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Charcoal-based Radon Reduction Systems for Ultra-clean Rare-event Detectors

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Abstract: Radon and its daughters constitute the most significant background in many rare event searches since they are continuously resupplied from detector materials. ^{222}Rn produces a particularly problematic background in the physics region of interest by the "naked" beta decay of its ^{214}Pb daughter nucleus. To reach high sensitivity in G3 dark matter search experiments, radon reduction in the entire circulation loop at high flow rate ($\mathcal{O}$(1,000's) SLPM[1]) is necessary. In this letter, we present one avenue to be pursued in developing feasible radon reduction systems based on vacuum swing adsorption technology for G3 experiments.

[1]standard liter per minute

1. Introduction

Radon is a radioactive noble gas that is re-supplied continuously from the decay chains of uranium and thorium present in practically every material of rare event detectors, and constitutes the dominant background source in many dark matter searches. Because radon is an inert gas, it dissolves in noble liquid detectors and cannot be removed with high temperature getters. Among the radon isotopes abundant in nature, ^{222}Rn ($\tau = 5.516$ days), a progeny of ^{238}U, is of particular concern. The beta decay of its daughter ^{214}Pb to the ground state of ^{214}Bi (6% b.r.) emits no gammas. This "naked" beta decay can end up in the low-energy region of interest for dark matter searches, survive the nuclear recoil discrimination cut, and be indistinguishable from low-energy nuclear recoils of rare particle interactions in the active volume of the detector. Discriminating against such background events is very challenging in the analysis.

Hardware mitigation is necessary to reduce the continuously re-supplied radon background for tonne scale and larger noble-liquid rare event searches, including dark matter direct-detection experiments. For radon reduction of multi-tonne noble-liquid detector systems, single trap approaches as those employed by the LZ experiment [1] become infeasible. We find that even for perfect radon traps, those which do not emanate radon from the charcoal itself, circulation speeds of 10,000 SLPM are needed to reduce radon concentration in a 50 tonne detector by 90%. This is faster by a factor of twenty than the highest circulation speeds currently achieved in dark matter detectors. We further find that the efficacy of vacuum swing adsorption systems, which have been employed very successfully at reducing atmospheric radon levels in clean-rooms at flow rates as high as 2,000 SLPM, is limited by the intrinsic radon activity of the charcoal adsorbent in ultra-low radon environments. Adsorbents with about 10 times lower intrinsic radon activity than in currently available activated charcoals would be necessary to build effective vacuum swing adsorption (VSA) systems operated at room temperature for rare event search experiments. If such VSA systems are cooled to about ($190\,K$) this factor drops from 10 to about 2.5. This may be in reach by the time G3 experiments can be realized. Other options, not pursued here, might include radon purification in the liquid phase.

2. A cold VSA for Radon Reduction

For a perfect in-line radon reduction system in the main circulation loop, the highest achievable radon reduction efficacy within the detector can be described by [2]

$$(\epsilon)_{max} = \frac{\tau}{\tau + T}, \tag{1}$$

where τ is the the radon lifetime (5.516 days), and T is the turnaround time of the entire detector mass[2]. This means that the maximum achievable radon reduction is ultimately limited by the main circulation flow rate of the detector. Based on this, a circulation speed of 10,000 SLPM is needed to reduce radon concentration in a 50 tonne G3 detector by 90%. This is faster by a factor of twenty than that achieved in the LZ experiment (500 SLPM). Scaling up charcoal based *single-trap* radon reduction systems (e.g. the one employed in the LZ experiment [1, 3]) for multi-tonne time projection chambers (TPCs) is impossible given the intrinsic radon emanation of currently-available charcoals, and impractical even if radon emanation were negligible [2].

Vacuum swing adsorption (VSA) systems have been developed for radon reduction in clean rooms for flow rates as high as 2,000 SLPM. This is in contrast to single-trap radon reduction systems whose performance is set by the steady-state radon output, which limits the flow rate (e.g. $0.5 - 2$ SLPM for the LZ inline radon reduction system (iRRS) employed in the auxiliary circulation loops). VSA systems are based

[2] The turnaround time is given by $T = M/(f\rho)$, where f is the carrier gas flow rate, M is the total carrier gas mass, and ρ is the carrier gas density.

on multi-trap systems — typically consisting of two charcoal columns — where the flow direction of the carrier gas is switched between the columns. Furthermore, in contrast to air purification systems, where the purged air is released back into the atmosphere, xenon is expensive, and needs to be captured and returned to the purification system, as shown schematically in Fig. (1). Therefore, rather than pumping and releasing the xenon gas into atmosphere, the radon-rich purge gas has to be returned to the inlet of the swing system. In such a system, the radon atoms become effectively trapped and accumulate in the feedback loop. Accumulation of radon atoms in the feedback loop continues until it is balanced by the decay of the radon atoms and steady state is reached. Note that such a system conveniently provides a mechanism for radon atoms to decay outside of the TPC detector. An improvement is to integrate a single-trap RRS, which is preferably cooled, in the feedback loop of the VSA system, shown schematically in Fig. (1), such that the radon-enhanced gas from the purge column passes through the single-trap RRS before it is fed back into the inlet of the VSA.

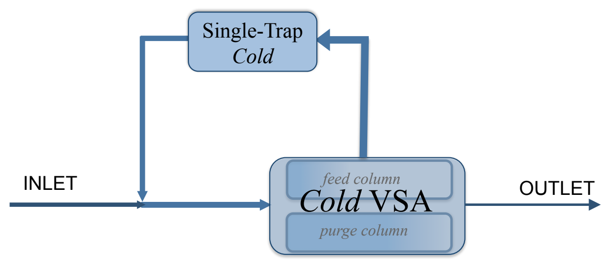

Figure 1: A schematic of a cold VSA system with a single, cold trap in the feedback loop for radon reduction in xenon. The single, cold trap greatly enhances the efficacy of the VSA system.

Since the radon content introduced to a VSA system due to the intrinsic activity of charcoal is typically much smaller than that in atmospheric air, it is mostly ignored in VSA systems used for radon reduction in clean rooms. Conversely, in a liquid xenon dark matter detector with a radon content as low as 1 atom/kg of xenon, the introduction of a charcoal trap could very well introduce more radon than it removes. Using a radon dynamics model in a VSA system developed in Ref. [2], it is estimated that ultra clean charcoal adsorbents with intrinsic radon activity of $0.05\,mBq/kg$ or less are necessary for swing adsorption technology to be viable for radon reduction systems considered at room temperature ($295\,K$), which is about a factor of 10 lower than the activities of currently available adsorbents. Because the charcoal adsorption coefficient increases with decreasing temperature following the Arrhenius Law [3], cooling the VSA down to $190\,K$ shows considerable promise. As shown in Ref. [2], the efficacy of the cooled VSA system becomes comparable to that of a VSA operated at room temperature but with significant relaxation on the demand for intrinsic charcoal activity. In fact, the demand drops from $0.05\,mBq/kg$ to $0.2\,mBq/kg$, which is only a factor of 2.5 lower than that of Saratech, the charcoal used in the LZ iRRS. This may be in reach by the time G3 experiments can be realized, as initial discussions with the German producer of the Saratech brand charcoal have revealed.

3. Conclusion

Vacuum swing adsorption systems, which have shown great success at reducing atmospheric radon levels in clean-rooms, have clear advantages over single-trap systems. They need to be modified so that they can capture and return the noble carrier gases to the purification system through a gas feedback loop rather than releasing them into the atmosphere. To make this technology viable for G3 experiments, ultra-low radon emanating adsorbents with intrinsic radon activity about a factor of 2.5 or better than currently available need to be developed while operating the VSA systems near $190\,K$.

References

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