# Sabbatical Proposal

G. P. Gilfoyle
Physics Department, University of Richmond
phone:804-289-8255, email: ggilfoyl@richmond.edu

The nuclear physics program at the University of Richmond is focused on the structure of matter and the transition from the hadronic picture of matter (atomic nuclei viewed as composed of protons and neutrons) to a more fundamental description in terms of quarks and gluons. We use the Thomas Jefferson National Accelerator Facility (JLab) in Newport News, VA to measure the charge and current distributions of the neutron by scattering a high-energy electron beam off a nuclear (deuterium) target. We are using JLab like a powerful electron microscope. In particular, we will measure the distribution of electric current in the neutron - a quantity known as the neutron magnetic form factor or by its mathematical symbol $G_M^n$. In JLab experiment E12-07-104 (spokesperson: Gilfoyle) we have collected data to measure $G_M^n$ at high $Q^2$ where $Q^2$ is the size of the momentum 'kick' imparted to the target by the electron beam. The higher the $Q^2$ the smaller the size of features we can image with the electron beam. We 'image' the neutron interior by extracting the properties (energy and momentum) of the debris from the collisions of the electron beam with the deuterium target. We are part of a large collaboration working to reconstruct, analyze, and simulate data from these experiments and many others from the CLAS12 detector housed in Hall B at JLab. The CLAS12 detector is a large (30-feet high) particle detector that records the passage of sub-atomic particles after the collisions. We typically collect about 30-40 terabytes of data per day during experiments (30,000 - 40,000 gigabytes). We have made a preliminary measurement of the CLAS12 neutron detection efficiency needed to precisely determine $G_M^n$ from the recent deuterium runs. We have also continued our work to develop and enhance the software tools used in our collaboration.

This is a sabbatical proposal to support the University of Richmond electromagnetic nuclear physics research program at JLab using the CLAS12 detector in Hall B. Dr. G.P. Gilfoyle is the principle investigator (PI) and full member of the CLAS Collaboration which operates CLAS12. The CLAS Collaboration is an organization consisting of about two hundred physicists from 43 institutions in 14 countries with the purpose to operate and maintain the CLAS12 detector and carry out its physics program. The PI's physics projects are listed in Table 1. The Richmond group has a joint program with the University of Surrey in the UK to support a masters student to do research at JLab. The group typically consists of the PI, 2-3 University of Richmond undergraduates, and a Surrey masters student. During sabbatical the PI will be stationed at JLab to take full advantage of the facilities and collaborators.

| Title | Label |
|---|---|
| Measurement of the Neutron Magnetic Form Factor at High $Q^2$ Using the Ratio Method on Deuterium (Gilfoyle: spokesperson and contact person) | E12-07-104 |
| CLAS12 Software | |
| Quark Propagation and Hadron Formation (Gilfoyle: co-spokesperson) | E12-06-117 |
| Precision measurement of the neutron magnetic form factor up to $Q^2 = 18\ (GeV/c)^2$ by the ratio method (different JLab collaboration) | E12-09-019 |

Table 1: Summary of physics projects of the Richmond group.

Our major focus now is on analysis of CLAS12 data collected recently to measure $G_M^n$, the magnetic form factor of the neutron. We are part of a broad program at JLab to measure the elastic, electromagnetic form factors consisting of seven experiments including two to measure $G_M^n$. The PI (Gilfoyle) is spokesperson and contact person for the CLAS12 $G_M^n$ experiment (JLab Experiment E12-07-104) and is a collaborator on the Hall A $G_M^n$ measurement (JLab experiment E12-09-019). Both experiments use methods pioneered in Hall B with the previous detector CLAS6 [1]. The PI is one of the lead authors on that work.

Our measurement uses the ratio of $e-n$ to $e-p$ scattering from a deuterium target to extract $G_M^n$. Deuterium is used as the target because it contains a single neutron and proton. We have completed the first round of deuterium runs as part of Run Group B in Hall B and accumulated 39 days of beamtime out of the 90 days approved for the Run Group over three time periods. We collected 43 billion triggers at three beam energies (10.2, 10.4, and 10.6 GeV). Initial calibration and analysis of the data sets are complete. The PI was run coordinator for the spring, 2019 and winter, 2020 run periods (total of 18 days). The run coordinator is responsible for the day-to-day operation of CLAS12 during data collection and to see that the physics program is fulfilled. The RC is also responsible for coordinating the CLAS12 operations with the JLab accelerator management and other JLab operations. The $G_M^n$ analysis is moving forward with the development of event selection criteria for the $e-n$ and $e-p$ events used in the ratio. Analysis projects like these at JLab typically take years to complete. Here, we have collaborated with Dr. B.Raue from Florida International University (FIU) and his doctoral student Ms. L. Baashen.

An essential quantity in our analysis is the neutron detection efficiency (NDE) to provide an accurate measure of the number of $e-n$ events. We rely on data from electron scattering on a hydrogen target to determine the NDE. Neutrons are electrically neutral and harder to detect than other, charged particles like protons. The NDE corrects for these missing neutrons in the $e-n/e-p$ ratio. We use the $^1\mathrm{H(e, e'\pi^+)n}$ nuclear reaction as a source of tagged neutrons and have extracted the NDE. Our preliminary results are the topic of a contributed talk at the fall, 2020 APS Division of Nuclear Physics (DNP) meeting [2]. The precision of our results at high neutron momentum (corresponding to high $Q^2$) is encouraging [2].

We also continued our commitment to develop software for the simulation, reconstruction, and analysis of CLAS12 data. We used codes written by two former Richmond undergraduates (K.Sherman and A.Balsamo) to extract the $G_M^n$ ratio from deuterium data and to determine the NDE from the hydrogen data. The codes were originally tested and validated using the physics-based simulation of the CLAS12 detector called *gemc*. Accurate simulations are an essential tool for the design and analysis of data from large particle detectors. The *gemc* simulation uses the same software 'factory' now used in proton beam cancer treatments. Both codes have been used successfully in the current $G_M^n$ analysis [3, 4, 5]. We also updated and expanded reconstruction software tests used to ensure consistent results from the code [6, 7] and determined the resolution of the reconstruction software in simulation [8].

During this sabbatical the PI will continue the collaboration with FIU and complete the analysis of the $G_M^n$ data and contribute to the software effort for CLAS12. The PI's sabbatical will occur during the later stages of the $G_M^n$ analysis so he will be well-positioned to contribute to that work. We have developed simulations to study ways to optimize the analysis, *e.g.* reduce neutral backgrounds and increase the signal size. We have just begun to study methods for *in situ* monitoring of the NDE using tagged neutrons from reactions like $^2\mathrm{H}(e, e'np)$ and others. We will continue our contributions to the CLAS12 software development coordinating our work with Dr. V.Ziegler who is the lead developer for the CLAS12 reconstruction code.

# 1 References


[1] J. Lachniet, A. Afanasev, H. Arenhövel, W. K. Brooks, G. P. Gilfoyle, D. Higinbotham, S. Jeschonnek, B. Quinn, M. F. Vineyard, et al. Precise Measurement of the Neutron Magnetic Form Factor $G_M^n$ in the Few-GeV$^2$ Region. *Phys. Rev. Lett.*, 102(19):192001, 2009.

[2] L. Baashen, B. Raue, C. Smith, and G.P. Gilfoyle. Measurement of the Neutron Magnetic Form Factor at High Q2 Using the Ratio Method on the Deuteron. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2020. EL.00006.

[3] K. Sherman and G.P. Gilfoyle. Study of the Neutron Detection Efficiency for the CLAS12 Detector. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2015. EA.00122.

[4] K. Sherman and G.P. Gilfoyle. Measuring the Neutron Detection Efficiency in CLAS12. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2016. EA.00047.

[5] Balsamo A., K. Sherman, and G.P. Gilfoyle. 'Analysis of Quasi-Elastic e-n and e-p Scattering from Deuterium. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2017. EA.00032.

[6] M. Armstrong, V. Ziegler, and G.P. Gilfoyle. Clas12 drift chamber reconstruction software unit test. CLAS12-Note 2020-02, Jefferson Lab, 2020. `https://misportal.jlab.org/mis/physics/clas12/viewFile.cfm/2020-002.pdf?documentId=67`.

[7] Armstrong M., V. Ziegler, and G.P. Gilfoyle. CLAS12 Drift Chamber Reconstruction Code Validation. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2019. HA.00075.

[8] A. Saina, V. Ziegler, and G.P. Gilfoyle. The CLAS12 Reconstruction Resolution. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2020. PA.00017.