"Cosmic Ray Muons in the Standard Model of Fundamental Particles"
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This experiment is an example of creating research experiences for early undergraduate students and exploring its potential benefits and challenges as an accessible strategy for community colleges, in the spirit of the report on improving undergraduate STEM education from the President's Council of Advisors on Science and Technology (PCAST, 2012).

Some of the goals included: measuring average flux, day/night flux, time dilation, relative energy spectra, decay curve, average lifetime of positive/negative muons in material, weak constant g_W, Fermi constant G_F, electric charge, muon mass, and the average Higgs energy density.

Using measurements of the muon flux at two different altitudes, taken from literature, we were able to calculate the factor by which lifetime has been dilated - the Lorenz γ factor $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$, and from that, the average kinetic energy, as $K_{av} = (\gamma - 1) m_\mu c^2$. Our results for $v = 2.206 \times 10^8$ m/s, $\gamma = 1.48$ and $K_{av} = 50.3$ MeV fit well 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 μs, meaning that a fraction of $e^{-5.789/2.165} = 0.069$, about 7% of the muons survive the descent. We recorded muon events over the course of one week, and have calculated the detector's exposed surface area as $A = (\pi * r * L) + (2\pi) * (r^2)$. The detector has also recorded the number of unclassified cosmic ray events. Our result for the flux of low-energy (< 160 MeV) muons is $\sigma = 0.78$ muons/s*m^2. We have not yet found a systematic difference between day and night muon fluxes. Our result of $\Phi_D/\Phi_N = 1.04 \pm 0.04$ indicates that there is virtually no statistical difference between day and night flux, and therefore that the sun is not a significant source of cosmic rays.

Our first experiment involved measuring the average lifetime of the muon. To accomplish this, we accumulated data over the period of a week using the scintillation muon detector. Then the data was imported and graphed, fitted to $N = N_0 e^{-\lambda t}$.

Here, N is the number of counts at the delay time t, N_0 is the initial number of counts, and λ is the decay rate. We were able to fit an exponential trend line to our curve. The equation for this curve gave us the value of 0.542ns for λ.

So $\tau = 1/\lambda$ gives us the average lifetime τ of a muon to be 1.85μs, based on data from the exponential graph. We also analyzed our smoothed out data giving us a linear equation: $\ln N = \ln N_0 - \lambda t$

The value for λ here appeared to be 0.474 which yields a τ of 2.11 (+/-) 0.07μs, which has an error of 4% from the accepted value in vacuum of 2.20μs. Our results have an uncertainty related to unreliable detector readings for very short decay times and an initial exclusion time built into our detector's program. An independent run of the experiment gave τ=2.165 (+ or -) 0.403μs.

Using the observed muon lifetime in the detector and taking positive muon lifetime τ^+ material to be equal to the accepted value of the free muon lifetime, and negative muon lifetime τ in the detector to be equal to the known lifetime in carbon, which is the material of our detector, we can theoretically estimate the ratio $\rho = N^+/N^-$ of fluxes of positive and negative muons in our detector, where τ_{obs} is our result (including muons of both signs).

We obtained for the charge ratio of atmospheric muons arriving at our laboratory within our detector's energy detection range as $\rho = N^+/N^- = 0.764$. Negative muons, in addition to decay, are absorbed by atomic nuclei in the reaction of muon capture. This absorption is impossible for positive muons, because they can only decay, and so have a longer lifetime. Free negative and positive muons should have exactly the same lifetime.

After solving the Standard Model's (SM) lifetime formula for the ratio $g_W^2/M_W c^2$ and using experimental W-boson mass of $M_W c^2 = 80.4$ GeV, we get as the dimensionless weak coupling constant $g_W = 0.680$. This has a 4% difference from the accepted value of 0.653.

The vacuum expectation value, vev, of the Higgs field, which determines the masses of all particles of SM, as calculated from our muon experiment by the SM formula, is $vev=2M_wc^2 /g_w = 236$ GeV. This value differs from the accepted value of 247 GeV by only 4%. In the SM, the electroweak force describes both the electromagnetic force, mediated by the photon exchange, and the weak force mediated by the heavy bosons W^+ , W^- and Z^0 . These mediators are related to the strengths of the electric and weak charge. Using the predictions of the SM, we can calculate the value of the elementary electric charge from our muon experiment.

According to the SM, $e=g\ \sin\theta\sqrt{\hbar c\varepsilon_0} = 1.72x10^{-19}$ C from our experiment, 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°. As a result, we have an error of 7.5% with the textbook value of the elementary electric charge $e=1.6x10^{-19}$C.

From the lifetime formula and our result for τ, we can, assuming other quantities have their known values, calculate some other general SM parameters, such as muon mass, the Fermi coupling constant, the ratio of g_w/M_wc^2. Our calculations demonstrate the interdependence of several fundamental constants within the Standard Model, as well as the importance of accurate μ lifetime measurements. The most surprising seems to be an ability to calculate electric charge value from a seemingly completely unrelated weak decay process. Our results agree well with the accepted values.

Summarizing, in our experiments we found the cosmic-ray muon flux, the muon’s mean lifetime and the relative energy spectrum of decay electrons. By using the relationships predicted by the well-tested formulas of the Standard Model of Particles from the muon decay lifetime (a weak process), we calculated the magnitude of the elementary electric charge and the average background energy of the Higgs field.

Cosmic-ray muons can be used to detect shielded (hidden) nuclear materials, produce images of the interiors of ancient structures, such as pyramids, and study the internal structure of volcanoes.

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