SNO+ Collaboration

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The SNO+ Experiment
A Multi-Purpose Particle Experiment

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

Adapted from Morgan Askins, DNP 18 and wwwkm.phys.sci.osaka-u.ac.jp
0νββ Decay
The Hunt for No Neutrinos

Double-Beta Decay
• SM process ($t_{1/2} \sim 10^{21}$ yr)
• Observed from several isotopes
• Energetically favored over β decay

Neutrinoless Double-Beta Decay
• Non-SM process ($t_{1/2} > 10^{25}$ yr)
• Only possible if ν is Majorana fermion
0νββ Decay
The Hunt for No Neutrinos

Signal Signature
- Monoenergetic peak at $Q_{ββ}$
- Need good energy resolution
- Need low background level

Choice of Isotope
- Two important parameters: $η$ and $Q_{ββ}$
- High $Q_{ββ}$: avoid natural radioactivity
- High $η$: 0νββ decay is extremely rare

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$η$ isotopic abundance (%)</th>
<th>$Q_{ββ}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>0.187</td>
<td>4.263</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>7.8</td>
<td>2.039</td>
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<tr>
<td>$^{82}$Se</td>
<td>9.2</td>
<td>2.998</td>
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<tr>
<td>$^{96}$Zr</td>
<td>2.8</td>
<td>3.348</td>
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<tr>
<td>$^{100}$Mo</td>
<td>9.6</td>
<td>3.035</td>
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<tr>
<td>$^{116}$Cd</td>
<td>7.6</td>
<td>2.813</td>
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<tr>
<td>$^{130}$Te</td>
<td>34.08</td>
<td>2.527</td>
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<tr>
<td>$^{136}$Xe</td>
<td>8.9</td>
<td>2.459</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>5.6</td>
<td>3.371</td>
</tr>
</tbody>
</table>

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
Liquid Scintillator
Let there be light!

\[ \alpha, \beta \ldots \]

\[ \text{LAB (solvent)} \quad \text{e-} \quad \text{Excitation} \]

\[ \text{Mostly Non-radiative} \quad \text{PPO (fluor, 2 g/L)} \]

- **High light yield**: \( \sim 10000 \) photons/MeV \( \sim 550 \) PMT hits/MeV
- **Great transparency**: attenuation length \( \sim 20 \) m
- **Compatibility with acrylic**
- **\( \alpha/\beta \) pulse shape discrimination**
- **Low toxicity**
- **Affordability**

Currently filling!
Scintillator Phase
In Action!

Interface between 20.25 t of LAB (PPO) and water
0νββ Decay at SNO+
Te-Loaded Scintillator

SNO+ Phase I: 0.5% natural Te (1.33 t $^{130}\text{Te}$)

The Cocktail:
- LAB + PPO (2 g/L) + bis-MSB (15 mg/L) + Te-ButaneDiol + DDA

- ~ 4 tons of TeA has been “cooling” underground since 2015.
- TeA purification and TeDiol synthesis plants commissioning now.
- Good optical transparency and light yield: ~ 460 PMT hits/MeV

Key Advantages of SNO+
- High statistics
- Scalability
- No need for enrichment
- Low backgrounds
  - Fiducialization
  - Purification

Adapted from Christopher Grant, DBD 18.
Backgrounds
And Where to Find Them

**Internal**
- $2\nu\beta\beta$
- Solar $^8B\nu$
- $^{238}\text{U}$ and $^{232}\text{Th}$-chain
- $(\alpha,n)$ reaction on $^{13}\text{C}$ or $^{18}\text{O}$
- Cosmogenics

**External**
- PMT’s
- Acrylic vessel
- Hold-down & hold-up ropes
- Water shielding
Backgrounds
And How to Reduce Them

• $^8\text{B}$:
  • Source term measured. Directionality in scintillator?
• Internals:
  • Measurement before Te loading. PSD of BiPo.
• Externals:
  • Measured in water phase. Fiducialization.
• $2\nu\beta\beta$:
  • Improve light yield for better energy resolution.
• Cosmogenic:
  • Purification, underground “cooling.”

• 5 years of Phase I
• Fiducial radius: 3.3 m
• $0\nu\beta\beta$ decay half-life sensitivity:

$$T_{1/2}^{0\nu} > 2.1 \times 10^{26} \text{ yr (90\% C.L.)}$$
The “Lobster” Plot
Probing the mass hierarchy

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 $0\nu\beta\beta$ decay.
- SNO+ Phase I will perform a competitive measurement of $0\nu\beta\beta$ decay with $^{130}\text{Te}$.
- SNO+ Phase II is currently under active R&D for higher sensitivity
  - Higher Te loading (4% ~ 10.6 t $^{130}\text{Te}$)
  - Upgrade PMT array, concentrators
  - Using a balloon vessel
  - …
Thank you!
Backup Slides
Future Prospect
SNO+ Phase II
Neutrino Mass

Bonus from $0\nu\beta\beta$ Decay Search

- For the $0\nu\beta\beta$ experiments, the observable is $t^{1/2}$. With Fermi’s golden rule:

\[
[t^{1/2}]^{-1} = G_{0\nu} |\mathcal{M}|^2 |f(m_i, U_{ei})|^2
\]

\[
f(m_i, U_{ei}) \equiv \frac{m_{\beta\beta}}{m_e}
\]

$m_{\beta\beta}$ is known as the “effective Majorana mass.”

\[
m_{\beta\beta} = \left| \sum_{i=1,2,3} e^{i\xi_i} |U_{ei}|^2 m_i \right|
\]
Mass Hierarchy

The ordering matters

- The oscillation experiments can only measure $\Delta m^2$.
  
  $$P_{\alpha \rightarrow \beta, \alpha \neq \beta} = \sin^2 (2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$$

- Up to now, we have only determined the sign of $\delta m_{21}^2$. Thus, we don't know the ranking of $m_3$ relative to $m_{1,2}$.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$m_{\beta\beta} = \sum_{i=1,2,3} e^{i\xi_i} |U_{ei}|^2 m_i$$