Muons in Borexino

SFB Block Meeting

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Overview

Motivation

Borexino Physics:

- Realtime spectroscopic measurement of solar neutrinos
  - ^{7}Be
  - ^{8}B at low energies
  - CNO,pep,pp
- Geoneutrinos
- Supernova Neutrinos

Neutrinodetection using liquid scintillator

Solar Neutrinos

- Energy production in the Sun: Fusion
- $4p \rightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e + 26.7\,\mathrm{MeV}$
- Main process: *pp*-cycle
- Alternativly: CNO-cycle
- CNO percentage depending on metallicity Z.
- Metallicity: Abundance of heavy elements ($>$ He)
- SSM: Neutrino flux dependent on Z

Solar Neutrinos: pp-cycle

Fusion in the Sun - $4p \rightarrow^4 \text{He} + 2e^+ + 2\nu_e + 26.7\,\text{MeV}$:

$$p + p \rightarrow d + e^+ + \nu_e \quad (pp) \qquad p + e^- + p \rightarrow d + \nu_e \quad (pep)$$

$$d + p \rightarrow {}^3\text{He} + \gamma$$

pp I:

$$^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + p + p$$

pp II:

$$^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$$

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

$$^7\text{Li} + p \rightarrow {}^4\text{He} + {}^4\text{He}$$

pp III:

$$^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$$

$$^7\text{Be} + {}^1\text{H} \rightarrow {}^8\text{B} + \gamma$$

$$^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_e$$

$$^8\text{Be} \leftrightarrow {}^4\text{He} + {}^4\text{He}$$

pp IV / HEP:

$$^3\text{He} + {}^1\text{H} \rightarrow {}^4\text{He} + \nu_e + e^+$$

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pp IV / HEP:

$$^3\text{He} + {}^1\text{H} \rightarrow {}^4\text{He} + \nu_e + e^+$$

CNO:

$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$$

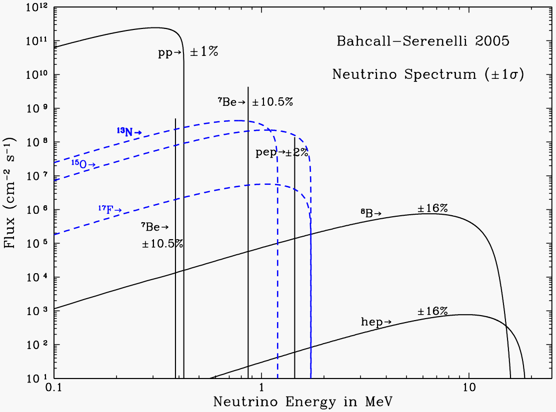
$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$$

$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$$

$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$$

$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He$$



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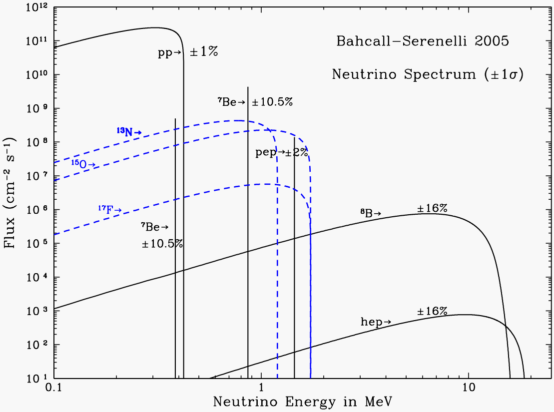

CNO Cycle / Neutrino Spectrum

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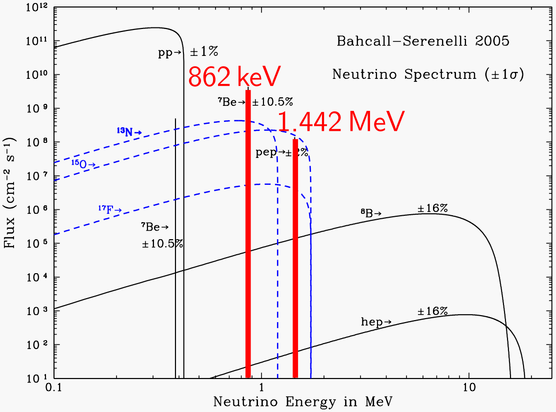
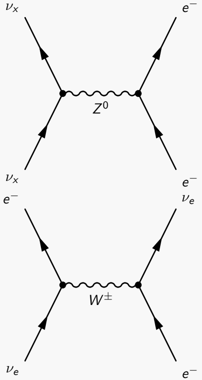
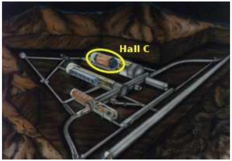


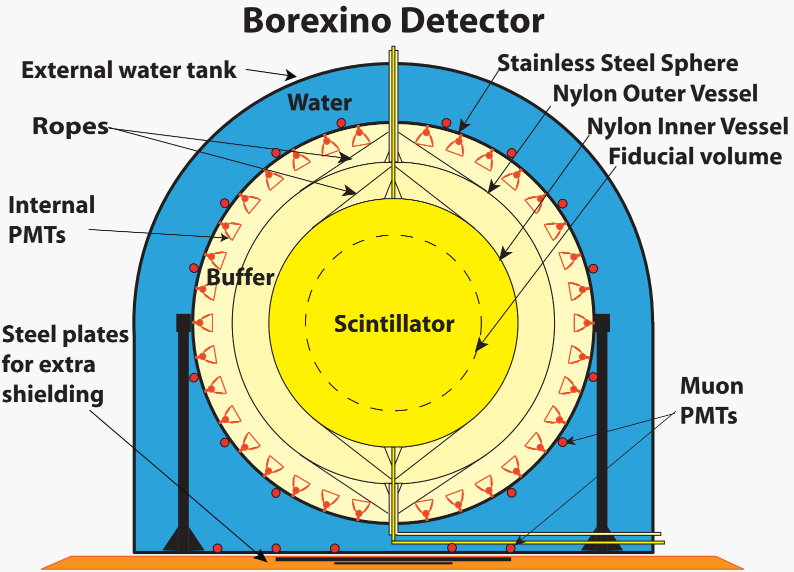
Neutrino Detection in Liquid Scintillators

- Scattering of neutrinos on electrons ($\nu_x + e^- \rightarrow \nu_x + e^-$)
- Cross section 6 times higher for electron type neutrinos
- Scattered electrons are detected by means of the scintillation light produced in the liquid scintillator
- Recoil electron profile is similar to that of Compton scattering of γ-rays
- Detection of scintillation light via PMTs

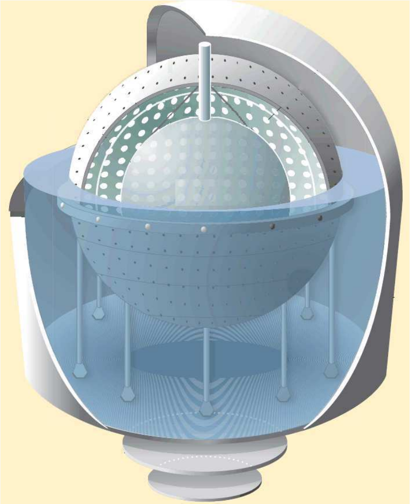


The Borexino Detector



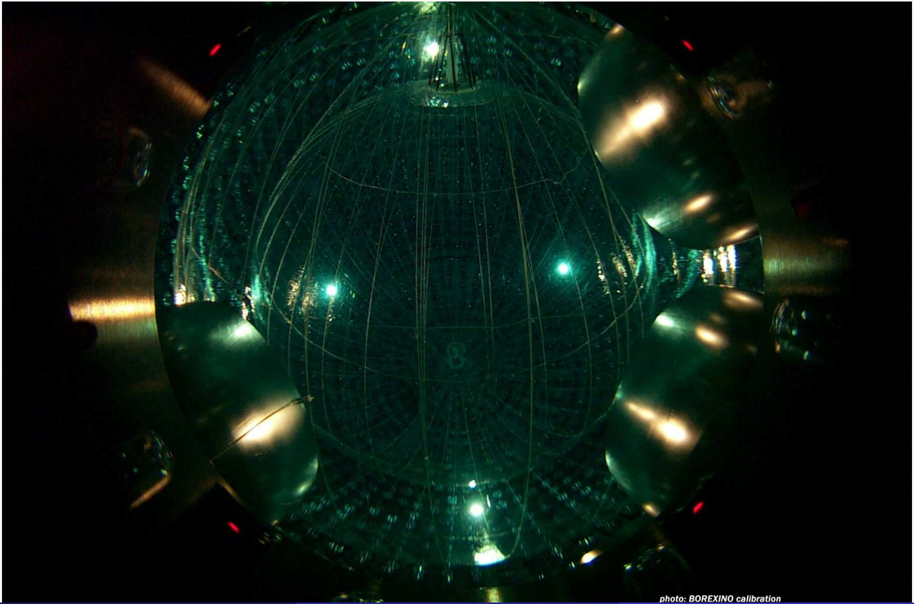

Borexino Detector
External water tank
Water
Ropes
Internal PMTs
Buffer
Scintillator
Steel plates for extra shielding
Stainless Steel Sphere
Nylon Outer Vessel
Nylon Inner Vessel
Fiducial volume
Muon PMTs

Detector Components



- Target: 300 tons of liquid scintillator contained in nylon vessel (⌀: 8.5 m)
- Stainless steel sphere (⌀:13.7 m) contains ∼1000 tons of buffer liquid
- Inside buffer: second nylon vessel (⌀: 11 m) as barrier for radon and other external background
- 2212 PMTs mounted on SSS
- Outer vessel: Čerenkov muon veto filled with 2.1 ktons of ultra pure water
- Total size: radius: 9 m, hight: 16.9 m

A View Inside



Detector Properties

- Covered by 1400 m of rock or 3800 m.w.e.
- No nuclear reactors nearby
- Approx. 5.5 m.w.e. shielding of the central volume from the rock
- $\rightarrow$ Predicted γ background in the fiducial volume is less than 0.5 counts/(day $\cdot$ 100 tons)

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- Limits neutrino observation to energies above 200 keV
- Trigger Rate: 15 Hz (Dominated by ^{14}C)

Main Background Sources

1. Cosmic muons are identified by Čerenkov veto
   - combined with pulse shape analysis: >99.99% efficiency

But: muon-induced background...

- Radio nuclides generated by spallation with long $T_{1/2}$

^{11}C 0.25 events/(day · ton)

^{10}C 5×10^{-3} events/(day · ton)

^{11}Be 1.5×10^{-3} events/(day · ton)

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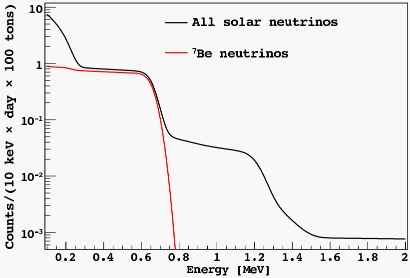
2. Radioactivity inside the detector
   - contamination from dust, scintillator, γs from SSS, PMTs

   Mainly:

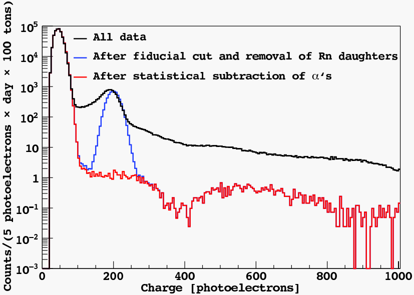
^{238}U	1.6×10^{-17} g/g
^{232}Th	6.8×10^{-18} g/g
^{40}K	$< 10^{-14}$ g/g
^{14}C	2×10^{-18} g/g
^{85}Kr	29 counts/day

^{7}Be Data – 192 Days of Data Taking

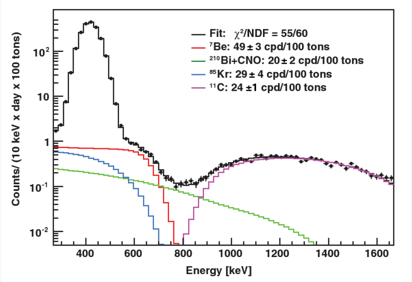
Expected:



Measured:

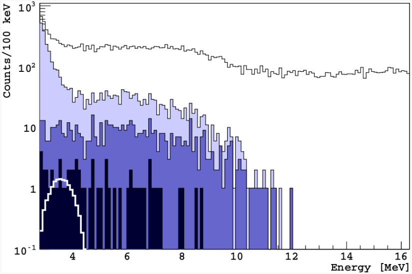


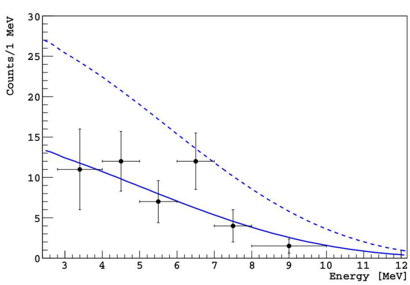
Fit:



- ^{14}C background dominates small energies
- ^{210}Po signal at 200 p.e.
- Clear compton edge at 380 p.e.
- Rise in spectrum due to ^{11}C cosmogenic events

^{8}B Data – 246 Days of Data Taking





Applied cuts:

- Muon cut
- Fiducial volume cut
- Statistical substraction of ^{208}Tl events

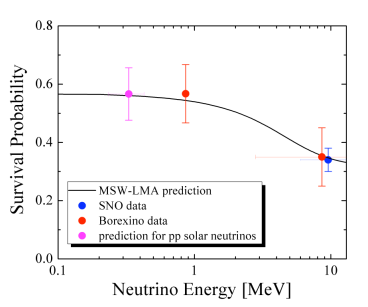
Results

- ^{7}Be-Neutrino Rate
  49 ± 3 events/(day· 100 tons)
- SSM with oscillation (large Z)
  48 ± 4 events/(day· 100 tons)
- SSM with oscillation (small Z)
  44 ± 4 events/(day· 100 tons)
- SSM without oscillation
  75 ± 4 events/(day· 100 tons)
- $P_{ee}^{^7\mathrm{Be}} = 0.56 \pm 0.10$

CNO contribution in the Sun 3.3 %

Agrees with MSW-LMA solution

- ^{8}B-Neutrino Rate
  $0{,}26 \pm 0{,}04_{\mathrm{stat}} \pm 0{,}02_{\mathrm{sys}}$ events/(day· 100 tons)
- Energy window: 2.8 – 16.3 MeV. $\bar{E} = 8.6$ MeV
- $P_{ee}^{^8\mathrm{B}} = 0.35 \pm 0.10$



The muon rate at GS is $\sim 1.16 \frac{\mu}{\text{day} \cdot \text{m}^2}$

About 4200 Muons pass the detector each day

- High energy deposition compared to solar ν
- $>$99.5% identified by Čerenkov Veto

Muons crossing only the outer vessel are not dangerous.

Muons passing the SSS are identified by

1. Pulse shape analysis
2. Outer Detector Trigger Flag (Hardware)
3. Presence of data in Outer Detector (Software)

Cosmogenics

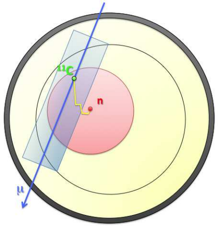
Uncorrelated cosmogenic events: $\mu + ^{12}\mathrm{C} \rightarrow \mu + ^{11}\mathrm{C} + n$

- ^{11}C: β^+-decay $T_{1/2} \sim$20 min
- e^+ signal between 1 and 2 MeV
- Not correlated to muon veto
- Same energy as *pep* and CNO neutrinos
- 25 counts per day and 100 tons

Solution: three fold coincidence

1. Reconstruct μ-track
2. γ from neutron capture shortly after muon
3. Delayed β^+-decay of C

Remove volume from fiducial volume for some $T_{1/2}$



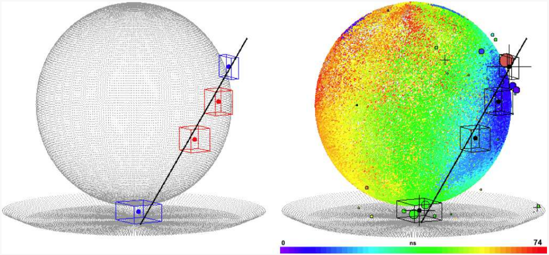
Muon Track Reconstruction

Outer detector - muon creates Čerenkov Light

1. Hit distribution of charge and time is created
2. Cluster recognition of PMTs that are close in space and time
3. Take two clusters most likely to produce track as entry and exit point

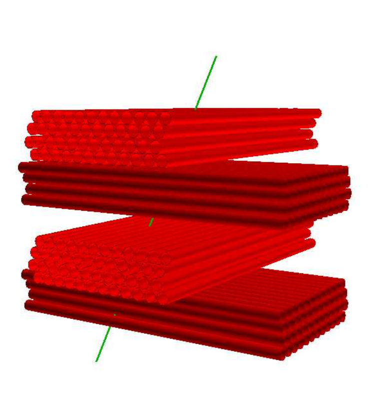
Inner detector - light from (quenched) scintillation and Čerenkov effect

1. Time distribution of hits is createtd
2. Barycenter of the hits in the first 5 ns indicates entry point
3. Angular orientation of simultanious hits: projection of track on sphere
4. Distance of the muon track to center is determined by visible light output and average time of all hits relative to start time in OD



Improving muon tracking: CMT

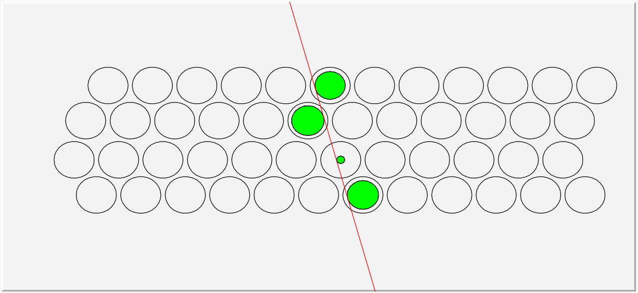
- CMT stands for **C**ompact **M**uon **T**racker.
- It uses drift-tube technology developed for OPERA.
- The tracker is made of four identical modules, arranged in four planes.
- Two planes are rotated at a stereo angle of 90°.



Drift-tube Modules

Each module consists of 48 aluminum drift-tubes.

- arranged in four layers à twelve tubes
- tube diameter of 38 mm
- 1 m long, total cross-section of $\approx 0.5 \times 0.15\,\text{m}^2$.
- gold-plated tungsten wire in the center (anode)
- operated at 2.35 kV



Operation

- Tracker is operated with a gas mixture of Ar/CO_2 at a ratio of 80/20 (safe).
- The gas is provided by a premixed gas bottle (lasts a few months).
- The tracker works at a pressure of $\approx 1000\,\text{mbar}$.
- The system is triggered by two layers of scintillators.
- Simple trigger logic (NIM), combined with a triggerboard.
- Support Boards used for setting thresholds, sending test pulses etc.

DAQ and Slow Control

Data aquisition and slow control are operated by on computer

Slow control:

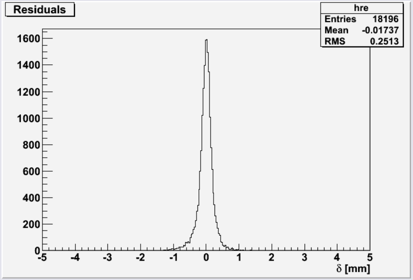
- Setting of threshholds
- Sending of testpulses (trigger and tubes)
- triggerconfiguration

DAQ

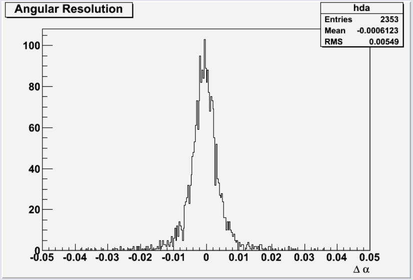
- Drift times are measured by two TDCs (96 channels each)
- TDCs are read out via Ethernet
- 4096 channels for a 3200 ns range
- Computer timestamp used for event time (only 1 s accuracy)

Performance

Spatial resolution $< 300\,\mu$m



Angular resolution $< 5\,$mrad



Spatial Resolution: RMS of residuals

Angular resolution: RMS of angle-differences divided by $\sqrt{2}$

Modifications for Borexino

Changed geometry to get a larger surface.

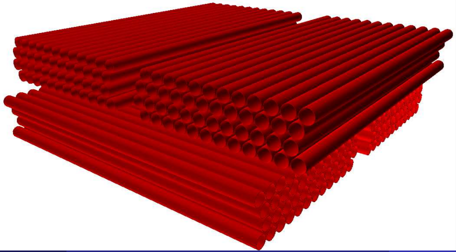
- Two modules next to each other in each plane.
- Only two planes (one at each stereo angle).

pro

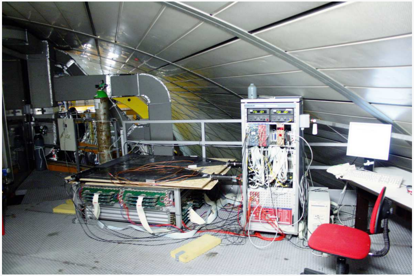
- $\approx 4\times$ larger surface
- compact ($\approx 1.2 \times 1.2 \times 0.5\,\mathrm{m}^3$)
- better angular acceptance

contra

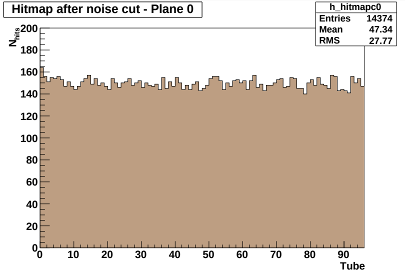
- smaller reconstruction efficiency ($\approx 93\%$)
- slightly lower resolution

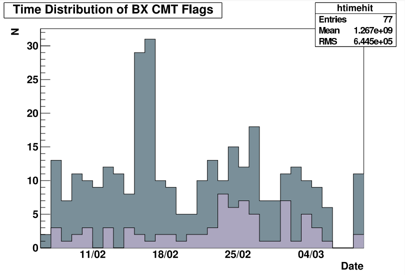


Setup @ Borexino



- Installation at Gran Sasso in November 2009
- Operation since Januar 2010
- Runs independently
- Trigger sets Flag in Borexino DAQ
- Remotely controlled via internet

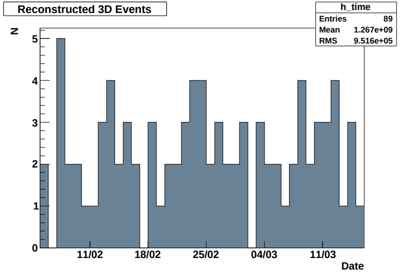




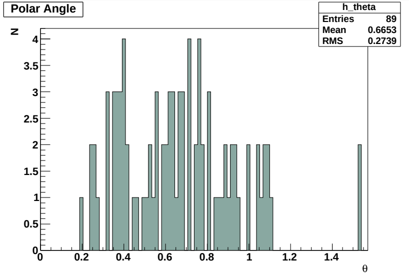
- DAQ running stable
- Triggerrate $\sim 0.03\,\mathrm{Hz}$
- Mainly due to noisy PMTs
- Fake trigger suppressed by demanding at least one fired tube

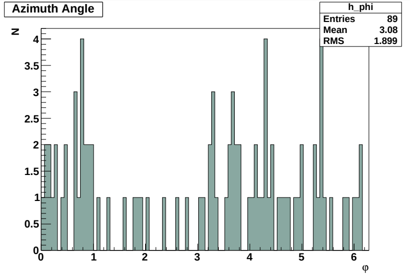
- Event: at least four hits in plane
- Less events than expected
- Not all BX events with CMT FLAG have an event
- Might be due to a defect triggerboard

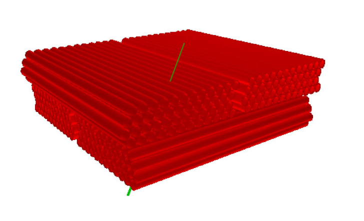
First Data



- Reconstruction demands at least fout hits per plane
- Reconstruction possible in ∼80% of all events
- Remaining events: mainly to few hits in lower plane

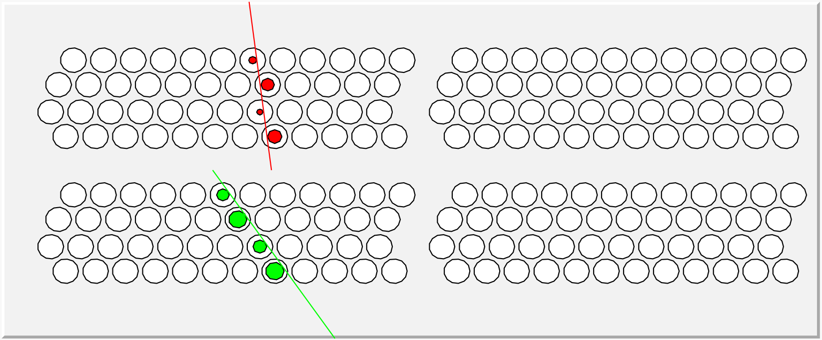






Event:

- 7. Feb. 2010 – 12:55:56 CET
- $\theta = 34.95^\circ$
- $\varphi = 10.41^\circ$
- Flag in BX DAQ



Summary and Outlook

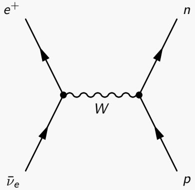
- Borexino is capable of detecting low energy neutrinos
- Detector is taking data since 2007
- First ^{7}Be data presented in 2008
- Upper limit for CNO contribution in the Sun: 3.3 %
- First ^{8}B measurement below 4.5 MeV presented in 2009
- Agreement with MSW-LMA solution.
- Detection of *pep* and CNO neutrinos seems feasible
- Interesting region dominated by cosmogenic background
- Muon tracking to be improved with help of CMT

8 Appendix

- Anti-Neutrino Detection in Liquid Scintillators
- The ^{7}Be Signal
- Detector Components
- Cuts
- Intrinsic Radioactivity
- Impact Parameter
- Geo Neutrinos

Anti-Neutrino Detection in Liquid Scintillators

- Detection via inverse β-decay ($p + \bar{\nu}_e \rightarrow e^+ + n$)
- Prompt annihilation signal of positron
- Second signal from neutron capture (2.2 MeV) after approx. 200 μs
- Coincidence in time
- Energy threshhold: 1.806 MeV
- Neutrino Energy correlated with prompt signal



Neutrinoenergy: $E_{\text{prompt}} = E_{\bar{\nu}_e} - \bar{E}_n - 0.8\,\text{MeV}$

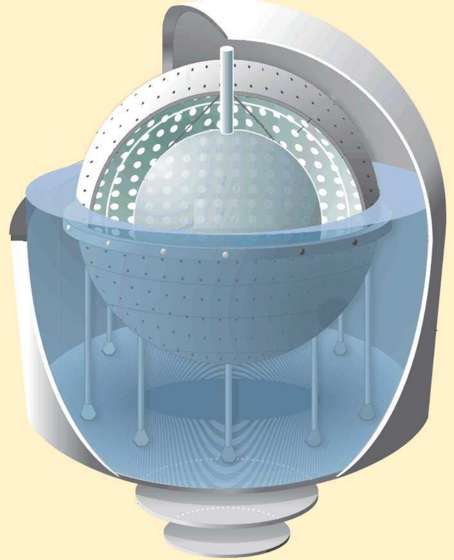
The ^{7}Be Signal

Low energy neutrinos can be detected by $\nu - e$ scattering in the scintillator

- ^{7}Be neutrinos are monoenergetic (862 keV).
- Compton-like scattering on electron
- Maximal recoil energy: 665 keV
- $\rightarrow$ Compton shoulder in energy spectrum

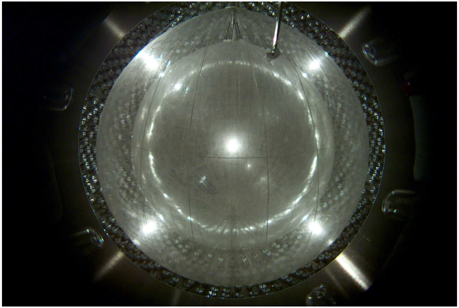
Monochromatic ^{7}Be neutrinos show two signaturs:

1. Recoil electron with clear Compton edge at 665 keV.
2. $\pm 3.5\%$ annual variation of the flux due to the Earth orbit eccentricity



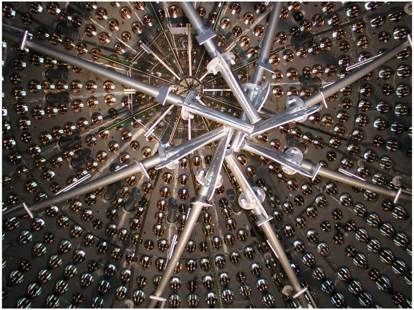
- 300-ton liquid scintillator
- contained in an 125 μm nylon inner vessel
- Radius: 4.25 m
- LS: pseudocumene (PC, 1,2,4-trimethylbenzene)
- doped with PPO (2,5-diphenyloxazole) 1.5 g/l

Outer Vessel - Buffer

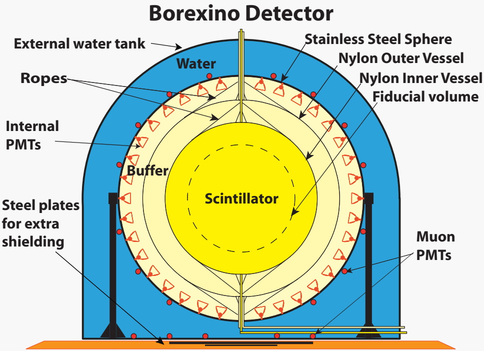


- 5.5 m radius
- pseudocumene
- 5.0g/l DMP (dimethylphthalate) to quench scintillation.
- OV is barrier against radon and other background contaminations from outside.

Stainless Steel Sphere

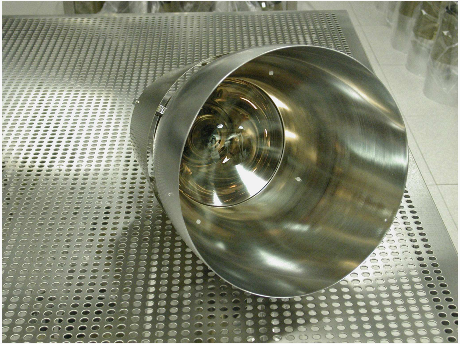


- Radius: 6.85 m
- Encloses PC-DMP buffer fluid.
- Approx. 1000 tons
- Support structure for PMTs



- Radius of 9 m
- Height of 16.9 m
- Filled with ultra pure water
- 208 PMTs acting as a Čenrenkov muon detector

Photo Multiplier



- 2212 8" PMTs (ETL 9351)
- uniformly distributed on the inner surface of the SSS
- Mostly equipped with aluminum light concentrators
- HV and readout shre one cable

Cuts for ^{7}Be Analysis (arXiv:0805.3843v2)

Events are selected by means of the following cuts:

1. Events must have a unique cluster of PMTs hits, to reject pile-up of multiple events in the same acquisition window.
2. Muons and all events within a time window of 2 ms after a muon are rejected.
3. Decays due to radon daughters occurring before the BiPo delayed coincidences are vetoed. The fraction surviving the veto is accounted for in the analysis.
4. Events must be reconstructed within a spherical fiducial volume corresponding approximately to 1/3 of the scintillator volume in order to reject external γ background. Additionally, we require the z-coordinate of the reconstructed vertex, measured from the center of the detector, to satisfy $|z|<1.7$ m in order to remove background near the poles of the inner nylon vessel.

The combined loss of fiducial exposure due to the cuts 1-3 is 0.7%. The fiducial cut 4 results in a fiducial mass of 78.5 tons.

Intrinsic Radioactivity

Radioactivity inside the detector

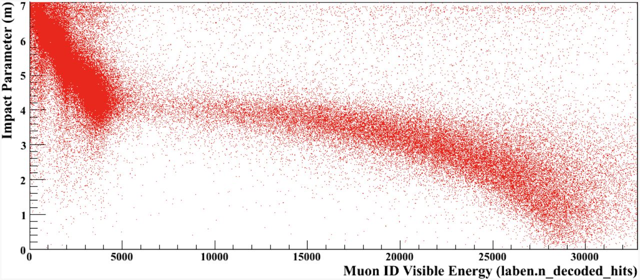
- ^{14}C in scintillator
- Contamination from SSS, PMTs, dust

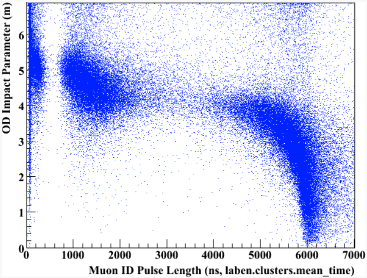
Isotope	Amount
^{14}C	10^{-18}g/g
^{238}U	$1.6 \pm 0{,}1 \times 10^{-17}$g/g
^{232}Th	$5 \pm 1 \times 10^{-18}$g/g
^{222}Rn	10^{-17}g/g
^{210}Po	7 events/day
^{40}K	$< 3 \times 10^{-18}$g/g

Determination of radioactive background:

- α-particles have discrete energies
- α-particles have different pulseshapes
- Many β-decays can be identified by coincidences from decay chains (Bi-Po)

Impact Parameter - taken from M. Wurm





Detection of Geo Neutrinos

Detection of geo neutrinos was reported this month (arXiv:1003.0284v1).

- 252.6 ton·yrs exposure
- $9.9^{+4.1}_{-3.4}$ geo neurino events