The Measurement of the Total Number of Up and Anti-Down Bar Quarks in a Sulfur Nucleus

Performing the measurement of quarks at the muon mass scale by comparing the lifetimes of muons undergoing leptonic decay and nuclear absorption

Zeno Chen, Arnav Thakrar, Kanishk Tihaiya, Anthony Song,
Faizdeenkhan Pathan
Quantum-Platers
Connecticut, USA

I. Introduction

According to the simple quark model, the total number of quarks in a nucleus is three times the total number of protons and neutrons. However, this simple model does not take into account virtual quarks and antiquarks, whose count depends on the scale at which the particles are resolved. We propose to determine the total number of up quarks and anti-down quarks inside an atomic nucleus at the muon mass scale by comparing the lifetime of negative muons bound to an atomic nucleus to that of free muons.

II. Why We Want to Go

One thing that every member of our group shares is the fact that we often lay awake in bed at 3 AM in the morning pondering the mysteries of the universe. Why is there more matter than antimatter? Why does gravity not fit in either classical or quantum mechanics? It is these questions that fuels our love of science and what often motivates us to get out of bed. For us, learning, researching, and thinking about science is a passion. Being able to come to CERN would be an amazing experience, as we would be able to tackle these very questions with the world's leading physicists, as well as gain first-hand knowledge on how these professionals go about conducting their experiments.

III. Experiment

Background:

Our proposal is centered around the topic of muon lifetimes and the interactions between muons and matter. In free space the muon lifetime is approximately 2.2 microseconds with its decay being governed by the weak nuclear force. However, when bound to an atomic nucleus it is shortened due to nuclear absorption. This effect is very small for light elements, but it makes a significant correction to the negative muon lifetime for atomic number $Z > 10$, and becomes the dominant effect for $Z > 13$. A simple model for estimating this effect is given in homework problem 1.9 of Ref. 4, where it is shown that the contribution of nuclear absorption to the total decay rate for muonic atoms scales like Z to the fourth power.

The binding of a negative muon to the nucleus occurs through the process of muon capture, where the electromagnetic force captures the negative muon to an orbit around the nucleus. After losing most of their kinetic energy through ionization energy loss, stopping muons are eventually thermalized in a sufficiently thick target and are quickly trapped in the inner orbit of one of the atoms. After the negative muon and nucleus bind (fig. 2), the muon orbits around the nucleus until it decays either through leptonic decay or absorption on a proton in the nucleus as described by the equation below:

Negative muon absorption in atom: $\mu^- + p^+ \rightarrow \nu_\mu + n$

This process is depicted in the left panel of figure 1.

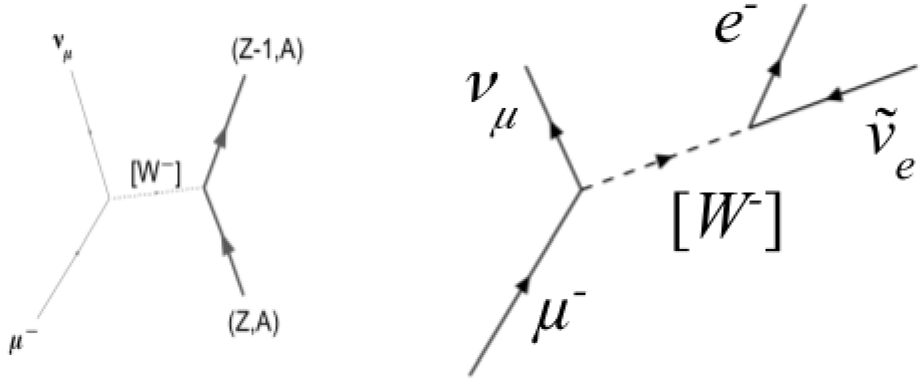

Figure 1: Feynman diagram of negative muon decay through nuclear capture (left) and leptonic decay (right).

The products of nuclear capture include a muonic neutrino and a neutron. The products of leptonic muon decay include a muon neutrino, an antielectron neutrino, and an electron, known as the Michel electron.

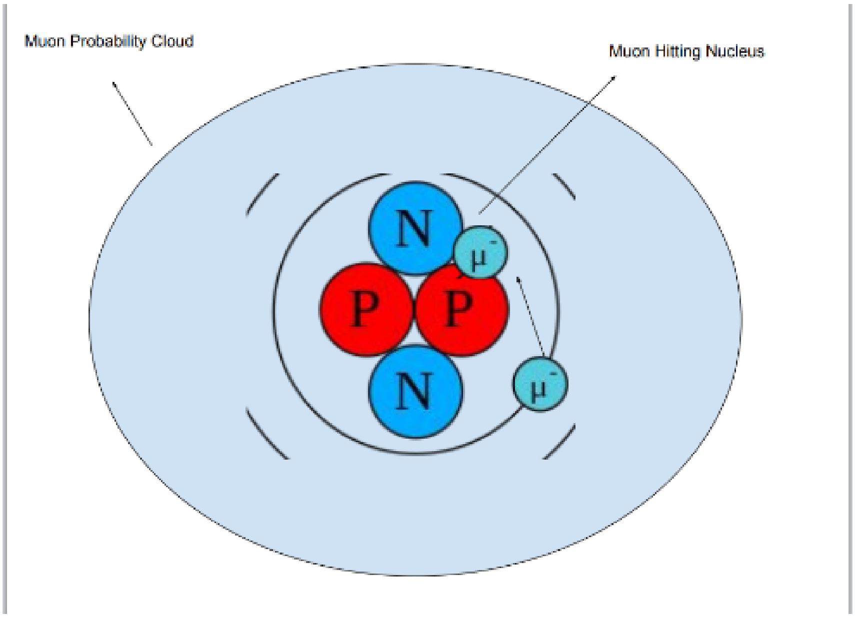

Figure 2 : Muon bound in the inner atomic orbit

(Nucleus for Helium 4 is shown for illustration purposes only)

Theory:

According to the naive quark model, the total number of quarks is a fixed function of the number of neutrons and protons, with two up quarks and one down quark per proton, and two down quarks and one up quark per neutron. In the case of the sulfur nucleus with 16 protons and 16 neutrons, this gives a total of 48 up quarks and 48 down quarks.

However, by performing this measurement at the scale of the muon mass, virtual antiquarks that contribute to muon decay will also be counted in addition to the 48 up quarks. Like the up quark, the anti-down quark is able to absorb a W^-, allowing it to contribute to muon decay as well, which will yield a higher number of quarks in our measurement because we will be measuring the total number of up + dbar quarks. The central idea is that depending on the scale or resolution used for the measurement, there will be a different number of quarks in the nucleus.

This measurement can be achieved by measuring the lifetime of muons bound to a sulfur nucleus compared to muons bound to a lighter nucleus such as oxygen or hydrogen by shooting a muon beam into a jar of water containing various amounts of sulfuric acid. By then taking the ratio of these two lifetime distributions, one can determine the decay constant for nuclear absorption, which carries information regarding the total number of up + anti-down quarks in the sulfur nucleus, as explained below.

Calculations:

For a negative muon bound to a nucleus with atomic number Z, the decay constant is $\lambda = \lambda_d + \lambda_c$, where λ_c is the decay constant for the hadronic process and λ_d is the decay constant for the leptonic process. The leptonic decay constant is related to the mean lifetime τ of a muon in free space through the relation $\lambda_d = \frac{1}{\tau}$.

The proposed experiment begins with the muon decay volume containing just water in which stopped negative muons are bound to an oxygen nucleus. The decay constant for a negative muon bound to an oxygen nucleus is denoted as λ_0, where $\lambda_0 = \lambda_d + \lambda_c(oxygen)$ In the course of the experiment, sulfuric acid is added to the decay volume so that a second lamba appears in the decay distribution, where that lamba is λ_1, and $\lambda_1 = \lambda_d + \lambda_c(sulfur)$. The value of λ_1 can be experimentally determined by forming the ratio of the lifetime distributions in sulfuric acid to pure water and fitting it to an exponentially decaying function plus a constant. Then $\lambda_c(sulfur)$ is simply obtained by subtracting λ_d from λ_1.

Following Perkins[4], one could use the measurement of $\lambda_c(sulfur)$ to estimate the weak coupling constant, α_w. The weak coupling constant is estimated by the strong interaction coupling constant multiplied by the ratio of the strong mean free path over the weak mean free path in nuclear matter. Perkins asserts that the strong coupling constant ~ 1 at the muon mass scale, and the mean free path for strong interactions in nuclear matter at the same scale is 1 fermi. Perkins' model for the weak mean free path is fc/λ_c, where *f* is the fraction of the time a bound muon spends in the interior of the nucleus:

$$f = \frac{4\pi}{3}R^3\frac{1}{\pi}(mc\,Z\frac{\alpha}{\hbar})^3 \approx 0.25A(Z\alpha)^3 \qquad (1)$$

where *R* is the mean charge radius of the nucleus and *m* is the mass of the muon.

However, if we go beyond Perkins' model, it is possible to calculate the muon decay rate from the ground state of muonic sulfur in terms of the Standard model parameters, effectively replacing $\alpha_w f$ with well determined constants:

$$\lambda_c = C_{SM} Z^3 m^3 n_q \tag{2}$$

where n_q is the total number of up + anti down quarks and C_{SM} is a combination of the well-known standard model parameters of the electro-weak interaction.

Experimental Setup:

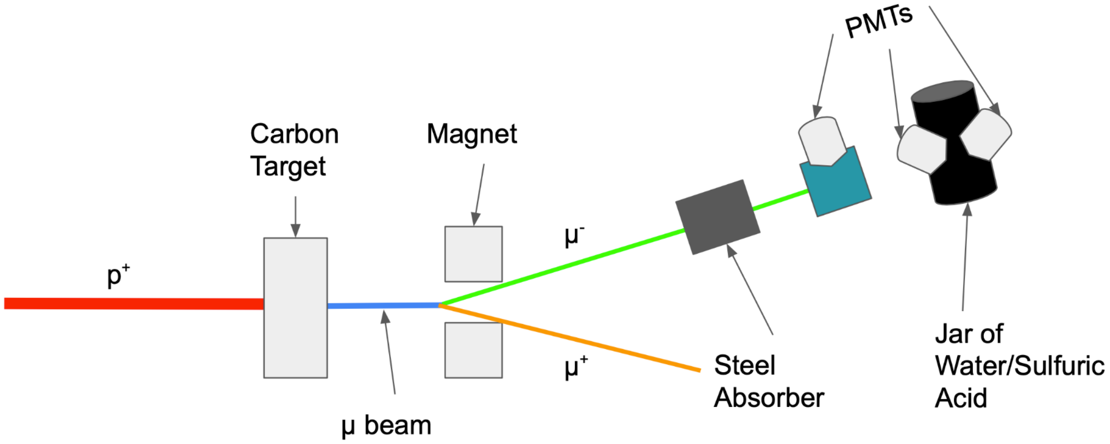

Figure 3: experimental setup

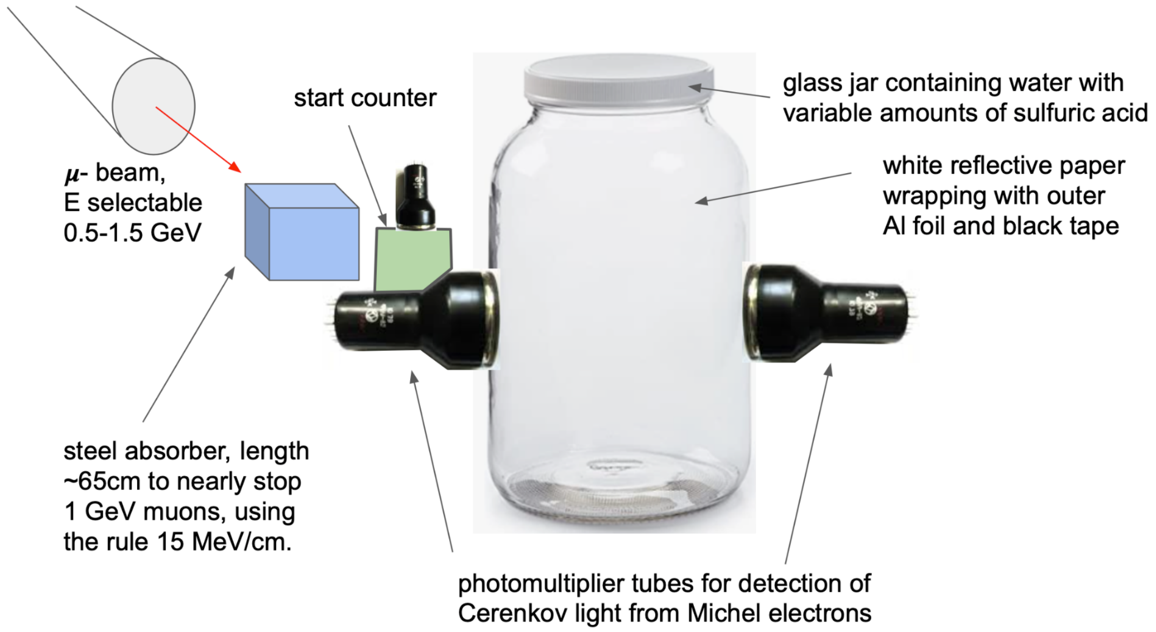

Figure 4: close-up of jar of water/sulfur

Procedure:

1. High energy protons collide into a carbon target and create pions, which quickly decay into into positive and negative muons
2. A magnetic dipole will separate the negative muons from the positive muons
3. A steel absorber will slow down the negative muon beam
4. Muons will hit the scintillator to produce a flash of light
    a. This first flash will be the start time for muons undergoing leptonic decay
5. Muons will enter the jar of water. Some of the muons will be absorbed in the nucleus and decay, while some muons will undergo leptonic decay.
6. The muons that undergo leptonic decay will give off a second flash of light from the Michel electron moving faster than the speed of light in water (Cherenkov radiation)
    a. This second flash will be the end time for muons undergoing leptonic decay

7. Add amounts of sulfuric acid into the water to create a dilute sulfuric acid solution, and repeat steps 6-8 to determine the new lifetimes of muons undergoing leptonic decay with sulfur in the solution.
8. Determine the lifetime of muons bound to the nucleus by looking at the rate of decline of second flashes.

IV. What We Hope to Take Away

Many of our team members plan to go into the STEM field, and so far, the only experience we have had in the scientific field are either school labs or small side projects. By being able to come to CERN, we would be able to learn from top scientists and see first-hand how experiments of international caliber are conducted. Furthermore, since many of our classmates have not yet taken physics, we hope to be able to share this opportunity with them, in hopes of kindling the same passion for science that we believe everyone should possess.

V. Acknowledgments

We are indebted to Dr. Richard Jones (University of Connecticut), for all the time and support he has given our team. He has truly been exceptional in guiding us through the scientific process-facilitating discussions, answering our questions, and most of all, encouraging our passion for physics. We truly could not have created this proposal without him.

Furthermore, we would like to thank Margherita Boselli and Markus Joos for the virtual tour of CERN. We learned many valuable concepts that were crucial to this proposal and we are extremely grateful for the opportunity.

Always Quantumplating,

Zeno, Arnav, Kanishk, Anthony, and Faizdeen

VI. References

Jaeger, G. (2019). Are virtual particles less real? *Entropy*, *21*(2), 141. https://doi.org/10.3390/e21020141

Knecht, A., Skawran, A. & Vogiatzi, S.M. Study of nuclear properties with muonic atoms. *Eur. Phys. J. Plus* 135, 777 (2020). https://doi.org/10.1140/epjp/s13360-020-00777-y

Measday, D. F. (2001). The nuclear physics of Muon Capture. *Physics Reports*, *354*(4-5), 243–409. https://doi.org/10.1016/s0370-1573(01)00012-6

Perkins, D. H. (2000). *Introduction to High Energy Physics*. Cambridge University Press.