Modeling the Leaching of $^{222}$Rn Daughters into the SNO+ Detector

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SNO+ Physics

- SNOLAB, Creighton Mine (2070m ≈ 6000 m. w. e)
- Linear Alkyl Benzene (LAB)

Physics Goals:
- Neutrino-less double beta decay
  \((^{130}\text{Te}-\text{loaded scintillator})\)
- Low energy solar neutrinos
- Geo and reactor anti neutrinos
- Supernova neutrinos
- Nucleon decay (water phase)
Backgrounds from the implanted radon daughters

- Stringent background limits
- Scintillator target goal: $^{238}\text{U} \sim 10^{-17}$ g/g [1]
- Level of $^{222}\text{Rn}$ in the lab air $\sim 131 \pm 6.7$ Bq/m$^3$ [2]
- Implanted radon daughters in the acrylic are a source of background for SNO+

Backgrounds:

$^{210}\text{Bi}$: Solar Phase
$(Q_\beta = 1.16$ MeV$)$

$^{210}\text{Po}$: $0\nu\beta\beta$ search
$(\alpha,n)$ interaction
2.2 MeV $\gamma$

Leaching model of $^{222}$Rn daughters

**Question:** How quickly will the surface contaminants leach into the liquid?

- Molecular leaching: first order process.

\[
\frac{dN(t)}{dt} = -k(T) N(t)
\]

- Temperature dependency:

\[
k(T) = A e^{-\frac{E_a}{RT}}
\]
Leaching rate measurements

• Bench-top measurements (spiked acrylic samples):
  - Activity of $^{210}\text{Pb}$: high efficiency gamma counter ($E = 46.5$ KeV)
  - Activity of $^{210}\text{Po}$: Silicon alpha counter ($E_{\alpha} = 5.3$ MeV)

• *In-situ* measurements of the activity.
  
  (All the measurements has been performed by Dr. Oleg Chkvoret.)

- Measurements were performed for different temperatures and into different media (UPW, LAB, Te+LAB, EDTA+UPW, etc.).

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Temperature[°C]</th>
<th>L.R.[1/day]</th>
<th>$\Delta$L.R.[1/day]</th>
<th>$\tau$[day]</th>
<th>$\Delta\tau$[day]</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>25</td>
<td>$2.2\times10^{-3}$</td>
<td>$2.2\times10^{-4}$</td>
<td>455</td>
<td>45</td>
<td>Bottom of AV</td>
</tr>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>25</td>
<td>$2.0\times10^{-3}$</td>
<td>$6\times10^{-4}$</td>
<td>500</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>12</td>
<td>$2.1\times10^{-3}$</td>
<td>$6.5\times10^{-4}$</td>
<td>476</td>
<td>143</td>
<td>EDTA Wash</td>
</tr>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>12</td>
<td>$4.8\times10^{-4}$</td>
<td>$1.15\times10^{-4}$</td>
<td>2083</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>95</td>
<td>$3.8\times10^{-4}$</td>
<td>$5.78\times10^{-5}$</td>
<td>2632</td>
<td>400</td>
<td>Spiked Acrylic</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>25</td>
<td>$1.5$</td>
<td>$0.35$</td>
<td>0.66</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>95</td>
<td>$2$</td>
<td>$0.5$</td>
<td>0.5</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>
A tool has been developed to determine the amount of desorbed contaminants.

- Fitting the model to the data points.
- Interpolate the leaching rate according to the temperature and the nature of contaminant.
- Determine the amount of desorbed contaminant through the equations.
- Output: discrete data set of activity + generate a plot
Concentration of $^{222}\text{Rn}$ daughters for a possible timeline

- Ethylenediaminetetraacetic acid (EDTA) suggested to accelerate the leaching process.
- Bismuth and polonium are in equilibrium with lead.
- Initial Activity $\sim 1.15 \text{kBq}$
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- 4 months UPW (12 °C)
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i. 4 months UPW ($12 \, ^{\circ}C$)
ii. 5 months of UPW + (0.027M) EDTA ($12 \, ^{\circ}C$)
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iv. 6 months of liquid scintillator
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The activity of the radon daughters reduced by 90% in less than 3 years with the suggested timeline.
Interpolation of the leaching constant for the water-fill

- Jan 27\(^{th}\)-28\(^{th}\) : water assay performed (water-fill since Oct 11\(^{th}\))
- The water level was monitored.
- Temperature was recorded: \(T_{avg} = 18.4 \, ^{\circ}C\)
- Using high efficiency gamma counter, specific activity of lead = \(0.26^{+0.04}_{-0.04} \text{ Bq/m}^3\)

- The leaching constant for \(18.4 \, ^{\circ}C\) was interpolated through the model.

\[ \log[k(T)] \]

\[ k_{18.4 \, ^{\circ}C} = 1.05^{+0.18}_{-0.19} \times 10^{-3} \, \text{[day}^{-1}] \]
Determination of desorbed lead during the water-fill

- Initial activity of the acrylic \( \sim 2.3 \pm 0.8 \) Bq/m\(^2\)
- Leaching per unit area:
  \[
  \frac{dC_a(t)}{dt} = -k(T)C_a(t) - \lambda C_a(t) \\
  \frac{dC_w(t)}{dt} = k(T)C_a(t) - \lambda C_w(t)
  \]
- Total specific activity of desorbed lead through a summation over the water levels:
  \[
  A(t) = \frac{\lambda}{V(t)} \sum_{i=1}^{t/\Delta \tau} C_w(t - i\Delta \tau) (h_{i+1} - h_i) \cdot 2\pi R
  \]
- Subtract the removed water (lead)

Calculated desorbed lead:
\[
A = 0.155^{+0.088}_{-0.071} \text{ Bq/m}^3
\]
Other sources of $^{210}$Pb in water

- Lead concentration in a blank sample of UPW
  - Water plant assay (August 2014) → $A = 0.047 \pm 0.010 \text{ mBq/m}^3$ (negligible)

- Diffusion of the radon in the lab air into the water
- Radon level inside the acrylic vessel ~ $(0.6703 \pm 0.0026) \times (131 \pm 6.7) \text{ Bq/m}^3$
- Partition coefficient of $^{222}\text{Rn}$ between UPW and air at $18.4 ^\circ \text{C}$ $\kappa = 0.266$

- Fick’s Law: $\frac{\partial C(z,t)}{\partial t} = D \Delta C(z,t)$

$$C_w(z,t) = \kappa C_{\text{air}} \left( 1 - \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{1}{(2n+1)} e^{-2(n+1)^2 \frac{D_t}{4h^2}} \sin \left( \frac{(2n+1)\pi z}{2h} \right) \right)$$

$$A(z,t) = \int C_w(z,t) \, dV$$
Radon diffusion into water

- Total activity of the diffused radon into water: 
  \[ A_w(t) = \sum_{i=0}^{i=t/\Delta t} \int_{0}^{h_i} C_w(z, t) S(z) \, dz \]
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- Generated a discrete data set to determine the amount of produced lead.

Radon concentration in water

Lead concentration from the radon in air
Conclusion: The leaching model works!

- Specific Activity of produced lead from the diffused radon in UPW: \( A = 0.012^{+0.003}_{-0.001} \text{ Bq/m}^3 \)
- Desorbed lead + lead from air: \( A_{\text{calculated}} = 0.169^{+0.085}_{-0.073} \text{ Bq/m}^3 \)
- Measured lead from the water assay: \( A_{\text{measured}} = 0.26^{+0.04}_{-0.04} \text{ Bq/m}^3 \)

- Calculated Activity is compatible with measured value to within 1 sigma.

- Diffusion of \(^{222}\text{Rn}\) from air into water is complicated due to the temperature gradient from the bottom of AV.
Thanks for your attention...

Special thanks to the SNO+ collaboration...

Questions?

Muon Cherenkov light observed during the dark run on December 2014...
Backup EDTA

- Ethylenediaminetetraacetic acid (EDTA) was suggested to accelerate the leaching rate.
- Has no effect on the leaching rate of $^{210}$Bi and $^{210}$Po
- UPW + EDTA (0.25M) accelerates the leaching process of $^{210}$Pb by factor of 30
Backup (Radon diffusion)

- Radon diffusion as a function of depth