Calibration of the SNO+ Scintillator Phase with an AmBe Neutron Source

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on behalf of the SNO+ collaboration

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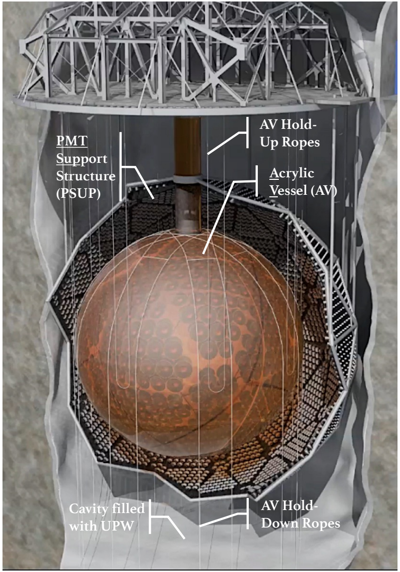
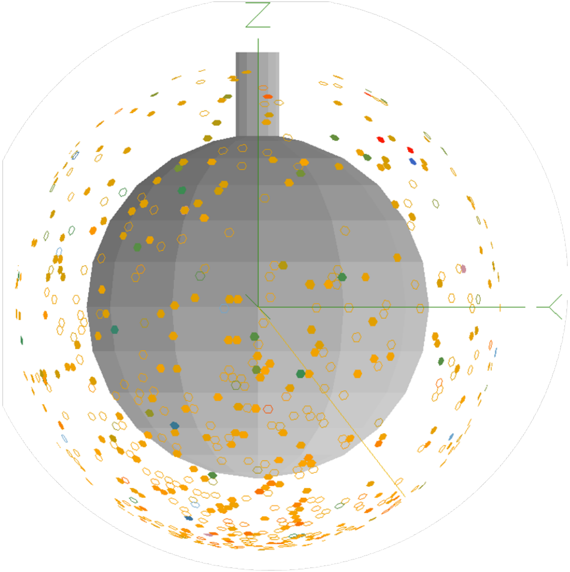
The SNO+ Detector

- Kilo-tonne scale liquid scintillator neutrino detector located 2 km underground at SNOLAB in Sudbury, Ontario.
- 12 m diameter Acrylic Vessel (AV) containing 780 tonnes of liquid scintillator.
- Extending 2.4 m in thickness is a 1500 tonne protective layer of Ultra-Pure Water (UPW) that sits in between the Photomultiplier Tube (PMT) array.
- ∼9500 PMTs mounted on a geodesic spherical support structure (PSUP).
- Structure suspended by hold-up and hold-down ropes in a 30 m tall cavity containing 5300 tonnes of UPW.

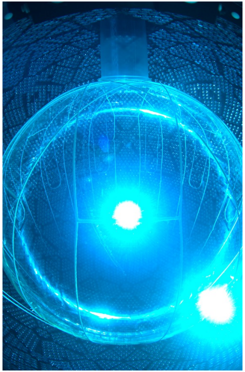


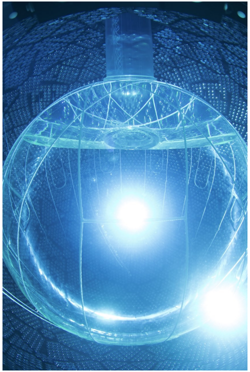
Detecting Scintillation Light

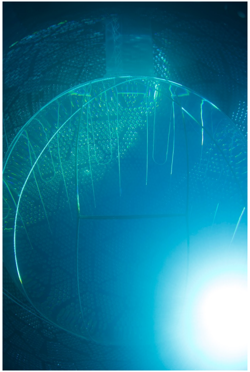
- Ionizing particles passing through the active volume excite the scintillator molecules, releasing photons.
- Light yield of ∼10,000 photons/MeV of deposited energy → about 330 PMT hits/MeV determined from calibration data.
  - Sets an energy threshold of ∼60 keV
- Event reconstruction relies on the PMT hit topology and relative PMT hit times of a given event:
  - Energy from # of PMT hits.
  - Position from photon time-of-flight.

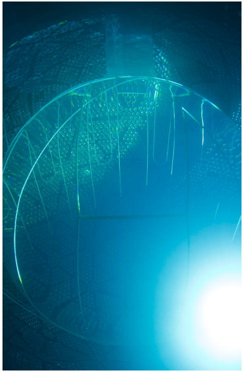


Experimental Phases & Physics Goals









Water Phase

- 2017 – 2019
- Invisible nucleon decay.
- First-ever evidence of reactor antineutrinos in water.
- ^{8}B solar neutrinos.

Partial-Fill Phase

- 2019 – 2022
- First-ever event-by-event directionality in scintillator.
- Preliminary reactor antineutrino measurement.

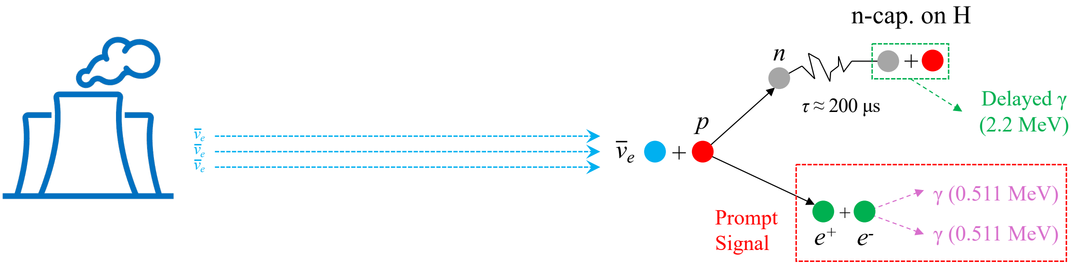
Full-Fill Phase

- 2022 – Present
- Solar, reactor, supernova & geoneutrinos.
- Evaluate backgrounds prior to $0\nu\beta\beta$ decay search.

Tellurium Phase

- Future
- Continuation of most of the scintillator phase physics program.
- Search for $0\nu\beta\beta$ decay in ^{130}Te.

Antineutrinos



Detection Principle

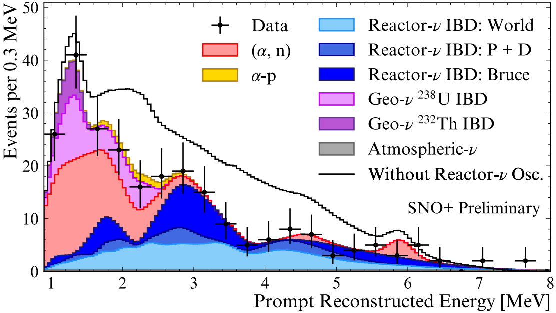
- Detected through the Inverse β Decay (IBD) reaction:

$$\overline{\nu}_e + p \longrightarrow e^+ + n$$

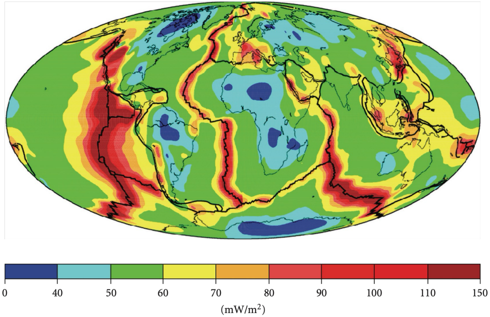
- Scintillation light produced by energy deposition of outgoing e^+ **(prompt signal)**.
- Outgoing n thermalizes and captures on H roughly 200 µs later, releasing a 2.2 MeV γ **(delayed signal)**.
- Coincident events are closely separated in space and time, allowing for powerful background reduction.

Geoneutrinos & Long Baseline Reactor Antineutrinos

Figure from James Page



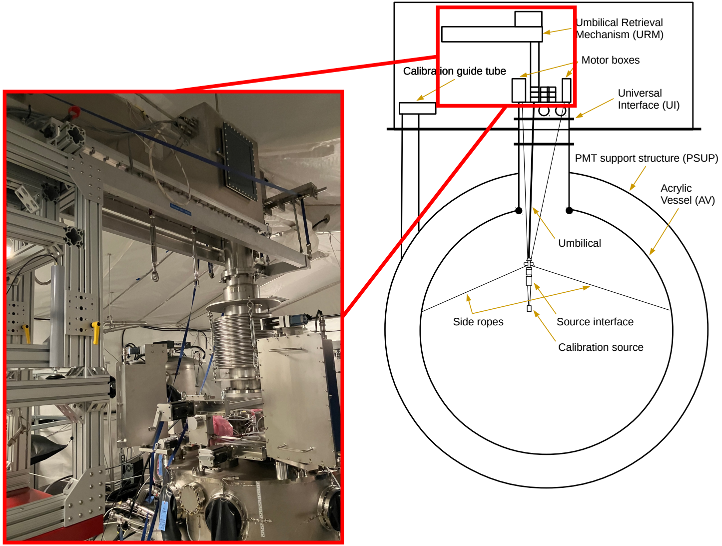
Cardoso, R. & Hamza, V.. (2011).



- 240-350 km baselines to Ontario nuclear reactors (Bruce, Darlington, Pickering) give good sensitivity to the oscillation parameters Δm^2_{21} and $\sin^2\theta_{12}$.
- Oscillation parameters contrained by shape of prompt IBD reconstructed energy spectrum.
- Geoneutrinos (antineutrinos emitted from U & Th decay chains within the Earth) provide a probe into Earth's radiogenic heat production and chemical composition.

Calibration Deployment Systems

- Calibration source attaches to an umbilical, and maneuvered by the Umbilical Retrieval Mechanism (URM).
- Cleanliness maintained via thorough source cleaning and supply of nitrogen cover gas during deployment (*see talk by Ryan Bayes*).
- AV side ropes secured to source pivot by tension, allowing manipulation in (x, y, z).
- Deployment systems used for neutron (^{241}Am-^{9}Be) and optical (laserball) sources.
  - *See talk by Jamie Grove on the SNO+ laserball.*



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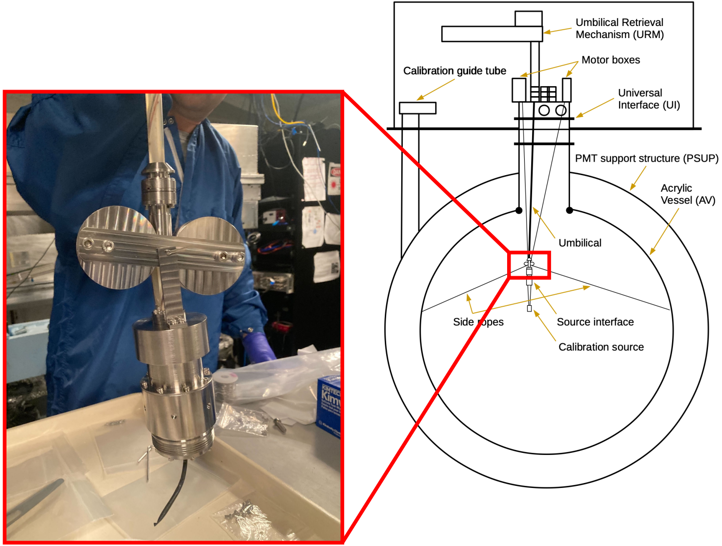

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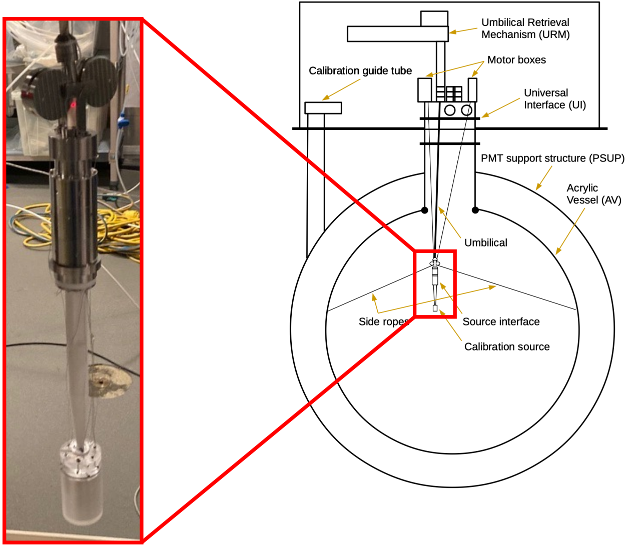
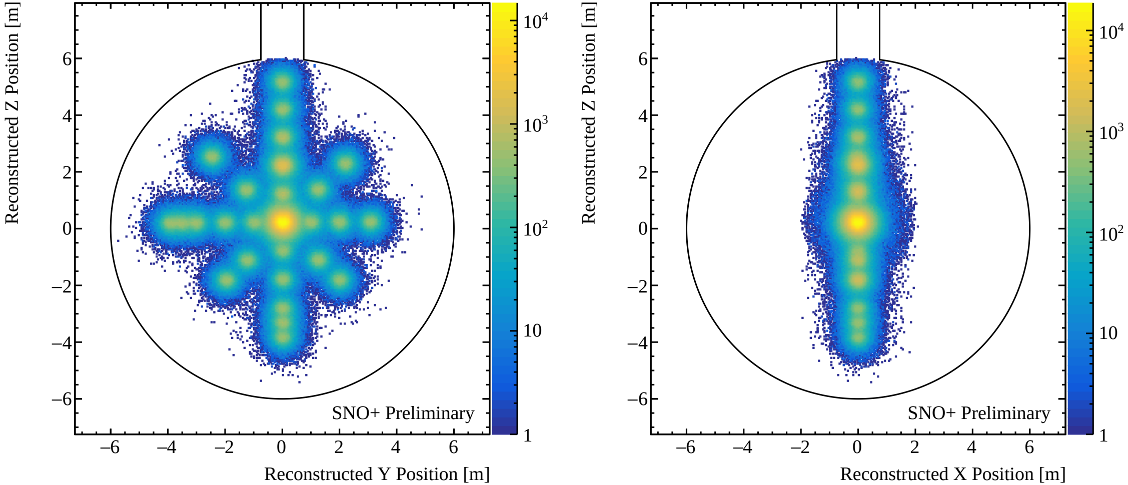


The AmBe Calibration Campaign



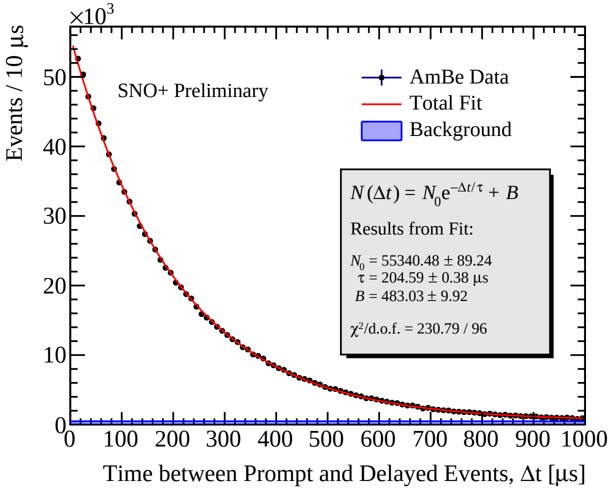
Coincident Events from the AmBe Source

Decay Scheme & Calibration Points

- Following the α-decay of ^{241}Am:

$$\alpha + {}^{9}\text{Be} \longrightarrow {}^{12}\text{C} + \text{n}$$

- ^{12}C produced in an excited state ∼60% of the time, de-exciting and releasing a 4.4 MeV γ **(prompt)**.
- About 200 µs later, the neutron captures on H, releasing a 2.2 MeV γ **(delayed)**.
- Time between coincident events exponentially distributed according to the neutron capture time τ.



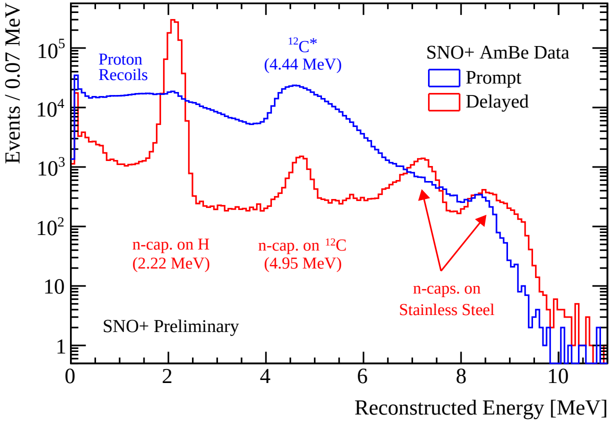
Coincident Events from the AmBe Source

Calibration Goals & Outcomes

1. **Delayed:**
   - Calibrate energy reconstruction algorithms from n-capture peaks.
   - Additional capture peaks from ^{12}C and stainless steel layer on source encapsulation hardware.

2. **Prompt:**
   - Proton recoils + 4.4 MeV γ's.
   - *Sensitive to ionization quenching from protons – important for reactor antineutrino analysis!*

3. Position reconstruction systematics constrained by differences in source manipulator and reconstructed positions.



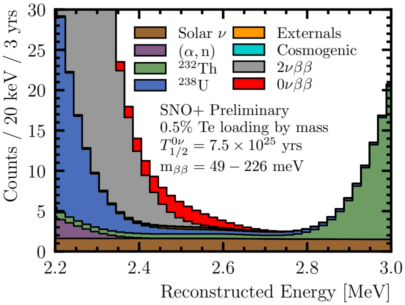
Summary

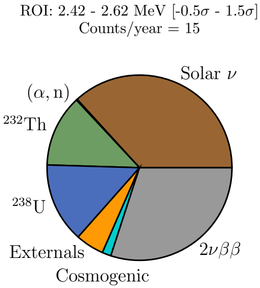
- SNO+ is a large-scale multipurpose neutrino detector with many physics goals.
- Recently, significant efforts have been dedicated to the calibration of the SNO+ detector in its pure liquid scintillator phase, as well as the measurement of reactor antineutrino oscillations.
- Expect the on-going analysis of AmBe calibration data to play a critical role in reducing systematic uncertainties in future reactor antineutrino analyses.
- More results to come!

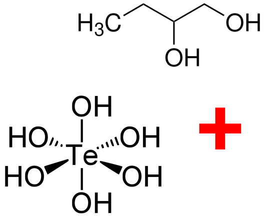
Thank You!

Backup Slides

Neutrinoless Double Beta Decay in ^{130}Te



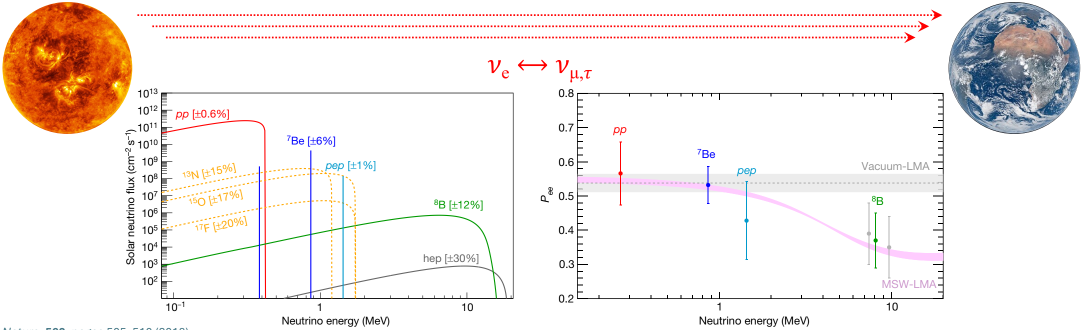




Telluric Acid (TeA) + 1,2-Butanediol (BD)

- ^{130}Te has high natural abundance (∼34%), thus requiring no isotopic enrichment.
- 0.5% natural Te-loaded scintillator by mass gives us 1.3 tonnes of ^{130}Te!
- At the required radio-purity levels, ROI dominated by $2\nu\beta\beta$ background and ^{8}B solar neutrinos.
- Metals do not readily dissolve in mineral oil, so combine TeA with BD to create an LAB-soluble complex.
- Developed purification and processing systems underground at SNOLAB for TeBD synthesis, while mitigating backgrounds induced by cosmogenics.

Solar Neutrinos at Lower Energies



Nature, **562**, pages 505–510 (2018)

- Neutrinos propagating through matter alter the vacuum oscillation parameters (MSW effect).
- Energy-dependent effect: lower energy solar neutrinos less affected by matter (*“vacuum-like”*).
- Survival probabilities have been well-measured at lower (**Borexino**) and higher energies (**SNO, Super-K**), but the transition region has not.
- Downward transition between low and high energy regimes is sensitive to the matter effect.
  → **Probing this regime would test the MSW mechanism.**