Applied Radiation and Isotopes 108 (2016) 92–99

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Shielding concepts for low-background proportional counter arrays in surface laboratories

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HIGHLIGHTS

- Optimization of a cosmic ray shield to measure environmental radioactive gases.
- Proportional counter sensitivity may reach ambient environmental ^{37}Ar concentrations.
- Variable length counter method evaluated for low concentration absolute gas counting.
- Feasibility of several hour duration preparation of gas samples for ^{37}Ar measurement.

ARTICLE INFO

Article history:
Received 11 November 2014
Accepted 8 December 2015
Available online 9 December 2015

Keywords:
Gas proportional counter system
Cosmic ray shielding
Low background radiation detection
^{37}Ar

ABSTRACT

Development of ultra low background gas proportional counters has made the contribution from naturally occurring radioactive isotopes – primarily α and β activity in the uranium and thorium decay chains – inconsequential to instrumental sensitivity levels when measurements are performed in above ground surface laboratories. Simple lead shielding is enough to mitigate against gamma rays as gas proportional counters are already relatively insensitive to naturally occurring gamma radiation. The dominant background in these surface laboratory measurements using ultra low background gas proportional counters is due to cosmic ray generated muons, neutrons, and protons. Studies of measurements with ultra low background gas proportional counters in surface and underground laboratories as well as radiation transport Monte Carlo simulations suggest a preferred conceptual design to achieve the highest possible sensitivity from an array of low background gas proportional counters when operated in a surface laboratory. The basis for a low background gas proportional counter array and the preferred shielding configuration is reported, especially in relation to measurements of radioactive gases having low energy decays such as ^{37}Ar.

1. Introduction

Low background radiometric measurement systems are typically located in underground laboratories to shield against cosmic-ray products (e.g., protons, neutrons, and muons) that create background event rates and ultimately limit a system's sensitivity reach. The effort to further improve the sensitivity of such underground systems, in one case, has led to the development of ultra low background gas proportional counters made from ultra-pure electroformed copper. These underground proportional counters are further operated in shields to exclude naturally occurring radiation in the laboratory from contributing signals to the detector system. As a consequence of these development efforts the proportional counters now produced have a contribution from naturally occurring radioactive isotopes – primarily α and β activity in the uranium and thorium decay chains – that is entirely inconsequential to instrumental sensitivity levels when the measurements performed in *above-ground* surface laboratories. This allows for a single-minded focus on re-addressing the challenge of the cosmic-ray product induced background contribution in an above-ground proportional counter system. This article presents the rational and conceptual design for a proportional counter array designed for above-ground operation, based upon an assessment of the background contributions from both cosmic-ray products and naturally occurring radioactivity. As a concrete example, measurement of environmental naturally occurring levels of ^{37}Ar is chosen as an application to explore.

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http://dx.doi.org/10.1016/j.apradiso.2015.12.033

2. Proportional counter backgrounds

Recent reported measurements and simulations presented below provide the basis for bracketing the expected performance of a ultra-low-background counter in a surface laboratory. This section describes the prior measurements and presents simulations used as a basis for inferring the detection system's expected sensitivity. To provide a concrete quantitative estimate, ^{37}Ar detection sensitivity is evaluated. The 2.8 keV emission after ^{37}Ar decay (Barsanov et al., 2007) provides an uncomplicated nearly single-point energy deposition within the proportional count gas (Xiang et al., 2007). Thus understanding the performance of the radiation detection is particularly simple allowing a straightforward discussion of background contributions. Furthermore the discussion of ^{37}Ar measurements is motivated by a desire to understand the ultimate reach of surface laboratory systems (Xiang et al., 2008, 2009) that ideally would have sensitivity to the naturally occurring levels of in the environment (Cao et al., 2009; Riedmann and Purtschert, 2011).

2.1. Surface cosmic-ray background

A previous gas proportional measurement of ^{37}Ar in a surface laboratory (Aalseth et al., 2011) provides a point of reference for understanding the backgrounds of a single detector, surface laboratory gas proportional counter system. The single proportional counter used in that measurement was an ultra-low background proportional counter (ULBPC) fabricated from ultra-pure electroformed copper (Aalseth et al., 2009). The ULBPC is roughly 9 in in length and 1 in in diameter with an internal volume of ~0.1 L and was operated in a lead shield consisting of 2 in, 4 in, and 8 in thick walls (top, sides, and bottom, respectively). Two 2 in thick polyvinyl toluene (PVT) cosmic-ray veto panels were placed above and below the shield, having 33 in × 14 in and 56 in × 19 in footprints, respectively. This shielding arrangement is *not* ideal due to the absence of cosmic-ray veto panel coverage on four sides. Nevertheless, as reported (Aalseth et al., 2011), the cosmic veto shield was able to reduce the background in the 1–20 keV measurement region by a factor of ~16.5. These results are reproduced in Fig. 1 and show that while the cosmic-ray veto panels reduced the background from cosmic rays, the fact that the *shape* of the background spectrum is unchanged implies the dominant background remains due to untagged (un-vetoed) cosmic ray products.

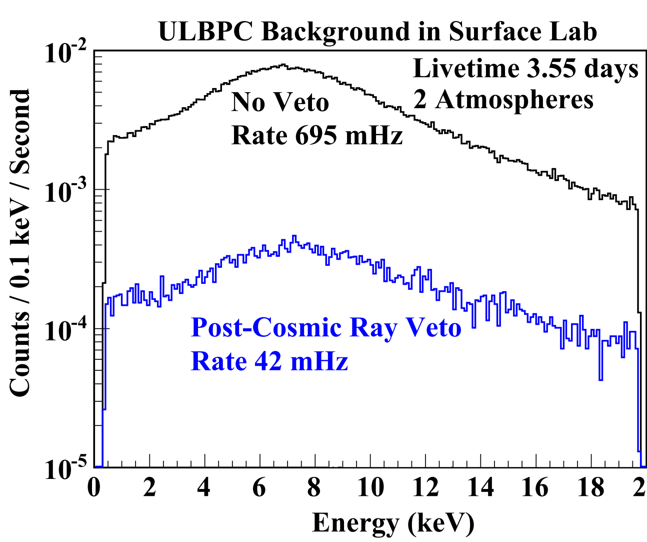

Fig. 1. The background from cosmic rays passing through an ULBPC, before and after application of the PVT-based cosmic-ray veto. Data was collected in a small shield located in a surface laboratory.

2.2. Shallow underground cosmic-ray background

Pacific Northwest National Laboratory (PNNL) operates a shallow underground laboratory in Richland, WA having an overburden of ~30 meters water equivalent overburden shielding against cosmic rays (Aalseth et al., 2012). The overburden of the underground laboratory acts as a shield against cosmic-ray products, stopping protons and reducing neutrons, both produced in the atmosphere by spallation processes. The cosmic-ray muon flux – a more penetrating cosmic-ray product – is reduced by ~85% in the underground laboratory and is used as the final quantitative metric for evaluating the effective depth of the underground laboratory (Aalseth et al., 2012).

The relevance of the underground laboratory to a surface laboratory measurement system is as a point of comparison for an ideal measurement sensitivity level. Detectors of the same ULBPC design described in Section 2.1 were deployed in the shallow underground laboratory. As noted in the previous section, the dominant background for these proportional counters systems, when operated on the surface, is the residual cosmic-ray (direct or induced) backgrounds despite the use of scintillator-based cosmic-ray veto detectors. Thus the measurement sensitivity of a ULBPC measurement made in the shallow underground facility sets a practical lower bound on the potential sensitivity one could hope to achieve in a surface laboratory measurement system.

Fig. 2 presents results from 19.0 live-days of background data collected from an ULBPC operated in the shallow underground laboratory (Aalseth et al., 2013). The proportional counter was located within a low background shield consisting of (1) a gas-tight enclosure, (2) an active anti-cosmic veto detector consisting of 5-cm-thick scintillating plastic panels covering five sides of the shield, (3) a layer of 30% borated polyethylene with a thickness (2.5 cm) selected to provide opacity for thermal neutrons, (4) a passive lead layer (15 cm) to limit external gamma-ray induced interactions, and (5) a passive high-purity copper inner layer with a thickness (7.6 cm) to limit induced interactions from bremsstrahlung gamma-ray production due to ^{210}Pb (~30 Bq/kg) in the passive lead layer. The proportional counter referred to here was operated at 7 atmospheres of pressure of P-10 counting gas.

The upper histogram of Fig. 2 is the gross detector counts while the lower histogram is the data remaining after the cosmic-ray veto system is employed to reject events (vetoed data). The post-cosmic ray veto data appears as a continuum background which is believed to be due to internal backgrounds (e.g. β, α, and

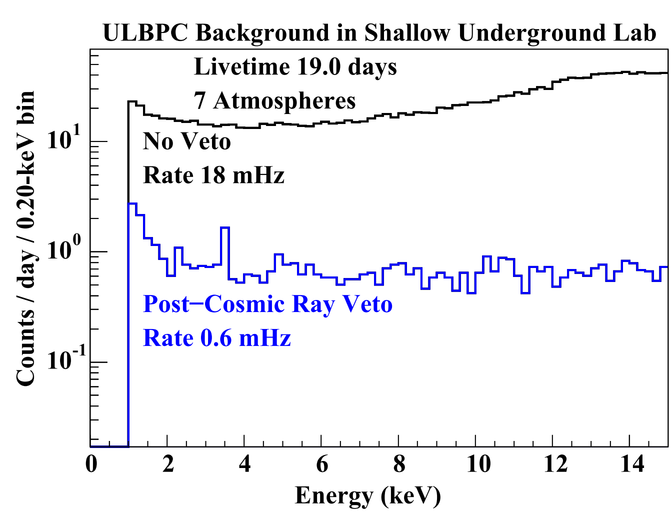

Fig. 2. The background in an ULBPC, before and after application of the scintillating plastic cosmic-ray veto. Data was collected in a proportional counter shield located in the PNNL shallow underground laboratory.