EXO-200 results

Belov V.A.
for EXO-200 coll.

24.10.2018
IV international conference on particle physics and astrophysics
Double beta decay

2νββ

2ν mode is a conventional 2nd order process in Standard Model discovered for many isotopes

0νββ

0ν mode is a hypothetical process always means New Physics. This is search for:
Lepton Number Violation
Majorana fermions

To reach high measurement sensitivity for 0ν mode one requires,
• High energy resolution
• Large Isotope mass
• Low background
The EXO-200 Collaboration

SLAC National Accelerator Laboratory, Menlo Park CA, USA — M Breidenbach, R Conley, T Daniels, 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 — J Daughheetee, R MacLellan

Friedrich-Alexander-University Erlangen, Nuremberg, Germany
G Anton, R Bayerlein, J Hoessl, P Hufschmidt, A Jamil, T Michel, M Wagenpfel, 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 Karelina, A Kuchenkov, V Stekhanov, O Zeldovich

University of Illinois, Urbana-Champaign IL, USA — D Beck, M Coon, S Li, L Yang

Stanford University, Stanford CA, USA — 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, M Tarka

Technical University of Munich, Garching, Germany — W Feldmeier, P Fierlinger, M Marino

TRIUMF, Vancouver BC, Canada — J Dilling, R Krückgen, Y Lan, F Retière, V Strickland

Yale University, New Haven CT, USA — Z Li, D Moore, Q Xia
Why xenon

*Energy resolution is poorer than the crystalline devices (~ factor 10), but...*

**Monolithic detector.** Xenon can form detection medium, allow self shielding, surface contamination minimized. Very good for large scale detectors.

**Has high Q value.** Located in a region relatively free from natural radioactivity.

**Isotopic enrichment is easier.** Xe is already a gas & $^{136}$Xe is the heaviest isotope.

**Xenon is “reusable”.** Can be purified & recycled into new detector (no crystal growth).

**Minimal cosmogenic activation.** No long lived radioactive isotopes of Xe.

**Energy resolution can be improved.** Using scintillation light/ionization correlation.

**Particle identification.** Slightly limited, but can be used to tag alphas from Rn chain.

... *admits a novel coincidence technique.* Background reduction by Ba daughter tagging (M.Moe PRC 44, R931, 1991).
EXO-200 detector

- Double Time Projection Chamber (TPC)
- 110 kg of liquid xenon in active volume enriched to 80.6% in $^{136}$Xe
- Reading both ionization and scintillation
- Drift field 564 V/cm
- Comprehensive material screening program
- Massive background shielding (> 50 cm of HFE, 5 cm of copper, 25 cm of lead)
- Located in salt mine at 1600 m.w.e.
Event reconstruction

- Signal finding. Digital filters are used on waveforms from U,V wires and APDs
- Parameters of pulses (t, E) are estimated for both charge and light
- Pulses are combined into clusters producing position and energy
- Size of cluster is estimated from rise time and number of wires affected
- Position is used in form of Standof Distance (SD) that is distance from any cluster to the nearest wall

Efficiency to get into SS:
- $2\beta 0\nu \approx 90\%$
- $\gamma 2.5\ \text{MeV} \approx 30\%$

But we don’t throw MS events away!
We use them in the fit to help predict background
Combining ionization and scintillation

Properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)


Mixing angle is chosen to optimize energy resolution at 2615 keV line.

EXO-200 has achieved ~ 1.2% energy resolution at the Q value. nEXO will reach resolution < 1%, sufficient to suppress background from 2νββ.
Optimal discrimination

Enhance $\beta/\gamma$ discrimination by use of additional information

Using a boosted decision tree (BDT) to distinguish between $0\nu\beta\beta$ and main $\gamma$-backgrounds

Fitting $0\nu\beta\beta$ discriminators
- Energy
- SS/MS
- BDT

$\Rightarrow \sim 15\%$ sensitivity improvement

~35% $\gamma$-rejection
~90% signal efficiency
## Data collection

### Phase-I
- Sep 2011 to Feb 2014
- Total live time 596.7 days
- Selected physics results
  - The most precise $2\nu\beta\beta$ measurement
  - Stringent $0\nu\beta\beta$ searches
    - Sensitivity $T_{1/2}^{0\nu\beta\beta} > 1.9 \times 10^{25}$ yr (90%CL)

### Phase-II
- Access regained 2015 after stop imposed by WIPP accident
- Jan – May 2016
  - Hardware upgrades
- Stable data taking since May 2016
- Run to the end in Dec 2018
  - About 4 years of data on disks
    - *Look forward for new results!*

---

![Cumulative Livetime Diagram](image-url)

- **Phase I**
  - WIPP accidents
  - No access to the detector
  - Xe remotely recovered
- **Phase II**
  - Data taking restart
    - Upgraded electronics
    - Deradonator
    - 12kV
2β0ν measurement

- Total exposure 177.6 kg·yr
- Background index in ROI \((1.5 \pm 0.2) \times 10^{-3} \text{/(kg·yr·keV)}\)
- **Sensitivity** \(3.7 \cdot 10^{25} \text{ yr} \) (90% CL)
- \(T_{1/2}(0νββ) > 1.8 \cdot 10^{25} \text{ yr}\)
- \(\langle m_{ββ} \rangle < 147–398 \text{ meV} \) (90% CL)

### Contributions to BQ±2σ

<table>
<thead>
<tr>
<th></th>
<th>Phase I, cts</th>
<th>Phase II, cts</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{232}\text{Th})</td>
<td>15.8</td>
<td>4.8</td>
</tr>
<tr>
<td>(^{238}\text{U})</td>
<td>9.4</td>
<td>4.2</td>
</tr>
<tr>
<td>(^{137}\text{Xe})</td>
<td>4.4</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>30.7±6.0</strong></td>
<td><strong>13.2±1.4</strong></td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>43</td>
<td>8</td>
</tr>
</tbody>
</table>

*Phys. Rev. Lett. 120, 072701*
Search for $^{134}$Xe decay

$^{134}$Xe $\rightarrow ^{134}$Ba $+ 2e^- (+2\bar{\nu}_e)$

Q value = $825.8 \pm 0.9$ keV

- Results from EXO-200 measurement
  
  Phys. Rev. D 96, 092001, 2017

- $T_{1/2}^{(2\beta 2\nu)} > 8.7 \times 10^{20}$ yr
  (Theoretical predictions $\sim 10^{24} - 10^{25}$ yr)

- $T_{1/2}^{(2\beta 0\nu)} > 1.1 \times 10^{23}$ yr

- Improved by factors of $10^5$ and 2 respectively compared to previous measurements.

- Lower scintillation noise in Phase II will improve search sensitivity
Deep neural networks

- Deep neural networks is a method of machine learning
- It found broad use in industry with extremely good results
- Raw waveforms were used in this study to directly extract parameters
- Network was trained using Monte-Carlo data

S. Delaquis et al 2018 JINST 13 P08023

- We were able to reconstruct energy and position
- Energy resolution is slightly better with DNN than with conventional reconstruction
- We also validated with real calibration data
- Work for event identification and classification has already started

\(^{228}\text{Th} \text{ spectra, SS events} \)
EXO-200 and beyond

- Operated a 200 kg scale LXe TPC for 5 years
- Made the most precise measurement of $^{136}$Xe halflife
- Measured residual backgrounds are very low
- Achieved stable electron lifetime of $\sim 3$ ms or better
- Utilized self-shielding in monolithic detector
- Demonstrated power of $\beta/\gamma$ discrimination (SS/MS)
- Upgraded electronics (get to 1.2% energy resolution !)

- It's time to think about tonne-scale experiment!
- We are entering the “golden era” of $\beta\beta$ decay experiments as detector sizes exceed interaction length
- 5000 kg homogenous liquid xenon detector nEXO
- It isn't just 30 EXO-200 experiments
- Our aim is to reach more than $\times 100$ sensitivity

nEXO pCDR
ArXiv: 1805.11142
Thank you
$2\beta^0\nu$ measurement

- Spectra from Phase-I and Phase-II are fitted separately
- Result comes from combination of profiles
- No statistically significant excess: combined p-value $\sim 1.5\sigma$

Systematics

<table>
<thead>
<tr>
<th></th>
<th>Phase I (%)</th>
<th>Phase II (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection efficiency</td>
<td>82.4 ± 3.0</td>
<td>80.8 ± 2.9</td>
</tr>
<tr>
<td>Shape differences</td>
<td>±6.2</td>
<td>±6.2</td>
</tr>
<tr>
<td>SS/MS fraction</td>
<td>±5.0</td>
<td>±8.8</td>
</tr>
</tbody>
</table>
EXO-200 progress

- Sensitivity
- 68% C.L. of limits
- Data limit
- √M·T projection

Phase-2 only limit (2018)

2012
2014
2018

Start of Phase-2

End of run

Sensitivity projection Jun 2015

$T_{1/2}$ [yr]

Exposure [kg · yr]
Comparison

**EXO-200**: this result, arXiv: 1707.08707
GERDA: arXiv:1710.07776
KamLAND-Zen: *PRL 117* (2016) 082503

**EXO-200**: this result, arXiv: 1707.08707
CUORE: talk by O. Cremonesi @ TAUP-2017
Sensitivity in *PRL 115* (2015) 102502
EXO-200 inside
EXO-200 overview
Xenon purity and radon level

Непрерывная циркуляция ксенона через высокотемпературные очистители SAES с использованием специально сконструированного насоса. [Neilson et al. (2011) arXiv:1104.5041v1]

Среднее время жизни электрона ~3 мс обеспечивает на максимальном времени дрейфа 110 мкс уменьшение сигнала <3%.

Восстановление после остановок занимает несколько дней
nEXO Ba tagging

Goal of barium tagging:
- Recover and identify xenon decay daughter barium if present
- Suppress background to almost background free

Several concepts are being investigated:

Conducting Probe
- Liquid Xe TPC
  - Ba\(^+\) ion sticks on probe surface
  - Ba\(^+\) ion \(\beta\beta\) decay

Cold probe\(^3\)
- Liquid Xe TPC
  - Ba\(^+\) ion captured in solid Xe on probe
  - Ba\(^+\) ion \(\beta\beta\) decay

Capillary extraction\(^4\)
- Liquid Xe TPC
  - Capillary extraction
  - Gas Xe
  - Ba\(^+\) “sucked” out of LXe through capillary into ion trap and identified laser fluorescence and MRTOF spectroscopy

---
