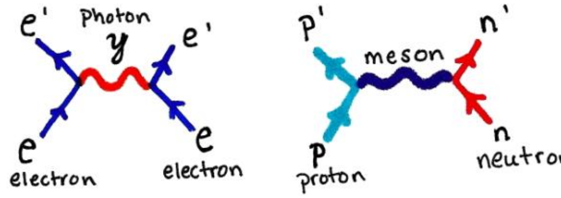
When we were in the fifth grade we learned that everything is made of matter. In our high school chemistry class we learn that all matter is made of atoms, which are made of electrons, neutrons and protons. Most people are content to leave it at that. There is, however, so much more to the structure of our fundamental makeup that we have yet to discover. There are yet smaller particles that make up what had been thought to be the most elementary particles themselves. There are seemingly endless possibilities for how these truly tiny particles interact, bond and form new particles. There is a mystery at the very core of what we are made of, and solving it has been the quest of particle physicists for decades.

In this paper I intend to study the smallest of matter to better understand the force that bonds these particles together. In order to do so, I will take a close look at the work of Dr. Tanja Horn, a research physicist studying the production of mesons in inelastic electron scattering to understand the substructure of the proton.

By the early 20th century it was widely accepted that there are four fundamental forces that describe nature: the electromagnetic force, the gravitational force, the weak nuclear force and the strong nuclear force. The strong nuclear force, or strong force, is the force that holds particles together at the most fundamental level. The force operates at a range of 10^{-15} meters, the same distance as the radius of the nucleus of a hydrogen atom.

In the 1930's there was a boom in scientific research into particle physics and in the years following dozens of new, sub-atomic particles were discovered, including the positron, neutrino and photon. Many scientists were curious how it was that the fundamental forces interacted with and governed these newly discovered particles. In 1935 Japanese scientist Hideki Yukawa began experimentation to find the mediating particle of the strong nuclear force. He believed this particle would work in much the same way a photon does in mediating the electromagnetic force: when two electrons collide, a photon is produced to carry the energy and momentum from one electron to the other, and is thus said to be mediating the electromagnetic force.

ELECTROMAGNET FORCE AND STRONG NUCLEAR FORCE



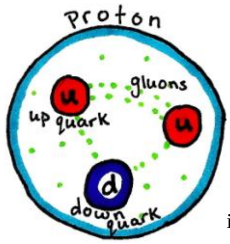
[i]

Through experimentation, Yukawa found that there was indeed a particle mediating the interaction of the strong force between a proton and a neutron: the meson. However, over the next 40 years, as many more advances were made in the field of elementary particle physics, Yukawa's definition of the meson became outdated and the standard model of particle physics we know today emerged.

The standard model acts for particle physics in much the same way the periodic table of elements does in chemistry. It describes all matter as being made up of tiny particles called quarks, leptons and gauge bosons. For our purposes we will focus on quarks, which are bound together to form larger particles via quantum chromo-dynamics (QCD). QCD replaced the theory of mesons as the fundamental mediating particle of the strong force. It is now believed that massless bosons (force mediating particles) called gluons carry the strong force between quarks, or what is called the color force of quarks. The color force is what enables quarks to bond and interact with other quarks. There are six flavors of quarks: up, down, strange, charm, top and bottom. Quarks also have a quality called color charge (red, green or blue) which describe the quark's strong interactions in the same way electric charge describes the electrical interactions of charged particles. Similarly to electrically charged particles quarks are relativistic, meaning that for every flavor and color of quark there is a quark with the opposite flavor or color. These are called anti-quarks. A proton is made up of three quarks, two up and one down. The mesons first described by

Yukawa are now considered to be a type of hadron particle, meaning they are governed by the strong force, and consist of a quark-anti-quark pair.

PROTON AND MESON QUARK STRUCTURE



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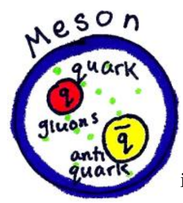
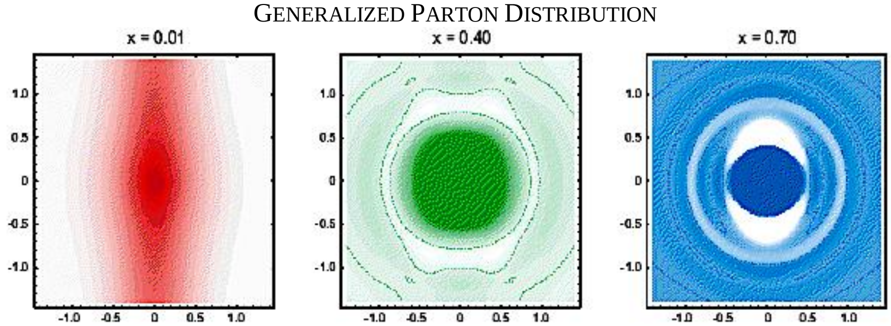


[iii]

In the late 1960's Richard Feynman proposed that the reason an electron beam is deflected when passing through a proton is that there are "point-like objects" within the proton that interact strongly with the electrons.[iv] These objects, called partons, have become the model for quark composition of nucleons (protons and neutrons that form the nucleus of an atom). This model, called Generalized Parton Distributions (GPDs) describes the placements, movements and momenta the quarks inside a nucleon. The GPDs is expressed in terms of x, a fraction of the momentum of the quarks over the momentum of the proton.

GENERALIZED PARTON DISTRIBUTION



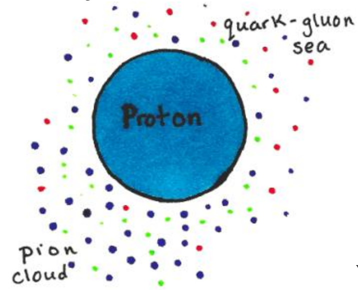
[v]

Understanding the GPDs of nucleons is the key to understanding the strong force and how quarks, and larger particles, bond together. However, it is incredibly difficult to study the GPDS of a nucleon such as the proton. According to the principle of confinement, it is impossible to isolate a free quark from its pair or triplet. QCD does, however, allow for quarks to behave "as quasi-free particles in deep inelastic scattering,"[vi] which may hold the key to solving the GPDs of the proton.

When we want to study far off planets and galaxies we launch a telescope to take pictures and send back data. When we want to study ecosystems we set off into the jungle and observe plants, animals and rocks. When we want to study elementary particles we smash things together–really hard. In order to understand how the particles are formed, how they are held together, and how they interact with one another–essentially how the strong force works–it is necessary to first break the particles down into their absolute simplest form. This can be done most effectively with a particle accelerator. In a particle accelerator, a stationary target particle is bombarded by other particles at high speeds. One common and very useful way of using a particle accelerator to study the makeup of the smallest of matter is called hard electron scattering. In hard electron scattering, electrons are shot at incredibly high speeds at a proton target. When the electrons meet the proton an inelastic collision ensues and very small particles are produced. Simply by using kinematics physicists know where to position powerful detectors and other analysis equipment in the path of these particles to capture various sets of data. By studying the particles that are produced by the collision, physicists can better understand how the quarks within the proton are held together by the strong (color) force.

One physicist who has been studying the strong force, hoping to unlock its many mysteries, is Dr. Tanja Horn. Dr. Horn received her PhD from the University of Maryland with her research into the strong force through an experiment with the pion form factor, known as the F_{pi} Experiment. Working with a group of physicists from around the world at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) in New Port News, VA, Dr. Horn set out to study the substructure of the proton. However, "looking inside a proton is not like looking inside a cell in biology class," she explained, "you cannot just open it up and see what is inside."[vii] Instead, the team looked at what is called the quark-gluon sea. The quark-gluon sea is a field of mesons surrounding a nucleon. These mesons, known as sea quarks, are virtual, meaning that they blink in and out of existence so rapidly that they can never be said to exist in any one place at any once time.

PROTON WITH QUARK-GLUON SEA AND PION CLOUD



[viii]

The team was particularly interested in the pion cloud, a cluster of virtual pions surrounding the proton. The pion is the simplest of the mesons, being comprised of an up quark and an anti-down quark, making it a seemingly perfect candidate for this experiment. Their goal was to determine the form factor of a pion, F_{pi} (whence the project gets its name). The form factor is a way of expressing multiple properties of a particle, including charge distribution, density and the workings of the strong force with in the particle. By studying the pion and finding its form factor the team hoped to compare it to the current model of hard scattering within QCD. If the two sets of data matched, it would be possible to calculate the GPDs of the proton.

In order to understand the structure of the pion, and in turn the proton, it was necessary to see it from three different viewpoints. The first is from a distance, to see the entire structure of a free pion. This snapshot was taken by a team of physicists lead by Luciano Canton of the University of Padova in 2001, and was crucial to understanding pion exchange.[ix] The second picture is that of the center of the pion, the quark pair itself. The third snapshot, the one the F_{pi} team hoped to find, is that of the boarder between the permanent quarks and the quark-gluon sea.

First, however, the team needed a pion, several pions actually. They produced these pions by firing an electron beam at the proton's virtual pion cloud, thus knocking the pions out of orbit around the proton. The pions were channeled into the High Momentum Spectrometer (HMS) in

Hall C of Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF), where they were analyzed in an existing detector.

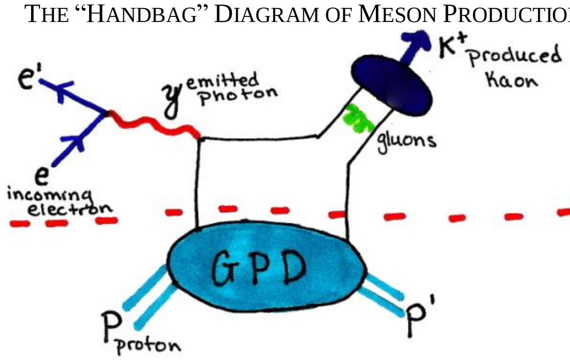
The team's findings, published in The American Physical Society *Physical Review Letters* in 2006, stated that

> results indicate that the pion form factor deviates from the charge-radius constrained monopole form at these values of Q^2 by one sigma, but it is still far from its perturbative Quantum Chromodynamics prediction[x]

in short, saying that the form factor calculated based on the experiment did not fit the QCD model for the given values of Q^2 (a value that can be thought of as a measure of the resolution).

Dr. Horn now turns her attention to the kaon, a close cousin to the pion. She is leading a team of researchers in association with Catholic University of America (CUA) on a new quest to understand the strong force. The kaon is a meson, made up of one up quark and one anti-strange quark. It is slightly heavier than the pion, with a mass of 493.667±0.013 MeV/C^2, almost 1,000 times heavier than an electron. By running an experiment with kaons similar to the F_{pi} project, Dr. Horn hopes to be able to take a much clearer snapshot of the quarks and how they move and interact within the smallest of particles. This data will be obtained by way of hard, or inelastic, scattering meson electroproduction, wherein electrons are scattered off a proton target producing mesons.

THE "HANDBAG" DIAGRAM OF MESON PRODUCTION



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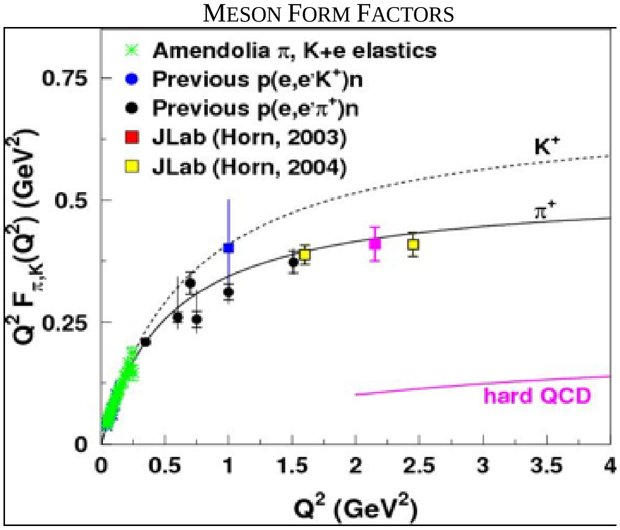
Above is a diagram of the reaction collision that will produce the desired kaon particles. An incoming electron collides with a proton, thus producing a photon and a meson, in this case a kaon. By studying the resulting kaons, it may be possible to understand the quark-structure (GPDS) of the proton that produced them, and in turn the strong (color) force that bonds the quarks within the proton. This experiment will also yield data that can be compiled into a definitive form factor for the kaon. As with the F_{pi} experiment, the hope is that this form factor for the kaon will match the model of the hard QCD. "We know everything that happens above the dotted line," explains Nathaniel Hlavin, a nuclear physics student at CUA working on the project, referring to the diagram of the reaction collision, "what we need to calculate is the bottom half. We will be able to do that if the kaon's form factor we calculate matches the pink line [shown below] of the hard QCD model."[xii] The current model projections do not predict a favorable kaon form factor. However, because there is no direct experimental evidence (the kaon projections have been based on results from pion experimentation) it is vital to calculate the actual kaon form factor to determine if the model itself is correct.

MESON FORM FACTORS

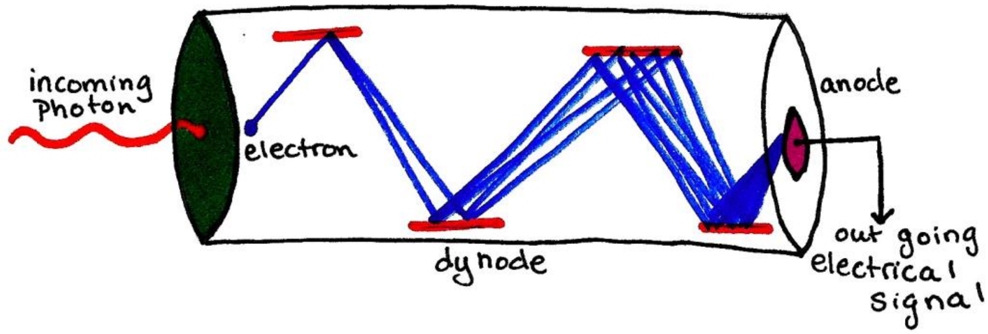


[xiii]

In order to study these kaons and gather this data, there must be a device capable of detecting the kaons resulting from the hard electron scattering. This is what Dr. Horn and her small team of graduate, undergraduate and even high school interns have dedicated the last several months to researching, designing and optimizing. There are several types of devices capable of this type of detecting, but due to budget and geometrical constraints, the team is designing an Aerogel Kaon Cherenkov Detector. This detector will be installed in the new Super High Momentum Spectrometer (SHMS) in Hall C of Jefferson Lab's CEBAF. This accelerator is specifically designed for "investigating the quark structure of the atom's nucleus,"[xiv] and works by scattering a powerful, constant electron beam at a stationary proton target. The particles resulting from these collisions are then channeled by a series of focusing magnets into various halls where they are detected, measured and/or analyzed by highly sensitive equipment. The CEBAF is due to receive a 12 GeV upgrade within the next three years, meaning that the energy with which the electron beam is fired will be increased from 6 gigaelectron volts to 12 gigaelectron volts. This upgrade will allow for more intense reactions and the use of more sensitive equipment such as the Aerogel Kaon Cherenkov Detector.

Silica Aerogel, the type proposed for the detector, is an incredibly light material, and is in fact the least dense porous solid in existence. It also acts as a scintillator, meaning that when charged particles, specifically kaons for this purpose, pass through the Aerogel faster than light passes through that same material a flash of light is emitted. This process, known as Cherenkov radiation, can be thought of as the light equivalent of a sonic boom, produced when an object moves through the air faster than the speed of sound. The Aerogel is placed in a light box and several Photomultiplier Tubes are positioned around the gel. These Photomultiplier Tubes (PMTs) capture the light radiation given off by the Aerogel and convert the photon light signal given off by the Cherenkov radiation into an electric signal. This happens via the photoelectric effect: the photon hits a photocathode, releasing an electron; this electron is accelerated through a series of dynodes which act as amplifiers, creating an "avalanche" [xv] of electrons that is channeled into an electric signal that can be read by the analyzing equipment.

PHOTOMULTIPLIER TUBE



[xvi]

(SEE ALSO FIGURE 1, APPENDIX)

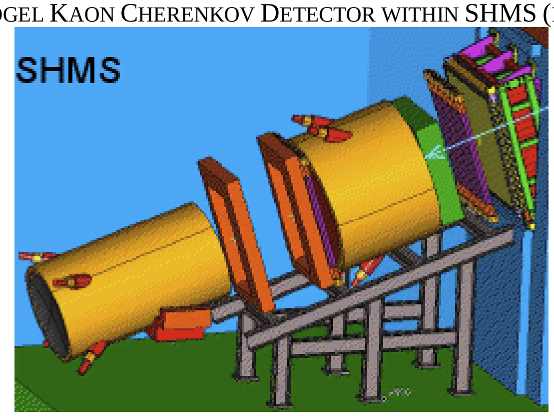
From here, the velocity and momentum on the kaons is calculated by the SHMS. These calculations are then used to determine the kaon's form factor. If the form factor conforms to the hard QCD model, it will then be possible to determine the GPDs of the proton.

The team is still in the preliminary stages of building the detector. In the summer of 2010, a group of additional student interns joined the project to help design the components for the detector. There were several pieces of the detector that needed extensive computer modeling. A Monte Carlo FORTRAN program called SimCherenkov, written by D.W. Higinbotham of Jefferson Lab and modified by the interns, was used to optimize these various factors.

First, the optimum index of refraction needed to be chosen for the Aerogel. The index of refraction is measured by "the speed of light in a vacuum divided by the speed of light in the medium."[xvii] It is very important to ensure that only kaon particles will emit a photon signal when passing through the Aerogel. Therefore, it is necessary to choose an index of refraction such that only kaons will emit a strong signal and protons will emit little or no signal. The risk of overlapping signals from kaons and protons can be avoided by finding a combination of a range of momenta and a refractive index such that the kaons emit a strong, detectable signal while the signal from the protons is minimal. However, because the range of momenta for the kaons passing through the detector is so wide, it must be broken down into sections, each with their own optimum refractive index for the Aerogel. For particles moving with momenta between 2 and 4 GeV, the ideal refractive index was calculated to be 1.030; for particles with momenta between 4 and 6 GeV/c, 1.015 is optimum. However for particles moving in the 6-8 GeV/c range there is no suitable index of refraction, in which case it will be necessary to use a method called kinematic separation to differentiate between kaons and protons. It was decided that a refractive index of 1.015 would be used for all subsequent calculations and design components, although both solutions of 1.015 and 1.030 will be needed to cover the full range of momenta (2-8 GeV/c).

The size and thickness of the Aerogel panel also had to be optimized. The space for the detector in the SHMS is very limited, only about 45cm wide.

PLACEMENT OF AEROGEL KAON CHERENKOV DETECTOR WITHIN SHMS (INDICATED BY GREEN BOX)



xviii

Logically, one can see that the Aerogel ought to be of a size and shape that allows for the maximum number of kaons to be detected without exceeding the space limitations. Because of the magnets that are used to focus the particles towards the detector, the spread of particles resembles an hourglass shape. There are two possible configurations for the Aerogel based on this distribution: an 110x100cm panel or a 90x60 cm panel. The 90x60 cm was chosen because it covers the area with the highest concentration of kaons, while not allowing too many peripheral particles to pass through the detector. A number of thicknesses of Aerogel were also tested, ranging from 5 to 10 cm. It was found that a panel 10cm thick produced the maximum number of photoelectrons, and was therefore the ideal choice for both the size restraints and the desired data output.

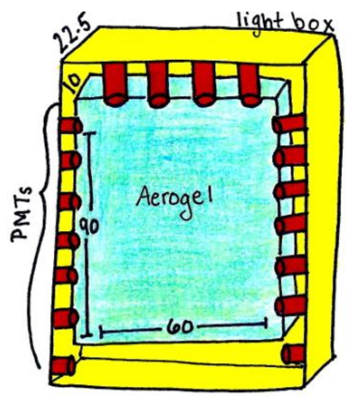
With the size and thickness of the Aerogel determined, the depth of the light box can also be decided. The key to optimum photoelectron collection is to actually decrease the surface area of the light box. This allows each of the PMTs to cover a greater percentage of the total Aerogel, and therefore provide more efficient photoelectron collection. The dimensions of the light box were also affected by the size limitation of the SHMS. With these two factors in mind, it was determined that the ideal depth for the light box was 22.5cm.

One of the most important steps in the process was also one of the most difficult: finding the optimum PMT configuration. Due once again to budget and size constraints, it was decided that PMTs with a radius of 5 inches are most suitable for this detector. Rigorous testing and computer modeling showed that the most ideal possible configuration was 6 PMTs placed on each of the wide sides of the light box and 4 placed along the top wall. This arrangement ensures the best collection of photoelectrons, and accommodates the previously optimized data for the dimensions of both the light box and the Aerogel panel. However, one additional PMT will be placed on each of the sidewalls to accommodate a larger Aerogel panel, should the team need a larger scintillator surface for further experiments.

In order to test some of the components for the Cherenkov detector, the team set up a small-scale experiment in the lab at the physics lab at CUA to count muons. Muons are leptons, but interact with scintillators in much the same way kaons do. In this experiment, two small scintillator panels are placed in a dark box (see Figures 2 and 3, Appendix). Each scintillator is attached to a PMT. The PMTs send separate signals to a series of analyzing equipment, where the signals go through a delay cable system, ensuring that the signals from each of the scintillators reaches the equipment at the same time. Only signals that are stronger than a certain threshold are allowed to enter a Coincidence Logic Unit. When a muon passes through both of the scintillator panels simultaneously, and the signals from each of the PMTs fire at the same time, the logic unit records what is called a coincidence. For each coincidence a counting device counts a muon "event," signaling that a muon has passed through both scintillators. The signals from the PMTs are also displayed on an oscilloscope, which displays the signals as an analogue wave. This data is then compared to the known average muon rate and if the two sets of data match, the team knows their equipment is functioning properly.

At this stage in the project there is little conceptual work left to do. From here it is necessary to draw the schematic diagrams so that the construction process can commence. Acquiring the materials for building the detector has proved a challenge in itself. Each PMT costs over $3,000 (hence the team's mantra of "Don't drop it!"[xix]). The team has two possible sources for the PMTs: Hamamatsu from Japan and Electron Tubes in the United Kingdom. There is a third option to procure second hand Photonis brand PMTs form Jefferson Lab or the Bates lab at Massachusetts Institute of Technology (MIT). The required amount of Aerogel could cost as much as $300,000 from Panasonic, the world's leading provider of large quantities of optically translucent Aerogel material. However, there may also be opportunity to use a panel of second hand Aerogel from MIT. Aerogel typically does not deteriorate with age, but it is vital to ensure that the older material does not show signs of wear. If the team is able to use the Aerogel panels from MIT, they may be able to purchase a third panel from Panasonic, giving the detector a wider range of indices. In the fall of 2010 Dr. Horn received a grant from the National Science Foundation of nearly $500,000 for the project. This will be just enough to cover the costs of construction and installation in the SHMS at Jefferson Lab. The project's projected completion timeline puts the team on track to install the detector following the completion of the 12 GeV upgrade at Jefferson Lab in 2014. Most detectors of this complexity and sensitivity take years to design and build. This kaon detector will take only 24 months.

Aerogel Kaon Cherenkov Detector



[xx]

The questions that are inevitably asked of all research scientists are, “What is this good for? What does it do? So what?” In the case of the kaon experiment at Jefferson Lab, a better understanding and model of the proton may lead to critical advances several fields. Methods of proton radiation therapy for treating cancer may become more precise in targeting and terminating tumor cells. Innovations in material sciences, engineering and chemistry based on a new understanding of the proton’s substructure may lead to the production more cost and energy efficient materials.

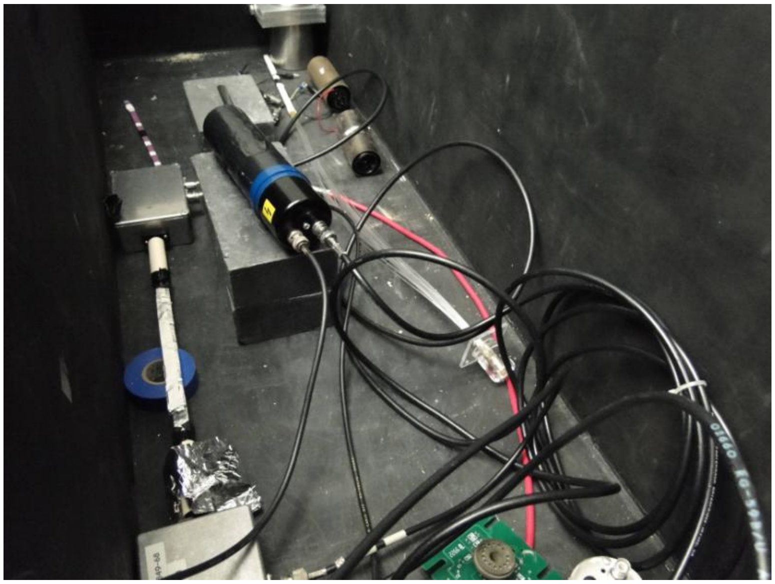
The biggest payoff, however, is a better understanding of matter and the force that binds the smallest of particles together. The data Dr. Horn and her team will be able to gather using their Aerogel Cherenkov Kaon Detector may hold the key to calculating the substructure of the proton. That is truly exciting.

APPENDIX

Figure 1

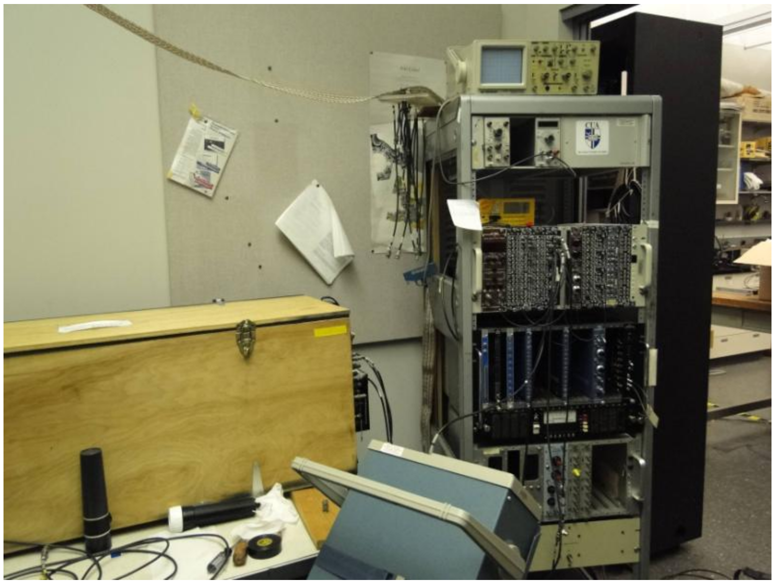
Photomultiplier Tube and scintillator panel in the lab at CUA
Photo credit: Dr. Tanja Horn, January 4, 2011

Figure 2



Scintillator panels and Photomultiplier Tubes in the dark box for muon counting experiment
Photo credit: Dr. Tanja Horn, January 4, 2011

Figure 3



Dark box, oscilloscope and analyzing equipment for muon counting experiment in the lab at CUA
Photo credit: Dr. Tanja Horn, January 4, 2011

NOTES

[i] Author's illustration

[ii]Author's illustration

[iii] Author's illustration

[iv] John L. Heilbron, *The Oxford Guide to the History of Physics and Astronomy* (New York, NY: Oxford University Press, 2005), p. 272

[v] Nathaniel Hlavin, "Computational Design for Aerogel Kaon Cherenkov Detector" (unpublished paper, Catholic University of America, Washington DC, August 2010) p. 2

[vi] Heilbron, p. 272

[vii] Tanja Horn, interview with author, January 4, 2011

[viii] Author's illustration

[ix] L. Canton, et al. "Three-Nucleon Portrait with Pion." *Cornell University Library,* (2001) arXiv:nucl-th/0103024v1

[x] T. Horn, et al. "Determination of the Pion Charge Form Factor at $Q^2 = 1.60$ and 2.45 $(GeV/c)^2$." *Physical Review Letters* vol. 97, no. 19 (2006): 192001

[xi] Author's illustration, based on figure from: Nathaniel Hlavin, "Computational Design for Aerogel Kaon Cherenkov Detector" p. 2

[xii] Nathaniel Hlavin, interview with the author, January 4

[xiii] Tanja Horn, "Factorization of short- and long-range Interaction in Charged Pion Production" (colloquium, The Catholic University of America, Washington DC, September 28, 2008).

[xiv] Thomas Jefferson National Accelerator Facility, "Accelerator Science," updated 6 December 2010, <http://www.jlab.org/accelphys.html> (cited January 5, 2011), para 1

[xv] Tanja Horn, interview with author, January 4, 2011

[xvi] Author's illustration

[xvii] C.R. Nave, "Index of Refraction," updated 2005, <http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/refr.html>, (cited January 5, 2011), para 1

[xviii] Figure from: N. Hlavin, S. Rowe, "Kaon Aerogel Cherenkov Detector," (presentation, The Catholic University of America, Washington DC, August 5, 2010)

[xix] Tanja Horn, interview with the author, January 4, 2011

[xx] Author's illustration

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