Measuring the average lifetime of cosmic rays muons

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Abstract

A scintillation mechanism was used to measure the mean lifetime of cosmic ray muons with the data collected from cosmic ray showers. The mean lifetime of muons was measured to be 2.43 ± 0.03 μs, in agreement with the current best value of 2.19703 ± 0.00004 μs [1].

1 Introduction

In this experiment the mean lifetime of cosmic ray muons in their rest frame will be measured. Muons are stopped in a large block of scintillator, where they subsequently decay into an electron/positron and two neutrinos. A short light pulse is produced by the stopping muon which is detected and amplified by a photomultiplier tube. When the muon decays a second pulse is produced by the emitted electron or positron. The signals from the photomultiplier are fed into an electronic circuit which determines the time delay between the two pulses. The circuit is connected to a PC which is used to read out the data. The experiment involves the set-up of the equipment, performing the actual measurement and the subsequent data analysis.

The purpose of this experiment is to understand how photomultiplier tubes and scintillators combined work as a particle detector, study the formation of muons from primary cosmic rays in the atmosphere, analyze the working of high speed electronic modules so that they can be used to obtain the time difference to calculate the lifetime, understand the workings of the multi-channel analyzer and realize how it is a crucial part of counting different voltage pulses in this experiment, and analyze how curve-fitting parameters influence the final answer.

2 Theoretical background

Muons are the fundamental particles and belong to the lepton family. These fundamental particles are heavier than electrons, with mass of about 105.7 MeV/c^2, carry one unit of fundamental charge and they are unstable. Muons (μ^-) and antimuons (μ^+) are created in the upper atmosphere ($\sim$ 15 km [2]) are secondary products of interactions between highly energetic cosmic rays and the nuclei of atmospheric particles. Once the cosmic ray particles have entered our atmosphere and interacted with the air molecules they begin a cascade of nuclear reactions starting from the top of the atmosphere all the way to ground. At ground level these are known as cosmic ray shower as shown in the Fig. 1.

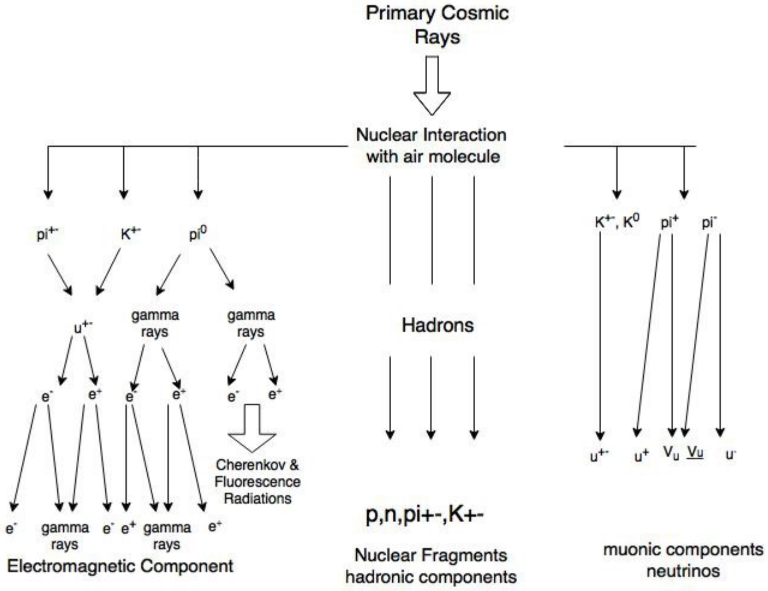

Figure 1: Schematic diagram of a cosmic ray interaction in the upper atmosphere (from Fraunfelder and Henley [3]).

Muons are formed by the decay of pions in our atmosphere. Pions are also formed in our atmosphere through the interaction of primary cosmic rays, i.e. mainly protons, with the nuclei in the upper atmosphere. The reactions in which pions decay to produce muons occur through weak interactions and are:

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \to \mu^+ + \nu_\mu$$

Since they interact weakly and have a mass much greater than that of the electron therefore muons are highly penetrating particles able to reach the ground. The "cascade" of muons detected at sea level is directionally dependent on the zenith angle, θ, as $\cos^2(\theta)$. It is therefore much more likely to detect muons traveling normal to the earth's surface than parallel.

2.1 Muon flux

The incident muon flux at sea level has the following relationship with θ (the zenith angle or the angle measured from the vertical) [2]:

$$I(\theta) = I_o \cos^2(\theta) \tag{1}$$

Here $I_o = 0.0083\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{str}^{-1}$.

For low energy incident muons the muon flux decreases in general as the angle increases. This is because at larger angles the muons have to penetrate a larger distance through the atmospheric layer of air particles to reach the ground. Therefore increasing angle increases the probability of the muons interacting with an air particle or decaying before reaching the ground. The exception to this general trend are the high energy muons which are mostly not affected and their flux steadily increases with increasing angle. Therefore one of the main parameter which concerns ones when performing such calculations is the amount of matter above any atmospheric layer through which these particles had to pass. This is atmospheric depth measured in g/cm^2. Temperature and density variations affect the interaction of cosmic ray particles and air molecules in the atmosphere.

Theoretically one can also calculate the muon lifetime in its rest frame using the Fermi's Golden rule. The Golden Rule provides ones with the decay rate for the muons which is given by:

$$\Gamma = \frac{G^2(m_\mu c)^5}{192\pi^3} \tag{2}$$

Here G is the Fermi constant and m_μ is the mass of the muon which is roughly equal to $106m_e$. The value of G is $1.136 \times 10^{-5}\ \mathrm{GeV}^{-2}$. The lifetime is then given by $\tau = \hbar/\Gamma$ [2].

3 The Lifetime Experiment

In this experiment the lifetime of the muon in its rest frame will be measured. When the muon stops in detector B the initial $\mathrm{AB\overline{C}}$ pulse is generated. This is followed by a second pulse generated by B as the muon decays and releases an electron or a positron depending on whether it is a μ^- or μ^+. Measuring the time difference between the $\mathrm{AB\overline{C}}$ and B pulses gives us an exponential time distribution, whose gradient gives the mean lifetime of the muon.

3.1 The Experimental Setup

The layout for this experiment is shown in Fig. 2. Three PMTs will be used in this experiment. The PMTs used with their respective model numbers were Hamamatsu E990MOD2 for the 20 mm and REXON RB14 − 8E for the 80 mm one. The PMTs and scintillators joined together are collectively referred to as the detectors. They are labelled as A, B and C respectively with detectors A and C

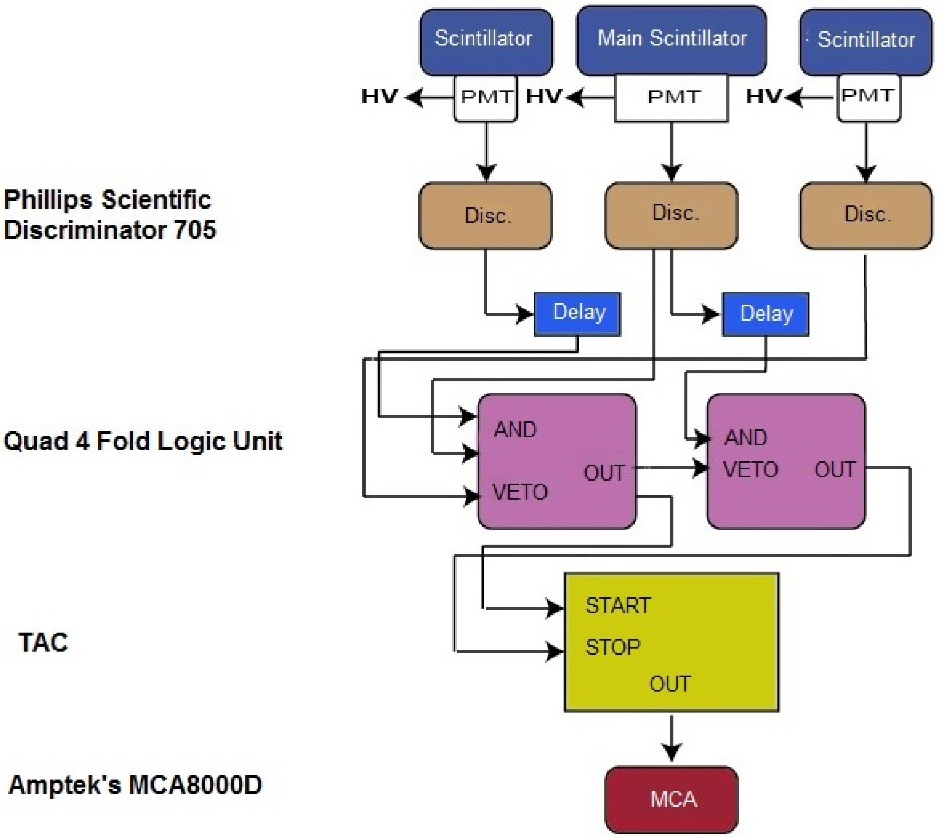

Figure 2: Schematic diagram of the Muon lifetime experiment.

being the identical smaller and the detector B being the larger one. The schematic diagram of the working of detectors as shown in the Fig. 3.

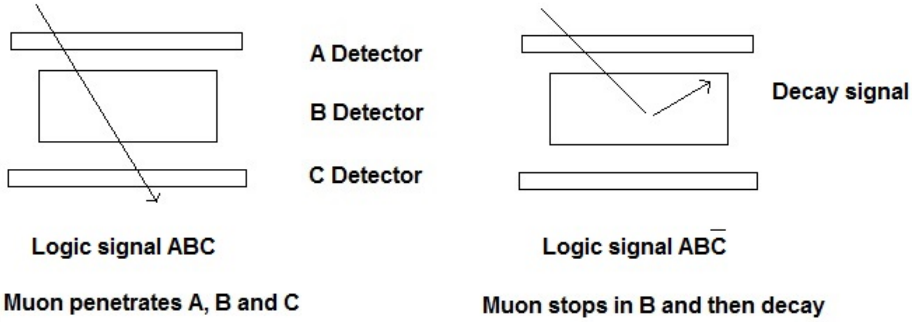

Figure 3: The three detectors are placed such that B is sandwiched between A and C for the experiment. When a muon passes through all three detectors, all three generate pulses. This is known as an ABC signal. When the muon is stopped in B, only A and B detector generate pulses. These together are known as the AB$\overline{C}$ signal.

The oscilloscope being used is PicoScope 5203 from Pico Technologies. Pulses from the PMT's are negative but not square as shown the in the Fig. 4. However the electronic logic units only work with negative square pulses which are also known as logic pulses. For this purpose, Phillips Scientific's Octal Discriminator Unit Module (Model 405) will be used. It contains eight discriminators. Each discriminator unit has the channels. The threshold of discriminator units of PMTs A and C will be kept at −48 mV and the threshold of discriminator unit of PMT B will be kept at −83 mV.

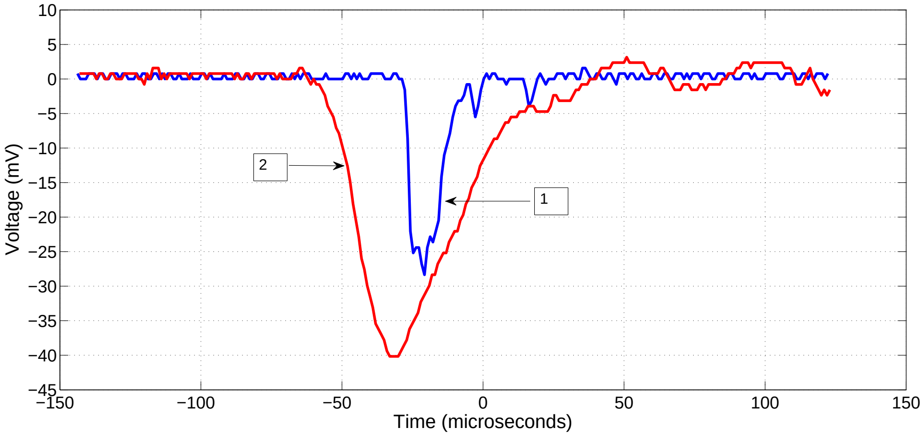

Figure 4: 1 and 2 represent the pulses from PMT A and B respectively without passing through discriminator. Pulse from PMT C would be very similar to pulse from A as both PMTs are identical

The pulse width and height of PMT A signal are 22.9 μs and 28.3 μs respectively. While for PMT B signal, the pulse width and height are 76 μs and 40 μs respectively.

4 Results and Analysis

In order to measure the lifetime, only $AB\overline{C}$ and the second pulse will be allowed to go ahead. For this purpose, Phillip Scientific's Quad Four Fold Logic Unit Module (Model 755) will be used. The module contains four logic units. Logic 1 will be used to generate $AB\overline{C}$ pulse. To generate a $AB\overline{C}$ signal, one need to AND the A and B signals, keeping the logic unit at coincidence level 2 so that it acts as an AND gate, and set C as the Veto input so that the signal is discarded if C pulse arrives. But to AND the A and B signals, they need to be in phase i.e the pulses should coincide in time and the width of B is increased such that it overlaps A and the width of C is increased such that it overlaps both A and B as shown in the Fig. 5.

As the A pulse arrives earlier, because the muon entered the A detector before entering the B, it needs to be delayed so as to brought in coincidence with the B pulse. This delay is empirically selected which is 33.5 ns in this experiment and done by a Stanford Research Systems delay box (Model DB64). Furthermore, the C pulse also has to delayed to coincide with A and B pulses so that it can veto them if the muon passes through all the three detectors.

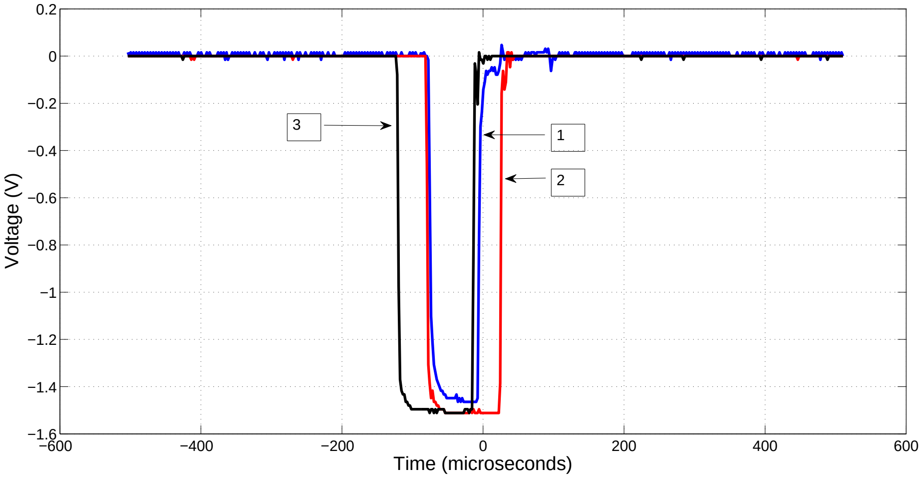

Figure 5: 1, 2 and 3 represent the pulses from A, B and C discriminator units in coincidence respectively. Pulse A delayed by 33.5 ns and pulse C delayed through 15 feet long coaxial cable.

Similarly, to generate B2 signal one need to input the B signal to a logic unit 2. But a B signal is also generated whenever a $AB\overline{C}$ is generated. To distinguish between the B pulse due to $AB\overline{C}$ signal and the actual B2 pulse, one need to input the $AB\overline{C}$ into the veto of the B logic unit. One also need to delay the B pulse so that it coincides in time with the veto $AB\overline{C}$ for properly vetoing and this delay is done by connecting a 15 feet long coaxial cable to the output coming out from the B discriminator by T-connector and set the logic unit 2 at coincidence level 1. Both pulses $AB\overline{C}$ and B2 are shown in the Fig. 6.

Now in order to measure the time interval between $AB\overline{C}$ and B2 pulses, Ortec TAC/SCA Model 567 will be used. $AB\overline{C}$ pulse has been fed into START and B2 pulse into STOP. The time to voltage scale of the TAC can be veried. For example if time scale of TAC has been set 10 μs, it means that for a time difference of 4 μs TAC would generate a positive square pulse of amplitude 4 V as shown in the Fig. 7. The output pulse range of the TAC is fixed and is from 0 to 10 V. If the time difference exceeds the time scale then that pulse is rejected and the TAC is reset. The TAC has two inputs the START and the STOP and one output called OUTPUT.

In this experiment AMPTEK's MCA8000D multi-channel analyser will be used to distinguish and count the positive square pulses according to their amplitude (voltage). This MCA accepts voltage pulses in the range 0–10 V which corresponds to the output voltage of the TAC. The MCA has a range of 8192 channels which means that it has a resolution of 10 V/8192 channels = 0.00122 V/channel. The muon lifetime experiments were generally run for around $70,000$ s. Data is taken from the MCA software, named "Amptek DppMCA", and analysed using Matlab.

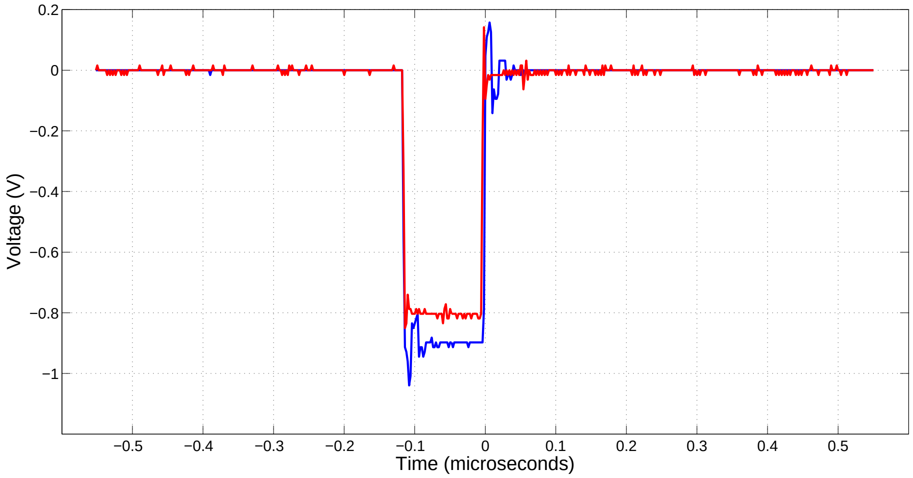

Figure 6: $AB\overline{C}$ and B2 pulses in coincidence. B2 has been delayed by 15 feet long coaxial cable in its path.

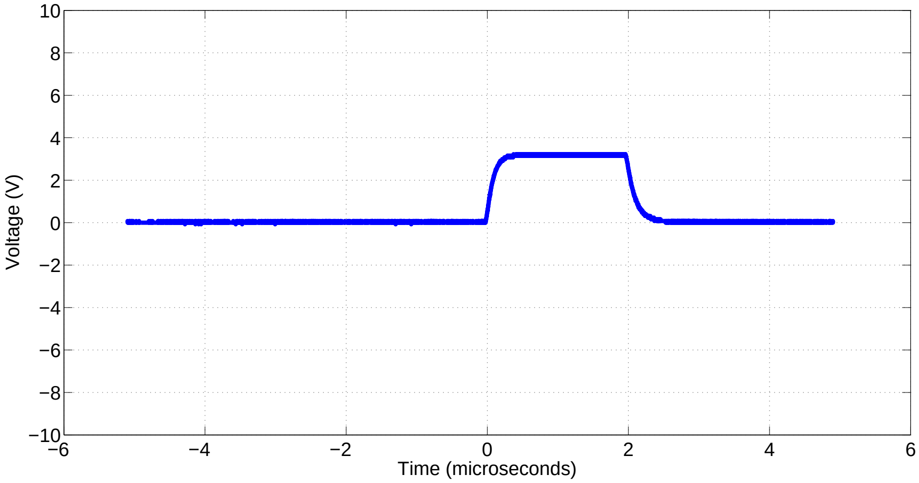

Figure 7: The TAC output signal observed on the digitial oscilloscope.

The relation of the activity of a radioactive source to time is given by $A(t) = Ae^{-t/\tau}$. Here τ is the mean lifetime of the particle and this is a universal law for all radioactive sources which decay including muons. The histograms, obtained from the MCA data, had the general form of a decaying exponential function. When the histograms were fitted with the function given by the Equ. 3 and the channel scale must also be converted to voltage using the 0.00122 V/channel scaling factor and then the voltage scale was converted to time scale using the 1 V/s scaling factor of the TAC which in this case was 1 V/μs the value of τ for that experimental run was obtained. A typical result for muon lifetime is shown in the Fig. 8.

$$F(x) = A(0.44e^{\frac{-t}{1.7}} + 0.56e^{\frac{t}{\tau}}) \tag{3}$$

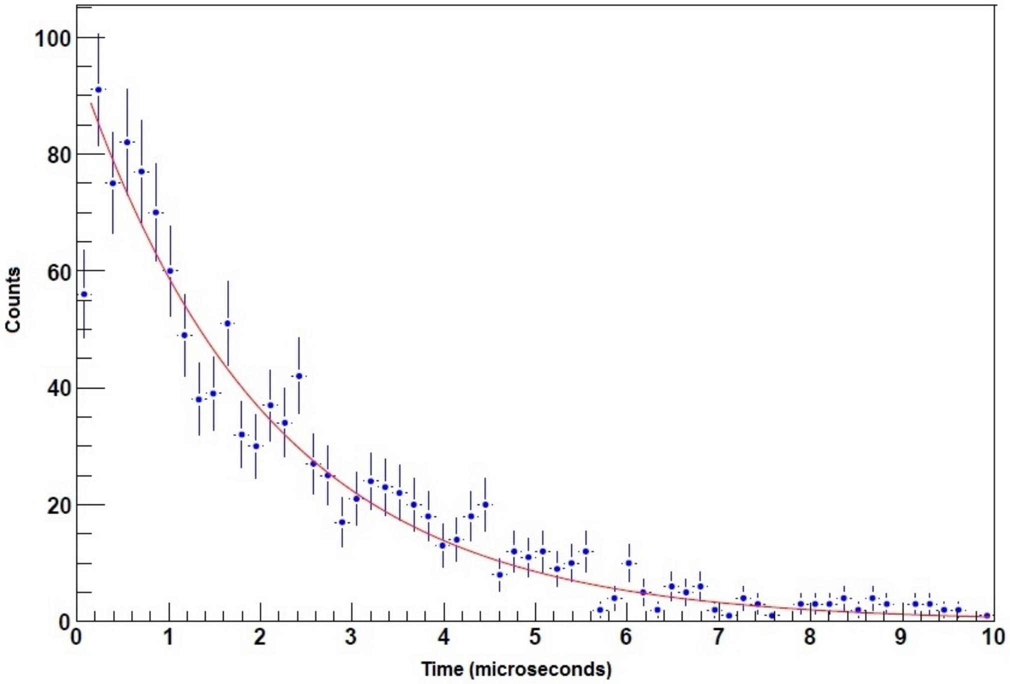

Figure 8: Unprocessed data with the fitted exponential curve.

After fitting the histogram, the program returned the values of A and τ. In Eq. 3 the first corresponds to μ^- and the second to μ^+. Their two respective weights of 0.44 and 0.56 were taken from the muon charge ratio R [4]. The value of A and the mean lifetime of the muon τ that one eventually got was:

$$A = 2.11 \pm 0.10$$

$$\tau = 2.43 \pm 0.03\ \mu\text{s}$$

Here ± 0.03 is the statistical uncertainty. This uncertainty was obtained by '**nlinfit**' command in Matlab. This function is used for curve-fitting process. It requires the data, a defined fitting function and the initial guess. After processing, it returns the values of the fitting parameters and the value of errors in the respective parameters. The actual value of the mean lifetime of the muon is within 2σ of measured value.

5 Conclusion and Discussion

The purpose of this experiment was to measure the experimental value of the mean lifetime of the muon. Hence that purpose is achieved and my experimental value is close enough to the theoretical value [2]. I have found strong evidence in support of the theory of special relativity and must appreciate its power to provide solutions and explanations where Classical Mechanics cannot. The muon serves as an excellent specimen for nuclear decay experiments. This experiment provides an opportunity to get acquainted with the realistic introduction to important concepts in experimental modern physics such as non-Gaussian distributions, nonlinear fitting, and useful equipment including scintillator detectors and photomultiplier tubes. This is a well-designed experiment, capable of very accurate and precise measurements of the muon lifetime.

6 Acknowledgments

First and foremost I offer my sincerest gratitude to my professor Dr. Sabieh Anwar, who has supported me throughout this experiment with his patience and knowledge whilst allowing me the room to work in my own way. He has taught me, both consciously and unconsciously, how good experimental physics is done. The joy and enthusiasm he has was contagious and motivational for me. I am also thankful for the excellent example he has provided as a successful physicist and professor.

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