Latest results from EXO-200 and status of nEXO

J. Farine, Laurentian University, Sudbury for the EXO–200 and nEXO collaborations
“Black box” theorem*: “0νββ decay always implies new physics”

There is no scenario in which observing 0νββ decay would not be a great discovery

➔ Majorana neutrinos
➔ Lepton number violation
➔ Probe new mass mechanism up to the GUT scale
➔ Probe key ingredient in generating cosmic baryon asymmetry

Neutrino masses have to be non-zero for 0νββ to be possible.

➔ Because the distinction between Dirac and Majorana particles is only observable for particles of non-zero mass.

Strictly speaking, this is the ONLY connection with neutrino masses relevant to discover new physics.

Hence it is appropriate to think of the sensitivity to new physics as scaling with $T_{1/2}$, irrespective of the neutrino mass scenarios. A $T_{1/2}$ sensitivity increase from $\sim 10^{26}$ to $\sim 10^{28}$ yr ($\sim 100x$), should be compared, e.g., to the $\sqrt{s}$ increase from Tevatron to LHC ($\sim 20$), although, admittedly, with a smaller array of channels for new physics.

The discovery potential was recently estimated for various proposals, assuming Type I seesaw, the free value of $g_A$ and using a Bayesian analysis with flatly distributed priors

(Agostini, Benato, Detwiler, PRD 96 (2017) 053001
also A. Caldwell et al., PRD 96 (2017) 073001)
EXO programme

I. EXO-200

• 200 kg of Xe, enriched in $^{136}$Xe @ 80%
• Taking data since 2010 @ WIPP, NM USA
• Publications:
  2011 – first observations of $2\nu\beta\beta$ in $^{136}$Xe
  2012 – first $0\nu\beta\beta$ results: $m_{\beta\beta} < 140$ meV
  2013 – (most) precise $T^{1/2}_{2\nu\beta\beta} = 2.17 \times 10^{21}$ yr
  2014 – improved sensitivity to $0\nu\beta\beta$ (Nature)
• Background at targeted / accounted levels

II. nEXO

• 5T of 90% enrXe – probe IH
• Low risk concept based on successes from EXO-200
• SNOLAB possible host lab

III. Possible futures

• Ba tagging
• Gas
  But first, probe nature at IH
Energy resolution

Particularly for large detectors, it is only one of the parameters used for background rejection:

- Energy measurement (for small detectors this is ~all there is).
- Event multiplicity (γ’s Compton scatter depositing energy in more than one site).
- For large, monolithic detectors, depth is powerful discriminant against background.
- α discrimination (from e⁻ / γ), possible in many detectors.

It is a real triumph of recent experiments that we now have discrimination tools in this challenging few MeV regime!

**Powerful detectors use most of (possibly all) these parameters in combination, providing the best possible background rejection and simultaneously fitting for signal and background.**
The EXO-200 TPC

Two almost identical halves reading **ionization** and **178 nm scintillation**, each with:

- 38 U triplet wire channels (**charge**)
- 38 V triplet wire channels, crossed at 60° (**induction**)
- 234 large area avalanche photodiodes (APDs, **light** in groups of 7)
- Wire pitch 3 mm (9 mm per channel)
- Wire planes 6 mm apart and 6 mm from APD plane
- All signals digitized at 1 MS/s, ±1024S around trigger
- Drift field 380 V/cm (Phase I) > 567 V/m (Phase II)

- Field shaping rings: copper
- Supports: acrylic
- Light reflectors/diffusers: Teflon
- APD support plane: copper; Au (Al) coated for contact (light reflection)
- Central cathode, U+V wires: photo-etched phosphor bronze
- Flex cables for bias/readout: copper on kapton, no glue

Comprehensive material screening program

Goal: 40 cnts/2y in 0νββ ±2σ ROI, 140 kg LXE
Copper vessel 1.37 mm thick
175 kg LXe, 80.6% enr. in $^{136}$Xe
Copper conduits (6) for:
• APD bias and readout cables
• U+V wires bias and readout
• LXe supply and return
Epoxy feedthroughs at cold and warm doors
Dedicated HV bias line

EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
The EXO-200 Detector

- **FRONT END ELECTRONICS**
- **VACUUM PUMPS**
- **VETO PANELS**
- **HV FILTER AND FEEDTHROUGH**
- **DOUBLE-WALLED CRYOSTAT**
- **LXe VESSEL**
- **LEAD SHIELDING**

- High purity Heat transfer fluid HFE7000
- > 50 cm
- 1.37 mm
- 25 mm ea
- > 25 cm
- 1.37 mm

The EXO-200 Detector
WIPP U/G site (1624 ± 22 mwe)

Muon veto
- 50 mm thick plastic scintillator panels
- surrounding TPC on four sides.
- $\varepsilon > 94\%$ for $\mu$ through TPC

Veto cuts (8.6% combined dead time)...
- 25 ms after muon veto hit
- 60 s after muon track in TPC
- 1 s after every TPC event

..New DAN has improved the overall efficiency! Publication imminent.
See Caio’s talk in this session and Thomas’ for IPP in Friday
Using event multiplicity to recognize backgrounds

Low background data

$^{228}$Th calibration source

$2\nu\beta\beta$
Combining Ionization and Scintillation

Rotation angle chosen to optimize energy resolution at 2615 keV

228Th source SS

Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

E. Conti et al.

By now this is a common technique in LXe

(σ/E resolution)

G. Gratta
2-neutrino half lives

**Discovery of 2ν mode in $^{136}$Xe**
*PRL 107, 212501 (2011)*

**Confirmation by KamLAND-Zen**
*PRC 85, 045504 (2012)*

\[ T_{1/2}^{2\nu\beta\beta} = \left( 2.165 \pm 0.016^{\text{stat}} \pm 0.059^{\text{syst}} \right) \times 10^{21} \text{ yr} \]


At 2.7%, this is still the best measurement of any 2ν mode* and the longest 2ν half life.

* Recent measurements in $^{130}$Te and $^{76}$Ge have almost-as-good accuracies

> Caio will provide an update on recent data analysis improvements (same session)
EXO-200 successfully completed its operation in 2018

Oct. 2018: End of physics data taking

Nov. 2018: Detector calibration campaign, including special sources

Dec. 2018: Detector decommissioning

Feb. 2019: Packed equipment leaving WIPP, on its way to SLAC for
End-of-Run Calibration Campaign

- **AmBe neutron source**
  - Calibration of high energy region and $^{137}$Xe $\beta$ spectrum.

- **Internal $^{220}$Rn and $^{222}$Rn sources**
  - High statistics lightmap
  - Tracer for Xe flow studies
  - Feasibility study for nEXO

- **Low electric field, high gain APD runs**
  - LXe physics studies
  - Data can be used to improve NEST simulation

- **High voltage test**
  - Increased the cathode voltage from -12 kV to -25 kV after training
  - Highest field (> 1kV/cm) achieved among all large scale LXe detectors

> this data will inform the detailed design of nEXO
Detector Decommissioning

Lead wall removal

Packed Xe plumbing

Packed Xe Bottles

Veto panel removal

Empty clean rooms
Some statistics

- ~ 3,600 days underground occupancy at WIPP
- ~ 260 kg yr exposure of $^{136}$Xe
- 30 publications, 27 Ph.D. theses and counting
- 10032 runs taken, ~ 100 TB data recorded
- ~ 100 Shifters, ~ 23,000 shifts taken (onsite/remote)
- 73318 daily log entries
- ~ 4500 cups of coffee underground

~ 60,000 $^{136}$Xe $2
\nu\beta\beta$ decay observed
EXO-200 0νββ Sensitivity

<table>
<thead>
<tr>
<th>Source</th>
<th>Sensitivity (yr)</th>
<th>90% CL Limit (yr)</th>
<th>$&lt;m_{\beta\beta}&gt;$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRL 109, 032505 (2012)</td>
<td>0.7x10^{25}</td>
<td>1.6x10^{25}</td>
<td></td>
</tr>
<tr>
<td>Nature 510, 229 (2014)</td>
<td>1.9x10^{25}</td>
<td>1.1x10^{25}</td>
<td></td>
</tr>
<tr>
<td>PRL 120 072701 (2018)</td>
<td>3.8x10^{25}</td>
<td>1.8x10^{25}</td>
<td>147-398</td>
</tr>
</tbody>
</table>
EXO-200 publications to date

- In preparation: “Search for Neutrinoless Double-Beta Decay with the Complete EXO-200 Dataset”
- J.B. Albert et al. "Search for 0νββ Decay with the Upgraded EXO-200 Detector" PRL 120 (2018) 072701
- J.B. Albert et al. "First Search for Lorentz and CPT Violation in ββ Decay with EXO-200" PRD 93 (2016) 072001
- J.B. Albert et al. "Search for 2νββ decay of 136Xe to the 0_1+ excited state of 136Ba with EXO-200" PRC 93 (2016) 035501
The EXO-200 Collaboration

University of Illinois, Urbana-Champaign IL, USA — D Beck, M Coon, J Echevers, S Li, L Yang
Indiana University, Bloomington IN, USA — JB Albert, SJ Daugherty
Laurentian University, Sudbury ON, Canada — B Cleveland, A Der Mesrobian-Kabakian, J Farine, C Licciardi, A Robinson, U Wichoski
University of Maryland, College Park MD, USA — C Hall
University of Massachusetts, Amherst MA, USA — S Feyzbakhsh, A Pocar, M Tarka
McGill University, Montreal QC, Canada — T Brunner, L Darroch, K Murray
University of North Carolina, Wilmington NC, USA — T Daniels
SLAC National Accelerator Laboratory, Menlo Park CA, USA — M Breidenbach, R Conley, J Davis, S Delaquis, A Johnson, LJ Kaufman, B Mong, A Odian, CY Prescott, PC Rowson, JJ Russell, K Skarpaas, A Waite, M Wittgen
University of South Dakota, Vermillion SD, USA — A Larson, R MacLellan
Stanford University, Stanford CA, USA — J Dalmasson, R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, B Lenardo, G Li, A Schubert, M Weber, S Wu
Stony Brook University, SUNY, Stony Brook, NY, USA — K Kumar, O Njaya
Technical University of Munich, Garching, Germany — P Fierlinger
TRIUMF, Vancouver BC, Canada — J Dilling, R Krücken, Y Lan, F Retière, V Strickland
Yale University, New Haven CT, USA — A Jamil, Z Li, D Moore, Q Xia
Shielding a detector from \(~\text{MeV}\) \(\gamma\)s is difficult!

**Example:**
\(\gamma\) interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

*Shielding \(\beta\beta\) decay detectors is much harder than shielding Dark Matter ones*

*We are entering the “golden era” of \(\beta\beta\) decay experiments as detector sizes exceed int lengths*
Moving forward, monolithic is key.

The current estimate of the nEXO sensitivity relies only on materials already tested for radioactivity and on hand (although not necessarily in sufficient amount).

### LXe mass (kg) vs. Diameter or length (cm)

<table>
<thead>
<tr>
<th>LXe mass (kg)</th>
<th>Diameter or length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>130</td>
</tr>
<tr>
<td>150</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
</tr>
</tbody>
</table>

2.5MeV γ attenuation length
8.5cm = ___

5kg   150kg   5000kg
Preliminary artist view of nEXO in the SNOLAB Cryopit
The nEXO TPC

Vacuum

HFE 7000

Outer Cryostat support structure
To water tank

Outer Cryostat, Dia ~4.5m

Inner Cryostat support structure

Inner Cryostat, Dia ~3.4m

TPC support structure

TPC

EXO-200 ~to scale

G. Gratta

EXO-200 ~to scale
Main technical changes on the EXO-200 theme

- Only one drift volume
- ASIC electronics in LXe
- Silica substrate charge collection tiles
- VUV SiPMs (~4.5m²)
- Little plastics in the TPC (Sapphire, Silica)
Test of prototype tiles in LXe is ongoing

Max metallization cover with min capacitance:

80 fF at crossings
0.86 pF between adjacent strips

Pulse shape is unusual, because of the absence of a shielding grid, but state of the art resolution for charge only has been achieved.


G. Gratta
After the first round of R&D, some 1cm² VUV devices now match our desired properties, with a bias of ~30V (as opposed to the 1500V of EXO-200 APDs)

"VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO" 
G. Gratta
nEXO sensitivity and discovery potential

What goes in the model is:
• the geometry,
• the radioactivity measured on existing materials (some from EXO-200, some “freshly” measured)
• physics well known to GEANT (mainly $\gamma$ transport)

Background in the central 2000 kg by component

G. Gratta
Particularly in the larger nEXO, background identification and rejection fully use a fit considering simultaneously energy, $e^{-}\gamma$ and $\alpha-\beta$ discrimination and event position.

→ The power of the homogeneous detector, this is not just a calorimetric measurement!

$0^{\nu}\beta\beta T^{1/2}=5.7\times10^{27}$ yr

G. Gratta
So, a simple “background index” is not the entire story.

- The innermost LXe mostly measures signal
- The outermost LXe mostly measures background
- The overall fit knows all this (and more) very well and uses all the information available to obtain the best sensitivity

Nevertheless, for the aficionados of “background index”, here it is, as a function of depth in the TPC. For the inner 3000 kg this is better than $10^{-3}$ (kg yr FWHM)$^{-1}$
Sensitivity as a function of time for the baseline design

- $g_A = g_A^{\text{free}} = -1.2723$
- Band is the envelope of NME:
  - QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
  - SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

G. Gratta
nEXO publications to date

they describe the detector, the experiment’s sensitivity and some results from the R&D

• “Imaging individual Ba atoms in solid xenon for barium tagging in nEXO” *
  Nature 569, 203–207 (April 2019)

• “Study of Silicon Photomultiplier Performance in External Electric Fields”
  2018_JINST_13_T09006 (September 2018)

• “nEXO pCDR”
  arXiv:1805.11142 (May 2018)

• ”Sensitivity and Discovery Potential of nEXO to $0\nu\beta\beta$ decay"

• “Imaging individual Ba atoms in solid xenon for barium tagging in nEXO”
  arXiv:1806.10694 (Jun 2018)

• “VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO”

• ”Characterization of an Ionization Readout Tile for nEXO“
  J.Inst. 13 P01006 (2018)

• ”Characterization of Silicon Photomultipliers for nEXO“

* Not nEXO baseline, nevertheless very exciting
Recent developments

• As per Nov’18, DOE has given CD-0 to “tonne-scale double-beta decay”
• This is not specifically nEXO, and does not involve funding
• But it allows the national labs to increase the intensity of their support
• SNOLAB is very engaged and contributes to the preparation of a CFI Proposal with engineers and project management

• The collaboration is growing: welcome Erica Caden (SNOLAB) and Simon Viel (Carleton)

• We are also appreciative for the strong support from the McDonald Institute

> See Thomas’s talk at the Friday IPP AGM for more details
University of Alabama, Tuscaloosa AL, USA — M Hughes, O Nusair, I Ostrovskiy, A Piepke, AK Soma, V Veeraraghavan
University of Bern, Switzerland — J-L Vuilleumier
Brookhaven National Laboratory, Upton NY, USA — M Chiu, G Giacomini, V Radeka, E Raguzin, S Rescia, T Tsang
University of California, Irvine, Irvine CA, USA — M Moe
California Institute of Technology, Pasadena CA, USA — P Vogel
Carleton University, Ottawa ON, Canada — I Badhrees, B Chana, M Elbeltagi, D Goeldi, R Gornea, C Jessiman, T Koffas, B. Veenstra, S. Viel, C Vivo-Vilches, J Watkins
Colorado State University, Fort Collins CO, USA — C Chambers, A Craycraft, D Fairbank, W Fairbank Jr, A Iverson, J Todd
Drexel University, Philadelphia PA, USA — MJ Dolinski, P Gautam, E Hansen, YH Lin, E Smith, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau, J Runge
Friedrich-Alexander-University Erlangen, Nuremberg, Germany — G Anton, J Hoessl, T Michel, M Wagenpfeil, T Ziegler
IBS Center for Underground Physics, Daejeon, South Korea — DS Leonard
IHEP Beijing, People’s Republic of China — G Cao, W Cen, Y Ding, X Jiang, P Lv, Z Ning, X Sun, T Tolba, W Wei, L Wen, W Wu, J Zhao
IME Beijing, People’s Republic of China — L Cao, X Jing, Q Wang
ITP Moscow, Russia — V Belov, A Burennkov, A Kobyakin, A Kuchenkov, V Stekhanov, O Zeldovich
University of Illinois, Urbana-Champaign IL, USA — D Beck, M Coon, J Echevers, S Li, L Yang
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Lawrentian University, Sudbury ON, Canada — K Bolduc, E Caden, B Cleveland, A Der Mesrobian-Kabakian, J Farine, C Liciardi, JF Ménard, A Robinson, M Walent, U Wichowski
Lawrence Livermore National Laboratory, Livermore CA, USA — J Brodsky, M Heffner, A House, S Sangiorgio, T. Stiegler
University of Massachusetts, Amherst MA, USA — S Feyzbakhsh, D Kodoff, A Pocar, M Tarka
McGill University, Montreal QC, Canada — S Al Kharusi, T Brunner, L Darroch, Y Ito, T Nguyen, D. Chen, T McElroy, K Murray, T Totev,
University of North Carolina, Wilmington, USA — T Daniels
Oak Ridge National Laboratory, Oak Ridge TN, USA — L Fabris, RJ Newby
Pacific Northwest National Laboratory, Richland, WA, USA — I Arquiqui, EW Hoppe, JL Orrell, G Ortega, C Overman, R Saldanha, R Tsang
Pennsylvania State University, University Park PA, USA — P Fierlinger
Rensselaer Polytechnic Institute, Troy NY, USA — E Brown, K Odgers
Université de Sherbrooke, Sherbrooke QC, Canada — S Charlebois, D Danovitch, H Dautet, R Fontaine, F Nolet, S Parent, JF Pratte, T Rossignol, N Roy, G St-Hilaire, J Sylvestre, F Vachon
SLAC National Accelerator Laboratory, Menlo Park CA, USA — S Delayas, A Dragone, G Hailer, LJ Kaufman, B Mong, A Odian, M Orunno, PC Rowson, K Skarpaas
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Yale University, New Haven CT, USA — A Jamil, Z Li, D Moore, Q Xia
EXO /related presentations at CAP

Monday 03 June 2019 – M1-8 – DNP
11:45 [2520] nEXO’s Outer Detector: Status and Prospects AL KHKARUSI, Soud
12:00 [2735] A linear quadrupole ion trap for barium tagging in nEXO LAN, Yang

Wednesday 05 June 2019 – W1-11 – DNP
10:45 [2725] Latest results from EXO-200 and status of nEXO FARINE, Jacques (this talk)
11:30 [2699] EXO-200 Results LICCIARDI, Caio > new DAN methods
11:45 [2664] Characterization and development of a new SiPM with high VUV sensitivity for the nEXO Experiment GALLINA, Giacomo

Wednesday 05 June 2019 – W1-7 – DAPI/PPD
11:00 [2490] 3D digital SiPM for medical imaging, particle physics and quantum key distribution PRATTE, Jean-Francois
12:00 [2533] Analog Electronics and SiPM Characterization for LOLX DE ST. CROIX, Austin

Thursday 06 June 2019 – R2-5 – DAPI/PPD
14:00 [2499] Goals and Scope of the Light-Only Liquid Xenon Project MCELROY, Thomas

Friday 07 June 2019 – IPP AGM
09:00 nEXO project update BRUNNER, Thomas > more on activities, demographics in Ca PM – SiPM Workshop – Fabrice Retiere
Conclusions

- EXO-200 was the first 100kg-class experiment to run and demonstrated the power of a large and homogeneous LXe TPC.

- A final $0\nu\beta\beta$ result is imminent

- This is clearly the way to go for tonne-scale detectors, as the power of the technique will further improve with increasing size.

- R&D in progress to finalize the design of nEXO, a 5-ton detector that will drastically advance the field, entirely covering the inverted hierarchy and with substantial sensitivity to the normal one.

- New and exciting results from the Ba tagging effort (not part of the nEXO baseline) suggest that there may be a path for a future upgrade beyond nEXO.

- nEXO design is maturing rapidly, with the pCDR design document posted and a detailed sensitivity analysis published some time ago

- DOE CD-0 mission need established
Thank You
In fact, $^{136}$Xe presents the possibility to confirm a $\beta\beta$ decay even by retrieving and tagging spectroscopically the Ba atom in the final state.

This is not necessary for nEXO to reach its design sensitivity and, indeed, it is not part of the design presented in the pre-CDR.

Nevertheless the “physics component” of this technique was recently demonstrated, including the ability to delete “old” Ba atoms with essentially no “memory effect”.

Plenty of engineering will be required to turn this result into a practical upgrade path for nEXO.
How does the sensitivity scale with background assumptions?

Asymptotic sensitivity for a potential upgrade using Ba tagging

All materials actually measured

Assumes some material radioactivity progress

G. Gratta
...and with energy resolution