

Sensitivity of a tonne-scale NEXT detector for neutrinoless double beta decay searches

The NEXT Collaboration

C. Adams,² V. Álvarez,²² L. Arazi,⁶ I.J. Arnquist,²⁰ C.D.R Azevedo,⁴ K. Bailey,² F. Ballester,²² J.M. Benlloch-Rodríguez,¹⁶ F.I.G.M. Borges,¹⁴ N. Byrnes,³ S. Cárcel,¹⁹ J.V. Carrión,¹⁹ S. Cebrián,²³ E. Church,²⁰ C.A.N. Conde,¹⁴ T. Contreras,¹¹ G. Díaz,²¹ J. Díaz,¹⁹ M. Diesburg,⁵ J. Escada,¹⁴ R. Esteve,²² R. Felkai,^{6,7,19} A.F.M. Fernandes,¹³ L.M.P. Fernandes,¹³ P. Ferrario,^{16,9} A.L. Ferreira,⁴ E.D.C. Freitas,¹³ J. Generowicz,¹⁶ S. Ghosh,¹¹ A. Goldschmidt,⁸ J.J. Gómez-Cadenas,^{16,9,a} D. González-Díaz,²¹ R. Guenette,¹¹ R.M. Gutiérrez,¹⁰ J. Haefner,¹¹ K. Hafidi,² J. Hauptman,¹ C.A.O. Henriques,¹³ J.A. Hernando Morata,²¹ P. Herrero,¹⁶ V. Herrero,²² Y. Ifergan,^{6,7} S. Johnston,² B.J.P. Jones,³ M. Kekic,²¹ L. Labarga,¹⁸ A. Laing,³ P. Lebrun,⁵ N. López-March,¹⁹ M. Losada,¹⁰ R.D.P. Mano,¹³ J. Martín-Albo,^{11,19} A. Martínez,¹⁶ M. Martínez-Vara,¹⁹ G. Martínez-Lema,^{19,21,b} A.D. McDonald,³ F. Monrabal,^{16,9} C.M.B. Monteiro,¹³ F.J. Mora,²² J. Muñoz Vidal,¹⁹ P. Novella,¹⁹ D.R. Nygren,^{3,a} B. Palmeiro,¹⁹ A. Para,⁵ J. Pérez,¹² M. Querol,¹⁹ A. Redwine,⁶ J. Renner,²¹ J. Repond,² S. Riordan,² L. Ripoll,¹⁷ Y. Rodríguez García,¹⁰ J. Rodríguez,²² L. Rogers,³ B. Romeo,^{16,12} C. Romo-Luque,¹⁹ F.P. Santos,¹⁴ J.M.F. dos Santos,¹³ A. Simón,⁶ C. Sofka,^{15,c} M. Sorel,¹⁹ T. Stiegler,¹⁵ J.F. Toledo,²² J. Torrent,¹⁶ A. Usón,¹⁹ J.F.C.A. Veloso,⁴ R. Webb,¹⁵ R. Weiss-Babai,^{6,d} J.T. White,^{15,e} K. Woodruff,³ N. Yahlali¹⁹

¹*Department of Physics and Astronomy, Iowa State University, 12 Physics Hall, Ames, IA 50011-3160, USA*

²*Argonne National Laboratory, Argonne, IL 60439, USA*

³*Department of Physics, University of Texas at Arlington, Arlington, TX 76019, USA*

⁴*Institute of Nanostructures, Nanomodelling and Nanofabrication (i3N), Universidade de Aveiro, Campus de Santiago, Aveiro, 3810-193, Portugal*

⁵*Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*

⁶*Nuclear Engineering Unit, Faculty of Engineering Sciences, Ben-Gurion University of the Negev, P.O.B. 653, Beer-Sheva, 8410501, Israel*

⁷*Nuclear Research Center Negev, Beer-Sheva, 84190, Israel*

⁸*Lawrence Berkeley National Laboratory (LBNL), 1 Cyclotron Road, Berkeley, CA 94720, USA*

⁹*Ikerbasque, Basque Foundation for Science, Bilbao, E-48013, Spain*

^aNEXT Co-spokesperson.

^bNow at Weizmann Institute of Science, Israel.

^cNow at University of Texas at Austin, USA.

^dOn leave from Soreq Nuclear Research Center, Yavneh, Israel.

^eDeceased.

- ¹⁰*Centro de Investigación en Ciencias Básicas y Aplicadas, Universidad Antonio Nariño, Sede Circunvalar, Carretera 3 Este No. 47 A-15, Bogotá, Colombia*
- ¹¹*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
- ¹²*Laboratorio Subterráneo de Canfranc, Paseo de los Ayerbe s/n, Canfranc Estación, E-22880, Spain*
- ¹³*LIBPhys, Physics Department, University of Coimbra, Rua Larga, Coimbra, 3004-516, Portugal*
- ¹⁴*LIP, Department of Physics, University of Coimbra, Coimbra, 3004-516, Portugal*
- ¹⁵*Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843-4242, USA*
- ¹⁶*Donostia International Physics Center (DIPC), Paseo Manuel Lardizabal, 4, Donostia-San Sebastian, E-20018, Spain*
- ¹⁷*Escola Politècnica Superior, Universitat de Girona, Av. Montilivi, s/n, Girona, E-17071, Spain*
- ¹⁸*Departamento de Física Teórica, Universidad Autónoma de Madrid, Campus de Cantoblanco, Madrid, E-28049, Spain*
- ¹⁹*Instituto de Física Corpuscular (IFIC), CSIC & Universitat de València, Calle Catedrático José Beltrán, 2, Paterna, E-46980, Spain*
- ²⁰*Pacific Northwest National Laboratory (PNNL), Richland, WA 99352, USA*
- ²¹*Instituto Gallego de Física de Altas Energías, Univ. de Santiago de Compostela, Campus sur, Rúa Xosé María Suárez Núñez, s/n, Santiago de Compostela, E-15782, Spain*
- ²²*Instituto de Instrumentación para Imagen Molecular (I3M), Centro Mixto CSIC - Universitat Politècnica de València, Camino de Vera s/n, Valencia, E-46022, Spain*
- ²³*Laboratorio de Física Nuclear y Astropartículas, Universidad de Zaragoza, Calle Pedro Cerbuna, 12, Zaragoza, E-50009, Spain*

ABSTRACT: The *Neutrino Experiment with a Xenon TPC* (NEXT) searches for the neutrinoless double beta ($0\nu\beta\beta$) decay of ^{136}Xe using high-pressure xenon gas TPCs with electroluminescent amplification. A scaled-up version of this technology with ~ 1 tonne of enriched xenon could reach, in a few years of operation, a sensitivity to the half-life of $0\nu\beta\beta$ decay better than 10^{27} years, improving the current limits by at least one order of magnitude. This prediction is based on a well-understood background model dominated by radiogenic sources. The detector concept presented here represents a first step on a compelling path towards sensitivity to the parameter space defined by the inverted hierarchy, and beyond.

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1 Introduction

Neutrinos are the only particles in the Standard Model that could be Majorana fermions, that is, completely neutral fermions that are their own antiparticles. Light Majorana neutrinos imply the existence of a new energy scale at a level inversely proportional to the observed neutrino masses [1]. This scale provides a simple explanation for the striking lightness of neutrinos [2–5], and is probably connected to several other open questions in fundamental physics. In particular, Majorana neutrinos could be related to the cosmological asymmetry between matter and antimatter through a mechanism known as leptogenesis [6].

The most sensitive known experimental method to verify whether neutrinos are Majorana particles is the search for neutrinoless double-beta ($0\nu\beta\beta$) decay [7]. In this hypothetical second-order weak process, a nucleus with atomic number Z and mass number A transforms into its isobar with atomic number $Z + 2$ emitting two electrons only. Such a process does not conserve total lepton number and requires the neutrino be a Majorana particle.

No evidence of $0\nu\beta\beta$ decay has been found so far. The best current limits on the half-life of the decay have been set by the KamLAND-Zen [8] and GERDA [9] experiments using, respectively, ^{136}Xe and ^{76}Ge as $0\nu\beta\beta$ source:

$$T_{1/2}^{0\nu}(^{136}\text{Xe}) > 1.07 \times 10^{26} \text{ years (90\% CL)},$$
$$T_{1/2}^{0\nu}(^{76}\text{Ge}) > 0.90 \times 10^{26} \text{ years (90\% CL)}.$$

The experimental goal for the coming decade is the exploration of the region of half-lives up to 10^{28} years. This will require experiments with exposures well beyond 1 tonne yr and background rates of the order of 1 count tonne $^{-1}$ yr $^{-1}$ or better [10]. Only a few of the experimental techniques presently considered will be able to attain those levels.

In this paper we discuss the reach of a tonne-scale version of the *Neutrino Experiment with a Xenon TPC* (NEXT) considering only minimal (and largely proven) improvements over the design of NEXT-100, the latest stage of the NEXT detector series, which is expected to start operation in 2021 at the Laboratorio Subterráneo de Canfranc (LSC), in Spain. NEXT combines good energy resolution, tracking, radio-purity and shielding to achieve strong sensitivity to $0\nu\beta\beta$ decay. As we discuss in this paper, a NEXT detector with active mass in the tonne range would be able to improve by more than one order of magnitude the current limits in $T_{1/2}^{0\nu}$.

The NEXT Collaboration is also pursuing a more radical approach to a tonne-scale experiment based on the efficient detection of the Ba $^{++}$ ion produced in the $0\nu\beta\beta$ decay of ^{136}Xe using *single-molecule fluorescence imaging* (SMFI) [11–15]. This technique has the potential to realize an effectively background-free experiment that could reach a sensitivity to $T_{1/2}^{0\nu}$ better than 10^{28} yr, but it is still the subject of intense R&D beyond the scope of the present article.

2 The NEXT experiment

2.1 Present status

NEXT is an international effort dedicated to the search for $0\nu\beta\beta$ decay in ^{136}Xe using high-pressure xenon gas time projection chambers (HPXeTPC) with amplification of the ionization signal by electroluminescence (EL). Such detectors take advantage of the inherently low fluctuations (i.e., small Fano factor) in the production of ionization electrons in xenon gas to achieve an energy resolution significantly better than those of other xenon-based experiments [16]. Moreover, in gaseous xenon double-electron and single-electron tracks — the $0\nu\beta\beta$ signal and its main background, respectively — at the energy of the decay ($Q_{\beta\beta} = 2458.1$ keV [17, 18]) have distinct features that can be used for event classification.

A series of detectors have proven the performance of the HPXeTPC technology in the key parameters required for the observation of $0\nu\beta\beta$ decay. The NEXT concept was initially tested in small scale, surface-operated detectors [19–23]. This phase was followed by the underground operation at the LSC of NEXT-WHITE [24], a radiopure detector of ~ 3.5 kg of active xenon mass at 10 bar. The results obtained with NEXT-WHITE include the development of a procedure to calibrate the detector using $^{83\text{m}}\text{Kr}$ decays [25], measurement of an energy resolution at 2.5 MeV better than 1% FWHM [26, 27], demonstration of robust discrimination between single-electron and double-electron tracks [28], and characterization of radiogenic backgrounds, demonstrating both the low radioactive budget of the apparatus and the accuracy of the background model [29, 30].

The NEXT-100 detector [31, 32], scheduled to start data taking in 2021, constitutes the third phase of the program. It is a radiopure HPXeTPC containing about 100 kg of xenon, enriched at $\sim 90\%$ in ^{136}Xe , at 15 bar pressure. The active region of the detector is

a cylinder 130 cm long and 100 cm in diameter (about 1 m³). Three highly-transparent metallic grids — known as cathode, gate and anode — separate the two main electric-field regions of the detector. The so-called drift region, between cathode and gate, contains a uniform field of ~ 500 V/cm, while a more intense field of 20 to 30 kV/cm accelerates the ionization electrons sufficiently to produce EL light in the 1-cm gap between gate and anode. Track reconstruction will be performed with the EL signals registered by a matrix of approximately 3 600 Hamamatsu silicon photomultipliers (SiPM) of 1.3×1.3 mm² active area placed 5 to 10 millimeters beyond the anode. The event energy will be measured with an array of 60 Hamamatsu R11410-10 photomultiplier tubes located behind the cathode. These PMTs will also record the primary scintillation that signals the initial time of the event. All of these elements are housed inside a 12 cm thick solid copper structure contained in a stainless-steel pressure vessel, and surrounded by a 20-cm thick shield made of staggered lead bricks held by a stainless-steel frame.

NEXT-100 will reach a sensitivity of about 6×10^{25} years after a run of 3 effective years [32]. The combination of good energy resolution, tracking-based signal identification and low-radioactive contamination results in a predicted background index for the detector of at most 4×10^{-4} counts keV⁻¹ kg⁻¹ yr⁻¹.

2.2 A NEXT detector with a tonne of xenon

The NEXT technology can be scaled up to $0\nu\beta\beta$ source masses in the tonne scale introducing several technological advancements already available. Figure 1 shows a possible design for a detector with an active volume of 2.6 m in diameter and an axial length of 2.6 m that would hold a mass of ¹³⁶Xe (when enriched to $\sim 90\%$ in that isotope) of 1109 kg at 15 bar. These dimensions and operational conditions are informed by R&D performed by the NEXT collaboration on the scalability of the NEXT-100 design in terms of number of electronic channels, size of the field-cage electrode grids and rating of the high-voltage feedthroughs. In what follows we refer to this general design as NEXT-1T.

Arguably, the most important change with respect to NEXT-100 would be the replacement of PMTs, expected to be the leading source of background in NEXT-100, with SiPMs, which are radiopure, pressure resistant and can provide large photosensitive coverage with high granularity at acceptable cost. Their use would not only remove a significant source of radioactivity, but also reduce the mechanical complexity of the detector, given that the PMTs have to be housed in a separate low-pressure region. However, SiPMs introduce one notable challenge: the dark count rate (DCR) in commercially-available SiPMs at the time of writing is still orders of magnitude higher than that of PMTs. While this DCR does not represent a problem for the detection of the EL-amplified ionization signal (known as S2), it does form accidental coincidences that can mimic the primary-scintillation signal (or S1) of low-energy events. While improvements in commercial SiPM technology continue to proceed rapidly, the collaboration is also pursuing R&D to enable the measurement of the drift position using existing SiPM technology. The most promising approaches are the use of large-area photon collectors surrounding the active volume of the TPC, or to moderately cool down the gas to reduce the SiPM DCR (typically, a temperature drop of 20 K results in a reduction of the DCR by up to an order of magnitude). With promising

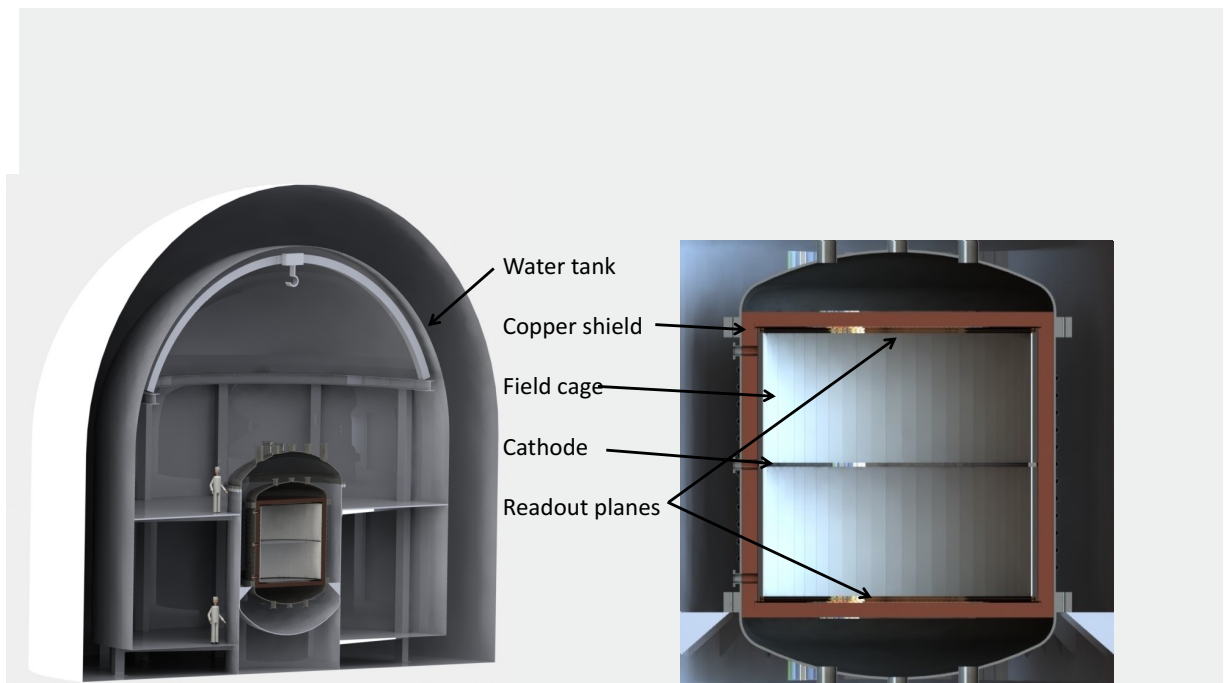


Figure 1. Left: Conceptual design of a tonne-scale NEXT detector inside a water tank. Right: Zoom-in on the internal structures of the detector.

preliminary results from both methods already in hand, we assume in this study that the axial position of events will be reconstructed with similar precision to what has been achieved in NEXT-WHITE.

The other major adjustment from NEXT-100 would be changing to a symmetric TPC design with a central cathode and two EL gaps. This modification halves the maximum drift length, easing the requirements on gas purity and high voltage. For example, the detector of 2.6 m would require ~ 65 kV at the central cathode to achieve a NEXT standard drift field of 500 V cm^{-1} , a value already within the target specifications of the NEXT-100 high-voltage feedthrough. The shorter drift length would reduce as well the average electron diffusion (proportional to the square root of the drift length), which impacts track reconstruction. Moreover, no buffer region would be required to protect sensors and electronics against high voltage discharges from the cathode, effectively increasing the active volume available for physics and maximizing the isotope use.

The field cage itself is expected to be an extrapolation of the current NEXT-100 design, which has been developed with scalability to the tonne scale and minimization of material mass and radioactivity as central concerns. The current design secures the field shaping rings using high-density polyethylene (HDPE) bars of the same length as the detector active region. Teflon panels are then fitted to the HDPE bars making the light reflector seen in Fig. 1. These Teflon reflectors are ~ 5 mm thick and constitute the majority of the mass of the field cage. The field cage is surrounded by an inner shield of 12 cm of copper that attenuates external gammas by several orders of magnitude before they reach the active volume. Developing the possibility to operate an EL readout at the meter scale was a major R&D effort performed by the Collaboration. Recent progress through R&D with photo-etched hexagonal meshes shows promise, with manufactures capable of producing meshes of the scale required for the tonne-scale experiment. These meshes can be tensioned sufficiently to operate at the field strengths envisioned and can sustain high energy

sparks without deformation. These developments indicate that the scaling of HPGXeTPC technology from the size of NEXT-100 to the tonne scale, according to the approaches discussed here, is technically viable.

For the purposes of this study, the detector is assumed submerged in a cylindrical water tank with dimensions to give 3 m of water shield on all sides of the active volume. This tank would allow for the tagging of muons if instrumented with PMTs as well as mitigating possible backgrounds emanating from the lab walls. Pure water is considered for this study but some level of doping to improve neutron-absorption cross sections is also under consideration. In any case, as will be discussed below, cosmogenic backgrounds from neutrons are not expected to be limiting in the present configuration.

3 Backgrounds at the tonne scale

Neutrinoless double beta decay events in NEXT consist of two electrons emitted from a common vertex and reconstructed as a single track with higher-energy deposits (or *blobs*) at both ends (see Figure 2) and total energy around the Q value of ^{136}Xe .

The relevance of any potential background source depends on its probability of generating a $0\nu\beta\beta$ -like track in the active volume of the detector with energy in the region of interest (ROI) around $Q_{\beta\beta}$. Our background model, described in this section, includes gamma rays from the uranium and thorium decay chains, radon-induced backgrounds, and activations of xenon and copper from neutrons generated by cosmic-ray muons. Other sources of background such as other muon-spallation products or solar neutrino interactions were considered and found to be sub-dominant.

3.1 Gamma ray backgrounds from solid detector materials

The main background source for most $0\nu\beta\beta$ experiments is natural radioactivity from long-lived contaminants in the detector materials. The uranium and thorium decay chains are particularly troublesome due to two de-excitation gamma lines from the decays of ^{214}Bi and ^{208}Tl . The latter (2614.5 keV, 99.75% intensity) is above the $Q_{\beta\beta}$ value of ^{136}Xe , but single-electron tracks from its photo-peak can lose energy via bremsstrahlung and fall in the region of interest. Likewise, successive Compton scatters occurring closely may be reconstructed sometimes as a single track with energy around $Q_{\beta\beta}$. The gamma line from ^{214}Bi (2447.7 keV, 1.55% intensity) is situated just below $Q_{\beta\beta}$, and thus its photo-peak can overlap with the signal peak due to the finite energy resolution of the detector.

These backgrounds can be mitigated and understood by careful radio-assay of all materials used in the construction of the detector. The NEXT Collaboration has undertaken extensive campaigns for the characterization of all materials used for the NEXT-WHITE and NEXT-100 detectors [33, 34], primarily using germanium spectroscopy and ICP-MS. Tonne-scale experiments will require measurements at even higher precision. Assays of new materials and at higher precision are ongoing at low radiation facilities at the LSC and *Pacific Northwest National Laboratory* (PNNL).

Gamma radiation emanating from laboratory walls and external support structure is unlikely to reach the inner detector through the water tank. For this reason we focus here on

sources close to the active volume. When selecting materials for these components a detailed study of the expected rate in the gammas mentioned above must be performed. Below we discuss the current status of material screening and the rejection power of the analysis, and in section 5 calculate the effect on the sensitivity of tonne-scale NEXT detectors.

The most important contributions to the NEXT background model derive from materials closest to the active volumes, particularly those with large mass such as copper. The NEXT-100 background model, which serves as the basis for our estimated backgrounds in NEXT-1T, includes only materials we have counted directly for NEXT. Recent literature reports materials with still lower contamination that are available. We report here sensitivities using both established activities based on the the NEXT-100 background model, and those that incorporate improvements using materials that have been reported in the literature by other collaborations we refer to the latter as the NEXT-1T background model. As our program of assay continues, it is in fact expected that the final background budget will be somewhat better than either of these cases, as new and cleaner materials are identified.

There are two primary materials where better radiopurity than that implied by the NEXT-100 background budget appears to be available. First, Teflon with an activity of approximately one order of magnitude less than the present NEXT-WHITE measurements in uranium and thorium have been reported [35, 36]. Second, the Kapton substrates for the SiPM support boards is likely to be improved. A new board design using fewer layers of Kapton in the laminate is presently being assayed at LSC with projections suggesting a reduction of a factor of 10. Recently-published work on radio-pure Kapton also suggests further reduction is possible [37].

After making these improvements, the material that dominates the radioactivity budget is copper. The NEXT copper is similar in activity to that assayed by other low-background experiments [38]. Further reductions in the activity of copper could be possible through advanced techniques such as electroforming [39]. However, these techniques are slow and expensive, and we do not consider electroformed copper in our baseline design, some further discussion is given in Sec. 6.

Backgrounds from the pressure vessel as well as any additional infrastructure outside the detector are efficiently mitigated by the inner copper shielding. They are assumed here to contribute at or below the 5% level to the full radioactive budget in this study. This number is informed by experience from NEXT-WHITE and NEXT-100, where present upper limits sit at approximately 5% of the total activity budget. Any additional external sources can be effectively mitigated by increasing the thickness of inner copper shielding without significant detriment to the total activity. This is because it effectively self-shields. Table 1 summarises the expected contributions given the simulated material masses.

3.2 Backgrounds from material radon emanation

Radon is another potential source of background, since it can diffuse from materials in the detector or gas system and enter the active xenon region. The primary radon-induced background derives from the daughter ^{214}Bi . This is a product of the ^{222}Rn chain, which has a half life of 3.8 days, making it more likely to diffuse into the active region than its shorter-lived relative ^{220}Rn , the latter being an insignificant background source for NEXT.

Fortunately, ^{222}Rn undergoes two decays before becoming ^{214}Bi , and previous NEXT measurements [29] show that these daughters plate out onto the cathode, with recombination being relatively infrequent in xenon gas. ^{214}Bi decays on the cathode are rejected with high efficiency by the detection of the emitted beta electrons (through fiducial cuts) and coincident decays of ^{214}Po . Rejection efficiency should only increase in a symmetric design.

For the present study we consider the internal radon backgrounds at a similar rate than that of the present generation of NEXT detectors [29], a pessimistic baseline. Additional contributions from airborne radon backgrounds are expected to be negligible. This is well justified based on experience with present-generation NEXT experiments, continuously flushed with radon-free air [29]. Considering that the NEXT-1T system will be submerged in purified water that effectively removes any contribution from radon in the surrounding environment, airborne radon is expected to be irrelevant for the ultimate background budget.

3.3 Backgrounds of cosmogenic origin

Cosmogenic backgrounds in NEXT derive from the neutron capture on detector materials, especially copper isotopes and ^{136}Xe . The main source of the neutrons that creates these potential backgrounds are atmospheric muons that reach the laboratory through the rock overburden.

Muons that produce significant fluxes of neutrons in underground laboratories are those with energies up to a few TeV. For this study we estimate the cosmogenic backgrounds from these muons in two example laboratory locations: Laboratori Nazionali del Gran Sasso (LNGS) and SNOLAB. The muon spectra are calculated using the MUSUN muon transport simulation code [40]. The most recent measurements for these locations give total fluxes of $3.432 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$ [41] for LNGS and $3.31 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ [42] for SNOLAB, which are used to normalize the spectra.

Muons are simulated originating from outside the water tank, evenly distributed over the upper surface and uniformly distributed in energy between 1 GeV and 3 TeV, then re-weighted to the predicted muon spectrum. Muons and all secondary particles are simulated through the water tank and detector geometry. The resultant activity considered in the same way as the other backgrounds with a few caveats: the activation expectation is calculated as an additional normalisation, and, since the events can induce activity over several ms, the activity must be considered as multiple possible triggers. These muon simulations are used to calculate the activation expectation of ^{136}Xe to ^{137}Xe per muon and per year. The resulting beta electrons from ^{137}Xe decay are passed through the NEXT analysis framework and are found to be rejected at the level of 10^{-4} .

Neutron capture produces two types of potential background, in the form of prompt activity from gamma radiation post capture, and the creation of long lived nuclei with decays at energies close to $Q_{\beta\beta}$. The former is dominated in NEXT by contributions from the capture of neutrons on the two main copper isotopes via the reactions $^{63,65}\text{Cu}(n, \gamma)^{64,66}\text{Cu}$ as well as contributions from captures on plastics and in the steel pressure vessel. The cascade photons from these reactions have energies up to tens of MeV, but tend to interact in the gas within a few ms of the passage of a muon. Most can be effectively vetoed by temporal

proximity to a muon, and the analysis need only select those without a muon detected in the water tank or TPC. A veto dead-time of 2 ms after the detection of a muon makes a negligible impact on detector live-time but drives the contribution of prompt cosmogenic backgrounds well below that of other backgrounds, to a level of $\sim 10^{-7}$ keV $^{-1}$ kg $^{-1}$ yr $^{-1}$ for LNGS and $\sim 10^{-9}$ keV $^{-1}$ kg $^{-1}$ yr $^{-1}$ for SNOLAB. This is sufficiently low that we do not consider it within the final background index.

Non-prompt backgrounds derive from production of long lived isotopes that later beta decay with Q-values above $Q_{\beta\beta}$. The dominant of these that can constitute background to the $0\nu\beta\beta$ search in ^{136}Xe is the beta-emitter ^{137}Xe which is produced by single neutron capture on ^{136}Xe ($^{136}\text{Xe}(n,\gamma)^{137}\text{Xe}$). ^{137}Xe decays with a half life of 3.8 minutes and a Q_{β} of 4.17 MeV. This background is difficult to veto by time coincidence with a selected muon due to the excessive deadtime that would be required.

Combining simulated expectations of ^{137}Xe production in the detector (implemented as in Ref. [43]) with the predicted muon flux yields an estimate for the yield of ^{137}Xe per year is obtained. This can be multiplied by the simulated acceptance factor to yield a background index contribution from cosmogenic ^{137}Xe . At the LNGS site this results in $\sim 5 \times 10^{-7}$ keV $^{-1}$ kg $^{-1}$ yr $^{-1}$, which is approximately 7% of the radiogenic contribution, whereas SNOLAB is $\sim 5 \times 10^{-9}$ keV $^{-1}$ kg $^{-1}$ yr $^{-1}$, which is approximately 0.1% of the radiogenic contribution. Further detailed studies of additional, sub-leading sources of cosmogenic background are ongoing, but these are not expected to make a significant impact to the ultimate experimental background, which remains primarily driven by radioactive contributions.

4 Simulation and analysis

This study follows the same methodology that was used to estimate the background index and sensitivity of the NEXT-100 detector [32], broadly validated with the data of NEXT-WHITE [23, 44]. Large datasets (of the order of 2×10^{10} simulated events) of the main backgrounds and a smaller dataset of the $0\nu\beta\beta$ signal (1.25×10^6 simulated events) were produced with NEXUS, the Geant4-based detector simulation developed by the NEXT Collaboration. NEXUS provides an output for each event as a collection of three-dimensional hits representing the ionization tracks left by charged particles in the active volume. An example of this is shown in the left column of Figure 2.

Each background source was simulated with sufficient statistics to give a statistical error at or below 10% in the final selected sample, signal events were generated to give a similar statistical error. However, unlike the gamma background events whose kinematics are built into Geant4, the $\beta\beta$ events were generated using the DECAY4 event generator [45] which accounts for the energy and angular distributions in $\beta\beta$ decays. A parameterization of the NEXT reconstruction was then used to form tracks according to the specific spatial resolution to be studied. A cut-based analysis was then used to assess the ability of the experiment to filter out backgrounds while retaining signal events.

For this study, two indicative parameterizations of the spatial resolution were used to assess the detector's performance with pure xenon (standard diffusion) and with a gas

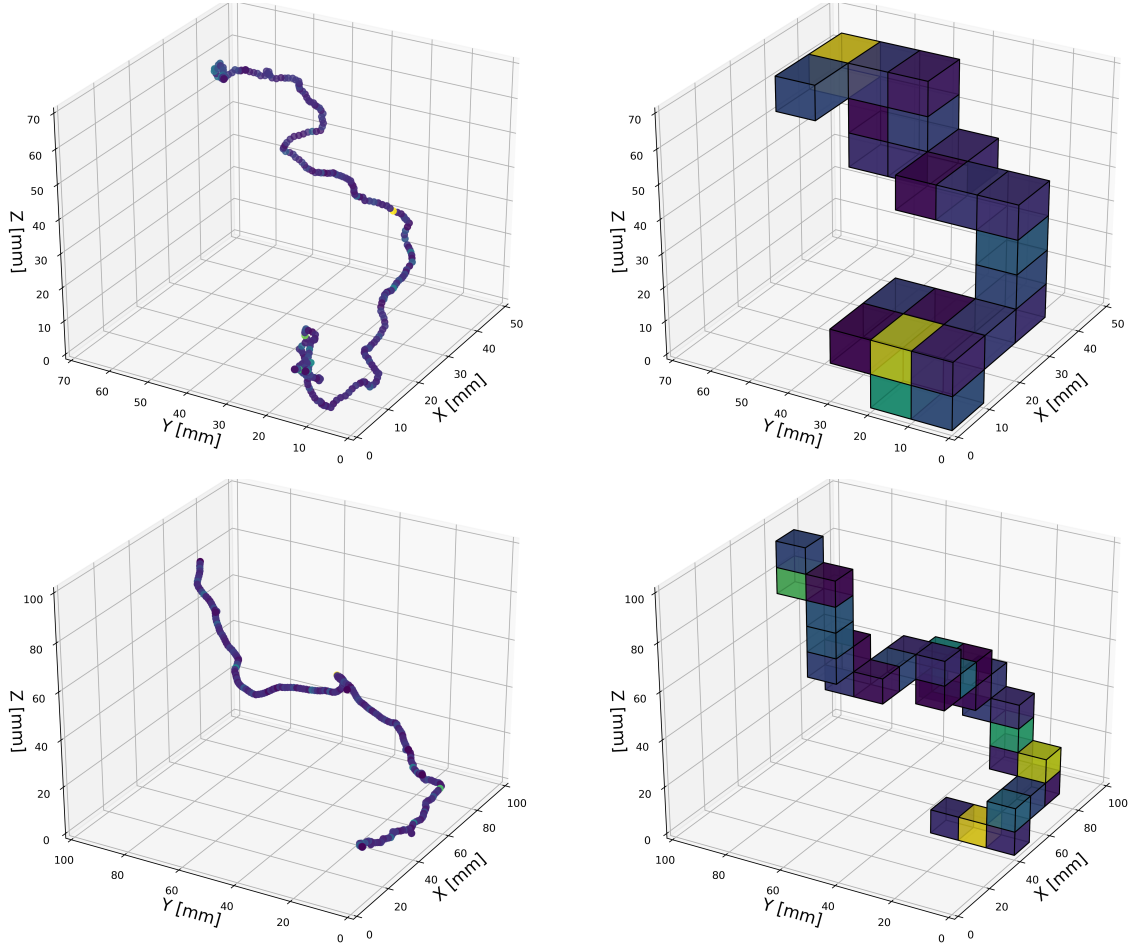


Figure 2. Monte-Carlo simulation of signal ($0\nu\beta\beta$ decay of ^{136}Xe) event; top panels) and background (single electron of energy equal to $Q_{\beta\beta}$; bottom panels) events in gaseous xenon at 15 bar. The ionization tracks left by signal events feature large energy deposits, or blobs, at both ends. In the left column, the tracks are shown as generated by the simulation, whereas in the right they have been binned into $10 \times 10 \times 10 \text{ mm}^3$ voxels.

additive, such as CF_4 or He (low diffusion). Energy resolution of 0.7% FWHM at $Q_{\beta\beta}$ was considered in all simulations. All energy deposits recorded in the detector were smeared according to a Gaussian distribution with a standard deviation which gives a FWHM energy resolution of 0.7% corresponding to the nominal energy resolution expected to be achieved in NEXT-100. An improved energy resolution of 0.5%, closer to the intrinsic resolution of pure xenon [19], was also studied, but the corresponding sensitivity improvements were marginal.

The impact of the differing spatial resolution was simulated by grouping energy deposits into cuboids (*voxels*) with dimensions chosen to mimic different possible diffusion conditions. The first parameterization chosen used voxels of dimension $10 \times 10 \times 10 \text{ mm}^3$ which gives a good representation of the reconstruction possible given a transverse root-mean-square (rms) diffusion of $\sim 8.5 \text{ mm}/\sqrt{\text{m}}$ and longitudinal rms diffusion of $\sim 4 - 5 \text{ mm}/\sqrt{\text{m}}$ corresponding

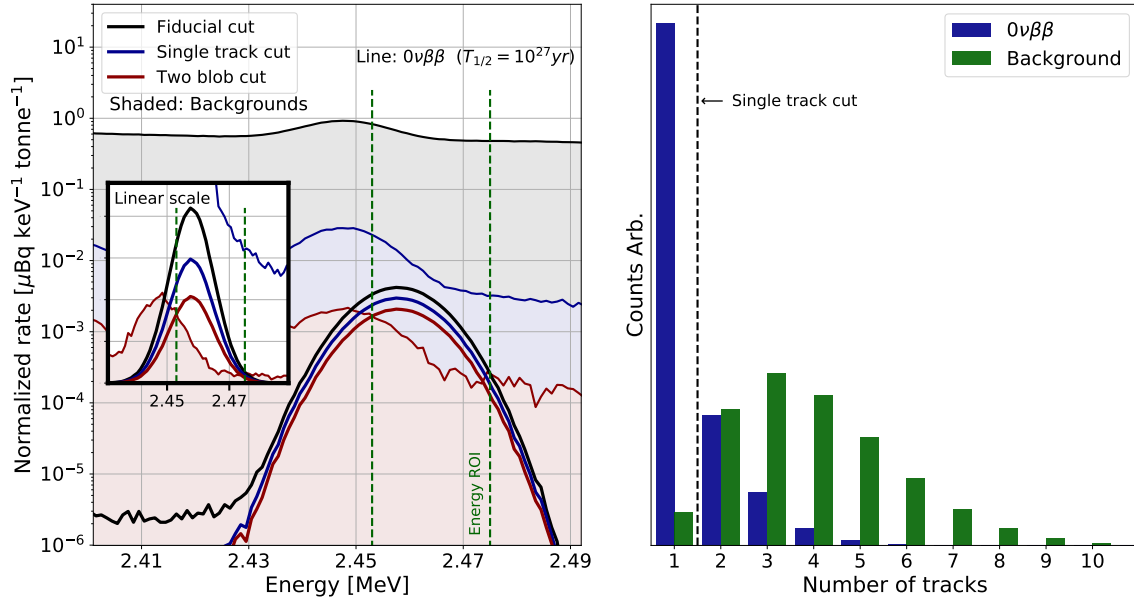


Figure 3. Left: histogram of all simulated events normalized by activity with the analysis cuts applied. Right: the track multiplicity for signal and background events.

to the measurements made by the collaboration for pure-xenon operation [22, 46]. A second parameterization at $3 \times 3 \times 3 \text{ mm}^3$ assumes an improvement in diffusion due to the addition of molecular or He additives to the gas [47–50]. An example of the hits being grouped into $10 \times 10 \times 10 \text{ mm}^3$ voxels can be seen in the right column of Figure 2.

All tracks built are subject to a series of cuts designed to accept only $0\nu\beta\beta$ events. The initial steps involve rejecting events with reconstructed energy far from $Q_{\beta\beta}$. This is achieved by strictly requiring energy between 2.4–2.5 keV (the *broad energy cut*). The surviving events are then required to have no voxels within 2 cm of the field cage nor within 2 cm of the anode or cathode. With these first two cuts, events which obviously enter from outside the active volume or which have energies far from the region of interest are efficiently rejected.

Once the broad energy and fiducial cuts have been applied, the surviving events are subject to the basic NEXT topological analysis. The voxels are grouped into tracks by treating each voxel as a node in a graph and applying the Breadth First Search (BFS) algorithm [51]. The details of the specific implementation of this algorithm can be found in Ref. [23]. The expected topology of a $\beta\beta$ event is a single continuous energy deposition as the two electrons share the same initial vertex and will be reconstructed together. At the two extremes there are high-density energy deposits, described hereafter as *blobs*, corresponding to the two Bragg peaks. Multi-particle background events will be reconstructed with more than one track, and those induced by single electrons either from the interaction of gamma radiation or from beta decays, while often producing a single track, can only have a blob at one extreme. Figure 2 shows an illustration of a signal (top) and background (bottom) event, in Monte Carlo truth (left) and after voxelization (right) at $10 \times 10 \times 10 \text{ mm}^3$ scale,

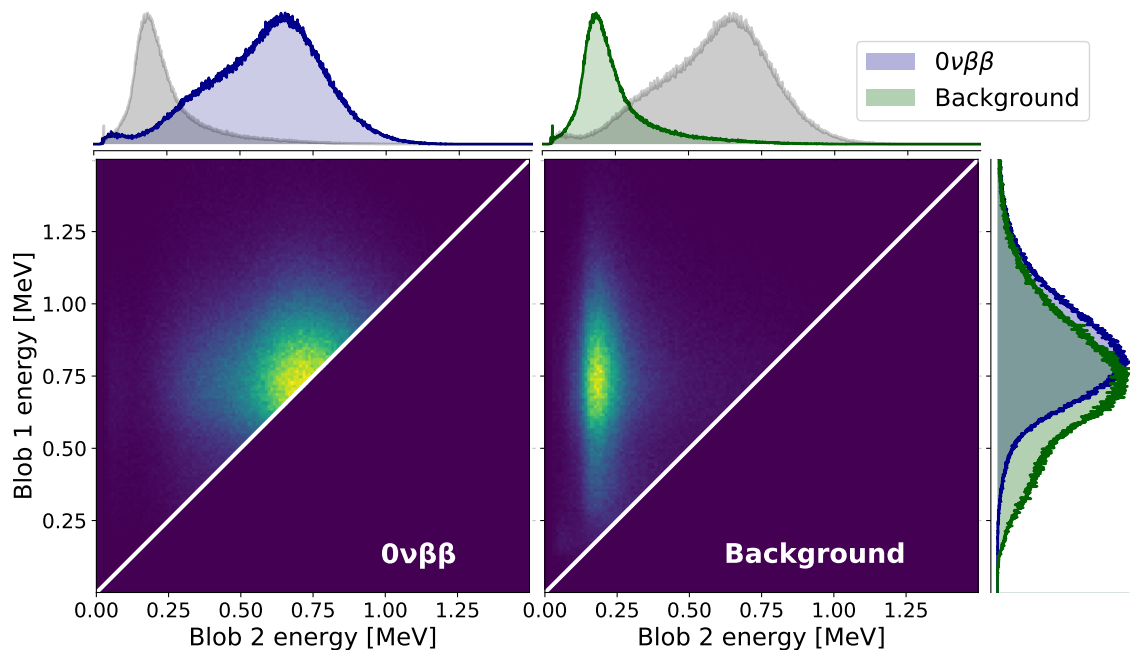


Figure 4. Histograms of the blob energies of signal and background events. The blobs are defined such that blob1 has higher energy.

respectively.

Events with more than one track are rejected as being most likely background. However, a non-negligible number of signal events are also reconstructed as multiple tracks. Energy loss via bremsstrahlung is possible and the photons can travel a significant distance before interacting which frequently results in multiple track signal events. The track multiplicity for signal and background events can be seen in Figure 3 right. The corresponding energy distribution for the signal and background events can be seen in Figure 3 (left) using a double beta decay half life of 10^{27} years, the NEXT-1T background model, and pure xenon (for example).

The remaining single-track events are then checked for the double electron condition (two-blob cut). The end-points of the tracks are identified as the two voxels at greatest distance from each other along the track and the energy is integrated within a sphere of fixed radius from each end-point. The radius chosen was optimised for each tracking parameterization with 18 mm chosen for $10 \times 10 \times 10$ mm³ voxels (pure xenon) and 15 mm for $3 \times 3 \times 3$ mm³ (low diffusion). The integrated energy in the regions is required to exceed a threshold chosen for each parameterization by using a test statistic to find the cut value which optimized the figure of merit ε/\sqrt{b} , where ε is the signal efficiency and b is the residual background. Figure 4 shows the blob distributions for all signal and background events generated, the figure of merit indicated a threshold of 500 keV as the best minimum for the integrated signal at the extreme with lower energy (blob 2). In this way we can effectively reject Compton electrons and other remaining backgrounds.

All events that remain are inherently fiducial, single track, with a blobs at both ends

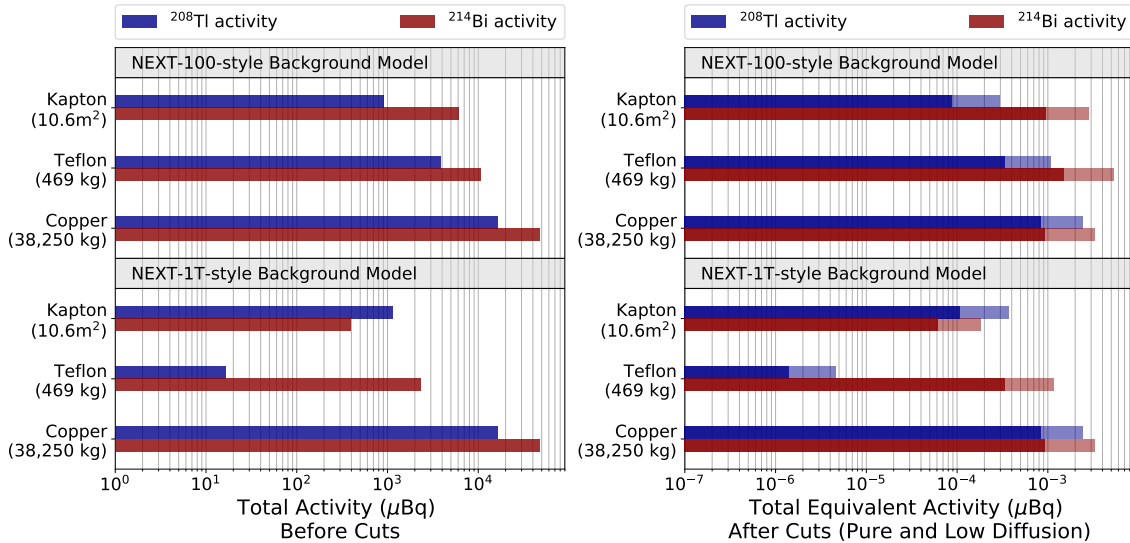


Figure 5. Left: Total background activity by region given for both background models considered. Right: Activity remaining after cuts applied for both background and for both detector performance considerations.

Pure xenon	Acceptance Factor [10^{-7}]		Total Background Index $NEXT-100 / NEXT-1T$
Region	^{208}Tl	^{214}Bi	$\text{c keV}^{-1}\text{kg}^{-1}\text{yr}^{-1}$
Field cage	2.83(17)	5.01(22)	8.307e-06 / 1.525e-06
Readout planes	3.29(19)	4.65(21)	4.080e-06 / 7.228e-07
Inner Shielding	1.47(12)	0.68(02)	7.429e-06 / 7.327e-06
Low-diffusion			
Field cage	0.86(09)	1.42(12)	2.388e-06 / 4.323e-07
Readout planes	0.95(10)	1.56(12)	1.352e-06 / 2.212e-07
Inner Shielding	0.50(07)	0.19(01)	2.292e-06 / 2.292e-07

Table 1. Acceptance factor, the probability of accepting an event as signal, combined with the activity produces the background index. Here for each detector region with an energy resolution of 0.7% FWHM for both spatial resolution cases. The background index is given for both activity cases studied: the NEXT-100 / NEXT-1T background models.

and have a total energy between 2.4–2.5 MeV, this subset of events is then searched for events that falls in a region of interest (ROI). The ROI is defined in an asymmetric manner around $Q_{\beta\beta}$; this was done to optimize the figure of merit previously mentioned (ϵ/\sqrt{b}). Utilizing an asymmetric ROI aids in rejecting ^{214}Bi photo-peak as seen in Figure 3 left. The events remaining in the ROI are then used to calculate the acceptance factors, the

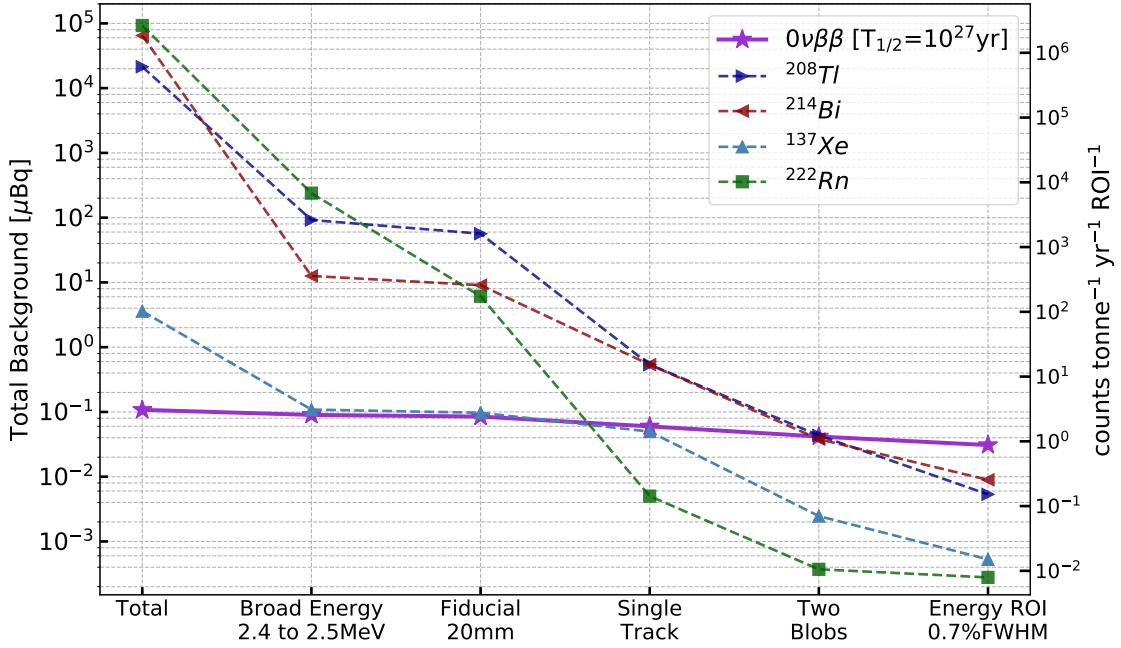


Figure 6. Total background activity as a function of the cuts for all sources considered. Here the half life of ^{136}Xe was assumed to be 10^{27} and is just for reference. The detector performance used here is 0.7% FWHM energy resolution and assuming Pure xenon for the diffusion, with the NEXT-1T background model and a location of LNGS.

ratio of events in the ROI to the total generated events.

For both the pure xenon and low diffusion configurations a set of unique acceptance factors were calculated for each detector component and for each background source. These are then combined with the mass of each material and the expected radioactive contamination. Wherever possible NEXT measured materials are considered, with reference to other published results complementing. This combination then yields a background index, which can be used to establish the expected sensitivity in each configuration and for each background model.

$$\text{Background Index} = \frac{\text{Acceptance Factor} \times \text{Activity (per unit mass)} \times \text{Component Mass}}{\text{Active Mass} \times \text{ROI}} \quad (4.1)$$

The mass of each detector component is determined from the volume of the Geant4 geometry and the density of the material, with the exception of the read-out planes, which are scaled according to surface area. These masses are summarised in Figure 5. In this figure we use the term equivalent activity to describe the activity that would have resulted in the level of background remaining after applying all cuts. The acceptance factors and background index for the radiogenic sources considered for each analysis set are reported in table 1.

The effectiveness of the cut-based analysis can be seen in Figure 6, where the effect of each cut on each background source can be seen. The fiducial cut does not reduce the activity from the gammas from bismuth and thalium since the attenuation length of gammas

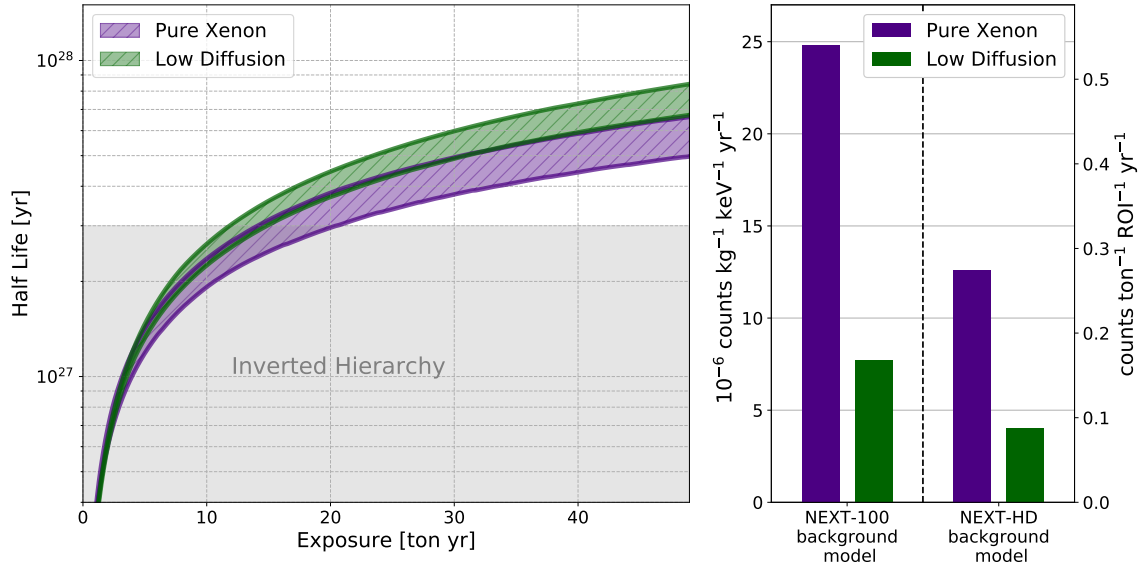


Figure 7. Left: Projected sensitivity to the ^{136}Xe $0\nu\beta\beta$ half-life with both the NEX-100 and NEX-1T background models for the pure xenon and low-diffusion cases; the band represents the span of the background model for the given diffusion assumption. Right: Background index for both background models and pure xenon and low diffusion mixtures.

of these energies is long so interaction within the fiducial volume is likely. However, when these gammas interact their energy and topology can be scrutinized and the power of the topological analysis is evident.

5 Predicted background index and sensitivity

The sensitivity of an experiment is defined as the median half-life which can be excluded at a given confidence level in many repetitions of an experiment providing a null observation. Based on the predicted activities and acceptance factors presented we can evaluate the median sensitivity of the tonne scale NEX-like detector.

The total background index for each analysis configuration was calculated by taking the radiogenic contribution plus an additional 20% to account for material contributions outside the copper shielding, the cosmogenic background for a siting location, and the possibility of radon contamination. Due to the low background nature the additional 20% do not impact the sensitivity in a major way. Figure 7 (right) summarises these numbers.

The background index from each set was used to generate a sensitivity curve following the Feldman-Cousins method for a 90% unified confidence interval [52]. These sensitivities were then used to construct a band that is dependent on detector performance for both NEX-100 and NEX-1T background models. The width of the band shows the difference between the models, as seen in Figure 7-left. Siting of the detector is not yet specified, though candidate underground laboratories include SNOLAB (6 km.w.e.), SURF (4.3 km.w.e.), LNGS (3.3 km.w.e.) and LSC (2.2 km.w.e.). For these studies, we assume siting at LNGS

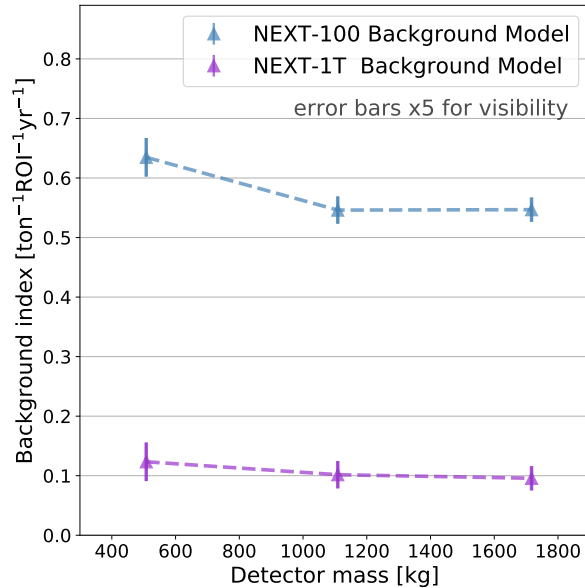


Figure 8. Background index vs a few detector sizes that were studied with the standard performance.

and the cosmogenic background contributions expected there. The resulting sensitivity bands can be seen Figure 7 (left).

The baseline detector design assumed in this study for NEX-1T uses ~ 1230 kg of xenon gas (1109 kg ^{136}Xe). Alternative detector masses were also studied to investigate the expected scaling behaviour. In addition to the default configuration, simulation sets were generated for detectors with dimensions of $2\text{ m} \times 2\text{ m}$ (505 kg), and $3\text{ m} \times 3\text{ m}$ (1704 kg). Each detector was analysed with the pure xenon configuration and both radiogenic models. A comparison of the rejection factors can be seen in Figure 8. No strong dependence of background index on detector size was observed.

High pressure xenon gas technology offers a scalable and modular approach to $0\nu\beta\beta$ searches, with tonne-scale sensitivity that depends primarily on exposure and not on the details of phasing or modularity. This can be elaborated on further by studying the radial dependence of the events which can be seen in Figure 9, which shows the uniformity of events in the detector. At the density of xenon considered the signal events are about 10 cm in length. The signal events are reduced when they are within 10 cm of the field cage due to event containment. In xenon gas the background will be uniform throughout the detector, since there is no self shielding such as that in liquid xenon detectors. However, the gas phase allows for a more detailed topological analysis such as that described in previous sections, which drastically reduces the backgrounds. This also implies that the gas phase detector utilizes a larger portion of total total volume as an active detector.

The symbiotic effects of the gas detector size and radial event profile imply the detector can be scaled to a significant size ($3\text{ m} \times 3\text{ m}$) without major consequences, and due to the radial nature multiple independent detectors could be operational without the need for excess isotope which is a major cost factor in building such experiments. Implying that

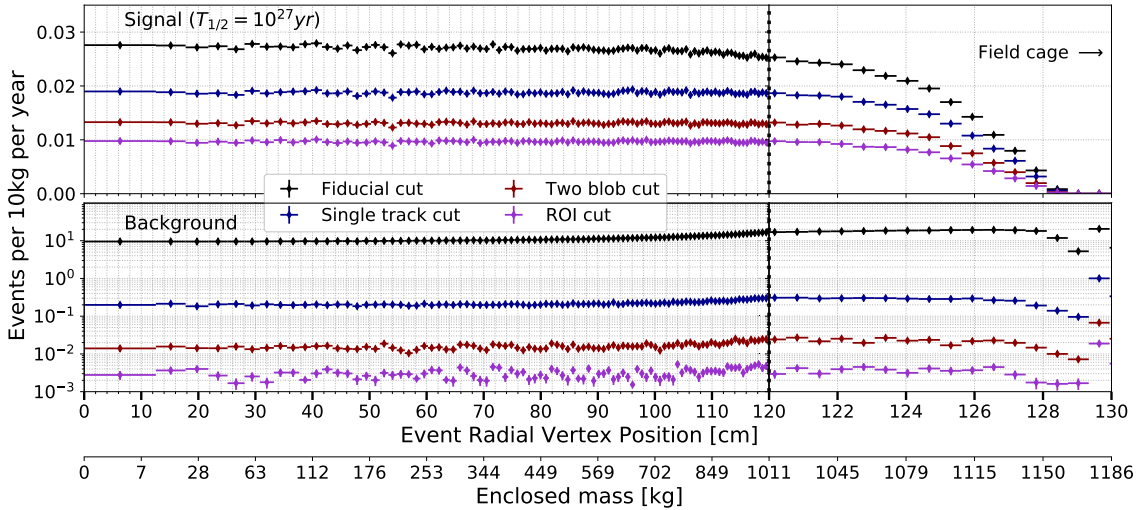


Figure 9. Radial cut profile uniformly binned by mass for all simulated events and normalized by activity.

the exposure from several identical tonne or multi-tonne detectors could be added to reach arbitrary large exposures as in Figure 7 (left).

6 Discussion and improvements

Presented in this paper is an example of a NEXT-like detector which holds a metric ton of enriched ^{136}Xe with an assumed energy resolution of 0.7% FWHM at $Q_{\beta\beta}$ and two cases of diffusion. While energy resolution better than 0.7% is theoretically and possibly achievable in xenon gas it is not a requirement. The effects of improved energy resolution were also considered and they do enhance the sensitivity however the enhancement is not very significant when compared to the cases of diffusion.

We consider the analysis presented to be conservative by design. For example previous studies showed radiogenic contribution from outside the copper shield to be approximately 5%. Assuming the siting location at LNGS is also a pessimistic, other experiments in this class only consider the deeper labs such as SURF and SNOLAB.

A particularly interesting development in the siting that shows the flexibility of a NEXT-like detector, is the suppression of neutron activations on ^{136}Xe by addition of a small amount of ^3He [53]. Reducing the yield ^{137}Xe inherently reduces the cosmogenic background index. With the addition of 0.1% ^3He by mass the activations will be reduced by an order of magnitude. This implies that the detector is not confined to operate at the deepest labs, and a shallower lab with the a muon flux one order of magnitude above LNGS would provide the same impact on the sensitivity as that presented in Figure 7.

A robust analysis is currently under development and could enhance the sensitivity reported here. A topological likelihood based analysis is also under consideration with improvement also expected. The main aim of these analyses is to improve signal efficiency

without increasing the background index. At the levels of background expected from the present analysis, the signal efficiency becomes the dominant factor affecting the projected sensitivity. This improvement will likely come from the handling of ambiguous cases, for example when a signal event undergoes bremsstrahlung and fails to pass the single-track cut.

As mentioned in section 3.1, radiopurity in NEXT-100 can be significantly improved through the replacement of PMTs by SiPMs, the availability of 10-fold purer PTFE and the reduction in Kapton thickness. However, the leading component in the NEXT-1T background model is the nearly 40 tonnes of copper that forms the inner shield. Presently, the only known method for improving the cleanliness of radiopure copper is by electroforming, which is a slow and expensive task. However, based on the attenuation length of the ^{214}Bi and ^{208}Tl gammas in copper, manufacture of the whole mass would not be necessary to gain a significant improvement. An inner shell of ~ 2 cm thickness would suffice to attenuate the flux, effectively self shielding the copper. Manufacturing 2 cm of copper on the scale required, equates to ~ 3800 kg, which is similar to amounts that other collaborations have produced. While electroformed copper is not considered as a baseline design its impact on the sensitivity is rather large since copper is the dominant background as seen in Figure 5, adding the electroformed copper would reduce this contribution by approximately one order of magnitude.

7 Conclusions

The NEXT experimental program has pursued a rigorous campaign of material radio-assay and R&D to advance the capabilities of xenon gas optical TPCs, with the goal of developing a discovery-class technology for neutrinoless double beta decay. The culmination of these developments is a technology that is flexible in terms of its operating conditions and environment, while still being a robust and modular detector with a background index that is very low, even at modest scales.

We have shown NEXT-like gas detector holding slightly over a tonne of active isotope can efficiently reject all background sources via topological and energy analysis, achieving a background index in the range of 0.09 to $0.27 \text{ ton}^{-1}\text{yr}^{-1}\text{ROI}^{-1}$. As a baseline we have considered a single detector with a tonne of active isotope. Larger detectors do not exhibit an increase in background rate, and several detectors can be deployed in parallel to reach multi-tonne target masses while still taking advantage of the full volume of active isotope. The techniques presented here offer a compelling path to achieve the sensitivity needed to cross the inverted hierarchy in neutrino mass-scale sensitivity, using high-pressure xenon gas TPC experiments.

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References

- [1] S. Weinberg, *Baryon and Lepton Nonconserving Processes*, *Phys. Rev. Lett.* **43** (1979) 1566–1570.
- [2] P. Minkowski, $\mu \rightarrow e\gamma$ at a Rate of One Out of 10^9 Muon Decays?, *Phys. Lett. B* **67** (1977) 421–428.
- [3] M. Gell-Mann, P. Ramond, and R. Slansky, *Complex Spinors and Unified Theories*, *Conf. Proc. C* **790927** (1979) 315–321, [[arXiv:1306.4669](#)].
- [4] T. Yanagida, *Horizontal gauge symmetry and masses of neutrinos*, *Conf. Proc. C* **7902131** (1979) 95–99.
- [5] R. N. Mohapatra and G. Senjanovic, *Neutrino Mass and Spontaneous Parity Nonconservation*, *Phys. Rev. Lett.* **44** (1980) 912.
- [6] M. Fukugita and T. Yanagida, *Baryogenesis Without Grand Unification*, *Phys. Lett. B* **174** (1986) 45–47.
- [7] J. J. Gómez-Cadenas, J. Martín-Albo, M. Mezzetto, F. Monrabal, and M. Sorel, *The search for neutrinoless double beta decay*, *Riv. Nuovo Cim.* **35** (2012) 29–98, [[arXiv:1109.5515](#)].
- [8] **KamLAND-Zen** Collaboration, A. Gando et al., *Search for Majorana Neutrinos near the Inverted Mass Hierarchy Region with KamLAND-Zen*, *Phys. Rev. Lett.* **117** (2016) 082503, [[arXiv:1605.02889](#)]. Addendum: *Phys. Rev. Lett.* **117**, 109903 (2016).
- [9] **GERDA** Collaboration, M. Agostini et al., *Probing Majorana neutrinos with double- β decay*, *Science* **365** (2019) 1445, [[arXiv:1909.02726](#)].
- [10] A. Giuliani, J. J. Gómez-Cadenas, S. Pascoli, E. Previtali, R. Saakyan, K. Schffner, and S. Schnert, *Double Beta Decay APPEC Committee Report*, [arXiv:1910.04688](#).

- [11] D. R. Nygren, *Detecting the barium daughter in ^{136}Xe $0\nu\beta\beta$ decay using single-molecule fluorescence imaging techniques*, *J. Phys. Conf. Ser.* **650** (2015) 012002.
- [12] B. J. P. Jones, A. D. McDonald, and D. R. Nygren, *Single Molecule Fluorescence Imaging as a Technique for Barium Tagging in Neutrinoless Double Beta Decay*, *JINST* **11** (2016) P12011, [[arXiv:1609.04019](#)].
- [13] **NEXT** Collaboration, A. D. McDonald et al., *Demonstration of Single Barium Ion Sensitivity for Neutrinoless Double Beta Decay using Single Molecule Fluorescence Imaging*, *Phys. Rev. Lett.* **120** (2018) 132504, [[arXiv:1711.04782](#)].
- [14] P. Thapa, I. Arnquist, N. Byrnes, A. A. Denisenko, F. W. Foss, B. J. P. Jones, A. D. McDonald, D. R. Nygren, and K. Woodruff, *Barium Chemosensors with Dry-Phase Fluorescence for Neutrinoless Double Beta Decay*, *Sci. Rep.* **9** (2019) 15097, [[arXiv:1904.05901](#)].
- [15] I. Rivilla et al., *Towards a background-free neutrinoless double beta decay experiment based on a fluorescent bicolor sensor*, [[arXiv:1909.02782](#)].
- [16] D. Nygren, *High-pressure xenon gas electroluminescent TPC for $0\nu\beta\beta$ decay search*, *Nucl. Instrum. Meth. A* **603** (2009) 337–348.
- [17] M. Redshaw, E. Wingfield, J. McDaniel, and E. Myers, *Mass and double-beta-decay Q value of Xe-136* , *Phys. Rev. Lett.* **98** (2007) 053003.
- [18] P. McCowan and R. Barber, *Q value for the double-beta decay of Xe-136* , *Phys. Rev. C* **82** (2010) 024603.
- [19] **NEXT** Collaboration, V. Álvarez et al., *Near-Intrinsic Energy Resolution for 30 to 662 keV Gamma Rays in a High Pressure Xenon Electroluminescent TPC*, *Nucl. Instrum. Meth. A* **708** (2013) 101–114, [[arXiv:1211.4474](#)].
- [20] **NEXT** Collaboration, V. Álvarez et al., *Initial results of NEXT-DEMO, a large-scale prototype of the NEXT-100 experiment*, *JINST* **8** (2013) P04002, [[arXiv:1211.4838](#)].
- [21] **NEXT** Collaboration, V. Álvarez et al., *Operation and first results of the NEXT-DEMO prototype using a silicon photomultiplier tracking array*, *JINST* **8** (2013) P09011, [[arXiv:1306.0471](#)].
- [22] **NEXT** Collaboration, D. Lorca et al., *Characterisation of NEXT-DEMO using xenon K_α X-rays*, *JINST* **9** (2014) P10007, [[arXiv:1407.3966](#)].
- [23] **NEXT** Collaboration, P. Ferrario et al., *First proof of topological signature in the high pressure xenon gas TPC with electroluminescence amplification for the NEXT experiment*, *JHEP* **01** (2016) 104, [[arXiv:1507.05902](#)].
- [24] **NEXT** Collaboration, F. Monrabal et al., *The NEXT-White (NEW) Detector*, *JINST* **13** (2018) P12010, [[arXiv:1804.02409](#)].
- [25] **NEXT** Collaboration, G. Martinez-Lema et al., *Calibration of the NEXT-White detector using $^{83\text{m}}\text{Kr}$ decays*, *JINST* **13** (2018), no. 10 P10014, [[arXiv:1804.01780](#)].
- [26] **NEXT** Collaboration, J. Renner et al., *Initial results on energy resolution of the NEXT-White detector*, *JINST* **13** (2018), no. 10 P10020, [[arXiv:1808.01804](#)].

- [27] **NEXT** Collaboration, J. Renner et al., *Energy calibration of the NEXT-White detector with 1% resolution near $Q_{\beta\beta}$ of ^{136}Xe* , *JHEP* **10** (2019) 230, [[arXiv:1905.13110](#)].
- [28] **NEXT** Collaboration, P. Ferrario et al., *Demonstration of the event identification capabilities of the NEXT-White detector*, *JHEP* **10** (2019) 052, [[arXiv:1905.13141](#)].
- [29] **NEXT** Collaboration, P. Novella et al., *Measurement of radon-induced backgrounds in the NEXT double beta decay experiment*, *JHEP* **10** (2018) 112, [[arXiv:1804.00471](#)].
- [30] **NEXT** Collaboration, P. Novella et al., *Radiogenic Backgrounds in the NEXT Double Beta Decay Experiment*, *JHEP* **10** (2019) 051, [[arXiv:1905.13625](#)].
- [31] **NEXT** Collaboration, V. Álvarez et al., *NEXT-100 Technical Design Report (TDR): Executive Summary*, *JINST* **7** (2012) T06001, [[arXiv:1202.0721](#)].
- [32] **NEXT** Collaboration, J. Martín-Albo et al., *Sensitivity of NEXT-100 to Neutrinoless Double Beta Decay*, *JHEP* **05** (2016) 159, [[arXiv:1511.09246](#)].
- [33] **NEXT** Collaboration, S. Cebrián et al., *Radiopurity assessment of the tracking readout for the NEXT double beta decay experiment*, *JINST* **10** (2015), no. 05 P05006, [[arXiv:1411.1433](#)].
- [34] **NEXT** Collaboration, S. Cebrián et al., *Radiopurity assessment of the energy readout for the NEXT double beta decay experiment*, *JINST* **12** (2017), no. 08 T08003, [[arXiv:1706.06012](#)].
- [35] D. S. Leonard et al., *Systematic study of trace radioactive impurities in candidate construction materials for EXO-200*, *Nucl. Instrum. Meth.* **A591** (2008) 490–509, [[arXiv:0709.4524](#)].
- [36] N. Abgrall et al., *The Majorana Demonstrator radioassay program*, *Nucl. Instrum. Meth.* **A828** (2016) 22–36, [[arXiv:1601.03779](#)].
- [37] I. J. Arnquist, C. Beck, M. L. di Vacri, K. Harouaka, and R. Saldanha, *Ultra-low radioactivity Kapton and copper-Kapton laminates*, *Nucl. Instrum. Meth. A* **959** (2020) 163573, [[arXiv:1910.04317](#)].
- [38] S. A. Kharusi, A. Alamre, J. Albert, M. Alfaris, G. Anton, I. Arnquist, I. Badhrees, P. Barbeau, D. Beck, V. Belov, et al., *nexo pre-conceptual design report*, *arXiv preprint arXiv:1805.11142* (2018).
- [39] N. Abgrall, I. J. Arnquist, F. Avignone Iii, H. O. Back, A. S. Barabash, F. Bertrand, M. Boswell, A. Bradley, V. Brudanin, M. Busch, et al., *The majorana demonstrator radioassay program*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **828** (2016) 22–36.
- [40] V. Kudryavtsev, *Muon simulation codes music and musun for underground physics*, *Computer Physics Communications* **180** (2009), no. 3 339 – 346.
- [41] **Borexino** Collaboration, M. Agostini et al., *Modulations of the Cosmic Muon Signal in Ten Years of Borexino Data*, *JCAP* **1902** (2019) 046, [[arXiv:1808.04207](#)].
- [42] **SNO** Collaboration, B. Aharmim et al., *Measurement of the Cosmic Ray and Neutrino-Induced Muon Flux at the Sudbury Neutrino Observatory*, *Phys. Rev.* **D80** (2009) 012001, [[arXiv:0902.2776](#)].

- [43] **NEXT** Collaboration, L. Rogers et al., *Mitigation of Backgrounds from Cosmogenic ^{137}Xe in Xenon Gas Experiments using ^3He Neutron Capture*, [arXiv:2001.11147](#).
- [44] J. Muñoz Vidal, *The NEXT path to neutrino inverse hierarchy*. PhD thesis, Valencia U., IFIC, 2017.
- [45] O. Ponkratenko, V. Tretyak, and Y. G. Zdesenko, *Event generator decay4 for simulating double-beta processes and decays of radioactive nuclei*, *Physics of Atomic Nuclei* **63** (2000), no. 7 1282–1287.
- [46] **NEXT** Collaboration, A. Simón et al., *Electron drift properties in high pressure gaseous xenon*, *JINST* **13** (2018), no. 07 P07013, [[arXiv:1804.01680](#)].
- [47] R. Felkai, F. Monrabal, D. González-Díaz, M. Sorel, N. López-March, J. J. Gómez-Cadenas, C. Adams, V. Álvarez, L. Arazi, C. Azevedo, et al., *Helium-xenon mixtures to improve the topological signature in high pressure gas xenon tpcs*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **905** (2018) 82–90.
- [48] C. Henriques, C. Monteiro, D. González-Díaz, C. R. Azevedo, E. Freitas, R. Mano, M. Jorge, A. Fernandes, J. Gómez-Cadenas, L. Fernandes, et al., *Electroluminescence tpcs at the thermal diffusion limit*, *Journal of High Energy Physics* **2019** (2019), no. 1 27.
- [49] A. McDonald, K. Woodruff, B. Al Atoum, D. González-Díaz, B. Jones, C. Adams, V. Álvarez, L. Arazi, I. Arnquist, C. Azevedo, et al., *Electron drift and longitudinal diffusion in high pressure xenon-helium gas mixtures*, *Journal of Instrumentation* **14** (2019), no. 08 P08009.
- [50] A. Fernandes, C. Henriques, R. Mano, D. González-Díaz, C. Azevedo, J. Gómez-Cadenas, E. Freitas, L. Fernandes, C. Monteiro, C. Adams, et al., *Electroluminescence yield in low-diffusion xe-he gas mixtures*, *arXiv preprint arXiv:1906.03984* (2019).
- [51] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introduction to algorithms*, pp. 531–539. The MIT Press, 3rd ed., 2009.
- [52] G. J. Feldman and R. D. Cousins, *Unified approach to the classical statistical analysis of small signals*, *Physical Review D* **57** (1998), no. 7 3873.
- [53] L. Rogers, B. Jones, A. Laing, S. Pingulkar, K. Woodruff, C. Adams, V. Álvarez, L. Arazi, I. Arnquist, C. Azevedo, et al., *Mitigation of backgrounds from cosmogenic ^{137}Xe in xenon gas experiments using ^3He neutron capture*, *arXiv preprint arXiv:2001.11147* (2020).