Solar and Geo Neutrino Physics with Borexino
RICAP - 2013

1. BOREXINO
2. Be-7 flux measurement
3. B-8 measurement
4. pep detection and CNO limit
5. Geoneutrinos
6. Future
on behalf of

the Borexino Collaboration
### 1. BOREXINO

Borexino is a low background Neutrino Detector for sub-MeV solar Neutrino (and other) studies.

Detecting Solar Neutrinos (and other rare phenomena) means:

- Low interaction rates: 0.1/1 event/day/ton of target mass
- Low energy (mostly <10 MeV, better if <2 MeV)
- Low threshold and low background
- Underground location to shield from cosmic rays

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Experimental site

Abruzzo, Italy
120 Km from Rome

Laboratori Nazionali del Gran Sasso
Assergi (AQ)
Italy
1400m of rock shielding
~3800 m.w.e.

External Labs

Borexino Detector and Plan
The Borexino Detector

Neutrino electron scattering
\( \nu e \rightarrow \nu e \)

**Stainless Steel Sphere:**
- 2212 PMTs
- ~ 1000 m³ buffer of pc+dmp (light quenched)

**Scintillator:**
270 t PC+PPO (1.4 g/l)

**Nylon vessels:**
(125 \( \mu \)m thick)
Inner: 4.25 m
Outer: 5.50 m
(radon barrier)

**Carbon Steel Plates**

Water Tank:
- \( \gamma \) and n shield
- \( \mu \) water Č detector
- 208 PMTs in water
- 2100 m³

20 legs
Filling phase of the Borexino detector (2007, Laboratorio del Gran Sasso)

- Scintillator
- Photomultipliers
- Water
- Nylon Vessels

11 m
Energy production in the Sun

**pp-cycle**
- >99% energy production
- 5 neutrino species

**CNO-cycle**
- <1% energy production
- 3 neutrino species

\[
\begin{align*}
\text{pp} & : & p^+ + p^+ & \rightarrow 2H + e^+ + \nu_e & (99.77\%) \\
& & & & (0.23\%) \\
& & & & (10^{-5}\%) \\
\text{hep} & : & ^2H + p^+ & \rightarrow ^3He + \gamma & (15.08\%) \\
& & & & (99.9\%) \\
& & & & (0.1\%) \\
\text{ppI} & : & ^3He + ^4He & \rightarrow ^7Be + \gamma & (84.92\%) \\
& & & & (99.9\%) \\
\text{ppII} & : & ^7Be + e^- & \rightarrow ^7Li + \nu_e & (15.08\%) \\
& & & & (99.9\%) \\
\text{ppIII} & : & ^8B & \rightarrow ^4He + ^4He & (15.08\%) \\
\end{align*}
\]
Solar Neutrino Spectrum

BPS(GS98) 2008
Neutrino Spectrum ($\pm 1\sigma$)

- pp $\rightarrow \pm 0.5\%$
- $^7\text{Be} \rightarrow \pm 5.8\%$
- pep $\rightarrow \pm 1.1\%$
- $^8\text{B} \rightarrow \pm 11.3\%$
- hep $\rightarrow \pm 15.5\%$

Gallium, Borexino, Chlorine

SuperK, SNO
Radiochemical experiments discovered Solar Neutrinos (1960s). The Sun is powered by nuclear fusion!

Kamiokande measured solar $v_e$ $^8$B neutrinos (1980s).

But detected $v_e$ flux $\sim 1/3$ of expected: “The Solar Neutrino Problem”

SNO measured (2000) the total $v_e$ and $v_x$ flux from $^8$B neutrinos demonstrating neutrino oscillations.
However: before Borexino, only radiochemical experiments could observe solar neutrinos below 1 MeV. Real-time experiments were sensible to > 5 MeV.

Open Issues

- Is MSW-LMA correct? How well can we test the model?
- Physics beyond the Standard Model can affect the features of the $P_{ee}$ dependence on neutrino energy.
- Probe the $P_{ee}$ transition region.
- How well are solar neutrino fluxes predicted by the SSM? Two competing models High and Low Metallicity.
2. Be-7 flux measurement

$E_e = 862 \text{ keV (monoenergetic)}$

$\Phi_{\text{NSM}} = 4.8 \cdot 10^9 \text{ } \nu \text{ s}^{-1} \text{ cm}^2$

$^7\text{Be} + e^- \rightarrow ^7\text{Li} + (\nu_e)$

Cross Section $\approx 10^{-44} \text{ cm}^2 \text{ (@ 1 MeV)}$

Electron recoil spectrum

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$^7$Be neutrinos

- Large flux: 100 times larger than $^8$B.
- Flux predicted with 7% uncertainty.
- Mono-energetic $E = 862$ keV.

$$46.0 \pm 1.5^{+1.6}_{-1.5} \text{ c/d \cdot 100 t}$$

$^7\text{Be} \nu_e$ flux: LMA

$$\Phi = (4.84 \pm 0.24) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$$
3. B-8 measurement

Analysis with 3 MeV threshold
Borexino rate: \( \approx 0.2 \text{ cpd} / (100 \text{ tons}) \)
Backgrounds:
- Muons, Neutrons
- External background
- Fast cosmogenics
- C-10, Be-11
- Tl-208, Bi-214

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\[ R = 0.22 \pm 0.04(\text{stat}) \pm 0.01(\text{syst}) \text{ cpd} / 100 \text{t} \ (\text{above 3 MeV}) \]

\textbf{8B neutrinos}

Lowering energy threshold to see increase in \( P_{ee} \) at lower energies.

\textbf{2010:} SNO (3.5 MeV, Phase I and II), Borexino (3 MeV)

\textbf{2011:} KamLAND (5.5 MeV), SNO (Phase III), SKIII (5 MeV)

All current observations consistent with expectations:
4. pep detection and CNO limit

Pep reaction:

\[ p + e^- + p \rightarrow d + \nu_e \]

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Monoenergetic 1.44 MeV neutrinos
pep and CNO neutrinos

- Tests of MSW-LMA with $^7$Be limited due to uncertainty in solar flux.
- pep flux predicted with higher precision, 1.2% uncertainty. Allows for more stringent tests of oscillation models. Also mono-energetic.
- CNO fluxes directly related to Solar Metallicity. Allows to discern between High Z and Low Z models.
- Fluxes 10 times smaller than $^7$Be. End points 1-2 MeV. $^{11}$C is the dominant background in Borexino.
Going for pep and CNO: $^{11}\text{C}$ tagging

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

$\tau$ (n capture): $\sim 250\mu s$

$n + p \rightarrow d + \gamma_{2.2\text{MeV}}$

$^{11}\text{C} \rightarrow ^{11}\text{B} + e^+ + \nu_e$

$\tau$ ($^{11}\text{C}$): $\sim 30\text{min}$

The main background for pep and CNO analysis is $^{11}\text{C}$, a long lived ($\tau=30\text{min}$) cosmogenic $\beta^+$ emitter with $\sim 1\text{MeV}$ end-point (shifted to 1-2MeV range)

$^{11}\text{C}$ Production Channels:

1. 95.5% with $n$: $(X,X+n)$
   - $X = \gamma, n, p, \pi^\pm, e^\pm, \mu.$
2. 4.5% invisible:
   - $(p,d); (\pi^+, \pi^0+p).$

$^{11}\text{C}$ rate = $(28.5 \pm 0.5)$ cpd

exp. pep rate $\sim 3$ cpd

RICAP Rome - May 2013
Going for pep and CNO: positronium

Electron/Positron discrimination due to Ps formation in positron events (D. Franco, G. Consolati and D. Trezzi, Phys. Rev. C 83 (2011) 015504)

FIG. 2 (color). Experimental distribution of the pulse-shape parameter (black data points). The best-fit distribution (dashed black line) and the corresponding $e^-$ (solid red line) and $e^+$ (solid blue line) contributions are also shown.
C-11 reduction strategy:

- Threefold coincidence (muon, neutron, C11)
- Pulse shape discrimination electron/gamma/positron (Ps formation)
- Multivariate fit with also energy and position

First pep measurement and the best CNO limit

\[ \Phi_{\text{pep}} (MSW - LMA) = (1.6 \pm 0.3) \times 10^8 \text{ cm}^{-2} \text{s}^{-1} \]

\[ \Phi_{\text{CNO}} (MSW - LMA) < 7.7 \times 10^8 \text{ cm}^{-2} \text{s}^{-1} \text{ (95\% CL)} \]
Solar neutrino components measured by Borexino
Neutrino Oscillations properties measured by Borexino

Solar electron neutrino survival probability as a function of neutrino energy LMA-MSW with standard neutrino interactions
5. Geoneutrinos

AntiNeutrinos emitted in beta decays of naturally occurring radioactive isotopes in the Earth’s crust and mantle

Moderate Nuclear Reactors bkgd at LNGS

Detection by Inverse Beta Decay (1.8 MeV thr.)

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

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Positron-Gamma (2.2 MeV) delayed coincidence
Search for positron/neutron-captured delayed coincidences in the Borexino detector
Main background sources:
• Li-9, He-8, untagged muons, accidentals………
• And of course nuclear reactors
• First observation published in 2010

New analysis based on 1353 days of data
1353 days in Borexino: antineutrino geo analysis

Nuclear Reactor component:

Found: 21 events above geo endpoint

Expected: 22.0 ± 1.6

Geoneutrinos vs Reactor neutrinos:

Free parameters
- Weight of Geo nu
- Weight Reactor nu

Th/U = 3.9 fixed (condhritic value)

68.27%, 95.45%, 99.73% Confidence level contour plots for geo and reactor neutrinos

Extreme expectations of BSE (Bulk Silicate Earth) model

Reactor signal expectation

(1 TNU = 1 Terrestrial Neutrino Unit = 1 event/year/10^{32} protons)
Best fit values:

\[
N_{geo} = (14.3 \pm 4.4) \quad \text{TNU} \quad S_{geo} = (38.8 \pm 12.0) \quad \text{TNU}
\]

\[
N_{reac} = 31.2_{-6.1}^{+7.0} \quad S_{reac} = 84.5_{-16.9}^{+19.3} \quad \text{TNU}
\]

Geofluxes

\[
\Phi(U) = (2.4 \pm 0.7) \times 10^6 \quad \text{cm}^2 \text{s}^{-1}
\]

\[
\Phi(Th) = (2.0 \pm 0.6) \times 10^6 \quad \text{cm}^2 \text{s}^{-1}
\]

If U, Th contributions are left free:

\[
\Phi(U) = (2.1 \pm 1.5) \times 10^6 \quad \text{cm}^2 \text{s}^{-1}
\]

\[
\Phi(Th) = (2.6 \pm 3.1) \times 10^6 \quad \text{cm}^2 \text{s}^{-1}
\]
6. Future (summary)

Borexino Phase II:
- pp detection
- CNO study
- Sterile Neutrino search (SOX)

Cycles of Purification (Water Extraction):
- Reduce $^{85}$Kr and $^{210}$Bi affecting the pep and CNO analyses
- Kr background reduced to a negligible rate
- Bi-210 reduced (tens of counts/day 100 tons) and possibly studied by means of the time evolution of Po-210 rate.

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CNO detection

CNO reactions are responsible for less than 1% of the Sun energy generation

However, this cycle should be dominant for higher mass stars

Given their small flux and low energy, neutrinos from CNO have never been measured directly.

pp detection

They make up more than 90% of the total flux and have never been directly observed.

Main source of background is C-14 and its pileup effect.

C-14 spectral shape and pileup
Short distance neutrino Oscillations with BoreXino (SOX)

Experimental anomalies which are difficult to accomodate in a simple 3-flavor scenario


Borexino can be used to perform a short baseline experiment with neutrino source

Exploration of parameters in the plane $(\Delta m^2_{14}, \sin^2 2\theta_{14})$

L/E of the order of eV$^2$
A. The Cr-51 source, with an activity of \(~10\) Mci

Obtained by irradiation of Cr-50.

3-months experiment to be performed in 2015

B. A Ce-144 antineutrino source can be used. Due to the antineutrino tag, the activity could be much smaller, in the 80 kCi range.

C. The Ce-144 source positioned at the center of the detector
Thank you for your attention (& selected bibliography)

Neutrino Oscillations

\[ |\nu_t\rangle = \sum_{i=1}^{3} U_{ti} |\nu_i\rangle \]

PMNS neutrino mixing matrix, analogous to CKM matrix for quarks

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = 
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[ \sin^2(2\theta_{12}) = 0.861^{+0.026}_{-0.022} \]

\[ \Delta m_{21}^2 = (7.59+0.21) \times 10^{-5} \text{ eV}^2 \]

\[ \sin^2(2\theta_{23}) > 0.92 \text{ [i]} \]

\[ \Delta m_{32}^2 = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2 \]

\[ 0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34) \]

Solution of the Solar Neutrino Problem is neutrino oscillation with matter (MSW) effect at Large Mixing Angle (LMA)

\[ P_{ee} = 1 - \sin^2 2\theta \sin^2 (\Delta m^2 L/4E_\nu) \]