



## Cosmic ray muon flux at the Sanford Underground Laboratory at Homestake

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### ABSTRACT

Measuring the muon flux is important to the Sanford Underground Laboratory at Homestake, for which several low background experiments are being planned. The nearly vertical cosmic ray muon flux was measured in three locations at this laboratory: on the surface ( $1.149 \pm 0.017 \times 10^{-2} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ ), at the 800 ft (0.712 km w.e.) level ( $2.67 \pm 0.06 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ ), and at the 2000 ft (1.78 km w.e.) level ( $2.56 \pm 0.25 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ ). These fluxes agree well with model predictions.

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### 0. Introduction

The Homestake Mine in Lead, South Dakota, USA was identified in 2007 as the final candidate site for the Deep Underground Science and Engineering Laboratory (DUSEL). In advance of the federal funds to further develop the mine, the South Dakota Science and Technology Authority (SDSTA), which operates the Sanford Underground Laboratory, is offering an early science program mainly to characterize aspects of the site environment. It is located at  $44.35^\circ \text{ N}$ ,  $103.77^\circ \text{ W}$ , with a surface elevation of 1620 m above sea level. Initially, the LUX (Large Underground Xenon) dark matter search [1] and the MAJORANA neutrinoless double beta decay experiment [2] will be located there. Measurements of external backgrounds, including cosmic ray muons as well as gammas and neutrons, will be of paramount importance to the design of these sensitive rare-event searches.

The differential muon flux at the 4850 ft (4.40 km water equivalent) level at Homestake was measured by Cherry et al. [3]. However, more measurements are needed to characterize the muon flux as a function of depth. This paper describes new measurements of the cosmic ray muon flux at three locations: the surface (in a building that provided  $\sim 1 \text{ m}$  w.e. of shielding), the 800 ft (0.712 km w.e.) level, and the 2000 ft (1.78 km w.e.) level.

We present a comparison between our reported flux and the model of Ref. [4], and we find agreement between our experimental results and that model.

Cosmic-ray muon flux as a function of depth has been studied by many experiments at underground facilities around the world. Measurements of the muon flux per unit solid angle as a function of slant depth from Castagnoli [5], Barrett [6], Miyake [7], WIPP [8], Soudan [9], Kamioka [10], Boulby [11], Gran Sasso [12,13], Fréjus [14] and Sudbury [15] have been used to develop a model, which can be used to predict the muon flux per unit solid angle as a function of depth [4].

### 1. Methods

The muon detector consists of four fast plastic scintillation counters (Saint-Gobain BC-408), each a square with a side length of  $30.5 \pm 0.1 \text{ cm}$ . As shown in Fig. 1, the distance from the top to the bottom counter is 64.0 cm. Two of these counters are 0.5 cm thick, and the others are 1.0 cm thick. Each is coupled by a trapezoidal acrylic lightguide to a Photonis XP2020 photomultiplier with Photonis VD124K base. Waveforms from each detector are recorded by a 12-bit flash analog-to-digital conversion module with a sampling frequency of 170 MHz; it filters the data onboard with field programmable gate arrays and transmits digitized pulses through an Ethernet interface to a standard personal computer.

The detector station also includes a 1.2 L liquid scintillation counter filled with Eljen Technologies EJ-301 or EJ-309 material. This counter has been used to study techniques for neutron counting in the underground environment; a future publication will quantify neutron backgrounds in the mine.

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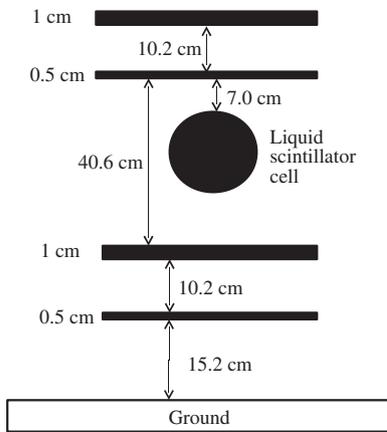


Fig. 1. Vertical positioning of elements of the muon detector.

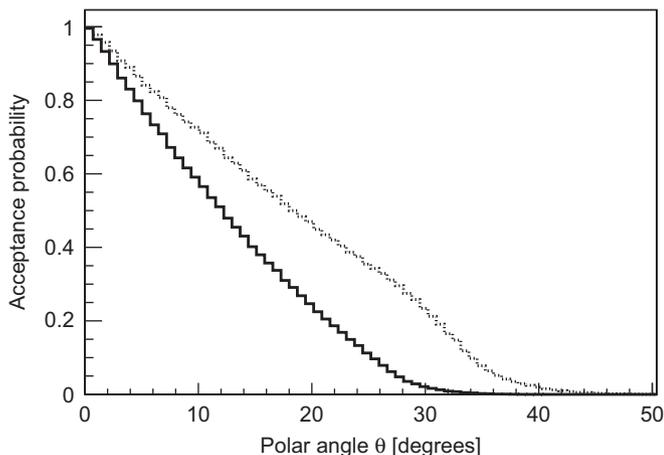


Fig. 2. Acceptance probability as a function of polar angle  $\theta$  for the four-fold coincidence analysis (solid line) or the three-fold coincidence analysis (dotted line).

The gamma ray flux at each of the sites is at the level of  $1 \text{ cm}^{-2} \text{ s}^{-1}$ ; the counting rate for background gamma events in each of the plastic scintillator detectors is, therefore,  $\sim 1 \text{ kHz}$ . Nearly all of the gamma flux is at energies of 2.5 MeV or less, as was reported in Ref. [16]. A substantial coincidence requirement is needed to distinguish cosmic ray muon events from the gamma background. At the 2000 ft depth, a two-fold coincidence analysis was found to be dominated by the gamma background, and at shallower depths they still represent a substantial correction. Consequently, all of our results are based on studies where we require that at least three of the four detectors record a pulse within a  $\sim 70 \text{ ns}$  time interval. Because of the higher counting rate and reduced sensitivity to several systematic uncertainties, we present the three-fold coincidence analysis as our primary result, and a four-fold coincidence analysis (where all four detectors are required to fire simultaneously) as a partially independent check. In particular, the agreement between the three-fold and four-fold coincidence results demonstrates that secondary particles such as high-energy electrons produced by muon interactions do not affect the counting rate substantially relative to the precision of this measurement.

A geometric Monte Carlo calculation was used to determine the solid angle accepted by each of these analysis methods. It took into account only the size and position of each of the detector elements, assuming straight muon tracks. As shown in Fig. 2, it was used to determine the acceptance probability as a function of polar angle  $P(\theta)$ , which was then integrated to determine the

accepted solid angle:

$$\Omega = 2\pi \int_0^{\pi/2} P(\theta) \sin\theta \, d\theta. \quad (1)$$

When a four-fold coincidence is required, the accepted solid angle is 0.226 sr; it is 0.457 sr when only a three-fold coincidence is required. If we assume an incident muon distribution proportional to  $\cos^2\theta$ , 90% of the flux in the three-fold coincidence analysis would be within  $25^\circ$  of vertical, while 90% of the flux in the four-fold coincidence analysis would be within  $19^\circ$  of vertical.

This Monte Carlo program was also used to study the systematic uncertainty arising from misalignment of the detector elements. A horizontal displacement of one detector element in this program by 2 cm, which is believed to represent the worst realistic possibility for the data collected on the 800 ft level, changed the calculated solid angle by a maximum of 0.4% for the three-fold coincidence analysis and 1.1% for the four-fold coincidence analysis. The alignment on other levels is believed to have been substantially better, with a maximum possible displacement of 1 cm.

The energy scales of the detectors were calibrated based on the observed pulse amplitude spectra for four-fold coincident events. All such events on the surface and at the 800 ft level were presumed to be minimum-ionizing particles that would give a most probable energy deposition of 1.0 MeV in the thin detectors and 2.0 MeV in the thick detectors. These energies were computed from the scintillator density of  $1.032 \text{ g/cm}^3$ , assuming the minimum-ionizing  $dE/dx$  given by the Bethe–Bloch equation [17]. At the surface and the 800 ft depth, there was sufficient statistical power to allow the calibration to be determined *in situ*. At the 2000 ft depth, a calibration from the surface was applied; this method would have been preferred at the 800 ft depth as well, but detector repairs required recalibration to be completed underground.

The digitization hardware thresholds were set as low as practical, corresponding to approximately 0.4 MeV for the thin detectors and 0.9 MeV for the thick detectors. Analysis thresholds were then established at 0.75 MeV in the thin counters and 1.5 MeV in the thick counters. These thresholds require a total energy deposition of at least 3 MeV for a three-fold coincidence, which is beyond the endpoint of the gamma spectrum, but still maintains an efficiency for muons that can be determined effectively.

The efficiency corrections associated with these energy cuts were determined from the data. At the surface, we assumed that all four-fold coincident events were caused by minimum-ionizing particles; other particles from atmospheric showers would have been shielded effectively by the  $\sim 1 \text{ m}$  w.e. provided by the building above the detector. Therefore, we computed the ratio of the number of events that passed the analysis cuts to the total number of recorded four-fold coincidences where only the hardware thresholds were used.

Having determined this efficiency on the surface, we then applied it to data collected at the 2000 ft level. The uncertainty associated with this procedure includes a statistical component from the finite number of coincidences at the surface. However, another part of the uncertainty is related to the stability of the detector gain, and, therefore, the energy scale, especially as the detector was being moved underground. We checked for these gain shifts using three standard beta/gamma calibration sources,  $^{22}\text{Na}$ ,  $^{60}\text{Co}$ , and  $^{90}\text{Sr}$ , collecting pulse height spectra before and after relocating the detector. Averaging the results from these sources, we found gain reductions of 0.8%, 2.0%, 4.7%, and 3.1% for the four detector elements. We corrected the energy scale in the analysis according to these results, and we treated the 1.0% uncertainty in each detector calibration as the systematic error for the efficiency in the result from the 2000 ft level. Examination

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