Geoneutrino flux measurement with Borexino detector

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the Borexino Collaboration
BOREXINO started data taking in 2007

- 278 t of liquid organic scintillator PC + PPO (1.5 g/l)
- (ν, e)-scattering with 200 keV threshold
- Outer muon detector
Borexino status

Acquires data non-stop from May 2007;
(problems with muons identification up to december; potential contamination of the data sample with muons daughter – excluded from all analyses)

now in Phase-II (after the calibration campaign and repurification)

Extremely clean LS and well-designed protection against external backgrounds

Far away from european nuclear power plants (~1000 km average distance): only 36 % of the total antineutrino signal in geo-nu window [0.9-2.6 MeV] Geo/Reactor ratio is 1.8 in Borexino;

Last analysis of geoneutrino:
~5½ years (Dec 15, 2007-Mar 8, 2015)
2056 days of live time in total.
1841.9 days after the muons cut
## Liquid Scintillator Radiopurity

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Typical abundance (source)</th>
<th>Borexino goals</th>
<th>Borexino-I</th>
<th>Borexino-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}$C / $^{12}$C, g/g</td>
<td>$10^{-12}$ (cosmogenic)</td>
<td>$\sim 10^{-18}$</td>
<td>$2.7 \cdot 10^{-18}$</td>
<td>$2.7 \cdot 10^{-18}$</td>
</tr>
<tr>
<td>$^{238}$U, g/g (214Bi-214Po)</td>
<td>$10^{-6}$-$10^{-5}$ (dust)</td>
<td>$\sim 10^{-16}$ (1 μBq /t)</td>
<td>$(1.6\pm0.1) \cdot 10^{-17}$</td>
<td>$&lt;9.7 \cdot 10^{-19}$ (95%)</td>
</tr>
<tr>
<td>$^{232}$Th, g/g (212Bi-212Po)</td>
<td>$10^{-6}$-$10^{-5}$ (dust)</td>
<td>$\sim 10^{-16}$</td>
<td>$(6.8\pm1.5) \cdot 10^{-18}$</td>
<td>$&lt;1.2 \cdot 10^{-18}$ (95%)</td>
</tr>
<tr>
<td>$^{222}$Rn ($^{238}$U), ev/d/100 t</td>
<td>100 atoms/cm$^3$ (air)</td>
<td>10</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{40}$K, g[K$_{nat}$]/g</td>
<td>$2 \cdot 10^{-6}$ (dust)</td>
<td>$\sim 10^{-15}$</td>
<td>$&lt;1.7 \cdot 10^{-15}$ (95%)</td>
<td>---</td>
</tr>
<tr>
<td>$^{210}$Po, ev//d/t</td>
<td>Surface contamination</td>
<td>$\sim 10^{-2}$</td>
<td>80 (initial), $T_{1/2}=134$ days;</td>
<td>2</td>
</tr>
<tr>
<td>$^{210}$Bi, ev/d/100 t</td>
<td>In equilibrium with $^{222}$Rn or $^{210}$Pb</td>
<td>Not specified</td>
<td>20-70</td>
<td>$\sim 20$</td>
</tr>
<tr>
<td>$^{85}$Kr, ev/d/100 t</td>
<td>1 Bq/m$^3$ (technogenic, air)</td>
<td>$\sim 1$</td>
<td>$30.4\pm5$ cpd/100t</td>
<td>$&lt;5$ (90% C.L.) compatible with 0</td>
</tr>
<tr>
<td>$^{39}$Ar, ev/d/100 t</td>
<td>17 mBq/m$^3$ (cosmogenic in air)</td>
<td>$\sim 1$</td>
<td>$&lt;&lt;^{85}$Kr</td>
<td>$&lt;&lt;^{85}$Kr</td>
</tr>
</tbody>
</table>
Detection of geo(anti)neutrino

- Earth (in contrast to the Sun) emits antineutrino.
  \[ \Phi_{\bar{\nu}} \sim 10^6 \text{cm}^{-2}\text{s}^{-1} \]
- Part of antineutrino in the U and Th decay chains is emitted with \( E > 1.8 \text{ MeV} \) (IBD threshold)
- Contributions from U and Th are distinguishable
- Oscillations are averaged:
  \[ <P_{ee}> = 0.548^{+0.012}_{-0.013} \]

\[ \bar{\nu} + p \rightarrow n + e^+ \]
\[ E_{\nu} > 1.8 \text{ MeV} \]
Main backgrounds in geo-neutrino measurements

1) **Reactor antineutrinos** (81% of the total antineutrino signal in KamLAND geo-nu window [0.9-2.6 MeV] and ~36% for the Borexino case): Geo/Reactor ratio 0.23 in KL vs 1.8 in Borexino;

2) **Cosmic muons** induced backgrounds, including cosmogenic production of ($\beta n$)-decaying isotopes (at LNGS the muons flux is of about factor 7 lower than at the Kamioka site)

3) **Internal radioactive contamination:** accidental coincidences, ($\alpha n$) reactions
Data selection for geo-neutrino analysis

• Total exposition is $907\pm44$ t·yr taking into account detection efficiency
• Antineutrino are detected using delayed coincidence tag from the inverse beta-decay on proton ($\sim 256$ μs)

\[
\bar{\nu}_e + p \rightarrow e^+ + n
\]
\[
\downarrow \approx 250 \ \mu s
\]
\[
n + p \rightarrow d + \gamma (2.2 \text{MeV})
\]

• $\sim 500$ p.e./MeV for electrons
• 438 p.e./2 x 511 keV $\gamma$'s
Set of antineutrino cuts

1. \( Q_{prompt} > 408 \text{ p.e.} : 3\sigma(E) \text{ above } 2m_e \)
2. \( 860 < Q_{delayed} < 1300 \text{ p.e} \)
3. \( \Delta R < 1 \text{ m} \)
4. \( 20 < \Delta t < 1280 \mu s \)
5. Pulse shape. \( g_{\alpha\beta}(\text{delayed}) < 0.015 \) : selecting e-like events (prompt signal from fast n is \( \alpha \)-like)
6. \( T_\mu > 2 \text{ ms} \) : fast neutrons after muon
7. \( T_\mu > 2 \text{ s} \) for every muon passing through internal detector. Long-lived cosmogenic (\( \beta n \)) isotopes. \( \sim 10\% \) of live time loss.
8. Multiplicity cut: no n-like events in \( \pm 2 \text{ ms} \) window
9. \( R_{IV}(\Theta,\phi) - R_{prompt}(\Theta,\phi) > 0.30 \text{ m} \) : dynamical, follows IV shape
10. FADC cut : independent check of candidates features with 400 MHz digitizing system

Total efficiency = $84.2 \pm 1.5\% \text{ (MC)}$. 77 candidates selected
## Summary of backgrounds

<table>
<thead>
<tr>
<th>Source</th>
<th>events</th>
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<tbody>
<tr>
<td>Cosmogenic $^9$Li and $^8$He</td>
<td>$0.194 \pm 0.015$ (stat)$^{+0.124}_{-0.088}$ (syst)</td>
</tr>
<tr>
<td>Fast neutrons from $\mu$ in Water Tank</td>
<td>$&lt; 0.01$ (90% CL) (measured)</td>
</tr>
<tr>
<td>Fast neutrons from $\mu$ in rock</td>
<td>$&lt; 0.43$ (90% CL) (MC)</td>
</tr>
<tr>
<td>Non-identified muons</td>
<td>$0.12 \pm 0.01$</td>
</tr>
<tr>
<td>Accidental coincidences</td>
<td>$0.221 \pm 0.004$</td>
</tr>
<tr>
<td>Time correlated background</td>
<td>$0.035 \pm 0.028$ (stat)$^{+0.006}_{-0.004}$ (syst)</td>
</tr>
<tr>
<td>Spontaneous fission in PMTs</td>
<td>$0.032 \pm 0.003$</td>
</tr>
<tr>
<td>$(\alpha,n)$ reactions in the scintillator $^{210}$Po</td>
<td>$0.165 \pm 0.010$ (stat)</td>
</tr>
<tr>
<td>$(\alpha,n)$ reactions in the buffer $^{210}$Po</td>
<td>$&lt; 0.66$ (90% CL)</td>
</tr>
<tr>
<td>$^{214}$Bi-$^{214}$Po</td>
<td>$0.009 \pm 0.013$</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$0.78 \ ^{+0.13}_{-0.10}$</td>
</tr>
</tbody>
</table>
Selected antineutrino spectrum (77 events)

\[ Q_{\text{vis}} = 438 \, \text{p.e.} (2\gamma) + Q(E_\nu - 1.8 \, \text{MeV}) \approx 500 \, \text{p.e./MeV} \]
Fit results

- Predicted reactor signal $87 \pm 4$ TNU

- $N_{\text{geo}} = 23.7^{+6.4}_{-5.7} \text{(stat)}^{+0.9}_{-0.6} \text{(syst)}$ events
  $S_{\text{geo}} = 43.5^{+11.8}_{-10.4} \text{(stat)}^{+2.7}_{-2.4} \text{(syst)}$ TNU

- $N_{\text{react}} = 52.6^{+8.5}_{-7.7} \text{(stat)}^{+0.7}_{-0.9} \text{(syst)}$ events
  $S_{\text{react}} = 96.5^{+15.6}_{-14.2} \text{(stat)}^{+4.9}_{-5.0} \text{(syst)}$ TNU

- Systematics: 4.8% on FV and 1% on the energy scale
$S_{\text{geo}} : S_{\text{react}}$ for fixed Th/U = 3.9

3.6 \cdot 10^{-9}$ probability of $N_{\text{geo}} = 0$

(5.9 $\sigma$)

For Th/U = 3.9:

$\Phi(U) = (2.7^{+0.8}_{-0.7}) \times 10^6$ cm$^{-2}$s$^{-1}$

$\Phi(\text{Th}) = (2.3^{+0.7}_{-0.6}) \times 10^6$ cm$^{-2}$s$^{-1}$

1, 3 and 5 $\sigma$ contours for $S_{\text{geo}} : S_{\text{react}}$ signals
Unconstrained U/Th analysis

1, 2 and 3 σ contours for $S_{U}:S_{Th}$ signals
Radiogenic heat
Signal from the mantle

- Total contribution from the Earth crust (Huang et al.) (LOC + ROC) is
  \( S_{geo}(Crust) = (23.4 \pm 2.8) \) TNU -> 12.75 ±1.53 events (+stat.smearing)

- subtraction of probability distributions for the total signal (from the fit) and pdf for crust (normal approximation). Non-physical values of difference are excluded and final p.d.f. renormalized to unity.

  \[
  p.d.f.(Mantle) = p.d.f. (Geo) - p.d.f.(Crust) : \\
  S_{geo}(Mantle) = 20.9^{+15.1}_{-10.3} \text{TNU}
  \]

  with a probability of 98% we observe at least 1 event from the mantle

- Note:
  - Mean value is bigger compared to a simple difference \(<S_{geo}> - <S(Crust)> = 43.5 - 23.5 = 20.1\) as a result of excluding non-physical values from p.d.f.
Antineutrino measurements with Borexino

<table>
<thead>
<tr>
<th>Year</th>
<th>Live time, days</th>
<th>Exposition t·yr</th>
<th>$N_{\text{cand}}$</th>
<th>$N_{\text{geo}}$</th>
<th>$S_{\text{geo}}$</th>
<th>TNU</th>
<th>$P(0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>537.2</td>
<td>252.6</td>
<td>21</td>
<td>$9.9^{+4.1}_{-3.4}$</td>
<td>$65.2^{+27.0}_{-22.4}$</td>
<td>3·10^{-5} (4.2σ)</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>1363</td>
<td>613 ± 26</td>
<td>46</td>
<td>$14.3^{+4.4}_{-2}$</td>
<td>$38.8^{+12.0}_{-\cdot12}$</td>
<td>6·10^{-6} (4.9σ)</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>2056</td>
<td>907±44</td>
<td>77</td>
<td>$23.7^{+6.5}_{-5.7}$</td>
<td>$43.5^{+12.1}_{-10.7}$</td>
<td>3.6·10^{-9} (5.9σ)</td>
<td></td>
</tr>
</tbody>
</table>

• In the core (Herndon) on the core/mantle border (Rusov и de Meijer)
• 5-10 TW will help to explain heating, convection, He3 anomaly, geomagnetism and some other problems.
• Both are critisized by geochemists
• Easy to test with geoneutrinos, Borexino excludes georeactor with 4.5 TW power at 95% C.L.

Forming the Moon from a georeactor at the core-mantle boundary 4.5 Ga

Forming the Moon from terrestrial silicate-rich material (2013)
R.J. de Meijer, V.F. Anisichkin, W. van Westrenen
Another measurement with Borexino?

• We have accumulated another ~1.5 yrs of data and will run at least 1 yr more in solar mode before SOX program (+ ~50% statistics)
• Tuning of the muon-veto cut will save 9% of live-time
• We consider the possibility to perform a spectral fit in all volume (+ ~50%)
• Better understanding of “external” background” is needed
Nuclear physics for geoneutrino studies
Contribution of elements from U and Th chains in total geoneutrino signal

<table>
<thead>
<tr>
<th>$i \rightarrow j$</th>
<th>$R_{i,j}$</th>
<th>$E_{\text{max}}$ (keV)</th>
<th>$I_k$</th>
<th>$\Delta I_k$</th>
<th>Type (%)</th>
<th>$S_{U}$ (%)</th>
<th>$S_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{234}$Pa$_m \rightarrow ^{234}$U</td>
<td>0.9984</td>
<td>2268.92</td>
<td>0.9836</td>
<td>0.002</td>
<td>first forbidden $(0^-) \rightarrow 0^+$</td>
<td>39.62</td>
<td>31.21</td>
</tr>
<tr>
<td>$^{214}$Bi $\rightarrow ^{214}$Po</td>
<td>0.9998</td>
<td>3272.00</td>
<td>0.182</td>
<td>0.006</td>
<td>first forbidden $1^- \rightarrow 0^+$</td>
<td>58.21</td>
<td>45.84</td>
</tr>
<tr>
<td></td>
<td>2662.68</td>
<td>0.017</td>
<td>0.006</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1894.32</td>
<td>0.0743</td>
<td>0.0011</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1856.51</td>
<td>0.0081</td>
<td>0.0007</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{212}$Bi $\rightarrow ^{212}$Po</td>
<td>0.6406</td>
<td>2254</td>
<td>0.8658</td>
<td>0.0016</td>
<td>first forbidden $1^{(-)} \rightarrow 0^+$</td>
<td>94.15</td>
<td>20.00</td>
</tr>
<tr>
<td>$^{228}$Ac $\rightarrow ^{228}$Th</td>
<td>1.0000</td>
<td>2069.24</td>
<td>0.08</td>
<td>0.06</td>
<td>allowed $3^+ \rightarrow 2^+$</td>
<td>5.66</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>1940.18</td>
<td>0.008</td>
<td>0.006</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[Diagram showing nuclear decay chains and isotopes]
$^{214}\text{Bi}$

<table>
<thead>
<tr>
<th>$E_{\gamma,\text{(max)}}$ [keV]</th>
<th>$S_U$ [%]</th>
<th>$S_{\text{U+Th}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1894</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2663</td>
<td>2</td>
<td>1.6</td>
</tr>
<tr>
<td>3272</td>
<td>58</td>
<td>42</td>
</tr>
</tbody>
</table>
CTF (4 tonne Borexino prototype)
Experimental spectrum of $^{214}$Bi (CTF) with superimposed fit

(CTF) \[ p_0 = 0.177 \pm 0.004 \text{ (stat)} +0.003 \text{ (sys)} \]. \hspace{1cm} (11)

This value is consistent with that reported in ToI \[17\]:
\[ p_0(\text{ToI}) = 0.182 \pm 0.006 \].

New Tol value:
\[ p_0 = 0.1910 \pm 0.0017 \]
Deviation from the allowed (universal) shape

\[ \phi(T_e) = p_0 \Phi(T_e) + \sum_{n>0} p_n \Phi_{\text{univ}}(T_e, Q - E_n) \]

\[ \Phi(T_e) = \Phi_{\text{univ}}(T_e, Q) \left( 1 + y \frac{T_e - \langle T_e \rangle}{\langle T_e \rangle} \right) \]
Results for signal from $^{214}$Bi

\[(\text{CTF})\]
\[s(\text{\textsuperscript{214}Bi}) = [1.42 \pm 0.03 \text{ (stat)} \pm^{+0.023}_{-0.008} \text{ (sys)}] \times 10^{-44} \text{ cm}^2\]

\[(\text{ToI})\]
\[s(\text{\textsuperscript{214}Bi}) = [1.46 \pm 0.05 \text{ (stat)}] \times 10^{-44} \text{ cm}^2\]

With spectral deformations:

\[s(\text{\textsuperscript{214}Bi}) = [1.48 \pm 0.01 \text{ (stat)} \pm 0.03 \text{ (sys)}] \times 10^{-44} \text{ cm}^2\]
Geoneutrino with Borexino.
Summary.

1) Geoneutrino detection is now extremely robust in Borexino: $5.9\sigma \ (3.6 \cdot 10^{-9})$;

2) $S_{geo}(LNGS)=43.5^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(syst) \ TNU$

3) The precision is still too low: $\sim 25\%$ for U+Th signal with fixed ratio $Th/U=3.9$, and much worse for the unconstrained $R(U)$ and $R(Th)$ measurements. Geological models for the moment can’t be discriminated;

3) Radiogenic heat is in $11$-$51 \ TW$ interval at 68% CL

4) The mantle contribute positive signal at 98% CL: $S_{mantle}=20.9^{+15.1}_{-10.3} \ TNU$