The measurement of the solar neutrino fluxes from the pp-chain with Borexino detector

Oleg Smirnov, JINR, Dubna
on behalf of Borexino collaboration

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BOREXINO (in operation from May, 2007)

- 278 t of liquid organic scintillator PC + PPO (1.5 g/l)
- $(\nu, e)$-scattering with low threshold (~200 keV)
- Outer muon detector

Stainless Steel Sphere 13.7 m Ø
Nylon Sphere 8.5 m Ø

2200 8" Thorn EMI PMTs (1800 with light collectors 400 without light cones)
Muon veto: 200 outward-pointing PMTs
100 ton fiducial volume
Nylon film Rn barrier

Scintillator
Pseudocumene buffer
Water buffer

Holding Strings
Stainless Steel Water Tank 18 m Ø
Steel Shielding Plates 8m x 8m x 10cm and 4m x 4m x 4cm
SSM pp neutrino flux \( \sim 6 \times 10^{10} \text{ cm}^{-2}\text{s}^{-1} \) (>90% of all solar neutrinos)

\( ^7\text{Be} \) 5\( \times 10^9 \text{ cm}^{-2}\text{s}^{-1} \) (~10%)

Others – much less
Detection

• Neutrino elastic scattering on electrons $\nu + e^- \rightarrow \nu + e^-$
• Both electron and non-electron flavours are detected (with $\sigma(\nu_e) \approx 6 \sigma(\nu_{\mu,\tau})$. Detected signal contains a mixture of both contributions: $P_{ee}\sigma(\nu_e) + (1 - P_{ee}) \sigma(\nu_{\mu,\tau})$
• Elastic scattering cross section for monoenergetic $\nu$ has “step-like” form (quasi-Compton) with $T_{max} = \frac{E_{\nu}}{1 + \frac{m_e}{2E_{\nu}}}$
Spectral contributions in the Borexino data

- $^{14}\text{C}$ (3.46 x 10$^6$)
- pp-$\nu$ (133)
- $^{210}\text{Po}$ (656)
- $^7\text{Be}$-$\nu$ (46)
- $^{85}\text{Kr}$ (35)
- $^{210}\text{Bi}$ (42)
- pep-$\nu$ (2.8)
- CNO-$\nu$ (5.3)

Counts / (day x 100 ton x 1 keV)

Energy [keV]
"Precision Measurement of the $^7$Be Solar Neutrino Interaction Rate in Borexino"

PRL 107, 141302 (2011)
Main components of $^7$Be analysis: data selections

- FV cut removes external background (R<3 m) and events associated with radon on the top of the IV (|Z|<1.67)
- Muon cut (dT<2 ms & dT<2 s) – removes events associated with cosmic muons (software and hardware muon definition)
- Data quality cuts – remove electronics noise
- Data selections include “mild” $\alpha/\beta$ cut to clean valley between $^{14}$C and $^{210}$Po from “stray” $\alpha$’s
7Be analysis

- Spectral components are constructed (analytical and MC method). Some contributions are free in fit, others are fixed (namely, CNO and other Solar neutrino fluxes).
- Fit is performed with free energy scale (MC) and free energy resolution parameters (analytical). In addition, in analytical fit the position of the $^{11}$C ($\beta^+$) spectrum starting point is free.
- Energy scale is modeled taking into account non-linearities (ionization quenching and Cherenkov light production)
- The scintillation is carefully modeled to fit the high statistics $^{210}$Po peak
- Independent measurement of $^{85}$Kr count is available, but $^{85}$Kr count was not constrained (the sensitivity of the fit is comparable to the precision of the measurement)
- Systematics: FV (1.5% from calibrations) and energy scale
Comparison of two response models (Gaussian and Generalized Gamma) with CTF data

(monoenergetic α with E=7.68 MeV were selected at the detector’s center r<60 cm)

\[
\frac{\chi_1^2}{\chi_2^2} = F(p, 67, 67) \quad p>99.99\%
\]
$^8\text{B}$ neutrino study: above $^{208}\text{Ti}$
Main components of $^8$B analysis

- FV cut removes external background (R<3 m) : 100 tonnes.
- Muon cut (dT<6.5 s; 30% of live-time loss) – removes events associated with long-lived isotopes produced in interactions with cosmic muons (software and hardware muon definition)
- Neutrons cut (dT<2 ms) for muons in the buffer
- $^{10}$C removal (tagging by coincidence with $\mu$+n)
- $^{214}$Bi removal (tagging by Bi-Po coincidence)
- $^{208}$Tl subtraction (estimated by $^{212}$Bi-Po coincidence)
- $^{11}$Be subtraction (estimated from events with dT<240 s and dR<2 m from the muon track)
pep-neutrino study: above $^{210}$Po peak

Background reduction in $^{11}$C - 91%
with 51.5% live-time loss
Main components of pep analysis: data selections

• FV cut removes external background (R<2.8 m and -1.8 <Z< 2.2 m) : 100 tonnes.
• $^{11}$C removal (tagging by TFC)
• Multivariate analysis, together with the “mai” spectral fit the following fits are performed:
  1. spectral fit of “after TFC” spectrum;
  2. the fit on the PSD in the $^{11}$C energy region;
  3. the fit on the radial distribution of events
Threefold coincidences (TFC)

\[ \mu + ^{12}C \rightarrow \mu + ^{11}C + n \]

\[ \Delta t \sim 250 \mu s: \]

\[ n + p \rightarrow d^* \rightarrow d + \gamma \text{ (2.2 MeV)} \]

\[ \Delta t \sim 30 \text{ min:} \]

\[ ^{11}C \rightarrow ^{11}B + e^+ + \nu \text{ (+ 0.96 MeV)} \]
50% of $\beta^+$ decays give ortho-positronium ($t_{1/2} = 3$ ns).

- Use boosted decision tree to optimize discrimination.
- Train, test, and build PDF with events cut by TFC.
Multivariate fit

- Binned likelihood fits in energy, radius, and BDT
- 2D energy-radius and energy-BDT PDFs
- Simultaneous fits to TFC accepted and rejected spectra (double background statistics)
pp-neutrino study: includes $^{14}$C and $^{210}$Po (Phase II measurement)
Main components of pp analysis

• Data selections: basically the same as for $^7$Be analysis, but without any potentially energy-dependent cuts;

• Analytical method only (too high statistics for the MC), but MC was used to tune the method.

• Independent $^{14}$C rate estimation;

• Pile-up events modeling (synthetic pile-up);

• Careful modeling of the energy response width;

• Careful modeling of the energy response shape
Independent $^{14}$C rate estimation using second cluster events

The $^{14}$C rate was determined independently from the main analysis, by looking at a sample of data in which the event causing the trigger is followed by a second event (in red) within the acquisition time window of 16 µs. The main events spectrum are shown in the same scale in black.
$^{14}$C rate estimation using second cluster events

Time acquisition window is 16 ms. Only the data with $\Delta T > 8$ ms were used (to exclude PMTs afterpulses). Fitting the data with theoretical $\beta$-spectrum shape we obtained:

$40 \pm 1$ Bq/100 t rate.

The corresponding $^{14}$C/$^{12}$C isotopical abundance is

$(2.7 \pm 0.1) \cdot 10^{-18}$ g/g

$^{14}$C $\beta$-spectrum has some deviations from the allowed shape parameterized as $S(E) = 1 + \alpha E$
Methods to construct pile-up

• Synthetic pile-up Data+Data
  – Real triggered events without any selection cuts are artificially overlapped with random data samples and processed with reconstruction code in a standard way

Fit of synth.pile-up with analytical function:
154±10 cpd/100 tones

Compatible with naïve rate estimation using $^{14}$C counting rate only (40 Bq/100 t).
Energy scale

Energy estimator: number of triggered pmts (Npmts) - Integer

Conversion of energy to Npmts depends on:

- Light yield (LY) – free
- Birks’ parameter (kB) - fixed at the value found from the calibration data (kB=0.0109 cm/MeV)
- Average number of live PMTs (NLive) – calculated for data set
- Geometric correction parameter (gc) fixed at value found with MC (no sensitivity in the low energy part)

\[ npmts = N_{Live} \cdot \frac{1 - e^{\frac{-Q(E)}{N_{Live}}}}{1 + gc \cdot \frac{Q(E)}{N_{Live}}} \]

\[ Q(E) = LY \cdot E \cdot f(k_B, E) \]

E→Q→Npmts conversion

The same as in \(^7\text{Be}\) analysis
Energy resolution

Energy resolution for npmt variable depends on:
(2 free):
• \( v_T \) - free. Takes into account spatial non-uniformity of the light collection (basically \(^{210}\)Po parameter because it has negligible contribution in the low energy part of the spectrum). The same for Po and \(^{14}\)C
• \( \sigma_{\text{int}} \) - free. Intrinsic line width (extra width compared to \( \sqrt{N_{\text{photons}}} \)) for \( \beta \)-particles (absent or negligible for \( \alpha \)).
• \( v_f \) - fixed at calculated value (variance of the number of live Pmts).
• \( v_1=0.17 \) - fixed at value found with MC (no sensitivity in the low energy part).

\[
\sigma^2_N = npmts \cdot \left(1 - \frac{npmts}{N_{\text{Live}}} \right) \left(1 + v_1\right) + \]

\[
npmts^2 \cdot (v_T \cdot npmts \cdot (1 + v_f) + v_f) + \]

\[
\sigma_{\text{int}}^2
\]

The same as in \(^7\)Be analysis
+ Intrinsic line width

Intrinsic resolution measured for an EJ301 liquid scintillator. Various colours represent the data obtained with different radiation sources placed at various angles. (figure from 2012 JINST 7 P06011)
Analytical description of Scintillation Line shape

Line shape – the shape of the detector’s response for uniformly distributed monoenergetic particle.

Generalized Gamma Function (\(^{7}\)Be analysis) substituted with Scaled Poisson

Reason: very high statistics of \(^{14}\)C (compared to \(^{210}\)Po in \(^{7}\)Be analysis)

\[
\chi^2 = \frac{258.4}{70}
\]

\[
\chi^2 = \frac{59.3}{70}
\]

The mean values and variances of both shapes are the same

10\(^7\) MC events in FV

\(<N>=60\)
Scaled Poisson vs GGF

\[ f(x) = \frac{\mu^{xs}}{(xs)!} e^{-\mu} \quad f(x) = 2 \beta^\alpha \frac{x^{2\alpha-1}}{\Gamma(\alpha)} e^{-\beta x^2} \]

<table>
<thead>
<tr>
<th></th>
<th>1σ</th>
<th>2σ</th>
<th>3σ</th>
<th>4σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauss</td>
<td>1.5 \cdot 10^{-1}</td>
<td>2.10 \cdot 10^{-2}</td>
<td>1.2 \cdot 10^{-3}</td>
<td>2.5 \cdot 10^{-5}</td>
</tr>
<tr>
<td>GGF</td>
<td>1.5 \cdot 10^{-1}</td>
<td>2.45 \cdot 10^{-2}</td>
<td>1.9 \cdot 10^{-3}</td>
<td>7.8 \cdot 10^{-5}</td>
</tr>
<tr>
<td>SP</td>
<td>1.5 \cdot 10^{-1}</td>
<td>2.45 \cdot 10^{-2}</td>
<td>2.0 \cdot 10^{-3}</td>
<td>8.4 \cdot 10^{-5}</td>
</tr>
</tbody>
</table>

Fraction of events in tail for 3 base functions (<N>=49.9, source at center)
Other factors influencing the scintillation line shape

- **Varying number of live PMTs**: could be taken into account precisely as we know NLivePmt for every event. The response function can be weighted over NLivePmts. The improvement of $\chi^2$ is of 2-3 with all the best parameters of the fit unchanged, and with a drawback of heavy calculations.

- **Additional spread because of the varying light collection efficiency over the detector**: small compared to the “statistical” line width, the “basic” shape remains unchanged.

- The decay of Po and decrease of NLivePmt in time lead to the higher “effective” LY for Po and lower “effective” variance of the Po line: could be calculated analytically following the $^{210}$Po decay rate ($\text{Fill}(1,1) \rightarrow \text{Fill}(1, R(^{210}\text{Po}(T)))$)
The results of the pp-spectral fit

\[ \chi^2 / \text{d.o.f} = 172.3 / 147 \]

- pp $\nu$: \(144 \pm 13\) (free)
- $^7\text{Be}\nu$: \(46.2 \pm 2.1\) (constrained)
- pep $\nu$: 2.8 (fixed)
- CNO $\nu$: 5.36 (fixed)
- $^{210}\text{Po}$: 0.06 (fixed)
- $^{210}\text{Bi}$: \(583 \pm 2\) (free)
- $^{14}\text{C}$: 39.8 \(\pm 0.9\) (constrained)
- Pile-up: \(321 \pm 7\) (constrained)
- $^{210}\text{Bi}$: 27 \(\pm 8\) (free)
- $^{85}\text{Kr}$: 1 \(\pm 9\) (free)

Fit range: 165-590 keV

N.B. fit was performed in the Npmt scale and only then converted to energy. This helps to preserve the energy response shape.
Values are obtained by varying the fit conditions, including the fit energy range, synthetic-versus-analytic pile-up spectral shape, and energy estimator. The distribution shown is peaked around reported value of 144 cpd/100 t.

Mean 144.2
RMS 9.844

+2% on the FV
## Solar neutrino fluxes: theory vs experiment

<table>
<thead>
<tr>
<th>Reaction</th>
<th>GS98</th>
<th>AGS09</th>
<th>cm$^{-2}$s$^{-1}$</th>
<th>Measurement</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>5.98±0.04</td>
<td>6.03±0.04</td>
<td>x10$^{10}$</td>
<td>6.14±0.61</td>
<td>all Solar BX</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.6±0.7</td>
<td></td>
</tr>
<tr>
<td>pep</td>
<td>1.44±0.012</td>
<td>1.47±0.012</td>
<td>x10$^{8}$</td>
<td>1.6±0.3</td>
<td>BX</td>
</tr>
<tr>
<td>$^7$Be</td>
<td>5.0±0.07</td>
<td>4.56±0.07</td>
<td>x10$^{9}$</td>
<td>4.87±0.24</td>
<td>BX</td>
</tr>
<tr>
<td>$^8$B</td>
<td>5.58±0.14</td>
<td>4.59±0.14</td>
<td>x10$^{6}$</td>
<td>5.2±0.3</td>
<td>SNO+SK+BX+KL SNO LETA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.25±0.16$^{+0.011}_{-0.013}$</td>
<td></td>
</tr>
<tr>
<td>hep</td>
<td>8.0±2.4</td>
<td>8.3±2.5</td>
<td>x10$^{3}$</td>
<td>&lt;2.3x10$^{4}$ 90% C.L.</td>
<td>SNO</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>2.96±0.14</td>
<td>2.17±0.14</td>
<td>x10$^{8}$</td>
<td>Integral CNO flux &lt;7.4x10$^{8}$ 90% C.L.</td>
<td></td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>2.23±0.15</td>
<td>1.56±0.15</td>
<td>X10$^{8}$</td>
<td></td>
<td>BX</td>
</tr>
<tr>
<td>$^{17}$F</td>
<td>5.52±0.17</td>
<td>3.40±0.16</td>
<td>x10$^{6}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Solar experiments vs models

Theory

- Green: $^7\text{Be}$
- Yellow: $^8\text{B}$
- Red: pp+pep
- Orange: pep
- Black: CNO

Exper.

Borexino
Borexino measured electron neutrino survival probability for 4 different nuclear reactions.
$^7\text{Be}$ & $^8\text{B}$ fluxes

SHP11:
A. M. Serenelli, W. C. Haxton and C. Pena-Garay,

GS98:
N. Grevesse and A. J. Sauval,
Space Sciences Reviews 85, 161 (1998)

AGSS09:
Aldo M. Serenelli et al 2009
ApJ 705 L123
Combining results on pp-neutrino

- All Solar + $^7$Be Borexino:
  \[ \Phi(pp) = (6.14\pm0.61)\times10^{10} \text{ cm}^{-2}\text{s}^{-1} \]

- Borexino only:
  \[ \Phi(pp) = (6.6\pm0.7)\times10^{10} \text{ cm}^{-2}\text{s}^{-1} \]

- Combined
  \[ \Phi(pp) = (6.37\pm0.46)\times10^{10} \text{ cm}^{-2}\text{s}^{-1} \text{ (7\%)} \]
## Solar neutrino fluxes and Solar luminosity

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Measurement</th>
<th>cm^{-2}s^{-1}</th>
<th>MeV/1ν</th>
<th>L x10^{26} W/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>6.37±0.46</td>
<td>x10^{10}</td>
<td>13.10</td>
<td>3.76±0.28</td>
</tr>
<tr>
<td>pep</td>
<td>1.6±0.3</td>
<td>x10^{8}</td>
<td>11.92</td>
<td>0.009±0.002</td>
</tr>
<tr>
<td>^7Be</td>
<td>4.87±0.24</td>
<td>x10^{9}</td>
<td>12.60</td>
<td>0.276±0.014</td>
</tr>
<tr>
<td>^8B</td>
<td>5.25±0.16</td>
<td>x10^{6}</td>
<td>6.63</td>
<td>(1.57±0.05)10^{-4}</td>
</tr>
</tbody>
</table>

Measured (0.4%) \[ L_\odot = 3.846 \cdot 10^{26} \text{ W/s} \]

\[ \sum L = (4.04 \pm 0.28) \cdot 10^{26} \text{ W/s} \]

90% C.L. lower limit for energy production is 3.68 \cdot 10^{26} \text{ W/s}, i.e. we can guarantee at 90% C.L. that no more than 0.15 \cdot 10^{26} \text{ W/s} (i.e. <4% of the total energy) is produced in reactions not cited in the table.