Outline

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Relevance of Double Beta Decay

II

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IV

Liquid Xenon Purity Monitor at Wright Lab
Outline

I. Relevance of Double Beta Decay
II. Experimental Approach and Sensitivity
III. nEXO - A Tonne Scale 0νββ Experiment
IV. Liquid Xenon Purity Monitor at Wright Lab
ARE NEUTRINOS THEIR OWN ANTI PARTICLES?

DOES THE HIGGS GIVE MASS TO NEUTRINOS?

WHY DID MATTER WIN OVER ANTIMATTER?
History of the Neutrino and Double Beta Decay

1896 — Discovery of the radioactivity by Becquerel
1914 — Chadwick finds first hints that the beta decay spectrum is continuous
1930 — Wolfgang Pauli introduced the neutrino to solve the problem of continuous $\beta$ spectra ($10^{21}$-$10^{22}$ yrs)
1935 — Maria Goeppert-Meyer introduces two-neutrino double beta decay
1937 — Ettore Majorana introduces Majorana nature for neutral particles
1937 — Giulio Racah stressed that the Majorana symmetry would fully describe a massive neutrino
1939 — Wendell Furry proposes neutrino-less double beta decay based on Majorana's and Racah's ideas ($10^{15}$-$10^{16}$ yrs)
1948 — Fireman conducts first 2vbb experiment with Sn-124 with a lower limit of $3 \times 10^{15}$ yr
1950 — Inghram and Reynolds first detect 2vbb of Te-130 with $1.4 \times 10^{21}$ yr
1956 — Reines and Cowan show first experimental evidence for neutrinos
1957 — Chien-Shiung Wu discovers maximal parity violation in the beta decay
1967 — Pontecorvo proposes flavor mixing of neutrinos
1968 — Davis makes first observation of solar neutrinos
1980 — Revival of 0vbb effort by (1) Detection of 30eV neutrinos (2) Light neutrinos being possible dark matter candidates (3) GUT theories with neutrino masses being naturally of Majorana type
1989 — LEP confirms that only 3 active weak flavors exist
1998 — Observation of neutrinos oscillation of neutrinos from the atmosphere by SuperKamiokande
2001 — Explanation of solar neutrino deficit through neutrino oscillation and MSW effect

Massless left-handed neutrinos make 0vββ impossible to detect

Neutrinos have mass after all and therefore 0vββ is possible again

What happened after this point?
What do we know about neutrinos?

1. No electric charge
   - Majorana or Dirac particle?

2. Weakly interacting through W and Z
   - Possible candidate for dark matter

3. Neutrinos have a non-zero mass
   - Different mass generation mechanism

MORE INTERESTING PHYSICS

- CP-Violation in the lepton sector
- Neutrino Mass Hierarchy
- Sterile Neutrinos
- Stability of neutrinos
- Magnetic moment of neutrinos
Process of Double Beta Decay

- Single beta decay is a well known process
Process of Double Beta Decay

- Single beta decay is a well known process
- However, impossible for 35 isotopes due to energy conservation (even-even nuclei are more bound than odd-odd nuclei)
Process of Double Beta Decay

- Single beta decay is a well known process
- However, impossible for 35 isotopes due to energy conservation (even-even nuclei are more bound than odd-odd nuclei)
- Neutrinoless version is helicity suppressed due to small neutrino mass
  - Only left-handed component of neutrino can interact with W

Schechter-Valle Theorem (Black-Box Theorem)

- Exchange of light Majorana neutrino is the simplest process.
- More complicated Feynman diagrams contribute with additional particles that are beyond the SM.
- Schechter-Valle Theorem ensures that the discovery of $0\nu\beta\beta$ guarantees the Majorana nature of neutrinos independent of the underlying process.

Heavy neutrino exchange

SUSY neutralino exchange

Majoron emission

Black-Box theorem
Type-I See-Saw Mechanism

- Add a Dirac mass term and a positive-chirality mass term to the Lagrangian
  \[ -\mathcal{L}_D = m_D (\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L) \]
  \[ -\mathcal{L}_R = \frac{1}{2} m_R (\bar{\nu}_R (\nu_R)^c + (\nu_R)^c \nu_R) \]

- Recasting everything into matrix form
  \[ -\mathcal{L}_{D+R} = \frac{1}{2} (\mathcal{N}_L)^c M \mathcal{N}_L \]
  \[ M = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \]
  \[ \mathcal{N}_L = \begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix} \]

- Diagonalizing the matrix
  \[ \mathcal{M} = U^T M U = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix} \]

- One can naturally get a small-scale active neutrino and a heavy GUT-scale sterile neutrino
  \[ m_1 \simeq \frac{m_D^2}{m_R} \sim 0.01 \text{ eV} \ll m_D \]
  \[ m_2 \simeq m_R \sim 10^{15} \text{ GeV} \]
Heavy Majorana Neutrino and Leptogenesis

- Matter and anti-matter should be equally abundant according to Inflation models
- Baryon asymmetry has been measured precisely by BBN and CMB observations

\[ \eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.19 \pm 0.15) \times 10^{-10} \]

"Sorry Doc, we had a load of Anti-Matter around 13 billion years ago, but it got lost when we moved"
Heavy Majorana Neutrino and Leptogenesis

• If neutrinos are Majorana, heavy neutrinos could decay into lepton and Higgs

• Sakharov’s conditions to create baryon asymmetry:
  1. Presence of lepton number violation process (true for 0νββ)
  2. CP-violation beyond what the SM predicts (0νββ can provide additional CP violation)
  3. Decay out of equilibrium (decay rate is slower than expansion of universe at a time when T ~ M)

• Sphaleron decay can convert Lepton asymmetry into Baryon asymmetry

→ Need connection between low energy CP-violation and GUT-scale CP-violation
Relevance of Double Beta Decay

Experimental Approach and Sensitivity

nEXO - A Tonne Scale 0νββ Experiment

Liquid Xenon Purity Monitor at Wright Lab
Observable in a Double Beta Decay Experiment

- We measure the sum energy of both electrons
- Key features for a future experiment
  - Good energy resolution
  - New background rejection techniques
  - Ultra-low radioactive components
Choice of Decay Isotope

- High Q-value to be well above natural radioactive decay chains
- High natural abundance of particular isotope
- Scalability to large mass

### Isotope

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life limit [yrs]</th>
<th>Natural Abundance [%]</th>
<th>Q-Value [MeV]</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>&gt; $1.4 \times 10^{22}$</td>
<td>0.187</td>
<td>4.2737</td>
<td>ELEGANT, CRESST-II</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>&gt; $8.0 \times 10^{25}$</td>
<td>7.8</td>
<td>2.0391</td>
<td>Heidelberg-Moscow, GERDA, MAJORANA, LEGEND</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>&gt; $3.6 \times 10^{23}$</td>
<td>9.2</td>
<td>2.9552</td>
<td>NEMO3</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>&gt; $1.1 \times 10^{24}$</td>
<td>9.6</td>
<td>3.0350</td>
<td>NEMO3</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>&gt; $4.0 \times 10^{24}$</td>
<td>34.5</td>
<td>2.5303</td>
<td>CUORICINO, CUORE</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>&gt; $1.07 \times 10^{26}$</td>
<td>8.9</td>
<td>2.4578</td>
<td>EXO-200, Kamland</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>&gt; $2.0 \times 10^{22}$</td>
<td>5.6</td>
<td>3.3673</td>
<td>NEMO3</td>
</tr>
</tbody>
</table>

- Very efficient at stopping penetrating radiation
  - High atomic number of $Z = 54$
  - High density of $\rho = 3 \text{ g/cm}^3$
  - Lower $W$-value of $W = 15.6 \text{ eV}$ and therefore higher ionization and scintillating light yield
The phase space factor is depending on the Q-value and the nuclear charge Z.

- Can be calculated analytically and with relatively high precision.
- By measuring the decay rate we can convert this to a upper limit on the effective Majorana neutrino mass.
  - Direct probe of the absolute neutrino mass scale.
- NME’s are difficult to calculate and rely on modeling the multi-particle wave functions.
Variations in Nuclear Matrix Elements

• Variations in modeling the nuclear structure
• Importance of better NME calculations

1. Consider background free experiment
   • Amount of exposure needed to be sensitive to a particular $m_{\beta\beta}$ goes as $|M^{0\nu}|^{-2}$
   • Uncertainty in NME of a factor of 3 will result in almost 1 order of magnitude uncertainty in amount of exposure needed

2. Choice of isotope is affected by uncertainties in NME

3. Reliable way to obtain information about neutrino masses once a half-life has been measured
   • Existing issue with quenched axial coupling $g_A$
Bands represent
- Uncertainties in Measured oscillation parameters ($3\sigma$)
- Unknown phases in neutrino mixing matrix
- Interplay between $0\nu\beta\beta$ and cosmology/\$\beta\$-decay
- Constraint of $m_{\text{light}}$ that is inconsistent with $m_{\beta\beta}$ upper limit
  ➡️ Suggests that neutrinos are Dirac
- Constraint of $m_{\text{light}}$ that is inconsistent with a measured non-zero $m_{\beta\beta}$
  ➡️ Additional lepton number violating processes other than the exchange of a light Majorana neutrino
The results for $^{136}$Xe based experiments is competitive with other isotopes such as $^{76}$Ge and $^{130}$Te.

Even though EXO-200 has lower limit than KamLAND-Zen, the sensitivities are very close.
Current Sensitivity of $0\nu\beta\beta$ Experiments

- Community shows good improvement in sensitivity for various isotopes over last years
- Exciting times are ahead of us!
Relevance of Double Beta Decay

Experimental Approach and Sensitivity

nEXO - A Tonne Scale 0νββ Experiment

Liquid Xenon Purity Monitor at Wright Lab
nEXO — Conceptual Design

- Successor of EXO-200
- Single Phase Time Projection Chamber
- Filled with 5 tons of liquid xenon
- Enriched to 90% in $^{136}\text{Xe}$
- Monolithic design with single drift volume
- $4\,\text{m}^2$ of VUV-sensitive Silicon Photomultiplier
- Modular charge readout tiles
- Uniform electric field of 400 V/cm
- Aimed for energy resolution of $\sigma/Q_{\beta\beta} = 1\%$
- Location at SNOLab (6010 m.w.e.)
Monolithic Design is the Key

- nEXO is a multi-parameter experiment, i.e. also using standoff distance for event discrimination
- Monolithic design and high stopping power of Xe allows
  - Outer volume to measure external background
  - Inner volume to be essentially background free and measure $0\nu\beta\beta$ signal
- Requires 3D reconstruction capability

2.5MeV $\gamma$ attenuation length 8.5cm = 130cm
Signal in a Liquid Xenon TPC
Ionizing radiation will either ionize or excite Xe atoms

- Xe* and Xe+ will form excimers that de-excite and produce scintillation light at 178nm

\[
\text{Xe}^+ + \text{Xe} \rightarrow \ldots \rightarrow 2\text{Xe} + h\nu + \ldots \\
\text{Xe}^* + \text{Xe} + \text{Xe} \rightarrow \ldots \rightarrow 2\text{Xe} + h\nu + \ldots 
\]
Signal in a Liquid Xenon TPC

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- Photons are immediately detected by the Silicon Photomultipliers at the barrel and provide a time stamp
Signal in a Liquid Xenon TPC

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- Electrons are drifted to charge collection tiles at the top
Signal in a Liquid Xenon TPC

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$$

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- Electrons are drifted to charge collection tiles at the top
- Charge collection tiles with 3mm pitch strips detect $\text{e}^-$
Signal in a Liquid Xenon TPC

- Ionizing radiation will either ionize or excite Xe atoms
- $Xe^*$ and $Xe^+$ will form excimers that de-excite and produce scintillation light at 178nm
  
  $$Xe^+ + Xe \rightarrow \ldots \rightarrow 2Xe + h\nu + \ldots$$
  $$Xe^* + Xe + Xe \rightarrow \ldots \rightarrow 2Xe + h\nu + \ldots$$

- Photons are immediately detected by the Silicon Photomultipliers at the barrel and provide a time stamp
- Electrons are drifted to charge collection tiles at the top
- Charge collection tiles with 3mm pitch strips detect $e^-$
- $0\nu\beta\beta$ charge is mostly contained within one strip
Signal in a Liquid Xenon TPC

- Ionizing radiation will either ionize or excite Xe atoms
- Xe* and Xe+ will form excimers that de-excite and produce scintillation light at 178nm

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\end{align*}
\]

- Photons are immediately detected by the Silicon Photomultipliers at the barrel and provide a time stamp
- Electrons are drifted to charge collection tiles at the top
- Charge collection tiles with 3mm pitch strips detect e-
- 0νββ charge is mostly contained within one strip
- Perpendicular strip provide position in x-y-plane
Charge Collection Tiles

- Anode consists of array of tiles
- Each tile is composed of a dielectric substrate
- Array of perpendicular conductive strip on top
- Advantages
  - Self-supporting
  - Built-in cold electronics on the back
  - Lower noise and radioactivity

Testing of Prototype Charge Collection Tile

- Measurements done in a LXe test setup
- $^{207}$Bi source for calibration
  - 570 keV gamma
  - 1063 keV gamma
- PMT was used as an event trigger
- Very good agreement between measurement and MC simulation
- Able to reproduce best xenon intrinsic charge-only resolution in literature of $\sigma/E = 5.5\%$ at 570 keV (Phys. Rev. B 68, 054201)
Detection of Scintillation Light

- LXe scintillation light is at 178nm ± 15nm (FWHM)
- 4m² of VUV-sensitive Silicon Photomultiplier
- Light readout is crucial for achieving 1% energy resolution goal
- This requires a 3% minimum light collection efficiency

\[ \epsilon = PDE \cdot PTE = 15\% \cdot 20\% = 3\% \]
Silicon Photomultiplier

- Thousands of photodiodes connected in parallel
- Each diode is operated in reverse bias above breakdown
- Absorbed photon may trigger an avalanche ($10^6$ gain) and generate a signal

$$PDE = P_{\text{trig}} \cdot \epsilon_{\text{geo}} \cdot QE$$

- Passive quenching of current
- Capable of single photon resolution
## Requirements for Silicon Photomultipliers

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photo-detection efficiency at 175-178nm in liquid Xenon</td>
<td>$\geq 15%$</td>
</tr>
<tr>
<td>Radio purity: contribution of photo-detectors to the overall background</td>
<td>$&lt; 1%$</td>
</tr>
<tr>
<td>Dark noise rate at -100°C</td>
<td>$\leq 50 \text{ Hz/mm}^2$</td>
</tr>
<tr>
<td>Average number of correlated avalanches per parent avalanche at -100°C</td>
<td>$\leq 0.2$</td>
</tr>
<tr>
<td>within 10 µs</td>
<td></td>
</tr>
<tr>
<td>Single photo-detector active area</td>
<td>$\geq 1\text{cm}^2$</td>
</tr>
<tr>
<td>Capacitance per area</td>
<td>$&lt; 50 \text{ pF/mm}^2$</td>
</tr>
<tr>
<td>Gain fluctuations + electronics noise</td>
<td>$&lt; 0.1 \text{ PE}$</td>
</tr>
</tbody>
</table>

### SiPM array prototype

### 252Cf spectrum

![SiPM array prototype and 252Cf spectrum](image-url)
State-of-the-Art Silicon Photomultiplier

- Stringent requirements are met by most recent FBK VUV-HD SiPMs
- More than 15% PDE and less than 20% CN
- Given our conservative assumptions on light collection efficiency we would be able to achieve (or even surpass) 1% energy resolution

A. Jamil et al., arXiv:1806.02220
The production of ionization electrons $Q$ and scintillation photons $S$ can be parametrized as

$$Q = \frac{E}{W} \cdot (1 - R) \quad S = \frac{E}{W} \cdot (S_i + R)$$

Anti-correlation causes smearing of energy resolution in each channel separately.

However, linear combination cancels fluctuations

$$O = S + Q = \frac{E}{W} \cdot (S_i + 1)$$

By rotating energy axis in the $E_c$ and $E_s$ plane one can get better energy resolution

$$E_{recon} = E_s \cdot \sin(\theta_{opt}) + E_c \cdot \cos(\theta_{opt})$$

$W = 15.6\,\text{eV}$ (effective energy to create electron-ion pair)
• Enhanced energy resolution by using light and charge energy

• Together with 3D event reconstruction this allows powerful discrimination of background and signal

• Background from gamma decay is predominantly Multi-Site (MS)

• Double Beta Decay signal is mostly Single-Site (SS)
Background Rejection

- Taking full advantage of
  - Energy
  - e-γ-discrimination
  - α-β-discrimination
  - Event position
- MC Toy simulation with 0νββ half-life of
  \[ T_{1/2}^{0ν} = 5.7 \times 10^{27} \text{ yr} \]
- Realistic modeling of background using EXO-200 radio-assay data
What goes into the model?

- Detailed geometry of nEXO
- Background model validated by EXO-200 material screening
- Internal components dominate background
- A single background rate doesn’t make sense for a big homogenous detector
  - For the 3 most inner tons we have less than 
    \[
    3 \cdot 10^{-3} \text{ events} \quad \text{(kg \cdot yr \cdot FWHM)^{-1}}
    \]
  - Also, 2νββ is negligible with 0.34 counts in 10 yrs in the entire LXe volume
Sensitivity of nEXO

- nEXO will reach a half-life sensitivity of about $10^{28}$ yr after 10 years of data taking
- Improvement over current best limit by two orders of magnitude
- This corresponds to an effective Majorana mass of $m_{\beta\beta} < 5.7 - 17.7$ meV at 90% CL
Relevance of Double Beta Decay

Experimental Approach and Sensitivity

nEXO - A Tonne Scale $0\nu\beta\beta$ Experiment

Liquid Xenon Purity Monitor at Wright Lab
Going from EXO-200 to nEXO

• Scaling the drift length from 20 cm to 130 cm is a challenge in LXe
  • LXe (170 K) has a higher boiling point compared to LAr (90 K)
  • In LAr impurities freeze out
• In EXO-200 we regularly achieved 3 ms electron lifetimes
• In nEXO we require an electron lifetime of at least 10 ms
  • Drastically reduce the amount of plastic (such as Teflon)
  • Better surface to volume ratio in nEXO
• Same recirculation time as in EXO-200 of about 2 days
• How to measure lifetimes of more than 10ms? How to drift electrons for more than 1 m?
Novel Approach to Measure Long Electron Lifetimes

- 5W Hamamatsu flash lamp knocks off electrons from photocathode
- Electrons are drifted into switching region
- Behlke HV switches provide a 20 kHz switching HV and trap electrons
  - < 100 ns rise time MOSFET
- After an effective drift length of > 1m electrons are collected at the anode
- 1D Frisch grids prevent pickup/induced currents onto anode and cathode
Status of Liquid Xenon Purity Monitor

- Gas handling system
- SAES MonoTorr Purifier
- Xe bottles
- Circulation pump
- Xe gas inlet
- LN$_2$ backup cooling
- HV Feedthrough
- Pulse tube Cryocooler
- Cu cold finger
- Xe cell
- Cu heat transfer jacket
Status of Liquid Xenon Purity Monitor

Samples loaded at bottom flange
Status of Liquid Xenon Purity Monitor

[Diagram of liquid xenon purity monitor system with valves and components labeled]

Legend:
- Manual Valve
- Regulator
- Auto-control valve

Initial fill

To vacuum system

Recirc pump

Flow controller

SAES Getter
Status of Liquid Xenon Purity Monitor
Status of Liquid Xenon Purity Monitor
Status of Liquid Xenon Purity Monitor
Status of Liquid Xenon Purity Monitor

- Initial test of Behlke switches were done to confirm rise and fall time
- Did transparency test of 1D Frisch grids
- First cool down of chamber within 10h
- Measurements of electron drift velocity in argon gas
- First liquefaction is planned for tomorrow
- Building own gated amplifier
Status of Liquid Xenon Purity Monitor

- Designing and testing gated amplifiers
  - Mitigate pick-up from switching HV
- Encountered significant charge injection noise from switches on boards
  - Investigating noise cancellation circuits
Status of Liquid Xenon Purity Monitor

- Designing and testing gated amplifiers
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## Conclusion

| I | In any case the discovery $0\nu\beta\beta$ implies new physics beyond the Standard Model |
|   | · Majorana fermions as new types of particles |
|   | · Violation of lepton number conservation |
|   | · CP-violation in the Lepton sector |
|   | · New mass generation mechanism through See-saw and introduction of super-heavy right-handed neutrino |
| II | LXe TPCs have proven to be a good technology for $0\nu\beta\beta$ search |
|   | · Monolithic design |
|   | · Multi-parameter search |
|   | · Large scale |
|   | Work required from theoretical side on NME calculations |
| III | nEXO has a projected half-life sensitivity of $\sim 10^{28}$ yr after 10 years of data taking |
|   | · Converts to a Majorana mass limit of less than 5.7-17.7 meV at 90% CL |
|   | · Will cover the inverted mass hierarchy completely and have significant sensitivity in the normal hierarchy |
|   | · Improvement of at least two orders of magnitude compared to best current results |
| IV | Yale LXe Purity Monitor is being commissioned |
|   | · First direct measurement of electron life-times greater than 10ms in LXe |
|   | · Allows detailed measurement of diffusion behavior |
|   | · Screening of materials for LXe compatibility |
It turns out that $0v\beta\beta$ (1st line) is by far the most sensitive to Lepton Number violation

- 100 kg of $0v\beta\beta$ source contains about $10^{27}$ nuclei
- Multiple years of observation
- Fermilab accelerator produces $10^{20}$ protons per year and consequently far less muons or kaons

\[
(Z, A) \rightarrow (Z + 2, A) + 2e^- \quad \text{with half-life } > 10^{25} \text{ yrs}
\]

\[
\mu^+ + (Z, A) \rightarrow e^- + (Z - 2, A) + 2e^- \quad \text{with branching ratio } \leq 10^{-12}
\]

\[
K^+ \rightarrow \mu^+ + \mu^+ + \pi^+ \quad \text{with branching ratio } \leq 3 \times 10^{-9}
\]

\[
\bar{\nu_e} \quad \text{emission from the Sun} \quad \text{with branching ratio } \leq 10^{-4}
\]
Influence of Energy Resolution on Sensitivity

Sensitivity vs. Energy Resolution

$^{136}\text{Xe}$ $0 \nu \beta\beta$ $T_{1/2}$ [yr]

$10^{15}$ $10^{14}$ $10^{13}$ $10^{12}$ $10^{11}$ $10^{10}$ $10^{9}$ $10^{8}$ $10^{7}$ $10^{6}$ $10^{5}$ $10^{4}$ $10^{3}$ $10^{2}$ $10^{1}$ $10^{0}$

Resolution $\sigma/Q_{\beta\beta}$ [%]

$nEXO$ EXO-200

$2\nu\beta\beta$ counts vs. Energy Resolution

$^{136}\text{Xe}$ $2\nu\beta\beta$ [cts/$(\text{FWHM} \, \text{kg y})$]

$10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^{0}$

Resolution $\sigma/Q_{\beta\beta}$ [%]

$nEXO$ EXO-200
Process of Double Beta Decay

- Single beta decay is a well known process
- However, impossible for 35 isotopes due to energy conservation (even-even nuclei are more bound than odd-odd nuclei)
- Neutrinoless version is helicity suppressed due to small neutrino mass
  - Right-handed anti-neutrino emitted at upper vertex
  - In the Majorana case this is equal to a right-handed neutrino
  - Due to the V-A nature of the weak interaction right-handed neutrinos are sterile
  - Since neutrinos have a non-zero mass helicity and chirality are not equal
  - Small left-chiral component of right-handed neutrino can interact at lower vertex and can be absorbed by W
0νββ as a Direct Probe of Neutrino Mass Hierarchy (Standard Mechanism)

- Bands represent
  - Uncertainties in Measured oscillation parameters (3σ)
  - Unknown phases in neutrino mixing matrix
  - Interplay between 0νββ and cosmology/β-decay
    - Constraint of $m_{\text{light}}$ that is inconsistent with $m_{\beta\beta}$ upper limit
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