Neutrinoless Double-Beta Decay and Direct Neutrino Mass Measurements

Yury Kolomensky
UC Berkeley/LBNL
DPF 2019
Disclaimer

• Many exciting developments: impossible to cover all
• Will focus on the future
  - Many excellent talks in the parallel session this afternoon
  - Also see backup slides
  - My apologies for any omissions!

Neutrino Physics Landscape

At least one $\nu$ has $m > 55$ meV

Neutrino mass hierarchy

- $\nu_e$
- $\nu_\mu$
- $\nu_\tau$

$\nu_e$

$\nu_\mu$

$\nu_\tau$

atmospheric $\sim 3 \times 10^{-3} \text{eV}^2$

solar $\sim 5 \times 10^{-5} \text{eV}^2$

$\nu_e$

$\nu_\mu$

$\nu_\tau$

$\nu_e$

$\nu_\mu$

$\nu_\tau$

$\nu_e$

$\nu_\mu$

$\nu_\tau$

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Neutrino Physics Landscape

- Compelling evidence for
  - Neutrino flavor-changing oscillations
  - (therefore) finite neutrino masses
  - Mixing angles are well measured

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- Open questions in ν Physics:
  - How many neutrinos?
    - ☐ Sterile neutrinos?
  - What is absolute scale of ν mass?
  - How are masses arranged?
  - Are neutrinos responsible for matter-antimatter asymmetry?
  - Majorana or Dirac neutrinos?
  - Is Lepton Number conserved?
Neutrinoless Double-Beta Decay

SM $2\nu\beta\beta$ decay $\tau \geq 10^{19}$ y

$0\nu\beta\beta$ $\tau \geq 10^{25}$ y
Neutrinoless Double-Beta Decay

• Observation of $0\nu\beta\beta$ would mean
  - Lepton number violation
  - Neutrinos are Majorana particles
  - Rate related to (effective) electron neutrino mass

\[ m_{\beta\beta} = \left| \sum_i m_i \cdot U_{ie}^2 \right| \]
Constraints on $m_{\beta\beta}$

\[ m_{\beta\beta} = \left| \sum_i m_i \cdot U_{i\ell}^2 \right| \]

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Constraints on $m_{\beta\beta}$

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The cumulative probability for $m_{bb}$ to be higher than 20 meV is $\frac{3}{4}$ for Inverted Ordering and $\frac{1}{2}$ for Normal Ordering.

Cosmology has a relatively small impact on this scenario. A quenching has an important but not dramatic 30% effect, reducing the discovery potential by $\frac{1}{3}$ for Inverted Ordering and $\frac{1}{2}$ for Normal Ordering.

Constraints on $m_{\beta\beta}$

- $T_{1/2} > 10^{27} \text{ y}$
- $T_{1/2} > 10^{28} \text{ y}$
- $T_{1/2} > 10^{26} \text{ y}$

Constraints on $m_{\beta\beta}$

High discovery potential independently of neutrino mass ordering

Discovery Opportunities

If the neutrino hierarchy is inverted, the light neutrino exchange is dominant. Next-generation experiments with sensitivity $T_{1/2} > 10^{27}$ years have a definite target.

Light neutrino mechanism: inverted hierarchy
Discovery Opportunities

If the neutrino hierarchy is inverted, the light neutrino exchange is dominant. Next-generation experiments with sensitivity $T_{1/2}>10^{27}$ years have a definite target.

If the neutrino hierarchy is normal, the leading contribution could come from short-range new physics effects. Factor of 10-100 improvement in sensitivity at next level. Complementarity to direct searches at the LHC.
Discovery Opportunities

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Discovery potential regardless of the neutrino hierarchy.
Challenges

Practical challenge: very rare process!

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<thead>
<tr>
<th>Half-life</th>
<th>Expected Signal (counts/tonne-year)</th>
</tr>
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<tr>
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<td>~50</td>
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<td>~5</td>
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Experimental challenge -- sensitivity scaling:

Non-zero backgrounds (most current experiments):

$$\left[ T_{1/2}^{0\nu} \right] \propto \varepsilon \cdot I_{\text{abundance}} \cdot \sqrt{\frac{\text{Mass} \cdot \text{Time}}{\text{Bkg} \cdot \Delta E}}$$
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Experimental challenge -- sensitivity scaling:

Non-zero backgrounds (most current experiments):

$$\left[ T^{0\nu}_{1/2} \right] \propto \varepsilon \cdot I_{\text{abundance}} \cdot \sqrt{\frac{\text{Mass} \cdot \text{Time}}{\text{Bkg} \cdot \Delta E}}$$

$$\left[ T^{0\nu}_{1/2} \right] \propto \varepsilon \cdot I_{\text{abundance}} \cdot \text{Mass} \cdot \text{Time}$$

(background-free, next generation)
Diverse Experimental Program

Ionization
- Tracking & Cal: SuperNEMO
- Crystals: GERDA, MAJORANA, LEGEND

Scintillation
- Liquid: KamLAND-Zen, SNO+

TPC: EXO, NEXT

CUPID (LUCIFER, LUMINEU, ...)

Phonons
- Bolometer: CUORE

Diagram by J.F. Wilkerson

SuperNEMO

GERDA

Majorana

EXO-200

NEXT

SNO+

KamLAND-Zen

CUORE

Yury Kolomensky: CUORE & CUPID

Diverse, Vibrant Program

0νββ - decay Experiments - Efforts Underway

NLDBD Sub Committee Report to NSAC

Assembly of all 19 towers is complete!

Construction Operation now (2014)

J.F. Wilkerson

April 18, 2015

Probing the Heart of Neutrinos with CUORE and CUPID

0νββ & ν mass
Diverse Experimental Program

Important to maintain:
- Multiple isotopes
- Technological tradeoffs
- Different systematics

Next generation:
Ideally 2-4 experiments worldwide

Ionization
- Tracking & Cal: SuperNEMO
- Crystals: GERDA, Majorana, LEGEND

Scintillation
- Liquid: KamLAND ZEN, SNO+

Phonons
- Bolometer: CUORE

Diagram by J.F. Wilkerson
Best Results to Date
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GERDA
Neutrino-2018
T_{1/2}(^{76}\text{Ge})>9\times10^{25} \text{ years}
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\( T_{1/2}(^{76}\text{Ge}) > 9 \times 10^{25} \text{ years} \)

KamLAND-Zen
PRL 117, 082503 (2016)
\( T_{1/2}(^{136}\text{Xe}) > 1.07 \times 10^{26} \text{ years} \)
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$T_{1/2}(^{76}\text{Ge}) > 9 \times 10^{25}$ years

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**CUORE**

PRL 120, 132501 (2018)

$T_{1/2}(^{130}\text{Te}) > 1.5 \times 10^{25}$ years
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$T_{1/2}(^{76}\text{Ge}) > 9 \times 10^{25}$ years

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Limits on $m_{\beta\beta}$ in 100 meV range
News: EXO-200 Completes Dataset

Combined Phase I + II: Total exposure = 234.1 kg.yr
[arXiv:1906.02723]

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

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

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

M. Dolinski

The experiment:
- Ultralow background single phase liquid Xe time projection chamber.
- ~100 kg Xe fiducial mass enriched to 80% in $^{136}$Xe.
- Data taking in two phases:
  - Phase I from 2011-2014
  - Phase II (with upgrades) from 2016-2018.

The analysis:
- Single site (SS)/multi-site (MS) discrimination
- 3-dimensional fit in both SS and MS: Energy+DNN+standoff distance.
**News: Majorana Demonstrator Results**

**76Ge**

**Sensitivity** $4.8 \times 10^{25} \text{ yr}$

**Limit** $T_{1/2}^{0\nu\beta\beta} > 2.7 \times 10^{25} \text{ yr} \ (90\% \text{ C.L.})$

$m_{\beta\beta} < (200 - 433) \text{ meV}$

**Majorana Demonstrator (SURF)**
- Enriched HPGe array
- High-purity electroformed Cu shield
- 30 kg of enriched $^{76}\text{Ge}$
- 15 kg of natural $^{76}\text{Ge}$
- 26 kg*yr of $^{76}\text{Ge}$ exposure

[arXiv:1902.02299]
Next Generation: LEGEND

Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

Phased $^{76}\text{Ge}$-based $0\nu\beta\beta$ program with discovery potential at a half-life beyond $10^{28}$ years

Enriched $^{76}\text{Ge}$ diodes (HPGe detectors): best energy resolution

LEGEND combines the best aspects of GERDA and MJD:

- Ultra-low background materials (MJ)
- Low-Z active veto (GERDA)

**LEGEND-200**

- Use existing GERDA infrastructure at LNGS
- Up to 200 kg
- BG goal: 1/5 of existing
- Start by 2021

**LEGEND-1000**

- Deep underground
- UG LAr
- Phased implementation
- BG goal: 1/30 of existing
  $(0.1 \text{ c/FWHM t y})$
Next-generation bolometric ton-scale experiment at LNGS

Mission: Discover $0\nu\beta\beta$ if $m_{\beta\beta} > 10$ meV (half-life in $^{100}\text{Mo} > 10^{27}$ years)

Mature concept based on:

**CUORE Achievements:**

- Ton-scale bolometric detector is technically feasible
- Operation and analysis of 1000 bolometers demonstrated
- Reliable data-driven background model constructed
- Infrastructure for next-generation experiment exists

**Scintillating Bolometer technology based on R&D by Lucifer/CUPID-0, Lumineu, CUPID-Mo**

- Baseline: 1500 enriched $\text{Li}_2\text{MoO}_4$ crystals (~250 kg of $^{100}\text{Mo}$)
- Demonstrated radio-purity, active background rejection
- Energy resolution ~5 keV demonstrated
- Total background of <0.1 counts/(ton*keV*year)
- Phased deployment options up to 1 ton of $^{100}\text{Mo}$
CUPID and CUPID-1T

CUPID Baseline

- \( \text{Li}_2\text{MoO}_4 \) crystals
- 250 kg of \(^{100}\text{Mo}\)
- CUORE cryostat
- Sensitivity: \( T_{1/2} > 1.5 \times 10^{27} \) years (IH)

CUPID-1T

- \( \text{Li}_2\text{MoO}_4 \) crystals
- 1000 kg of \(^{100}\text{Mo}\)
- New cryostat
- Sensitivity: \( T_{1/2} > 9.2 \times 10^{27} \) years (NH)

Potential Geometry

- Considered 5 cm cubic crystals
- Aimed for 2000 kg of \( \text{Li}_2\text{MoO}_4 \)
- Increased radius by 15 cm, height by 45.5 cm
- Considered 5 cm cubic crystals with 1.5 cm lateral separation, 0.8 cm vertical
- Arranged in towers of 4 like in CUORE

Fig 1: 5 cm cubic CUPID 1T detector

Fig 2: Top view

T. Dixon
nEXO (SNOLab)

5000 kg of liquid $^{136}\text{Xe}$

Active background discrimination

Sensitivity $T_{1/2}>9 \times 10^{27}$ years, $m_{\beta\beta}<5-20$ meV

G. Gratta

- "Sensitivity and Discovery Potential of nEXO to $0\nu\beta\beta$ decay" Phys. Rev. C 97 (2018) 065503.
NEXT Idea: Gas $^{136}$Xe/$^{82}$SeF$_6$ TPC

NEXT (Spain): Electro-luminescence HPXe TPC
PANDA-X III (China): Electron HPXe TPC
Also SeF$_6$ ion-drift TPC

Key features:
- Event topology (background suppression, kinematics)
- Energy resolution <1% FWHM

Demonstrator (NEXT-100): ~2020
Ton-scale: NEXT-HD (~2025), NEXT-Bold with barium tagging technology
NLDBD with Theia

• Large-scale detector (50-100 kton)
• Water-based LS target
• Fast, high-efficiency photon detection with high coverage
• Deep underground (e.g. Homestake)
• Isotope loading (Gd, Te, Xe, Li…)
• Flexible! Target, loading, configuration
  ➝ Broad physics program, including 0νββ!

8-m radius balloon with high-LY LS & isotope
7-m fiducial volume
5% nat Te or 3% enr Xe, 10 years
Normal hierarchy sensitivity

T_{1/2} > 1.5 \times 10^{28} \text{ yrs (Te)}
T_{1/2} > 2.7 \times 10^{28} \text{ yrs (Xe)}
(90\% \text{ CL})
m_{\beta\beta} < 5.4 (4.8) \text{ meV Te (Xe)}

G.D. Orebi Gann
Future $0\nu\beta\beta$ Discovery Potential

G. Benato, YGK
Neutrino Mass Measurement in $\beta$ Decay

Kinematics: $\frac{dN}{dE} \propto p_\nu = \sqrt{(Q_\beta - E_e)^2 - m_\beta^2}$

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_{\nu i}^2$$

Present limits:
Mainz: $m_\nu < 2.3$ eV (95% C.L.) [C. Kraus et al., EPJC 40, 447 (2005)]
Troitsk: $m_\nu < 2.05$ eV (95% C.L.) [V.N. Aseev et al., PRD 84, 112003 (2011)]
Techniques and Experiments

Magnetic Adiabatic Collimation combined with an Electrostatic Filter

KATRIN

Cyclotron Radiation Emission Spectroscopy (CRES)

Cartoon from BM & JF 2009

Project 8

Bolometers
Absorber
Source
Thermometer
Membrane

MARE, HOLMES, ECHO
KATRIN: KArlsruhe TRItium Neutrino experiment

H. Robertson
KATRIN Status

KATRIN

First tritium data!

Column density:
\(2 \times 10^{17} \text{T}_2 \text{ cm}^{-2}\)

Resolution:
\(~2.8 \text{ eV base width}\)

Expecting to report on neutrino mass in September 2019.
Trapping coils arranged to provide deep and shallow traps.

Commissioned using krypton gas, but optimized for tritium gas flow.

Goal: Provide a first demonstration of CRES technique using tritium
**First tritium from Phase II (Oct 2018):**

- The spectrum describes the data very well.
- No events recorded past the endpoint.
- Currently taking a new 100 day run to complete Phase II (ongoing).
Conclusions and Outlook

• Neutrinoless Double Beta Decay: discovery science
  - Lepton Number Violation from low to high mass scales
  - Next generation (ton-scale) projects will improve half-life sensitivity by 1-2 orders, probe IH region $m_{\beta\beta} \sim 10$ meV
  - Another order of magnitude in sensitivity with next-next generation experiments

• Direct measurements of neutrino mass
  - Exciting results coming soon

• Expect new results this Fall:
  - CUORE, KamLAND-Zen, KATRIN
Conclusions and Outlook

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Exciting future ahead!
## Parallel Session: Wednesday Afternoon

<table>
<thead>
<tr>
<th>Time</th>
<th>Title</th>
<th>Presenter</th>
<th>Location</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:00</td>
<td>The current status and future prospects of KamLAND-Zen</td>
<td>Mr Zhenghao Fu</td>
<td>West Village G 104, Northeastern University</td>
<td>16:00 - 16:15</td>
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<tr>
<td></td>
<td>Suppression of Cosmic Muon Spallation Backgrounds in KamLAND-ZEN Using Convolutional Neural Network</td>
<td>Mr Aobo Li</td>
<td></td>
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<tr>
<td></td>
<td>The search for neutrinoless double beta decay with EXO-200</td>
<td>Andrea Pocar</td>
<td>West Village G 104, Northeastern University</td>
<td>16:30 - 16:50</td>
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<td>17:00</td>
<td>The nEXO Double-Beta Decay Experiment</td>
<td>Brian Mong</td>
<td>West Village G 104, Northeastern University</td>
<td>16:50 - 17:10</td>
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<td>The NEXT Neutrinoless Double Beta Decay Experiment</td>
<td>Mr Jonathan Haefner</td>
<td>West Village G 104, Northeastern University</td>
<td>17:10 - 17:25</td>
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<td>Barium Tagging for the NEXT Neutrinoless Double Beta Decay Experiment</td>
<td>Mr Nicholas Byrnes</td>
<td>West Village G 104, Northeastern University</td>
<td>17:25 - 17:40</td>
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<td>The Search for Neutrinoless Double-Beta Decay at SNO+</td>
<td>Meng Luo</td>
<td>West Village G 104, Northeastern University</td>
<td>17:40 - 17:55</td>
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<td>News from IUPAP Neutrino Panel</td>
<td>Kate Scholberg</td>
<td>West Village G 104, Northeastern University</td>
<td>17:55 - 18:00</td>
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Backup
Future Experiments: Discovery Probability

Bayesian probability for $3\sigma$ $0\nu\beta\beta$ discovery, folding current prior on $m_{\beta\beta}$

$0\nu\beta\beta$ Rate and Neutrino Mass

\[
\Gamma = \frac{1}{\tau} = G_F^2 \Phi(Q,Z) |M_{0\nu}|^2 <m_{\beta\beta}>^2
\]

- **0\nu\beta\beta rate**
- **Phase space** $\propto Q^5$
- **Nuclear matrix element**
- **Effective neutrino mass**

**0\nu\beta\beta peak** preferred

- **high Q candidates preferred**
- **large phase space**
- **low background**

$[2039 \text{ keV } (^{76}\text{Ge}) \leftrightarrow 4271 \text{ keV } (^{48}\text{Ca})]$

$^{238}\text{U } \gamma$ end at 2.4 MeV

$^{232}\text{Th } \gamma$ end at 2.6 MeV

$\tau^{0\nu} \sim 10^{24} - 10^{26}$ years: large mass and extremely low backgrounds needed (underground labs, ultra purity materials, active rejection of backgrounds)
$0\nu\beta\beta$ Isotopes: Figures of Merit

\[ F = G_F^2 \Phi(Q,Z)|M_{0\nu}|^2 m_e^2 \text{ [y}^{-1}] \]

(Want as high as possible)
$0\nu\beta\beta$ Isotopes: Figures of Merit

$$F = G_F^2 \Phi(Q,Z) |M_{0\nu}|^2 m_e^2 \text{ [y}^{-1}\text{]}$$

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0νββ Isotopes: Figures of Merit

\[ F = G_F^2 \Phi(Q,Z) |M_{0\nu}|^2 m_e^2 \ [y^{-1}] \]

(Want as high as possible)
Current State of the Art: $^{76}\text{Ge}$

**GERDA (Italy)**
- Enriched HPGe array
- LAr active shield
- 18 kg of enriched $^{76}\text{Ge}$ (Phase I)
- 40 kg of enriched $^{76}\text{Ge}$ (Phase II)

**MAJORANA DEMONSTRATOR (USA)**
- Enriched HPGe array
- High-purity electroformed Cu shield
- 30 kg of enriched $^{76}\text{Ge}$
- 15 kg of natural $^{76}\text{Ge}$
Current State of the Art: $^{136}$Xe

KamLAND-Zen (Japan)
Xe-doped liquid scintillator
750 kg of enriched $^{136}$Xe

EXO-200 (USA)
LXe TPC
200 kg of enriched $^{136}$Xe
CUORE

- First ton-scale bolometric detector: 988 TeO$_2$ detectors operating at $\sim$10 mK temperature
  - 742 kg of TeO$_2$ $\rightarrow$ 206 kg of $^{130}$Te
- Excellent cryogenic performance
- Energy resolution 7.7 keV with improvements underway
- Background in ROI (0.014±0.002) counts/(kg*keV*year), consistent with design goal of 0.01 counts/(kg*keV*year)
- First results after 2 months of data taking in 2017:
  - T$_{1/2}^{0\nu\beta\beta}(^{130}$Te)$>1.5\times10^{25}$ years (with CUORE-0/Cuoricino)
  - m$_{\beta\beta}$\textless110-520 meV [PRL 120, 132501 (2018)]
  - 5-year sensitivity: T$_{1/2}>9\times10^{25}$ years; m$_{\beta\beta}$\textless45-211 meV
CUPID Collaboration

INFN Sezione di Milano Bicocca and University of Milano Bicocca, Italy
INFN Sezione di Roma and Sapienza University of Rome, Italy
INFN Sezione di Roma and Gran Sasso Science Institute, Italy
INFN Laboratori Nazionali del Gran Sasso, Italy
INFN Sezione di Bologna and University of Bologna, Italy
INFN Laboratori Nazionali di Frascati, Italy
INFN Laboratori Nazionali di Legnaro, Italy
INFN Sezione di Padova, Italy
INFN Sezione di Genova and University of Genova, Italy
CSNSM Orsay, France
CEA Saclay, France
IPNL Lyon, France
LAL Orsay, France
SIMAP Grenoble, France
Universidad de Zaragoza, Spain
Argonne National Laboratory, USA
Lawrence Berkeley National Laboratory and University of California, Berkeley, USA
Cal Poly, San Luis Obispo, USA
Massachusetts Institute of Technology, USA
University of South Carolina, USA
University of California Los Angeles, USA
Virginia Tech, USA
Yale University, USA
University of Science and Technology of China, China
Fudan University, China
Shanghai Jiao Tong University, China
KINR Kiev, Ukraine
ITEP Moscow, Russia
NIIC Novosibirsk, Russia
Li$_2$MoO$_4$ Scintillating Bolometers

**CUPID-Mo**

- **10-12/2017**
- **21-19.3 mK**

- **enrLMO-4**
- **enrLMO-3**
- **enrLMO-2**
- **enrLMO-15**

**With M3 foil**

$\text{DP}_{\alpha+t}/\gamma(\beta) = 14$

**0ν\beta\beta & ν mass**

**Light yield (keV / MeV)**

- **γ(β) events**
- **α events**
- **nuclear recoils**

**Li$_{107}$MoO$_{4}$ LMO2t, AmBe, rc-data (290 h), Run311, LSM**
Scintillating Bolometer Pilot Experiments

CUPID-0/Se @ LNGS: Zn\textsuperscript{82}Se: 2017-2019

CUPID-0/Mo @ Modane: Li\textsubscript{2}\textsuperscript{100}MoO\textsubscript{4}: 2019
KamLAND-Zen
\( T_{1/2}^{0\nu} > 1.07 \times 10^{26} \text{ yr} \)

(sensitivity 5.6\times10^{25} \text{ yr})

\[ \langle m_{\beta\beta} \rangle < (61 - 165) \text{ meV} \]
• KamLAND-Zen 800 started physics data taking on January 22, 2019 with ~745 kg of enriched xenon.

• Balloon is larger and cleaner than that for KamLAND-Zen 400, which currently sets the world’s best limit at $>1 \times 10^{26}$ yrs.

• Current KLZ 800 sensitivity for simple single volume analysis for five year run is $>3 \times 10^{26}$ yrs and $>4 \times 10^{26}$ yrs for more aggressive cuts.
Conceptual design
Rough extrapolation of BG estimation & sensitivity

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<th>KamLAND-Zen 800 2.3-3.7 MeV</th>
<th>KamLAND2-Zen 2.38-2.58 MeV</th>
<th>KamLAND2-Zen High P</th>
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<td>$2\nu 2\beta$</td>
<td>7.4</td>
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<td>$\sigma_E$</td>
<td>&lt;0.15</td>
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<td>$^{10}\text{C}$</td>
<td>1.3</td>
<td>0.18</td>
<td>$\sigma_E$</td>
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<td>0.05</td>
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</tr>
<tr>
<td>[/100kgXe/y]</td>
<td></td>
<td></td>
<td></td>
<td>0.09</td>
</tr>
<tr>
<td>FV (loading)</td>
<td>100 (380)</td>
<td>300+ (745)</td>
<td>1000 (1000)</td>
<td>1000 (1000)</td>
</tr>
<tr>
<td>[kgXe]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Expected) reach</td>
<td>61-165 meV</td>
<td>40 meV</td>
<td>20 meV</td>
<td>&lt;20meV</td>
</tr>
<tr>
<td></td>
<td>$1.07\times10^{26}$ yr</td>
<td>$5\times10^{26}$ yr</td>
<td>$2\times10^{27}$ yr</td>
<td>$&gt;2\times10^{27}$ yr</td>
</tr>
</tbody>
</table>

L. Winslow
Deep Learning appears very effective at identifying background events (arXiv:1812.02906) and will be one of the key ingredients to achieve an ultimate sensitivity of $>5 \times 10^{26}$ yrs.
NEXT experiment

Co-spokespersons:
D. Nygren
J.J. Gomez-Cadenas

Funded by:

USA
Argonne
Fermilab
Iowa State University
Pacific Northwest National Laboratory

Spain
IFIC
Universitat de Girona
Universidad de Zaragoza

Portugal, Israel, Colombia
University of Aveiro
University of Antonio Nariño
NEXT-White (taking data)

**Time Projection Chamber:**
- 5 kg active region (@10 bar), 50 cm drift length

**Pressure vessel:**
- 316-Ti steel, 30 bar max pressure

**Tracking plane:**
- 1792 SiPMs, 1 cm pitch

**Energy plane:**
- 12 PMTs, operating at vacuum, 30% coverage

**Mother can:**
- 12 cm copper plate that separates pressure from vacuum and ads shielding.

**Inner shield:**
- Copper, 6 cm thick

**Energy resolution**
- Event = 2018

**Topological signature**
- Event = 27294

**Signal**
- MC data - all runs

**Background**
- $\mu = 65.8$, $\sigma = 5.5$, $R = 1.18$, $R_{SP} = 0.811$
- $\mu = 155.0$, $\sigma = 8.22$, $R_{SP} = 0.884$

M. Sorel
Total Background rate: 
\[ < 4 \times 10^{-4} \text{ cts / keV kg year} \]

Global detection efficiency: 
28 %
Two approaches developed in parallel:
- Phase 1, High Definition: incremental approach, using/improving existing technology.
- Phase 2, Barium Tagging: based on disruptive new concept (SMFI Ba++ tagging).

Phased approach
- ~1 ton of 136Xe introduced per phase.
- Ultra pure materials. SiPMs as the only sensor.

Phase 1:
- Improves topological signature, improves energy resolution
- Reduces radioactive budget (no PMTs)
- Energy plane made of large area SiPMs (design similar to that of Dark Side)
- Potential to reduce SiPM dark count by cooling detector
- $2.6 \times 10^{-6}$ cts / keV·kg·year total background rate

Phase 2:
- Tracking and energy measured in anode.
- Cathode implements Barium Tagging System
- Virtually background free
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The SNO+ Experiment
A Multi-Purpose Particle Experiment

- One experiment, lots of physics
  - **Water Phase** (2017-18)
    - Detector calibration
    - Background measurement
    - Nucleon decay *(published!)*
    - $^8\text{B}$ solar $\nu$ *(published!)*
    - Reactor anti-$\nu$
  - **Scintillator Phase** (2019)
    - Background measurement
    - Low energy solar $\nu$
    - Geo and reactor anti-$\nu$
  - **Te+scintillator Phase** (2020 - )
    - $0\nu\beta\beta$ search with $^{130}\text{Te}$
    - $t_{1/2}$ measurement of $2\nu\beta\beta$
    - Geo and reactor anti-$\nu$
  - Supernova $\nu$ in all phases!
The SNO+ Experiment

Detector Overview

- Located in SNOLAB, ON, Canada
- ~ 2 km underground (~ 6 km.w.e)
- Low cosmic $\mu^-$ rate (~ 3 / hr)
- Class-2000 clean room
- Reuses SNO detector with some “+’s”
  - Upgraded DAQ and electronics
  - New hold-down ropes
  - New calibration system
  - New scintillator plant
  - New Te purification & synthesis plant
Backgrounds
And How to Reduce Them

ROI: 2.42 - 2.56 MeV [-0.5\(\sigma\) - 1.5\(\sigma\)]
Counts/Year: 9.47

- \(^{8}\text{B}\) ν ES
- 2νββ
- \((\alpha, \text{n})\)
- External γ
- Internal U chain
- Internal Th chain

-\(^{8}\text{B}\):
  - Source term measured. Directionality in scintillator?
- Internals:
  - Measurement before Te loading. PSD of BiPo.
- Externals:
  - Measured in water phase. Fiducialization.
- 2νββ:
  - Improve light yield for better energy resolution.
- Cosmogenic:
  - Purification, underground "cooling."

- 5 years of Phase I
- Fiducial radius: 3.3 m
- 0νββ decay half-life sensitivity:
  \[ T_{1/2}^{0\nu} > 2.1 \times 10^{26} \text{ yr (90\% C.L.)} \]
Summary
Take-Home Messages

• SNO+ has finished water phase and published the physics results.

• SNO+ is currently filling with scintillator and will start Te loading next year to search for 0νββ decay.

• SNO+ Phase I will perform a competitive measurement of 0νββ decay with $^{130}$Te.

• SNO+ Phase II is currently under active R&D for higher sensitivity
  
  • Higher Te loading (4% ~ 10.6 t $^{130}$Te)  
  • Upgrade PMT array, concentrators  
  • Using a balloon vessel  
  • …
Theia

- Large-scale detector (50-100 kton)
- Water-based LS target
- Fast, high-efficiency photon detection with high coverage
- Deep underground (e.g. Homestake)
- Isotope loading (Gd, Te, Li...)
- Flexible! Target, loading, configuration

→ Broad physics program!

Concept paper - arXiv:1409.5864
White paper coming soon!

Detector image product of RAT-PAC
NLDBD with Theia

G.D. Orebi Gann

50 kton water-based liquid scintillator detector
High coverage with fast photon detectors
Deep underground
8-m radius balloon
with high-LY LS & isotope
7-m fiducial, 5% $^{\text{nat}}\text{Te}$ or 3% $^{\text{enr}}\text{Xe}$, 10 years

$T_{1/2} > 1.5 \times 10^{28}$ yrs (Te)
$T_{1/2} > 2.7 \times 10^{28}$ yrs (Xe)
(90% CL)
$m_{\beta\beta} < 5.4 \ (4.8) \text{ meV Te (Xe)}$
Use frequency measurement of cyclotron radiation from single electrons:

- Source transparent to microwave radiation
- No e- transport from source to detector
- Leverages precision inherent in frequency techniques

\[ f_c = f_{c,0} = \frac{1}{2\pi} eB \]

\[ E_{\text{kin}} = \frac{m_e c^2}{2} + E_{\text{kin}} \]

\[ E_{\text{kin}} \leq 100 \text{ eV} \]

A. L. Schawlow

O. Heaviside

B. Monreal and JAF, Phys. Rev D80:051301
Copper waveguide

Kr gas lines

Magnetic bottle coil

Gas cell

Phase I:

Proof-of-Principle with gaseous $^{83m}$Kr demonstrated

J. Formaggio
Phase I:

Proof-of-Principle with gaseous $^{83m}$Kr demonstrated

First light from electrons in $^{83m}$Kr

Spectrum from electrons in $^{83m}$Kr (15 eV FWHM)