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Radon daughter plate-out measurements at SNOLAB for polyethylene and copper

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ABSTRACT

Polyethylene and copper samples were exposed to the underground air at SNOLAB for approximately three months while several environmental factors were monitored. Predictions of the radon-daughter plate-out rate are compared to the resulting surface activities, obtained from high-sensitivity measurements of alpha emissivity using the XIA UltraLo-1800 spectrometer at Southern Methodist University. From these measurements, we determine an average ^{210}Pb plate-out rate of 249 and 423 atoms/day/cm^2 for polyethylene and copper, respectively, when exposed to radon activity concentration of 135 Bq/m^3 at SNOLAB. A time-dependent model of alpha activity is discussed for these materials placed in similar environmental conditions.

1. Introduction

Many low-background experiments are placed deep underground to shield from cosmic rays. Extreme care is taken to account for and to avoid accumulation of radiocontaminants on material surfaces, which is made all the more challenging by the high radon activity typically present in underground laboratories. Radon daughters in air can plate out onto and implant within experiment materials, and these daughters can give rise to neutron and gamma-ray backgrounds from (α,n) and Bremsstrahlung interactions, respectively. Useful metrics for this implantation process are the plate-out rate (implanted atoms/area/time) or plate-out height (height under which it is assumed 100% of all radon daughters will plate onto the surface below).

After a series of short (< 1 h) decays, ^{210}Pb ($t_{1/2}$ = 22.3 yr) comprises the majority of remaining contaminants. This isotope decays via β emission to ^{210}Bi, which subsequently β decays ($t_{1/2}$ = 5 d) to ^{210}Po. This study focuses on the 5.3 MeV alphas from ^{210}Po decays ($t_{1/2}$ = 138 d). These alphas can interact with ^{13}C nuclei in polyethylene (commonly used as a neutron shield) and generate neutrons through (α,n) reactions. For dark matter direct detection experiments, neutrons are a challenging background because they deposit energy in a way that can mimic the signals expected from dark matter interactions. As a result, it is important to understand how contamination from radon and its progeny can lead to neutron backgrounds and how they evolve over time.

2. Estimating backgrounds in polyethylene

Several forms of polyethylene, $(C_2H_4)_n$, are commercially available. This study focuses on high-density poly-ethylene (HDPE) which has density of 0.941–0.965 g/cm^3. With a natural abundance of 1.07(8)% [1], ^{13}C accounts for 0.36% of all atoms in HDPE.

A modified version of SOURCES-4C [2,3] was used to model (α,n) reactions in HDPE, resulting in an expectation of 7.3×10^{-8} n/s/cm^3 for 1 Bq/g of ^{210}Pb activity (assuming secular equilibrium) in the bulk of the polyethylene (*cf.* Fig. 1). Polyethylene shielding exposed to a high-radon environment such as SNOLAB would quickly become contaminated with residual ^{210}Pb. Though the ^{210}Pb would be implanted near the surface, and some alphas from the ^{210}Po decays would be emitted away from the bulk, there is still the possibility these alphas could interact with ^{13}C on an exiting trajectory. For the purposes of a conservative estimate, any alpha activity on or near the surface is considered as having the potential to create neutron backgrounds.

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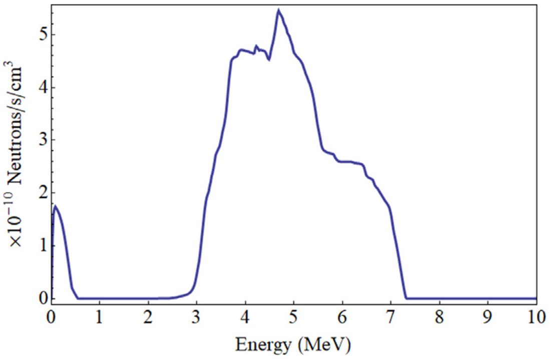

Fig. 1. SOURCES-4C neutron spectrum from 1 Bq of ^{210}Pb contamination in each gram of polyethylene (assuming ^{210}Po is in secular equilibrium).

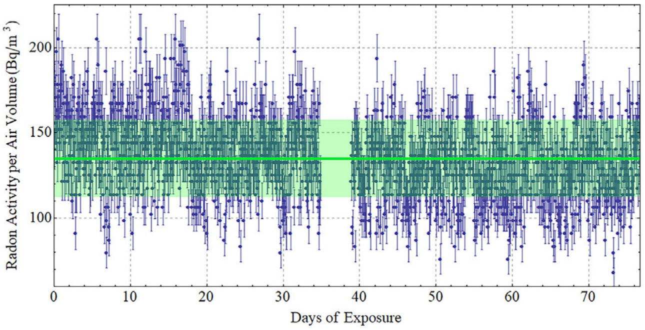

Fig. 2. Radon activity per m^3 at SNOLAB during the exposure period as measured by a RadStar RS300. The average measured value of 135 Bq/m^3 (green line) and associated 1σ standard deviation (shaded band) are also shown.

Table 1
Average environmental values of the experiment location within SNOLAB, with one standard deviation calculated from the population of data points. Dust particles were monitored with a ParticleScan CR, radon activity with a RadStar RS300, and temperature and humidity with a Lascar EL-USB-2-LCD+. The large particle-count standard deviation results from (a few) intermittent periods during which the level briefly exceeded $10^4 \geq 0.3$ μm particles per ft^3. This was observed in the vicinity of the experimental setup and is likely due to installation of wiring in a nearby area and some pressure testing of copper lines. However, throughout the exposure period, the SNOLAB (lab wide) particle monitors (which measure particles > 0.5 μm) recorded levels consistent with a Class 2000 environment or better.

Data	Average	σ
Particles ≥ 0.3 μm (pp. ft^3)	238	679
Radon (Bq/m^3)	135	23
Temperature (K)	293.3	0.4
Humidity (%)	57.9	1.6

3. Experimental setup & environment

3.1. Cavern environment

The experimental site is located at SNOLAB, a Class 2000 clean room laboratory 6800 ft below the surface in Lively, Ontario, Canada. The setup was located in Room 127 in an area referred to as the Ladder Labs (see Fig. 3). During the exposure at SNOLAB, environmental factors were continuously monitored including radon, temperature, relative humidity, and counts of dust particles ≥ 0.3 μm. The instruments used to record these data were located on a table immediately adjacent to the samples at Site 1 (see Table 1 and Figs. 2, 3). We monitored these values such that we could either rule out or include possible effects from fluctuating environmental factors. Radon levels in the laboratory area are known to seasonally vary from ∼125 to 135 Bq/m^3 whereas the level at the surface is around 6 Bq/m^3 [4].

Table 2
Position information for each exposure location used. Height is measured as the distance from the floor to the surface of the panels. Two polyethylene samples were placed at each location and four copper samples were placed at Site 1. The variety of locations was motivated to test for variations in plate-out height due to position and proximity to nearby walls.

Site number	Room number	Nearest wall (m)	Height (m)
1	127	3.63	0.94
2	127	0.38	0.94
3	127	3.63	2.01
4	131	0.38	0.94

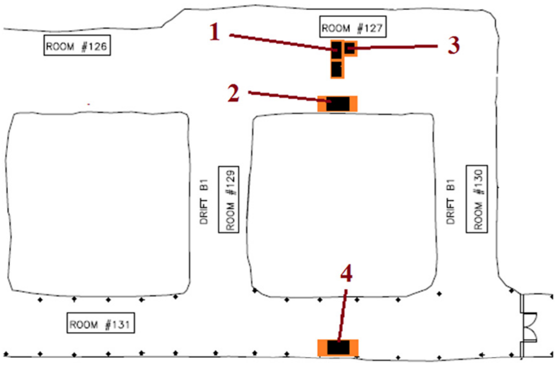

Fig. 3. Map of the four exposure sites in the Ladder Labs at SNOLAB (*cf.* Table 2).

3.2. Panels & placement

A total of ten HDPE panels were used, all cut from the same 122 cm×244 cm sheet (purchased from Johnston Industrial Plastics, Ontario, Canada), each panel of dimensions 30.5 cm×30.5 cm×0.5 cm. We chose this sample size to optimize the sensitivity of the UltraLo-1800 spectrometer that was used to perform the pre- and post-exposure surface assays in this study. The panels were set in pairs at four different locations in SNOLAB with varying height and room position to test for variations in plate-out from position and proximity to nearby walls (see Table 2 and Fig. 3). Each pair was set immediately adjacent to one another with each panel laid flat.

Four copper panels were also placed at Site 1, each of dimension 15.25 cm×30.5 cm×0.64 cm. Every panel was placed on a non-conducting surface for the duration of the exposure. During shipment to and from SNOLAB, all panels were sealed inside two nitrogen-flushed static dissipative nylon bags with an outer polyethylene bag. The polyethylene bag was used as a general protection around the inner bags while the nylon bags were chosen for their low radon permeability [5].

For the trip to SNOLAB, the panels were laid face-to-face with no air gaps. For the return trip, the panels were packed in pairs (one pair from each site, upward-facing sides pointed inward) with a small air gap between panels to best maintain the integrity of the surfaces. The bags were once again nitrogen back-filled to limit any plate-out that might occur during shipment.

4. Analysis & results

4.1. Pure ^{210}Po Model

Because the expected alphas come from the short-lived daughter (^{210}Po) of a long-lived parent (^{210}Pb), a model for the number of ^{210}Po atoms over time is built from the Bateman equation [6]:

$$N_{Po}(t) = N_{Pb}(0)\frac{\lambda_{Pb}}{\lambda_{Po} - \lambda_{Pb}}\left(e^{-\lambda_{Pb}t} - e^{-\lambda_{Po}t}\right) \tag{1}$$

Due to the comparatively short half-life of ^{210}Bi (∼ 5 days), we neglect it in setting up Eq. (1). To account for a particular number of ^{210}Pb