• Neutrino theory - what we still don’t know

• Double beta decay theory
  • Experimental approaches
  • The SNO+ approach

• Evolution of SNO+
  • SNO -> SNO+
  • Water phase
    • Invisible nucleon decay
    • Solar spectra
    • Neutron capture

• Scintillator Fill
  • Solar physics
  • Reactor neutrinos
  • Geo neutrinos

• Te-loaded Fill
  • Double beta challenges and sensitivity
Neutrino Oscillations

Neutrino flavour states we observe are linear super-positions of neutrino mass states

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau 
\end{pmatrix} =
\begin{pmatrix}
U_{e1}, U_{e2}, U_{e3} \\
U_{\mu 1}, U_{\mu 2}, U_{\mu 3} \\
U_{\tau 1}, U_{\tau 2}, U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix} = U_{\text{MNS}}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[U_{\text{MNS}} = U_{23}U_{13}U_{12}\]

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{+i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

where \(c_{ij} = \cos \theta_{ij}\) and \(s_{ij} = \sin \theta_{ij}\).

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U_{\alpha i}^* e^{-i m^2 i L / 2E} U_{\beta i} \right|
\]

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta_{ij}) \sin^2\left(\frac{\Delta m^2_{ij}1.27L}{E}\right)
\]

http://www.hyper-k.org/en/img/waves.jpg
Neutrino Masses

- Oscillations probe \( \Delta m^2 \)
- Remaining Questions:
  - Why is \( m_\nu \ll m_{\text{quark}} \)?
  - Mass Ordering – sign of \( \Delta m_{23} \)
  - Absolute Mass Scale
Neutrino Nature

Dirac Particle

- Requires unnaturally small coupling to Higgs field to explain small neutrino masses
- Right handed neutrinos not observed

\[ \mathcal{L} = -m_D \bar{\nu}_L \nu_R + h.c. \]

Majorana particle

- \textbf{neutrino} = \textbf{antineutrino}
- Violates L conservation
- Small masses explained by the see-saw mechanism

\[ \mathcal{L} = -m_M \bar{\nu}_R^c \nu_R + h.c. , \]

\[ \nu_R^c = i \gamma^2 \nu_R^* , \]

\[ M = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \]
Neutrino Nature

Dirac Particle

• Requires unnaturally small coupling to Higgs field to explain small neutrino masses
• Right handed neutrinos not observed

Majorana particle

neutrino = antineutrino
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\[ \nu_R^c = i \gamma^2 \nu_R^* \]

\[ \mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \]
Neutrinoless Double Beta Decay
Neutrinoless Double Beta Decay

\[(A,Z) \rightarrow (A,Z+2) + 2 \, e^- + 2 \nu_e\]
Double Beta Decay

Only occurs for 35 known isotopes

\[ \delta(A, Z) = \begin{cases} 
+\delta_0 & Z, \text{Neven (A even)} \\
0 & A \text{ odd} \\
-\delta_0 & Z, \text{N odd (A even)} 
\end{cases} \]

Semi-empirical mass formula

\[ m = Z m_p + (A - Z) m_n - E_B \]

Binding energy

\[ E_B = a_V A - a_s A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A, Z) \]

Volume term
Surface term
Coulomb term
Asymmetry term
Pairing term
Majorana mass

\[
(t_{1/2}^{0\nu})^{-1} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2
\]

\[
\alpha Q_{\beta\beta}^5
\]

\[
\langle m_{\beta\beta} \rangle = \left| \sum_i U_{e_i}^2 m_i \right|
\]

Nuclear Matrix Elements

Phase space factor
Majorana mass

\[ (t_{0\nu}^{1/2})^{-1} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2 \]

Phase space factor

\[ \alpha Q^5_{\beta\beta} \]

Nuclear Matrix Elements

\[ \langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right| \]
Other mechanisms for $0
\nu\beta\beta$

- R-parity violating supersymmetry
- Left-right extensions of standard model

Schechter Valle Theorem
- The existence of any $0\nu\beta\beta$ mode would imply an effective Majorana mass term
Nuclear matrix elements

\[(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2\]

Phase space

Nuclear Matrix Element

• Many bodied calculation – relies on models
• Factor 2-3 uncertainty
• Propagates into uncertainty on neutrino mass

arXiv:1610.06548
Neutrinoless Double Beta Decay

\[
(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2
\]

- Phase space
- Nuclear Matrix Element

Experiment options
- Select isotopes with favourable phase space
- Select isotopes with favourable matrix elements
  - Beware large uncertainty / differences between models
- Select isotopes with large abundance or good enrichment opportunity
- Good energy resolution
- Low Backgrounds in region of interest (ROI)
Experimental Sensitivity

$0\nu\beta\beta$ limits

$m_{\beta\beta} [\text{eV}]$

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$m_{\text{lightest}} [\text{eV}]$

$m_{\beta\beta}$

$\Delta m_{23}^2<0$

$\Delta m_{23}^2>0$

$\Delta m_{23}^2>0$

$\Delta m_{23}^2<0$

$^76\text{Ge claim}$

$0\nu\beta\beta$

Degenerate

Inverted

Normal

$\sim 10\text{kg}$

$\sim 100\text{kg}$

$\sim 1000\text{kg}$

$\sim 10000\text{kg}$

$m_{\beta\beta} = \left| \sum_{i} m_i \cdot U_{i e}^2 \right|$
Experimental Sensitivity

\[ m_{\beta\beta} = | \sum_i m_i \cdot U_{ie}^2 | \]

- Degenerate
- Inverted
- Normal

\( \Delta m_{23}^2 > 0 \)
\( \Delta m_{23}^2 < 0 \)

\( \sim 10\text{kg} \)
\( \sim 100\text{kg} \)

\( ^{76}\text{Ge claim} \)
Backgrounds

• **Source = Detector**
  - Limits ‘passive’ material and associated background contributions

• **Source + Detector**
  - Ability to swap isotope, overcome technology limitations

\[
T_{1/2} \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}
\]

Backgrounds scale with detector mass

\[
T_{1/2} \propto a \epsilon Mt
\]

Background free

\[
T_{1/2}^{0\nu\beta\beta}(n_{\sigma}) = \frac{\ln 2}{n_{\sigma}} \cdot N \cdot \epsilon \cdot \frac{\sqrt{t}}{\sqrt{(b \cdot M + c)\delta E}}
\]

Scaling backgrounds

Constant backgrounds
Background sources

- Looking at Q-values ~2-4MeV range
- Intrinsic radioactive isotopes in detector materials
  - $^{238}$U and $^{232}$Th chains (highest gamma 2.6MeV)
- Cosmogenic isotopes
  - Longer lived isotopes created by muons, p, n
- Solar Neutrinos
- $2\nu\beta\beta$
- + specifics
Location

Muon flux = 70 muons/day
Class-2000 clean room lab
Main goal: $0\nu\beta\beta$ search
Load large amount of isotope into homogeneous detector
Statistical identification of $0\nu\beta\beta$ peak over well understood background model
Very low energy background experiment

Potential for other physics:
• Solar Neutrinos
• Reactor Neutrinos
• Geo Neutrinos
• SuperNova Neutrinos
• Invisible Nucleon Decay
The SNO+ detector

2km underground in SNOLAB, ~6000 MWE

- 780 tons of Liquid scintillator

- Contained in an Acrylic vessel (AV) 12 m diameter

- Shielded by 7 kT Ultra-pure water

- Viewed by ~9500 PMTs (8") mounted on 17 m diam. Structure

- New calibration systems

- New DAQ and readout cards

- Loaded with 0.5% double beta decay isotope (Te130)

- Held-down by new rope system

- New interface and cover gas system
Filling SNO+

• After SNO – empty
AV cleaning

Top – Suspended platform

Outside on top!

One last polish

Bottom – Rotating platform
Installed before water fill

Successfully tested the hold-down rope net, by letting cavity water go above level inside AV, applying a 280,000 lb load (127 tons, the full load) to the rope net.
Filling SNO+

• Phase 0 – water fill

Fill inner and outer Volumes with UPW simultaneously
Filling SNO+

- Phase 0 – water fill

Found leaks in cavity liner 😞 Drain to find and repair leaks
Water Filling

• Boating trips to install new calibration system
New Calibration systems

SNO: Deployed sources

SNO+: External source
Embedded LED/Laser Light Injection Entity (ELLIE)
New calibration systems: ELLIE

Will provide continuous calibrations throughout SNO+ operation

- **Timing (T)ELLIE:**
  - 91 injection positions
  - Monochromatic (~520nm) from LEDs
  - Light coverage of entire inward-facing detector

- **Scattering module (SM)ELLIE**
  - 12 injection points (three at each of four locations)
  - Multiple wavelengths from lasers

- **Attenuation module (AM)ELLIE**
  - Eight injection points (two at each of four locations)
  - Multiple wavelengths (tbc)
ELLIE Installation

20/10/2016
Jeanne Wilson
TELLIE data

PMT Occupancy scale
Grey = offline,
purple = <0.03%, red ~6%

AV reflection

Beam spot – direct light
New calibration systems: (SM)ELLIE

4x fixed wavelength laser heads (375nm 407nm, 446nm and 495nm)

One continuously tunable ‘supercontinuum’ laser with a range from 450 – 800 nm.
Filling SNO+

- Phase 0 – water fill. May 4\textsuperscript{th} 2017 – Oct 2018
Water Phase Physics Measurements
Calibrations – $^{16}$N source

Internal $^{16}$N calibration source (~6.1 MeV gamma)
Source was deployed along 3 axes throughout the detector volume:
Measured intrinsic radioactivity of the water inside the AV:
- $R < 4.3$ meters
- $4.0 < E < 5.6$ MeV

1D fit in isotropy parameter $\beta_{14}$ for $^{214}$Bi and $^{208}$Tl components

$g_{\text{U}}/g_{\text{H}_2\text{O}}: (8.6 \pm 0.7\,\text{(stat)} + 2.4\,(\text{sys}) - 1.6\,(\text{sys})) \times 10^{-14}$

$g_{\text{Th}}/g_{\text{H}_2\text{O}}: < 2.7 \times 10^{-14}$ (95% C.L.)
Measure background radioactivity from AV, ropes, external H$_2$O and PMTs
Box Analysis and Likelihood Fit

<table>
<thead>
<tr>
<th>Source</th>
<th>Analysis Method</th>
<th>Results (measured/expectation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMTs</td>
<td>Box Analysis</td>
<td>$^{208}$Tl: $1.16 \pm 0.02$ (stat)$^{+1.09}_{-0.46}$ (syst)</td>
</tr>
<tr>
<td>AV + ropes</td>
<td>Likelihood Fit</td>
<td>$^{214}$Bi: $1.69 \pm 0.86$ (stat)$^{+3.62}_{-4.10}$ (syst)</td>
</tr>
<tr>
<td></td>
<td>Likelihood Fit</td>
<td>$^{208}$Tl: $0.00 \pm 0.09$ (stat)$^{+0.95}_{-0.21}$ (syst)</td>
</tr>
</tbody>
</table>

SNO+ Preliminary

- AV+Ropes
- External Water
- PMT
- Internal Water
Measurement of $^8$B Solar Neutrino Flux with very low backgrounds.

Best signal:background achieved in water to date. Good measurement even with small data set. Spectrum paper in preparation.
Invisible Nucleon Decay

• Invisible nucleon decay modes – deposit no visible energy in detector.
  
  eg. $N \rightarrow 3\nu$

• See $\gamma$ from de-excitation of residual nucleus.

\[
\begin{align*}
^{16}\text{O} & \rightarrow ^{15}\text{O}^* \rightarrow ^{15}\text{O} + \gamma \\
\gamma (6-7\text{MeV}) & \rightarrow \text{e}^- 
\end{align*}
\]

• Detect $\gamma$ in SNO+ water phase with good efficiency and very little background
Nucleon Decay Search

• Comparison of signal and background

![Graph showing MC Simulations including 8B Solar neutrinos, Reactor anti-neutrinos, Internal U & Th, External U & Th, Proton Decay (2.1x10^29 y, SNO), and Neutron Decay (5.8x10^29 y, KamLAND).]
Nucleon Decay Search

• Comparison of signal and background – dinucleon
Invisible Nucleon Decay Analysis

- Data was split into 6 data sets, during each of which the background levels were relatively stable. Each set has its own analysis cuts and background estimates.
- 114.7 days of livetime used for the background and nucleon decay analysis, running through December 2017.
- 2 independent blind analyses conducted.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Livetime</th>
<th>$T_e$ (Likelihood)</th>
<th>$T_e$ (Counting)</th>
<th>$\cos \theta_{\text{sun}}$</th>
<th>$R$</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.05 days</td>
<td>(5, 10) MeV</td>
<td>(5.75, 9) MeV</td>
<td>(-1, 0.80)</td>
<td>(0, 5.45) m</td>
<td>(-6, 4) m</td>
</tr>
<tr>
<td>2 ($z &gt; 0$)</td>
<td>14.85 days</td>
<td>(5, 10) MeV</td>
<td>(5.95, 9) MeV</td>
<td>(-1, 0.75)</td>
<td>(0, 4.75) m</td>
<td>(0, 6) m</td>
</tr>
<tr>
<td>2 ($z &lt; 0$)</td>
<td>14.85 days</td>
<td>(5, 10) MeV</td>
<td>(5.45, 9) MeV</td>
<td>(-1, 0.75)</td>
<td>(0, 5.05) m</td>
<td>(-6, 0) m</td>
</tr>
<tr>
<td>3</td>
<td>30.68 days</td>
<td>(5, 10) MeV</td>
<td>(5.85, 9) MeV</td>
<td>(-1, 0.65)</td>
<td>(0, 5.30) m</td>
<td>(-6, 6) m</td>
</tr>
<tr>
<td>4</td>
<td>29.44 days</td>
<td>(5, 10) MeV</td>
<td>(5.95, 9) MeV</td>
<td>(-1, 0.70)</td>
<td>(0, 5.35) m</td>
<td>(-4, 6) m</td>
</tr>
<tr>
<td>5</td>
<td>11.54 days</td>
<td>(5, 10) MeV</td>
<td>(5.85, 9) MeV</td>
<td>(-1, 0.80)</td>
<td>(0, 5.55) m</td>
<td>(-6, 0) m</td>
</tr>
<tr>
<td>6</td>
<td>23.19 days</td>
<td>(5, 10) MeV</td>
<td>(6.35, 9) MeV</td>
<td>(-1, 0.70)</td>
<td>(0, 5.55) m</td>
<td>(-6, 6) m</td>
</tr>
<tr>
<td>Bin-width</td>
<td>—</td>
<td>0.1 MeV</td>
<td>0.1 MeV</td>
<td>0.1</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Removes solar neutrinos
Selects lowest bg regions in detector
Full Spectral Fit - neutron
Full Spectral Fit - proton

Counts / 114.7 Days / 100 keV

SNO+ Preliminary + Data

- Likelihood Fit
- Internal $^{214}$Bi / $^{208}$Tl
- External $^{214}$Bi / $^{208}$Tl
- $^8$B Solar \( \nu \)
- Reactor \( \nu \)
- Atmospheric \( \nu \)
- Proton Decay

\( T_e [\text{MeV}] \)
### Results of the Spectral Fit at 90% C.L.

<table>
<thead>
<tr>
<th>Mode</th>
<th>SNO+ Limits (years)</th>
<th>Current Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>$2.49 \times 10^{29}$</td>
<td>$5.8 \times 10^{29}$ [KamLAND]</td>
</tr>
<tr>
<td>p</td>
<td>$3.56 \times 10^{29}$</td>
<td>$2.1 \times 10^{29}$ [SNO]</td>
</tr>
<tr>
<td>pp</td>
<td>$4.68 \times 10^{28}$</td>
<td>$5.0 \times 10^{25}$ [Borexino]</td>
</tr>
<tr>
<td>pn</td>
<td>$2.57 \times 10^{28}$</td>
<td>$2.1 \times 10^{25}$ [Tretyak et. al.]</td>
</tr>
<tr>
<td>nn</td>
<td>$1.25 \times 10^{28}$</td>
<td>$1.4 \times 10^{30}$ [KamLAND]</td>
</tr>
</tbody>
</table>

---

**Graphs:**

- Neutron Decay Counts / Day
- Proton Decay Counts / Day
AmBe Calibration – neutron capture

• Internally deployed AmBe neutron source for efficiency of inverse beta decay event detection of anti-neutrinos

• Coincidence selection applied to source:
  • Prompt: $\geq 17$ Nhit for 4.4 MeV $\gamma$ from $^{12}\text{C}^*$
  • Delayed: $7 \leq$ Nhit $< 17$ for 2.2 MeV $\gamma$ from n-capture on H
  • $\Delta\%$ within 1 ms

Efficiency for tagging neutrons under these conditions is 46%

$\tau = 208.2 \pm 2.1 \mu$s
Muon Induced Neutrons

**Aim**
Measure the multiplicity of neutrons produced by cosmic muons

**Why?**

**Data vs Theory**

![Graph showing neutron yield vs mean muon energy with fit to data and MC predictions](image)

30% error @ SNO+ $<E>$

**What?**

1. Tag and reconstruct muons.
2. Find neutron efficiency for each track via MC.
3. Doped data driven particle selection.
   - Splice random event windows with pruned reconstructed neutron information.
   - Optimise selection.
4. Estimate background rate per track.
5. Carry out Maximum Log Likelihood fits between data and expected multiplicity, given track efficiency and expected background.
6. Produce compatibility of data with models tested.

**Rare signal searches**
- Neutron backgrounds constitute a background for various rare single searches e.g. DM searches
Filling SNO+

• Phase 1 – pure scintillator fill
24/10/18 ->

Scintillator is less dense than water.
Fill inner AV from the top, remove H₂O from bottom
Scintillator of choice Linear Alkylbenzene (LAB)
- **Compatible with acrylic**
- High light yield
- Optical transparency
- Low scattering
- Fast decay, different for alpha/beta
- High flash point, low toxicity
- Density = 0.78g/cm$^3$

Properties:
- 450 observed photons per MeV
- Resolution of 5% at 1 MeV
- $k_B = 71.9 \pm 3.9 \, \mu m/MeV$

We can observe the difference between αs and βs in scintillator timing response. Allows for Particle ID in observed events.
Scintillator Delivery and Purification
Purification Plant - LABPPO

- Multi-stage distillation
  - Remove heavy metals, improve UV transparency
- Pre-purification of PPO concentrated solution
- Steam/N₂ stripping under vacuum
  - Remove Rn, Kr, Ar, O₂
- Water extraction
  - Remove Ra, K, Bi
- Metal scavengers
  - Remove Bi, Pb
- Microfiltration
  - Remove dust

**Target levels:**
- \(^{85}\text{Kr}: 10^{-25} \text{ g/g}\)
- \(^{40}\text{K}: 10^{-18} \text{ g/g}\)
- \(^{39}\text{Ar}: 10^{-24} \text{ g/g}\)
- U: \(10^{-17} \text{ g/g}\)
- Th: \(10^{-18} \text{ g/g}\)
Scintillator delivery
Filling SNO+

• Phase 1 – pure scintillator fill

• Characterise scintillator response and background levels
• “Source Out” Double beta search analysis
• Circulate scintillator to purify
• Solar physics?
• Reactor Neutrino Measurement
• Geo Neutrino Measurement
• SuperNova Live
Tension between solar and KamLAND

⇒ 2σ tension between preferred value of $\Delta m^2_{21}$ from KamLAND and solar data

- $\Delta m^2_{21}$ preferred by KamLAND predicts steep upturn at solar spectrum and smaller D/N asymmetry
- More precise measurements of $\Delta m^2_{21}$ by reactor (JUNO,RENO-50) and solar experiments may help.

- NSI ($\varepsilon \sim 0.3$) can reconcile solar and KL data

⇒ flatter spectrum at intermediate E-region
⇒ larger D/N asymmetries can be expected

Escrihuela et al, PRD80 (2009)
Coloma et al, PRD96 (2017)
Maltoni & Smirnov, EPJ 2015
• Inverse beta decay gives clear coincidence signal in scintillator (and Te-loaded Scintillator), low background
• Expect $0.7e^{-5}$ statistical sensitivity on $\Delta m_{12}^2$ with 3 months of data
• SNO+ has potential to resolve KamLAND-Solar tension
Geo Neutrinos – Scintillator Phase

- Expect 30 geo-ν events per year in SNO+
- 1st measurement in North America
- Results help to distinguish between different geo-physics models
Filling SNO+

• Phase 2 – Te-loading

Load natural Te (34% $^{130}$Te into the scintillator)
First batch in storage underground
Cosmogenic cool-down since January 2015

Telluric Acid
Wear dust mask, safety glasses, gloves and coveralls when exposed to poweder.
See IASPS
Second Delivery – September 2016
Loading the scintillator

Load Te into scintillator with Butanediol

- TeBD very transparent and soluble in LAB liquid scintillator
- Expect ~400 p.e./MeV

SNO+ phase 1
loading: 0.5%
= 1333 kg of isotope
Telluric acid purification

0.5% Te target levels:
- $1.3 \times 10^{-15} \text{g/g } ^{234}\text{U}$
- $5 \times 10^{-16} \text{g/g } ^{232}\text{Th}$

Need $10^4$-$10^5$ factor reduction for cosmogenically activated $^{60}\text{Co}$, $^{110m}\text{Ag}$, $^{126}\text{Sn}$, $^{88}\text{Zr}$, $^{88}\text{Y}$, $^{124}\text{Sb}$

Purification technique relies on solubility of TeA in water based on pH

$$\text{Te(OH)}_6 \leftrightarrow \text{Te(OH)}_5\text{O}^-+\text{H}^+$$

Insoluble soluble

Force TeA to recrystallise by adding Nitric acid, let it precipitate out and drain the ‘dirty’ liquid

Cosmogenic reactivation
Lozza & Petzoldt, Cosmogenic activation of a natural tellurium target, Astroparticle Physics. DOI: 10.1016/j.astropartphys.2014.06.008
Commissioning now underway
Diol Plant

Note: Space is limited underground!
Backgrounds

**LAB-PPO**
$^{238}\text{U}, ^{232}\text{Th}, ^{14}\text{C}$
Solar $^8\text{B}\nu$

**Tellurium**
$^{238}\text{U}, ^{232}\text{Th}, ^{210}\text{Po}$
$2\nu\beta\beta$
Residual cosmogenically activated isotopes:
$^{60}\text{Co}, ^{131}\text{I}$

**Implanted Radon daughters in AV**
$^{210}\text{Pb}, ^{210}\text{Bi}, ^{210}\text{Po}$

**Externals:**
$^{214}\text{Bi}, ^{208}\text{TI} \gamma$ from PMTs, AV, Ropes, H$_2$O

**Thermal neutrons:**
Capture on H to 2.2MeV $\gamma$:
Muon induced neutrons, ($\alpha,n$)
Bi-Po Rejection 1

Different event triggers (simulation)

Rejection criteria: $\Delta T(\beta-\alpha) < 24 \times T_{1/2}^{214\text{Po}}$

- $\text{Nhits}(\alpha) > 50$
- if($\Delta T > 500\text{ns}$), $\Delta R(\beta-\alpha) < 1.5m$

Calculated rejection efficiency ($\alpha > 400\text{ns after } \beta, R < 3.5m$):

- $\varepsilon_{214} = 99.9975\%$, $\varepsilon_{212} = 99.999\%$

20/10/2016

Jeanne Wilson
BiPo Rejection 2


Step in cumulative time distribution

Likelihood difference for time residual PDFs for beta and alpha vs 0νββ

Same event trigger (simulation)
Methods sensitive to scintillator optics:
- Light yield
- Timing

< 4 BiPo total / year in ROI
Random PileUp

Reconstructed mean time

PMT hits prior to event trigger

Time anisotropy of PMT hits

Spatial anisotropy of PMT hits

20/10/2016

Jeanne Wilson
Random PileUp

Expect 36.3 pileup events / year in 0νββ ROI before rejection
⇒ 0.23 events/year after cuts
SNO+ Sensitivity

LAB+PPO+bisMSB+Te(0.5%)+Diol
390 PMT hits / MeV

Sensitivity: $T_{1/2} > 1.9 \times 10^{26}$ years (5 years)
Sensitivity: $T_{1/2} > 1.9 \times 10^{26}$ years (5 years)
SNO++ R&D: HQE PMTs, higher Te loading
Sensitivities and Outlook
Sensitivities and Outlook

\[
M^{0\nu} \sqrt{G^{0\nu} \times 10^{18} \text{yr}} \left( \frac{g_A}{1.25} \right)^2
\]

\[
T_{1/2}^{0\nu} \quad (\text{yrs})
\]

\[
\langle m_{\beta\beta} \rangle (\text{eV})
\]

\[
m_{\text{lightest}} (\text{eV})
\]

arXiv:1610.06548
What if you see a signal?

• Scrutinize analysis
  • Blind search?

• Rule out all potential backgrounds

• Does it scale with isotope mass? Livetime?

• Is the signal seen with different isotopes? Experiments?
SNO+: What if we see a Bump?

1. Measure non-Te backgrounds before loading.
2. Agree with model?
   - Yes: Add Te and run.
   - No: Continue purification.
3. Excess above expected backgrounds?
   - Yes: Re-purify Te, further running.
   - No: Set lifetime limit.
4. Set lifetime limit.
5. Excess persists at same level?
   - Yes: Increase Te load.
   - No: Remove Te.
6. Excess scales?
   - Yes: Consider alternate isotope or enrichment.
   - No: Increase Te load.
SUMMARY

• SNO+ is running and has produced first (water) physics results
  • Detector operating stably with low backgrounds and well understood response
  • New limits on invisible modes of nucleon decay
  • Publications imminent

• SNO+ is now filling with liquid scintillator
  • Potential to measure reactor m12 and geo-neutrinos in short scintillator run
  • Characterise Source-out backgrounds for...

• $^{130}$Te double beta decay search
  • Main physics goal of SNO+