Solar Neutrino Results and Future Opportunities with Borexino

Frank Calaprice
Princeton University
For the Borexino Collaboration

Other Talks on Borexino

Aldo Ianni, 10:45 AM Wed Plenary Session

"Solar Neutrinos and the Solar Model"

Oleg Smirnov, 16:40 PM Wed Neutrino Session

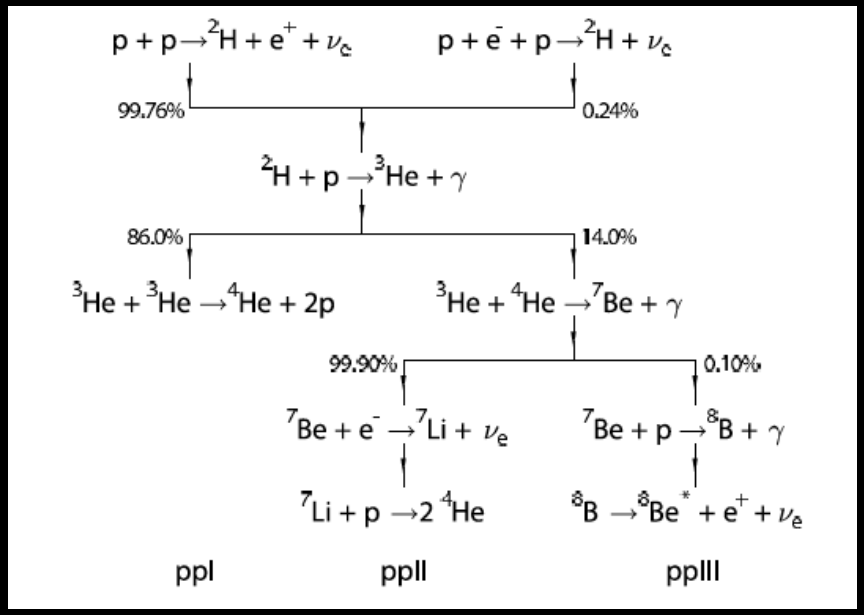
"SOX: Short distance Neutrino Oscillations with BoreXino"

Historical Notes

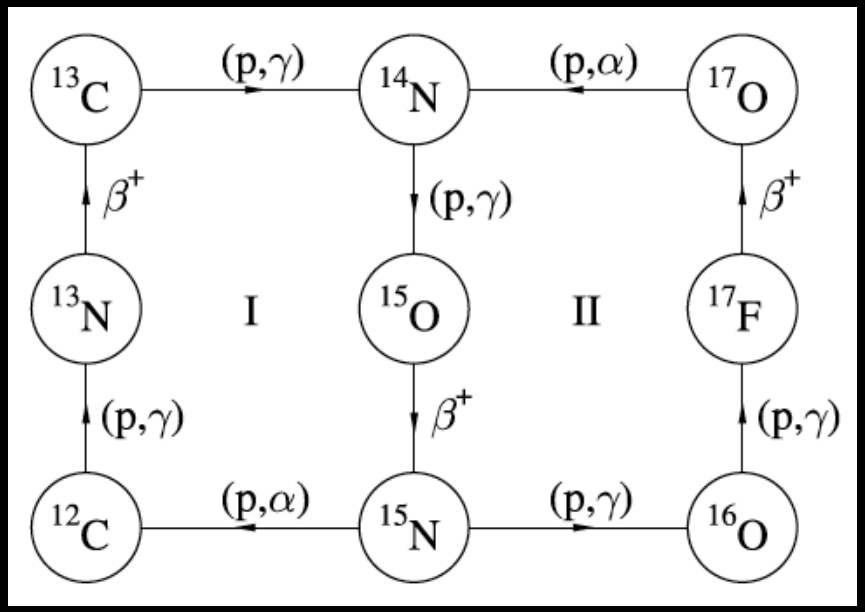
- **Borexino is a liquid scintillator detector developed to measure low energy solar neutrinos.**
- **R&D with the Counting Test Facility aimed for background with [U], [Th] < $5x10^{-16}$ g/g.**
- **First Borexino data in 2007 had backgrounds 25-70 times lower than initial requirements.**
  - [U] < $2x10^{-17}$ g/g
  - [Th] < $7x10^{-18}$ g/g.
- **Low background enabled the first measurement of ^{7}Be neutrinos, followed in 2008-2010 by**
  - **pep and ^{8}B solar neutrinos**
  - Geo-neutrinos
  - Searches for rare decays.
- **A second phase started in 2010 with scintillator re-purification to reduce backgrounds**
  - Goal: pp and CNO neutrinos.
- **Backgrounds are much improved:**
  - [U] ~1.6×10^{-19} g/g (100 times lower!)
  - [Th] < 1.2×10^{-18} g/g (> 6 times lower).
  - ^{85}Kr and ^{210}B also much lower (critical for pp and CNO)
- **Yet lower backgrounds needed for CNO.**

Solar Nuclear Fusion Cycles

The pp cycle

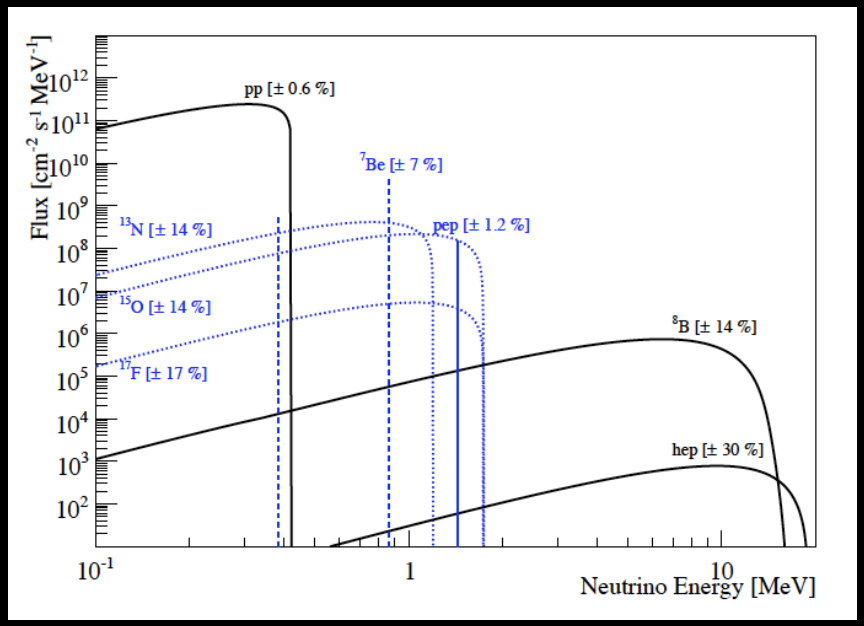


The CNO cycle

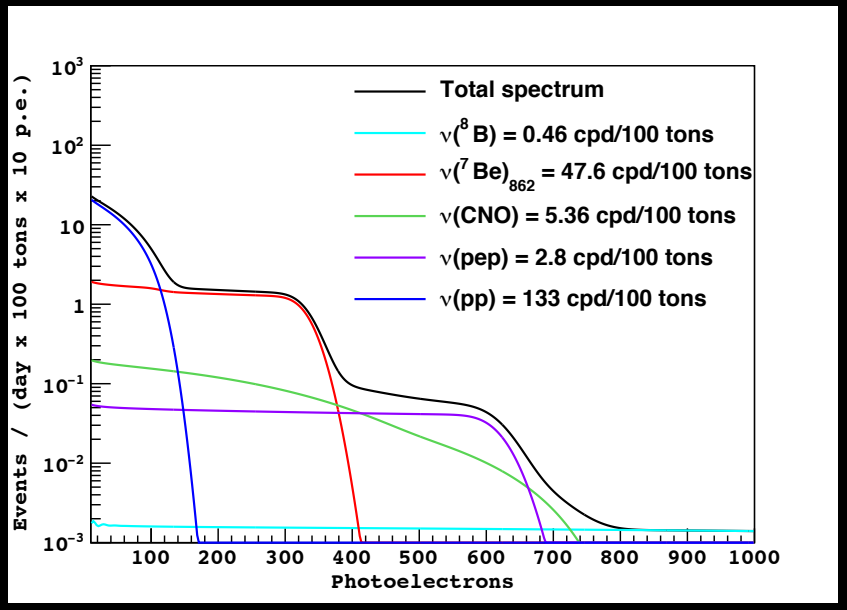


Solar Neutrino Spectra

Neutrino Energy Spectrum



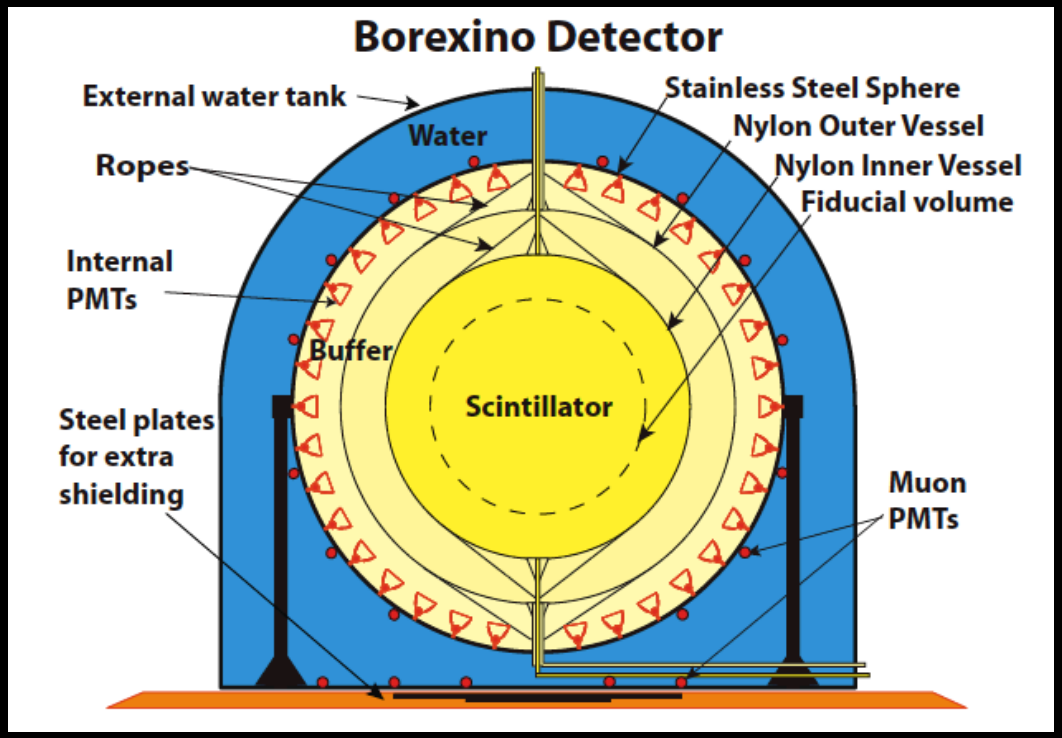
Neutrino-Electron Elastic Scattering Energy Spectrum



Overview of the Borexino Detector

(Mostly Active Shielding)

- Shielding Against Ext. Backgnd.
  - Water: 2.25m
  - Buffer zones: 2.5 m
  - Outer scintillator zone: 1.25 m
- Main backgrounds: in Liq. Scint.
  - $^{14}C/^{12}C$
    - 10^{-18} g/g. cf. 10^{-11} g/g in air CO_2
  - U, Th impurities
  - ^{222}Rn daught (^{210}Pb, ^{210}Bi, ^{210}Po)
  - ^{85}Kr
- Light yield (2200 PMT's)
  - Detected: 500 p_e/MeV (~4%)
- Pulse shape discrimination.
  - Alpha-beta separation



Strategy for Low Background

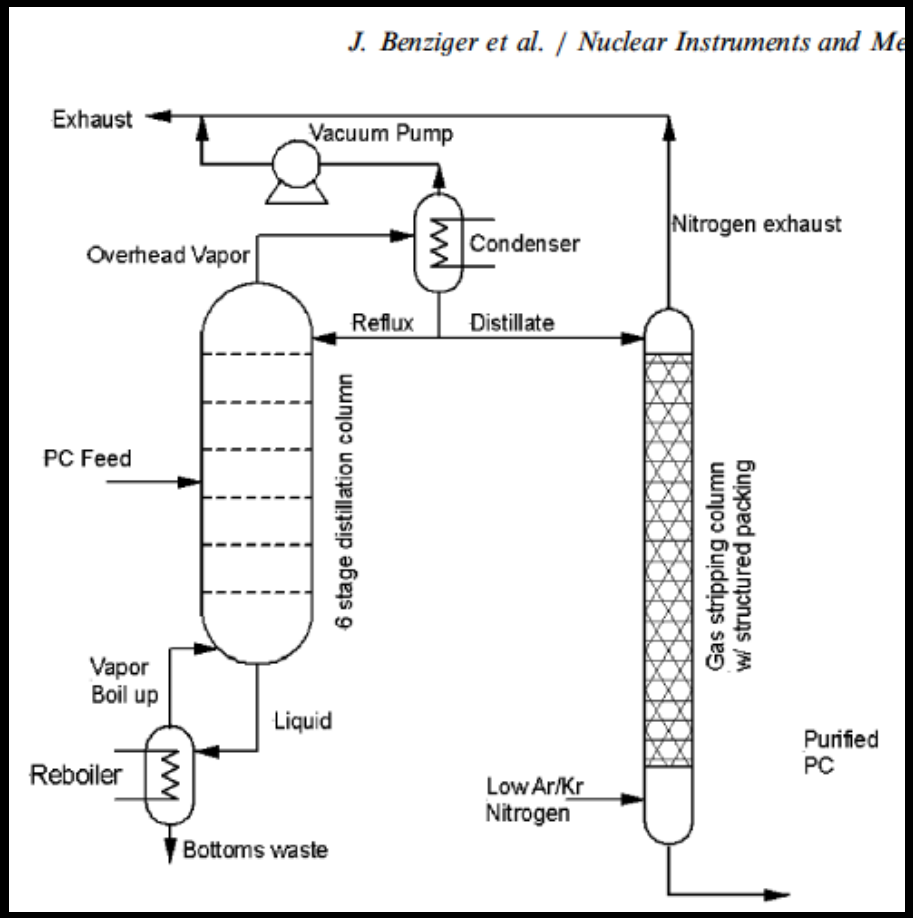
- **Water and scintillator shielding against external background**
  - Reduce PMT and other external backgrounds to predictable low levels based on measured radioacitvity in materials.

- **Scintillator Vessel Construction**
  - Use low radioactvity nylon.
  - Avoid surface radioactivity by fabrication in clean-room with low-radon air.

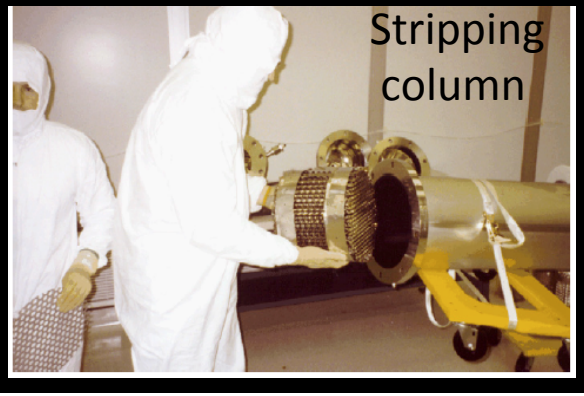
- **Scintillator Purification System for PC & PPO**
  - Standard chemical processes with high cleanliness and low radioactivity.
  - In-line purification during filling.
  - Re-purification in "loop" mode.

- **Pre-fill detector with high purity water for final cleaning.**
  - Fill scintillator on top of water while draining water from bottom.
  - In retrospect this may have been a mistake.

Distillation and Gas Stripping Columns for Pseudocumene (PC)



Radio-pure (LAK) nitrogen (Heidelberg)
Simgen, Heusser, Zusel, Appl. Rad. 61, 213 (2004)



Assembly of distillation & stripping columns In Princeton Low-Radon Cleanroom.

Purification of Wavelength Shifter (PPO) by Water Extraction and Distillation

- PPO was found to have a high level of K that could be reduced by water extraction.
- A concentrated solution of PPO in PC was purified by water extraction then distillation.
- Recent studies show that LNGS de-ionized water has significant ^{210}Pb and ^{210}Po.
- New studies also indicate that simple distillation done here is ineffective for removing ^{210}Po.

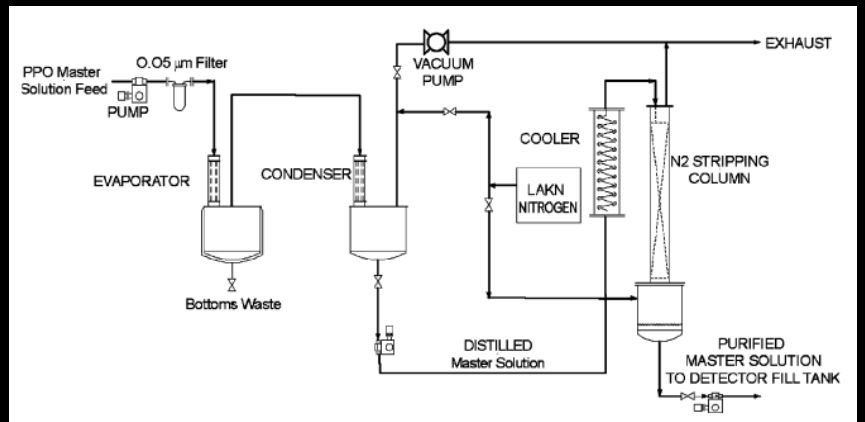
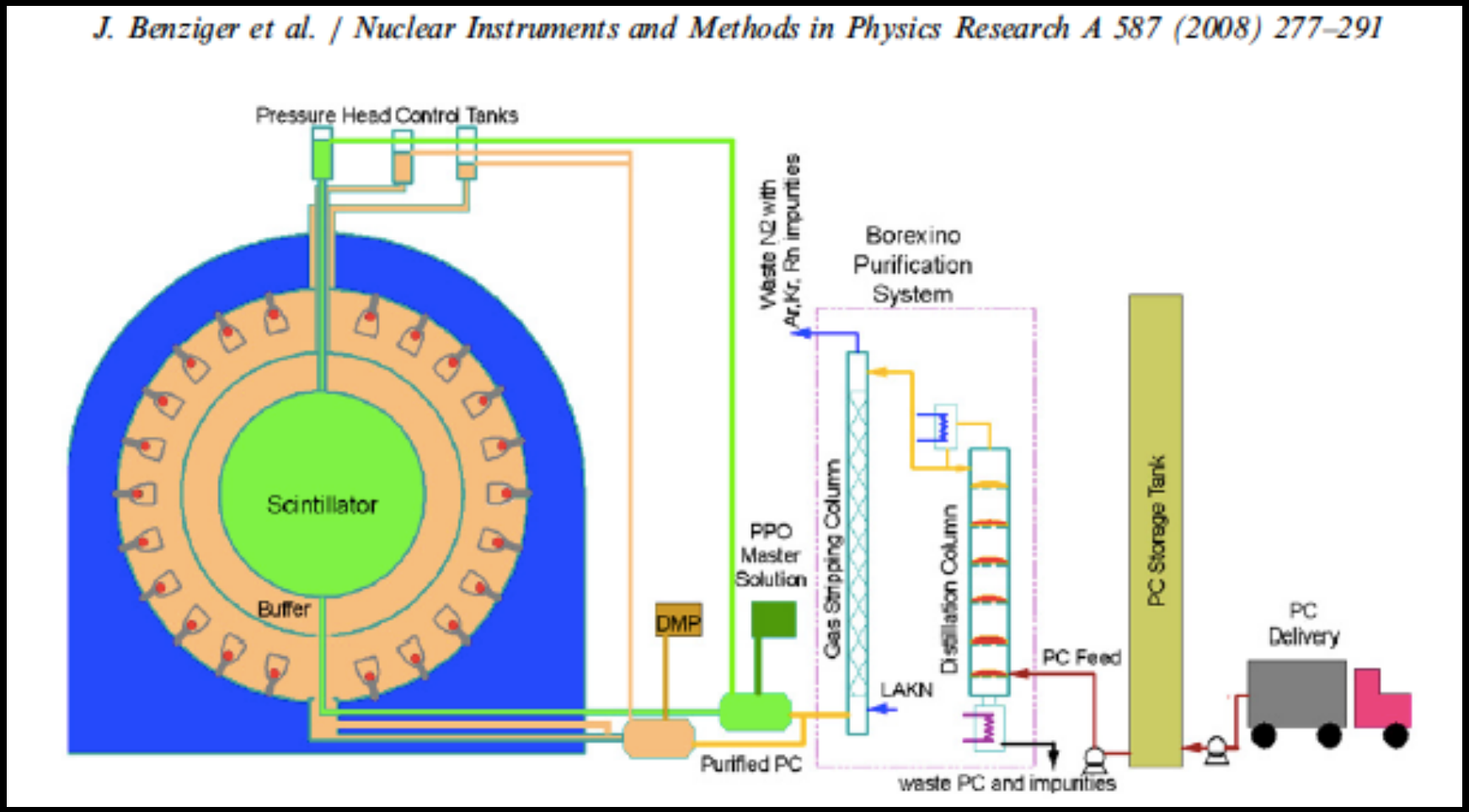


Fig. 6. Process flow for the semi-batch distillation of the PPO/PC master solution.

Afer water extraction, the PPO purification plant used the above simple evaporator to distill the PPO-PC "master solution".
Water extraction may have introducedf ^{210}Po that was not removed by distillation.

Pseudocumene Purification During Filling Operations.



Borexino Energy Spectra

PRL 107 141302 (2011)

Data are based on 740.7 live days between May 16, 2007 and May 8, 2010.

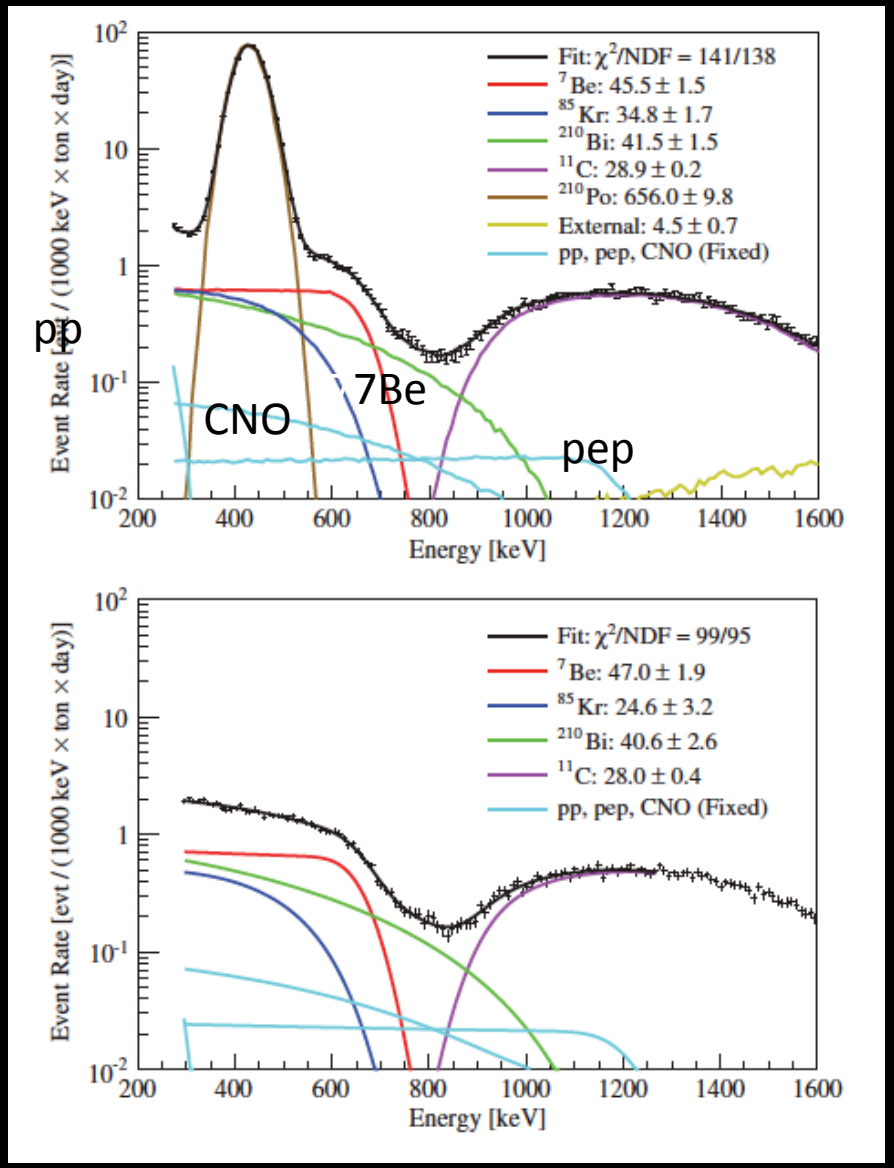
Prominent backgrounds are:

^{210}Po ^{210}Bi ^{85}Kr & ^{14}C (not shown)

CNO obscured mainly by ^{210}Bi due to similar shape.

The ^{210}Po alpha rate was very high but saved by alpha/beta pulse shape discrimination.

The pep was measured by applying cuts to reduce the ^{11}C background.



Borexino Neutrino Measurements

Solar Neutrino rates (cpd/t)

- ^{7}Be: 0.460 ± 0.023 Phys. Rev. Lett. 107 141302 (2011)
- ^{8}B: 0.0022 ± 0.0004 Phys. Rev. D 82, 033006 (2010)
- pep: 0.031 ± 0.005 Phys. Rev,. Lett. 108, 051302 (2012)

Geo-neutrinos

- Total 14.3 ± 4.4 events Phys. Letts. B722, 295 (2013)

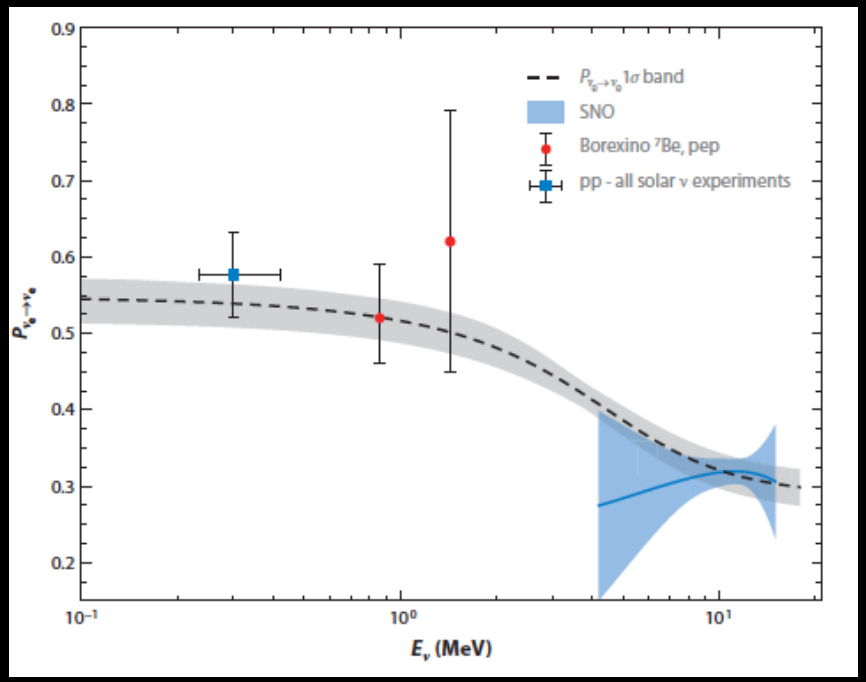
Electron Neutrino Survival Probabilities

The MSW predicted transition from vacuum to matter-enhanced oscillations generally agrees with measurements of pp, ^{7}Be, pep, and ^{8}B neutrinos.

The centroid of SNO's ^{8}B low threshold data falls below the MSW curve with decreasing energy, but the significance is not high.

The transition region is sensitive to new physics. e.g non-standard interactions, sterile neutrinos.

Improving pep, and low energy ^{8}B data motivated by new physics sensitivity.



W.C. Haxton, R.G. Hamish Robertson, and Aldo M. Serenelli, Annu. Rev. Astron. Astrophys. 2013. 51:21–61

Future Solar Neutrino Program

1. **Improve accuracy of ^{7}Be and pep measurements.**
   - Neutrino rates could provide accurate prediction of power produced by nuclear reactions.
   - Comparing neutrino-related power to total solar luminosity could reveal new physics? Sterile neutrino tension? (H. Robertson)

2. **Non-standard interactions in vacuum- matter oscillations transition.**

3. **Measure CNO neutrinos**
   - Confirm proton burning process for stars more massive than Sun.
   - CNO neutrino rate determines C, N abundances in core.
     - Clarify the "solar metallicity problem"
     - Haxton, Serenelli, and others suggest planetary accretion could explain difference in metal abundance in photospheric and helioseismology data.
     - High metalicity rate would support such possibilities.

Re-Purification of BX Scintillator 2010-2011

- **Future Solar Program requires lower background.**
  - ^{210}Bi < CNO (5 cpd/100t) might allow separation of CNO and ^{210}Bi spectra.

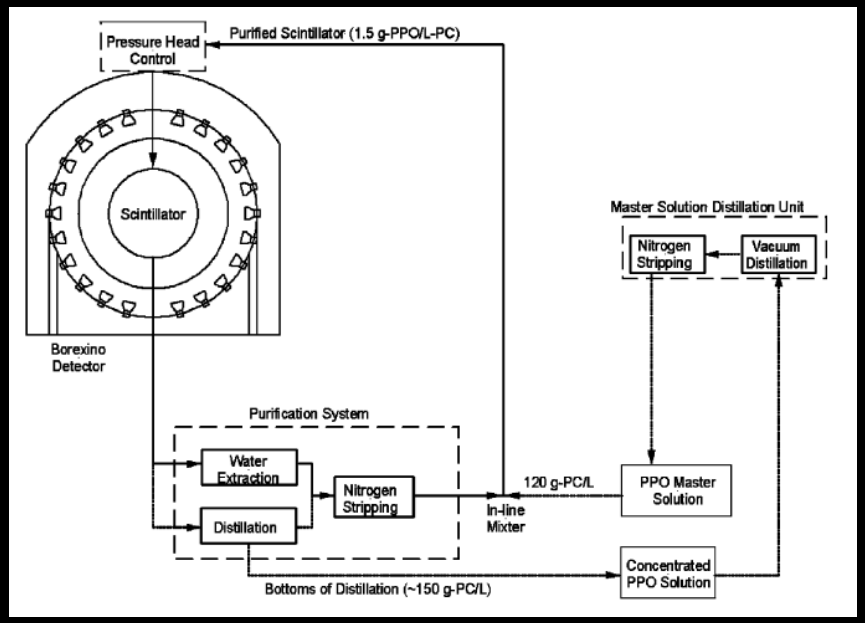
- **From 2007 to 2010 the ^{210}Bi background increased.**
  - ^{210}Bi rate: 15 → 70 cpd/100t (cause: scintillator operations, other?)
  - ^{85}Kr rate: 30 cpd/100t (constant)

- **To reduce background, scintillator was re-purified using two processes:**
  - Water extraction to remove ^{210}Pb (^{210}Bi) and other similar (e.g., ^{226}Ra)
  - Nitrogen stripping to remove ^{85}Kr and other volatiles.

- **Six purification operations were done, each of about 1 month duration.**
  - Each operation processed all 320 m^3 scintillator in the detector once.
  - Data were acquired to evaluate backgrounds after each operation.

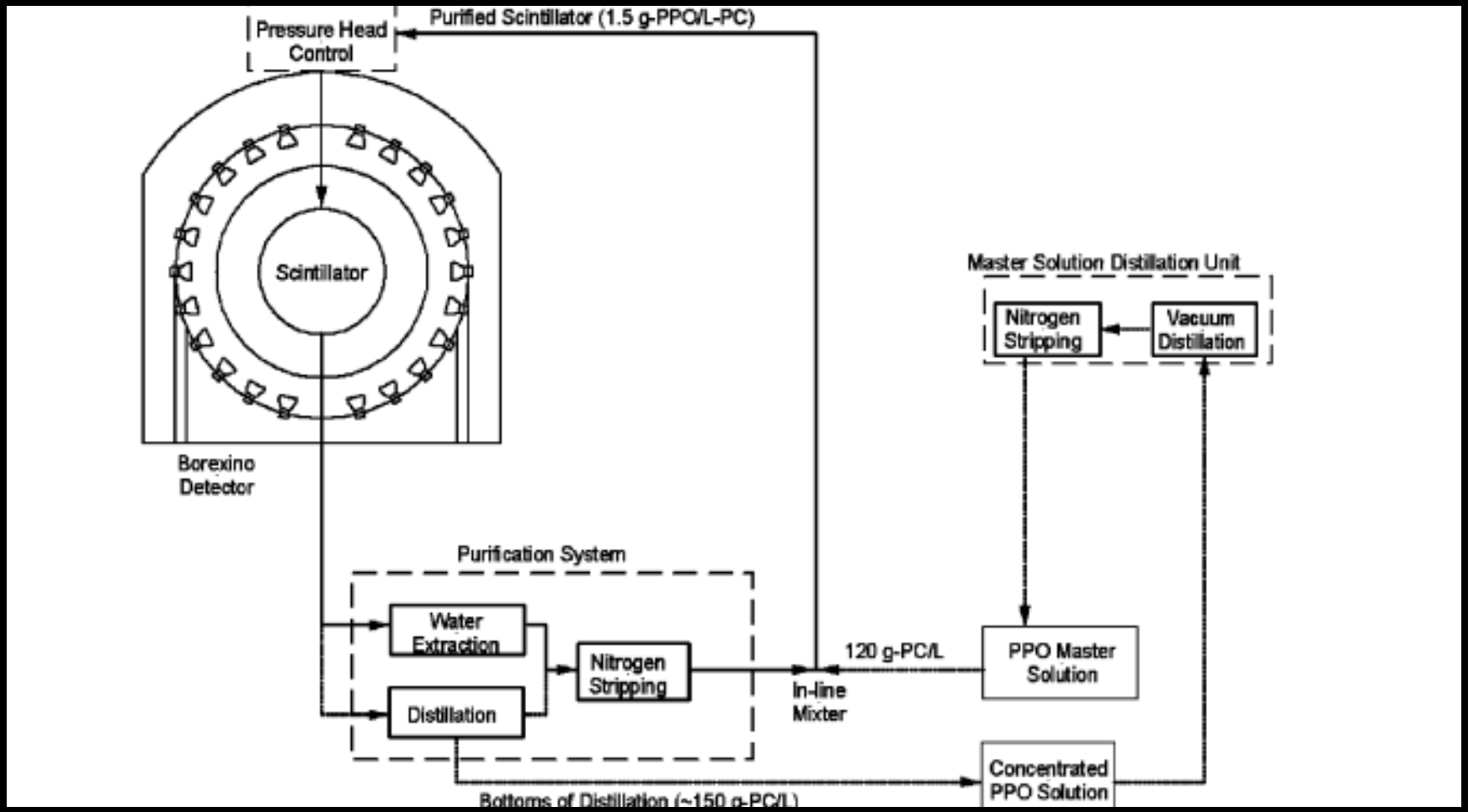
Background Reduction with Loop Purification of Liquid Scintillator

- "Loop" purification is achieved by draining fluid from bottom of vessel, passing it through purification system, and returning to the top.
- Processes available are:
  - Water extraction or distillation
  - Nitriogen stripping (^{85}Kr)



Borexino Re-Purification Systems

Options for Water Extraction or Distillation followed by N_2 Stripping



Results of 6 cycles of Re-purification

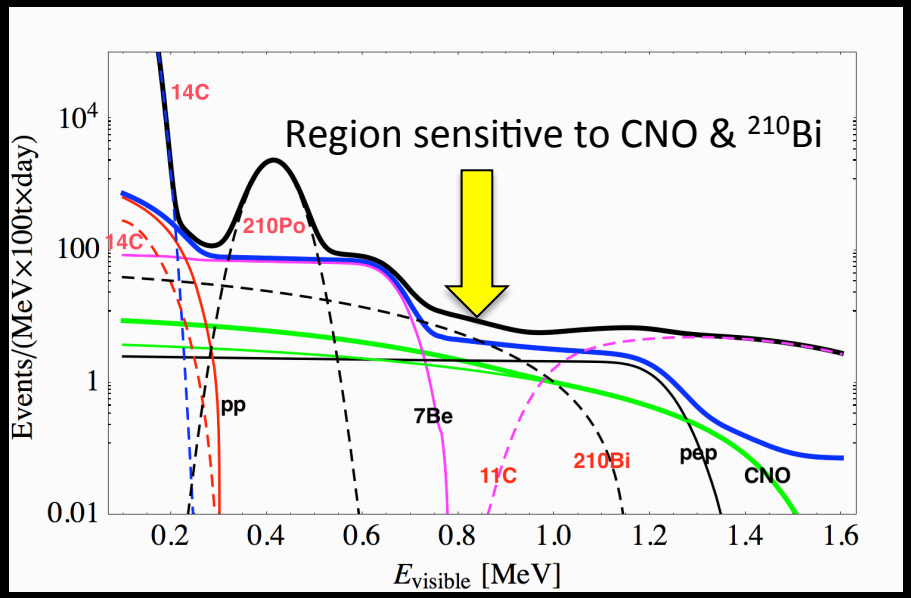
- ^{85}Kr: 30 cpd/100t → < 5 cpd/100t
- ^{210}Bi: 70 cpd/100t → 20 ± 5 cpd/100t
- ^{210}Po: Essentially not reduced! Why?
- ^{238}U (^{226}Ra): [(53 ± 5) → (1.6 ± 0.6)] x 10^{-19} g/g

  ^{214}Bi-^{214}Po Reduction factor = 33. 7 events/100t/yr.
- ^{232}Th: [(3.8 ± 0.8 → < 1.2] x 10^{-18} g/g (95% CL)

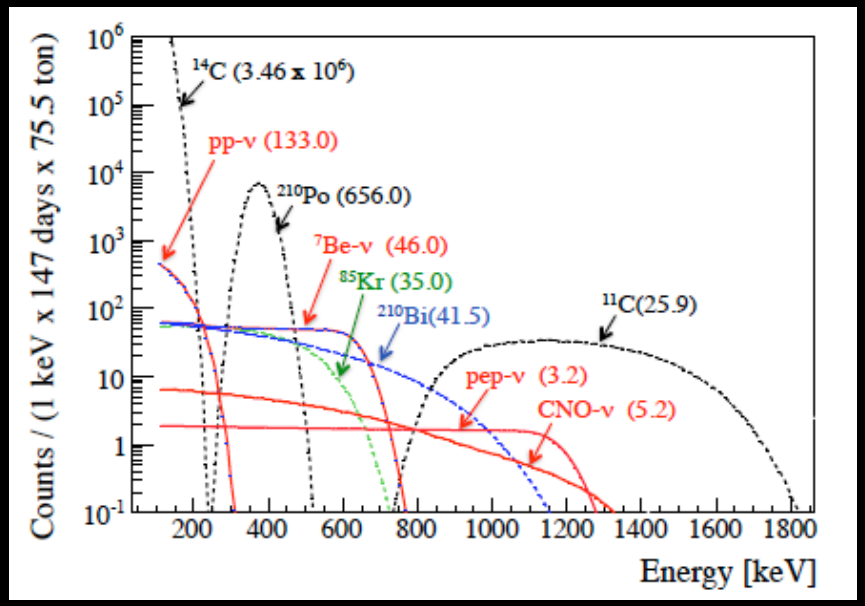
  ^{212}Bi-^{212}Po Reduction factor > 3. 2 ev./100t in 600 d

Rates before purifcation are based on 153.6 ton-yr exposure taken in 740.7 d between May 16, 2007 and May 8, 2010. See Borexino Coll. arXiv 1308.0443v1.

Backgrounds before & after Water Extraction + N_2 Stripping



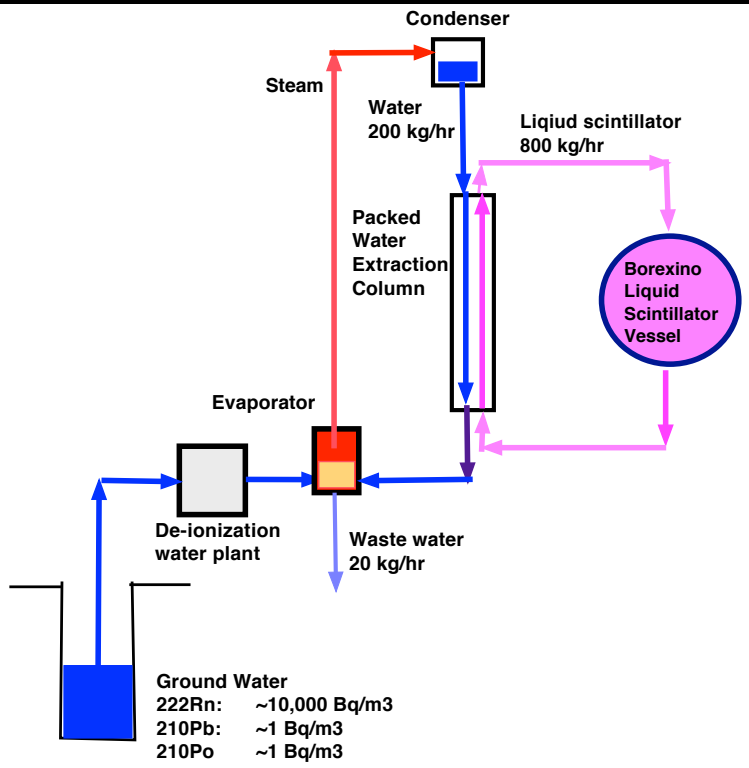
After re-purification 2012-2013
(with ^{11}C cuts)



Before re-purification 2008-2010
Without ^{11}C cuts. See arXiv1308.0443v1.

Water Extraction and Nitrogen Stripping Performed 2010-2011

- Contacting high purity water with scintillator can remove radioactive impurities from the scintillator.
  - Works best if impurities have higher affinity for water, e.g., polar species, but can also be effective if not.
- For water extraction, we use LNGS ground water purified by the following:
  - Reverse osmosis and Ion-exchange (de-ionization water plant)
  - Single stage evaporator distillation.
- Ground water has high levels of radioactivity.
  - ICPMS studies show that ^{238}U, ^{232}Th, ^{40}K are removed effectively by de-ionization.
  - ^{222}Rn is very high (10,000 Bq/ton), but can removed by de-gasification, e.g. N2 stripping.
  - Radon daughters ^{210}Pb, ^{210}Bi, and ^{210}Po had not been studied until recently.
  - New data show that de-ionization processes are not very effective in removing ^{210}Pb and ^{210}Po.
  - The <u>main radioactivity</u> in Borexino de-ionized water is ^{210}Po.



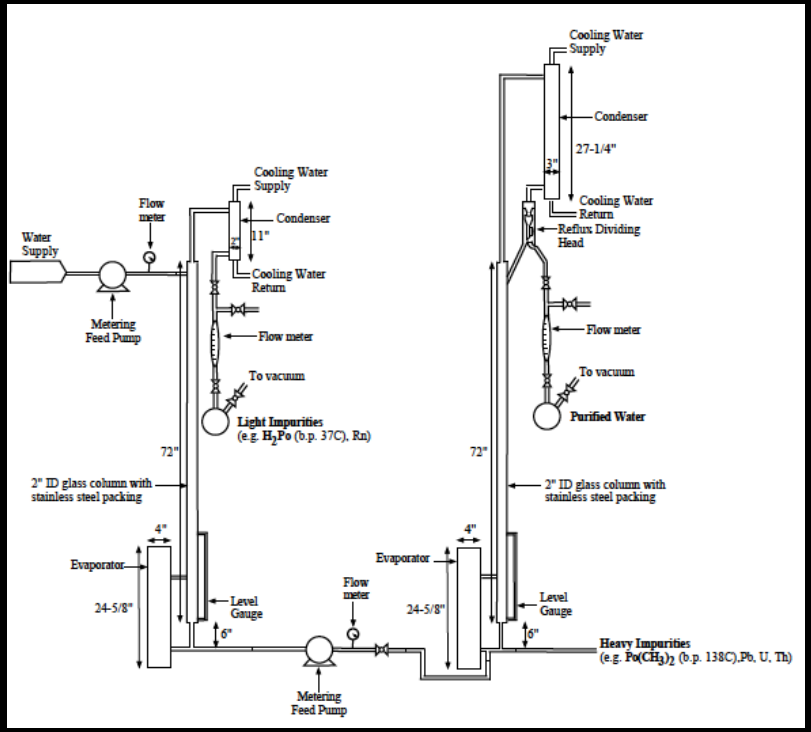
The water extraction system.
N_2 stripping column used in series

Volatile Polonium Compounds!!!

- ^{210}Po assumed Po was non-volatile, and would be reduced by distillation.
- Recent studies provide evidence that some of the ^{210}Po in well water is a volatile compound produced by biological (bacteria) processes.
  - "Bio-Volatilization of Polonium: Results from Laboratory Analyses", N. HUSSAIN, T. G. FERDELMAN, T. M. CHURCH, Aquatic Geochemistry 1: 175-188, 1995
  - "Impact of microorganism on polonium volatilization", N. Momoshima, et. al. J. Radioanalytical and Nuclear Chemistry 272, 413 (2007)
- Dimethyl polonium: Boiling point ~138 C (est.)
- Poor removal of ^{210}Po by de-ionization and ineffective distillation due to volatile polonium compound could explain problems Borexino has had with this isotope.
  - Very likely a problem for other low background experiments.

New Distillation System to Remove ^{210}Po and ^{210}Pb from Ground Water.

- A small-scale distillation system was designed are tested at Princeton to remove dimethyl polonium from ground water.
  - A tall column with structured packing and high reflux was designed for x1000 reduction.
- Princeton well water, noted for its high radon levels, made it easy to measure the polonium before and after distillation.
- Results:
  - When system was operated as simple evaporator, the ^{210}Po was not separated. Explains many problems.
  - When operated with full column and high reflux, the output water showed no measurable ^{210}Po.
  - Reduction factor > 300.



Small prototype distillation system with two 6-foot column 2 l/hr capacity.
Students : B.Russell, C. Aurup, W. Taylor

Summary/Conclusions

- **Initial scintillator purification and other measures produced low backgrounds in Borexino.**
  - Solar neutrino rates measured: ^{7}Be, pep, ^{8}B
  - High ^{210}Po background was compensated with alpha/beta pulse shape discrimination.

- **Future research toward CNO and pp neutrinos, requires lower background.**
  - Lower levels of ^{85}Kr and ^{210}Bi (^{210}Pb) are especially important.

- **Scintillator re-purification worked!**
  - Water extraction and N_2 stripping were both effective.
  - ^{85}Kr, ^{210}Bi, ^{238}U, ^{226}Ra, ^{232}Th all reduced significantly.
  - No indication that reduction of ^{210}Bi would not continue.
  - ^{210}Po not reduced, but triggered studies of water.

- **Discovered that de-ionization systems are ineffective on ^{210}Pb and ^{210}Po in ground water.**
  - Presence of volatile ^{210}Po compound in ground water claimed by others.
  - High levels of ^{210}Pb and ^{210}Po will limit future efforts to lower background unless reduced

- **Confirmed presence of volatile polonium, and removed it with fractional distillation.**
  - It's high efficiency will be effective for removing ^{210}Pb.

- **Water extraction with better water can reduce backgrounds and set stage for CNO.**
  - Results should be helpful to future SNO+ solar program.

The End

Studies of Water Radioactivity 2011-2013

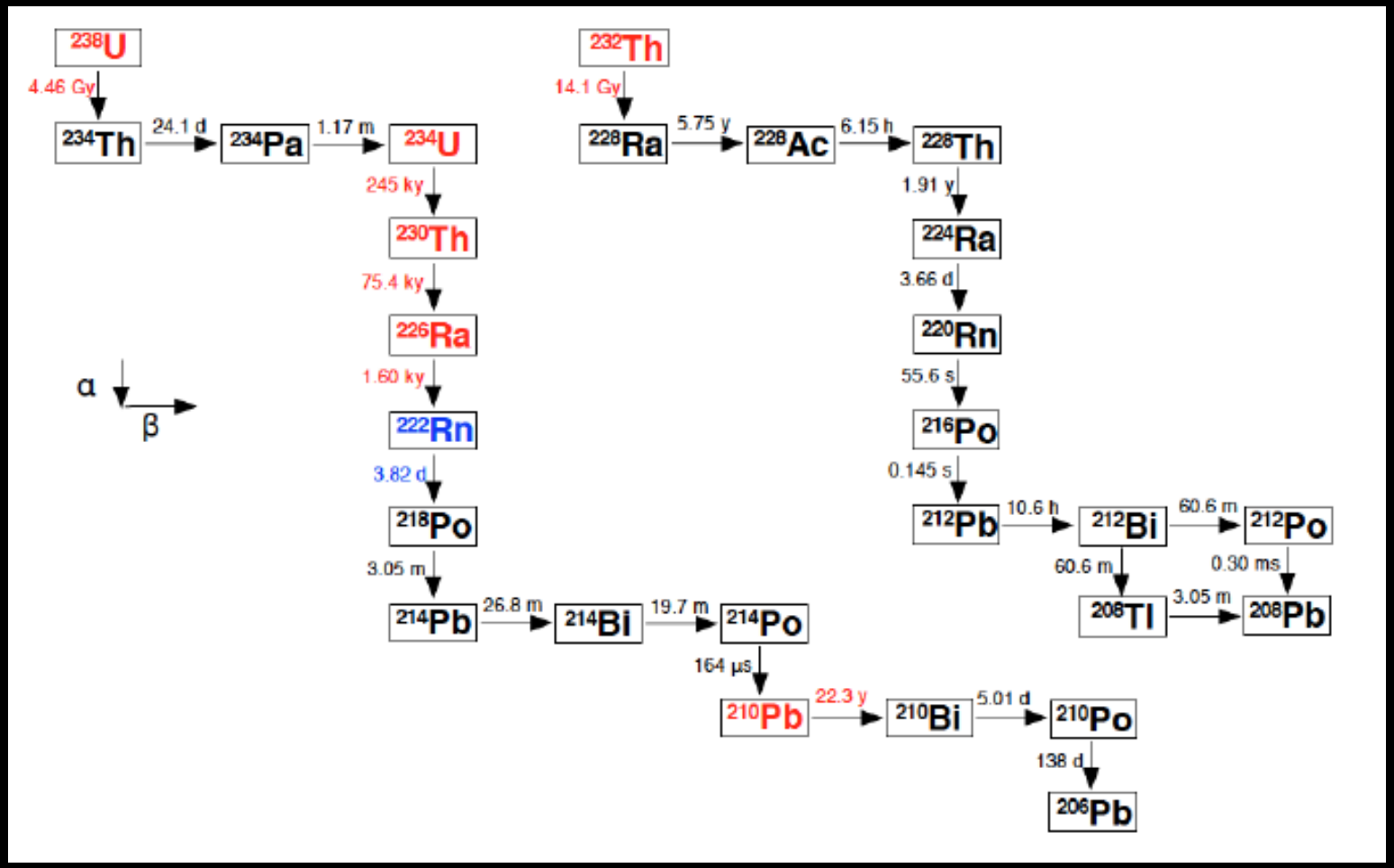
- Increases in ^{210}Bi and ^{210}Po during some of the water extraction cycles led to suspicions that the purified water was contaminated witj these isotopes.
- Measurements showed that the "purified" LNGS well-water was contaminated with ^{210}Pb and ^{210}Po at problematic concentrations.

1. Measured ^{222}Rn (1000 Bq/m3) and its daughter ^{210}Po (1 Bq/m3) in the raw LNGS water.
2. Measured reduction factors of ^{210}Po and ^{210}Pb in the water purification system.
   - Discovered that de- ionization processes have poor removal efficiency for Po and Pb (10-1000)
3. Measured reduction of ^{210}Pb and other non-volatiles in single stage evaporator used in water extraction system. (100-1000)

- Estimated radioactivity in water after de-ionization and evaporation:
  - ^{210}Pb: 1 -10 μBq/m3
  - ^{210}Po: 0.1- 1.0 mBq/m3 (assumes same evaporator reduction as Pb)

- Scintillator Radioactivity after Water Extraction
  - ^{210}Bi (^{210}Pb): 20 cpd/100t = 2 μBq/m3
  - ^{210}Po ~1000 cpd/100t = ~0.1 mBq/m2
- Conclusion:
  - Reasonable estimates indicate radioactivity in water is problematic!!

A Primer on U and Th Decay Chains



A lower ^{210}Bi rate compared to ^{210}Po implies a chemical separation process that removes Pb more efficiently than Po.

Increase in ^{210}Bi (^{210}Pb) Background

- The ^{210}Bi background was very low at the start of Borexino data acquisition in 2007.
- Due to a combination of scintillator operations to cope with a leak in the nylon vessel, and possibly other effects, the ^{210}Bi background increased with time.

Year	2007	^{210}Bi + CNO = 15 ± 6 cpd/100ton [1]
Year	2010	^{210}Bi = 75 cpd/100t [2]

References:

1. BX Collaboration Phys. Lett., B658:101–108, 2008
2. R. Saldanha Ph.D. Thesis Princeton Univ. 2011.

Studies of Water Radioactivity 2011-2013

- Increases in ^{210}Bi and ^{210}Po during some of the water extraction cycles led to suspicions that the purified water contained these isotopes.
- Measurements showed that the "purified" LNGS well-water was contaminated with ^{210}Pb and ^{210}Po at problematic concentrations.

1. Measured ^{222}Rn and its daughter ^{210}Po in the raw LNGS water.
   - ^{222}Rn by Heidelberg group using gas counter: ~10,000 Bq/m^3
   - ^{210}Po by alpha counting of ^{210}Po deposited on Ag foils: ~1 Bq/m3
   - ^{210}Pb inferred from ^{210}Po, and other studies. ~1 Bq/m3
2. Measured reduction factors of ^{210}Po and ^{210}Pb in the water purification system (uses de-ionization processes).
   - ^{210}Pb reduction factor: ~1000 (cf. Mg ~ 10^6)
   - ^{210}Po reduction factor: ~10
3. Measured reduction of ^{210}Pb and other non-volatile stable elements in single stage evaporator used in water extraction system.
   - Reduction factors: 100-1000 (ICPMS)
4. Estimated radioactivity in water after de-ionization and evaporation:
   - ^{210}Pb: 1 -10 μBq/m3
   - ^{210}Po: 0.1- 1.0 mBq/m3 (assumes same evaporator reduction as Pb)

- Scintillator Radioactivity after Water Extraction
  - ^{210}Bi (^{210}Pb): 20 cpd/100t = 2 μBq/m3
  - ^{210}Po ~1000 cpd/100t = ~0.1 mBq/m2
- Conclusion:
  - The numbers are reasonable estimates and indicate radioactivity in water is problematic.