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Development of apparatus for mean-lifetime measurement of cosmic-ray muons using plastic scintillation detectors and FLASH-ADC/FPGA-based readout electronics

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ABSTRACT

Introduction: This paper presents the development and results of an apparatus for measuring the mean lifetime of cosmic-ray muons. **Methods**: The apparatus uses three plastic scintillation detectors and a readout electronics system based on Flash Analog Digital Converter (Flash-ADC) and Embedded Field Programmable Gate Array (FPGA). The readout system has 8-bit resolution and a 125 Msample/sec sampling rate. The system's trigger and data collection are controlled through a computer interface based on LabVIEW^{TM}. The readout electronics are calibrated with an accuracy of 8 nsec/TDC channel. **Results**: Over 6000 events were recorded during the measurements performed at ground level using aluminum as the muon stopping material, and the muon decay time spectrum was obtained and fit with a combination of two exponential components and a constant background. The mean lifetimes of negative and positive muons were determined. **Conclusion**: Our results indicate that the mean lifetimes of negative and positive muons in aluminum are 0.70 $\pm$ 0.24 μsec and 2.05 $\pm$ 0.16 μsec, respectively.

Key words: mean lifetime of cosmic-ray muons, cosmic rays, Flash-ADC, FPGA

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INTRODUCTION

Cosmic-ray muons were first discovered in 1936 by Carl Anderson and Seth Neddermeyer while studying cosmic radiation at Caltech. The mean lifetime of cosmic-ray muons was later confirmed in 1937 through a cloud chamber experiment conducted by J.C. Street and E.C. Stevenson. The only natural source of muons is cosmic rays from outer space interacting with Earth's atmospheric molecules, mainly oxygen and nitrogen. The average flux of muons at sea level is approximately 1 muon/cm2/minute. Muons are unstable elementary particles that come in two types: negative (μ-) and positive (μ+). The mean lifetime of negative and positive cosmic-ray muons in air is known to be 2.1969811$\pm$0.000022 μs[1]. However, the mean lifetime of negative muons in a material is not constant, as it can be affected by the weak interaction between muons and nuclei. For instance, in aluminum, the mean lifetime of negative muons has been determined to be 0.8646 $\pm$ 0.0012 μsec[2,3].

Several experiments aimed at understanding cosmic-ray muons have been conducted, and this is still an active field of research, with various setups and modern devices. In Vietnam, at the VATLY laboratory in Hanoi, there have been several studies on cosmic-ray muons[4,5]. Our previous works include the study of the angular distribution of cosmic rays at ground level[6] and the cosmic-ray muon-induced background on a germanium detector through Geant4 simulation[7]. In experiment[6], two plastic scintillation detectors were used to measure the angular distribution of cosmic rays, and high-tech Flash-ADC/FPGA-based technology was used for the readout electronics. Our previous publications[8–10] have also involved the use of the Flash-ADC/FPGA-based readout electronic for gamma spectra measurements and cosmic-ray determination.

In this article, we describe the development of an apparatus for measuring the mean lifetime of cosmic-ray muons. Three plastic scintillation detectors are used to detect muon decay, and the readout electronic employs a high-speed Flash-ADC (8 bit resolution, 1000 mV, 125 Msample/sec) and embedded FPGA technology. The computer interface for controlling the system's trigger and data taking is written on the LabVIEW^{TM} Platform[11]. The mean lifetime of negative and positive cosmic-ray muons is measured using aluminum as the muon stopping material. This work was conducted at the Department of Nuclear Physics at the University of Science in Ho Chi Minh City in collaboration with the Nomachi group at the Research Center of Nuclear Physics in Osaka University. The

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results of this work can be useful for educational purposes, allowing students to learn about coincidence techniques and lifetime measurement using advanced devices.

EXPERIMENTAL SET-UP

Experimental arrangement

The schematic system for measuring the cosmic-ray muons mean lifetime, as shown in **Figure 1**, includes three scintillation detectors, an aluminum plate, Flash-ADC/FPGA-based readout electronics, and a LabVIEW computer interface. The scintillation detectors, shown in **Figure 2**, consist of plastic scintillator plates (BC404 type, manufactured by Bicron [12]) and Hamamatsu-made H6410 photomultiplier tubes (PMT) [13] connected via light guides. The scintillation plates, light guides, and PMTs are covered by aluminum foil and black plastic sheets to avoid external light. The PMTs operate with a negative high voltage supply (Opton-2NC-*, Manufactured by Matsusada Precision [14]). Scintillators 1 and 2 are 10 cm x 20 cm x 1 cm thick, and scintillator 3 is 30 cm x 20 cm x 1 cm thick. The aluminum plate, used as the muon stopping material, is 30 cm x 20 cm x 5 cm thick and positioned between the scintillators. The arrangement of the detectors and aluminum plate is shown in **Figure 3**.

The experimental technique is straightforward. Cosmic-ray muon candidates are stopped in the aluminum target and decay to electrons or positrons. Two upper scintillation detectors are used to trace incoming cosmic-ray muons, and the third is used to trace decayed electrons/positrons from muons. Here, aluminum material is used to increase the muon capture rate and consequently the muon decay probability. The readout electronic is built from Flash-ADC of 8-bit 125-Msample/sec and Embedded FPGA-based trigger. Analog signals originating from three scintillation detectors are fed into ADC inputs of the Flash-ADC, i.e., ADC1, ADC2, and ADC3 and digitized with a sampling clock of 125 MHz, i.e., 8 nsec/sample. Digitalized data of ADC1, ADC2, and ADC3 continuously flow to the FPGA. For triggering, a coincidence between three ADCs is set. Data are then stored in the buffer memory, and time-digital conversion (TDC) is performed to obtain the time difference in terms of the TDC channel between ADC1-2 and ADC3. A clock of 125 MHz is used for the ADCs and TDC. The TDC-channel event is transferred to the computer via the RS-232 port. The diagram of the readout electronics of the Flash-ADC and FPGA is described in **Figure 4**.

The clock of 125 MHz used in the Flash-ADCs (i.e., 8 nsec/sample) and TDC; clock of 50 MHz used in the FPGA.

Triggering and "gate" window

The measurement of the cosmic-ray muon's mean lifetime is performed using a coincidence technique between three ADC inputs. Energy threshold levels are set for scintillators 1, 2, and 3 to select the cosmic-ray region, as described in a previous work [3]. The coincidence of the three detectors is set with the condition of (det1 and det2) and (not det3). A 15 μsec "gate" window is open to record the time difference between the muon stopping in the aluminum plate and its decay into electrons/positrons. The triggering and "gate" window for muon lifetime measurement is shown in **Figure 5**.

RESULTS

TDC time calibration

The TDC time calibration of the readout system was performed using a pulse generator, as described in **Figure 6**a. The pulse generator produced pulses of 20 nsec width and had a variable frequency. The output from the three channels of the pulse generator was fed into three ADC inputs of a Flash-ADC/FPGA system. The third channel (Ch3) was delayed with a known value in comparison to channels 1 and 2. A clock of 125 MHz was used for TDC, as described in **Figure 6**b. The TDC calibration between ADC1, 2, and 3 was shown to be linear, as shown in **Figure 7**, with a formula of TDC channel = 0.125 x time (nsec), where 1 TDC channel = 8 nsec. The TDC channel resolution was 8 nsec, which was deemed sufficient for time measurement of cosmic-ray muon decay.

Measuring the mean lifetime of cosmic-ray muons

Measuring the mean lifetime of cosmic-ray muons

The measurement is carried out within a week of continuous data collection. The TDC spectrum, represented by the blue curve in **Figure 8**, between scintillators 1, 2, and 3 is shown. The time scale was measured up to 15 microseconds. Nearly 6000 events were recorded, and the TDC spectrum of cosmic-ray muon decay in aluminum was found to follow an exponential distribution.

DISCUSSION

The mean lifetime of cosmic-ray negative and positive muons in aluminum can be calculated from the exponential distribution in the TDC spectrum displayed in

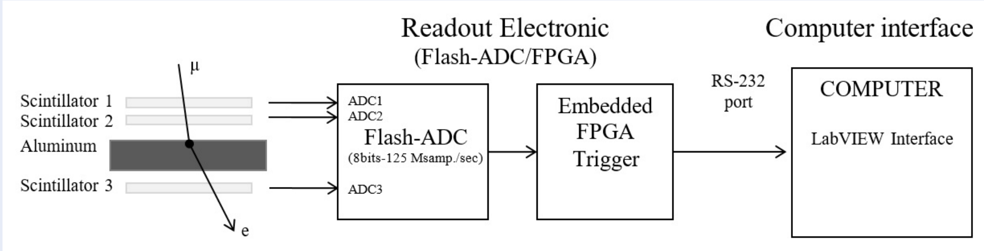

Figure 1: **Schematic diagram of the muon lifetime measurement apparatus.**

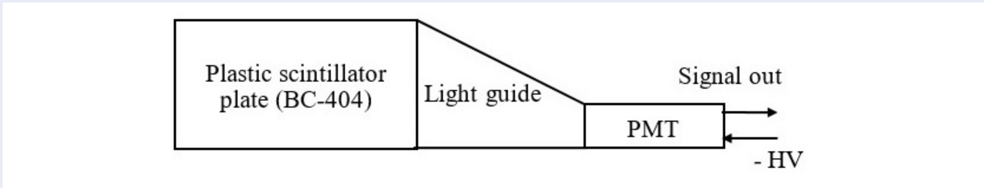

Figure 2: **Schematic design of a plastic scintillation detector.**

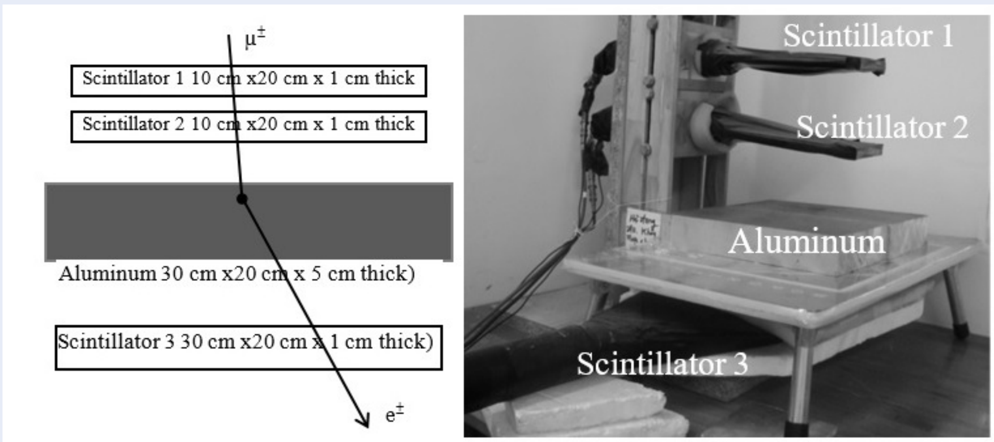

Figure 3: **Arrangement with 3 scintillation detectors and an aluminum plate for measuring the mean lifetime of cosmic-ray muons.**

Figure 8. To determine the mean lifetime, a fitting of the TDC spectrum was performed using the following formula with two exponential components and a constant background: "$y = a_1.e^{-t/T_1} + a_2.e^{-t/T_2} + background$" where parameters of a_1, a_2, T_1, T_2, and *background* are free fitting parameters. T_1 and T_2 correspond to the mean lifetimes of negative and positive muons, respectively. t is the TDC channel, and y is the count number. Based on the fitting curve in **Figure 8**, T_1 was calculated as 0.70±0.24 (μsec) and T_2 as 2.05±0.16 (μsec), which are the mean lifetimes of negative and positive muons, respectively. The results were compared to reference data in **Figure 9**, and it was found that there is good agreement within the statistical error bar.

CONCLUSIONS

The work presented an apparatus for measuring the mean lifetime of cosmic-ray muons. It consisted of three plastic scintillation detectors, a readout electronic with a Flash-ADC/FPGA-based system for triggering and data acquisition, and a computer interface with LabVIEW^{TM}. Calibration of the readout system using a pulse generator resulted in a time reso-

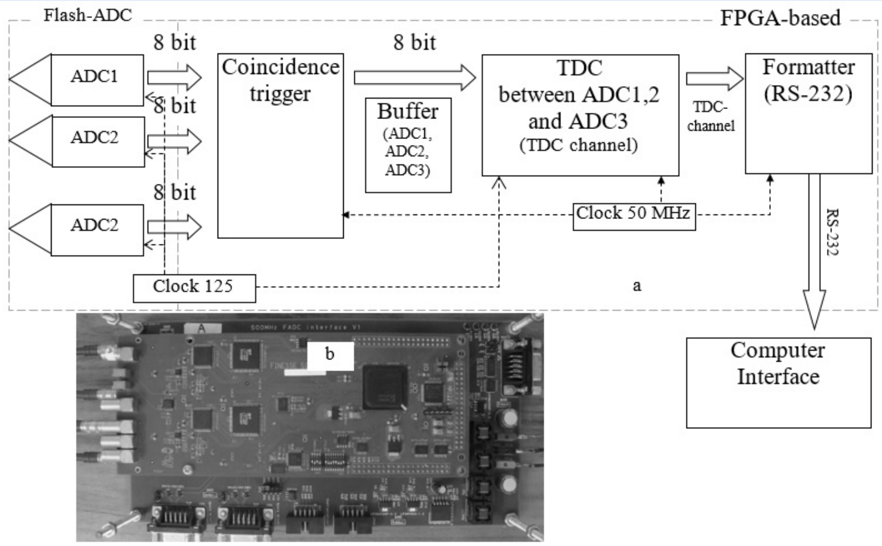

Figure 4: **Diagram (a) and photo (b) of the readout electronics of Flash-ADC/FPGA.**

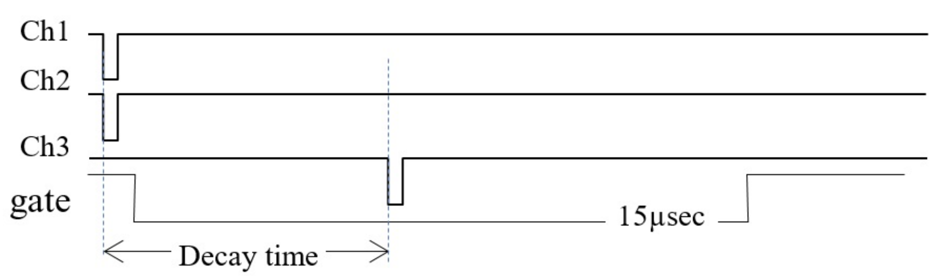

Figure 5: **Triggering and "Gate" window.**

lution of 8 nsec/TDC channel, suitable for measuring muon decays. After a week of continuous data collection, the TDC spectrum of cosmic-ray muons was found to follow an exponential distribution, and the mean lifetime of both positive and negative cosmic-ray muons was determined and found to be consistent with reference data. The results of this experiment demonstrate the effectiveness of the apparatus in measuring the mean lifetime of cosmic-ray muons.

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We thank Prof. Masaharu Nomachi and Prof. Takahisa Itahashi, Osaka University for supporting plastic scintillation detectors. This work was funded by Vietnam National University, Ho Chi Minh City under Grant number B2022-18-01.

ABBREVIATIONS

ADC: Analog Digital Converter
FPGA: Field Programmable Gate Arrays
TDC: time digital converter
MHz: megahertz
μ-: Negative muon
μ+: Positive muon

AUTHOR CONTRIBUTION

Vo Hong Hai designed and performed all experiments and wrote the paper. Nguyen Tri Toan Phuc did data analysis. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

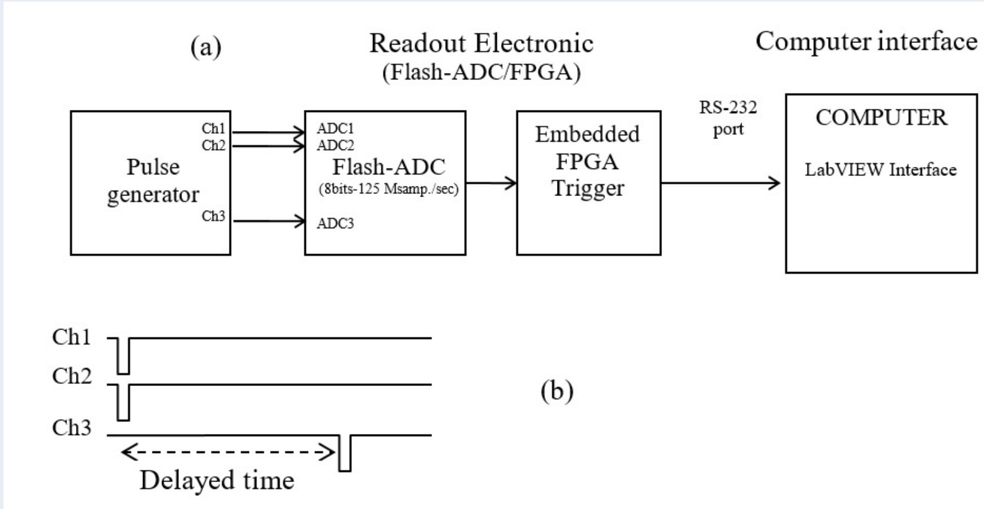

Figure 6: **TDC time calibration of the readout system between ADC1, 2 and ADC3**. a. Scheme for setup. b. signal Inputs.

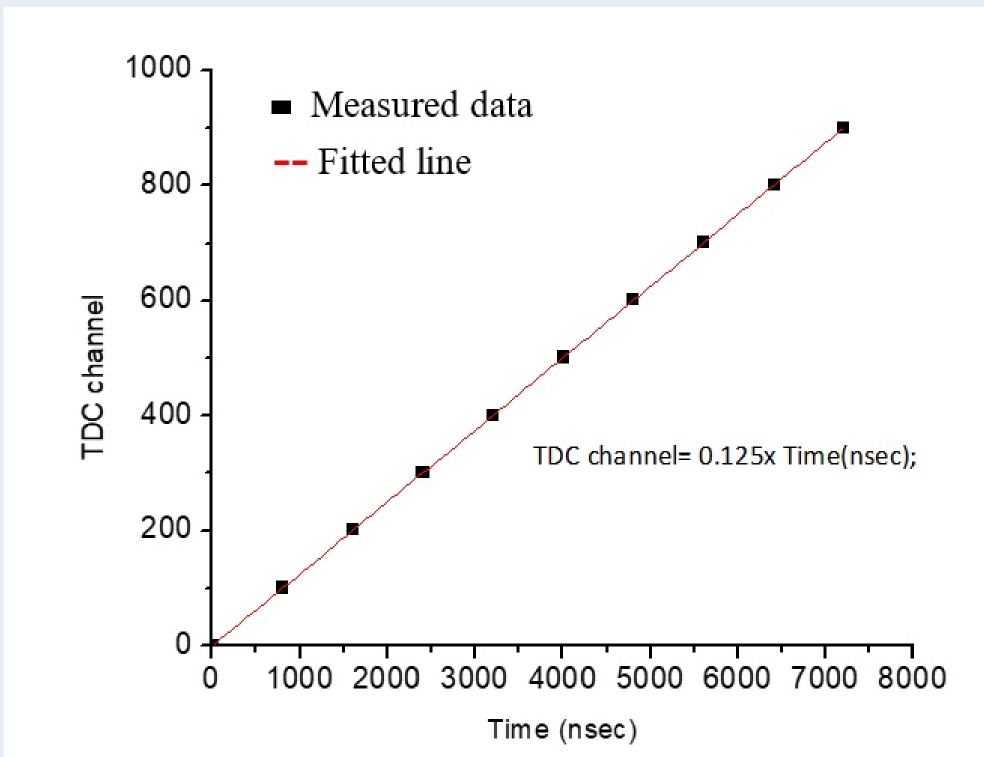

Figure 7: **TDC calibration between ADC1,2 and ADC3 for readout electronics (Flash-ADC/FPGA).** 1 TDC channel = 8 nsec.

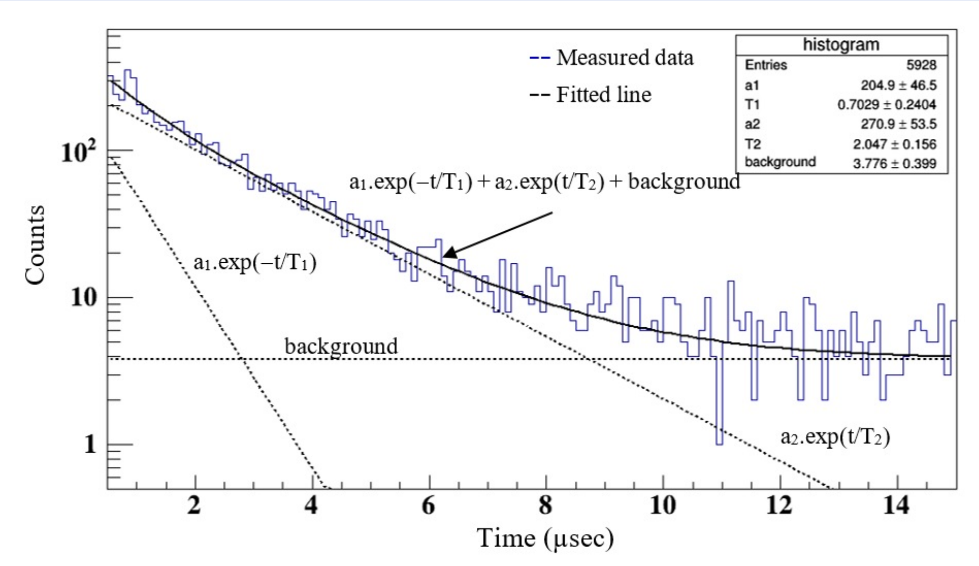

Figure 8: **Experimental result of the mean lifetime of cosmic-ray muons**. Here, a - Blue curve is the TDC spectrum between scintillators 1 and 2 and scintillator 3, b- The solid line is a fitting curve with two exponential components in which each exponential component, the dashed line, represents cosmic-ray negative and positive muons in aluminum.

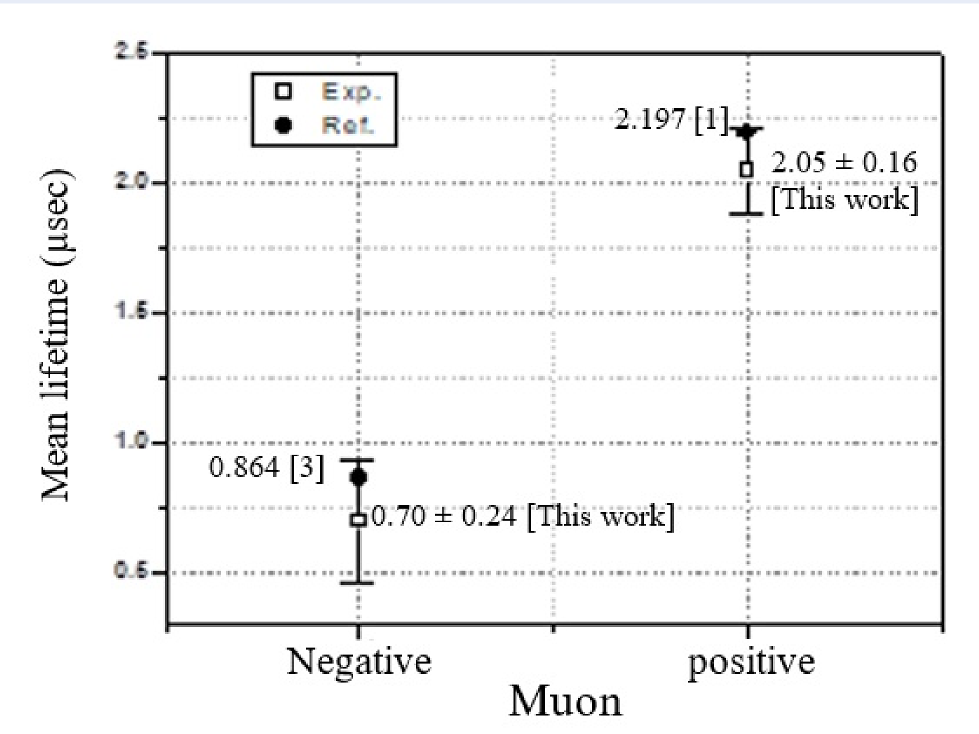

Figure 9: **Comparison of the mean lifetime of μ- and μ+ between this work and references [1,3].**

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