Recent Results from Borexino

Dominik Jeschke
on behalf of the Borexino Collaboration
Technical University of Munich

ICPPA 2016
The 2nd International Conference on Particle Physics and Astrophysics
Moscow, October 10 – 14, 2016
The Borexino Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

St. Petersburg Nuclear Physics Inst.

Technische Universität München

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

SKOBELTSYN INSTITUTE OF NUCLEAR PHYSICS
LOMONOSOV MOSCOW STATE UNIVERSITY

JULICH

FORSCUNGSZENTRUM

JINR Dubna

TECHNISCHE UNIVERSITÄT DRESDEN

JINR

LOMONOSOV MOSCOW STATE UNIVERSITY

GSI

CENTER FOR ADVANCED STUDIES
Istituto Nazionale di Fisica Nucleare
Why Borexino?

Neutrinos produced in solar fusion processes:
- Test solar modelling (ASTRO - )
- Study of neutrino oscillations (PARTICLE - PHYSICS)

Experiment design goal: $^7\text{Be-}\nu$

Design threshold: \(~250\text{ keV}\)
The Borexino Detector

Located at LNGS

**Scintillator Core:**
270 t PC + PPO (1.5 g/l)

**Nylon Vessels:**
125 μm thick
Inner: 4.25 m radius
Outer: 5.50 m radius (radon shield)

Detection reaction:
Neutrino – Electron scattering
\( \nu + e^- \rightarrow \nu + e^- \)

**Stainless Steel Sphere:**
13.7 m diameter
2212 PMTs
34% optical coverage

**Buffer Region:**
\(~1000 \text{ t PC + DMP light quencher}\)

**Water Tank:**
2.1 kt water
208 PMTs on floor and SSS
\( \gamma \) and fast neutron shield
\( \mu \) veto detector
Borexino Time Line

Phase I:
First direct $^7$Be $\nu$ measurement (2007)
$^7$Be $\nu$ precision measurement (5%, 2011)
$^8$B $\nu$ measurement above 3 MeV (2010)
First direct pep $\nu$ measurement (2012)
Strongest CNO limit (2012)
Geo $\nu$ observation (2010)

Phase II:
First direct pp $\nu$ measurement (2014)
Geo $\nu$ spectroscopy (2015)
pp-$\nu$ Analysis

Neutrino energy < 420 keV
Electron recoil energy < 264 keV
Analysis threshold: 165 keV
Radiochemical experiments: 233 keV threshold

Independent constrain on $^{14}$C (40 ± 1) Bq

Synthetic pile-up: $^{14}$C+$^{14}$C, $^{14}$C+$^{210}$Po ...

$^{14}$C
$^{210}$Po
Synthetic
pile-up
$^{210}$Bi
$^{85}$Kr
CNO $\nu$
$^7$Be $\nu$
$^{pp}\nu$
$^{pp}\nu$

Events (c.p.d. per 1001 per keV)

Energy (keV)

Energy estimator: number of hit PMTs

Counts / 1 N a t e

Energy estimator: number of hit PMTs
**pp-ν Results**

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

**Measurement:**
\[ 144 \pm 13 \text{ cpd / 100 t} \]

**Expected:**
\[ 131 \pm 2 \text{ cpd / 100 t} \]

**Null hypothesis rejected at 10 σ**

**Measured Flux:**
\[ \Phi_{pp} = (6.6 \pm 0.7) \cdot 10^{10} \text{cm}^{-2}\text{s}^{-1} \]

- Confirms LMA-MSW
- Confirms SSM – compatible with low & high metallicity
- Future Borexino inspired experiments to reach uncertainty level
- Confirms Sun’s stability over $10^5$ years
Borexino pp-Chain Neutrino Results

1st direct detection
10% precision (Nature 2014)

1st direct detection
20% precision (PRL 2012)

Lowest threshold (3 MeV)
20% precision (PRD 2010)

1st direct detection
5% precision measurement (PRL 2011)
## Solar Neutrino Results

<table>
<thead>
<tr>
<th>Species</th>
<th>Rate [cpd / 100 t]</th>
<th>Flux [cm(^{-2})s(^{-1})]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>(144 \pm 13 \pm 10)</td>
<td>((6.6 \pm 0.7) \cdot 10^{10})</td>
<td>Nature512(2014)7515</td>
</tr>
<tr>
<td>(^7\text{Be})</td>
<td>(46.0 \pm 1.5^{+1.5}_{-1.6})</td>
<td>((4.48 \pm 0.24) \cdot 10^{9})</td>
<td>PRL107(2011)141302</td>
</tr>
<tr>
<td>pep</td>
<td>(3.1 \pm 0.6 \pm 0.3)</td>
<td>((1.6 \pm 0.3) \cdot 10^{8})</td>
<td>PRL108(2012)051302</td>
</tr>
<tr>
<td>(^8\text{B})</td>
<td>(0.22 \pm 0.04 \pm 0.01)</td>
<td>((2.4 \pm 0.4 \pm 0.1) \cdot 10^{6})</td>
<td>PRD82(2010)033006</td>
</tr>
<tr>
<td>CNO</td>
<td>&lt; 7.9 (95% C.L.)</td>
<td>&lt; 7.7 \cdot 10^{8} (95% C.L.)</td>
<td>PRL108(2012)051302</td>
</tr>
</tbody>
</table>

\(^7\text{Be}:\)
1. Absence of day-night asymmetry
2. Yearly modulation

**Cosmogenic backgrounds:**
1. Seasonal modulation of muon flux
2. Detailed studies of neutrons and cosmogenics

**Geo-neutrinos**

**Rare processes:** Best limit on e\(^-\) decay (2015)
Geo Neutrinos

Anti-neutrinos produced in radioactive decays in Earth’s crust and mantle

<table>
<thead>
<tr>
<th>Decay</th>
<th>Half life ([10^9 \text{yr}])</th>
<th>Maximum (\nu) Energy ([\text{MeV}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{238}\text{U} \rightarrow ^{206}\text{Pb} + ^{4}\text{He} + 6e + 6 \bar{\nu}_e)</td>
<td>4.47</td>
<td>3.26</td>
</tr>
<tr>
<td>(^{232}\text{Th} \rightarrow ^{208}\text{Pb} + ^{4}\text{He} + 6e + 6 \bar{\nu}_e)</td>
<td>14.0</td>
<td>2.25</td>
</tr>
<tr>
<td>(^{40}\text{K} \rightarrow ^{40}\text{Ca} + e + \bar{\nu}_e (89%))</td>
<td>1.28</td>
<td>1.311</td>
</tr>
</tbody>
</table>

Detection via Inverse Beta Decay:

\[ \bar{\nu}_e + p \rightarrow n + e^+ (\rightarrow 2\gamma (511 \text{ keV each})) \]
\[ n + H \rightarrow D + \gamma (2.2 \text{ MeV}) \]

Signature: Prompt signal: \(e^+\) annihilation
Delayed signal: 2.2 MeV \(\gamma\)
Neutron capture time: \(\sim 250 \mu\text{s}\)

Detection Threshold: 1.8 MeV
\(\rightarrow \) K not visible
Th/U ratio 3.9 as from chondritic model

Distribution of long-lived radioisotopes & radiogenic heat contribution to total balance
Understand: Magnetic field, mantle convection, plate tectonics...
Geo Neutrinos: Results

Exposure: \((907 \pm 44) \text{ t} \cdot \text{yr}\)
77 coincidences found
Background not caused by reactors: \(\sim 0.8\) events

<table>
<thead>
<tr>
<th></th>
<th>Events</th>
<th>Flux [TNU]</th>
<th>Expected [TNU]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>(52.7^{+9.2}_{-9.3})</td>
<td>(96.6^{+20.5}_{-19.2})</td>
<td>((87 \pm 4)) (after oscillations)</td>
</tr>
<tr>
<td>Geo</td>
<td>(23.7^{+7.4}_{-6.3})</td>
<td>(43.5^{+14.5}_{-12.8})</td>
<td>Model dependent</td>
</tr>
</tbody>
</table>

1,2,3 \(\sigma\) contours
Null hypothesis rejected at 5.9 \(\sigma\)

\(1\text{TNU} = 1\text{ev/yr/10}^{32}\text{protons}\)
Geo Neutrinos: Implications

\[ S_{\text{EXPECTED}} = S_{\text{LOCAL CRUST}} + S_{\text{REST OF CRUST}} + S_{\text{MANTLE}} \]

43.5 ± 11.1
(Measurement)

9.7 ± 1.3
(geological, -physical, -chemical study)

13.7 ± 2.5
(Model)

20.9^{+15.1}_{-10.3}
(likelihood)

No mantle contribution excluded at 98% C.L.

Consistent with different BSE models

Possibility to dissentangle Th and U contributions & probe different models
Borexino Phase II: Goals & Prospects

\( ^7\text{Be flux} \): Uncertainty \( \sim3\% \) & seasonal modulation
\( \text{pep flux} \): Evidence \( >3\sigma \)
\( ^8\text{B flux} \): Reduced threshold and uncertainty
\( \text{pp flux} \): Possible update
\text{Geo-neutrinos}: Update
\text{CNO flux}: Improved limit & possibly first detection
  \( \rightarrow \) Probe solar metallicity

<table>
<thead>
<tr>
<th>Model</th>
<th>CNO neutrino flux ([10^8 \text{ cm}^{-2} \text{s}^{-1}])</th>
<th>Expected count rate in Borexino ([\text{cpd / 100 t}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Z SSM</td>
<td>3.76 ± 0.60</td>
<td>( \sim3.7 )</td>
</tr>
<tr>
<td>High Z SSM</td>
<td>5.24 ± 0.84</td>
<td>( \sim5.3 )</td>
</tr>
<tr>
<td>( \Delta )</td>
<td></td>
<td>28%</td>
</tr>
</tbody>
</table>
Conclusions

- Almost full solar neutrino spectroscopy
- Leading limit on CNO neutrino flux
- Geo neutrino observation at $5.9 \sigma$
- Made possible by unprecedentedly high radio-purity

Phase II: ~4.5 yr accumulated data + ~1.5 yr until start of SOX
6 yr of high quality data

- Phase II priority: Improved limit on CNO or measurement
- Huge effort made to control temperature & prevent convective motions
- Update of other solar neutrino fluxes & geo neutrinos
Thank you for your attention
Experimental Side

External labs ~120 km North-East of Rome

Laboratori Nazionali del Gran Sasso

Underground labs accessible via highway tunnel

Located straight under Monte L’Aquila
Shielded by 3800 m.w.e.
Reduced $\mu$ flux by $\sim 10^6$
Borexino Energy Spectrum

Basic Data Selection
1. Raw spectrum
2. Muon Cut
3. Fiducial Volume Cut
Borexino Backgrounds

Borexino's inner scintillator core is the radio-cleanest spot on Earth!

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Before Purification</th>
<th>After Purification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}\text{C}/^{12}\text{C}$</td>
<td>$(2.69 \pm 0.06) \times 10^{-18}$</td>
<td>unchanged</td>
</tr>
<tr>
<td>$^{85}\text{Kr}$</td>
<td>$(30 \pm 5)$ cpd/100 t</td>
<td>$\leq 5$ cpd/100 t</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>$\sim 500$ cpd/100 t</td>
<td>unchanged</td>
</tr>
<tr>
<td>$^{210}\text{Bi}$</td>
<td>$\sim 40$ cpd/100 t</td>
<td>$\sim 20$ cpd/100 t</td>
</tr>
</tbody>
</table>

$^{40}\text{K}$, $^{39}\text{Ar}$ below detection limit
$^{238}\text{U}$, $^{232}\text{Th}$ $< 10^{-18}$ g/g (unprecedented)
$^{222}\text{Rn}$ $\sim 1$ cpd/100 t
Borexino Calibration Campaigns

2008 – 2011: 3 internal and 2 external calibration campaigns

Energy calibration:
MC tuned with several $\gamma$ sources
Resolution $\sim 5%/\sqrt{E}$ [MeV]

Position Reconstruction:
Rn source in 182 positions
Fiducial volume uncertainty 2% (pp-analysis)

Calibration shall be repeated before end of Phase II (2017)
Cosmogenic $^{11}$C Reduction – Three Fold Coincidence

$\mu + ^{12}$C $\rightarrow$ $\mu + ^{11}$C + n

$\tau = 29.4 \text{ min}$

$\sim 250 \mu s$

$n + p \rightarrow D + \gamma (2.2 \text{ MeV})$

$^{11}$C $\rightarrow$ $^{11}$B + $e^+ + \nu_e$
Cosmogenic $^{11}$C Reduction – Three Fold Coincidence

Already applied in Phase I pep neutrino analysis (2012): 90% $^{11}$C reduction at ~50% surviving exposure

Phase II goal: Same or better $^{11}$C reduction at ~65% surviving exposure

→ Improved algorithms
→ Stable and continuousDAQ (duty cycle >95%)
Pulse Shape Discrimination ($e^+ / e^-$)

Delayed $e^+$ annihilation signal through formation of ortho-positronium

Difference in pulse shape of $e^+ \& e^-$

Definition of **Boosted Decision Tree** parameter to discriminate between $e^+ \& e^-$
Multivariate maximum-likelihood fit:

1. TFC-subtracted energy spectrum
2. TFC-enhanced energy spectrum (complementary)
3. Radial event distribution
4. PS-BDT parameter ($e^+/e^-$)

Aiming to fit all components simultaneously: (pp+ $^7$Be+pep/CNO)
CNO & $^{210}$Bi

$^{210}$Bi & CNO: quasi-degenerate

$^{210}$Pb

$T_{1/2} = 22.3$ yr

$E = 0.06$ MeV

$BR = 81$

$^{210}$Bi

$T_{1/2} = 5.0$ d

$E = 1.2$ MeV

$^{210}$Po

$T_{1/2} = 138.4$ d

$E = 5.3$ MeV

At least 10% precision → Stability needed!

Constrain $^{210}$Bi from its daughter in secular equilibrium $^{210}$Po

Clear $\alpha$ peak

stable

$^{206}$Pb
$^{210}\text{Po} - \text{Instabilities}$

Detector operations induce $^{210}\text{Po}$ contaminations
→ No operations during Phase II data taking

Equilibrium still broken:
Temperature changes induce $^{210}\text{Po}$ fluctuations
→ Possibly due to convective currents

Complete fluidodynamic simulation of currents ongoing
Controlling the Temperature

- 65 new calibrated T probes, internal and external installed
- 2 probes measuring T in Hall C
- 0.1 °C absolute accuracy
- 0.01 °C resolution stability

Thermal insulation of whole detector
- 20 cm mineral wool + reflective layer
- May to December 2015
- Active T controll installed to be activated at need
Dec 2015: Insulation completed
2015 Jul: Water loop off
2015 May: First insulation ring
Impact on $^{210}$Po

- Summers
- Winters
- Insulation

$^{210}$Po rate

Cubes

Time:
- 2013/04/24
- 2013/11/28
- 2014/07/04
- 2015/02/07
- 2015/09/13
- 2016/04/18

Top

Bottom