University of Richmond Sabbatical Report

G.P. Gilfoyle

This report describes the goals, work, and accomplishments of Dr. Gerard P Gilfoyle during his sabbatical year (fall 2022 - spring, 2023) spent at the Thomas Jefferson National Accelerator Facility (known as Jefferson Lab or JLab) in Newport News, Va. Dr. Gilfoyle's research at JLab is focused on uncovering the fundamental nature of matter in the Universe. We know that everyday matter is composed of atoms which have a small, dense nucleus surrounded by a cloud of very light electrons. The nucleus itself is made of heavy particles - proton and neutrons (known collectively as nucleons) that account for nearly all of the matter we see around us. However, when we delve deeper into the nucleus and the nucleons the picture is cloudier. In each nucleon we see a trio of small, light, point-like objects called quarks held together by a force, called the strong force. We even have a theory to describe the strong force (quantum chromodynamics or QCD), but it cannot yet be solved under the conditions existing in nucleons and nuclei. This trio of quarks, called valence quarks, form part of the substructure of the nucleon, but oddly only carry about 1% of the mass of the nucleon. Most of that mass arises from the strong force that binds the particles together. That force is transmitted by other particles called gluons and these gluons pack a huge amount of energy in a tiny nucleon. If there is a lot of energy, then Einstein's famous equation $E = mc^2$ tells us there will be mass. There is so much energy in the nucleon that it creates about 99% of the nucleon mass. Mass may not be a fundamental property of matter, but rather an 'emergent' property, that arises as a product of the forces binding the quarks together - not the simple sum of the masses of the constituents. At this early stage we are realizing the nucleon interior consists of a dense soup of quarks and gluons that pop in and out of existence moving at high speeds (close to the speed of light) forming and reforming different combinations of matter.

This is where JLab comes in. Its mile-long, racetrack-shaped accelerator (known by its acronym CEBAF) is like a huge electron microscope that illuminates the interior of the nucleus. It is used to generate high-energy electron beams ($E_{beam} = 12$ GeV) that are the most precise in the world for a machine like this one. At four points around the perimeter of the accelerator are end stations holding large particle detectors optimized for different types of experiments. Dr. Gilfoyle is part of a large collaboration (about 200 physicists) that operates and maintains one of the large particle detectors in Hall B at JLab called CLAS12. CLAS12 is a large (about four stories high) machine built to detect and track the debris from collisions of the electron beam with a variety of nuclear targets. The scattered particles leave electronic 'traces' of their passage in the CLAS12 subsystems that are gathered together and saved on disk for later analysis. The detector has more than 100,000 possible 'traces' or readouts and collects 20-30 terabytes of data per day when running. Those raw data are processed to reconstruct the properties of each track created in a collision using a large computational 'farm' at JLab and sophisticated computer algorithms including artificial intelligence. With all this high technology we hope to understand atomic nuclei at a deeper level in terms of the fundamental components of the protons and neutrons - the quarks and gluons.

The goals of Dr. Gilfoyle's sabbatical are (1) the analysis of a measurement of the properties of the magnetism and the electric currents in the neutron and (2) the continued development, testing, and validating of software for CLAS12 data reconstruction and analysis. Gilfoyle's work in nuclear physics has been supported by the US Department of Energy (Grant Contract Number DE-FG02-96ER40980) since 1990. For goal (1) Dr. Gilfoyle is part of a team analyzing data to extract the magnetic form factor of the neutron, a quantity known by its mathematical symbol as G_M^n which describes the distribution of magnetism in the neutron. For goal (2) Gilfoyle's team of University of Richmond undergraduates and masters students from the University of Surrey continues to work with JLab scientific staff to validate and improve the CLAS12 software.

One of Jefferson Lab's main goals is to unravel the quark-gluon structure of nuclei. The ratio, R, of electron-neutron $(e-n)$ to electron-proton $(e-p)$ scattering on deuterium is being used to probe G_M^n. A high energy electron beam from the JLab accelerator strikes a cold, liquid deuterium target which consists of a single proton and single neutron. Events are selected where the scattering is elastic, *i.e.*, the kinetic energy is conserved so no energy is lost in the interaction. This collision is a bit like playing pool with tiny, tiny billiard balls. From the data the size and strength of the magnetic interaction in the neutron and how it varies with a quantity called Q^2 is extracted. This Q^2 measures the violence of the collisions (nearly head-on collisions are more forceful than more distant, glancing ones). There is a broad program at JLab to measure G_M^n and similar observables for both the electric and magnetic properties for both the proton and neutron. These results will be a key challenge to theoretical physicists building the models and mathematics to accurately describe the strong force and the quark-gluon structure of the nucleon.

The analysis and calibration of the G_M^n experiment is well advanced. Gilfoyle is a member of the CLAS Collaboration (about 200 physicists) and is working closely with Dr. Brian Raue and Lamya Baashen in the nuclear physics group at Florida International University (FIU). The measurement (JLab experiment E12-07-104) is based on a proposal approved by the JLab Program Advisory Committee (PAC). The PAC is responsible for evaluating, approving and guiding the physics program at JLab. Gilfoyle was the lead author of the original proposal. Data collection began in 2019 and finished in 2020 using CLAS12.

The key steps in the analysis are described here. (1) Elastic events have to be selected from a large inelastic background where a significant amount of energy is left in the residual nucleus. To do this task protons and neutrons are detected in CLAS12 at forward angles relative to the incoming electron beam $\theta < 35^\circ$. Elastic scattering is assumed and with the conservation laws, the momenta of the scattered electron and nucleon can be used to calculate the precisely known electron beam energy in different ways with multiple combinations of angles and momenta. Two-dimensional plots are created of these combinations of angles and momenta to see and separate the elastic events. However, an inelastic background is still visible. (2) To filter out this inelastic background, the angle θ_{pq} between the direction of the momentum transferred to the nucleon by the electron beam and and the direction of detected nucleon is extracted. Elastic nucleons will be emitted with a small θ_{pq}, *i.e.* in the same direction as the electron momentum 'kick' applied to the nucleon by the scattered electron. For $\theta_{pq} < 2.5^\circ$ a dramatic drop in the inelastic background is seen for both $e-n$ and $e-p$ events. The distribution of the recoil mass W also shows a clear peak close to the expected nucleon mass for both $e-n$ and $e-p$ events which validates this procedure. (3) Acceptance matching is applied to each event to ensure the angular range in CLAS12 for detecting $e-n$ and $e-p$ events is the same. For each event elastic scattering is assumed and the trajectory of the nucleon through CLAS12 is calculated. Both trajectories are required to strike the active region of the detector. If either nucleon misses, the event is skipped.

There are still corrections to the ratio R required before the final extraction of G_M^n is complete. The most important is the neutron detection efficiency (NDE) to correct the measured $e - n$ yield. It is one of the largest components of the systematic uncertainty of G_M^n. Comparison of past measurements at different laboratories reveals considerable tension among those experiments possibly due to variations in detector performance and efficiency. To measure the neutron detection efficiency a proton (not deuterium) target is used (cold, liquid hydrogen instead of liquid deuterium). A reaction is selected which produces a scattered electron, a neutron, and a particle called a pion in CLAS12. The momentum of the scattered electron and pion are measured which, again using the conservation laws, enable one to predict where the neutron should be detected in CLAS12. This reaction is a source of 'tagged' neutrons where we can determine the momentum of the neutron. These neutrons are then detected in CLAS12 and the efficiency can be inferred. This work holds the potential to push the measurement of the NDE to a high neutron momentum which will double the current upper limit on precise measurements of G_M^n.

Some of these NDE results and a study of simulations of the NDE reaction were the subject of two University of Richmond undergraduate posters presented at the fall, 2022 Division of Nuclear Physics (DNP) meeting (Ryan Sanford and Jessie Hess respectively). More work on extracting the G_M^n ratio and the NDE was presented by Lamya Baashen of FIU in a contributed talk at the DNP meeting. Gilfoyle has presented this work to informal graduate student groups at JLab and also at a recent collaboration meeting for the group making some of the other similar measurements at JLab.

For goal (2) the software work is coordinated with the JLab staff. A joint program exists between the University of Richmond and the University of Surrey in the UK to support a masters students for ten months using Gilfoyle's Department of Energy grant. The Surrey students are required to engage in a significant research year as part of their degree requirements. DOE funding supported these students who are stationed at JLab.

Surrey masters student Rocco Monteiro was stationed at JLab in 2022 and worked on testing the performance of algorithms to separate good events from background data in CLAS12. When large beam currents are incident on the target a shower of stray particles can be produced as the beam passes through the entrance and exit windows of the volume holding the liquid hydrogen or deuterium targets. These stray particles create random, background, 'hits' in CLAS12 that make identifying the 'true' tracks more difficult. Mr. Monteiro studied how the implementation of constraints on track candidate parameters in CLAS12 effected the software reconstruction performance. It proved to be useful for the reduction of fake tracks and the improvement of the reconstruction efficiency in the Central Detector at high beam currents. He presented his work at the fall, 2022 DNP meeting.

The expected electron beam currents in CLAS12 have been achieved, but the efficiency of the software reconstruction is about 15-20% lower than expected. This effect is due to background hits in some of CLAS12 subsystems that are close to the target. Adding another, specialized, fast detector layer will help to reject these background hits, and isolate correct hits on a track. A Micro Pattern Gaseous Detector (MPGD) is being studied using μRWELL technology research and development for a large area, lightweight device is underway. Gilfoyle has started work on developing the simulation of the electronic readout of the detector. The CLAS12, physics-based simulation code called *gemc* has been built on one of the computers in the Richmond nuclear physics lab and the existing code with the initial simulation of the μRWELL is being tested to understand the performance parameters (like the propagation velocity of a strip). One of the choices for the electronic readout is a VMM3 chip. A simulation of the pulse shape of the signal in the VMM3 has been written and tested in *gemc*.