PSoC based Cosmic Muons Detector

Using PSoC chip for cosmic muons detection and muon lifetime estimate

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The muon—the short-lived cousin of the electron—could be the key to understanding relationships between other fundamental particles. And it holds a mystery all its own.

In the 1930s, scientists thought they had matter figured out. Matter was atoms; atoms were protons, neutrons and electrons; and that was that. Then they discovered the **muon**—a surprisingly heavy cousin of the electron with no apparent purpose other than to baffle scientists. The muon was so unexpected that, regarding its discovery, Nobel laureate Isidor Isaac Rabi famously quipped, “Who ordered that?”

Out of the 16 particles in the **Standard Model**, the muon is becoming the focus of research for more and more physicists, who seek both to understand its unique properties and to use it as a probe of the rest of the subatomic world. “Muons are special,” says Chris Polly, a Fermilab physicist involved in muon research. “They are light enough to be produced copiously, yet heavy enough that we can use them experimentally to uniquely probe the accuracy of the Standard Model.”

Even though the muon is one of the most accessible subatomic particles, it has its share of characteristics that make it enigmatic and exciting.

Muons are about **200 times heavier** than the electron. While this larger mass makes them interesting, it also makes them **unstable**. Whereas electrons live forever, muons exist for only about **two microseconds**—or two millionths of a second—before they decay. But for particle physicists, who work with particles traveling close to the speed of light, two microseconds is, essentially, forever.

…”

From an article of Sarah Charley – Symmetry a Fermilab/SLAC publication

**Acknowledgments**

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Introduction

Cosmic rays, at sea level, have plenty of muons. They come from the interaction of primary cosmic with nuclei of atmosphere. Cosmic muons can be detected rather simply with scintillation detectors and it is also possible to measure the muon lifetime.

Now we want to describe the last equipment we built with the aim to measure with precision the muon lifetime. It consists of a plastic scintillator coupled with a PMT and an electronic circuit based on a PSoC which performs the time measure between the muon passage in the scintillator and the muon decay. The data are stored in a SD Card and sent via serial communication to a PC which runs the software to acquire data and to make the statistical analysis.

Experimental Setup

The image below shows the generation of the two light pulses (short arrows) used in determining the muon lifetime. One light pulse is from the slowing muon (dotted line) and the other is from its decay into an electron or positron (wavy line).

The muons that come to rest then live a relatively long time, on the order of order microseconds, inside the scintillator; but eventually each of them decays in an electron (positron) plus a neutrino and a antineutrino. Nearly all of the rest energy (105 MeV) of the stopped muons appears as kinetic energy of the three particles; on average, the electron (positron) gets a third of this energy, about 35 MeV. (The two neutrinos carry away the rest of the energy undetectably). But such an electron is a charged particle, itself certain to cause ionization as it moves through the scintillator. Conveniently, the typical energy deposited in this ionization process is about the same as that deposited by a muon-in-transit, or a muon stopping, so the very same scintillator/PMT configuration is also suitable for detecting stopped muons subsequently decaying at rest.

To measure the muon's lifetime, we are interested in only those muons that enter, slow, stop and then decay inside the plastic scintillator. Such muons have a total energy of only about 160 MeV as they enter the tube. As a muon slows to a stop, the excited scintillator emits light that is detected by a photomultiplier tube (PMT), eventually producing a logic signal that triggers a timing clock. A stopped muon, after a bit, decays into an electron, a neutrino and an anti-neutrino. Since the electron mass is so much smaller than the muon mass, μe/me ~ 210, the electron tends to be very energetic and to produce
scintillator light essentially all along its path. The neutrino and anti-neutrino also share some of the muon’s total energy but they entirely escape detection. This second burst of scintillator light is also seen by the PMT and used to trigger the timing clock. The distribution of time intervals between successive clock triggers for a set of muon decays is the physically interesting quantity used to measure the muon lifetime. The images below shows the experimental setup with the “scintillator can” and the signal processing electronic part.
Signal Processing

The image below shows the signal processing chain, from the PMT to the PC for data acquiring and data processing.

Trans-Impedance Amplifier

The -negative- signal from the PMT, which is powered with a high voltage at around 1 kV, is amplified with a trans impedance amplifier (TIA). The scheme below shows the schematic of the TIA, the operational amplifier has to be very fast (wide band op amp) in order to preserve the timing of the original signal produced by the PMT. The signal produced in output by the amplifier is inverted with respect the input, so it has a positive swing from 0 level to about the maximum level of 2 V.
**Fast Comparator**

The amplified signal is sent to a fast comparator, with adjustable threshold, which has the aim to produce a square pulse signal for the pulses generated by the muon passage inside the plastic scintillator. Acting on the threshold it is easy to select only those pulses coming from muons excluding the “noise” from background radioactivity, because the muons generate pulses rather high while the background pulses remain below 100-200 mV. So we set the threshold at 300 mV. With this value we obtain a pulse rate of around 5-7Hz, that is 300 – 400 CPM.
PSoC (Programmable System-on-Chip) is a family of microcontroller integrated circuits by Cypress Semiconductor. These chips include a CPU core and mixed-signal arrays of configurable integrated analog and digital peripherals. A PSoC integrated circuit is composed of a core, configurable analog and digital blocks, and programmable routing and interconnect. The configurable blocks in a PSoC are the biggest difference from other microcontrollers. PSoC has three separate memory spaces: paged SRAM for data, Flash memory for instructions and fixed data, and I/O Registers for controlling and accessing the configurable logic blocks and functions.

PSoC resembles an ASIC: blocks can be assigned a wide range of functions and interconnected on-chip. Unlike an ASIC, there is no special manufacturing process required to create the custom configuration — only startup code that is created by Cypress’ PSoC Designer (for PSoC 1) or PSoC Creator (for PSoC 3 / 4 / 5) IDE.

PSoC resembles an FPGA in that at power up it must be configured, but this configuration occurs by loading instructions from the built-in Flash memory. PSoC most closely resembles a microcontroller combined with a PLD and programmable analog. Code is executed to interact with the user-specified peripheral functions (called “Components”), using automatically generated APIs and interrupt routines. PSoC Designer or PSoC Creator generate the startup configuration code. Both integrate APIs that initialize the user selected components upon the users needs in a Visual-Studio-like GUI.

In our application we used the model PSoC 5LP. For development we used both the CY8CKIT-059 kit and the more complete board CY8CKIT-050, both are shown in the images below:
The aim of the PSoC component is mainly to acquire the pulse signals from the comparator, count them and select the pulses which are coming from a muon decay; in this latter case the aim is to measure the time interval between the two pulses, the first pulse from the muon and the second pulse from the electron (positron) generated in the muon decay: this duration is the decay time of the muon. In details the tasks accomplished by the PSoC are the followings:

- Read and show on display the fast comparator threshold;
- Acquire the muon pulses from the comparator and generate for each pulse a 40ns-fixed pulse;
- Measure the time interval between two consecutive pulses (40ns pulses): if this time is less than 20μs it is a muon decay event, otherwise it is not;
- Count the muon pulses and calculate the rate value and the σ value;
- Count the muon decay events and calculate the rate value and the σ value;
- Show on display the data;
- Write on SD card the acquired data;
- Send the acquired data to the PC via serial communication;
Firmware

The PSoC 5LP (CY8CYKIT-059) has been programmed with the development system PSoC Creator, freely downloadable from the manufacturer’s website. Using this tool, with a rich and simple graphical interface, the chip is programmed and all the used components are defined and configured. We go through the main points of the project.

Clock Signals

The system is synchronized by means of a series of clock signals, the main of which is the BUS_CLK that has a frequency of 50MHz (this frequency is set in configuration and depends on the characteristics of the circuit that is being achieved), it synchronizes the operation of all the components. The period of this signal is 20ns, this is important because it corresponds to the minimum duration of the signals that can be managed correctly by the system. Signals shorter than 20ns may be managed incorrectly or may not be read by the system. In our project we have established for the signals a minimum duration of 40ns, well above the limit of 20ns.
Pulse Generator

The pulses produced by the fast comparator are the input signals of the PSoC processing chain. Since the pulses may have variable durations, downstream it is placed a D-type Flip Flop with external RC network to obtain a **clean pulse of 40ns**. The latter also produces a further pulse of 0.01s used to turn on a LED in order to give a **visible feedback** of the capturing event.

Pulse Counter

The pulses are sent to digital counters which perform the pulse counting. There is also a counter that counts the seconds so as to measure the duration of the counting operations.
Time Interval Measurements

The time interval between two pulses is measured with a timer. The time interval is measured between the rising edge of the pulses.

Control Buttons

The system is equipped with three buttons and a LED that lights up when you press any of the three buttons. The functions of the three buttons are as follows:
- Reset Counters
- Start / Stop Counting
- Display Switch
The following images show the electronic part and the data shown on the display:
Pulse Examples

In the picture below you can see the typical PMT pulse produced by the muon passage in the scintillator. The FWHM is about 40ns, while the amplitude is about 200mV.

The picture below shows various PMT pulses, with amplitude ranging from 100mV to 300mV and duration ranging from 40ns to about 120ns.
The picture below shows both the PMT pulse and the output pulse of the amplifier. The duration is the same while the signal amplitude, positive, goes up to 1.5V.

The picture below shows both the PMT pulse and the output pulse of the fast comparator.
The picture below shows both the PMT pulse and the 40ns pulse generated by the PSoC. The latter is delayed with respect to the PMT pulse of around 40ns.

The picture below shows the jitter of the 40ns pulse generated by the PSoC. From the traces it can be estimated in less than 20ns.
The picture below (obtained increasing the persistence of the scope display) shows the muon pulse plus two pulses generated by the muon decay and the corresponding PSoC pulses.
Software Interface

The PSoC board is interfaced to the PC by means of a serial communication. In the PSoC project this is done with the UART component. The serial connection is the same connection used for programming and debugging.

The image below shows the entire setup with scintillator, electronics and PC for data acquisition.

The software used for data analysis is the application realized by Prof. Coan and Prof. Ye which can be downloaded, with documentation, from their site www.mtphys.com.

The image below is a screenshot of the software.
The application reads and records the data which are sent from the PSoC. It performs the counting of muons, the counting of muon decays, it calculates the rates and, mainly, it fits the decay data with exponential law determining the muon lifetime.

In the image below we report the results after collecting about 5000 events.

![Muon Decay Time Histogram](image)

The decay constant value is equal to a $2.080 \pm 0.035 \mu s$.

This value is between the value measured in vacuum, $2.197 \mu s$, which is valid for the positive muons and the characteristic value of negative muons equal to $2.043 \pm 0.003 \mu s$, slightly less because of the interaction of negative muons with nuclei of the scintillator.

The measurements are in good agreement with the expected and predicted by theory.