Design of an Experiment to Study Weak Interactions in Muon Decay

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(Dated: August 12, 2004)

Two detection methods are explored, using both Monte Carlo simulations and experimental measurement of muon absorption in Cu. We propose an architecture where the trajectory of a cosmic ray muon is measured with drift chambers before it is stopped in a thin (1 mm) Cu slab. Then, the trajectory of the decay electron is also measured with drift chambers before its energy is finally measured with a CsI scintillator. We estimate that such a detection architecture could measure the decay electron energy to within 5 MeV, and the trajectory of decay electrons to within 20 degrees.

I. INTRODUCTION

The goal of this project is to design an experiment that will allow a student to verify that decay of cosmic ray muons obeys the parity-violating weak interaction. This interaction gives the distribution of decay electrons to be [1]

$$\frac{dN}{d\theta} \sim [2x^2(3-2x)][1+(\frac{1-2x}{3-2x})\cos\theta], \tag{1}$$

where $x = \frac{E_e}{m_\mu/2}$, E_e is the energy of the decay electron, m_μ is the muon mass, and θ is the angle between the electron trajectory and the muon spin. Verification of this distribution clearly requires measurement of the decay electron energy and trajectory. Additionally, since the muon spin is polarized along its trajectory, a measurement of the muon trajectory is also needed. If the decay electron energy spectrum can be measured accurately, one may also find the muon mass, as the maximum energy for a decay electron is $m_\mu/2$.

There are many ways one could design a detector to make such a measurement. When evaluating each method, one must consider not only how accurately it can measure each of the desired parameters, but also how much effort it would require to build and operate, as well as the availability of the required equipment and materials.

One such design incorporates many parallel thin copper sheets, with detection wires placed in each gap between sheets, as depicted in Fig. 1a. There must be a minimum of two perpendicular sets of detection wires per gap, to allow measurement of particle position in each of the two dimensions parallel to the sheets, however more sets may be desired to get a more accurate measurement of the particle trajectory.

For this detector to make a measurement, a muon must enter it and stop in one of the copper plates. It then decays, emitting a positron or electron. The measured particle positions are used as input to a fit that incorporates the energy loss and angular deflection distributions for a copper sheet of the thickness used to determine the path and energy of each particle.

Another design, shown in Fig. 1b, utilizes drift chambers to measure particle trajectories, and CsI scintillating crystals to measure decay electron energies. The trajectory of an

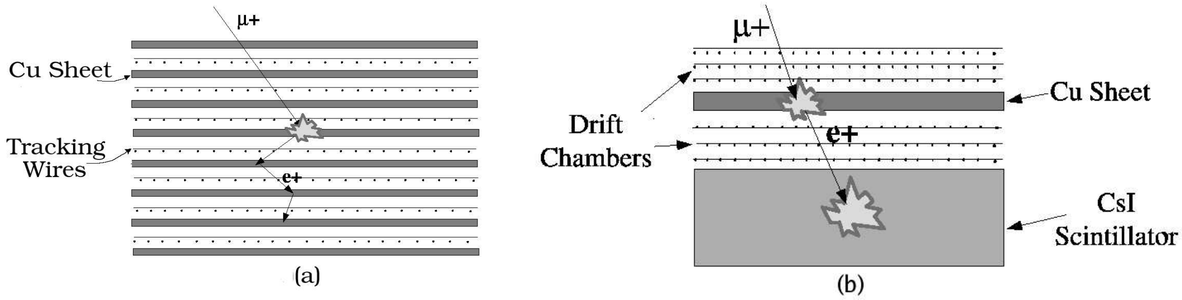


FIG. 1: Two possible designs for an experiment to measure weak interaction properties in muon decay. (a) This design implements many parallel layers of Cu both to stop cosmic ray muons and to act as a calorimeter for the electrons or positrons emitted in muon decay. Particle position is measured by sense wires in each layer, and particle trajectory and energy are determined by a global fit to all measured positions. (b) A second design again uses Cu to stop incident muons, but uses a CsI scintillating crystal to measure the energy of electrons and positrons from muon decay. Particle trajectories are determined by drift chambers, positioned as shown.

incident muon is measured by drift chambers before it is stopped in a Cu plate and decays. The trajectory of the decay electron is in turn also measured by drift chambers, and its energy is measured by a CsI scintillating crystal.

II. MEASUREMENT OF MUONS STOPPED BY A THIN CU SHEET

As both designs investigated implement sheets of Cu to stop cosmic ray muons, we must determine the rate at which muons will stop in a thin Cu sheet in order to estimate the rate at which either detector will accumulate data. We intend to incorporate this into a student laboratory, so the detection apparatus must allow the students to accumulate sufficient data for comparison to Eq. 1 within a few days.

We used 2 plastic scintillators, one placed 4.5 cm above the other, to measure the rate at which muons passed through the volume contained between the two detectors. A muon hit was recorded each time both scintillators measured an even simultaneously (to within limits of the electronics). The rate of muon hits was measured both with and without a thin Cu sheet placed between the two scintillators. We assumed that any drop in the rate of muon hits when the Cu sheet is present must be due to muons stopping within the Cu sheet. This method is advantageous because any background present in the measured rate of muon hits should not be affected by the presence of a Cu sheet, and therefore will not affect our measurement of the rate at which muons stop in the sheet. One possible issue with this method is that the rate at which cosmic ray muons reach the earth's surface can vary over time, but we measured this rate several times during each experimental run, and found it to be constant to within the errors of the experiment.

We found the rate at which muons stop in a 0.7 mm thick Cu sheet to be $9.6 \pm 0.8 \times 10^{-4}$ muons/cm^2·sec, while the rate was $1.44 \pm 0.08 \times 10^{-3}$ muons/cm^2·sec for a 1.4 mm thick Cu sheet. We conclude that the rate at which muons stop in a Cu sheet of arbitrary thickness is $1.1 \pm 0.2 \times 10^{-3}$ muons/cm^2·sec·mm. Since the scintillators are not perfectly efficient, some muons will not be detected, and therefore some muons that stop in the Cu will also not be recorded. Accordingly, we consider this rate to be a lower limit on the actual value.

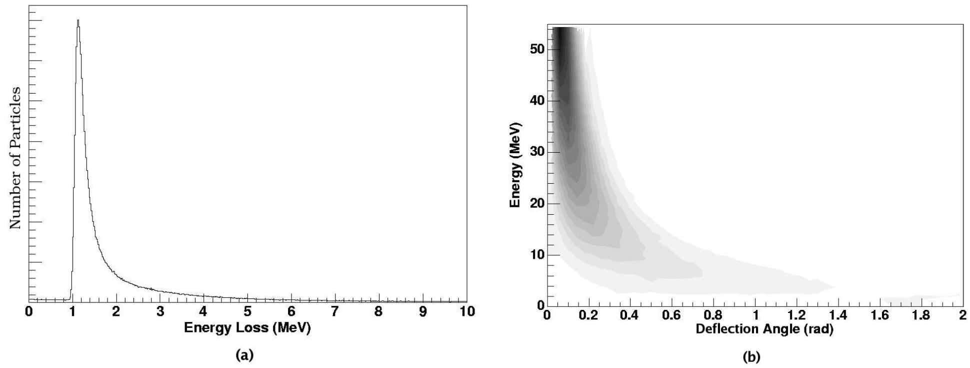


FIG. 2: Results of GEANT4 simulations modeling electrons penetrating a 1 mm thick Cu sheet. (a) Distribution of energy lost by electrons while passing through a Cu sheet. This distribution is too wide to allow correlation of initial particle energy to the number of Cu sheets penetrated. (b) Distribution of change in particle trajectory while passing through a Cu sheet compared to particle energy. This distribution does not change enough with particle energy to allow significant information about particle energy to be derived from changes in particle trajectory.

III. SIMULATION OF DETECTOR GEOMETRIES

To compare the two methods presented we utilized Monte Carlo simulations, with particle interactions simulated using the GEANT4 libraries [2] and with particle distribution generation and data acquisition handled by the ROOT analysis package [3].

For the first detector design to be effective, we must be able to relate the energy of an incident particle to the path it takes through the many layers of Cu present in the detector. We had hoped to be able to simply correlate the number of layers that the particle penetrates to its energy, however, as Fig. 2a shows, this is not the case. The energy that a particle loses as it passes through each layer can vary too greatly, and therefore the total number of layers that a particle of a given energy could penetrate also can vary greatly.

We then considered that particles of higher energy tend not to scatter as much as they pass through each layer, so perhaps we could gain additional information about particle energy by looking at changes in trajectory as the particles pass through each layer. Fig. 2b shows that this approach was not successful either, as the dependence of trajectory changes on energy is too weak to provide significant information. Specifically, we had hoped to gain additional information about higher energy particles, but the trajectory change distribution for a 30 MeV electron is almost indistinguishable from that of a 50 MeV particle, meaning that we would gain nothing in this range.

It is possible that if one used many, very thin Cu sheets this approach could be made to work. However, we examined the case of 20 layers of Cu, each 1 mm thick, and found that, even when we incorporated both scattering and penetration distributions into a global fit of particle trajectories, we still could not make an accurate measurement of initial particle energy. We therefore deemed this method to be impractical, and began to explore other possibilities.

The second detector geometry considered, which uses a CsI scintillator to measure particle energy, proved to be much more effective. When a particle enters a scintillator, it is absorbed and produces a shower of lower energy particles and photons, which in turn are also absorbed

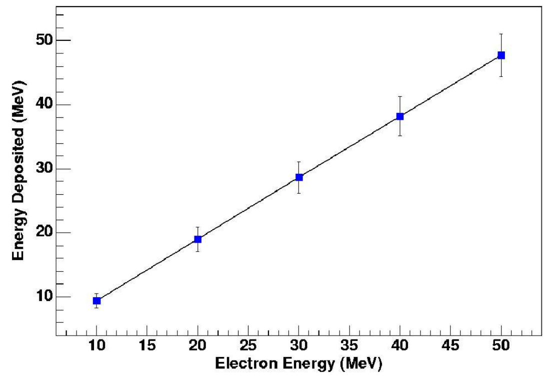


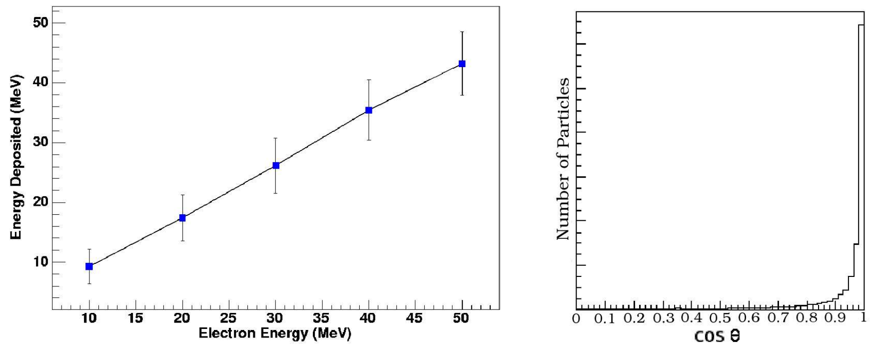
FIG. 3: Results of GEANT4 simulations of energy deposited in a 20×30×30 cm CsI scintillator. Energy deposited is compared to electron energy upon entering the scintillator. This plot illustrates that the scintillator can measure electron energy to within 3 MeV.

producing more particles and photons. The scintillator is very efficient at measuring particle energy provided that all such particles produced remain inside the scintillating material. Therefore, we must find maximum scintillator thickness that any significant number of such particles can penetrate, and construct our detector with at least this thickness. We also must design an algorithm to reject particles incident on the scintillator too close to the edge or at too large of an angle to the normal, as these particles are likely to produce a shower that does not remain within the scintillating material.

We have readily available a large number of CsI crystals that are approximately rectangular solids measuring about $30 \times 5 \times 5$ cm. This led us to consider placing six of them side by side, to make a square 30×30 cm, and then examine thicknesses we could create by stacking up layers of such squares. We used GEANT4 to simulate electrons incident to the scintillator at its center, perpendicular to the surface, and measured the energy deposited. We performed this simulation for thicknesses from 5 to 30 cm, and found 20 cm to be the optimal thickness. The result of this simulation for a thickness of 20 cm is shown in Fig. 3. At this thickness, the electron energy can be measured to within 3 MeV. There is little gain from increasing the thickness to 30 cm, suggesting that most particles from a shower are absorbed within a thickness of 20 cm.

We also must consider that, in an actual detector, muons will be absorbed throughout the Cu plate and will emit positrons and electrons in all directions. If a particle strikes the scintillator too close to its edge, it is likely that some of the particles from the resulting shower will escape out the edge of the scintillator. Additionally, if a particle strikes the surface of the scintillator at too large an angle to the normal, it is likely that some particles from the shower will escape back out the same surface from which the initial particle entered. For this detector to be effective, we must not include such events in our data. Therefore, we examine the particle trajectories measured by the drift chambers and reject any particles that enter the scintillator at angles above 60 degrees, less than 3 cm from any edge, or in such a manner that if the particle were to continue in a straight line its path through the scintillator would be less than 15 cm.

We performed a simulation, again using GEANT4, in which muons at rest were placed evenly throughout a 30×30 cm Cu plate 2 mm thick. The muons were allowed to decay into electrons, which then had to cross a 3 cm gap (representing the space occupied by the drift chambers) before reaching the scintillator, which measured $30 \times 30 \times 20$ cm. The results of



(a) (b)

FIG. 4: Results of GEANT4 simulations for a detector following the design shown in Fig. 1b, with a $30 \times 30 \times 20$ cm CsI scintillator and a Cu plate 2 mm thick, with a spacing of 3 cm between the Cu plate and the scintillator to allow room for the drift chambers. (a) Comparison of energy deposited in a CsI scintillator to initial electron energy. Escaping the Cu plate distorts electron energy slightly, but it can still be measured to within 5 MeV. (b) Distribution of electron trajectory distortion due to escaping from the Cu plate, where θ is the angle between the initial trajectory and the trajectory after escaping the plate. Most particles have $\cos(\theta) > 0.95$, corresponding to their trajectories being distorted by less than 20 degrees.

this simulation are shown in Fig. 4a, and demonstrate that in a real detector we should be able to measure the energy of positrons and electrons from muon decay to within 5 MeV.

We also must determine how accurately we can measure the trajectory of the emitted electrons and positrons. To do this, we performed a simulation where we placed muons at rest evenly throughout the thickness of a Cu plate with the dimensions we plan to use in the detector, and compared the trajectories of the emitted decay electrons upon creation to their trajectories after escaping the Cu plate. The results of this analysis are displayed in Fig. 4b, and show that we should be able to measure electron and positron trajectories to within 20 degrees.

Finally, using our measurement of the rate at which cosmic ray muons stop in a sheet of Cu, we estimate that about 2 muons/sec would be stopped in a Cu sheet of the dimensions we plan to use. In the simulation described above, only about 10% of the total muons stopped in the plate produced decay electrons whose energies could be measured in the scintillator. However, in an actual detector, we would also place a Cu plate below the CsI crystal, which would allow us to examine the trajectories of decay electrons emitted nearly opposite the path of the incident muon, and would also double the total number of measurements we could make. This amounts to a net 0.4 measurements per second, which is sufficient to allow an experiment to be conducted within a few days.

IV. CONCLUSIONS

We find that a detection geometry where a Cu plate stops muons, drift chambers measure particle trajectories and a CsI scintillator measures the energy of electrons and positrons from muon decay will be able to make the measurements that we desire in a reasonable amount of time. We predict that such a detector would be able to the energy of electrons or positrons from muon decay to within 5 MeV, and their trajectories to within 20 degrees.

By comparison, a detection geometry based solely on thin layers of Cu would not be able to measure energies or trajectories accurately, and would be difficult to construct as many layers would be required to make a reasonable measurement.

V. ACKNOWLEDGMENTS

I would like to thank my advisor, Jim Alexander, of Cornell University, for his guidance throughout this project. Additionally, I would very much like to thank Rich Galik, also of Cornell, for organizing the REU program that included this project, and for his continual support throughout the program. This work was supported by the National Science Foundation REU grant PHY-0243687 and research co-opertaive agreement PHY-9809799.

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