Control of Radon Daughters in the DEAP-3600 Acrylic Vessel

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DEAP Collaboration

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Single-Phase Liquid Argon

Dark matter
Experiment with
Argon and
Pulse-shape discrimination

3600kg LAr in a clean spherical acrylic vessel coated with wavelength shifter

Estimated light yield: 8 pe/keV

Backgrounds: < 0.2
Exposure: 1000kg FV for 3 years

Goal: $10^{-46}\text{cm}^2$ sensitivity for 100 GeV WIMP
## Background Control

<table>
<thead>
<tr>
<th>Source</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radon in liquid argon</td>
<td>Charcoal traps; passivated SS lines</td>
</tr>
<tr>
<td>Betas and gammas</td>
<td>Pulse-shape discrimination</td>
</tr>
<tr>
<td>Neutrons</td>
<td>Screening of components; Plastic (hydrogen) around LAr; Control of alphas in acrylic $^{13}\text{C}(\alpha,n)$</td>
</tr>
<tr>
<td><strong>Alphas at acrylic surface</strong></td>
<td><strong>This talk</strong></td>
</tr>
</tbody>
</table>
### Types of Surface Alphas

<table>
<thead>
<tr>
<th>Path</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Fraction of E in TPB (Light yield of TPB less than LAr)</td>
</tr>
<tr>
<td>F2</td>
<td>Full energy in TPB only</td>
</tr>
<tr>
<td>F3</td>
<td>TPB + liquid argon (Much higher light production than WIMP scatter)</td>
</tr>
</tbody>
</table>

Could overlap DM signal

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![Diagram showing types of surface alphas with labels F1, F2, and F3 in different layers of material: Acrylic, TPB, and Argon.](image)
Control Strategy

Limit exposure to $^{222}$Rn during manufacture to control long-lived $^{210}$Pb

Resurface AV under vacuum after construction

Coat AV with pure TPB under vacuum
Radiopurity Requirements

<table>
<thead>
<tr>
<th></th>
<th>Acrylic Vessel Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant background</td>
<td>Surface events from bulk contamination</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>0.3 ppt</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>1.3 ppt</td>
</tr>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>$1.1 \times 10^{-8}$ ppt (= 31mBq/tonne)</td>
</tr>
</tbody>
</table>

Limits correspond to 0.01 events in 3 tonne-years.
We take credit for position reconstruction but not pulse-shape discrimination for alphas in TPB.

$^{210}\text{Pb}$ is a daughter of $^{222}\text{Rn}$ and can exist out of equilibrium with the higher isotopes of the $^{238}\text{U}$ chain.

We must quantify the exposure of acrylic material to $^{222}\text{Rn}$, especially as Radon is soluble in acrylic.
Meeting the Requirements

• Interplay between design of AV and material cleanliness.
  – Must make vessel out of a pure-monomer panel.
  – Can not cast it as a sphere.
  – Start with panels and thermally form them into shape.

• Years of effort assessing optical properties
  – Multiple samples from five suppliers

• Gamma assay

• Verification of contamination levels
  – Advertisement: See poster by Corina Nantais
Process (1/2)

Large petrochemical plant (eastern industrial seaboard of Thailand)

Fractional distillation last stage of process.

Air introduced with distillation to inhibit spontaneous polymerization.

MMA from ThaiMMA
MMA = methyl methacrylate, acrylic monomer

Our MMA not stored at ThaiMMA.
Truck filled off continuous flow.

Connection for MMA and air return

Polyethelene hose
Clean hose to sealed SS storage tank.

Storage at RPTAsia

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Process (2/2)

Reactor: proprietary additives<2%

Mould Prep in HEPA-filtered room

Nylon dams on moulds

(Short term storage)

Pour

Stack moulds for Hydroclave. Panels “cooked” under water for ~ 1 week.
Construction of Sphere from 5 panels

Most panels for DEAP were 96” x 128” x 4.5” thick
Five panels thermoformed into sphere
Once Panels Are Formed....

Radon penetrates into solid PMMA a distance of 0.17mm - Wojcik NIM B61 (1991) pp8-11

The resurfacer will deal with lead left behind by normal (~5Bqm⁻³) air.

Once the panels are formed we are most concerned with the vessel underground at SNOLAB (~120Bqm⁻³) and when the vessel is at elevated temperatures (annealing)
One Unit of Radon Contamination

- If MMA is moved into a closed volume, the radon in the volume will enter the MMA.
- Using $\rho(\text{MMA}) \cong 1 \text{ tonne/m}^3$ and the decay constants of $^{222}\text{Rn}$ and $^{210}\text{Pb}$ we obtain

$$A^{(210)\text{Pb}} \left[ \frac{\text{mBq}}{\text{tonne}} \right] = 0.46 \ A^{(222)\text{Rn}} \left[ \frac{\text{Bq}}{\text{m}^3} \right]$$

This is one unit of radon contamination.
Production: 12 tonnes/hour with 15m³/hour air in distillation.

1.25 units contamination

\[ A^{(222\text{Rn})} = 3.5 \pm 2.0 \text{ Bq/m}^3 \]

1 unit of contamination

\[ A \approx 5\text{ Bq/m}^3 \]
Radon Loads (2/2)

1 unit of contamination

A = 6.3 Bq/m³

Reactor: proprietary additives <2%

Pour

short term Storage
+ 1 unit
10.3 Bq/m³

+ 1 unit
A = 10.3 Bq/m³

Storage at RPTAsia

Mould Prep in HEPA-filtered room

Nylon dams on moulds

Stack moulds for Hydroclave.
Panels “cooked” under water for ~ 1 week.

Chris Jillings: Radon Daughters in DEAP-3600 Acrylic Vessel
### Estimated $^{210}\text{Pb}$ Loads

<table>
<thead>
<tr>
<th>Location</th>
<th>AV Shell</th>
<th>RPT Asia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distillation [cont. units]</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>Storage [cont. units]</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Truck [cont. units]</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$A(^{222}\text{Rn})$ [Bq/m$^3$]</td>
<td>3.5±2</td>
<td></td>
</tr>
<tr>
<td>Expected $^{210}\text{Pb}$ [mBq/tonne]</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>MMA Storage tank [cont. units]</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Reactor Vessel [cont. units]</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Post-reactor storage [cont. units]</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Moulds [cont. units]</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$A(^{222}\text{Rn})$ [mBq/m$^3$]</td>
<td>6.3 to 10.8</td>
<td>10 to 17</td>
</tr>
<tr>
<td>Expected $^{210}\text{Pb}$ [mBq/tonne]</td>
<td>10 to 17</td>
<td>14 to 21</td>
</tr>
<tr>
<td><strong>Total $^{210}\text{Pb}$ [mBq/tonne]</strong></td>
<td><strong>14 to 21</strong></td>
<td><strong>14 to 21</strong></td>
</tr>
</tbody>
</table>
Detailed Radon Diffusion Calculations

\[
\frac{\partial C}{\partial t} = D \frac{d^2 C}{dx^2} - \lambda C
\]

\[
\frac{C_{j}^{n+1} - C_{j}^{n}}{\Delta t} = D \frac{C_{j+1}^{n} - 2C_{j}^{n} + C_{j-1}^{n}}{(\Delta x)^2} - \lambda C_{j}^{n}
\]

Stability \( \equiv \frac{2D\Delta t}{(\Delta x)^2} \leq 1 \)

Need the solubility, \( S \), to know the concentration in the first layer of acrylic.

\( S = S(T) \) and \( D = D(T) \)
Parameters

• Use Wojcik NIM B61 (1991) pp8-11

• CheFEM, The Sanchez-Lacombe equation of state is used over the complete temperature range, diffusion based on the Free Volume theory for diffusion and the mass transfer is based on Maxwell-Stefan equation for diffusion (chemical potentials from Sanchez Lacombe in combination with the Free Volume expression are used for the mass transfer = permeation calculation)

• \( D = D_0 \exp \left( -\frac{\Delta E_d}{RT} \right) \) [cm\(^2\)/s]

• \( S = S_0 \exp\left(-\frac{\Delta H_s}{RT}\right) \frac{76 T}{273} \) [g cm\(^{-3}\)/g cm\(^{-3}\)]

• \( R = 1.986e-3 \) kcal/mol

• \( D_0 = 481.5; \Delta E_d = 16.14 \)

• \( S_0 = 3.55e-4; \Delta H_s = -3.32 \)
Rn more mobile at high temperature

**Diffusion Constant for Rn in PMMA**

![Graph showing the diffusion constant for Rn in PMMA as a function of temperature. The graph illustrates a linear increase in the diffusion constant with increasing temperature.](image)
... but less soluble

Solubility of Rn in PMMA

[g cm⁻³ / g cm⁻³] vs Temperature [°C]
AV in Oven with Lid for Radon-Reduced Air

- Source of heated Radon-reduced air
- Vent
- Temperature Sensor cable
- Sense Line for Rad7

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RRA verified with Durridge Rad7*

* Thanks to Ian Lawson for assistance with the Rad-7.
Calculated $^{210}\text{Pb}$ Activity

(Preliminary)

(Diffusion equation with measured temperatures and activities.)
Conclusions

• A physically strong, optically transparent, radiologically pure acrylic vessel is being built for the DEAP experiment.
• Extensive QA including multiple site visits and excellent co-operation with Reynolds Polymer Technology (Colorado, USA) and RPTAsia (Rayong, Thailand) has resulted in a vessel that will meet DEAP’s background requirements.
• To achieve this the vessel was made of virgin monomer with a known radon-exposure history.
• Care was taken during annealing to keep Radon diffusion within acceptable limits.
• With suitable care, a future experiment could improve on our work.