Low Background Methods in Underground Astroparticle Physics
Solar Neutrino Experiments

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“Energy production in stars”

The pp chain

H. Bethe (1906-2005)
Measurements of Solar Neutrinos
50-year quest to suppress background for detecting rare neutrino signals

1. Radiogenic Detectors:
   - Chlorine $^{37}\text{Cl}(\nu_e, e^-)^{37}\text{Ar}$: $^7\text{Be}, ^8\text{B}$: → Solar neutrino problem
   - GALLEX, SAGE $^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$: pp, $^7\text{Be}, ^8\text{B}$ → Too few pp neutrinos!
   - Neutrino produces radioactive atom which counted off-line. This avoids many backgrounds.

2. Large Water Cherenkov Detectors
   - Kamiokande, Super-K $^8\text{B} \nu$-e$^-$ elastic scattering: → Atmospheric Neutrino Oscillations.
   - SNO charged+neutral currents with $^8\text{B}$ neutrinos: → Solar Neutrino Oscillations
   - $^8\text{B}$ neutrinos with $E_\nu > 5 \text{ MeV}$ with directionality avoids many backgrounds except for neutrons.

3. Liquid Scintillator Detectors:
   - Borexino (2007-2017): pp, pep, $^7\text{Be}, ^8\text{B}$, neutrinos
   - Kamland (2013) $^7\text{Be}$ ν’s
   - With low threshold energy and no directionality, backgrounds are unavoidable.
In 1964 Davis and Bahcall propose a large detector containing chlorine solvent containing chlorine to confirm Bethe’s theory for the Sun’s energy source.

The need for a deep underground lab to avoid cosmogenic background was appreciated very early.

Another requirement was the need for a small low-background ionization counter to detect the $^{37}$Ar produced by neutrinos.

The background challenges get more difficult without the advantages of the radiogenic detectors.

In 1965-67, Davis builds the 615 ton chlorine ($\text{C}_2\text{Cl}_4$) detector underground in the Homestake Gold Mine in South Dakota at a depth of 4800 mwe.
Chlorine Data 1970-1994
First Detection of Solar Neutrinos

Final rate: $\langle \sigma \phi \rangle = 2.56 \pm 0.16 \pm 0.16$ SNU
Predicted: $\langle \sigma \phi \rangle = 8.00 \pm 0.97$ SNU
Discrepancy: Factor of $\sim 3$ too low.
Gallium Radiochemical Methods

$^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$
Sensitive to pp neutrinos

Gallex-GNO

• 30 tons of Ga in form of GaCl$_3$ in solution.
• $^{71}\text{Ge}$ forms gaseous compound of $^{71}\text{GeCl}_4$ when produced in the tank.
• The $^{71}\text{GeCl}_4$ is flushed out of the tank with N$_2$, gas then counted in small proportional counter.
• Efficiency of extraction measured by introducing known amounts of Ge carrier gas.

SAGE

• 50 tons of metallic Ga operated at 30 C as molten metal.
• Operating 1989 to 2016 in Baksan in Caucasus.
• Chemistry produces $^{71}\text{GeH}_4$ for extraction and counting.
• Efficiency of extraction measured by introducing known amounts of Ge carrier gas.
Summary of Gallex/GNO & SAGE Results

• Gallex-GNO:
  • 73.1 +/- 6.1 (stat) +/- 2.7 (syst) SNU (Gallex)
  • 62.9 +/- 5.4 (stat) +/- 2.5 (syst) SNU GNO

• SAGE:
  • 65.4 +/- 3.1 (stat) +/- 2.7 (syst) SNU

SAGE+Gallex+GNO: 66.1 +/- 3.1 SNU

Standard Model Prediction: 126.6 +/- 4.2 SNU

Missing solar neutrinos confirmed.
Gallium Experiments

Serious solar neutrino problem:

• Two independent experiments.
• Extraction efficiency checked with intense sources.
• $\text{pp}$ neutrinos dominant and constrained by solar luminosity.
• The uncertainty in solar model prediction for $^8\text{B}$ is not involved here.

Neutrino oscillations?

Gallium neutrino source data
Large Imaging Water Cherenkov Detectors

- 1970’s- Proton decay predicted in Grand Unified Theories.
  - Expected lifetime: < $10^{31}$ years

- 1978- Motivated by search for proton decay, imaging water Cherenkov detector developed by Sulak, et. al. for Irvine-Michigan-Brookhaven (IMB) Experiment

- Kamiokande water detector also developed in Japan by Masatoshi Koshiba (who later won Nobel Prize with Ray Davis for detecting solar neutrinos.)
  - Large 50 cm PMT’s developed by Hamamatsu to enhance light collection.
Kamiokande Detector

- 44.5 kton water Cherenkov detector.
  - Started 1983
- Depth: 2700 meters water equivalent (mwe)
- Two water layers.
  - Outer for veto of cosmic rays.
  - Inner for signal.
  - Both instrumented with special 50-cm PMTs developed by Hamamatsu.
- Outer veto and water purification system developed to reduce background and lower threshold to allow detection of $^8$B neutrinos
- Size 19 m $\phi$ x 22 m height similar to Borexino water tank
- The Super- K detector was constructed later.
Electrons in water struck by neutrinos recoil and produce Cerenkov radiation ring.

Direction and energy of recoil electron measured.

Large PMT’s and purification of water permit threshold to be lowered from 30 MeV to ~8 MeV.

$^8$B neutrinos ($E_{\text{max}} = 14$ MeV) detected with direction to Sun.

Rate is $\sim 1/2$ of expected, confirming Davis deficit.

High energy and directionality provide signal above background.
The Chlorine and Kamioka rates are dominated by $^8\text{B}$ neutrinos, with predictions that could be uncertain.

The gallium results are dominated by the robust flux of pp neutrinos, which is constrained by the solar luminosity.

With four experiments observing the neutrino deficit in mid-1990’s, the “solar neutrino problem” suddenly became a real problem, with strong possibility of neutrino oscillations.
Super Kamiokande

50 kton Water Cherenkov detector-built 1996
• 39 mϕ x 42 m height
• 2 water layers
• Fiducial volume 22,000 m$^3$
• 11,000 50-cm diameter PMT’s.

Several phases with on-going solar neutrino measurements.
• Upturn in $\nu_e$ survival probability at low E.

Discovered atmospheric neutrino oscillations 2004.
The SNO Detector

Designed to search for neutrino oscillations by detecting decrease in $\nu_e$ and increase of $\nu_\mu$ and $\nu_\tau$.

- Designed to measure charged ($\nu_e$) and neutral current ($\nu_e\nu_\mu\nu_\tau$) neutrino reactions on deuterons.

  - Charged: $\phi_{CC}$; $d(\nu_e,e^+)nn$
  - Neutral: $\phi_{NC}$; $d(\nu_e,\nu_e')pn$
  - Electron scatter: $\phi_{ES}$; $e^-(\nu_\mu,\nu_\tau)e^-$

- 1000 tons D$_2$O
- 12 m diameter acrylic vessel
- 1700 tons Inner Shield H$_2$O
- 9500 PMTs, 90% coverage
- 6000 mwe overburden

- Detecting free neutrons poses severe background from trace levels of U, and Th. Trace impurities can be in the D$_2$O, the acrylic vessel, H$_2$O outside the vessel, in the rock, etc.

- The was the first solar neutrino experiment to need clean rooms, low radioactivity materials, assay methods, precision cleaning, and more to avoid background due to natural radioactivity in the detector and environment.
The Background Challenge for SNO
Detecting neutrons produced in neutral current reaction.

• No directionality to suppress background- need very low neutron background.
• Employed three redundant methods to detect neutrons to check consistency.
  1. Detect neutron by capture on deuteron in the water (Nov 1999 – May 2001)
     • \( n + d \rightarrow ^3\text{He} + \gamma \)
       \[ \sigma = 0.5 \text{ mb}; \ E_\gamma = 6.25 \text{ MeV} \]
       Cerenkov radiation from Compton scattered electrons, or e+,e- pairs.
  2. Detect neutron capture on \(^{35}\text{Cl}\) after adding 2 ton high purity NaCl (2001-2003)
     • \(^{35}\text{Cl} + n \rightarrow ^{36}\text{Cl} + \gamma\)'s.
     • \( \sigma = 44 \text{ b}; \ E_\gamma = 8.6 \text{ MeV} \)
     • Compton scattered electron Cerenkov radiation
  3. Detect neutrons with an array of ultralow background detector modules filled with \(^3\text{He}\) gas.
     • \( n^+ ^3\text{He} \rightarrow ^3\text{H} + p \)
     • \( \sigma = 5333 \text{ b}; \ Q = + 764 \text{ keV} \)
     • Measure ionization signal is each gas proportional counter.
Neutron backgrounds

- Neutrons produced by $\gamma$-ray photo-disintegration of deuterons.
  - Gamma rays from $^{238}\text{U}$ and $^{232}\text{Th}$
  - $^{214}\text{Bi}$ 2447 keV, $^{232}\text{Th}$ 2615 keV.
- Requirements for U and Th in D$_2$O.
  - $[\text{U}] < 3.0 \times 10^{-14}$ gU/g
  - $[\text{Th}] < 3.5 \times 10^{-15}$ gTh/g
- Measured U and Th in water after major purification effort.
  - $[\text{U}] = 1.8 \times 10^{-14}$ gU/g
  - $[\text{Th}] = 1.6 \times 10^{-15}$ gTh/g
- U and Th at ppt trace levels in the acrylic vessel that contains the heavy water was another critical challenge.

Phase 2 experimental results

$$\phi_{\text{CC}} = 1.68^{+0.06}_{-0.06} \pm 0.08 \text{ (stat.)}^{+0.09}_{-0.09} \text{ (syst.)},$$
$$\phi_{\text{ES}} = 2.35^{+0.22}_{-0.22} \pm 0.15 \text{ (stat.)}^{+0.15}_{-0.15} \text{ (syst.)},$$
$$\phi_{\text{NC}} = 4.94^{+0.21}_{-0.21} \pm 0.38 \text{ (stat.)}^{+0.38}_{-0.38} \text{ (syst.)},$$
$$\frac{\phi_{\text{CC}}}{\phi_{\text{NC}}} = 0.340^{+0.023}_{-0.023} \pm 0.029 \text{ (stat.)}^{+0.031}_{-0.031} \text{ (syst.)}.$$
Neutrino Oscillations Discovered
Super K and SNO
2015 Nobel Prize in Physics

Too few upward $\nu_\mu$'s observed.
Oscillatory in L/E observed

Atmospheric Neutrinos

Takaaki Kajita - Super K. & Art McDonald - SNO
Nobel Prize Physics 2015 - Neutrino Oscillations

$\phi_{CC}/\phi_{NC} = 0.301 +/- 0.033$

Solar Neutrinos
The Borexino Detector
(All zones are active detectors with PMT read-out)

• Shielding Against External Background
  • Water: 2.25m
  • Buffer zones: 2.50 m
  • Outer scintillator zone: 1.25 m

• Self-shielding within Liquid Scintillator
  • Inner vessel scintillator: 300 ton
  • Fiducial volume: 100 ton
  • Scintillator shielding: 200 ton

• Thin radio-pure nylon vessels
  • Film extruded from special radio-pure pellets.
  • Vessels fabricated in first low-radon cleanroom.
  • Small $\gamma$-background from nylon vessel
    • Due to low-mass, radio-pure nylon, and clean surface

• Main background in fiducial volume:
  • Radioactivity in liquid scintillator
  • Reduced by purification systems.

• Scintillator internal radioactivity background:
  • Powerful on-line precision cleaned purification systems produce ultra-low levels of U, Th, K in scintillator.
  • $^{14}$C is $10^7$ times lower than modern biogenic carbon.
  • Radon daughters $^{210}$Pb-$^{210}$Bi-$^{210}$Po are problem for CNO
Solar Neutrino Spectra

Neutrino Energy Spectrum

Neutrino-Electron Elastic Scattering Energy Spectrum

- Total spectrum: $\nu(B) = 0.46$ cpd/100 tons
- $\nu(\beta\beta) = 47.6$ cpd/100 tons
- $\nu(CNO) = 5.36$ cpd/100 tons
- $\nu(\text{pep}) = 2.8$ cpd/100 tons
- $\nu(\text{pp}) = 133$ cpd/100 tons
Low Backgrounds for Direct Detection of Solar Neutrinos in Borexino

• Counting Test Facility: 1992-1995
  • Demonstrated very low $^{14}$C in Liquid Scintillator.
  • Low background vessel and scintillator purification system methods developed.

• Borexino construction 1996-2002
  • Delay: 2002-2005

• Phase 1 Data: 2007-2010
  • First direct detection of solar neutrinos
  • $^7$Be, pep, $^8$B neutrinos measured.

• Inner Vessel Leak 2008
  • Scintillator fluids operations carried out to reduce leak rate in scintillator vessel.
  • Reduce DMP concentration in buffer zones to balance densities of buffers with scintillator.
  • Fluid operations contaminated scintillator purification system that later impacted scintillator re-purification.

• Scintillator re-purification: 2010-2011
  • Backgrounds lowered:
  • $[U], [Th]: 10^{-18}$g/g $\rightarrow \sim10^{-19}$g/g
  • $^{85}$Kr, $^{210}$Bi reduced.

• Phase 2 Solar Neutrino Data: 2011-2016
  • First direct measurement of pp neutrinos, 2014
  • New results for pp, pep, $^7$Be. TAUP 2017.
  • $^8$B result to be released soon.

• Detector & Purification Upgrades: 2014-2016
  • Water extraction system upgraded to improve removal of $^{210}$Pb/$^{210}$Bi/$^{210}$Po
  • Temperature stabilization improved with thermal insulation on Water Tank to prevent convection currents that move $^{210}$Po on IV surface into FV.

• Phase 3 Solar Neutrinos: > 2017
  • Second scintillator re-purification.
  • CNO neutrinos?
Spectrum Taken in First 6 weeks of Data-2007

Clear $^7$Be $\nu$ signal, but mysterious rates for $^{210}$Pb(22y)-$^{210}$Bi(5d)-$^{210}$Po(138d)

July 24-28 2017

TAUP 2017: Topics in Astroparticle and Underground Physics
Sudbury, ON, Canada
Phase I Energy Spectra

Data based on 740.7 live days May 16, 2007 to May 8, 2010.

• **Clear $^7$Be signal**
  • Box-like spectrum shape easily fit for measurement of $^7$Be solar neutrinos with accuracy of 5%.

• **Prominent backgrounds:**
  • $^{210}$Po, $^{210}$Bi, $^{85}$Kr, $^{11}$C, & $^{14}$C (not shown)
  • $^{210}$Bi ($^{210}$Pb) increased to ~40 cpd/100t
    • Scintillator operations to reduce leak in Scintillator Vessel increased $^{210}$Po and $^{210}$Pb.
  • $^{210}$Po increased, then decayed to ~650 cpd/100t.
    • Separated by $\alpha/\beta$ pulse shape discrimination.

• **pep and CNO obscured by $^{210}$Bi**
  • Box spectrum and cuts to reduce the $^{11}$C. (muon track, neutron, other) yielded pep measurement.
  • CNO more difficult- still underway.
Borexino Phase I Solar Neutrinos
Milestone in Low Background Counting

✓ $^7\text{Be}$ 46.0 cpd/100t ± 5% PRL 2011
✓ $^8\text{B}$ (> 3 MeV) 0.22 cpd/100t ± 19% PRD 2010
✓ pep 3.1 cpd/100t ± 22% PRL 2012

Direct Measurement of Neutrinos in pp-chain

✓ CNO limit: < 7.9 cpd/100t PRL 2012
CNO expected: 3, 5 cpd/100t LM, HM.
Background Reduction by Scintillator Purification for Phase 2

- Scintillator re-purification was carried out from July 13, 2010 to August 11, 2011.
- Six cycles of “water extraction” and “nitrogen tripping” were used to remove non-volatile and volatile radioactive impurities.
  - Each cycle purified the full 300 m$^3$ of scintillator in a “loop” flow mode.
- Scintillator purification was successful in lowering backgrounds, and set the stage for acquiring Phase 2 data reported here at TAUP 2017.
- The $^{210}$Po was not satisfactory. Plant contamination to reduce DMP in buffers to reduce vessel leak, followed by inadequate cleaning, is suspected as a major cause.
- More recent studies revealed that $^{210}$Pb, and especially $^{210}$Po, are not removed efficiently from ground water by standard water purification systems.
  - New facilities to produce ultrapure water by fractional distillation have since been installed.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Initial impurity</th>
<th>Final impurity</th>
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<tbody>
<tr>
<td>$^{85}$Kr</td>
<td>30 cpd/100t</td>
<td>&lt;5 cpd/100t</td>
</tr>
<tr>
<td></td>
<td>Reduced: &gt;6</td>
<td></td>
</tr>
<tr>
<td>$^{238}$U ($^{226}$Ra) $^{214}$Bi - $^{214}$Po</td>
<td>$5.3 \times 10^{-18}$ gU/g Reduced: &gt;77</td>
<td>$&lt;8 \times 10^{-20}$ gU/g $&lt;0.8$ c/100t/y</td>
</tr>
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<td>$^{238}$U ($^{226}$Ra) $^{214}$Bi - $^{214}$Po</td>
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</tr>
<tr>
<td>$^{232}$Th $^{212}$Bi - $^{212}$Po</td>
<td>$3.8(8) \times 10^{-18}$ gTh/g Reduced: &gt;3</td>
<td>$&lt;1 \times 10^{-18}$ gTh/g $&lt;0.8$ c/100t/y</td>
</tr>
<tr>
<td>$^{210}$Bi</td>
<td>70 cpd/100t Reduced: x4</td>
<td>17.5 cpd/100t</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>Increased in first 2 cycles 20 → 45 cpd/t</td>
<td>Decreased during Cycles 4-6 return to ~20 cpd/t and decaying.</td>
</tr>
</tbody>
</table>
# Borexino Phase 1, 2
## Solar Neutrino Measurements

<table>
<thead>
<tr>
<th>Neutrino</th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>Not done.</td>
<td>134±9.6%, 144±16% (2014)</td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>46.0 ± 5% (ground state branch)</td>
<td>48.3 ± 2.7%</td>
</tr>
<tr>
<td>pep</td>
<td>3.1 ± 22 %</td>
<td>2.5 ± 18%</td>
</tr>
<tr>
<td>$^8\text{B}$</td>
<td>0.22 ± 19%</td>
<td>Not available yet.</td>
</tr>
</tbody>
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Presented by G. Testera, this session, TAUP 2017

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**Phase 1**

**Phase 2**

![Graph](image1.png)

![Graph](image2.png)
Preparing for Borexino Phase 3
Solar Metallicity and CNO Neutrinos

Strategy for CNO Neutrinos

• The expected CNO rate is 3 to 5 cpd/100t for low and high metallicity, respectively. Measuring CNO can help determine metallicity.

• Thr CNO rate is about the same rate and energy range as pep neutrinos, which was measured to 18%.

• The difficulty is the spectrum shape:
  • Box-like and distinctive for pep - easy
  • Continuous and undistinctive for CNO - hard

• Overcoming this difficulty:
  • Achieve secular equilibrium in $^{210}\text{Pb}$ decay chain in FV
    • Measure $^{210}\text{Po}$ alpha decay with PSD as substitute for $^{210}\text{Bi}$.
  • Reduce the $^{210}\text{Bi}$ ($^{210}\text{Pb}$) rate.
    • The purification system was recently upgraded for this.

Decay chain of $^{210}\text{Pb}$-$^{210}\text{Bi}$-$^{210}\text{Pb}$

• If isolated, the A=210 nuclei in the FV of the scintillator will be in secular equilibrium after a time long compared to the 138-d half life of $^{210}\text{Po}$.

• However, $^{210}\text{Po}$ from decay of $^{210}\text{Pb}$ on the scintillator vessel can be released and carried into the FV by convection currents driven by temperature changes, spoiling secular equilibrium.

• Thermal insulation of the detector suppresses temperature changes and convection currents.
Thermal Insulation of Water Tank
Reduces Temperature Changes & Convective Currents that Move $^{210}\text{Po}$
Rockwool: 20 cm thickness
$k = 0.03 \text{ W/m/K}$

Before Insulation

During Insulation
Upgrade of Borexino Water Extraction System

Previous and upgraded system with new fractional distillation columns

Previous 2010

New 2016

Replace groundwater with water stored for 5-10 years. 210Po “dead”
Summary

• As the 50-year history of solar neutrino research shows, there has been considerable progress in reducing backgrounds that has enabled measurement of rare events in underground particle astrophysics, especially solar neutrinos.

• It is now becoming common to have cleanrooms with low-radon air, sensitive assay equipment to measure trace levels of radioactivity in detector parts, and computer software to simulate backgrounds in complicated detectors.

• Future experiments in underground particle astrophysics will continue to improve low-background methods, possibly moving fabrication to underground sites to avoid cosmic ray activation of sensitive parts.

• The field is vibrant with important science and fun challenges ahead.
The End
The CNO Cycle

Lights up most of the stars we see at night, but only 1% of Sun's energy.

The CNO neutrino flux depends on $^{12}\text{C}$ abundance.
Rate depends on “metallicity”, abundance of elements heavier than $^4\text{He}$.