The search for Majorana neutrinos with a background-free gaseous Xenon TPC at the tonne scale

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Abstract.

The next generation of neutrinoless double beta decay search experiments aims to reach sensitivities to this half-life of the process up to $10^{28}$ years. This will require tonne scale detectors with almost no background in their region of interest, which represents a large improvement with respect to current technologies. With this scenario, the NEXT collaboration presents two parallel developments: NEXT-High Definition and NEXT-Barium atOM Light Detection. The first is based on the incremental improvement of the current pressure gas xenon technology, and the second is based on the use of a barium tagging technology.

1. Introduction

Neutrinos being neutral standard model fermions are the only candidates to be Majorana particles. Their Majorana nature, particles being identical to their antiparticles, remains as one of the big open questions in particle physics as it can impact our understanding of the matter/anti-matter asymmetry in the Universe [1], and will also reveal the existence of a new energy scale inversely proportional to the neutrino mass [2]. Therefore the impact of such a discovery not only in particle physics but also in cosmology is clear.

The only realistic way to determine the Majorana nature of the neutrino is by observing a neutrinoless double beta decay process ($\beta\beta_{0}\nu$), a hypothetical second-order weak process in which a nucleus of atomic number $Z$ and mass number $A$ transforms into its $Z + 2$ isobar emitting two electrons.

The current generation of $\beta\beta_{0}\nu$ experiments have target masses with hundreds of kg of the target isotope and find no experimental evidence of such a process. Typically, half-life limits at the $10^{26}$ year level [3, 4] with background rates in the region of interest from four counts to a few hundred counts per tonne per year [5] have been achieved.

The challenge for the next generation experiments is to explore the region up to $10^{28}$ years, requiring the development of detectors at the tonne scale with less than 1 count per year in the region of interest. This requires not only improvement of the current radioactive budget of the different experiments, but also the development of new technologies capable of improving the current background rejection potential.
2. NEXT-HD

The NEXT-high definition (NEXT-HD) detector will imply an incremental approach towards a tonne scale detector based in the previous NEXT xenon high pressure gaseous detectors using the accumulated experience of the collaboration. Some changes in the current technology are required in order to reduce the background budget and to improve the background reduction techniques. These improvements will include the replacement of PMTs by SiPMs, operating with a cold gas, and the use of additives to reduce diffusion.

2.1. SiPM detector and cold gas

One of the major contributions to the NEXT budget of radioactivity are the PMT sensors and bases. Their replacement by SiPMs with radiopure substrates will reduce the final background level by a factor two. By removing the PMTs we can now operate a symmetric TPC with two planes of SiPMs sensors. In order to accomodate the large dynamic range required to measure both S1 and S2 signals and also the different requirements of topology and energy measurements we plan to use SiPMs of two different sizes (3x3 and 1x1 mm$^2$) at 5 mm pitch. The 1x1mm$^2$ will be used to reconstruct the event topology while the 3x3 mm$^2$ will be used for both S1 measurement and energy reconstruction of the events in the opposite side of the detector, thus replacing the current function of the PMTs.

![Figure 1. Evolution of the SiPMs dark counts as a function of the operating temperature.](image1)

![Figure 2. CAD of the axolotl0 detector at Ben-Gurion University. The main objective of this detector is to evaluate the characteristics of cold gas TPCs.](image2)

However, the use of SiPMs will require the operation with cold xenon in order to reduce the large dark current of this sensor (see figure 1). Changing the operating conditions of the detector can have an impact on the intrinsic xenon resolution. While at constant pressure no large effects are expected, exploring the phase space of viable operation with cold gas is necessary. Currently the group at Ben-Gurion University is commissioning a detector that will allow us to evaluate the characteristics of a high pressure gas xenon electroluminescent TPC at different temperatures from 200 K up to room temperature (Fig. 2).

2.2. Gas Mixtures

The background rejection potential of the NEXT technology can be improved by reducing the electron large diffusion in pure xenon. The use of additives in xenon is limited as most of
them have a negative impact on the energy resolution by reducing the scintillation. The NEXT collaboration has a very active R&D programme exploring the use of different gas mixtures to reduce the electron diffusion without affecting the energy resolution. In particular xenon-CH4 (Figure 3) [6] mixtures, with sub-percent parts of the hydrocarbon, and xenon-helium mixtures with a larger fraction of helium in this case (Figure 4) [7, 8, 9] are showing promising results.

![Figure 3](image3.png)  
**Figure 3.** Transvers diffusion of electrons at different xenon-CH4/CF4/CO2 (Blue/Red/Black) concentrations.

![Figure 4](image4.png)  
**Figure 4.** Electroluminescent yield of pure xenon and xenon-helium (70:30) at different values of the reduced field.

3. NEXT-BOLD

NEXT-Barium atOm Light Detection (NEXT-BOLD) is a detector based on the exploitation of Ba\(^{++}\) tagging to obtain a background free detector at the tonne scale and beyond. Tagging the daughter ion produced in a \(\beta\beta\nu\) decay has been pursued for many years. The detection of this ion would allow for a positive identification of the signal events as there is no other radiative process capable of creating this new ion. While other collaborations like nEXO have made enormous progress in this direction [10], operation in the gas phase allows us to use molecular sensors that change their fluorescent capabilities once they capture a barium ion. This technique, known as Single Molecule Fluorescent Imaging (SMFI) and awarded the Nobel Prize in Chemistry in 2014, has been extensively used in biology and was proposed as a tool to identify single barium ions in a xenon TPC by D. Nygren in 2015 [11] followed by a proof-of-concept [12]. However, adapting this technique that is well understood in wet media like biological systems to dry mediums as in the case of a gaseous TPC required a solution to several issues: development of molecules that shine in a dry gas, operation of targets with a large number of molecules and so a large background, development of vacuum compatible optics, to mention but a few.

Intense R&D is ongoing in the NEXT collaboration, initial proof-of-concept has been achieved [13] and since then development of dry shining molecules [14] and also bi-color molecules that allow for an extra separation from the non-chelated state [15] have been produced.

4. Conclusions

The next generation of double beta decay experiments seek to reach a lifetime of \(10^{27}\) years. This requires tonne scale detectors with background rates below 1 evt/tonne/year in the region of interest. The NEXT collaboration currently pursues two paths towards this objective: NEXT-HD and NEXT-BOLD. NEXT-HD is an incremental approach based on the reduction of the
Figure 5. Observation of single molecule chelated with a Barium ion.

Figure 6. Emission spectra of a the bicolor molecule with and without Ba++ for excitation light of 250 nm (green, blue) and an excitation light of 400 nm (olive, cyan).

current NEXT radioactive budget and the improvement of the topological signature by reducing the electron diffusion using gaseous mixtures. On the other hand, NEXT-BOLD aims to implement a barium tagging system using the SMFI technique to obtain a truly background free experiment. In this direction an intense R&D effort is ongoing inside the collaboration with great progress in the last year.

5. Acknowledgments
The NEXT Collaboration acknowledges support from: ERC under AdG 339787-NEXT; Horizon 2020 under MSCA No. 674896, 690575 and 740055; the Spanish MINECO and the MICINN under FIS2014-53371-C04, RTI2018-095979, the Severo Ochoa Program SEV-2014-0398 and the Maria de Maetzu Program MDM-2016-0692; the GVA of Spain under PROMETEO/2016/120 and SEII/2017/011; the Portuguese FCT under PTDC/FIS-NUC/2525/2014, UID/FIS/04559/2013, PD/BD/105921/2014, SFRH/BPD/109180/2015 and SFRH/BPD/76842/2011; the U.S. DoE under DE-AC02-06CH11357 (Argonne National Laboratory), DE-AC02-07CH11359 (Fermilab), DE-FG02-13ER42020 (Texas A&M) and DE-SC0019223 / DE-SC0019054 (UTA).

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