Experimental evidence of electron neutrino oscillations and validation of MSW-LMA model with Borexino

Margherita Buizza Avanzini for the Borexino Coll.
BEFORE SOLAR NEUTRINOS... THE SUN BURNING

98% of energy through the pp chain

CNO? Just 2% of energy...
BEFORE SOLAR NEUTRINOS... THE SUN BURNING

98% of energy through the pp chain

GNO? Just 2% of energy...

But what about neutrinos?!
SOLAR NEUTRINOS

Standard Solar Model (BPS09) predicts **fluxes** and **spectra** of $\nu_e$:

Real time Cherenkov experiments can investigate only the final part of $^8$B spectrum.

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The **survival probability** of $\nu_e$ for the MSW-LMA solution:

**VACUUM REGION**: low energy, oscillations like in the vacuum.

**VACUUM-MATTER TRANSITION**: in between

**MATTER REGION**: high energy, oscillation affected by the matter effect (MSW effect)
THE MSW-LMA SOLUTION

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- **VACUUM REGION**: low energy, oscillations like in the vacuum.
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- **MATTER REGION**: high energy, oscillation affected by the matter effect (**MSW effect**)

\[ \nu_e \] real time experiment with energy threshold of detected electron at about **4 MeV** ($\approx 10^{-4}$ of the total flux) $\rightarrow$ **matter region**.

**What new with Borexino??**
THE BOREXINO EXPERIMENT

For the first time in real time:

- **Test of Standard Solar Model**: precise measurement of $^7\text{Be}$ neutrino flux!
- **Test of MSW-LMA solution** at low energy!
- BOREXINO can measure ALSO $^8\text{B}$ neutrinos!
- Energy threshold for $^8\text{B}$ neutrinos down to **3 MeV** (electron energy)!

**First real time experiment for low energy solar neutrinos!**

- Main goal: $^7\text{Be}$ flux measurement
- But also: measure of $^8\text{B}$ neutrinos!!!
- And for the future... **pep** and **pp**
**THE BOREXINO DETECTOR**

**Water Tank:**
- γ and n shield
- μ water Ch detector
- 208 PMTs in water
- 2100 m$^3$

**Scintillator:**
- 270 t PC+PO in a 125 μm thick nylon vessel

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

**Stainless Steel Sphere:**
- 2212 photomultipliers
- 1350 m$^3$

**Software cut at 3m,**
- defining the Fiducial Volume (100tons)

**Detection of solar ν through the elastic scattering** on electrons in high purified scintillator (300tons).
R_{7Be} = 49 \pm 3_{\text{stat}} \pm 4_{\text{sys}} \text{ c/d/100 tons}
\textbf{EXPECTED RATE SSM+MSW-LMA}

Whole energy spectrum: $\sim 0.5 \text{ c/d/100 tons}$

Above $5 \text{ MeV}$: $\sim 0.14 \text{ c/d/100 tons}$

BUT we can decrease the threshold down to $3 \text{ MeV}$ !!!
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8B NEUTRINO FLUX MEASUREMENT (1)

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Why the energy threshold at 3MeV??
2.6MeV gammas from $^{208}\text{Tl}$ coming from the PMTs reaching the FV

Setting the threshold at 3MeV
BACKGOUND SOURCES (above 3MeV)

DATA SPECTRUM BEFORE THE ANALYSIS

Rate: 50 c/d/100 t

live-time: 345.3 d

Signal/Bkg ratio < 1/150 !!!

HARD GOAL!
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HARD GOAL!

- Cosmic muons
- High energy $\gamma$ (4.9 MeV) from neutron capture on $^{12}$C
- Cosmogenic isotopes
  - $^{214}$Bi and $^{208}$Tl from vessel contamination of $^{238}$U and $^{232}$Th
  - $^{214}$Bi and $^{208}$Tl from internal contamination of $^{238}$U and $^{232}$Th

Ad hoc technique for each kind of background !!!
BACKGROUND SOURCES (above 3MeV)

MUONS AND COSMOGENIC NEUTRONS

Study of the pulse shape in the scintillator ≠ point-like events!!
+ rejection of gamma from n capture, in coincidence with the µ
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COSMOGENIC ISOTOPES

Study of cosmogenic isotopes through the coincidence with the father muon.
Rate measurements in agreement with Kamland results (arXiv:0907.0066)
\[ ^{214}\text{Bi} \] \[ \beta \rightarrow ^{214}\text{Po} \] \[ \alpha \rightarrow ^{210}\text{Pb} \]

\[ \tau = 236 \ \mu s \]

Search for fast coincidences in time and space between

**BACKGROUND SOURCES (above 3MeV)**
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$^{214}\text{Bi CONTAMINATION}$

Searching for fast coincidences in time and space between $^{214}\text{Bi}$ and $^{214}\text{Po}$

$^{214}\text{Bi} \xrightarrow{\beta} \tau = 236$ $\mu$s $\xrightarrow{\alpha} ^{210}\text{Pb}$

FIDUCIAL VOLUME CUT

Radon contamination from the vessel... diffusion and decay in $^{214}\text{Bi}$ and $^{208}\text{Tl}$

$\rightarrow$ Necessity of a radial cut at 3m
$^8\text{B NEUTRINO FLUX MEASUREMENT (2)}$

**ENERGY SPECTRUM OF OUR DATA**

- After muons rejection
- After cosmogenic rejection
- After radial cut

![Energy Spectrum Graph](image)
RESULTS ON THE $^8$B $\nu$ MEASUREMENT (1)

Comparison data/MonteCarlo for 345.3 d of livetime:

Phys. Rev. D82, 033006, 2010
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Statistically subtracted
RESULTS ON THE $^8$B ν MEASUREMENT (2)

$R_{8B} (E>3\text{MeV}) = 0.217 \pm 0.038_{\text{stat}} \pm 0.008_{\text{sys}} \text{ c/d/100 tons}$

$R_{8B} (E>5\text{MeV}) = 0.134 \pm 0.022_{\text{stat}} \pm 0.008_{\text{sys}} \text{ c/d/100 tons}$
- $^7$Be + constraint on pp: experimental evidence in the vacuum region!!!
- $^8$B: 2 new points in the matter region!!!
$P_{ee}(^7\text{Be}) / P_{ee}(^8\text{B}) = 1.93 \pm 0.75$

Vacuum/matter ratio @ 1.9 $\sigma$ level !!

Using data from the same apparatus !!
WHAT ELSE?? DAY-NIGHT ASYMMETRY !!

- **MSW mechanism**: $\nu_\mu$ interaction in the Earth could lead to a $\nu_e$ regeneration effect

- The size of the effect depends on:
  - detector **latitude**
  - neutrino **energy**
  - oscillation **parameters**

- **Very small effect expected with MSW-LMA**:
  - LOW solution predicts a large ADN effect
  - LMA and LOW predict similar $^7$Be absolute values but very different ADN

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J. Bahcall et al., JHEP07(2002)05
**WHAT ELSE?? DAY-NIGHT ASYMMETRY !!**

\[
ADN = \frac{N - D}{(N + D)/2}
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ADN STUDY IN BOREXINO

Although already excluded by reactor+radiochemical data, **Borexino alone** can add an independent confirmation.

The $^7\text{Be}$ flux is obtained from the separate full fits of the day and night spectra

- $^7\text{Be}$ Day spectrum: 387.46 days
- $^7\text{Be}$ Night spectrum: 401.57 days

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ADN = \frac{N - D}{(N + D)/2} = 0.007 \pm 0.073 \text{ (stat)}
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**Borexino alone validates the MSW-LMA model!!!**

New analysis in progress with 2/3 times better sentitivity
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ADN MAY PROBE NEW PHYSICS

Mass Varying Model


Very large predicted effect:

\[ \text{ADN} = -23\% \]

(note negative sign!)

Borexino alone excludes the Mass Varying Model !!!
AND FOR THE FUTURE?!

$^8\text{B}$ and $^7\text{Be}$ NEUTRINOS!!

- Reduce the error on $^7\text{Be}$ flux down to 5%
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  ➞ better constraint also on pp neutrinos

- Reduce the energy threshold on \(^8\text{B}\) neutrino measurement down to 2MeV 
  ➞ approaching the unexplored region between 1 and 3 MeV !!!
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$^7\text{Be}$, $^8\text{B}$ and pep NEUTRINOS!!

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- Reduce the energy threshold on $^8\text{B}$ neutrino measurements down to 2MeV
  - approaching the unexplored region between 1 and 3 MeV !!!

- Pep measurement:
  fundamental test of $P_{ee}$ in an unexplored energy region!!