CIPANP 2018
Neutrino Mass and Neutrino Mixing parallel session

Search for neutrinoless double-beta decay with SNO+

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Overview of SNO+

- **SNO+** is a large liquid scintillator detector located in **SNOLAB, Canada**

- Successor to SNO (Sudbury Neutrino Observatory)

- ~ 780 tonnes of **tellurium-loaded** liquid scintillator

- Main goal: Look for the **neutrinoless double-beta decay** process

- Other physics goals: Solar, supernovae and reactor neutrinos, geoneutrinos, nucleon decay

- **Three phases:**
  - Water phase
  - Scintillator phase
  - Te-loaded scintillator phase
The SNO+ collaboration

~150 collaborators, 24 institutes, 6 countries, 1 detector

University of Alberta
Armstrong Atlantic State University
University of California Berkeley / Berkeley National Lab
Boston University
Brookhaven National Lab
University of Chicago
University of California Davis
T.U. Dresden
Lancaster University
Laurentian University
LIP Lisbon
University of Liverpool
National Autonomous University of Mexico
University of North Carolina
Norwich University
SNOLAB
University of Oxford
University of Pennsylvania
Queen's University
Queen Mary University of London
University of Sussex
TRIUMF
University of Washington
Double-beta decay process

- **2-neutrino double-beta decay**
  - Allowed by the Standard Model
  - **Conserves** lepton number
  - Occurs when beta decay is forbidden
  - Observed for 11 isotopes – $T_{1/2} \sim 10^{18} - 10^{24}$ years

- **Neutrinoless double-beta decay**
  - **Violates** lepton number conservation
  - Can occur if neutrinos are **Majorana** particles
  - Hunted after by numerous experiments
Double-beta decay rates and sensitivity

- Rate of double-beta decay:

\[ \text{Rate} \sim (T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M^{0\nu}|^2 <m_{\beta\beta}^2/m_e^2 \]

with:
- \( T_{1/2}^{0\nu} \) = half-life
- \( G^{0\nu} \) = Phase space factor
- \( |M^{0\nu}|^2 \) = Nuclear matrix element
- \( m_{\beta\beta} \) = Effective neutrino mass
- \( m_e \) = Lightest neutrino mass

And \( <m_{\beta\beta}> = |\sum U_{ei}^2 m_i| \) (i=1..3)

- Recent mass hierarchy results are favoring a normal hierarchy
- Inverted hierarchy domain hasn't been probed yet
Double-beta decay signature

2 main approaches are currently used by the community:

- High energy resolution
- Distinctive energy signature
- Small detectors → Lower decay rates but distinct signature

- Lower energy resolution
- Well-understood backgrounds
- Large detectors → Higher decay rates but more subject to backgrounds

The SNO+ approach

Te has a long 2ν2β half-life (~7 x 10^{20} years) and a large natural abundance
SNOLAB is located 2 km underground in the Creighton mine in Sudbury, Ontario.
The SNO+ detector

- ~ 6000 m.w.e. rock overburden
- **Inner and outer shielding:**
  - Pure water
  - 7000 tonnes in total
- **Support structure:**
  - Diameter ~ 18 meters
  - Holds ~9300 PMTs → 54% coverage
- **Acrylic vessel:**
  - Diameter ~ 12 meters
  - Thickness ~ 5 cm
- **Target volume:**
  - Water phase: **Pure water**
  - Scintillator phase: **LAB*** (+ 2g/L PPO**)
  - Tellurium phase: + 1330 kg **130Te**
  - New hold down rope system, new calibration systems, new DAQ and readout systems

*LAB: Linear Alkyl Benzene
**PPO: 2,5-diphenyloxazole (fluor)
Calibrating SNO+

Light calibration

In-situ measurement of:
- PMT responses and efficiencies
- Water/scintillator properties

Optical fibers
- System of fixed fibers coupled to LEDs/lasers
- 106 different locations
- Different wavelengths
### Calibrating SNO+

#### Light calibration

- **In-situ measurement of:**
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- **Optical fibers**
  - System of fixed fibers coupled to LEDs/lasers
  - 106 different locations
  - Different wavelengths

- **Laserball and underwater cameras**
  - Deployed diffusing sphere
  - 40 different locations, several dyes
  - Position pinpointed by cameras
  - Deployable Cherenkov source
Calibrating SNO+

Light calibration

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Radioactive source calibration

Measurement of efficiencies and systematics associated to energy and position reconstruction

- Sources deployable throughout the detector
- Various gamma and neutrons sources

Several calibration systems (light and sources) successfully deployed during the water phase!
Invisible nucleon decay

**Neutron → invisible**

\[
\begin{align*}
\text{16}_O & \rightarrow \text{15}_O^* \\
\text{n} & \rightarrow \text{3}\nu
\end{align*}
\]

De-excitation gammas:
- 6.32 MeV (41%)
- 7.01 MeV (4%)

**Proton → invisible**

\[
\begin{align*}
\text{16}_O & \rightarrow \text{15}_N^* \\
\text{p} & \rightarrow \text{3}\nu
\end{align*}
\]

De-excitation gammas:
- 6.18 MeV (44%)
- 7.03 MeV (2%)
Invisible nucleon decay lifetime:

\[ \tau > \frac{N_{\text{nucleons}} \times \epsilon \times f_T}{S_{90\%}} \]

- \( N_{\text{nucleons}} \times \epsilon \times f_T \) efficiency
- \( S_{90\%} \) livetime
- \( \tau \) expected signal events

30 background counts in ROI expected after 6 months of data taking

90\% CL expected limits

- \( \tau_n > 1.2 \times 10^{30} \) years (best limit from KamLAND is 5.8 \( \times 10^{29} \) years)
- \( \tau_p > 1.4 \times 10^{30} \) years (best limit from SNO is 2.1 \( \times 10^{29} \) years)
SNO+ Scintillator phase - Physics

Reactor antineutrinos

Solar neutrinos

Geoneutrinos

Supernova neutrinos

Broad range of neutrino physics!
**Lower threshold** makes SNO+ sensitive to a wider range of solar neutrinos

**SNO+ aims at measuring both CNO and pep neutrinos**
- Study solar metallicity
- Study neutrino oscillations and matter effects

**Requires very low levels of contamination** (Borexino levels)

**SNOLAB's rock overburden is a major advantage** to limit the amount of cosmogenic backgrounds
Antineutrinos detected through Inverse Beta Decay on H → Coincidence (e^+,n)

- About 100 reactor neutrinos expected per year
- Mostly from local reactors
- New measurement of \( \Delta m_{12}^2 \) could help understand the solar-reactor tension (~1.5\( \sigma \))

- A few tens of geoneutrinos expected per year
LAB shipped from CEPSA BECANCOUR, Quebec to SNOLAB

Stored aboveground and shipped underground in railcars

Purification takes place underground in a dedicated plant:
- Multi-stage distillation
- Metal scavenging
- Water extraction
- $\text{N}_2$ gas stripping

→ Commissioning ongoing

Target levels (g/g)

<table>
<thead>
<tr>
<th>Element</th>
<th>Target Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$&lt; 10^{-17}$</td>
</tr>
<tr>
<td>Th</td>
<td>$&lt; 10^{-18}$</td>
</tr>
<tr>
<td>Kr</td>
<td>$&lt; 10^{-25}$</td>
</tr>
<tr>
<td>K</td>
<td>$&lt; 10^{-18}$</td>
</tr>
<tr>
<td>Ar</td>
<td>$&lt; 10^{-24}$</td>
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Detector filling with LAB planned over the summer
Tellurium phase expected after understanding the backgrounds and detector response during the scintillator phase

Initial Te loading → 0.5% natTe by weight
(1300 kg $^{130}$Te)

Tellurium has to be loaded in LAB using an organo-metallic complex (Te acid) and a solvent (butanediol)

Mixture:
- LAB → Liquid scintillator
- PPO → Fluor (2 g/L)
- Bis-MSB → Wavelength shifter (15 mg/L)
- Te-ButaneDiol → Tellurium complex

Advantages:
- High light yield (~400 p.e./MeV) achieved even at higher Te-loadings
- Long attenuation length
- No intrinsic UV absorption lines
- Good α/β time discrimination
Tellurium acid has been underground for more than 3 years to “cool down” after exposure to cosmics.

**Dedicated “Te plant”:**
- Filter insoluble contaminations
- Use of nitric acid to crystallize and precipitate Te acid in order to drain soluble contaminations

Purification also removes metals created upon cosmic activation on Te ($^{60}\text{Co}$, $^{110m}\text{Ag}$, $^{88}\text{Y}$, etc..)

**Dedicated “Diol plant”** to mix purified Te acid and butanediol

### Target levels

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<tr>
<td>U</td>
<td>$&lt; 1.3 \times 10^{-15}$ Bq/kg</td>
</tr>
<tr>
<td>Th</td>
<td>$&lt; 5 \times 10^{-16}$ Bq/kg</td>
</tr>
</tbody>
</table>

$\rightarrow > 10^4$ contamination reduction from raw Te

Underground cooling and purification reduce cosmogenics.
SNO+ Tellurium phase - Expected signal and backgrounds

SNO+ background estimation

ROI: 2.49 - 2.65 MeV [-0.5\(\sigma\) - 1.5\(\sigma\)]
Count/Year: 12.4

- Cosmogenic
- 2\(\nu\)\(\beta\)
- (\(\alpha\), n)
- External \(\gamma\)
- Internal U chain
- Internal Th chain
- 8\(B\) v ES

\(8B\) solar: Flat ES spectrum
Internal U/Th: BiPo coincidences
External gamma: From PMTs, water, etc..
(\(\alpha\),n): Coincidence upon neutron capture
2\(\nu2\beta\)
Cosmogenics: Te activation

13 events per year in ROI

SNO+ expected energy spectrum

- 0\(\nu\)\(\beta\beta\) (100 meV)
- 2\(\nu\)\(\beta\)
- (\(\alpha\), n)
- U chain
- Th chain
- External
- 8\(B\) vES
- Cosmogenic

5 years of data taking
\(M_{\beta\beta} = 100\) meV
Nominal 0.5% Te-loading
After 1 year: $T^{0\nu}_{1/2} > 0.8 \times 10^{26}$ years
$m_{\beta\beta} < 75.2$ meV

After 5 years: $T^{0\nu}_{1/2} > 1.9 \times 10^{26}$ years
$M_{\beta\beta} < 50.6$ meV

A possible Phase II with a higher Te loading would aim at reaching a limit $> 10^{27}$ years
SNO+ is a large liquid scintillator detector with a broad range of physics goals.

SNO+ is currently taking data in its water phase and will set limits on nucleon decay processes.

Scintillator fill will start in the summer.

SNO+ with scintillator will be sensitive to solar, reactor and geoneutrinos and will measure the intrinsic backgrounds for the Te phase.

Te-loading expected in 2019.

THANK YOU FOR YOUR ATTENTION
BACK-UP
Background model details

- LS mixture: LAB + PPO (2 g/L) + bis-MSB(15 mg/L) + \( ^{nat} \)Te(0.5% loading)
- Fiducial Volume = 3.5 m
- 100% rejection of \(^{214}\)BiPo
- 98% rejection of \(^{212}\)BiPo
- 390 PMT hits/MeV
- ROI = [2.49 –2.65] MeV
Water phase calibration

AmBe coincidence $\Delta T$

$^{241}$Am$^\text{m}$Be calibration data with normal trigger settings

$^{16}\text{N}$ energy and position reconstruction

Light injection through optical fiber
Phase 1 – Solar results

Best Fit $\Phi_B = 6.56^{+1.06}_{-1.01} \, \text{(stat.)}^{0.33}_{-0.58} \, \text{(syst.)} \times 10^6 \, \text{cm}^{-2} \, \text{s}^{-1}$

Includes Oscillations

$4.5 < T_e < 15.0 \, \text{MeV}$