Searching for neutrinoless double beta decays with nEXO

Raymond Tsang, University of Alabama

on behalf of

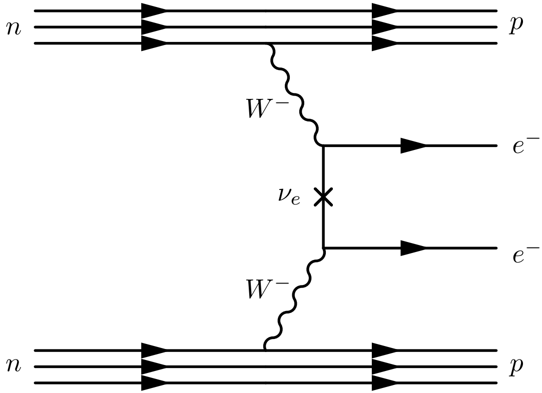
the nEXO collaboration

Oct 12, 2023

Next Generation Nucleon Decay and Neutrino Detectors 2023
Procida, Italy

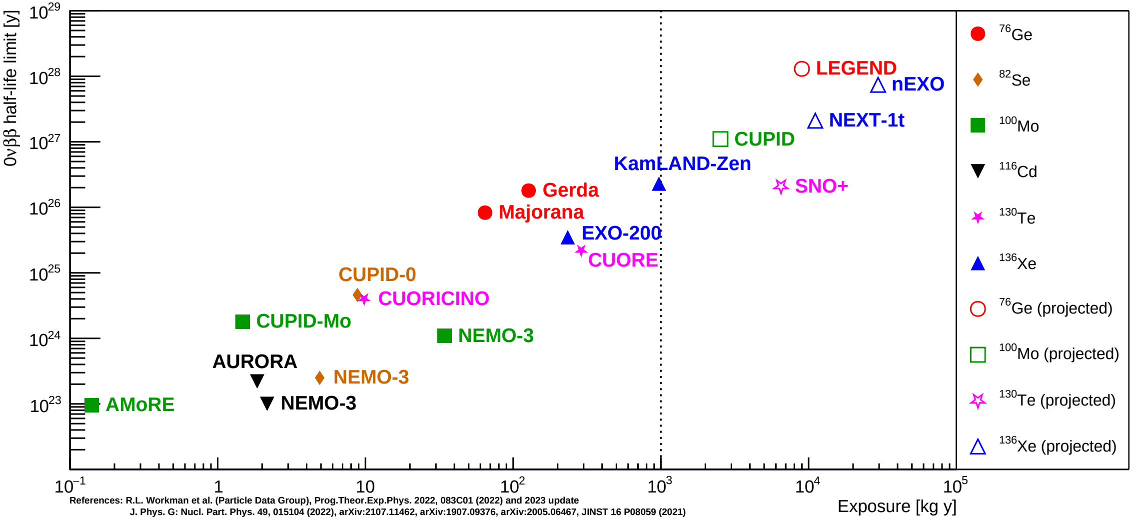
Why search for $0\nu\beta\beta$?

- Enabled by non-zero neutrino mass
- Observation of $0\nu\beta\beta$ always implies new physics *
  - Lepton number violation
  - Majorana fermions: A new class of particles
  - Matter-antimatter asymmetry
- The search for $0\nu\beta\beta$ goes beyond measuring the Majorana mass of neutrinos.



*[J. Schechter and J.W.F. Valle, PRD 25 2951-2954 (1982)]

$0\nu\beta\beta$ landscape – Why tonne-scale?



Towards the next generation:

- Need a **ton** of $\beta\beta$ emitter
- Extremely low background
- and various technical challenges

Extraordinary discovery requires extraordinary evidence

- Multiple experiments
- Different isotopes and detection technologies
- Different decay energies

The 2023 Long Range Plan

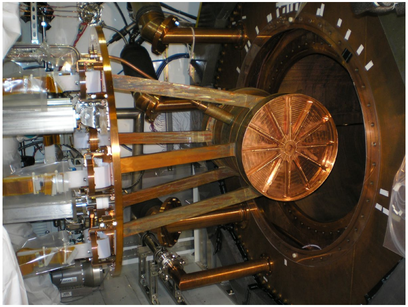
- The 2023 Long Range Plan for Nuclear Science was made public last week on Oct 4, 2023.
- The writing was lead by the Nuclear Science Advisory Committee (NSAC), which advises the US DOE, supported by numerous White papers from the nuclear physics community.
- $0\nu\beta\beta$ experiments are mentioned in Recommendation 2:

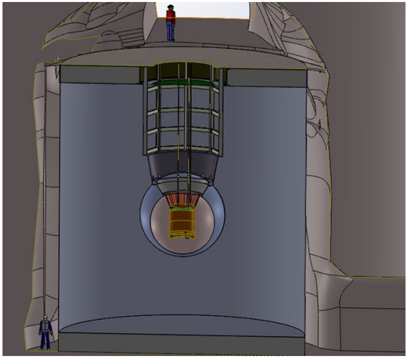
> **RECOMMENDATION 2**
> **As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.**

- It shows the community's unwavering support for the building of $0\nu\beta\beta$ experiments.

Milestones of the EXO program

- 2001: The EXO program began.
- 2010: EXO-200 detector was built.
- 2011: EXO-200 began taking data.
- 2014: The nEXO collaboration was formed.
- May 2018: nEXO Pre-Conceptual Design Report (pCDR)
- Nov 2018: CD-0 (Mission need) for tonne-scale $\beta\beta$ decay search
- Dec 2018: EXO-200 stopped taking data.
- Feb 2021: nEXO's first budget review by DoE
- Jul 2021: DoE portfolio review for project comparison
- Jan 2022: Project start
- **Now: Continue R&D**





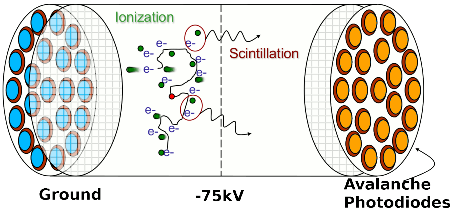
EXO-200 – a successful experiment and demonstrator

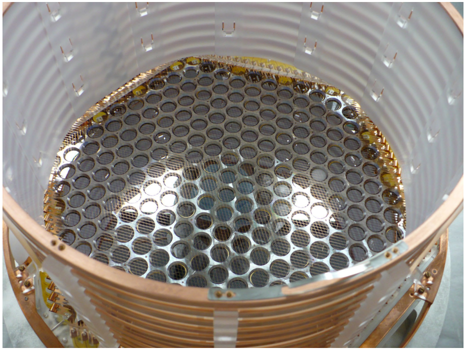
Features:

- Liquid xenon (LXe) time projection chamber (TPC)
- 200 kg of Xe enriched to 80% in ^{136}Xe
- 2 drift volumes separated by a central cathode
- Ionization: Charge collection wires
- Scintillation: Avalanche Photodiodes
- Waste Isolation Pilot Plant, New Mexico, USA.
- Overburden: 1623 m.w.e.
- Operational from 2011 to 2018

EXO-200's major achievements:

- First observation of $2\nu\beta\beta$ of ^{136}Xe [PRL 107, 212501 (2011)]
- Most precise measurement of ^{136}Xe $2\nu\beta\beta$ half-life to-date: $\tau^{2\nu}_{1/2} = (2.165 \pm 0.016 \pm 0.059) \times 10^{21}$ y [PRC 89, 015502 (2014)]
- Limit on ^{136}Xe $0\nu\beta\beta$ half-life: $\tau^{0\nu}_{1/2} > 3.5 \times 10^{25}$ y (90% C.L.) [PRL 123 161802 (2019)]





Next step: scale up!

nEXO

160+ collaborators

34 institutions

9 countries

1 goal: Find $0\nu\beta\beta$

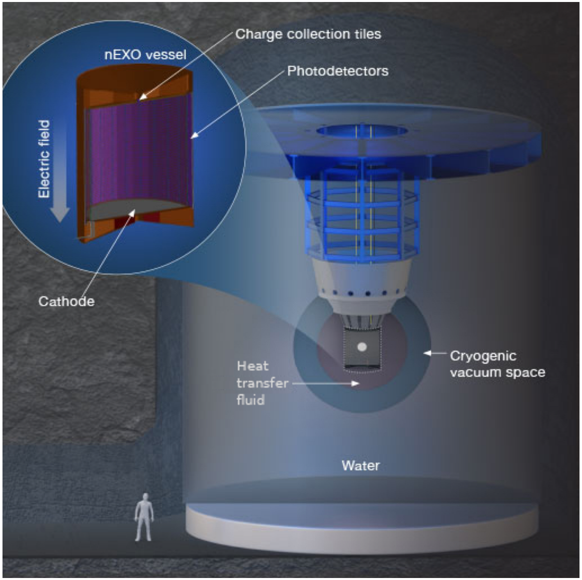
nEXO experiment and design

Features:

- Single phase single volume LXe TPC
- 5 tonnes of LXe enriched to 90% in ^{136}Xe
- Ionization: Charge collection tiles
- Scintillation: Silicon Photomultipliers (SiPM)
- Location: SNOLAB with 6010 m.w.e. overburden

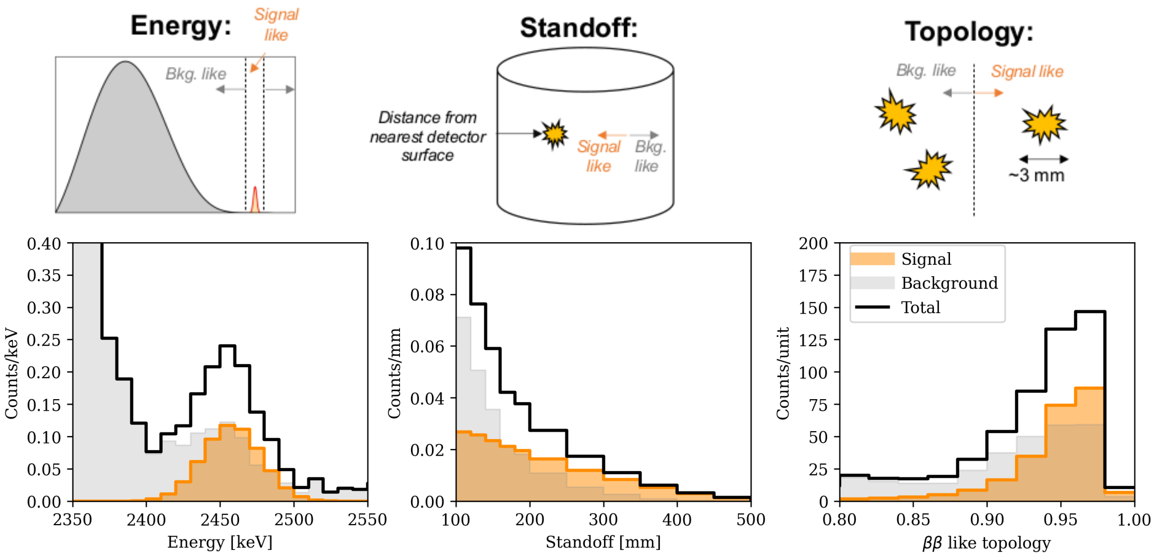
Improvements over EXO-200:

	EXO-200:	*nEXO:*	Improvements:
Vessel and cryostat	Thin-walled commercial Cu w/HFE	*Thin-walled electroformed Cu w/HFE*	Lower background
High voltage	Max voltage: 25 kV (end-of-run)	*Operating voltage: 50 kV*	Full scale parts tested in LXe prior to installation to minimize risk
Cables	Cu clad polyimide (analog)	*Cu clad polyimide (digital)*	Same cable/feedthrough technology, R&D identified 10x lower bkg substrate and demonstrated digital signal transmission
e⁻ lifetime	3-5 ms	*5 ms (req.), 10 ms (goal)*	Minimal plastics (no PTFE reflector), lower surface to volume ratio, detailed materials screening program
Charge collection	Crossed wires	*Gridless modular tiles*	R&D performed to demonstrate charge collection with tiles in LXe, detailed simulation developed
Light collection	APDs + PTFE reflector	*SiPMs around TPC barrel*	SiPMs avoid readout noise, R&D demonstrated prototypes from two vendors
Energy resolution	1.2%	*1.2% (req.), 0.8% (goal)*	Improved resolution due to SiPMs (negligible readout noise in light channels)
Electronics	Conventional room temp.	*In LXe ASIC-based design*	Minimize readout noise for light and charge channels, nEXO prototypes demonstrated in R&D and follow from LAr TPC lineage
Background control	Measurement of all materials	*Measurement of all materials*	RBC program follows successful strategy demonstrated in EXO-200
Larger size	>2 atten. length at center	*>7 atten. length at center*	Exponential attenuation of external gammas and more fully contained Comptons



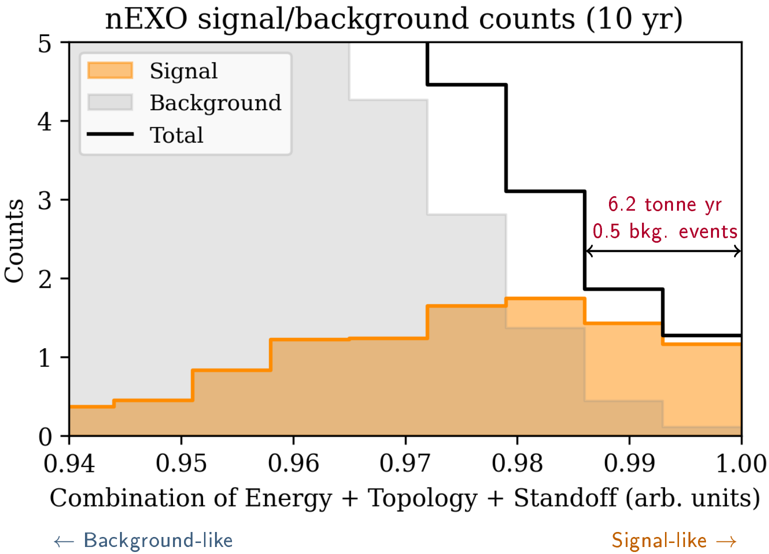
Multi-observable analysis

nEXO can robustly identify a signal event by measuring multiple observables.



Assumed signal: $\tau_{1/2} = 7.4 \times 10^{27}$ year.
(Potential 3-σ discovery by nEXO.)

Multi-observable analysis



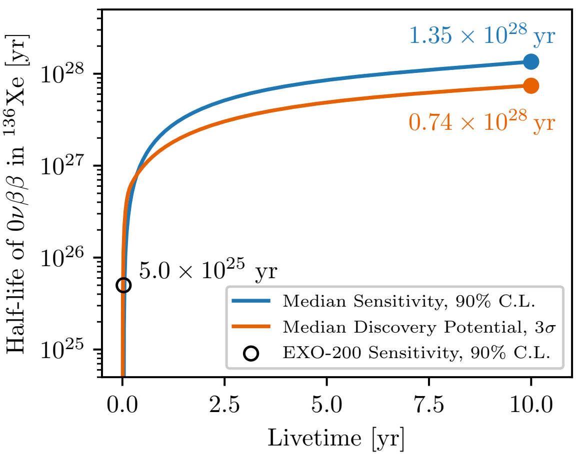
Combining three quantities:

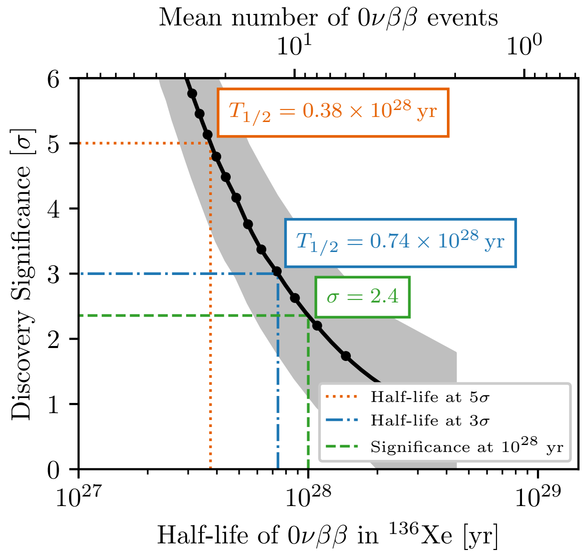
- 3D voxels are ranked by signal-to-background ratio.
- Then, arranged into a single dimension by proper ordering.
- "Background-free" in the combined parameter

Not a 1D peak search!

Assumed signal: $\tau_{1/2} = 7.4 \times 10^{27}$ year.
(Potential 3-σ discovery by nEXO.)

Sensitivity projection

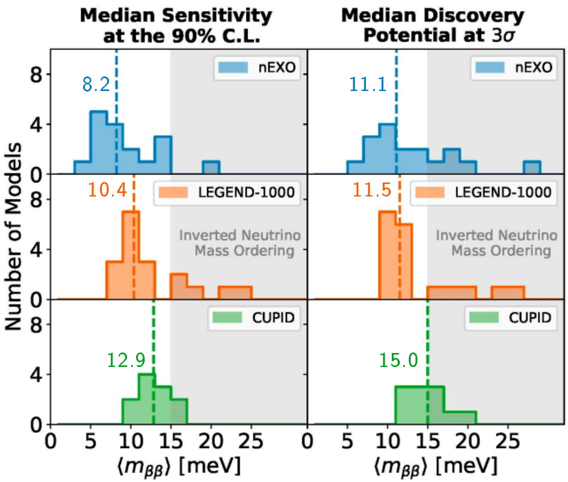




[J. Phys. G: Nucl. Part. Phys. 49 015104 (2022)]

- KamLAND-Zen limit: $\tau_{1/2} > 2.3 \times 10^{26}$ years at 90% C.L. [PRL 130 051801 (2023)]
- Still a lot of room for discovery!

Comparison with other experiments



NMEs used:

Method	Year	Citation
IBM	2015	PRC 91 034304 (2015)
NSM	2008	PRL 100, 052503 (2008)
IBM	2020	PRD 102, 095016 (2020)
QRPA	2014	PRC 89, 064308 (2014)
NSM	2016	PRC 93, 024308 (2016)
QRPA	2015	PRC 91, 024613 (2015)
QRPA	2018	PRC 98, 024608 (2018)
NSM	2018	JPS Conf. Proc. 23, 012036 (2018)
QRPA	2013	J. High Energ. Phys. 2013, 25 (2013)
QRPA	2013	PRC 87, 064302 (2013)
QRPA	2013	PRC 87, 045501 (2013)
QRPA	2018	PRC 97, 034315 (2018)
QRPA	2010	Nucl.Phys.A 847 (2010) 207
EDF	2013	PRL 111, 142501 (2013)
EDF	2015	PRC 91, 024316 (2015)
QRPA	2018	PRC 97, 045503 (2018)
EDF	2017	PRC 96, 054310 (2017)
QRPA	2015	PRC 91, 024613 (2015)
EDF	2010	Prog.Part.Nucl.Phys. 66 (2011) 436

Half-lives used [$\times 10^{28}$ years]:

	90% sens.	3σ disc.	Ref.
nEXO	1.35	0.74	[JP G: NPP. 49 015104 (2022)]
LEGEND	1.6	1.3	[arXiv:2107.11462]
CUPID	0.15	0.11	[arXiv:1907.09376]

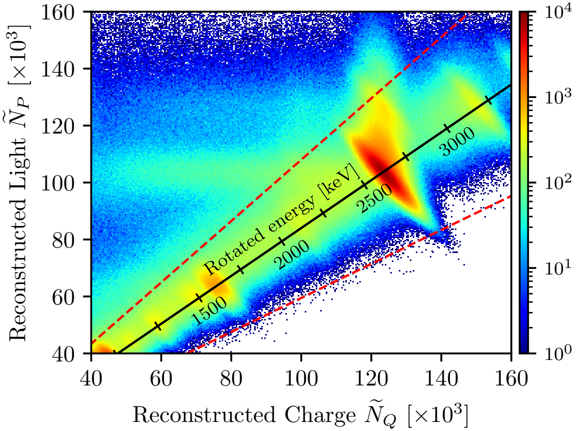
- Included all published NMEs that have not been superseded by later publications
- Difference among experiments is small compared to difference among NMEs.

nEXO's unique strengths

1. Homogeneous **2. Scalable** **3. Confirmation possible**

A monolithic homogeneous detector is well-suited for a $0\nu\beta\beta$ search.

- Gamma background identification and rejection with advanced topological reconstruction
- Sufficiently good energy resolution to suppress $2\nu\beta\beta$ background to a negligible level
- Internal radon background removal by alpha tagging
- Measures backgrounds precisely in situ enabling a multi-dimensional analysis
- Uninstrumented center creates a "background-free" region.

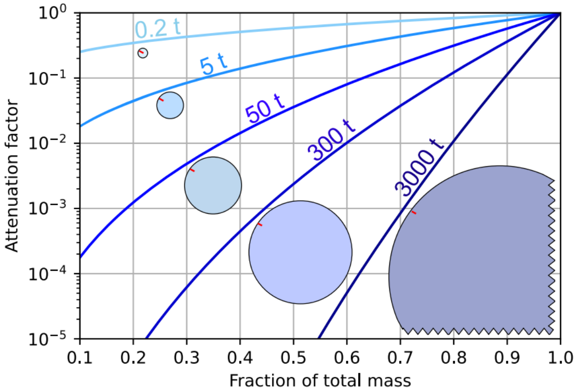


nEXO's unique strengths

1. Homogeneous **2. Scalable** **3. Confirmation possible**

There is a feasible path forward to scale up to beyond 100t in case of a non-discovery.
[A. Avasthi et al., Phys. Rev. D 104, 112007 (2021)]

- The advantages of a homogeneous detector improve with size
- Sufficient enrichment capacitiy exists. Xenon enrichment is well understood and cost effective.
- Recirculating Xenon reduces risk, as the purification system can be upgraded if unexpected backgrounds are discovered and/or if new technology becomes available. (Note that xenon has no long-lived, unstable isotopes.)



nEXO's unique strengths

1. Homogeneous **2. Scalable** **3. Confirmation possible**

Ability to perform a follow-up experiment with the same hardware in case of a discovery.

- Perform a follow-up experiment with non-enriched or depleted xenon if the half-life is sufficiently short:
  - A genuine signal would not be observed with depleted xenon.
  - Enhance confidence that an observation of $0\nu\beta\beta$ has been made.
- Re-deploy the same enriched Xe in another experiment for independent confirmation.
  - The xenon can be retrieved and used in another experiment.
- Barium tagging is a possible upgrade to unambiguously identify $\beta\beta$ decays.

nEXO R&D status

- Pre-Conceptual Design Report in 2018
- First sensitivity projection in 2018
- Updated sensitivity projection in 2022
- Status of R&D beyond pre-CDR, including
  - Background control
  - SiPMs
  - Charge collection
  - Calibration
  - and more

nEXO Pre-Conceptual Design Report

nEXO

Abstract

The projected performance and detector configuration of nEXO are described in this pre-Conceptual Design Report (pCDR). nEXO is a tonne-scale neutrinoless double beta ($0\nu\beta\beta$) decay search in ^{136}Xe, based on the ultra-low background liquid xenon technology validated by EXO-200. With $\simeq 5000$ kg of xenon enriched to 90% in the isotope 136, nEXO has a projected half-life sensitivity of approximately 10^{28} years. This represents an improvement in sensitivity of about two orders of magnitude with respect to current results. Based on the experience gained from EXO-200 and the effectiveness of xenon purification techniques, we expect the background to be dominated by external sources of radiation. The sensitivity increase is, therefore, entirely derived from the increase of active mass in a monolithic and homogeneous detector, along with some technical advances perfected in the course of a dedicated R&D program. Hence the risk which is inherent to the construction of a large, ultra-low background detector is reduced, as the intrinsic radioactive contamination requirements are generally not beyond those demonstrated with the present generation $0\nu\beta\beta$ decay experiments. Indeed, most of the required materials have been already assayed or reasonable estimates of their properties are at hand. The details described herein represent the base design of the detector configuration as of early 2018. Where potential design improvements are possible, alternatives are discussed.

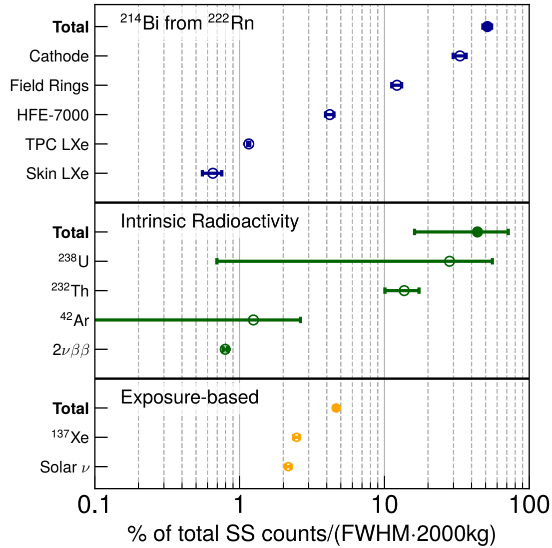
This design for nEXO presents a compelling path towards a next generation search for $0\nu\beta\beta$, with a substantial possibility to discover physics beyond the Standard Model.

Minor revisions, Aug 12, 2018

[arXiv:1805.11142]

Background

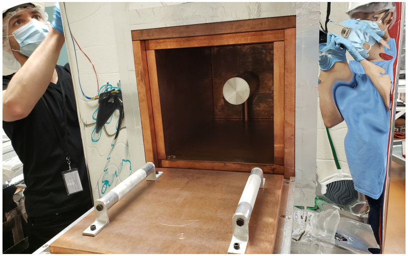
- Background sources
  - Gamma background from U/Th
  - Outgassed radon
  - Exposure to dust, radon, and cosmic rays
- Following EXO-200's successful strategy: Assay everything!
- Techniques used:
  - Gamma spectrometry
  - Neutron activation analysis (NAA)
  - Inductively coupled plasma Mass spectrometry (ICP-MS)
  - Electrostatic collection and liquid scintillator counting
  - α-counting
  - Accelerator mass spectrometry (AMS)



Intrinsic U/Th radioactivity

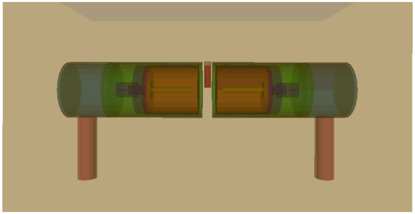
Gamma spectrometry

- Re-installed HPGe detector at SURF in Mar 2023 which has been running since.



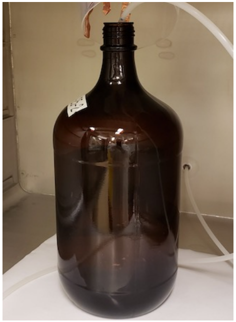
NAA

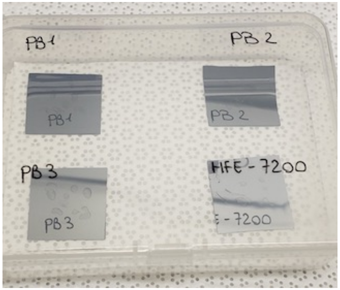
- New capability being developed: γ-γ coincidence NAA [RT et al., JINST 16 P10007 (2021)]
- Plan to activate a sapphire sample at MITR and to be counted at TUNL



Measurement of U/Th/^{210}Po in HFE (Heat transfer fluid)

- α decays of ^{210}Po in HFE may produce ^{137}Xe via (α, n)
- Reduced volume by 10000$\times$ via evaporation to enhance sensitivity
- Quantified ^{210}Po by α counting with ^{209}Po tracer
- Measured ^{210}Po at a few μBq/kg
- Placed limits on U/Th at a few fg/g by ICP-MS.

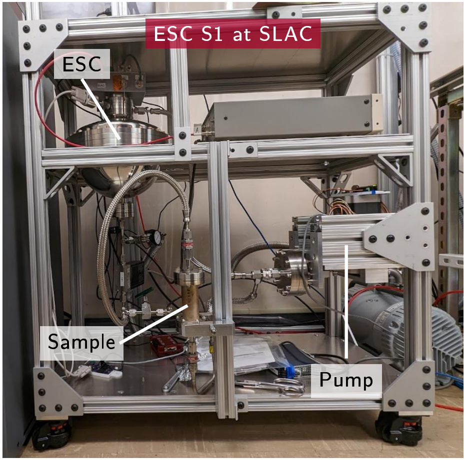




Radon counting

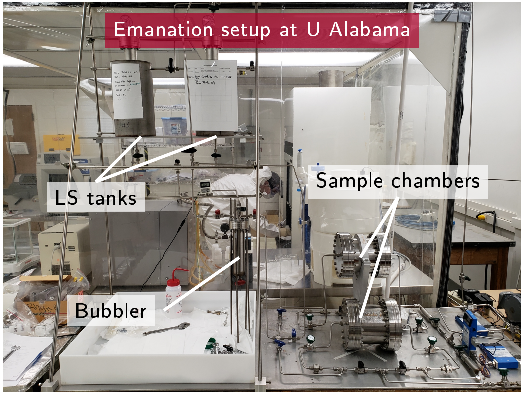
Electrostatic collection (ESC)

- Measures with a PIN diode the energy of air-borne alpha particles from Rn progeny
- Currently, 3 ESCs, one of them being commissioned.
- Sensitivity: 30 μBq in 4 weeks
- Working to confirm EXO-200 radon measurement independently.



Liquid scintillator counting

- Counts Bi-Po coincidence by viewing radon loaded liquid scintillator with a PMT
- Revived the setup that screened samples for LZ
- Sensitivity: $\sim$200 μBq in 4 weeks



Exposure-based backgrounds and tracking

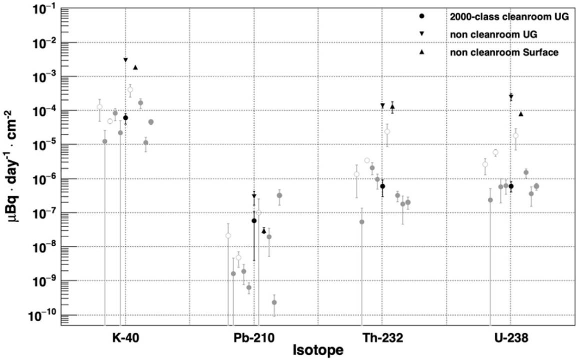
Exposure-based background sources:

- Cosmogenic activation while above ground
  - Performed exhaustive search for potential background contributors among activation products
  - No major background sources identified
- Dust deposition on parts
  - Studied U/Th deposition at various locations in SNOLAB [M.L. di Vacri et al., NIM A 994, 165051 (2021)] [M.L. di Vacri et al., NIM A 1056, 168700 (2023)]
  - U/Th deposition rate: 10^{-6} to 10^{-7} μBq d^{-1} cm^{-2} in clean areas.
  - Dust composition dependent on local activity.
- Radon progeny deposition on parts
  - ^{137}Xe production by (α, n)
  - Studied deposition lengths of radon progeny [D. Chernyak et al., PRC 107, 065802 (2023)]
  - Deposition rates similar for all materials
  - Ventilation rate is an important factor

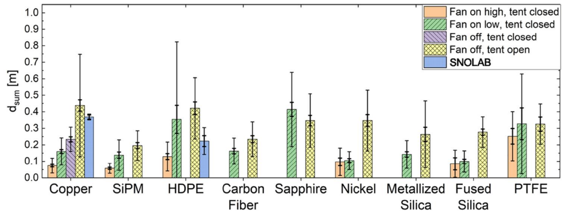
Mitigation measures:

- Cleanrooms with radon-reduced air
- Handling and cleaning protocols
- Parts tracking database

Dust deposition at SNOLAB:

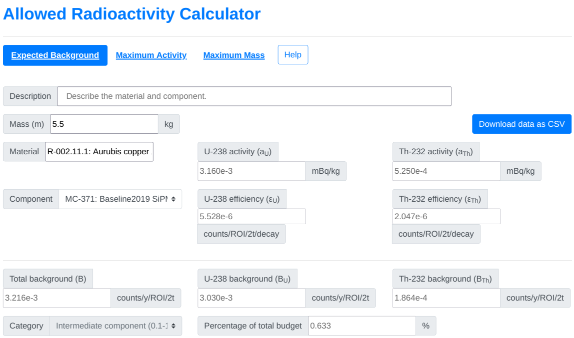


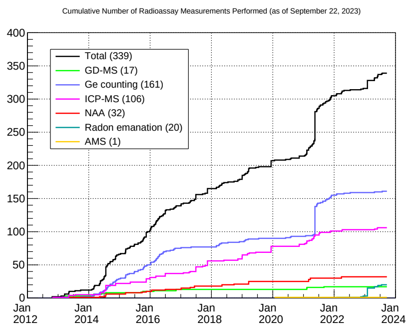
Radon daughter plateout:



Radioassay data management

- Data management needs fulfilled by materials database
  [RT et al., NIM A, 1055, 168477 (2023)]
  - Database for storage and retrieval, including published EXO-200 radioassay data:
    [D.S. Leonard et al., NIM A 591, 490 (2008)]
    [D.S. Leonard et al., NIM A 871, 169 (2017)].
  - Tools for detector design
- Auto-generated spreadsheet for background and sensitivity calculations
  - Facilitates the interpretation of radioassay data
- Has been in use since 2014
  - Stored more than 300 radioassay records from nEXO, in addition to 343 radioasay records from EXO-200.
  - Further integration with other software tools used by the collaboration

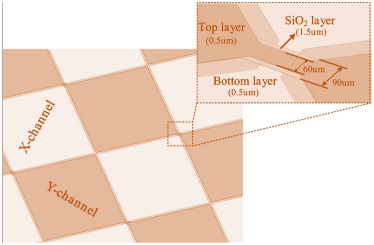




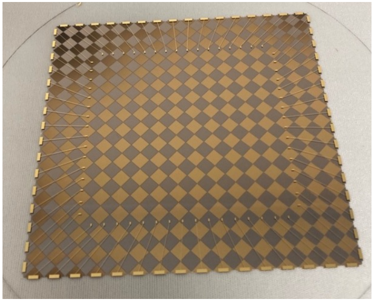
Charge detection

- Metal pads as anode to collect ionization electrons
- 120 10×10 cm^2 quartz tiles surface-coated with linked Au+Ti pads.
- Read out by custom cryo ASIC.
- Developed production of low-background flat cables with manufacturer. [I. Arnquist et al. NIM A 959 163573 (2020)]
- R&D focus: cold electronics, fabrication, and integration

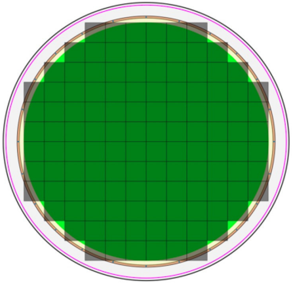
Au+Ti pad (6 mm diagonal)



Tile (10×10 cm^2)

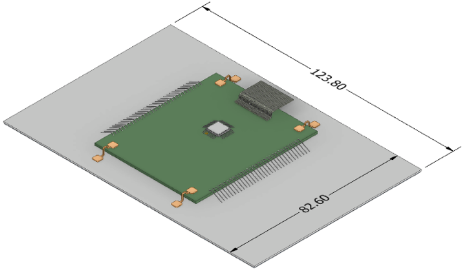


Full assembly (120 tiles)



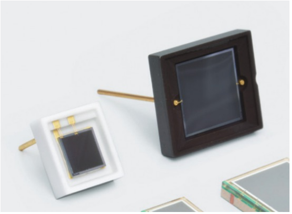
Light detection

- Silicon photomultiplers (SiPM) to detect VUV (175 nm) scintillation light from Xe
- 1 cm^2 units are ganged into channels of 6 cm^2, then arranged into 96 cm^2 tile modules.
- Modules are installed on the 24 staves inside the TPC barrel covering 4.6 m^2.
- Devices from 2 vendors that meet nEXO requirements have been identified through numerous studies.
  [G. Gallina et al., EPJC 82 1125 (2022)]
  [G. Gallina et al., NIM A 940, 371 (2019)]
  [A. Jamil et al., IEEE TNS 65, 11, 2823-2833 (2018)]

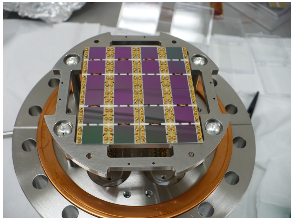


- R&D focus: Cold electronics, wire bonding and integration

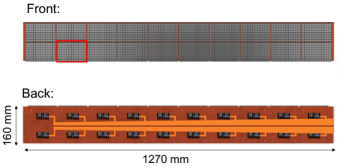
SiPM unit (1×1 cm^2)

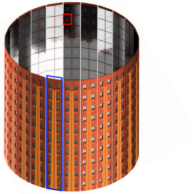


Module (96 cm^2)



Stave (20 modules) / Full assembly (24 staves)

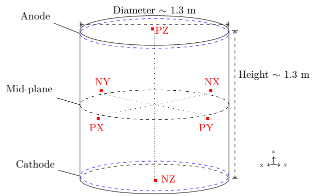




Calibration

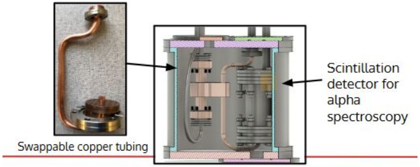
External gamma sources

- Six sources around the TPC deployed in guide tubes for periodic monitoring
- Successfully used in EXO-200
- R&D: Hardware and simulation



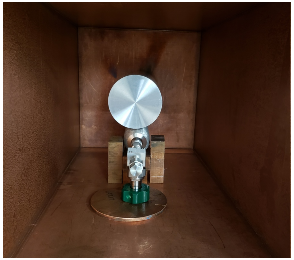
^{222}Rn injection

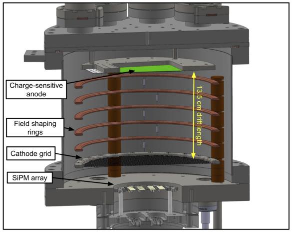
- Measure lightmap with alpha decays
- Demonstrated in EXO-200
- R&D: Rn transport study with ^{220}Rn



^{127}Xe calibration source

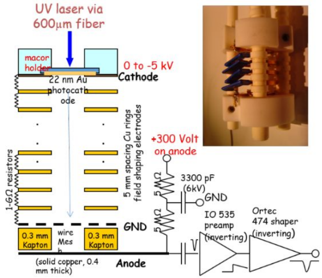
- Inject ^{127}Xe ($\tau_{1/2} = 36.3$ d) created by neutron activation of ^{126}Xe.
- Gamma rays ranging from 145 to 618 keV.
- Proof of concept: [B.G. Lenardo, C.A. Hardy, RT, et al., JINST 17 P07028 (2022)]





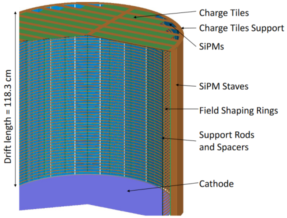
Laser driven photocathodes

- Demonstrated measurements of electron drift parameters [O. Njoya et al., NIM A 972, 163965 (2020)]



TPC vessel, HV, and Xenon

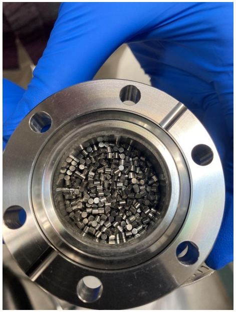
- TPC vessel made of electroformed Cu (EFCu)
- Field cage consisting of rings of EFCu separated by resistive spacers
- Held together by ultem (or sapphire) tensioning rods.
- R&D: Rn distillation column.



- Electric field: 400 V/cm.

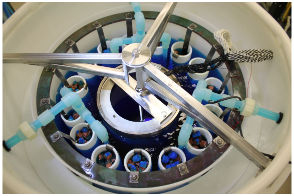
Low Rn emanation getter

- Investigating alternative getter material with lower radon background.
- Promising results in purification tests.
- R&D focus: radium removal.



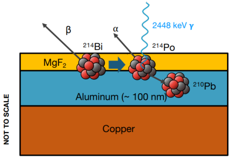
Electroforming

- TPC cylinder to be electroformed intact
- Fluid dynamics modeling of electroforming bath
- Mixing uniformity improved



Cathode R&D

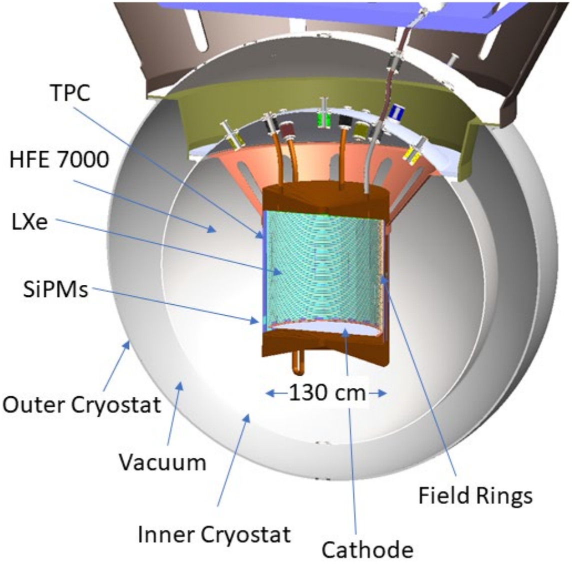
- Electron-beam welded Cu cathode
- Investigating MgF_2 coating for background rejection
- Decays of Rn plated out on cathode are a major background.
- Investigating tagging ^{214}Bi decays with reflective coating on cathode



Cryostat

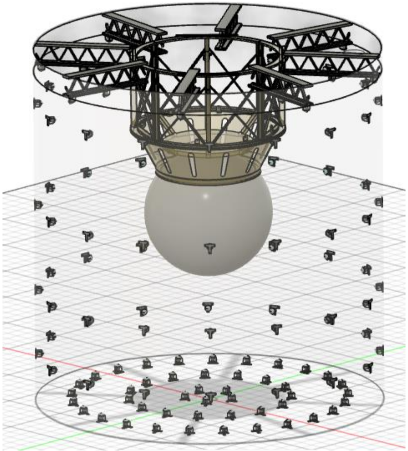
- TPC submerged in 32 tonnes of HFE, a heat transfer fluid
- Contained in a cryostat consisting of nested spheres made of carbon fiber composite (CFC)
- Liner made of chemically vapor deposited Ni
- Much larger CFC vessels have previously been made.

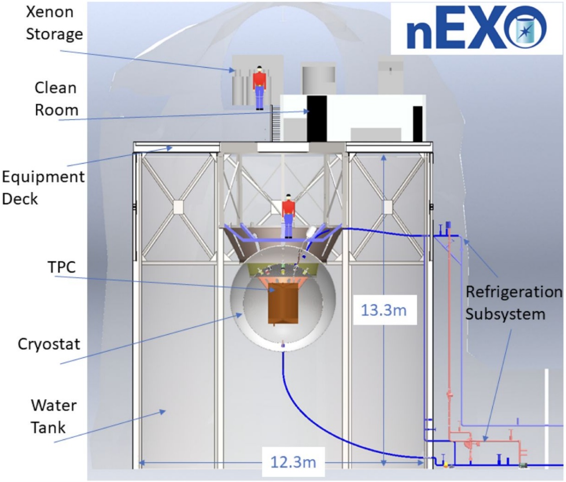
https://www.spacex.com/media/making_life_multiplanetary_transcript_2017.pdf



Outer detector

- Shield against γ-rays coming from the wall of the cavern
- Moderate and stop neutrons coming also from the wall of the cavern
- Detect cosmic radiation with active water-Cherenkov muon veto





- 12.3 m in diameter and 12.8 m in height containing 1.5 kt of water
- 125 8-inch (203 mm) PMTs of 500 from Daya Bay.
- Laser/LED fibre optic system for calibration

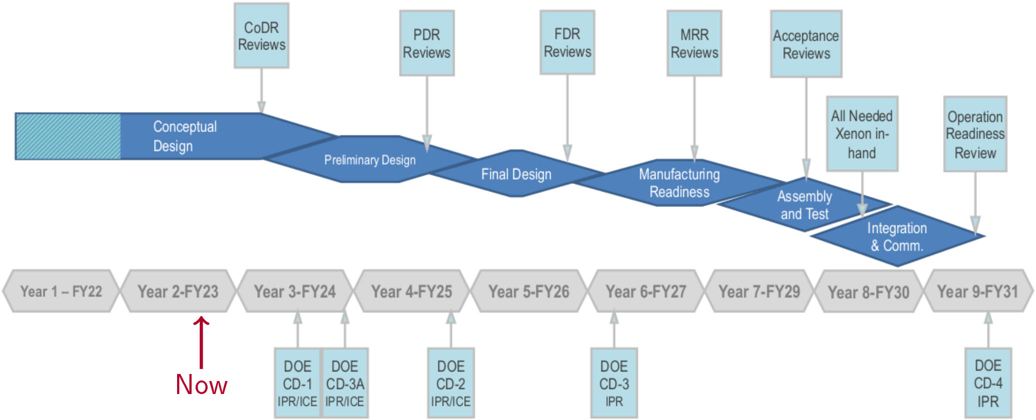
Papers published

Paper title	Journal reference
An integrated online radioassay data storage and analytics tool for nEXO	NIM A 1055 168477 (2023)
Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO	EPJC 82 1125 (2022)
Development of a 127Xe calibration source for nEXO	JINST 17 P07028 (2022)
nEXO: Neutrinoless double beta decay search beyond 10^{28} year half-life sensitivity	JP G: NPP 49 015104 (2022)
Event reconstruction in a liquid xenon Time Projection Chamber with an optically-open field cage	NIM A 1000 165239 (2021)
Reflectivity of VUV-sensitive Silicon Photomultipliers in Liquid Xenon	JINST 16 P08002 (2021)
Reflectivity and PDE of VUV4 Hamamatsu SiPMs in Liquid Xenon	JINST 15 P01019 (2020)
Characterization of the Hamamatsu VUV4 MPPCs for nEXO	NIM A 940 371-379 (2019)
Imaging individual barium atoms in solid xenon for barium tagging in nEXO	Nature 569 203–207 (2019)
Simulation of charge readout with segmented tiles in nEXO	JINST 14 P09020 (2019)
nEXO pre-conceptual design report	arXiv:1805.11142
VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO	IEEE TNS 65 11 2823-2833 (2018)
Characterization of an Ionization Readout Tile for nEXO	JINST 13 P01006 (2018)
Sensitivity and discovery potential of nEXO to neutrinoless double beta decay	PRC 97 065503 (2018)
Study of Silicon Photomultiplier Performance in External Electric Fields	JINST 13 T09006 (2018)
Characterization of Silicon Photomultipliers for nEXO	IEEE TNS 62 4 1825-1836 (2015)
Spectroscopy of Ba and Ba^+ deposits in solid xenon for barium tagging in nEXO	PRA 91 022505 (2015)

R&D has been progressing in earnest!

Summary and notional timeline

- nEXO has a mature design. The collaboration is working to further refine it.
- With 10 years of livetime, nEXO is projected to achieve:
  - Sensitivity at 90% C.L.: $\tau_{1/2} = 1.35 \times 10^{28}$ years or $\langle m_{\beta\beta} \rangle = 8.2$ meV (median).
  - 3-σ discovery potential: $\tau_{1/2} = 7.4 \times 10^{27}$ years or $\langle m_{\beta\beta} \rangle = 11.1$ meV (median).
- Next milestone: Conceptual Design Review (CoDR)



Grazie per l'attenzione!
Thank you for your attention!

Majorana mass

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

where

- $T_{1/2}^{0\nu}$ is the half-life of $0\nu\beta\beta$.
- $\langle m_{\beta\beta}\rangle$ is the Majorana mass.
- $G_{0\nu}$ is the phase space factor.[†]
- $g_A = 1.27$ is the axial coupling.
- $M^{0\nu}$ is the Nuclear Matrix Element (NME) which depends on the nuclear model used.

The NME is the largest source of theoretical uncertainty.

[†] J. Kotila and F. Iachello, Phys Rev C 85, 034316 (2012)

Neutrino masses

	Expression	Method
Simple sum	$m_{sum} := \sum_{i=1}^{3} m_i$	Cosmological limit
Incoherent sum	$\langle m_\beta \rangle := \sqrt{\sum_{i=1}^{3} m_i^2 \lvert U_{ei} \rvert^2}$	Direct measurement
Coherent sum	$\langle m_{\beta\beta} \rangle := \lvert \sum_{i=1}^{3} m_i U_{ei}^2 \rvert$	$0\nu\beta\beta$

Xe procurement

- Xenon enrichment is well known and cost effective
- EXO-200 had 200 kg of xenon enriched up to 80% with 136Xe
- Since, KAMLAND-Zen used 745 kg of xenon enriched up to 90% with 136Xe
- nEXO will need about 5 times what is already available
- nEXO has identified at least two western suppliers each with enough enrichment capacity for the entire production at competitive price

Xenon scintillation mechanism

Excitation:

$$Xe \rightarrow Xe^*$$

$$Xe^* + Xe \rightarrow Xe_2^*$$

$$Xe_2^* \rightarrow 2Xe + h\nu$$

Ionization:

$$Xe \rightarrow Xe^+ + e^-$$

$$Xe^+ + Xe \rightarrow Xe_2^+$$

$$Xe_2^+ + e^- \rightarrow Xe^{**} + Xe$$

$$Xe^{**} \rightarrow Xe^* + heat$$

$$Xe^* + Xe \rightarrow Xe_2^*$$

$$Xe_2^* \rightarrow 2Xe + h\nu$$

- Scintillation light: 175 nm (VUV).
- No self-quenching.
- Recombination depends on electric field.

Radioassay instruments available

	Dedicated + Have access + Requested	Institutions	Th/U Sensitivity [ppt]
HPGe	4 + 9 + 1	UA, SURF, SNOLAB	300/150 AG, 2.3/1.2 UG
ICP-MS	1 + 2 + 1	PNNL, IHEP, CUP	1/1 routine, 0.008/0.01
GD-MS	0 + 1 + 0	NRC	10/10
NAA	3 + 0 + 1	UA	1/1 routine, 0.02/0.02
Rn	8 + 0 + 8	SNOLAB, SLAC	5 atoms d^{-1}
α	2 + 0 + 1	UA, PNNL, SLAC	^{210}Po: 30 mBq/m^2

Location: SNOLAB