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nEXO light detection system

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Abstract. nEXO is a future 5-tonne scale liquid xenon time projection chamber (TPC) experiment looking for hypothetical neutrinoless double beta decay of isotope ^{136}Xe. To attain the projected half-life sensitivity of 10^{28} years, it aims to achieve an energy resolution of 1% or better at the Q-value ($Q_{\beta\beta}$= 2.458 MeV) of the decay. nEXO plans to employ silicon photomultipliers (SiPMs) on the lateral surface of the cylindrical TPC to detect the light signals. Newly developed SiPMs sensitive to vacuum ultraviolet (VUV) light will be directly used for the detection of scintillation photons (λ = 175nm) in liquid xenon. For achieving the target energy resolution, the light detection system must have high photon detection efficiency, low correlated avalanche noise and low dark noise rate. The SiPM devices from two vendors are considered for the light detection system in the experiment. The primary goal of this research project is to characterize the VUV-SiPMs and measure their various features like gain, crosstalk, afterpulsing, dark noise rate, reflectivity and photon detection efficiency. Along with all these measurements, a monitoring tool will be required to test the large number of SiPMs before installing them in the detector. Current-voltage(IV) curve characterisation is being explored as a quick quality-testing tool for the performance of SiPM.

1. Introduction

The search for neutrinoless double beta decay ($0\nu\beta\beta$) has attracted a great deal of attention after the discovery of neutrino oscillations which confirmed that the neutrinos are massive in nature [1,2,3]. Neutrino oscillation experiments not being sensitive to Dirac or Majorana nature and absolute mass of neutrino, other experimental approaches are taken towards revealing these fundamental aspects of neutrino physics. Neutrinoless double beta decay is a hypothetical nuclear process in which a nucleus (A,Z) decays to an another nucleus (A,Z+2) and two electrons without any emission of antineutrinos. Observation of this decay would violate the lepton number conservation and would confirm that neutrinos are Majorana particles i.e. they are their own antiparticles [4,5].

2. nEXO detector

nEXO is a single phase time projection chamber (TPC) filled with 5 tonnes of liquid xenon (LXe) enriched at 90% in ^{136}Xe. The nEXO TPC is designed to detect both ionization and scintillation light, in order to utilize the anti-correlation between these two and hence improve the detector energy resolution. Figure 1 shows the conceptual sketch of the nEXO detector. The charge is collected at the top of the TPC with silica tiles patterned with crossed metallic strips [6,7]. Scintillation light is collected by a large area ($4.5m^2$) of vacuum ultraviolet (VUV)

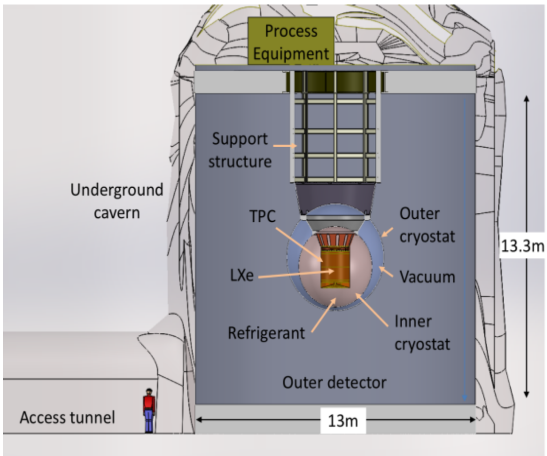

Figure 1. The nEXO detector shown in SNOLAB cryopit[3]

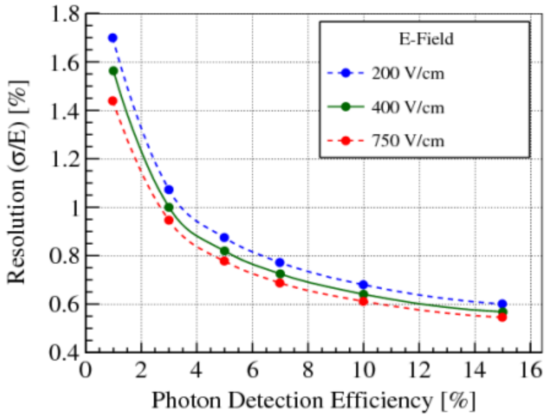

Figure 2. Energy resolution as a function of the light detection efficiency at different electric fields[3]

sensitive silicon photomultipliers (SiPMs) installed on the lateral surface of the TPC barrel. The SiPMs will cover the entire inner wall of the TPC between the field cage and the inner cryostat [6,8].

Among the isotopes for double-beta decay, ^{136}Xe is one of the attractive candidates explored in neutrinoless double beta decay experiments. The Q-value of $0\nu\beta\beta$ for ^{136}Xe is quite high at $Q_{\beta\beta} = 2458.07 \pm 0.31$ keV [9]. Xenon has high scintillation and charge yield making it an ideal target as well as detection medium.

Recent calculation results have projected the median sensitivity to $0\nu\beta\beta$ decay half-life of 1.35×10^{28} yr at 90% CL with 10 years of data taking [6,10]. In order to achieve the target half-life sensitivity, an energy resolution of 1% or better by detector at the Q value of $0\nu\beta\beta$. Efficient scintillation light collection is one of the important factors responsible for improving energy resolution in nEXO. Considering the charge collection efficiency to be ideal, the fluctuations in light detection efficiency will have greater impact on overall detector resolution. As shown in Figure 2, for 1% resolution, photon detection efficiency for SiPMs should be 3% or better at an electric field of 400V/cm in the detector. Thus, the nEXO collaboration puts great efforts towards SiPM characterization in order to select the optimal candidate for their scintillation light detection system [6].

3. nEXO photon detection system

A SiPM is a solid state photodetector which is an array of small Geiger mode single photon avalanche diodes (SPADs). Compared to conventional photodiodes, SiPMs are more compact and radiopure, operate at low bias voltages, are insensitive to magnetic field with high avalanche gain (10^6) and low dark noise rate at lower temperatures [11,12].

Recently developed VUV sensitive SiPMs are planned to be installed in nEXO to detect the 175nm scintillation light of liquid xenon. The primary specifications of SiPMs required for the nEXO light detection system are listed in Table 1. VUV sensitive SiPM devices from two manufacturers, Hamamatsu and Fondazione Bruno Kessler (FBK), have been successfully tested for nEXO. Different measurements like gain, dark noise rate, photon detection effciency and correlated noise have been taken for both SiPM devices. Results of these measurements are presented in [8,13,14]. Both devices have signficanlty lower dark noise rate than required by nEXO. Similarly, correlated noise rate values are also consistent with requirements for both

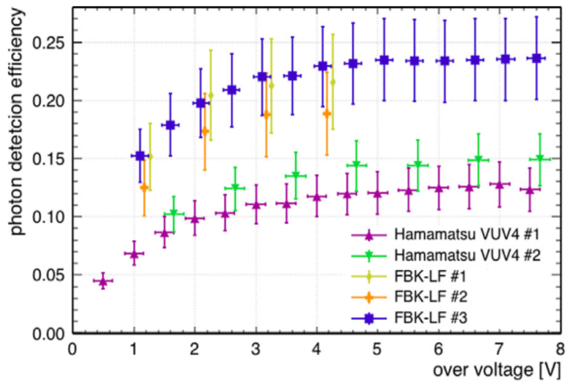

Figure 3. Photon Detection Efficiency (PDE) as a function of the over voltage for two Hamamatsu VUV4 MPPCs and three FBK-LF SiPMs [13].

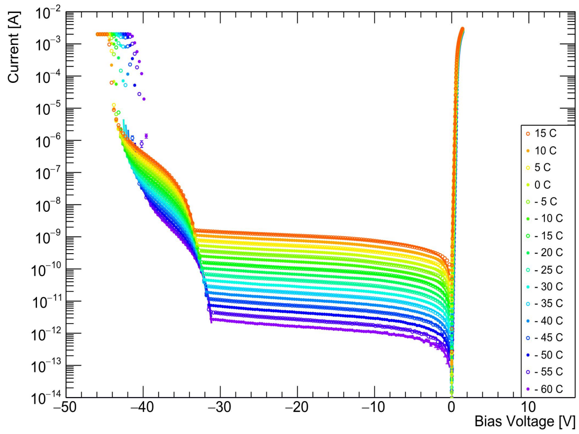

Figure 4. Current-voltage (IV) characterization of FBK-LF SiPM as a function of temperature.

devices. Photon detection efficiency (PDE) at 189nm is higher for FBK than Hamamatsu devices as shown in Figure 3.

The overall photon detection efficiency (ϵ_o) is the product of photon transport efficiency and the probability of photon hitting a SiPM gets absorbed and triggers an avalanche. The reflectivity of the SiPM surface is an important factor affecting the probability that a photon gets absorbed in a SiPM. The higher the reflectivity of SiPM, the lower will be the overall photon detection efficiency of the detector. In addition to this, the optical behaviour of SiPM for liquid xenon scintillation light has to be well-understood in order to efficiently simulate the light transport and events in the detector. The results for reflectivity measurements at different angles of incidence for both Hamamatsu and FBK devices are discussed in [15].

Table 1. List of key parameters for the nEXO light detection system and the corresponding SiPM device requirements at a temperature 165K.

Parameter	Value
Overall light detection efficiency	$\epsilon_o > 3\%$
SiPM PDE (175nm, normal incidence)	$\epsilon_{PD} > 15\%$
Dark noise rate	$< 50\text{Hz/mm}^2$
Correlated avalanche rate	<0.2
Electronic noise	<0.1 PE

4. IV characterization

nEXO aims to develop IV characterisation as a quick quality monitoring tool for large scale SiPM testing towards detector construction. An IV characterstic model is being developed to represent the behaviour in both forward and reverse bias region. The goal of this analytical model is to retrieve the empirical SiPM parameters from IV curves. One of the most important operational parameters is the breakdown voltage (V_{br}). The breakdown voltage of SiPM is the voltage above which the electric field in micro-cell is high enough that any free carrier (created by an absorbed photon or thermally generated carrier) can trigger an avalanche [16]. The value of the breakdown voltage for SiPM can be extracted from the Landau fit function of logarithmic derivative (d(lnI)/dV)[17,18].

Figure 4 shows the IV curves for VUV-FBK devices in both forward as well as reverse bias region. The dark IV data were taken over a range of temperatures for FBK low field SiPM devices in a vacuum, efficiency, reflectance and absorbance (VERA) setup at TRIUMF. The points in plot are data points and the solid line represents the IV fit. The breakdown voltage extracted from IV curves showed an increasing trend with the temperature. Apart from this, other parameters like gain, dark noise rate and correlated avalanche rate will be extracted using the fit model and pulse data of SiPMs will be used to compare and validate the results.

In conclusion, the nEXO collaboration has identified two newly-developed VUV-sensitive SiPM candidates for light detection in the upcoming low-background liquid xenon experiment. The SiPM from FBK meet the nEXO requirements. The Hamamatsu SiPMs also meet the nEXO requirements, although they achieve lower PDE. With modest improvements in PDE they qualify as an alternative to FBK. Our dedicated research and development program continues to characterize SiPM candidates and towards large-scale integration. Along with this, efficient quality monitoring tools are being developed, such as IV characterization for SiPM mass-production testing during detector construction.

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