The search for neutrinoless double beta decay with EXO-200

Andrea Pocar
University of Massachusetts, Amherst
Outline

- Neutrinoless double beta decay
- EXO-200
  - Detector
  - Recent results
- Outlook
$0\nu\beta\beta$ decay = new physics

**Observation of $0\nu\beta\beta$ decay**
- massive, Majorana neutrinos
- lepton number violation ($\Delta L = 2$)
- new mass scale of nature

**$0\nu\beta\beta$ rate**
- absolute neutrino mass (model dependent)

possible probe for understanding the matter dominance in the universe through leptogenesis (via $\Delta(B-L)$)

[Schechter and Valle, 1982]
Different physics can contribute to the decay

- LNV dynamics at $M >> \text{TeV}$
  - Only low energy manifestation are the three light neutrino flavors
- LNV dynamics at $M \sim \text{TeV}$
  - Contribution to $0\nu\beta\beta$ decay not related to light neutrino masses
  - Related to $pp \rightarrow e\bar{e}jj$ at LHC
- Additional Majorana states

After V. Cirigliano

Giunti-Zavanin 1505.00978, JHEP07(2015)171
The history of $0\nu\beta\beta$ decay experiments in one slide

...we are kind of a stubborn bunch

Slide courtesy of G. Gratta
Data courtesy of S. Elliott and the PDG.
Not all results are necessarily shown.
why Xenon?

✓ known purification technology
✓ simplest enrichment (~1 tonne of \(^{enr}Xe\) already available for science)
✓ scalable technology (also demonstrated by dark matter searches)
✓ can be re-purified and transferred between detectors

✓ allows for particle ID, event topology (\(\alpha/\beta\), multiplicity for \(\beta/\gamma\), standoff)
✓ LXe provides superior self-shielding
✓ standard 2\(\nu\beta\beta\) is the slowest (among practical isotopes)
  \((T^{0\nu1/2} \sim 2 \times 10^{21} \text{ y})\)

* energy resolution:
  Ge/bolometers > GXe > LXe > liquid scintillator
✓ might allow for daughter (barium) tagging
The EXO-200 Collaboration

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
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, R Gornea, C Jessiman, T Koffs, D Sinclair, B Veenstra, 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, EV Hansen, YH Lin, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau
Friedrich-Alexander-University Erlangen, Nuremberg, Germany — G Anton, J Hoessl, P Hufschmidt, T Michel, M Wagenpfeil, S Schmidt, G Wrede, T Ziegler
IBS Center for Underground Physics, Daejeon, South Korea — DS Leonard
IHEP Beijing, People's Republic of China — G Cao, W Cen, T Tolba, L Wen, J Zhao
ITEP Moscow, Russia — V Belov, A Burenkov, M Danilov, A Dolgolenko, A Karelin, A Kuchenkov, V Stekhanov, O Zeldovich
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, G Li, A Schubert, M Weber, S Wu
Stony Brook University, SUNY, Stony Brook, NY, USA — K Kumar, O Njoya
Technical University of Munich, Garching, Germany — W Feldmeier, P Fierlinger, M Marino
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
The EXO-200 detector

HV FILTER AND FEEDTHROUGH

FRONT END ELECTRONICS

VACUUM PUMPS

VETO PANELS

HIGH PURITY HEAT TRANSFER FLUID (HFE7000, 4 tonnes) > 50 cm thick ea

DOUBLE-WALLED CRYOSTAT 25 mm thick ea

LXe Cu VESSEL 1.4 mm thick (TPC inside)

LEAD SHielding > 25 cm

VETO PANELS
the EXO-200 TPC

half TPC

Teflon reflector tiles

Cathode mesh (two ‘bikinis’)

Charge collection wires in front of LAAPDS (sensitive to 175 nm)

acrylic supports

Field shaping rings

~40 cm
**EXO-200 timeline**

- Operation concluded in Dec 2018, with 1181.3 days of live time
- Phase I from Sep 2011 to Feb 2014
  - Stringent limit for $0\nu\beta\beta$ search, *Nature* **510**, 229 (2014)
- Phase II operation begins on Jan 31, 2016 with system upgrades
- This talk, new results with complete dataset!
Combining Ionization and Scintillation energy to enhance energy resolution

Anti-correlation between scintillation and ionization in LXe known since early EXO R&D

EXO-200 Phase-II: energy resolution

- De-noising adapted for Phase II as well in new analysis
- Proper Modeling of mixed collection/induction wire signals
- Energy resolution ($\sigma/E$) at $Q_{\beta\beta}$ value (design goal 1.6%)
  - Phase I: 1.35+-0.09%
  - Phase II: 1.15+-0.02%

- Front end readout electronics
  - Reduce APD readout excess noise
- Cathode HV increased from -8 kV to -12 kV
- Software De-noising to optimize energy calibration
Topological event reconstruction

Low bg data

228Th calibration source

• X/Y (U/V) position from charge signals on crossed-wire planes (9 mm pitch)

• Z position from ionization charge drift time (1 MHz sampling, ~6 mm resolution)

• Software De-noising to optimize energy calibration

• TPC allows the rejection of gamma backgrounds because Compton scattering results in multiple energy deposits.

• SS/MS discrimination is a powerful tool for background rejection as well as for signal discovery.

A Compton event in EXO-200
EXO-200 papers

J.B. Albert et al. "Search for 0νββ Decay with the Upgraded EXO-200 Detector" PRL120(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 01+ excited state of 136Ba with EXO-200" PRC 93 (2016) 035501
Position reconstruction

- Previous analyses require all events having full 3D position
- Some events have partial 3D reconstruction, i.e. small energy deposit having complete collection on U-wire, but no V signals (higher threshold, lower induction signal amplitude)
- Now require >60% of energy deposits having 3D position, only recovering MS events
- Recovers almost all previously cut 0νββ events (10%) in MS due to small bremsstrahlung deposit
- Average SS fraction is 12% in the energy range $Q_{\beta\beta} \pm 2\sigma$ for Th-228 source deployed near the cathode
Light/charge ratio for particle ID

- Requires 2D light/charge energy calibration and good understanding of detector
- Light/charge ratio distributions validated by comparison between data/simulation using source and 2νββ data

- Powerful for α rejection, as well as poorly reconstructed β/γ with anomalous light/charge ratio (e.g. edge events)
- A similar approach was first used in our ‘cosmogenics’ paper, JCAP04(2016)029
• Tighter event coincidence cut

• Event coincidence cut:
  • Originally designed to remove time-correlated events, e.g. Bi-Po event, potential muon induced long-lived decay products …
  • Comprehensive cosmogenic background studies (*JCAP* 1604 (2016) no.04, 029) later found no evidence of contributions from such muon-induced isotopes
  • Reducing time cut window from 1s to 0.1 s is still sufficient for rejecting Bi-Po

* 0νββ detection efficiency increased from ~80% to 97.8±3.0% (96.4±3.0%) for Phase I (II)
Background rejection for SS events

- Standoff distance:
  - γ-rays from the periphery of the detector are exponentially attenuated towards the center

- SS cluster parameters:
  - number of wires with charge collection signals (transverse direction)
  - pulse rise time (longitudinal/drift direction)
  - already used in previous release, Phys. Rev. Lett. 120, 072701 (2018)
Background rejection for MS events

- 0νββ events in MS from small energy depositions due to bremsstrahlung (γ’s Compton scatter)
- Distinct features in number, energy distribution and spatial spread of energy depositions
- Higher background rejection than in SS, MS is dominated by backgrounds
Background discrimination with DNN

- Discriminator built on a deep neural network (DNN)

- DNN trained on images built from U-wire waveforms

- Signal/background identification efficiency correlates with the true event size based on truth information in simulation

- Indicates the network can pick up correct features on the waveform to reconstruct event, (find wire signals, cluster signals into energy deposits), thus to discriminate signal and background
Verification of DNN discrimination

- Data/MC agreement validated with different data:
  - $\gamma$: Ra-226, Th-228, Co-60 calibration sources
  - $\beta$: $2\nu\beta\beta$ data

- Showed consistent and reasonable agreement

- Differences between data/MC are included as systematic uncertainties on the normalization of backgrounds within $Q_{\beta\beta} \pm 2\sigma$

arXiv:1906.02723
Analysis strategy on full Phase II data set

• Blind analysis

• SS/MS classification

• 3-dimensional fit for both SS and MS sets: Energy + DNN + standoff distance
  • Energy, event topology and spatial information
  • Make the most use of multi-parameters for background rejection
  • SS, MS relative contributions constrained by SS fraction

• Improvement of $\approx 25\%$ on the $0\nu\beta\beta$ half-life sensitivity compared with using energy spectra + SS/MS alone
the EXO-200 full Phase II results

2019 release uses machine learning (DNN) for improved signal-to-background discrimination
EXO-200 results

Phase I+II: 234.1 kg·yr $^{136}$Xe exposure
Limit $T_{1/2}^{0νββ} > 3.5 \times 10^{25}$ yr (90% C.L.)

$\langle m_{ββ} \rangle < (93 – 286)$ meV

Sensitivity 5.0x10$^{25}$ yr

No statistically significant signal observed

2019: arXiv 1906.02723
EXO-200 results

Phase I+II: 234.1 kg·yr $^{136}$Xe exposure

Limit $T_{1/2}^{0νββ} > 3.5 \times 10^{25}$ yr (90% C.L.)

$\langle m_{ββ} \rangle < (93 - 286)$ meV

Sensitivity $5.0 \times 10^{25}$ yr

<table>
<thead>
<tr>
<th>(counts)</th>
<th>$^{238}$U</th>
<th>$^{232}$Th</th>
<th>$^{137}$Xe</th>
<th>Total</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>12.6</td>
<td>10.0</td>
<td>8.7</td>
<td>32.3±2.3</td>
<td>39</td>
</tr>
<tr>
<td>Phase II</td>
<td>12.0</td>
<td>8.2</td>
<td>9.3</td>
<td>30.9±2.4</td>
<td>26</td>
</tr>
</tbody>
</table>

Background contribution to $Q \pm 2\sigma$

No statistically significant signal observed
Comparing isotopes

A comparison to experiments using other isotopes requires assumptions on the mass mechanism and the matrix elements.
Summary, conclusions, outlook

- The search for neutrino-less double beta decay (0νββ) is one of the top scientific priorities in nuclear and particle physics.

- Xenon is an excellent isotope for large double beta decay experiments. LXe TPC’s, including EXO-200, have proven to be scalable (>100x), low background detectors for rare event searches over the past 1.5 decades.

  - EXO-200 was the first 100-kg-scale (1 kmole) experiment to run, inspiring the 25-fold scale up, nEXO.


- EXO-200 has released the results of a search for 0νββ decay of Xe-136 with its full dataset with a sensitivity close to the best ones in the field (T_{1/2} > 5 \times 10^{25} \text{ yr}; lower half-life limit on the process: > 3.5 \times 10^{25} \text{ yr}).

- EXO-200 has paved the way to a 5-tonne LXe enriched Xe-136 TPC experiment, nEXO (next talk).