THE NEXT EXPERIMENT FOR DOUBLE BETA DECAY SEARCHES

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THE NEXT COLLABORATION

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A xenon gas time projection chamber with electroluminescent amplification. Primary scintillation (S1) establishes the start-of-event time; secondary scintillation (S2) is used for calorimetry and tracking. Specialised sensor arrays for each measurement.
Intrinsic energy resolution of xenon gas close to 0.3% at 2.5 MeV. Fano factor of xenon significantly smaller in gaseous phase (0.15) than in liquid (>20).
Emission of scintillation light by atoms excited by a charge accelerated by an electric field. High, linear amplification gain with sub-Poissonian fluctuations.
Signal events (two electron tracks with a common vertex) feature dE/dx blobs at both ends, unlike most common background events (single electrons).
THE NEXT PROJECT

- **DEMO**
  - (1 kg)
  - (2010–2014)
  - Prototyping of detector concept

- **NEW**
  - (10 kg)
  - Test underground, radiopure operation

- **NEXT-100**
  - (100 kg)
  - (2019–2021)
  - Neutrinoless double beta decay searches

- **NEXT-2.0**
  - (Ton scale)
  - (2021– ...)
  - Discovery?
NEXT-WHITE (NEW)
12 Hamamatsu R11410

2000+ SensL 1-mm² SiPMs
NEXT-WHITE (NEW)
The gas loop has two SAES MC4500-902 ambient temperature getters (cold getters) and one SAES PS4-MT50-R-535 hot getter. The three getters can be operated in parallel to allow large flow operations. The normal mode of operation is to circulate only through the hot getter, given the large radon contamination introduced by the cold getters. Indeed, recirculation through the hot getter only is a must in a physics run. However, during commissioning, circulation through the cold getters is necessary.
The gas loop has two SAES MC4500-902 ambient temperature getters (cold getters) and one SAES PS4-MT50-R-535 hot getter. The three getters can be operated in parallel to allow large flow operations. The normal mode of operation is to circulate only through the hot getter, given the large radon contamination introduced by the cold getters. Indeed, recirculation through the hot getter only is a must in a physics run. However, during commissioning, circulation through the cold getters (or both cold and hot getters) allows a faster purification of the gas and is an acceptable strategy provided sufficient time is allowed after closing the cold getters for the radon to decay.

The compressor, shown in figure 19, was manufactured by SERA. The inlet takes gas at a pressure between 5 bar and 10 bar. The maximum outlet pressure is 25 bar. The total leak rate of the compressor has been measured to be smaller than 0.19 g yr$^{-1}$. The compressor has a triple diaphragm system that prevents catastrophic losses of xenon and gas contamination in case of an abrupt diaphragm rupture.

The flow direction inside the active volume of the detector is from the anode to the cathode. The gas enters just behind the tracking plane copper plate (See sec. 6) and exits through a VCR 1/2" port just after the cathode. With this configuration, the clean gas enters directly into the amplification region.

8.3 Cryo-recovery system

Figure 20: Left: A picture of the two NEXT cryo-bottles. Right: A drawing showing the design of the second bottle (the first one is similar).

Recovery of the xenon under normal operation conditions is achieved by connecting two cryo-bottles (figure 20 left) to the recirculation loop and to the expansion tank (so that one can recover the xenon stored there in the event of an emergency evacuation). One of the bottles is used to recover normal xenon, while the other will be used to recover enriched xenon. Each bottle is...
The NEXT-White setup in Hall A at the Laboratorio Subterráneo de Canfranc.
T_{1/2} = 1.83 h
\alpha = 2010
E = 32.1517(5) keV

T_{1/2} = 154.4 ns
\alpha = 17
E = 9.4058(3) keV

The dependence of the light detected by the photomultipliers depends on the lateral position, while the dependence of the light detected by the photomultipliers depends on the vertical position.

The energy plane on the right:

Amplitude (pes)

Time (\mu s)

Amplitude (pes)

Time (\mu s)

Amplitude (pes)

Time (\mu s)
Figure 3: Evolution of the average lifetime during Run IVc.

Figure 4: Calibration maps. See text for details.
Figure 5: Resolution obtained using krypton calibrations as a function of $Z$ and $R$.

The bottom-left panel is the lifetime map, showing stratification of the lifetime in the detector. The average error of the map is of the order of 3%. Notice that for a lifetime of $4$ ms, the maximum charge lost is 12%. The charge is recovered using the lifetime map, and the relative error introduced in the energy residual is equal to the relative error in the lifetime, so the maximum error of the procedure is $\pm 0.4\%$.

Figure 5 shows the resolution obtained with krypton after corrections. Notice that for low $Z$ (no charge loss due to attachment) and low $R$ (center of detector, small geometrical corrections), the resolution approaches 3.5%, or 0.45% at $Q$ (FWHM, $1/e$ extrapolation). Even for larger values of $R$ and $Z$ the resolution stays below 4.5% (0.55% FWHM at $Q$).

In conclusion, krypton calibrations allow us to apply corrections to our data, producing geometrical and lifetime maps. The energy resolution that we obtain at low energy approaches the intrinsic resolution in xenon.

3 Energy resolution at high energies

NEW has recently demonstrated excellent energy resolution 1, and further developments have been made since this time. Here we report on the current status of calibrations with high energy sources ($^{137}$Cs and $^{232}$Th). The general locations at which these sources were placed are described in Fig. 6. In addition to these sources, radioactive $^{83}$mKr was present in the detector, and triggers on the resulting low-energy (41.5 keV) events were taken simultaneously and analyzed separately to construct energy correction maps that could be used to address geometrical and electron lifetime effects on the energy resolution.

We show results from a single run at 10.1 bar pressure, though many such runs have been obtained and can be combined in the future for a higher-statistics analysis. All data were processed with the analysis software IC, beginning with raw sensor waveforms and producing maps containing...
Figure 6: Approximate placement of the two $^{232}$Th sources and $^{137}$Cs source used in the present analysis (not drawn to scale).

Energy information (S1 and S2) from the PMT plane and 2D maps of the SiPM plane. This information was further processed to reconstruct each event as a set of individual hits containing position and energy information ($x$, $y$, $z$, $E$). The event energy was corrected hit-by-hit for geometrical non-uniformities and effects due to electron attachment. Correction was also made for an additional effect in which the total event energy was observed to decrease as a function of the maximum extent of the track in the z-direction. The full spectrum of corrected energies is shown in Fig. 7.

Figure 7: The fully corrected spectrum of high-energy events in NEW 10-bar calibration data. The energy calibration used here was a linear fit to the means of the 4 peaks discussed below in section 3.1 and shown in Fig. 8.

3.1 Energy resolution

Here we demonstrate the energy resolution of NEW by presenting fits to several energy peaks after application of all corrections and with selected fiducial cuts. In all cases the fiducial cuts are applied.

Figure 9: (Top) Distribution with applied fiducial cuts and (bottom) fit - 2 Gaussians summed with a second-order polynomial - to isolated energy depositions corresponding to energies near those of the xenon x-ray lines. Extrapolation to $Q$ is done following a simple statistical law $1/pE$.

Figure 10: (Top) Applied fiducial cuts and (bottom) fit - a Gaussian summed with a second-order polynomial - to the Cs photopeak. Extrapolation to $Q$ is done following a simple statistical law $1/pE$.

Figure 11: (Top) Applied fiducial cuts and (bottom) fit - a Gaussian summed with an exponential - to the $e^+e^-$ double-escape peak of the $^{208}$Tl photopeak. Extrapolation to $Q$ is done following a simple statistical law $1/pE$.

3.1.4 Tl photopeak ($\approx 2.6$ MeV)

The longest tracks analyzed, those most difficult to correct due to the wide topological extent of each single event, were those produced by full-energy depositions of the 2614.5 keV $^{232}$Tl photopeak, shown in Fig. 12.

Figure 8: (Top) Distribution with applied fiducial cuts and (bottom) fit - 2 Gaussians summed with a second-order polynomial - to isolated energy depositions corresponding to energies near those of the xenon x-ray lines. Extrapolation to $Q$ is done following a simple statistical law $1/pE$.

Figure 12: (Top) Applied fiducial cuts and (bottom) fit - a Gaussian summed with a second-order polynomial - to the Cs photopeak. Extrapolation to $Q$ is done following a simple statistical law $1/pE$.

Figure 13: (Top) Applied fiducial cuts and (bottom) fit - a Gaussian summed with an exponential - to the $e^+e^-$ double-escape peak of the $^{208}$Tl photopeak. Extrapolation to $Q$ is done following a simple statistical law $1/pE$.
Predicted energy resolution at $Q$ value of Xe-136 (2.5 MeV) close to 0.75% FWHM, consistent with the measurement at the photopeak of the Tl-208 gamma (2.6 MeV).
3.1.4 Tl photopeak ($\sim 2.6$ MeV)

The longest tracks analyzed, those most difficult to correct due to the wide topological extent of each single event, were those produced by full-energy depositions of the $^{208}$Tl photopeak, shown in Fig. 12.

$\mu = 1597.0$
$\sigma = 5.86$
$R = 0.862\%$
$R_{\beta\beta} = 0.694\%$
Backgrounds from radon activity inside the detector have been measured in NEW, and their impact on the sensitivity of NEXT-100 has been evaluated.
Low-background data taking proceeding after detector calibration campaign. NEXT background model assessed using these data.

Several improvements in the setup have reduced the background in a factor of ~4 over the last few months:

- New radiopure components in field cage.
- Radon-free air introduced in lead shielding.
- Additional layer of shielding added.
The use of this information will allow the tuning of the background model.

Entries correspond to the scale factor of each isotope with respect to the nominal model.

The comparison of the background model described previously with the Run-IVb data is shown in the figure. Data (black dots) are superimposed on the best-fit values for each isotope. The diurnal oscillation of the background is evident from the data.

The rate (Hz/keV) is shown as a function of energy (keV) for different isotopes. The figure on the right shows the rate (Hz/mm²) as a function of R² (mm²). The data points are shown with error bars, and the best-fit models are indicated with different colors.

The chi-squared values for the best-fit models are reported in the legend. For example, BF MC: 2.19 ± 0.15, BF ⁰²⁰Co: 3.70 ± 0.22, BF ⁶⁰K: 0.76 ± 0.12, BF ⁶⁰⁰Bi: 2.08 ± 0.34, BF ⁶⁰⁶Tl: 1.86 ± 0.58, and BF ¹³⁶Xe: 1.00 ± 0.00.
Figure 26: Efficiency of the topological two-blob selection as a function of energy, for both signal MC events (red) and all-background MC events (blue). The peak in the background efficiency around 1,600 keV is physical, and due to Tl-208 double-escape (double-electron) events in the background MC sample.

Figure 27: Event rates (in Hz/keV) as a function of corrected event energy, after inclusive (blue histogram), fiducial (orange) and topological (green) cuts. Run-IVb data are shown in the left panel, and nominal background MC expectations are shown in the right panel.

We believe that we are now ready to perform a sensitive analysis as soon as 136Xe-enriched operations will start.

As a final remark, and in view of future 0⌫ searches in NEXT-White and NEXT-100, a background study in the neighborhood of the 136Xe Q-value at 2,458 keV has also been made.

Figure 28 shows a zoom of the event energy distribution in a 200 keV wide region around Q, between 2,358 and 2,558 keV, in both Run-IVb data and nominal MC. Note that in this case the energy spectra have not been rescaled to unit exposure, that is, converted to event rates. The Run-IVb data exposure is 27.2 days, while the MC exposure is 5.91 yr, about a 80 times larger exposure. Thirty-eight events are found in the nominal MC, corresponding to about 0.5 expected events for a 27.2 d data exposure. Monte-Carlo tuning as described in Sec. 5 would bring this estimate to about 1 event.

Data-MC comparison of background distributions in the energy region of interest for neutrinoless double beta decay searches.
Figure 1: Field cage design. Left: Front view showing all the layers (From the outside to the inside: Copper shielding described in section ??, two polyethylene sheets for electrical insulation, copper rings for field shaping with HDPE support struts, light reflector). Right: Side view of the FC with the polyethylene insulater visible on the outside in light green and the light reflector visible in the inside in white.

5. Peripheral Components

Figure 1 shows the current complete model of the field cage, all subcomponents, and some peripheral elements. On the left, the outermost layer is the copper shield that attenuates the radioactive backgrounds originating in the pressure vessel and detector surroundings. Its thickness is optimized at 12 cm, with the requirement that the radioactive backgrounds from the copper, and all other volumes external to it, be smaller than the internal backgrounds (that is, field cage and sensor planes). The thickness corresponds to \( \approx 4 \) interaction length for 3-MeV gammas, i.e., the high-energy gammas penetrating the shield are attenuated by at least 2 orders of magnitude. However, as the buffer volume is easier to change in size than the more delicate design of the field cage rings and cathode and other delicate functional parts, the copper buffer here is increased to X thickness to match the outer diameter of the current field cage design.

Internal to this, in light green, are two layers of quarter inch polyethylene which are wrapped inside the internal structure, and will protect against sparking which otherwise would occur between the copper rings kept at high...
Figure 16: Left: Cathode sitting in S-hooks from aluminum table with weights hanging from wires while they stretch. Right: piece of debris found on one of the wires during inspection which then got replaced. The wire was then taken across to hole on opposite side of the frame, feed through the hole then tied to .45lb weight through rubber grommet. The weights were made from aluminum stock plates with a hole drilled in the corner and rubber grommets inserted for the wire to go through so that it wouldn’t crimp against a rough metal edge. Weights alternate every other wire which side of the frame they are hanging from so that weights are distributed all around the frame as shown in 16 left.

A final check is done by eye using light reflections and checking everything reflects uniformly across each wire shown in 17. The weights are then hung for a week so wire stretching can occur then set screws secured and weights cut off.

3.4. Interfaces

The cathode interfaces to the field cage and to the high voltage feed-through. One idea is to have the HV cable come in tangentially to the Cathode and through a round metal “bracket” fixed to the cathode itself. The “bracket” can have a oval tipped set screw that when tightened makes a secure connection with the HV cable. All, we need to work on this.

Figure 21: Calculated deflections of unsupported mesh and a mesh with a single point of “magic post” support material within the EL region. Comparisons of deflection without any support posts, and with a single point support are shown in Fig. 26. It is clear that a small number of supports considerably alleviate the difficulties in mesh tensioning.

Because we have opted for a resistive anode, a fully conductive gate mesh is admissible. Because of the need to support a significant tension, radiopurity and structural constraints primarily limit our considerations to 304 stainless steel as the mesh material. The work function of stainless steel is 8eV which should be above the photoelectric threshold for 175nm light, even in the high field region of the EL region. We plan to test this in a test stand at UTA.

Figure 24: Left: Demonstration of wires spaced close together in x with a few support wires in y that can be tensioned tighter. Right: Successful prototype of the individual wired method with wires going both up and down and alternating between a set screw for rough tensioning and a vented bolt plus ferrule for fine tuning. One end of each wire is tied around a ferrule which sits inside a hollow screw that can be turned to adjust the wire tension, wire-by-wire. The other end is fixed by a set screw in a similar mechanism to that used in the cathode. To provide extra support similar to a mesh, a smaller number of wires would be spread out linearly in y. These wires would be able to be tensioned tighter than the x wires without deforming the frame which would in turn support the x wires and minimize deflection due to electrostatic forces. The primary challenge to this approach is the great complexity and likely great expense involved in manufacturing the frame, which has thin holes drilled linearly through the frame, needing a depth of 8 centimeters at the outside edges. Also for the tension to be properly transferred to the wires there must be a smooth round directly lined up with the hole for the wire to run along as it is pulled up or down. This could possibly be solved by making the frame in two halves then securing them together, so long as it is secured well enough it does not come apart when weights are being hung. Another challenge that would need to be addressed is the thickness of the frame. Currently we are looking at 25 mm thick which would be 12.5 mm into the EL interface region of just the frame itself, not counting the additional hardware. This would require a mounting scheme for the anode that holds it inside the gate frame but we believe this is solvable.
NEXT-100: SENSITIVITY

Background rate (10^{-5} counts keV^{-1} kg^{-1} yr^{-1})

- Pressure vessel
- PMTs
- PMT enclosures
- Enclosure windows
- EP support plate
- SiPM boards
- SiPMs
- Field-cage barrel
- Shaping rings
- Electrode rings
- Anode plate
- FC resistor chain
- Inner shield
- Outer shield

Exposure (kg year)

Half-life $T_{1/2}$ (10^{25} years)

- Ti-208
- Bi-214

NEXT-100 should demonstrate a background rate competitive with HPGe detectors: a few counts per ton and year in ROI.

Ample room for improvement in several areas:

- Reconstruction algorithms (i.e. better energy resolution and topological discrimination).
- Radiopurity (e.g. get rid of PMTs).
- Low-diffusion gas mixtures and denser tracking plane to improve tracking signature.

Last but not least: gaseous xenon could make possible a true background-free experiment via tagging of the barium decay product.
Tagging of the Ba ion produced in a double beta decay would result in a zero-background experiment. It has been actively explored in gaseous and liquid xenon for 15+ years.
SMFI is a technique from biochemistry with proven single-ion resolution that was awarded a Nobel prize in chemistry in 2014. A non-fluorescent molecule becomes fluorescent upon chelation with an incident ion.

Calcium and barium are congeners: many dyes developed for Ca are also expected to respond to Ba. Can we use SMFI to identify a single Ba ion in a xenon gas volume?

Strong fluorescence from Fluo3 and Fluo4 under chelation with Ba++ ions.

The image shows a weak solution of barium perchlorate salt on a total internal reflection microscope developed at UTA.

Each spot is a single barium ion.

Brighter spots are near the microscope surface, dimmer ones are deeper in the sample.

In a xenon detector, dye would be deposited as a monolayer: only brightest spots at constant depth expected.
First demonstration of single barium ion resolution!

Neutrinoless double beta decay searches are the most promising (likely the only) way to establish that neutrinos are Majorana particles.

The current generation of experiments is exploring the degenerate region of neutrino masses. Going forward, double beta decay experiments will require exposures well above $10^3$ kg yr and background rates below 10 counts tonne$^{-1}$ yr$^{-1}$.

NEXT has proven that a GXe TPC can provide both high energy resolution and tracking for event identification. NEXT-100 will probably be the most sensitive experiment using $^{136}$Xe, according to the background rate measured in NEXT-White.

There’s a clear path to improve NEXT towards the ton scale: reach energy resolutions close to the intrinsic limit (<0.5% FWHM) and improve the rejecting power of the tracking signature.

R&D on chemical tagging of Ba ions undergoing, with very promising results so far.