SOCIETY OF PHYSICS STUDENTS
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SPS Chapter Research Award Proposal

Project Proposal Title	Atmospheric Muons as a Probe for the Higgs Vacuum Energy and of the Lead Stopping Power
Name of School	Northern Virginia Community College
SPS Chapter Number	4963
Total Amount Requested	$1,024.00

Abstract

Using a single scintillation detector, we will measure muon's lifetime, atmospheric flux, energy spectra and perform calculations within the Standard Model of Particles (SM) of the Higgs field vacuum expectation value and of electric and weak charges. We will then shield the detector and find the muon stopping power in lead.

Proposal Statement

Overview of Proposed Project

Research question – Muon is one of the twelve fundamental particles of matter, having the longest free-particle lifetime. We will answer the question of muon's lifetime at rest by detecting time delay between arrival of the muon and appearance of the decay electron in our single scintillation detector. From this we will find the ratio g_w/M_W of the weak coupling constant g_w (a weak analog of the electric charge) to the mass of the W-boson M_W. Vacuum expectation value v of the Higg's field will be calculated from our muon experiment in terms of muon mass m_μ and muon lifetime τ.

Using known experimental value for $M_W c^2$ = 80.4 GeV we will find the weak coupling constant g_w. Using the SM relation $e=g_w \sin\theta\sqrt{\hbar c\varepsilon_0}$ with the experimental value of the Z_0-photon weak mixing angle $\theta=29^o$ we will find the value of the elementary electric charge e. In this experiment we will also determine the sea-level fluxes of low-energy (<160 MeV) and high-energy (several GeV) cosmic muons, and we will answer the question about the energy-dependent muon stopping power in lead by shielding the detector with lead plates and bricks and using the attenuated values of flux.

Motivation – This research project will explore the interdependence of several fundamental constants of nature within the Standard Model, as well as the importance of accurate μ^- lifetime measurements, from which other information can be derived. The most surprising seems to be an ability to calculate elementary electric charge value from a seemingly completely unrelated, non-electric weak decay process. Equally surprising seems to be a chance to calculate the average energy of all-penetrating Higgs field, responsible for the masses of all elementary particles and itself being the manifestation of the recently discovered Higgs boson. This project will also investigate ionization losses of energy by high-energy particles in lead at different muon energies in different lead shields and could compare our measurements of the stopping power in lead with the existing world data.

Our experiment on muon stopping power at low energies is very distinct from most other muon experiments, which rely on two scintillation counters working in coincidence, to identify muons. We with our single detector identify muons by their unique decay signature.

Brief description – Muons are present in the secondary cosmic ray showers in the atmosphere, reaching the sea level. Muon decays into three other leptons through an exchange of the weak vector bosons W+/W-. From our measured muon lifetime we will find the ratio g_w/M_W of the weak coupling constant g_w to the mass of the W-boson M_W. Vacuum expectation value v of the Higg's field will be then calculated from our muon experiment as $v=2M_Wc^2/g_w =(\tau m_\mu c^2/6\pi^3\hbar)^{1/4}m_\mu c^2$ in terms of muon mass m_μ and muon lifetime τ. The weak coupling constant g_w and the value of the elementary electric charge e will be found, using known particle masses, as will the separate sea-level fluxes of low-energy (<160 MeV) and high-energy cosmic muons. Beyond these measurements and calculations, this project entails shielding the detector with increasing thicknesses of lead plates to find the energy-dependent muon stopping power in lead.

Research goals of the project—The purpose of this experiment is to investigate muons. Specifically, we will be investigating muons on several fronts. This includes: muon lifetime (in material and in vacuum), average flux density in air and after passing different layers of lead shielding of muons with kinetic energies below 160 MeV and of muons with any energy, Standard Model applications: finding the universal weak charge and the elementary electric charge, calculating the vacuum expectation value of the Higgs Field, plotting energy spectra of muons and of decay electrons, and finding the muon stopping power in lead and its energy dependence in low-energy area <160 MeV and in high-energy interval of several GeV.

SPS connection – Since its creation 26 years ago, our SPS Chapter bases its activities on research. This experiment and its support by SPS are important because it will show that the first- and second-year students at community colleges can be doing valuable experiments at the most fundamental level. Using high-energy cosmic ray particles available freely at the college physics lab, they can experiment with two (actually, four, if we include the two undetectable neutrinos) of the 12 elementary particles of nature. The research process and results will be distributed and shared at physics conferences, in potential publications, and with VA legislators.

Background for Proposed Project

Lifetime from muon decay analysis—Muons decay through the intermediate emission of W bosons according to:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

mass $= 207m_e = 105.7\ \mathrm{MeV}/c^2$ of μ

Our decay data will be fitted with an exponential curve, $N = N_0e^{-\lambda t}$, where λ is the decay rate, and the average muon lifetime is then taken to be $\tau=1/\lambda$. Standard Model (SM) implications of our lifetime value [1]: using the formula

$$\tau = \frac{1}{\Gamma} = \left(\frac{M_W}{m_\mu g_w}\right)^4 \frac{12\hbar(8\pi)^3}{m_\mu c^2}$$

with M_W mass of the W-boson, m_μ - mass of the muon, and g_w – the strength of the weak nuclear force responsible for the muon decay, and h-bar and c are Planck's constant and the speed of light, respectively, we can find the ratio $g_w^2/M_W c^2$ and using experimental W-boson mass of $M_W c^2 = 80.4$ GeV, we will obtain the dimensionless weak coupling constant g_w [2]. It should immediately provide us with the vacuum expectation value, v, of the Higgs field, which determines the masses of all particles of SM:

$$v=2M_W c^2/g_w$$

In the Standard Model 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. Using the predictions of the SM, we can calculate the value of the elementary electric charge from our muon experiment. According to the SM, $e=g_w \sin\theta\sqrt{\hbar c\varepsilon_0}$, so using the accepted value of the weak angle ϑ mixing photon with the Z^0 boson as 29°, we should be able to find the electric charge from this experiment.

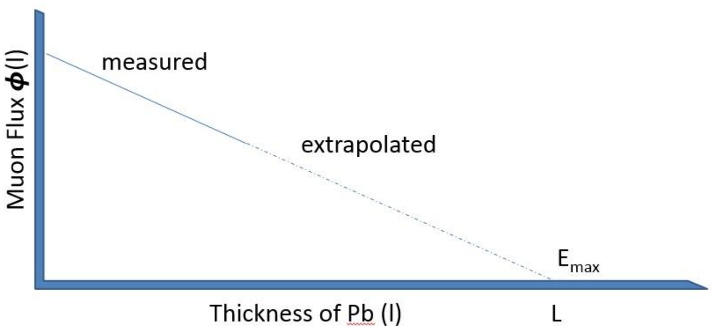
Flux—Muon flux will be found from flux = N/tA, with N our particle count and t and A are time of data acquisition and the absorbing area of the detector. We do not differentiate between negative muons and positive antymuons; both are counted [3]. This is a direction-averaged value, since muons that arrive laterally travel through a thicker layer of atmosphere and many are absorbed in air before reaching the detector [4]. We will collect information on two components of the total muon flux: the low-energy <160 MeV stopping muon component, and the high-energy >160 MeV passing-through component. The measurement will be done without and with different number of the lead plates, and both fluxes will be plotted versus the lead thickness. Muons make up more than half of our expected high-energy flux, the rest being electrons, positrons and gamma-photons. There are about 100 muons of any energy per square meter per second at sea level, which we hope to observe in our high-energy recordings. In our low-energy flux we expect to have about 100 times less intensity [5].

Energy Spectra—Each time a cosmic ray particle hits the detector, it releases energy. The detector then reports the energy of the particle, as well as the energy of the emitted electron (in arbitrary units), tallying these events afterwards. We will graph the cosmic ray energy of unspecified particles passing through our detector, as well as the energy of stopped muons and of decay electrons, accounting for the errors in our readings [6,7,8].

Stopping power—From our flux data we will derive the muon stopping power of lead, defined as $-dE/dx = -(dE/dl)/\rho$, E is kinetic energy, $x = l\,\rho$ is the parameter convenient for tabulation, but l is the actual length traversed in Pb. So we will be looking for dE/dl = energy lost by muon on one cm depth in lead. This may be compared with known values. The accepted absolute value at minimal ionization for muons in lead is $dE/dx = 1.22$ MeV cm^2/g; with the lead density of $\rho = 11.350$ g/cm^3 we will expect to have $dE/dl = \rho dE/dx =$ 11.350 x 1.122 MeV/cm = 12.73 MeV/cm. The stopping power of our detector, made mostly from carbon, can be similarly found as 1.543 g/cm3 x 1.787 MeV cm2/g = 2.757 MeV/cm, with data taken from carbon dioxide. Multiplying this number by the height of our cylindrical detector, we received the 160 MeV as the energy of most energetic muons stopped by our detector and so amenable to their identification as muons decaying at rest with an emission of the detectable electron. With our maximal lead shielding of 5 cm we expect a 40% drop in the muon flux at low energy.

Expected Results

Muon Stopping Power in Lead: From our graph of muon flux $\phi(l)$ below, we can find $L= \phi_0/(d\phi/dl)$ as the range until stopped of our most energetic muons at E_{max}. Then we will receive mean dE/dl = Emax/L = Emax $(d\phi/dl)/\phi_0$. Our experimental muon lifetime τ will be compared with the accepted value of 2.197 µs; our calculated (from our τ) gw = $8(3\pi 3\hat{h}/2\tau m_\mu c2)1/4(M_W/m_\mu)$ with accepted $g_w = 0.653$, and our calculated $e = g_w \sin\vartheta\sqrt{\hbar c \varepsilon_0}$ with the textbook value of 1.6x10-19 C, and our calculated v = $2MWc2/g_W\sqrt{\hbar c} = (2\tau m\mu c2/3\pi 3\hbar)1/4\ (m\mu c2/4\sqrt{\hbar c})$ with accepted v=236 GeV/$\sqrt{\hat{h}c}$. A tolerable agreement to within several percent will confirm the accessibility of high-energy physics experiments to early undergraduate students.



Description of Proposed Research - Methods, Design, and Procedures

Equipment and Supplies

For this research project, we already have our muon detector and its associated software. Our equipment is comprised of a single cylindrical plastic scintillation detector coupled to a 5" diameter photomultiplier tube, 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.

Procedure and Design—The muon trigger is sent out only if muon has decayed in the detector. Dead time will be set to 230 ns (not to have two triggers within that time). Ramp reset time will be set at 35 µs. If a second (coincidence) event happens within this time, it will be considered a muon decay event.

Due to the low rate of cosmic muons and small volume of the detector to collect enough data we will run 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. Energy spectra in arbitrary units of stoppable muons and of decay electrons will also be collected.

After performing the first part (no lead shielding) of the experiments, we will begin the new series of experiments using four lead plates 12"x12"x1/2" and six 25-lb lead bars 2"x4"x8" from McMaster-Carr (http://www.mcmaster.com/#). We will build a supporting structure for lead plates and bars to be positioned above our detector. We will be running the data acquisition for a period of one week for each lead plate configuration around the detector, collecting simultaneously muon decay times, low-energy stoppable muon fluxes, and the fluxes of higher-energy cosmic particles, for which we could only assume, that they are mostly muons. The main result here: the muon stopping power of lead.

Plan for Carrying Out Proposed Project

Personnel and Expertise

Members of Dr. Majewski's Research Group: Society of Physics Students, NVCC, Annandale

- **Barazandeh, Cioli** – SPS Chapter President, Project Lead. Ms. Barazandeh, an APS and SPS member, is a young scientist who has completed many physics-related courses, including advanced courses related to particles, radiation and aero/astro studies. She has also attended educational workshops outside of school, such as those offered by Brookhaven National Laboratory, and exerts effort for outreach and recruitment for SPS.
- **Other members of the SPS Research Group:** Mervin Phanfon-Yengo, Maryam Mohagheghi, Sepehr Samiei, Vincent Cordrey, Phu Bui, Angel Gutarra-leon. Vincent Cordrey and Angel Gutarra-leon have participated in two years of undergraduate physics research with our group.

Research space—This research will be performed in a lab on the NVCC, Annandale Campus. Equipment and tools needed will be made available.

Institutional Commitment—Northern Virginia Community College allows the SPS group to research in laboratory space on the Annandale campus. This includes the use of supplies and general equipment, as well as access to facilities such as the machine shop, printing services, libraries and a writing center.

Equipment—The equipment is comprised of a single cylindrical plastic scintillation detector coupled to a 5" diameter photomultiplier tube, 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.

Faculty Advisors—The primary faculty advisor is Dr. Walerian Majewski, a highly experienced high-energy physicist, instructor and mentor, who has worked with SPS students at NVCC for 26 years. Other faculty will be available as needed.

Institutional Collaborations The scintillation detector was donated by the Thomas Jefferson National Accelerator Facility in Newport News, VA.

Project Timeline

The research project timeline begins with our muon detection system as well as the pricing for lead plates and bricks that has been completed. By May 1 the data collection will be completed. The calculations and analysis of the data will be available for work on posters and possible papers. The following months will be presentations at the Virginia Academy of Sciences (May 2017), including the VAS Undergraduate Research Showcase on the VA Capitol in Richmond, VA; at the SESAPS meeting in the fall; at the Conference for Undergraduate Women in Physics CUWiP; at the Conference for Undergraduate Underrepresented Minorities in Physics; at SPS Area 4 regional meeting; at the Fall 2017 meeting of the CS-AAPT. The Interim Report will be completed by May 31 and the Final Report by December 31. Additional outreach and presentation events for the College community are planned during this whole project.

Budget Justification

Personnel, Consultants, Equipment —No funding is requested.

Supplies/Equipment accessories—Funding is requested for the purchase of four lead plates 12"x12"x1/2" ($157 each) and six 25-lb lead bars 2"x4"x8" ($66 each) from McMaster-Carr (http://www.mcmaster.com/#). The total amount requested is $1024. These materials are absolutely necessary for our major research goal – to find lead stopping power for muons.

Bibliography

[1] NIST Physical Measurement Laboratory. n.d. http://www.physics.nist.gov (accessed 2015)

[2] Reitner R A, Romanowski T A, Sutton R B and Chidley B G 1960 Precise measurements of the mean lives of μ + and μ - mesons in carbon. *Physical Review Letters* **5.1** 22-3

[3] Ye J and Coan T E n.d. *Muon Physics* (Report of Rutgers University)

[4] Pierce M and Tekniska K April 2003 *Measuring the Lifetime of Cosmic Ray Muons* (Report, Section of Experimental Particle Physics)

[5] L3 Collaboration et al 2004 Measurement of the atmospheric muon spectrum from 20 to 3000 GeV *Physics Letters B* **598** 1-2; 15-32

[6] Schwartz M D 2014 *Quantum Field Theory and the Standard Model.* (Cambridge: Cambridge University Press)

[7] Griffith D 2008 *Introduction to Elementary Particles.* (Verlag: Wiley-VCH)

[8] Quigg C 2013 *Gauge Theories of the Strong, Weak and Electromagnetic Interactions.* (Princeton: Princeton University Press)