Sensitivity of the NEXT-100 detector to neutrinoless double beta decay

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Abstract. A high pressure xenon gas time projection chamber with electroluminescent amplification (EL HPGXe TPC) searching for the neutrinoless double beta ($0\nu\beta\beta$) decay offers: excellent energy resolution [1, 2] (0.5 – 0.7% FWHM at the $Q_{\beta\beta}$), by amplifying the ionization signal with electroluminescent light, and tracking capabilities [3], as demonstrated by the NEXT collaboration using two kg-scale prototypes. The NEXT collaboration is building an EL HPGXe TPC capable of holding 100 kg (NEXT-100) of xenon isotopically enriched in $^{136}$Xe. The installation and commissioning of the NEXT-100 detector at the Laboratorio Subterráneo de Canfranc (LSC) is planned for 2018. The current estimated background level for the NEXT-100 detector is of $4 \times 10^{-4}$ counts/keV-kg-yr or less in the energy region of interest [4]. Assuming an energy resolution of 0.75% FWHM at the $Q_{\beta\beta}$ and a $0\nu\beta\beta$ signal efficiency of about 28%, this gives an expected sensitivity (at 90% CL) to the $0\nu\beta\beta$ decay half life of $T_{0\nu1/2} > 6.0 \times 10^{25}$ yr for an exposure of 275 kg yr. A first phase of the NEXT experiment, called NEW, is currently being commissioned at the LSC. The NEW detector is a scale 1:2 in size (1:10 in mass) of the NEXT-100 detector using the same materials and photosensors and will be used to perform a characterization of the $0\nu\beta\beta$ backgrounds and a measurement of the standard double beta decay with neutrinos ($2\nu\beta\beta$). An 8 sigma significance for the $2\nu\beta\beta$ signal in the NEW detector has been estimated for a 100-day run.

1. Introduction

One of the most promising technologies to search for the $0\nu\beta\beta$ decay is an asymmetric high pressure xenon gas (HPGXe) time projection chamber (TPC) with electroluminescent (EL) amplification. The NEXT collaboration is building an EL HPGXe TPC capable of holding 100 kg (NEXT-100) of xenon isotopically enriched with $^{136}$Xe. The installation of NEXT-100 at the LSC is planned for 2018. This technology offers excellent energy resolution [1, 2] (0.5 – 0.7% FWHM at the $Q_{\beta\beta}$), by amplifying the ionization signal with electroluminescent light, and tracking capabilities [3], as demonstrated by the NEXT collaboration using two kg-scale prototypes.

The EL amplification is essential to get a linear gain avoiding avalanche fluctuations and to fully exploit the excellent Fano factor of xenon in gas to obtain excellent energy resolution. In NEXT, the EL light is collected by an array of photomultipliers located behind the cathode (energy measurement) as well as by a dense array of silicon photomultipliers (topology measurement) located behind the anode. The tracking capability allows for the distinction of signal events (the two electrons emitted in a $0\nu\beta\beta$ decay), reconstructed as a continuous track.
with larger energy depositions (blobs) at both ends, and background events (mainly due to single electrons, from $^{208}\text{Tl}$ and $^{214}\text{Bi}$, with kinetic energy comparable to the end-point of the $0\nu\beta\beta$ decay) reconstructed as a track with only one end-of-track blob [5].

NEXT is an international collaboration that includes research groups from Spain, Portugal, USA, Russia, and Colombia. The NEXT research program has been organized into four stages: 1) demonstration of the EL HPGXe TPC technology with $\sim 1$ kg detectors (NEXT-DEMO and NEXT-DBDM); 2) characterization of the backgrounds for the $0\nu\beta\beta$ signal and measurement of the $2\nu\beta\beta$ decay with a 10 kg detector called NEXT-WHITE (NEW) at the Laboratorio Subterráneo de Canfranc (LSC); 3) search for the $0\nu\beta\beta$ decay with the NEXT-100 detector at the LSC and 4) scale up and further development to reduce backgrounds and enhance the topological signature for a 1 tonne-scale EL HPGXe TPC.

2. Sensitivity of the NEXT-100 detector to $0\nu\beta\beta$ decay

The most important background source in NEXT comes from radioactive impurities in the detector components from the uranium and thorium series, particularly $^{208}\text{Tl}$ and $^{214}\text{Bi}$, whose photo-peaks lie around the hypothetical $0\nu\beta\beta$ peak of $^{136}\text{Xe}$ ($Q_{\beta\beta} = 2.458$ MeV).

A thorough campaign of radiopurity measurements have been performed from 2011 to 2016 to estimate the activity of the $^{208}\text{Tl}$ and $^{214}\text{Bi}$ background sources in the most relevant components of the NEXT-100 detector. On the other hand, an estimate of the $0\nu\beta\beta$ signal and background detection efficiencies, for the $0\nu\beta\beta$ event selection in the NEXT-100 detector, has been evaluated using Monte Carlo (MC) simulations.

A $0\nu\beta\beta$ candidate event requires that: 1) only one track is reconstructed fully contained within the fiducial volume of the detector (defined by excluding a region of 2 cm around the boundaries of the active volume); 2) the reconstructed track features a blob at both ends; 3) the energy of the event is within the region of interest (ROI) $2.448 < E < 2.477$ MeV. This selection gives an efficiency of 28% for $0\nu\beta\beta$ signal events, while the natural radioactive backgrounds, $^{208}\text{Tl}$ and $^{214}\text{Bi}$, are suppressed by more than 6 orders of magnitude and the background from $2\nu\beta\beta$ decays is completely negligible.

Taking into account the contribution of each detector subsystem from the material-screening measurements and the $0\nu\beta\beta$ event selection, the estimated overall background rate in NEXT-100 is of $4 \times 10^{-4}$ counts/keV-kg-yr or less in the ROI [4]. Assuming an energy resolution of 0.75% FWHM at the $Q_{\beta\beta}$ and a $0\nu\beta\beta$ signal efficiency of about 28%, this gives an expected sensitivity (at 90% C.L) to the $0\nu\beta\beta$ decay half life of $T_{1/2}^{0\nu} > 6.0 \times 10^{25}$ yr for an exposure of 275 kg yr.

Figure 1 shows the expected sensitivity (at 90% C.L) of the NEXT-100 detector to the $0\nu\beta\beta$ half-life and to the $m_{\beta\beta}$ as a function of the accumulated exposure for an estimated background rate of $4 \times 10^{-4}$ counts/keV-kg-yr in the ROI.

3. NEXT-WHITE background expectations and sensitivity to $2\nu\beta\beta$ decay

The NEW detector is the first phase of the NEXT experiment to operate underground and is currently being commissioned at the LSC. NEW is a scale 1:2 in size (1:10 in mass) of NEXT-100.
using the same materials and photosensors [6]. A similar background model as for the NEXT-100 detector has been developed for the NEW detector considering both depleted and enriched $^{136}$Xe runs. The NEW background model is particularly detailed, as it considers potential contributions from four isotopes ($^{40}$K, $^{60}$Co, $^{214}$Bi, $^{208}$Tl) and 17 detector components, for a total of 68 background sources.

A similar event reconstruction and selection as the one developed for the NEXT-100 $0\nu\beta\beta$ analysis has been performed using MC simulations to search for $2\nu\beta\beta$ in NEW, the main difference being the looser energy requirement ($0.6 < E < 2.8$ MeV). Figure 2-left shows the expected energy spectrum for events passing the $2\nu\beta\beta$ event selection. Taking into account the material-screening measurements and the $2\nu\beta\beta$ event selection, a significance of 8 sigmas for a 100-day run is estimated for the $2\nu\beta\beta$ measurement, as shown in Fig. 2-right.

![Energy Spectrum and Background Contributions](image)

Figure 2: Left: expected energy spectrum in NEW for the $2\nu\beta\beta$ selection. Right: contributions to the background rate of NEXT-100 from different detector components. An asterisk (*) indicates that the contribution corresponds to a positive measurement of the activity of the material.

4. Prospects

Further developments to reduce backgrounds and to fully exploit the potential of the tracking signature (e.g. using deep learning techniques and different gas mixtures to reduce diffusion) are being studied by the NEXT collaboration to enhance the sensitivity to the $0\nu\beta\beta$ decay for a one tonne-scale EL HPGXe TPC.

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