Understanding the Sun with neutrinos: results from the Borexino experiment

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Outline

Motivation:
solar neutrinos
neutrino oscillations

Borexino:
the detector
signal and background

Solar neutrino results:
7Be
8B
pep and CNO
Future plans

Conclusion
The Sun

energy production by nuclear fusion
(hydrogen burning)

$$4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e + 26.7\text{ MeV}$$

predict solar neutrino flux from solar luminosity:

1370 W/m^2 (at earth) => 6.5 x 10^{10} \nu/cm^2 s

light (photons) takes 10^5-10^6 years from core to surface

neutrinos escape from the core
real-time information from the solar core
(~ 8 minutes delay)
Nuclear reactions in the solar core

**pp cycle**

\[ p + p \rightarrow ^2\text{H} + e^+ + \nu_e \]

99.77%  

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

84.7%  

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

\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]

13.8%  

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

13.78%  

\[ ^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He} \]

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

0.02%  

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

\[ ^8\text{B} \rightarrow ^4\text{He} + ^4\text{He} \]

\[ ^{12}\text{C} + ^1\text{H} \rightarrow ^{13}\text{N} + \gamma \]

13C + e^+ → ν

\[ ^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ → \nu \]

\[ ^{14}\text{N} + ^1\text{H} \rightarrow ^{15}\text{O} + \gamma \]

\[ ^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ → \nu \]

\[ ^{15}\text{N} + ^1\text{H} \rightarrow ^{12}\text{C} + ^4\text{He} \]

\[ ^{16}\text{O} + ^1\text{H} \rightarrow ^{17}\text{F} + \gamma \]

\[ ^{17}\text{F} \rightarrow ^{17}\text{O} + e^+ → \nu \]

\[ ^{17}\text{O} + ^1\text{H} \rightarrow ^{14}\text{N} + ^4\text{He} \]

**CNO cycle**

<1% of energy  

poorly known  

not directly measured yet
The **Standard Solar Model**

The SSM is the theoretical framework which is used to make predictions on the solar neutrino fluxes.

[Serenelli et al. 2011](#)
The **Standard Solar Model**

The SSM is the theoretical framework which is used to make predictions on the solar neutrino fluxes.

Recent improvements in the SSM ( >2004):

- new determination of $^{14}\text{N}(p,\gamma)^{15}\text{O}$ cross section reduced CNO fluxes by a factor $\sim 2$
- a factor of 2 better accuracy for $^{3}\text{He}^{(4}\text{He},\gamma)^{7}\text{Be}$ cross section
- new opacities calculations
- more accurate solar surface abundancies
- improved 3D models

$\Rightarrow$ suggest lower metalliclicity Z
# Prediction of Solar Neutrino Fluxes

<table>
<thead>
<tr>
<th>Source</th>
<th>Neutrino Flux [cm$^{-2}$s$^{-1}$]</th>
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<th>Difference [%]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>SSM-GS98</td>
<td>SSM-AGS09</td>
<td></td>
</tr>
<tr>
<td>pp</td>
<td>$5.98(1\pm0.006)\times10^{10}$</td>
<td>$6.03(1\pm0.006)\times10^{10}$</td>
<td>0.8</td>
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<td>pep</td>
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<td>CNO total</td>
<td>$5.24 \times 10^{8}$</td>
<td>$3.76 \times 10^{8}$</td>
<td>28.3</td>
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**But:** low Z models are in conflict with helioseismology ($R_{CZ}, Y_{surf}$)

Can solar neutrino measurements decide?
The Solar neutrino problem

Objective of the first solar neutrino experiment:
“...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.”
(Bahcall, PRL 12, 300, 1964)

<table>
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<th>Experiment</th>
<th>Data/ SSM</th>
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<tr>
<td>Homestake $(\nu_e^{37} \text{Cl} \to ^{37} \text{Ar} + e)$</td>
<td>$0.34 \pm 0.03$</td>
</tr>
<tr>
<td>Sage + Gallex $(\nu_e^{71} \text{Ga} \to ^{71} \text{Ge} + e)$</td>
<td>$0.56 \pm 0.04$</td>
</tr>
<tr>
<td>Superkamiokande $(\nu_x + e \to \nu_x + e)$</td>
<td>$0.46 \pm 0.02$</td>
</tr>
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finally solved by the SNO experiment:

CC: $\nu_e + d \to p + p + e^-$
NC: $\nu_x + d \to p + n + \nu_x$

$$\frac{\phi_{\text{NC}}^{\text{SNO}}}{\phi_{\text{SSM}}} = 1.01 \pm 0.12$$

solar neutrino flux is compatible with SSM

neutrinos undergo flavor conversion: neutrino oscillations
Solar neutrino oscillations are well approximated by 2-flavor mixing:
\[
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix} = \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix} \begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

Only $\nu_e$ are produced in solar fusion and detected by (most) experiments. In vacuum, the survival probability is
\[
P_{ee} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)
\]

Due to the large distance and loss of coherence, $P_{ee}$ takes an average of
\[
P_{ee} = 1 - \frac{1}{2} \sin^2 2\theta \approx 0.6
\]
Solar Neutrino Oscillations in Matter

Matter is made of $e^-$ (no $\mu$, $\tau$)
- coherent $\nu$-$e^-$ scattering affects oscillations
- $\nu_e$ interactions different from $\nu_{\mu\tau}$
- “effective potential” for $\nu_e$ different from $\nu_{\mu\tau}$
  (Wolfenstein, '78)

Resonance effect  (Mikheyev & Smirnov, 1985)
- adiabatic conversion in matter with slowly varying density

MSW Effect in the Sun:
- Low energy neutrinos (pp $\nu$) $\rightarrow$ oscillations as in vacuum
  \[ P_{ee} \approx 1 - \frac{1}{2} \sin^2 2\theta \approx 0.6 \]
- High energy neutrinos ($^8$B $\nu$) $\rightarrow$ matter enhanced
  oscillations
  \[ P_{ee} \approx \sin^2 \theta \approx 0.3 \]
- Transition region between 1-4MeV
The MSW – LMA oscillation scenario

Large Mixing Angle

Global analysis of solar neutrino data + KamLAND:
\[ \Delta m_{21}^2 = 7.6 \cdot 10^{-5} \text{ eV}^2 \]
\[ \theta_{12} = (34 \pm 3)^\circ \]

Oscillations in vacuum probability averages over long distances, \( P_{ee} \approx 0.6 \)

Matter-enhanced oscillations interaction with solar matter increases osc. probability, \( P_{ee} \approx 0.3 \)

Schwetz et al. 1103.0734
Solar Neutrinos: what next?

- real-time spectroscopy of low energy neutrinos: $^7$Be, pep, CNO, pp
  (99% of solar neutrino flux is < 1 MeV)

![Solar Neutrino Spectra](image)

Cerenkov-experiments (SNO, SuperK)
< $10^{-4}$ of the total solar neutrino flux
Solar Neutrinos: what next?

- real-time spectroscopy of low energy neutrinos: $^7$Be, pep, CNO, pp (99% of solar neutrino flux is < 1 MeV)

- neutrino physics:
  - test transition region MSW to vacuum oscillations (1 – 4 MeV)
  - precision measurement $\theta_{12}, \Delta m_{21}^2$
  - Non-Standard Interactions

- solar physics:
  - high Z/ low Z SSM
  - test luminosity constraint $L_\nu = L_\odot$
  - determination of CNO: important for heavy stars
The Borexino Detector

**Target:** 300t PC + PPO (1.5 g/l) in 8.5m Ø nylon vessel (0.1 mm)

**Fiducial volume:** 100t (6 m Ø)

**Buffer:** 900t PC + DMP (5g/l) in 13.7m Ø stainless steel sphere

**Rn diffusion barrier** (11m Ø)

**2200 8” PMTs** (1800 with concentrators)

**Muon veto:** 208 8” PMTs
2200 t H₂O in steel tank 18m Ø
taking data since May 2007
Borexino: detection principle

- elastic scattering on electrons in organic liquid scintillator
  \[ \nu_e \rightarrow W \rightarrow e^- \]

- detection via scintillation light:
  + low energy threshold
  + good energy & position resolution
  but:
  - no direction measurement
  - no distinction of \( \nu \) induced events from other \( \beta \) events

\[ \Rightarrow \text{extreme radiopurity of the scintillator required} \]

shielding, material selection, purification
Radiopurity constraints

No specific signature of neutrino events except recoil energy of scattered e⁻  
=> Background suppression is crucial

Intrinsic contamination of the liquid scintillator:

<table>
<thead>
<tr>
<th>Background</th>
<th>Typical abundance (source)</th>
<th>Goal</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹⁴C/¹²C</td>
<td>10⁻¹² (cosmogenic) g/g</td>
<td>~ 10⁻¹⁸ g/g</td>
<td>~ 2 x 10⁻¹⁸ g/g</td>
</tr>
<tr>
<td>²³⁸U (by ²¹⁴Bi-²¹⁴Po)</td>
<td>2 x 10⁻⁵ (dust) g/g</td>
<td>10⁻¹⁶ g/g</td>
<td>(1.6 ± 0.1) x 10⁻¹⁷ g/g &lt; 9.7 x 10⁻¹⁹ g/g (2012)</td>
</tr>
<tr>
<td>²³²Th (by ²¹²Bi-²¹²Po)</td>
<td>2 x 10⁻⁵ (dust) g/g</td>
<td>10⁻¹⁶ g/g</td>
<td>(5 ± 1) x 10⁻¹⁸ g/g &lt; 2 x 10⁻¹⁸ g/g (2012)</td>
</tr>
<tr>
<td>²¹⁰Po</td>
<td>Surface contamination</td>
<td>~1 c/day/t</td>
<td>2007: 70 c/d/t</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2012: 4 c/d/t</td>
</tr>
<tr>
<td>⁴⁰K</td>
<td>2 x 10⁻⁶ (dust) g/g</td>
<td>~10⁻¹⁸ g/g</td>
<td>&lt; 3 x 10⁻¹⁸ (90%) g/g</td>
</tr>
<tr>
<td>⁸⁵Kr</td>
<td>1 Bq/m³ (air)</td>
<td>~1 c/d/100t</td>
<td>(28 ± 7) c/d/100t &lt; 6 c/d/100t (2012)</td>
</tr>
<tr>
<td>³⁹Ar</td>
<td>17 mBq/m³ (air)</td>
<td>~1 c/d/100t</td>
<td>&lt;&lt; ⁸⁵Kr</td>
</tr>
</tbody>
</table>
Detector Calibration (2009)

Detector response vs position:
- 100 Hz $^{14}$C+$^{222}$Rn in scintillator in ~ 200 positions

Quenching and energy scale:
- Beta: $^{14}$C, $^{222}$Rn in scintillator
- Alpha: $^{222}$Rn in scintillator
- Gamma: $^{139}$Ce, $^{57}$Co, $^{60}$Co, $^{203}$Hg, $^{65}$Zn, $^{40}$K, $^{85}$Sr, $^{54}$Mn
- Neutron: AmBe

Light Yield ~ 500 p.e./MeV

$\sigma(E)/E \approx 4.5\%/\sqrt{E}$

fiducial volume uncertainty: 1.3%

energy scale uncertainty (0-2 MeV): < 1.5 %
Borexino Expected Solar ν Spectrum

Spectrum with irreducible backgrounds:
Data reduction

$^{14}\text{C}$ determines low energy threshold

$^1\text{Be}$ window

$^{210}\text{Po}$

$^{11}\text{C}$

$\alpha$'s subtracted

raw data

muons subtracted

Fid. Volume cut

740 days

$\text{[count/5pe-day-100t]}$

$\text{[Charge]}$

$100 \quad 200 \quad 300 \quad 400 \quad 500 \quad 600 \quad 700 \quad 800 \quad 900 \quad 1000$

$10^{-1} \quad 1 \quad 10 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \quad 10^8$

$1 \text{ MeV}$

$7\text{Be}$ window
A spectral fit is applied including the following signal + all intrinsic background components.

- $^7$Be, $^{85}$Kr, $^{14}$C, $^{11}$C
- $^{210}$Bi (very similar to CNO in this limited energy region)
- pp, pep, $^8$B, and CNO neutrinos fixed at SSM-LMA value

Fit with and without statistical subtraction of $^{210}$Po events, based on $\alpha/\beta$ pulse shape discrimination.

Two independent ways (MC based and analytical) were applied.
Precision measurement of $^7\text{Be}$ neutrino rate

**Systematics**

<table>
<thead>
<tr>
<th>Source</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger efficiency and stability</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Live time</td>
<td>0.04</td>
</tr>
<tr>
<td>Scintillator density</td>
<td>0.05</td>
</tr>
<tr>
<td>Sacrifice of cuts</td>
<td>0.1</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>$^{+0.5}_{-1.3}$</td>
</tr>
<tr>
<td>Fit methods</td>
<td>2.0</td>
</tr>
<tr>
<td>Energy response</td>
<td>2.7</td>
</tr>
<tr>
<td>Total Systematic Error</td>
<td>$^{+3.4}_{-3.6}$</td>
</tr>
</tbody>
</table>

**740 live days**

$^7\text{Be} \quad 46.0 \pm 1.5^{+1.5}_{-1.6} \text{(syst)}$

$^{85}\text{Kr} \quad 31.2 \pm 1.7 \text{(stat)} \pm 4.7 \text{(syst)}$

$^{210}\text{Bi} \quad 41.0 \pm 1.7 \text{(stat)} \pm 2.3 \text{(syst)}$

$^{11}\text{C} \quad 28.5 \pm 0.2 \text{(stat)} \pm 0.7 \text{(syst)}$

combined error: 4.5%

Implications of the $^7$Be measurement

- electron equivalent flux (862 keV line): $(2.78 \pm 0.13) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$
  no oscillation excluded @ $5.0 \sigma$

- assuming MSW-LMA:
  $f_{^7\text{Be}} = \frac{\phi}{\phi_{\text{SSM}}} = 0.97 \pm 0.09$

- including all solar experiments + luminosity constraint:
  $f_{\text{pp}} = 1.013 ^{+0.003}_{-0.010}$  
  $f_{\text{CNO}} < 1.7\%$ (95 \% C.L.)

$P_{\text{ee}} = 0.51 \pm 0.07$ @ 862 keV

no power to resolve low/high metallicity problem
Absence of day-night asymmetry for $^7$Be $\nu$


MSW: a possible regeneration of electron neutrinos in the matter (within the Earth during night): effect depends on the oscillation parameters and on energy.

$$A_{dn} = 2 \frac{R_N - R_D}{R_N + R_D} = \frac{R_{diff}}{\langle R \rangle}$$

$A_{DN} = 0.001 \pm 0.012$ (stat) $\pm 0.007$ (syst)

- in agreement with MSW-LMA;
- LOW region excluded at $>8.5 \sigma$ with solar neutrinos only: for the first time without the use of reactor antineutrinos (KamLAND) and the assumption of CPT symmetry.

Borexino: Night-day spectrum

**solar neutrino data WITHOUT Borexino**

**solar neutrino data WITH Borexino**

$A_{DN}$ excludes @ 99.73% CL
Low threshold measurement of the $^8$B solar $\nu$

Borexino energy spectrum after muon subtraction:
246 live days

2.6 MeV $\gamma$’s from $^{208}$Tl on PMTs and in the buffer

Borexino threshold: 2.8 MeV

Expected (MSW-LMA) count rate due to $^8$B neutrinos above 2.8 MeV:

$0.26 \pm 0.03$ c/d/100 tons

Signal/Background ($>2.8$ MeV):
~ 1/6000

Major background sources:

- Muons
- Gammas from neutron capture
- Radon emanation from the nylon vessel
- Short lived ($t < 2$ s) cosmogenic isotopes
- Long lived ($t > 2$ s) cosmogenic isotopes ($^{10}$C)
- Bulk $^{232}$Th contamination ($^{208}$Tl)
Low threshold measurement of the $^8$B solar $\nu$

$^7$Be and $^8$B flux measured with the same detector

Borexino $^8$B flux above 5 MeV agrees with existing data (SNO, SuperK)

Neutrino oscillation is confirmed at 4.2 $\sigma$
The first pep ν measurement

Expected pep interaction rate: 2-3 cpd/100t

Main background: $^{11}\text{C}$, $^{210}\text{Bi}$, external $\gamma$

$^{210}\text{Bi}$ and CNO: very similar spectral shape

$^{11}\text{C}$ reduction:
- Three Fold Coincidence (muon + neutron + C11)
- Novel pulse shape discrimination: $e^+ / e^-$ discrimination
  

Multivariate analysis:
- fit of the energy spectra
- fit the radial distribution of the events (external $\gamma$ background is not uniform)
- fit the pulse shape parameter

11C reduction: Threefold coincidence (TFC)

\[ \mu + ^{12}C \rightarrow \mu + ^{11}C + n \]
\[ ^{11}C \tau \sim 30 \text{ min} \]
\[ \rightarrow + p \rightarrow d + \gamma \]
\[ \rightarrow ^{11}B + e^+ + \nu_e \]

in Borexino:
\~ 4300 muons/day
\> 250 neutrons /day
\~ 25 11C /day

11C reduction: Threefold coincidence (TFC)

Interaction point and 11C production point

m\(u^on\)

cylindrical cut around muon
+ spherical cut around \(\gamma\)
removes 90% of C11 residual exposure 48.5%

Effect of TFC on the spectrum

![Graph showing the effect of TFC on the spectrum.](attachment://graph.png)
**pep and CNO neutrinos: results**

**pep neutrinos:**
- Rate: $3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{sys}}$ cpd/100 t
- $\Phi_{\text{pep}} = (1.6 \pm 0.3) \times 10^8$ cm$^{-2}$ s$^{-1}$
- No oscillations excluded at 97% C.L.
- Absence of pep solar $\nu$ excluded at 98%

**CNO neutrinos:**
- only limits, strong correlation with $^{210}\text{Bi}$
- CNO limit obtained assuming pep @ SSM
  CNO rate $< 7.1$ cpd/100 t (95% c.l.)
- $\Phi_{\text{CNO}} < 7.7 \times 10^8$ cm$^{-2}$ s$^{-1}$ (95% C.L.)
- the strongest limit to date
- not sufficient to resolve metallicity problem

Physics implication of the Borexino results

MSW-LMA confirmed (7Be, pep and 8B measurement)

LOW excluded (solar only) by day-night-asymmetry
## Predicted vs. measured solar neutrino fluxes

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<tr>
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<th>Flux [cm$^{-2}$s$^{-1}$] SSM-GS98</th>
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**high metallicity**  
**low metallicity**  

metallicity problem cannot be resolved with present data

Goals (solar neutrinos):

• reach $3\sigma$ significance of pep signal (reduce $^{210}$Bi background)
• measure $^7$Be neutrinos to 3% (reduce $^{85}$Kr and $^{210}$Bi backgrounds)
• improve $^8$B measurement with low energy threshold (statistics)
  => test MSW
• improve limit on CNO neutrinos (reduce $^{210}$Bi background!)
  => probe metallicity
• direct detection of pp neutrinos (very challenging, need to improve knowledge on $^{14}$C spectrum and pile-up effects)
**210Bi and 210Po in Borexino**

- **last part of the 238U chain:**
  - 210Pb → 210Bi → 210Po → 206Pb (stable)
  - 210Po not stable
  - not in equilibrium
  - not a surprise: seen in the CTF (prototype)
  - origin not clear (surface contamination of filling tubes?)
  - introduced Po210 with every operation
  - now at ~ 3.5 c/d/t
CNO Neutrino Measurement

Main background: $^{210}$Bi, β-decay

similar spectral shapes


Constraining $^{210}$Bi rate looking at

time evolution of $^{210}$Po decay rate:

$^{210}$Po $R(t=0) = 2000$ cpd/100 t

$M = 100$ ton

$\Delta t = 1$ year
Conclusions

• **Phase 1** of the Borexino experiment **successfully concluded**
  • First detection and 5% measurement of solar $^7\text{Be}$ neutrinos
  • $^8\text{B}$-$\nu$ at low energy (>3 MeV), $^7\text{Be}$-$\nu$ day-night
  • First detection of pep solar neutrinos

• Scintillator purification was successful, and **Phase 2 is starting**
  • rich program on solar neutrino physics:
    – probe MSW through $^8\text{B}$ at low energy, pep and more precise $^7\text{Be}$
    – attempt to detect pp in real time
    – possible interesting upper limit on CNO, probe solar metallicity

• on our wish list: a galactic Supernova
Borexino References

• **Solar neutrino results**
  – \(^{7}\text{Be}\) at 10\% + \(f_{\text{pp}}/f_{\text{CNO}}\): PhysRevLett 101, 091302 (2008)

• **Other physics:**
  – Cosmic muon flux and annual modulation in Borexino, JINST 1205, 015, 2012

• **Search of rare processes**
  – Anti-neutrinos from unknown sources, PLB 696 (2011) 191-196
  – Limits on Pauli forbidden transitions on 12C, PRC 81 (2010) 034317
  – Search for solar axions from \(p(d,3\text{He})a\), PRD 85 (2012) 092003

more interesting results to come
Thank you for the attention!