 ns, and the charge must be within the range of the channel corresponding to the valleys on both sides of the single-photon peak. By estimating the fraction of after-pulse counts in the total counts, we obtained the after-pulse rates at different temperatures. By analyzing the after-pulse rate results, an unclear temperature effect was found, and no obvious linear relationship was observed between them.

3.4 Energy resolution

When the single-photon signal is measured, most of the signal obtained by the FADC is step noise, which overlaps with the single-photon signal and even other multiphoton signals. Therefore, other signals will inevitably be doped when acquiring a single-photon signal. As many photons are detected on the SiPM, the mean value of the single-photon peak obtained by fitting the estimated charge distribution deviates from the mean value of the real single-photon distribution, thus affecting
the energy resolution of the charge measurement. The energy resolution of a single photon is defined as

$$\delta = \frac{\Delta E}{E},$$  \hspace{1cm} (3.3)

where $\Delta E$ is the sigma value after fitting the single-photon peak, and $E$ is the difference between the mean value after fitting the single-photon and the step. The measured energy resolution results at different temperatures are shown in Fig. 10. The result analysis revealed that the energy resolution is affected by temperature. As the temperature decreases, the energy resolution increases, but as the over-voltage increases, the energy resolution remains stable. Therefore, the energy resolution of SiPMs can be improved by reasonably controlling the temperature and the over-voltage.

![Figure 10. Energy resolution distribution at different temperatures.](image)

**Figure 10.** Energy resolution distribution at different temperatures.

![Figure 11. Time distribution of −20°C (left), and the time distribution at different temperatures (right).](image)

**Figure 11.** Time distribution of −20°C (left), and the time distribution at different temperatures (right).

### 3.5 Time distribution

SiPMs are photodetection devices with speedy time responses. In the experiments, the transit time and transit time dispersion, which characterize the temporal characteristics, were studied. They refer to the time from the light incident event on the photocathode surface to the appearance of the output pulse and fluctuations in the transit time of all single-photon pulses on the photocathode surface, respectively.
During the pulse waveform analysis, the transit time was challenging to estimate because the baseline shifted generally. Therefore, the time distribution to study the time characteristics of the SiPMs in the pulse analysis is the sigma value obtained by fitting the time distribution corresponding to the maximum pulse peak value in the pulse waveform with a Gaussian function (Fig. 11 (left)). In the figure, the photon signal is mainly concentrated between the time 400–480 ns, and the SiPM time resolution of SiPM is 9.8 ns. By studying the time distribution of different temperatures, it was observed that the time parameter is basically not affected by temperature (Fig. 11 (right)).

4 Conclusion

In conclusion, we built an automatic and accurate low-temperature measurement system to study the single photoelectron spectrum (SPE), dark noise, energy resolution, optical crosstalk, and after-pulse of SiPMs at different temperatures. In the experiment, the variation trends of the SiPM performance parameters are as follows: the optical crosstalk decreases as the temperature and the over-voltage decrease and increase, respectively. A clear distinction exists between −30°C and −40°C. Also, the SiPM gain increases with decreasing temperature, and the energy resolution increases with decreasing temperature and stabilizes at 0.2 with increasing over-voltage. Therefore, low-temperature conditions can increase the SiPM gain, improve its energy resolution, and reduce noise interference, such as optical crosstalk. Hence, we can effectively reduce the noise from SiPMs by reasonably controlling their over-voltages and operating temperatures, thereby improving the detector’s sensitivity and meeting the experimental requirements of extremely low-background detection.

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