Radon reduction in Dark Matter Detectors

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This work is supported by
Radon - what is it and why is it bad?

1. radioactive noble gas
2. dissolves in LXe and cannot be removed with hot gas purifying getters
3. $^{222}\text{Rn}$ is a product of $^{238}\text{U}$ decay (everywhere)
   mean life of $\tau_{\text{Rn}} = 5.516 \text{ day}$
   $= 7943 \text{ min}$
4. $^{222}\text{Rn}$ is resupplied continuously from detector components
   • dominant background in DM searches
   • cannot currently purify all 10 t of LXe
   • focus on gaseous areas which are particularly bad
5. $^{214}\text{Pb}$ naked $\beta^-$ decay can mimic Dark Matter signals
In-line Radon reduction system

- reduce 20 mBq by a factor of 20 at a flow rate of 0.5 slpm
  
i. N = τ_{Rn} A (= 5,516 d * 1.0 mBq) = 476 Rn atoms (steady-state population)

- sequestration of atoms in activated carbon trap until most $^{222}$Rn nuclei decay
  
i. think gas chromatography: $v(Xe)/v(Rn)$ (-85 C) ≈ 1000

- to obtain removal of 90%, sequestration time $\geq \ln(10) \cdot \tau_{Rn} = 12.7$ days
### Activated Charcoals tested

<table>
<thead>
<tr>
<th>Charcoal</th>
<th>Density (g/cm³)</th>
<th>Surface area (m²/g)</th>
<th>Spec. activity (mBq/kg)</th>
<th>Price ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shirasagi</td>
<td>0.45</td>
<td>1,240</td>
<td>101 ± 8</td>
<td>27</td>
</tr>
<tr>
<td>CarboAct</td>
<td>0.28</td>
<td>1,000</td>
<td>0.23 ± 0.19</td>
<td>15,000*</td>
</tr>
<tr>
<td>Saratech</td>
<td>0.60</td>
<td>1,340</td>
<td>1.71 ± 0.20</td>
<td>35</td>
</tr>
<tr>
<td>Saratach (HNO₃)</td>
<td>0.60</td>
<td>1,340</td>
<td>0.51 ± 0.09</td>
<td>135</td>
</tr>
</tbody>
</table>

Density of graphite: 2.26 g/cm³

* provided by Carter Hall

* 1/3 of price of gold
Elution Curves

small trap: 0.1 l

Saratech (0.1 l trap)
½ SLPM, 1 atm, 70 g, 295 K
τ = 189 min

HNO₃ etched Saratech
½ SLPM, 1.7 atm, 447 g, 189 K
τ = 1792 min

medium trap: 1.0 l

vastly different transition times for various charcoal types
Dynamic Absorption Coefficient

**N₂, Ar carrier gas**

- **Temperature, (K)**
  - 295, 290, 285, 280, 275, 270, 265, 260, 255, 250

- **Inverse temperature, (1000/K)**
  - 3.4, 3.5, 3.6, 3.7, 3.8, 3.9

- **222-Rn adsorption coefficient, (kG)**
  - 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50

**Xe carrier gas**

- **Temperature, (K)**
  - 300, 280, 260, 240, 220, 200

- **Inverse temperature, (1000/K)**
  - 3.4, 3.5, 3.6, 3.7, 3.8, 3.9

- **222-Rn adsorption coefficient, (kG)**
  - 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5

**Expectation:**
- i. N₂ and Ar carrier gas follow exponential rise w/ inverse temp (Arrhenius law)
- ii. Xe carrier gas on Saratech follows Arrhenius law (more or less)

**Surprises:**
- i. Xe carrier gas on CarboAct violates Arrhenius law (???)
- ii. kₐ with Xe carrier gas is about 10x – 50x smaller than in He, N₂, and Ar carrier gas
Adsorption of Xenon gas on Charcoal

- Xenon gas adsorption: ca 1.6 kg / kg of charcoal
  - Increases linear with decreasing temperature
  - Increases only slightly with pressure
- Ar, N₂ and He gas adsorption: tiny (below 20 g/kg of charcoal)
Small Rn trap for LZ (GXe)

\[ N_{out} = N_{in} e^{-\frac{m}{m^*}} + \frac{dN}{dm} m^* \left(1 - e^{-\frac{m}{m^*}}\right) \quad m^* = \frac{f \tau_{Rn}}{k_a} \]

- \( dN/dm \): specific activity (Saratech: 0.51 mBq/kg)
- Need 6 kg of etched Saratech to reduce Rn concentration to 1 mBq at 0.5 slpm
- Interestingly, lowest achievable Rn concentration does NOT depend on total mass
  \( N_{out} \) (min) = 0.70, 0.45 mBq
  \( N_{out} \) (min) = 2.80, 1.80 mBq

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Full Rn trap for LZ?

- Current in-line system (10 kg of etched Saratech)
  i. suppresses Rn concentration in GXe space >20x to about 0.7 mBq
  ii. cannot be used to purify all 10 t of Xe at 500 slpm:
    • takes $T_v = 58.5$ hrs (2.5 days) to turn over 10 t of Xe
    • only slightly shorter than the radon half-live ($\tau = 3.8$ days)
    • how much can you reduce Rn concentration?

max Rn reduction:
$R_{T_v}/R_{em} = \tau / (\tau + T_v)$
Full Rn trap for LZ?

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  - ii. cannot be used to purify all 10 t of Xe at 500 slpm:
    - takes $T_v = 58.5$ hrs (2.5 days) to turn over 10 t of Xe
    - only slightly shorter than the radon life time ($\tau = 5.52$ days)
    - how much can you reduce Rn concentration?
    - can only reduce Rn concentration by 70% (3.3x) at best (ie dN/dm = 0)
    - true for any RRS (carbon trap, distillation tower, ...)
    - need 2,000 slpm to reduce it by 90% (10x)

max Rn reduction

$\tau / (\tau + T_v)$
Full Rn trap for LZ?

- Current In-line system (10 kg of etched Saratech)
  i. suppresses Rn concentration in GXe space >20x to about 0.7 mBq
  ii. cannot be used to purify all 10 t of Xe at 500 slpm:
    - takes $T_v = 58.5$ hrs (2.5 days) to turn over 10 t of Xe
    - only slightly shorter than the radon half-live ($\tau = 3.8$ days)
    - how much can you reduce Rn concentration?
    - can only reduce Rn concentration by 69% (3.2x) at best (ie $dN/dm = 0$)
    - true for any RRS (carbon trap, distillation tower, ...)
    - need 2,000 slpm to reduce it by 90% (10x)
Large Carbon trap for LZ?

\[ N_{out} = N_{in} e^{-\frac{m}{m^*}} + \frac{dN}{dm} m^* \left( 1 - e^{-\frac{m}{m^*}} \right) \]

\[ m^* = \frac{f \tau_{Rn}}{k_a} \]

- Current in-line system (10 kg of etched Saratech)
  i. 0.5 slpm
    - suppresses Rn concentration in GXe space >20x to about 0.7 mBq
    - \( m^* = 1.4 \) kg
    - \( N_{out} \) (min) = 0.7 mBq
  ii. at 500 slpm
    - \( m^* = 1,370 \) kg
    - for 10 kg trap: \( Rn_{out} = 45 \) mBq > \( Rn_{in} \)
      first term dominates
    - for (very) large trap: \( Rn_{out} = 700 \) mBq >> \( Rn_{in} \)
      second term dominates
    - \( N_{out} \) (min) = 700 mBq (for large trap)
      (remember: traps 1.6 kg Xe / kg of charcoal)

Does Not Work
What about a Vacuum Swing System?

- Shown to reach > 99% efficiency of removing Rn from room air
  - purge gas is exhausted
  - Rn levels in room air about 100 – 200 Bq/m³
- Could this work for Xe?
  - Xe expensive
  - need to return into circulation path before VSA
  - Rn levels in xenon typically around 2 μBq/kg (ie 20 mBq for 10 tons of Xe)
Ideal VSA system with feedback purge

- Radon trapped in purple loop and slowly decays away
- If we assume: specific activity of carbon is negligible
- For 99% efficient trap, at steady state 54.6% of Rn atoms escape VSA system, which corresponds to 32% radon reduction in LZ
Radon trapped in purple loop and slowly decays away
- CCT increases time Rn atoms spend in feedback loop before entering back into VSA
- If we assume: specific activity of carbon is negligible
- For 99% VSA efficiency, and 20% CCT efficiency: 4.2% of Rn atoms escape VSA!!
- For 90% VSA efficiency, and 20% CCT efficiency: 32.7% of Rn atoms escape the VSA system, which corresponds to 47% radon reduction in LZ
Ideal VSA for LZ?

- Rn reduction within LZ given the performance of ideal VSA and Carbon trap for 500 slpm

- Rn reduction within LZ is defined by: \( \frac{R_{n,rrs}}{R_{n,em}} \)

- The maximum reduction of Rn in LZ with a perfect RRS is 69.9% at a flow rate of 500 slpm

Would Work – But ...
Realistic VSA for LZ

- If adding Rn contribution from the trap, assuming
  - 60 kg of Saratech in VSA
  - 0.51 mBq/kg specific activity
  - 500 slpm
  - 20 mBq into the LZ
    -> N_out = 20.1 mBq > N_in (-0.5% efficient)
    -> trap will add more Rn
    -> does not work

- How could it work?
  - If specific activity: 0.01 mBq/kg: 50x smaller than currently available
    -> 85% efficient
    -> 60% reduction of Rn in LZ
    -> would work, but really hard to achieve (w/ charcoal-based traps)

  -> use trap that does not emanate Rn
Conclusions

- Rn will become an even larger issue with larger Xe DM experiments

- For **10 tons Xe** detectors:
  - need flow rates of 2,000 slpm wo reduce Rn concentration 10x
  - at 500 slpm (or below) best we can do is to reduce initial concentration 3.3x for any kind of RRS (even for systems w/ zero specific activities)
  - carbon traps of any flavors will not work (unless specific activities -> 0)
  - not studied distillation tower performance

- For G3: ~50 tons Xe detectors:
  - need to further suppress 2 μBq/kg Rn concentration
  - or end up with 100 mBq (maybe reduce to ~30 mBq)
  - Rn likely dominant background source
Backup
The Langmuir Adsorption Model

- **Idea:**
  1. Adsorption surface is immersed in a gas in which equilibrium has been established b/w gas molecule that get adsorbed (ie trapped) and those that escape (through therm. excitation)
  2. Adsorbing surface forms at most a monoatomic layer
  3. \( A_{\text{max}} \) = total area of adsorption surface, \( A \) = area occupied by monoatomic layer

- **Consequence:**
  1. In equilibrium: prob. of trapping an additional molecule: \( A_{\text{max}} - A \)
  2. prob. for adsorbed molecule to be liberated: \( c A \)

### Graph: Langmuir Isotherm

- **at 1 bar:**
  - avg rate of collision / unit area: 3.5 ns !!
  - Xe saturates charcoal almost completely
  - AND immediately
    1. really scared us before we built the trap
    2. but (somewhat) consistent with data
**Arrhenius Equation**

\[ k = A e^{-\frac{E_a}{k_bT}} \]

- \( k \): rate constant, \( E_a \): activation energy (J), \( k_b \): Boltzmann constant (J/K), \( T \): temperature (K)

- describes temperature dependence of chemical reaction rates

- Thus: when a reaction has a rate constant that obeys Arrhenius' equation, a plot of \( \ln(k) \) versus \( T^{-1} \) gives a straight line!