The first year of Borexino data

Heavy Quarks and Leptons
June 5-9, 2008 - Melbourne (Victoria)

Davide Franco
on behalf of the Borexino Collaboration
Milano University & INFN
Neutrino Production In The Sun

**pp chain:**
- \( pp, \ pep, \ ^7\text{Be}, \) and \( ^8\text{B} \nu \)

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

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

“\( \text{pep} \)”

- \( ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + p + p \)
- \( ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \)
- \( ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e \)
- \( ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \)
- \( ^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu_e \)

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

**CNO cycle:**
- \( ^{13}\text{N}, \ ^{15}\text{O}, \) and \( ^{17}\text{F} \nu \)

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

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

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

- \( ^{7}\text{Be} \rightarrow ^{7}\text{Li} + \nu_e \)
- \( ^{7}\text{Be} \rightarrow ^{7}\text{B} + \gamma \)
- \( ^{8}\text{B} \rightarrow ^{8}\text{Be} + e^+ + \nu_e \)

- \( ^{8}\text{Be} \rightarrow ^{4}\text{He} + ^{4}\text{He} \)

- \( ^{4}\text{He} \rightarrow ^{4}\text{He} + ^{4}\text{He} \)

Flux (cm\(^{-2}\) s\(^{-1}\))

Neutrino Energy in MeV

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Solar Neutrino Spectra

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Gallex  GNO
Homestake  Sage
SNO  SuperK (real time)

Borexino (real time)
The Solar Physics with Borexino

One fundamental input of the Standard Solar Model is the *metallicity* of the Sun - abundance of all elements above Helium:

- The Standard Solar Model, based on the old metallicity derived by Grevesse and Sauval (Space Sci. Rev. 85, 161 (1998)), is *agreement within 0.5 in %* with the solar sound speed measured by helioseismology.

- Latest work by Asplund, Grevesse and Sauval (Nucl. Phys. A 777, 1 (2006)) indicates a metallicity *lower by a factor ~2*. This result destroys the agreement with helioseismology.

<table>
<thead>
<tr>
<th>[cm$^{-2}$ s$^{-1}$]</th>
<th>pp $(10^{10})$</th>
<th>pep $(10^{10})$</th>
<th>hep $(10^3)$</th>
<th>$^7$Be $(10^9)$</th>
<th>$^8$B $(10^6)$</th>
<th>$^{13}$N $(10^8)$</th>
<th>$^{15}$O $(10^8)$</th>
<th>$^{17}$F $(10^6)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS05 AGS 98</td>
<td>6.06</td>
<td>1.45</td>
<td>8.25</td>
<td>4.84</td>
<td>5.69</td>
<td>3.07</td>
<td>2.33</td>
<td>5.84</td>
</tr>
<tr>
<td>BS05 AGS 05</td>
<td>5.99</td>
<td>1.42</td>
<td>7.93</td>
<td>4.34</td>
<td>4.51</td>
<td>2.01</td>
<td>1.45</td>
<td>3.25</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>-1%</td>
<td>-2%</td>
<td>-4%</td>
<td>-12%</td>
<td>-23%</td>
<td>-42%</td>
<td>-47%</td>
<td>-57%</td>
</tr>
</tbody>
</table>

**Solar neutrino measurements can solve the problem!**
Solar Physics Goals

- First ever observations of **sub-MeV neutrinos** in real time
- Check the balance between photon **luminosity** and neutrino luminosity of the Sun
- **CNO** neutrinos (direct indication of metallicity in the Sun’s core)
- **pep** neutrinos (indirect constraint on *pp* neutrino flux)
- Low energy (3-5 MeV) $^8$B neutrinos
- Tail end of **pp neutrino spectrum**?
Neutrino Physics Goals

Test of the **matter-vacuum oscillation transition** with $^7$Be, pep, and low energy $^8$B neutrinos

Check of the **mass varying neutrino model** (Barger et al., PRL 95, 211802 (2005))

Limit on the **neutrino magnetic moment** by analyzing the 7Be energy spectrum and with Cr source

Moreover: **geoneutrinos and supernovae**
Abruzzo
120 Km da Roma

Laboratori Nazionali del Gran Sasso
Assergi (AQ)
Italy
~3500 m.w.e

Borexino – Rivelatore e impianti

Laboratori esterni
Detection principles and \( \nu \) signature

- **Borexino** detects solar \( \nu \) via their **elastic scattering off electrons** in a volume of **highly purified liquid scintillator**
  - Mono-energetic \( 0.862 \text{ MeV} \) \(^7\text{Be} \) \( \nu \) are the main target, and the only considered so far
  - Mono-energetic pep \( \nu \) , CNO \( \nu \) and possibly pp \( \nu \) will be studied in the future

- **Detection via scintillation light:**
  - Very low energy threshold
  - Good position reconstruction
  - Good energy resolution

**BUT…**

- No direction measurement
- The \( \nu \) induced events can’t be distinguished from other \( \beta \) events due to natural radioactivity

- **Extreme radiopurity of the scintillator** is a must!

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Typical \( \nu \) rate (SSM+LMA+Borexino)

![Graph showing typical neutrino rate](image)
Borexino Background

Expected solar neutrino rate in 100 tons of scintillator ~ 50 counts/day (\( \sim 5 \times 10^{-9} \text{ Bq/Kg} \))

Just for comparison:

Natural water \( \sim 10 \text{ Bq/Kg} \) in \(^{238}\text{U},^{232}\text{Th}\) and \(^{40}\text{K}\)

Air \( \sim 10 \text{ Bq/m}^3 \) in \(^{39}\text{Ar},^{85}\text{Kr}\) and \(^{222}\text{Rn}\)

Typical rock \( \sim 100-1000 \text{ Bq/m}^3 \) in \(^{238}\text{U},^{232}\text{Th}\) and \(^{40}\text{K}\)

**BX scintillator must be 9/10 order of magnitude less radioactive than anything on earth!**

- Low background nylon vessel fabricated in hermetically sealed low radon clean room (~1 yr)
- Rapid transport of scintillator solvent (PC) from production plant to underground lab to avoid cosmogenic production of radioactivity (\(^{7}\text{Be}\))
- Underground purification plant to distill scintillator components.
- Gas stripping of scintillator with special nitrogen free of radioactive \(^{85}\text{Kr}\) and \(^{39}\text{Ar}\) from air
- All materials electropolished SS or teflon, precision cleaned with a dedicated cleaning module
**Detector layout and main features**

**Scintillator:**
270 t PC+PPO in a 150 μm thick nylon vessel

**Stainless Steel Sphere:**
2212 PMTs
1350 m³

**Nylon vessels:**
Inner: 4.25 m
Outer: 5.50 m

**Water Tank:**
γ and n shield
μ water Č detector
208 PMTs in water
2100 m³

**Carbon steel plates**

**20 legs**
PMTs: PC & Water proof

Nylon vessel installation

Installation of PMTs on the sphere
## Borexino background

<table>
<thead>
<tr>
<th>Radiosotope</th>
<th>Concentration or Flux</th>
<th>Strategy for Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
<td><strong>Source</strong></td>
<td><strong>Typical</strong></td>
</tr>
<tr>
<td>μ</td>
<td>cosmic</td>
<td>~200 s(^{-1}) m(^{-2})</td>
</tr>
<tr>
<td></td>
<td>at sea level</td>
<td></td>
</tr>
<tr>
<td>Ext. γ</td>
<td>rock</td>
<td></td>
</tr>
<tr>
<td>Int. γ</td>
<td>PMTs, SSS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water, Vessels</td>
<td></td>
</tr>
<tr>
<td>14C</td>
<td>Intrinsic PC/PPO</td>
<td>~10(^{-12})</td>
</tr>
<tr>
<td>238U</td>
<td>Dust</td>
<td>~10(^{-5})-10(^{-6}) g/g</td>
</tr>
<tr>
<td>232Th</td>
<td>Organometallic (?)</td>
<td>~10(^{-5}) (dust) (in scintillator)</td>
</tr>
<tr>
<td>7Be</td>
<td>Cosmogenic (12C)</td>
<td>~310(^{-2}) Bq/t</td>
</tr>
<tr>
<td>40K</td>
<td>Dust, PPO</td>
<td>~210(^{-6}) g/g (dust)</td>
</tr>
<tr>
<td>210Pb</td>
<td>Surface contam. from 222Rn decay</td>
<td></td>
</tr>
<tr>
<td>210Po</td>
<td>Surface contam. from 222Rn decay</td>
<td></td>
</tr>
<tr>
<td>222Rn</td>
<td>air, emanation from materials, vessels</td>
<td>~10 Bq/l (air)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~100 Bq/l (water) (scintillator)</td>
</tr>
<tr>
<td>39Ar</td>
<td>Air (nitrogen)</td>
<td>~17 mBq/m(^{3}) (air)</td>
</tr>
<tr>
<td>85Kr</td>
<td>Air (nitrogen)</td>
<td>~1 Bq/m(^{3}) in air</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Expected Spectrum
The starting point: no cut spectrum

Measured Spectrum
- All data after basic selection cuts

Expected Spectrum
- Total Spectrum
- $^7\text{Be}$

Counts/(10 keV x day x 100 tons)

Energy [MeV]

Photoelectrons [pe]
Spectrum after FV cut (100 tons)

Energy [MeV]

Counts/(10 keV x day x 100 tons)

Measured Spectrum
- All data after basic selection cuts
- After fiducial volume cut

Expected Spectrum
- Total Spectrum
- $^7$Be

Radial distribution in the $^7$Be energy range

Radial distribution of muon induced neutrons
\( \alpha/\beta \) statistical subtraction
pulse shape analysis

Measured Spectrum:
- All data after basic selection cuts
- After fiducial volume cut
- After statistical subtraction of \( \alpha \)'s

Expected Spectrum:
- Total Spectrum
- \(^7\text{Be}\)
- CNO + pep
- \(^{14}\text{C}\)
- \(^{11}\text{C}\)
- \(^{10}\text{C}\)

\( R < 3.8 \, \text{m} \)
\( \text{FV (R < 3 m)} \)
New results with 192 days of statistics

- $\chi^2$/NDF = 185/174
- $^7$Be: $49\pm3$ cpd/100 tons
- $^{210}$Bi+CNO: $23\pm2$ cpd/100 tons
- $^{85}$Kr: $25\pm3$ cpd/100 tons
- $^{11}$C: $25\pm1$ cpd/100 tons
New results with 192 days of statistics

- $^7\text{Be}: 49\pm3$ cpd/100 tons
- $^{10}\text{B}i+\text{CNO}: 20\pm2$ cpd/100 tons
- $^{35}\text{Kr}: 29\pm4$ cpd/100 tons
- $^{11}\text{C}: 24\pm1$ cpd/100 tons

Fit: $\chi^2$/NDF = 55/60
Systematic and Final Result

Estimated 1σ Systematic Uncertainties* [%]

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Scintillator Mass</td>
<td>0.2</td>
</tr>
<tr>
<td>Fiducial Mass Ratio</td>
<td>6.0</td>
</tr>
<tr>
<td>Live Time</td>
<td>0.1</td>
</tr>
<tr>
<td>Detector Resp. Function</td>
<td>6.0</td>
</tr>
</tbody>
</table>

*Prior to Calibration

Expected interaction rate in absence of oscillations:
75±4 cpd/100 tons

for LMA-MSW oscillations:
48±4 cpd/100 tons, which means:

\[
f_{\text{Be}} = 1.03^{+0.24}_{-1.03}
\]

7Be Rate: 49±3_{stat}±4_{syst} cpd/100 tons , which means

\[
f_{\text{Be}} = 1.02 \pm 0.10
\]
After Borexino

Solar Neutrino Survival Probability

- $^7$Be LMA Prediction
- $^7$Be LMA-MSI Prediction
- MaVaN Prediction
- SNO Data
- Current Borexino Data
- Ga Data after Borexino

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Constraints on $pp$ and CNO fluxes

Combining Borexino 7Be results with other experiments, the expected rate in Clorine and Gallium experiments is

$$R_l \ [\text{SNU}] = \sum_i R_{l,i} f_i P_{ee}^{l,i}$$

where

- $R_{l,i}$ and $P_{ee}^{l,i}$ are calculated in the hypothesis of high-Z SSM and MSW LMA
- $R_{k}$ are the rates actually measured by Clorine and Gallium experiments
- $f^8B$ is measured by SNO and SuperK to be 0.87 ±0.07
- $f^7\text{Be} = 1.02 \pm 0.10$ is given by Borexino results

Plus luminosity constraint:

$$0.919 f_{pp} + 0.075 f_{\text{Be}} + 0.0068 f_{\text{CNO}} = 1$$

$$f_{pp} = 1.004^{+0.008}_{-0.020}$$

best determination of pp flux!
Neutrino Magnetic Moment

Neutrino-electron scattering is the most sensitive test for $\mu_\nu$ search

\[
\left( \frac{d\sigma}{dT} \right)_W = \frac{2G_F^2 m_e}{\pi} \left[ g_L^2 + g_R^2 \left( 1 - \frac{T}{E_\nu} \right)^2 - g_L g_R \frac{m_e T}{E_\nu^2} \right]
\]

EM current affects cross section:
spectral shape sensitive to $\mu_\nu$
sensitivity enhanced at low energies (c.s. $\approx 1/T$)

\[
\left( \frac{d\sigma}{dT} \right)_{EM} = \mu_\nu^2 \frac{\pi \alpha_{em}^2}{m_e^2} \left( \frac{1}{T} - \frac{1}{E_\nu} \right)
\]

A fit is performed to the energy spectrum including contributions from $^{14}\text{C}$, leaving $\mu_\nu$ as free parameter of the fit

<table>
<thead>
<tr>
<th>Estimate</th>
<th>Method</th>
<th>$10^{-11} \mu_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperK</td>
<td>$^8\text{B}$</td>
<td>&lt;11</td>
</tr>
<tr>
<td>Montanino et al.</td>
<td>$^7\text{Be}$</td>
<td>&lt;8.4</td>
</tr>
<tr>
<td>GEMMA</td>
<td>Reactor</td>
<td>&lt;5.8</td>
</tr>
<tr>
<td>Borexino</td>
<td>$^7\text{Be}$</td>
<td>&lt;5.4</td>
</tr>
</tbody>
</table>
What next?
- **pep** and CNO ν fluxes
  - software algorithm based on a three-fold coincidence analysis to subtract efficiently cosmogenic $^{11}$C background
  - Muon track reconstruction

- $^8$B at low energy region (3-5 MeV)

- pp seasonal variations (?)

- High precision measurements
  - systematic reduction
  - calibrations

- geoneutrinos

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Conclusion

- Borexino opened the study of the solar neutrinos in real time below the barrier of natural radioactivity (4 MeV)
  - Two measurements reported for $^7$Be neutrinos
  - Best limits for $pp$ and CNO neutrinos, combining information from SNO and radiochemical experiments
  - Opportunities to tackle $pep$ and CNO neutrinos in direct measurement

- Borexino will run comprehensive program for study of antineutrinos (from Earth, Sun, and Reactors)
- Borexino is a powerful observatory for neutrinos from Supernovae explosions within few tens of kpc
- Best limit on neutrino magnetic moment. Improve by dedicated measurement with $^{51}$Cr neutrino source
BackUp
Expectations

Solar Neutrino Survival Probability

- $^{7}\text{Be}$ LMA Prediction
- $^{7}\text{Be}$ LMA-MSI Prediction
- MaNeN Prediction
- SNO Data
- Current Borexino Data
- Ga Data after Borexino
- Predicted Borexino Sensitivities

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Spectrum after $\mu$ subtraction (above $^{14}\text{C}$)

- $\mu$ are identified by the OD and by the ID
  - OD eff: $\sim 99%$
  - ID analysis based on pulse shape variables
    - Pulse mean time, peak position in time
  - Estimated overall rejection factor:
    - $> 10^4$ (still preliminary)
The starting point: no cut spectrum

$^{14}\text{C}$ dominates below 200 KeV

$^{210}\text{Po}$ NOT in eq. with $^{210}\text{Pb}$

Mainly external $\gamma$s and $\mu$s

Statistics of this plot: ~ 1 day
Spectrum after FV cut (100 tons)

- Clear $^7$Be shoulder
- $^{210}$Po
- $^{11}$C
- Radial distribution in the $^7$Be energy range
- Fast coincidence ($^{214}$Bi-Po and $^{212}$Bi-Po) subtraction

Radial distribution of muon induced neutrons
\( \alpha/\beta \) statistical subtraction

Pulse shape analysis

No radial cut

R < 3.8 m

FV (R < 3 m)

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Large scintillator detector potential