BOREXINO - Status and Calibration

International Workshop on "Double Beta Decay and Neutrinos"
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Borexino Collaboration

- College de France (France)
- Technische Universität München (Germany)
- JINR Dubna (Russia)
- Kurchatov Institute Moscow (Russia)
- MPI Heidelberg (Germany)
- Jagellonian University Cracow (Poland)
- INFN – Milano (Italy)
- INFN – Genova (Italy)
- INFN – Perugia (Italy)
- INFN – LNGS (Italy)
- Princeton Univeristy (USA)
- Virginia Tech (USA)

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• Designed to spectroscopically measure low energy solar neutrinos, especially $^7\text{Be}$
• Liquid Scintillator Spectrometer
• $\nu + e^{-} \rightarrow \nu^{'} + e^{-}$
  • Charged Current
  • Neutral Current
Borexino

\[ 7\text{Be} + e^- \rightarrow 7\text{Li} + \nu_e \]

Monochromatic \( E_\nu = 862 \text{ keV} \)

\( \Phi_{SSM} = 4.8 \times 10^9 \text{ v/sec/cm}^2 \)

Expected rate (LMA) is \( \sim 35 \) counts/day between 0.25-0.8 MeV

\[ \nu_e \quad \leftrightarrow \quad \nu_x \]

\[ v - e \text{ scatt. CC} \]

\[ v - e \text{ scatt. NC} \]

\[ \sigma \approx 5.3 \times 10^{-45} \text{ cm}^2 \]

\[ \sigma \approx 1 \times 10^{-45} \text{ cm}^2 \]
Science in Borexino

- Measure $^7$Be solar neutrinos (0.25-0.8 MeV)
  - Measured vs MSW-LMA predicted event rate
  - $1/r^2$ solar signature

- Study CNO and pep (~1-2 pep ev/d) neutrinos (0.8-1.3 MeV) (rejection of $^{11}$C cosmogenic background – proven in CTF hep-ex/0601035)

- Geoneutrinos (10 – 30 ev/year)

- Supernova Neutrinos (~120 ev from GC supernova)


- ...
Publications (since 2002)

- The Nylon Scintillator Containment Vessels for the Borexino Solar Neutrino Experiment.
  - J. Benziger et al. Feb 2007: physics/0702162
- Supernova neutrino detection in Borexino.
- Search for electron antineutrino interactions with the Borexino counting test facility at Gran Sasso.
- Experimental scintillator purification tests with silica gel Chromatography.
- Cosmogenic 11C production and sensitivity of organic scintillator detectors to pep and CNO neutrinos.
- Radon permeability through nylon at various humidities used in the Borexino experiment.
- New experimental limits on violations of the Pauli exclusion principle obtained with the Borexino Counting Test Facility
- Ultra-traces of 226Ra in nylon used in the Borexino solar neutrino experiment.
- A Sampling Board Optimized for Pulse Shape Discrimination in Liquid Scintillator Applications
- The measurements of 2200 ETL9351 type photomultipliers for the Borexino experiment with the photomultiplier testing facility at LNGS
- The photomultiplier tube testing facility for the Borexino experiment at LNGS
- Precision measurements of time characteristics of the 8" ETL9351 series photomultiplier
- Light concentrators for Borexino and CTF
- A multiplexed optical-fiber system for the PMT calibration of the Borexino experiment.
• **Search for the Solar pp- neutrinos with an upgrade of CTF detector**
  • Smirnov O., Zaimidoroga O., Derbin A.

• **Setting of the Predefined Multiplier Gain of a Photomultiplier.**
  • O. Ju. Smirnov

• **New experimental limits on heavy neutrino mixing in B-8 decay obtained with the Prototype of the Borexino Detector**

• **Study of the neutrino electromagnetic properties with the Prototype of the Borexino Detector**

• **New limits on nucleon decays into invisible channels with the BOREXINO Counting Test Facility**

• **Search for electron decay mode e → γ + ν with prototype of Borexino detector.**

• **Measurements of extremely low radioactivity levels in BOREXINO.**
  • Astroparticle Physics 18 (2002) 1.

• **Science and Technology of Borexino: A Real Time Detector for Low Energy Solar Neutrinos**
  • Astroparticle Physics 16 (2002) 205.

• **Search for neutrino radiative decay with a prototype Borexino detector**
  • Derbin A., Smirnov O.

• **Resolutions of a large volume liquid scintillator detector.**
  • O. Ju. Smirnov.
    Instruments and Experimental Techniques, 2003 No 2

• **Effects of absorption and reemission of photons in large scintillation counters on the quantities measured by an observing phototubes.**
  • G. Ranucci.

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Main challenge in Borexino: Radiopurity → Shell Structure

Components of the detector:

- Scintillator: 1,2,4-Trimethylbenzene (PC) + PPO (1.5 g/l) (300 t, 100 t fiducial mass)
- Nylon inner vessel (d = 8.5 m) - Nylon outer vessel
- Buffer liquid: PC + DMP (1040 ton)

- Stainless steel sphere (d = 13.7 m)
- ~2200 inner phototubes – ~1800 with light guides
- Outer Muon veto: 210 PMTs + tyvek panels
- External buffer of ultra-pure water
- Water Tank
- Calibration equipment
- Electronics and DAQ
View of SSS with PMTs and Light Guides Installed
Nylon Vessels in SSS prior to inflation (2004)
Inflated Nylon Vessels in SSS

Borexino

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Filling with Ultrapure Water

Borexino
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Water (on top) is replaced by Scintillator
May 15, 2007: Borexino completely filled with Scintillator!
Motivation for Calibration

Precision neutrino science:
- Systematics need to be known
- \(1/r^2\) solar signature

Challenges in Borexino:
No event signature (only spectroscopic)
A. Radiopurity
   Requirements defined design, construction and filling
B. Energy
   Quenching – different energy response to \(\alpha,\beta,\gamma\) \(\Rightarrow\) Cal. sources
C. \(\alpha/\beta\) separation (pulse shape discrimination)
   is critical due to \(^{210}\text{Po}\) + other \(\alpha\) sources at low energies
   spatial and energy dependence \(\Rightarrow\) Cal. sources
D. Fiducial Volume \(\Rightarrow\) Cal. sources
   Definition of absolute mass
   Solar signal \(1/r^2\) (Stability of FV over time)
   Characterization of external background
Borexino Calibration

A variety of calibration and monitoring systems are planned:

• Making use of intrinsic radioactivity ($^{14}$C, Radon BiPo, neutron capture, …)

• Laser pulses distributed to all PMT’s with a fiber optics splitting system
  ⇒ Timing calibration
  ⇒ Gain adjustment via detection of the single photoelectron peak

• External sources (Th) located in the SSS close to the light guides
  ⇒ Check the stability over time of the overall detector response

• Internal sources inside the scintillator (Virginia Tech Source Calibration System)
  ⇒ Position reconstruction calibration
  ⇒ Energy calibration (and spatial dependence)
  ⇒ $\alpha/\beta$ Discrimination ( " " )
• CCD Cameras with capability to precisely locate objects inside the detector; a ≤ 2% uncertainty in the fiducial volume definition translates into ~ ±2 cm (part of the Virginia Tech Source Calibration System)

• Laser beams with different wavelengths through the buffer and laser excitation of the scintillator
  ⇒ Stability monitoring of the optical properties
  ⇒ Tuning of Monte Carlo

• Blue LED’s + fibers for the outer muon veto detector
Novel approach to source calibration system:
A) Mechanical insertion to approximate position
B) Precise optical position determination
Source Insertion System (SIS)

- Maps out cylinders in IV
- Neutrally buoyant in scintillator
- Source changing is box at same pressure as IV
- Only approximate source position
Source Insertion System
Calibration Sources

- Possible $\alpha$-sources:
  - $^{238}\text{U}$ (4.2 MeV), $^{232}\text{Th}$ (4.0 MeV), $^{222}\text{Rn}$ (5.6 MeV), $^{210}\text{Po}$ (5.4 MeV)
- Radon was used in the Borexino Counting Test Facility (CTF)
- U and Th have long half lives
  - Contamination concern
- Radon has short half life
  - Higher energy

- Sources are made with scintillator from inner vessel (IV)
- Vial is evacuated and loaded with source material
- Scintillator is then pumped from IV
- When it is sure that the scintillator being pumped is from the IV, source is loaded with scintillator
The Optical Source Locating System

Goals:
- Locate Internal Sources to +/- 2cm
- Locate Internal Fiber Optics
- Monitor Vessel Shapes
- Provide Photos for PR

Strategy:
- Mount cameras at approximately orthogonal positions and use triangulation to reconstruct position
- Use LEDs (with PMTs on, but trigger disabled) on objects to locate
- 7 cameras ➔ 14 independent numbers to determine x,y,z
Source Locating System

- Camera Kodak DC290 with additional fish-eye lens
- Mounted in Stainless steel housings
- The Borexino Counting Test Facility (CTF) was equipped with 3 cameras
- Borexino has 7 cameras installed
Pictures from the CTF

Featured in:
- Alitalia in-flight magazine
- INFN 50th anniversary book

- Cover of “Proceedings of the 5th International Topical Workshop at LNGS on Solar Neutrinos: Where Are the Oscillations?“
- Italian Photography Magazines
Control of Cameras and Lights

Software:

Hardware:

Cameras & Lights are controlled remotely, fully automated
Challenges

- Cameras are not pin-hole
- Cameras are multi-lens systems that project 3d space onto a 2d image
- CCD image plane may not be perpendicular to optical axis, lenses may be misaligned
- Installed Orientation of camera must be determined with pixel accuracy

⇒ The resulting image is distorted

Corrections are necessary
Camera Calibration - Strategy

- Each camera/lens system must be calibrated
- Fit camera roll, pitch, yaw
- Fit CCD x, y pixel offsets and scale
- Fit lens parameters
- Use known positions of PMTs
Roll, Pitch and Yaw

- **Roll**
- **Pitch**
- **Yaw**
CCD Offset and Scale

Optical axis

x and y offset

x

y
Radial & Decentering Correction for Optical Distortion

Radial correction:

\[ r' = \sum_i c_i r^i \]

Decentering correction:

\[
\begin{pmatrix}
    x' \\
    y'
\end{pmatrix} = \begin{pmatrix}
    r' \cos \phi \\
    r' \sin \phi
\end{pmatrix} + p_1 \begin{pmatrix}
    r'^2 \\
    r'^2 + 2 r'^2 \cos^2 \phi
\end{pmatrix} + p_2 \begin{pmatrix}
    r'^2 \\
    r'^2 + 2 r'^2 \sin^2 \phi
\end{pmatrix} + 2 p_2 r'^2 \cos \phi \sin \phi + 2 p_1 r'^2 \cos \phi \sin \phi
\]

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About 100 calibration pts / camera
Additional Correction: “Tweak”

Problem:
- Consumer Kodak camera DC290 with Nikon lens
- Focus and zoom not locked
- Each picture has $x, y$ shift and scale factor which need to be corrected for on a case-by-case basis (without this one gets only $\pm 5$ cm position)

Solution:
- Turn on in-camera LEDs for every picture.
  Use two points (four numbers) to correct scale and shift.
- The software can do this correction automatically, by finding known reference LEDs
Projection of rays from the six ‘other’ cameras. Their intersection should ideally be at a single point.
Largely automated system for source position reconstruction
VT Calibration System already in Use

Finding the Location of Nylon Vessel South Pole

Borexino

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Borexino

Determining the shape of the Nylon Vessels

Mark tangential interface of vessels

⇒ Calibration Software finds Position in space
VT Calibration System already in Use

**Result:**

Radii of Inner & Outer Vessel as a function of $\Phi$

- Buoyancy is visible
- Use vessel shape for Position reconstruction
- Monitor vessel shape Over time (Background Interpretation)

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Conclusions and Status

Borexino:

• The detector is filled & running.

VT Source Calibration System:

• The Source Locating System is fully operational
• With 7 cameras, +/- 2 cm seems obtainable ⇒ Fiducial Volume +/- 2%
• System is tested and works
• First uses to determine the Shape & Position of the vessels successful
• To be done:
  • Final Installation of Source Insertion Box
  • Production of calibration sources