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A cosmic Ray Muon Experiment: a Way to Teach Standard Model of Particles at Community Colleges

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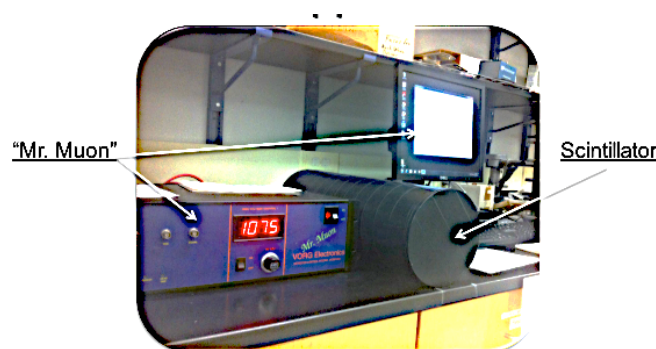
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Abstract. This experiment is an example of research for early undergraduate students and of its benefits and challenges as an accessible strategy for community colleges, in the spirit of the report on improving undergraduate STEM education from the US President's Council of Advisors on Science and Technology. The goals of this project include measuring average low-energy muon flux, day/night flux difference, time dilation, energy spectra of electrons and muons in arbitrary units, muon decay curve, average lifetime of muons. From the lifetime data we calculate the weak coupling constant g_w , electric charge e and the Higgs energy density.

1. Experiment

In our first experiment, we measured the muon average lifetime.

1.1. Our system.

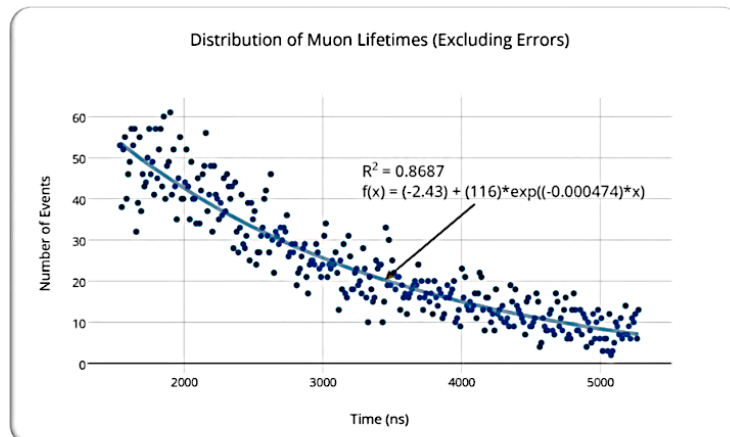


Single cylindrical plastic scintillation detector coupled to a 5" diameter PMT; its power supply voltage (set at 1060 V)/control box; an ADC card PCI-DAS4020/1 sitting in the computer, and the associated data analysis software. The muon trigger is sent out only if muon has decayed in the detector. Dead time set to 230 ns (not to have two triggers within that time). Ramp reset time is set at 35 μ s: if a second (coincidence) event happens within this time, it is considered a muon decay event. Our detector only stops and identifies - by their emitted electron - muons of kinetic energy <160 MeV



(calculated from the stopping power of 2 MeV/(g/cm²) typical for relativistic muons at minimum ionization). Due to low rate of cosmic muons and small volume of the detector to collect enough data we ran the data acquisition each time for a period of one week, collecting simultaneously muon decay times, low-energy stoppable muon fluxes, and the fluxes of high-energy non-differentiated cosmic particles (muons making up more than half of this overall flux, according to the existing literature data). Energy spectra in arbitrary units of stoppable muons and of decay electrons were also collected.

2. Results



2.1. Mean lifetime.

We fitted the data to the exponential decay formula

$$N = N_0 e^{-\lambda t} \tag{1}$$

where λ is the decay rate. This yielded 0.542 ns⁻¹ for λ . So $\tau=1/\lambda$ gives the average lifetime τ of a muon to be 1.85 μ s. We also analysed our smoothed-out data fitting them to a linear graph of: $\ln N = \ln N_0 - \lambda t$. The value for λ appeared to be 0.474, yielding a τ of 2.11 (+/-) 0.07 μ s, with an error of 4% from the accepted value in vacuum of 2.20 μ s [1]. An independent run of the experiment gave

$$\tau=2.165 (+ \text{ or } -) 0.403\mu\text{s}. \tag{2}$$

2.2. Charge Ratio.

With observed muon lifetime, positive muon lifetime τ^+ as the accepted value of free muon lifetime, and negative muon lifetime τ^- as known lifetime in carbon, detector material, we estimated the ratio

$$Q = N^+ / N^- \tag{3}$$

of fluxes of positive and negative muons, where τ_{obs} is our result (including muons of both signs). We obtained the charge ratio of muons in our detector's energy detection range, $Q = N^+ / N^- = 0.764$ [2]. Negative muons both decay and are absorbed by atomic nuclei during muon capture. Positive muons only decay, so they have longer lifetime [3]. Free negative and positive muons have the same lifetime.

3. Calculated Results

3.1. Energy and Time of Flight.

Using measurements of the muon flux at two different altitudes from similar experiments in literature, was the calculated the factor by which lifetime has been dilated - the Lorenz γ factor.

$$\tag{4}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

From that, the average kinetic energy was

$$K_{av} = (\gamma - 1)m_{\mu}c^2 \quad (5)$$

The results for $v = 2.206 \times 10^8$ m/s, $\gamma = 1.48$ and $K_{av} = 50.3$ MeV fit with expectations, as our detector can only record muon events of energies < 160 MeV. With this speed, the average time of flight is $5.789 \mu\text{s}$, meaning that a fraction of $e^{-5.789/2.165} = 0.069$, about 7% of the muons survive the descent [4].

3.2. Flux.

Our result for the flux of low-energy (< 160 MeV) muons is $\sigma = 0.78$ muons/s*m² [5]. We found no systematic difference between day and night muon fluxes. Our result of $\Phi_D/\Phi_N = 1.04 \pm 0.04$ indicates that the sun is not a significant source of cosmic rays.

4. Standard Model (SM) -Derived Relations

From the lifetime formula and our result for τ , we can, assuming other quantities have known values, calculate general SM parameters, such as the ratio of $g_w/M_w c^2$. Our calculations show interdependence of fundamental constants within the SM. The most surprising is an ability to calculate electric charge value from an apparently unrelated weak decay process. Our results agree with accepted values [6].

4.1. Weak Coupling Constant.

After solving the SM lifetime formula [7] for the ratio $g_w^2/M_w c^2$ and using experimental W-boson mass of $M_w c^2 = 80.4$ GeV and our value for τ , we get as the dimensionless weak coupling constant $g_w = 0.680$. This has a 4% difference from the accepted value of 0.653 [8].

4.2. Elementary Electric Charge.

In the SM, the electroweak force contains both electromagnetic force, mediated by the photon exchange, and weak force mediated by the heavy bosons W^+ , W^- and Z^0 . Using predictions of the SM, we calculate elementary electric charge from our experiment. According to the SM,

$$e = g_w \sin\theta \sqrt{\hbar c \epsilon_0} = 1.72 \times 10^{-19} \text{C} \quad (6)$$

if we use our experimental value of g_w and take the accepted value of the weak angle mixing photon with the Z^0 boson as 29° [1]. As a result, we have an error of 7.5% with the textbook value of the elementary electric charge $e = 1.6 \times 10^{-19} \text{C}$ [1].

4.3. The vacuum expectation value, vev, of the Higgs field

It determines the masses of all particles of SM; as calculated from our muon experiment by the SM vev formula [7], it is

$$(\hbar c)^{1/2} (\text{vev}) = (2M_w c^2 / g_w) = 236 \text{ GeV}. \quad (7)$$

This value differs from the accepted value of 247 GeV by 4%.

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