Astroparticle Physics 93 (2017) 70–75

Contents lists available at ScienceDirect

Astroparticle Physics

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

Muon flux measurements at the davis campus of the sanford underground research facility with the MAJORANA DEMONSTRATOR veto system

N. Abgrall[a], E. Aguayo[b], F.T. Avignone III[c,d], A.S. Barabash[e], F.E. Bertrand[d], A.W. Bradley[a], V. Brudanin[f], M. Busch[g,h], M. Buuck[i], D. Byram[j], A.S. Caldwell[k], Y-D. Chan[a], C.D. Christofferson[k], P.-H. Chu[l], C. Cuesta[i], J.A. Detwiler[i], C. Dunagan[k], Yu. Efremenko[m,*], H. Ejiri[n], S.R. Elliott[l], A. Galindo-Uribarri[d], T. Gilliss[o,h], G.K. Giovanetti[o,h], J. Goett[l], M.P. Green[p,d,h], J. Gruszko[i], I.S. Guinn[i], V.E. Guiseppe[c], R. Henning[o,h], E.W. Hoppe[b], S. Howard[k], M.A. Howe[o,h], B.R. Jasinski[j], K.J. Keeter[q], M.F. Kidd[r], S.I. Konovalov[e], R.T. Kouzes[b], B.D. LaFerriere[b], J. Leon[i], A.M. Lopez[m], J. MacMullin[o,h], R.D. Martin[j,u], R. Massarczyk[l], S.J. Meijer[o,h], S. Mertens[a], J.L. Orrell[b], C. O'Shaughnessy[o,h], N.R. Overman[b], A.W.P. Poon[a], D.C. Radford[d], J. Rager[o,h], K. Rielage[l], R.G.H. Robertson[i], E. Romero-Romero[m,d], M.C. Ronquest[l], C. Schmitt[a], B. Shanks[o,h], M. Shirchenko[f], N. Snyder[j], A.M. Suriano[k], D. Tedeschi[c], J.E. Trimble[o,h], R.L. Varner[d], S. Vasilyev[f], K. Vetter[a,s], K. Vorren[o,h], B.R. White[d], J.F. Wilkerson[o,h,d], C. Wiseman[c], W. Xu[l,t], E. Yakushev[f], C.-H. Yu[d], V. Yumatov[e], I. Zhitnikov[f],
(The Majorana Collaboration)

[a] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[b] Pacific Northwest National Laboratory, Richland, WA, USA
[c] Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
[d] Oak Ridge National Laboratory, Oak Ridge, TN, USA
[e] National Research Center "Kurchatov Institute" Institute for Theoretical and Experimental Physics, Moscow, Russia
[f] Joint Institute for Nuclear Research, Dubna, Russia
[g] Department of Physics, Duke University, Durham, NC, USA
[h] Triangle Universities Nuclear Laboratory, Durham, NC, USA
[i] Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, WA, USA
[j] Department of Physics, University of South Dakota, Vermillion, SD, USA
[k] South Dakota School of Mines and Technology, Rapid City, SD, USA
[l] Los Alamos National Laboratory, Los Alamos, NM, USA
[m] Department of Physics and Astronomy, University of Tennessee, Knoxville, TN, USA
[n] Research Center for Nuclear Physics and Department of Physics, Osaka University, Ibaraki, Osaka, Japan
[o] Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC, USA
[p] Department of Physics, North Carolina State University, Raleigh, NC, USA
[q] Department of Physics, Black Hills State University, Spearfish, SD, USA
[r] Tennessee Tech University, Cookeville, TN, USA
[s] Department of Nuclear Engineering, University of California, Berkeley, CA 94720, US
[t] Department of Physics, University of South Dakota, Vermillion, SD, USA
[u] Department of Physics, Engineering Physics and Astronomy, Queen's University, Kingston, Canada

* Corresponding author.
E-mail address: yefremen@utk.edu (Yu. Efremenko).

http://dx.doi.org/10.1016/j.astropartphys.2017.01.013

ARTICLE INFO

Article history:
Received 26 February 2016
Revised 12 December 2016
Accepted 3 January 2017
Available online 16 February 2017

Keywords:
Cosmic
Ray
Flux

ABSTRACT

We report the first measurement of the total muon flux underground at the Davis Campus of the Sanford Underground Research Facility at the 4850 ft level. Measurements were performed using the MAJORANA DEMONSTRATOR muon veto system arranged in two different configurations. The measured total flux is $(5.31 \pm 0.17) \times 10^{-9}$ μ/s/cm^2.

1. Introduction

The Davis Campus at the Sanford Underground Research Facility (SURF) [1], located in the former Homestake gold mine, is situated at a depth of 4850 ft near the city of Lead, SD, USA. SURF has become a prime site for low background science in the United States since the inauguration of its Davis Campus in 2012. Accurate characterization of the muon flux and average rock density is important for understanding cosmic-ray-induced backgrounds not only in existing experiments presently deployed at SURF, but also for future projects. A previous measurement of the vertical muon flux at the 4850-ft level has been reported [2], and the total muon flux was measured for the 800- and 2000-ft levels [3] at SURF. The total muon flux at the 4850-ft level was calculated to be $(4.4 \pm 0.1) \times 10^{-9}$μ/s/cm^2 [4]. In this article, we present a first measurement of the total muon flux at the 4850-ft level using the MAJORANA DEMONSTRATOR muon veto system. We compare our measurement to previous work, and to our own simulation of muon transport from the surface to the experiment using geological measurements of the average rock density of the SURF overburden.

The MAJORANA DEMONSTRATOR is an array of enriched and natural high-purity germanium (HPGe) detectors that are used to search for the zero neutrino double-beta ($\beta\beta(0\nu)$) decay of the isotope ^{76}Ge. The details of the experiment's design are given in Ref. [5] and only key aspects required for this result are discussed here. The specific goals of the MAJORANA DEMONSTRATOR are to:

1. Demonstrate a path forward to achieving a background rate at or below 1 count/(ROI-t-y)in the 4-keV region of interest (ROI) around the 2039-keV Q-value for ^{76}Ge $\beta\beta(0\nu)$ decay. This is required for tonne-scale germanium-based searches that will probe the inverted-ordering neutrino-mass parameter space for the effective Majorana neutrino mass in $\beta\beta(0\nu)$ decay.
2. Show technical and engineering scalability toward a tonne-scale instrument.
3. Perform searches for additional physics beyond the Standard Model, such as dark matter and axions.

The MAJORANA Collaboration has designed a modular instrument composed of two cryostats built from ultra-pure electroformed copper, with each cryostat capable of housing over 20 kg of HPGe detectors. The MAJORANA DEMONSTRATOR contains 30 kg of detectors fabricated from Ge material enriched to 88% in ^{76}Ge and another 15 kg fabricated from natural Ge (7.8% ^{76}Ge). The modular approach allows us to assemble and optimize each cryostat independently, providing a fast deployment with minimal effect on already-operational detectors.

Starting from the innermost cavity, the cryostats are surrounded by a compact graded shield composed of an inner layer of electroformed copper, a layer of commercially sourced C10100 copper, high-purity lead, an active muon veto, borated polyethylene, and pure polyethylene shielding. The cryostats, copper, and lead shielding are enclosed in a radon exclusion box and rest on an over-floor table that has openings for the active muon veto and polyethylene shielding panels situated below the detector. The entire experiment is located in a clean room at the 4850 ft level of SURF. A high-level summary of shield components is shown in Fig. 1.

A large fraction of the plastic scintillator panels comprising the active muon-veto system were operated in different configurations at the experimental site during Ge detector constructions and commissioning. We used the resulting data to measure the total muon flux at the Davis Campus at SURF for the first time.

2. The MAJORANA DEMONSTRATOR muon veto system

The MAJORANA DEMONSTRATOR muon veto system was designed to completely enclose the passive copper and lead shield within two layers of scintillating panels while minimizing gaps. Each layer is composed of 2.54-cm-thick EJ-204B scintillating acrylic sheets encapsulated within Al cladding. These detector panels have various shapes and dimensions resulting in a total area of ~ 37 m^2. The DEMONSTRATOR uses a total of 32 veto panels, including twelve that reside within openings of the overfloor table in two orthogonal orientations. The data presented in this paper is based on the operation of two configurations, one with 12 veto panels requiring two-fold coincidence, and one with 14 veto panels requiring three-fold coincidence. The arrangement of the veto panels used for each configuration is shown in Fig. 2. More details on each configuration are given in Sections 3 and 4 below.

Light from each individual panel was read out by a single 1.27-cm photomultiplier tube (PMT) with wavelength shifting fibers embedded into grooves machined in the scintillator. The panel components were optimized to provide high light output, good light collection uniformity, and excellent muon-detection efficiency

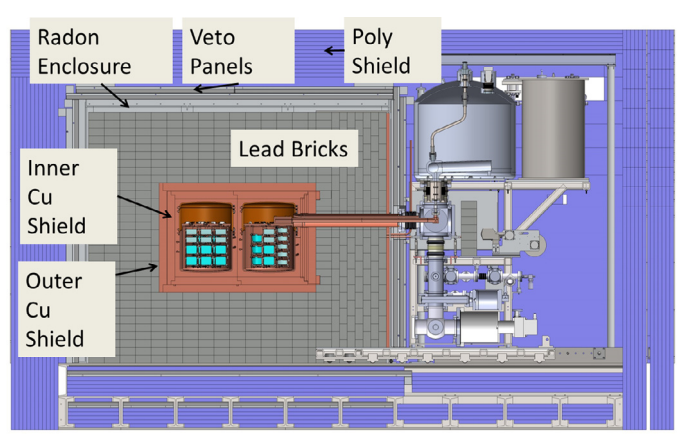

Fig. 1. The shield system in cross section, shown with both cryostats installed.