NEXT: Searching for the $\beta\beta^{0\nu}$ Decay at the LSC

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The goal of the NEXT collaboration is the sensitive search of the neutrino-less double beta decay ($\beta\beta^{0\nu}$) of ^{136}Xe at the LSC. After a successful R&D phase, a first large-scale prototype of a high-pressure gas-Xenon electroluminescent TPC (NEW) is being operated at LSC since 2016. NEW is a 10-kg radiopure detector meant to understand the relevant backgrounds for the $\beta\beta^{0\nu}$ search and to perform a measurement of the two neutrino mode of the double beta decay ($\beta\beta^{2\nu}$). The first phase of the NEW physics program comprises the commissioning of the detector and the data taking with calibration sources. This phase has allowed to understand the detector capabilities in terms of energy resolution and event topology reconstruction. The operation of NEW is setting the grounds for the construction of the NEXT-100 detector: a TPC holding 100 kg of ^{136}Xe and reaching a sensitivity to the $\beta\beta^{0\nu}$ half-life of 6×10^{25} y after 3 years of data taking. The latest results of the NEW detector as well as the status of the NEXT-100 project are presented.

Keywords: NEXT; neutrinos; double-beta.

1. Searching for the $\beta\beta^{0\nu}$ decay

In the search for the $\beta\beta^{0\nu}$ process, the different experimental approaches need to be designed upon three main building blocks: 1) a good energy resolution to suppress the backgrounds from the $\beta\beta^{2\nu}$ decay and the natural radioactivity, 2) good extra handles to reduce the $\beta\beta$ like events coming from the natural radioactivity, and 3) a scalable detector technology so larger fiducial masses are feasible in case no $\beta\beta^{0\nu}$ is observed. Several experiments are ongoing implementing a more or less balanced compromise among these three building blocks, but no signal has been observed. The goal for the current generation of $\beta\beta$ experiments is to reach sensitivities down to a neutrino effective mass ($\langle m_\nu \rangle$) of ~ 100 meV. In case the $\beta\beta^{0\nu}$ decay is not detected, the next generation of experiments will aim at sensitivities of $\langle m_\nu \rangle \sim 20$

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meV, fully covering the so-called degenerate neutrino spectrum. This will require an increase of the fiducial masses of about an order of magnitude, as well as new background reduction techniques.

2. The NEXT approach: a gas-Xe TPC

The NEXT (*Neutrino Experiment with a Xenon TPC*¹) collaboration finds an optimal compromise of the above three requirements by using a gas ^{136}Xe TPC, operating at high pressure (10-15 bar). ^{136}Xe is known to be a suitable isotope for the $\beta\beta^{0\nu}$ search (high $Q_{\beta\beta}$, long $\beta\beta^{2\nu}$ half-life, ...). In a TPC, xenon is also a good detector material: it produces both scintillation light and ionization electrons when charged particles interact. The former is used to determine the start time of the event (t_0), while the latter provides the energy deposited and the event topology. Due to the lower density and fluctuations in the ionization process, operation in gas provides better tracking capabilities and energy resolution than in liquid.

The NEXT TPC is designed according to the *SOFT* (Separated-Optimized Function for tracking) concept: separated and optimized technical solutions for energy and tracking measurements. The ionization charge is drifted to the anode with an electric field (~ 0.3 kV/cm at 15 bar), where secondary scintillation is produced by means of the electroluminescence process (EL) in a region with a higher field (~ 20 kV/cm at 15 bar). This allows to measure both scintillation and ionization signals with the same photosensors, as well as to optimize the energy resolution with respect to a charge-based signal amplification, which implies larger fluctuations. The readout plane behind the cathode is devoted to perform the energy and t_0 measurements (*energy plane*), and consists of an array of low-radioactivity photomultipliers (PMTs). The readout plane behind the anode is meant to track the charged particles (*tracking plane*), and is made of a dense array of silicon photomultipliers (SiPMs).

3. A successful R&D phase

The feasibility of this technological approach has been proved with two prototypes, NEXT-DBDM and NEXT-DEMO, which took data from 2009 to 2013. The NEXT-DBDM detector, built and operated at the Lawrence Berkeley National Laboratory, is a small TPC of 8 cm drift length equipped with 19 PMTs. Its main goal is to achieve a near-intrinsic energy resolution. Resolutions of $\sim 1\%$ FWHM for 662 keV gamma rays (as shown in left panel of Fig. 1) have been obtained at 10 and 15 atm, while $\sim 5\%$ FWHM for 30 keV fluorescence xenon X-rays². These results extrapolate to $\sim 0.5\%$ FWHM at the $Q_{\beta\beta}$ of ^{136}Xe . The NEXT-DEMO detector, built and operated at IFIC, is a larger scale prototype (30 cm drift length) meant to demonstrate also the tracking capabilities. The detector holds 1-2 Kg of xenon and it is equipped with 19 Hamamatsu R7378A PMTs in the energy plane and 256 Hamamatsu SiPMs in the tracking plane, thus implementing for the first time the

SOFT concept ^{3,4}. As shown in the right panel of Fig. 1, an energy resolution of 1.6%, which extrapolates to 0.7% FWHM at $Q_{\beta\beta}$, has been obtained ⁵.

The NEXT-DEMO prototype has also proved the topological signature in the NEXT TPC concept ⁶. In a high-pressure xenon TPC, the $\beta\beta$ events have a distinctive topological signature: a continuous track ending in two larger energy depositions (*blobs*) corresponding to the Bragg-like peaks when the electrons stop. On the contrary, background electron events are characterized by a single blob. Using single electrons (e^+e^- pairs) from ^{22}Na (^{208}Tl) decays as a background (signal) sample, the rejection power based on the energy at the end-points (see Fig. 2) was estimated. A background rejection factor of 24.3 ± 1.4 (stat.)%, with an efficiency of 66.7 ± 0.6 (stat.)% for signal events, was obtained consistently for data and Monte Carlo.

4. NEXT-NEW: physics at the LSC

After demonstrating the calorimetric and tracking capabilities of the NEXT SOFT TPC in the R&D phase, the NEXT collaboration is now conducting the first physics stage of the project: the operation of the NEXT-NEW detector at the Canfranc Underground Laboratory (LSC). The goal of NEXT-NEW is threefold: 1) validate

Fig. 1. Left: Energy spectrum of 662 keV electrons in the NEXT-DBDM detector. Right: Energy spectrum of 511 keV electrons in the NEXT-DEMO detector.

Fig. 2. Energy distribution at the end-points of the tracks coming from ^{22}Na decay (left) and those coming from the ^{208}Tl decay (right) for blob candidates.

the technological solutions to be adopted in a larger detector containing 100 kg of xenon: NEXT-100, 2) validate the radiopurity of the detector operating underground, measuring the ^{214}Bi and ^{208}Tl related backgrounds, 3) demonstrate the physics capabilities of the detector by measuring the half-life of the $\beta\beta^{2\nu}$ decay once operated with enriched ^{136}Xe . The detector, whose design is shown in left panel of Fig. 3, contains about 5 kg (active volume) of xenon when operating at 15 bar, and has a drift length of ~ 60 cm. The energy plane consists of 12 Hamamatsu R11410-10 PMTs, while the tracking plane is equipped with 1800 SeneSL 1x1 mm SMD C SiPMs. The pressure vessel is made of stainless steel and can hold up to 30 bar. In order to reduce the external and vessel backgrounds, an inner shield of 6 cm of copper surrounds the active volume. The detector was built at LSC during 2015, and it has been operated on a stable basis since then. NEXT-NEW is placed in the main experimental hall of the LSC, on a seismic platform and inside a lead castle (20 cm thick), as shown in the right panel of Fig.3.

A calibration campaign has been performed between 2016 and 2017, taking data at 7 bar (2.5 kg of depleted Xe) from different calibration sources. In particular, ^{83}Kr and ^{22}Na data have been used for low and medium energy calibrations, respectively, while ^{56}Co data have been used to explore the topological capabilities of NEXT-NEW.

A ^{83}Rb source inserted in the gas system decays in ^{83}Kr which is rapidly distributed uniformly throughout the chamber. ^{83}Kr decays in turn emitting electrons leading to a point-like (few mm in extent) energy deposition of 41.5 keV. The krypton decays provide thereby a powerful tool to characterize the detector: they allow for the measurement of the drift velocity and mean lifetime of the electrons in the gas, as well as for the energy resolution and its geometric dependence. During 2017, an electron lifetime between 1.5 and 2 ms has been obtained. This value is expected to increase to about 3 ms upon further recirculation of the gas through a hot getter. A geometric map of energy corrections has also been obtained and applied to get an energy resolution of 4.5% FWHM at 41.5 keV, as presented in the left panel of Fig. 4.

The ^{22}Na source has been deployed in the detector using lateral and axial ports built in the detector vessel. An external NaI scintillator tags the backward 511-keV

Fig. 3. The NEXT-NEW detector. Left: detector design. Right: NEXT-NEW at LSC, with the lead castle open.

gamma following the β^+ decay, which is used as a trigger. The measured energy spectrum, once corrected by the electron lifetime and the geometric dependence obtained with ^{83}Kr , is shown in the right panel of Fig. 4. The 511 keV photo-peak, the X-ray escape peak, the Compton edge and the Xenon X-rays (~ 30 keV) are clearly visible. The energy resolution has been computed for both the X rays and the photo-peak, yielding 6.6% FWHM at 29.7 keV and 2.3% FWHM at 511 keV. These values are consistent with the one obtained with ^{83}Kr and extrapolate to less than 1% FWHM at the $Q_{\beta\beta}$ of Xe.

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 are produced at several energies. Such tracks are topologically identical to a $\beta\beta$ signal in NEXT (although shorter due to the lower energy) and can be used to evaluate the detector capability of distinguishing between single and double electron events. In Fig. 5, an example of single electron (left) and e^+e^- (right) tracks is shown: while the first exhibits only one blob in one the extremes, two clear blobs are present in the second. These tracks have been reconstructed with a ML-EM⁷ algorithm.

Fig. 4. Left: corrected energy spectrum of ^{83}Kr applying a radial fiducial cut of less than 16 cm. The extrapolation of the energy resolution to $Q_{\beta\beta}$ assumes only the statistical dependence. Right: energy spectrum of ^{22}Na .

Fig. 5. Single electron (left) and electron-positron (right) tracks from ^{56}Co data.

Beyond the calibration campaign, the internal radon activity has also been measured for various operating conditions. The Rn activity is derived from the alpha production rate induced in the fiducial volume by ^{222}Rn and its alpha-emitting progeny. According to these measurements and under conservative assumptions, the Rn-induced backgrounds are expected to be negligible in the search of the $\beta\beta^{0\nu}$ decay.

5. NEXT-100: the degenerate land

The ultimate NEXT detector to search for the $\beta\beta^{0\nu}$ decay down to $\langle m_\nu \rangle \sim 100$ meV is NEXT-100. This detector scales up the technological implementation in NEXT-NEW, holding a fiducial mass of 100 Kg of ^{136}Xe . By means of Monte Carlo techniques, validated in ⁶, the background rejection factors for the different event selection cuts have been computed. According to this rejection factor and an extensive radiopurity measurement campaign⁸, the final expected background rate in NEXT-100 is $\sim 4 \times 10^{-4}$ counts/keV·kg·year⁹. This value can be further reduced by means of track identification techniques based on deep neural networks¹⁰. This very low background rate will allow the NEXT-100 detector to reach a sensitivity to the $\beta\beta^{0\nu}$ half-life of $T_{1/2}^{0\nu} > 6.0 \times 10^{25}$ year (90% C.L) for an exposure of 300 kg·year ($\langle m_\nu \rangle = 80\text{--}160$ meV depending on the nuclear matrix elements considered).

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