Terrestrial Muon Flux Measurement at Low Energies for Soft Error Studies

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***Abstract*—A large volume scintillator detector has been used to measure the terrestrial stopping muon rate under different conditions of location, altitude, shielding and weather to determine the range of variation of the low energy muon flux. About 1 year of data has been collected under different conditions. This data can then be used to compare with cosmic ray muon simulations and to estimate the soft error rate due to direct ionization of muons.**

***Index Terms*—Cosmic ray muons, direct ionization, FLUKA, neutrons, plastic scintillator detector, soft error rate.**

I. INTRODUCTION

COSMIC ray muons are produced by the interaction of galactic cosmic rays, most of which are protons, in the Earth's atmosphere, producing pions and kaons which decay quickly into muons. Muons can be either positively or negatively charged and the ground level flux of greater than 1 GeV muons is approximately $70/\mathrm{m}^2/\mathrm{s}/\mathrm{sr}$. The terrestrial muon energy spectrum and flux are well characterized above 200 MeV energy as a function of altitude and latitude both with measurements and simulations [1]–[3]. Muon beams from the M20 channel at TRIUMF were used in 2010 [4], [5]to demonstrate that low energy muons can cause single event upsets in ≤ 65 nm CMOS SRAMs through direct ionization. The muons of interest for soft errors are below 5 MeV in energy as the muons must stop in the active region of the device for maximum energy deposition.

The peak energy loss for muons in silicon occurs at an energy of about 10 keV. A 5 MeV muon has a 1 mm range in silicon. There are older measurements of the flux of low energy and stopping terrestrial muons [6], [7]but in most cases these measurements did not identify the particles as muons. There are more recent measurements of stopping muons [8]aimed at providing data for correlations with meteorological conditions but these measurements did not look at the variation in muon rate with location.

A large volume $(40,000\ \mathrm{cm}^3)$ plastic scintillator detector and data acquisition system has been used at TRIUMF to identify stopping muons through their decay to an electron or a positron and to measure the incident muon energy and flux. The detector volume is large enough so that the muon stopping rate for a particular location can be determined in about 24 hours with 0.6% statistics. The muon is identified by its decay into an electron or positron depending on its charge with the positive muon having a lifetime of $2.197\ \mu$s [9]and a negative muon a shorter lifetime due to nuclear capture in the stopping material prior to decay. The negative muon lifetime in plastic scintillator is $2.028 +/- .002\ \mu$s [10]. The expected lifetime of the cosmic ray muons as measured by the detector will lie between these values depending on the ratio of positive to negative muons.

As the flux of stopping muons will be affected by the proximity of local materials such as building walls, ceilings or nearby shielding, the detector is portable so that measurements can be made under a variety of conditions such as location in a building, near to thick concrete walls or shielding, altitude and latitude. The detector is able to measure the muon lifetime sufficiently accurately that the ratio of positive muons to negative muons can be determined to an accuracy of about 10%. An advantage of the TRIUMF laboratory is that there are low energy muon beams available that can be used to calibrate the energy and time response of the detector.

These detector measurements are being made to provide a database to compare with simulations using the best available terrestrial cosmic ray codes. These calculations are being carried out using the FLUKA code [11]in collaboration with CERN.

II. DETECTOR DESIGN

Scintillator bars (Bicron BC-400) of dimensions 10 cm × 10 cm × 100 cm were used at TRIUMF for a previous experiment [12]. Each scintillator is read out with 2 inch PMTs (Philips XP2262) at either end through a tapered light guide. For the stopping muon detector four of these bars are mounted on a frame and supported on a wheeled steel cart for portability. The bars are wrapped with a light reflector and light sealing plastic (total thickness ~ 0.4 mm). The bars can be mounted in a 1×4 (horizontal), 2×2 or 4×1 (vertical) configuration to provide rough information about muon angular distributions.

The electronics required are also mounted on the cart so that the portable system requires only a 115 V connection and a laptop for remote operation. A CAEN VME 12 bit 250 MS/s digitizer is used to read out each PMT measurement. Other supporting equipment includes a VME crate, programmable high

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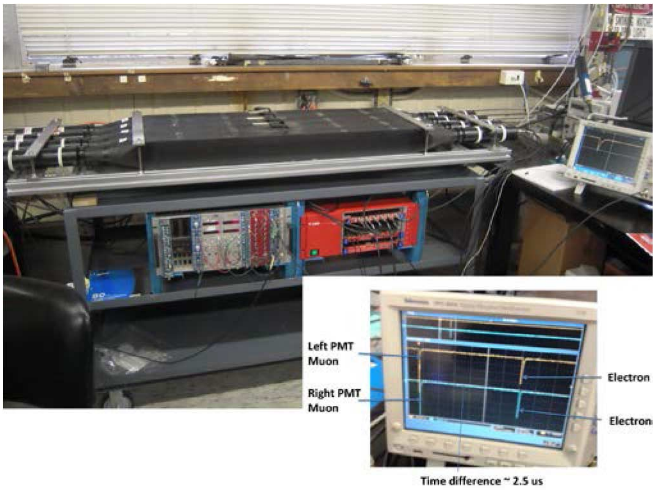

Fig. 1. Photo of the detector with an oscilloscope trace of a stopping muon showing the decay electron after 2.5 μs. Stopping muons are identified by the second pulse occurring within 20 μs.

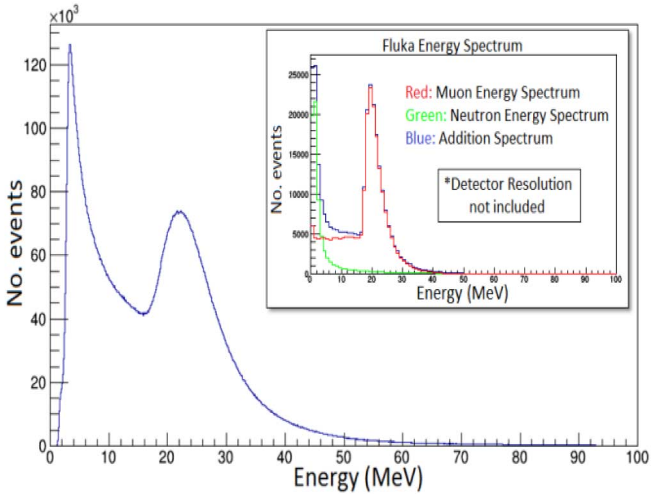

Fig. 2. Passing through muon and neutron energy spectra. Deposited energy is proportional to the pulse height for the muons and other charged particles. Neutrons require a nuclear interaction in the plastic with the recoil protons or light ions being detected so their full energy is not detected.

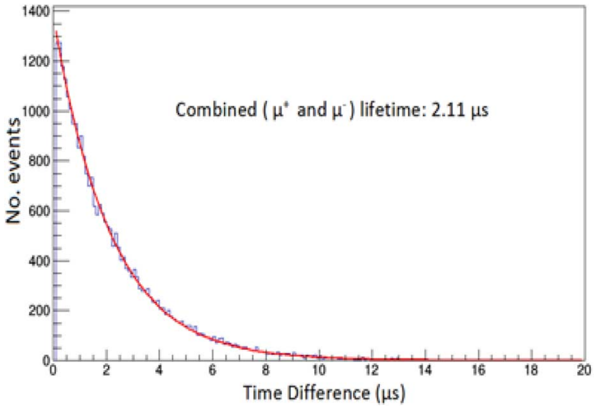

Fig. 3. Time spectrum of the muon decays fitted to an exponential decay with the mean lifetime of 2.11 μs.

voltage modules for the PMTs and a VME-USB bridge to connect to a laptop computer.

The data acquisition system uses the standard TRIUMF MIDAS program with pre-analysis using the CERN ROOT system [13].

The detector was assembled and commissioned in May 2014. Fig. 1 shows a photo of the detector and a typical oscilloscope trace of a stopping muon followed by the decay electron or positron.

III. MEASUREMENT PROGRAM

TRIUMF has a muon channel M11 that can provide muons with energies up to about 150 MeV with 5% energy resolution and a given charge. The detector was configured in the 2×2 arrangement and muon beams of different energies were made to stop in either the first detector below 40 MeV or the second one up to 60 MeV. The motivation was to check the particle energy calibration and to measure the decay lifetime for positive and negative muons. The muon lifetimes were found to be consistent with expectations confirming the accuracy of the CAEN digitizer.

The detector was then moved around the site as well as offsite to check the effect of different locations and conditions on the muon rates. These conditions include variation with time due to weather and solar conditions, variation with local shielding using a well shielded tunnel and variation with altitude. In all cases both the passing through muon rate and the stopping rate were measured.

The typical stopping rate in the 4 scintillators is about 16-18 per minute while the passing through rate of energetic muons is about 120-130 per second. A 40 MeV muon stops in a range of 10 cm in scintillator while a passing though GeV muon (minimum ionizing) deposits about 23 MeV. Fig. 2 shows a typical pulse height or energy spectrum of all detected particles with the minimum ionizing peak due to passing through muons and the low energy tail due to cosmic ray neutrons as well as muons passing though the corners of the scintillator. About 80% of charged cosmic ray particles detected at ground level are muons. The insert shows the predicted location of the passing muon peak and the neutron energy spectrum as calculated using FLUKA. The detector energy resolution of about 15% FWHM is not included in the calculation.

Fig. 3 shows the muon lifetime spectrum for a typical 24-hour run together with the fitted exponential decay curve. A lifetime of 2.11 μs corresponds to an equal number of stopping μ^+ and μ^-. The time spectrum beyond 10 μs shows a small number of events due to random coincidences.

The stopping muons that are identified by the decay electron/positron occurring within 20 μs have an energy spectrum as shown in Fig. 4. This energy spectrum has been corrected for the random events, approximately 10% of the total events. These random coincidences are due to two events in a single scintillator bar occurring in the 20 μs window that mimic the stopping muon followed by a decay electron/positron. These events can be produced by charged particles such as passing muons, neutron-induced charged particles or random noise in the photomultiplier tube. They can be separated from the decay muon events by looking in the $10 - 20$ μs window where less than 1% of the events can be due to muon decays because of the

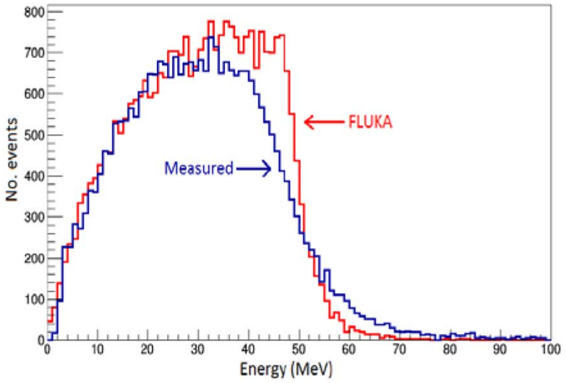

Fig. 4. Energy spectrum of stopping muons in the detector. A 40 MeV muon has a range of about 10 cm in scintillator but higher energies are possible for muons at larger angles. The FLUKA curve is a simulation of the stopping muon energy spectrum.

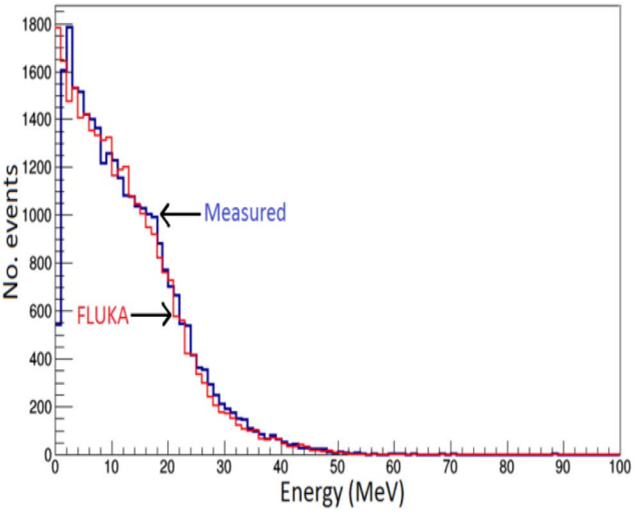

Fig. 5. Energy spectrum of the decay electrons or positrons. The maximum electron energy from muon decay is 53 MeV. The FLUKA curve is a simulation of the expected spectrum shape.

2.11 μs lifetime. The energy spectrum of these random events from $10 - 20$ μs is dominated by the more frequent passing through muons and this spectrum is doubled in each energy bin to represent the random events from $0 - 20$ μs. It is then subtracted from the original measured spectrum to give the true stopping muon spectrum as shown in Fig. 4. The segmentation of the detector into 4 bars turns out to be an important advantage as it reduces the random coincidence rate by a factor 16.

The decay electrons or positrons have an energy spectrum as shown in Fig. 5. Also shown are the predicted spectra from FLUKA cosmic ray muon simulations as described later in this paper.

Most of the measurements were taken in and around the buildings on the TRIUMF site in Vancouver: lat. 49.247 long. -123.230 alt. 60 m. There are locations where there are well-shielded underground tunnels to check muon attenuation as well as general purpose multistory laboratory buildings with varying thicknesses of walls and ceilings. The high altitude measurement was made at Cypress Mountain in West Vancouver: lat. 49.396 long. -123.204 alt. 923 m.

TABLE I
VARIATION OF THE MUON RATES WITH LOCATION AND SHIELDING

Location and Elevation	**Shielding** Concrete equiv. thickness	**Passing Muon Rate** muons/second	**Stopping Muon Rate** muons/minute
Meson Hall M11 Area Elev. 52 m	0.5 m but near thick walls	124.3-141.8 8 days	17.11-18.30 8 days
Metal Storage Shed Elev. 60 m	0 m	132.6-141.5 12 days	15.45-16.77 12 days
Cypress Mountain Elev. 923 m	0 m	164.1-175.2 4 days	19.68-20.74 4 days
ARIEL Bldg. Level 2 Elev. 68 m	0.2 m	125.4-134.4 32 days	17.06 – 19.46 32 days
Beam Tunnel Underground Elev. 52 m	4.0 m	57.5-58.4 13 days	9.9-10.5 13 days

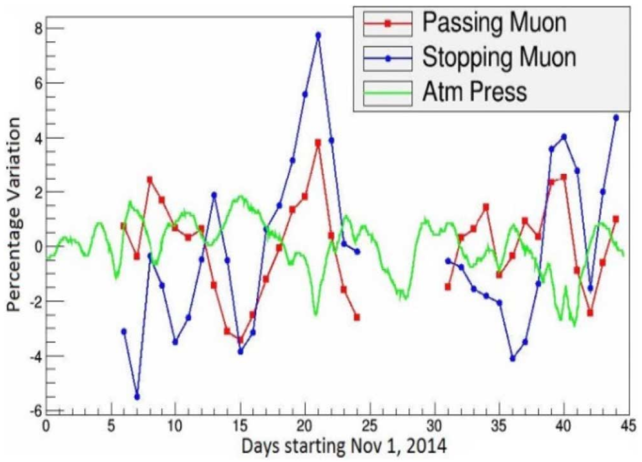

Fig. 6. Daily variation of muon passing and stopping rates compared with the barometric pressure.

Table I summarizes the results of a selection of data taken with the detector moved to different locations. The fluxes are the average number of events measured in 24 hour intervals for the number of days shown.

A daily data run was carried out over 6 weeks in one location to check weather and other variations and the muon rates are shown as a percentage variation from the average in Fig. 6. Also shown is the barometric pressure for this time period using measurements taken with an on-site weather station. The time variation of the muon rate is roughly anti-correlated with atmospheric pressure and is at the 10% level.

Fig. 7 shows the energy spectra for a 24 hour run on one scintillator bar for passing through and stopping muons at ground level as compared with inside a tunnel covered with 4 m equivalent concrete. This well-shielded location underground resulted in a reduction by a factor of 2.2 for energetic cosmic rays while the stopping muon rate decreased by a factor 1.8. The neutrons would be expected to be attenuated by a factor greater than 100.

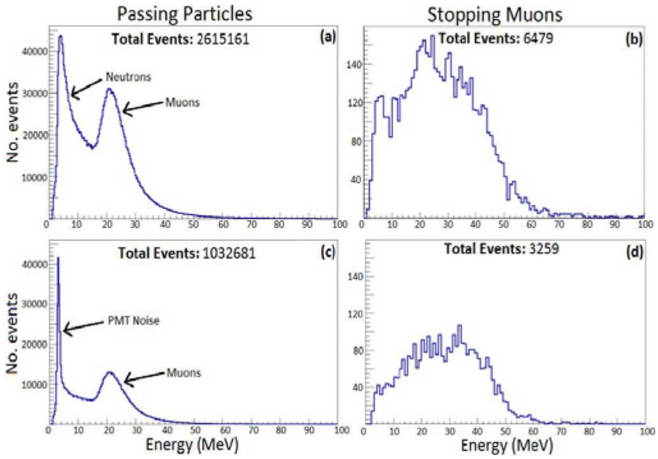

Fig. 7. The spectrum of passing and stopping muons at ground level (a,b) and in the tunnel (c,d) showing the reduced total rates and attenuation of the neutron component in the passing spectrum.

Overall the presence of nearby building walls causes a slight increase in stopping muon rate compared with an open field measurement.

IV. Summary of Results

The stopping muon rate has been found to be more constant than the overall cosmic ray rate as a function of building shielding and altitude. An altitude increase of 863 m (2683 ft.) produced an increase in the high energy cosmic ray rate of 30% while the stopping muon rate increased by about 10-15%. For this altitude change cosmic ray neutrons would be expected to increase by a factor 2 [14].

There were no observed anomalies in the daily muon rates that could be correlated with solar activity. However no attempt has been made to remove the atmospheric pressure variations to check for other effects.

For the purposes of soft error calculations due to direct ionization of muons the stopping rate per gram of scintillator can be determined and related to the stopping rate per gram of silicon. A stopping rate of 18 muons per minute in the detector corresponds to about 0.025 stopping muons ($\mu^+ + \mu^-$) per gram of silicon per hour. This flux can be used to determine a terrestrial soft error rate based on the muon beam measurements and simulations. Several groups have measured the upset rate due to low energy muons using the muon channel M20 at TRIUMF which delivers low energy positive muons [5][15]. The measured cross sections and a knowledge of the sensitive volumes of the devices can then be used to determine the terrestrial upset rate based on the measured stopping muon rate as presented in this paper. The lifetime of the stopping muons shows that there are equal numbers of positive and negative muons at low energies. Negative muons could have a larger SER due to the competing process of muon capture on the silicon nucleus which can produce additional charged particles. Siefert [15]has shown by simulations that negative muon capture is a small effect on the SER while Serre [16]shows that it could be similar in size to the direct muon ionization effect. Unfortunately accelerator sources of low energy negative muons have much lower fluxes than for positive muons so measurements are difficult. However the conclusion of this and the other referenced studies is that for present technologies the cosmic ray muon-induced SER is much lower than that for neutrons at ground level. This study also shows that local environments cannot increase the terrestrial muon rate significantly.

FLUKA calculations are being used to understand the detector response to muons and neutrons as well as to predict the muon stopping rates for the different locations of altitude and latitude and presence of nearby shielding Some of these results are presented in the previous graphs showing that the response of muons in the plastic scintillator is reasonably well understood. The stopping muon energy spectrum is not exactly as predicted by FLUKA on the high energy side but this may be due to the simulation method used where the incident muon spectrum is not corrected for azimuthal angle. More precise calculations are being carried out in collaboration with CERN to consider this effect and to determine how well the cosmic ray codes fit the measured data, or to specify further measurements that could be useful. This parallel effort on simulations will be reported in a future paper.

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