# NEXT: Searching for the $\beta\beta^{0\nu}$ decay in the Canfranc Underground Laboratory

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Although different techniques are used to search for the neutrinoless double beta decay, the common challenges for all the existing or planned experiments are to achieve a good energy resolution and large background rejection factors. The NEXT collaboration addresses these two challenges with a high-pressure gas-Xenon electroluminescent time projection chamber (TPC), where the isotope $^{136}$Xe is used as both the source and the detection medium. The capabilities of this technology have been demonstrated with two small prototypes, NEXT-DBDM and NEXT-DEMO, which were built and operated between 2009 and 2013. The energy resolution has been measured to be below 1% at the $Q_{\beta\beta}$ value of $^{136}$ Xe, while the reconstruction of the electron tracks provides a powerful background identification handle. A larger prototype containing 10 kg of Xe, NEXT-NEW, is being built in the Canfranc Underground Laboratory. This detector will start operation in 2015 with the goal of measuring the $\beta\beta 0\nu$ background and the $\beta\beta^{2\nu}$ decay. Given the scalability of the TPC technology, NEXT-NEW will set the grounds for the NEXT-100 detector (100 kg of $^{136}$Xe) that will be operated in the LSC in 2017, searching for the $\beta\beta 0\nu$ decay up to a half-life of about $6\times10^{25}$ years after 3 years of data taking.

*The European Physical Society Conference on High Energy Physics*
*22-29 July 2015*
*Vienna, Austria*

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PoS(EPS-HEP2015)082

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

The results from oscillation experiments in the last decades have demonstrated that neutrinos are massive particles and that individual lepton numbers are not conserved. A direct consequence is the renewed interest in the double beta ($\beta\beta$) decay experiments. $\beta\beta$ decay is a nuclear transition in which two neutrons bound in a nucleus are simultaneously transformed into two protons plus two electrons. The decay mode in which two neutrinos are emitted ($\beta\beta^{2\nu}$) has been observed in many nuclei. However, if neutrinos are massive Majorana particles, the neutrinoless $\beta\beta$ ($\beta\beta^{0\nu}$) decay may be also possible. The detection of the $\beta\beta^{0\nu}$ process would prove the Majorana nature of neutrinos, providing also a measurement of the so-called *neutrino effective mass* $\langle m_\nu \rangle$:

$$\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 \, m_i \right| , \tag{1.1}$$

where $m_i$ are the neutrino mass eigenstates and $U_{ei}$ are elements of the neutrino mixing matrix.

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 beyond the claim by a subgroup of the Heidelberg-Moscow [1] collaboration, which is in strong tension with [2, 3, 4]. The goal for the current generation of $\beta\beta$experiments is to reach sensitivities down to $\langle m_\nu \rangle \sim 100$ meV, thus unambiguously refuting or confirming this claim. In case the $\beta\beta^{0\nu}$decay is not detected, the next generation of experiments will aim at sensitivities of $\langle m_\nu \rangle \sim 20$ 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 TPC concept

The NEXT (*Neutrino Experiment with a Xenon TPC*, [5]) collaboration finds an optimal compromise of the above three requirements by using a gas $^{136}$Xe TPC, operating at high pressure (10-15 bar). Xenon is the only noble gas that has a $\beta\beta$-decaying isotope ($^{136}$Xe) and no other long-lived radioactive isotope. $^{136}$Xe natural abundance is almost 9% and further enrichment can be easily achieved by centrifugation. Its $Q_{\beta\beta}$ value is relatively high (2459 keV) and the half-life of $\beta\beta^{2\nu}$ mode is of the order of $10^{21}$year [6, 7], thus being a suitable isotope as far as backgrounds are concerned. In addition, the xenon produces both primary scintillation light and ionization electrons when charged particles interact with it, thus providing two different signals in a TPC. The scintillation light is used to determine the start time of the event $t_0$, while the ionization eletrons provide the energy deposited and the event topology. With respect to liquid $^{136}$Xe the gas allows for for tracking of the charge particles due to its lower density ($86\times10^{-3}$g/cm$^3$), and for a better energy resolution due to the lower fluctuations in the ionization process (with an intrinsic limit of about 0.3% FWHM at $Q_{\beta\beta}$).

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 ($\sim$ 0.3 kV/cm at 15 bar), where secondary scintillation is produced by means of the electroluminiscence process (EL) in a region with a higher field ($\sim$ 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. R&D: technology performance

The feasibility of the technological solutions proposed by NEXT has been proved with two main prototypes, NEXT-DBDM and NEXT-DEMO, which took data from 2009 to 2013. The NEXT-DBDM detector, built and operated at 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) has been obtained at 10 and 15 atm, and $\sim$5% FWHM for 30 keV fluorescence xenon X-rays [8]. These results extrapolate to $\sim$0.5% FWHM at the $Q_{\beta\beta}$of $^{136}$Xe, significantly improving the energy resolution obtained with liquid xenon TPCs.

The NEXT-DEMO detector, built and operated at IFIC, is a larger scale prototype (30 cm drift length) meant to achieve an energy resolution of $\sim$1% FWHM at $Q_{\beta\beta}$ and to demonstrate the tracking capabilities of a high-pressure $^{136}$Xe TPC. 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 [9, 10]. 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 [11].

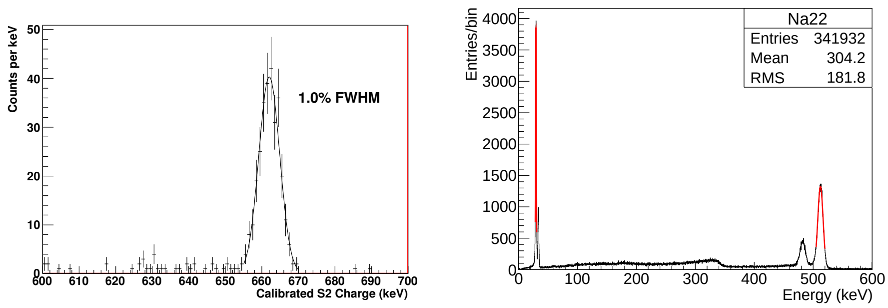


**Figure 1:** Left: Energy spectrum of 662 keV electrons in the NEXT-DBDM detector. Right: Energy spectrum of 511 keV electrons in the NEXT-DEMO detector.

The NEXT-DEMO prototype has also proved the topological signature in the NEXT TPC concept [12]. 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. Single electrons resulting from the interactions of $^{22}$Na 1275 keV gammas and electron-positron pairs produced by conversions of gammas from the $^{228}$Th decay chain have been used to represent the background and the signal in a double beta decay. These data have been used to develop algorithms for the reconstruction of tracks and the identification of the energy deposited at the end-points (Fig. 2), providing an extra background rejection factor of $24.3 \pm 1.4$ (stat.)%, while maintaining an efficiency of $66.7 \pm 0.6$ (stat.)% for signal events. As the results using Monte Carlo samples are consistent, the NEXT simulation developed by the collaboration has been validated and can be used to estimate the rejection factors and efficiencies in the near-future detectors: NEXT-NEW and NEXT-100.

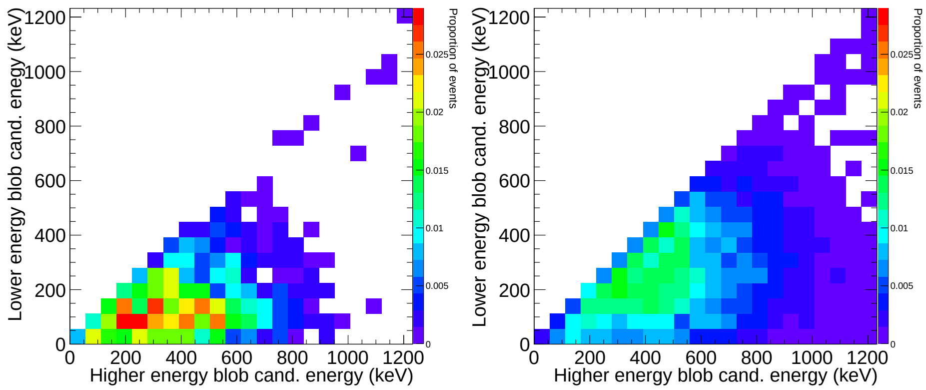


**Figure 2:** Energy distribution at the end-points of the tracks coming from $^{22}$Na decay (left) and those coming from the $^{208}$Tl decay (right) for blob candidates.

## 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 entering the first physics stage. The NEXT-NEW detector, being built at Canfranc Underground Laboratory (LSC), is the first phase of the NEXT project operating underground. The goal of NEXT-NEW is threefold: 1) validate the technological solutions to be adopted in a larger detector containing 100kg 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 10 kg of xenon and has a drift length of $\sim$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 backgrounds coming, an inner shield of 6 cm of copper surrounds the active volume.

The detector is being built at LSC during 2015. The energy plane has been installed in Summer and the tracking plane and the field cage will be ready by the end of the year, when the detector will become fully operative. NEXT-NEXT will operate on a sismic platform and inside and lead castle which are currently available at the main experimental hall of the LSC. The collaboration has already acquired 100 kg of depleted Xe and 100kg of enriched $^{136}$Xe and the gas system for the TPC is also in place. Right panel of Fig.3 show the NEXT-NEW vessel at the LSC, inside the open lead castle.

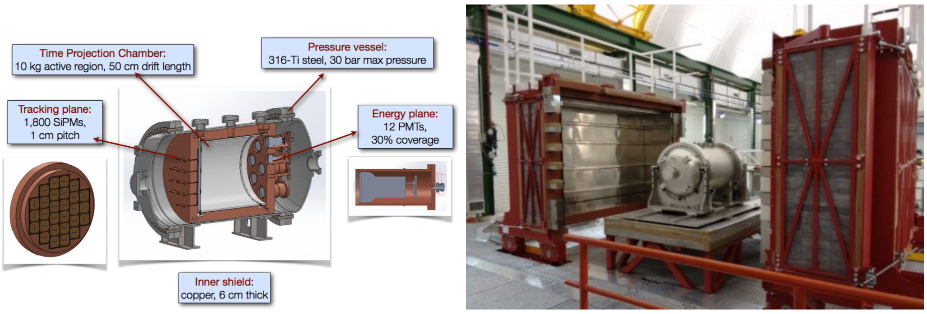


**Figure 3:** The NEXT-NEW detector. Left: detector design. Right: NEXT-NEW at LSC.

## 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. The main parts of NEXT-100 are shown in Fig. 4. The pressure vessel is made of a radio pure steel-titanium alloy. The vessel dimensions are 130 cm inner diameter and 222 cm length, with 1 cm thick walls. The inner copper shield is made of ultra-pure copper bars and is 12 cm thick, with a total mass of 9 000 kg. The light tube is made of thin teflon sheets coated with TPB (a wavelength shifter). The energy plane is made of 60 PMTs housed in copper enclosures (cans), so they can hold the pressure. The tracking plane is made of 7000 SiPMs arranged into dice boards. This detector is expected to start taking data in 2017.

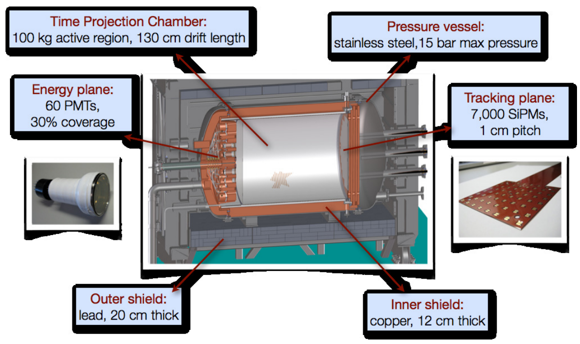


**Figure 4:** Simplified design of the NEXT-100 detector.

An extensive screening and material selection process is underway for NEXT-100. Most of the materials of the different components of the NEXT-NEW detector, to be also used in NEXT-100, have been screened in order to assure low radioactivity levels. The measurements based on Glow Discharge Mass Spectrometry and gamma-ray spectroscopy using ultra-low background germanium detectors at the LSC are already available [13]. The radioactivity values obtained for some materials like copper and stainless steel are very competitive.

By means of Monte Carlo techniques, validated in [12], the background rejection factors for the different event selection cuts have been computed. It is worth remarking the role of the topology cut requiring two blobs for $\beta\beta$ tracks: it yields a signal efficiency of about 70% while rejecting about 90% of the remaining background events. According to this rejection factor, the final expected background rate in NEXT-100 is $\sim 5 \times 10^{-4}$counts/(keV·kg·year). This very low background rate will allow the NEXT-100 detector to reach a sensitivity to the $\beta\beta^{0\nu}$ half-life of $T_{1/2}^{0\nu} > 4.6 \times 10^{25}$ year for an exposure of 300 kg·year ($\langle m_\nu \rangle$=70-190 meV depending on the nuclear matrix elements considered).

## Acknowledgments

The NEXT experiment is supported by the following agencies and institutions: the *European Research Council* (ERC) under the Advanced Grant 339787-NEXT; the *Ministerio de Economía y Competitividad* of Spain under grants CONSOLIDER-Ingenio 2010 CSD2008-0037 (CUP), FPA2009-13697-C04, FIS2012-37947-C04 and FIS2014-53371-C4; the Portuguese FCT and FEDER through the program COMPETE, project PTDC/FIS/103860/2008; and the Fermi National Accelerator Laboratory under U.S. Department of Energy Contract No. DE-AC02-07CH11359.

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