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SiPM Readout Technique in a High Pressure Xenon Electroluminescent TPC for neutrinoless $\beta\beta$ decay searches

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The NEXT-100 experiment aims at searching the neutrinoless double beta decay ($\beta\beta0\nu$) of the ^{136}Xe isotope, using a Time Projection Chamber (TPC) filled with 100 kg of enriched and highly pressurized gaseous xenon. The experiment site is the Canfranc Underground Laboratory (LSC) in the Spanish Pyrenees.

In the NEXT TPC, the excitation and ionization signals produced by the interaction of charged particles in the xenon gas are both used for the identification of $\beta\beta0\nu$ events. The ionization signal, which is proportional to the energy deposited by the particles, is amplified through the electroluminescence process that converts proportionally the charge signal to an optical signal, with intrinsically low statistical fluctuations. This optical signal, read out by Photomultiplier Tubes (PMTs) and Silicon Photomultipliers (SiPMs), provides information on the energy and topology of the events that is only possible in gaseous xenon.

In this paper, we address the SiPM readout technique of the NEXT experiment, implemented and extensively tested during the last years in the prototype NEXT-DEMO, and its upgrade for the upcoming NEXT physics run with the detector NEXT-WHITE (NEW). The latter, presently being installed at the LSC, is aimed at measuring the two-neutrino double-beta ($\beta\beta2\nu$) decay mode of the ^{136}Xe isotope with 10 kg of enriched xenon. The NEXT-100 detector, which integrates the technological solutions of its smaller scale detector models (DEMO and NEW), will be operated right after the completion of the NEW detector physics program.

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1. Introduction

Neutrinoless double beta decay ($\beta\beta0\nu$) is a very slow nuclear transition (lifetime $> 10^{25}$ years) between two nuclei, (Z, A) → (Z+2, A) + 2 e^-, which may occur if neutrinos have mass and are identical to their antiparticles (i.e. Majorana particles). Neutrino oscillation experiments have proven that neutrinos have mass by determining the differences in neutrino squared masses. These measurements provide lower limits to the mass values, but not the masses themselves. The observation of the $\beta\beta0\nu$ transition would provide a direct information about the Majorana neutrino mass scale, besides establishing that neutrinos are Majorana particles. The $\beta\beta0\nu$ transition, which is forbidden by the Standard Model of particle physics, has not been observed to date. Recently, a limit of the effective Majorana mass of the electron neutrino of $\langle m_{\beta\beta}\rangle < (120-250)$ meV has been established by the xenon-based experiments EXO-200 and KamLAND-Zen.

The sensitivity of a $\beta\beta0\nu$ experiment to effective neutrino masses $<$ 100 meV requires facing major experimental challenges related to the critical factors that determine the experimental sensitivity, namely: the detector energy resolution that precisely defines the region of interest (ROI) around $Q_{\beta\beta}$, where the $\beta\beta0\nu$ energy peak is expected, and the detection efficiency in this region; the rate of background events from natural radioactivity that covers the searched $\beta\beta0\nu$ signal; and the scalability to large isotope masses.

The NEXT-100 experiment [1], the latest xenon-based experiment in the field, uses a high pressure gaseous xenon TPC and electroluminescence amplification of the ionization signal produced by the interaction of particles with the gas. This technique, which has been proven to combine very good energy resolution ($<$ %1 FWHM at $Q_{\beta\beta}(^{136}\text{Xe}) = 2457.8$ keV) and topological signature of the events, may allow an unambiguous identification of the $\beta\beta0\nu$ signal and provide a chance for discovery. A summary of the NEXT detector concepts and their implementation is addressed in section 2. In section 3, we describe the NEXT optical tracking technique with SiPMs. In section 4 we discuss our prospects for novel VUV sensitive SiPMs for noble gas detectors.

2. The NEXT detector

The NEXT-100 detector is an asymmetric TPC of 1.4 m diameter and 1.3 m drift length, filled with 100 kg of gaseous xenon to be operated at 10-15 bar pressure, enriched at 90% with the ^{136}Xe isotope. In the TPC, the energy deposition from a charged particle in the xenon gas produces scintillation (optical signal S1) and ionization, as depicted in figure 1-left. The ionization electrons are drifted towards the TPC anode by an electric field of about 500 V/cm, which prevents the electron-ion recombination. At the anode, the electrons penetrate a region between two transparent and parallel meshes, where a high electric field of typically $\sim$ 2 kV/cm/bar accelerates them, which excites the xenon atoms. The latter decay emitting light known as electroluminescence (EL) or secondary scintillation (S2), with a gain of typically 1000 photons/electron. This optical amplification process features very small statistical fluctuations, resulting in a high resolution in the energy measurement using the EL signal. The energy measurement is provided by the energy plane at the TPC cathode instrumented with 60 radiopure PMTs (Hamamatsu R11410) enclosed in copper cans, which protect them from the high pressure and interface them with the xenon volume through sapphire windows. The PMTs record also the primary scintillation (S1) which provides the time reference for the data acquisition and the start-of-event time (T0).

In the xenon gas at 10 bar pressure, the charged particles have extended tracks (few cms), which can be recorded using the EL signal, for the distinction of the $\beta\beta$ events from background particles. Indeed, the tracks of $\beta\beta$ particles have a distinctive topology in the gas: a long twisted track ended at both sides by a blob of higher energy deposition. The NEXT-100 tracking readout, located right behind the EL grids, and instrumented with SiPMs, is aimed at providing a 3 dimensional image of the particle tracks, as detailed in the next section. The full implementation of the NEXT-100 detector concepts has been performed in the TPC prototype NEXT-DEMO developed at IFIC, containing 1 kg of pure gaseous xenon at 10 bar pressure. NEXT-DEMO is the largest xenon gas TPC with electroluminescence and optical readout, constructed and successfully operated to date. Extensive data taking during years 2011-2014, with different radioactive sources (^{22}Na, ^{60}Co, ^{137}Cs and ^{228}Th), allowed the achievement of the main experimental goals of the NEXT demonstrator, namely: i) energy resolution extrapolates to 0.5-0.7% FWHM at $Q_{\beta\beta}$ [2], ii) in-vessel calibration of the SiPMs and characterization of the TPC using point-like energy depositions from 30 keV K_α X-rays from xenon fluorescence [3], iii) 75% background rejection from the topological signature of particle events in the $\beta\beta0\nu$ region of interest [4], iv) development of the main technological solutions for the construction of NEXT-100 detector [5].

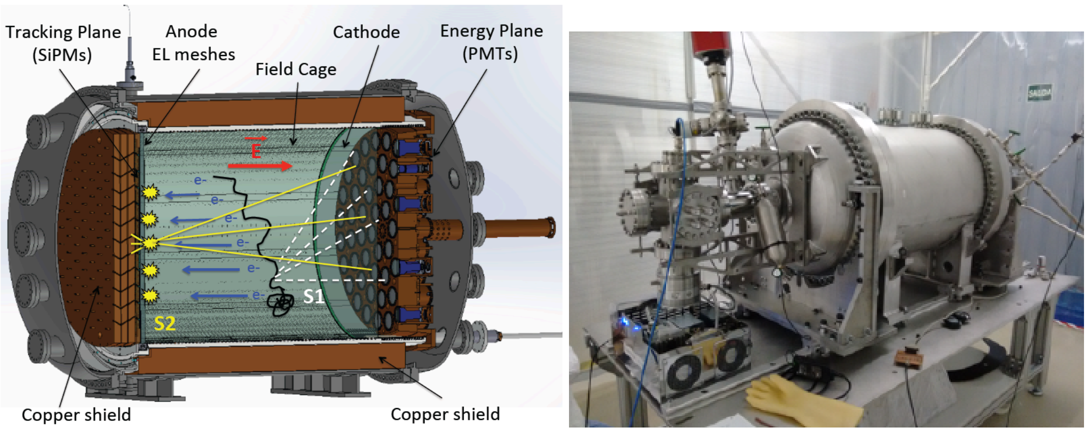

Figure 1: (left) Section view of NEXT-100 TPC. The EL light (S2) generated by the electrons drifted to the anode, provides the energy signal in the PMTs and the tracking signal in the SiPMs. (right) NEW TPC in the LSC clean room during July 2015. This TPC has 50 cm drift length.

The physics program of NEXT-100 is scheduled in two steps corresponding to two stages of the detector development: i) measurement of the $\beta\beta2\nu$ mode of the ^{136}Xe decay, during years 2015-2016, using the TPC NEXT-WHITE (or NEW) operated underground with 10 kg of enriched xenon; ii) measurement of the $\beta\beta0\nu$ mode with NEXT-100, right after the completion of NEW physics program. The NEW TPC is presently installed at the LSC with its energy plane (12 PMTs Hamamatsu R11410) fully mounted and successfully tested since July 2015 (see figure 1-right).

3. The SiPM readout technique in NEXT

The electroluminescence signal (S2) builds up in the EL region near the TPC anode, several

hundreds of μs after the start-of-event, determined by the primary scintillation signal (S1). It has a much larger duration (a few μs) than the primary scintillation (of a few ns) and a much larger yield, proportional to the number of ionization charges entering the EL region and to the reduced electric field used to accelerate them. The NEXT-100 tracking plane, located few millimeters right behind the grounded anode mesh, is instrumented with about 7000 SiPMs arranged as a matrix of imaging pixels spaced by 1 cm, as shown in figures 2 and 3. This spacing corresponds to the maximum size of the transverse diffusion of the ionization charges expected for 1 m drift length in the NEXT-100 TPC. The choice of SiPMs as imaging cells is motivated mainly by their small size down to 1 mm^2, high signal levels similar to standard PMTs and moderate cost. Their main drawback so far for a xenon-based detector is their non sensitivity to the xenon scintillation light (peak at 172 nm). This limitation is overcome using a wavelength shifter, Tetraphenyl Butadiene (TPB), that absorbs the xenon scintillation and re-emits it in the blue spectral region (peak at 430 nm).
The SiPMs in the NEXT tracking plane record the EL signals produced in their direct field of view, and provide the transversal (x-y) dimensions of the tracks. The longitudinal dimension (z) of the tracks is provided by the drift time and velocity, of 1 mm/μs, of the ionization electrons drifting to the anode. The EL signals are recorded and digitized in time intervals of 1 μs during the full electron drift time (of 1 ms in the NEXT-100 TPC), which consequently defines a resolution of 1 mm for tracking along the drift axis (z).

The tracking readout of NEXT-DEMO, described in detail in [6], is made of an array of 256 SiPMs (Hamamatsu MPPC S10362-11-050P), arranged in 4 Cuflon boards instrumented with 64 SiPMs each, as shown in figure 2-left. The SiPM-boards were coated with TPB by vacuum evaporation. The conversion efficiency of vacuum-evaporated TPB-coatings as a function of thickness and their ageing effects when exposed to VUV light at the xenon scintillation wavelength is reported in ref. [7].

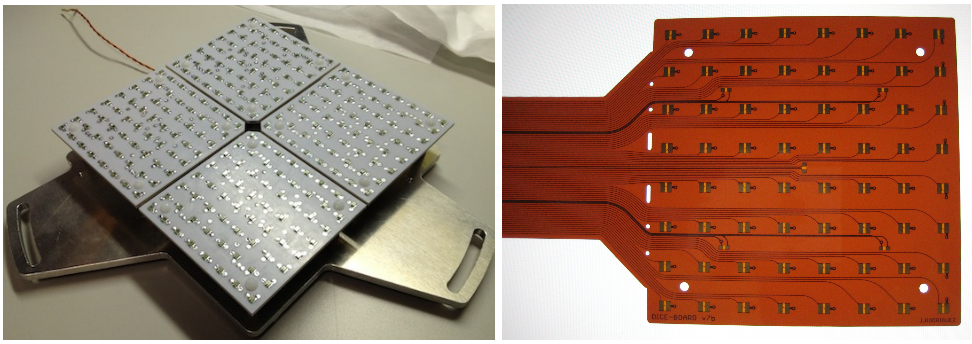

Figure 2: (left) NEXT-DEMO tracking plane composed of 4 SiPM-boards. (right) Kapton SiPM-boards of NEW and NEXT-100 tracking planes.

The tracking plane of NEW is instrumented with about 1800 SiPMs SensL MicroFC-10035-SMT-GP, arranged in 28 Kapton boards (KB) as shown in figure 2-right, temperature sensors (NTC) and one LED for calibration. The use of SensL SiPMs is mainly motivated by their low radioactivity levels in ^{208}Tl and ^{214}Bi, compatible with the background, compared to Hamamatsu SiPMs used in NEXT-DEMO (see ref. [8]). They have furthermore lower dark-noise level and sensitivity to temperature variations. The Kapton boards are also one order of magnitude less radioactive than the Cuflon boards. In addition, they allow to solder the SiPMs in an oven which was not possible with the Cuflon boards in which the SiPMs were hand soldered. The Kapton boards have a pigtail cable which transports the SiPM signals, ended by a commercial connector (from Hirose Electric Co). In the NEW tracking plane, TPB is not applied directly on the SiPM boards for practical reasons. Instead, a quartz plate coated with Indium-Tin-Oxide (ITO), for electric conductivity, and TPB will replace the anode mesh with similar transparency. The upgrades of the NEXT-DEMO tracking plane electronics for NEW address mainly: the increase of channels per front-end boards, the automatic adjustments of offsets and parameters, the reduction of power dissipation and the detector-coupled noise. The Kapton boards connectors and the processing electronics will be located behind the copper shield, placed behind the tracking plane, as depicted in figure 3-left. The tracking plane of the NEW detector will be installed and tested in the upcoming weeks.

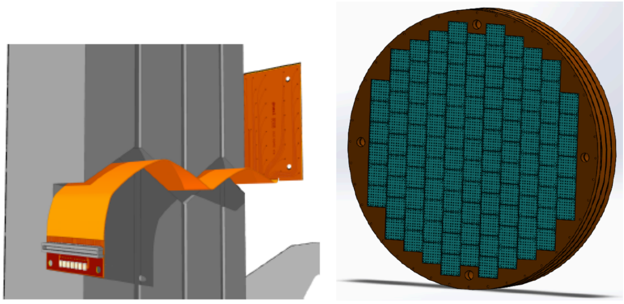

Figure 3: (left) Drawing of a Kapton SiPM-board with its cable tail and connector, shown in its working position behind the copper plates of 12 cm total thickness, used to shield the xenon active volume from external radioactivity. (right) Drawing of NEXT-100 tracking plane made of 111 Kapton SiPM-boards.

4. Tests of novel SiPMs for noble gas detectors

The increased interest in SiPMs in noble gas detectors for $\beta\beta$ decay and Dark Matter experiments is encouraging the development of VUV-sensitive SiPMs by the manufacturers. Two Hamamatsu VUV-sensitive prototypes of 3×3 mm^2 and a pixel size of 50 μm, referenced by the manufacturer as VUV2-A0023 (sample 1) and VUV2-A0024 (sample 2), have been tested in our laboratory. Our first tests of the response to VUV light of these devices consisted in measuring their average number of avalanches per incident photon, using a dedicated setup depicted in figure 4. The measurements were performed in the spectral range from 160 nm to 300 nm using a deuterium lamp coupled to a vacuum monochromator (MC) from Princeton Instruments (model VM-502) for the wavelength selection. The MC was coupled to a vacuum chamber, in which the photosensors were positioned at a chosen distance from the light output. The light intensity from the MC output was controlled through the opening of its output slit, which was manually varied from 0 to 3 mm. After the MC slit, a fused silica diffusor with 220 grit polishes (Thorlabs DGUV10-220) was placed for diffusing the light. The MC and the vacuum chamber were connected to a primary pump and two turbo-molecular pumps, which allowed to perform the measurements at a vacuum level close to 10^{-4} mbar. The incident number of photons on the SiPMs was measured with a PMT (Hamamatsu R8520-0SEL) calibrated by the manufacturer and operated without gain, i.e. with the output current taken at the first dynode. The SiPMs sample 1 and sample 2 were biased at the operation voltages of 66.73 V and 67.05 V respectively, as indicated by Hamamatsu, which corresponds to a gain of 1.25×10^6 at 25^{o}C.

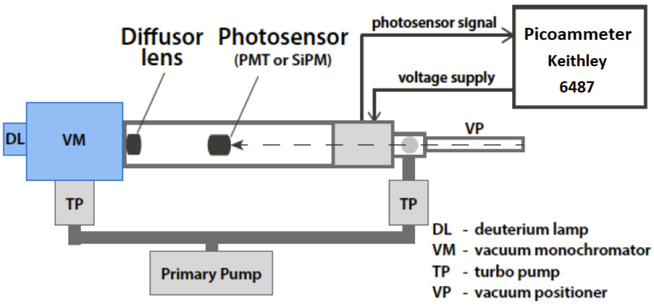

Figure 4: Experimental setup used to measure the response to VUV light of the VUV-sensitive SiPM samples.

The photocurrent response of the two SiPM samples to VUV light at 170 nm as a function of the opening of the MC output slit, or correspondingly different illumination intensities, are shown in figure 5-left. The average number of avalanches per photon of the SiPM samples as a function of wavelength, shown in figure 5-right, is determined as the ratio of the recorded photons in the SiPMs to the number of incident photons. This definition is only valid at low illumination levels, in the region of linear response of the SiPMs, i.e. at MC slit openings thinner than 1.5 mm, the photosensors being at the same position from the light source.

The response curves of the SiPMs shown in figure 5-right, have to be corrected for the SiPM gain, which has to be precisely measured at the temperature inside the vacuum chamber, probably different from the room temperature. They show however, that the average number of avalanches per incident photon of the tested samples at 170 nm is close to 25%, similar to the value of 30% measured by Hamamatsu which uses the same photocurrent method. The SiPM sample 2 has a higher response than sample 1, being both biased to have the same gain. Further measurements are necessary to determine the absolute photodetection efficiency of these devices in the VUV range (i.e. the number of avalanches per incident photon, precluding those induced by cross-talk photons and afterpulses), and test them under high pressure conditions. Besides these essential features, the radioactivity levels in ^{208}Tl and ^{214}Bi of these VUV-sensitive SiPMs is a crucial issue which will determine their possible use in $\beta\beta$ experiments.

5. Summary and outlook

The SiPM-based tracking readout of the NEXT-100 detector and its implementation in the NEXT-DEMO and NEXT-WHITE (NEW) TPCs is described. The tracking plane of NEW, which will be operated underground in the upcoming months for the $\beta\beta2\nu$ decay measurements of the ^{136}Xe, is presently being installed. Preliminary tests of novel VUV-sensitive SiPMs are also presented with encouraging results. Further tests are necessary to assess their possible use in xenon-based underground experiments.

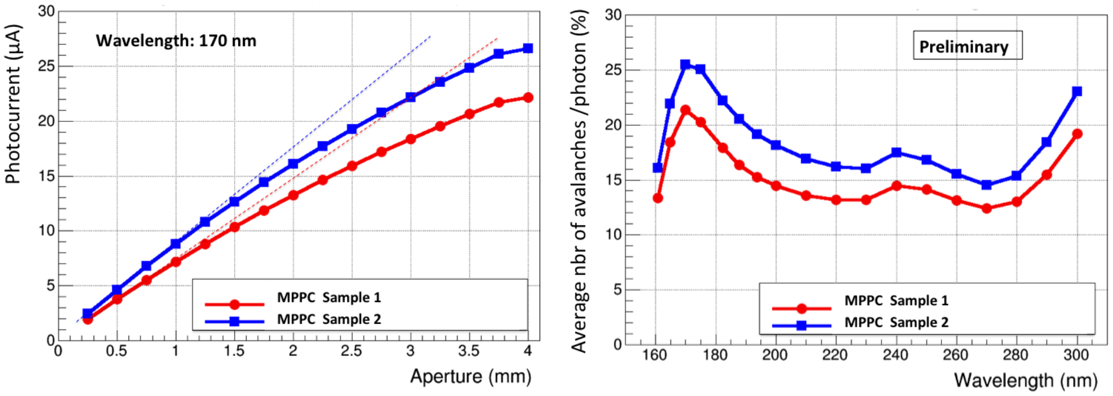

Figure 5: (left) Response of the VUV-sensitive SiPM samples as a function of the MC slit aperture; (right) Average number of avalanches per incident photon of these samples, obtained with a MC slit opening of 1 mm, as a function of the wavelength in the VUV-UV spectral region.

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