The BetaCage, an Ultrasensitive Screener for Surface Contamination

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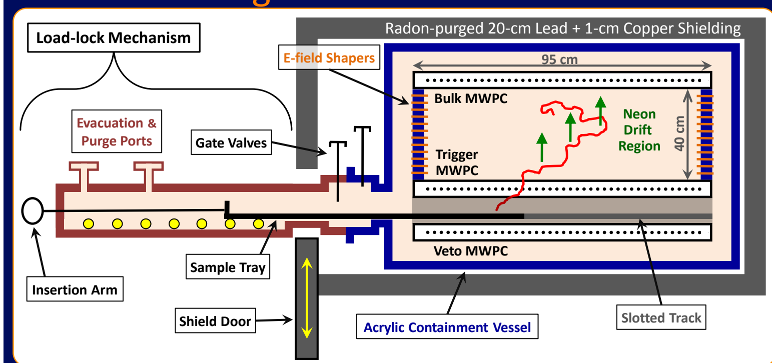
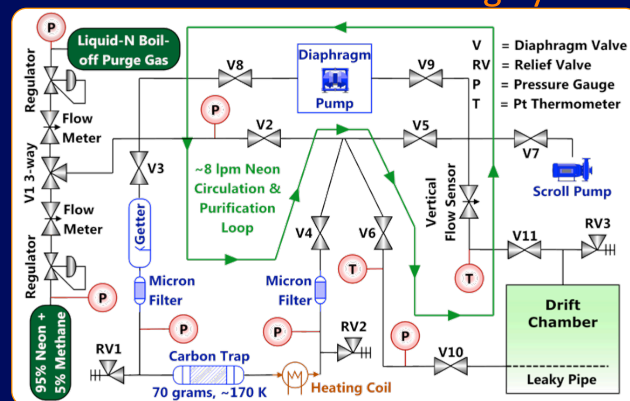
Material screening for identifying low-energy electron emitters and alpha-decaying isotopes is now a prerequisite for rare-event searches (*e.g.*, dark-matter direct detection and neutrinoless double-beta decay) for which surface radiocontamination has become an increasingly important background. The BetaCage, a gaseous neon time-projection chamber, is a proposed ultra-sensitive (and nondestructive) screener for alpha- and beta-emitting surface contaminants to which existing screening facilities are insufficiently sensitive. Our sensitivity goals are 0.1 betas (per keV-m^2-day) and 0.1 alphas (per m^2-day), where the former will be limited by Compton scattering of external photons in the screening samples and (thanks to tracking) the latter is expected to be signal-limited; radioassays and simulations indicate backgrounds from detector materials and radon daughters should be subdominant. We report on details of the background simulations and detector design that provide the discrimination, shielding, and radiopurity necessary to reach our sensitivity goals for a chamber with a 95x95 cm^2 sample area positioned below a 40 cm drift region and monitored by crisscrossed anode and cathode planes consisting of 151 wires each.

Detector Design



Gas Handling System

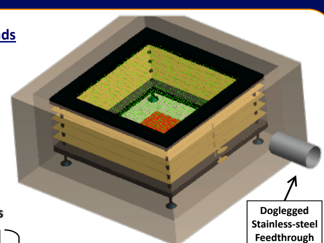


Beta Sensitivity

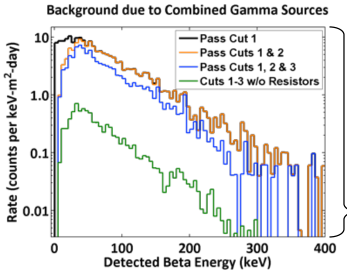
Geant4 Monte Carlo Simulation of β Backgrounds

Detector model (from the outside in):

- 15-cm thick outer **Lead** (shielding)
- 5-cm thick, low-activity inner **Lead** (shielding)
- 1-cm thick OFE **Copper** (shielding, field shapers)
- 2-mm thick **Stainless Steel** (feedthrough for signals)
- 750 kg of **Acrylic** (containment vessel, field shapers)
- 40 kg of **Noryl** (MWPC frames)
- Ten 50-g **Resistors** (voltage division for drift field)
- 60x60 cm^2 **Sample** area



Background due to Combined Gamma Sources



Background Reduction via Reconstruction

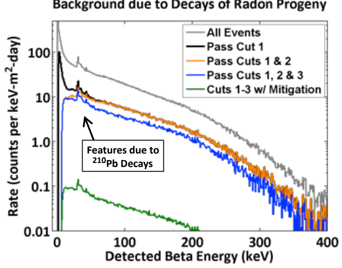
Conditions for isolating tracks from sample:

- **Data Cut #1:**
  - <1 keV in veto MWPC & >1 keV in trigger MWPC
- **Data Cut #2:**
  - >5 keV deposited in drift region (bulk MWPC)
- **Data Cut #3:**
  - Fully contained in fiducial drift region

Betas Produced by Compton Scattering of Photon Sources

Betas from Decay of Pb & Bi Isotopes

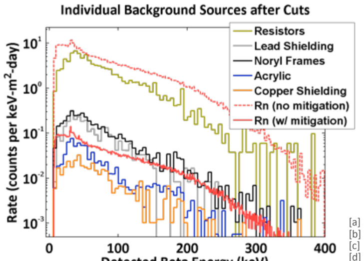
Background due to Decays of Radon Progeny



Betas from Radon Daughters

- Assume ^{222}Rn background of >10^3 decays/day:
  - Simulate 1,300 early decays/day (^{214}Pb & ^{214}Bi)
  - Fewer late decays/day (^{210}Pb & ^{210}Bi)
    - → 22.3 years/3.8 days ≈ 2000x fewer (at first)
    - → 22.3 years/3 years ≈ 7.5x fewer (after 3 years)
    - → Assume 1/10th as many decays (conservative)
  - Assume 70% of decays originate on trigger wires
    - → Rn daughters are generally positively charged
    - → Trigger MWPC is most negative potential near drift region's large gas volume (attracts progeny)
  - Remaining decays from veto wires & bulk gas (30%)
- **Mitigation assumes x100 reduction**

Individual Background Sources after Cuts

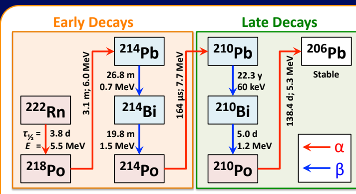


Assumed Activities of Photon Sources

mBq/kg	^{238}U	^{232}Th	^{40}K
Resistors [a]	6,000	5,000	35,000
Noryl [b]	<3	<1	5
Lead [c]	3,000 ^{210}Pb		
Acrylic [a]	<0.12	<0.04	<1.5
Copper [d]	0.08	0.012	0.04
Stainless Steel [a,e]	<1	<10	<4

[a] Community Material Assay Database, *radiopurity.org*
[b] U/Th→UMN Gopher HPGe & Caltech ICP-MS; K→UC Davis NAA
[c] PLOMBUM low-activity lead, *www.plombum.republika.pl*
[d] E. Aprile *et al.*, Phys. Rev. D83 (2011) 082001
[e] SS feedthrough contributes negligibly to beta background

Radon Mitigation



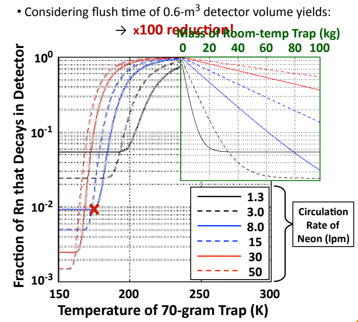
Radon Sources (in terms of ^{222}Rn decays/day):

- **Emanation ≈ 1000** (continuously sourced)
  - Assumes ~90x lower than achieved by DRIFT-IIa [3]
  - Mitigate with carbon trap or careful materials selection
- **Neon ≈ 0.5–500** (sourced per fill of detector volume)
  - Assumes levels similar to argon measurements in [4]
  - Mitigate either with carbon trap or wait weeks to decay
- **Environment ≈ 1000 Bq/m^3** (continuously sourced)
  - High external level due to underground location
  - For PMMA vessel, mitigate with low-radon purge
  - For gas handling system, require leak tightness of:
    - → ~10^{-6} mbar L/s downstream of carbon trap
    - → ~10^{-2} mbar L/s upstream of carbon trap [5]

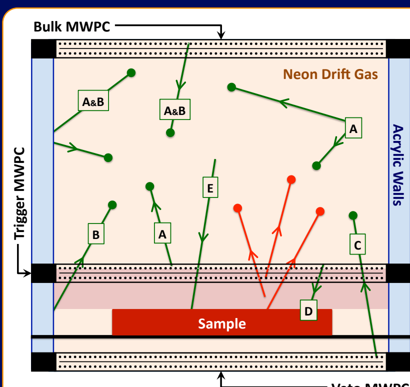
[1] Blucher GmbH 102688, see *www.bluecher.com/en/technology*
[2] K.P. Strong & D.M. Levins, *DOE Nuclear Air Cleaning Conference* (1978)
[3] S. Burgos *et al.*, NIM in Physics Research A, 584 (2008) p. 114
[4] H. Sigmen & G. Zuzel, Applied Radiation and Isotopes, 67 (2009) p. 922
[5] Mitigation allows use of relatively leaky mini-diaphragm circulation pump

Radon Mitigation via Cooled Carbon Trap

- Relatively small tube: L = 25-cm (length) & φ = 2.5-cm (diameter)
- 70 grams of high-quality synthetic carbon [1]:
  - ρ = 0.6 g/cm^3 (density) & S = 1342 m^2/g (surface area)
- For Q = 8 lpm (circulation flow rate) & T = 170 K (trap temperature):
  - $\mu_s = 4Q/\pi\varphi^2 \approx$ 26 cm/s (superficial velocity through trap)
  - $k_a(S,T) \approx 1.4\text{x}10^7$ cm^3/g (dynamic adsorption coefficient) [2]
  - $\tau_{trap} = Tk_a\rho L/(273\text{ K})\mu_s \approx$ 56 days ('punch-through' time) [2]
  - Survival fraction for radon atoms entering the trap:
    - → $e^{-\tau_{trap}/5.52\text{ d}} \approx 3.8\text{x}10^{-5}$
  - Considering flush time of 0.6-m^3 detector volume yields:
    - → **x100 reduction!**



Alpha Sensitivity



Near-perfect Rejection of Alpha Background

- Alpha emitters in gas & on surfaces (Rn & progeny)
- Easily reject most tracks via reconstruction:
  - A. **Insufficient energy in trigger MWPC**
  - B. **Not fully contained in fiducial drift region**
  - C. **Too much energy in veto MWPC**
  - D. **Insufficient energy in bulk MWPC**
  - E. **dE/dx at far end of track not large**
- Most dangerous alphas emitted from:
  - **Drift gas & cathode wires directly above sample**
  - **Surface of sample** (following Rn-daughter implantation)

Simulated 5 MeV Alpha Tracks