NEXT : Neutrino Experiment with high pressure Xenon gas TPC

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Abstract

The search of the neutrinoless double-β decay address the major Physics goals of revealing the nature of the neutrino and setting an absolute scale for its mass. The observation of a positive $\beta\beta^{0\nu}$signal, the unique signature of Majorana neutrinos, would have deep consequences in particle physics and cosmology. Therefore, any claim of observing a positive signal shall require extremely robust evidences. NEXT is a new double-β experiment which aims at building a 100 kg high pressure ^{136}Xe gas TPC, to be hosted in the Canfranc Underground Laboratory (LSC), in Spain. This paper address the novel design concept of NEXT TPC believed to provide a pathway for an optimized and robust double-β experiment.

Key words: Neutrinoless double-β decay, High pressure xenon gas, TPC, Electroluminescence.

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1. Introduction

Neutrino oscillation experiments have shown unambiguous evidence that at least two neutrinos have non-zero mass. The nature of the neutrino which determines the mass generation mechanism is a major Physics question. A robust discovery of the neutrinoless double-β decay would reveal the neutrino as Majorana, i.e. a neutral particle identical to its antiparticle, and would demonstrate the violation of the lepton number. Such important discoveries, should they occur, may require detectors with active mass M of hundreds to thousands of kilograms of isotopes and unsurpassed energy resolution and background rejection capability. This presents major technical challenges to the $\beta\beta^{0\nu}$ community.

One of the leading contemporary experiment in the field uses large mass of liquid xenon (LXe) [1]. LXe has attractive features, however the more advantageous properties of the xenon gaseous phase at densities below $0.55 \approx g/cm^3$, may give the opportunity for a more optimized $\beta\beta^{0\nu}$ experiment.

2. The NEXT experiment

NEXT stands for Neutrino Experiment with a Xenon TPC. This is a double beta decay experiment, recently funded and approved for operation in the new underground facility, the Canfranc Underground Laboratory (LSC) in Spain. The purpose of NEXT is to build and operate at the LSC a 100 kg high pressure xenon gas (HPGXe) TPC, enriched with ^{136}Xe isotope, to measure its double-β decay, both with and without neutrinos.

The advantages of xenon are manifold: it is the only noble gas that has a $\beta\beta$ decaying isotope, ^{136}Xe, with high natural abundance (8.9%). It can be easily enriched by centrifugation at a reasonable cost. It has a high enough $Q_{\beta\beta}$ value (2480 keV) which minimizes the overlap of the $\beta\beta^{2\nu}$ and $\beta\beta^{0\nu}$ populations. It does not have other long-lived radioactive

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isotopes, and responds to the passage of particles by a prompt (< 100 ns) scintillation light ($\lambda_{max} =$ 175 nm) that can be used as a start-of-event time t_0 [2]. These features show up xenon as an attractive $\beta\beta$ source that can be used at the same time as a tracking medium in a Time Projection Chamber [3].

The experimental efforts made so far with xenon TPCs for WIMP and $\beta\beta^{0\nu}$ decay searches focused primarily on LXe [1,3]. However, valuable investigations with small (< 5 kg) HPGXe TPC systems during the last decade have revealed outstanding features of the xenon gas for the double-β decay search. It is indeed known from the response to a deposited energy of pure xenon in liquid and gas phases, that energy resolution, measured by ionization, deteriorates as the density of the xenon increases [4]. This is attributed to the growth of large fluctuations in the energy partition between free ionization and excitation as density increases in pure xenon. In addition, the HPGXe phase offers the possibility to record the topological signature of the $\beta\beta$ events, which is a crucial handle for background rejection. The extrapolation of a small HPGXe TPC performances to a large-scale (100 kg) radio-pure HPGXe TPC has not been attempted so far for the $\beta\beta^{0\nu}$ decay search. It is however believed possible if the appropriate technical approach is developed [5]. The design concept of NEXT, detailed below, is an attempt to take up this ambitious experimental enterprise.

2.1. *SOFT electroluminescent TPC: a novel design concept*

The baseline design of NEXT is driven by the stringent requirements of the $\beta\beta^{0\nu}$ experiment and the cost-effectiveness of the different possible experimental configurations. The characteristic signature from $\beta\beta$ events is two electrons whose energies add up to $Q_{\beta\beta}$ (2480 keV). The NEXT TPC should be able to efficiently capture the true $\beta\beta$ events by recording the energy of the two electrons, while rejecting to the greatest extent the backgrounds that could mimic the true events signature. An energy resolution of $\sim$ 1% is required as well as a 3-D complete information on the signal topology, based on the 2-D tracks reconstruction and the accurate definition of the start-of-event time t_0. An additional stringent requirement of the experiment is minimizing the background due to natural radioactivity from the detector components and from the surroundings. All these factors determine to a crucial extent the detector sensitivity to the effective neutrino mass [6].

Measurements with small HPGXe systems [7–9], have shown that ultra-high energy resolution is possible using electroluminescence (EL). In an EL HPGXe chamber, the charges from the primary ionization produced by the energy deposition in the gas are drifted to the anode, where two parallel transparent mesh-grids define the EL-generating gap. The electrons in this gap are accelerated by a moderate electric field ($\sim$ 3-5 kV/cm/bar), producing a proportional UV light (EL) with extremely low fluctuations. Conversely, in any gain device based on electron avalanche multiplication (e. g. GEMs), the initial fluctuations in the primary charges are amplified, which deteriorates the energy resolution. The secondary scintillation contains the energy and the topological signature of the events, that can be read out using low-noise photosensors. Assuming a perfect reflectivity of the chamber walls, the desired number of photons (typically ≈ 1000 per electron) reaching the anode can be generated by tuning the field between the mesh-grids. The electroluminescent TPC appears therefore to be the appropriate baseline for the design of the NEXT TPC.

However, the conventional EL TPC configuration [5] cannot be applied as it is to NEXT. This TPC is symmetric with a central transparent cathode and a multi-wire anode plane at each end-cap to provide an optical gain of $\sim$ 300 through EL. Such modest gain requires a high photosensor coverage at the anode planes for the t_0 and energy measurements. Also, depending on the event localization and scintillation origin (primary or secondary), these photosensors have to record a number of photo-electrons per individual event ranging from one to thousands. This poses the difficult challenge of recording the different signal components with the same photosensor devices. To resolve this difficulty, a novel design approach called separated-optimized functions for tracking (SOFT) is considered. This is based on the use of different photosensor technologies for recording energy and tracks, respectively, at each end-cap of the TPC: PMTs behind the cathode for the energy and t_0 measurements and Multi-Pixel Photon Counters (MPPCs) behind the EL mesh-grids (anode) for tracking, as shown in Figure 1. This approach allows to solve the problem of a large dynamic range, as the gain of the photosensors acting as tracking cells can be made lower than the gain of those acting as energy cells. This solution is in addition cost-effective because it reduces by an or-

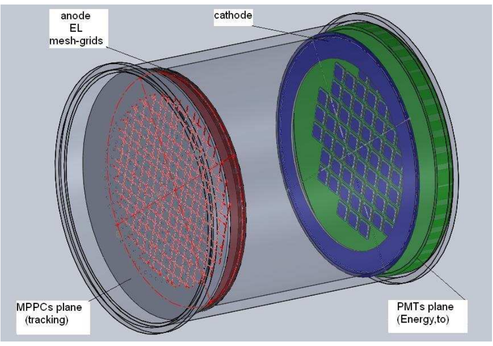

Fig. 1. The separated tracking function in the anode side (left plane) performed by MPPCs and energy function in the cathode side (right plane) performed by PMTs.

Fig. 2. The MPPCs in the tracking plane are positioned into a matrix at a pitch of about 1 cm (left). PMT used in NEXT R&D: R8520-06SEL from Hamamatsu Photonis (right).

der of magnitude the number of expensive and not enough radio-pure PMTs, and optimizes the coverage of the tracking plane with cheap, radio-pure MPPCs. Other competitive technologies for tracking, as Micro-Megas and APDs, are also being investigated.

The chamber layout of NEXT TPC is a cylinder filled with pure xenon gas at a density $\rho \approx 0.05$ g/cm^3 which corresponds to about 10 bar pressure at room temperature. Both the drift length and the diameter of the chamber are 140 cm, which corresponds to 108 kg fiducial mass. Before this TPC we call NEXT-100 is built, a 1:10 scale radio-pure prototype (NEXT-10) will be constructed to develop all the relevant issues of the experiment.

2.2. *The energy and the start-of-event t_0*

The energy resolution is determined by the total fluctuations in the measurement of the primary ionization. These fluctuations include intrinsic and technical factors. The intrinsic factor is related to the Poisson-like statistical fluctuations in the primary ionization yield and to the ionization-to-excitation partition represented by the Fano factor. The major technical factors affecting energy resolution are electron attachment to electronegative impurities in the gas, electron losses by the grid structures (limited transparency), gain processes and electronic noise.

The intrinsic energy resolution is defined as $2.35 \times \sqrt{FW/E}$, where E is the deposited energy, W is the average energy for producing an electron/ion pair ($\approx$ 22 eV), and F is the Fano factor for gaseous xenon. The measured value of F for HPGXe is $F_{GXe} = 0.15 \pm 0.02$ [2]. The intrinsic resolution in HPGXe is thus $\delta E/E \approx 2.7 \times 10^{-3}$ FWHM at $Q_{\beta\beta}$=2.48 MeV.

The simplified assumption that the various factors are statistically uncorrelated and gaussian allows to add them quadratically. This assumption, not completely true, provides an insight into the resolution power of different TPC approaches. The intrinsic and technical fluctuation sources have been estimated in a gas proportional scintillation counter with one PMT viewing a high-field parallel-grid optical amplifier [5]. The expected energy resolution for this system is found to be $\delta E/E \approx 5 \times 10^{-3}$ FWHM at $Q_{\beta\beta}$=2.48 MeV. In LXe, the large fluctuations in the partitioning of energy to ionization produce an anomalous Fano factor $F_{LXe} \approx 20$ which is about two orders of magnitude larger than in gaseous xenon. One can therefore argue that a 1% energy resolution is possible in a large HPGXe multi-PMT system using EL, provided that a careful calibration of the multi-PMT system and a stringent control of the xenon gas purity are achieved. The PMTs must be operated at a sufficient gain to detect with high efficiency single photo-electron pulses due to the primary scintillation emitted several μs prior to electroluminescence.

2.3. *The 2-D tracks reconstruction*

In HPGXe systems, the electron energy is deposited in a track of length dependent on the gas pressure. Simulations indicate that, at a pressure of 10 bar, a tracking length of about 30 cm is sufficient to provide a topological signature that allows to reject background. At higher pressure, tracks are too short to be used efficiently for this purpose. $\beta\beta$ events have a distinctive topological signature: a long cord, tortuous because of multiple scattering, ended by two blobs corresponding to ranging-out electrons (Figure 3). In LXe systems, the electrons deposit all their energy in a blob. It is therefore more difficult for a LXe detector to distinguish between a $\beta\beta$ event and a gamma interaction that deposits an energy in the vicinity of $Q_{\beta\beta}$ by photoelectric or

Compton effect.

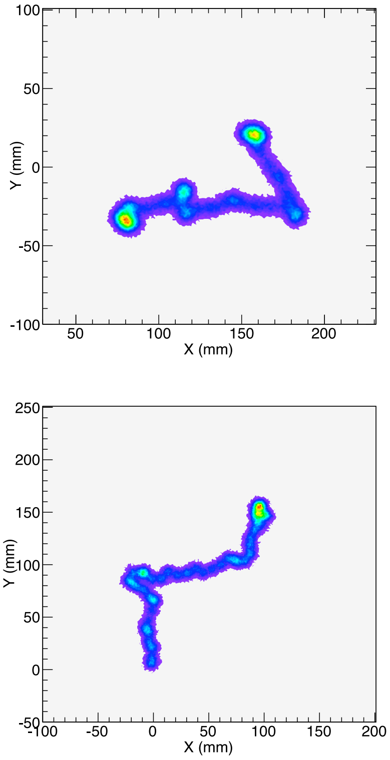

Fig. 3. The topological signature of a $\beta\beta$ event in NEXT is a cord with a blob at each end corresponding to two ranging-out electrons (top). One electron track ended by one blob (bottom).

The tracking plane of NEXT TPC should provide a 2-D pixelization of the order of the transverse diffusion ~ 1 cm, at a reduced cost per unit of sensitive area. Current simulations have indeed shown that an optimal signal-to-pixel ratio is achieved with a pixel size of about 1 cm^2. Multi-Pixel Photon Counters (MPPCs) appear therefore as attractive candidates due to their small size (1 to 9 mm^2 active area), low cost (an order of magnitude cheaper than PMTs) and very low radioactivity levels. They have in addition, high detection efficiency and high gain (10^5-10^6). A drawback of MPPCs is however their sensitivity to temperature which should be stabilized during operation. The MPPCs behind the anode will be positioned into a ceramic or PTFE matrix (Figure 2) at a pitch optimized for tracking in the SOFT TPC.

3. Summary and prospects

NEXT is a $\beta\beta^{0\nu}$ experiment recently funded and approved for operation in the new Canfranc Underground Laboratory (LSC). The NEXT collaboration aims at building a 100 kg HPGXe TPC enriched with ^{136}Xe isotope to measure its $\beta\beta^{0\nu}$ decay. A novel electroluminescent TPC design called SOFT is being developed, based on the separation of the energy and tracking functions. This approach is believed to provide a near-intrinsic energy resolution as well as an efficient background rejection capability via the $\beta\beta$ event topological signature. Finally, the compactness of NEXT TPC allows to consider its scalability to the ton-scale if the performance goals of the smaller prototypes are met. NEXT may thus offer a robust pathway for a credible evidence of a positive $\beta\beta^{0\nu}$ signal.

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