Detection of Liquid Xenon Scintillation Light with a Silicon Photomultiplier

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Abstract

We have studied the feasibility of a silicon photomultiplier (SiPM) to detect liquid xenon (LXe) scintillation light. The SiPM was operated inside a small volume of pure LXe, at -95\textdegree{}C, irradiated with an internal \textsuperscript{241}Am \textalpha{} source. The gain of the SiPM at this temperature was estimated to be $1.8 \times 10^6$ with bias voltage at 52 V. Based on the geometry of the setup, the quantum efficiency of the SiPM was estimated to be 22\% at the Xe wavelength of 178 nm. The low excess noise factor, high single photoelectron detection efficiency, and low bias voltage of SiPMs make them attractive alternative UV photon detection devices to photomultiplier tubes (PMTs) for liquid xenon detectors, especially for experiments requiring a very low energy detection threshold, such as neutralino dark matter searches.

Key words: SiPM, Liquid Xenon, Dark Matter

PACS:

1 Introduction

The SiPM\textsuperscript{[1]} is a promising Avalanche Photodiode (APD) variant consisting of 576 silicon micro pixels per square mm of detector surface. Each pixel is a $21 \times 21 \mu m^2$ independent photon micro-counter operating in limited Geiger mode with gain of $10^6$. All SiPM pixels are connected to the common load, so the output signal is the sum of all signals. Thus a proportional signal is created by the sum of the digital micro-APD (pixel) signals. The main features of SiPM

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are low excess noise factor, low bias voltage (50 V), and excellent timing (30 ps for 10 photoelectrons). SiPMs have a low excess noise factor comparable to the Hybrid Photodiode (HPD)[2] because the gain mechanism relies on counting how many of the micro-APDs have fired. The SiPM noise is high at room temperatures[1], but is reduced significantly when operated at cryogenic temperatures. The photon detection efficiency is similar to a PMT, but comes from the product of a higher quantum efficiency (QE) multiplied by the ratio of sensitive area to the total detector area. It is thus well-suited to a purely solid state solution to LXe scintillation detection.

Liquid xenon is a very good scintillation material for various applications of particle detection[3,4,5,6]. The Columbia group, in particular, is interested in development of a liquid xenon time projection chamber (TPC) for Compton imaging of MeV sources in high energy astrophysics [7], and more recently, in the development of a dual phase (liquid/gas) TPC for the direct detection of dark matter particles in the form of WIMPs (Weakly interacting massive particles)[8]. In all these applications, efficient detection of the LXe scintillation is key to the sensitivity of the detector and its minimum energy threshold.

The wavelength of liquid xenon scintillation light is centered around 178 nm [9], making its detection a challenge. Currently, the TPC for the XENON Dark Matter Search[8] uses compact metal channel PMTs to detect both primary and proportional scintillation light produced by WIMP nuclear recoils. These PMTs (R9288 and R8520), produced by Hamamatsu Photonics Co., have typical quantum efficiencies of 20% at liquid xenon temperature (−95°C).

In the development phase of the XENON TPC, we have tested alternative UV photon sensors in liquid xenon, including multi-channel plate PMTs (MCP-PMT) and large area avalanche photodiodes (LAAPDs). The SiPM is another very promising device, which can detect a small amount of light with a very good single photoelectron detection capability. Here we summarize our first attempt to detect liquid xenon scintillation light with a small SiPM immersed in liquid xenon.

2 Experimental Apparatus

The LXe detector used for the test of the SiPM is the same one used for testing different light sensors, including the Hamamatsu metal channel PMT[10] and the LAAPD[11]. The detector consists of a 6 cm diameter stainless steel electrode with a radioactive alpha source $^{241}$Am deposited in its center. The $1 \times 1$ mm$^2$ SiPM (type Z, serial number 217) was mounted on a Teflon support plate facing the source plate. A blue LED was also mounted on the Teflon plate. The distance between source and SiPM was 4.7 mm. The detector was
pumped down to a vacuum level of $10^{-8}$ Torr and baked out for 36 hours before filling with LXe. Xe gas, purified through a SAES getter\footnote{http://www.saesgetters.com/}, was condensed in the detector vessel, cooled by a bath of liquid nitrogen and alcohol mixture at $-95^\circ$C. Fig.1 shows a schematic of detector, gas system and electronics. A scope trace of the blue LED signal as detected by SiPM is shown in Fig. 2.

The scintillation photons, absorbed by the SiPM, produce photoelectrons which are consequently amplified inside the silicon via a Geiger mode avalanche. The SiPM electrical signal is fed into a charge sensitive pre-amplifier, followed by an ORTEC 450 shaping amplifier. A test pulse generator is used to calibrate electronics chain system.

3 Results

3.1 Calibration

The great advantage of a SiPM is that it is self-calibrating, since its single photoelectron sensitivity can be used for calibration. The resulting low amplitude part of the $\alpha$-source spectrum is shown in Fig. 3. Note the excellent resolution (low excess noise factor) that allows up to 11 photoelectron peaks to be clearly distinguished. Each single photoelectron peak is fitted using a Gaussian function. The fitted mean value is plotted versus peak number (number of photoelectrons) in Fig. 4, clearly showing a linear behavior.

3.2 Gain measurement

We have estimated the SiPM gain $g$ with a calibrated test pulse signal as follows:

$$g = \frac{V_t C}{q A} \cdot \frac{M_1}{M_t}$$

where $V_t$ and $M_t$ are the test pulse amplitude and channel number in the MCA spectrum, respectively. $C$ is the capacitance of the charge sensitive pre-amplifier. $M_1 \approx 6.2$ is number of channels corresponding to a single photoelectron and $q$ is the elementary electronic charge. $A \approx 27$ is the gain of the amplification system used in this measurement. Based on these values, the SiPM gain is estimated to be around $1.8 \times 10^6$ at the operation voltage of 52 V.
Fig. 1. The chamber insert used for the Columbia Nevis test is shown above with the SiPM, source and LED clearly illustrated. The whole arrangement is immersed in purified liquid xenon. Included is a diagram showing the complete detector, with the gas filling system, and data acquisition system (DAQ).

Fig. 2. LED signal detected by silicon photomultiplier as seen on the screen of oscilloscope.
Fig. 3. Amplitude distribution for $^{241}$Am particle scintillations. Low amplitude part of the spectra.

Fig. 4. Mean amplitude after pedestal subtraction versus peak number. Fit - linear function. The MCA offset from the channel number of zero photoelectron peaks in Fig.3 is subtracted.
3.3 Quantum Efficiency Estimation

In Fig. 5 the $^{241}$Am $\alpha$-source energy spectrum, measured with the SiPM bias voltage at 52 V, is shown.

![MCA Distribution](image)

Chi2 / ndf = 121.7 / 38
Constant = 3109 ± 13.65
Mean = 349.6 ± 0.1074
Sigma = 19.27 ± 0.1895

Fig. 5. Amplitude distribution for $^{241}$Am particle scintillations. Fit - Gaussian function.

Since the SiPM signal is calibrated in units of photoelectrons, the average number of photoelectrons detected from LXe scintillation light induced by $^{241}$Am $\alpha$ particles is determined to be 55 p.e.

The total number of scintillation photons striking the SiPM can be calculated using the energy of $\alpha$ particle (5.48 MeV), the average energy needed to produce single scintillation photon in LXe (19.6 eV for $\alpha$ particle [12]), and the geometrical acceptance of the SiPM detector. For the detector geometry used in the tests, the average number of scintillation photons produced by one 5.48 MeV $\alpha$ particle striking the SiPM surface is $N_{ph} = 1006$ photons. Thus the measured photon detection efficiency is $\varepsilon = \frac{55\text{p.e.}}{1006\text{ph.}} = 5.5\%$. The quantum efficiency of the SiPM (QE) can be calculated as $\varepsilon = QE \times A$, where $A$ is the active area ratio of the device. Assuming $A = 0.254[1]$, we infer a $QE = 22\%$ including the probability of initiating the Geiger avalanche.
4 Conclusion

A silicon photomultiplier was tested for the first time in LXe to detect its scintillation light at $\lambda = 178$ nm, at an operation temperature at $-95^\circ C$. A high quantum efficiency of 22% has been demonstrated. Large arrays of SiPMs offer a promising solid state photodetector approach for reading out LXe detectors in applications ranging from $\gamma$-ray astrophysics to particle physics and medical imaging.

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