Radon reduction in Dark Matter Detectors

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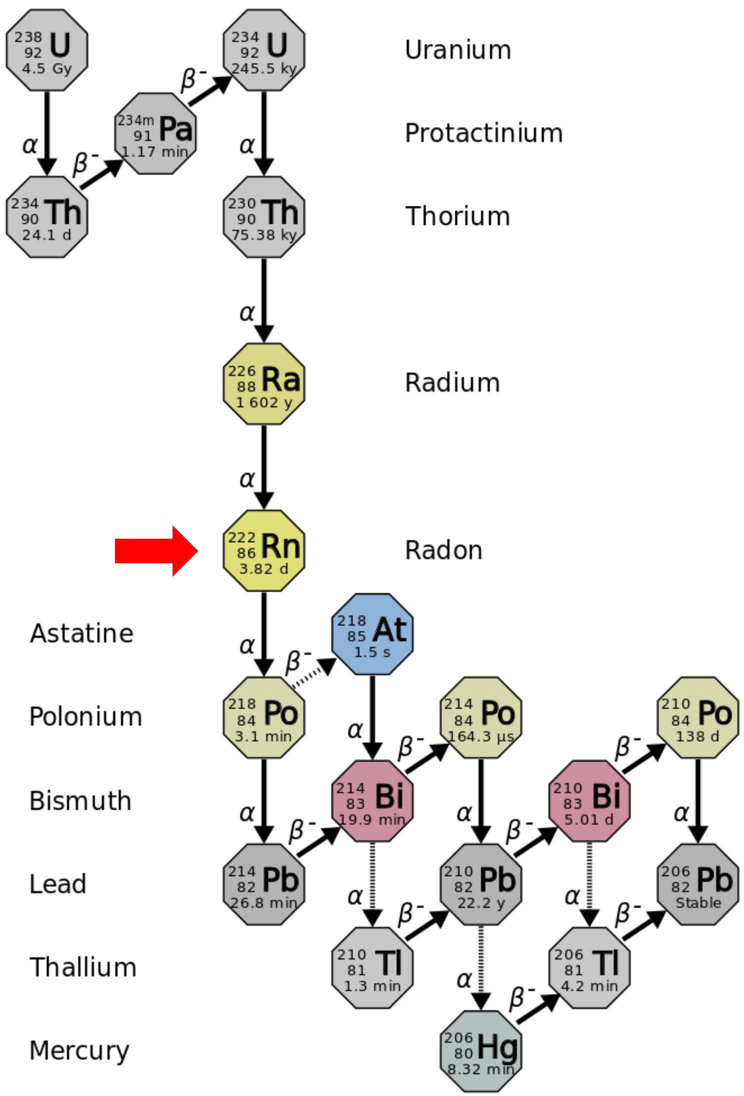
This work is supported by

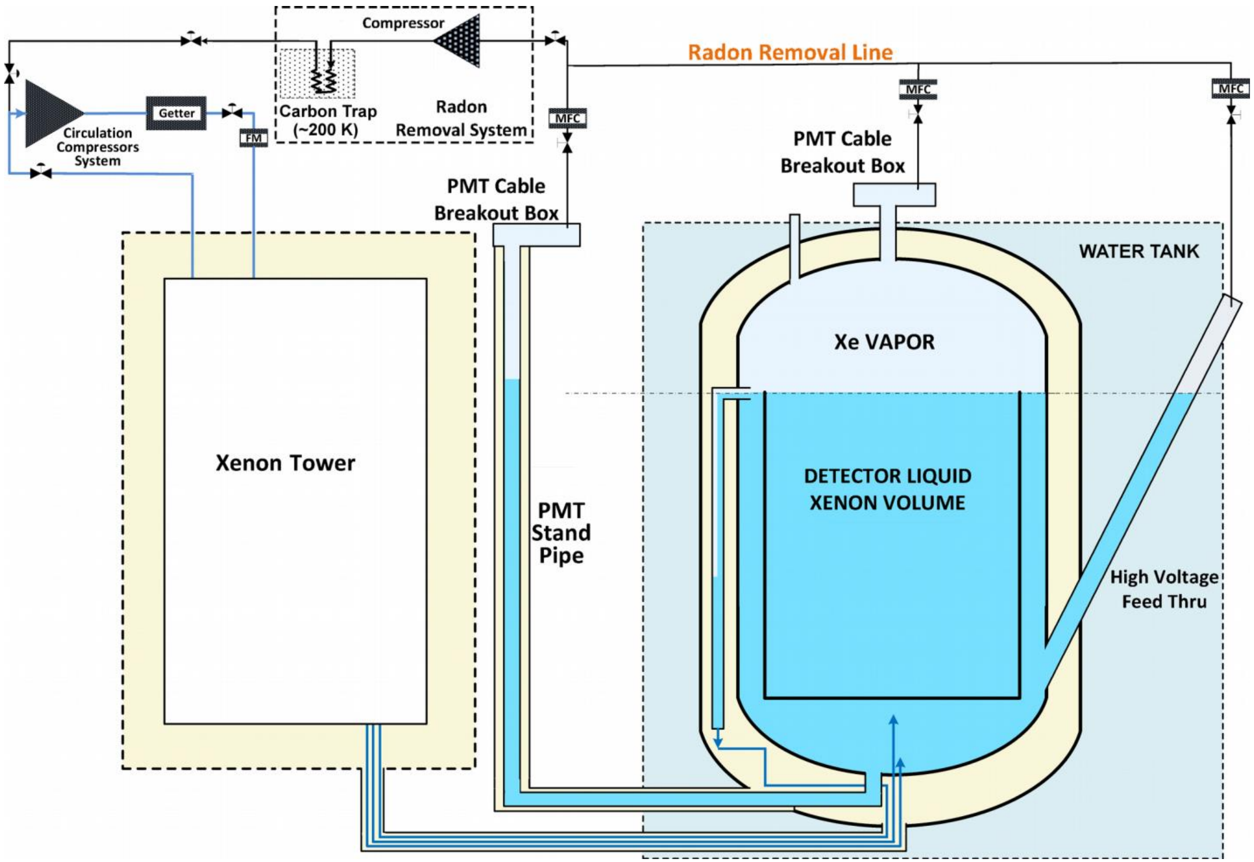
Radon - what is it and why is it bad?



1. radioactive noble gas
2. dissolves in LXe and cannot be removed with hot gas purifying getters
3. ^{222}Rn is a product of ^{238}U decay (everywhere)
   mean life of τ_{Rn} = 5.516 day
   = 7943 min
4. ^{222}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}Pb naked β$^-$ decay can mimic Dark Matter signals

In-line Radon reduction system

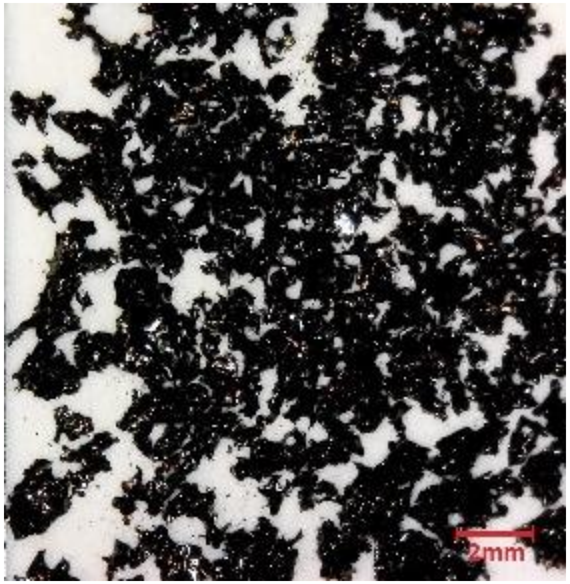
- reduce 20 mBq by a factor of 20 at a flow rate of 0.5 slpm
    i. $N = \tau_{Rn} A$ (= 5,516 d * 1.0 mBq) = 476 Rn atoms (steady-state population)
- sequestration of atoms in activated carbon trap until most ^{222}Rn nuclei decay
    i. think gas chromatography: v(Xe)/ v(Rn) (-85 C) ≈ 1000
- to obtain removal of 90%, sequestration time ≥ $\ln(10) \cdot \tau_{Rn}$ = 12.7 days



Activated Charcoals tested

Saratech

CarboAct



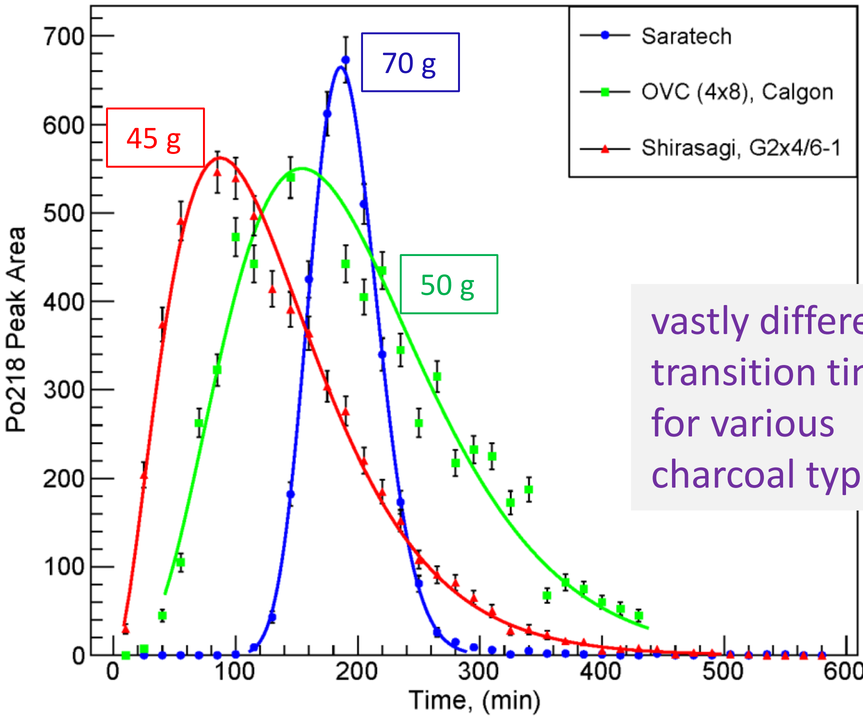
Shirasagi

Charcoal	Density (g/cm³)	Surface area (m^2/g)	Spec. activity (mBq/kg)	Price ($/kg)
Shirasagi	0.45	1,240	101 ± 8	27
CarboAct	0.28	1,000	0.23 ± 0.19	15,000*
Saratech	0.60	1,340	1.71 ± 0.20	35
Saratach (HNO_3)	0.60	1,340	0.51 ± 0.09	135

Density of graphite: 2.26 g/cm^3 provided by Carter Hall * 1/3 of price of gold

Elution Curves

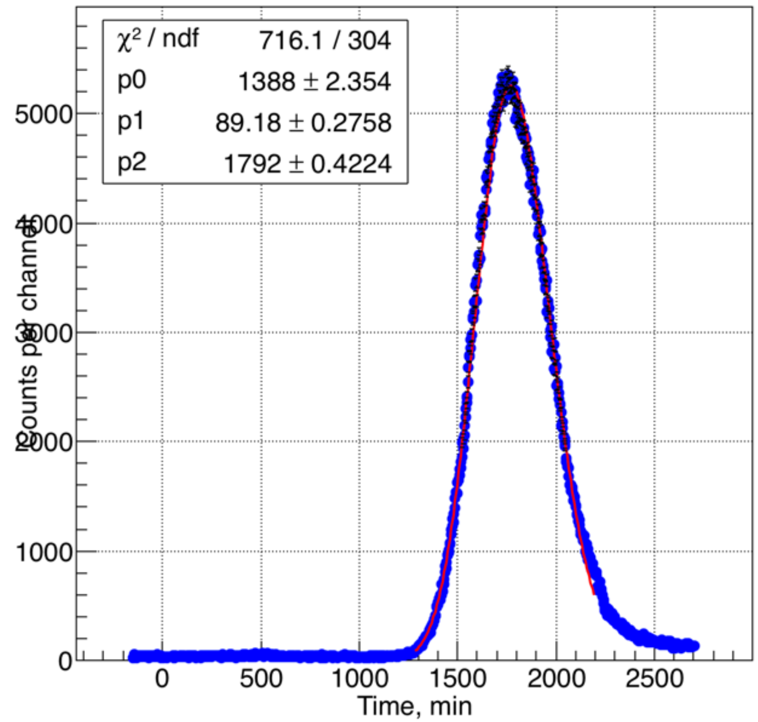
small trap: 0.1 l



vastly different transition times for various charcoal types

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

medium trap: 1.0 l



HNO_3 etched Saratech
½ SLPM, 1.7 atm, 447 g, 189 K
τ = 1792 min

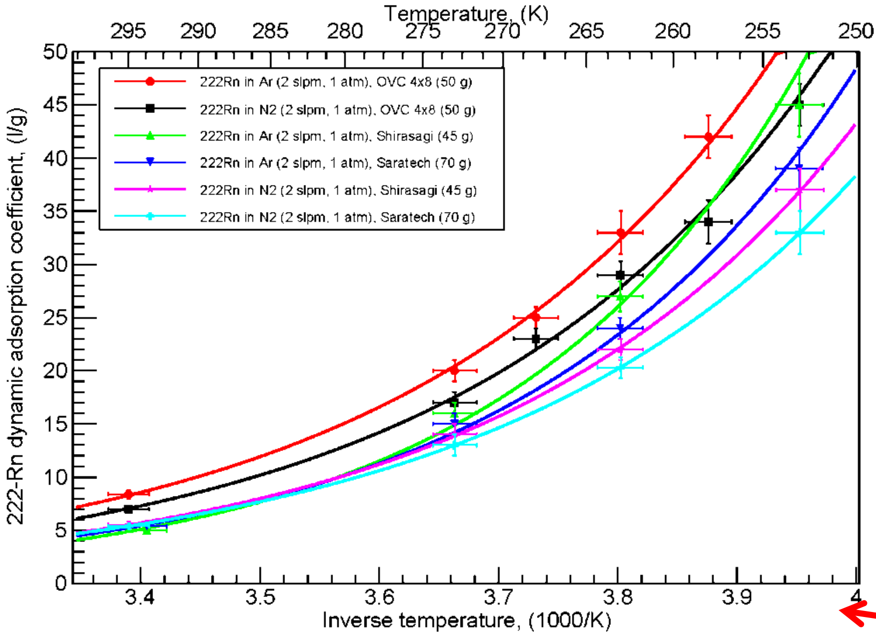
$$\tau = \frac{k_a m}{F},$$

k_a-adsorption coefficient, m-carbon mass (g),

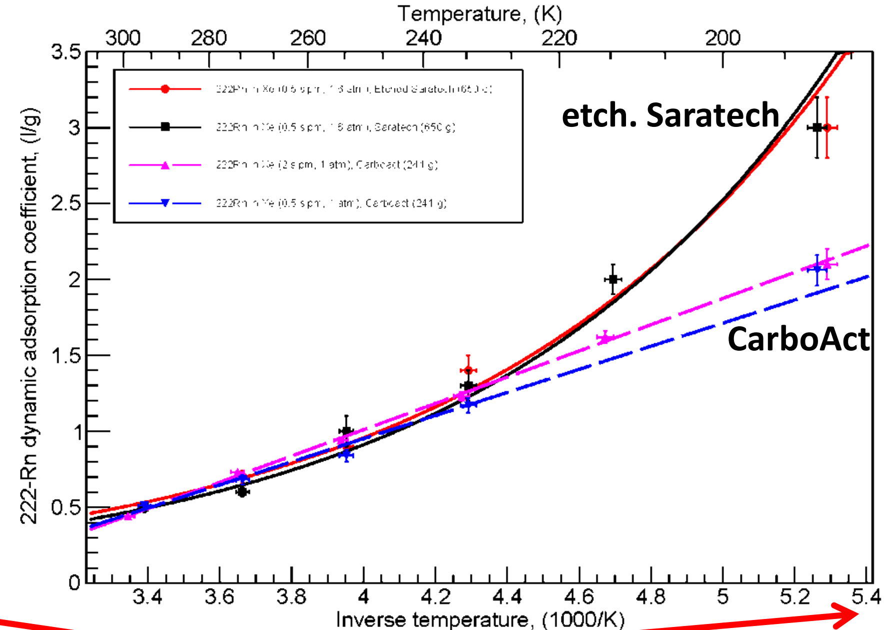
τ – *breakthrough time* (min), F-flow rate (SL/min)

Dynamic Absorption Coefficient

N_2, Ar carrier gas



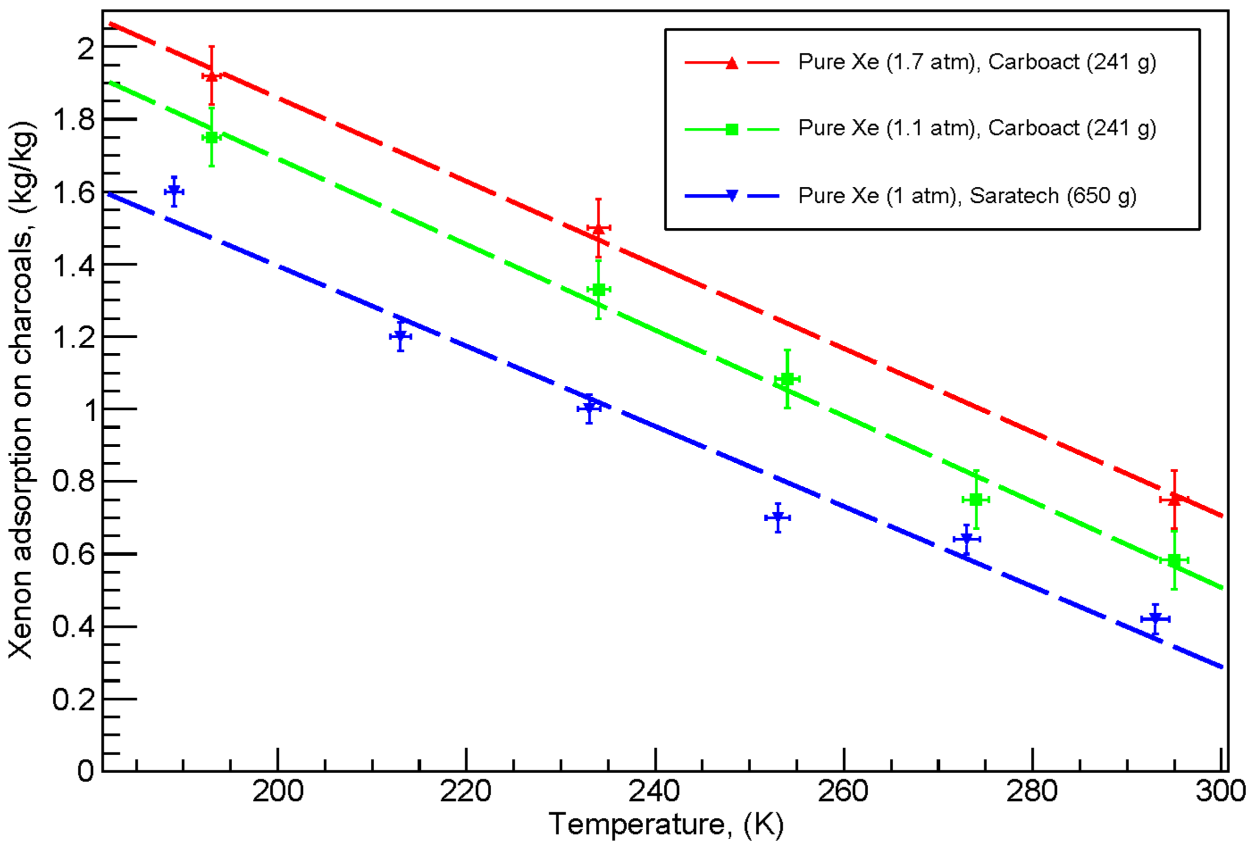
Xe carrier gas



different range

- Expectation:
  i. N_2 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 follows Arrhenius law (???)
  ii. k_a with Xe carrier gas is about 10x – 50x smaller than in He, N_2, and Ar carrier gas

Adsorption of Xenon gas on Charcoal

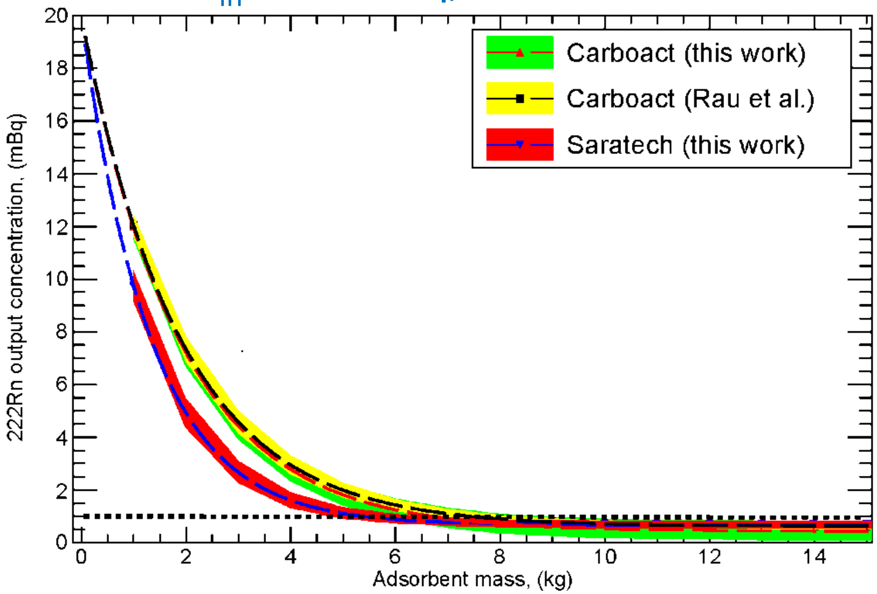


- Xenon gas adsorption: ca 1.6 kg / kg of charcoal
  - i. Increases linear with decreasing temperature
  - ii. Increases only slightly with pressure
- Ar, N_2 and He gas adsorption: tiny (below 20 g/kg of charcoal)

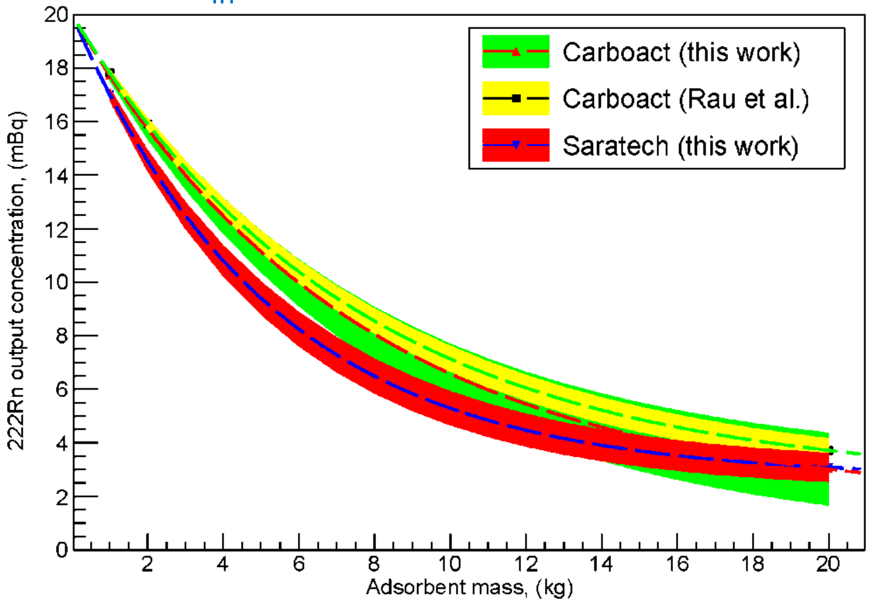
Small Rn trap for LZ (GXe)

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

N_{in} = 20 mBq, f = 0.5 SLPM



N_{in} = 20 mBq, f = 2.0 SLPM



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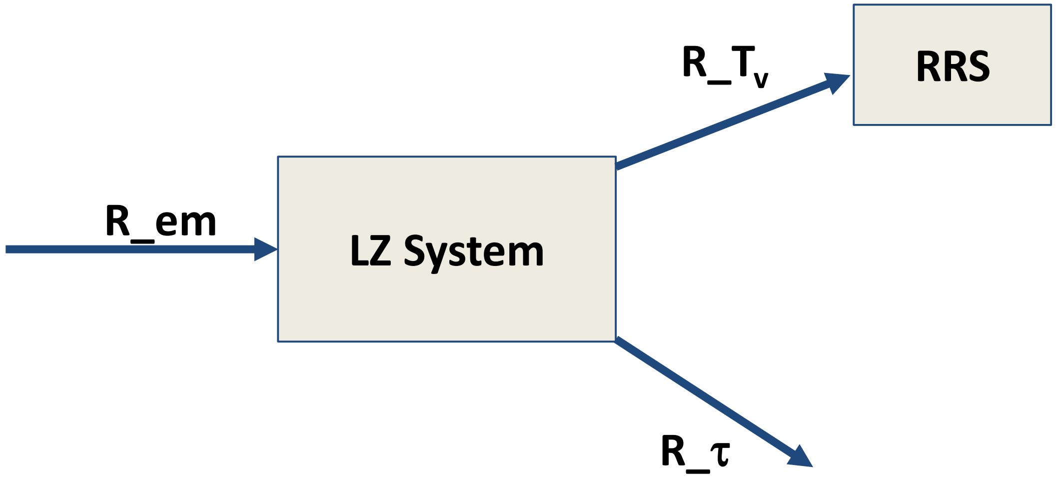
- dN/dm: specific activity (Saratech: 0.51 mBq/kg)
- Need 6 kg of etched Saratech to reduce Rn concentration to 1 mBq at 0.5 slpm
- Interestingly, lowest achievable Rn concentration does NOT depend on total mass

N_{out} (min) = 0.70, 0.45 mBq

N_{out} (min) = 2.80, 1.80 mBq

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 (τ = 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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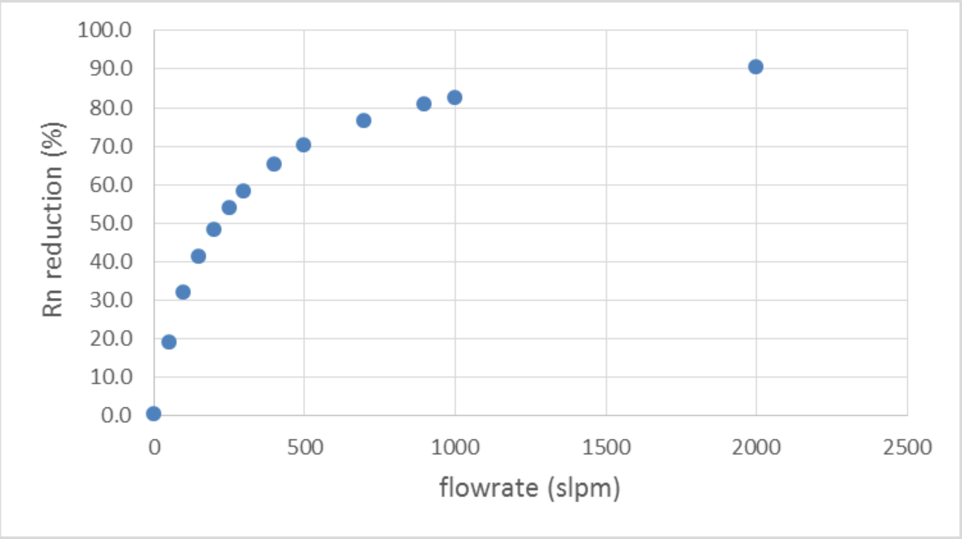
    i. suppresses Rn concentration in GXe space >20x to about 0.7 mBq
    ii. cannot be used to purify all 10 t of Xe

    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 life time (τ = 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)

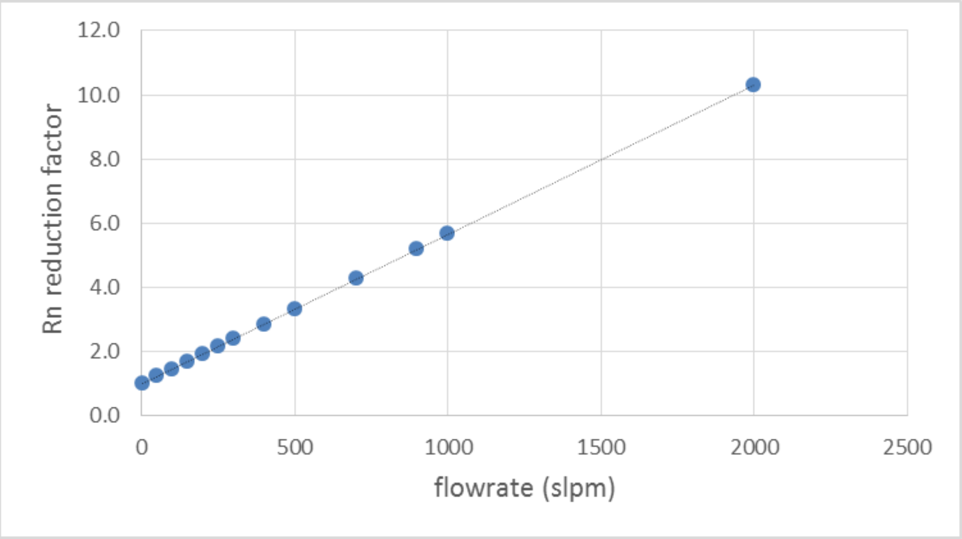
max Rn reduction

$\tau / (\tau + T_v)$



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 (τ = 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?

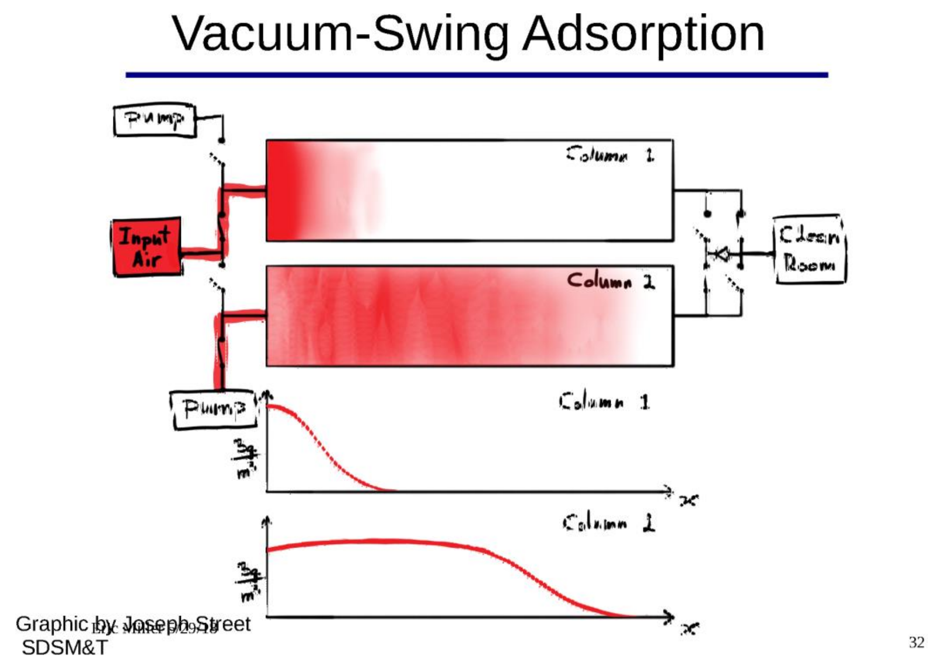
$$N_{out} = N_{in} e^{-\frac{m}{m^*}} + \frac{dN}{dm} m^* (1 - e^{-\frac{m}{m^*}}) \qquad m^* = \frac{f \tau_{Rn}}{k_a}$$

- 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)

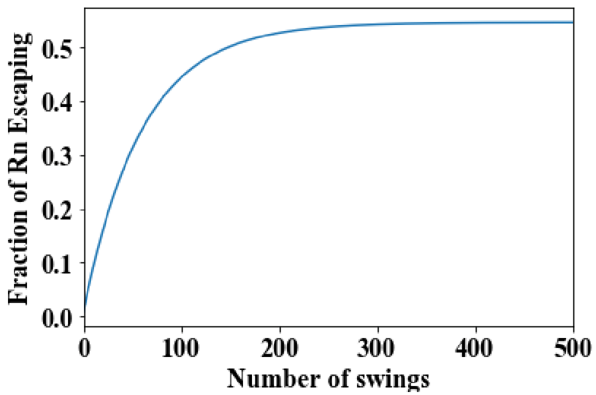
Does Not Work

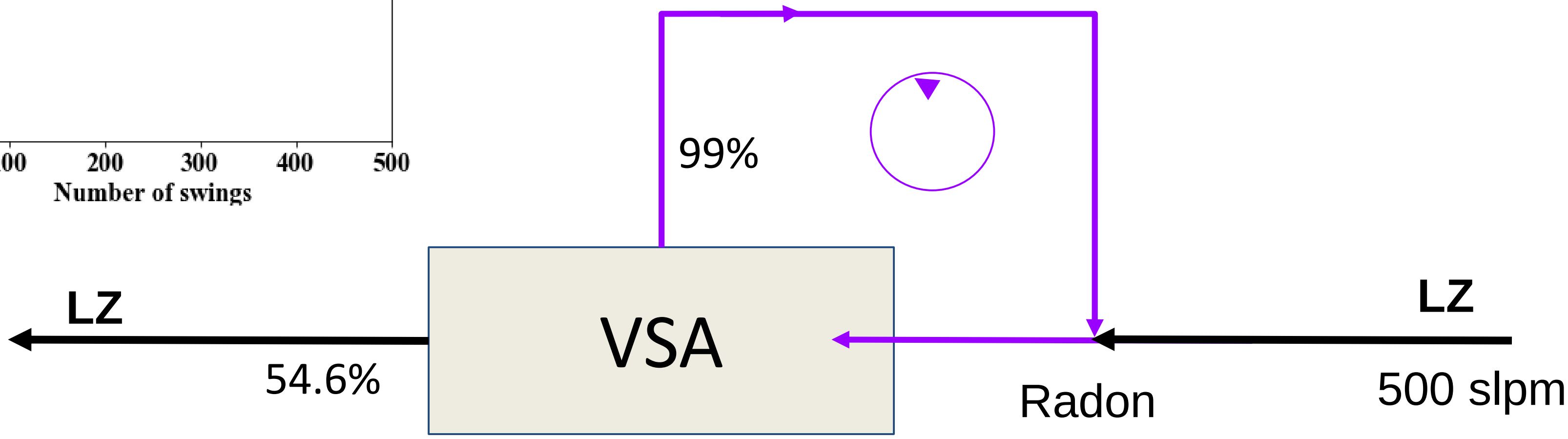
What about a Vacuum Swing System?

- Shown to reach > 99% efficiency of removing Rn from room air
  - purge gas is exhausted
  - Rn levels in room air about 100 – 200 Bq/m^3
- 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)



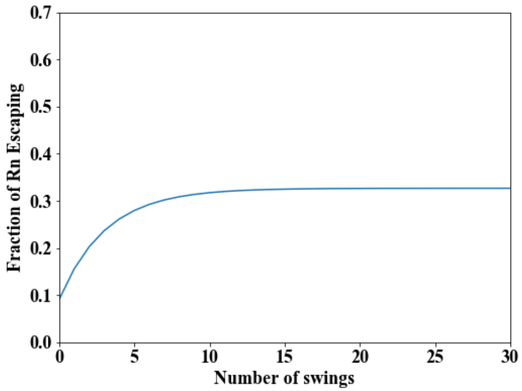
Ideal VSA system with feedback purge

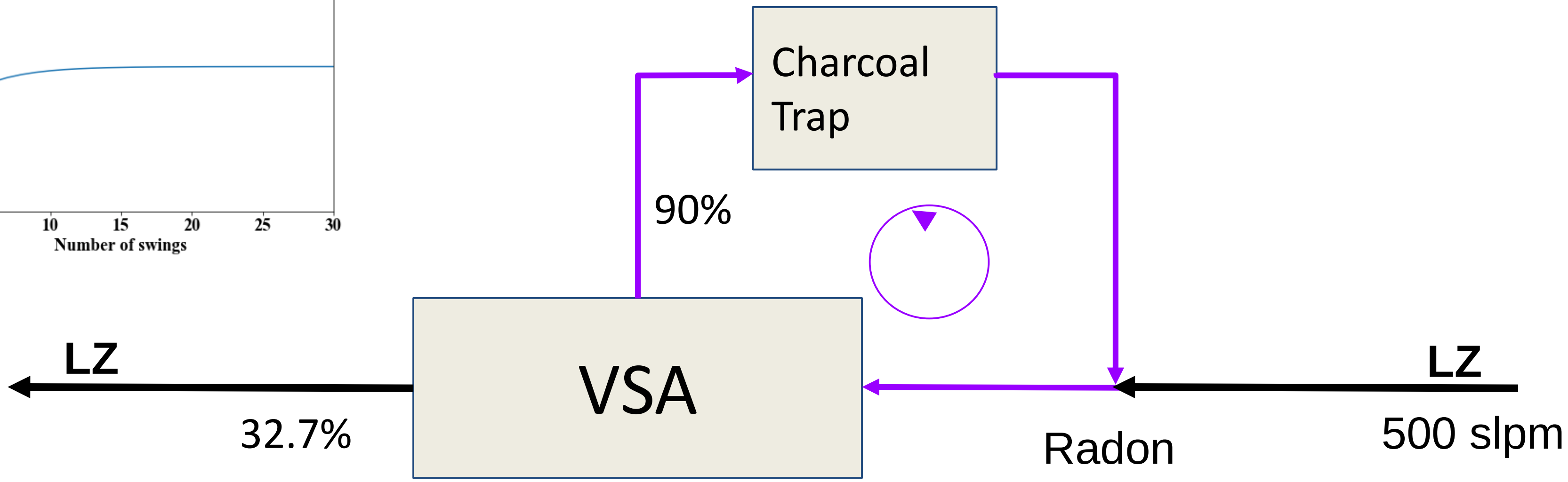




- Radon trapped in purple loop and slowly decays away
- If we assume: specific activity of carbon is negligible
- For 99% efficient trap, at steady state 54.6% of Rn atoms escape VSA system, which corresponds to 32% radon reduction in LZ

Ideal VSA with Cold Charcoal Trap

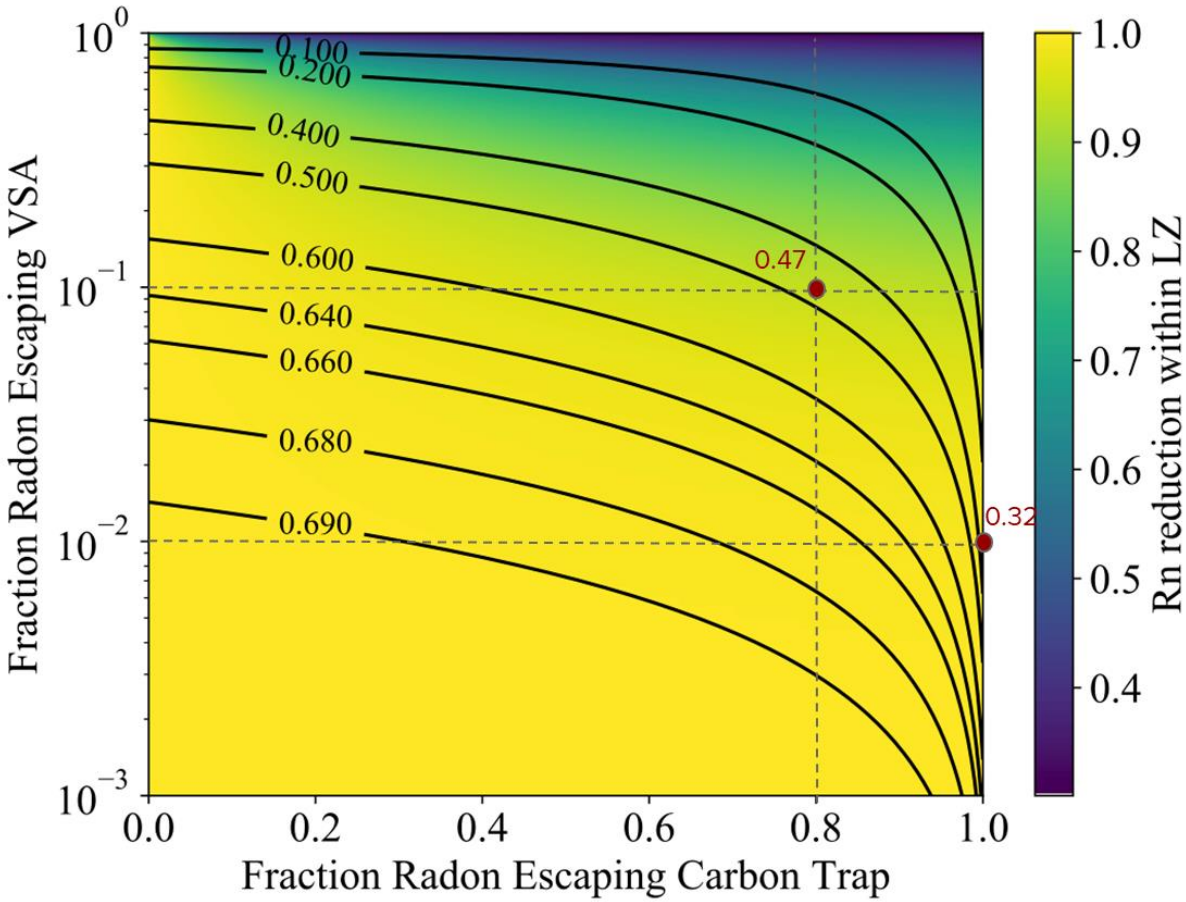




- Radon trapped in purple loop and slowly decays away
  - CCT increases time Rn atoms spend in feedback loop before entering back into VSA
- If we assume: specific activity of carbon is negligible
- For 99% VSA efficiency, and 20% CCT efficiency: 4.2% of Rn atoms escape VSA!!
- For 90% VSA efficiency, 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:
  Rn_rrs / Rn_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 specifc 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

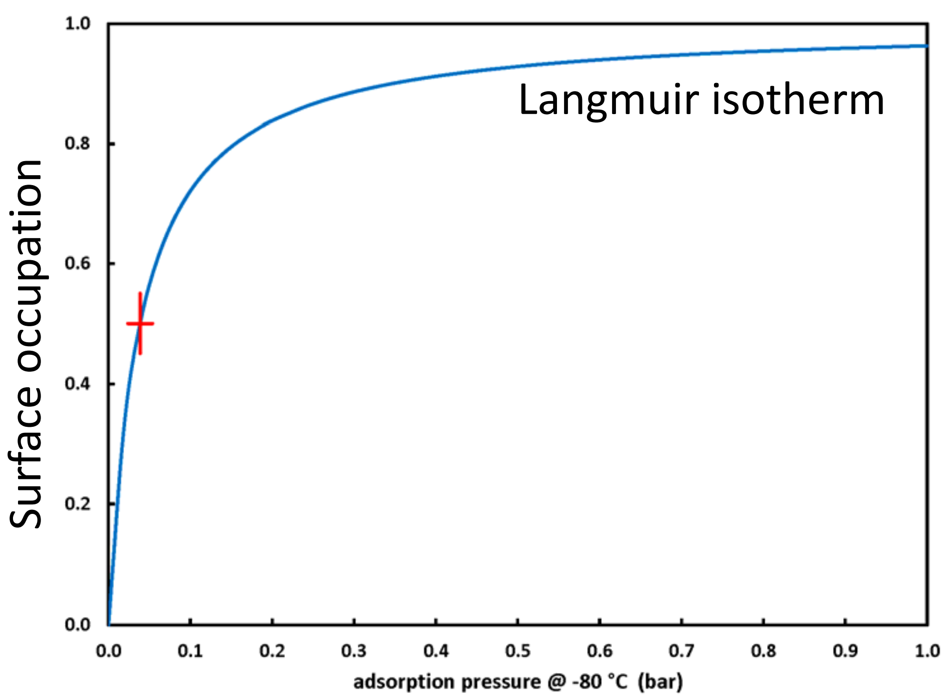
- For 10 tons Xe detectors:
  - need flow rates of 2,000 slpm wo reduce Rn concentration 10x
  - at 500 slpm (or below) best we can do is to reduce initial concentration 3.3x for any kind of RRS (even for systems w/ zero specific activities)
  - carbon traps of any flavors will not work (unless specific 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:
  i. 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)
  ii. Adsorbing surface forms at most a monoatomic layer
  iii. A_{max} = total area of adsorption surface, A = area occupied by monoatomic layer
- Consequence:
  i. In equilibrium: prob. of trapping an additional molecule: A_{max} - A
     prob. for adsorbed molecule to be liberated: c A



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

Arrhenius Equation

$$k = Ae^{\frac{-E_a}{k_b T}}$$

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!