Nuclear Inst. and Methods in Physics Research, A 890 (2018) 84–95

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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

Photoelectron yields of scintillation counters with embedded wavelength-shifting fibers read out with silicon photomultipliers

Akram Artikov [c], Vladimir Baranov [c], Gerald C. Blazey [d], Ningshun Chen [f], Davit Chokheli [c,g], Yuri Davydov [c], E. Craig Dukes [f], Alexsander Dychkant [d], Ralf Ehrlich [f], Kurt Francis [d], M.J. Frank [e], Vladimir Glagolev [c], Craig Group [f,*], Sten Hansen [b], Stephen Magill [a], Yuri Oksuzian [f], Anna Pla-Dalmau [b], Paul Rubinov [b], Aleksandr Simonenko [c], Enhao Song [f], Steven Stetzler [f], Yongyi Wu [f], Sergey Uzunyan [d], Vishnu Zutshi [d]

[a] *Argonne National Laboratory, Argonne, IL 60439, USA*
[b] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[c] *Joint Institute for Nuclear Research, Dubna, 141980, Russian Federation*
[d] *Northern Illinois University, DeKalb, IL, 60115, USA*
[e] *University of South Alabama, Mobile, AL 36688, USA*
[f] *University of Virginia, Charlottesville, VA 22904, USA*
[g] *High Energy Physics Scientific-Research Institute of Iv. Javakhishvili, Tbilisi State University (HEPI-TSU), Tbilisi, 0186, Georgia*

A R T I C L E I N F O

Keywords:
mu2e
Scintillator
Cosmic
Veto
Muon
Photomultipliers

A B S T R A C T

Photoelectron yields of extruded scintillation counters with titanium dioxide coating and embedded wavelength shifting fibers read out by silicon photomultipliers have been measured at the Fermilab Test Beam Facility using 120 GeV protons. The yields were measured as a function of transverse, longitudinal, and angular positions for a variety of scintillator compositions, reflective coating mixtures, and fiber diameters. Timing performance was also studied. These studies were carried out by the Cosmic Ray Veto Group of the Mu2e collaboration as part of their R&D program.

1. Introduction

The Mu2e experiment will search for the neutrino-less conversion of a muon into an electron in the presence of an aluminum nucleus at a single-event sensitivity of about 3×10^{-17} [1]. This represents a sensitivity improvement of four orders of magnitude relative to the current best limit on this process [2]. The observation of this process would signal the existence of charged lepton-flavor violation at a level far beyond what is expected from the standard model predictions [3].

A major background for this experiment will be due to cosmic-ray muons that can produce several processes mimicking the signal. These cosmic-ray induced background events, which will occur at a rate of about one per day, must be suppressed by four orders of magnitude in order to achieve the sensitivity goals of Mu2e. To do this, an active veto will surround the primary Mu2e detection apparatus on five sides in order to detect penetrating cosmic-ray muons. The veto will consist of more than 5000 scintillation counters arranged in four layers, each counter is 20 mm thick by 50 mm wide and with varying lengths. This paper describes measurements made with the prototype counters for the Mu2e Cosmic Ray Veto (CRV).

2. Counter description

The counters tested here were all $3000 \times 50 \times 20$ mm^3. They were extruded at the FNAL-NICADD Extrusion Line Facility [4]. The polystyrene base of each counter was STYRON 665 W. Four different scintillator composition/coating mixtures were tested, and are listed in Table 1. The primary dopant was always 2,5-diphenyloxazole (PPO, 1% by weight). The secondary dopant was either 1,4-bis (5-phenyloxazol-2-yl) benzene (POPOP) or 1,4-bis (2-methylstyryl) benzene (bis-MSB). A co-extruded reflective coating of 0.25 mm nominal thickness surrounded the core. This outer reflective coating was added through material injected from a second extrusion machine (co-extruder) that mixed the polystyrene and TiO_2 pellets. Each counter also had two co-extruded holes of nominal 2.6 mm diameter into which wavelength-shifting (WLS) fibers were placed. A cross-sectional view of a counter is

* Corresponding author.
E-mail address: rcg6p@virginia.edu (C. Group).

https://doi.org/10.1016/j.nima.2018.02.023
Received 19 September 2017; Received in revised form 17 January 2018; Accepted 4 February 2018
Available online 14 February 2018

Table 1
Scintillator dopants and coatings.

Name	Primary dopant	Secondary dopant	Coating
A	1% PPO	0.03% POPOP	15% TiO_2
B	1% PPO	0.03% POPOP	30% TiO_2
C	1% PPO	0.05% POPOP	30% TiO_2
D	1% PPO	0.05% bis-MSB	30% TiO_2

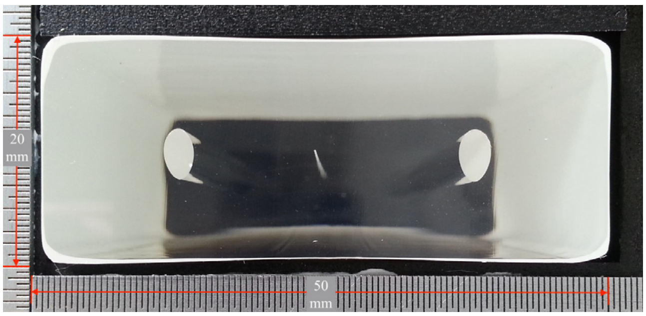

Fig. 1. Photo from the end of a typical counter. The shape of the counter, the holes, and the TiO_2 coating are visible. Tick marks are spaced by 0.5 mm.

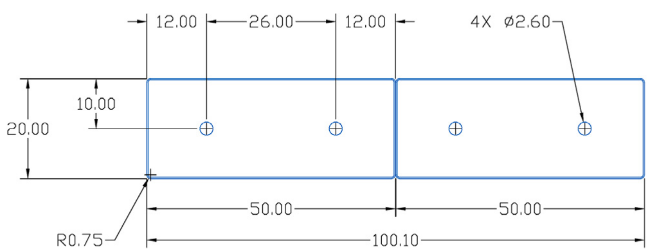

Fig. 2. Dicounter end view showing fiber positions. Dimensions (mm) are nominal: actual values are slightly different.

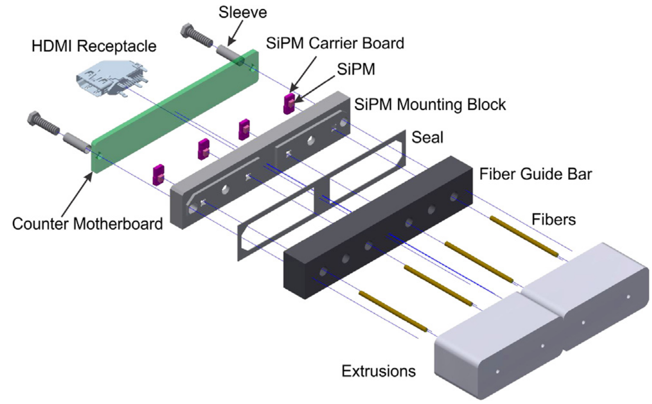

Fig. 3. Exploded view of the end of a dicounter showing the fiber guide bar, SiPM mounting block, SiPM carrier boards, SiPMs, and counter motherboard. The flasher LEDs and pogo pins that are soldered to the counter motherboard are not shown.

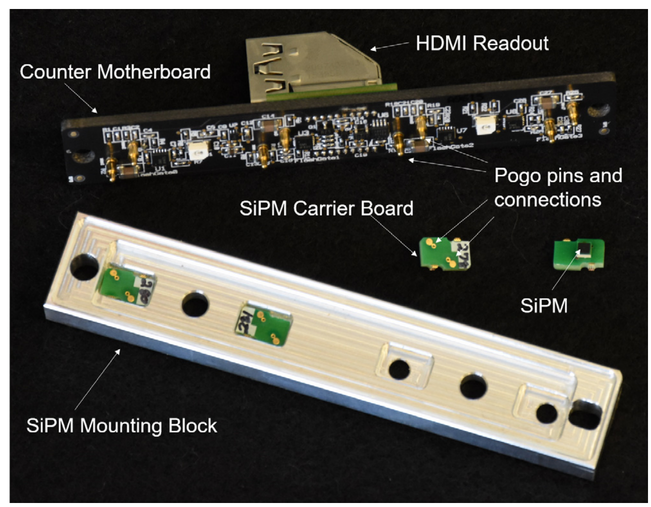

Fig. 4. The components used in the electronic readout of the dicounters.

shown in Fig. 1, where the shape of the counter, the holes, and the TiO_2 coating are visible.

Counters were assembled into full dicounters at the University of Virginia. The counters were first glued into pairs called dicounters, using 3M DP420 epoxy [5], producing the profile shown in Fig. 2. The fibers were then placed into the four dicounter holes. The WLS fibers were Kuraray double-clad Y11 doped with 175 ppm K27 dopant, and were non-S-type [6]. Counters with three different fiber diameters were studied: 1.0, 1.4, and 1.8 mm. The fibers were not glued in the extrusion holes, nor were they constrained in any fashion to lie in the holes. At each end of the dicounter an acetal fiber guide bar was glued to the extrusions using 3M DP100 epoxy [7]. At the same time the WLS fibers were glued into funnel-shaped channels in the fiber guide bars using the same epoxy. The fibers, protruding from both ends of the dicounters, were cut off using a hot knife and the fiber guide bars were then fly cut, which served to polish the fiber ends.

Light captured in the fibers was read out at both ends by $2.0{\times}2.0$ mm^2 (model S13360-2050VE, 1584 pixels, pixel size of 50 μ) Hamamatsu silicon photomultipliers (SiPMs) [8]. These surface-mount, through-silicon via (TSV) devices were chosen because they have a thin (0.1 mm) epoxy layer which allows closer proximity between the fiber and photosensor. Radiation damage from neutrons is a concern. The devices described in this paper had not been irradiated. Ref. [9] studies the SiPM radiation hardness and its impact on CRV performance.

The SiPMs were soldered to small 8.61×5.61 mm^2 circuit boards, called SiPM carrier boards, that sat in rectangular wells in an anodized aluminum fixture called the SiPM mounting block. Proper registration of the SiPMs to the fibers is critically important in obtaining the maximum light yield, particularly for the 1.8 mm diameter fibers when mated to the 2.0×2.0 mm^2 SiPMs. The SiPM mounting blocks were precisely aligned to the fiber guide bars by internally threaded sleeves that were glued into holes on either end of the fiber guide bar. A rubber seal between the fiber guide bar and the SiPM mounting block was used to make the assembly light tight. An exploded view of the dicounter end is given in Fig. 3 and a photograph of its components is shown in Fig. 4.

The SiPMs were electrically connected via spring-loaded pins (pogo pins) to a small circuit board called the counter motherboard (CMB). The pogo pins gently pushed down on the SiPM carrier boards, pressing the SiPMs up against the fiber ends. The opaque counter motherboard formed the top of the aluminum SiPM mounting block making the SiPM assembly fixture light tight. The counter motherboard has two flasher LEDs (not used in the tests described here), a thermometer, and an HDMI receptacle. Efforts were made to minimize the extent of the end assembly which, including the HDMI receptacle, still protruded 37 mm beyond the extrusions.

Signals from the CMB were carried out to a 64-channel front end board (FEB) via a short HDMI cable. The FEB provided bias to the SiPMs, signal pre-amplification and shaping, analog-to-digital conversion at 12.6 ns intervals (1/79.5 MHz), and high-speed serial links via Ethernet to a readout controller or a stand-alone computer [10].