Solar Neutrinos with Borexino
Low Background Lessons for the JinPing Laboratory

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Solar Neutrinos with Borexino

First experiment to directly detect solar neutrinos below the 3 MeV background wall.

A breakthrough made possible by “brute force” low-background methods.

• On-going research toward measurements of pp and CNO neutrinos
Solar Nuclear Fusion Cycles

The pp cycle

\[
p + p \rightarrow ^2\text{H} + e^+ + \nu_e\quad \text{(99.76\%)}
\]

\[
p + e^- + p \rightarrow ^2\text{H} - \nu_e\quad \text{(0.24\%)}
\]

\[
^2\text{H} + p \rightarrow ^3\text{He} + \gamma
\]

\[
^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p
\]

\[
^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e
\]

\[
^7\text{Li} + p \rightarrow ^2\text{He}
\]

\[
^7\text{Be} + p \rightarrow ^8\text{B} + \gamma
\]

\[
^8\text{B} \rightarrow ^8\text{Be}^+ + e^- + \nu_e
\]

The CNO cycle

\[
^{13}\text{C} \rightarrow (p,\gamma) \rightarrow ^{14}\text{N} \rightarrow (p,\alpha) \rightarrow ^{17}\text{O}
\]

\[
^{13}\text{N} \rightarrow \beta^+ <1.2\text{ MeV} \rightarrow ^{14}\text{O}
\]

\[
^{14}\text{O} \rightarrow (p,\gamma) <1.7\text{ MeV} \rightarrow ^{15}\text{F}
\]

\[
^{14}\text{N} \rightarrow (p,\gamma) <1.7\text{ MeV} \rightarrow ^{15}\text{O}
\]

\[
^{15}\text{O} \rightarrow \beta^+ <1.7\text{ MeV} \rightarrow ^{16}\text{O}
\]

\[
^{15}\text{O} \rightarrow (p,\gamma) \rightarrow ^{16}\text{O}
\]

4/10/2014
Solar Neutrinos at Jin Ping
Neutrino Detection

Neutrino-electron elastic scattering

\[ \nu + e^- \rightarrow \nu + e^- \]

- Contributions from charged and neutral currents.
- Measure energy of recoil electron by number of detected scintillation photons.
  - With 500 \( p_e/\text{MeV} \), energy resolution is about 5% at 1 MeV.
- Position of event is measured by photon time-of-flight.
  - Position resolution is 10-15 cm.
- Threshold energy is about 60 keV (due to \(^{14}\text{C} \) background).
- Calorimetric measurements - no directional sensitivity.
Solar Neutrino Spectra

Neutrino Energy Spectrum

Neutrino-Electron Elastic Scattering Energy Spectrum

\[ \text{Events} / (\text{day} \times 100 \text{ tons} \times 10 \text{ p.e.}) \]

- Total spectrum
- \( \nu(\beta) = 0.46 \text{ cpd}/100 \text{ tons} \)
- \( \nu(^7\text{Be})_{\beta\text{es}} = 47.6 \text{ cpd}/100 \text{ tons} \)
- \( \nu(\text{CNO}) = 5.36 \text{ cpd}/100 \text{ tons} \)
- \( \nu(\text{pep}) = 2.8 \text{ cpd}/100 \text{ tons} \)
- \( \nu(\text{pp}) = 133 \text{ cpd}/100 \text{ tons} \)

X2 for keV
# Borexino Results 2007-2012

## Solar Neutrinos

<table>
<thead>
<tr>
<th>Source</th>
<th>Date</th>
<th>Reaction</th>
<th>Rate</th>
<th>±</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ 7Be</td>
<td>2011</td>
<td>46.0 cpd/100t</td>
<td>± 5%</td>
<td>PRL</td>
<td></td>
</tr>
<tr>
<td>✓ 8B (&gt; 3 MeV)</td>
<td>2010</td>
<td>0.22 cpd/100t</td>
<td>± 19%</td>
<td>PRD</td>
<td></td>
</tr>
<tr>
<td>✓ Pep</td>
<td>2012</td>
<td>3.1 cpd/100t</td>
<td>± 22%</td>
<td>PRL</td>
<td></td>
</tr>
<tr>
<td>✓ CNO limit</td>
<td>2012</td>
<td>&lt; 7.9 cpd/100t</td>
<td>PRL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>✓ 7Be day/night asy.</td>
<td>2012</td>
<td>A = 0.001 ± 0.014</td>
<td>PLB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>✓ 7Be annual modulation</td>
<td>2012</td>
<td>PLB</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Geo-neutrinos

<table>
<thead>
<tr>
<th>Source</th>
<th>Date</th>
<th>Rate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Geo-neutrinos</td>
<td>2013</td>
<td>14.3 ± 3.4 eV/(613 t-yr)</td>
<td>PLB</td>
</tr>
</tbody>
</table>

## Rare Processes

<table>
<thead>
<tr>
<th>Source</th>
<th>Date</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Test of Pauli Exclusion Principle in Nuclei</td>
<td>2010</td>
<td>PRC</td>
<td></td>
</tr>
<tr>
<td>✓ Solar axion upper limit</td>
<td>2012</td>
<td>PRD</td>
<td></td>
</tr>
</tbody>
</table>
MSW theory of neutrino oscillations in the Sun predicts a transition in survival probability of $\nu_e$ from vacuum oscillations below 2 MeV to matter effect oscillation at higher energy.

The effect has been observed.

Reducing the uncertainty in pep neutrino rate will improve the confirmation of this MSW feature, and tighten constraints on non-standard interactions.
Solar $\nu$'s as Probes of Neutrino-Matter Interactions
Non-standard Interactions

Friendland, Lunardini, Pena-Garay 2004

Friedland and Shoemaker 2012
Data are based on 740.7 live days between May 16, 2007 and May 8, 2010.

Prominent backgrounds are:

- $^{210}$Po, $^{210}$Bi, $^{85}$Kr, $^{11}$C & $^{14}$C (not shown)

CNO obscured mainly by $^{210}$Bi due to similar shape.

The $^{210}$Po alpha rate was high, but rejected by alpha/beta pulse shape discrimination.

The pep was measured by applying cuts to reduce the $^{11}$C. (muon track, neutron, other)
Overview of the Borexino Detector
(Mostly Active Shielding)

- Shielding Against Ext. Backgnd.
  - Water: 2.25 m
  - Buffer zones: 2.5 m
  - Outer scintillator zone: 1.25 m
  - $^{14}\text{C}/^{12}\text{C}$
    - $10^{-18}\text{ g/g}$, cf. $10^{-11}\text{ g/g}$ in air CO$_2$
  - U, Th impurities
  - Cosmogenic $^{11}\text{C}$ ($t_{1/2} = 20\text{ min}$)
  - $^{222}\text{Rn}$ daught ($^{210}\text{Pb}$, $^{210}\text{Bi}$, $^{210}\text{Po}$)
  - $^{85}\text{Kr}$ (air leak)
- Light yield (2200 PMT’s)
  - Detected: $500\text{ p}_e/\text{MeV} (\sim 5\%)$
- Pulse shape discrimination.
  - Alpha-beta separation
Borexino External $\gamma$-Background

External Gamma Ray Sources

External Gamma Ray Attenuation

4/10/2014 Solar Neutrinos at Jin Ping
Main Low-Background Features of Borexino

• Water and Scintillator Shielding (Collaboration)
  – Purified for ultra-low internal radioactivity.

• Scintillator Containment Vessel (Princeton)
  – Nylon balloon with small mass and low radioactivity
  – Built in low-radon cleanroom to avoid $^{210}\text{Pb}$ (22 yr)

• Scintillator Purification System (Princeton)
  – Pseudocumene (PC) & 1.5 g/l PPO
  – Distillation, water extraction, and $\text{N}_2$ gas stripping.
Nylon Scintillator Containment Vessel
Fabricated in special Princeton Low-Radon Cleanroom

First hermetically sealed cleanroom with low-radon air was developed to avoid surface radioactivity due to $^{222}\text{Rn}$ daughters:
$\Rightarrow ^{210}\text{Pb}$ (22 yr).

Fabrication time: > 1 yr
Low-radon cleanrooms are now more common in low-background research.
Low Background Nylon Vessel

• A leak in Nylon Vessel started a few months after initial filling.
  – Cause may have been buoyant force due to sudden temperature change
  – Adjusting density of buffer to match density of scintillator reduced leak.

• Continued operation showed very low $^{222}$Rn emanating from nylon vessel.
  – Total rate of $^{214}$Bi-$^{214}$Po rate is less than 10 cpd, consistent with earlier measurements of emanation from nylon.
  – No significant source of surface particulate radioactivity.

• $^{210}$Pb still being determined from $^{210}$Po.
  – It could be about x100 bigger than 210Pb
  – No evidence (yet) for leaching of $^{210}$Pb into scintillator.

Distribution of $^{214}$Bi-$^{214}$Po events near Nylon Vessel: ~ 2 month counting time.
Total rate is excellent: ~ 5 cpd.
Pseudocumene Purification During Filling Operations.
Distillation, Stripping, Water Extraction Columns
“Precision cleaned”, then assembled in low-Rn cleanroom

Radio-pure (LAK) nitrogen (Heidelberg)

Assembly of distillation & stripping columns
In Princeton Low-Radon Cleanroom.
Energy spectrum with backgrounds

\[ 11^C \]

\[ 210^{Po} \]

\[ 210^{Bi} \]

\[ 85^{Kr} \]

\[ \text{CNO} \]
CNO with Borexino?

- **CNO rate (cpd/100t):**
  - High metallicity: 4.5
  - Low metallicity: 3.0

- **Backgrounds (cpd/100t)**
  - $^{11}$C (from muons): 28.9 -> 0.3 SNO JInPing?
  - $^{210}$Bi (from $^{210}$Pb): 41 -> 20 -> 1?
  - External gammas: 4.5 (fit to spectrum)

- **Yes, but**
  - Deeper is better to reduce $^{11}$C
  - Lower external background is desirable
    - More shielding + lower radioactivity PMTs
Re-Purification of the Liquid Scintillator Toward “Very Low” Background

• Lower Backgrounds for pp and CNO neutrinos.
  – $^{210}\text{Bi}$ obscures CNO and pep neutrinos.
  – $^{85}\text{Kr}$ interferes with $^7\text{Be}$ neutrinos

• Purification of scintillator by “water extraction” and “nitrogen stripping” was carried out 2010-2011.
  – Backgrounds reduced significantly; enabled pp neutrino data
  – More reduction still needed for CNO neutrinos.
Background Reduction with Loop Purification of Liquid Scintillator

• “Loop” purification is achieved by draining fluid from bottom of vessel, passing it through purification system, and returning to the top.

• Processes available are:
  – Water extraction or distillation
  – Nitrogen stripping ($^{85}$Kr)
Water Extraction and Nitrogen Stripping Performed 2010-2011

- Contacting high purity water with scintillator can remove radioactive impurities from the scintillator.
  - Works best if impurities have higher affinity for water, e.g., polar species, but can also be effective if not.

- For water extraction, we use LNGS ground water purified by the following:
  - Reverse osmosis and Ion-exchange (de-ionization water plant)
  - Single stage evaporator distillation.

- Ground water has high levels of radioactivity.
  - ICPMS studies show that $^{238}$U, $^{232}$Th, $^{40}$K are removed effectively by de-ionization.
  - $^{222}$Rn is high (10,000 Bq/ton), but can removed by de-gasification with N$_2$.
  - Radon daughters $^{210}$Pb, $^{210}$Bi, and $^{210}$Po studied recently (see below).

The water extraction system.
N$_2$ stripping column used in series
Results of 6 cycles of Re-purification

- $^{85}$Kr: $30\text{ cpd/100t} \rightarrow < 5\text{ cpd/100t}$
- $^{238}$U ($^{226}$Ra): $[(530 \pm 50) \rightarrow < 8 \times 10^{-20}\text{ gU/g]}$ Reduction factor $> 77$ ($< 0.8\text{ count/100t/yr}$).
- $^{232}$Th: $[(3.8 \pm 0.8 \rightarrow < 1.0] \times 10^{-18}\text{ gTh/g]}$ Reduction factor $> 3.$ ($< 0.8\text{ count./100t/yr}$)
- $^{210}$Bi: $70\text{ cpd/100t} \rightarrow 20 \pm 5\text{ cpd/100t}$
- $^{210}$Po: Essentially not reduced!! WHY???

Backgrounds before & after Water Extraction + N$_2$ Stripping

Before re-purification 2008-2010
Rates in parentheses are in cpd/100t.
Without $^{11}$C cuts. See arXiv1308.0443v1.

After re-purification 2012-2013
(with $^{11}$C cuts)
Radon in air deposits $^{210}$Pb (22 yr) on nylon foil, which later contaminates scintillator with $^{210}$Bi (1 MeV $\beta$) and $^{210}$Po (5 MeV $\alpha$).
Spectacular Results for U and Th.

• The low levels of U and Th (< 1 c/y/100ton) are the lowest levels ever achieved in a counting experiment.

• Results show promise for accurate pep neutrino measurement with future deeper detectors, free of cosmogenic $^{11}$C.

• Also promising is use of liquid scintillators for neutrino-less double beta decay: Kamland-Zen & SNO+.
  
  – Background from 2448 keV $^{214}$Bi and 2614 keV $^{208}$Tl gamma rays could be absent for multi-ton detectors.
Improving Water Extraction for a Lower Background.

• Discovered radon daughter radioactivity in water “purified” by de-ionization.
  – $^{210}\text{Pb}$ moderately reduced; $^{210}\text{Po}$ poorly reduced.
• Discovered volatile compound of $^{210}\text{Po}$ difficult to separate by distillation.
  – Dimethyl polonium- boiling point 138 C.
  – Produced by micro-organisms in groundwater
• Constructed and tested fractional distillation system that removes $^{210}\text{Po}$ and $^{210}\text{Pb}$ effectively.
Brooke Russell ‘11 found papers on volatile Po & directed team of rising seniors and technical specialist Allan to develop and test a new distillation system that worked beautifully to remove $^{210}$Po.

For a Professor it doesn’t get better than that!
Moving toward the Ultimate Background for CNO

• Reduce $^{210}\text{Pb}$ and $^{210}\text{Po}$ radioactivity in water used for water extraction.
  – Fractional distillation system was designed and tested for removing $^{210}\text{Po}$ from well water.

• Upgrade existing water extraction system to accommodate fractional distillation.
  – Two new columns will be added to existing evaporators.
Borexino Water Extraction Systems
Current & Proposed Upgrade with 2 Fractional Distillation Columns

Current System

Proposed System
Neutrinos from the pp cycle
Most measured- a pp neutrino measurement is coming from new Borexino data.

Neutrinos from the CNO cycle
Measurement of CNO neutrinos seem possible with lower background. We’re going for it, but a deeper detector to suppress $^{11}\text{C}$ is better. SNO+?

Future opportunities to study the Sun.
The low-backgrounds achieved by Borexino show what is possible in future solar neutrino research.
Conclusions

• Borexino achieved internal scintillator and external backgrounds low enough to measure $^7$Be, pep, $^8$B solar neutrinos by ($\nu$,e) elastic scattering.

• Reduction of scintillator background has been demonstrated that should allow first measurements of pp and CNO neutrinos.

• A deeper, larger detector will enable more accurate solar neutrino measurements, especially for CNO neutrinos that will address metallicity.
Internal Background Estimation

Borexino like design

- ~30cm steel shielding
  Ignore external gammas
- 12m steel sphere
- Low radioactivity steel
  ~1mBq/kg U, Th, K
  ~10mBq/kg Co
- Low radioactivity PMTs
  ~1mBq/PMT U, Th, Co
  ~10mBq/PMT K
  ~50% PMT coverage
- ~1m buffer liquid
Internal Background Estimation

Radius distribution of residual gamma background from detector components

CNO neutrino
250-1500 keV
~5cpd/100ton
may be up to 150 ton

8B neutrino
1600-3200 keV
~0.2cpd/100ton
maybe up to 50 ton