The NEXT experiment: neutrinoless double beta decay searches at the LSC

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Abstract. NEXT is a proposed 100-kg high-pressure xenon gas TPC that will search for neutrinoless double beta decay in $^{136}$Xe. Such a detector, thanks to its excellent energy resolution and its powerful background rejection provided by the distinct double beta decay topological signature, may become one of the leading experiments of the field. The project is proceeding through a fast research and development phase. The first prototypes, containing about 1 kg of pressurized xenon will be taking data in 2010, and the final detector, NEXT-100, is planned to run in late 2013 at the Laboratorio Subterráneo de Canfranc (LSC), Spain.

1. Introduction
Neutrinos, unlike the other Standard Model fermions, could be Majorana particles, that is, truly neutral particles indistinguishable from their antiparticles. The existence of Majorana neutrinos may have very deep physics implications. For example, they provide a natural explanation for the smallness of neutrino masses, the so-called seesaw mechanism [1–4]. Furthermore, Majorana neutrinos, through leptogenesis, could have induced the baryon asymmetry of the Universe [5].

The only practical way to establish experimentally that neutrinos are their own antiparticles is the detection of neutrinoless double beta decay ($\beta\beta^0\nu$). This is a hypothetical, very slow nuclear transition in which a nucleus with $Z$ protons decays into a nucleus with $Z + 2$ protons and the same mass number $A$, emitting two electrons that carry essentially all the energy released ($Q_{\beta\beta}$). Such a process occurs if and only if neutrinos are massive, Majorana particles [6,7]. Also, $\beta\beta^0\nu$ violates lepton number conservation, and is therefore forbidden in the Standard Model.

Any source of lepton number violation (LNV) can induce $\beta\beta^0\nu$ and contribute to its amplitude. If we assume, nevertheless, that the dominant LNV at low energies is the Majorana mass term for the neutrino, the rate of $\beta\beta^0\nu$ is proportional to the effective Majorana mass of the $\nu_e$:

$$m_{\beta\beta} = \left| \sum_i m_i U_{ei}^2 \right|,$$

where $m_i$ are the neutrino mass eigenstates and $U_{ei}$ are elements of the neutrino mixing matrix. Therefore, a measurement of the $\beta\beta^0\nu$ decay rate would provide direct information on neutrino masses [8].

The most sensitive limit to date was set by the Heidelberg-Moscow (HM) experiment [9]: $T_{1/2}^{0\nu}(^{76}\text{Ge}) \geq 1.9 \times 10^{25}$ years. A subset of this collaboration claimed to observe evidence for a $\beta\beta^0\nu$ signal, with a best value for the half-life of $1.5 \times 10^{25}$ years (95% CL), resulting in an
effective Majorana mass of 0.39 eV [10]. The claim has been subject of severe criticism [11]. Nevertheless, this controversial result, together with the observation of neutrino oscillations [12] (which proves that neutrinos have a non-null mass, an essential condition for $\beta\beta^0\nu$ to exist) have revived the interest in neutrinoless double beta decay searches, and several new experiments with sensitivity to $m_{\beta\beta}$ up to $\sim 100$ meV are currently under design and construction.

2. High-pressure xenon for $\beta\beta^0\nu$ searches

Double beta decay experiments are, in general, calorimeters searching for a small peak at $Q_{\beta\beta}$ in their energy spectrum. This is a challenging task: backgrounds from natural radioactivity are abundant in this region of energies and can easily overwhelm the signal peak. Good energy resolution is therefore very important, because increases the signal-to-noise ratio, but it is not enough by itself. Indeed, experiments based on germanium diodes (such as HM), devices with excellent energy resolution, have been background-limited. Consequently, all new-generation experiments try to exploit other signatures, such as event reconstruction, to further discriminate between signal and background.

A high-pressure xenon gas (HPXe) TPC can provide both good energy resolution and event topological information for $\beta\beta^0\nu$ searches. Double beta decay events have a distinctive topological signature in HPXe that can be used to reject backgrounds: an ionization track, of about 30 cm long at 10 bar, tortuous due to the multiple scattering, an with larger deposition (blobs) in both ends (see Figure 1). The Gotthard experiment [13], consisting in a small xenon TPC ($\sim 5$ kg) operated at 5 bars, proved the utility of this signature, achieving an impressively low background rate of about 0.01 counts/keV/kg/year. However, the detector suffered of a modest energy resolution, 6.6% FWHM at $Q_{\beta\beta}$, probably due to the the use of conventional avalanche amplification in a wire plane, and to the addition of methane (4%) to the xenon (in order to increase the drift velocity and to suppress diffusion), that quenched the primary signals.

Measurements in other small HPXe systems [14, 15] have shown that optimal energy resolution, $<0.5\%$ FWHM at $Q_{\beta\beta}$, is possible using electroluminescence (EL) for the amplification of the signals: the charges from primary ionization are accelerated by a moderate electric field ($\sim 3–4$ kV/cm/bar), producing a proportional emission of UV light with sub-
poissonian fluctuations. This performance seems independent of the gas pressure below some 50 bar.

Additionally, good energy resolution can also be obtained at low pressure using new-generation avalanche amplification devices such as microbulk Micromegas [16,17].

Xenon is the only noble gas that has a $\beta\beta$-decaying isotope, $^{136}$Xe. Its $Q_{\beta\beta}$-value is high enough (2458 keV) to be used in a $\beta\beta 0\nu$ experiment. The natural abundance of the isotope is 9%, but it can be enriched by centrifugation at a reasonable cost. In addition, xenon does not have any other long-lived radioactive isotopes, and being a noble gas, it can be easily purified.

3. The NEXT experiment
The Neutrino Experiment with a Xenon TPC (NEXT) [18] will search for $\beta\beta 0\nu$ in $^{136}$Xe using a 100 kg HPXe electroluminescent TPC. The project is approved for operation in the Canfranc Underground Laboratory (LSC), Spain. Following ideas in [19], the TPC will have separated readout systems for calorimetry and tracking to facilitate both measurements.

The detection process is as follows. Particles interacting in the HPXe transfer their energy to the medium through ionization and excitation. The excitation energy is manifested in the prompt emission of VUV ($\sim$175 nm) scintillation light. The ionization tracks (positive ions and free electrons) left behind by the particle are prevented from recombination by a strong electric field. Negative charge carriers drift then toward the TPC anode, entering a region with an even more intense electric field. There, further VUV photons are generated isotropically by the EL process. Therefore, both scintillation and ionization produce an optical signal, to be detected with a photosensors array (PMTs) located behind the cathode or in the chamber sides. The detection of the primary scintillation light constitutes the start-of-event ($t_0$), whereas the detection of EL light provides an energy measurement. EL light can be used also for tracking by detecting it with an array of photosensors (MPPCs, for example) located behind the anode. An alternative to this may be the use of microbulk Micromegas for both the energy measurement and the tracking.

The experiment is proceeding through a fast research and development phase. Currently, several prototypes of moderate size are being analyzed and will provide us with a better understanding of the technology. By early 2011, the NEXT Collaboration will decide on the definitive design of the NEXT-100 detector, to be installed in the Laboratorio Subterráneo de Canfranc (Spain) in 2013.

4. Backgrounds and sensitivity of NEXT
The importance of a background source in NEXT depends on the energy resolution and also on the track identification capabilities of the detector. Besides, NEXT is a fully active detector: background events with charged particles entering the active volume can be rejected defining a fiducial volume few centimeters away from the chamber walls. The reliability of such a veto depends on the accuracy of the $t_0$ measurement. Only high-energy photons can create signal-like tracks (through Compton interactions, pair-creation and photoelectric absorption) far from the detector walls.

The $\beta\beta 0\nu$ peak of $^{136}$Xe is located in the energy region of the naturally-occurring radioactive processes. Although the half-life of the parents of the natural decay chains is comparable to the age of the universe, it is very short compared to the desired half-life sensitivity of the new $\beta\beta 0\nu$ experiments ($10^{26}$ years). For that reason, even a small quantity of these nuclides creates significant event rates. Only those processes with energy around or above $Q_{\beta\beta}$ and able to mimic a signal track can become a background. In our case, the dangerous radioactive isotopes are $^{208}$Tl and $^{214}$Bi, from the thorium and uranium series, respectively.

The daughter of $^{208}$Tl emits a de-excitation photon of 2614 keV with a 100% intensity. The Compton edge of this gamma is at 2382 keV, well below $Q_{\beta\beta}$. However, the scattered gamma
can interact and produce other electron tracks close enough to the initial Compton-electron so they are reconstructed as a single object falling in the energy Region of Interest (ROI). Pair-creation events are not able to produce single-track events in the ROI. Photoplastic electrons are produced above our ROI but can lose energy via bremsstrahlung and populate the window, in case the emitted photons escape out of the detector.

After the decay of $^{214}$Bi, its daughter emits a number of de-excitation gammas with energies above 2.3 MeV. The gamma line at 2447 keV (intensity: 1.57%) is very close to $Q_{\beta\beta}$. Energy resolution is essential to separate it from the signal peak. The gamma lines above $Q_{\beta\beta}$ have low intensity (below 0.1%), but their Compton spectra can produce background tracks in the ROI.

All materials contain $^{208}$Tl and $^{214}$Bi impurities in a given amount. Careful selection of radio-pure components —some of them with activities as low as 1 $\mu$Bq/kg — and purification of the xenon is mandatory.

In addition, one has to worry about radon gas: either $^{222}$Rn (half-life of 3.8 d) from the $^{238}$U chain or $^{220}$Rn (half-life of 55 s) from the $^{232}$Th chain. As a gas, it diffuses into the air and produces background in the detector proximities. This contamination can be translated into $^{214}$Bi, for the $^{222}$Rn, or into $^{208}$Tl, for the $^{220}$Rn, their only decay products affecting the experiment. Radon may be eliminated from the TPC volume by recirculation of the xenon through appropriate filters. Also, some underground laboratories have installed charcoal scrubbers into the airstream to remove radon from the detector proximities.

Cosmic particles can also affect our experiment by producing high energy photons or activating materials. This is the reason why double beta decay experiments are conducted deep underground. At these depths, muons are the only surviving cosmic ray particles, but their interactions with the rock produce neutrons and electromagnetic showers. Active or passive shieldings will be used to minimize this background contribution. The NEXT Collaboration is considering two possible approaches for the shielding: a lead castle or a water tank.

Taking into account background estimates, signal detection efficiency and background rejection factors, we have evaluated the sensitivity of the NEXT experiment to $m_{\beta\beta}$. The result is shown in Figure 2. In a few years of data-taking, NEXT will be able to fully explore the degenerate hierarchy of neutrino masses, possibly outperforming most of the existing proposals.

![Figure 2. Sensitivity of NEXT-100 to $m_{\beta\beta}$ for an estimated level of background in the ROI of 0.4 counts/keV/ton/year.](image-url)
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References
[1] Minkowski P 1977 Phys. Lett. B67 421
[2] Gell-Mann M, Ramond P and Slansky R 1979 (Preprint Print-80-0576 (CERN))
[3] Yanagida T 1979 Proc. Works. on the Baryon Number of the Universe and Unified Theories (Tsukuba, Japan)
[4] Mohapatra R N and Senjanovic G 1980 Phys. Rev. Lett. 44 912
[5] Fukugita M and Yanagida T 1986 Phys. Lett. B174 45
[6] Schechter J and Valle J W F 1982 Phys. Rev. D25 2951
[7] Hirsch M, Kovalenko S and Schmidt I 2006 Phys. Lett. B642 106–110 (Preprint arXiv:hep-ph/0608207)
[8] Bilenky S M, Faessler A and Simkovic F 2004 Phys. Rev. D70 033003 (Preprint arXiv:hep-ph/0402250)
[9] Baudis L et al. 1999 Phys. Rev. Lett. 83 41–44 (Preprint arXiv:hep-ex/9902014)
[10] Klapdor-Kleingrothaus H V, Dietz A, Harney H L and Krivosheina I V 2001 Mod. Phys. Lett. A16 2409–2420 (Preprint arXiv:hep-ph/0201231)
[11] Aalseth C E et al. 2002 Mod. Phys. Lett. A17 1475–1478 (Preprint arXiv:hep-ex/0202018)
[12] Gonzalez-Garcia M C and Maltoni M 2008 Phys. Rept. 460 1–129 (Preprint arXiv:0704.1800 [hep-ph])
[13] Luscher R et al. 1998 Phys. Lett. B434 407–414
[14] Akimov D Y et al. 1996 Nucl. Instrum. Meth. A379 484–487
[15] Fernandes L M P et al. 2010 JINST 5 P09006 (Preprint arXiv:1009.2719 [astro-ph.IM])
[16] Balan C et al. 2010 (Preprint arXiv:1009.2960 [physics.ins-det])
[17] Cebrian S et al. 2010 (Preprint arXiv:1009.1827 [physics.ins-det])
[18] Grañena F et al. (NEXT Collaboration) 2009 (Preprint arXiv:0907.4054 [hep-ex])
[19] Nygren D 2009 Nucl. Instrum. Meth. A603 337–348