Organic Scintillator and Tellurium Purification Techniques of the SNO+ Double Beta Decay Experiment
SNO+ Physics Goals

- Neutrinoless Double Beta Decay of $^{130}\text{Te}$
- Low Energy Solar Neutrinos
- Reactor Antineutrinos
- Geo-Neutrinos
- Supernova-ν

Three stages:
- Water phase
- Liquid scintillator phase
- Te-loaded liquid scintillator
SNO+ Detector

780t of liquid scintillator (LAB+PPO)

PSUP = PMT Support Structure
~9500 PMT, 54% Coverage

Acrylic Vessel (AV)
Φ=12m, thickness=5cm

Light water (H2O) shielding
- 1700t internal
- 5300t external

Urylon Liner/Radon Seal

Norite Rock

Low cost
High flash point: 130°C
Low toxicity

Light attenuation length:
20 m at 420 nm

High light yield (>10,000 photons/MeV)

Smallest scattering of all scintillating solvents investigated
SNO+ Detector

**Internal Radioactivity**
Traces of radioisotopes (U/Th chain, $^{40}$K, etc) in the scintillator

**External Gammas**
from decays in the acrylic, water, PMTs, etc.

**Cosmogenics**
Neutrons and radionuclides from spallation and hadronic showers

**Cosmic Ray Muons**
$\mu$, $n$, $\gamma$, $\alpha$, $\beta$, $n$, $p$, $^{11}$C...
SNO+ Detector

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**Cosmic Ray Muons**
$n, \gamma, \alpha, \beta, \mu, n, p,^{11}C...$
Are neutrinos their own anti-particles?

- **2νββ (Dirac)**
  \[(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2ν_e\]
  \[\sim 10^{18} - 10^{21}\ \text{years}\]

- **0νββ (Majorana)**
  \[(A, Z) \rightarrow (A, Z + 2) + 2e^-\]
  \[> 10^{25}\ \text{years}\]

- With the Mass Mechanism:
  \[\left(T^{0ν}_{1/2}\right)^{-1} = G^{0ν} \cdot |M^{0ν}|^2 \cdot \left<m_{ββ}\right>^2\]
  \[\left<m_{ββ}\right>^2 = \left|\sum_i U_{ei}^2 m_{vi}\right|^2\]

D.B.D. experiments need good energy resolution, low backgrounds, and large amounts of isotope.
**130°Te Double Beta Decay**

- **Selection of the best isotope for SNO+**
  - High natural abundance (34%)
  - $T_{1/2}^{2n\beta\beta} = 7 \times 10^{20}$ years one of the longest $2\nu\beta\beta$
  - High $Q_{\beta\beta} = 2526.97$ keV
  - High light yield
  - Successfully loaded in the liquid scintillator

High $Q$ value reduces backgrounds and increases the phase space & decay rate. Large abundance makes the experiment cheaper.
Scintillator Purification Plant

- Multi-stage distillation
  - Dual-stream PPO distillation
  - Removes heavy metals
  - Improves UV transparency

- N₂ / steam stripping
  - Removes Rn, Kr, Ar, O₂

- Water extraction
  - Removes Ra, K, Bi

- Metal scavenging
  - Removes Bi, Pb

- Microfiltration
  - Removes 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: \(10^{-18}\ \text{g/g}\)
Telluric Acid Production

- Te extracted from mine (depth ~ 300 m) in April 2014
  - Visit to the production site prior to start of processing
  - QA/QC tests on samples from each barrel before approval to send to SNOLAB

3.8 tonnes of Te(OH)$_6$, corresponding to ~2.1 tonnes Te, or ~0.26% Te loading

- Shipped to SNOLAB (January 7$^{th}$ 2015)
  - Transported underground on January 19$^{th}$ 2015
  - Testing one sample from one of the barrels to cross-check previous results
Telluric Acid Purification

- The purification technique relies on solubility of TeA in water based on pH
  - $\text{Te(OH)}_6 \leftrightarrow \text{Te(OH)}_5\text{O}^- + \text{H}^+$
    - in-soluble soluble
  - Insoluble contamination
    - Dissolve in water, and filter
  - Soluble contamination
    - Force TeA to recrystallize by adding Nitric Acid, let it precipitate out, and drain the “dirty” liquid
- The process can be made tellurium selective
Telluric Acid Purification

- **0.5% Tellurium Target levels:**
  - $1.3 \times 10^{-15}$ g/g in $^{238}$U ($3 \times 10^{-8}$ Bq/kg)
  - $5 \times 10^{-16}$ g/g in $^{232}$Th ($1.2 \times 10^{-9}$ Bq/kg)
  - (raw Te $\sim 10^{-11}$ g/g U/Th, $10^{-4}$ Bq/kg)

- **Cosmogenic contamination from activation on Te**
  - $^{60}$Co, $^{110m}$Ag, $^{126}$Sn, $^{88}$Zr, $^{88}$Y, $^{124}$Sb
  - Rejection needed $10^4$-$10^5$
Telluric Acid Purification Plant

Target 200 kg TeA / batch
~50 “working” days to purify 8 tonnes
Telluric Acid Purification Plant
\( \nu\nu\beta\beta \) LS Requirements

- Reach high tellurium concentration
  - 0.5\% Te in 780 tonnes of scintillator

- Preserve good optics of the cocktail
  - Transparency, Scattering, Light Yield

- Maintain high purity of the scintillator
  - U/Th reduction factor
  - Cosmogenic activation
The TeDiol Complex

- **Tellurium loading in Linear Alkyl Benzene**
  - Through direct mixing in of an organometallic complex of Tellurium

- **Butane-Diol based Te complex ("TeDiol")**:

  ![Chemical Structures]
  - **Telluric Acid**
  - Diolization (boiling)
  - Butanediol
  - TeDiol+LAB (mixing)
  - in SNO+
  + 6 H₂O
The TeDiol Complex

- Tellurium loading in Linear Alkyl Benzene
  - Through direct mixing in of an organometallic complex of Tellurium

- Butane-Diol based Te complex ("TeDiol"):
The Diol Assay

- Identified distributor in Japan, Kowa-Co.
  - High quality and affordable (8 tonnes needed)
  - $^{14}C/^{12}C$ to confirm its non-biogenic origin
  - Accelerator Mass Spectrometry at uOttawa:
    - Sample #1: $(14.3 \pm 1.2) \times 10^{-16}$ Blank #1: $(26.0 \pm 7.4) \times 10^{-17}$
    - Sample #2: $(4.8 \pm 1.2) \times 10^{-16}$ Blank #1: $(2.5 \pm 1.2) \times 10^{-17}$

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The Diol Assay

- **Gamma-ray spectrometry**
  - High Purity Ge (HPGe) detector at SNOLAB
    - $^{238}$U < 3.13 ppb
    - $^{232}$Th < 0.26 ppb
    - $^{40}$K < 386.56 ppb

- **Neutron Activation Analysis**
  - NAA at UC Davis
    - $^{238}$U < 0.3 ppb
    - $^{232}$Th < 3.3 ppb
    - $^{nat}$Na ~ ppm -> a fraction of which is $^{22}$Na
The Diol Assay

- Tracing sodium contamination with NAA

TRIGA-type research reactor in Sacramento, owned and operated by UC Davis

Na \((2.2 \pm 1.0)\) ppb
The Diol Purification

- Bench-top distillation with radio spikes
  - $^{228}\text{Th}$ spike in 1,2-Butanediol
    - Low T (70 °C, 80 mTorr)
      - Initial activity mBq/g: 72
      - Distillate activity mBq/g: <0.014
      - Reduction factor: >5100
    - $^{224}\text{Ra}$
      - Initial activity mBq/g: 72
      - Distillate activity mBq/g: <0.013
      - Reduction factor: >5500
  - High T (170 °C, 225 Torr)

<table>
<thead>
<tr>
<th></th>
<th>Initial activity Bq/g</th>
<th>Distillate activity µBq/g</th>
<th>Reduction factor</th>
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<tr>
<td>$^{228}\text{Th}$</td>
<td>1.94</td>
<td>7 ± 1</td>
<td>280 000</td>
</tr>
<tr>
<td>$^{224}\text{Ra}$</td>
<td>1.94</td>
<td>13 ± 5</td>
<td>150 000</td>
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The TeDiol Plant

Produce TeDiol at a 250-kg batch scale to match the throughput of the Telluric Acid Purification Plant.
The TeDiol Plant
**Backgrounds Budget**

- **$(\alpha, n)$**
  - Alpha-capture on $^{13}\text{C}/^{18}\text{O}$
  - Neutrons produced
  - Capture of thermal neutrons
  - Delayed coincidence tag

- **$^{8}\text{B} \nu \text{ES}$**
  - $^{8}\text{B}$ solar neutrinos:
    - Flat spectrum
    - Constrained by SNO/SK data
    - Limited by resolution

- **Cosmogenics**
  - Mitigation: purification + "cool-down" UG
  - $< 1\text{eV/yr}$ in RoI-FV
  - Further reduction if needed: multi-site events

- **External $\gamma$**
  - From AV, ropes, water, PMTs
  - Fiducial volume (20%) cut
  - 50% extra rejection multi-site cuts

- **Internal U chain**

- **Internal Th chain**

- **Internal U/Th**
  - $^{214}\text{BiPo}, ^{212}\text{BiPo}$
  - B-$\alpha$ delayed coincidence tagging
  - 100% rejection in RoI
  - In-window trigger: $x50$ rejection
\( \nu \beta \beta \) Sensitivity

- **1.3 tonnes of \(^{130}\)Te in LAB (at 0.5\% nat-Te)**
- \([-0.5; +1.5]\) \( \sigma \) around \( Q_{\beta \beta} \)
- 400 NHits/MeV (\( \sim 4\% \Delta E \) )
- Fiducial Volume: 20\% total

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**ννββ Sensitivity**

- **1.3 tonnes of $^{130}$Te in LAB (at 0.5% nat-Te)**
  - [-0.5; +1.5] σ around $Q_{ββ}$
  - 400 NHits/MeV (~4% ΔE)
  - Fiducial Volume: 20% total

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ννββ Schedule

- 2017-2018
  - Scintillator plant commissioning
  - Scintillator fill
    - Unloaded scintillator phase (short)
    - Evaluation of backgrounds for ννββ
  - Commissioning of the Tellurium plant(s)

- 2018-2019
  - Tellurium loading
  - Begin ννββ phase
Backgrounds Budget

- Current sensitivity studies assume that in the background budget, solar neutrinos would be the dominant factor.
  - $2\nu\beta\beta$ spectrum "leaks" into the ROI [8.5/23.2 c-yr]
    - Improved energy resolution with good optics
  - External backgrounds ($^{208}\text{Ti}$, $^{214}\text{Bi}$) [3.5/23.2 c-yr]
    - Minimized with proper fiducialisation, and PSD
  - Internal backgrounds and detector response
    - U/Th [3.8/23.2 c-yr] and cosmogenics [0.1/23.2 c-yr] reduced by purification & cooling
    - Bi-Po/(α,n) tagged with space-time coincidence
    - $^{210}\text{Po}-2\nu\beta\beta/^{210}\text{Bi}-2\nu\beta\beta$ pile-up events reduced based on PMT-hit time distribution
    - Apply the "source-in – source-out " approach
  - Flat $^8\text{B}$ (ES) e⁻ normalized to known flux [7.2/23.2 c-yr]
SNOLAB Facility

- Depth = 2070 m (6000 m.w.e.)
- 60 muons/day in SNO+
- 10,000 sq ft class-2000 clean room
Calibration Hardware

New (Re)Design

New Technology
Calibration Sources

- Need Double encapsulation
  - Limitation for $^{222}\text{Rn}$, $^{90}\text{Y}$

- Radioactive and optical sources $\alpha$, $\beta$, $\gamma$, $n$, with laser injection laserball and Cherenkov

<table>
<thead>
<tr>
<th>Type</th>
<th>$\gamma$</th>
<th>$\beta$</th>
<th>$\alpha$</th>
<th>$n$</th>
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<tr>
<td>Src.</td>
<td>$^{57}\text{Co}$</td>
<td>$^{60}\text{Co}$</td>
<td>$^{48}\text{Sc}$</td>
<td>$^{24}\text{Na}$</td>
</tr>
<tr>
<td>MeV</td>
<td>0.1 (sum)</td>
<td>2.5 (sum)</td>
<td>3.3 (sum)</td>
<td>4.1 (sum)</td>
</tr>
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$\sim 7.12 \text{s}$
Light emitted from the support structure from 92 fibres installed between PMTs. Each gives $10^3$-$10^5$ photons/pulse.
**νββ Sensitivity in Phase II**

- **Improve sensitivity by improving**
  - Light yield and going to higher loading
    - Improve current technique
  - Higher QE PMTs
    - Improved concentrators
    - Coverage to 80%

- **Goal:** 3% nat. Te loading
  - ~ 8 tonnes $^{130}$Te
  - Higher QE PMTS
  - $T_{1/2}^{0ν}$ onbb $\sim 10^{27}$ yr
**2x the Light Yield and same absorption with alternative approach at 3% Te**

![Graph showing light yield improvement](image_url)

*Courtesy of Minfang Yeh of BNL*