Precision measurement of the $^7$Be solar neutrino flux and its day/night asymmetry with Borexino

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On behalf of the Borexino collaboration
Solar neutrinos: The Standard Solar Model

Most recent update: Serenelli, Haxton and Pena-Garay arXiv:1104.1639

PROTON-PROTON CYCLE:
~99% of the sun energy

CNO CYCLE:
<1% of the sun energy
Astrophysics:
Open issues: solar metallicity controversy
• Metallicity (the abundance of elements heavier than He) is used as input in the Standard Solar Model;
• The neutrino fluxes depend on it;
• Differences as large as 30-50% (for CNO);
• Differences of ~9% for $^7$Be nu

Neutrino oscillations:
Precision measurements of solar neutrino sources at low energies probe $P_{ee}$ in the vacuum to matter transition region which is sensitive to new physics

<table>
<thead>
<tr>
<th>Sources</th>
<th>High-metallicity $\Phi(\nu \text{ sec}^{-1} \text{ cm}^2)$</th>
<th>Low-metallicity $\Phi(\nu \text{ sec}^{-1} \text{ cm}^2)$</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<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>
</tr>
<tr>
<td>$pep$</td>
<td>$(1.44(1\pm0.012)\times10^{8})$</td>
<td>$(1.47(1\pm0.012)\times10^{8})$</td>
<td>2.0</td>
</tr>
<tr>
<td>$hep$</td>
<td>$(8.04(1\pm0.300)\times10^{9})$</td>
<td>$(8.31(1\pm0.300)\times10^{9})$</td>
<td>3.3</td>
</tr>
<tr>
<td>$^7Be$</td>
<td>$(5.00(1\pm0.070)\times10^{9})$</td>
<td>$(4.56(1\pm0.070)\times10^{9})$</td>
<td>9.4</td>
</tr>
<tr>
<td>$^8B$</td>
<td>$(5.58(1\pm0.140)\times10^{6})$</td>
<td>$(4.59(1\pm0.140)\times10^{6})$</td>
<td>19.8</td>
</tr>
<tr>
<td>$^{13}N$</td>
<td>$(2.96(1\pm0.140)\times10^{9})$</td>
<td>$(2.17(1\pm0.140)\times10^{9})$</td>
<td>31.6</td>
</tr>
<tr>
<td>$^{15}O$</td>
<td>$(2.23(1\pm0.150)\times10^{6})$</td>
<td>$(1.56(1\pm0.150)\times10^{6})$</td>
<td>33.5</td>
</tr>
<tr>
<td>$^{17}F$</td>
<td>$(5.52(1\pm0.170)\times10^{6})$</td>
<td>$(3.40(1\pm0.160)\times10^{6})$</td>
<td>53.0</td>
</tr>
</tbody>
</table>

• Solar Model: Serenelli, Haxton and Pena-Garay arXiv:1104.1639
• High metallicity GS98 = Grevesse et al. S. Sci. Rev. 85, 161 (’98);
Solar neutrino oscillations before Borexino

- Solar neutrinos undergo oscillations in their path from Sun to Earth;
- Preferred region of the oscillation parameter space is the so-called “LMA solution”: $\Delta m^2 = 7.6 \times 10^{-5}$ eV$^2$; $\tan^2 \theta = 0.468$
Main goal: detecting low energies solar neutrinos, in particular $^7$Be neutrinos;
Detection principle: scattering of neutrinos on electrons $\nu_x + e^- \rightarrow \nu_x + e^-$
Detection technique: large mass of organic liquid scintillator;
Technique advantages: high light-yield (higher than Cerenkov)
Technique disadvantages: no directional information (unlike Cerenkov);

Signal is indistinguishable from background: high radiopurity is a MUST!

- The expected rate of solar neutrinos in 100tons of BX scintillator is $\sim$50 counts/day which corresponds to $\sim 5 \times 10^{-9}$ Bq/Kg;
- Just for comparison:
  - Natural water is $\sim 10$ Bq/Kg in $^{238}$U, $^{232}$Th and $^{40}$K
  - Air is $\sim 10$ Bq/m$^3$ in $^{39}$Ar, $^{85}$Kr and $^{222}$Rn
  - Typical rock is $\sim 100$-1000 Bq/m$^3$ in $^{238}$U, $^{232}$Th and $^{40}$K

BX scintillator must be 9/10 order of magnitude less radioactive than anything on earth!
Background suppression: 15 years of work

- **Internal background:** contamination of the scintillator itself
  \((^{238}\text{U}, ^{232}\text{Th}, ^{40}\text{K}, ^{39}\text{Ar}, ^{85}\text{Kr}, ^{222}\text{Rn})\)
  - Solvent purification (pseudocumene): distillation, vacuum stripping with low Argon/Kripton N2 (LAKN);
  - Fluor purification (PPO): water extraction, filtration, distillation, \(N_2\) stripping with LAKN;
  - Leak requirements for all systems and plants < \(10^{-8}\) mbar·liter/sec;

- **External background:** \(\gamma\) and neutrons from surrounding materials
  - Detector design: concentric shells to shield the inner scintillator;
  - Material selection and surface treatment;
  - Clean construction and handling;

Background suppression: achievements

- Contamination from \(^{238}\text{U}\) and \(^{232}\text{Th}\) chain are found to be in the range of \(\sim 10^{-17}\) g/g and \(\sim 5 \times 10^{-18}\) g/g respectively;

- More than one order of magnitude better than specifications!

- Three backgrounds out of specifications: \(^{210}\text{Po}, ^{210}\text{Bi}\) and \(^{85}\text{Kr}\). More about it later
Borexino is located under the Gran sasso mountain which provides a shield against cosmic rays (residual flux = 1 m /m² hour);

Core of the detector: 300 tons of liquid scintillator contained in a nylon vessel of 4.25 m radius (PC+PPO);

1st shield: 1000 tons of ultra-pure buffer liquid (pure PC) contained in a stainless steel sphere of 7 m radius;

2214 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

2nd shield: 2000 tons of ultra-pure water contained in a cylindrical dome;

200 PMTs mounted on the SSS pointing outwards to detect light emitted in the water by muons crossing the detector;

Only the innermost 100 tons of scintillator (R<3m) are considered in the analysis, in order to further reduce the external background.
Borexino started taking data on May 15th 2007
Published results on solar neutrinos

\( ^{7}\text{Be} \) neutrinos
- After two months of data taking published first measurement of \( ^{7}\text{Be} \) flux total error (stat+sys) 17%;
- In 2008 published an update of the result with total error reduced to 10%

\( ^{8}\text{B} \) neutrinos
- In 2010 published measurement of \( ^{8}\text{B} \) solar neutrino rate; with low threshold (3MeV) on the kinetic energy of the scattered electron;

In this talk: two new results
- New precision measurement of \( ^{7}\text{Be} \) solar neutrino flux (error 4.6%);
- Measurement of a null day/night asymmetry of the \( ^{7}\text{Be} \) neutrino flux (error 1.4%);

What has made the improvement possible?
- Reduced statistical error (~ 4 times more data);
- Reduced systematic error thanks to calibrations
Reducing the systematic error: calibrations

Two calibration campaigns performed in 2009 inserting several types of sources ($\alpha$, $\beta$, $\gamma$) in over 300 positions;

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$\gamma$</th>
<th>$\beta$</th>
<th>$\alpha$</th>
<th>Neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{57}$Co</td>
<td>$^{139}$Ce</td>
<td>$^{203}$Hg</td>
<td>$^{85}$Sr</td>
</tr>
<tr>
<td>0.122</td>
<td>0.165</td>
<td>0.279</td>
<td>0.514</td>
<td>0.834</td>
</tr>
</tbody>
</table>
Energy scale

- Light quenching introduces non-linearities in the energy scale: it is crucial to have several calibration points throughout the entire energy window of interest;

- Thanks to the calibration campaigns the uncertainty on the energy scale between (0,2)MeV is less than 1.5%;

- Study of uniformity of detector response as a function of position;
- Calibrations were also fundamental to fine-tune the Montecarlo inputs

Position reconstruction and FV definition

- Position reconstruction is important to define Fiducial Volume
- Check performance of the position reco algorithm: the position of the source is determined independently by a CCD camera system with a precision of ~2cm

- Calibrations allowed to reduce the systematic error on the Fiducial Volume determination from 6% down to +0.5% -1.3%;
New result on $^7$Be rate
(arXiv:1104.1816)
Selection criteria: total statistics after ~750 days normalized to 100tons

- RAW spectrum no cuts
- muon + muon daughter cut
- FV cut

14C, unavoidable in organic scintillator

210Po (from the lines?)
- decays alpha (t ~200 day)
- not in equilibrium with U chain

7Be neutrino shoulder

1 MeV
Extraction of the $^7$Be rate

- In order to extract the neutrino signal a fit is performed including signal + all residual background components ($^{85}$Kr, $^{210}$Bi, $^{210}$Po, $^{11}$C);
- Two independent methods to describe the shape of the components of the spectral fit: a MonteCarlo based one and an analytical one;
- Fit performed on the spectrum with and without statistical subtraction of the $^{210}$Po alpha component;

$^7$Be - rate (862 keV line) = $46.0 \pm 1.5$ (stat) counts/(day $\times$ 100tons)
Systematic error

- Main improvement on the systematic error with respect to previous measurement is on Fiducial Volume and Energy response;

<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</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</td>
</tr>
</tbody>
</table>

\[ ^{7}\text{Be - rate (862 keV line)} = 46.0 \pm 1.5 \text{ (stat)}^{+1.5}_{-1.6} \text{ (sys) counts/(day \times 100tons)} \]
Implications on solar physics

Implications on metallicity controversy

• ~9% difference between the predicted $^7$Be flux in case of high or low metallicity
• ~20% difference for $^8$B
• Fit to the available solar nu data BX included leaving free $f_{Be} = \Phi_{Be}/\Phi_{Be}(SSM)$ and $f_B = \Phi_B/\Phi_B(SSM)$

BX measurement cannot discriminate between High and Low metallicity

Implications on other solar neutrino sources

• The result of BX + solar experiments + solar luminosity constraint allows to precisely determine pp flux and set a limit on CNO flux
• $f_{pp} = \Phi_{pp}/\Phi_{pp}(SSM)$
  $f_{CNO} = \Phi_{CNO}/\Phi_{CNO}(SSM)$

$$f_{pp} = 1.013^{+0.003}_{-0.010}$$
$$f_{CNO} < 2.5 \text{ at 95\% C.L.}$$
Implications on oscillation

$^{7}$Be rate (862 keV line) = $46.0 \pm 1.5$ (stat) $^{+1.5}_{-1.6}$ (sys) cpd / 100tons

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Expected rate (cpd/100t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No oscillation + High Metallicity</td>
<td>74 ± 4</td>
</tr>
<tr>
<td>No oscillation + Low Metallicity</td>
<td>67 ± 4</td>
</tr>
</tbody>
</table>

No-oscillation hypothesis rejected at 5$\sigma$

Implications on $v_e$ survival probability $P_{ee}$

$P_{ee} = 0.51 \pm 0.07$ (E=862 keV)

Note that Borexino total error (4.6%) is now smaller than the theoretical uncertainty on the $^7$Be flux prediction from SSM (7%).
Day/Night asymmetry of $^7\text{Be}$ rate

(arXiv:1104.2150)
In the MSW framework, the neutrino rate at Night (when neutrinos cross Earth) could be significantly larger than the rate during the Day, because of regeneration effect;

\[ A_{dn} = 2 \frac{\Phi_n - \Phi_d}{\Phi_n + \Phi_d} \]

If we define

• In the MSW frame, \( A_{dn} \) depends on the value of the oscillation parameters and on the neutrino energy.
• For the \(^{7}\)Be energies and for parameters in the LMA region, \( A_{dn} \) is expected to be very small (~0);

• In principle, \( A_{dn} \) could be different from zero for different values of the oscillation parameters: for example for the so-called LOW solution- \( \Delta m^2 (10^{-8} - 2 \times 10^{-6} ) \text{eV}^2 \) - \( A_{dn} \) would be between 10% and 80%;
• Some exotic models, like Mass Varying neutrinos, foresee a large Day/Night asymmetry of the opposite sign (-23%)

It is important to study the Day/Night asymmetry at \(^{7}\)Be energies
Day/Night asymmetry of $^7$Be neutrinos

- Divide spectrum in day and night (Day=360.35 d and Nights=380.63 d);
- Subtract day from night spectrum;
- Fit the residual spectrum with the $^7$Be shoulder + constant;
- It is consistent with 0;

$A_{dn} = 0.001 \pm 0.012^{\text{(stat)}} \pm 0.007^{\text{(sys)}}$

No asymmetry within errors

<table>
<thead>
<tr>
<th>Source of error</th>
<th>Error on $A_{dn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live-time</td>
<td>$&lt;5\cdot10^{-4}$</td>
</tr>
<tr>
<td>Cut efficiencies</td>
<td>0.001</td>
</tr>
<tr>
<td>Variation of $^{210}$Bi with time</td>
<td>$\pm 0.005$</td>
</tr>
<tr>
<td>Fit procedure</td>
<td>$\pm 0.005$</td>
</tr>
<tr>
<td>Total systematic error</td>
<td>0.007</td>
</tr>
</tbody>
</table>
Low solution excluded at more than 8σ by Borexino data only

Strong confirmation of the LMA without relying on anti-neutrino kamLAND data
Borexino has been taking data successfully since 2007;

- Thanks to its unprecedented levels of radiopurity it is the only experiment capable of studying the low energy portion of the solar neutrino spectrum;

- I presented two new results recently achieved by Borexino, namely, the precision measurement of the $^7$Be neutrino flux (error $<5\%$) and the absence of its day/night asymmetry;

- Compared with the latest SSM predictions, our results reject the no-oscillation hypothesis at $5\sigma$ and provides a precision measurement of the oscillation probability $P_{ee}$ in the vacuum dominated regime;

- It is the first time that the absence of day/night asymmetry at the $^7$Be energies has been precisely assessed

STAY TUNED FOR MORE BOREXINO RESULTS IN THIS CONFERENCE!