The NEXT experiment for neutrinoless double beta decay searches

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Abstract. The goal of the NEXT experiment is the observation of the neutrinoless double beta decay in $^{136}$Xe using a gaseous xenon TPC with electroluminescent amplification and specialized photodetector arrays for calorimetry and tracking. After a prototyping period (2009-2014) where the technique was demonstrated, the Collaboration has completed the construction and started the operation of its first phase (NEXT-White or NEW) in the Laboratorio Subterráneo de Canfranc, in the Spanish Pyrenees, with the objectives of measuring in-situ the NEXT background model and the two-neutrino mode of the double beta decay under a radiopure regime. After running NEW, the Collaboration will operate a bigger detector, NEXT-100, which will look for the neutrinoless decay mode.

1. The NEXT experiment
Neutrinoless double beta ($\beta\beta_{0\nu}$) decay is a hypothetical process where two neutrons in a nucleus transform into two protons emitting only two electrons and no neutrinos. The detection of such a decay would demonstrate that neutrinos are Majorana particles and that total lepton number is not conserved. No experimental evidence of the decay has been found so far, with the most sensitive searches estimating the half-life of the decay, in the case of the $^{136}$Xe isotope, to be longer than $1.07 \cdot 10^{26}$ years [1].

The Neutrino Experiment with a Xenon TPC (NEXT) [2] will search for $\beta\beta_{0\nu}$ decay using a high-pressure gaseous xenon time projection chamber. A schematic of the detection concept is shown in Figure 1. Charged particles passing through the active volume of the chamber ionize and excite the gas, causing a prompt scintillation signal that we call S1. The ionization signal is amplified, after drifting to the anode, using the electroluminescence of xenon, that is, the emission of proportional, secondary scintillation light after atomic excitation by a charge accelerated by an intense electric field.

The difference in time between this second scintillation signal, called S2, and S1 gives the longitudinal position of the event. The electroluminescence region is located close to a tracking plane composed of SiPM detectors, while the so-called energy plane, which uses PMTs to detect the light, is on the opposite side of the chamber. This way, the light detected by the tracking plane is concentrated around the transverse position of the ionization signal, whereas the light arriving at the PMTs is diffuse and only weakly dependent on the transverse position of the signal.

The experimental signature of $\beta\beta_{0\nu}$ decay consists in a fixed energy deposition equal to the energy difference between the decaying nucleus and its daughter. In addition, if produced
in high pressure gas, the two emitted electrons deposit their energy at a known rate along erratic paths due to multiple scattering, until they become non-relativistic. At the end of the trajectory, a higher energy deposition occurs (Bragg peak). This behaviour is unique to double beta decay and can be used to discriminate signal (double electron events with two end-points of higher energy) from background (mainly single electron events with only one end-point of higher energy).

The NEXT detector concept provides excellent energy resolution, close to 0.5% at the Q value of $^{136}$Xe [3]. The unique trace left in the detector by the decay makes track reconstruction an additional powerful handle to reject background [4].

2. The NEW detector

The NEXT-White (NEW), named after Prof. James White, detector is a prototype of $\sim$50 cm of drift length, which contains about 5 kg of xenon mass in the active volume at 15 bar. Its purposes are to validate the technology choices for the final, 100 kg detector (NEXT-100), and to measure the background and the two-neutrino mode of the $^{136}$Xe double beta decay.

NEW consists of a cylindrical stainless-steel vessel, designed to withstand more than 20 bar of pressure, mounted on a seismic pedestal and surrounded by a lead castle (20 cm thick) that shields the detector against the high-energy gamma flux from the rocks of the laboratory. Inside the vessel a 6-cm thick radiopure copper shield protects the active volume from the radiation coming from the outside, including the vessel itself. The readout planes are supported by 12-cm thick copper plates, and consist of 12 Hamamatsu R11410-10 photomultipliers (PMTs) and 1792 SensL C series silicon photomultipliers (SiPMs).

The PMTs (see Fig. 2-left) are 3-inch diameter and radiopure, with good quantum efficiency in the VUV and blue regions. The resulting photocathode coverage of the energy plane is about 30%. Since the PMTs cannot withstand high pressure, the volume containing them is separated from the rest of the detector and maintained in an atmosphere of nitrogen at 1 bar. The PMTs are coupled to the field cage via sapphire windows coated with TPB, to shift the VUV light emitted by xenon to blue to have a better transmission through the windows.

The SiPMs of the tracking plane (Fig. 2-right) are mounted on 28 Kapton boards, each with $8 \times 8$ sensors separated by 1 cm with the nonsensitive areas covered with a reflective teflon layer to improve the light collection on the PMTs. The plane is positioned behind a 3-mm thick quartz plate coated with a conductive Indium Tin Oxide layer, which constitutes the anode. The quartz plate is also coated with TPB, since SiPMs are not sensitive to VUV light. The plate defines the ground end of the EL region, the other end being a stainless steel mesh, kept at negative voltage.
Figure 2. Energy (left) and tracking (right) plane of NEW.

The field cage is made of a high density polyethylene tube, which holds copper rings designed to shape the electric field. Inside the rings, a 1-cm thick teflon cylinder, coated with TPB, serves as a reflector of light. The NEW field cage creates a homogeneous electric field of $300 \text{ V cm}^{-1}$ in the active volume, and a field of $2-3 \text{ kV cm}^{-1} \text{ bar}^{-1}$ in the EL region.

3. Calibration runs
NEW has been running in calibration mode since October 2016 with depleted xenon, showing a high operational stability. Over the course of the runs the detector has been calibrated using a number of radioactive sources: $^{83}\text{Kr}$ for geometric calibration and $^{22}\text{Na}$ and $^{56}\text{Co}$ for medium to high energy calibration. Additional calibration with radioactive sources is a procedure that will be carried out regularly throughout NEXT physics runs in order to monitor the variations in sensor responses in time and reconstruct events correctly.

$^{83}\text{Kr}$ is a metastable state of Kr, which decays emitting electrons that deposit their energy (about 41 keV in total) in a very small region of the gas (few mm in extent). The krypton is produced by the decay of $^{83}\text{Rb}$ zeolites inserted in the gas system, and diffuses rapidly, distributing uniformly throughout the whole chamber. Because of this, krypton is very useful for characterizing the detector, in particular for measuring the drift velocity and mean lifetime of the electrons in the gas, both of which are affected by the level of impurities. In addition, by producing an energy deposition in a very small region, almost point-like, the geometric dependence of the light detection can be measured with precision.

Several different data runs have been analyzed to perform a stable characterization of the detector, obtaining a drift velocity of 0.97 millimeters per microsecond and a mean electron lifetime of 1.5 milliseconds. Lifetime is still improving thanks to the continuous recirculation of the gas through the getters of NEW.

The lifetime and the geometrical factors extracted from krypton can be used to correct the energy measurements of the events and improve the energy resolution of the detector. Figure 3- left shows how, due to the attachment of electrons to impurities in the gas, the charge detected in the PMT plane decreases with increasing drift time. The electron lifetime is calculated by fitting an exponential function to the data, and allows one to correct the detected charge for the attachment effect. On the other hand, Figure 3- right shows the map of the geometric XY correction factors extracted from point-like $^{83}\text{Kr}$ events.

After correcting for these effects and applying a fiducial cut of $R \leq 100 \text{ mm}$ and $z \leq 100 \text{ mm}$, a resolution of $(4.03 \pm 0.03)\% \text{ FWHM}$ (with the error coming from the fit) for the krypton peak has been found, as shown in Fig. 4- left. When considering the full active volume of the chamber
the resolution is $(4.86 \pm 0.03)\%$ FWHM. When applying the corrections to events coming from the sodium source, the 511 keV photoelectric peak and its x-ray escape peak are clearly visible and distinguishable (Fig. 4-right).

Finally, a $^{56}$Co source has been used to study the topological reconstruction and its rejection power. Since $^{56}$Co has several lines above the pair-production threshold, electron-positron pairs can be produced at several energies. Such tracks are topologically identical to a two electron signal in NEXT and, therefore, can be used to test the power of the the detector capability of distinguishing between single and double electron events.

To reconstruct these events, the Collaboration uses a ML-EM reconstruction method in a similar way as in PET reconstruction. With this approach detailed tracks are obtained. Figure 5 shows an example of single electron and $e^+e^-$ tracks of $\sim$1.6 MeV. The background rejection potential of the experiment can be seen just by looking how the end-points of the tracks are different between them: the single electron events only have one higher energy end-point, while both end-points of the two electron tracks are higher energy depositions.
Figure 5. Single electron (left) and electron-positron (right) tracks from a $^{56}$Co source, reconstructed with a ML-EM algorithm [5].

4. Conclusions
The first phase of NEXT, the NEW detector, has been running at LSC in a stable way for a year, demonstrating energy resolution and tracking capabilities with calibration sources. Early results from the calibration run already show great promise and the potential of the detection technique of the experiment. The calibration runs will be finished by the end of the year. In 2018, a first low background run with depleted xenon will be carried out, followed by the search for the two-neutrino mode with enriched xenon.

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