Water Purification in Borexino

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On behalf of the

Borexino Water Working Group:
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• M. Balata, L. Ioannucci, S. Nisi (Laboratorio Nazionale del Gran Sasso)
• A. Goretti, A. Ianni (Princeton University)

• Low Radioactivity Experiments
• Water as a Radiopure Shielding
• Water Purification in Borexino
• Results and Perspectives

Borexino Detector Filling in 2007
Low Radioactivity Experiments

Astroparticle Physics

Particle & Nuclear Physics

Astrophysics & Cosmology

Research topics:
- Solar Neutrinos
- Double Beta Decay
- Proton Stability
- Geoneutrinos
- Supernovae detection
- ....

Impact on fundamental physics (Weak Interactions, Neutrino Oscillation, Standard Model)

Physics experiments in which the signal searched for is swamped in a very high (dominant) background
1700 m of rock to shield against cosmic rays

3 Experimental Halls, each the size of a football field
**Scintillator:**
270 t PC+PPO (1.5 g/l)
in a 150 µm thick
inner nylon vessel (R = 4.25 m)

**Buffer region:**
PC+DMP quencher (5 g/l)
4.25 m < R < 6.75 m

**Outer nylon vessel:**
R = 5.50 m
(222Rn barrier)

**Water Tank:**
γ and n shield
µ water Č detector
208 PMTs in water
2100 m³

**Stainless Steel Sphere:**
R = 6.75 m
2212 PMTs
1350 m³

**Carbon steel plates**

20 steel legs
Detectors using water as a shielding or as a detecting medium

KamLAND
1000t
Running since 2002.

Borexino

300t
Running since 2007.

Super-Kamiokande
20000 t
Running since 1996.

SNO+

1000t
Starting in 2012

12/04/2013
LRT - LNGS, April 2013
What is the matter with a Low Background Experiment?

**SIGNAL**

- 50 events/day in 300 tonnes of liquid scintillator in Borexino (Be-7 signal)

**BACKGROUNDs**

- Cosmic Rays (even underground!) will need to be reduced by a factor \( \approx 10^3 \)
- Radioactivity of Materials. For U, Th, K normal concentrations, say as an example, \( 10^{-11} \text{ g/g} \) of \( ^{238}\text{U} \)

\[
dN(U^{238}) = \frac{0.693}{T_{1/2}} N = \frac{0.693}{1.64 \times 10^{12}} \frac{3 \times 10^{-3} \text{ g} \times 6 \times 10^{23}}{238 \text{ g}} = 3 \times 10^6 / \text{d}
\]

\( 300 \text{ t} \times 10^{-11} \text{ gU}^{238}/\text{g} = 3 \text{ mg U}^{238} \)

Signal to Noise ratio can be as low as \( 50 / 3 \times 10^6 \) !!
Water as a Radiopure Shielding (e.g. in Borexino)

Widely used in Low Radioactivity Experiments:

- Cheap
- Widely available
- Flexible shielding
- Can be purified
- Can be used for cleaning

Requirements for the Water Shield in (CTF) Borexino: $5 \times 10^{-6}$ Bq/kg

\[ 4 \times 10^{-13} \text{ g}^{238}U / \text{g} \]
Impurities in the Water

- **Inorganic salts**
  \[ Ba^{++}, Ca^{++}, Fe^{++}, H^+, K^+, Mg^{++}, Na^+, OH^-, Br^-, Cl^- \ldots \]
  Usually present in underground water at a TDS (Totally Dissolved Solids) of \( 10^2 – 10^3 \) mg/l. They are responsible for a total conductivity of about 150 \( \mu S/cm \) at LNGS.

- **Organic matter**
  \[ \text{Bacteria, Silica, Hydrocarbons...} \]
  Does not contribute to conductivity but can introduce radio-impurities and spoil transparency. Measured by TOC and Bacterial tests.

- **Dissolved gases**
  \[ CO_2, Kr, Ar, Rn \]
  Significant radioactivity problem mainly because of Rn-222 of the U chain, highly soluble in water. Does not contribute to conductivity except for \( CO_2 \) dissolution.
Water Conductivity

Perhaps the most important single parameter, besides direct counting of ions contributing to conductivity.

Units (conductivity, resistivity):

\[
\sigma = \text{Siemens/cm} = S/cm \quad S = \Omega^{-1}
\]

Equilibrium Constant of water \( \rightarrow \) self-ionization:

\[
H_2O + H_2O \rightleftharpoons H_3O^+ + OH^- 
\]

Water molecules dissociate into \( H_3O^+ \) and \( OH^- \). Concentrations are \( 1.00 \times 10^{-7} \text{ mol} \cdot \text{dm}^{-3} \) at 25 °C.

\[
\rho \leq 18.3 \text{ M\(\Omega\)} \cdot \text{cm} \at 25 \: ^{0}\text{C}
\]

Perfectly pure water: 18.3 M\(\Omega\) cm @ 25°C.
A synopsis of Water Purification Techniques
Reverse osmosis (RO):

- A membrane-technology filtration method
- Pressure applied to a solution when it is on one side of a selective membrane
- The solute is retained on the pressurized side of the membrane
- The pure solvent is allowed to pass to the other side

- The membrane (Thin Film Composite) does not allow large molecules or ions to pass through the pores

Reverse Osmosis efficiently removes large molecules and ions. It is a very broadly used purification technique.

Membrane grade porosity down to 10 MW. Typically will bring water up to:

\[ \rho \approx 1 \, M\Omega \cdot cm \, @ \, 25 \, ^\circ C \]
Continuous Deionization:

- Based on the Ion Exchange capability of Mixed Beds and their transport capability in an electric field.
- Anions and cations are removed by the Mixed Bed.
- Selective membranes are used to concentrate ions or cations.
- The applied electric field helps removing ions effectively.
- The electric field regenerates the Mixed Bed

\[ \rho \rightarrow 18.3 \ M \Omega \cdot cm \ @ \ 25 \ ^\circ C \]
Gas Stripping:

- A physical separation process where some components are removed from a liquid stream by a vapor stream.
- Can be in gas mode or vacuum mode (gas is absent but a vacuum is pulled)
- Can have co-current or countercurrent mode
- Can be carried out in a packed column to enhance the interface area between the liquid and the gas phase

Rn-222 in underground water can be as high as 10 Bq/kg

Requirements for the Water Shield in (CTF) Borexino: $5 \times 10^{-6}$ Bq/kg
Water Purification in Borexino

Requirements: produce high purity water for:

- Counting Test Facility (now hosting DarkSide) filling
- Borexino Filling
- Purification Processes (e.g. Water Extraction of Scintillator)
- Cleaning

- Built in 1993 (for CTF) to treat raw LNGS water
- Reduce U, Th from $10^{-10}$ g/g
- Reduce Rn-222 from 10,000 Bq/m$^3$ = 10 Bq/kg

$^{222}$Rn $< 3.4 \times 10^{-6}$ Bq/kg

$^{226}$Ra $< 1 \times 10^{-6}$ Bq/kg

The Borexino Water System is operational since 1994

- M.G. Giammarchi, Ultrapure Water 16 (1999) 76.
Borexino Main Water Purification Plant

Hall C of LNGS

Operational group for the system:
M. Balata, L. Ioannucci, S. Nisi, A. Ianni, A. Goretti
### Summary of the Water Purification System performance (Bq/kg)

<table>
<thead>
<tr>
<th></th>
<th>Water in</th>
<th>Water out</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238</td>
<td>$\sim 10^{-3}$</td>
<td>$3 \times 10^{-7}$</td>
</tr>
<tr>
<td>Ra-226</td>
<td>$0.3$</td>
<td>$&lt; 1 \times 10^{-6}$</td>
</tr>
<tr>
<td>Rn-222</td>
<td>$10$</td>
<td>$&lt; 3.4 \times 10^{-6}$</td>
</tr>
<tr>
<td>Th-232</td>
<td>$10^{-3}$</td>
<td>$3 \times 10^{-7}$</td>
</tr>
<tr>
<td>K-40</td>
<td>$10^{-3}$</td>
<td>$&lt; 1.6 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Unfortunately, no real clue on Pb or Po isotopes. Pb-208 measured as a tracer with hi-resolution mass spectrometry.

**Measurement techniques:**

- High resolution mass spectrometry (ICPMS)
- Neutron Activation
Conclusions

- Water Purification: an established technology in low background experiments (Superkamiokande, SNO, Kamland)
- Borexino features a reliable water plant (about 20 years of operation)
- More to understand in the future: Po, Pb
- The water plans has been recently refurbished
- To become a facility for LNGS experiments in general!
Thank you for your attention
Some water does not really need to be purified
Strontium-selective resins → also sensitive to Pb
A. Musilek et al., 2° International Conference on Po and Radioactive Pb Isotopes

EDTA technique to remove metals

Seeded Ultrafiltration Technique, microfileters coated with HTiO,Dtio (Th,Ra,Pb)

Acrylic beads coated with MnOx (Ra)

Silver deposition for Po determination
Po and Pb Radioisotopes

They are located at the end of U, Th radioactive chains.
The Actinium and Neptunium series (a less important role in experiments)
Borexino single photoelectron spectrum to search for Solar Neutrinos

Po-210 alpha decay

Not in equilibrium with Rn-222

Concentration of Po-210 in our scintillator before the analysis cuts

\[
\frac{3 \times 10^{-16}}{3 \times 10^8} g = 10^{-24}
\]

\[
P(Po210) = 10^6 \times 210 \times 1.6 \times 10^{-24} g = 3 \times 10^{-16} g
\]
Concentration of Pb-210 in our scintillator

Cannot measure by analytic methods.
Can measure by counting.
But in doing this we face all radioactivity components

\[ N = \frac{T_{1/2}}{0.693} \frac{dN}{dt} = \frac{22.3}{0.693} \text{ yr} \frac{23}{d} = 500 \text{ atoms} \]