European Strategy Preparatory Group

Contributed paper

NEXT a high-pressured xenon-based experiments for ultimate sensitivity to a Majorana neutrino

The NEXT collaboration

a Executive Summary

In this paper we describe:

1. *An innovative type of Time Projection Chamber*, which used high-pressure xenon gas (HPGXe), moderate electric fields and electroluminescence amplification of the ionization charge as the basis of a 3D apparatus, capable of fully reconstructing the energy and topological signal of rare events.
2. *A specific design* of such HPGXe TPC, the NEXT-100 detector, that will search for $\beta\beta0\nu$ events using 100–150 kg of xenon enriched in the isotope ^{136}Xe. NEXT-100 has completed an accelerated and very successful R&D period and is in construction phase. It will take data at the Canfranc Underground Laboratory (LSC) in Spain. The commissioning run is foreseen in late 2013 or early 2014.
3. *Physics arguments* that suggest that the HPGXe technology can be extrapolated to the next-to-next generation (e.g, a fiducial mass of 1 ton of target), which will fully explore the Majorana nature of the neutrino if the mass hierarchy is inverse.

We point out that the NEXT program may be of great interest for the European Strategy, both for technological reasons (the intrinsic interest of the innovative HPGXe detectors with EL amplification and solid state sensor readout) and its large physics potential. We point out that xenon is the easiest and cheapest target for a future 1 ton detector and that the NEXT program can be complementary to the diode and bolometer based detectors (e.g, GERDA, CUORE), in much the same way as the Majorana and EXO experiment are considered complementary in the USA.

We thus propose that the European Strategy includes the development of a large HPGXe detector, for $\beta\beta0\nu$ (and eventually for DM searches).

b Neutrinoless double beta decay and Majorana neutrinos

Double beta decay ($\beta\beta$) is a very rare nuclear transition in which a nucleus with Z protons decays into a nucleus with $Z+2$ protons and the same mass number A. The decay can occur only if the initial nucleus is less bound than the final nucleus, and both more than the intermediate one. There are 35 naturally-occurring isotopes that can undergo $\beta\beta$. Two decay modes are usually considered:

- The standard two-neutrino mode ($\beta\beta2\nu$), consisting in two simultaneous beta decays, $(Z,A) \rightarrow (Z+2,A) + 2\ e^- + 2\ \overline{\nu}_e$, which has been observed in several isotopes with typical half-lives in the range of 10^{18}–10^{21} years.
- The neutrinoless mode ($\beta\beta0\nu$), $(Z,A) \rightarrow (Z+2,A) + 2\ e^-$, which violates lepton-number conservation, and is therefore forbidden in the Standard Model of particle physics. An observation of $\beta\beta0\nu$ would prove that neutrinos are massive, Majorana particles. No convincing experimental evidence of the decay exists to date.

The implications of experimentally establishing the existence of $\beta\beta0\nu$ would be profound. First, it would demonstrate that total lepton number is violated in physical phenomena, an observation that could be linked to the cosmic asymmetry between matter and antimatter through the process known as *leptogenesis*. Second, Majorana neutrinos provide a natural explanation to the smallness of neutrino masses, the so-called *seesaw mechanism*.

Several underlying mechanisms — involving, in general, physics beyond the Standard Model — have been proposed for $\beta\beta0\nu$, the simplest one being the virtual exchange of light Majorana neutrinos. Assuming this to be the dominant one at low energies, the half-life of $\beta\beta0\nu$ can be written as:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 m^2_{\beta\beta}. \tag{1}$$

In this equation, $G^{0\nu}$ is an exactly-calculable phase-space integral for the emission of two electrons; $M^{0\nu}$ is the nuclear matrix element of the transition, that has to be evaluated theoretically; and $m_{\beta\beta}$ is the *effective Majorana mass* of the electron neutrino:

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

where m_i are the neutrino mass eigenstates and U_{ei} are elements of the neutrino mixing matrix. Therefore, a measurement of the $\beta\beta0\nu$ decay rate would provide direct information on neutrino masses.

c Experimental aspects

The detectors used in double beta decay experiments are designed to measure the energy of the radiation emitted by a $\beta\beta$ source. In the case of $\beta\beta0\nu$, the sum of the kinetic energies of the two released electrons is always the same, and corresponds to the mass difference between the parent and the daughter nuclei: $Q_{\beta\beta} \equiv M(Z, A) - M(Z+2, A)$. However, due to the finite energy resolution of any detector, $\beta\beta0\nu$ events are reconstructed within a non-zero energy range centered around $Q_{\beta\beta}$, typically following a gaussian distribution. Other processes occurring in the detector can fall in that region of energies, thus becoming a background and compromising drastically the experiment's expected sensitivity to $m_{\beta\beta}$.

All double beta decay experiments have to deal with an intrinsic background, the $\beta\beta2\nu$, that can only be suppressed by means of good energy resolution. Backgrounds of cosmogenic origin force the underground operation of the detectors. Natural radioactivity emanating from the detector materials and surroundings can easily overwhelm the signal peak, and consequently careful selection of radiopure materials is essential. Additional experimental signatures that allow the distinction of signal and background are a bonus to provide a robust result.

The Heidelberg-Moscow experiment set the most sensitive limit to the half-life of $\beta\beta0\nu$ so far: $T^{0\nu}_{1/2}(^{76}\text{Ge}) \geq 1.9 \times 10^{25}$ years. In addition, a subgroup of the experiment observed evidence of a positive signal, with a best value for the half-life of 1.5×10^{25} years, corresponding to a Majorana neutrino mass of about 0.4 eV. The claim was very controversial, and still awaits an experimental response.

d The next generation of $\beta\beta0\nu$ experiments

The observation of neutrino oscillations (which implies that neutrinos are massive particles, an essential condition for $\beta\beta0\nu$ to exist) and the HM result prompted a new generation of $\beta\beta0\nu$ experiments that promises to push the current limits down to neutrino masses of about 100 meV or better. The status of the field has recently been reviewed (J.J. Gómez-Cadenas *et al.*, *The search for neutrinoless double beta decay*, Riv. Nuovo Cim. **35** (2012), `arXiv:1109.5515`). Among the proposed and on-going experiments, one can find many different experimental techniques, each one with its pros and cons. In order to compare them, a figure of merit, the experimental sensitivity to $m_{\beta\beta}$, is normally used:

$$m_{\beta\beta} = K\, \sqrt{1/\varepsilon}\, \left(\frac{b \cdot \Delta E}{M \cdot t}\right)^{1/4} \tag{3}$$

where ε is the detection efficiency, ΔE is the energy resolution window where the $\beta\beta0\nu$ signal will be reconstructed, b is the background rate (in counts per year, kilogram of $\beta\beta$ isotope and keV) in the region of interest, M is the $\beta\beta$ isotope mass and t is the data-taking time. The simultaneous optimization of all these parameters is a challenging problem, and consequently, many different approaches have been proposed. Some emphasize the energy resolution and the detection efficiency, like the germanium calorimeters (GERDA, MAJORANA) or the bolometers (CUORE). Others, such as EXO, combine self-shielding with good event fiducialization. The NEXT experiment, described here, combines good energy resolution, a low background rate and the possibility to scale-up the detector to large masses of $\beta\beta$ isotope.

e The NEXT TPC and its innovative concepts

The Neutrino Experiment with a xenon TPC (NEXT) will search for $\beta\beta0\nu$ in ^{136}Xe using a high-pressure xenon gas (HPXe) time projection chamber (TPC).

Xenon is a suitable detection medium, providing both scintillation and ionization signals. The isotope ^{136}Xe, with a natural abundance of $\sim 9\%$, is a $\beta\beta$ emitter. Its Q-value (2458 keV) is high enough for $\beta\beta0\nu$ searches, and its $\beta\beta2\nu$ mode is slow ($\sim 2.3 \times 10^{21}$ years), making the requirement for good energy resolution less stringent than for other $\beta\beta$ sources. In addition, the process of isotopic enrichment is relatively simple and cheap compared to that of other $\beta\beta$ isotopes, and consequently ^{136}Xe is the most obvious candidate for a future multi-ton $\beta\beta$ experiment. Xenon has no other long-lived radioactive isotopes that could become a background.

A HPXe TPC offers major advantages for the search of neutrinoless double beta decay: (a) **good energy resolution**, close to that dictated by the Fano factor of xenon, $\sim 0.3\%$ FWHM at $Q_{\beta\beta}$; (b) **tracking** capabilities, that provide a powerful signature to discriminate between signal (two electron tracks with a common vertex) and background (mostly, single electrons); (c) a **fully active and homogeneus** detector; and (d) **scalability** of the technique to larger masses of source isotope.

The design of NEXT is optimized for energy resolution by using proportional electroluminescent (EL) amplification of the ionization signal. 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 (178 nm) scintillation light. The ionization tracks (positive ions and free electrons) left behind by the particle are prevented from recombination by an electric field (0.5 kV/cm). Negative charge carriers drift toward the TPC anode, entering a region, defined by two highly-transparent meshes, with an even more intense electric field (3.5 kV/cm/bar). There, further VUV photons are generated isotropically by electroluminescence. Therefore, both scintillation and ionization produce an optical signal, to be detected with a sparse plane of PMTs located behind the cathode. The detection of the primary scintillation light constitutes the start-of-event, whereas the detection of EL light provides an energy measurement. Electroluminescent light provides tracking as well, since it is detected also a few mm away from production at the anode plane, via a dense array (1 cm pitch) of 1-mm^2 SiPMs. This *separated, optimized function for tracking* (SOFT) with light sensors is a novel instrumental concept developed for the experiment.

f Development of the NEXT project: R&D and prototypes

The NEXT project started formally in 2009 when the NEXT collaboration, submitted a *Letter of Intent*, (`arXiv:0907.4054`) to the Laboratorio Subterráneo de Canfranc (LSC). Between 2009 and 2012 the NEXT R&D program has focused in the construction, commissioning and operation of two large prototypes:

1. **NEXT-DBDM**, a prototype equipped with an energy plane made of 19 Hamamatsu R7378A PMTs, sensitive to the VUV light and pressure-resistant up to 20 bar. This prototype can hold up to 2 kg of xenon at 15 bar. The fiducial volume is a cylinder of 16 cm in length and 16 cm in diameter (a proportion similar to the length to diameter ratio in NEXT-100). The main goal of this prototype was to perform detailed energy resolution studies. The detector is operating at LBNL.

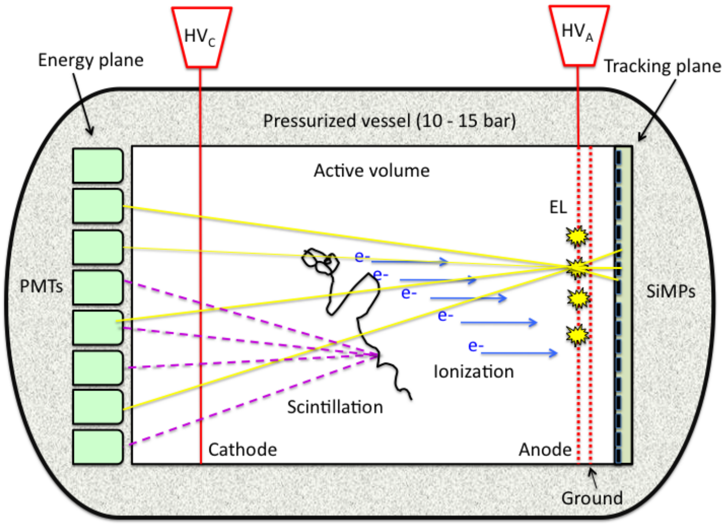

Figure 1: The detection process in the NEXT TPC: EL light generated at the anode is recorded in the photosensor plane right behind it and used for tracking. It is also recorded in the photosensor plane behind the transparent cathode and used for a precise energy measurement.

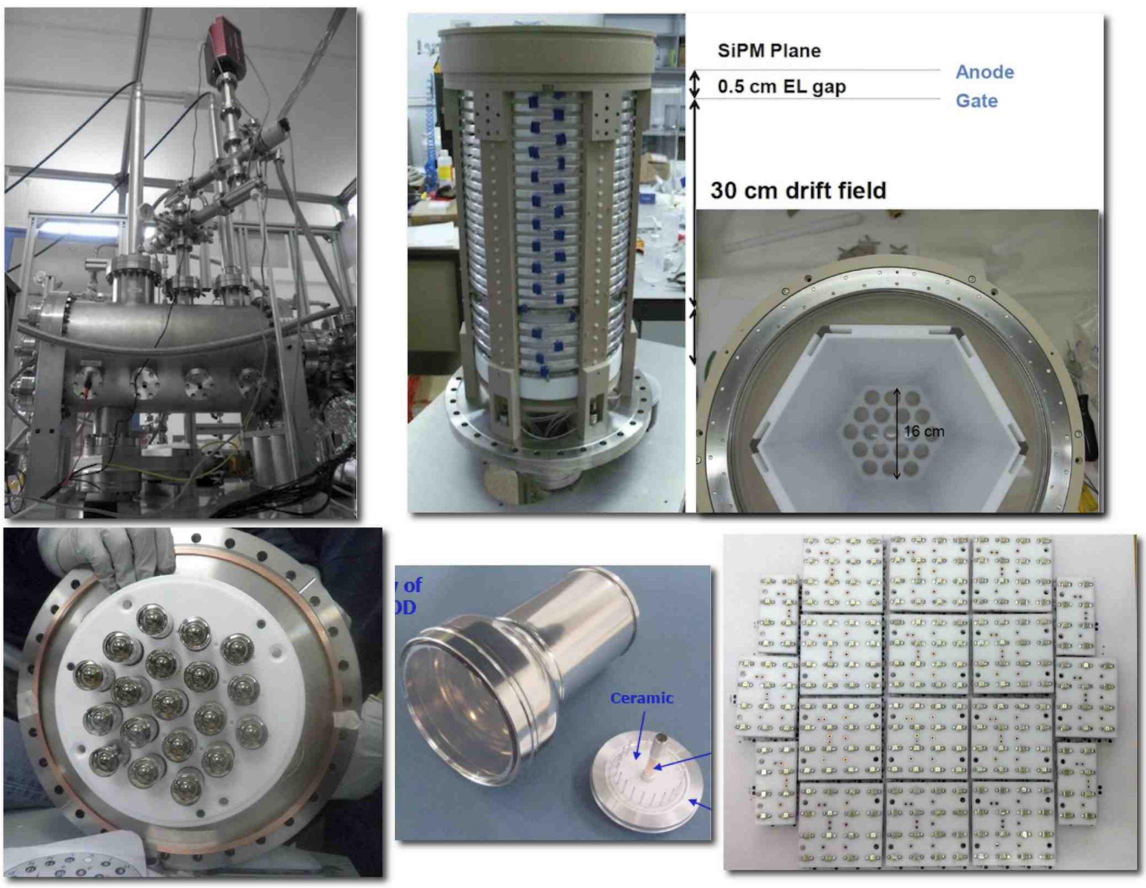

Figure 2: The NEXT-DEMO prototype. From left to right and from top to bottom: (a) The pressure vessel, showing the HVFT and the mass spectrometer, (b) the field cage, which provides 30 cm drift lenght, (c) the light tube, made of Teflon panels, showing the honey comb for the PMT plane, (d) the energy plane equipped with 19 Hamamatsu R7378A PMTs, (e) the PMTs to be used in NEXT-100, (f) the tracking plane, equipped with 300 Hamamatsu MPPCs.

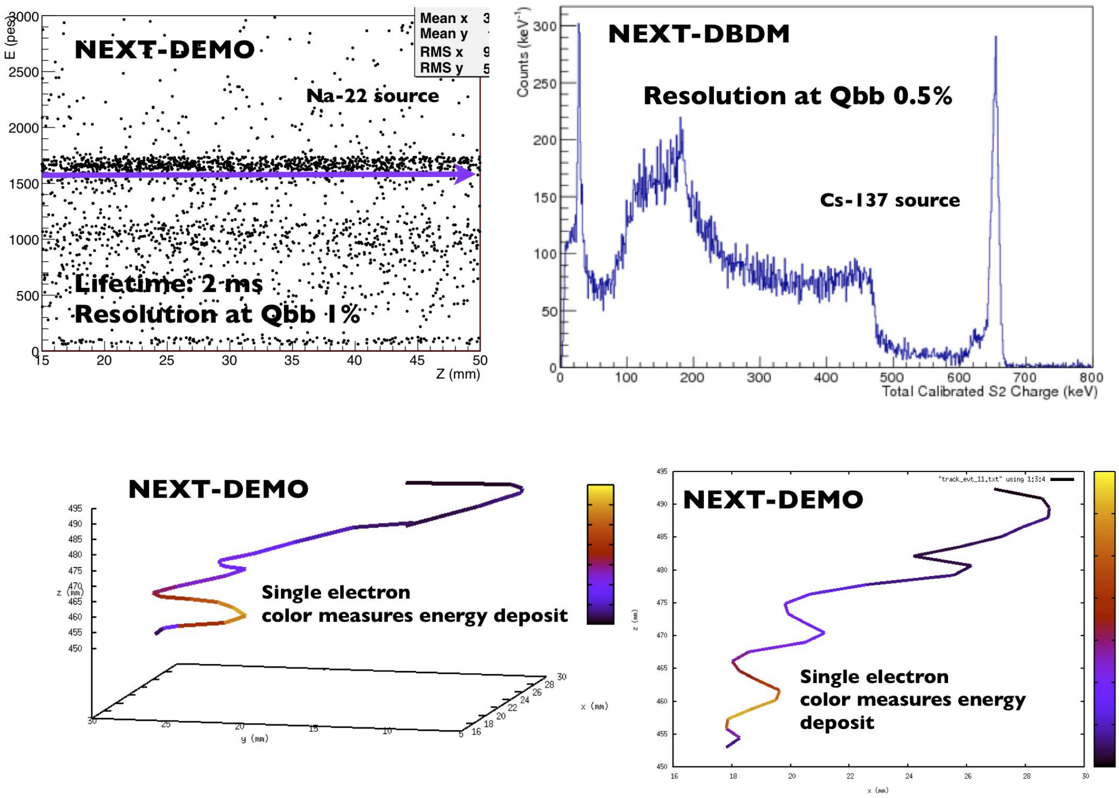

Figure 3: Top-Left: Energy vs Z measured with NEXT-DEMO (Na-22 source) showing excellent lifetime (larger than 2 ms) and good energy resolution. Top-right: The energy resolution measured by NEXT-DBDM using a ^{137}Cs radioactive source (in a restricted, central region) extrapolates to $\sim$0.5% FWHM at the energies of ^{136}Xe decay. Bottom: An electron of 511 keV recorded by NEXT-DEMO. The track starts as a mip and the energy increases until the maximum is reached at the end of the track. NEXT-DEMO measures an energy resolution using Na-22 sources that extrapolates to 1% FWHM in the full fiducial volume.

2. **NEXT-DEMO** (Figure 2). This is a larger prototype, operating at IFIC, Valencia. The pressure vessel has a length of 60 cm and a diameter of 30 cm. The vessel can withstand a pressure of up to 15 bar. The maximum capacity of the detector is 10 kg but in its current configuration (the fiducial volume is an hexagon of 16 cm diameter and 30 cm length) it holds 4 kg at 10 bar. NEXT-DEMO is also equipped with an energy plane made of 19 Hamamatsu R7378A and a tracking plane made of 300 Hamamatsu MPPCs. The main goals of this prototype are: (a) to demonstrate track reconstruction and the performance of MPPCs (coated with a wavelength shifter, TPB, to make them sensitive to xenon VUV, see *SiPMs coated with TPB : coating protocol and characterization for NEXT*, `arXiv:1201.2018`) (b) to test long drift lengths and very high voltages (up to 50 kV in the cathode and 25 kV in the anode), (c) to understand gas recirculation in a large volume, including operation stability and robustness against leaks; (d) to understand the transmittance of the light tube, with and without TPB. In summary, to demonstrate the technology to be used by the NEXT-100 detector.

The intense R&D has resulted in a Conceptual Design Report (CDR, `arXiv:1106.3630`) and a Technical Design Report (TDR, `arXiv:1202.0721`), where the final detector concept is defined, including the background model and the most relevant results of the prototypes, namely an excellent energy resolution and tracking capabilities, as illustrated in Figure 3.

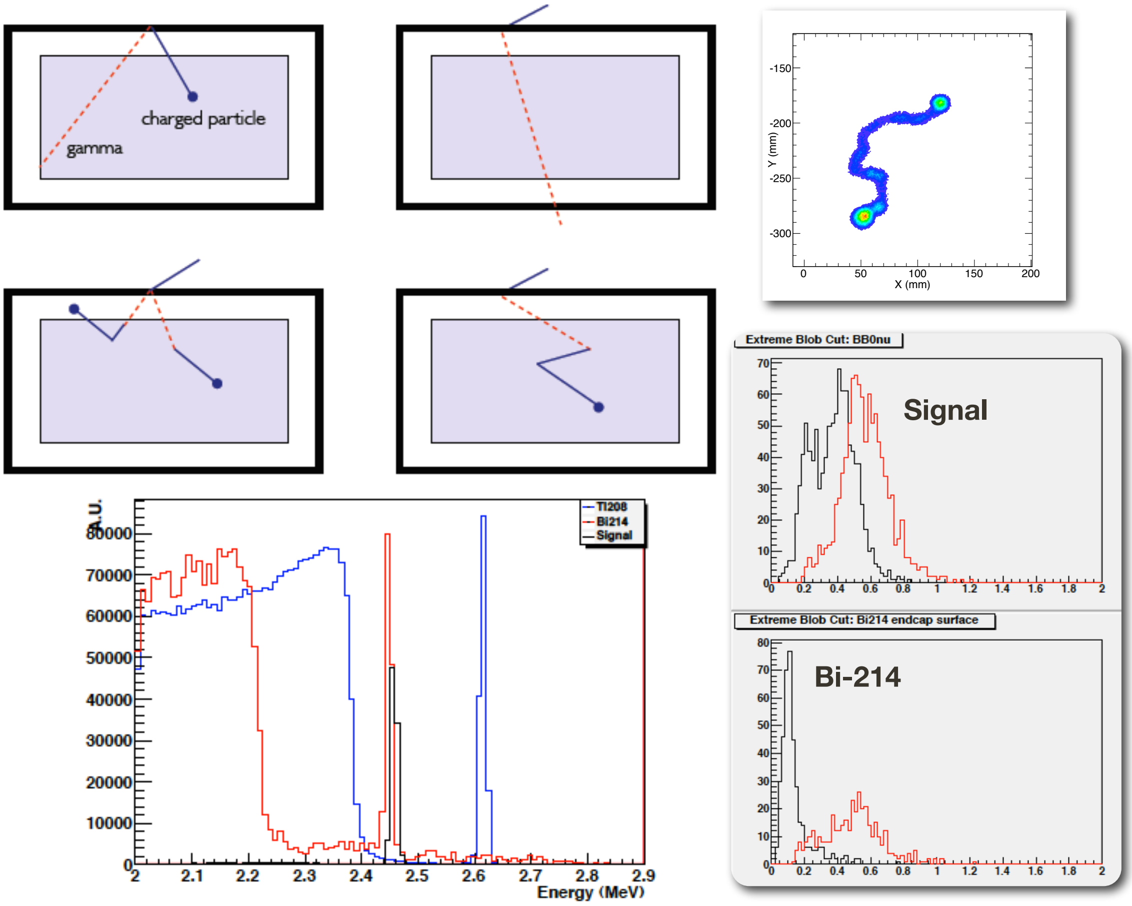

Figure 4: The rejection power of NEXT is due to a combination of: (top-left) full 3D reconstruction, (bottom-left) excellent energy resolution and (right, top and bottom) the availability of a topological signature.

Table 1: NEXT radioactive budget. The contribution from the Matryoshka includes LC, PV and ICS (see text).

	^{214}Bi	^{208}Tl
Matryoshka	1.0×10^6	1.6×10^5
Energy plane	8.6×10^5	2.3×10^5
Tracking plane	3.2×10^5	8.2×10^4
Field cage	8.2×10^5	1.7×10^5
FEE	7.2×10^5	6.2×10^5

g Physics potential of NEXT

The reasons for the excellent sensitivity of NEXT are thoroughly discussed in the TDR and can be summarized as follows:

- **It is a radiopure experiment**, in which the external (laboratory rock, cosmic muons, etc.) and internal (pressure vessel, PMTs, etc.) background flux is reduced to a small level. This is achieved designing NEXT as a *matryoshka*, or russian doll. The outermost layer of the matryoshka is a shield made of lead (the lead castle, LC), which attenuates the background from the LSC walls by 6 orders of magnitude (e.g, the ^{208}Tl photons are attenuated from $\sim 10^{12}$ per year to $\sim 10^{6}$ per year). The pressure vessel (PV) is the next layer, and the inner copper shield (ICS) the innermost and more radioclean layer of the matryoshka. In addition, all the NEXT components are selected and screened for low background. Of particular importance are the PMTs, whose activity is only 0.4 mBq of ^{214}Bi and 0.3 mBq of ^{208}Tl per unit. Our TDR shows a full quantification of the different contributions to the NEXT radioactive budget, summarized in Table 1. Notice that the leading contribution to the budget (e.g, in the ^{214}Bi contamination) of the matryoshka (including LC, PV and ICS), energy plane, field cage and front end electronics, FEE (shielded by the ICS) are very similar. The total radioactive budget is 3.7×10^{6} decays per year due to ^{214}Bi and 1.3×10^{6} decays per year in the ^{208}Tl channel.
- **It has a very good background rejection factor** ($\sim 2 \times 10^{-7}$), possible thanks to:
  1. **The full 3D imaging of the event** (in Figure 4, top left, one can see that only photons that interact in the fiducial volume leaving no charged trace in the detector are a source of potential background).
  2. **The excellent energy resolution** (Figure 4 shows, with arbitrary normalization, the signal –in black–, and the two dominant backgrounds, e.g, the 2.4 MeV gamma emitted by ^{214}Bi –in red– and the 2.6 MeV gamma emitted by ^{208}Tl –in blue–. The resolution, essential to separate the signal from these backgrounds, is 0.5% FWHM, as measured by our prototypes).
  3. **The availability of a topological signature**. Figure 4 (top, right), shows the characteristic signature of the two-electrons signal, which exhibits two blobs at the end of the reconstructed track (one blob per electron stopping in the chamber). In contrast, background electrons are produced by Compton or photoelectric interactions, and are characterized by a single blob (and often by a satellite cluster corresponding to the emission of 35 keV fluorescence X-rays by xenon, see Figure 3, right). Figure 4 (bottom, right), shows the energy distribution of reconstructed blobs (according to MC simulation), for the signal (top) and the background (^{214}Bi events, bottom). While the signal identifies two blobs of equal energy, the second blob in the background is due to reconstruction effects and has much smaller energy. The difference between both distributions, plus the identification of the fluorescence X-ray yields an additional background suppression not available in other experiments. Notice that the background rate (5×10^{6} decays per year in total) multiplied by the rejection factor results in 1 background event a year, a rate of the same order than that due to the $\beta\beta0\nu$ decays of a 50 meV neutrino.

The combination of excellent energy resolution, topological signature, large mass and a radio-clean detector results in an experiment with an excellent physics potential, as demonstrated in a recent papers (for example JCAP **06** (2011) 007, `arXiv:1109.5515`), where it is shown that NEXT can be among the most sensitive experiments of the next generation, reaching a sensitivity close to 50 meV. Notice that NEXT is one of the few experiments that can be scaled up to a mass in the ton range. A HPXe TPC operating at 20 bar would need 10 m^3 to hold 1 ton of gas. This is challenging but not unfeasible, in particular after the experience gained with NEXT-100.

To summarize, NEXT is based in the innovative concepts of a HPGXe purely electroluminescent SOFT TPC. Its ultimate energy resolution is much closer to that of germanium crystals and tellurium

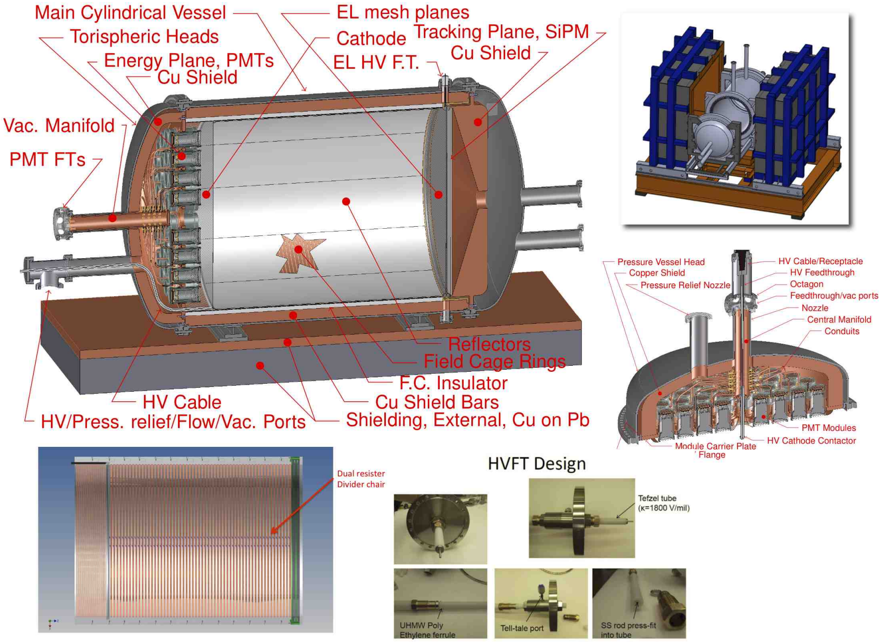

Figure 5: Final design of the NEXT-100 detector. The pressure vessel, made of radiopure steel-Ti alloy can take up to 20 bar pressure and hold 150 kg of xenon at 15 bar. An ultra-pure inner copper liner shields the residual radioactivity emanating from the vessel. The field cage is made of copper rings and the EL grids of titanium wires. A very reflective teflon light tube (coated with TPB) allows maximum light collection. Energy is measured by radio-pure Hamamatsu PMTs enclosed in ultra-pure copper cans and coupled to the gas by sapphire windows. Tracking is measured by MPPCs coated with TPB.

bolometers than any of the other large-scale experiments being proposed or built. But NEXT has also the distinctive advantage of providing a topological signal (tracking of the two electrons), and being a scalable detector, able to deploy a large mass, in the range of the 1 ton of isotope. As such, it can become one of the best $\beta\beta0\nu$ experiments of the field, capable to fully explore the inverse hierarchy.

h Construction and commissioning of NEXT-100 at LSC

The intense R&D carried out by the NEXT collaboration has resulted in a Technical Design Report (TDR, `arXiv:1202.0721`), where the final detector concept is defined.

Figure 5 shows a drawing of the NEXT-100 apparatus, revealing all the major subsystems. These are: the pressure vessel (PV); the Inner Copper Shield (ICS); the field cage (FC) which includes the electrical system (e.g, a transparent cathode and a transparent EL grid and anode), as well as the light tube (LT); the energy plane (EP), made of PMTs; the tracking plane (TP), made of MPPCs; and the external shielding, a lead castle.

- **The pressure vessel**, consisting in a main cylindrical vessel (130 cm inner diameter, 222 cm length, 1cm thick walls) and torispherical heads. The PV is made of radiopure 316Ti alloy and its total mass is 1 200 kg. Its activity is 1.9 mBq/kg in ^{238}U — or 214Bi — and 1 mBq in ^{232}Th — or 330 μBq/kg in ^{208}Tl—. The design of the PV has been carried out by the LBNL and IFIC groups. The PV will be built by a Spanish firm.

- **The inner copper shield**, made of ultra-pure copper bars, 12 cm thick, with a total mass of 9 000 kg. The ICS attenuates the radiation coming from the external shells of the Matryoshka (including the PV and the external lead shield) by a factor of 100. After the ICS the residual activity is 32 mBq.

- **The field cage**. Its main body is a high density polyethylene (HDPE) cylindrical shell with a 2.5 cm wall thickness, contributing about 35 mBq to the radioactive budget. The drift region consists of OFHC copper strips connected with low background resistors. The rings and resistors add 10 mBq to the radioactive budget. The drift voltage is 0.3 kV/cm, and the drift length 127 cm. The NEXT-DEMO and NEXT-DBDM prototypes have shown that long drift distances, excellent resolution and good tracking can be achieved with these parameters. The FC is being built by Texas A&M.

- **The light tube**, consisting of thin sheets of Tetratex^{TM} (TTX), fixed over a 3M^{TM} substrate. The TTX will be vacuum coated with tetraphenyl butadiene (TPB) wavelength shifter to maximize the light yield. The mass of the LT is very small, resulting in a negligible activity. The LT will be built and coated at IFIC.

- **The energy plane**, made of 60 PMTs, sitting behind a transparent cathode and covering 32.5% of the cathode area. The PMTs will record both primary scintillation light (thus measuring the event t_0) and secondary, EL light. The model is R11410–10 from Hamamatsu. These are large tubes, with a 3" photocathode and low levels of activity of the order of 0.4 mBq per unit in the uranium and 0.3 mBq per unit in the thorium series. The QE of the R11410-10 model is around 25% both in the VUV and in the blue region. The PMTs will be tested at IFIC, prior to installing them into individual pressure resistant, vacuum tight copper enclosures (cans) coupled to sapphire windows. The cans are all connected via individual pressure resistant, vacuum tight tubing conduits to a central manifold. The PMT cans are maintained at vacuum well below Paschen minimum, avoiding sparks and glow discharge across PMT pins. The total activity from the EP is 35 mBq, dominated by the PMTs themselves. The PMT enclosures and vacuum manifold are being fabricated at LBNL.

- **The tracking plane**, made of MPPCs sitting behind the transparent EL grids. The MPPCs are manufactured by Hamamatsu and the chosen model is S10362-11-050P. This small device has an area of 1mm^2, 400 pixels per sensor and very large particle detection efficiency (PDE) in the blue region. It is very cost effective and its activity is very low. The MPPCs will be mounted in Dice Boards (DB), at a pitch of 1.1 cm (see Figure 2). The DBs are square boards made of *cuflon* (PTFE fixed to a copper back plane), containing 8×8 pixels. In total we need 7 000 pixels. The TP contributes less than 15 mBq, including mechanical supports, grids and cables. The DBs will be assembled at several NEXT institutes. The front-end electronics, designed by LBNL, UPV and IFIC is inside the gas, shielded behind a thick copper plate. Our design consists of a very simple front-end, very low power ADCs and a digital data merger stage (FPGA) to be placed inside the detector. The electronics will be mounted in a ring around the tracking plane and shielded behind the ICS, contributing about 25 mBq to the radioactive budget.

- **The gas system**, which is designed with high–redundancy and emergency recovery procedures to be capable of pressurizing, circulating, purifying, and depressurizing the detector with xenon and other test gases (such as argon) with negligible loss, and without damage to the detector. There is a high priority on avoiding loss of enriched xenon (EXe). Our design parameters call for a maximum leakage, EXe through seals (recoverable) of 100 g/yr and a maximum loss to atmosphere of 10 g/yr.

- **The lead castle**, (Figure 5 (top, right)) provides 20 cm of lead as the external NEXT shield.

The design of all these systems has proceeded during 2011 and will extend, for most of them, until the second quarter (Q2) of 2012. The different parts will be built, mainly in Spain (PV, LC, LT, TP) and USA (FC, EP). The construction period will be from Q2 2012 to Q2 2013. There will be a commissioning run with argon and natural xenon (NXe) during Q3 and Q4 of 2013. The commissioning run will not include the ICS, and will only include a partial LC. In addition the gas system will not include the most sophisticated parts needed for the enriched xenon run. The detector will be upgraded (installation of the ICS, completion of LC, upgrade of the gas system) in Q1 and Q2 2014. A second commissioning run, with the full detector will start in Q3 2014. The enriched xenon run could start in Q4 2014 or Q1 2015.

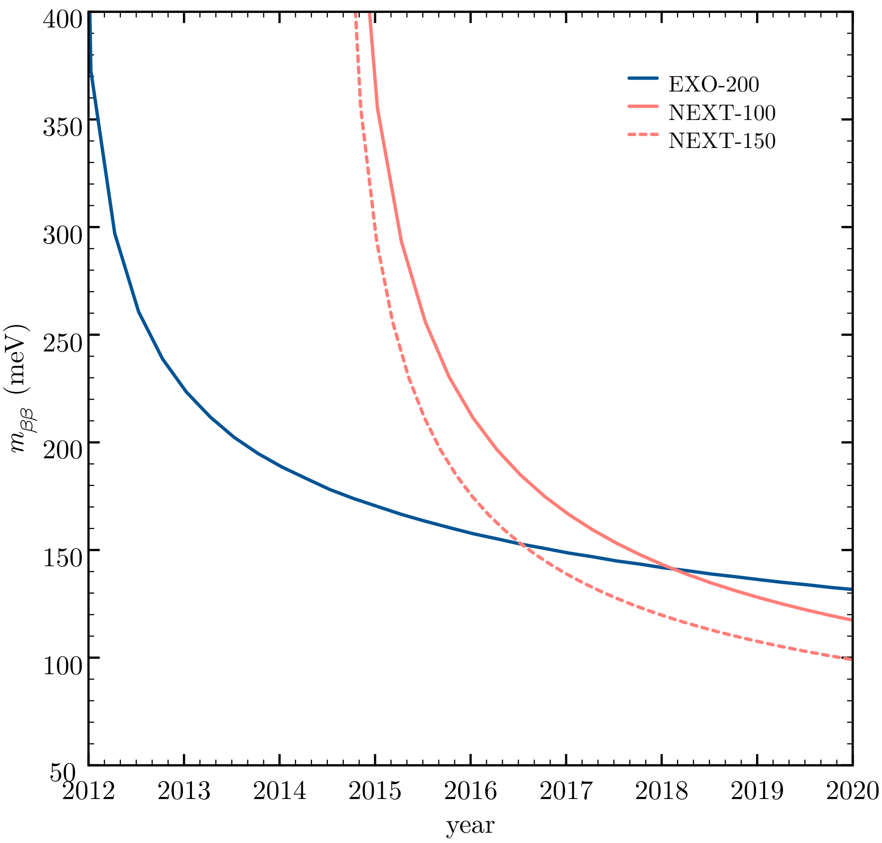

Figure 6: Sensitivity of NEXT versus sensitivity of EXO. The calculation assumes a conservative overall exposure efficiency of 50%. A resolution of 4% (1%) FWHM is used for EXO (NEXT) as measured by both experiments. The background in the ROI is 1.5×10^{-3}counts/(keV · kg · y) (0.8×10^{-3}counts/(keV · kg · y)) as measured by EXO and computed in the NEXT TDR. Since NEXT can run with 150 kg of mass (operating the detector at 15 bar) the corresponding sensitivity curve is also included. It is assumed that NEXT physics run starts in mid 2014.

i Recent experimental results and its implications

The most stringent limit in the search for $\beta\beta0\nu$ events has been produced this year (2012) by EXO-200 (arXiv:1205.5608). EXO-200 is a liquid-xenon (LXe) TPC operating at WIPP (USA). Liquid xenon has a number of advantages, including a considerable power of shelf-shielding against the backgrounds (alas, at the expense of expensive, enriched xenon). The advantages of EXO-200 are its compactness and simplicity. The disadvantages, compared to NEXT, are a relatively poor energy resolution and a poorer topological signature. Although events are clearly located, and site rejection of Compton electrons is possible, the density of LXe does not allow for the observation of the electron tracks. The EXO experiment is pioneering background suppression using Ba tagging. The technique is still in the R&D phase.

EXO-200 deploys a total mass of 200 kg of enriched liquid xenon (at 85%). About half of this mass is used for self-shielding. The energy resolution measured by the collaboration in their recent paper is 4% FWHM at $Q_{\beta\beta}$. This is achieved by using the anti-correlation between ionization and scintillation signals. The background rate measured in the Region of Interest (ROI) by the collaboration is 1.5×10^{-3}counts/(keV · kg · y).

EXO-200 has searched for $\beta\beta0\nu$ events with a total exposure of 120.7 days and an active mass of 98.5 kg, which corresponds to 79.4 kg of Xe-136. The total exposure is 32.5 kg·y. Their background model predicts 4 events in the region of 1σ around $Q_{\beta\beta}$ and 7.5 events in the 2σ region. They observe

1 event in the 1σ ROI and 5 events in the 2σ ROI. A limit:

$$T_{1/2}^{\beta\beta0\nu} > 1.6 \times 10^{25}\text{yr}$$

is extracted from this observation. The limit is considerably better than the experiment sensitivity (e.g, the probability of observing one background event when 4 are expected is only 5%).

The negative results of EXO-200 already question seriously the claim of a discovery by the subset of the Moscow-Heidelberg collaboration led by Klapdor. The GERDA experiment running in LNGS since November 2011, with a background index an order of magnitude smaller that the previous germanium experiments, will also scrutinize the Klapdor claim in the next several months, directly on the same isotope.

Sensitivity of NEXT versus sensitivity of EXO. The calculation assumes a conservative exposure of 32.5 kg·y for EXO-200 and NEXT-100 (with 100 kg total mass). A resolution of 4% (1%) FWHM is used for EXO (NEXT) as measured by both experiments. The background in the ROI is 1.5×10^{-3}counts/(keV $\cdot$ kg $\cdot$ y) (0.8×10^{-3}counts/(keV $\cdot$ kg $\cdot$ y)) as measured by EXO and computed in the NEXT TDR. Since NEXT can run with 150 kg of mass (operating the detector at 15 bar) the corresponding sensitivity curve is also included. It is assumed that NEXT physics run starts in mid 2014.

Figure 6 compares the sensitivity of NEXT-100 with that of EXO-200, assuming the parameters described in EXO recent paper and in NEXT-100 TDR and considering also the possibility that NEXT-100 runs with 100 or 150 kg of enriched xenon (the detector is designed to run at 10 bar with 100 kg of Xenon and at 15 bar with 150 kg). We assume that the NEXT-100 detector starts its physics run in mid 2014. The sensitivity of NEXT would cross that of EXO after 2 years of running if 150 kg are deployed or after some 3 years for 100 kg. In a 5 years running the sensitivity of NEXT improves that of EXO.

This has two consequences. The first one is that, if a discovery is made by EXO or GERDA, NEXT will be in a optimal position to check the claim adding extra handles such as the topological signature. The second one is that, if no discovery is made by these experiments, NEXT has a window of opportunity for a discovery, in particular if 150 kg of mass are deployed.

j The NEXT generation: boldly go to one ton

If no discovery is made by the current generation of experiments (all of them operating in the range of 100 kg), the full exploration of the inverse hierarchy requires detectors of larger mass (at least 1 ton), extremely low specific background, and excellent resolution.

We argue that the potential of NEXT is extraordinary for the next generation (1 ton isotope mass) of $\beta\beta0\nu$ experiments. There are many reasons for that:

1. **Energy resolution:** NEXT-100 target energy resolution is 1% FWHM at $Q_{\beta\beta}$, but the results obtained by our prototypes show that a resolution as good as 0.5% FWHM can be achieved. We argue that operation of NEXT-100 will provide the needed know-how to achieve such resolution in the whole chamber fiducial volume.

2. **Topology:** The fact that NEXT can characterize the topological signature of the $\beta\beta0\nu$ electrons is a major advantage of the technique. But the topological signature can be improved if the right gas mixture is found. Adding a very small amount of gas such as TEA/TMA to Xenon, could reduce the diffusion and improve the drift velocity.

3. **Scaling to 1 ton:** At 20 bar the xenon could be fitted in 10 m^3. This is a large, but feasible TPC. Notice that, unlike almost any other element, one ton of xenon can be acquired at a reasonable cost. In fact, one ton of enriched xenon already exists, pooling together the KamLAND-Zen, EXO and NEXT experiments.

Figure 7 compares the sensitivity of NEXT with that of EXO, assuming improved parameters for both detectors in the 1-ton regime. EXO resolution is still 4%, while the resolution of NEXT is

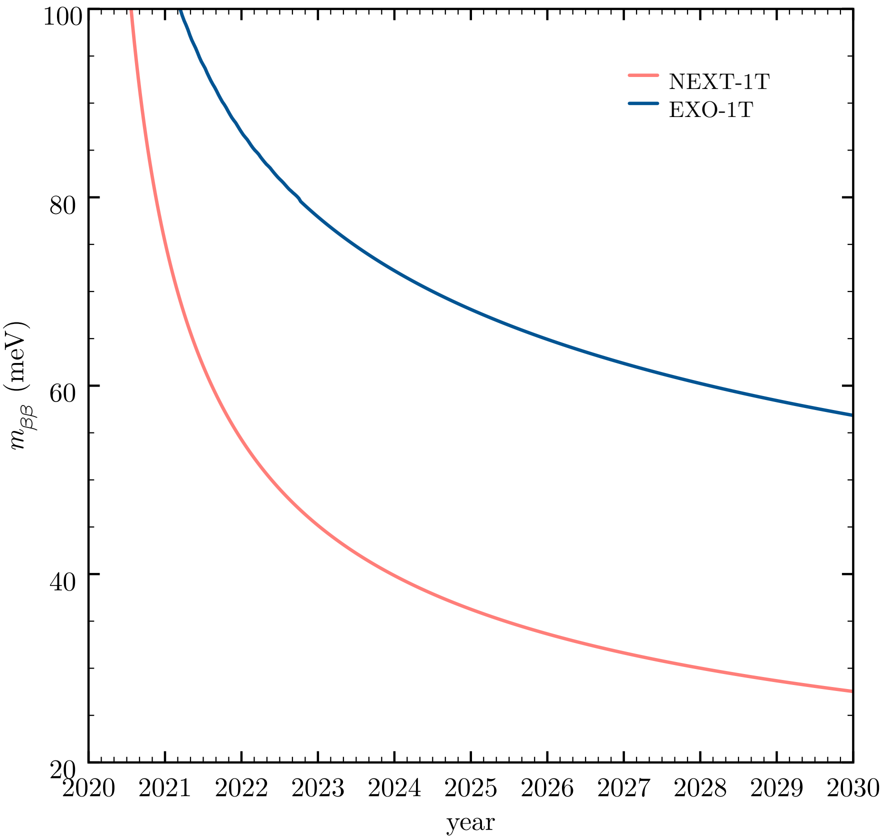

Figure 7: The Sensitivity of NEXT versus that of EXO-200 in the 1-ton regime. The calculation assumes a overall exposure efficiency of 70%. EXO resolution is still 4%, while the resolution of NEXT is assumed to be improved to 0.5% FWHM (as achieved by our prototypes). The background in the ROI for EXO is assume to be 0.7×10^{-3}counts/(keV $\cdot$ kg $\cdot$ y) (EXO best predictions) and the background in the ROI for NEXT is 0.2×10^{-3}counts/(keV $\cdot$ kg $\cdot$ y), obtained with an improved topological signature. Notice that NEXT can eventually cover the full inverse hierarchy.

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It is important, however, to insist that Figure 7 does not describe the actual performance of detectors, but only its potential. In the case of EXO, a marginal improvement in resolution may be possible, but in the case of NEXT our prototypes show that an extraordinary resolution of 0.5% can indeed be achieved. The challenge, of course, is to run a full 1-ton detector with the same overall resolution as a small 1 kg prototype. Operation of NEXT-100 detector will be essential as an intermediate step. Analogously, we believe that the potential of the topological signature will result in background rate in the ROI in the vicinity of 10^{-4}counts/(keV $\cdot$ kg $\cdot$ y). But this has to be demonstrated, in particular by NEXT-100.

The bottom line, however, is that it appears clear that the high pressure gas technology can be extrapolated to 1 ton after the NEXT-100 stage, providing one Xenon-based experiment capable to explore the inverse hierarchy. However, such a detector would require a very strong collaboration, appropriate funding and very sound technological support.

We believe that this is an extraordinary opportunity for $\beta\beta0\nu$ physics in Europe. NEXT-100 will be the only Europe-based Xenon detector, with a large potential to either confirm or outperform EXO-200 in the next 5 years, which are also critical to develop the technology to embark into a 1-ton scale experiment. At such a scale NEXT could become a truly European experiment, benefiting from the large experience existing in Europe in the field, as well as from the strong technological support of CERN.