Geo-neutrino results with Borexino

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International Conference on Particle Physics and Astrophysics 2015

October 06, 2015
Why geo-neutrinos? --

Geo-neutrinos are messengers from the Earth interior
-- especially of interest for the mantle knowledge

Radioactive decays inside the crust and the mantle of the Earth
-- $^{238}$U, $^{235}$U, $^{232}$Th decay series as well as $^{40}$K decay are involved and produced $\nu_e$ and anti-$\nu_e$ called geo-neutrinos

Differents Earth models exist (cosmo-chemical, geochemical, geodynamical etc...) and do not agree between themselves
-- Geo-neutrinos as a new source of information

Geo-neutrino measurements
-- Which geo-neutrinos? --

-- Anti-\(\bar{\nu}_e\) detection through inverse \(\beta\) decay interactions
-- \(\rightarrow\) Threshold at 1.8 MeV

\[
\begin{array}{cccccc}
\text{Element} & 2^{38}\text{U} & 2^{35}\text{U} & 2^{32}\text{Th} & 4^{0}\text{K}(\bar{\nu}_e) & 4^{0}\text{K}(\nu_e) \\
\hline
\tau_{1/2} \text{ (year)} & 4.47 \times 10^9 & 7.04 \times 10^8 & 1.40 \times 10^{10} & 1.28 \times 10^9 & 1.28 \times 10^9 \\
Q \text{ (MeV)} & 51.7 & 46.4 & 42.7 & 1.311 & 1.505 \\
Q_{\bar{\nu}_e} \text{ (pJ)} & 0.634 & 0.325 & 0.358 & 0.103 & - \\
\# \bar{\nu}_e & 6 & 4 & 4 & 1 & - \\
\mathcal{R}_{\bar{\nu}_e}(\bar{\nu}_e/(\text{g} \cdot \text{s})) & 7.46 \times 10^4 & 3.20 \times 10^5 & 1.63 \times 10^4 & 2.31 \times 10^5 & - \\
\# \nu_e & - & - & - & - & 1 \\
\mathcal{R}_{\nu_e}(\nu_e/(\text{g} \cdot \text{s})) & - & - & - & - & 2.77 \times 10^4 \\
E_{\text{max}} \text{ (MeV)} & 3.26 & 1.23 & 2.25 & 1.311 & 0.044 \\
\end{array}
\]

-- Only anti-\(\nu_e\) from \(2^{38}\text{U}\) and \(2^{32}\text{Th}\) decay series can be detected
Geo-neutrinos oscillation? --

-- Anti-$\nu_e$ from $^{238}\text{U}$ and $^{232}\text{Th}$ do oscillate

--> Survival probability of the geo-neutrinos:

$$P_{ee} = \cos^4 \theta_{13} \left( 1 - \sin^2(2\theta_{12}) \sin^2 \left( 1.27 \frac{\Delta m^2_{21}(\text{eV}^2)L(\text{m})}{E(\text{MeV})} \right) \right) + \sin^4 \theta_{13}$$

--> Oscillation length around 100 km $<< R_{\text{Earth}}$

--> Reasonable assumption of an averaged survival probability:

$$\langle P_{ee} \rangle = \cos^4 \theta_{13} \left( 1 - \frac{1}{2} \sin^2(2\theta_{12}) \right) + \sin^4 \theta_{13} = 0.55 \pm 0.03$$

-- Warning: not used for anti-$\nu_e$ from nuclear reactors (individual calculations)

Mixing angles and mass square differences are taken from Phys. Rev. D 89, 093018 (2014)
-- Detecting anti-$\nu_e$ --

-- Anti-$\nu_e$ detection through inverse $\beta$ decay interactions

$\bar{\nu}_e + p \rightarrow e^+ + n$

**Prompt signal (positron):**

- $e^+$ scintillation + annihilation
- $E_{\text{prompt}} \approx E_\nu - T_n - 0.8$ MeV

**Delayed signal (neutron):**

- $n$ capture on H
- $E_{\text{delayed}} \approx 2.2$ MeV
- $\Delta t \approx 260$ $\mu$s
-- The Borexino detector --

Fiducial volume 30 cm from the nylon vessel (used for the geo-neutrino analysis)

(used for solar neutrino analyses)
-- Selecting anti-$\nu_e$ --

-- Prompt signal: 1 MeV $\approx$ 500 p.e.
-- $Q_{prompt} > 408$ p.e.
-- Fiducial Volume Cut (FVC)

-- Delayed signal:
-- 860 < $Q_{delayed}$ < 1300 p.e.

-- Coincidence:
-- 20 < $\Delta t$ < 1280 $\mu$s
-- $\Delta R$ < 100 cm

-- 2 s dead time window applied after an internal muon and 2 ms dead time window applied after an external muon
-- No neutron event in the 2 ms time window before the prompt signal and in the 2 ms time window after the delayed signal

77 candidates
(2056 days of data taking between December 2007 and March 2015, 1842 days after muon cuts, exposure of $5.5 \times 10^{31}$ proton$\times$year)
-- Anti-$\nu_e$ energy spectra --

-- $Q_{\text{prompt}}$ spectrum contains both the geo-neutrino and the anti-$\nu_e$ from nuclear reactors (and the backgrounds)

--> Since $E_{\text{max}}(^{238}\text{U}) = 3.26$ MeV and $E_{\text{max}}(^{232}\text{Th}) = 2.25$ MeV, geo-neutrinos stand in the 4 first bins of the $Q_{\text{prompt}}$ spectrum

\begin{itemize}
  \item \textbf{Data}
  \item \textbf{Reactor neutrino}
  \item \textbf{Best-fit U+Th with fixed chondritic ratio}
  \item \textbf{U free parameter}
  \item \textbf{Th free parameter}
\end{itemize}

\begin{align*}
9^\text{Li}-8^\text{He} & \quad 0.194^{+0.125}_{-0.089} \\
\text{Accidental coincidences} & \quad 0.221 \pm 0.004 \\
\text{Time correlated} & \quad 0.035^{+0.029}_{-0.028} \\
(\alpha, n) \text{ in scintillator} & \quad 0.165 \pm 0.010 \\
(\alpha, n) \text{ in buffer} & \quad < 0.51 \\
\text{Fast n’s (μ in WT)} & \quad < 0.01 \\
\text{Fast n’s (μ in rock)} & \quad < 0.43 \\
\text{Untagged muons} & \quad 0.12 \pm 0.01 \\
\text{Fission in PMTs} & \quad 0.032 \pm 0.003 \\
214^\text{Bi}-214^\text{Po} & \quad 0.009 \pm 0.013 \\
\text{Total} & \quad 0.78^{+0.13}_{-0.10} \\
& \quad < 0.65 \text{ (combined)}
\end{align*}

Very low background (except for reactor background)!
--- Reactor background ---

--- Anti-$\nu_e$ from nuclear reactors are the main background (despite Italy is a nuclear free country)---

--- Estimation of the expected number of events from the spectral components of $^{235}$U, $^{238}$U, $^{239}$Pu and $^{241}$Pu---

--- Monte Carlo have been developed in order to take into account the 446 nuclear reactors running during the period of interest---
-- Fit analysis --

-- Unbinned maximum likelihood fit of the prompt energy spectrum of our anti-$\nu_e$ candidates (background components constrained)

-- Assuming a Th/U mass ratio of 3.9 (also called chondritic ratio), our best fit values are:

$$N_{geo} = 23.7^{+6.5}_{-5.7} \, (stat) \, ^{+0.9}_{-0.6} \, (syst)$$
$$N_{react} = 52.7^{+8.5}_{-7.7} \, (stat) \, ^{+0.7}_{-0.9} \, (syst)$$

which, in terms of TNU*, becomes:

$$S_{geo} = 43.5^{+11.8}_{-10.4} \, (stat) \, ^{+2.7}_{-2.4} \, (syst)$$
$$S_{react} = 96.6^{+15.6}_{-14.2} \, (stat) \, ^{+4.9}_{-5.0} \, (syst)$$

The hypothesis that $S_{geo} = 0$

is rejected at 5.9 $\sigma$

* 1 TNU = 1 event detected over 1 year exposure of $10^{32}$ target protons at 100 % efficiency
-- Fit analysis with U and Th left free --

-- Fit leaving the U and Th spectral contributions as free parameters

-- Demonstration of the possibility to discriminate the contributions from U and Th

--> Larger exposure needed


Best fit value compatible with the chondritic ratio of 3.9
-- Bulk Silicate Earth (BSE) models describe both the crust and the mantle

-- Different BSE models:
   1) Cosmochemical
   2) Geochemical
   3) Geodynamical

<table>
<thead>
<tr>
<th>BSE $S_{\text{geo}}$ [TNU]</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Low -</td>
<td>- High -</td>
</tr>
<tr>
<td>23.6</td>
<td>31.44</td>
</tr>
<tr>
<td>26.6</td>
<td>35.24</td>
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<tr>
<td>28.4</td>
<td>37.94</td>
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<td>39.34</td>
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<td>33.3</td>
<td>44.24</td>
</tr>
<tr>
<td>35.1</td>
<td>46.64</td>
</tr>
</tbody>
</table>

$S_{\text{geo}} = 43.5^{+12.1}_{-10.7}$ TNU from the Borexino fit analysis

Borexino results in agreement with BSE models
Radiogenic heat

Understanding the Earth’s energy budget
Radiogenic heat production for U and Th between 23 and 36 TW

Assuming a chondritic ratio of 3.9 and \( m(K)/m(U) = 10^4 \), the total terrestrial radiogenic power is:

\[
P(U + Th + K) = 33^{+28}_{-20} \text{ TW}
\]

(to be compared with the global terrestrial power \( P_{\text{tot}} = 47 \pm 2 \text{ TW} \))
-- Accessing geo-neutrinos from the mantle --

-- Measured signal = BSE signal = crust signal + mantle signal
where crust* = local crust (LOC) + rest of the crust (ROC)

-- Borexino:
   - $S_{geo}$ (total) = 43.5$^{+12.1}_{-10.7}$ TNU
   - $S_{geo}$ (crust) = 23.4 ± 2.8 TNU

\[
\begin{aligned}
S_{geo} \text{ (mantle)} &= 20.9^{+15.1}_{-10.3} \text{ TNU} \\
\end{aligned}
\]

-- KamLAND:
   - $S_{geo}$ (mantle) = 5.0 ± 7.3 TNU

The hypothesis that $S_{geo}$ (mantle) = 0
is rejected at 98% C.L.

Is there a natural nuclear reactor standing inside the Earth?

-- Monte Carlo built such that $^{235}\text{U}/^{238}\text{U} = 0.75/0.25$ (Pu set to 0)
-- Fit above 1510 p.e. in order to get rid of the geo-neutrino spectrum
-- Background components normalized, reactor component constrained to the theoretical value

$N_{\text{georeact}} < 8.4$ (10.5) events at 90% C.L. (95% C.L.)

$P_{\text{georeact}} < 3.4$ (4.2) TW at 90% C.L. (95% C.L.)
-- Conclusion --

-- We report an updated measurement of geo-neutrinos with Borexino

-- From 2056 days of data taking, Borexino alone is able:
   --> to reject the null geo-neutrino signal at 5.9 σ
   --> to claim a geo-neutrino signal from the mantle at 98% C.L.
   --> to restrict the radiogenic heat production for U and Th between 23 and 36 TW

-- Signal-to-background ratio of the order of 100
   --> Real time spectroscopy of anti-ν_e

-- Upper limit for a 3.4 TW georeactor (4.2 TW) at 90% C.L. (95% C.L.)
Thank you for your attention
-- $^{238}$U decay chain --
-- $^{232}$Th decay chain --